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Effect Of Ferroelectric ($BaTiO_3$) On Radiation Shielding Features Of $Na_2B_4O_7$ -MoO_3 -TeO_2 -V_2O_5 Glass System

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Abstract:
This article explains the effect of $BaTiO_3$ on $xBaTiO_3$-(78-x)$Na_2B_4O_7$-10TeO_2-10MoO_3-2V_2O_5 (x=0-20 insteps of 5) glass systems. By using Phy-X computational technique LAC, MAC, HVL, MFP, N_{eff}, Z_{eff}, EBF and EABF were obtained over the photon energy range 0.015-15MeV. Both LAC and MAC were followed Beer Lambert's law expect at some photon energies this was explained by K-absorption edges. The incorporation of $BaTiO_3$ was observed to significantly enhance the photon attenuation characteristics of the glass system. This is evidenced by a marked reduction in both the half-value layer (HVL) and the mean free path (λ), indicating superior shielding efficiency. The increase in EBF and EABF with $BaTiO_3$ content suggests enhanced photon interaction probabilities, thereby contributing to greater photon retention within the shielding material. The analysis of EBF and EABF for BNMTV glass systems highlights the importance of glass composition and thickness in determining shielding effectiveness.

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I. Introduction:

Radiation is a form of energy transferred from one place to another place in the form of either particle or wave. Now a day we are using radiation in medical fields for radiation therapy, in nuclear fields for energy production and also in research fields. In this modern era it became a common friend in our lives because of advancement of technology. The long term exposure of this radiation, cause to damage of human cells. So to protect and minimize the risk of patients and workers from this exposure need radiation shielding materials. Lead is most conventional material for radiation shielding but due to its toxicity researches have been focused on alternative for this Lead based systems. Glasses are most important materials to used as shielding materials because of their stability, compositional durability, density and ease of making etc[1-5].

This work investigates the potential of a novel BNMTV glass series, modified with varying proportions of $BaTiO_3$ for gamma-ray shielding applications. A systematic analysis was conducted to determine fundamental shielding properties, such as the linear attenuation coefficient (LAC), mass attenuation coefficient (MAC), half-value layer (HVL), and mean free path (MFP). Additionally, the energy-dependent variations of the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) were examined to elucidate the shielding performance and interaction probability of the glasses. The findings aim to establish the viability of these lead-free glasses as effective and environmentally benign radiation shields.

II. Experimental:

Glass series with the following composition $xBaTiO_3$-(78-x)$Na_2B_4O_7$-10TeO_2-10MoO_3-2V_2O_5 (x=0-20 insteps of 5) was prepared by melt quench method and named as BNMTV series. Analytical grade chemicals (FLUKA make) of high purity $BaTiO_3$, MoO_3, $Li_2B_4O_7$, TeO_2 and V_2O_5 with appropriate masses are measured by using mono-pan balance then placed in an agate mortar to blend the mixture of chemicals. This form of powder was taken into a crucible to heat on a furnace in the range of temperature 1200-1280K for one hour. Homogeneous melt was formed by heating; this molten sample was pressed between two stainless steel plates which were maintained at a temperature of 500K for 5 hours to remove thermal stresses in the samples. Transparent and bubble free glass samples were formed. Composition of the glasses along with measured density values which were measured by using Archimedes principle as shown in Table 1. Phy-X software was used to obtain radiation shielding parameters in the photon energy range 0.015 to 15MeV. Effect of $BaTiO_3$ on shielding parameters observed.

Glass code	$BaTiO_3$	$Na_2B_4O_7$	TeO_2	MoO_3	V_2O_5	Density(g/cc)
BNMTV-1	0	78	10	10	2	2.4833
BNMTV-2	5	73	10	10	2	2.6022
BNMTV-3	10	68	10	10	2	2.6759
BNMTV-4	15	63	10	10	2	2.7956

BNMTV-5	20	58	10	10	2	2.8643

Table 1. Composition of BNMTV glasses in mole% and density values

III. Results And Discussion:

LAC and MAC:

When radiation passes through the material its intensity decreases within the material this is called attenuation of radiation. Beer Lambert's Law gives the intensity of radiation as a function of distance from the entry point of radiation within the material

$I=I_oe^{-\mu t}$ (1)

Here I_o is the intensity of incident radiation and I is the intensity of radiation after travelling a distance t from entry point of the radiation in the material. μ is linear attenuation coefficient (LAC) of the material; it measures how fast is the radiation attenuates in the material. μ/ρ is defined as Mass attenuation coefficient (MAC). Greater is the value of LAC and MAC better is the glass for radiation shielding. The energy dependence of the LAC and MAC for the BNMTV glass series was investigated over a photon energy range of 0.015 to 15MeV, as illustrated in Fig.1 and Fig.2 respectively.

