DETERMINATION OF EFFECTIVE ATOMIC NUMBER AND EFFECTIVE ELECTRON DENSITY OF WROUGHT ALUMINUM ALLOY 7017 FOR DIFFERENT PHOTON ENERGIES

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ABSTRACT

The effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of wrought aluminum alloy 7017 has been estimated by determining the mass attenuation coefficient (μ_m), experimentally using narrow collimated beam transmission method with radioactive point sources of different γ–energies [(0.0595 MeV), (0.662 MeV), (1.173 MeV & 1.332 MeV)]. The transmitted γ-photons were detected and recorded by a NaI(TI) scintillation detector with resolution of 8.5% for 661.16 KeV of ^{137}Cs. The linear attenuation coefficient (μ_l), total atomic cross section (σ_t), total electron cross section (σ_e) and photon mean free path (λ) for different γ–energies have been reported. The experimental results determined were compared with the theoretical values obtained using X-COM and semi empirical approach based on mixture rule for all photon energies. The experimental values are in good agreement with theoretical values.

Keywords: Mass Attenuation Coefficient, Linear Attenuation Coefficient, Effective Atomic Number, Effective Electron Density.

I. INTRODUCTİON

The study of absorption of gamma radiation in shielding material is an important subject in the field of radiation physics. It is potentially useful in the development of semi-empirical formulations of high accuracy [1]. The interaction of high energy photons with matter is important in radiation medicine, biology, nuclear engineering and space technology. The study of parameters such as mass attenuation coefficient (μ_m), linear attenuation coefficient (μ_l), total atomic cross-section (σ_t), electronic cross-section (σ_e), effective atomic number (Z_{eff}), electron density (N_{eff}), mean free-path (λ) are important parameters in understanding the physical properties of composite materials. They are very important in many applied fields like nuclear diagnostics, radiation protection, nuclear medicine and radiation dosimetry.

Mass attenuation coefficient is a measurement of how strongly a substance absorbs or scatters radiation at a given wavelength, per unit mass. Mass attenuation coefficient can be used to derive other photon interaction parameters. Linear attenuation coefficient (μ_l) describes the fraction of a beam of X-rays or γ- rays that is absorbed or scattered per unit thickness of the absorber.

In 1982 Hubbell published tables of mass attenuation coefficients and the mass energy absorption coefficients for 40 elements and 45 mixtures and compounds over an energy range of 1 keV to 20 MeV. These tables,

although widely used, can now be replaced by the Hubbell and Seltzer tabulation for elements (Z=1 to 92) and 48 additional substances of dosimetric interest [1]. Berger and Hubbell developed the theoretical tables and computer program (XCOM) for calculating attenuation coefficients for elements, compounds and mixtures for photon energies from 1keV to 100 GeV[2, 3]. Recently, this well-known and much used program was modified to the Windows platform by Gerward et al. [4], and the Windows version is being called WinXCom. The scattering and absorption of gamma radiations are related to the density and atomic number of each element. In composite material like an alloy, it is related to density and effective atomic number. The knowledge of mass attenuation coefficients of alloys is of prime importance in the determination of effective atomic number. A single number therefore, cannot represent the atomic number uniquely across the entire energy range, since the partial interaction cross-sections depend on different element numbers [5]. The parameter "effective atomic number" has a physical meaning and allows many characteristics of material to be visualized with this number. The effective atomic number (Z_{eff}) of composite material is defined as the ratio of total atomic cross-section, to the total electronic cross-section [6, 7]. Attenuation coefficient and effective atomic number for many materials were reported [1-16]. In the present work, the mass attenuation coefficients and other photon interaction parameters of wrought aluminum alloy 7017 at [(0.0595 MeV), (0.662 MeV), (1.173 MeV & 1.332 MeV)] gamma energies are determined and are compared with the values obtained using semi empirical relations based on mixture rule and also with the values obtained from XCOM.

II. EXPERIMENTAL METHOD

Transmission experiments has been carried out with narrow beam good geometry setup (Gamma ray densitometer) shown in Fig.1. The setup with the source vault, collimators and the lead vault housing, the detector has been used for measuring the incident and transmitted intensities to determine the attenuation coefficient. The gamma rays are well collimated using lead collimators of cylindrical shape and a circular aperture of 6 mm diameter along the axis of the source and the detector. The signal is detected by NaI (Tl) scintillation detector of 3×3 inch crystal under a high bias voltage of 1000 volts. The detector was shielded with a lead housing to reduce the radiation coming directly from the source scattered from the surroundings. The attenuation measurements were made with multichannel analyzer. The weak detector pulse is fed to the preamplifier which then enters the linear amplifier. The linear amplifier has two main functions of shaping the pulse and amplitude gain. The multi-channel analyzer (MCA) has been designed to work in conjunction with this setup. The amplified pulse is then fed to the MCA, which converts the analog signal into a digital signal using an analog to digital converter (ADC). Here, software installed in the MCA, is used to control the functions and other settings including the analysis of the spectrum. The energy and the efficiency of the system were calibrated using a certified standard source.

