Effect of reinforcement phase loading on the dosimetry response of a Polycarbonate/Bismuth Oxide nanocomposite for beta particles

Shahryar Malekie *[1], Seyed Musa Safdari [2], Sedigheh Kashian [1], Morteza Akbari [2], Arjang Shahvar[1]

[1] Radiation Application Research School, Nuclear Science and Technology Research Institute, Karaj, Iran
[2] Department of Nuclear Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
*E-mail address: smaleki@aeoi.org.ir

Abstract
In this experimental work, Polycarbonate/Bismuth Oxide (PC-Bi_2O_3) nanocomposites were prepared in various concentrations of 0, 30, and 50 wt% with thicknesses of 1 mm and irradiated by a pure beta-emitter source of ^{90}Sr. To fabricate the electrodes, copper sheets with thickness of 100 µm were attached to the top and bottom surfaces of the samples using the silver paste. Then, electric current as the dosimetry response was measured at various dose rates ranging from 30-102 mSv/h at a fixed voltage of 400 V using an electrometer. Results showed that increasing the Bi_2O_3 wt% led to improvement in the dosimetry response linearly at various dose rates. Also, the amounts of sensitivities for the samples of 0, 30, and 50 wt% were measured as 20.3, 28.6, and 33.3 nC·mSv^{-1}·cm^{-3}, respectively. Regarding the mechanism of beta interaction with a polymer-heavy metal oxide nanocomposite, the Bremsstrahlung radiation can be considered as a dominant effect.

Keywords: Beta-ray Dosimeter, PC-Bi_2O_3 nanocomposite, Dose Rate, Strontium-90, Sensitivity.

Introduction
Detection and dosimetry of ionizing radiation are essential issues in the nuclear industry. Recently, polymer-nanocomposites as promising materials have been used as radiation sensors, detectors, dosimeters, and shields [1-7]. The interaction mechanisms of the beta particles with matter are categorized into two sections, electron excitation and ionization. Electrons interact with the particles traversing the material via the Coulomb electric field [8]. In addition, low Z materials, including organic polymers, are excellent absorbers of charged particles such as beta-rays, which will provide high sensitivity for charged particle detection. For a polymer-heavy metal oxide nanocomposite, the amount of sensitivity for detecting the beta-rays can be controlled via the weight fractions of the inclusions in the polymer matrix. Generally, various factors affect the dosimeter response of this material, including polymer crystallinity, the weight percentage of metal oxide nanoparticles or reinforcement phase loading, dispersion state of the inclusions into the polymer matrix, thickness of the nanocomposite, and other factors.
This research aims to investigate the response linearity of a novel real-time beta-ray dosimeter based on PC-Bi_2O_3 nanocomposite.

Experimental
Pure PC, 30, and 50 wt% PC-Bi_2O_3 nanocomposites were synthesized with thicknesses of 1 mm using the solution casting method. The synthesis details have been explained in our previous work [1]. PC as a polymer matrix and Bi_2O_3 nanoparticles with the average size of 90-210 nm as nano-fillers were used with densities of 1.2 g/cm^3 and 8.9 g/cm^3, respectively. Also, Strontium-90 (^{90}Sr) was chosen as a pure beta-emitter source. The ^{90}Sr decays to ^{90}Y with a half-life of 28.78 years, with beta particle energy of 546.2 keV. the ^{90}Y, which emits beta and gamma, converts to ^{90}Zr with a half-life of 64 hours, with beta particle energy of 2.28 MeV [9].

Results and discussion
The surface morphology of the prepared 50 wt% PC-Bi_2O_3 nanocomposite was analyzed by Field Emission Scanning Electron Microscopy (FESEM). As can be observed from Fig. 1, a cross-sectional view of the sample showed an appropriate dispersion state of the Bi_2O_3 nanoparticles into the PC matrix.

