2.1 OUTLINE OF THE CHAPTER

The present measurements, related with energy loss and higher order moments of energetic ions in various metallic foils, are carried out by utilizing the facilities available at Inter University Accelerator Centre (IUAC), New Delhi, India. In this study, for covering energetic ions with $Z_1 = 2 - 8$, we considered He, Li, C and O ions in the energy region $\sim 0.25 - 7.00$ MeV/n. For He ion, Am$^{241}$ source is used while Li, C and O ions are generated and accelerated through 15 UD Pelletron accelerator. Therefore, for these measurements, different experimental setups are used. In the subsequent sections, a brief description of 15UD Pelletron accelerator, experimental setups, experimental procedure to carry out the measurements and methods of data analysis is given.

2.2 PELLETRON ACCELERATOR

A 15UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi, India is a tandem type electrostatic accelerator, capable to accelerate any ion from proton to uranium up to energy of 200 MeV, depending upon the nature of ion [1-5]. This accelerator is installed in vertical configuration in an insulating tank (26.5 m in length and 5.5 m in diameter), which is filled with SF$_6$ as an insulating gas. Inside this tank, there is a high voltage terminal, which is about 1.52 m in diameter and 3.61 m in height, and can be charged to a high potential that can be varied from 4 to 15 MV. This terminal is connected to the tank vertically through ceramic titanium tubes, also known as accelerating tubes. A potential gradient is maintained through these tubes from high voltage to ground, from top of the tank to the terminal as well as from terminal to the bottom of the tank. Negative ions produced through the ion source are injected in the accelerator and are accelerated towards the terminal. In the terminal, negative ions stripped off few electrons and thereby converted into positive ions, which are further accelerated as they proceed to the bottom of the tank, at ground potential. As a result, the ions emerging out from the accelerator gain the energy given by
where \( q \) is number of positive charges on the ion after stripping and \( V \) is the terminal potential. These accelerated ions are analysed to the required energy through bending (analyzer) magnet, and directed to desired experimental area with the help of multiport switching magnet, which can deflect the beam into any of the seven beam lines in beam hall.

The major components used to generate and accelerate the ions through 15UD Pelletron Accelerator are shown in Fig. 2.1, as a block diagram, and described briefly as:

**Ion Source**

In this accelerator, SNICS (Source of Negative Ions by Cs Sputtering) is used as an Ion Source (IS) to generate ions from solid materials. SNICS consists of an ionizer, sputter cathode and an extractor. There is a Cs canal in which Cs is heated to produce vapours, which are allowed to strike on the ionizer. Now, current is passed through the ionizer to increase its temperature and consequently starts acting as the ionizing surface. Cs vapours hitting this ionizer leave the surface as Cs\(^+\) ions. The cathode which is placed at a negative potential contains the material of which the ions are to be generated. Cs ions get accelerated towards the cathode and sputter out the negative ions. These negative ions are extracted out of the source with the extractor (EXT) electrode, which is placed at positive potential.

**Injector System**

These negative ions, extracted from SNICS source, are focussed by Einzel Lens (EL) and are accelerated by deck potential after passing through five General Purposes Tubes (GPTs). Initially by adjusting the extractor and focus voltage, the beam is focussed on the Double Slit (DS) in the object plane of the Injector Magnet (IM), which is at about 1.8 m before the magnet. The position and size of the beam is continuously monitored at the Beam Profile Monitor (BPM) before the DS. Looking at the BPM, the beam is centrally aligned (in the

\[
E = (q + 1)V
\]
Experimental Arrangements and Data Analysis

beam tube) using the Electrostatic Steerer (ES) after the GPTs and focussed by changing extractor and focus voltages. Then the beam current is measured by the Faraday Cup (FC) after the DS. By adjusting the ion source parameters, extractor and focused voltages, the optimum beam current is obtained. Hereafter, the magnetic field in the injector magnet is adjusted (by adjusting the current of the magnet power supply accordingly) so that singly charged negative ion beam of a particular mass can pass through the magnet and get doubly focussed at the Double Slit (DS) at the image plane of the magnet (at 1.8 m after the down). The position and focussing of the beam selected by the magnet is monitored by the next BPM and the beam current of that beam is measured by FC following it. Afterwards, using two sets of Electrostatic Quadrupole (EQ) triplets, the beam is focused at the entrance of the accelerating column/tank.

