

Article

The Radiation Shielding Performance of Polyester with TeO_2 and B_2O_3

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Abstract: In this research, polymers were fabricated through combining polyester, boron oxide (B_2O_3), and Tellurium oxide (TeO_2). B_2O_3 has good neutron absorption and TeO_2 is not only highly dense (5.670 g/cm^3) but also environment-friendly, compared to PbO , as well as being a good photon absorber. The radiation protection features for five investigated samples were examined utilizing an HPGe detector and point sources Am-241, Cs-137, and Co-60. The accuracy of the experimental setup of this experiment was proven through the linear attenuation coefficient (LAC) values obtained from the theoretical (XCOM) and experimental (HPGe) values of the newly developed polymers. The attained results showed that the values of LAC decrease with increasing energy. Moreover, at low energy, a noteworthy increase was found for the LAC values with the addition of TeO_2 . Due to the increase in TeO_2 content of the polymers, the value of the half value layer (HVL) decreases from 6.073–4.193 cm at energy 0.662 MeV, from 7.973–5.668 cm at energy 1.173 MeV, and 8.514–6.061 cm at energy 1.333 MeV. The values of the effective atomic number (Z_{eff}) showed an improvement with the increase in TeO_2 content in the polymers. For example, at energy 0.150 MeV, the Z_{eff} values of the prepared sample followed this decreasing trend - PBT-40 > PBT-30 > PBT-20 > PBT-10 > PBT-0.

Keywords: polyester; TeO_2 ; attenuation coefficient; HPGe; effective atomic number

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1. Introduction

Gamma rays are a form of high-energy electromagnetic radiation emitted by atomic nuclei [1]. These days, there is a danger from unprotected ionizing radiation due to the utilization of radiation in our daily lives, such as in nuclear power, radiation medicine, and aerospace exploration. The protection of the operators and devices used in ionizing radiation surroundings have thus become an important research subject to minimize the hazardous impacts through the innovation of better shielding materials [2]. Numerous diseases have occurred in human bodies due to the effects of chronic radioactive radiation absorption [3]. The high penetration ability of X-rays and gamma-rays has created dangerous products in the bio-network [2]. Not only people but instruments as well are affected by the absorption of radiation [4]. Of late, to overcome the drawbacks of typical shielding absorbers, scientists have been engrossed in figuring out how to fabricate conditional absorbers [5].

Polymer enhanced radiation defenses have gained increasing attention due to their non-toxicity and light weight in numerous applications [6]. In the health sector, nuclear power plants, and mobile nuclear devices, the addition of lead-free elements to polymer composites has generated considerable curiosity [7]. Polymer technology has been combined with lead shields which have a better shielding ability than those comprising other materials; however, their drawbacks include their heavy weight as well as their toxicity [8]. Sayyed et al. formed a novel silicon rubber (SR) by adding numerous ratios

of micro- and nano-sized MgO for evaluation of their shielding capacity at the energy limit between 59.6 and 1333 keV. This newly formed silicon rubber showed suitability in medical requirements, especially low-energy limits [9]. Karabul et al. enthusiastically researched the shielding efficacy of Bi_2O_3 and WO_3 -based micro- and nano-particle-sized epoxy against photon incidence. Nano dopants demonstrated a better ability to reduce the radiation's hazardous impact, compared to micro dopants for the same quantity of components. Additionally, the most successful results came from the greatest concentration of Bi_2O_3 and WO_3 micro- and nano-particle containing epoxy used with low gamma-ray utilizing machines such as those used with roentgen, mammography, or PET scans [10]. The research of Li et al. identified the shielding capability of the Er_2O_3 -containing epoxy matrix. Their results showed that the shielding ability of the studied $\text{BF}/\text{Er}_2\text{O}_3$ composites in the low energy range 31–80 keV was greater than those containing aluminum [5]. Considering this previous research, this study combined TeO_2 and B_2O_3 with polymer in the interest of enhancing the shielding capability of these materials. Traditional borate glass has a high thermal stability and low melting point [11]; borate glasses have lower melting temperatures with near-ultraviolet to near-infrared optical transparency (~ 300 nm to ~ 2.5 μm) with a strong bond strength and greater thermal stability than silicates, phosphates, oxide glasses, etc. [12]. Additionally, the transition temperature of borosilicate glass is less than SiO_2 glasses [13,14].