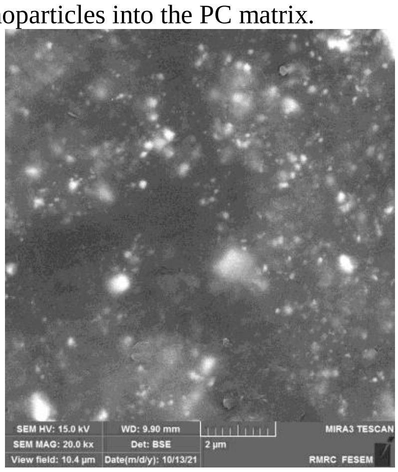

Figure 1. Exhibition of FESEM for the 50 wt% PC-Bi_2O_3 nanocomposite.

As depicted in Fig. 2, to irradiate the samples, a beta irradiation system model Buchler BSS-BA containing

^{90}Sr reference source with an initial activity of 50 mCi (production date 1978), which is located in Secondary Standard Dosimetry Laboratory (SSDL) Karaj-Iran, was used at different source-surface distances (SSDs) according to Table 1.

A Supermax Standard Imaging electrometer was used to measure the electric charge during irradiation at fixed time steps of 15 seconds. To verify the calibration of this system, an extrapolation chamber, a sensitive current measuring system and a sophisticated evaluation procedure have to be used according to the Safety Series No. 16 [10-13].

Table 1. The values of SSDs for ^{90}Sr and corresponding dose rates

SSD (cm)	Dose Rate (mSv/h)
30	102.436
35	75.259
40	57.620
45	45.527
50	36.877
55	30.477

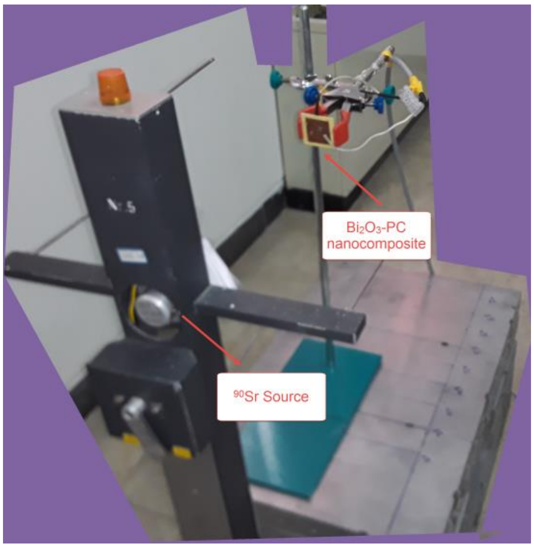

Figure 2. Experimental setup to measure dosimetry response of the PC-Bi_2O_3 nanocomposite.

As shown in Fig. 3, increasing the reinforcement phase loading led to increasing the dosimetry response linearly at various dose rates ranging from 30-102 mSv/h. Also, the values of sensitivities for different reinforcement phase loadings, namely 0, 30, and 50 wt% were measured as 20.3, 28.6, and 33.3 nC·mSv^{-1}·cm^{-3}, respectively. To justify this effect, it can be mentioned that at higher Bi_2O_3 wt%, due to increasing the probability of occurring Bremsstrahlung secondary radiation and increasing the amount of total stopping power of the electrons, the dosimetry response will be increased subsequently. Regarding the mechanism of beta interaction with the PC-Bi_2O_3 nanocomposite material, the Bremsstrahlung radiation can be considered as the dominant effect due to the presence of the heavy metal oxide nanoparticles in the polymer matrix. At higher concentrations above the 50 wt%, the agglomeration will be observed in the nanocomposite, in which the dosimetry response will be affected subsequently.

It should be mentioned that each measurement was repeated four times, thus the uncertainty was obtained regarding the random and systematic errors related to precision of the electrometer system during the measurement.

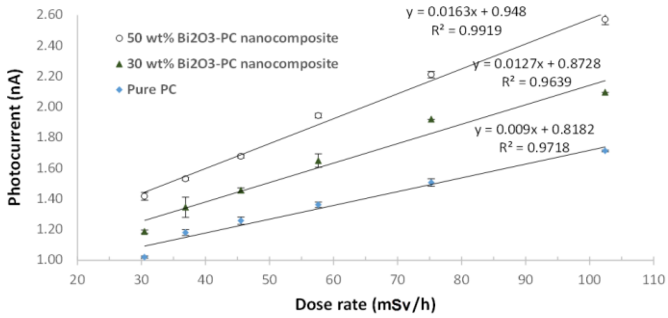

Figure 3. Dosimetry response of 0, 30, and 50 wt% samples irradiated with ^{90}Sr exhibiting a maximum 1.9% standard deviation (1σ).