Accelerator Tank

This tank supports the high potential terminal consisting of thirty 1 MV modules, 15 on either side of the terminal. The upper portion of the column above the terminal is referred as the low energy section and the portion below the terminal as the high energy section. Two shorted sections with no potential gradient, commonly known as Dead Sections, are provided in the low and high energy column sections for equipment housing. The Low Energy Dead Section (LEDS) is also provided with an electrostatic quadrupole lens while High Energy Dead Section (HEDS) is equipped with a second foil stripper assembly. The charging of the high voltage terminal to 15 MV is done by using the Pelletron charging chain. There are two independent sub systems with one charging chain in each so that each chain is required to supply 100 µA. The terminal also has an offset quadrupole triplet lens with variable apertures and Faraday cup to select the desired charge state after stripping. These ions with a particular charge state are further accelerated downward. The matching electrostatic quadrupole triplet in the terminal, in conjunction with the offset quadrupole helps to focus the beam so that it serves as an object for the remaining sections of the accelerating column and the Magnetic Quadrupole (MQ) outside the accelerating
Fig. 2.1: Block diagram of 15UD Pelletron Accelerator.
column and gets doubly focused at the Double Slit (DS) placed before the Analyser Magnet (AM). The distance of the DS from the AM is twice its bending radius. Hence, the next image is formed at the Single Slit (SS) placed beyond the Analyser Magnet (AM).

**Analyser Magnet**

The Analyser Magnet (AM) bends the vertical beam from the accelerator into the horizontal direction (i.e. bending angle equal to 90°) to divert it towards the beam hall. Apart from bending the beam, AM makes the beams clean by providing an energy selection. The magnetic field is calibrated for energy of different types of ion-beams. With the help of downstream Single Slit (SS), analyser magnet also provides reference for energy stabilisation. The entrance and exit edge angle (26.6°) of this magnet provides the axial focusing resulting in a double focussed waist at the downstream single slit (SS). The image formed at SS further serves as object for the next focussing combination of the Magnetic Quadrupole (MQ) and Switching Magnet (SM). The image formed by this combination is at the next slit position on beam line at desired beam angle (0°, ±15°, ±30°, ±45°). Further transporting is now left to the beam line magnetic quadrupoles. The Magnetic Steerers (MS) are provided to keep the beam moving along the axis of the transporting elements and the tubes.

**Switching Magnet**

The Switching Magnet (SM) is a horizontal bending semi circular magnet, which bends the beam into seven beam lines - General Purpose Scattering Chamber (GPSC), Gamma Detector Array (GDA), Material Science (MSC), Superconducting LINAC Booster, Heavy Ion Reaction Analyser (HIRA), Accelerator Mass Spectroscopy (AMS) and Radiation Biology (RB) located at different angles 45°, 30°, 15°, 0°, -15°, -30°, -45°, respectively.

By utilizing this accelerator, Li, C and O ion beams at two different energies are generated.
EXPERIMENTAL SETUPS AND NUCLEAR ELECTRONICS

The present measurements are carried out in two different setups. The experiments with Li, C and O ions are performed in Low Flux Chamber attached with General Purpose Scattering Chamber (GPSC) and for alpha (He) ion, Alpha chamber is used. The brief description of these setups is as follows.

2.3.1 Low Flux Chamber

As already mentioned in section 2.2, out of the seven beam lines, one beam line is dedicated to General Purpose Scattering Chamber (GPSC). The low flux chamber is an additional attachment to GPSC at an angle of 15° with respect to the primary beam direction. Fig. 2.2 shows the photograph of low flux chamber attached to GPSC. Initially primary beam from the Pelletron accelerator is scattered by a thin gold foil (~ 330 nm) mounted on a scattering ladder, which is adjusted at the centre of the GPSC (Fig. 2.3). In the low flux chamber, there is a provision of introducing a target ladder with vertical motion in both downward and upward direction, in order to facilitate the passage of the scattered beam through the desired target foil. The low flux chamber can be isolated from the main GPSC as and when the replacement of target ladder is desired. This helps in maintaining the vacuum in the main chamber without any disturbance.
As mentioned above, scattering ladder can move in upward and downward direction and can also rotate about its own axis without disturbing the vacuum of the GPSC. Additionally, there is a provision to mount multiple scattering foils on the scattering ladder. In our experiments, four thin Au foils (thickness around ~330 nm) are mounted on the scattering ladder. Although single scattering foil is sufficient, to scatter the ion beam, in the whole experiment but the idea behind using the four scattering foils was to overcome the chance of damaging the scattering foil during experiment. Along with Au scatterer, a quartz crystal was also mounted on the scattering ladder in order to see the ion beam in GPSC beam line.