Due to their significant density and large atomic number, tellurite glasses have the most applications [15]; the shielding ability of tellurite glass is greater than that comprising Pb glass and concrete [16]. Moreover, increasing the quantity of TeO_2 increases the radiation shielding capability [17]. Tellurium oxide glasses have a transparency ability near the UV to mid-IR spectrum, with low melting points and low transition temperatures [18].

In this work, the attenuation coefficients of new polyester composites doped with boron and tellurium oxides using photons emitted from three radioactive sources (Am-241, Co-60, and Cs-137) were studied by an experimental method and compared with the results of X-COM.

2. Materials and Methods

2.1. Sample Preparation

The main components for the composition of the samples were polyester, boron oxide (B_2O_3), and Tellurium oxide (TeO_2). Liquid transparent polyester with a characteristic density of 1.225 g/cm^3 , tensile strength (73.3–103) MPa, and thermal conductivity of 0.17 W/m.K was used as a matrix material with its stiffener (where for every 50 g of polyester, 2 g of stiffener was added). B_2O_3 was used in a fixed percentage during the preparation because it absorbs neutrons well, while TeO_2 was added because it has a relatively high density (5.670 g/cm^3), is environmentally safe, compared with PbO , and is considered a good photon absorber. The samples were prepared in the proportions specified in Table 1 so that each required quantity was gradually mixed at room temperature to avoid bubbles and then it was placed in plastic molds and left to dry for 24 h. Prepared samples are shown in Figure 1.

Table 1. Samples code, compositions, and densities.

Sample Code	Composition (wt %)			Density ($\text{g}\cdot\text{cm}^{-3}$)
	Polyester	B_2O_3	TeO_2	
PBT-0	85	15	0	1.428
PBT-10	75	15	10	1.556
PBT-20	65	15	20	1.709
PBT-30	55	15	30	1.896
PBT-40	45	15	40	2.128

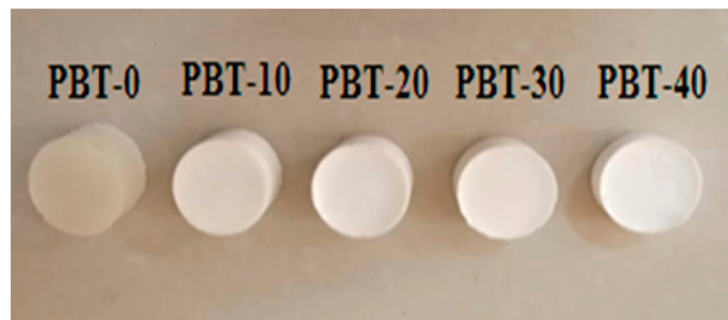


Figure 1. The prepared study samples.

2.2. Sample Measurements

The attenuation coefficients were experimentally determined using an HPGe detector and different point radioactive sources. A geometric measurement was designed using a collimator as shown in Figure 2. The distance between the source and the sample was 15 cm, while the distance from the sample to the detector was about 4 cm. The intensity in the presence (I) and absence (I_0) of the sample was measured under the same conditions; from these intensities, the Linear Attenuation coefficient (LAC) could be determined by the following equation [19–22].

$$LAC = \frac{-1}{x} \ln \frac{I}{I_0} \quad (1)$$

where, x , represents the thickness of the prepared sample. The other shielding parameters for mortar samples reinforced with Fe_2O_3 nanoparticles were calculated based on the previous works [23–29].

