NEUTRON SHIELDING PROPERTIES OF A BORATED HIGH-DENSITY GLASS

by

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The neutron shielding properties of a borated high density glass system was characterized experimentally. The total removal macroscopic cross-section of fast neutrons, slow neutrons as well as the linear attenuation coefficient of total gamma rays, primary in addition to secondary, were measured experimentally under good geometric condition to characterize the attenuation properties of (75-x) B_2O_3-$1Li_2O$-5MgO-5ZnO-$14Na_2O$-xBaO glassy system. Slabs of different thicknesses from the investigated glass system were exposed to a collimated beam of neutrons emitted from ^{252}Cf and ^{241}Am-Be neutron sources in order to measure the attenuation properties of fast and slow neutrons as well as total gamma rays. Results confirmed that barium borate glass was suitable for practical use in the field of radiation shielding.

Key words: shielding material, fast neutron, slow neutron, removal cross-section, gamma ray

INTRODUCTION

Ionizing radiation has harmful effects on human health and environment., The same applies to nuclear technologies accompanied with several hazardous situations for living organisms. Therefore, it was necessary to develop technologies for protecting against nuclear radiation [1, 2]. Hence, the shielding material against nuclear radiation was born and attracted a great deal of attention [3, 4]. The most important radiations in the field of protective materials are neutrons and gamma-rays because they are the most penetrating for different materials [5]. The effectiveness of shielding varies with the type and energy of radiation and also according to the desired purpose of the shielding [6]. Often a combination of three materials is desirable that includes heavy materials, light materials, and neutron-absorbing materials to omit the slow neutrons through absorption of the neutron shield [7]. The shielding of neutrons introduces many complications because of a wide range of the energy that must be considered and the secondary production of gamma rays. To choose neutron shielding materials, the most important is to moderate the neutron to low energies, where neutron can readily be captured in materials with high absorption cross section [8, 9]. The most effective moderators are elements with low atomic number; and therefore hydrogen containing materials are the major efficient components of most neutron shields, such as water and paraffin. However, water shields have the disadvantage of needing maintenance; also, evaporation can lead to a potentially dangerous loss of shielding effectiveness, while paraffin is flammable. If the neutron energy is sufficiently high, inelastic scattering with heavy nuclei can take place in which the recoil nucleus is elevated to one of its excited states during the collision. The nucleus quickly de-excites; emitting a gamma ray, and the neutron loses a greater fraction of its energy than it would in an equivalent elastic collision [10-12]. Inelastic scattering and the subsequent gamma ray emission play an important role in the shielding of high-energy neutrons. Materials with good inelastic scattering properties are the heavy elements, such as iron and lead, which used to offset this decrease in cross section with increased neutron energy [13]. These materials can cause a large change in neutron energy after colli-

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sion for high-energy neutrons, while they have a little effect on the neutrons at lower energy, below 0.1 MeV [14, 15]. The ^{10}B is effective for absorbing epithermal neutrons (energy range 0.1 eV to 10 eV), and was included as a neutron absorber in various materials, *e. g*. borated graphite, boron carbide, Boral, and boron oxide [16, 17].

Present work was focused on the study of impregnation of boron oxide in the glassy samples in addition to a study on the influence of barium in the form of BaO (ρ = 5.73 gcm^{-3}) on the attenuation properties of slow and fast neutrons as well as the total gamma rays.

SAMPLES PREPARATION

Pure, commercially available, raw materials were used to prepare a glassy system of the composite (75-x) B_2O_3-1Li_2O-5MgO-5ZnO-14Na_2O-xBaO (where x = 0, 10, 20, 30, 40, and 50 mol %) by the melt-quenching technique with dimensions 4 cm 4 cm and different thicknesses (0.6 cm-1.02 cm). The dry powders were mixed, homogenized and then melted at a temperature of 1000 °C for 4 hours in porcelain crucibles. Once a homogeneous free bubble liquid was obtained, it was poured into a stainless steel mold and then annealed at a temperature of 400 °C for 4 hours to eliminate internal stress. Then the glass samples were cooled down to room temperature. Transparent and homogenous glass samples were obtained. Finally glass slab samples as shown in fig. (1) were polished until smooth surfaces were observed.

