

Stopping Force of 0.1 MeV/u – 0.5 MeV/u Heavy Ions in Thin Metallic Foils by Time of Flight Spectrometry

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ABSTRACT

The work presented here is aimed at determining the stopping force of heavy ions in pure metallic foils using time of flight spectrometry and comparing the data obtained from experiments with data obtained from predictive stopping force models (SRIM, DPASS and CasP). This is done to improve the predictive accuracy of heavy ion stopping in matter by the stopping force models. The experimental data obtained from this work will be added to the relevant database for the improvement of predictive stopping force models, due to the lack of data of heavy ion stopping in matter.

This work describes energy loss measurements, which were done using the tandem accelerator at iThemba LABS TAMS on the ERDA (Elastic Recoil Detection Analysis) beam line, of heavy ions (silicon, oxygen, titanium and copper) through (cobalt, platinum and palladium) thin foils using a Time of Flight – Energy spectrometer (ToF-E). In addition to energy loss measurements, depth profiling of the thin metallic foils was also carried out at iThemba LABS TAMS using RBS technique. Energy loss measurements, together with thickness measurements from RBS technique, were used to determine the stopping force of the different ion-target combinations.

The use of the thick scatter target makes it possible to produce recoil ions of different species which are poly-energetic and the ToF-E, which is responsible for energy loss measurements, can separate the recoil ions by mass. The combination of these two apparatus makes it possible to measure the energy loss of different recoil ions across a wide range of energies with only one experimental run.

The results presented in this work show a comparison of experimental stopping force and stopping force obtained from predictive models with ion energies between 0.1 MeV/u – 0.4 MeV/u. The results show, with some exceptions, that there is an agreement with stopping force trends between the experimental data and theoretical data with a variation in energy, although there are discrepancies in the stopping force predictions. The discrepancies in stopping force can be attributed largely to ion-atom interactions which are not accounted for in the predictive models.

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To my parents Stephen “Steve” and Rachel “Ounooi” Nkwashu and siblings Dimpho and Orediretse Nkwashu thank you for the continued support and encouragement, ke leboga go menagane.

Thank you to all my friends and all extended family, may the almighty bless you abundantly.

I praise and give thanks to the one above, the almighty, for giving me the opportunity, strength, knowledge and determination to start and successfully complete this project.

Dedication

To my parents, Stephen Ramaupa and Rachel Khutsahalo Nkwashu for the love, support and always believing in me.

DECLARATION

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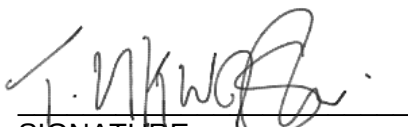
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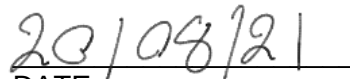
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List of Acronyms

CasP – Convolution Approximation for Swift Particles

DPASS – Dataset Pass

ERDA/HI-ERDA – Elastic Recoil Detection Analysis/ Heavy Ion ERDA

IAEA – International Atomic Energy Agency

IBA – Ion Beam Analysis

ICRU – International Commission on Radiation Units and Measurements

LSS – Lindhard, Scharff and Schiott theory

MCP – Multi-channel plates

MIDAS – Maximum Integrated data Acquisition System

PIXE – Particle Induced X-ray Emissions

RBS – Rutherford backscattering Spectrometry

SBD – Surface Barrier Detector

SEM – Scanning Electron Microscope

SNICS – Source of Negative Ions

SRIM – Stopping and Range of Ions in Matter

TAMS – Tandem Accelerator Mass Spectrometer

ToF/ToF-E – Time of Flight/ ToF and Energy Spectrometer

TRIM – Transport of Ions in Matter

Chapter 1

Introduction

Knowledge of stopping force¹ in matter is of critical importance for applications and measurements that are dependent on ion transport in matter. These applications and/or measurements include research in experimental physics and materials science, including in particular semiconductor fabrication, ion beam materials analysis, materials modification and ion implantation. Stopping force applications are also found in the medical field and these include the use of ionising radiation for tumour suppression in radiation therapy. In parallel with these practical applications and more, experimental stopping force data is needed for continual validation of theoretical and semi-empirical computational codes [1, 2, 3, 4].

The study of stopping force was pioneered by Niels Bohr, Ernest Rutherford and Joseph John Thomson in the early 1900's [1]. All the advancements made by Bohr, Rutherford, Thomson and other physicists are documented in the introductory chapter of *Stopping and range of ions in matter* written by Ziegler, et al [2]. Bohr and Thomson's models were based on classical physics and are still valid, for a lot of cases, with minor modifications to their results [2].

The likes of Bohr, Rutherford and Thomson paved the way for further research in stopping force and as a result stopping force has since been studied extensively [2, 5, 6]. Although a lot of experimental work has been done on light ion stopping force, not a lot has been done on measurement of heavy ion² stopping force in matter [2, 7]. The lack of experimental data in heavy ion stopping force has spurred the need for research in heavy ion interaction with solid matter.

¹ *Stopping force* is a more recent term as opposed to the traditional '*stopping power*'. *Stopping force* has been adopted in this work because by its definition, energy loss per unit distance, it is dimensionally equivalent to force.

² Heavy ions in this context refers to $Z \geq 4$ ions

1.1. Ion Beams in Materials Research

Ion beam technologies have proved to be powerful tools in the continuously growing field of materials science and research. Ion beams are used for analysis and tailoring the physical and/or chemical properties of thin films, surfaces and interfaces. Materials like nanostructures can be formed or modified and nanocomposite materials can be synthesised with new properties not otherwise observed in materials in their natural states [8].

Ion beam modification of materials is achieved by ion implantation or ion irradiation. These are unique approaches to altering the near surface region of a wide range of solid materials.

1.1.1. Ion Beam Analysis

A good example of the practical importance of accurate stopping force of ions in matter is in ion beam analysis (IBA). IBA is a collective term used for several powerful materials characterization techniques that use an energetic ion beam to investigate a material's elemental and/or structural information. The three mostly used IBA techniques include: Rutherford Backscattering Spectrometry (RBS), which is used to measure the thickness and depth profiles of heavy elements in thin films, Particle Induced X-ray Emissions (PIXE), an IBA technique used to obtain the elemental composition of a sample that is otherwise unknown, and Elastic Recoil Detection Analysis (ERDA), which measures the energies of a recoiling target nuclei to determine the elemental concentration and depth profiles in thin films [9, 10].

Depth sensitivity forms a crucial part of IBA. This is firmly dependent on stopping force, and therefore inaccurate stopping force values render the IBA inadequate for film thickness and depth profiling measurements. For example (RBS) and (ERDA) require ions, both light ions and heavy ions, to be backscattered or recoiled from the surface and deeper layers of a target material. From measuring the energy of the backscattered or recoiled ions it is possible to obtain the depth at which the ions are backscattered or recoiled from, provided stopping force is known accurately [11].

1.1.2. Ion Beam Modification of Materials

When an ion beam traverses a solid, it continuously changes direction, loses energy and sometimes changes its charge state. The ions will either eventually come to a complete stop within the material (this is known as implantation) or they move right through the material (the ion beam is then said to be transmitted or reflected). The ion beam creates recoil atoms of the target as it moves through the solid and this leads to a collision cascade. Primary beams and ions can also knock target atoms out of place either on the surface or within the target (these are known as sputtering or point defects). In the case of a collective energy transfer (e.g. with swift heavy ion irradiation), the structure of the solid can be changed (e.g. track formation) and more extended defect structures (e.g. voids) can be generated. Furthermore, the implanted ions and in some cases also the recoils (e.g. mixing in layered targets) cause changes of the local chemical composition. The processes explained above are known as ion beam materials modification [6, 8]. Knowledge of the ion energy loss rate or stopping force is key to describing the ion matter collision process.

1.2. Problem Statement

Theoretical and semi-empirical calculations, like SRIM [12], CasP [13] and DPASS [14], can predict light ion stopping in matter reasonably well. Unfortunately, this is not the case with heavy ions, especially in the Bragg peak region, due to the complex nature of heavy ion interactions with matter. Semi-empirical codes and current theory are limited by making too many assumptions which apply to light ion collisions, but which do not apply to more complex collision systems. Therefore there is a need for more experimental data to aid the development and improvement of theory, as well as refinement of existing semi-empirical codes to describe heavy ion-matter interactions more accurately.

1.3. Aim and Objectives

The aim of was to experimentally determine the stopping force of oxygen (^{16}O), silicon (^{28}Si) titanium (^{48}Ti) and copper (^{64}Cu) heavy ions in pure cobalt (^{59}Co), platinum (^{195}Pt) and palladium (^{106}Pd) metal thin films carried out at iThemba LABS TAMS. The ultimate goal was to add new data to the global database of experimental stopping force data needed to improve the predictive accuracy of current models of heavy ion stopping in matter.

