

GAMMA-RAYS AND CHARGE PARTICLE INTERACTION OF SR CO-DOPED CSI(TL) SCINTILLATOR

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Abstract

In this study, the mass attenuation coefficient (μ_m), the effective atomic number (Z_{eff}) and the effective electron density (N_{eff}) of Sr Co-Doped CsI(Tl) scintillator were measured at different gamma ray energies which irradiated with eight different photon energies using Compton scattering technique. The experimental results were compared with the theoretical (WinXcom) values. The results show that the values of μ_m , Z_{eff} and N_{eff} increased toward the decrease of gamma ray energies. The charge particle interaction using SRIM program was also investigated and reported.

Keywords: Mass attenuation coefficient; SRIM; Gamma-rays; Scintillator

Introduction

Scintillators have played a major role in the development of modern physics and are widely used in many fields, including oil exploration, high-energy physics, nuclear medicine, and security check. The important requirements for materials to be used as scintillators are high light yield, good energy resolution, fast decay time, high density (ρ), high effective atomic number (Z_{eff}), good thermal stability, and a low afterglow intensity (Tariwong *et al.*, 2022). Many old and new scintillators were developed for various objectives such as high energy physics for special experiments (CaMo₄),

industry (BGO, LYSO and LuYAP) and medical therapy (GAGG, CeBr₃, and LaBr₃) (Swiderski *et al.*, 2014; David *et al.*, 2015; Khodadoost and Araghi, 2019).

CsI(Tl) is a classic scintillator and very popular for application in various fields because of good energy resolution, high light yield, fast decay time and high density. Nowadays, the researcher intends to develop many classic scintillators for enhanced by co-doped with some elements such as Ce³⁺, Eu²⁺ and In⁺ (Swiderski *et al.*, 2014; David *et al.*, 2015; Khodadoost and Araghi, 2019).

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Generally, the interactions of gamma-rays and charge particles are also important for applying the interaction database in scintillation experiments. There is less literature available concerning the initial photon and charge particle interaction with Sr Co-Doped CsI(Tl) scintillator (Gerward *et al.*, 2004; Ziegler *et al.*, 2010). Hence, studying gamma rays and charged particles is particularly intriguing as it provides valuable data for future research.

Consequently, this research is focused on the primary theoretical and experimental study of the interaction with Sr Co-Doped CsI(Tl) scintillator and will be compared with CsI(Tl) scintillator using the WinXCom software and Compton experimental. The μ_m , Z_{eff} and N_{eff} were also reported and discussed. The charge particle was also reported in the parameter the mass stopping power and project range using the SRIM program.

Theory and experiment

This work explores the potential of Sr Co-Doped CsI(Tl) scintillator for radiation detection applications by delving into its interactions with gamma rays and charged particles. It utilizes equations and derivations to unveil the underlying physical processes.

Total mass attenuation coefficient

Quantifying the photon interaction probability per unit mass, the mass attenuation coefficient (μ/ρ) can be expressed as:

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

where, $\sum_i$ represents the summation over all elements in the compound or mixture, w_i is the weight fraction of the i -th element, $(\mu/\rho)_i$ is the mass attenuation coefficient of the i -th element.

The mass attenuation coefficient (μ_m) of experimental was calculated following:

$$\mu_m = \frac{\ln(i_0/i)}{\rho t}, \quad (2)$$

When ρ is the material density (g/cm^3), i_0 is the initial intensity, i is the intensity of the attenuated beam, and t is thickness of the shielding material (cm) (Singh *et al.*, 2006).

The effective atomic number and the effective electron density

The effective atomic number is the number of electrons that interact with photons in the unit electron per atom. The relationship can be evaluated using the equation (Chanthima *et al.*, 2012; 2017).

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \quad (3)$$

The number of electrons is present in each amount of the substance that is interacting. It is the probability interaction between an electron and a photon and depends on the electron density value (Chanthima *et al.*, 2012, 2017).

$$N_{eff} = \frac{\mu_m}{\sigma_{t,el}} \quad (4)$$

Compton Scattering

For high-energy photons, Compton scattering dominates the interaction with loosely bound electrons in the scintillator. Its energy transfer from photon to electron is captured by:

$$E_{\gamma'} = E_{\gamma} / (1 + E_{\gamma} / (m_e c^2) (1 - \cos\theta)) \quad (5)$$

Where, E_{γ} is the incident photon energy, $E_{\gamma'}$ is the scattered photon energy, m_e is the electron rest mass, c is the speed of light, θ is the scattering angle. This equation highlights the scattered photon's energy decrease due to energy imparted to the recoiling electron. The dependence on scattering angle implies a spectrum of scattered photon energies for a given incident photon energy.

