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Preliminary investigation of polycarbonate-bismuth oxide composite as a sensitive volume of a dose-calibrator for beta-rays

Shahryar Malekie[a,*], Seyed Musa Safdari[b], Sedigheh Kashian[a], Morteza Akbari [b]

[a] *Radiation Application Research School, Nuclear Science and Technology Research Institute, P. O. Box 3148643111, Karaj, Iran*
[b] *Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran*

HIGHLIGHTS

- Polycarbonate/Bismuth Oxide nanocomposites was considered as a beta-ray dosimeter.
- Stopping power and range of electrons were calculated at various energies using ESTAR.
- The 50 wt% nanocomposite with thickness of 1 mm was fabricated.
- The sample was exposed to P-32 source with average energy of 695 keV in different activities.
- The response of the sample in the range of 4 to 6 mCi was linear.

ABSTRACT

Polycarbonate-bismuth oxide composite has been used as a beta-ray sensor in the previous works. Calculation of two main quantities namely stopping power and range of electrons in this material can be useful to evaluate the optimal thickness of the sensor. Thus, in this study, the range of electrons and stopping power of polycarbonate/bismuth oxide composite for several pure beta-emitters were estimated using the ESTAR program. Simulation findings indicated that the amount of concentration of the heavy metal oxide particles into the composite is an important factor to determine the range and stopping power of the electrons. Also, in the experimental phase, the response of the 50 wt% nanocomposite with thickness of 1 mm against the beta-rays of the P-32 source at the average energy of 695 keV in different activities was measured using an electrometer at a constant voltage of 800 V. Results showed that the response of the sample ranging from 4 to 6 mCi was linear with $R^2 = 0.9757$.

KEYWORDS
Beta sensor
ESTAR Program
PC-Bi_2O_3 Nanocomposite
Phosphorus-32
Stopping Power

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1 Introduction

Ionizing radiation detection and dosimetry are critical challenges in the nuclear industries. Polymer nanocomposites were explored as radiation sensors, detectors and dosimeters (Safdari et al., 2022; Veiskarami et al., 2022; Aghdam et al., 2023; Mosayebi et al., 2019, 2017; Malekie et al., 2016; Malekie and Ziaie, 2015). The dose-calibrator device, in which noble gases are usually applied as the sensitive volume, is used to measure the activity of sources used in the nuclear medicine. Since, the noble gases provide a relatively low response due to their low density, in this research, a solid state material, namely polycarbonate-bismuth oxide (PC-Bi_2O_3) composite was explored as a sensitive volume in dose-calibrator for beta-rays.

Beta particles interact with matter through the two processes: electron excitation and ionization, both of which use the Coulomb electric field to interact with electrons (Kang et al., 2020; Attix, 2008; Yanagida, 2018). Continuous-slowing-down approximation (CSDA) is used to interpret the loss of electron energies through the friction (Borg, 1996; Miramonti, 2002; L'Annunziata, 2016). Emission of radiation from nuclei is caused by the inelastic scattering of orbital electrons and secondary electrons, while excitation and ionization of primary electrons are formed by hard electron collisions. Elements lose only a small fraction of energy in soft collisions or elastic scattering (Kang et al., 2020). Several radioisotopes decay by emitting electrons as beta-minus, which travel at a high velocity (Knoll, 2010).

In order to detect the beta-rays, various scintillators

*Corresponding author: smaleki@aeoi.org.ir

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are usually utilized. Low Z materials like organic polymers, which are good at absorbing charged particles, can also be used to detect the beta-rays with high sensitivity (Miramonti, 2002; Torrisi, 1997; Ghergherehchi et al., 2010; Quaranta et al., 2002; Tam et al., 2018). Gas-flow proportional counters and scintillators exhibit several problems regarding their limitations due to hygroscopicity and scalability (Tam et al., 2018).

Radiation detection relies heavily on the thickness of a solid sensor considering the charge particle equilibrium (CPE). The stopping power and range of electrons can be determined using the ESTAR program in a compound (Berger et al., 1999). It is possible to determine the optimum thickness of the sensitive volume material through the calculation of range and stopping power quantities of the electrons at the various energies. The PC-Bi_2O_3 nanocomposite response as a beta-ray sensor was initially examined by the authors in the previous works (Safdari et al., 2022; Malekie et al., 2022). Mehrara et al (Mehrara et al., 2021), investigated this material at various concentrations for gamma-ray shielding purposes. Also, Safdari et al. (Safdari et al., 2022), explored the radiation detection sensitivity of this material for beta-pure emitters using the Sr-90 source at various dose rates. In this work, various beta-pure emitters are explored, in which, the response of the detection was validated by P-32 experimentally. Based on the calculations related to the range and stopping power of the electrons at certain energies, it is possible to optimize the thickness of the sensor subsequently. Therefore, in this research, the calculations related to the range of electrons and their stopping power in PC-Bi_2O_3 composite at different reinforcement phase loadings at energies up to 3 MeV are examined. Finally, in the experimental phase, the response of the 50 wt% PC-Bi_2O_3 nanocomposite against the beta-rays of the P-32 source at different activities is measured.

