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Cadmium Sulfide Quantum Dot Particles (CdSQD) Dispersed in Poly Methyl Methacrylate as an Effective Gamma Counter for the Scintillation Detector

[1, 4] Askari Mohammad Bagher, [2] Beheshti - Marnani Amir Khosro, [3] Mirzaei Mahmoud Abadi Vahid, [1] Seifi Majid, [1] Tavakoli Banizi Zoha, [3] Hosseini Ranjbar Abbas and [5] Batool Tahamipour

[1] Department of Physics, University of Guilan, Rasht 41335-1914, Iran
[2] Department of Chemistry, Payame Noor University, Tehran, Iran
[3] Faculty of Physics, Shahid Bahonar University of Kerman, Kerman, Iran
[4] Department of Physics, Payame Noor University, Tehran, Iran
[5] Young Researchers and Elite Club, Sirjan Branch, Islamic Azad University, Sirjan, Iran
[2] Tel.: +989132985611
E-mail: Beheshti@pnu.ac.ir

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Abstract: The synthetic material, cadmium sulfide quantum dot particles (CdSQD), using a hydrothermal method was dispersed in poly methyl methacrylate (PMM) polymer. In order to study the synthesized quantum dot particles, X-ray diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) techniques were applied. Transmission electron microscopy (TEM) and *scanning electron microscopy* (SEM) images were also used to study the surface morphology of synthetic quantum dot particles. Energy-dispersive X-ray spectroscopy (EDX) test was done for identification of constituent percent of prepared material. Optical properties of CdSQD particles were evaluated by UV-visible and photoluminescence spectroscopy (PL). Finally the capability of CdSQD particles dispersed in poly methyl methacrylate (CdSQD@PMM) as a scintillator material was investigated by photomultiplier tube (PMT) test. The result of PMT test along with statistical studies showed that the CdSQD@PMM can be applied as a crystalline promising material in the field of inorganic scintillator detectors regarding to the efficiency and economic aspects.

Keywords: Scintillation detector, Gamma counter, CdS quantum dot particles, Poly methyl methacrylate, PMT test.

1. Introduction

Scintillator detectors are widely used in various sciences such as nuclear physics and analytical chemistry [1, 3]. They have three main parts [4]: the scintillator crystalline which absorbs the high energy radiations (such as gamma and X-rays) and converts them to a the visible photons [5], the photo multiplier device that is responsible for conversion of the visible photons to electrons and for their multiplication, and the output electrons that are converted to an electronic signal and counted by an electronic circuit. The most important feature of the detector is its rough proportionality of the number of produced photons to the energy of in-coming radiation. Typically, it has a high sensitivity to the wavelengths less than 2 Å [6-7].

The florescent materials can also absorb the energy of radiation and convert it to photons in a few microseconds [8-9]. These kinds of materials are widely used in the scintillation devices [10]. A most required feature of the material is their transparency to the out-coming photons [11]. Inorganic scintillators such as LiI(Tl) [12] and CsI(Tl) [13] are the most suitable transparent crystals. On the other hand, the organic scintillators in comparison to the inorganic ones have generally low transparency [14].

In the current work considering both critical features of the scintillator crystals, photoluminescence and transparency, poly methyl methacrylate (PMM) dispersed with fluorescent quantum dot particles of cadmium sulfide (CdSQD@PMM) [15-16] have been studied. The structure and photo properties of the quantum dot particles and capability of hybrid preparation as scintillation applications were investigated by XRD, FTIR, SEM, TEM, EDX and PMT test. In addition, it is expected that the synthetic hybrid, CdSQD@PMM, possesses the appropriate flexibility with anti humidity properties due to its organic nature of the polymer. The softness and flexibility of the hybrid can also help toleration against shocks and vibrations. Finally, the results of PMT test evaluated by meaningfulness statistical parameters (T and Chi-squared) proved the promising application of the synthetic hybrid as an economic and effective materials in comparison to the expensive trade devices.

2. Materials and Methods

The cadmium sulfate octa hydrate (CdS.8H2O) and thioglycolic acid (TGA) were obtained from Merck. Poly methyl methacrylate and Dimethyl formamid (DMF) as the polymer solvent, were purchased from Sigma Aldrich.

