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Determination of Effective Atomic Number and Mass Attenuation Coefficient of 5070 wrought Aluminum alloy with Multi Energetic photons

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Abstract

The total mass attenuation coefficients μ_m, for wrought aluminum alloy 5070 were measured at 59.5, 661.16, 1173, 1332keV photon energies. The sample was exposed with ^{137}Cs, ^{60}Co and ^{241}Am radioactive point sources using narrow beam transmission arrangement. The gamma-rays were counted by a NaI (Tl) detector with resolution of 8% of photon energy. Total atomic and electronic cross-sections (σ_t and σ_e), effective atomic number (Z_{eff}), electron density (N_{el}) and photon mean free path (λ) have been determined using the obtained μ_m values for 5070 aluminum alloy. The experimental values have been compared with theoretical values estimated from mixture rule and XCOM, and the agreement is found to be good.

Keywords: Mass attenuation coefficient, effective atomic number, effective electron number, total atomic electronic cross section.

Introduction

In view of the extensive use of the radioactive sources in medicine, agriculture, industry etc., the study of photon atom interaction in different materials has gained importance in recent years. Since these interactions involve various compounds with different compositions, that the effective atomic number of a material composed of several elements cannot be expressed by a single number, it can be concluded that it is an energy dependent parameter due to the different partial photon interaction processes with matter for which the various atomic numbers in the material have to be weighted differently. The effective atomic number Z_{eff} for the total and partial gamma ray interactions in alloys are equally important. A number of investigations on effective atomic numbers for total and partial photon interactions have been reported in the literature. Including both theoretical[1-10] and experimental[11-25] studies covering a wide range of energies from a few keV up to several GeVs. There was a study on few compounds in which the effective atomic number has been determined using the ratio of elastic-to-inelastic scattering[26-27]. Similar studies have been carried out on various types of mixtures like metallic alloys, compounds; other composite materials including biological tissues, polymers, cements etc. In the present work, wrought aluminum alloy 5070 is subjected to attenuation studies at 59.5, 661.6, 1173, 1332keV photon energies to estimate the corresponding effective atomic number values for total photon interactions. Two different theoretical techniques, semi empirical approach, XCOM programme have been used for obtaining the values and these are in good agreement with experimental values.

Material and Methods

Transmission experiments with the narrow beam (good-geometry) setup were used for measuring the incident and transmitted intensities, to determine the attenuation coefficient. Further calculations of the cross sections (atomic and electronic), effective atomic numbers and electron densities were performed. Three gamma sources were used in the present work so that the above parameters were studied at four different energies. The alloy studied in the present work was 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 at about 813 K and hot rolled to obtain 12mm - 15mm thick plates. These alloy plates were precipitation strengthened by heat treatment (aging). The chemical composition of 5070 is Al 92.55% Cu 0.25% Mg 4.5 Si 0.25% Fe 0.4% Mn 0.8% Cr 0.3% Zn 0.8% Ti 0.15% The sample material was shaped in to a cuboid, for measuring the attenuation, this cuboid slice is stacked on the detector, the intensities of the transmitted photons were determined by choosing the counting time as 30 minutes, counts were recorded under the photo peaks, as statistical uncertainty was to be kept as low as possible. The dimensions of the samples were measured with a screw gauge with the tolerance of ±0.01mm.

The experiment was performed at the Radiation Application Laboratory at Central Instrumentation Centre at Kakatiya University, Warangal, India. The experimental setup in the present work is shown in figure-1. The gamma rays are well collimated using collimators of cylindrical shape and a circular aperture of 6mm diameter between the source and the detector.

The signal is detected by NaI (Tl) scintillation detector of 3×3 inch crystal and a high bias voltage of 1000 volts. A lead shield surrounds the detector to reduce the undesired external radiation. The weak detector pulse enters the preamplifier (or preamp.), the pulse then enters the linear amplifier which has two main functions pulse shaping and amplitude gain, for which the multi-channel analyzer has been designed. The amplified pulse is then fed to the Multi-Channel Analyzer (MCA), which converts the analog signal into a digital through an analog to digital converter (ADC). The energy and the efficiency of the system were calibrated using a certified standard source.