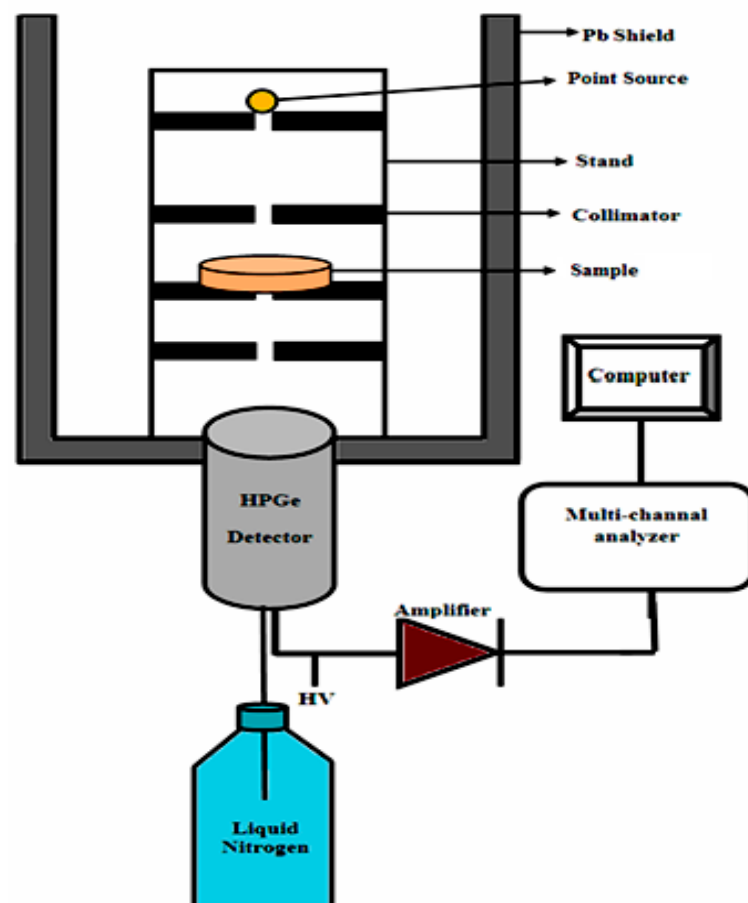


Figure 2. The arrangement of the experimental work.

3. Results and Discussion

Figure 3 compares the theoretical and experimental linear attenuation coefficients (LAC) of the five investigated samples. For all the tested samples, the theoretical and experimental values are very close. For example, at 0.662 MeV, PBT-0's theoretical LAC value is 0.114 cm^{-1} while its experimental LAC value is 0.111 cm^{-1} , a deviation of 2.82%. Meanwhile, PBT-40's respective LAC values at the same energy are 0.165 cm^{-1} and 0.161 cm^{-1} , a deviation of 2.67%. For all the tested values, the calculated deviation is less than 3% for PBT-0, less than 4% for PBT-10, PBT-20, and PBT-40, and less than 5% for PBT-30. These results prove the ability of the experimental setup to measure the LAC values of the newly developed polymers accurately. Therefore, we can use the experimental values with great certainty when further evaluating the radiation shields.

