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Measurement of Energy Loss of Relativistic Electrons in Aluminum Foil

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Abstract
The energy loss of relativistic electrons in thin aluminum foil has been measured to understand the mechanism of interaction of electrons with matter. The 948 keV and 1022 keV internal conversion electrons emitted by a Bi^{207} internal conversion source are allowed to pass through the aluminum foils of various thicknesses. The energies of the incident and transmitted internal conversion electrons have been measured using a Si(Li) detector coupled to 8K multichannel analyzer. The measured energy loss has been compared with the theoretical values predicted by NIST-ESTAR program and Batra's semi empirical formula.

1. Introduction

Energy loss of electrons and positrons in matter measured as stopping power of the material is a necessary ingredient for many parts of basic science, medical applications and technological applications. Accurate thickness of the thin foils can be evaluated from the experimental and theoretical values of the energy loss of electrons in them. The base of radiotherapy namely radiation dosimetery totally depends on the accurate value of energy loss measured as stopping power of electrons in matter. In view of these applications, the study of interaction of electrons and positrons in matter has been a subject of experimental as well as theoretical interest in recent years. Energy loss of electrons and positrons in matter depends on their incident energy and the atomic number of the target atom. The low energy electron interactions are mainly collision process, and that of high energy electron interactions are both collision and radiative process. The probability of these processes can be understood by measuring the stopping power of the electrons in the medium.

In this direction, several investigators have calculated and measured the stopping power of positrons and electrons in various materials. The total stopping power of the electron is the mean energy loss due to ionization, excitation and radiative processes.A variety of stopping power formulas are proposed by different authors to predict theexperimental results in different energy region[1–7]. Sugiyama[5] derived an accurate energy loss formula for 10eV-10 keV electron using Rohrlich and Carlson[8] formula. Gumus derived simple stopping power formulas for low energy[9]and intermediate energy[10,11] electrons in elemental solids, using modified Bethe-Bloch formula. Recently, Batra et al. have proposed simplified formulas to calculate the total stopping power of low energy (T≤0.5Mev)[12] and intermediate energy (0.3MeV≤T≤5.0MeV)[13] electrons and positrons in any substance, within an accuracy of ±4%. P.B.Pal et al.[14] derived a simple empirical formula for the total stopping power for electrons and positrons of energy between 5 to 1000 MeV in any element within an accuracy of ±10%.

CASINO[15] & ESTAR[16] are the computer programs to calculate stopping power with good accuracy. TRIM/SRIM codes are most popular computer simulated methods using ZBL stopping model by Ziegler and Biersack[17]. Paul and Schinner[18,19]collected a large amount of stopping power data for projectiles from ^{3}Li to ^{18}Ar and fitted them to produce a table of stopping powers. Using an improved version of their program MSTAR, one can calculate the stopping power for any ion ($3 \geq Z1 \leq 18$) at specific energies from 0.001 to 1000 MeV/nucleon and for any element, mixture or compound.

Several investigators [20–29] have measured the stopping power of electrons in different materials at energies greater than 5MeV. Very few measurements are carried out in the lowenergy region. G.Garc et al.[30] has measured the energy loss of low-energy electrons in the range of 0.01keV to 10 keV in toluene. Yang et al.[31] have measured the energy loss and energy straggling of mono-energetic positrons in the energy range of 1-10 keV in carbon foils of various thickness, using micro channel plate. They have compared their measured values with theoretical value predicted by CASINO[15] and ESTAR[16] and Batra et al.[13].

2. Theory

Interaction of electrons with matter can be understood by measuring the stopping power and energy straggling. Stopping power is a measure of the energy loss by the electron in the matter and energy straggling is a measure of the energy distribution around the mean energy loss. The linear stopping power, expressed in MeV/mm of any material is the space gradient of the residual kinetic energy of the primary radiation. The density dependence of linear stopping power can be removed by dividing it by the density of the material to get the Mass Stopping Power, MSP in (MeV-cm^2/gm).

