

COMPARATIVE STUDY ON THE EFFECTS OF Cs₂O AND SrO DOPING WITH BOROSILICATE GLASS FOR CHARGED PARTICLES AND GAMMA-RAYS SHIELDING

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Abstract

The comparative study on Cs₂O and SrO doping with borosilicate glass for charged particles and gamma-rays shielding were calculated using SRIM program and WinXCom program. The trend of μ_m shows the values of the Cs-Sr sample more than the No-Cs-Sr sample because of the influence of the Cs and Sr elements. The Z_{eff} and N_{eff} values found the same trend and the value of the Cs-Sr sample was more than the No-Cs-Sr sample. The HVL result shows an increasing value when the photon energy increases. The TMPS of the No-Cs-Sr sample is higher than the Sr-Cs sample which means that Sr-Cs has a better potential to stop charged energy. For the proton particle, the results show that the Sr-Cs values are less than the No-Cs-Sr sample in all the energy ranges and the same trend with the alpha particle. The result of ion distribution shows consistency according to both TMSP and PR.

Keywords: Effective atomic number; The mass attenuation coefficient; SRIM

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Introduction

Glass is an amorphous material that can be applied in many fields such as for use in industry, interiors, imitation jewelry, and for specific applications. There are many advantages of glass materials because they are completely recyclable material, transparent, withstand high temperatures, low-cost to prepare, and variety of chemical formulations. Borosilicate glass is the popular host for applied in any field due to its low coefficient of thermal expansion, harder and stronger than soda-lime glass which the former of this glass is made from SiO₂ and Bi₂O₃. From specific applications, some types of glass materials can be used for charged particles and gamma-rays/X-rays shielding materials in the radiation room, but it should know the shielding properties before any is applied (Singh *et al.*, 2014).

The mass attenuation coefficients (μ_m), the atomic cross-section, the effective atomic number (Z_{eff}), and the electron density (N_{eff}) are the basic gamma-rays/X-rays shielding properties which can be theoretical calculations using such as WinXCom and Phy-X program (Gerward *et al.*, 2004). On the other hand, the charge particle properties can be used SRIM program to calculate (Ziegler *et al.*, 2010). The borosilicate glass is very interesting for applied to be a glass shielding material if the chemicals are properly such as Bi, W, Cs, and Gd elements or using chemicals containing high 'z' elements and high density but it should be considered the melting temperature. Many researchers have studied borosilicate glass such as Kilicoglu studies of the nuclear radiation shielding performance of borosilicate glasses (Kilicoglu *et al.*, 2023), Salama studies of gamma radiation and neutron shielding properties of transparent alkali borosilicate glass containing lead (Salama *et al.*, 2019), and Esawii studies of high impact tungsten-doped borosilicate glass (Esawii *et al.*, 2022).

In this study, the comparative of borosilicate glass was made using surrogate wastes composed of Cs and Sr elements, as representative of highly radioactive nuclides generated during spent nuclear fuel management were studied (Choi *et al.*, 2022). The parameters of gamma-rays/X-rays shielding properties such as the μ_m , Z_{eff} , N_{eff} and half values layer (HVL) were reported using the WinXCom program in the range of 15 keV to 15 MeV. The charge particle parameters were computed using the SRIM program and total mass stopping power, the projected ranges, and ion distribution were reported in the range of 10 keV to 10 MeV for proton and alpha particles.

Theoretical Background

The glass formula used in this study is 50SiO₂: 10B₂O₃: 13Na₂O: 2Li₂O: 3.69Cs₂O: 1.23SrO: 2.94BaO: 17.14Nd₂O₃ (Sr-Cs) and 54.92SiO₂: 10B₂O₃: 13Na₂O: 2Li₂O: 2.94BaO: 17.14Nd₂O₃ (No_Cs-Sr). Both glass formulas were compared from gamma-rays shielding and charge particle properties.

