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# The mass attenuation coefficients, effective atomic numbers and effective electron densities for GAGG:Ce and $CaMoO_4$ scintillators

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ABSTRACT

In this study, the mass attenuation coefficient ($\mu_m$), the effective atomic number ($Z_{eff}$) and the effective electron density ($N_{eff}$) of $Gd_3Al_2Ga_3O_{12}$:Ce (GAGG) and $CaMoO_4$ scintillators were measured at different gamma ray energies. The samples were irradiated with eight different photon energies using Compton scattering technique. The scattered photons from $^{137}$Cs source were detected by NaI(Tl) scintillation detector in an ordinary counting system. The experimental results were compared with the theoretical (WinXcom) values. The results show that the experimental values of$\mu_m$, $Z_{eff}$ and $N_{eff}$ of GAGG are higher than those of $CaMoO_4$ and all values are in good agreement with the theoretical ones. The values of$\mu_m$, $Z_{eff}$ and $N_{eff}$ increased toward the decrease of gamma ray energies. The partial interactions of the crystals were also investigated.

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## 1. Introduction

Inorganic scintilltors have an important role available for the detection of ionizing radiation of which a handful are suitable for use in nuclear engineering, space technology, agricultural and particularly in nuclear medicine, i.e., Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) (Yeom et al., 2013). The experiment for determination of the mass attenuation coefficient ($\mu_m$), is important for scintillator because of the experimental data of the $\mu_m$ shows probability of interaction and this data can be used for development and characterizations of new scintillation materials. Moreover, the total atomic cross-section ($\sigma_{t,a}$), the electronic cross-section ($\sigma_{t,el}$), the effective atomic number ($Z_{eff}$) and the effective electron density ($N_{eff}$) are the basic quantities required in determining the penetration of X-rays and gamma ray when they interact with matters. All mentioned parameters can be calculated using $\mu_m$ value. The$\mu_m$ is a measure of probability of interaction that occurs between incident photons and matter per unit mass per unit area thickness of the material encountered (Gupta and Sidhu, 2014). Accurate values of $\mu_m$ are required to provide essential data in diverse fields such as nuclear diagnostics (computerized tomography), radiation protection, radiation dosimetry, gamma ray fluorescence studies, radiation physics, shielding, security screening and etc. (Gounhalli et al., 2012). Many literature reported the experimental and theoretical investigations on photon interaction in different materials such as glasses (Kaewkhao and Limsuwan, 2010; Singh et al., 2006; Sharma et al., 2006; Kaewkhao et al., 2010; Limkitjaroenporn et al., 2011; Yasaka et al., 2014), amino acids (Turşucu et al., 2013; Chaitali et al., 2016; Prashant and Pravina, 2014; Pravina and Govind, 2013), alloys (Narender et al., 2013; Han and Demir, 2009a,b,c, Han et al., 2012), natural minerals (Han et al., 2009), polymers (Kucuk et al., 2013), gemstones (Medhat, 2012; Korkut et al., 2011; Kaewkhao et al., 2012), semiconductors (Erzeneoğlu et al., 2006) and superconductors (Cevik and Baltas, 2007).

Hine, 1952 pointed out that, for photon interactions in composite materials, a single number cannot uniquely represent the atomic number across the entire energy region, as in the case of pure elements. This number, for composite materials, is known as "effective atomic number" ($Z_{eff}$) and it varies with energy. The effective electron density ($N_{eff}$) is effective electron per unit mass of composite materials and can be calculated from $Z_{eff}$.

In this work, the calcium molybdate ($CaMoO_4$) and cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$:Ce or GAGG:Ce) were chosen for the study because they are very

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important scintillator and can be used in specific important applications. $CaMoO_4$ is one of the inorganic scintillator intensively studied for application in the very important experiment of neutrinoless $^{100}$Mo double beta decay experiments in AMoRE (Advanced Mo Based Rare Experiment). $^{100}$Mo is a good double beta decay candidate due to high transition energy (3034 keV) (Belogurov et al., 2005). The main properties of $CaMoO_4$ scintillators were also presented (Annenkov et al., 2008).

An ideal scintillation material for positron emission tomography (PET) would have high light yield, high density and effective atomic number, fast decay time, emission wavelength that matches well with the spectral sensitivity of the photodetector and low non-proportionality (Yeom et al., 2013). Cerium doped gadolinium aluminum gallium garnet ($Gd_3Al_2Ga_3O_{12}$:Ce or GAGG:Ce) is an attractive candidate for many applications such as PET and gamma spectroscopy due to very good properties of GAGG crystal such as high density, good energy resolution, high light yield, low non-proportionality and inexpensive to manufacture (Yeom et al., 2013). Moreover, GAGG:Ce does not contain natural radioactivity, since it does not uses Lu, which produce simultaneously beta-gamma emissions of natural Lu-176 that affect the minimum detectable activity limits of a system (David et al., 2015).