3. Synthesis of CdS Quantum Dot Particles (CdSQD)

About 50 μl of TGA was added to 0.01 molar solution of cadmium sulfate. It was agitated for 10 minutes then after continuing with adding drop wise of sodium sulphid of 0.01 molar and stirred for another 10 minutes. The prepared solution was transferred to a stainless steel autoclave and exposed to 140 °C for 30 minutes through the hydrothermal condition. The obtained precipitate was centrifuged and washed with deionized water and ethanol for three times. Finally the product was dried in an oven at 60 °C for 6 hours.

4. Preparation of CdSQD@PMM

About 0.005 gr of poly methyl methacrylate powder was dissolved in 3 milliliters of DMF and then 0.001 g of the prepared CdSQD particles was added to the mixture. The prepared gel was sonicated for 15 minutes. The obtained hybrid was dried in an oven at 40 °C for 6 hours.

5. Characterization of Synthetic Hybrid

To study of structural features of the prepared material, X-ray diffraction (XRD) and FTIR spectra of prepared CdSQD were obtained. Field emission SEM (FESEM) and TEM images were also obtained for confirmation of synthesis of quantum dot CdS. EDX analysis also endorsed the composition of constituents of synthetic CdSQD. In order to study the energy level of the defects on the surface and interface of the materials, the photoluminescence properties of prepared CdSQD was observed.

6. Results and Discussion

6.1. XRD Characterization of CdSQD

The XRD spectrum of quantum dot CdS particles is shown in Fig. 1. As can be seen, the peak at 2θ=25.8, 43.2 and 51.3 appeared can be related to crystalline plates (111), (220) and (311) of cubic phase of CdSQD particles. The average size of the crystalline particles was calculated with the Scherrer equation (Eq. (1) [17].

$$D = \frac{0.9\lambda}{\beta COS\,\theta}, \tag{1}$$

where D is the size of particles; β is the full width at half maximum in radian wavelength of Cu-Kα radiation. The value D for CdSQD was obtained to be 3.9 nm.

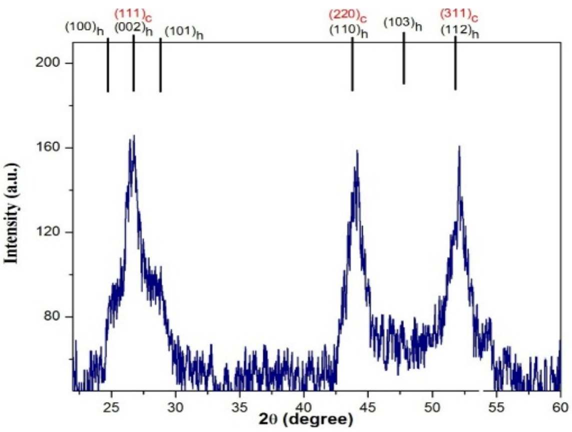

Fig. 1. XRD spectrum of CdSQD.

6.2. FTIR Characterization of CdSQD

The spectrum of CdSQD particles is shown in Fig. 2. The strong bands were seen in 1005, 1130, 1616 and 3412 cm^{-1} and weak bands at 606, 1377, 650 and 1565 cm^{-1}. The broad band at 3912 cm^{-1} represents the stretching vibration related to OH groups of water molecule. The very weak band at 2930 cm^{-1} also indicates the vibration stretching of CH bond which may be considered as the residual of organic reagents used in synthesis process. The small band seen at 541 cm^{-1} can be related to S-S bonds.

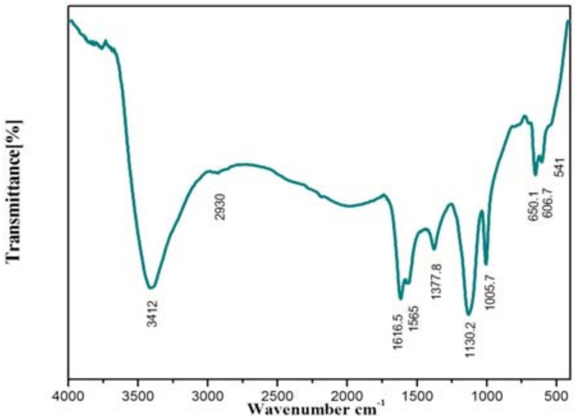

Fig. 2. FTIR spectrum of CdSQD.

