Inorganic Chemistry Communications 77 (2017) 55–58

Contents lists available at ScienceDirect

Inorganic Chemistry Communications

journal homepage: www.elsevier.com/locate/inoche

Short communication

Co-shielding of neutron and γ-ray with bismuth borate nanoparticles fabricated via a facile sol-gel method

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ARTICLE INFO

Article history:
Received 28 December 2016
Received in revised form 26 January 2017
Accepted 28 January 2017
Available online 1 February 2017

Keyword:
Radiation shielding
Nanoparticles
Bismuth borate
Sol-gel

ABSTRACT

Developing state-of-the-art materials for protecting human from unwanted ionizing radiations is urgent and significant for the rapid development of nuclear facilities. Here, bismuth borate nanoparticles have been fabricated via a facile sol-gel process. Characterization with X-ray diffraction, scanning electron microscopy, and transmission electron microscopy reveals that the product is composed of high-purity orthorhombic $Bi_6B_{10}O_{24}$ phase and exhibits a typical single crystal with the size ranging from 100 to 300 nm. The product has an excellent ability to jointly attenuate both neutron and γ-ray. This significant work provides a material with not only good radiation shielding but also other fascinating features, such as environment-friendly.

After the Fukushima nuclear accident, the potential risks of ionizing radiations (such as alpha, neutron and γ-ray) have drawn extensive attention across the whole world [1]. So the need for state-of-the-art materials that efficiently protects human from the unwanted radiations is growing. It asks for the materials with more multifunction than excellent radiation shielding [2]. Above all, a good ability to jointly attenuate both γ-ray and neutron is of vital importance due to the strongest penetrability and distinct characteristics among the various radiations [3]. Particularly, the weight and cost of material applied in aerospace should also be balanced [4]. Besides, the materials can bear mechanical loading and extreme conditions (such as high temperature) during use [2,3].

Due to nanometer effects, nanomaterials can effectively promote radiation shielding, such as γ-ray, neutron [2,3]. In general, high *Z* (atomic number) nanomaterials, such as lead, are found to enhance the collision with high energy photons and availably promote the attenuation of γ-ray [5]. And low *Z* (atomic number) nanomaterials, such as boron, display greater thermal neutron attenuation than their micron counterparts [6]. However, these types of materials only attenuate either neutron or γ-ray and cannot be applied to mixed radiations. In order to shield a mixed neutron and γ-ray, both low *Z* and high *Z* nanomaterials are generally blended as a composite [7]. Nevertheless, the large difference in the density of the two materials is a great negative factor for their compatibility and dispersion that degrades the integrated performance of composites [8]. Importantly, it is well-known that lead is detrimental to human health and environmental safety. Lead-free high *Z* materials, such as bismuth [9], have recently attracted scientific community for radiation shielding. Therefore, designing nanostructures that chemically bond low *Z* and lead-free high *Z* materials are very urgent and significant.

Recently, some bismuth borate compounds have been synthesized by solid state sintered reaction and sol-gel method [10,11]. However, the solid state sintered method need high sintering temperature and long sintering time that leads to the agglomeration of the particles and a wide range of particle size distribution. In contrast, the sol-gel method can promote raw materials to reach atomic level mixing, which reduces particle size of the material to micrometer or nanometer level. Meanwhile, the sintering temperature and time can be lowered significantly.

In this paper, H_3BO_3 and $Bi(NO_3)_3\cdot 5H_2O$ are used as reactant to prepare a bismuth borate by sol-gel method. In order to effectively disperse the reactant, complex agent with EDTA and citric acid is introduced. In addition, the products are determined via X-ray diffractometer (XRD), emission scanning electron microscopy (SEM) and transmission electron microscopy (TEM) technologies. Besides, the shielding properties of γ-ray and neutron for the product are examined. For comparison, the radiation shielding of a mixture with Bi_2O_3 and B_2O_3 that has the same molar mass with the product is also surveyed.