EXPERIMENTAL SET-UP

Fast neutron and total gamma ray measurements

Measurements were carried out for the investigated glassy barriers using a collimated beam of fast neutrons and gamma rays emitted from 5 mCi ^{252}Cf source with neutron yield of 1.721 10^7 neutrons per second. Special detector collimator was used to eliminate the side scattered radiation to enhance the discrimination capability. The neutron-gamma crystal organic scintillation spectrometer with stilbene scintillator of dimension 4 cm 4 cm was used to measure the recoil proton and electron pulse amplitude distributions. Experimental layout of the measuring system was presented in fig. (2). Fast neutron and total gamma ray fluxes transmitted through different barriers of glass samples under investigation were used to perform the attenuation properties of such glass, where the shielding parameters of fast neutrons and total gamma rays were obtained.

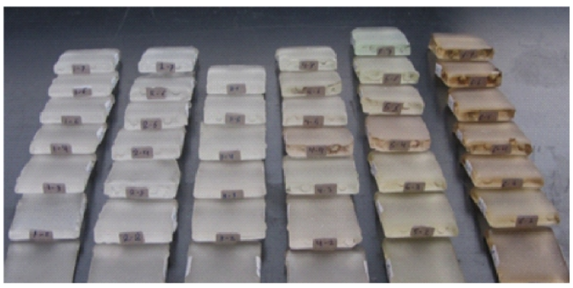

Figure 1. The prepared samples in bulk form

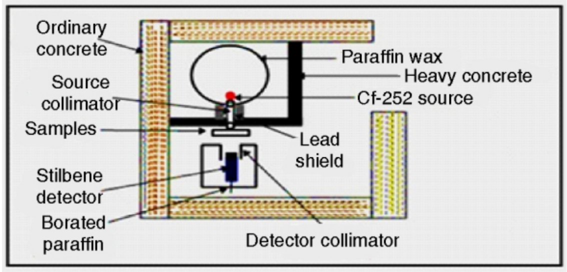

Figure 2. Experimental layout

Slow neutron measurements

A collimated beam of neutrons emitted from ^{241}Am-Be source of activity 0.2 TBq and neutron yield of (1.1-1.4) 10^7 neutrons per second was slowed down, by a Perspex block, to measure the slow neutron attenuation in the investigated glassy system. The transmitted beam of neutrons was measured under a good geometric condition using ^{3}He counter as shown in fig. (3). The shielding parameters of slow neutrons were deduced from the attenuation curves.

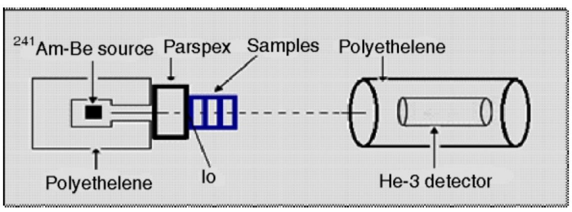

Figure 3. Schematic diagram of slow neutron measurements

RESULTS AND DISCUSSION

Total removal macroscopic cross-section of fast neutrons

The fast neutron spectra were measured behind glass barriers of different thicknesses as given in fig. (4). It is denoted from such figure that, the measured transmitted fast neutron spectra have nearly the same behavior behind all investigated barriers. It is worth to