6.3. Morphological and Elemental Analysis Studies

In order to study the morphological of CdSQD particles, FESEM and TEM images were obtained. Fig. 3 shows the TEM images of spherical shape of CdS quantum dot particles which obviously depends on the size of particles less than 10 nm. FESEM image of CdSQD is shown in Fig. 4. It suggests the homogeneity of synthetic particles with the lowest impurity and amorphous phases.

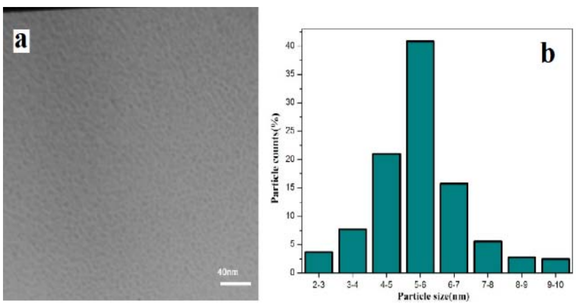

Fig. 3. (a) The TEM image of CdS nanoparticles,
(b) Particle size distribution histogram.

Elemental analysis was also done using EDX. As it is shown in Fig. 5, the existence of cadmium and sulphur is being confirmed in the synthetic CdSQD.

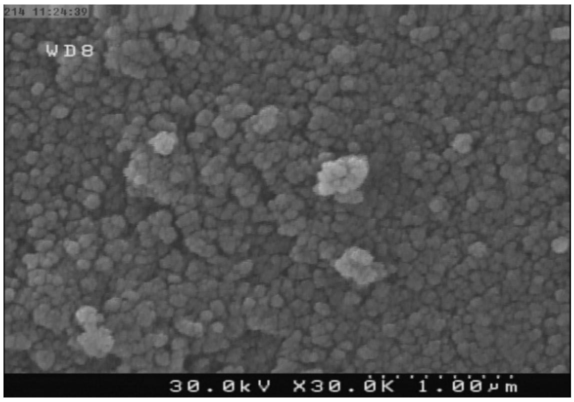

Fig. 4. FESEM image of CdSQD.

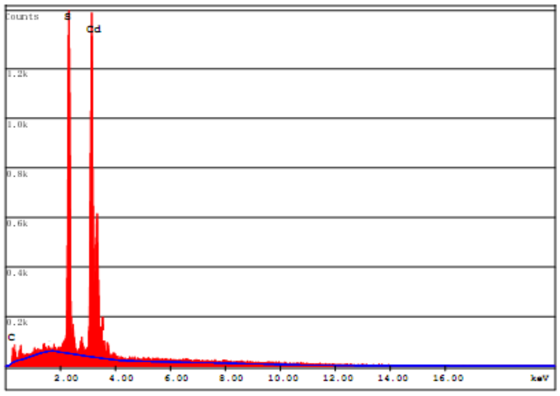

Fig. 5. EDX spectrum of elemental analysis of CdSQD.

6.4. Study of Photoluminescence (PL) Properties of Synthetic CdSQD

The photoluminescence properties of CdSQD particles was investigated by an exciting 380 nm radiation at room temperature. The prepared material showed a broad emission spectrum in the range of 450 to 620 nm. According to the spectrum (Fig. 6) three individual peaks are seen: the weak peaks are considered as the blue emission and the strong one is considered as the green–yellow emission at maximum of 556 nm.