Bismuth borate nanoparticles have been fabricated by a facile sol-gel method, which was parallel to other sol-gel methods with minor modifications [10]. Typically, 2.42 g $Bi(NO)_3\cdot 5H_2O$ was dissolved in 10 ml 10% HNO_3, and then stoichiometric 1.46 g EDTA were added into the solution. Second, H_3BO_3 and citric acid were dissolved in 20 ml deionized water and was blended with the mixture obtained with the first step. Third, ammonia was used to adjust the pH (pH = 8– 9) of mixture

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http://dx.doi.org/10.1016/j.inoche.2017.01.034
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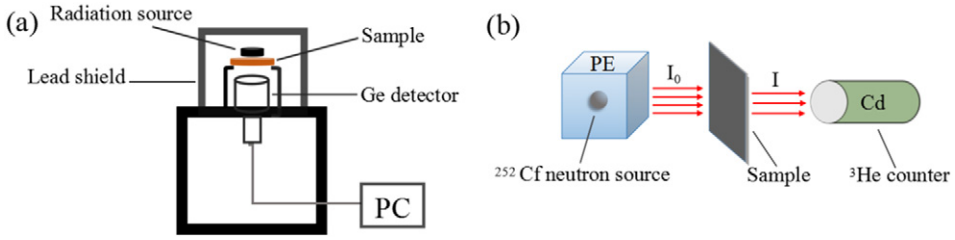

Fig. 1. Diagram of radiation shielding test, (a): γ-ray, (b): thermal neutron.

under continuous stirring until the mixture turned to clear sol through excess water evaporation at 80 °C for 6 h. After that, an obtained white sol was dried at 90 °C in an oven to obtain a light-gray xerogel and then was grinded into a powder. Finally, the powder was sintered at 600 °C for 4 h to produce the resulted product.

3 g as-prepared product was added into 20 ml xylene solution with 2 g polystyrene (PS) under fast stirring. Then, the mixture was poured into a circular mold with 4.5 cm diameter. After drying, the sample for radiation shielding testing was obtained. For comparison, another sample composed of Bi_2O_3 and B_2O_3 with an identical mole ratio of Bi and B to the product was also prepared according to the same method. Finally, the thickness of the samples is 2.5 mm.

The crystal structure of product was characterized employing X-ray diffractometer (PANalytical X'Pert PRO) with Cu Ka radiation (λ = 1.5418 Å), over the scanning range of 3–80°. Morphology observation was studied by field emission scanning electron microscopy (FESEM, Carl Zeiss Ultra 55) equipped with the system of EDS analysis. Besides, the product was ultrasonically dispersed in ethanol and deposited onto a carbon coated copper grid for transmission electron microscopy (TEM, Carl Zeiss Libra 200FE), selected area electron diffraction (SAED), high-resolution transmission electron microscopy (HRTEM) studies. Fig. 1 displays the diagram of radiation shielding test. The γ-ray shielding was determined using a high-purity germanium γ spectrometer with two γ-ray sources, including a mixed Eu-155 and Na-22 (E ~ 86 keV, 105 keV, 511 keV and 1274 keV) and Cs-137 (E ~ 661 keV). The attenuation parameters to γ-ray can be evaluated from mass attenuation coefficients (μ_m). The formula can be simply expressed [12]:

$$I_{(t)} = I_0 e^{-\mu_m \rho t}$$

where $I_{(t)}$ and I_0 are the dose of the penetrated and incident γ-ray by subtracting PS background, respectively. ρ is the volume density, and t is the thickness of the material. The ability to attenuate thermal neutron was carried out using ^{252}Cf neutron source at an energy of 0.025 eV. And a He-3 counter that was packed with cadmium at lateral was used to measure neutron counts. Neutron absorption of the sample can be expressed by the flux attenuation (I_0/I), where I and I_0 are the intensities of the transmitted and incident neutron.