The principle of μ_m base on compulation using WinXCom program is depicted in Equation 1.

$$\mu_m = \mu / \rho = \sum_i w_i (\mu / \rho)_i \quad (1)$$

Where $(\mu_m)_i$ is mass attenuation coefficient for individual element in glass matrix, w_i is the weight fraction of element (Gerward *et al.*, 2004).

The μ_m data from WinXCom program can be use for calculating the atomic cross section ($\sigma_{t,a}$), electronic cross section ($\sigma_{t,el}$) including Z_{eff} parameter of the glass matrix, as depicted in Equation 2 (Gerward *et al.*, 2004).

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} = \frac{\mu_m / N_A \sum_i (w_i / A_i)}{(1 / N_A) \sum_i \frac{f_i A_i}{Z_i} (\mu_m)_i} \quad (2)$$

The N_{eff} can be calculated from the relationship as shown in Equation 3.

$$N_{eff} = \frac{\mu_m}{\sigma_{t,el}} \quad (3)$$

The half value layer (HVL) refers to a material's capacity to halve the intensity of radiation, this value is depicted in Equation 4.

$$HVL = \frac{\ln 2}{\mu} \quad (4)$$

The total mass stopping power (MSP) refers to the rate at which charged particles, such as alpha and proton, lose energy per unit depth and density as they traverse a substance. This phenomenon, described by the Bethe-Bloch formula (Ziegler *et al.*, 2010):

$$TMSP = -\frac{1}{\rho} \frac{dE}{dx} = 2\pi N_A m_e r_e^2 c^2 \frac{Z}{A \beta^2} \left[\ln \left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (5)$$

where

- $r_e = e^2/m_e c^2$ classical electron radius
 $2\pi m_e r_e^2 c^2 = 0.1535 \text{ MeV g}^{-1}\text{cm}^2$
 $m_e =$ electron mass = $9.110 \cdot 10^{-31} \text{ kg}$
 $N_A =$ Avogadro's number = $6.022 \cdot 10^{23} \text{ mol}^{-1}$
 $I =$ mean ionization(*excitation*) potential of target
 $\rho =$ material density
 $Z =$ atomic number of absorber medium
 $A =$ atomic weight of absorber medium
 $z_e =$ charge of the incident particle
 $\beta = v/c$ of incident particle
 $\gamma = 1/\sqrt{1 - \beta^2}$
 $\delta =$ density effect correction (vital at high energy)
 $C =$ shell correction (already vital at low energy)
 $W_{max} =$ maximum kinetic energy imparted to an e^- in a single collision $\cong 2m_e c^2 (\beta\gamma)^2$, for $M \gg m_e$.

Results and Discussion

The study on Cs_2O and SrO doping with borosilicate shielding glass were computed using SRIM program and WinXCom program for charged particles and gamma-rays shielding, respectively. The gamma-ray shielding properties show the mass attenuation coefficient of Sr-Cs and No_Cs-Sr glasses sample as shown in Figure 1, in the range of 15 keV to 15 MeV. The result found that the graph showed discontinuities due to the absorption edges of elements of both samples. The glass formula with Cs-Sr sample, the element Sr (38), Cs (55), Ba (56) and Nd (60) show at K-shell with energy 16 keV, 36 keV, 37 keV and 44 keV, respectively. The results of glass formula with No_Cs-Sr sample show the element Ba (56) and Nd (60) show at K-shell with energy 37 keV and 44 keV, respectively. The absorption edge typically occurs at lower energy and depends on the element in the glass matrix. Moreover, the μ_m trend show the values of Cs-Sr sample more than No_Cs-Sr sample because of the influence of Cs and Sr element.