The objectives to achieving the aim(s) are:

- Acquire thin films from the Lebow Company with a manufacture specified thickness of 200 nm.
- The thin films were then characterized to confirm the composition and thickness using RBS technique. Post characterization of the thin films, energy loss measurements were carried out using the heavy ion ERDA facility at iThemba LABS (TAMS) on the.
- Thereafter data reduction and analysis were carried out to determine the stopping force of different ions in the thin metal foils.

1.4. Dissertation Outlines

Chapter 1, the introductory chapter, provides a general background and overview into stopping force and its relevance in ion-matter interactions. This chapter informs on the basic idea of the project and includes the project motivation, aim and objectives. Chapter 2, on Theory and Literature review, dives deeper into stopping force by further discussing the relevant theory and ongoing developments in the field of ion beam–matter interactions, with emphasis on stopping ion beams in matter. Chapter 3, Experimental design and methodology, describes how the experiment was set up and conducted. This includes a description of the target foils and their characterization, ion beam production from the accelerator and the experimental design, conditions and a detailed description of the Time of Flight spectrometer used for the beam energy loss measurements through the target foils. Chapter 4, on Results and Discussion, deals with the processing, analysis and interpretation of the results of foil characterizations, energy loss measurements and stopping force evaluation. Chapter 5, the final chapter, provides a summative discussion of the results obtained from the experiment followed by a conclusion, where comment on the result and experiment as a whole is given. Chapter 5 also provides details on where the experiment can be improved and what could have been done better for future work and projects.

Chapter 2

Theory and Literature Review

2.1. Stopping Force

When an ion beam penetrates solid matter, a series of collisions occur between the ion beam and the atoms' nuclei and/or electrons in the target material. Once the ion beam enters the target material, energy and momentum is transferred from the projectile to the target materials nuclei or electrons due to Coulomb interactions [4, 12, 15]. The ion beam loses energy, E , per penetration depth, X , where X is the total distance travelled by the ion beam measured from the surface of the target. The energy lost by the ion beam as it traverses through the material is known as stopping force, and given by [11]:

$$[S] = -\frac{dE}{dX} \quad (2.1)$$

The ion beam penetrating a material interacts with the target atoms in one of two general and independent mechanisms at a time: nuclear energy losses or electronic energy losses [15]. It can therefore be said that stopping force can be further separated into nuclear stopping and electronic stopping, both of which are further discussed in sections 2.1.1 and 2.1.2 respectively [11]. With the separation of the two components of stopping force, the total stopping force is given by:

$$[S] = -\frac{dE}{dX} = -\left[\left(\frac{dE}{dX}\right)_n + \left(\frac{dE}{dX}\right)_e\right] \quad (2.2)$$

where the subscripts n and e represent nuclear and electronic stopping, respectively.

Applications which utilise ion stopping, e.g. IBA techniques like RBS or ERDA, are not sensitive to target thickness, but rather to areal density. Therefore, the stopping cross-section (ε) is a better quantity to use, as is done in ref [11]. To get the stopping cross-section, the stopping force is divided by the atomic density N ;

$$\varepsilon = -\frac{1}{N} \frac{dE}{dX} = [S] \frac{1}{N} \quad (2.3)$$

Figure 2.1 which is a general description of stopping force as a function of ion energy, clearly shows that both nuclear and electronic stopping force are strongly dependent on ion energy i.e. ion velocity [11]. At very low ion energies stopping is mainly due to nuclear stopping. At low, intermediate and high ion energies, up to where ion velocity is close to the Thomas-Fermi velocity (v_f), which is given by $Z_1^{2/3}v$, where maximum stopping power lies (also known as the Bragg peak region) electronic stopping becomes more dominant [11, 16, 17]. Stopping for ions at significantly high velocities or relativistic energies is outside the scope of this study. All regions and theories mentioned above are explained in further detail below.

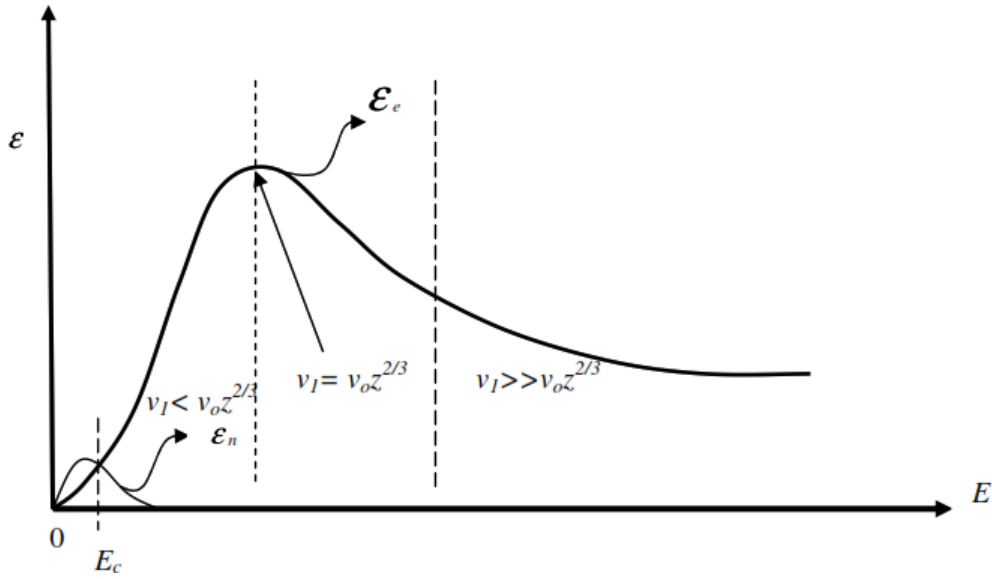


Figure 2.1: Description of stopping force as a function of ion energy from ref [17]

2.1.1. Nuclear Stopping

Nuclear stopping occurs due to elastic collisions between an ion and the target nucleus, whereby all processes that result in the slowing down of the ion result in a transfer of momentum from the ion to the atom as a whole [11, 18]. Nuclear stopping force is dominant for very low energy heavy ions, as shown in figure. 2.1, with stopping power in the region of eV/Å. It contributes very little to heavy ion stopping in matter beyond the critical energy, E_c [12, 15].

Nuclear stopping is described with the use of a classical collision system between two charged particles. Therefore, it can be said that the elastic collisions/scattering of an ion at very low velocities and a target nucleus can be described by interatomic potentials between the ion and target atom. At these low energies there is a screening of nuclear charges by the electron sub-system. The screening of charges makes obtaining a clear description of the interatomic potentials rather challenging. To overcome this challenge a universal screening function $\Phi_u(x)$ is used to obtain the universal interatomic potential which is given by [12]:

$$V_u = \frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 r} \Phi_u\left(\frac{r}{a_u}\right) \quad (2.4)$$

Where Z_1 and Z_2 are the atomic numbers of the ion and target respectively, e is the electron charge, ϵ_0 is the permittivity of free space, r is the interatomic distance and a_u is the screening radius. $\Phi_u(x)$, and a_u are fitted functions. One of the most widely accepted and used screening functions has been proposed by Ziegler, Littmark and Biersack [2], where they used the Harte-Fock charge distribution method to obtain the interatomic potentials of a number of atom pairs.

When an ion with an initial energy E_o and mass M_1 collides with a stationary atom with mass M_2 , the following happens: kinetic energy is transferred from the ion to the target atom, the ion is deflected by the target atom with an energy E_1 and the stationary atom is recoiled by the incoming ion with an energy E_2 . The ion and target atom move off in trajectories that are at angles Φ and θ respectively, with respect to the incident ion direction. The position of the incident ion, M_1 , relative to that of the target atom, M_2 , is given by h , the impact parameter. Figure 2.2 shows a schematic diagram of the geometry of an elastic collision between an energetic ion and a stationary atom.

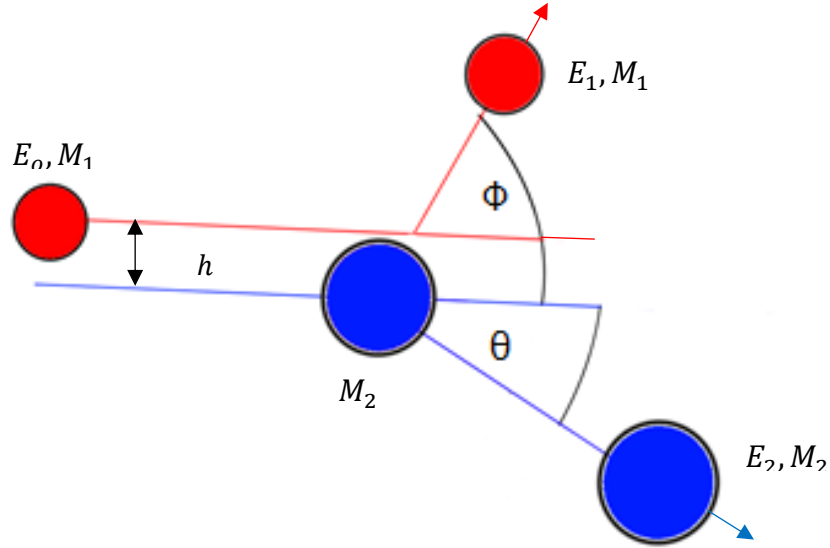


Figure 2.2: Schematic diagram showing collision between a projectile ion and a stationary atom

Interatomic potentials are used to calculate the kinetic energy, T , transferred from the projectile ion to the stationary atom during the collision. For an elastic collision like in this case, both energy and momentum are conserved. This makes it possible to calculate the kinetic energy transferred during the collision. The kinetic energy transferred is given by [2]:

$$T = 4E_0 \frac{M_1 M_2}{(M_1 + M_2)^2} \cos^2(\theta) \quad (2.5)$$

when using the laboratory frame of reference, and

$$T = 4E_0 \frac{M_1 M_2}{(M_1 + M_{12})^2} \sin^2\left(\frac{\theta_c}{2}\right) \quad (2.6)$$

when using the centre of mass (CM) frame of reference. The angle θ_c is the angle of recoil in the centre of mass system.

