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Determination of Effective Atomic Number and Electron Density of Wrought Aluminum Alloy 7010 for Multi-Energetic Photons

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Abstract

The effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of wrought aluminum alloy 7010 has been determined by measuring mass attenuation coefficient (μ_m), total atomic cross section (σ_t) and total electron cross section (σ_e) with radioactive point source of different γ-energies viz. 59.5, 661.16, 1173 and 1332 keV. 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 experimental results determined were compared with the theoretical values obtained using XCOM and semi empirical approach for all photon energies. The photon mean free path (λ) and linear attenuation coefficient (μ_l) for these energies have been reported. The experimental values are in good agreement with theoretical values.

Keywords: *Mass attenuation coefficient, linear attenuation coefficient, effective atomic number, effective electron density*

1. Introduction

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 many 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

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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]. Reports of attenuation coefficient and effective atomic number for many materials are published by several authors [1-16]. In this work, we have measured the mass attenuation coefficients and the effective atomic numbers of wrought aluminum alloy 7010 at 59.54 kev, 661.16 kev 1173 kev and 1332 kev gamma photon energies, and then compared these parameters using semi empirical relations and the values obtained using XCOM program.

2. Experimental Method

Alloy 7010 has chemical composition of 89.66% Al, 6.3% Zn, 2.3% Mg, 1.55% Cu, 0.14% Zr, 0.03% Fe and 0.02% Si by weight. The alloy studied in the present work was prepared by ingot metallurgy route. The alloy 7010 has been heat treated at 723K for solutionizing. It has been soaked at that temperature for 24 hours. For precipitation strengthening it has been water quenched. For aging, the alloy has been heat treated at 433K for 18 hours, and at 448K for 8 hours. Annealing has been done at 685K for 3 hours and has been allowed to cool naturally.

Gamma ray attenuation experiment with narrow beam setup was used for measuring the incident and transmitted intensities and thereby calculated the attenuation coefficients. Further, the atomic cross section, electronic cross section, effective atomic number and electron density were calculated. Three gamma sources with four different energies were used in the study of the above parameters. The sample material was made into a cuboid with finely polished surfaces. For attenuation measurement, this cuboid sample is placed in the gamma path to the detector. The intensities of transmitted photons were determined by choosing the acquisition time of 30 minutes. Counts were recorded under the photo peaks. To reduce the statistical uncertainty and to keep it as low as possible, the experiment was repeated five times. The dimensions of the samples were measured using a screw gauge.

The experiment was performed at the Radiation Application Laboratory at Central Instrumentation Centre at Kakatiya University. The gamma rays are well collimated using collimators between the source and the detector. The collimators have a cylindrical shape and a circular aperture of 6mm diameter. The signal is detected by NaI (*Tl*) scintillation detector of 3×3 inch crystal and a high bias voltage of 1000 volts is applied. To reduce the undesired external radiation, the detector is placed in a thick lead shield. Figure 1 shows the entire setup with the source vault, collimators and the lead vault housing the detector. 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 sample was exposed to 59.5, 661.16, 1173 and 1332 keV photons emitted by 10 mCi Am-241, 30 mCi Cs-137 and 10 mCi Co-60 radioactive point sources. The sample was placed between the source and the detector. The distance between the radioactive point source with sample and the sample to detector were 12cm and 4cm, respectively. For the sample, incident intensity I_0 (before attenuation) and transmitted intensity I (after attenuation) were measured by a high resolution NaI (Tl activated) detector. A very narrow collimator is ideal to avoid scattered radiations reaching the detector. But the narrow

collimator reduces the count rate and adversely affects the counting statistics. Therefore, a balanced collimator size depending on the strength of the source has been used.