Conclusions

This experimental research studied the effect of reinforcement phase loading on the dosimetry response of a Polycarbonate/Bismuth Oxide nanocomposite. Thus, three loadings of the Bi_2O_3 nanoparticles, namely 0, 30, and 50 wt% were subjected to beta-irradiation using a ^{90}Sr source. Results showed that increasing the reinforcement phase loading led to increasing the dosimetry response linearly at various dose rates.

This exploration demonstrated that the cost-benefit Polycarbonate/Bismuth Oxide nanocomposite could be considered as a novel real-time beta-ray dosimeter to be used in the radioactive monitoring systems for medical and industrial applications.

Acknowledgements

This work was extracted as a Master's thesis by Mr S. M. Safdari, MSc student at Islamic Azad University, Science and Research Branch, Tehran. We appreciate those who supported us in handling this research, especially the staff of NSTRI of Iran, which resulted in the success of this study.

References

[1] R. Mehrara, S. Malekie, S.M. Saleh Kotahi, S. Kashian, Introducing a novel low energy gamma ray shield utilizing Polycarbonate Bismuth Oxide composite, Scientific Reports, 11 (2021) 10614.
[2] M. A. Hosseini, S. Malekie, F. Kazemi, Experimental evaluation of gamma radiation shielding characteristics of Polyvinyl Alcohol/Tungsten oxide composite: A comparison study of micro and nano sizes of the fillers, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, (2021),166214.
[3] A. Rahimi, F. Ziaie, N. Sheikh, S. Malekie, Calorimetry System Based on Polystyrene/MWCNT Nanocomposite for Electron Beam Dosimetry: A New Approach, Nanotechnologies In Russia, 15 (2020) 175–181.
[4] A. Mosayebi, S. Malekie, A. Rahimi, F. Ziaie, Experimental study on polystyrene-MWCNT nanocomposite as a radiation dosimeter, Radiation Physics and Chemistry, 164 (2019) 108362.
[5] S. Malekie, F. Ziaie, S. Feizi, A. Esmaeli, Dosimetry characteristics of HDPE-SWCNT nanocomposite for real time application, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 833 (2016) 127-133.
[6] A. Intaniwet, C.A. Mills, M. Shkunov, P.J. Sellin, J.L. Keddie, Heavy metallic oxide nanoparticles for enhanced sensitivity in semiconducting polymer x-ray detectors, Nanotechnology, 23 (2012) 235502.
[7] O. Korostynska, K. Arshak, D. Morris, A. Arshak, E. Jafer, Radiation-induced changes in the electrical properties of carbon filled PVDF thick films, Materials Science and Engineering: B, 141 (2007) 115-120.
[8] H. Kang, S. Min, B. Seo, C. Roh, S. Hong, J.H. Cheong, Low energy beta emitter measurement: A review, Chemosensors, 8 (2020) 106.
[9] M.F. L'Annunziata, Radiation physics and radionuclide decay, in: Handbook of Radioactivity Analysis, Elsevier, 2012, pp. 1-162.
[10] International Atomic Energy Agency, Calibration of Radiation Protection Monitoring Instruments, Safety Reports Series No. 16, (2000).
[11] International Organization for Standardization, Reference Beta Radiations for Calibrating Dosemeters and Doseratemeters and for Determining their Response as a Function of Beta Radiation Energy, ISO Standard 6980 (E), Geneva (1984).
[12] Ehrlich, M., Pruitt, J.S., Soares, C.G., Standard Beta-Particle and Monoenergetic Electron Sources for the Calibration of Beta-radiation Protection Instrumentation, Rep. NUREG-CR-4266, NBSIR-85-3169, Nuclear Regulatory
Commission, Washington, DC (1985).
[13] Boehm, J., A measuring and calibration system for currents down to 1017, Atomkernenergie 27 (1976) 139.