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Mass Attenuation Coefficient and Effective Atomic Number of Ag/Cu/Zn Alloy at Different Photon Energy by Compton Scattering Technique

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Abstract

Mass attenuation coefficients and effective atomic numbers of Ag/Cu/Zn alloy (14.80%/57.61%/27.59% weight fraction) were determined at energy range 220 to 662 keV using gamma rays transmission method. The photon energy has been changed by Compton scattering technique. The results show that, the experimental values of mass attenuation coefficients and effective atomic numbers are in good agreement with the theoretical values with less than 1% of error. The mass attenuation coefficients and effective atomic numbers were decreased with increasing of gamma rays energies due to the higher photon interaction probability of Ag/Cu/Zn alloy at lower energy.

Keywords: alloy; mass attenuation coefficient; effective atomic number

1. Introduction

The total attenuation cross-section and effective atomic number are basic quantities required in determining the penetration of X-ray and gamma rays in matter [1]. The knowledge of mass attenuation coefficients, atomic and electronic cross sections and effective atomic number is useful for understanding

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their physical properties [2] such as in biological and other important materials is of significant interest for industrial, biological, agricultural and medical applications [3].

In 1982 Hubbell published tables of mass attenuation coefficients and the mass energy absorption coefficients for 40 elements and 45 mixtures and compounds over energy range from 1 keV to 20MeV. These tables, although widely used, should now be replaced by the Hubbell and Seltzer tabulation for all elements (Z=1-92) and 48 additional substances for dosimetric interest [4].

Berger and Hubbell developed the theoretical tables and computer program (XCOM) for calculating mass attenuation coefficients for elements, compounds and mixtures for photon energies from 1 keV to 100 GeV[5,6]. Recently, this well known and much used program was transformed to the Windows platform by gerward et al. [7]; and the Windows version is being called WinXCom.

From the mass attenuation coefficient, a number of related parameters can be derived, such as the mass energy absorption coefficient, the total interaction cross-section, the molar extinction coefficient, the effective atomic number and the effective electron density [4]. Reports of attenuation coefficient and effective atomic number for any materials are published by several authors [1-18].

In this work, we have measured the mass attenuation coefficients and the effective atomic numbers of Ag/Cu/Zn alloy at different photon energy and then compare these parameters with theory using WinXCom program [7]. The photon energy has been changed by Compton scattering technique.

2. Theory

2.1 Compton Scattering

The inelastic scattering of X-rays and gamma rays from electrons had been known for a decade when the American researcher A.H. Compton showed the relationship between incident and scattered gamma ray energies to be [19]

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

where $E_{\gamma'}$ is the scattered gamma rays energy, E_γ is the incident gamma rays energy, θ is the scattering angle, and m is the electron rest mass. This formula is easily derived by assuming a relativistic collision between the gamma ray and an electron initially at rest. Of course, under normal circumstances, all the electrons in a medium are not free but bound. If the energy of the photon, however, is of the order of keV or more, while the binding energy of the electron is of the order of eV, the electron may be considered at rest. The collision is inelastic in the sense that one photon is absorbed and another of different frequency and momentum is emitted.

2.2 Gamma-rays transmission

The mass attenuation coefficient is written as [10]

$$\mu_m = \frac{\ln(I_0/I)}{\rho t} \tag{2}$$

Where ρ is the density of material (g/cm^3), I_0 and I are the incident and transmitted intensities and *t* is the thickness of absorber (cm).

Theoretical values of the mass attenuation coefficients of mixture or compound have been calculated by WinXCom, base on mixture rule [4].

$$\mu_{\mathrm{m}} = \sum_{\mathrm{i}} \mathrm{w}_{\mathrm{i}} (\mu_{\mathrm{m}})_{\mathrm{i}} \quad (3)$$

Where w_i is weight fraction of element in alloy, $(\mu_{\mathrm{m}})_{\mathrm{i}}$ is mass attenuation coefficient for individual element in alloy.

