Research Article

Bekir Oruncak*

**Gamma-ray shielding properties of Nd$_2$O$_3$-added iron–boron–phosphate-based composites**

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**Abstract:** Radiation may be hazardous for human cells when absorbed more than the required dose. Hence, radiation protection processes is required, and the development of shielding materials are of main concern. Here, the gamma ray shielding properties of iron–boron–phosphate-based composite samples have been studied. The linear attenuation coefficients ($\mu$, cm$^{-1}$) and related parameters have been simulated using Phy-X/PSD software for gamma energies in the range of $10^{-2}$ to $10^5$ MeV. It was found that the Nd$_2$O$_3$ rate in iron–boron–phosphate-based composites is important in terms of radiation shielding.

**Keywords:** radiation shielding, gamma ray attenuation, composite materials

1 **Introduction**

The world has been exposed to radiations since the beginning of universe due to the long half-life of radio-nuclides. Recently, there has also been artificial radiation, which is produced to be used in many different fields. Thus, humans may be exposed to radiation by ionizing radiation emitted by both the radioactive sources and also technically produced radiation. Therefore, human protection from the hazardous effect of this radiation should be studied. For these purposes, radiation dosimetry is developed by studying the interactions of radiation with matter, dosimetry for medical radiation, radiation shielding, etc. [1–4]. Thus, this requires radiation protection in three main ways: time, distance and shielding. This is due to the effect of ionizing radiation that cannot be completely avoided, but it can be diminished. The conventional shielding material is lead (Pb), as it has an extremely large radiation absorption power. On the other hand, it has several significant drawbacks such as considerably high toxicity due to its heavy metal character [5–7]. Therefore, non-lead and non-lead-based radiation shielding materials are under development by many researchers to protect radiation.

In order to select suitable materials, their nuclear features should be defined, which is expressed by the following parameters: the linear attenuation coefficient (LAC), half-value layer (HVL), tenth-value layer (TVL), mean free path (mfp), effective atomic number ($Z_{\text{eff}}$), and effective electron density ($N_{\text{eff}}$) [8–10]. Thus, many studies were carried out for these purposes. For example, concrete is useful for radiation shielding because of its economical advantage and is simple to form complicated geometries [11–20]. Besides concrete, which is widely used as building materials, many research studies have been performed to investigate radiation shielding properties of different materials using different methods [21–39]. Simulation and other prediction techniques are important in this field as experimental studies are not always possible [40–50].

On the other hand, improvement needs to be done on the radiation shielding materials, as use of radiation is increasing day by day. Therefore, in this study, the gamma ray shielding properties of newly developed composites where Nd$_2$O$_3$ was added at five different rates, will be investigated using Phy-X/PSD software.

2 **Materials and method**

The radiation shielding properties of five different iron–boron–phosphate-based composite samples have been obtained. The iron–boron–phosphate-based composites selected from ref. [51] with chemical composition determined from the formula $5\text{MoO}_3-(9.5 - x)(3.6\text{Fe}_2\text{O}_3 -$ $\text{B}_2\text{O}_3 - 5.4\text{P}_2\text{O}_5) - x\text{Nd}_2\text{O}_3$ where $x = 0, 2, 4, 6, 8$ (mol%) were synthesized. The detailed composite contents are tabulated in Table 1 [51]. The relation between Nd$_2$O$_3$ rate and densities of the composite is shown in Figure 1.
Table 1: Chemical properties of composites (mol%) [51]

| Code | Nd<sub>2</sub>O<sub>3</sub> rate | B<sub>2</sub>O<sub>3</sub> | P<sub>2</sub>O<sub>5</sub> | Fe<sub>2</sub>O<sub>3</sub> | MoO<sub>3</sub> | Density (g cm<sup>-3</sup>) |
|------|-------------------------------|----------------|----------------|----------------|----------------|-----------------|
| N0   | 0                             | 9.5           | 51.3          | 34.2           | 5              | 2.926           |
| N2   | 2                             | 9.3           | 50.22         | 33.48          | 5              | 3.057           |
| N4   | 4                             | 9.1           | 49.14         | 32.76          | 5              | 3.160           |
| N6   | 6                             | 8.9           | 48.06         | 32.04          | 5              | 3.273           |
| N8   | 8                             | 8.7           | 46.98         | 31.32          | 5              | 3.372           |

![Figure 1: Relation between the Nd<sub>2</sub>O<sub>3</sub> rate and densities of the composites.](image)

In order to research the radiation shielding capability of a material, the linear attenuation coefficients (LAC, \( \mu \) cm<sup>-1</sup>) is a basic parameter and it is also used to obtain other parameters in radiation dosimetry. The LAC and other parameters such as the mean free path (mfp), half value layer (HVL), tenth value layer (TVL), effective atomic number (\( Z_{eff} \)), and effective electron density (\( N_{el} \)) at gamma ray energies of 10<sup>-3</sup> to 10<sup>5</sup> MeV have been simulated using Phy-X/PSD online program developed by Sakar et al. [52,53].

The LAC (\( \mu \) cm<sup>-1</sup>) is expressed by the Beer–Lambert law given in equation (1)

\[
N = N_0 e^{-\mu x},
\]

where \( N_0 \) and \( N \) are the number of gamma rays before and after passing through, respectively, and \( x \) is the thickness of materials.