The sample was exposed to 59.5, 662.16, 1173 and 1332keV photons emitted by 50 mCi Am-241,100mci Cs-137 and 10 mCi Co-60 radioactive point sources, respectively. I_o and I are the intensities before and after attenuation were measured by a high resolution NaI(Tl) detector. 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 12cm and 4cm, respectively. The measurements for the sample were carried out for five times for each energy value. Photon spectra were recorded in the following order firstly, source spectrum recorded with source but without sample and the incident spectrum (without attenuation) I_0 was obtained. The transmitted spectrum recorded with source and sample I (after attenuation) was obtained. In both the spectra the photo-peak had Gaussian distribution. The peak areas have been calculated from the spectrum obtained for each measurement. The each spectrum was recorded for sufficient time (30min) to accumulate an adequate number of counts under the photo peak. In this work, Io (without attenuation) and I (after attenuation) intensity measurements and μ_m calculations were carried out for the photon energies (59.5, 661.6, 1173, 1332keV).

Analysis of Data: The relations used in the present work are summarized in this section. The mass attenuation coefficients for wrought aluminum alloy 5070 at different 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 the 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 µm for any chemical compound or mixture of elements is given by mixture rule.

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

Where wi is the weight fraction (the proportion by weight) $(\mu_m)_i$ 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 ith element and ni is the number of formula units.

The total atomic atomic cross-section (σt) for materials can be obtained from the measured values of µm 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, NA is the Avagadro's number.

The total electronic cross-section (σe) for the element is expressed by the following equation

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i N_i}{Z_i} (\mu_m)_i = \frac{\sigma_t}{Z_{eff}} \quad (5)$$

Where fi denotes the fractional abundance of the element I with respect to the number of atoms such that f1+f2+f3+f4+….fi =1
Zi is the atomic number of ith element

The total atomic atomic cross-section (σt) and total electronic cross-section (σe) are related to the effective atomic number (Zeff) of the material through the following relation

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \quad (6)$$

The effective electron number or electron density (Neff) (number of electrons per unit mass) can derived by using the following relation:

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \quad (7)$$

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

$$\lambda = \frac{\int_0^\infty x \exp(-\mu x) dz}{\int_0^\infty \exp(-\mu x) dx} = \frac{1}{\mu} \quad (8)$$

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

Results and Discussion

Mass attenuation coefficient (μ_m) and total photon interaction cross-sections (σ_a and σ_e) of wrought aluminum alloy 5070 have been tabulated in table 1. It is evident from the table that the measured values of these parameters were in good agreement with those obtained theoretically and from values of XCOM. The experimental μ_m values for alloy 5070 tend to be smaller than their theoretical value. This is due to the presence of other trace elements in the chemical composition of alloy 5070. Furthermore, this difference might be from experimental setup, counting and efficiency errors. It is clearly seen from figure- 2a that variations of μ_m depend on the photon energy and chemical compositions of wrought aluminum alloy 5070. The μ_m values of alloy 5070 decrease with increasing photon energy. Experimental as well as theoretical values of effective atomic number have been tabulated in table 1. and are found to be in good agreement moreover it has been observed from table 1 that the effective atomic numbers of alloy 5070 is same for different energies this is due to the alloy contain 90% of atoms are aluminum. The dependence on the atomic number indicates that materials having high Z_{eff} absorb powerfully incoming photons. The variation of Z_{eff} with photon energy has been shown graphically in figure- 2f. In all materials, the interaction (such as absorption and scattering) of gamma-rays are related to Z_{eff} value of materials and the energy of photons. There is energy transfer from photon to matter in these interactions. Although the dependence on the photon energy is dominant in interaction with low energies, it can be negligible at high energies. N_e values were determined using μ_m and σe values and given in table 1. It can be seen that the value of N_e is found to be same for different energies. This expected behavior for electron densities can be explained on the similar basis as for Z_{eff}.. For total photon interaction process the variation of μ_m, Z_e and N_e with photon energy region. The variations of N_e with photon energy for total interaction processes are similar to that of Z_{eff} and can be explained in the similar manner. The linear attenuation coefficient (μ_l) is determined for wrought aluminum alloy 5070 by using μ_m. of the alloy From the figure-2c. It is clear that the linear attenuation coefficient is inversely proportional to energy. When the photons energy increases, the transmitted photons increase and the absorbed photons decrease, as a result the linear attenuation coefficient decreases. The definition which is associated with linear attenuation coefficient is the mean free path; it represents the distance between successive interactions. Mathematically, it is the inverse of the linear attenuation coefficient, the direct relation between it and energy is found, and it explains why the number of interactions becomes higher when the distance between the interactions gets smaller. The variation of impact factor of alloy 5070 as a function of energy is shown in figure-2b. Another important parameter that affects the transmission photons is cross-section (atomic, and electronic cross-section), which has an inverse relation with energy as shown in figure-2d. and figure-2e. and is associated with the mean free path definition.