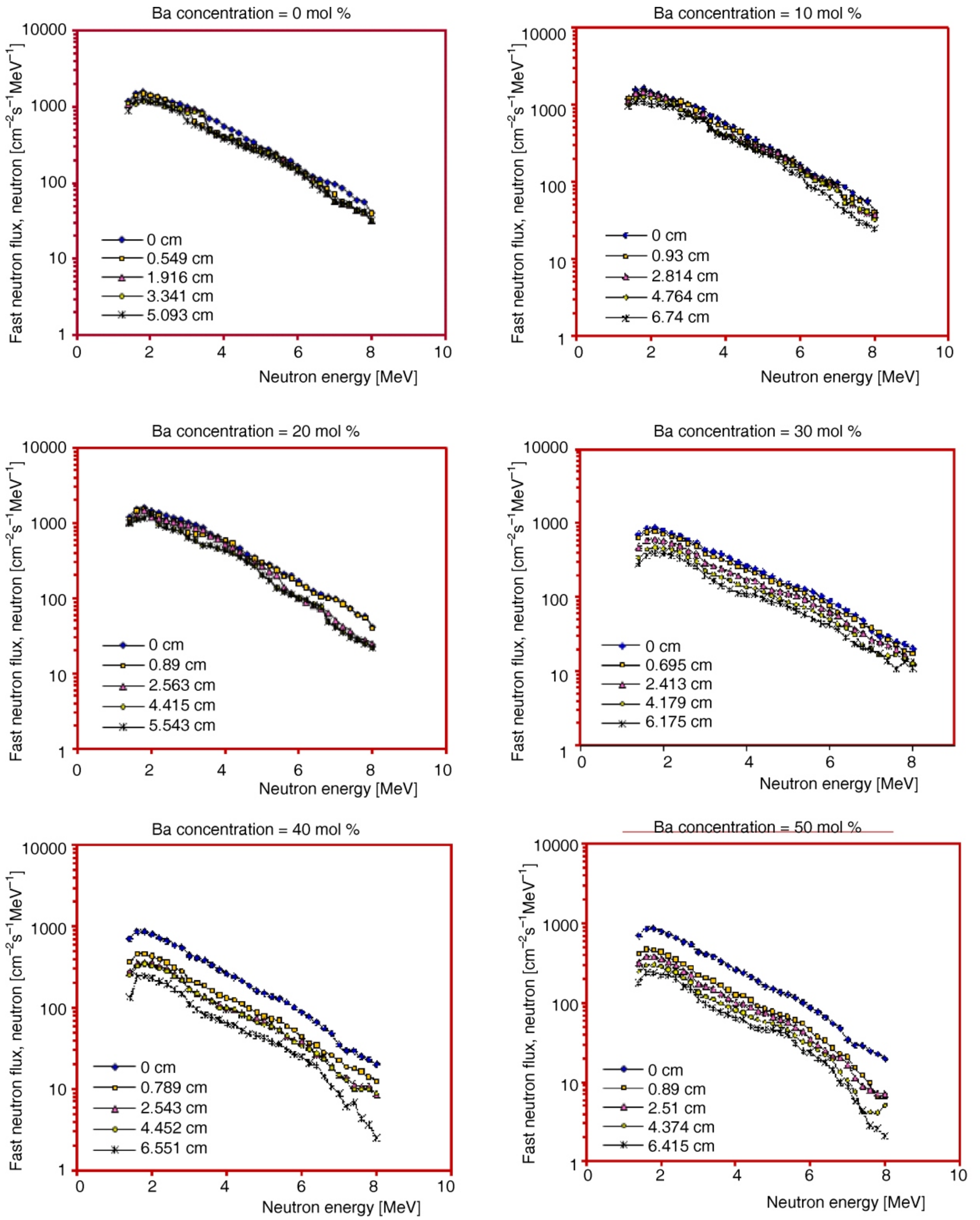

Figure 4. Fast neutron spectra behind different barriers of the investigated glass samples

mention that the neutron spectra initially emitted from the irradiation cell does not show any sharp maxima or minima, and therefore it is quite suitable to be used for the determination of the investigated glass barriers cross-sections by the transmission method. The figure also showed that the flux decreased as the glass thickness increased for the transmitted fast neutrons. The total integral fluxes for the region of neutron energies from 1.4-8 MeV were used to perform the attenuation relations of fast neutrons transmitted through the investigated glass barriers of thickness varying from 0 cm up to 6.74 cm. The transmitted fast neutron flux through glassy barriers was given as a function of barrier thickness. Figure 5 showed the relation between total removal macroscopic cross-sections (Σ_F) of fast neutrons, which were deduced from the attenuation curves, and

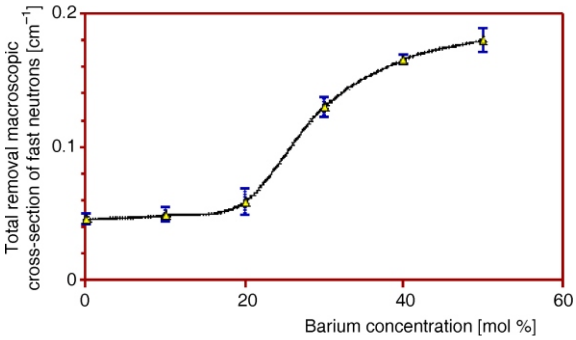

Figure 5. Variation of total removal macroscopic cross-section of fast neutrons with Ba concentration in glass samples