2 Methodology

2.1 Simulation methodology

Since, different sources at various energies are used in the nuclear medicine, in the simulation phase, the data related to several sources were calculated, and in the experimental phase, according to the laboratory limitations, only the P-32 beta-emitter was used. Therefore, in this research, in the simulation phase, several radioisotopes namely C-14 (156 keV), S-35 (167 keV), Pm-147 (224 keV), P-33 (248 keV), Ca-45 (252 keV), Cl-36 (714 keV), Tl-204 (766 keV), and P-32 (1.71 MeV) at various energies were chosen as pure beta-emitter sources. The ESTAR program was used to determine the range and stopping power of the electrons after beta irradiation with various weight fractions of heavy metal oxide fillers (Berger et al., 1999). The ability of a radiation sensor to detect the ionizing radiation is largely dependent on how the radiation interacts with the material (Knoll, 2010). According to the Bethe-Bloch formula, the linear stopping power of a material for charged particles is defined as the material energy loss for that particle divided by the length of the associated path, in which it depends on the velocity and charge of the particles, the density of the absorber atoms, and the average potential of ionization and excitation. Also, there is another quantity entitled as the mass stopping power, which is independent of the density of the material and is obtained by dividing the stopping power by the density of the material with unit of MeV.cm^2.g^{-1}.

2.2 Experimental procedure

In the experimental section, firstly, the 50 wt% PC-Bi_2O_3 nanocomposite with dimensions of 4 cm4 cm and thickness of 1 mm was prepared. The details of the fabrication and preparation of the nanocomposite are descried in our previous works (Safdari et al., 2022; Mehrara et al., 2021). At first, the nanocomposite was placed at different distances from the pure beta emitter of P-32 source with initial activity of 60 mCi exhibiting a maximum beta energy of 1.71 MeV (average energy of 695 keV) with half-life of 14.3 d (Dahmen et al., 2016). Then, the amount of photocurrent was measured using the SuperMAX Standard Imaging electrometer at a constant voltage of 800 V in time intervals of 15 s. The activity of the P-32 source was measured using a dose-calibrator model Capintec CRC-25R. In Fig. 1, the setup of measurement is depicted.

3 Results and Discussion

3.1 Simulation results

Figure 2 shows the range of electrons vs. Bi_2O_3 wt% at various energies related to common beta emitters. As shown in this figure, for each energy, the range of electrons in the composite is linearly decreased as the Bi_2O_3 wt% increases. Adding the Bi_2O_3 particles into the polymer matrix may result in increasing the secondary radiation through the Bremsstrahlung phenomenon. Bremsstrahlung radiation interacts with the composite atoms, causing incident beta particles to lose energy.

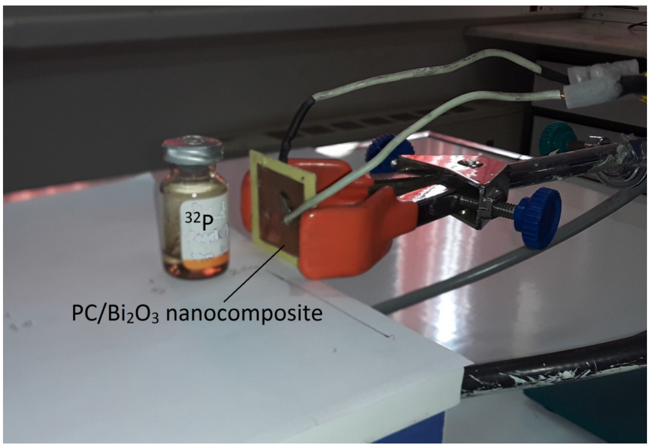

Figure 1: Setup of the measurement in this research, including the P-32 source in the glass vial, the PC-Bi_2O_3 nanocomposite was connected to the electrometer to read the leakage current.