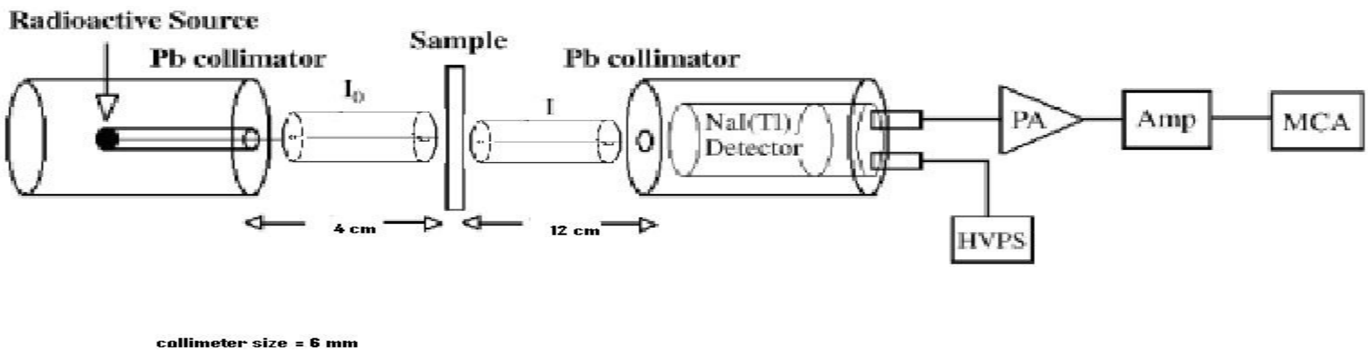

Figure-1
Block diagram of gamma ray absorption setup

Table-1
mass attenuation coefficient, linear attenuation coefficient, mean free path, total atomic, electron cross sections ,effective atomic number, effective electron number of wrought aluminum alloy 5070 at different energies

energy	59.54kev			661.16kev			1173kev			1332kev		
methods	x-com	Emp-formula	Exptl	x-com	Emp-formula	Exptl	x-com	Emp-formula	Exptl	x-com	Emp-formula	Exptl
$\mu_m (10^{-2})$	30.800	30.849	31.050	7.47	7.47	7.51	5.68	5.677	5.742	5.32	5.320	5.352
$\mu_l (10^{-2})$	82.651	82.675	83.214	20.017	20.017	20.132	15.217	15.213	15.386	14.258	14.259	14.343
λ	1.210	1.210	1.202	4.996	4.996	4.967	6.574	6.5732	6.499	7.014	7.013	6.972
$\sigma_T(10^{-24})$	13.949	13.953	14.044	3.378	3.378	3.398	2.567	2.567	2.597	2.406	2.406	2.420
$\sigma_e (10^{-25})$	10.621	10.620	10.690	2.572	2.572	2.587	1.955	1.955	1.977	1.832	1.832	1.843
$Z_{effective}$	13.134	13.134	13.134	13.134	13.134	13.134	13.134	13.134	13.134	13.134	13.134	13.134
$N_{eff}(10^{23})$	2.904	2.904	2.904	2.904	2.904	2.904	2.904	2.904	2.904	2.904	2.904	2.904