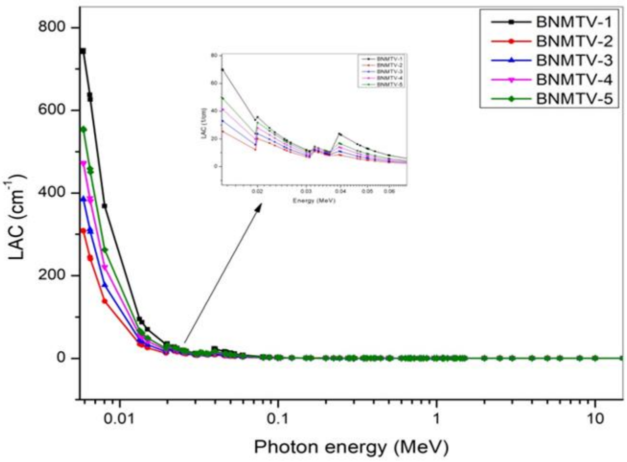

Fig 1. Variation of LAC with photon energy of BNMTV glasses

The data reveal a general trend of decreasing attenuation coefficients with increasing photon energy. However, this decreasing trend is interrupted by distinct discontinuities observed in the vicinity of 19, 31, and 38keV. These abrupt increases are attributable to the photoelectric effect, specifically corresponding to the K-absorption edges of constituent elements: Molybdenum (~20keV), Tellurium (~31.8keV), and Barium (~37.4keV). At these critical energies, a sharp rise in photon interaction probability occurs due to the resonant absorption by K-shell electrons, leading to the observed peaks in the attenuation spectra. For photon energies beyond 40keV, the Compton scattering process becomes the dominant interaction mechanism, accounting for the subsequent gradual decline in the attenuation coefficients [6-11].

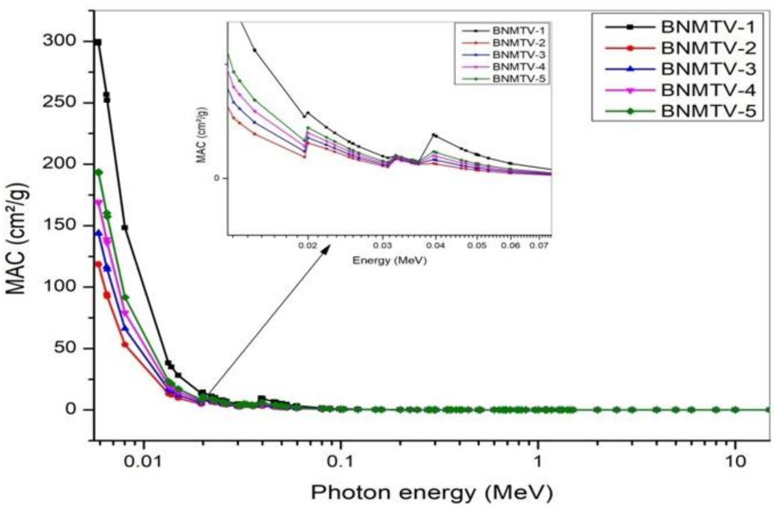

Fig 2. Variation of MAC with photon energy of BNMTV glasses

Half-Value Layer (HVL) and Mean Free Path (MFP):

As radiation passes through the glass material its intensity decreases, the amount of thickness for which intensity of incident radiation becomes half is known as half value layer (HVL). Relation between HVL ($d_{1/2}$) and LAC (μ) is given by

$$d_{1/2}= \frac{ln2}{\mu} \qquad (2)$$

Behavior of the HVL with photon energy and also with $BaTiO_3$ mole% as shown in Fig. 3. As LAC depends on energy of photon, HVL also depends on energy of photon, for low energy photons $d_{1/2}$ value is nearly zero for all BNMTV glasses. HVL value is increased from BNMTV-1glass to BNMTV-2 glass whereas BNMTV-2 glass to BNMTV-5 glass decreased systematically bay increasing $BaTiO_3$ mole %. Lower is the value of $d_{1/2}$ better is the material for shielding.