Fig. 2.3: Inner view of GPSC.

2.3.2 Alpha Chamber

Alpha Chamber is cylindrical in shape, made up of stainless steel material. In this chamber, there are three different types of holders fixed at different positions and are aligned in the same vertical direction. The lower and upper holders are used for mounting the alpha source (Am$^{241}$) and charged particle detector, respectively. Middle holder is a multiple target holder, where one can mount five target foils simultaneously (Fig. 2.4). The arrangement of this multiple target holder is such that it can rotate about its own axis in such a way
that the each target foil can be aligned exactly in between source and detector. Also, in order to maintain the vacuum, the vacuum pump is connected at the bottom of the chamber. The outer view of alpha chamber is shown in Fig. 2.5.

![Inner view of Alpha Chamber](image1.png)

**Fig. 2.4: Inner view of Alpha Chamber.**

![Outer view of Alpha Chamber](image2.png)

**Fig. 2.5: Outer view of Alpha Chamber.**
2.3.3 Nuclear Electronics

The ions after passing through the target foils are detected through the charged particle detector and obtained signals are suitably processed through various nuclear electronic components like Pre-amplifier, Pulsar, Amplifier, Single Channel Analyzer (SCA), Gate and Delay Generator (GDG), Analog to Digital Convertor (ADC) etc. [6-7]. The block diagram of nuclear electronics used in present experiments is shown in the Fig. 2.6. The brief description of the detector and the nuclear electronic components is given as under.

Charged Particle Detector

In the present experiments, partially depleted PIPS (Passivated Implanted Planar Silicon) detector is used. CANBERRA (PD150-15-300AM) is the detector model. The area, depletion depth and reverse bias supply of the detector are 150 mm$^2$, 300 µm and 60V respectively.

Detector Bias Supply

In order to bias the detector, the detector is connected to the bias power supply (Model: ORTEC 710 QUAD 1-kV). During the reverse biasing, bias supply is increased at slow rate till the 60V voltage is achieved. The slow increment of supply voltage is necessary to avoid the damaging of the detector.

Pre-amplifier

Pre-amplifier is used to amplify the weak signal, obtained from a detector, and derive it through the cable that connects the preamplifier with the rest of the nuclear electronics. In order to maximize the signal to noise ratio in the output
pulse, the pre-amplifier is positioned as close as possible near the PIPS detector. The closeness of the pre-amplifier with the detector also minimizes the capacitive loading at the pre-amplifier input and as a result reduces the output noise level. Here, the preamplifier also serves as impedance matching device between high impedance detector and the low impedance coaxial cable that transmits the detector amplified signal to main amplifier. Here, ORTEC 142A model of pre-amplifier is used to amplify the detector output.

Amplifier

The amplifier is used to amplify the signal, obtained through pre-amplifier, and shape the signal to a convenient form for the further processing. Here, the amplifier must always preserve the information of interest. For timing information, a fast response is necessary while for pulse height information, a linear relationship between input and output amplitude must be preserved. For pulse height information, an adjustable gain over a wide range is provided so as to allow a scale adjustment in a spectrum analyser.

In the present experiment, linear amplifier (Model: Silena-7611/L) and delay amplifier (Model: ORTEC-427A) are used to achieve the above said purposes.

Single Channel Analyzer

The single channel analyzer (SCA) is used to sort the incoming signals, according to their pulse height. In SCA, there are two discriminators with two independent thresholds namely lower level and upper level threshold. Thus, SCA allows only those signals, which lie in between upper and lower threshold. SCA, model ORTEC-551, is used in the present experiments.

Gate and Delay Generator

Gate and delay generator (GDG) is a triggerable module, which generates variable width gate pulses ranging from few nanoseconds to as long as a few seconds. Generally, gate generator can be triggered with an input logical signal, and in certain cases, it operates manually. The gate pulse then may be used to activate a certain device. These modules are also equipped with an end marker.
signal which is a logic pulse issued at the end of the gate pulse. This feature can then be used as an active logic signal delay. In the present experiments, ORTEC-417A model is used.