SRIM simulation

Charged particles (electrons, positrons, protons, etc.) interacting with the scintillator can significantly influence energy deposition and signal generation. They investigate these processes using theoretical models and Monte Carlo simulations as the SRIM program. The average energy dissipated by a charged particle as it moves through a substance can be described by its mass stopping power.

Mass stopping power

The mass stopping power (MSP) is the charged particles to lose energy per depth per density. When a charge particle (alpha and proton) travels through a substance, its energy gradually diminishes until it stop, as described by the Bethe-Bloch formula (Braibant *et al.*, 2012):

$$\text{TMSP} = -\frac{1}{\rho} \frac{dE}{dx} = 2\pi N_A m_e r_e^2 c^2 \frac{Z}{A} \frac{Z_e^2}{\beta^2} \left[\ln \left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right] \quad (10)$$

where

$$r_e = e^2 / m_e c^2 \text{ classical electron radius} \\ 2\pi m_e r_e^2 c^2 = 0.1535 \text{ MeV g}^{-1} \text{cm}^2$$

m_e = electron mass = $9.110 \cdot 10^{-31}$ kg
 N_A = Avogadro's number = $6.022 \cdot 10^{23}$ mol $^{-1}$
 I = mean ionization(excitation) potential of target
 ρ = 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
 $\gamma = 1/\sqrt{1 - \beta^2}$
 δ = 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 $M \gg m_e$.

The project range (PR) is one of parameter to define the charge particle and were used estimating particle transport in various simulation applications. PR values can be computed by equation as (Kavaz *et al.*, 2019):

$$R(\beta) = \left(\frac{M}{Z^2}\right) R_p(\beta) \quad (7)$$

When, $R_p(\beta)$ is project range (PR) for charged particles. β is heavy particles with the same initial velocity.

Results and Discussion

The photon interactions of CsI(Tl) and CsI(Tl)+Sr scintillators in energy range of 0.001 to 10^5 MeV using WinXcom program. Figure 1. show the μ_m in the scintillator, the photoelectric absorption, Compton scattering, and the pair production found the three major interaction that it called the partial interaction. Moreover, the result found that the μ_m slightly decreased when energy increase from 0.001 to 105 MeV. The graph showed discontinuities for both scintillators at the low energy because of the absorption edges of elements Cs (55) and I (53) show at 55M2, 55M1 (1.065 keV and 1.217 keV) of Cs. The L and K shell of Cs element show at 55L3, 55L2, 55L1, and 55K show at 5.012 keV, 5.359 keV, 5.714 keV and 35.98 keV. At the M, L and K shell of I element show at 53 M1, 53 L3, 53 L2, 53 L1, 53 K of the energy 1.072 keV, 4.557 keV, 4.852 keV, 5.188 keV, and 33.17 keV, respectively. The absorption edge depends on many factors such as the atomic number, the energy of the photon, and the uniqueness of the atom.

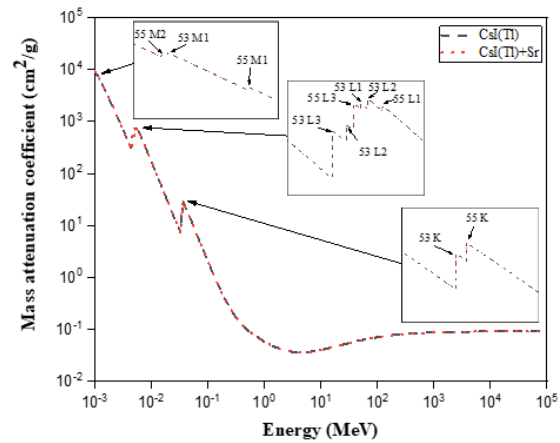


Figure 1. The mass attenuation coefficient of CsI(Tl) and CsI(Tl)+Sr at 0.001 to 105 MeV.

From the experiment part using Compton experiment, the μ_m , Z_{eff} and N_{eff} values were slightly increased toward the decrease of gamma ray energies range of 224-662 keV as shown in Figures 2 - 4, The trend showed a slight increase because the atomic number of Cs (55) and I (53) is not a big difference as well as the impurity (Tl and Sr) of this scintillator does not influence change in these values because it is doped in a very small amount. Furthermore, the graph shows a similar trend between CsI(Tl) and CsI(Tl)+Sr for the same reason as mentioned above.