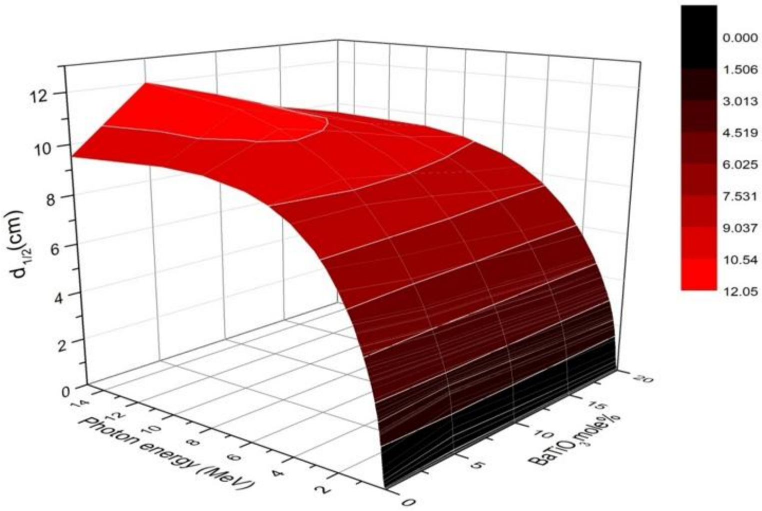

Fig 3. Variation of HVL with photon energy of BNMTV glasses

Mean free path (λ) is another important parameter; it gives the distance travelled by a photon between two successive interactions within the material. λ value ranges from 59μm to 14.63cm for BNMTV glasses. It was observed that the MFP value was decreased with $BaTiO_3$ additions for any photon energy, so the interactions of high energy photons are increasing with addition of $BaTiO_3$ content. Variation of λ with photon energy for BNMTV glasses as shown in Fig.4 and observed increasing trend with photon energy. For low energy photons, rate of increase of λ is small whereas for higher energy photons it was increased rapidly. The incorporation of $BaTiO_3$ was observed to significantly enhance the photon attenuation characteristics of the glass system. This is evidenced by a marked reduction in both the half-value layer (HVL) and the mean free path (λ), indicating superior shielding efficiency. These findings highlight the critical role of compositional engineering in developing advanced radiation shielding glasses, especially for applications involving high-energy photons [12-14]. Clearly it shows inverse relation to μ. Relation between them is given by

$$\lambda=1/\mu \qquad (3)$$

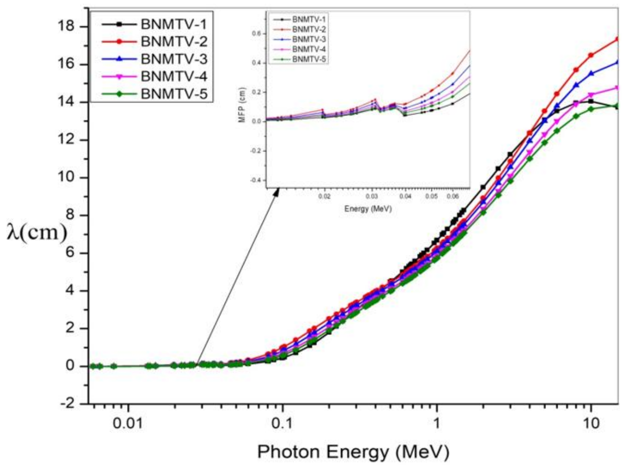

Fig 4. Variation of MFP with photon energy of BNMTV glasses

Z_{eff} and N_{eff}:

To understand interaction gamma rays with BNMTV glasses we need another two important parameters those are effective atomic number (Z_{eff}) and effective electron density (N_{eff}). Zeff is the equivalent atomic number of the composite glass to how radiation interacts with a single atom of atomic number. Variation of Z_{eff} and N_{eff} with photon energy for BNMTV glasses as shown in Fig.5 and Fig.6 respectively.