**Pulser**

Pulser is used to stimulate the output of the detector and provides a means of checking electronic instruments in a pulse processing system. It has 1% overall accuracy, good stability as a function of temperature and time. It also calibrates to read directly in terms of equivalent energy deposited in a detector. ORTEC-480 model is used in the experiments.

**Analog to Digital Convertor**

Analog to Digital Convertor (ADC) (Model: Philips 7164) is used to convert analog signals to equivalent digital signals. These digital signals fed to the Personal Computer (PC) and appear as energy spectrum, in terms of channel versus counts.

In summary, the weak signals generated by detector are amplified and shaped through various electronic components and converted analog to digital signals and finally stored in online computer.

### 2.4 METALLIC FOILS

#### 2.4.1 Selection of Metallic Foils

In the present study, Al, Ti, Ni, Ag, Tb, Ta and Au metallic foils are selected as target materials. These metals are selected due to the reasons that (a) these are chemically stable and therefore do not oxidize during the experiment, (b) these are easy to roll, (c) Very limited experimental measurements related with energy loss and higher order moments in these foils are available, (d) these cover the wide range of target atomic number with $Z_2=13$–79 and thus a general behaviour of energy loss and related moments of considered ions can be commented. From application point of view, we can use these metallic foils as degrader and absorber in various ion beam based experiments.
2.4.2 Procurement of Metallic Foils

The presently selected metallic foils are procured from STREM Chemical, USA. The quoted thickness, purity and density of each metallic foil are given in Table 2.1.

**Table 2.1** Thickness, purity and density of metallic foils.

<table>
<thead>
<tr>
<th>Metallic Foil</th>
<th>Quoted Thickness (mg/cm²)</th>
<th>Purity</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>6.86</td>
<td>5N5</td>
<td>2.702</td>
</tr>
<tr>
<td>Ti</td>
<td>57.39</td>
<td>2N7</td>
<td>4.5189</td>
</tr>
<tr>
<td>Ni</td>
<td>22.24</td>
<td>3N</td>
<td>8.8955</td>
</tr>
<tr>
<td>Ag</td>
<td>133.01</td>
<td>3N</td>
<td>10.473</td>
</tr>
<tr>
<td>Tb</td>
<td>510.26</td>
<td>3N</td>
<td>8.23</td>
</tr>
<tr>
<td>Ta</td>
<td>830.05</td>
<td>3N5</td>
<td>16.601</td>
</tr>
<tr>
<td>Au</td>
<td>482.78</td>
<td>3N5</td>
<td>19.311</td>
</tr>
</tbody>
</table>

![RBS Spectra of Al, Ni and Au metallic foils.](image)

**Fig. 2.7:** RBS spectra of Al, Ni and Au metallic foils.
Since some metals are sensitive to environmental conditions and get oxidized in air, therefore the purity of the presently used metallic foils is checked through Rutherford Backscattering spectroscopy. Fig. 2.7 presents the RBS spectra for Al, Ni and Au metallic foil. It is clear from this Fig. that no undesired peak appears, which confirms the purity of the metal.

2.4.3 Rolling of Metallic Foils

In our experiments, self supporting metallic foils with variety of thickness were required. In order to obtain different thicknesses, we rolled the procured metallic foils with the hardened roller machine (Fig. 2.8). In this machine, there are two cylindrical rollers with a small gap, where we can place the metallic foils. But, if we place the metallic foils directly, then there is a probability of entering the impurities from the surface of rolling cylinder into the foil, during rolling. To avoid such problem, we firstly put the metallic foil in the mirror polished folded stainless steel plate and then introduce it in between the cylindrical rollers. These stainless steel plates are commercial available.

Fig. 2.8: Hardened Roller machine.
At the time of procurement, the mirror polished side of these plates was covered with the thin plastic sheets. In order to use these plates, we removed the plastic sheets and washed with alcohol and then folded manually (Fig. 2.9). After this, such folded plate was inserted between the cylindrical rollers, without metallic foil, and rolled it to make its inner surface smooth and non-sticky. Hereafter, small metallic piece, under consideration, was introduced in these steel folded plates and again inserted in the machine’s rollers (Fig. 2.10). Now by applying uniform pressure at slow rate, we rolled the metallic foil through the steel plates. After couple of rounds, area of metallic foil increased and consequently thickness decreased. In this way, we rolled all the considered metallic foils, for different durations, to obtain the different thicknesses.

Fig. 2.9: Stainless steel plate used for rolling the metallic foil.