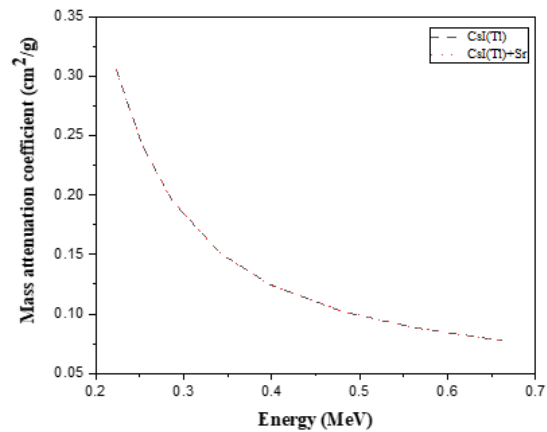


Figure 2. The total mass attenuation coefficient of CsI(Tl) and CsI(Tl)+Sr at Compton energy

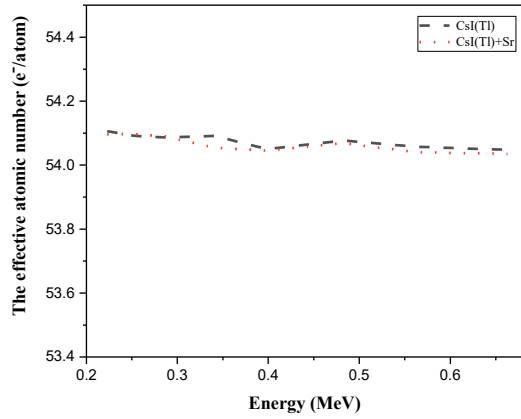


Figure 3. Effective atomic number of CsI(Tl) and CsI(Tl)+Sr at Compton energy

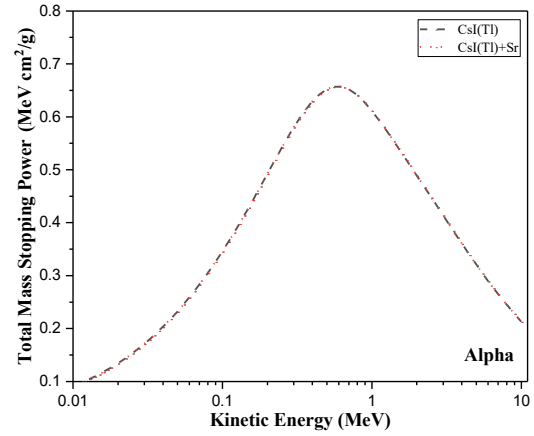


Figure 5. Total mass stopping power of CsI(Tl) vs. CsI(Tl)+Sr at 0.01 to 10 MeV.

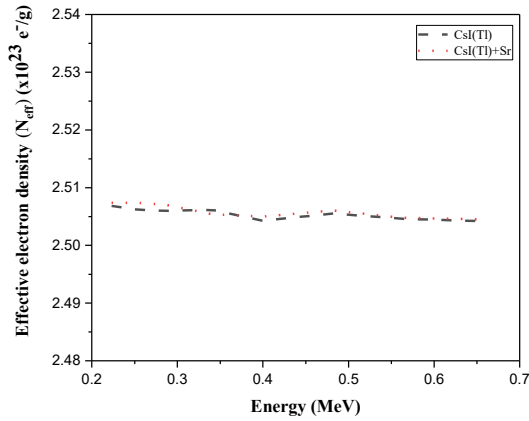


Figure 4. Effective electron density of CsI(Tl) and CsI(Tl)+Sr at Compton energy

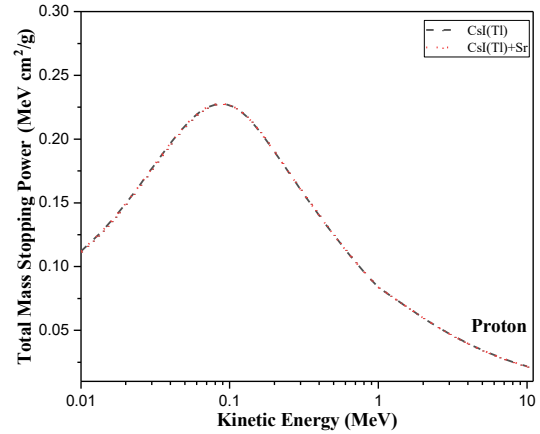


Figure 6. Total mass stopping power of CsI(Tl) vs. CsI(Tl)+Sr at 0.01 to 10 MeV.