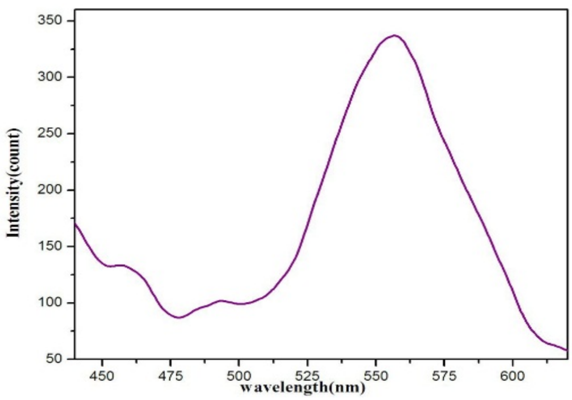

Fig. 6. Photoluminescence spectra of CdSQD particles.

As can be seen the PL spectrum of CdSQD particles consists of two parts: the first one is in the range of 420-500 nm which is referred to the band edge emission and the second part is range 530-620 nm which is referred to the surface defect emission.

7. Photomultiplier Tube (PMT) Experiments

All the tests were done in room temperature by ^{60}Co source in a few second ranges with the set up shown in Fig 7. The CdSQD@PMM hybrid that was uniformly covered on a glass slide, placed exactly between the ^{60}Co source as the gamma emitter and the PMT input slit. The counts of released photons were recorded 8 times in absence of the hybrid CdSQD and in the presence of the hybrid where the counts reached to the constant value. Fig. 7 shows the diagram of PMT test.

Fig. 7. The setup of the PMT test.

As illustrated in curve Fig. 8(b) they obtained spectrum shows a peak at channel 793 with 28402 counts in absence of CdSQD@PMM. Regard to impermeability of the PMT chamber relative to external radiations, the existence of this peak could be related to electron generation resulted from gamma beam.