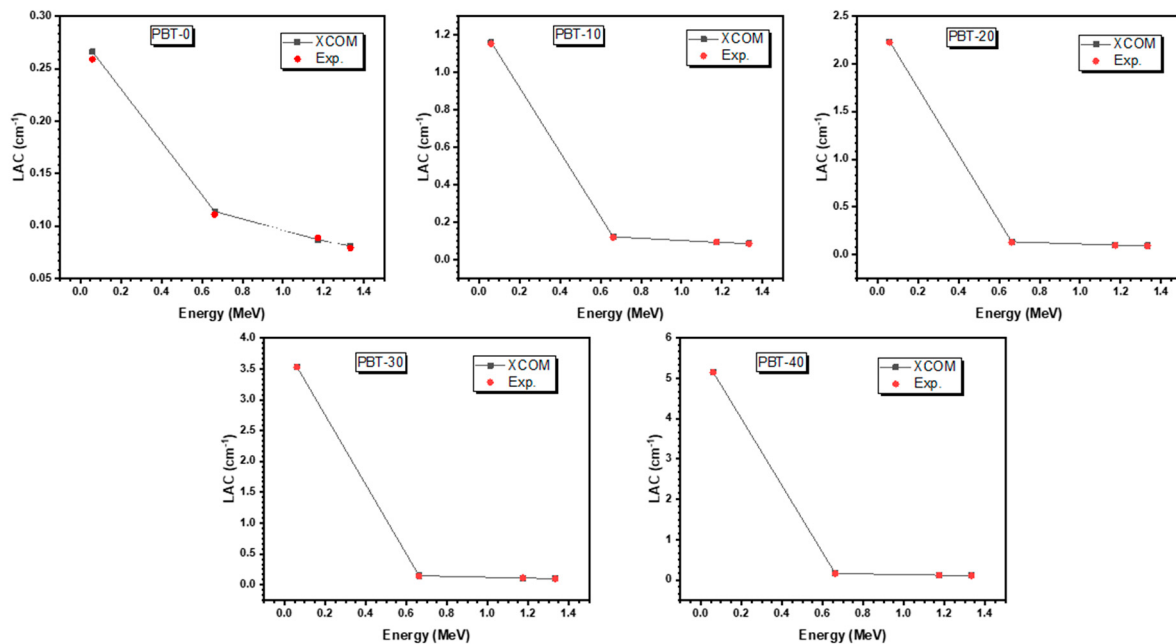


Figure 3. The theoretical and experimental LAC of the five investigated samples.

Figure 4 plots the LAC of the prepared polymers at various energies to test the influence of increasing energy on the LAC values. Additionally, the figure also demonstrates the effect of altering the composition of the polymers on their LAC values. The LAC values decrease with increasing energy. For example, PBT-0's LAC decreases from 0.266 to 0.081 cm^{-1} between 0.06 and 1.333 MeV . The LAC values drastically change with the addition of TeO_2 , which is most prominently seen when comparing the LAC values for PBT-0, which has no TeO_2 , with the other polymers that do have some TeO_2 . The LAC values for PBT-0 and PBT-40 at 0.06 MeV are 0.266 and 5.161 cm^{-1} and 0.081 cm^{-1} and 0.114 cm^{-1} , respectively at 1.333 MeV . Furthermore, though the addition of TeO_2 causes a notable increase in the LAC values, the rate at which the values increase at low energies such as 0.06 MeV is very high due to the power of the photoelectric effect. This effect is highly dependent on the atomic number of the shield; however, at higher energies, the rate at which the LAC values increase with increasing TeO_2 content is reduced. At low energies, the probability of absorption is greater where the photoelectric effect occurs, so at low energy, the LAC is very sensitive to TeO_2 concentration. On the other hand, at high energy, the possibility of scattering is larger than the absorption, so the LAC is relatively unchanged with increasing TeO_2 concentration.

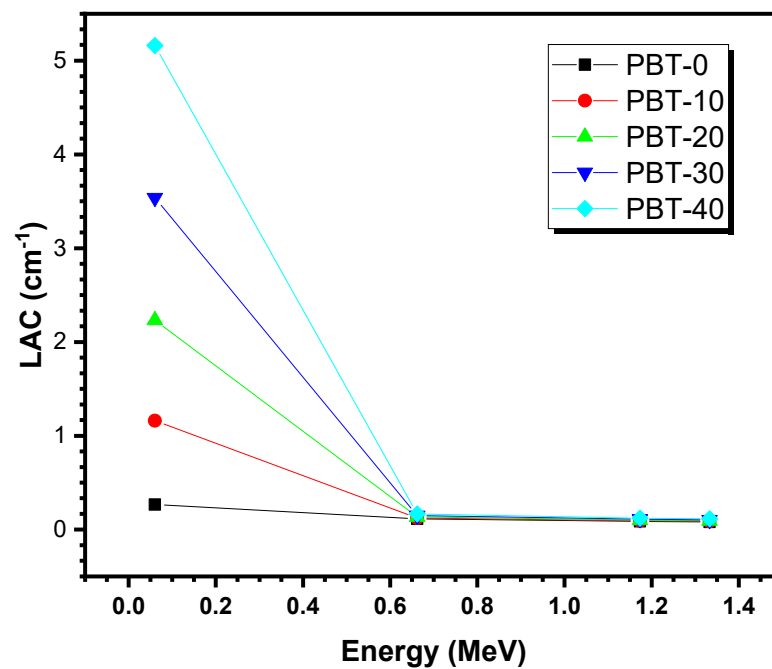


Figure 4. The linear attenuation coefficient (LAC) of the prepared polymer samples.