Nuclear stopping is then calculated from integrating the kinetic energy transfer across all impact parameters and is given by [2]:

$$S_n = 2\pi \int_0^{h_{max}} T(E, h) h \cdot dh \quad (2.7)$$

2.1.2. Electronic Stopping

Electronic stopping is an inelastic collision whereby an energetic ion interacts with the electrons of the target atom [15, 11]. Electronic stopping force is dominant for light ions from low energies and for heavy ions at high energies, with stopping power in the region of keV/Å [15].

The process of electronic stopping is complicated when compared to nuclear energy loss. The reason is that energy loss due to electronic stopping comprises different energy loss processes, with each process following its own statistical law [2]. Electronic energy loss processes include: excitation and ionisation of the target atoms, excitation and/or electron-capture of the ion itself and direct transfer of energy via electron to electron collisions to name a few [2]. Due to the complexity of electronic stopping force, it is difficult to describe it using just one theory. As a result electronic stopping is described using a few theories, all of which are dependent on the Fermi velocity which is given by:

$$v_f = v_0 Z_1^{2/3}, \quad (2.8)$$

where

$$v_0 = \frac{e^2}{\hbar}, \quad (2.9)$$

is the Bohr velocity and e and $\hbar$ represents the electron charge and modified Planck's constant respectively [2, 19]. Figure 2.3 shows a description of the different electronic stopping regimes and the theories that govern each energy range.

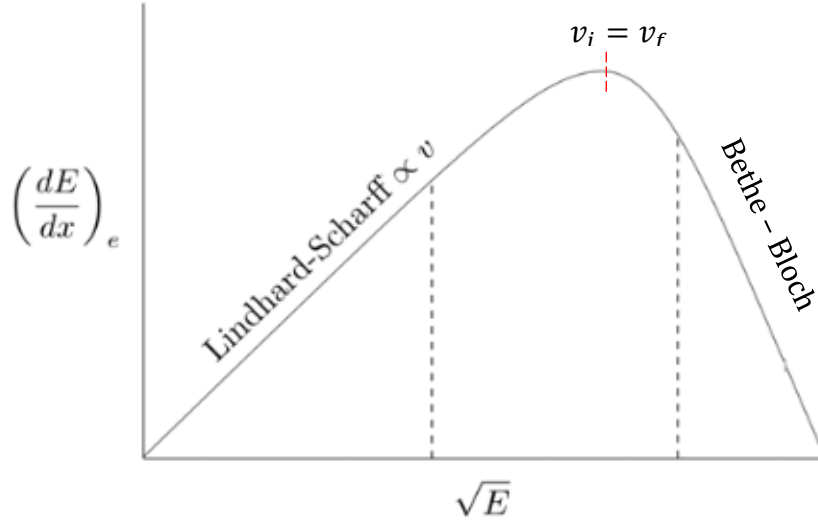


Figure 2.3: schematic description of the 3 different regimes of electronic stopping force and different theories used to describe them [17].

At the high, non-relativistic, energy region, where ion velocities (v_i) are significantly higher than the Thomas-Fermi velocity ($v_i \gg v_f$) the ion considered is stripped of all its electrons. The electronic energy loss in this region is directly proportional to the square of the ion charge. In this region electronic stopping is described by the Bethe-Bloch formula, hence the region is termed the Bethe-Bloch region as shown in figure 2.3 [2, 16, 20]. The Bethe-Bloch theory is discussed in further detail in section 2.2.3.

At low energies the Bethe-Bloch formula breaks down due to the inner shell electrons not contributing to energy loss and the increased chance of the projectile being neutralised. At the low energy region, where ion velocities (v_i) are much less than the Thomas-Fermi velocity ($v_i \ll v_f$), electrons in the target material have a higher velocity than the incident ion. As a result there is no direct energy loss. The electronic energy loss in this region is directly proportional to the ion velocity [2, 16, 20]. Stopping force in this region is described using the LSS Theory (Lindhard Scharff Schiott theory) [11, 16, 21]. The LSS theory is discussed in further detail in section 2.2.2.

At the intermediate energy region, ion velocities (v_i) are approximately equal to the Thomas-Fermi velocity ($v_i \approx v_f$). The maximum stopping force lies in this region and this is known as the Bragg peak region. At this intermediate energy region the ion is partially stripped of its electrons. No theoretical model has yet been devised to describe stopping in this energy range [2].

2.2. Theoretical and Semi Empirical Stopping Force Models

In simple terms, theoretical stopping force models either use one theory or a variety of stopping force theories to predict the stopping force for a wide range of ion target combinations. On the other hand, semi empirical stopping force models use both experimental data and stopping force theories to predict the stopping of different ion target combinations.

2.2.1. Bohr Theory

Bohr used classical mechanics to predict the stopping force of heavy ions traversing through matter with the use of a single formula [22]. With this one formula Bohr tried to describe stopping force within one theory for the first time in the history of stopping force research [23]. The theory of Bohr is given by the following equation:

$$S = \frac{4\pi e^4 Z_1^2 Z_2^2}{mv^2} \ln \left(\frac{Cmv^3}{Z_1 e^2 \omega_o} \right), \quad (2.10)$$

where C is a constant equal to 1.1229, e is the electron charge, m is the rest mass of an electron, v is the velocity of the projectile, Z_1 and Z_2 are the atomic numbers of the penetrating particle and target material respectively, and ω_o is the frequency of the electron in the target atom. Bohr's theory is valid only if $k = 2Z_1 v_0 / v \gg 1$ [24, 25].

2.2.2. Lindhard, Scharff and Schiott Theory (LSS Theory)

The Lindhard, Scharff and Schiott theory or simply known as the LSS theory uses the Thomas-Fermi model to roughly describe the electronic stopping of both light and heavy ions in matter at low velocities (i.e. at velocities lower than the Bohr velocity or velocities of up to 40 keV/u) [26, 27, 28]. Electronic stopping at low velocities, where the LSS theory is dominant is shown in figure 2.3. Stopping of ions in matter can be described by both inelastic electronic scattering as well as nuclear stopping, both of which are accounted for in the LSS theory [28].

The electronic stopping cross-section of heavy ions with low velocity is given by [26]:

$$S_e = \left(-\frac{dE}{dX} \right)_e = \zeta_e \times 8 \times \pi \times e^2 \times a_0 \times N \left[\frac{Z_1 Z_2}{\left(Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}} \right)^{\frac{3}{2}}} \right] \left(\frac{v}{v_0} \right) \quad (2.11)$$

Where ζ_e is the correction factor of order $Z_1^{\frac{2}{6}}$, a_0 is the Bohr radius, N is the atomic density of the target, Z_1 and Z_2 are the atomic numbers of the incident ion and target material respectively, and v and v_0 are the ion velocity and Bohr velocity, respectively.

2.2.3. Bethe-Bloch Theory

The Bethe-Bloch theory describes the electronic stopping of high velocity, non-relativistic, ions in matter (with velocities greater than the Bohr velocity or in the range of 10 MeV/u – 2 GeV/u) [29].

The electronic stopping of fast ions, where the Bethe-Bloch theory is dominant as shown in figure 2.3, is given by [30]:

$$S_e = \frac{4\pi Z_1^2 Z_2 e^4}{mv^2} \ln \ln \left(\frac{2mv^2}{I} \right) \quad (2.12)$$

where Z_1 and Z_2 are the atomic numbers of the projectile and target respectively, m and v is the atomic mass and velocity of the ion respectively, and I is the average ionisation potential of the target.

For the Bethe-Bloch theory to be operational two assumptions need to be made: the first assumption is that the projectile is faster than the target electrons and is completely stripped of all its electrons, the second assumption is that the atomic mass of the projectile is much higher than the mass of the target electrons [12].

2.2.4. Convolution Approximation for Swift Particles (CasP)

The Convolution approximation for swift Particles (CasP) code is a free software package by Grande and Schwietz that is readily available online at <http://www.casp-program.org/> [31]. CasP uses numerical calculations of electronic energy transfer Q_e (energy transfer caused by target atom excitation and ionisation), for each impact parameter h of the collision, to calculate the total electronic stopping force S_e (or equivalent stopping cross-section). The electronic energy transfer and electronic stopping force are calculated using the appropriate screening function. The use of the correct screening function, allows to treat non-linear equilibrium energy-loss phenomena [13].