The alloy studied in the present work has been prepared by ingot metallurgy route. The alloy was melted in the air, in the induction furnace and cast iron moulds were used to obtain ingots. These ingots were subsequently homogenized and hot rolled to obtain 12 mm – 15 mm thick plates. The dimensions of the samples were measured with a screw gauge upto an accuracy of ± 0.01 mm.The alloy plates were precipitation strengthened by heat treatment, aging.

Alloy 7017 has chemical composition of 92.08% Al, 5.17% Zn, 2.26% Mg, 0.13% Zr, 0.28% Mn, 0.04% Fe and 0.04% Si by weight. The sample was shaped into a cuboid for measuring the attenuation. The sample was placed

between the source and the detector. The distance between the radioactive point source with sample and the sample to detector was 8 cm and 6 cm, respectively. The sample was irradiated with [(0.0595 MeV), (0.662 MeV), (1.173 MeV & 1.332 MeV)] photons emitted by 50 mCi Am-241, 100 mci Cs-137 and 10 mCi Co-60 radioactive point sources respectively. I_o and I the intensities before and after attenuation were measured by a high resolution detector. The measurements on sample were carried out five times at each energy value. In every case the photo-peak had Gaussian distribution. The peak areas have been estimated from the spectrum obtained for each measurement. Each spectrum was recorded for 30 minutes to record an adequate number of counts under the photo peak.

Fig. 1 The Experimental Setup

III. THEORY

The relations used in the present work are summarized in this section. Mass attenuation coefficients for the different materials and energies are determined by performing transmission experiments. This process is described by the following equation:

$$I = I_0 \exp(-\mu_m t) \quad (1)$$

Where I_0 and I are un- attenuated and attenuated photon intensities

$\mu_m = \mu/\rho$ (cm^2/g) is the mass attenuation coefficient

t (g/cm^2) is sample mass thickness (the mass per unit area)

The total mass attenuation coefficient μ_m for any chemical compound or mixture of elements is given by mixture rule [6]:

$$\mu_m = \sum_i w_i (\mu_m)_i \quad (2)$$

Where w_i is the weight fraction

$(\mu_m)_i$ is the mass attenuation coefficient of ith element

For a material composed of multi elements the fraction by weight is given by

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \quad (3)$$

Where A_i is the atomic weight of the i^{th} element and n_i is the number of formula units.

The total atomic cross-section (σ_t) for materials can be obtained from the measured values of μ_m using the following relation

$$\sigma_t = \frac{\mu_m N}{N_A} \quad (4)$$

Where $N = \sum_i n_i A_i$ is atomic mass of materials (5)

N_A is the Avagadro's number.

Total electronic cross-section (σ_e) for the element is expressed by the following equation

$$\sigma_e = \frac{1}{N_A}\sum \frac{f_i N_i}{Z_i}(\mu_m)_i = \frac{\sigma_t}{Z_{eff}} \quad (6)$$

Where f_i denotes the fractional abundance of the element i with respect to the number of atoms such that $f_1+f_2+f_3+f_4+\ldots\ldots f_i=1$

Z_i is the atomic number of i^{th} element

The total atomic cross-section (σ_t) and total electronic cross-section (σ_e) are related to the effective atomic number (Z_{eff}) of the material through the following relation

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (7)$$

Effective electron number or electron density (N_{eff}) (number of electrons per unit mass) can be calculated using the following relation:

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \quad (8)$$

The average distance between two successive interactions, called the photon mean free path (λ), is given by

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x) dz}{\int_0^\infty \exp(-\mu x) dx} = \frac{1}{\mu_l} \quad (9)$$

Where (μ_l) is linear attenuation coefficient and x is the absorber thickness.

The uncertainty in the measured physical parameters depends on uncertainty in the furnace temperature and measurement of the mass attenuation coefficient, which has been estimated from errors in intensities I_0, I and thickness (l) using the following relation

$$\Delta(\mu_m) = \frac{1}{\rho l}\left[\left(\frac{\Delta I_0}{I}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\ln\frac{I_o}{I}\right)^2 + \left(\frac{\Delta l}{l}\right)^2\right]^{1/2} \quad (10)$$

where ΔI_0, ΔI and Δl are the errors in the intensities I_0, I and thickness l respectively. In this experiment, the intensities I_0 and I have been recorded for the same time and under the same experimental conditions. Estimated error in these measurements was around 1%.