The photon interaction data are very important for both of crystals. Until now, there is no data on photon interactions of $CaMoO_4$ and GAGG:Ce crystals In this paper, the photon interaction properties of $CaMoO_4$ and GAGG scintillation crystals have been studied. The$\mu_m$, $Z_{eff}$ and $N_{eff}$ of both crystals were investigated for eight different photon energies in the range of 223–662 keV. The experimental values obtained by the Compton scattering technique were compared with the calculated theoretical data using WinXcom program.

## 2. Theory

### 2.1. Compton scattering

The Compton scattering process is the interaction the incident gamma ray and an electron in the absorbing material. It is most often the predominant interaction mechanism for gamma ray energies typical of radioisotope sources. The expression that relates the energy transfer and the scattering angle for any given interaction can be simply derived by writing simultaneous equations for the conservation of energy and momentum (Knoll, 2000). The Compton scattering requires that the light is viewed as a particle and not just a wave because it is the collision of the photon with the electron results in the exchange of energy, which accounts for the shift in energy. The energy imparted to the recoil electron is given by the following equation (Trousfanidis, 1983).

$$E'_\gamma = \frac{E_\gamma}{1 + (1 - \cos\theta)E_\gamma / m_0c^2} \tag{1}$$

where $E'_\gamma$ is the scattered gamma ray energy, $E_\gamma$is the incident gamma ray energy, $\theta$ is the scattering angle and $m_0c^2$ is the rest-mass-energy of the electron (551 keV).

### 2.2. Computation of mass attenuation coefficient ($\mu_m$)

If a material of thickness t is placed in the path of a beam of gamma radiation, the intensity of the beam is attenuated according to the Beer–Lambert's law:

$$I = I_0 \exp^{-\mu t} \tag{2}$$

where $I_0$ is the incident gamma ray intensity when measured without sample and $I$ is transmitted gamma ray intensity when it pass through the sample, $t$ is the sample thickness (cm). A more convenient parameter coefficient characterizing a given material is the density independent mass attenuation coefficient by the following relation (Gerward et al., 2004).

$$\mu_m = \mu/\rho \left(\mathrm{cm}^2\ \mathrm{g}^{-1}\right) = \frac{\ln I_0}{\frac{I}{\rho t}} \tag{3}$$

Theoretical values of the mass attenuation coefficient of mixture or compound have been calculated by WinXcom (Gerward et al., 2001, 2004), based on the rule of mixture

$$\mu_m = \sum_i w_i (\mu_m)_i \tag{4}$$

where $w_i$ is the weight fraction of element in scintillation crystal, $(\mu_m)_i$ is µass attenuation coefficient for individual element in scintillation crystal. The value of mass attenuation coefficient can be used to determine the total atomic cross-section ($\sigma_{t,a}$) by the following relation (Limkitjaroenporn et al., 2011):

$$\sigma_{t,a} = \frac{(\mu_m)_{crystal}}{N_A \sum_i^n \left(\frac{w_i}{A_i}\right)} \tag{5}$$

where $N_A$ is Avogadro's number, $A_i$ is the atomic weight of constituent element of scintillation crystal. The total electronic cross-section ($\sigma_{t,el}$) for the element is also expressed by the following formula (Limkitjaroenporn et al., 2011):

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \tag{6}$$

where $f_i$ is the number of atoms of element $i$ relative to the total number of atoms of all elements in alloy, $Z_i$ is the atomic number of each element in scintillation crystal. Total atomic cross-section and total electronic cross-section are related to the effective atomic number ($Z_{eff}$) of the compound through the formula (Limkitjaroenporn et al., 2011):

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \tag{7}$$

The effective electron density ($N_{eff}$) can be defined as the number of electrons per unit mass, and it can be mathematically written as follows (Kaewkhao et al., 2008):

$$N_{eff} = \frac{\mu_m}{\sigma_{t,el}} \tag{8}$$

Calculation procedures and formula for mass attenuation coefficients and effective atomic number were explained in our previous papers (Chanthima et al., 2012; Kaewjang et al., 2014; Kaewkhao et al., 2010, 2011; Limkitjaroenporn and Kaewkhao, 2014).