2.2.5. Dataset PASS (DPASS)

DPASS (Dataset PASS) is a code that tabulates output data from the PASS code developed in 2000 by Andreas Schinner and Peter Sigmund [32]. The PASS (DPASS) code is based on an extension of the binary theory of electronic stopping, which is a generalised theory of alpha particles stopping in matter developed by Niels Bohr. DPASS corrects for the clear discrepancies that exist between experimental data and data from the PASS code in the velocity range around and below the Bohr velocity [14]. DPASS is freely available online at <https://www.sdu.dk/en/dpass> [32]. DPASS predicts stopping force (stopping cross sections) for projectile ions in target atoms from Hydrogen to Uranium over a vast energy range within lower and upper limits of 0.001 MeV/u and 1000 MeV/u, respectively, in units of 10^{-15}eVcm^2 , MeVcm^2/mg or eV/nm [32]. To estimate stopping in compound targets, the Bragg additivity rule then has to be applied, using the ratios of the constituent elements in the compound.

2.2.6. Stopping and Range of Ions in Matter (SRIM)

Probably the most widely used stopping force predictive model, Stopping and Range of Ions in Matter (SRIM) is a compilation of computer codes to calculate the stopping force/cross-section of any ion-target combinations. SRIM incorporates the different theoretical models applicable over different energy ranges. It further uses experimental corrections to fundamental parameters such as the mean ionisation potential and the shell correction factor

of the target atoms [23]. One of the most inclusive programmes used by SRIM is a Monte Carlo simulation programme known as TRIM (Transport of Ions in Matter) which calculates the interaction of energetic particles with matter. TRIM is able to make a few accurate approximations (using approximations such as The Magic Formula: Atom-Atom Collisions and The Free Flight Path to name a few) of the interactions that occur between the ion and atoms in the target during a collision [12]

2.3. Validation of Theoretical and Semi-Empirical Models

Comparison between experimental stopping force data and stopping force theory and/or data generated from semi-empirical stopping force codes is important for continual improvement of theory and predictive codes. The International Atomic Energy Agency (IAEA) has a vast database of stopping force for different ion-target combinations over a wide range of energies. The database contains experimental figures and/or graphs from published stopping force data. The International Commission on Radiation Units and Measurements (ICRU) committed three reports, report 37, 49 and 73, to stopping force which can be found at [33], [21], and [34] respectively. The reports include stopping data for electrons and positrons, protons and alpha particles and heavy ions respectively [35].

A good example of theory vs. experimental stopping force data is the work of Cantero et al. [36] whereby experimental and theoretical stopping data for zinc (for ions from H to B) were compared using the Shellwise Local Approximation (SLPA) together with the transport cross-section, for inner shell corrections and the valence electrons. The results showed that the theoretical and experimental data were in good agreement. They tried to replicate the zinc stopping force data results with C and O ions with no luck. The CasP code due to Schwiets and Grande however showed a good agreement between theory and experimental data [37].

Like theoretical descriptions of stopping force, semi-empirical models have also been developed for a long time. Their accuracy has also been investigated, with some observations for the more common models being for light ions (H and He), where SRIM and the ICRU report 49 describe stopping force with a high accuracy. For Li to Ar, MSTAR and SRIM also describe stopping force with a relatively high accuracy as well. ICRU report 73 tends to overshoot stopping of ions K to U with energies above 100 MeV/u. In this energy range the non-perturbative Lindhard-Sorensen theory has to be used to describe stopping [11, 35].

2.4. Stopping Force Measurement Techniques

2.4.1. Transmission of a Mono-Energetic Ion Beam Trough a Thin Film

In its simplest form the transmission of a mono-energetic ion beam through a free-standing thin film is shown in figure 2.4, where a ion beam of energy E_0 , typically from a particle accelerator, traverses (or transmits) through the thin film and exists with an energy of E_f . With this stopping force measurement technique, stopping force is determined for a single energy at a time for each experiment. This method has a practical limitation, because knowledge of stopping force requires a large range of energies, this means the initial beam energies need to be changed for a lot of data points to determine the stopping force over a large range of beam energies [11, 21].

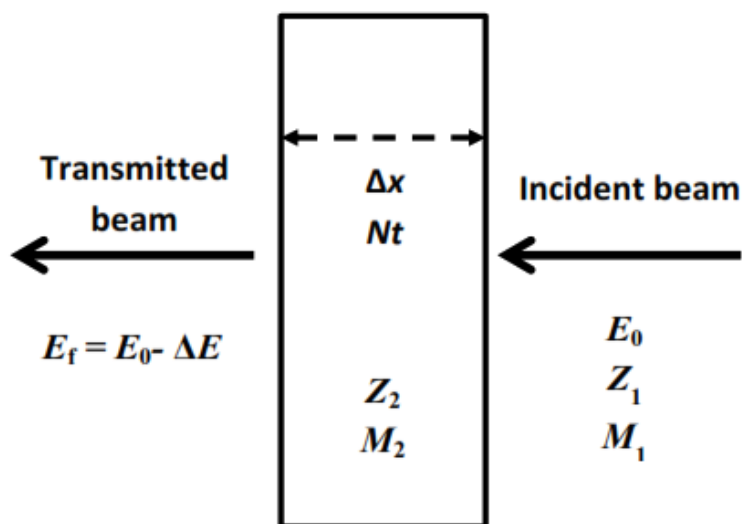


Figure 2.4: Schematic representation of the ion beam transmission stopping force measurement method [14]

2.4.2. Other Implementations of the Transmission Method

The transmission measurement method can be implemented with other different measurement techniques while still maintaining ion transmission in thin films, with ions either being mono-energetic or poly-energetic. A simple example of other implementations includes

removing the exit energy detector in the basic set up and replacing it with a $\Delta E - E$ detection system or a Bragg ionisation chamber [37].

Another method to measuring stopping force by using the transmission method was proposed by Linguori Neto et al. [38]. The method uses only one surface barrier detector which is partially covered with the thin film of interest. The incident ions strike the thin film and the detector simultaneously and the obtained energy spectrum shows two distinct peaks. Therefore the energy loss through the film is obtained from the difference in the peak energies measured [39]. Other implementations of the direct transmission method are described in the works of Ribas et al. [40] and Bergsmann et al. [41].

2.4.3. Backscattering Measurements from Thin Films

The ion backscattering stopping force measurement method is similar to the transmission method in that it uses thin films to measure energy loss. With the backscattering technique the thin film is deposited on a bulk substrate and a standard RBS experiment is performed for a given beam energy. The energy loss within the thin film is obtained from the energy width of the signal from the Rutherford Backscattering Spectrometry experiment. The energy loss within the thin film is obtained from the energy width of the signal from the RBS detector. The signal width is obtained from the energy of the particles scattered from the surface of the thin film (E_1) and the energy of particles scattered from the interface of the bulk substrate and the thin film (E_2). Energy loss is subsequently given by the difference between E_2 and E_1 . It is important to note that energy loss is dependent on the energy loss by the particle on the way in and on the way out [11, 21]. Figure 2.5 shows a simplified schematic representation of the measurement method.

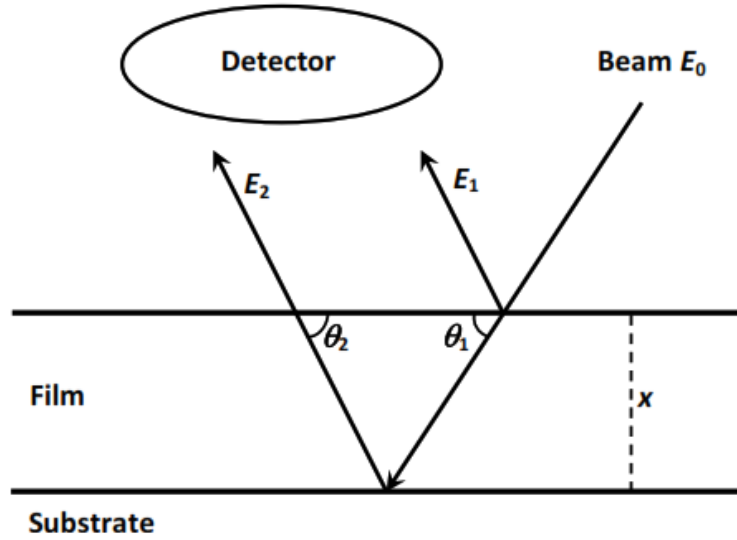


Figure 2.5: Schematic representation of backscattering measurements from thin films stopping force measurement method [14].