The half value layer (HVL) of the polymers was calculated against energy and plotted in Figure 5. The aim of this figure is to compare the thicknesses of the polymers with each other to shield 50% of the incoming radiation and to study the impact of TeO₂ on this thickness. At 0.06 MeV, the HVL for PBT-0 is equal to 2.604 cm, which drastically drops to 0.597 cm when adding 10 wt% TeO₂, 0.311 cm when 20% TeO₂ is added, and to 0.134 when 40% TeO₂ is added. In other words, the HVL values decrease from 2.604 to 0.134 cm when the TeO₂ content in the polymers increases from 0 to 40% at 0.06 MeV. When examining the HVL at other energies, the same trend can be found. At 0.662 MeV, the HVL values decrease from 6.073 to 4.193 cm due to the change in TeO₂ content, from 7.973 to 5.668 cm at 1.173 MeV, and from 8.514 to 6.061 cm at 1.333 MeV.

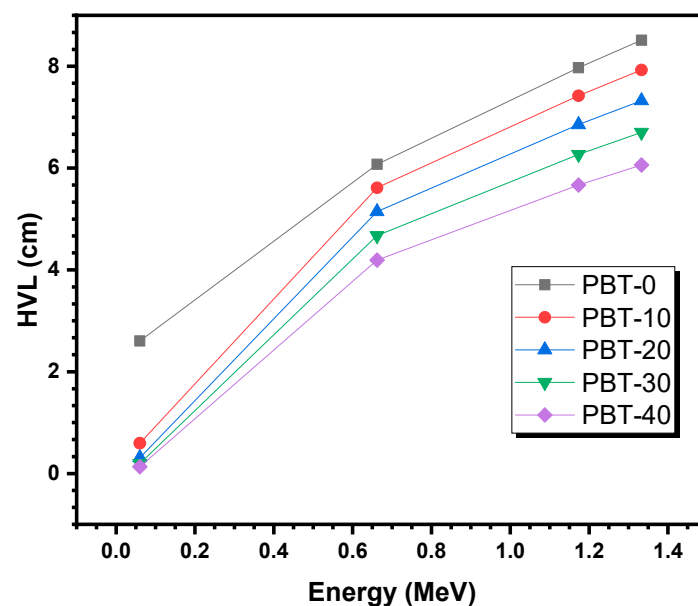


Figure 5. The half value layer (HVL) of the polymer samples.

Figure 6 illustrates the MFP of the PBT-0 and PBT-40 polymers (the polymers with 0 and 40% TeO_2 , respectively). The results of this figure confirm the conclusions obtained in the HVL figure; mainly, that the addition of TeO_2 causes a notable reduction in the thickness of the polymer required to adequately attenuate the photons. For instance, PBT-0's MFP value is 3.756 cm at 0.060 MeV, while PBT-40's MFP at the same energy is equal to 0.194 cm. Meanwhile, at 1.333 MeV, they are equal to 12.283 and 8.745 cm for PBT-0 and PBT-40, respectively.

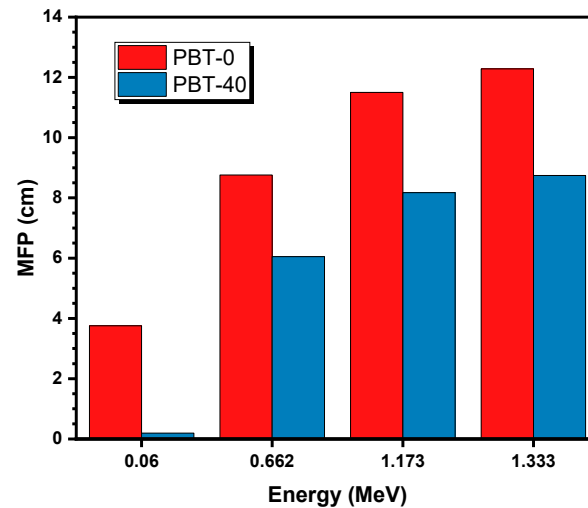


Figure 6. The mean free path (MFP) of the PBT-0 and PBT-40 polymer samples.