## 3. Experimental setup

GAGG and $CaMoO_4$ scintillation crystals with the size of $10 \times 10 \times 8$ mm$^3$, and $10 \times 10 \times 10$ mm$^3$ respectively were obtained from Kyungpook National University (Korea). The density of GAGG and $CaMoO_4$ crystals are 6.63 g/cm$^3$ and 4.20 g/cm$^3$, respectively. The schematic arrangement of Compton scattering technique for

mass attenuation coefficient measurement is shown in Fig. 1. The source system was mounted on a composite of adjustable stands movable in transverse direction for proper beam alignment. The $^{137}$Cs (662 keV) radioactive source of 15 mCi strength was obtained from the Office of Atom for Peace (OAP), Thailand. The aluminum rod was used as the scattering rod. The scattered gamma rays were measured on a rotatable 2" × 2" NaI(Tl) scintillator detector in the scattering plane having an energy resolution of 8% at 662 keV (BICRON model 2M2/2), with CANBERRA photomultiplier tube base model 802-5. The optimum set up distances between the source to the scatterer and between the scatterer to the detector were found to be 20 cm. The spectra were measured using a CANBERRA PC-based multi-channel analyzer (MCA). The spectrum on the MCA of detector gave instance counts in each of 1024 bins divided by voltage. To measure the angular dependence of Compton scattering, we first performed a calibration on the relating channel number of the MCA spectrum with known energy of gamma-ray sources for various angles of the scatter detector. The scattering angles were used to produce gamma-ray of different energies. (Limkitjaroenporn et al., 2013). Kaewkhao et al. (2012) had applied the Compton scattering technique for measuring the mass attenuation coefficient and the validity and energy calibration of the system had been confirmed. The procedure for measuring the mass attenuation coefficient of glass samples at different gamma-ray energies was described in our previous work (Limkitjaroenporn et al., 2013; Kaewkhao et al., 2012).

## 4. Results and discussion

The mass attenuation coefficient values for GAGG and $CaMoO_4$ scintillation crystals were calculated from the intensities of incident ($I_0$) and transmitted ($I$) gamma rays measured for each energy. The corresponding theoretical values were calculated using WinXcom program (Gerward et al., 2004) for comparison. From Table 1, it is clearly seen that the mass attenuation coefficient of GAGG is higher than that of $CaMoO_4$, especially in the lower energy, reflecting that more photon interactions with GAGG crystal. This is due to the higher density of GAGG compared with $CaMoO_4$. Also, the GAGG consists of heavier element. This resulted in the higher light yield of GAGG (46,000 Photon/MeV) (Kamada et al., 2012) as compared with that of $CaMoO_4$ (6510 Photon/MeV) (So et al., 2012). The total mass attenuation coefficients of both crystals decrease with the increase of gamma rays energy (Fig. 2), indicates the dependence of total mass attenuation coefficient values on the photon energy. This result shows the higher probability of photons interaction in the lower photon energy while the interaction is reduced with the increase of photon energy. The experimental values of mass attenuation coefficient are in good agreement with the theoretical values. The relative difference percentage (% RD) in this work is less than 3% for all experimental data. As can be seen in Fig. 2, the uncertainty for each experimental data is small, reflecting the good precision of the measurement.

The partial interactions (photoelectric absorption, coherent and incoherent scatterings) of both crystals were calculated and the results are shown in Table 2. The coherent scattering interactions were found to have small effects on GAGG and $CaMoO_4$ crystals in this energy range. All partial interactions were higher at the low gamma rays energy. From Fig. 3, it can be seen that the incoherent scattering is the main interaction of $CaMoO_4$ crystal in this energy region. But for the case of GAGG, at the lower energy than 280 keV, the photoelectric absorption is main interaction. The $CaMoO_4$ has higher incoherent scattering than GAGG, but the total mass attenuation coefficient is lower. This is due to the higher photoelectric absorption of GAGG and the photoelectric absorption has shown to be a stronger effect on the total mass attenuation coefficient value in both crystals. Moreover, the difference in the total mass attenuation coefficient values of both crystals was found to be larger in the lower energy due to the photoelectric absorption process.

Table 3 presents the effective atomic numbers ($Z_{eff}$) as determined by Eq. (7). It is seen that with increasing the gamma ray energy, a very high effective atomic number of GAGG crystal (48.27) is decreased to 26.60 electrons/atom while for $CaMoO_4$ it is decreased from 20.13 to 16.15 electrons/atom. The theoretical values ($Z_{eff}(th)$) were found to be the same trend which are in good agreement with the experimental values as shown in Fig. 4. The mass attenuation coefficient results were found to be the same trend and showing that the interaction probability is strongly related to the effective atomic number.