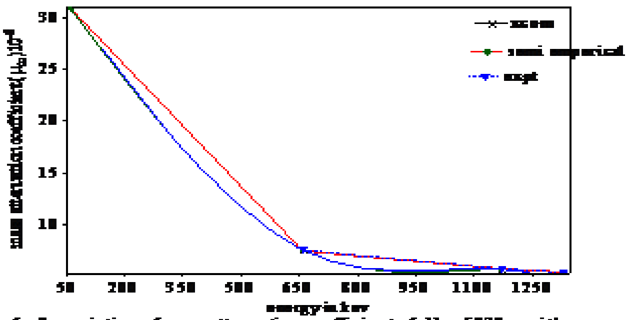

fig.2a variation of mass attenuation coefficient of alloy 5070 with energy

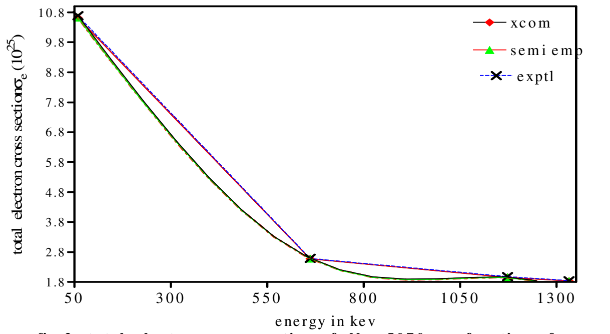

fig.2e.total electron cross section of alloy 5070 as a function of energy

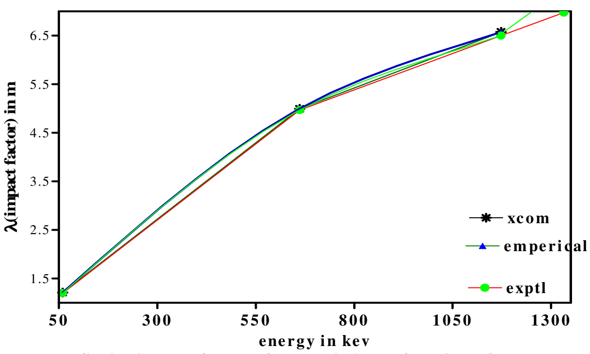

fig.2b. impact factor of alloy 5070 as a function of energy

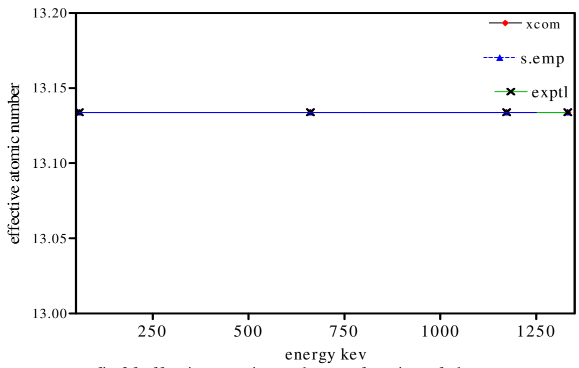

fig.2f.effective atomic number as afunction of photon energy

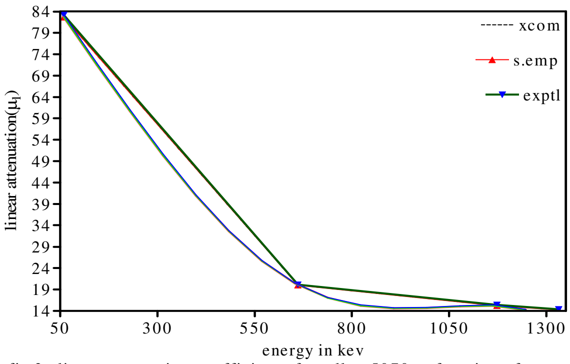

fig.2c.linear attenuation coefficient of an alloy 5070 as function of temperature

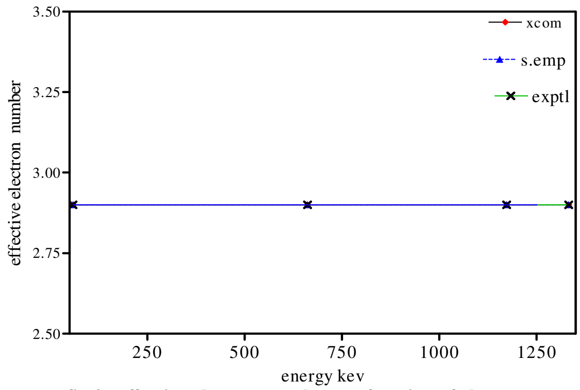

fig.2g.effective electron number as afunction of photon energy

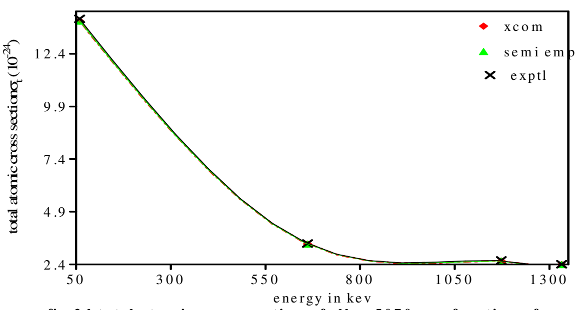

fig.2d.total atomic cross section of alloy 5070 as a function of energy

Conclusions

This study has been undertaken to get some information on the mass attenuation coefficients (μ_m) and related parameters (σ_a, σ_e, Z_{eff} and N_e) for wrought aluminum alloy 5070 Results of study show that μ_m is dependent on the chemical composition of the sample. The obtained μ_m values decrease with increasing photon energy. Also, the variation of σ_a and σ_e with energy is identical to μ_m. N_e is closely related to Z_{eff} and energy dependence of N_{el} and Z_{eff} is the same.

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