ESTAR[16] is a computer-readable web databases of NIST to generate the stopping power, which is the same as those tabulated in ICRU Report-37[32] for 72 materials at a standard grid of 81 kinetic energies between 10 keV and 1000MeV. It can also calculate similar tables for any other element, compound or mixture at any set of kinetic energy between 1 keV and 10GeV.

ESTAR[16] calculates the collisional stopping power from the theory of Bethe[33], with a density effect correction evaluated according to Sternheimer[34]. Radiative stopping powers are evaluated with a combination of theoretical Bremstrahlung cross section described by Seltzer and Berger[35]. Analytical formula using a high-energy approximation are used above 50MeV, accurate numerical results of R.H.Pratt et al.[36] below 2 MeV and interpolation in the intermediate energy region from 2MeV to 50MeV.

R.K.Batra and M.L.Sehgal[13] derived an empirical formula for total MSP of the electron or positron of incident kinetic energy from 0.3 MeV to 5.0 MeV using Rohrlich and Carlson[8] formula as

$$MSP\ (MeV cm^2/gm) = (mZ + c)\frac{\gamma^2}{[\gamma^{(a^{\pm}Z + b^{\pm})} - 1]}$$

where γ represents the total energy of e^+ or e^- in unit of the rest mass of electron; The values of constant $a^+ = -0.0038$, $a^- = -0.0040$, $b^+ = 1.8402$ and $b^- = 1.8160$; The values of constants m and c depends on the atomic number of the absorber as in table 1.

Table 1. *Numerical values of m and c.*

Atomic Number (Z)	m (MeV-cm^2/gm)	c (MeV-cm^2/gm)
$1 \leq Z \leq 10$	-0.0330	1.3230
$10 \leq Z \leq 36$	-0.0097	1.0911
$36 \leq Z \leq 92$	-0.0048	0.9156

3. Experimental Details

3.1. Internal Conversion Source, Bi^{207}

We have opted the Bi^{207} as the source of IC electrons, as it emits wide spectrum of IC electrons, all of which can be used simultaneously for the MCA calibration under the same environmental conditions. The source is electroplated on a platinum foil and encapsulated in stainless steel of 1.52 cm outer diameter with 18.8 mg/cm^2 thick beryllium window to prevent the source spilling and contamination. This source is supplied by New England Nuclear and marketed by Nuclear Enterprises private Ltd.

Bi^{207} nucleus emits 481.699, 555.399, 975.699 and 1049.399 keV IC electrons as per the decay scheme of Bi^{207} nucleus shown in figure 1. After correcting for the attenuation by the beryllium window of the source and the air column between the source and detector, the effective energies of the emitted electrons becomes 443.9821, 518.8410, 941.7412 & 1015.5587 keV respectively.