The effective electron density values ($N_{eff}$) of GAGG and $CaMoO_4$ crystals as determined from Eq. (8) are shown in Table 3. Fig. 5 presents the comparison of theoretical and experimental $N_{eff}$ values. It is seen that the $N_{eff}$ value of GAGG crystal are in the range

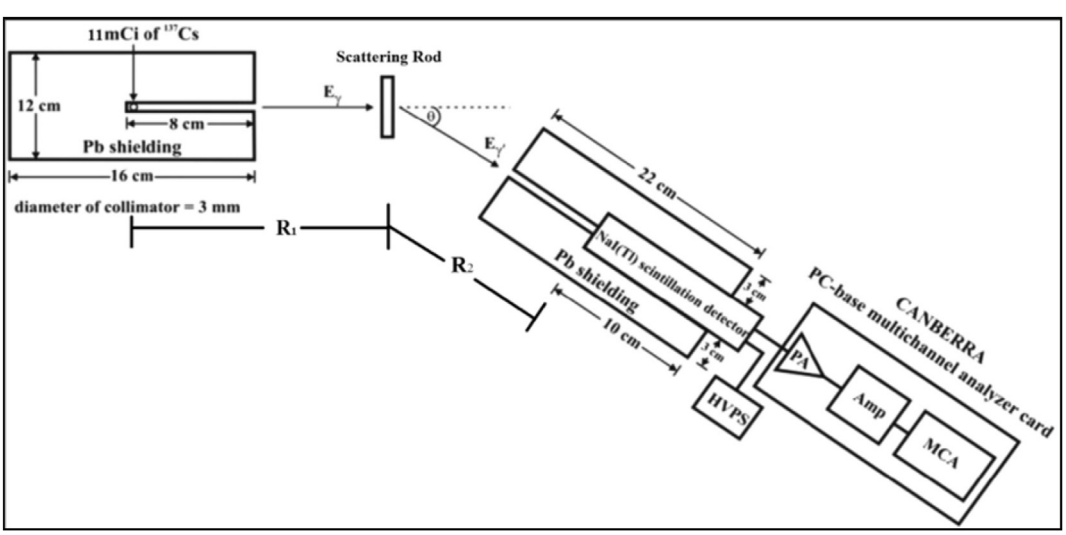


**Fig. 1.** Schematic of the Compton scattering technique for mass attenuation coefficient measurement.

**Table 1**
Mass attenuation coefficients of GAGG and $CaMoO_4$ scintillation crystals at different gamma ray energies.

| E′(keV) | GAGG | | %RD | $CaMoO_4$ | | %RD |
|---|---|---|---|---|---|---|
| | $\mu_m$ (*th*) ($\times 10^{-2}$ cm$^2$/g) | $\mu_m$ (*ex*) ($\times 10^{-2}$ cm$^2$/g) | | $\mu_m$ (*th*) ($\times 10^{-2}$ cm$^2$/g) | $\mu_m$ (*ex*) ($\times 10^{-2}$ cm$^2$/g) | |
| 662.00 ± 18.00 | 7.99 | 8.00 ± 0.04 | 0.12 | 7.58 | 7.60 ± 0.05 | 0.26 |
| 562.68 ± 27.80 | 9.05 | 9.00 ± 0.24 | 0.59 | 8.26 | 8.43 ± 0.29 | 2.05 |
| 481.59 ± 20.50 | 10.36 | 10.34 ± 0.26 | 0.17 | 8.99 | 9.02 ± 0.12 | 0.31 |
| 398.97 ± 16.00 | 12.53 | 12.59 ± 0.33 | 0.50 | 10.06 | 10.32 ± 0.39 | 2.58 |
| 340.83 ± 16.20 | 15.10 | 15.41 ± 0.38 | 2.02 | 11.16 | 11.08 ± 0.43 | 0.71 |
| 287.28 ± 15.60 | 19.21 | 18.96 ± 0.48 | 1.32 | 12.72 | 12.64 ± 0.52 | 0.62 |
| 252.98 ± 14.20 | 23.51 | 23.31 ± 0.55 | 0.85 | 14.21 | 14.52 ± 0.55 | 2.18 |
| 223.02 ± 12.20 | 29.43 | 29.85 ± 0.83 | 1.41 | 16.16 | 15.78 ± 0.75 | 2.35 |