The measurements for the sample were carried out five times for each energy. Photon spectra were recorded in the following order. Firstly, source spectrum was recorded with source and without sample, the incident spectrum was obtained. Then, the transmitted spectrum was recorded with sample. In both the spectra, the photo-peak had Gaussian distribution. Finally, by integrating the incident spectrum and the transmitted spectrum over the selected width of the photo-peak, incident intensity I_0 and transmitted intensity I were obtained. The peak areas have been calculated for each measurement recorded for sufficient time (30min) to limit the uncertainty to less than 1%. The signal-to-noise ratios of the spectra of the samples were in an acceptable region for a good-quality sample.

Figure 1. The Experimental Setup

3. 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:

$$I = I_0 \exp(-\mu_m t) \tag{1}$$

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]:

$$\mu_m = \sum_i w_i (\mu_m)_i \tag{2}$$

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

$$w_i = \frac{n_i A_i}{\sum_i n_i A_i} \tag{3}$$

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

$$\sigma_t = \frac{\mu_m N}{N_A} \tag{4}$$

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

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

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

$$Z_{eff} = \frac{\sigma_t}{\sigma_e} \tag{7}$$

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

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

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

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

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

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

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.

4. Results and Discussion

The mass attenuation coefficients have been calculated at the photon energies 59.5, 661.16, 1173, 1332keV. 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 shown in the Table 1. It is clearly seen 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 effective atomic numbers (Z_{eff}) for wrought aluminum alloy 7010 at photon energies 59.5, 662.16, 1173, 1332keV have been calculated and the results have been displayed in Figures (2a to 2f) as function of photon energies. The calculated and the measured mass attenuation coefficient versus effective atomic number of alloy 7010 have been displayed in Figures. The calculated and measured effective electron density as a function of photon energy is shown in Table.1. It can be noticed in Figures 2a to 2f that experimental and calculated results are in a good agreement. It can be concluded from both calculated and measured results that the mass attenuation coefficients, the effective atomic and electron density depend on incoming photon energies and compounds of the materials.

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.

5. Conclusions

The present experimental study has been undertaken to get information on the μ_m and related parameters (Z_{eff}, N_{eff}, $_t$ and $_e$) for wrought aluminum alloy 7010. We have demonstrated that the μ_m is a useful and sensitive physical quantity to determine the Z_{eff} and N_{eff} 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 $_t$ and $_e$ 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_{eff} and N_{eff} are useful parameters for alloys. The results of this study will be helpful to 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, $_t$, $_e$, Z_{eff} and N_{eff} for wrought aluminum alloy 7010 are not available in the literature. Moreover, the results of this work can stimulate both experimental and theoretical research for alloys.

Acknowledgements

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Table-1
μ, μ_l, σ_t, σ_e, Z_{eff}, N_{eff}. and λ Values (Comparison between Experimental, Theoretical and X- c om) of 7010 Alloy at Different γ-energies

Energy	59.54kev			661.16kev			1173kev			1332kev		
Photon interaction 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
$\mu_m (10^{-2})$	40.20	40.19	40.35	7.46	7.46	7.38	5.66	5.66	5.69	5.31	5.31	5.35
$\mu_l (10^{-2})$	113.48	113.34	113.77	21.03	21.03	20.81	15.97	15.97	16.04	14.97	14.97	15.07
λ	0.88	0.88	0.88	4.75	4.75	4.80	6.26	6.26	6.23	6.68	6.68	6.63
$\sigma_T (10^{-24})$	18.87	18.85	18.92	3.50	3.50	3.46	2.65	2.65	2.67	2.49	2.49	2.51
$\sigma_e (10^{-25})$	13.89	13.87	13.92	2.57	2.57	2.55	1.95	1.95	1.96	1.83	1.83	1.84
$Z_{effective}$	13.59	13.59	13.59	13.59	13.59	13.59	13.59	13.59	13.59	13.59	13.59	13.59
$N_{eff}(10^{23})$	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90