The value of mass attenuation coefficients can be used to determine the total atomic cross-section ($\sigma_{t,a}$) by the following relation [4]

$$\sigma_{t,a} = \frac{(\mu_m)_{alloy}}{N_A \sum_i^n (w_i / A_i)} \quad (4)$$

Where N_A is Avogradro's number, A_i is atomic weight of constituent element of alloy. Also the total electronic cross-section ($\sigma_{t,el}$) for the element is expressed by the following formula [4]

$$\sigma_{t,el} = \frac{1}{N_A} \sum_i^n \frac{f_i A_i}{Z_i} (\mu_m)_i \quad (5)$$

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 the i^{th} element in alloy. Total atomic cross-section and total electronic cross-section are related to effective atomic number (Z_{eff}) of the compound through the formula [16]

$$Z_{eff} = \frac{\sigma_{t,a}}{\sigma_{t,el}} \quad (6)$$

3. Experimental Setup

The compositions of 14.80%/57.61%/27.59% fractional weight for Ag/Cu/Zn alloy was analyzed by energy dispersive x-rays fluorescence spectrometer (Panalytical Minipal-4).The thickness (0.05 mm) of the Ag/Cu/Zn alloy was measured using a micrometer. Density of glass samples were measured by Archimedes' principle using distills water as the liquid. The density is calculated according to the formula;

$$\rho = \frac{w_A}{w_A - w_B} \rho_{distillwater} \quad (7)$$

Where w_A is the weight of the sample in air, w_B is the weight of the sample in water and density of distill water is 1 g/cm^3.

The experimental arrangement is shown in Fig. 1. The source system was mounted on a composite of adjustable stands. This setup can move in the transverse direction for proper beam alignment. The ^{137}Cs radioactive source of 15 mCi (555 MBq) strength was obtained from the Office of Atom for Peace (OAP), Thailand. The aluminium rod was used the scattering rod. The Compton scattered γ-rays were measured on a rotatable scintillator detector in the scattering plane by using the 2″×2″ NaI(Tl) detector having an energy resolution of 8% at 662 keV (BICRON model 2M2/2), with CANBERRA photomultiplier tube base model 802-5. The optimum distance between the source and the scatterer was chosen to be 20 cm and that between the scatterer and detector, 20 cm. The spectra were recorded 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 perform a calibration relating the channel number of the MCA spectrum to the energy of known gamma-ray sources. We vary the angle of the scatter detector and acquire measurements on the MCA. The different angles (θ) were used to produce the different gamma rays energies.

The gamma rays energy spectrum for the NaI(Tl) detector was a Gaussian shaped peak. For each full energy peak, the centroid and full width at half maximum (FWHM) of the full energy peak were obtained from Gaussian fitting software of Canberra MCA.

The statistical error of scattered gamma rays in this experiment were calculated from full width at half maximum (FWHM) of the full energy peak. The width of a Gaussian distribution is related to the standard deviation σ by [19]

$$FWHM = 2\sqrt{2\ln 2}\sigma \quad (8)$$

An optimum sample thickness ($0.5 \le \mu x \le 5.0$) was selected in this experiment on the basis of the Nordfors criteria [20, 21]. To measure mass attenuation coefficient, we placed the sample between the scattering rod and detector, and detection the acquired MCA spectra of the scattered gamma rays photopeak through sample thickness at different angles. Integrated count rates were determined from Gaussian fits and used to determine an attenuation coefficient.

The statistical error in this experiment calculated from the standard error of 3 items (i) ray-sum measurement, which calculated from experiment, the ray-sum is product of linear attenuation coefficient (μ) with thickness (x), (ii) density measurement and (iii) thickness measurement [17]. Finally, the total standard error has been determined by combining errors for the ray-sum measurement, density measurement and thickness measurement in quadrature.