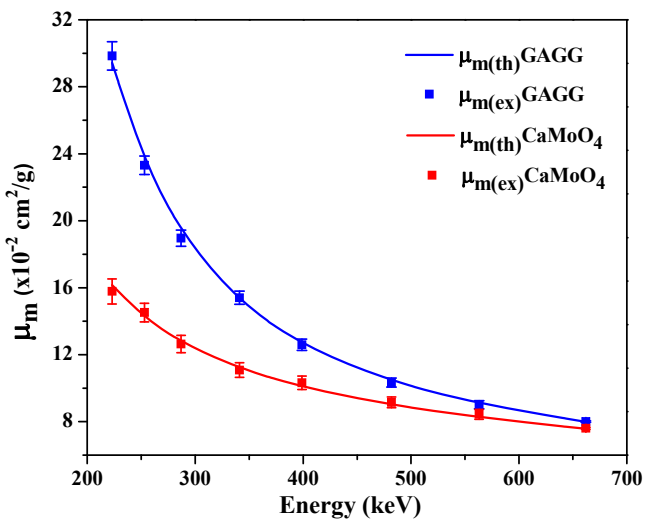


**Fig. 2.** Mass attenuation coefficients of GAGG and $CaMoO_4$ crystals in the energy region from 223.02 to 662.00 keV.

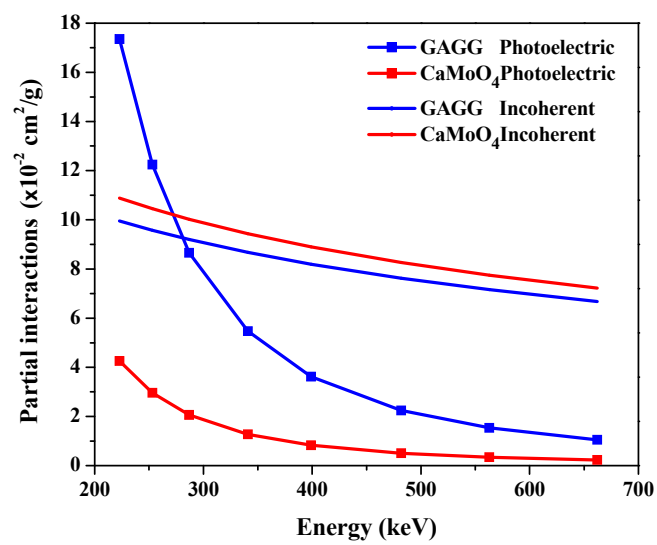


**Fig. 3.** Partial interactions of GAGG and $CaMoO_4$ crystals in the energy region from 223.02 to 662.00 keV.

of $3.00 \times 10^{23}$ to $5.45 \times 10^{23}$ electron/g and those of $CaMoO_4$ are in the range of $2.92 \times 10^{23}$ to $3.64 \times 10^{23}$ electron/g. These values increased with decreasing the gamma ray energy. The results indicate that there are more interactions of the crystals with gamma rays at lower energy, reflecting more virtual electron density at lower energy. In this case, GAGG has higher effective electron density compared with that of $CaMoO_4$ crystals. It means that there is more photon interactions in GAGG, thus it can absorb more photon energy and result in higher light yield.

## 5. Conclusion

The photon interaction properties of GAGG and $CaMoO_4$ scintillation crystals have been studied at different photon energies using Compton scattering technique. The scattered photons from $^{137}$Cs source were detected by NaI(Tl) scintillation detector. The results show that the mass attenuation coefficient, effective atomic number and effective electron density decreased with increasing the gamma ray energy which are in good agreement with theoretical values. GAGG crystal has higher value of mass attenuation coefficient than that of $CaMoO_4$ crystal. Similar results were observed for their effective atomic number and effective electron density. The partial interaction results showed the decrease in photoelectric and incoherent values with increasing energy. It was shown that the incoherent scattering was the main interaction of $CaMoO_4$ crystal in this energy region. However, for the case of GAGG, at a lower energy of less than 280 keV, the photoelectric

**Table 2**
Partial interactions of scintillation crystals at different gamma ray energies.

| E′(keV) | GAGG | | | $CaMoO_4$ | | |
|---|---|---|---|---|---|---|
| | Photoelectric ($\times 10^{-2}$ cm$^2$/g) | Coherent ($\times 10^{-2}$ cm$^2$/g) | Incoherent ($\times 10^{-2}$ cm$^2$/g) | Photoelectric ($\times 10^{-2}$ cm$^2$/g) | Coherent ($\times 10^{-2}$ cm$^2$/g) | Incoherent ($\times 10^{-2}$ cm$^2$/g) |
| 662.00 ± 18.00 | 1.05 | 0.26 | 6.68 | 0.23 | 0.12 | 7.23 |
| 562.68 ± 27.80 | 1.54 | 0.36 | 7.16 | 0.34 | 0.17 | 7.75 |
| 481.59 ± 20.50 | 2.25 | 0.49 | 7.62 | 0.51 | 0.23 | 8.26 |
| 398.97 ± 16.00 | 3.62 | 0.71 | 8.19 | 0.83 | 0.33 | 8.90 |
| 340.83 ± 16.20 | 5.47 | 0.96 | 8.68 | 1.27 | 0.45 | 9.44 |
| 287.28 ± 15.60 | 8.66 | 1.32 | 9.20 | 2.06 | 0.62 | 10.02 |
| 252.98 ± 14.20 | 12.25 | 1.68 | 9.58 | 2.96 | 0.80 | 10.46 |
| 223.02 ± 12.20 | 17.35 | 2.13 | 9.95 | 4.26 | 1.01 | 10.88 |

**Table 3**
Effective atomic numbers and effective electron densities of scintillation crystals at different gamma ray energies.