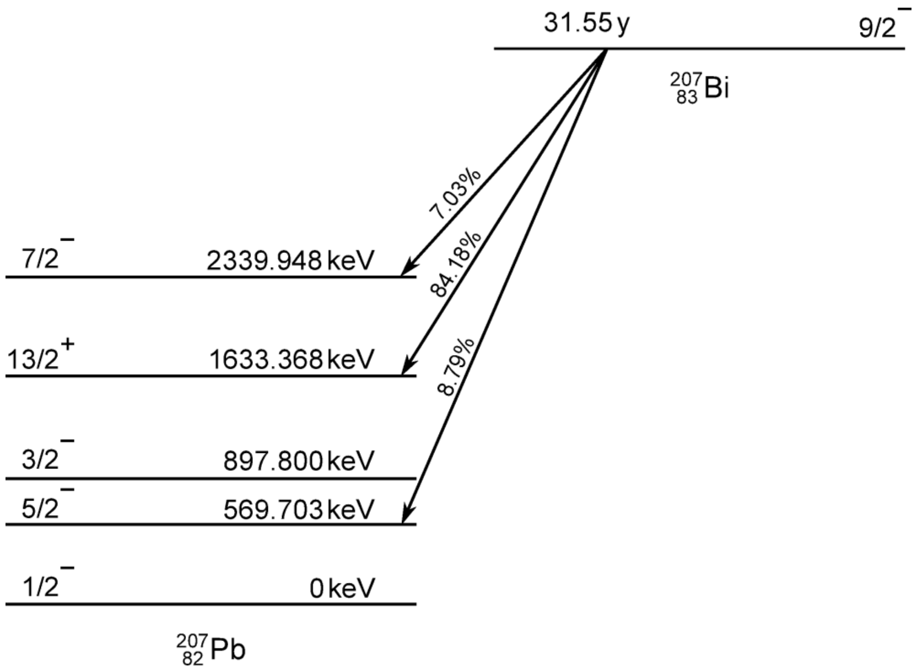

Figure 1. *Decay scheme of Bi^{207} nucleus.*

3.2. The Detector and the Spectrometer

The selection-grade NE Si(Li) detector used in this experiment has 0.2cm depletion thickness and 15cm^2 active area. A bias of 390V is applied to the detector from HV-503. The output of the detector is connected to a charge sensitive ORTEC preamplifier of charge sensitivity 15 mV/MeV (Si equivalent). This preamplifier is coupled to a delay line amplifier and then to 8K multichannel analyzer.

3.3. The Absorber

Absorbers are the pure aluminum foils obtained from Sigma-Aldrich Inc. Their thicknesses were determined using a traveling microscope and a sensitive balance. Uniformity of the foil thickness is confirmed by acquiring the spectrum transmitted through different regions of the foils.

3.4. Experimental Setup

We have used two collimators C1 and C2 to achieve good geometry in the present experiment. The collimator, C1 is placed near the source and C2 near the detector. The absorber is placed between the collimators C1 and C2. The entire assembly was placed in a light tight box. The experimental arrangement used for measuring the MSP of relativistic electrons from Bi^{207} IC source is as shown in figure 2.

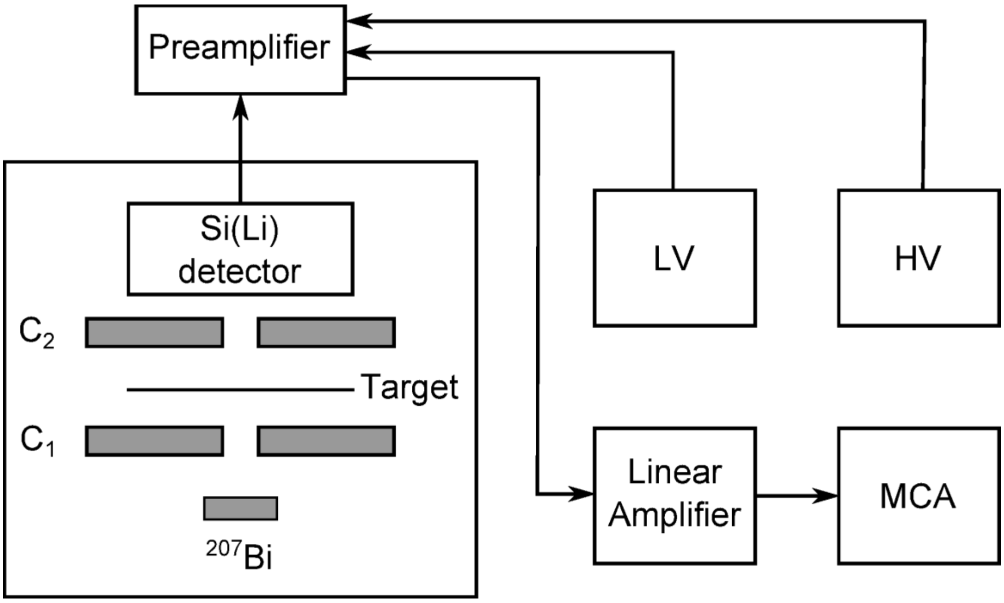

Figure 2. *Experimental arrangement: C1, Source collimator; C2, Detector collimator;LV, Low voltage unit; HV, High Voltage Unit; MCA, Multi Channel Analyzer.*

4. Procedure

The stability of the spectrometer is confirmed by constantly checking the channel numbers corresponding to the peak positions over the period of experiment. The data is acquired over a long period of time so that the total counts under each peak are more than 10,000 counts and hence the counting error is less than 1%.