Fig. 2.10: Stainless steel plate with metallic foils in between cylindrical rollers of Hardened Roller machine.
In order to obtain the desired thicknesses of the metals, thickness of the foils is checked, after different rolling time, through gravimetric method. Further, thickness uniformity of rolled foils is ascertained using micrometer (least count = 1µm) and adopting energy loss method, wherever applicable. The overall error in thickness measurements is found to be ~2-5%. The range of thickness, obtained after rolling, for each metal is presented in Table 2.2.

**Table 2.2:** The quoted thickness and thickness range of metallic foils obtained after rolling.

<table>
<thead>
<tr>
<th>Metallic Foil</th>
<th>Quoted Thickness (mg/cm²)</th>
<th>Thickness range after rolling (mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>6.86</td>
<td>1.53 – 5.16</td>
</tr>
<tr>
<td>Ti</td>
<td>57.39</td>
<td>0.77 – 13.29</td>
</tr>
<tr>
<td>Ni</td>
<td>22.24</td>
<td>1.74 – 10.67</td>
</tr>
<tr>
<td>Ag</td>
<td>133.01</td>
<td>2.05 – 17.18</td>
</tr>
<tr>
<td>Tb</td>
<td>510.26</td>
<td>2.46 – 13.23</td>
</tr>
<tr>
<td>Ta</td>
<td>830.05</td>
<td>4.60 – 15.33</td>
</tr>
<tr>
<td>Au</td>
<td>482.78</td>
<td>4.03 – 17.21</td>
</tr>
</tbody>
</table>

**2.4.4 Stack Formation of Metallic Foils**

In order to develop a combination of various thicknesses of a particular metal, its foils in the form of a stack (staircase type) were mounted on a collimator, leaving its small portion as blank area. Just for illustration, Fig. 2.11 shows the outlines of such a staircase type stack of Au metal. Such collimators mounted with varying thicknesses of metallic foils were fixed on the target ladder and finally this target ladder was introduced in the low flux chamber (Fig. 2.12).

**Fig. 2.11: Stack formation of Au metallic foils.**
2.5 EXPERIMENTAL MEASUREMENTS

As discussed in section 2.3, experimental measurements related with Li, C and O ions are carried out in low flux chamber while for He (alpha) ions, measurements are performed in the alpha chamber. Therefore, due to different experimental setups, the experimental technique/procedure is different, so discussed separately in the following subsections.

2.5.1 Experimental Arrangement for Li, C and O ions Related Measurements

In this arrangement, the primary ion beam (Li/C/O) generated from Pelletron accelerator is scattered from a thin Au foil (330 nm) and mounted on the scattered ladder fixed at the GPSC. This scattered beam is allowed to pass normally through varying thicknesses of metallic foils of different metals by adjusting each collimator one by one in front of the beam, through the vertical motion of the target ladder (kept in the low flux chamber), before being finally detected by the detector.

![Block diagram of experimental setup used for Li, C and O ions related measurements.](image-url)
Fig. 2.12 presents the schematic diagram of the experimental arrangement. The detector output is stored in online computer after processing through the suitable nuclear electronics, as discussed in the section 2.3. As an illustration, Fig. 2.13 presents such energy spectra for C (7.01 MeV/n) ions in Ni metal, where each spectrum corresponds to a particular thickness of the Ni foil. It is clear from this Fig that peak of energy spectra shifts towards the lower channel side with the increase of thickness of the metallic foil.

The beauty of the present experimental setup is that the energy spectrum without and with metallic foils of varying thicknesses is recorded simultaneously. Thus all such spectrums contain the same contribution due to beam energy spread from the accelerator, straggling in the Au scatter and detector resolution and thereby nullifying the errors emerged due to these factors.
By following the above procedure, the energy spectra for Li (5.68 & 7.11 MeV/n), C (4.51 & 7.01 MeV/n) and O (4.91 & 6.16 MeV/n) ions in different thicknesses of Al, Ti, Ni, Ag, Tb, Ta and Au metallic foils are recorded and analyzed for measurements of energy loss and higher order moments.

2.5.2 Data Analysis

2.5.2.1 Energy loss ($-dE/dx$) measurements

In order to cover a broad energy range, we recorded the energy spectra for Li, C and O ions at two different energies, in varying thicknesses of considered metallic foils.