Theoretical values for the mass attenuation coefficients can also be obtained by Win Xcom program [17]. This program is based on mixture rule to calculate the partial and total mass attenuation coefficients for all elements and mixtures at standard as well as selected energies.

IV. RESULTS AND DISCUSSION

The mass attenuation coefficients have been calculated at the photon energies [(0.0595 MeV), (0.662 MeV), (1.173 MeV & 1.332 MeV)] The values obtained experimentally are compared with theoretical values calculated by using semi-empirical relations (1, 2 and 3) of section-3 and with the values of X-Com and are found to be in good agreement, as seen in the Table 1. It is clear that mass attenuation coefficient depends on photon energy and chemical content. The mass attenuation coefficient of a material decreases because probability of absorption reduces with increasing incident photon energies which results in the increase in the transmission of photons through it. The total experimental uncertainty of mass attenuation coefficient values depend on the uncertainties of peak area evaluation, mass thickness measurements, experimental system, counting statistics, and efficiency errors and so on. Using the mass attenuation coefficient, the parameters linear attenuation coefficient (μ_l), total atomic cross-section (σ_t), electronic cross-section (σ_e), effective atomic number (Z_{eff}), electron density (N_{eff}), mean free-path (λ) for wrought aluminum alloy 7017 at different photon energies have been calculated and the results have been displayed in Fig's (2-5) as function of photon energies.

Although the dependence of σ_τ and σ_e on the photon energy is dominant at low energies, it is negligible at high energies The Z_{eff} and the N_{eff} remains constant and are found to be independent of photon energy for a compound. The electron density is closely related to the effective atomic number and hence has the same qualitative energy dependence, as effective atomic number. Total photon cross-section and electron cross-section (σ_t and σ_e) decreases with the increase in photon energy. Lastly, the photon mean free path (λ) for a compound found to be increasing with the photon energy. This is due to the decrease in the probability of interaction of photons in the material with the increase in energy. The variation in mass attenuation coefficient is due to the influence of other alloying elements present in the alloy. The agreement between the calculated values from semi empirical relations, XCOM and experimental results is good. However the presence of alloying elements in wrought aluminum alloy create a different environment in aluminum matrix, this could bring a change in the binding forces, chemical surroundings and distortion in crystallinity. But these changes in the aluminum matrix induced by the alloying elements are not considered when the values of mass attenuation coefficients were computed by XCOM and empirical relations. But the influence of these effects, discussed above, reflects in experimental measurements.

Hence the experimental values for the mass attenuation coefficients of aluminum alloy slightly differ from the calculated values. Further, the difference might arise in the values of μ_m obtained from experiment and calculation due to experimental setup and it's counting efficiency errors. Measured values of other photon interaction parameters like atomic cross section and electronic cross section show almost similar behavior as that of mass attenuation coefficient. The linear attenuation coefficient (μ_l) is determined for this alloy by using μ_m of the alloy. From the Table-1 it is clear that the linear attenuation coefficient is inversely proportional to energy. This is because as energy increases, the transmitted photons increase and the absorbed photons decrease, and hence linear attenuation coefficient decreases. The linear attenuation coefficient is related to the mean free

path which is the distance between successive interactions and mean free path is the inverse of the linear attenuation coefficient.

Table-1

μ, μ_l, σ_t, σ_e, Z_{eff}, N_{eff}. and λ values (comparison between experimental, theoretical and X-com) of 7017 alloy at different γ-energies

E[MeV]	0.0595			0.662			1.173			1.332		
Parameter	X-Com value	Empirical value	Expt. Value	X-Com value	Empirical value	Expt. Value	X-Com value	Empirical value	Expt. Value	X-Com value	Empirical value	Expt. Value
$\mu_m (10^{-2})$ m^2kg^{-1}	366.3	366.305	364.03	74.4	74.6162	74.1	56.67	56.6722	56.1	53.12	53.1278	52.1
μ_l m^{-1}	1010.99	1011	1004.72	205.344	205.941	204.516	156.409	156.415	154.836	146.611	146.633	143.796
$\lambda(10^{-4})$ m	9.89131	9.89117	9.95299	48.6988	48.5577	48.8959	63.9349	63.9324	64.5845	68.2076	68.1975	69.543
$\sigma_T (10^{-24})$ barn/atom	8.14957	8.14969	8.09906	1.65528	1.66009	1.6486	1.26081	1.26086	1.24813	1.18183	1.18201	1.15914
$\sigma_e (10^{-25})$ barn/atom	2.84565	2.84569	2.82801	0.57799	0.57967	0.57566	0.44025	0.44027	0.43582	0.41267	0.41273	0.40475
$Z_{effective}$	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387	28.6387
$N_{eff}(10^{24})$ electron/g	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723	1.28723