| E′(keV) | GAGG | | $CaMoO_4$ | | GAGG | | $CaMoO_4$ | |
|---|---|---|---|---|---|---|---|---|
| | $Z_{eff}$ (th) ($e^-$/atom) | $Z_{eff}$ (ex) ($e^-$/atom) | $Z_{eff}$ (th) ($e^-$/atom) | $Z_{eff}$ (ex) ($e^-$/atom) | $N_{eff}$ (th) ($\times 10^{-23}$) | $N_{eff}$ (ex) ($\times 10^{-23}$) | $N_{eff}$ (th) ($\times 10^{-23}$) | $N_{eff}$ (ex) ($\times 10^{-23}$) |
| 662.00 ± 18.00 | 26.60 | 26.64 ± 0.01 | 16.15 | 16.21 ± 0.01 | 3.00 | 3.01 ± 0.01 | 2.92 | 2.93 ± 0.01 |
| 562.68 ± 27.80 | 27.72 | 27.56 ± 0.06 | 16.32 | 16.66 ± 0.01 | 3.13 | 3.11 ± 0.01 | 2.95 | 3.01 ± 0.01 |
| 481.59 ± 20.50 | 29.20 | 29.15 ± 0.07 | 16.54 | 16.59 ± 0.01 | 3.30 | 3.29 ± 0.01 | 2.99 | 3.00 ± 0.01 |
| 398.97 ± 16.00 | 31.75 | 31.91 ± 0.10 | 16.95 | 17.39 ± 0.01 | 3.58 | 3.60 ± 0.01 | 3.06 | 3.14 ± 0.01 |
| 340.83 ± 16.20 | 34.70 | 35.40 ± 0.13 | 17.44 | 17.32 ± 0.01 | 3.92 | 4.00 ± 0.02 | 3.15 | 3.13 ± 0.01 |
| 287.28 ± 15.60 | 39.12 | 38.60 ± 0.18 | 18.25 | 18.12 ± 0.01 | 4.42 | 4.36 ± 0.02 | 3.30 | 3.27 ± 0.01 |
| 252.98 ± 14.20 | 43.28 | 42.91 ± 0.23 | 19.05 | 19.46 ± 0.01 | 4.89 | 4.84 ± 0.03 | 3.44 | 3.52 ± 0.01 |
| 223.02 ± 12.20 | 48.27 | 48.96 ± 0.41 | 20.13 | 19.66 ± 0.02 | 5.45 | 5.53 ± 0.05 | 3.64 | 3.55 ± 0.02 |

absorption was the main interaction. The $CaMoO_4$ has higher incoherent scattering than that of GAGG, but its total mass attenuation coefficient is lower. This is due to a higher photoelectric absorption of GAGG and the photoelectric absorption has shown to have strong effects on the total mass attenuation coefficient value for both crystals, especially in the lower energy range.