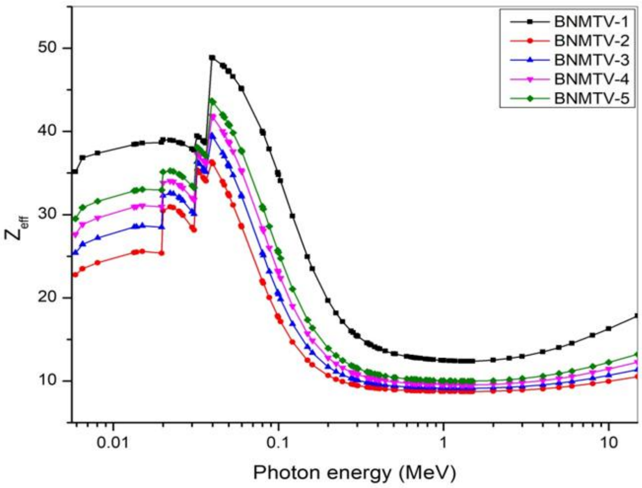

Fig 5. Variation of Z_{eff} with photon energy of BNMTV glasses

Z_{eff} shows different behavior in different regions of photon energy, it is increased with increase of $BaTiO_3$ content. Photon energy range 0.4-2MeV it shows decreasing behavior because of Compton scattering, other than this energy range Z_{eff} shows increasing behavior. Photo electric absorption and pair production dominant at Lower and higher energy ranges respectively. The BNMTV-0 composition exhibited the highest effective atomic number (Z_{eff}) across the investigated energy range. This is consistent with its high refractive index, which signifies enhanced electronic polarizability and consequently a greater cross-section for photon interactions [15-19].

Radiation is directly interacts with the electrons that are present in the glass system, so the number electrons present in the glass system per unit mass or volume to interact with the photons is also a needed quantity, this is denoted by N_{eff}. This quantity shows nearly similar behavior to that of Z_{eff} with radiation energy.

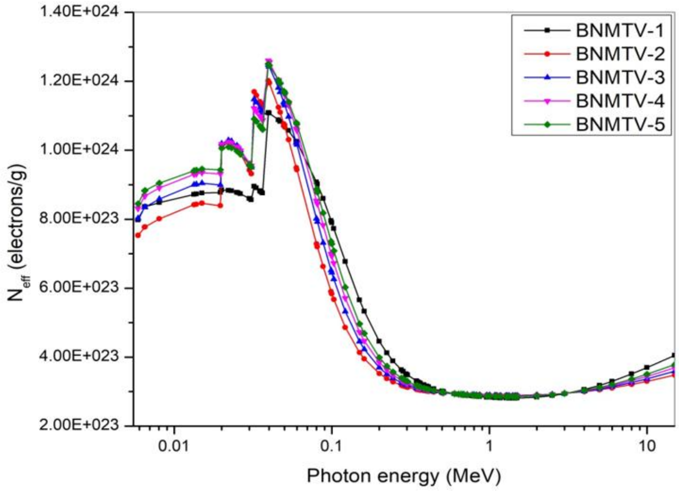

Fig 6. Variation of N_{eff} with photon energy of BNMTV glasses

Buildup factors:

Buildup factors are arises because of contribution of scattered photons. The conventional exponential attenuation law was obtained by considering uncollided photons. When radiation passes through the material secondary photons are produced by Compton scattering, these photons contribute significantly to the total intensity. Ignorance of this contribution can lead to critical underestimation of exposure and absorbed dose.

Buildup factors were introduced to quantify the contribution of scattered photons and those are EBF and EABF. The buildup factors for BNMTV glasses, considering various thicknesses up to 40 mean free paths (mfp) are shown in Fig.7 and Fig.8. Both EBF and EABF are depending on photon energy, penetration depth, and glass composition. At lower photon energies, particularly around 30 keV, and 60keV, a high buildup factor is observed, which can be attributed to the strong photoelectric absorption by elements such as Ba and Te. This absorption leads to subsequent de-excitation processes, contributing to increased photon interactions within thicker glass samples. As photon energy increases, Compton scattering becomes the dominant interaction mechanism, leading to further increases in EBF and EABF values. This effect is particularly pronounced at intermediate photon energies, around 0.8MeV, where the probability of Compton scattering is at its peak. For BNMTV glasses with varying compositions, the presence of heavy element such as Ba plays a significant role in influencing the buildup factors.