One of the most common and simplest backscattering measurements from thin films is performed at two different angles of incidence or detection (by either tilting the sample or using two different detectors). The surface energy approximation then the energy loss as:

$$E_1 - E_2 = \left(\frac{K \cdot S(E_0)}{\sin \theta_1} + \frac{S(KE_0)}{\sin \theta_1} \right) \quad (2.13)$$

The use of two different geometries results in two equation which results in two unknowns $S(E_0)$ and $S(KE_0)$, S is the stopping. K is known as the kinematic factor [11].

2.4.4. Bulk Sample Method

The stopping force measurement techniques described in sections 2.4.1 to 2.4.4 depend on the use of thin films to measure energy loss. Thin films are difficult to obtain with the required thickness, they are often difficult to handle and their stability under experimental conditions may be very poor.

One way of solving issues that arise due to the use of thin films is to use bulk (or thick) samples to measure energy loss. In essence the bulk sample method involves collecting the RBS spectrum of the bulk sample to measure energy loss. The RBS spectrum depends on the sample (characterisation of the samples' composition and impurity needs to be done), experimental conditions (which are known), and fundamental data (data such as stopping

force and all the relevant cross-section(s)). Therefore, if everything else is known, the resulting RBS spectra is dependent on the stopping [14]. The bulk sample method is simple to conduct when compared to the methods discussed in the previous sections, due to the elimination of thin films in the measurement process [42, 43].

2.4.5. Resonance Energy Shift Methods

For the resonance energy shift method to be successful, an element with a known sharp resonance in the scattering cross-section is used. A thin film made with the material to be studied is deposited on a bulk substrate which contains the element with a known resonance peak. A measurement run is carried out on the bare substrate and the incident beam energy noted. Then a second run is carried out on the substrate now coated with the film of interest. The incident beam energy will then have to be adjusted upwards when the thin film is present to achieve resonance. The energy loss in this case is given by the difference in energy lost by the beam through the film in order to get to the initial resonance energy [11]. Other than the challenges faced when using thin films, resonance energy shift method is carried out at specific beam energies, where resonance can be used, it therefore has a limited energy range [11].

2.4.6. Inverted Doppler Shift Attenuation Method

The Doppler shift attenuation is a method of determining the lifetime of an excited nucleus. If the excited nucleus is in motion, the energy is Doppler shifted. The Doppler energy in that case depends on both the lifetime and velocity of the excited nucleus. The excited nucleus loses energy as it traverses through the material, i.e. it slows down, and as a result the Doppler shift will change. As a result stopping force can be calculated if the lifetime of the nucleus is known [11, 44]. This method is performed with a wide range of ions at energies that are suitable for IBA. The data analysis is rather difficult due to the presents of other excited nuclei when the primary nuclei decaying via nuclear reactions [45].

2.4.7. Transmission of a Broad Energy Beam through a Thin Film

Probably the most recent measurement method of stopping force, the transmission in thin films of an ion beam with various energies is similar in principle to that of the transmission in thin films of a mono-energetic ion beam measurement method. The main difference between the two measurement methods is the ability to measure stopping force over a wide range of energies in the latter. This means the stopping force of several ions for a given thin film can be done with a single experiment. This measurement method is normally carried out with the aid of a Time of Flight – Energy (ToF-E) spectrometer, as is done in this work. Section 3.3.3 gives a detailed description of the Time of Flight – Energy spectrometer [11, 46].

The production of an ion beam with a wide range of energies is made possible by a scatter target. A primary mono-energetic beam strikes a thick scatter target. The primary ion beam either scatters forward from the target or recoils atoms from the target. The beam recoiled/scattered from the target has ions with a wide range of energies, from zero to the maximum energy allowed by kinematics [21].

The ability to measure, with high accuracy, energy loss across a wide range of energies in one measurement run, and the fact that the measurement technique is readily available are two of the major reasons this stopping force measurement technique was used for this project. The ability of the spectrometer to separate scattered/recoiled atoms by mass is also a big advantage, and a contributing factor to the use of this technique, this means it is possible to measure energy loss of two or more incident atoms in a single measurement.

Chapter 3

Experimental Design and Methodology

The Johannesburg campus of iThemba LABS (Laboratory of Accelerator Based Sciences) hosts a 6 MV tandem accelerator which is used for Accelerator Mass Spectrometry (AMS), Ion Beam Analysis and Ion Beam Materials Modification. The IBA facilities at iThemba LABS (TAMS) include helium and proton RBS, heavy ion ERDA as well as PIXE. Current efforts are geared towards implementation of Total Ion Beam Analysis (TIBA) with the use of a large scattering chamber [47]

Prior to energy loss measurements, the thin films used for the experiment were sourced and characterised. The thin foils were purchased from the Lebow Company® which specialises in the production of thin foils of a wide range of thickness ($0.02\text{ }\mu\text{m}$ - $25\text{ }\mu\text{m}$) for different purposes in industry and research [48]. RBS (Rutherford Backscattering Spectrometry) was used to ascertain the thickness of the target foils.

The foils purchased for this work are freestanding cobalt (Co), palladium (Pd) and platinum (Pt) foils. The foils were supplied on a stainless steel frame with an aperture of 50 mm. The nominal thickness of each foil according to the manufacturer was $0.2\text{ }\mu\text{m}$. Figure 3.1 shows the thin films used in this work mounted on the thin foil holder ready to be mount in the chamber.



Figure 3.1: Pt, Co, Pd thin foils mounted on a foil holder, with one hole on the holder left vacant.

3.1. Foil Characterisation

3.1.1. Measurement of Foil Thickness – RBS

Rutherford backscattering spectrometry (RBS) is the most common of Ion Beam Analysis (IBA) methods, and can be used to determine the thickness of films and depth-profiles of almost all elements in a target sample with a single measurement [6, 49, 50]. It is a non-destructive analysis method; this means there is minimal sputtering away of the targets' surface layers [6]. It is primarily used to measure the thickness (depth profiling) of semiconductor thin films and multi-layered materials [6]. Other uses of RBS include: areal concentration measurements (atoms/cm²), crystal quality and impurity lattice site analysis, impurity measurements. It can also be used to measure the thickness of polymer layers, optical coatings and catalyst films [6, 49, 50, 51].

The technique involves elastic collisions between high energy light ions (usually MeV light ions such as Hydrogen and Helium) and the target surface and/or sub-surface atoms. The energy of the backscattered ions is then measured, using a surface barrier semiconductor detector, through large backscattered angles with respect to the incident ion beam [49]. The principle of RBS shown in figure 3.2 below.

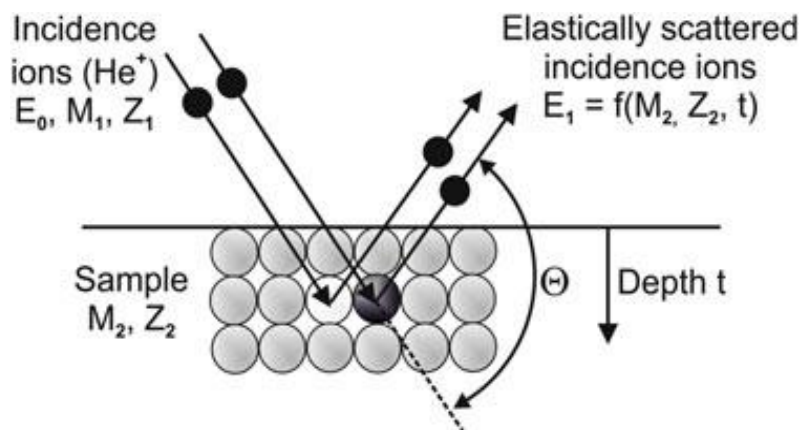


Figure 3.2: Schematic representation of RBS, where a light incident ion, with mass m_1 and energy E_0 , collides with target atom, with mass m_2 , and is scattered at a large angle Θ [45].

Considering the schematic diagram above, if momentum and energy are conserved, then the energy (E_1) of the elastically scattered ion is dependent on the mass (M_2) of the target [50, 51]. Figure 3.2 suggests that energy is also lost as the ion moves through the target [6]. Energy loss of ions scattered at the surface is due to momentum transfer between the incident ion and the target atom. The energy (E_1) of the scattered ion is given by:

$$E_1 = E_0 K, \text{ Where: } K = \left(\frac{\sqrt{1 - \left(\left(\frac{M_1}{M_2} \right) \sin \Theta \right)^2} + \left(\frac{M_1}{M_2} \right) \cos \Theta}{1 + \left(\frac{M_1}{M_2} \right)} \right)^2 \quad (3.1)$$

Where:

- E_0 – is the energy of the incident particle
- K – is the kinematic factor and is a characteristic of the target material.
- M_1 and M_2 – are the mass of the incident ion and target atom respectively.
- Θ – Is the scatter angle.

Equation 3.1 is valid for extremely thin films and/or surface atoms of a target material. When a target sample is thick, the energetic ion penetrates the sample, and the ions are scattered at different depths within the target. The ion then loses energy with both inward and outward movements, this is shown in figure 3.3 below. As a result, there is a shift in the surface energy of target atoms buried at different depths towards lower energies [50, 51]. The relationship between this shift in energy and target sample thickness is given by:

$$\Delta E = KE_0 - E_1 = \left[\frac{KS_{in}}{\sin \gamma} + \frac{S_{out}}{\sin \delta} \right] x \quad (3.2)$$

where:

- ΔE is the shift in energy that is observed when ions are scattered at a depth x below the target sample surface.
- γ and δ are the entrance and exit angles of the ions.