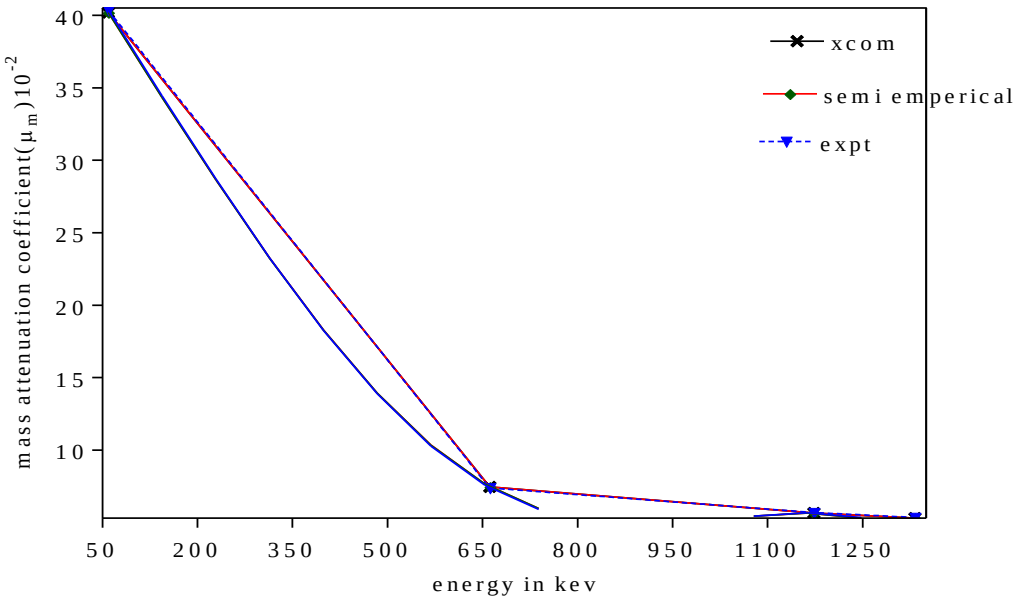

fig.2a.mass attenuation coeficient of alloy 7010 as a function of energy

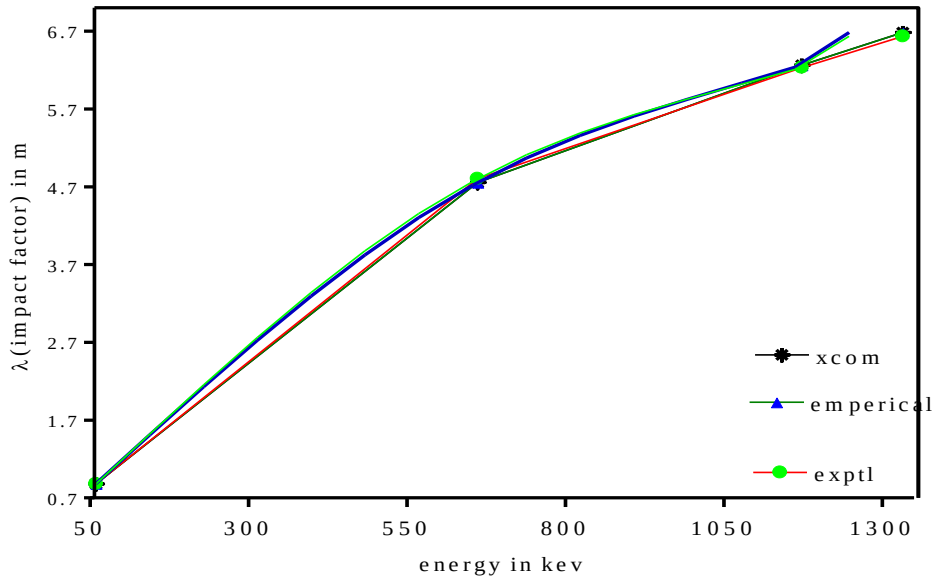

fig.2b impact factor of an alloy 7010 aws a function of energy