4.1. Incident Spectrum & MCA Calibration

After confirming the long term stability of the instrument, the spectrum of incident IC electrons of ^{207}Bi is acquired and it is shown in figure 3. From this figure, we notice that the spectrum consists of four peaks corresponding to 443.98, 518.84, 941.74 and 1015.56keV. All these four peaks are fitted to four Exponentially Modified Gaussian (EMG) to get the channel numbers corresponding to the most probable energies of these peaks as in figure 3. A plot of the energies of the conversion electrons against their most probable channel number called calibration graph of the Si(Li) detector spectrometer is given figure 4. From the calibration graph, the calibration constant was found to be (0.2738 ± 0.0002) keV/channel.

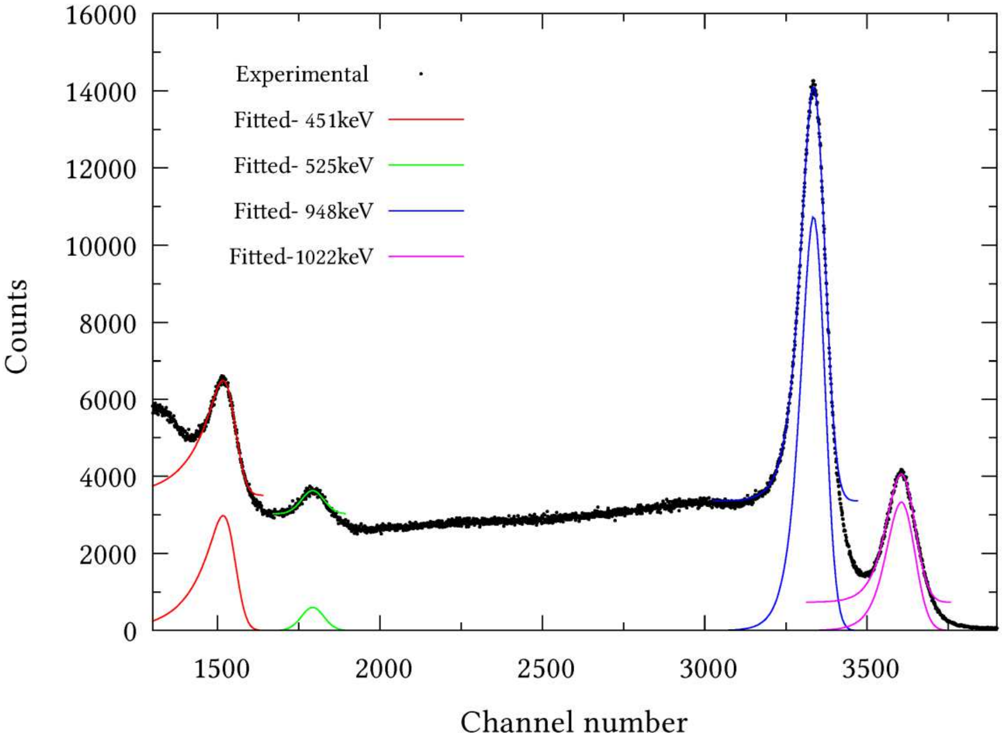

Figure 3. *Incident Bi^{207} spectrum with individual peak fitted to EMG.*

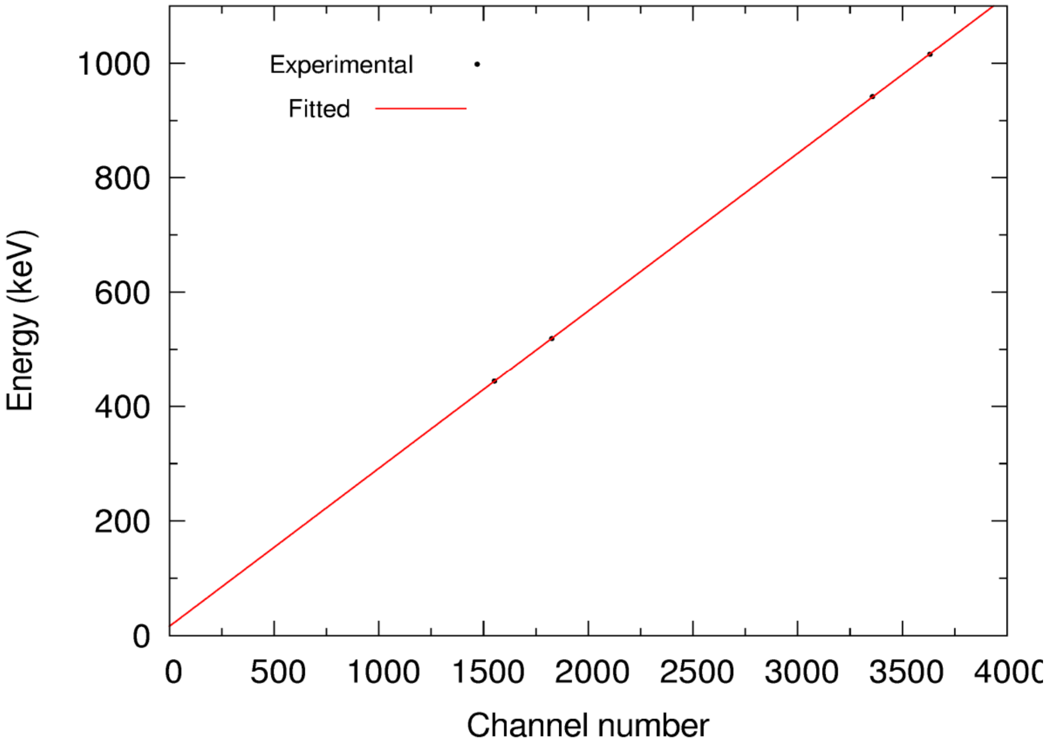

Figure 4. *Calibration Graph.*

4.2. Transmitted Spectra &MSP

The transmitted spectrum is acquired by placing the aluminum foils of various thicknesses in between the collimators C1 and C2. In the transmitted spectra, the FWHM of the IC electrons of energies 942 &1016 keV alone is evaluated and used to measure their MSP in the aluminum absorber. Figures 5 and 6 presents the peak-fitted spectra of the IC electrons of energies 942 and 1016 keV transmitted through different thicknesses of the aluminum foil.

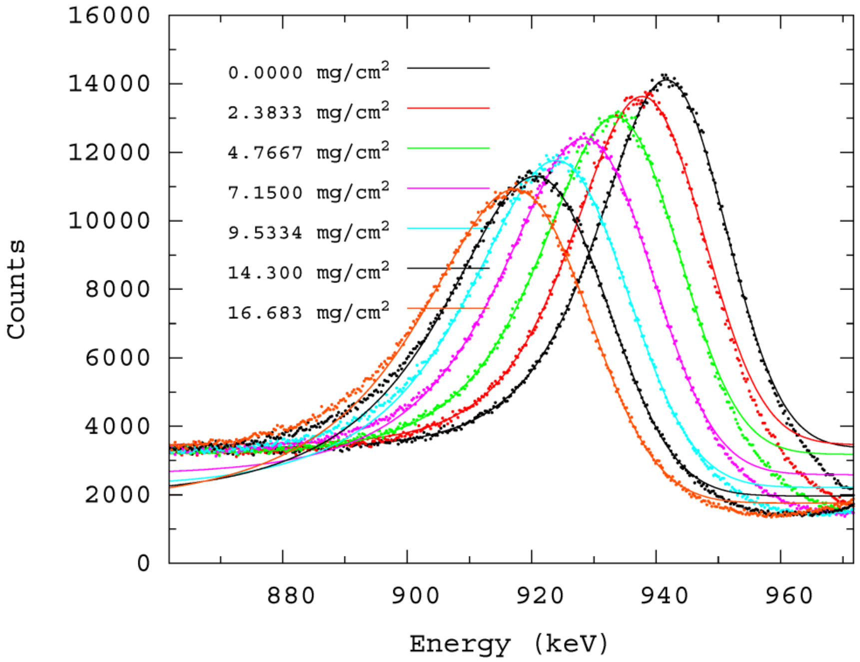

Figure 5. *Spectrum of 942 keV IC electrons transmitted through Al foils of various thicknesses.*