With the purpose to understand the method of energy loss measurement, here, we considered the case of C (4.51 & 7.01 MeV/n) ions in Ni metal only. These energy spectra are analyzed with Origin software to measure the centroid of the peaks. With the help of these measured centroids, the residual energies are determined corresponding to different thicknesses of the metallic foils. Through the least square fit, these residual energies are plotted against metal thicknesses for each incident ion’s energy (Figs. 2.14 & 2.15) and then combined in a single plot (Fig. 2.16).

![Figure 2.14: Polynomial fit between thicknesses and residual energies for C (7.01 MeV/n) ions after passing through Ni metallic foils.](image-url)
Fig. 2.15: Polynomial fit between thicknesses and residual energies for C (4.51 MeV/n) ions after passing through Ni metallic foils.

Fig. 2.16: Polynomial fit between thicknesses and residual energies for C (4.51 & 7.01 MeV/n) ions after passing through Ni metallic foils.
Table 2.2: Least square fit coefficients and R-squared value of He, Li, C and O ions in metallic foils.

<table>
<thead>
<tr>
<th>Metallic Foil</th>
<th>A ( (\times 10^3) )</th>
<th>B ( (\times 10^2) )</th>
<th>C</th>
<th>R-squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion – He</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>-92.4326</td>
<td>61.51</td>
<td>6.18573</td>
<td>0.994</td>
</tr>
<tr>
<td>Ti</td>
<td>-143.921</td>
<td>-57.5826</td>
<td>7.44316</td>
<td>0.999</td>
</tr>
<tr>
<td>Ni</td>
<td>-114.863</td>
<td>-90.0066</td>
<td>8.50328</td>
<td>0.991</td>
</tr>
<tr>
<td>Ag</td>
<td>-164.548</td>
<td>-123.302</td>
<td>11.7204</td>
<td>0.999</td>
</tr>
<tr>
<td>Tb</td>
<td>-177.669</td>
<td>-158.616</td>
<td>14.0755</td>
<td>0.997</td>
</tr>
<tr>
<td>Ta</td>
<td>-160.697</td>
<td>-217.09</td>
<td>16.8059</td>
<td>0.996</td>
</tr>
<tr>
<td>Au</td>
<td>-137.931</td>
<td>-232.577</td>
<td>17.0059</td>
<td>0.997</td>
</tr>
<tr>
<td>Ion – Li</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>-18.2462</td>
<td>-61.8159</td>
<td>75.9295</td>
<td>0.999</td>
</tr>
<tr>
<td>Ti</td>
<td>-24.0034</td>
<td>-48.8246</td>
<td>83.53</td>
<td>0.999</td>
</tr>
<tr>
<td>Ni</td>
<td>-22.1104</td>
<td>-76.2892</td>
<td>92.742</td>
<td>0.999</td>
</tr>
<tr>
<td>Ag</td>
<td>-26.9089</td>
<td>-102.259</td>
<td>117.626</td>
<td>0.999</td>
</tr>
<tr>
<td>Tb</td>
<td>-30.5995</td>
<td>-131.033</td>
<td>141.009</td>
<td>0.999</td>
</tr>
<tr>
<td>Ta</td>
<td>-32.1582</td>
<td>-143.241</td>
<td>151.161</td>
<td>0.999</td>
</tr>
<tr>
<td>Au</td>
<td>-30.9663</td>
<td>-157.305</td>
<td>155.377</td>
<td>0.999</td>
</tr>
<tr>
<td>Ion – C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>-3.09362</td>
<td>-18.496</td>
<td>37.5036</td>
<td>0.999</td>
</tr>
<tr>
<td>Ni</td>
<td>-3.03993</td>
<td>-21.7784</td>
<td>39.8973</td>
<td>0.999</td>
</tr>
<tr>
<td>Ag</td>
<td>-3.59066</td>
<td>-30.9216</td>
<td>51.6411</td>
<td>0.999</td>
</tr>
<tr>
<td>Tb</td>
<td>-3.60209</td>
<td>-45.947</td>
<td>63.843</td>
<td>0.999</td>
</tr>
<tr>
<td>Ta</td>
<td>-3.10486</td>
<td>-59.9982</td>
<td>72.585</td>
<td>0.999</td>
</tr>
<tr>
<td>Au</td>
<td>-3.77881</td>
<td>-55.9135</td>
<td>73.6313</td>
<td>0.998</td>
</tr>
<tr>
<td>Ion – O</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>-1.22737</td>
<td>-13.4523</td>
<td>25.0605</td>
<td>0.999</td>
</tr>
<tr>
<td>Ni</td>
<td>-1.1914</td>
<td>-15.4984</td>
<td>26.8125</td>
<td>0.999</td>
</tr>
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<td>0.998</td>
</tr>
<tr>
<td>Tb</td>
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<td>-32.164</td>
<td>41.5104</td>
<td>0.997</td>
</tr>
<tr>
<td>Ta</td>
<td>-1.61102</td>
<td>-29.498</td>
<td>44.7591</td>
<td>0.999</td>
</tr>
<tr>
<td>Au</td>
<td>-1.43639</td>
<td>-37.5439</td>
<td>51.4027</td>
<td>0.998</td>
</tr>
</tbody>
</table>
During fitting, we observed that second order polynomial fit \( x = aE^2 + bE + c \) is the best one and R-square (coefficient of determination) value lie very close to unity. These fitting coefficients are given in Table 2.2.

