Study on gamma-ray shielding properties of lead tellurite glass systems using PHITS

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Abstract. The gamma-ray shielding properties, mass attenuation coefficient, mean free path and half value layer of lead tellurite glass systems were investigated in the photon energy range of 0.015–15 MeV using particle and heavy ion transport code system (PHITS) with the use of narrow beam transmission technique. The gamma shielding efficiency of studied glass systems was compared to that of standard concretes in terms of mean free path and half value layer. The obtained results show that PHITS is very capable for investigation of radiation shielding properties to good accuracy with maximum percentage differences of less than 2% comparing to the results by XCOM database. This will make a useful alternative technique for studying radiation parameters of other glasses, for which no experimental results are available.

1. Introduction
Glass shielding materials with unique properties in terms of optical transparency and absorbing high energy radiation have been widely received much attention in the recent years because of its applications to different fields, medical technology, nuclear and radiation protection [1]. Tellurite glass is a type of glass which well known its remarkable specific properties, such as high reflective index, excellent thermal stability, and low melting temperature [2]. Some tellurite glasses added with lead oxide (PbO) were successfully prepared and explored their structural and optical properties in the visible and UV regions [3, 4]. Unfortunately, there is a lack of experimental result in terms of radiation shielding properties for these glass systems.

Recently, Monte Carlo simulation codes by carefully modelling the geometry have been recognized as an effective tool in the investigation of gamma ray shielding properties when experiments are limited or hard to make a measurement [5, 6]. PHITS (Particle and Heavy Ion Transport code System) is a multi-purpose tool for simulating particle transport phenomena developed by JAEA (Japan Atomic Energy Agency) and several other institutes. This code has widely used in many studies in the fields of accelerator and detector design, particle therapy, and cosmic radiation, etc. [7]. With the various nuclear reaction models and atomic data libraries, PHITS code makes it possible to simulate photon interactions in glass material with accurate results.

This study is to investigate the mass attenuation coefficients, mean free path and half value layer for lead tellurite glass systems as radiation shields in the photon energy range of 0.015–15 MeV using PHITS code and compared these parameters with the obtained results by XCOM database. Moreover, radiation shielding efficiency of studied glass systems compared to that of shielding concrete in terms of the mean free path and half value layer is discussed.
2. Materials and methods

2.1. Material specification of glass sample

A series of lead tellurite glasses were considered according to an experimental study prepared using melt quenching technique [4]. Each glass sample was defined considering the weight of each element and densities as listed in table 1.

| Glass composition (mol%) | Sample code | Elements (wt%) | Density (g/cm³) |
|--------------------------|-------------|----------------|-----------------|
| 100 TeO₂                 | TePb0       | 20.0495 Te 79.9505 Pb 0 4.930 |
| 10 PbO – 90 TeO₂         | TePb10      | 18.3172 Pb 69.1983 Te 12.4845 5.371 |
| 15 PbO – 85 TeO₂         | TePb15      | 17.4998 Pb 64.1254 Te 18.3748 5.611 |
| 20 PbO – 80 TeO₂         | TePb20      | 16.7127 Pb 59.2397 Te 24.0476 5.843 |
| 25 PbO – 75 TeO₂         | TePb25      | 15.9540 Pb 54.5310 Te 29.5149 6.048 |
| 30 PbO – 70 TeO₂         | TePb30      | 15.2224 Pb 49.9899 Te 34.7877 6.231 |