Fig. 2 shows XRD patterns of the product. Clear diffraction peaks indicate the product is a well-crystallized structure. All the peaks can be readily indexed to the orthorhombic phase of $Bi_6B_{10}O_{24}$ (JCPDS file, no. 01-070-0154), with lattice constants of a = 6.5320 Å, b = 7.7330 Å and c = 18.5660 Å, and space group of Pnma. No peaks of other matter can be observed, indicating a high-purity orthorhombic $Bi_6B_{10}O_{24}$ has been gained. The sharp and strong peaks demonstrate that $Bi_6B_{10}O_{24}$ is a well-crystallized structure. XRD patterns suggest that the product is a kind of high-purity bismuth borates that are chemically bonded bismuth, boron as well as oxygen atoms as a compound under the sol-gel process.

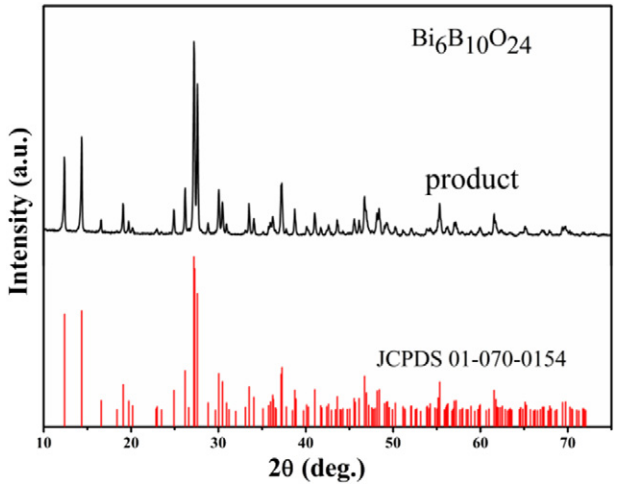

Fig. 2. X-ray diffraction patterns of the product.

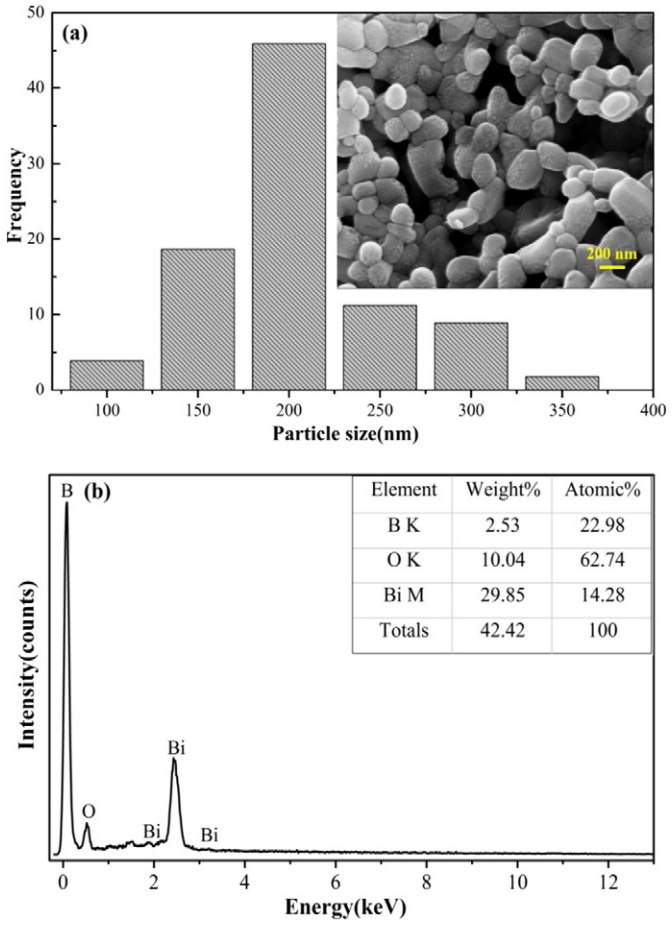

Fig. 3. SEM results and particle size distribution of the product, (a): morphology and particle size distribution (b): EDS elemental analysis.