Figure 5 and Figure 6 show the MSP of alpha particle and proton particle of CsI(Tl) and CsI(Tl)+Sr scintillators. The results found that the ultimate alpha particle (${}^4_2\text{He}$) is kinetic energy range 0.3–1.1 MeV, and the highest MSP of protons (${}^1_1\text{H}$) is in the kinetic energy range of 0.07–0.1 MeV, respectively. The loss of kinetic energy of ${}^4_2\text{He}$ more than ${}^1_1\text{H}$ because the alpha particles have a greater electric charge but move at slower speeds compared to protons, the MSP varies with the number of ion charges and inversely with the square of the velocity as equal energy levels. This relationship can be expressed as follows. Figure 7 and Figure 8 show the PR of CsI(Tl) and CsI(Tl)+Sr scintillators at 0.01 to 10 MeV. The PR values of both particles (alpha and proton) show increasing trends with decreasing kinetic energy and the same trend for both crystals. The PR value of ${}^4_2\text{He}$ and ${}^1_1\text{H}$ showed at 67.58 μm and 604.72 μm , respectively.

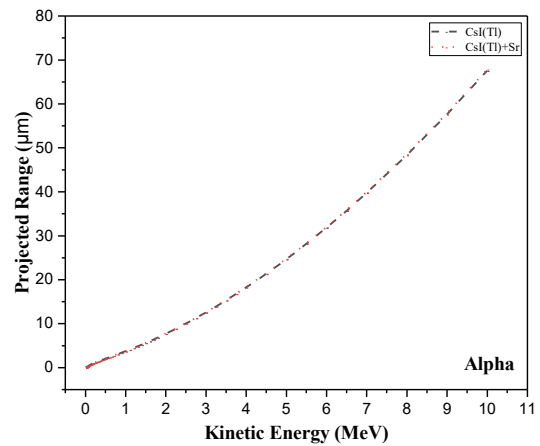


Figure 7. Project range of CsI(Tl) vs. CsI(Tl)+Sr at 0.01 to 10 MeV.

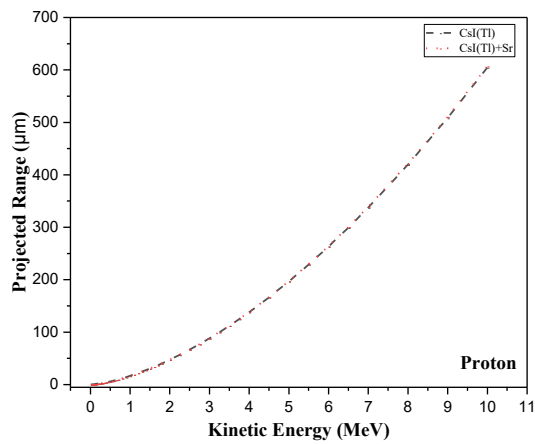


Figure 8. The total mass attenuation coefficient of CsI(Tl) and CsI(Tl)+Sr at Compton energy

The 2D-ion distribution of CsI(Tl) and CsI(Tl)+Sr at 10 keV with alpha particle and ion range of CsI(Tl) and CsI(Tl)+Sr at 10 keV with alpha particle were shown in Figure 9. The values of both crystals found the same trend because the impurity is added very small percentage. The values of alpha particle of both crystals show the ion range values 1059 Å and 1050 Å, respectively. Figure 10 shows 2D-ion distribution of CsI(Tl) and CsI(Tl)+Sr at 10 keV with proton particle and ion range of CsI(Tl) and CsI(Tl)+Sr at 10 keV with proton particle. The values of proton particle of both crystals show the ion range values 1315 Å and 1329 Å, respectively that is a higher target depth than alpha particle, indicates that the alpha particles have lower penetrating power compared to protons