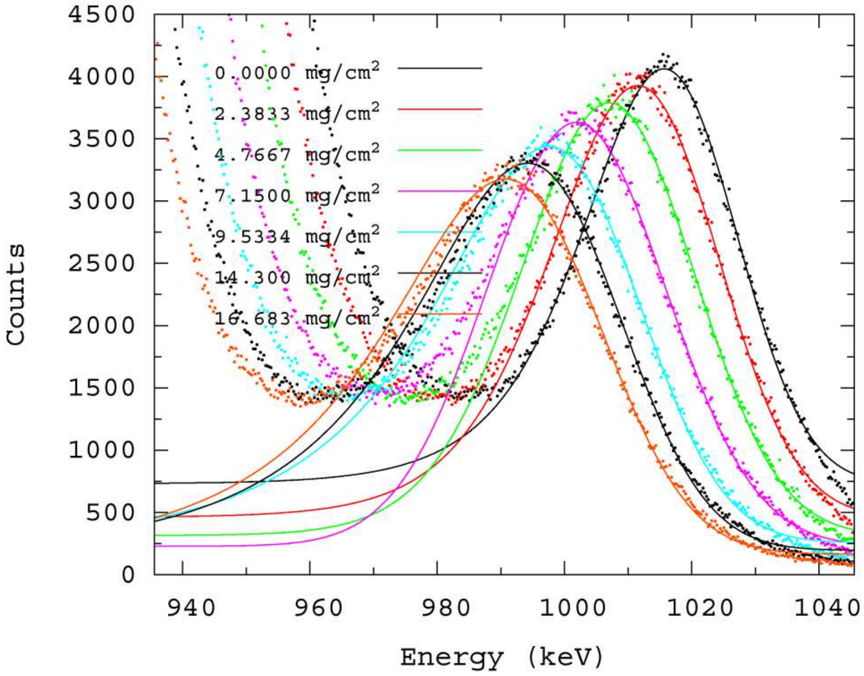

Figure 6. *Spectrum of 1016 keV IC electrons transmitted through Al foils of various thicknesses.*

From the figure 5, we notice that as the foil thickness increases, the energy of the 942 keV IC peak decreases and its FWHM increases. The difference between most probable energy values of the transmitted and the incident spectra is taken as the energy loss in aluminum foil. These values are given in table 2 and figure 7 as a function of thickness. Since the foils are too thin, the slope of these lines are measured as the average energy loss per unit path length i.e., MSP of aluminum. For the sake of comparison we have also shown the energy loss values predicted by ESTAR[16] and Batra et al. [13] as a function of thickness.

The above procedure is repeated for 1016 keV IC electrons. Table 3 gives the energy loss of 1016 keV IC electron as a function of thickness of aluminum foils. A plot of energy loss as a function of target thickness is given in figure 8.

5. Results and Discussion

We have measured the energy loss of 942 and 1016 keV IC electrons in thin aluminum foils of thickness ranging from 2 to 17 mg/cm^2. The measured energy loss values are compared with the theoretical values computed using ESTAR program [16] and Batra's formula [13] as shownin tables 2 and 3. From these tables, we notice that the measured values agrees well with the theoretical values predicted by ESTAR program[16] as well as Batra et al. semi empirical formula[13] within the experimental uncertainties.

We have also plotted the energy loss of 942 and 1016 keV IC electrons in aluminum foil as a function of the absorber thickness as in figures 7 and 8. The foils being thin, the slope of these plots are taken as the MSP of the electrons in aluminum at that energy. The MSP evaluated in this manner are presented in table 4. From this table, we notice excellent agreement between MSP values obtained by our experiment and that predicted by ESTAR program[16]. Batra's semi empirical formula [13] underestimates the actual MSP values by 1.5% at 942 keV and 1.8% at 1016 keV. In fact, this uncertainty is well within ± 4% claimed by them.