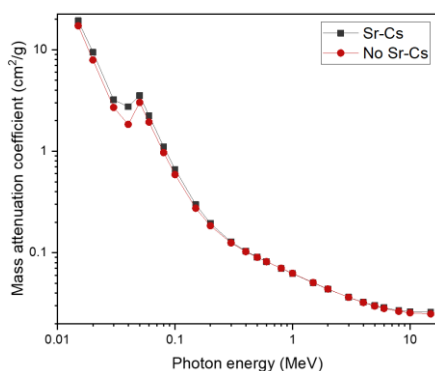


Figure 1. The μ_m of Sr-Cs and No_Cs-Sr glasses in the range of 15 keV to 15 MeV

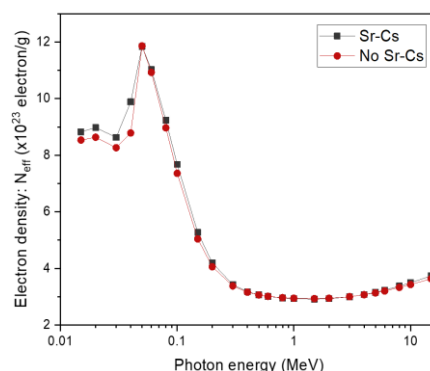


Figure 3. The N_{eff} of Sr-Cs and No_Cs-Sr glasses in the range of 15 keV to 15 MeV

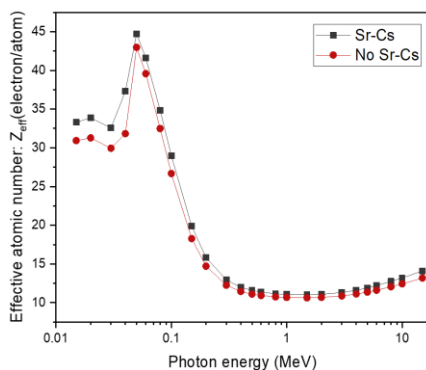


Figure 2. The Z_{eff} of Sr-Cs and No_Cs-Sr glasses in the range of 15 keV to 15 MeV

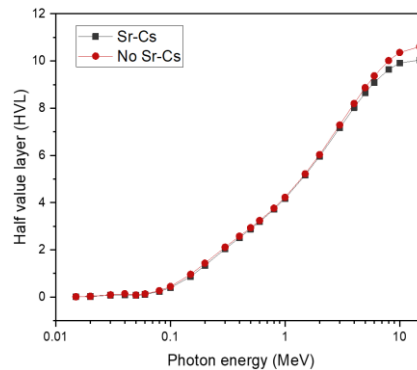


Figure 4. The HVL of Sr-Cs and No_Cs-Sr glasses in the range of 15 keV to 15 MeV

Figures 2 and 3 show the Z_{eff} and N_{eff} , respectively, both values found the same trend and the value of Cs-Sr sample more than No-Cs-Sr sample indicating that high probability more gamma-rays interaction in the glass matrix of Cs-Sr sample. Figure 4 shows the HVL of Sr-Cs and No-Cs-Sr sample in the range of 15 keV to 15 MeV. The result shows increasing value when the photon energy increased. The difference between the two examples is evident at higher energy levels. In the case of Sr-Cs, the half-value layer decreases significantly compared to No-Cs-Sr sample. This

indicates that Sr-Cs sample has better gamma-rays/X-rays shielding capabilities than No-Cs-Sr sample.

The total mass stopping power (TMPS) of Sr-Cs and No-Cs-Sr glasses in the range of 10 keV to 10 MeV for proton and alpha particles are shown in Figure 5. The ultimate peak of proton (^1_1H) and alpha (^4_2He) particle show in the range of 0.03-0.1 MeV for proton particle and 0.3-1.1 MeV for alpha particle. The TMPS of No-Cs-Sr sample higher than Sr-Cs sample which means that Sr-Cs has a better