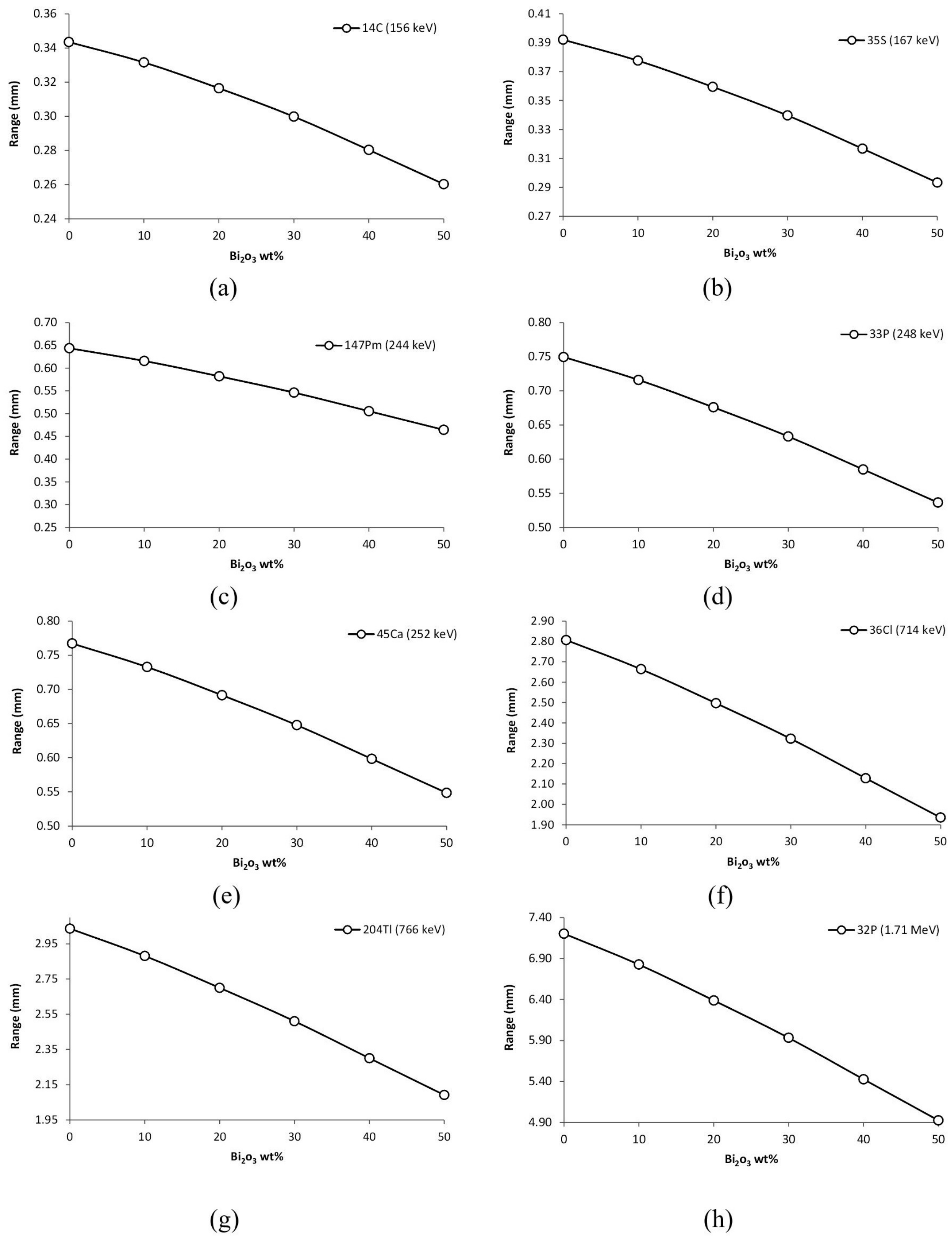

Figure 2: Determining the range of electrons at various weight fractions at (a) 156 keV, (b) 167 keV, (c) 244 keV, (d) 248 keV, (e) 252 keV, (f) 714 keV, (g) 766 keV, and (h) 1.71 MeV using the ESTAR program.

As can be shown from Fig. 3, the range of electrons vs. energy is depicted for various Bi_2O_3 concentrations. Thus, increasing the energy of electrons led to greater amount of the range for electrons.