Table 2. *Measured & theoretically predicted values of energy loss of 942 keV IC electrons in Al.*

Foil Thickness (mg/cm^2)	**Transmitted Energy (keV)**	**Energy Loss**		
		Measured (keV)	**Batra etal.[13] (keV)**	**ESTAR[16] (keV)**
0.0000	941.5758	0.0000	0.0000	0.0000
2.3833	937.8583	3.7174	3.4967	3.5464
4.7667	934.3760	7.1997	6.9934	7.0928
7.1500	930.1960	11.3798	10.4901	10.6393
9.5334	925.7855	15.7902	13.9868	14.1857
11.9167	923.3365	18.2392	17.4836	17.7321
14.3001	920.6617	20.9141	20.9803	21.2785
16.6834	916.5332	25.0426	24.4770	24.8249

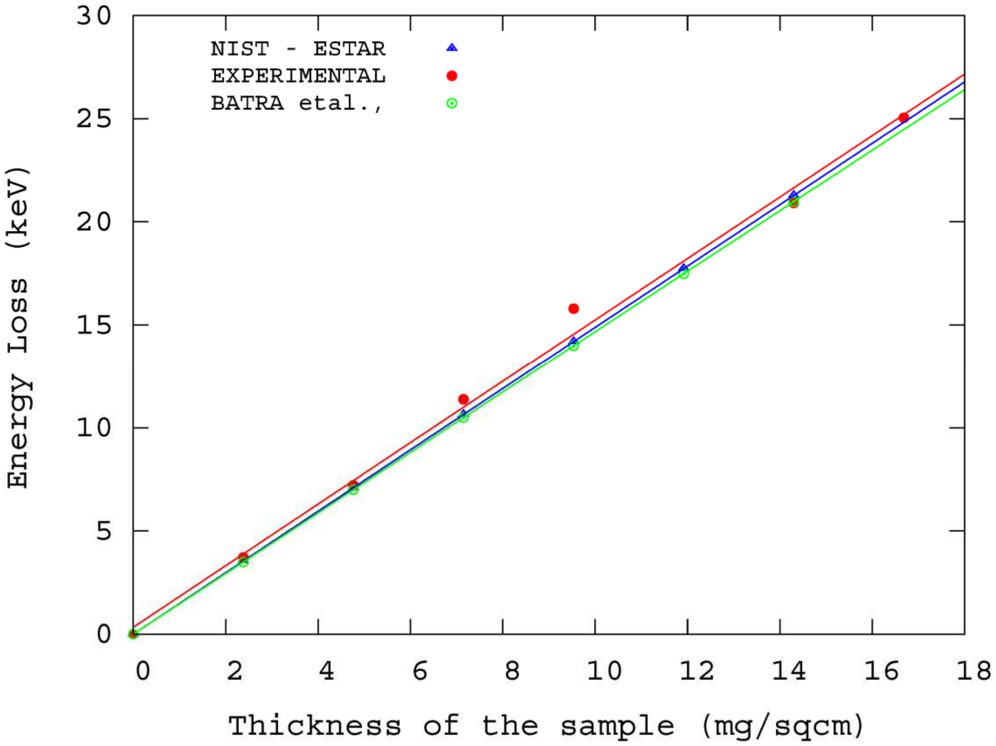

Figure 7. *Energy loss of 942 keV IC electrons as a function of aluminum foil thickness.*

Table 3. *Measured & theoretically predicted values of energy loss of 1016 keV IC electrons in Al.*

Foil Thickness (mg/cm^2)	**Transmitted Energy (keV)**	**Energy Loss**		
		Measured (keV)	**Batra et al.** [13] **(keV)**	**ESTAR**[16] **(keV)**
0.0000	1015.6497	0.0000	0.0000	0.0000
2.3833	1011.8910	3.7587	3.4830	3.5393
4.7667	1008.2804	7.3693	6.9660	7.0785
7.1500	1003.8402	11.8095	10.4490	10.6178
9.5334	999.7533	15.8964	13.9320	14.1571
11.9167	996.9313	18.7183	17.4150	17.6963
14.3001	994.4675	21.1822	20.8980	21.2356
16.6834	990.7579	24.8918	24.3810	24.7749