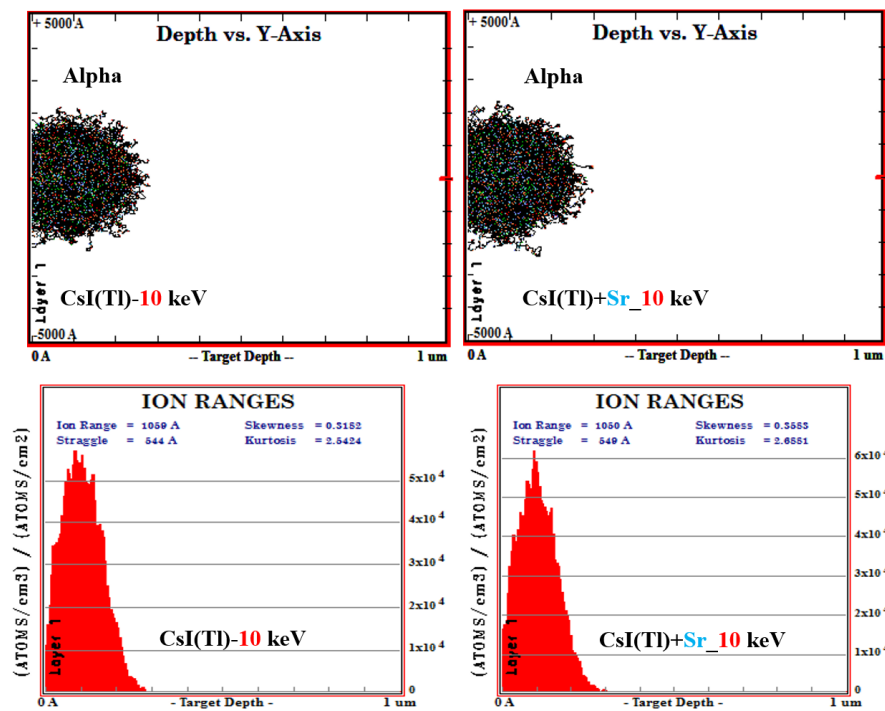


Figure 9. 2D-ion distribution of CsI(Tl) and CsI(Tl)+Sr at 10 keV with alpha particle and ion range of CsI(Tl) and CsI(Tl)+Sr at 10 keV with alpha particle

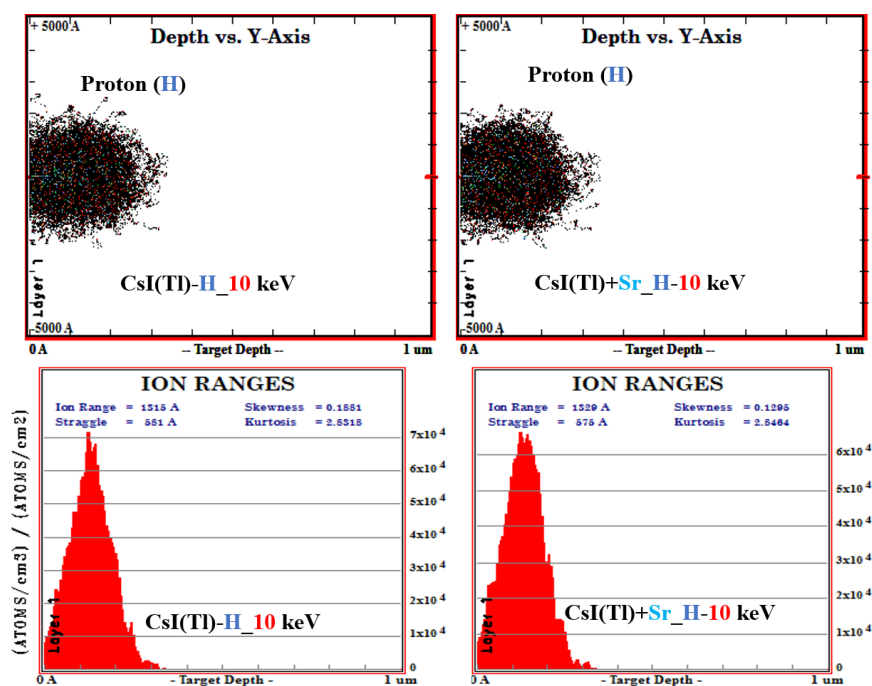


Figure 10. 2D-ion distribution of CsI(Tl) and CsI(Tl)+Sr at 10 keV with proton particle. and ion range of CsI(Tl) and CsI(Tl)+Sr at 10 keV with proton particle

Conclusions

The gamma-rays and charge particle interaction study of the CsI(Tl)+Sr were completed. The results showed the μ_m , Z_{eff} , and N_{eff} depends on the photon energy ranges. The μ_m , Z_{eff} and N_{eff} values were slightly increased toward the decrease of gamma ray energies range of 224-662 keV. TMSP of the alpha particle tends to be higher than that of the proton. The projected range of alpha and protons particles in the CsI(Tl)+Sr increases with increasing energy. Moreover, the projected range of the proton is higher than that of the alpha particle when at the same energy.

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