![Comparison of measured \(-dE/dx\) values of C (4.51 MeV/n), C (7.01 MeV/n) and C (4.51 & 7.01 MeV/n) ions in Ni metallic foils.](image)

In order to determine energy loss \((-dE/dx)\) value at energy \( E \), firstly the thickness values corresponding to \( E - \Delta E/2 \) and \( E + \Delta E/2 \) are deduced from such plots (Figs. 2.14 – 2.16), and then divided the difference of these two energies by the difference in foil thicknesses. Here, \( \Delta E \) is of the order of 10% of the energy \( E \). In this way, \(-dE/dx\) values at different energies in Ni metal are determined. These energy loss \((-dE/dx)\) values for C (4.51 MeV/n), C (7.01 MeV/n) and C (4.51 & 7.01 MeV/n) are shown in Fig. 2.17. It is observed from this Fig. that the maximum deviation in overlapping energy region is hardly 5%.

Adopting the above procedure, \(-dE/dx\) values of Li, C and O ions, in Al, Ti, Ni, Ag, Tb, Ta and Au metallic foils are determined in the energy region ~ 1.00 - 7.00 MeV/n at a fixed interval of 0.25 MeV/n. These energy loss \((-dE/dx)\) results are given in Chapter-3.
2.5.2.2 Range measurements

The range of C (7.01 MeV/n) and O (6.16 MeV/n) ions in Al, Ti, Ni, Ag, Tb, Ta and Au metals is determined, through an extrapolated fitted curve, between residual energy and the corresponding foil thickness. Fig. 2.18 shows such a plot for C (7.01 MeV/n) ion in Ni metal. The error due to extrapolation is found to be less than 4%.

Fig. 2.18: Extrapolated fitted curve between residual energies and thicknesses, for C (7.01 MeV/n) ions in Ni metal.

The measured range results for considered ion-metal combinations are presented in Chapter-3.

2.5.2.3 Energy loss straggling measurements

For the energy loss straggling, first, the Full Width at Half Maxima (FWHM) of the recorded spectra is determined using Origin software and then by applying the following relation [8-27], straggling is measured.

\[ \delta E_{\text{Meas.}} = \sqrt{(FWHM)_{\text{with}}^2 - (FWHM)_{\text{without}}^2} \]  

(2.2)
where subscripts with and without corresponds to with and without metallic foil respectively.

FWHM is basically equal to $2(2 \ln 2)^{1/2} \Omega$, where $\Omega$ is the stragglng standard deviation. From the standard error in standard deviation corresponds to spectra (with and without metallic foil) and propagating the errors through standard method, the standard error in the measured straggling value are determined [28].

In order to estimate the contribution of inhomogeneity in metallic foil, in energy loss straggling, the approach developed by Besenbacher et al. [29] is followed. According to this approach, the straggling standard deviation ($\Delta \Omega_{\Delta x}$) due to foil inhomogeneity ($\Delta x$) is given as

$$\Delta \Omega_{\Delta x}^2 = \left( -\frac{dE}{dx} \right)^2 (\Delta x)^2$$

(2.3)

and the measured energy loss straggling values are corrected accordingly.

By following the above procedure, the energy loss straggling of Li (5.68 & 7.11 MeV/n), C (4.51 & 7.01 MeV/n) and O (4.91 & 6.16 MeV/n) ions in varying thicknesses of considered metallic foils are measured. These measured straggling values along with corresponding standard error are given in chapter-4.