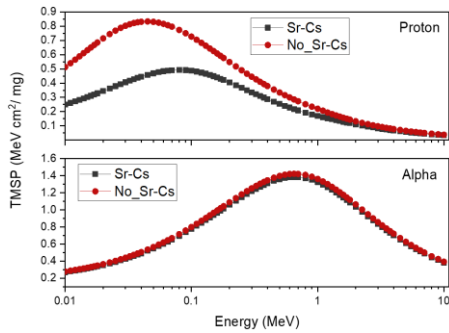


Figure 5. The total mass stopping power of Sr-Cs and No-Cs-Sr glasses in the range of 10 keV to 10 MeV for proton and alpha particles

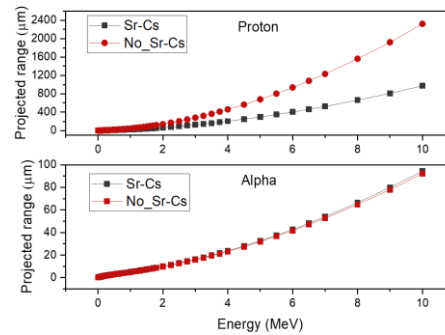
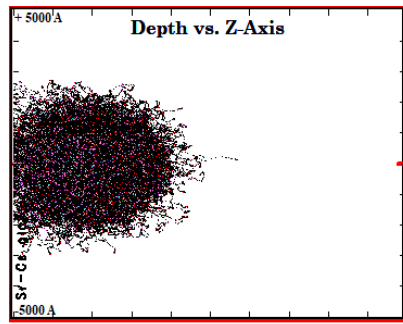


Figure 6. The projected ranges of Sr-Cs and No-Cs-Sr glasses in the range of 10 keV to 10 MeV for proton and alpha particles

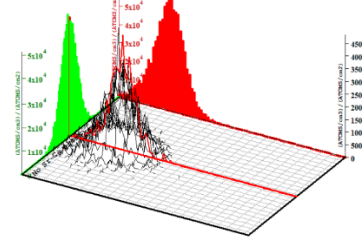


Proton 10 keV (Sr-Cs)

Ion Distribution

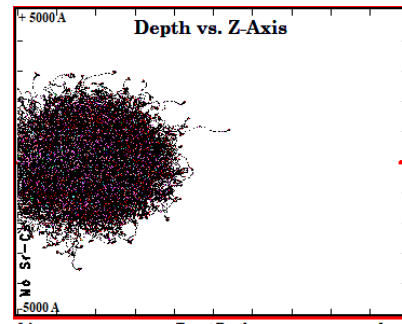
Ion Range = 2196 Å Skewness = -0.290

Straggle = 685 Å Kurtosis = 3.228



Plot Window goes from 0 Å to 1 um; cell width = 100 Å
Press F10 to speed plot. Rotate plot with Mouse.

Ion = H (10. keV)

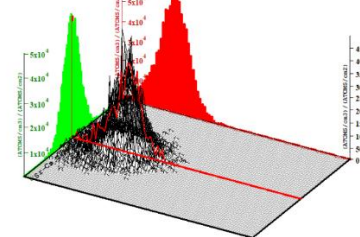


Proton 10 keV (No-Cs-Sr)

Ion Distribution

Ion Range = 2243 Å Skewness = -0.321

Straggle = 700 Å Kurtosis = 3.296



Plot Window goes from 0 Å to 1 um; cell width = 100 Å
Press F10 to speed plot. Rotate plot with Mouse.

Ion = H (10. keV)

Figure 7. Ion distribution of Sr-Cs and No-Cs-Sr glasses in the energy at 10 keV with proton particle

potential to stop charged energy. The TMPS of both particles was increased as the total mass increased until reaching the ultimate peak. Afterward, it gradually decreases with increasing energy. The TMSP varies with the number of ion charges and inversely with the square of the velocity at equal energy levels.