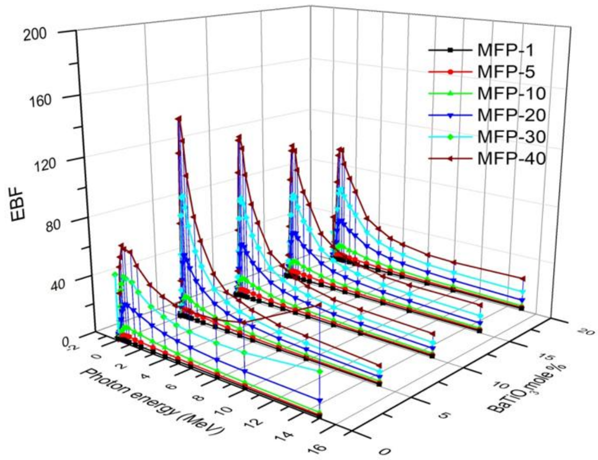

Fig 7. Variation of EBF with photon energy of BNMTV glasses

The increase in EBF and EABF with $BaTiO_3$ content suggests enhanced photon interaction probabilities, thereby contributing to greater photon retention within the shielding material. Additionally, at higher photon energies, secondary photon production through processes such as electron-positron annihilation further amplifies the buildup effect, especially at greater depths. Comparative analysis of EBF across different photon energy levels reveals that at lower energies (0.015–0.15MeV), the values remain relatively low, with EBF approaching unity for specific glass compositions and depths. This behavior suggests that narrow beam transmission conditions are sufficient at these energy levels. However, as photon energy increases beyond 1.5MeV, the buildup factor becomes more dependent on the effective atomic number (Z_{eff}) of the glass, with Compton scattering playing a dominant role [20-21].

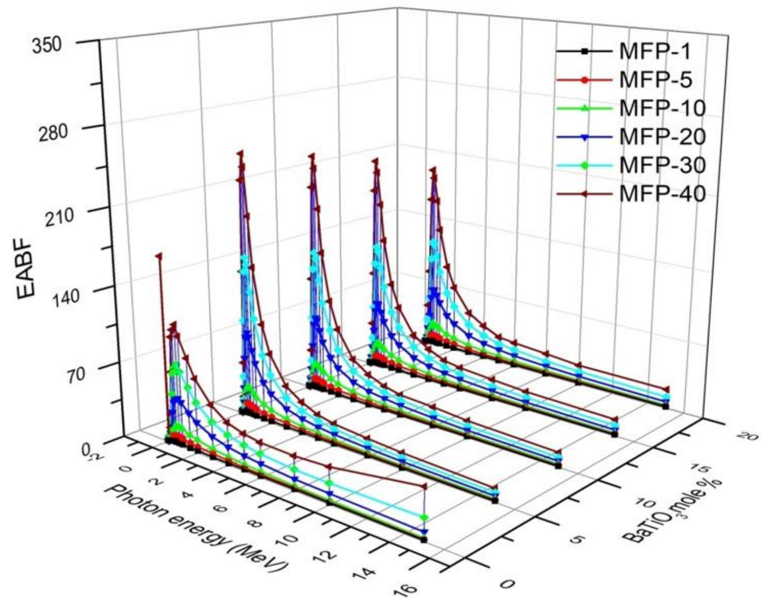

Fig 8. Variation of N_{eff} with photon energy of BNMTV glasses

Overall, the analysis of EBF and EABF for BNMTV glass systems highlights the importance of glass composition and thickness in determining shielding effectiveness. These findings underscore the necessity of accounting for photon buildup effects in practical radiation shielding applications, ensuring accurate dosimetric assessments and optimized material design.

IV. Conclusions:

Different concentrations of $BaTiO_3$ were used to fabricate BNMTV glass system. Density was increased with increase of $BaTiO_3$ content, density of $BaTiO_3$ is greater than Li2B4O7 this might be the reason for incremental behavior in density. Radiation shielding parameters were calculated in the range of photon energy 0.015-15MeV. LAC and MAC followed similar trends with energy of photons that is decreasing trend except at 19, 31, and 38keV photon energies and this is explained by K-absorption edges of Molybdenum (~20keV), Tellurium (~31.8keV), and Barium (~37.4keV). Half-Value Layer ($d_{1/2}$) and Mean Free Path (λ) were also calculated as expected they both have shown inverse relation with each other. λ value ranges from 59µm to 14.63cm for BNMTV glasses. Z_{eff} and N_{eff} are shown different behavior in different regions of photon energy; these are increased with increase of $BaTiO_3$ content. By considering secondary electrons Buildup factors EBF and EABF were also measured. At lower photon energies, particularly around 30keV, and 60keV, a high buildup factors are observed, which can be attributed to the strong photoelectric absorption by elements such as Ba and Te. Overall, gamma radiation shielding capacity of BNMTV glasses was improved with $BaTiO_3$ addition.

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