2.5.2.4 Skewness and Kurtosis (Higher order moments) measurements

As discussed in chapter-1, higher order moments are the parameters which measure the asymmetry associated with non-Gaussian energy loss distribution curve [30]. Such asymmetry is observed when the mean of energy loss distribution deviates from the mode of the distribution. As mentioned in the literature, these parameters which represent the asymmetry can be well defined by splitting the energy spectra about the mode into two half Gaussian spectra by using Two Piece Normal Distribution (TPND) function [31-34]. Such TPND function is defined as

$$f(x) = \begin{cases} c \exp \left( -\frac{1}{2\Omega_1^2} (x - x_0)^2 \right) & \text{if } x \leq x_0 \\ c \exp \left( -\frac{1}{2\Omega_2^2} (x - x_0)^2 \right) & \text{if } x \leq x_0 \end{cases}$$

(2.3)
where \( c = \frac{1}{\sqrt{2\pi (\Omega_1 + \Omega_2)}} \); \( \Omega_1 \) and \( \Omega_2 \) are the standard deviations of two Gaussian distributions made for each recorded spectrum by splitting about the mode and taking the replica of left portion about the mode value \( \langle x_0 \rangle \) towards the right side and vice-versa. Here \( \Omega_1 \) is the standard deviation associated with left portion and \( \Omega_2 \) is the standard deviation of the right portion of the same spectrum.

Using \( \Omega_1 \) and \( \Omega_2 \) values of recorded energy spectra and adopting other fundamental relations [31], Skewness and Kurtosis of Li, C and O ions in varying thicknesses of considered metallic foils are measured through the following relations:

\[
\gamma = \frac{\langle (\Delta E - \langle\Delta E\rangle)^3 \rangle}{\langle (\Delta E - \langle\Delta E\rangle)^2 \rangle^{3/2}} \tag{2.4}
\]

and

\[
\beta = \frac{\langle (\Delta E - \langle\Delta E\rangle)^4 \rangle}{\langle (\Delta E - \langle\Delta E\rangle)^2 \rangle^2} \tag{2.5}
\]

These measured skewness values also consist of contributions due to broadening of blank (without metallic foil) spectrum and different energy loss before and after passing through the given thickness of the metallic foils. These contributions are eliminated from the measured values by following suitable procedure [34]. The details of procedure and measured results are given in Chapter - 5.

2.5.3 Experimental Arrangement for He ion Related Measurements

As discussed in section 2.3, in the alpha chamber, there are three holders, where we can put ion source, target metallic foils and detector. Here, Am\(^{241}\) source is used as a source of He (5.486 MeV) ion and these ions are detected through PIPS detector (Model: PD150-15-300AM) and both are mounted on their respective holders. The metallic foils are mounted on the multiple target
holders, which is placed in between the source and the detector. The block diagram of the experimental arrangement is shown in Fig. 2.19.

In the present experiment, out of five mounting positions, four positions are used to mount the metallic foils of different thicknesses and one position is kept free to record the blank (reference) spectrum. Thereafter, the multiple target holder is adjusted in such a way that active area of He source, a particular metallic foil and detector lies in the same line. After achieving the required vacuum, the nuclear electronics is made ON and energy spectrum is recorded online on the PC. In this way, we recorded five energy spectrums, four with metallic foils and one without metallic foil in a single run, without disturbing the vacuum of the chamber. By following this procedure, energy spectra of He ion after passing through different thicknesses of Al, Ti, Ni, Ag, Tb, Ta and Au metallic foils are recorded.

![Block Diagram of Alpha Chamber](image)

**Fig. 2.19: Block diagram of Alpha chamber.**

### 2.5.3.1 Data Analysis

The analysis part of these recorded energy spectra is almost same as described in section 2.5.2, with minor difference [35-37].

During analysis, we observed that the energy spectra of He ions are tailed in the lower energy side. This may be mainly due to the mixing of 5.443 MeV He ions, whose relative abundance is about ~12% [6]. In order to avoid the
contribution of this energy, the mirror image of right portion of the energy spectrum is taken on the left side about the mean value and as a result the symmetric (Gaussian) spectrum is obtained.

After obtaining the centroids and FWHMs of the recorded spectra, energy loss, range and energy loss straggling of He ions in considered metallic foils are measured, by following the same procedure as discussed in section 2.5.2.
References