Figure 6 shows the projected ranges (PR) of Sr-Cs and No-Cs-Sr sample for proton and alpha particles. PR is one of the parameters to define the charged particle and was used in estimating particle transport in various simulation applications. For the proton particle, the results show that the Sr-Cs values are less than the No-Cs-Sr sample at all the energy ranges and the same trend with alpha particles. The results indicate that the Sr-Cs sample provides better charge particle shielding than the No-Cs-Sr sample because it exhibits superior absorption of both proton and alpha particles. The ion distribution of Sr-Cs and No-Cs-Sr samples in the energy at 10 keV with proton and alpha particles were shown in Figures 7 and 8. The proton particle values of Sr-Cs and No-Cs-Sr samples show the ion range values 2196 Å and 2243 Å, respectively. For the alpha particle values of Sr-Cs and No-Cs-Sr samples show

the ion range values 1523 Å and 1555 Å, respectively. The result of ion distribution shows consistency according to both TMSP and PR.

Conclusions

The computational of Sr-Cs and No-Cs-Sr glass samples was successful for gamma-rays and charge particle properties. The trend of μ_m shows the values of the Cs-Sr sample more than the No-Cs-Sr sample because of the influence of the Cs and Sr elements. The Z_{eff} and N_{eff} values found the same trend and the value of the Cs-Sr sample was more than the No-Cs-Sr sample. The HVL result shows an increasing value when the photon energy increases. The TMPS of the No-Cs-Sr sample is higher than the Sr-Cs sample which means that Sr-Cs has a better potential to stop charged energy. For the proton particle, the results show that the Sr-Cs values are less than the No-Cs-Sr sample in all the energy ranges and the same trend with the alpha particle. The result of ion distribution shows consistency according to both TMSP and PR.

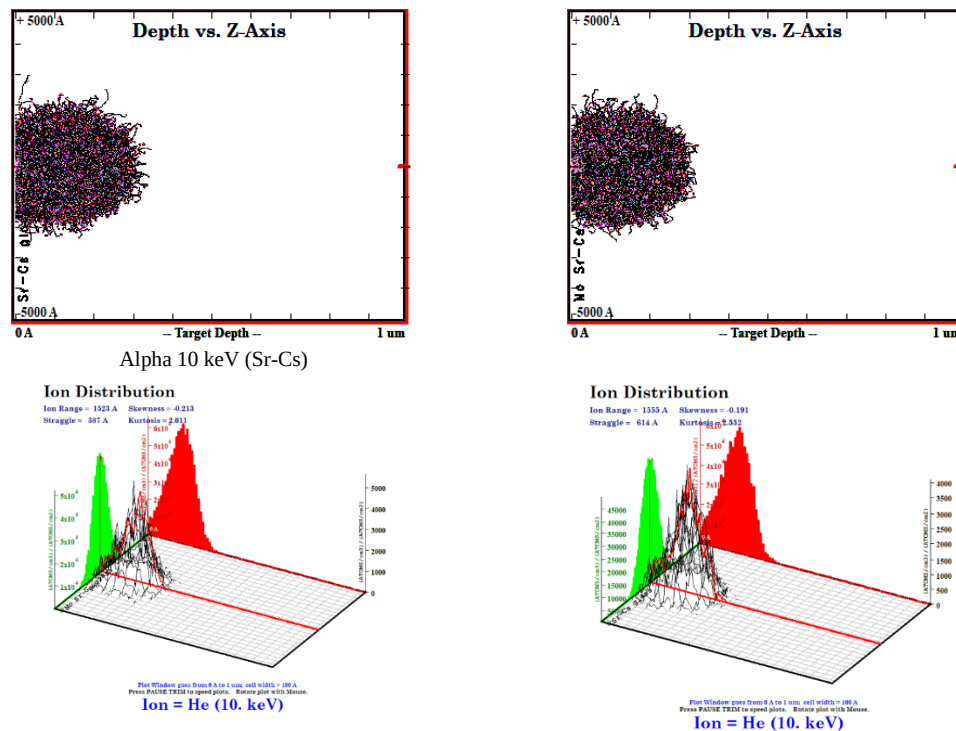


Figure 8. Ion distribution of Sr-Cs and No-Cs-Sr glasses in the energy at 10 keV with alpha particle

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