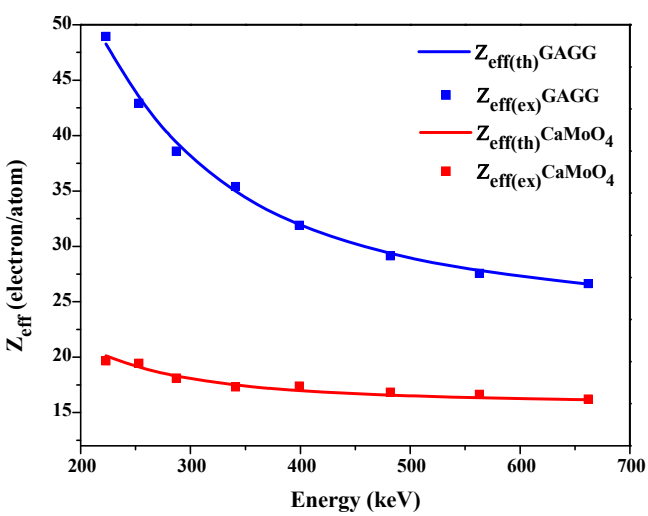


**Fig. 4.** Effective atomic numbers of GAGG and $CaMoO_4$ crystals in the energy region from 223.02 to 662.00 keV.

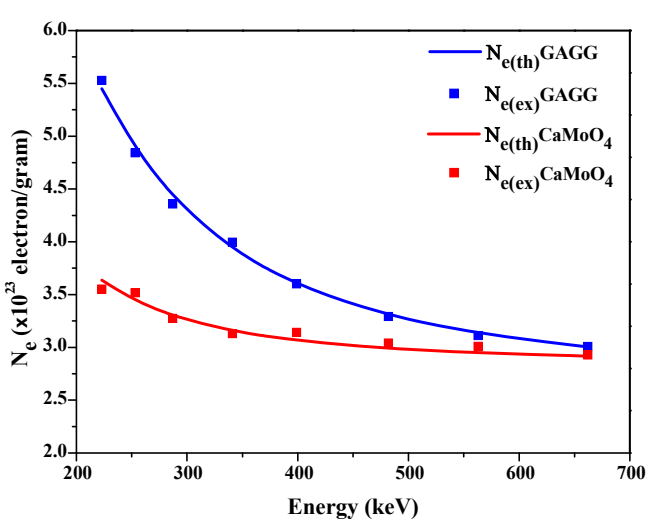


**Fig. 5.** Effective electron densities of GAGG and $CaMoO_4$ crystals in the energy region from 223.02 to 662.00 keV.

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## References

Annenkov, et al., 2008. Development of CaMoO4 crystal scintillators for double beta decay experiment with $^{100}$Mo. Methods 584, 334–345.
Belogurov, et al., 2005. $CaMoO_4$ scintillation crystal for the search of $^{100}$Mo double beta decay. IEEE Trans. Nucl. Sci. 52, 1131–1135.
Cevik, U., Baltas, H., 2007. Measurement of the mass attenuation coefficients and electron densities for BiPbSrCaCuO superconductor at different energies. Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms 256, 619–625.
Chaitali, V.M., Rajkumar, M.L., Pravina, P.P., 2016. Effective atomic number and electron density of amino acids within the energy range of 0.122-1.330 MeV. Radiat. Phys. Chem. 125, 14–20.
Chanthima, N., Kaewkhao, J., Limsuwan, P., 2012. Study of photon interactions and shielding properties of silicate glasses containing $Bi_2O_3$, BaO and PbO in the energy region of 1 keV to 100 GeV. Ann. Nucl. Energy 41, 119–124.
David, S., Georgiou, M., Fysikopoulos, E., Loudos, G., 2015. Evaluation of a SiPM array coupled to a Gd3Al2Ga3O12:Ce (GAGG: Ce) discrete scintillator. Phys. Med. 31, 763–766.
Erzeneoğlu, S., Icelli, O., Gurbulak, B., Ates, A., 2006. Measurement of mass attenuation coefficients for holmium doped and undoped layered semiconductors InSe at different energies and the validity of mixture rule for crystals around the absorption edge. J. Quant. Spectrosc. Radiat. Transf. 102, 343–347.
Gerward, L., Guilbert, N., Jensen, K.B., Levring, H., 2001. X-ray absorption in matter. Reengineering XCOM. Radiat. Phys. Chem. 60, 23–24.
Gerward, L., Guilbert, N., Jensen, K.B., Levring, H., 2004. WinXCom—a program for calculation X-ray attenuation coefficients. Radiat. Phys. Chem. 71, 653–654.
Gounhalli, S.G., Shantappa, A., Hanagodimath, S.M., 2012. Studies on effective atomic numbers and electron densities of some chemical explosives in the energy range 1 KeV–100 GeV. J. Chem. Pharm. Res. 4, 2545–2563.
Gupta, S., Sidhu, G.S., 2014. Gamma-rays absorption studies of garnet series of gemstones at 1 kev to 100 GeV: theoretical calculation. IOSR J. Eng. 4, 01–08.
Han, I., Demir, L., 2009a. Studies on effective atomic numbers, electron densities from mass attenuation coefficients in $Ti_xCo_{1-x}$ and $Co_xCu_{1-x}$ alloys. Nucl. Instrum. Methods Phys. Res. B 267, 3505–3510.
Han, I., Demir, L., 2009b. Mass attenuation coefficients, effective atomic and electron numbers of Ti and Ni alloys. Radiat. Meas. 44, 289–294.
Han, I., Demir, L., 2009c. Determination of mass attenuation coefficients, effective atomic and electron numbers for Cr, Fe and Ni alloys at different energies. Nucl. Instrum. Methods Phys. Res. B 267, 3–8.
Han, I., Demir, L., Sahin, M., 2009. Determination of mass attenuation coefficients, effective atomic and electron numbers for some natural minerals. Radiat. Phys. Chem. 78, 760–764.
Han, I., Aygun, M., Demir, L., Sahin, Y., et al., 2012. Determination of effective atomic numbers for 3d transition metal alloys with a new semi-empirical approach. Ann. Nucl. Energy 39, 56–61.
Hine, G.J., 1952. Phys. Rev. 85, 725.
Kaewjang, S., Maghanemi, U., Kothan, S., Kim, H.J., Limkitjaroenporn, P.,