The effective atomic number (Z_{eff}) of the five investigated polymer samples are graphed in Figure 7. Because of the radioisotopes used in this study, the radiation shielding parameters could only be reported at four energies. In order to examine the shielding properties at a wide energy range, the Z_{eff} of the current polymers was calculated between 0.015 and 15 MeV. First, a spike in the values occurs around 0.030 MeV, which is due to the K-absorption edge of Te (this is evident by the fact that no spike occurs for PBT-0, which contains no Te). Aside from this rise in values, at low energies, the Z_{eff} values of all five samples decrease with increasing energy. Meanwhile, in the middle energy range, the values stay mostly constant, and at higher energies, they increase. For example, PBT-10's Z_{eff} values are 21.26 at 0.015 MeV, 18.88 at 0.050 MeV, 8.64 at 0.100 MeV, 5.07 at 0.500 MeV, 5.08 at 3 MeV, and 6.03 at 15 MeV. In addition, the Z_{eff} values increase as the TeO_2 content in the polymers increases. For instance, PBT-0's Z_{eff} value is 4.63 at 0.150 MeV, while PBT-10's Z_{eff} is 6.37, PBT-20's is 8.36, PBT-30's is 10.64, and PBT-40's is 13.30.

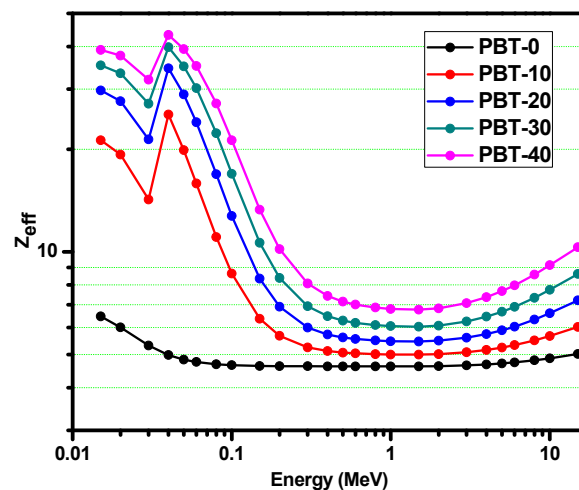


Figure 7. The effective atomic number (Z_{eff}) of the five investigated polymers.

4. Conclusions

The gamma radiation shielding properties of boron oxide (B_2O_3) and TeO_2 containing polymers were examined at energies 0.0595, 0.6617, 1.173, and 1.333 MeV. The LAC, HVL, and Z_{eff} of the five prepared samples PBT-40, PBT-30, PBT-20, PBT-10, and PBT-0 were evaluated. The values of LAC obtained from the theoretical (XCOM program) and experimental (HPGe) results indicated the accuracy of the experimental setup. At 0.06 MeV, the LAC values for the samples PBT-0 and PBT-40 were found at 0.266 cm^{-1} and 5.161 cm^{-1} , respectively, as well as 0.081 cm^{-1} and 0.114 cm^{-1} , respectively, at energy 1.333 MeV. Results showed that the values of LAC decrease with increasing energy. Additionally, at low energy, a remarkable increase has been found for the LAC values with the addition of TeO_2 . At energy 0.06 MeV, the values of HVL decreased from 2.604–0.134 cm when the TeO_2 content in the polymers was increased from 0 to 40%. The addition of TeO_2 causes a notable reduction in the thickness of the polymer required to adequately attenuate the incoming photons. In addition, the values of Z_{eff} increased with the increase in TeO_2 content in the polymers. At energy 0.150 MeV, the values of Z_{eff} 's were PBT-0 (4.63) < PBT-10 (6.37) < PBT-20 (8.36) < PBT-30 (10.64) < PBT-40 (13.30). Considering all of the shielding parameters, it can be said that a higher concentration of TeO_2 content enhances the shielding capacity of the prepared polymer.