In principle, measurement of this energy shift allows for the determination of the target film.

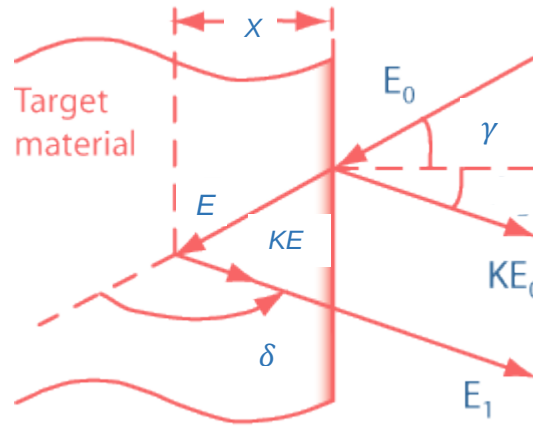


Figure 3.3: Schematic diagram of ions scattering from a depth, x , in a thick target sample

To perform RBS analysis, it is crucial that the following equipment is available: a low voltage accelerator, typically a Van de Graff or tandem accelerator and all necessary ion beam accessories, to produce suitable energetic ions. A target chamber is also required to house the target sample and requisite detectors and electronics to detect, and process signals ion-target interaction signals so as to analyse the energy of the scattered ions [50]. Figure 3.4 shows a schematic diagram of the RBS instrumentation.

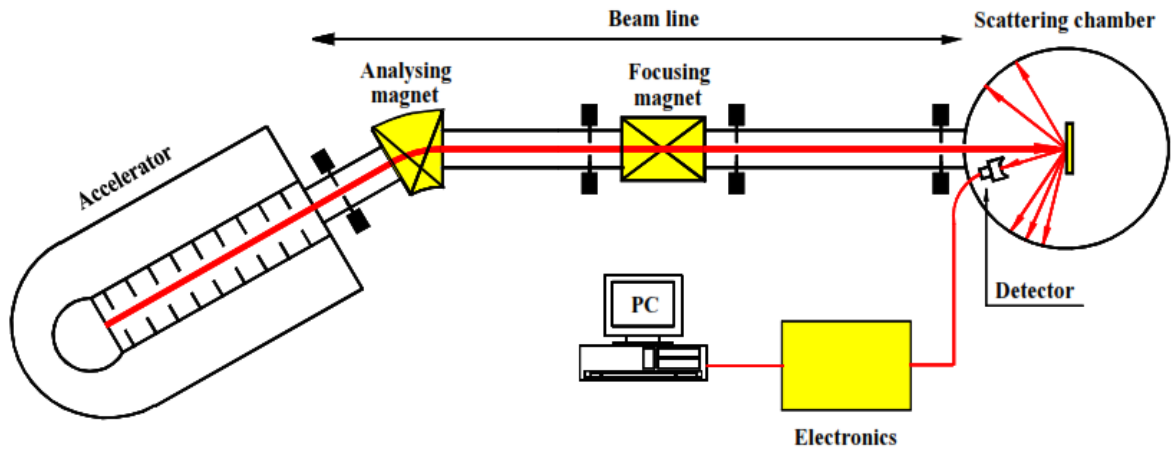


Figure 3.4: Schematic diagram showing the instrumentation of RBS [46]

For this work a 2 MeV He^+ ion beam was used together with a silicone surface barrier detector sitting at a backscattering angle of 150° , with an energy resolution of approximately 25 keV. The signal from the detector and the RBS electronic modules were processed using the OMDAQ data acquisition system. The raw data was analysed using SIMNRA [52].

3.1.2. Thickness Evaluation Using SIMNRA

The RBS data was analysed using SIMNRA version 7.02 software code [52]. SIMNRA is a computer programme for the simulation of Ion Beam Analysis (IBA) spectra from a number of analytical techniques that include RBS, elastic backscattering spectrometry with non-Rutherford cross-sections (EBS), nuclear reaction analysis (NRA), elastic recoil detection analysis (ERDA), medium energy ion scattering (MEIS), neutron-induced elastic recoil detection analysis (n-ERDA), neutron-induced nuclear reaction analysis (n-NRA), with a wide range of ion energy (circa 100 keV to many MeV). SIMNRA is able to calculate a large number of ion-target combinations, including that of heavy ions and any geometry [52, 53].

The programme uses SigmaCalc by Gurbich for cross-section calculations of non-Rutherford backscattering and nuclear reactions for a vast number of ion-target combinations. This makes it possible to obtain accurate data on elastic backscattering and nuclear reaction simulations [52, 53]. SIMNRA has a graphic user interface that allows the user to input the measurement parameters that include beam species, energy, scattering angle and detector type. Prior to calculating the backscattering spectrum, the target material has to be defined, and finally the cross-section used needs to be selected [52, 53, 54]. The simulation is then an iterative procedure that entails modifying the target sample parameters (thickness and elemental composition) and calculating a theoretical energy spectrum of backscattered particles until the best theoretical fit to experimental spectra is obtained.

3.2. Experimental Setup for Stopping Force Measurements

Energy loss measurements were carried out at the tandem accelerator at iThemba LABS TAMS on the ERDA (Elastic Recoil Detection Analysis) beam line. iThemba LABS TAMS houses a 6 MV tandem accelerator manufactured by High Voltage Engineering®. Figure 3.5 shows a schematic diagram of the accelerator vault floor plan at iThemba LABS TAMS. The following subsections describe the major components of the accelerator and measurement setup; the ion source, the accelerator column, the target chamber, and the Time of Flight (ToF) spectrometer used for the detection of recoil particles.

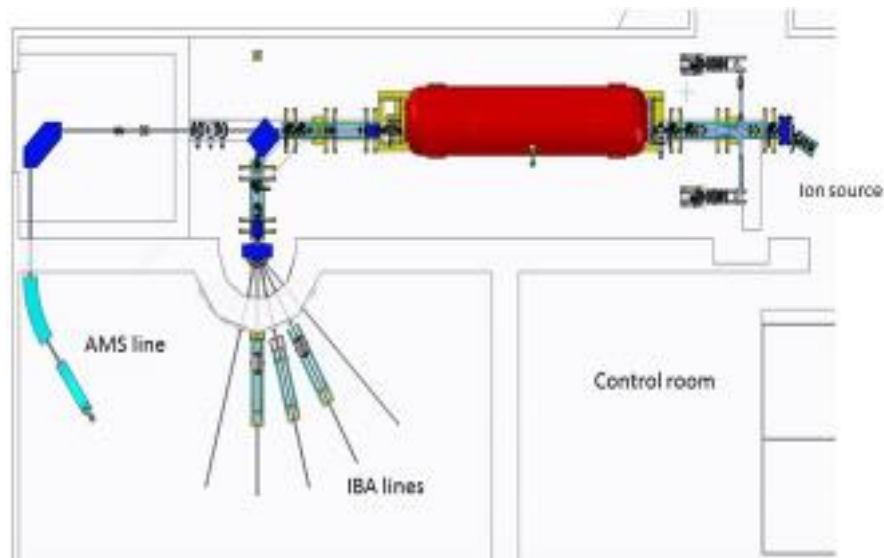


Figure 3.5: iThemba LABS accelerator vault Floor plan.

3.2.1. The SNICS Ion Source

SNICS (Source of Negative Ions by Caesium Sputtering) is a sputter ion source that is able to produce negative ions, of almost all solid materials, by simply bombarding the target material of choice with positive caesium ions. See figure 3.6 for a schematic diagram of a SNICS ion source construction [55, 56].

The material, in powder form, from which an ion beam is desired is placed in the cathode. The ion source has an external oven (which is also known as a caesium reservoir) where the caesium is heated to high temperatures to produce caesium vapour. The vapour flows into the ion source, where a portion of the caesium vapour condenses and adheres to the surface of the cooled cathode and some of the caesium vapour hits the surface of the heated ionizer. At the ionizer the caesium boils away and is ionized in the process. The positive caesium ions are then accelerated towards the cathode where they sputter particles out of the powdered target through the layer of caesium on the cathode's surface. Some materials are sputter negative ions while other materials sputter neutral or positive ions, the neutral and positive sputter ions pick up electrons as they traverse through the cold caesium layer on the cathode's surface. Due to the low electron affinity of caesium, this produces negative sputter ions [55, 56, 57, 58]. The ion source is kept at a negative potential and the extractor is kept

at high positive potential with respect to the ion source. The ions are then extracted from the ion source and injected into the accelerator [57, 58].