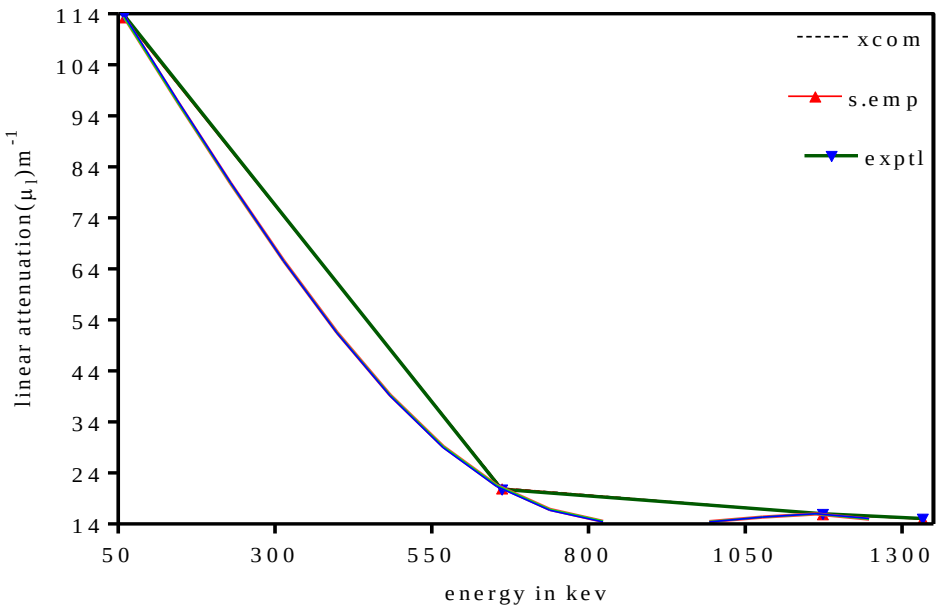

fig 2c. linear attenuation coefficient of alloy 7010 as a function of energy

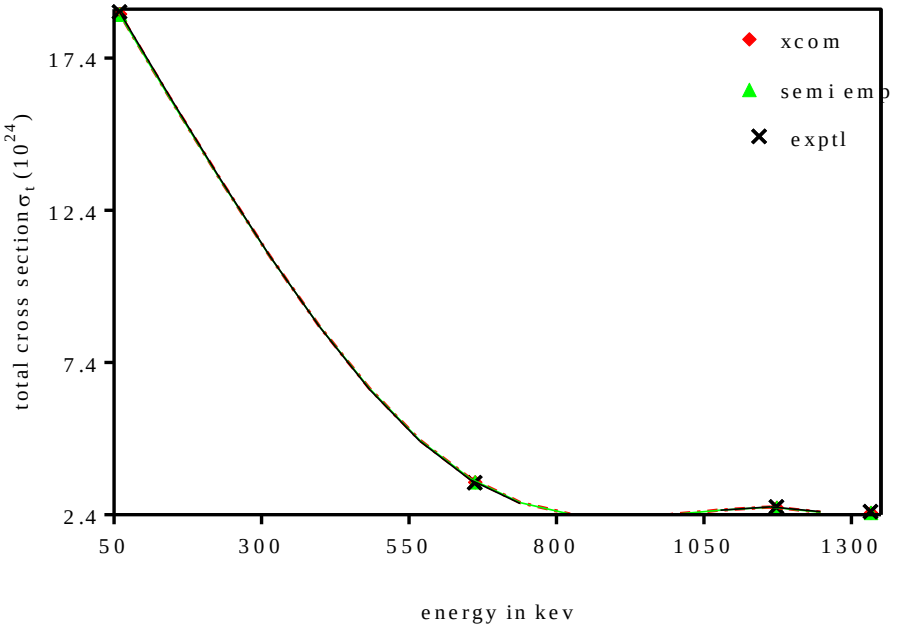

fig.2d. total atomic cross section of alloy 7010 as a function of temperature.