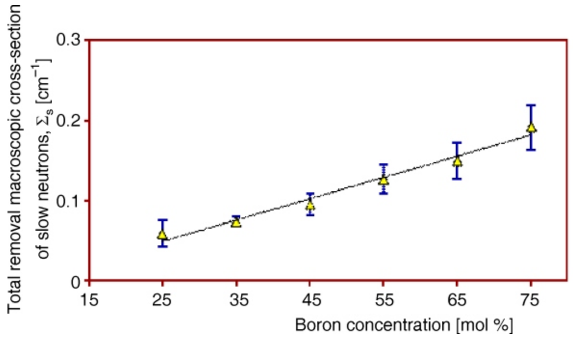

Figure 6. Total removal macroscopic cross-sections of slow neutrons in glass samples

the mol percentage of barium in the glassy barriers. It can be seen that, the value of Σ_F did not show any appreciable increase up to 20 mol% of barium concentration, while at higher concentrations an appreciable increase in Σ_F was observed. This could be attributed to the removal of fast neutrons up to 20 mol% barium concentration via inelastic scattering (*n*, *n*/γ) which has not provedwas not so effective. While for Ba concentrations between 20 to 50 mol %, which is the maximum concentration of our choice, the increment of Ba follows by a higher removal macroscopic cross-section for fast neutrons via inelastic scattering process which may be followed by radiation capture process for slow down neutrons with boron nuclei. The half value thickness (HVL) and relaxation length (λ) for fast neutrons were listed in tab. 1. Figure 5 and tab. 1 showed that, the attenuation properties of fast neutron increased as the barium concentration increased up to 50 mol %.

Total removal macroscopic cross-section of slow neutrons

The total removal macroscopic cross-sections of slow neutrons (Σ_S), deduced from the attenuation curves, were plotted versus boron concentration as shown in fig. 6. It is clear that, the values of Σ_S increased as the boron concentration i ncreased up to 75 mol %.

For slow neutrons, the half value thickness (HVL) and relaxation length (λ) were listed in tab. 2. The obtained results showed that, the attenuation properties of slow neutron improved as the boron concentration increased.

Total linear attenuation coefficients

The obtained results for total gamma ray spectra, primary in addition to secondary, transmitted through different barriers of glass media, were given in fig. 7. Such figure showed also the initial primary gamma spectra emitted directly from the irradiation cell. The total gamma ray spectra, transmitted through different barriers of glass media, had an irregular pattern in shapes and attenuation profile. However, the displayed spectra showed that, the total gamma flux was not decreased regularly as the glass barriers increased.

Some peaks were observed at different gamma photon energy in the spectra behind glass barriers. Main peak was observed at photon energy 2.3 MeV in all investigated samples. This peak was due to γ-ray initially emitted from ^{252}Cf source. Another peak was observed at photon energy of about 6.5 MeV in samples with barium concentrations 10, 20, 30, and 40 mol %. This peak was due to the inelastic scattering of fast neutrons with barium nuclei (*n*, *n*/γ), which disappeared at 50 mol % barium concentration; this may be attributed to the barium concentration, high enough to absorb secondary γ-ray at such energy. Pronounced peak was observed in the gamma spectra at photon energy 4 MeV in samples with barium concentrations 40 and 50 mol %. Such peak may be due to gamma rays produced from radiative capture of slow neutrons by boron nuclei in glass sample.