Kaewkhao, J., 2014. New gadolinium based glasses for gamma-rays shielding materials. Nucl. Eng. Des. 280, 21–26.
Kaewkhao, J., Limsuwan, P., 2010. Mass attenuation coefficients and effective atomic numbers in phosphate glass containing $Bi_2O_3$, PbO and BaO at 662 keV, nuclear instruments and methods in physics research section a: accelerators, spectrometers. Detect. Assoc. Equip. 619, 295–297.
Kaewkhao, J., Laopaiboon, J., Chewpraditkul, W., 2008. Determination of effective atomic numbers and effective electron densities of Cu/Zn alloy. J. Quant. Spectrosc. Radiat. Transf. 109, 1260–1265.
Kaewkhao, J., Pokaipisit, A., Limsuwan, P., 2010. Study on borate glass system containing with $Bi_2O_3$ and BaO for gamma-rays shielding materials: comparison with PbO. J. Nucl. Mater. 399, 38–40.
Kaewkhao, J., Kirdsiri, K., Limkitjaroenporn, P., Limsuwan, P., Park, J.M., Kim, H.J., 2011. Interaction of 662 keV gamma-rays on bismuth based glass matrices. J. Korean Phys. Soc. 59 (2), 661–665.
Kaewkhao, J., et al., 2012. Measurement of mass attenuation coefficients of blue sapphire at different photon energy by Compton scattering technique. Appl. Mech. Mater. 103, 71–75.
Kamada, K., et al., 2012. Crystal growth and scintillation properties of Ce doped $Gd_3(Ga, Al)_5O_{12}$ single crystals. IEEE Trans. Nucl. Sci. 59, 2112–2115.
Knoll, Glenn E., 2000. Radiation Detection and Measurement. John Wiley & Sons, New York, United States of America, pp. 48–55.
Korkut, T., Korkut, H., Karabulut, A., Budak, G., 2011. A new radiation shielding material: amethyst ore. Ann. Nucl. Energy 38, 56–59.
Kucuk, N., Cakir, M., Isitman, N.A., 2013. Mass attenuation coefficients, effective atomic numbers and effective electron densities for some polymers. Radiat. Prot. Dosim. 153, 127–134.
Limkitjaroenporn, P., Kaewkhao, J., 2014. Gamma-rays attenuation of zircons from cambodia and south africa at different energies: a new technique for identifying the origin of gemstone. Radiat. Phys. Chem. 103, 67–71.
Limkitjaroenporn, P., Kaewkhao, J., Limsuwan, P., Chewpraditkul, W., 2011. Physical, optical, structural and gamma-ray shielding properties of lead sodium borate glasses. J. Phys. Chem. Solids 72, 245–251.
Limkitjaroenporn, P., Kaewkhao, J., Asavavisithchai, S., 2013. Determination of mass attenuation coefficients and effective atomic numbers for Inconel 738 alloy for different energies obtained from Compton scattering. Ann. Nucl. Energy 53, 64–68.
Medhat, 2012. Study of the mass attenuation coefficients and effective atomic numbers in some gemstones. J. Radio Anal. Nucl. Chem. 293, 555–564.
Narender, K., Madhusudhan, R.A.S., Gopal, K.R.K., Gopi, K.N., Ashok, R.K., 2013. Determination of effective atomic number and mass attenuation coefficient of 5070 wrought aluminum alloy with multi energetic photons. Res. J. Phys. Sci. 1, 1–5.
Prashant, S.K., Pravina, P.P., 2014. Measurements of mass attenuation coefficient, effective atomic number and electron density of some amino acids. Radiat. Phys. Chem. 98, 86–91.
Pravina, P.P., Govind, K.B., 2013. Studies on mass attenuation coefficient, effective atomic number and electron density of some amino acids in the energy range 0.122–1.330 MeV. Radiat. Phys. Chem. 92, 22–27.
Sharma, G., Singh, K., Manupriya, S., Mohan, H., Singh, H., Bindra, S., 2006. Effects of gamma irradiation on optical and structural properties of PbO–Bi2O3–B2O3 glasses. Radiat. Phys. Chem. 75, 959–966.
Singh, N., Singh, K.J., Singh, K., Singh, H., 2006. Gamma-ray attenuation studies of PbO–BaO–$B_2O_3$ glass system. Radiat. Meas. 41, 84–88.
So, J.H., et al., 2012. A study of $CaMoO_4$ crystals for the AMoRE Experiment. In: IEEE Nuclear Science Symposium and Medical Imaging Conference Record, 1987-1990.
Trousfanidis, N., 1983. Measurement and Detection of Radiation, first ed. Hemisphere Publishing, New York,United States of America.
Turşucu, A., Önder, P., Demir, D., Öznülüer, T., 2013. Studies on mass attenuation coefficient, effective atomic number and electron density of some amino acids. Int. J. Phys. Sci. 8, 147–156.
Yasaka, P., Pattanaboonmee, N., Kim, H.J., Limkitjaroenporn, P., Kaewkhao, J., 2014. Gamma radiation shielding and optical properties measurements of zinc bismuth borate glasses. Ann. Nucl. Energy 68, 4–9.
Yeom, J.Y., Yamamoto, S., Derenzo, S.E., Spanoudaki, V.C., Kamada, K., Endo, T., Levin, C.S., 2013. First performance results of Ce:GAGG scintillation crystals with silicon photomultipliers. IEEE Trans. Nucl. Sci. 60, 988–992.