The radiation mean free path (mfp) in the composite is described as the average penetration length of gamma rays in the composite and is given by equation (2):

\[
mfp = \frac{1}{\mu}.
\]

Other radiological parameters of HVL and TVL are expressed as the composite thickness to stop 50 (half) and 10% of gamma rays, respectively, and they are obtained using equations (3) and (4) respectively:

\[
HVL = \frac{\ln(2)}{\mu},
\]

\[
TVL = \frac{\ln(10)}{\mu}.
\]

The \( Z_{eff} \) and electron density (\( N_{el} \)) are obtained using equations (5) and (6), respectively,

\[
Z_{eff} = \frac{\sigma_a}{\sigma_{el}},
\]

\[
N_{el} = \left( \frac{\mu}{\rho} \right)_{material}.
\]

where \( \sigma_a \) and \( \sigma_{el} \) are the total atomic and electric cross sections, respectively, and they are obtained using equations (7) and (8):

\[
\sigma_a = \frac{1}{N} \sum \frac{f_i A_i}{Z_i} \left( \frac{\mu}{\rho} \right)_i,
\]

In equation (6), \( N \) is the Avogadro’s number, \( \mu/\rho \) is the total mass attenuation coefficients, \( A_i \) and \( w_i \) are atomic weights (in g) and fractional weights of the constituent of materials, respectively,

\[
\sigma_{el} = \frac{1}{N} \sum f_i \frac{A_i}{Z_i} \left( \frac{\mu}{\rho} \right)_i,
\]

where \( f_i \) is the atomic number of element \( i \) and \( Z_i \) is the atomic number of the \( i \)th elements in a mixture.

3 Results and discussion

The gamma ray shielding properties of iron–boron–phosphate-based composites which is formulated as 5MoO<sub>3</sub>–(9.5 – \( x \))(3.6Fe<sub>2</sub>O<sub>3</sub>–B<sub>2</sub>O<sub>3</sub>–5.4P<sub>2</sub>O<sub>5</sub>)–xNd<sub>2</sub>O<sub>3</sub> where \( x = 0, 2, 4, 6, 8 \) (mol%) were investigated by simulating the parameters LAC, mfp, HVL, TVL, \( Z_{eff} \), and \( N_{el} \).

The obtained LAC results for five different samples are displayed in Figure 2 as a function of gamma ray energies. It is obvious from Figure 2 that the distribution of LAC decreased when the gamma ray energies increased. But, this behavior changed with the changing gamma energy range. For example, at low gamma ray energy, the LAC decreased sharply and a smooth decrease was seen at the middle energy range and it is almost
constant at high energies. This is due to the different gamma ray absorption mechanisms for different energy ranges [54,55].

The behavior of LAC for gamma ray energies of 0.662, 1.173, and 1.332 MeV are displayed in Figure 3 for all materials. It may be seen from this figure that the LAC decreased linearly when gamma ray energies is increased. It is also clearly seen from this figure that the highest value of LAC has been obtained for N6 type and the lowest value is for the N0 type material. This shows that the addition of Nd$_2$O$_3$ to composites improved the LAC value. This is also seen in Figure 4 where the LAC values have been displayed as a function of the Nd$_2$O$_3$ rate in composite samples. The addition of Nd$_2$O$_3$ into composite samples increased the density of the composite samples. The LAC dependence on the density of the material is displayed in Figure 5. As seen in Figures 4 and 5, the LAC increased linearly with the increasing Nd$_2$O$_3$ rate in the composites. The linear correlation constant for gamma ray energies of 0.662, 1.173, and 1.332 MeV are above 96%. This is in agreement with the work done in the literature [56,57].

The obtained radiological parameters mfp, HVL, and TVL are displayed in Figure 6 where it is seen that these parameters have a nonlinear relation and thus completely inverse distribution of LAC has been obtained. Thus, for all three parameters, the highest values are obtained for N8 and the lowest values for N0 samples. It may be seen from these figures that results for all samples are

![Figure 2: Variation of LAC with gamma ray energies.](image1)

![Figure 3: Variation of LAC with gamma ray energies for all composites.](image2)

![Figure 4: Variation of LAC with Nd$_2$O$_3$ rated in composites.](image3)
close to each other at low energies while differences can be seen at high energies.

The simulated $Z_{\text{eff}}$ and $N_{\text{eff}}$ have been displayed as a function of gamma ray energies in Figures 7 and 8, respectively. It is clearly seen from these figures that all quantities are dependent on the gamma ray energy and the distributions show similar behaviour. Moreover, the values decreased at gamma energies of 0.1–1 MeV. For N0 samples, the values for both quantities are higher than others while it is much higher for $Z_{\text{eff}}$.

4 Conclusion

The gamma ray shielding properties of Nd$_2$O$_3$-added composite materials have been investigated in terms of LAC and other parameters. The simulations were performed with the Phy-X/PSD program. The gamma ray energy was in the range of $10^{-3}$ to $10^5$ MeV. From this work, it was seen that the LAC decreased with the increasing gamma
The conducted research is not related to either human or animal use.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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