Table 1. Calculated radiation parameters of fast neutrons for glass samples under investigation

Parameter	Ba = 0 [mol %]	Ba = 10 [mol %]	Ba = 20 [mol %]	Ba = 30 [mol %]	Ba = 40 [mol %]	Ba = 50 [mol %]
HVL [cm]	15.04	14.12	11.75	5.32	4.18	3.84
λ [cm^{-1}]	21.69	20.37	16.95	7.68	6.04	5.54

Table 2. Radiation attenuation parameters of slow neutrons for glass samples under investigation

Parameter	B = 25 [mol %]	B = 35 [mol %]	B = 45 [mol %]	B = 55 [mol %]	B = 65 [mol %]	B = 75 [mol %]
HVL [cm]	11.79	9.37	7.28	5.48	4.63	3.62
λ [cm^{-1}]	17.01	13.51	10.50	7.91	6.68	5.22

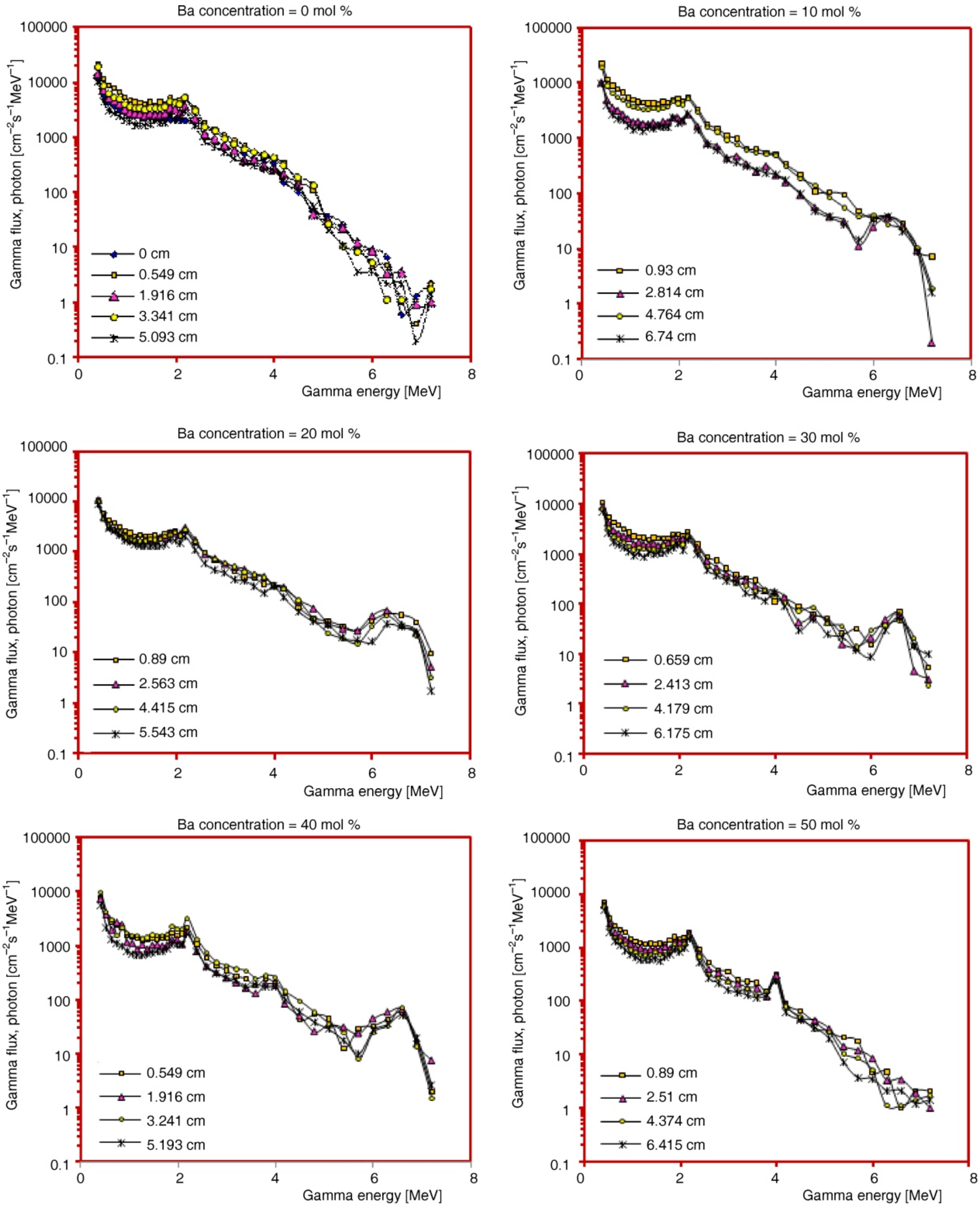

Figure 7. Total gamma ray spectra behind different barriers

The attenuation relations for integral flux of total gamma rays, (in the energy range from 0.407 to 7.19 MeV) measured behind the investigated glass barriers, were used to derive the total linear attenuation coefficients [μ_T, cm^{-1}] and were plotted as a function of barium concentration, as shown in fig. 8. μ_T of γ-rays showed a very slight increase with barium concentration up to 20 mol %. This can be attributed to balance between the absorption term and the new produced γ-rays term. While an appreciable increase in μ_T was observed at higher concentrations up to 50 mol %, which meant that the absorption term exceeded the production term. Strange result was obtained at barium concentration 40 mol %.

The half value thickness (HVL) and relaxation length (λ) for total gamma rays were listed in tab. 3.

Table 3. Radiation parameters of total gamma rays for glass samples under investigation

Parameter	Ba = 0 [mol %]	Ba = 10 [mol %]	Ba = 20 [mol %]	Ba = 30 [mol %]	Ba = 40 [mol %]	Ba = 50 [mol %]
HVL [cm]	10.16	12.06	09.55	05.68	12.16	05.05
λ [cm^{-1}]	14.66	17.39	13.77	08.20	17.54	07.28

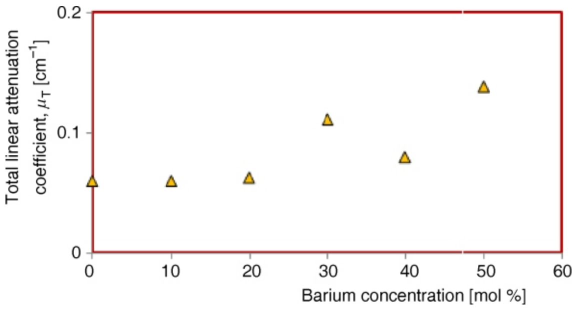

Figure 8. Total linear attenuation coefficients of γ-rays in glass samples

CONCLUSION