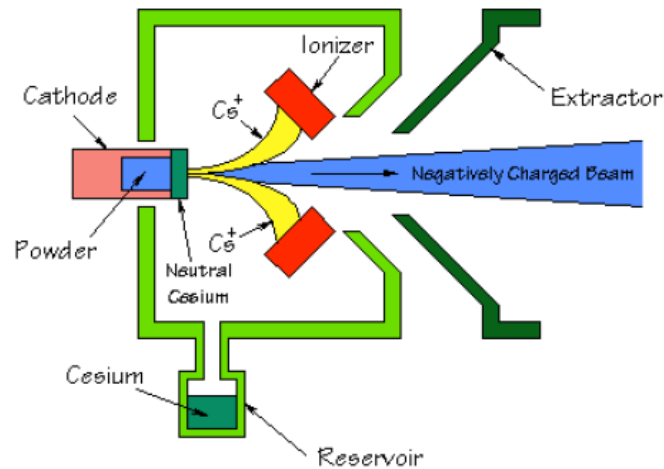


Figure 3.6: Schematic Diagram of a SNICS ion source [58]

3.2.2. The Tandem Accelerator Column

A tandem accelerator is a modified form of a Van de Graff accelerator. The tandem accelerator is a two stage accelerator, meaning it accelerates ions twice, first by attraction then by repulsion [59].

The TAMS tandem accelerator has a high voltage terminal (6 MV) placed inside a pressure tank, which is filled with an electrically insulating gas sulphur hexafluoride (SF_6) [59]. Singly charged ($-1e$) negative ions from the SNICS source are accelerated from ground towards the positive terminal via coulomb attraction. The negative ions have an energy equal to the voltage at the terminal i.e. eV [59]. At the high voltage terminal, negative ions are passed through a low pressure nitrogen or argon gas (which is known as stripper gas) or extremely thin carbon foils (which is known as stripper foil). As the negative ions pass through the stripper they lose electrons due to the charge exchange process, and as a result the negative ions become positively charged. The positive ions experience a second stage of acceleration. As they exit the high pressure tank, the ions are accelerated towards ground potential by repulsion [60]. Figure 3.7 shows a schematic diagram of a tandem accelerator and how it works. The resulting kinetic energy of exiting positive ions is then given by:

$$E = eV + qV, \quad (3.3)$$

where: e is the electron charge, q is the positive charge state of the ions. Therefore equation 3.3 shows that the final kinetic energy depends on the charge state of the ion [60]. In this work a 40 MeV Au^{8+} ion beam with a current of 15 nA was used. The ion beam was then steered into the ERDA target chamber where the target samples of interest (SiO_2 , Cu and Ti) were mounted.

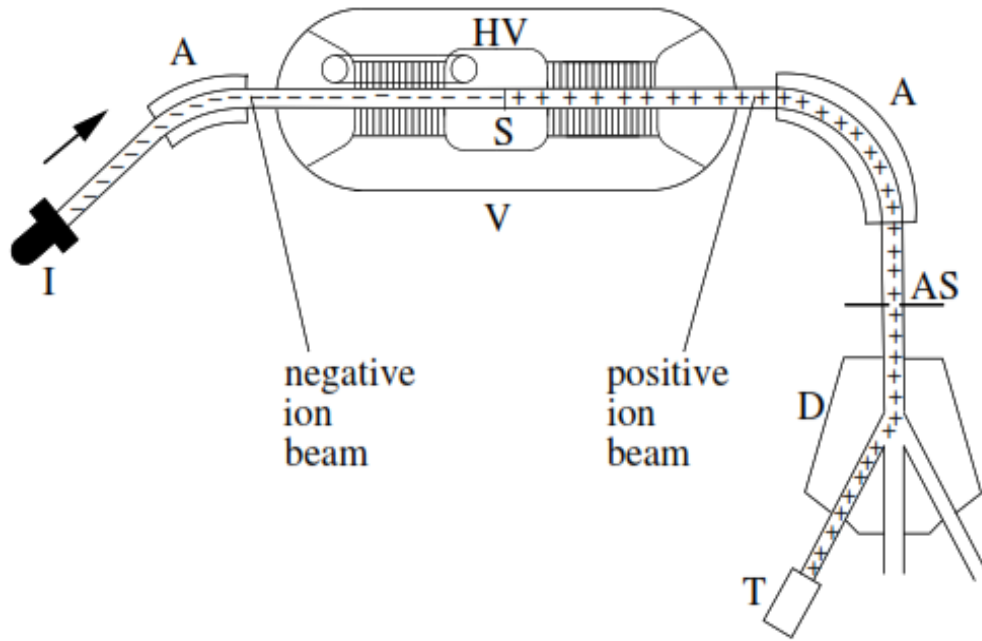


Figure 3.7: Schematic diagram of a tandem accelerator in operation [60].

3.2.3. ERDA Setup

The ERDA set up was used to recoil and/or scatter atoms from suitable target samples. The incident beam's approach angle was at a 15° grazing incidence to the sample surface.

The ERDA detector setup, which sits at an angle of 30° with respect to the incident primary beam, comprises of a Time of Flight and Energy (ToF-E) spectrometer. The ToF-E spectrometer is used to measure the time of flight and energy of recoil/scatter atoms in coincidence. The coincidence measurement of time of flight and energy of the recoil/scatter atoms leads to a separation of different atoms by mass. The separation by mass results in a 2D scatter plot; the scatter plot shows different loci, each corresponding to a different element each with its own unique mass [61]. See appendix 1 for the 2D scatter plots of the different ion target combinations.

Standard nuclear instrument modules are used to process the signals from the detectors. The modules include constant fraction discriminators for fast timing, a time to digital converter and an analogue to digital converter for the energy detector, a silicon SBD. The data acquisition software was custom built at iThemba LABS, based on the MIDAS software platform which is available online [62]. Using ROOT data analysis platform, it is possible to extract an energy spectra from the different loci described above. The energy spectra is obtained by the conversion of the ToF axis into a linear energy axis by re-binning event energies calculated using the measured ToF for each event.

3.2.4. ToF vs Energy Detector

The ToF-E spectrometer is an energy spectrometer that uses two detectors to measure the time of flight of recoil or scatter atoms between the two timing detectors. The first detector is used as a start detector and the second detector is used as a stop detector. Both timing detectors are transparent to the atom of choice and do not alter the energy and/or trajectory of the particle of interest appreciably [63, 64]. Knowing the distance between the two detectors ($l = 0.6$ m), the time of flight (t) of the projectile particle of interest, and the mass of the projectile (m), the incident energy (E) of the particle is then given by the non-relativistic formula [64]:

$$E = \frac{1}{2} \cdot m \cdot \frac{l^2}{t^2} \quad (3.4)$$

Conversely, measuring E and t makes it possible to separate the detected atoms by mass. The ToF-E spectrometer is made up of two carbon foil based micro-channel plate (MCP) time detectors which are 0.6 m apart and a silicon Surface Barrier detector (SBD) placed 6cm behind the second detector. See figure 3.8 for schematic diagram of the ToF-E experimental setup and figure 3.9 for pictures of the timing detectors. Figure 3.9 (on the left) shows timing detector T1 mounted inside the target chamber, and figure 3.9 (on the right) shows timing detector T2 and SBD mounted on a flange mounted at the end of the spectrometer.