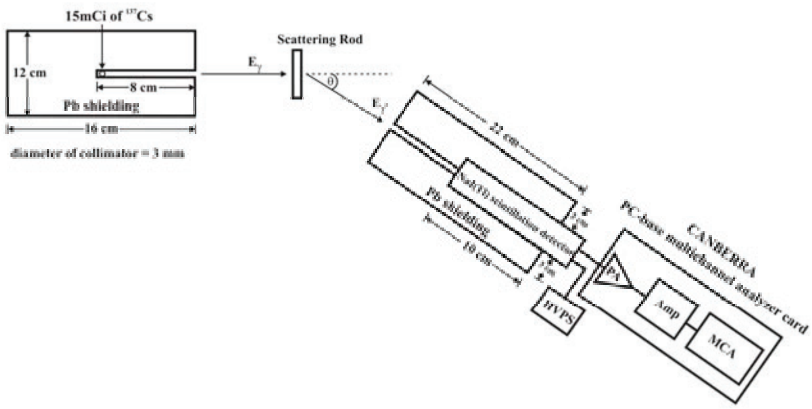

Fig. 1. Schematic of the Compton scattering experiment

4. Results and discussions

Gamma ray spectrometer is calibrated by using standard calibration sources at different energies (^{241}Am 59.5 keV, ^{133}Ba 356 keV, ^{22}Na 511 keV and ^{137}Cs 662 keV). Each of the calibration sources is placed at the scatterer position and its spectrum is recorded. The FWHM of the Compton photopeaks higher than FWHM of point sources attributed to Compton scattering experiment several broadening effects contributing to our statistical error, and some negligible effects relevant to higher resolution measurements. Inherent to our experimental setup is the spread of the beam profile ($\Delta\theta \approx 3^o$) of the ^{137}Cs source over the surface of the scatter detector that contributes to a Gaussian spread of measured scattering events. The Fermi motion of electrons in the detector has a finite momentum distribution contributing to Lorentzian line broadening beyond the resolution of the NaI scintillator. Additionally, the motion of electrons about the binding potential of the nucleus. Doppler broadens the apparent energy of incident photons from our source, thereby broadening the Compton peak for a given scattering angle[22]. The scattered gamma ray energies and statistical error at different angles shown in Table 1. The theoretical values ($E'_{\gamma(th)}$) were calculated by using Eq. (1) and the experimental values ($E'_{\gamma(ex)}$) were measured. The relative difference between theoretical values and experimental values showed the results less than 1%, this results reflect the good geometry in detection system setup for Compton scattering experiment .

Table 1. The scattered gamma rays energies at different angles

θ (deg)	$E'_{\gamma(th)}$ (keV)	$E'_{\gamma(ex)}$ (keV)	%RD
30	564.09	562.68 ±27.82	0.25
45	479.90	481.59 ±17.07	0.35
60	401.76	398.97 ±16.01	0.69
75	337.72	340.83 ±15.77	0.92
90	288.39	287.28 ±15.62	0.39
105	251.63	252.98 ±14.13	0.54
120	224.92	223.02 ±12.22	0.84

% RD = [(Theoretical value – Experimental value)/ Theoretical value] x 100

The mass attenuation coefficients of Ag/Cu/Zn alloy as shown in Table 2 were evaluated from incident (I_0) and transmitted (I) intensities and compare with theoretical values were calculated by WinXCom program [7]. By using the experimental data of total mass attenuation coefficients, the effective atomic numbers (Z_{eff}) have been determined using Eq. (6) and shown in Table 2. Fig. 2 and Fig. 3 showed the good agreement between experimental values and theoretical values of mass attenuation coefficients and effective atomic numbers respectively. It has been found that the mass attenuation coefficients and effective atomic numbers were decreased with increasing of gamma rays energies. From the decreasing of these parameters, we obtained the photon interaction probability is decrease with higher gamma rays energy, these results showed the mass attenuation coefficients and effective atomic numbers of this work (Ag/Cu/Zn alloy) is higher than Cu/Zn alloy in published literature [16]. It is due to Ag component in alloy.