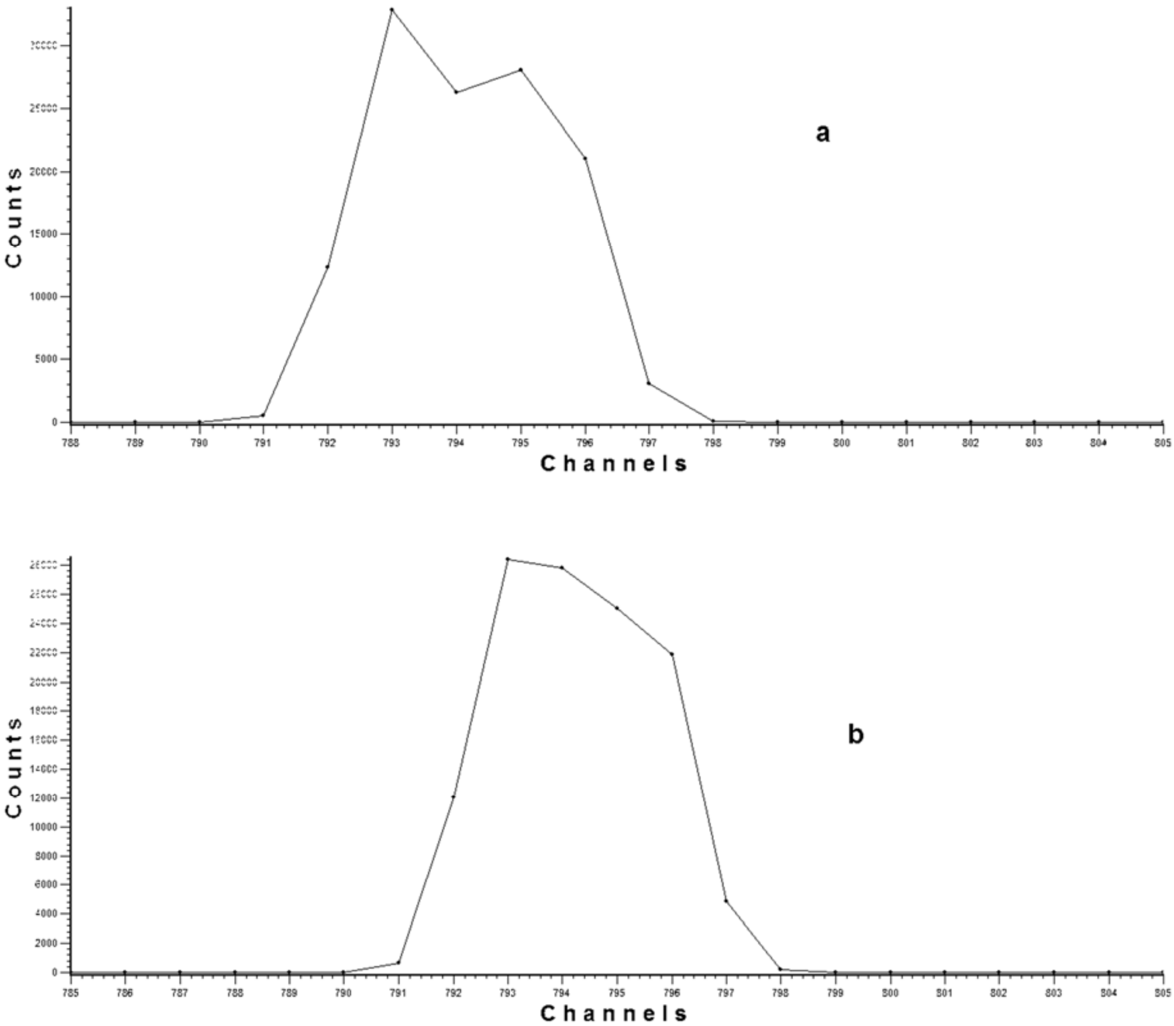

Fig. 8. The PMT spectrum of (a) in presence, (b) in absence of CdSQD@PMM.

In the Fig. 8 (a) in addition to similar peak observed in curve b, there is another peak at channel 795 with count 28048. The mentioned peak can be due to electron generation resulted from visible photons that originated from gamma photon discharge in CdSQD@PMM structure.

8. The Meaningful Tests of T and Chi-squared

Considering the lack of systematic error (null hypothesis, H_0), the meaningful tests, T test and chi-squared test were used to compare the averages of data and the meaningfully of frequency of data distribution, respectively [18-20]. As the source of the data presented in Table 1 are the same, the Eq. (2) was used for the T test.

$$t = \frac{(\overline{\chi_1} - \overline{\chi_2})}{S_{pooled}\sqrt{\frac{1}{N_1} - \frac{1}{N_2}}}, \quad (2)$$

$$S_{pooled}{}^2 = \frac{(N_1 - 1){S_1}^2 + (N_2 - 1){S_2}^2}{N_1 + N_2 - 2}, \quad (3)$$

where the $\overline{\chi_1}$ and $\overline{\chi_2}$ are the averages of the column A and B of Table 1, respectively, N_1 and N_2 are the number of data of column A and B of Table 1, S_{pooled} represents the accumulated standard deviation which is calculated from Eq. (3) and S_1 and S_2 are the standard deviations of column A and B of Table 1, respectively.

Table 1. The data obtained from PMT test in 100 seconds at room temperature.

Number of tests	In the presence of the gamma source and in the absence of the hybrid	In the presence of the gamma source and the hybrid
1	120799	124147
2	119312	125272
3	121605	129704
4	121601	131838
5	121609	135236
6	121605	135686
7	121599	141664
8	121604	139785

The obtained T volume of 5.18 is obviously higher than the critical volume reported in 99 % confidence level (3.50) [18]. Thus, the difference between two averages due to the presence and absence of synthetic hybrid implies that the meaningfulness and orientating of scintillation process is beyond the random and unpredictable errors.

The Chi –square test was also applied to the data using Eq. (4). It was obtained to be 2133.36 which is much higher than the critical value of 14.07 in the references [18]. It shows the meaningfulness of the difference between the data obtained from the hydride exposed with gamma beam.

$$\chi^2 = \sum \frac{|O-E|^2}{E}, \quad (4)$$

where O is the observed frequency and E is the desired frequency (roughly the same volume for average).

9. Conclusions

The dispersion of quantum dot CdS particles in poly methyl methacrylate could emit significant amount of visible photon when interacting with gamma rays. This would be a good characteristic of scintillation process. The composition of CdSQD and poly methyl methacrylate is highly transparent to visible light which in turn decreases the self-absorption of produced photons and efficiency enhancement.

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