In spite of the fact that the maximum beta energy of P-32 is 1.71 MeV, but the average energy of the electrons is 695 keV. Thus, as depicted in Fig. 3-f, we considered the thickness of the material composite as 1 mm for this

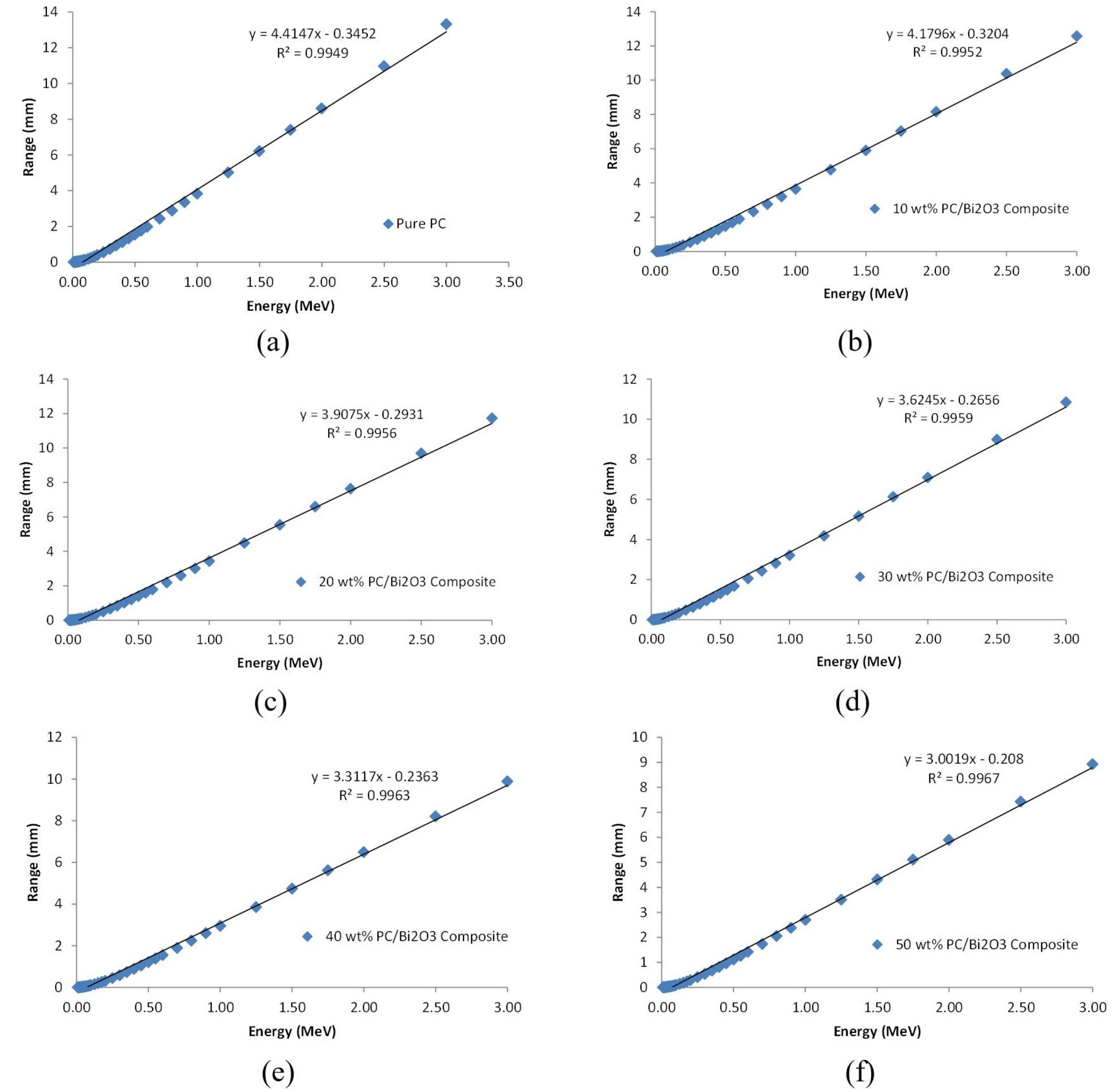

Figure 3: Determining range vs. energy at various concentrations for (a) pure PC, (b) 10, (c), 20, (d), 30, (e), 40, and (f) 50 wt% PC-Bi_2O_3 composite.

purpose (50 wt%). It should be noted that, increasing the thickness of the sensitive volume will probably increase the response of the measurement, but, the recombination possibility of the ions will be increased due to reduction of the electric field in the sensitive volume. Therefore, the optimum thickness of the sensitive volume material is an important issue.

Also, total mass stopping power vs. energy for various concentrations of the inclusions in the PC-Bi_2O_3 composite is depicted in Fig. 4 using the ESTAR program. The total mass stopping power of the electrons decreases as the Bi_2O_3 wt% in the polycarbonate matrix increases at the specified and constant energy. Regarding the Bethe-Bloch formula, more reinforcement phase results in a higher effective atomic number for the composite. Also, electron total mass stopping power falls gradually up to 1.25 MeV before increasing to 3 MeV.