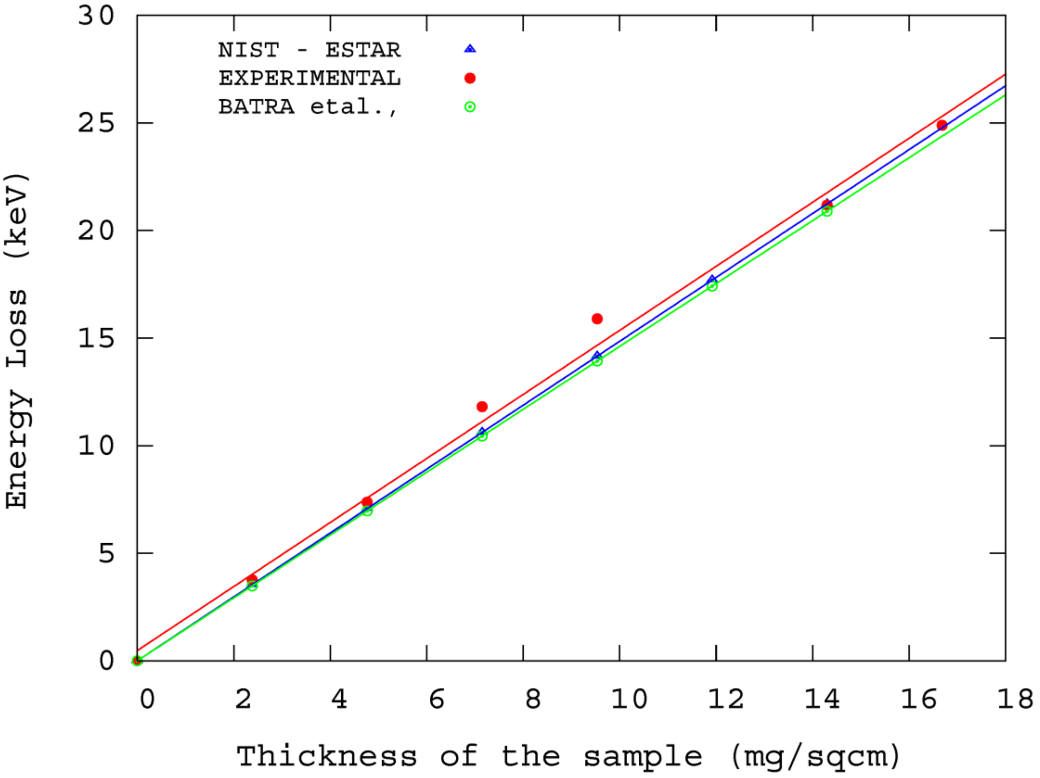

Figure 8. *Energy loss of 1016 keV IC electrons as a function of aluminum foil thickness.*

Table 4. *Summary of the result showing the experimental &theoretical values of MSP with fitting error for the 942 keV &1016 keV IC electrons of* ^{207}*Bi in Al*

Energy (keV)	**Measured MSP MeV-cm^2/gm**	**MSP by Batra's formula**[13] **MeV-cm^2/gm**	**MSP by ESTAR program**[16] **MeV-cm^2/gm**
942	1.4904 ± 0.0469	1.4671± 0.00001	1.4880 ± 0.00001
1016	1.4883 ± 0.0503	1.4614± 0.00001	1.4850 ± 0.00001

6. Conclusion

We have measured the energy loss and mass stopping power of 942 and 1016 keV electrons in aluminum foil using Si(Li) detector spectrometer. The measured energy loss and MSP values of the 942 and 1016 keV electrons agrees closely with the results predicted byESTAR program [16]. Though Batra's semi empirical formula [13] is simple and versatile, it underestimates the actual MSP values by 1.5% at 942 keV and 1.8% at 1016 keV.

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