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References

- Hassan, A.M.; Wang, Z.; Liu, W.-B.; Wang, J.; Zhigang, Y.; Khan, M.; Ali, M.M.M.; Geldiyev, R.; Diaby, M.; Derradji, M. Thermal stability and gamma ray shielding properties of tungsten borides/epoxy micro-composites. *Radiat. Phys. Chem.* **2021**, *189*, 109769. [CrossRef]
- Ali, M.M.M.; Li, Z.; Zhao, H.; Rawashdeh, A.; Al Hassan, M.; Ado, M. Characterization of the health and environmental radiological effects of TENORM and radiation hazard indicators in petroleum waste—Yemen. *Process Saf. Environ. Protect.* **2021**, *146*, 451–463. [CrossRef]
- Wojcik, A.; Obe, G.; Lisowska, H.; Czub, J.; Nievaart, V.; Moss, R.; Huiskamp, R.; Sauerwein, W. Chromosomal aberrations in peripheral blood lymphocytes exposed to a mixed beam of low-energy neutrons and gamma radiation. *J. Radiol. Prot.* **2012**, *32*, 261. [CrossRef]
- Hine, G.J. The effective atomic numbers of materials for various gamma-ray processes. *Phys. Rev.* **1952**, *85*, 725–734.
- Li, R.; Gu, Y.; Zhang, G.; Yang, Z.; Li, M.; Zhang, Z. Radiation shielding property of structural polymer composite: Continuous basalt fiber reinforced epoxy matrix composite containing erbium oxide. *Compos. Sci. Technol.* **2017**, *143*, 67–74. [CrossRef]
- Hosseini, S.H. Study on hard X-ray absorbing properties of nanocluster polyaniline. *Mater. Sci. Semicond. Process* **2015**, *39*, 90–95. [CrossRef]
- Şahin, N.; Bozkurt, M.; Karabul, Y.; Kılıç, M.; Ozdemir, Z.G. Low cost radiation shielding material for low energy radiation applications: Epoxy/Yahyalı Stone composites. *Prog. Nucl. Energy* **2021**, *135*, 103703. [CrossRef]
- Korkut, T.; Umac, Z.I.; Aygün, B.; Karabulut, A.; Yapıcı, S.; Şahin, R. Neutron equivalent dose rate measurements of gypsum-waste tire rubber layered structures. *Int. J. Polym. Anal. Charact.* **2013**, *18*, 423–429. [CrossRef]