Table 2. Total mass attenuation coefficients and effective atomic numbers of Ag/Cu/Zn alloy

E (keV)	$\mu_{m(th)}$ ($\times10^{-2}$ cm^2/g)	$\mu_{m(ex)}$ ($\times10^{-2}$ cm^2/g)	%RD	$Z_{eff(th)}$ ($e^-/atom$)	$Z_{eff(ex)}$ ($e^-/atom$)
662	7.33	7.12 ±0.19	2.90	31.12	30.22 ±0.81
562.68	7.98	7.86 ±0.19	1.48	31.17	30.71 ±0.74
481.59	8.73	8.49 ±0.19	2.71	31.24	30.39 ±0.68
398.97	9.70	9.68 ±0.19	0.17	31.34	31.29 ±0.61
340.83	10.89	10.70 ±0.19	1.73	31.49	30.94 ±0.55
287.28	12.29	12.38 ±0.19	0.74	31.66	31.89 ±0.49
252.98	13.88	13.64 ±0.19	1.75	31.90	31.34 ±0.44
223.02	15.56	15.63 ±0.19	0.46	32.08	32.22 ±0.39

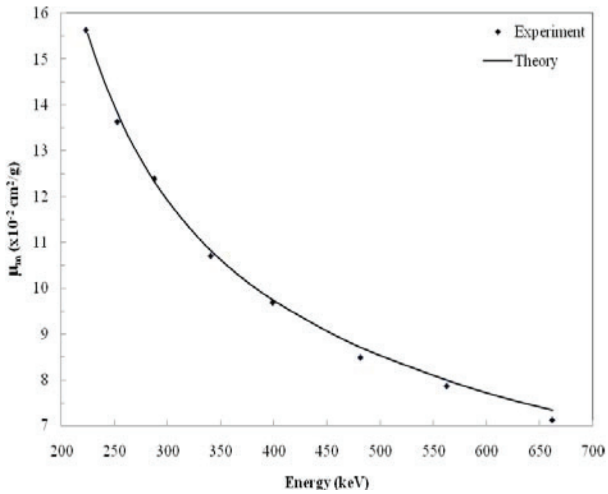

Fig. 2. Variation of mass attenuation coefficient values for the Ag/Cu/Zn alloy as a function energy. The line is theoretical value and point in this figure is experimental value

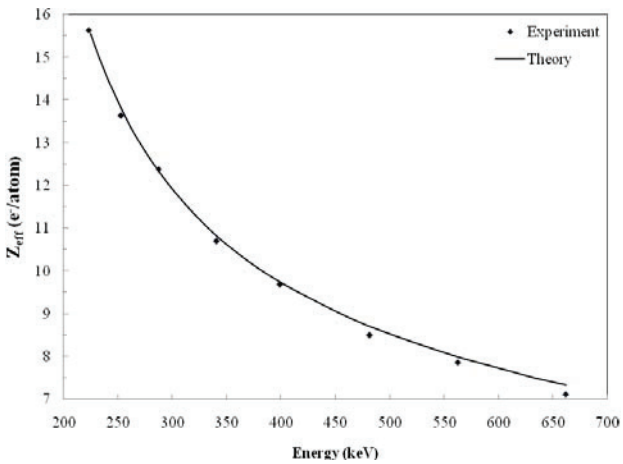

Fig. 3. Variation of Effective atomic number values for the Ag/Cu/Zn alloy as a function energy. The line is theoretical value and point in this figure is experimental value

5. Conclusions

In the Compton scattering experimental setup, there are corresponding of scattered gamma rays energies between theoretical and experimental values, this reflect the superb detection system setup. The mass attenuation coefficients and effective atomic numbers of Ag/Cu/Zn alloy were measured at the different energy of γ-rays using the Compton scattering technique. The results are good agreement with the theoretical values. In this range of gamma rays energy (220 to 662 keV), the mass attenuation coefficients and effective atomic numbers decrease with increasing of gamma rays energy. This attributed to the higher photon interaction probability of Ag/Cu/Zn alloy at lower energy.

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