Synthesis of novel transparent glass materiel was studied regarding the shielding properties of fast, slow neutrons, and total gamma rays. Integral flux values of fast and slow neutrons decreased exponentially with increasing the barium and boron concentration respectively. The γ-ray shielding for such samples were effective at barium concentration exceedsing 20 mol % up to 50 mol % as an option, in which it agrees with what was obtained in our previous work done on the same samples for pure gamma emitter [18]. Obtained results for neutrons and gamma rays may be useful for nuclear research community and shielding design of hot cells.

AUTHORS' CONTRIBUTIONS

The sample preparation was done by A. Saeed. The material properties work was done by M. M. El-Okr, A. M. Abou El-azm, Y. H. Elbashar. The radiation measurements and their data analysis were carried out by A. Saeed, R. M. El Shazly, M. N. Hussien Comsan, W. A. Kansouh, A. R. El-Sersy.

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СВОЈСТВА СТАКЛА ВИСОКЕ ГУСТИНЕ ТРЕТИРАНОГ БОРОМ У ЗАШТИТИ ОД НЕУТРОНСКОГ ЗРАЧЕЊА

Експериментално су одређена заштитна својства стакла високе густине третираног бором од неутронског зрачења. Ради карактеризације атенуационих својстава система стакла (75-x) B_2O_3-1Li_2O-5MgO-5ZnO-14Na_2O-xBaO, у условима добре геометрије мерења, одређени су укупни макроскопски ефикасни пресек за уклањање брзих и спорих неутрона и линеарни коефицијент слабљења укупног гама зрачења, примарног и секундарног. Како би се измерила атенуациона својства брзих и спорих неутрона и укупног гама зрачења, плоче различитих дебљина испитиваног стакла излагане су колимисаном снопу неутрона емитованих из извора ^{252}Cf и ^{241}Am-Be. Резултати потврђују да је стакло са баријумом и бором погодно за практичну примену у области заштите од зрачења.

Кључне речи: заштитни материјал, брзи неутрон, спори неутрон, ефикасни пресек за уклањање, гама зрачење