9. Sayyed, M.I.; Al-Ghamdi, H.; Almuqrin, A.H.; Yasmin, S.; Elsafi, M.A. Study on the gamma radiation protection effectiveness of nano/micro-MgO-reinforced novel silicon rubber for medical applications. *Polymers* **2022**, *14*, 2867. [\[CrossRef\]](#)
10. Karabul, Y.; İçelli, O. The assessment of usage of epoxy based micro and nano-structured composites enriched with Bi₂O₃ and WO₃ particles for radiation shielding. *Results Phys.* **2021**, *26*, 104423. [\[CrossRef\]](#)
11. Sadeq, M.S.; Abdo, M.A. Effect of iron oxide on the structural and optical properties of alumino-borate glasses. *J. Ceram. Int.* **2021**, *47*, 2043–2049. [\[CrossRef\]](#)
12. Parandamaiah, M.; Kumar, K.N.; Babu, S.; Reddy, S.V.R.; Ratnakaram, Y.C. Dy³⁺ doped lithium sodium bismuth borate glasses for yellow luminescent photonic applications. *Int. J. Eng. Res. Appl.* **2015**, *5*, 126–131.
13. Aktas, B.; Yalcin, S.; Albaskara, M.; Aytar, E.; Ceyhan, G.; Turhan, Z. Effect of Er²O₃ on structural, mechanical, and optical properties of Al²O₃-Na²O-B²O₃-SiO₂ glass. *Radiat. Phys. Chem.* **2022**, *584*, 121516. [\[CrossRef\]](#)
14. Aliyu, U.S.; Geidam, I.G.; Otto, M.S.; Hussaini, M. Sciences investigations of the elastic moduli of Er₂O₃ NPs NPs doped TeO₂-B₂O₃-SiO₂ glasses using theoretical models. *Niger. Soc. Phys. Sci.* **2022**, *4*, 9–15. [\[CrossRef\]](#)
15. Sayyed, M.I.; Akyildirim, H.; Al-Buriah, M.S.; Lacomme, E.; Ayad, R.; Bonvicini, G. Oxyfluoro-tellurite-zinc glasses and the nuclear-shielding ability under the substitution of AlF₃ by ZnO. *Appl. Phys. A* **2020**, *126*, 88.
16. Tekin, H.O.; Sayyed, M.I.; Manici, T.; Altunsoy, E.E. Photon shielding characterizations of bismuth modified borate silicate tellurite glasses using MCNPX Monte Carlo code. *Mater. Chem. Phys.* **2018**, *211*, 9–16.
17. Çelikkilek, M.; Ersundu, A.E.; Aydin, S. Preparation and characterization of TeO₂-WO₃-Li₂O glasses. *J. Non. Cryst. Solids.* **2013**, *378*, 247–253. [\[CrossRef\]](#)
18. Sharma, S. *Metallic Glass-Based Nanocomposites*; CRC Press: Boca Raton, FL, USA, 2019. [\[CrossRef\]](#)
19. Dong, M.; Xue, X.; Yang, H.; Li, Z. Highly cost-effective shielding composite made from vanadium slag and boron-rich slag and its properties. *Radiat. Phys. Chem.* **2017**, *141*, 239–244. [\[CrossRef\]](#)
20. Sayyed, M.I.; Hannachi, E.; Slimani, Y.; Khandaker, M.U.; Elsafi, M. Radiation shielding properties of bi-ferroic ceramics added with CNTs. *Radiat. Phys. Chem.* **2022**, 110096. [\[CrossRef\]](#)
21. Mhareb, M.H.A. Physical, optical and shielding features of Li₂O-B₂O₃-MgO-Er₂O₃ glasses co-doped of Sm₂O₃. *Appl. Phys. A* **2020**, *126*, 71. [\[CrossRef\]](#)
22. Alajerami, Y.S.; Drabold, D.; Mhareb, M.H.A.; Cimat, K.L.A.; Chen, G.; Kurudirek, M. Radiation shielding properties of bismuth borate glasses doped with different concentrations of cadmium oxides. *Ceram. Int.* **2020**, *46*, 12718–12726. [\[CrossRef\]](#)
23. Kamislioglu, M. An investigation into gamma radiation shielding parameters of the (Al:Si) and (Al+Na): Si-doped international simple glasses (ISG) used in nuclear waste management, deploying Phy-X/PSD and SRIM software. *J. Mater. Sci. Mater. Electron.* **2021**, *32*, 12690–12704. [\[CrossRef\]](#)
24. Al-Hadeethi, Y.; Sayyed, M.I.; Barasheed, A.Z.; Ahmed, M.; Elsafi, M. Fabrication of Lead Free Borate Glasses Modified by Bismuth Oxide for Gamma Ray Protection Applications. *Materials* **2022**, *15*, 789. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Gökç, H.S.; Canbaz-Öztürk, B.; Çam, N.F.; Andıç-Çakır, Ö. Gamma-ray attenuation coefficients and transmission thickness of high consistency heavyweight concrete containing mineral admixture. *Cem. Concr. Compos.* **2018**, *92*, 56–69. [\[CrossRef\]](#)
26. HGökçe, S.; Yalçinkaya, Ç.; Tuyan, M. Optimization of reactive powder concrete by means of barite aggregate for neutrons and gamma rays. *Constr. Build. Mater.* **2018**, *189*, 470–477.
27. Yasaka, P.; Pattanaboonmee, N.; Kim, H.J.; Limkitjaroenporn, P.; Kaewkhao, J. Gamma radiation shielding and optical properties measurements of zinc bismuth borate glasses. *Ann. Nucl. Energy* **2014**, *68*, 4–9. [\[CrossRef\]](#)
28. El-Khatib, A.M.; Elsafi, M.; Almutiri, M.N.; Mahmoud, R.M.M.; Alzahrani, J.S.; Sayyed, M.I.; Abbas, M.I. Enhancement of Bentonite Materials with Cement for Gamma-Ray Shielding Capability. *Materials* **2021**, *14*, 4697. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Cheewasukhanont, W.; Limkitjaroenporn, P.; Kothan, S.; Kedkaew, C.; Kaewkhao, J. The effect of particle size on radiation shielding properties for bismuth borosilicate glass. *Radiat. Phys. Chem.* **2020**, *172*, 108791. [\[CrossRef\]](#)