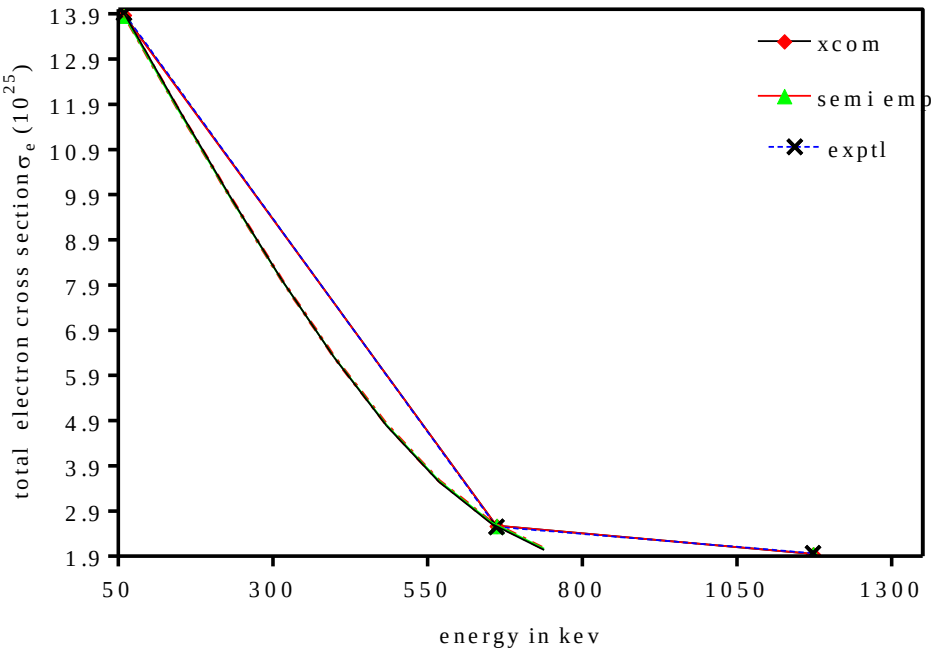

fig.2e.electon cross of section of alloy 7010 as a function of energy

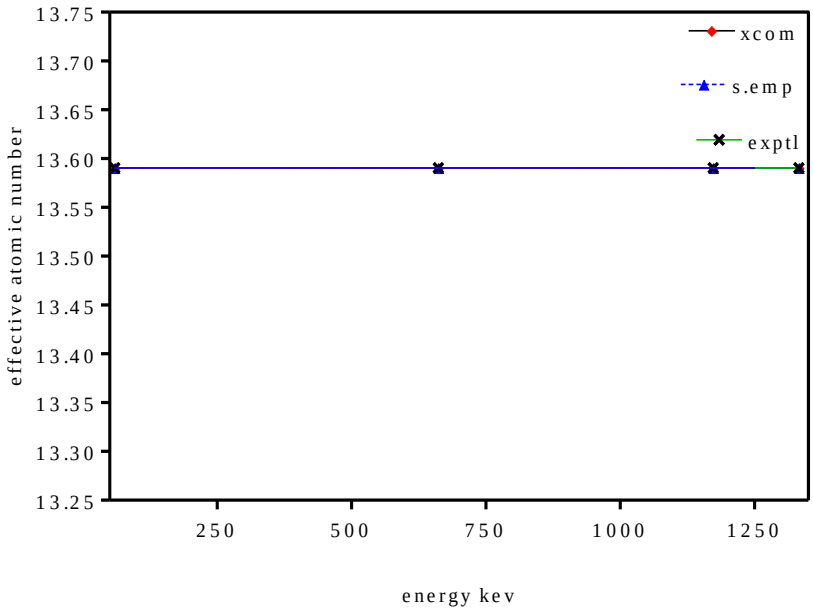

fig.2c. effective atomic number of alloy 7010 as a function of energy

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