3.2 Experimental results

As can be seen from Fig. 5, at the experimental phase, the amount of electric current as the response was measured at different activities of the P-32 source at the fixed voltage of 800 V for the 50 wt% PC-Bi_2O_3 nanocomposite. Results showed that the response of the sample in the range of 4 to 6 mCi was linear exhibiting the $R^2 = 0.9757$.

By examining the linearity of the response of this nanocomposite material in other energies, we hope to build an activity measurement tool as a dose-calibrator in the future. More research should be done in this field.

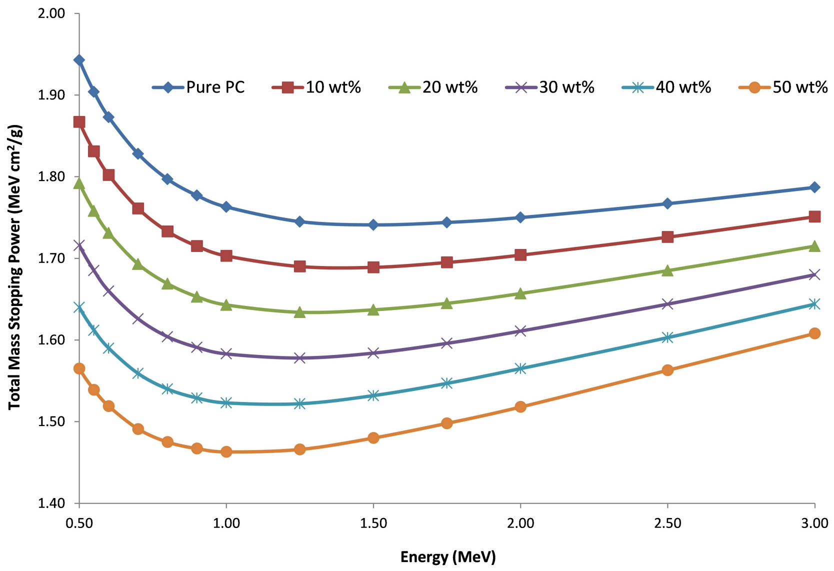

Figure 4: Application of ESTAR program to determine the stopping power of the electrons up to 3 MeV in the PC-Bi_2O_3 composite at various concentrations.

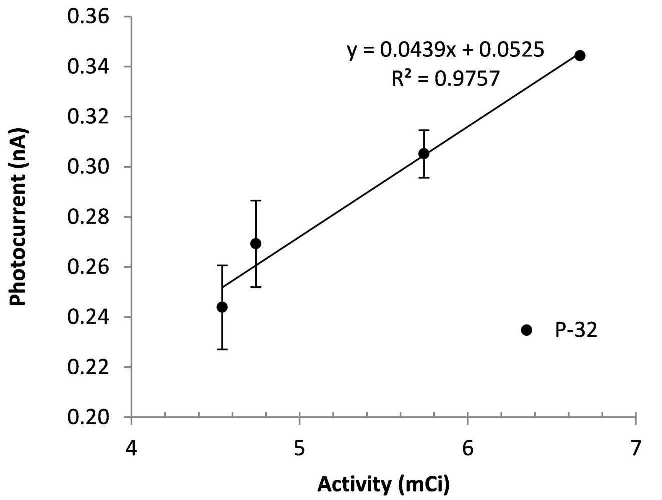

Figure 5: Response of the 50 wt% PC-Bi_2O_3 nanocomposite sensor to P-32 beta-ray source at various activities.

4 Conclusions

For polycarbonate-bismuth oxide composite up to 50 Bi_2O_3 wt%, the ESTAR program was used to determine the range and stopping power using the different pure beta-emitters such as Tl-204 (766 keV), S-35 (167 keV), Pm-147 (224 keV), P-33 (248 keV), Ca-45 (252 keV), C-14 (156 keV), Cl-36 (714 keV), and P-32 (1.71 MeV), in which, the response of the detection was validated by P-32 experimentally. In a polymer matrix with a constant weight percent of inclusions, increasing the energy of electrons led to increase the range of electrons. Electron total mass stopping power also exhibited a decreasing trend gradually up to 1.25 MeV, after that was increased up to 3 MeV. The amount of heavy metal oxide particles exhibited a significant impact on the sensor features. Therefore, to calculate the optimal thickness of the beta sensor, the calculations presented in this article can be useful and practical for future works.

In the experimental phase, response of the 50 wt% sample with thickness of 1 mm against the beta-rays of the P-32 source in different activities was measured using an electrometer at a constant voltage of 800 V. Results showed that response of the sample ranging from of 4 to 6 mCi was linear with $R^2 = 0.9757$. Finally, the polycarbonate-bismuth oxide nanocomposite can be used as a dose-calibrator in the nuclear medicine.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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