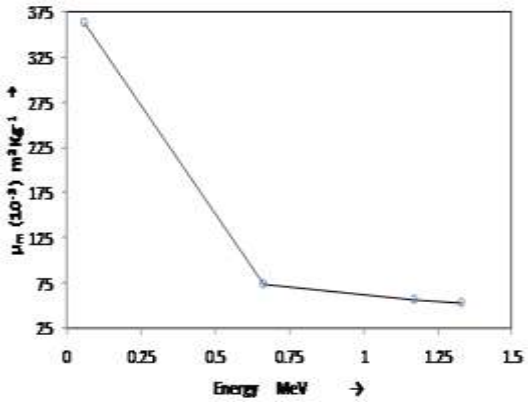

Fig.2 Mass attenuation coefficient vs Photon energy

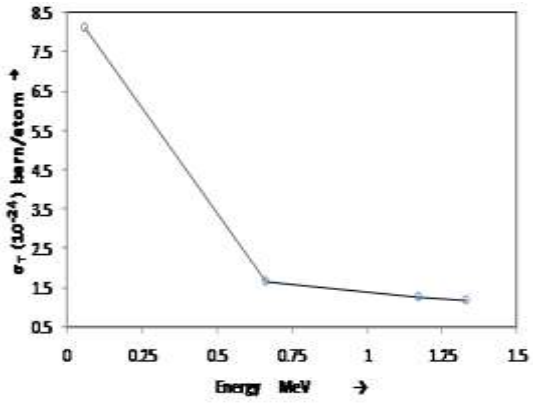

Fig.3 Total cross-section vs Photon energy

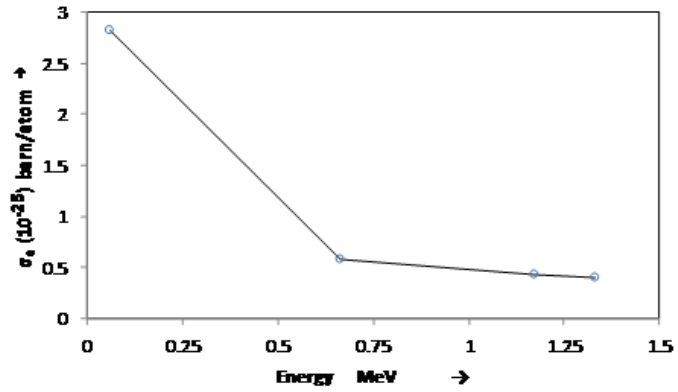

Fig.4 Electron Cross-Section vs Photon Energy

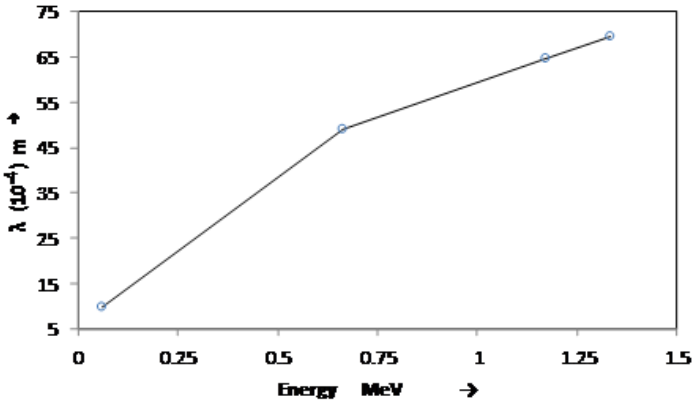

Fig.5 Mean Free Path vs Photon Energy

V. CONCLUSIONS

The present experimental study has been undertaken to determine the μ_m and related parameters for wrought aluminum alloy 7017. It can be conclude that the μ_m is a useful and sensitive physical quantity to determine the Z_{eff} and N_{eff} and other photon interaction parameters for alloys. In the interaction of photon with matter, μ_m values are dependent on the physical and chemical composition of the elements in the sample. The μ_m values of alloy decrease with increase in photon energy. Also, the variation of $\square_t$ and $\square_e$ with energy is identical to μ_m. The N_{eff} is closely related to the Z_{eff} and energy dependence of N_{eff} is the same as $Z_{eff.}$. In the present study, it is evident that the μ_m , Z_{ef}f and N_{eff} are useful parameters for alloys. The results of this study will be helpful in better understanding, of how the mass attenuation coefficients change with variation of the atomic and electronic number for different alloy compositions. To the best of our knowledge, experimental and theoretical investigations of the μ_m, $\square_{t,}$ $\square_{e,}$ Z_{eff} and N_{eff} for wrought aluminum alloy 7017 are not available in the literature. Moreover, the results of this work can stimulate both experimental and theoretical research for alloys.

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