2.2. Monte Carlo simulation

Narrow beam transmission geometrical was simulated to investigate photon attenuation coefficients of proposed glasses. A schematic diagram of PHITS total simulation geometry is shown in figure 1. A glass sample with various thicknesses (d) was placed between radiation source, detector, and lead collimators with aperture 0.4, 0.6 and 0.2 cm. The gamma-ray source defined as a disk source with 0.5 cm diameter emitting along the primary axis of the cylinder was placed 66 cm from the face of the detector. The detector considered in this simulation is a NaI crystal, with height in crystal 7.62 cm and diameter 7.62 cm. In PHITS, “t-track” tally was used to obtain photon fluence in the detector cell determined by the sum of the track length per source divided by the volume of the cell. Incident (ϕ₀) and transmitted (ϕ) photon fluence were tallied and applied in the Lambert-Beer law to calculate mass attenuation coefficients:

\[
\frac{\mu}{\rho} = \ln \left( \frac{\phi_0}{\phi} \right) \rho d
\]

where \( \mu/\rho \) represents the linear attenuation coefficient and \( \rho \) is the density of the sample. From the \( \mu/\rho \) values we can determine the half value layer (HVL) and mean free path (MFP) as depicted in Ref [5]. The number of particles histories for each simulation was 10⁶ – 10⁷ values so that our tally results have statistical error of less than 0.1%.

2.3. XCOM calculation

A photon cross sections database called XCOM was used to calculate total attenuation coefficients for various compounds in the energies range of 1 keV–100 GeV. The mass attenuation coefficients for the selected glass systems at some energy range were computed by designating the weight fraction (\( w_i \)) for each component [8]:

\[
\frac{\mu}{\rho} = \sum_{i} w_i \left( \frac{\mu}{\rho} \right)_i
\]

where \( \left( \frac{\mu}{\rho} \right)_i \) is the total mass attenuation coefficient of the ith element which obtained directly from XCOM database.
3. Results and discussion

We applied a statistical method to confirm the validity of the calculated results by PHITS. Percentage difference (PD) [9] was utilized to quantify the difference among the mass attenuation coefficient ($\mu/\rho$) values for all glass samples presented in figure 2 for the energy range from 0.015–15 MeV. Our results show that these parameters from PHITS are quite consistent with XCOM results, for which the PD values between both methods range from 0.0007% to 1.7631%. The variation in the $\mu/\rho$ for lead tellurite glasses with photon energy in the range of 0.015–15 MeV is shown in figure 3. The $\mu/\rho$ values in low energy range are relatively high. While higher energy region, the decrease to become almost constant which is due to the dominance of partial photon interactions [10]. At some low photon energies, it was also observed that the discontinuous peaks in the $\mu/\rho$ values because of K-absorption edge of Te and Pb elements in the selected glass. Moreover, the $\mu/\rho$ of the studied glasses increases with the increase of PbO concentration due to the increase in weight fraction of higher atomic number of Pb compared to Te element.

The half value layer (HVL) is an important quantity, which indicates that the shielding material will be effective in term of the thickness requirement to attenuate the incident gamma ray intensity by 50%. Besides, the mean free path (MFP) is an average distance travelled by photon in a material before an interaction. The variation of HVL and MFP of the lead tellurite glasses which was compared to that of some shielding concretes investigated by Ref. [11]; ordinary, ilmenite-ilmonite, ilmenite and steel-scrap with the various photon energy is presented.

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**Figure 1.** PHITS total simulation geometry.

**Figure 2.** PD values between theoretical results with both theoretical results.

**Figure 3.** Variation of mass attenuation coefficient with incident photon energy.
in figure 4 and figure 5. It is obviously seen that the HVL and MFP values decrease with the increasing in content of PbO as well as illustrating that radiation shielding properties are enhanced with the addition of PbO. As shown in the comparison study for TePb0–TePb30 glasses, the values of these parameters are lower than that of the common shielding concretes. Therefore, it can be concluded that the gamma-ray shielding properties, all lead tellurite glass systems have higher effective than these concretes.

4. Conclusion
We have investigated radiation shielding parameters in terms of $\mu/\rho$, HVL, and MFP for lead tellurite glasses in the photon energy range of 0.015–15 MeV using PHITS and XCOM. The simulated and calculated results from two methods are not far from each other. The comparison results of studied glass systems with radiation shielding concrete are superior to those of concretes. The simulation geometry technique by PHITS is found appropriate to be used as an alternative approach to study shielding parameters of other glass systems for which there is no experiment result.

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