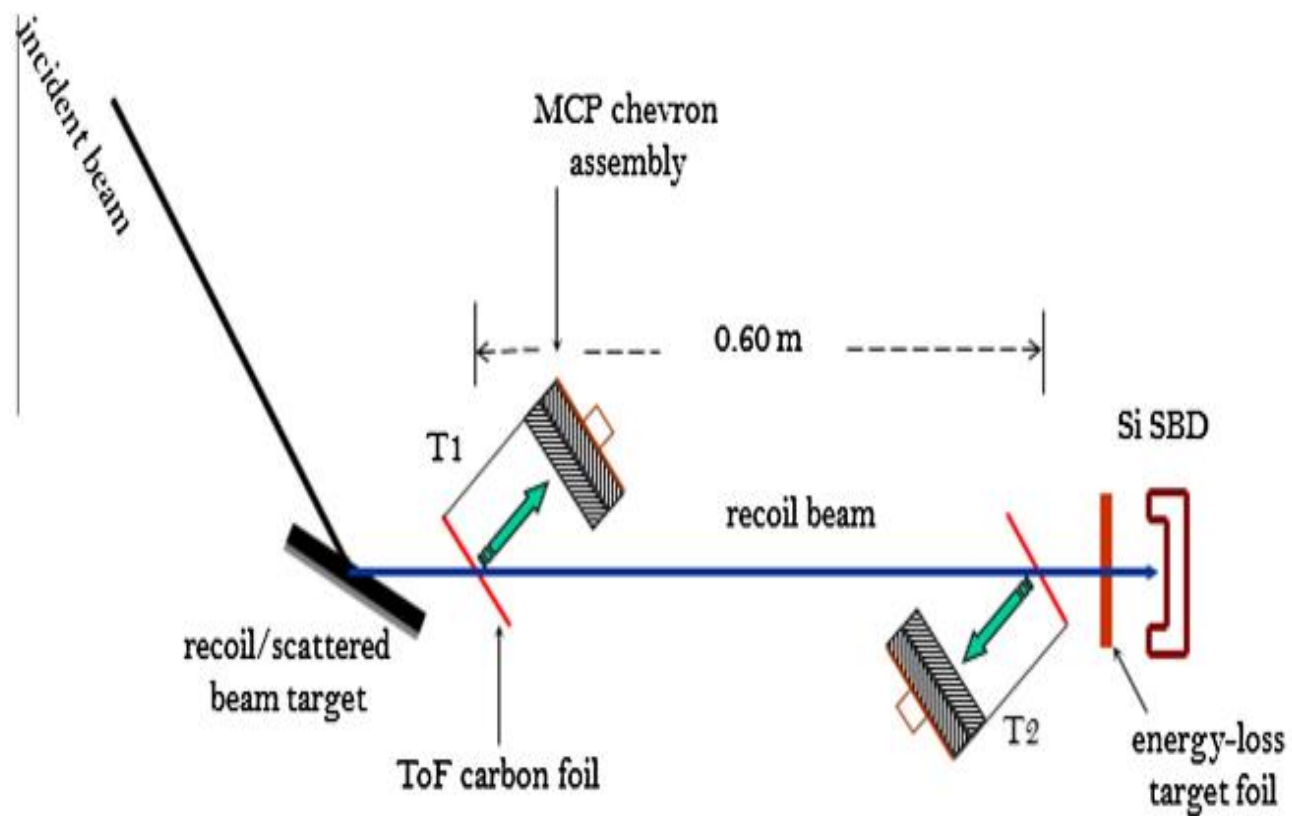


Figure 3.8: ToF and Energy spectrometer setup at iThemba LABS [46].

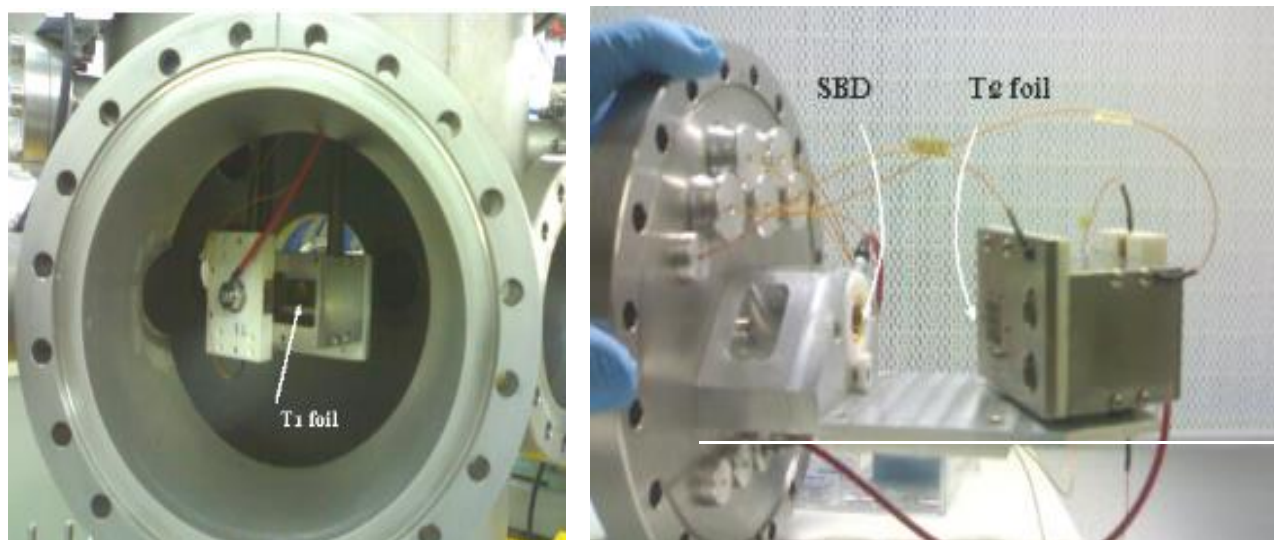


Figure 3.9 Timing detector T_1 on the left and timing Detector T_2 on the right.

Each timing detector has a $20 \mu\text{g}/\text{cm}^2$ thick carbon foil mounted attached to a metal frame (B) with an opening radius of 8 mm for T_1 and 12 mm for T_2 . When recoil or scattered ions pass through each carbon foil, electrons are ejected. There is an electric field applied between the carbon foil and the MCP assembly which accelerates the electrons towards the MCPs. At the MCP the electron signal is multiplied to produce a large timing signal output. Figure 3.10 shows a schematic diagram of the operational process for the timing detectors.

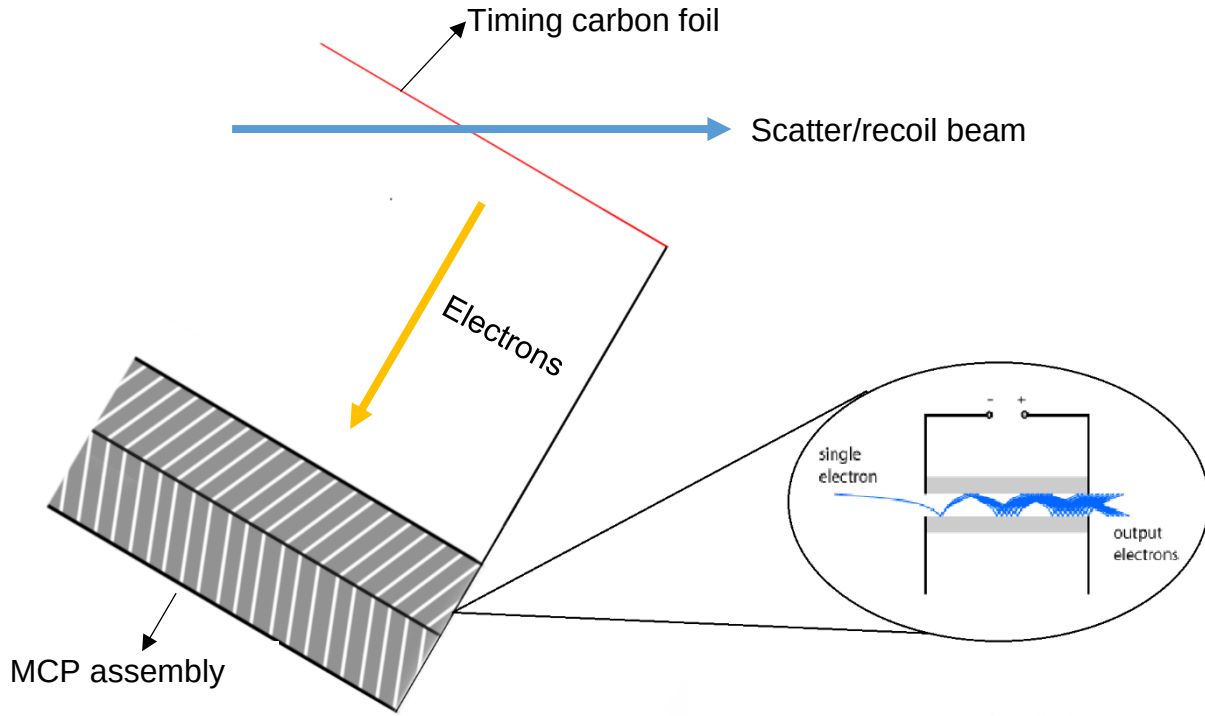


Figure 3.10: Schematic diagram of the carbon foil- and MCP-based timing detectors.

To calibrate the spectrometer for time of flight and energy, atoms of known energy are used, i.e. atoms knocked off or scattered from the surface of the recoil/scatter target.

If the energy (E_i) of the incident primary ion beam and mass (M_i) of the ions that make up the primary ion beam are known, it is possible to obtain the theoretical energy (E_r) of the recoil atoms, of mass M_r , that are sputtered from the surface (atoms with highest energy) of the recoil target using the following equation [46, 65]:

$$E_r = E_i K \quad (3.5)$$

where K is known as the kinematic factor and is given by:

$$K = \frac{4M_i M_r}{(M_i + M_r)^2} \cos^2 \theta \quad (3.6)$$

Once the theoretical energy is obtained, it is important to correct for the energy lost (ΔE_{T1}) by each ion when it traverses through the carbon thin film in the first timing detector. Therefore equation 3.4 becomes:

$$E'_r = E_r K - \Delta E_{T1} \quad (3.7)$$

Once energy correction is done it is then possible to calculate the time of flight of the ions over the known distance between the ToF detectors and the mass of the transiting ion. To calibrate the ToF spectrometer the 2D scatter plot of different elements were projected onto the ToF axis to obtain the time of flight spectra for the different ions. This procedure is illustrated detail in chapter 4.

3.2.5. Energy Loss Measurement and Stopping Force Evaluation

To measure the energy loss of the projectile recoil/scatter atoms through the target foil of interest, the foil is inserted between the second timing detector and the Si SBD as shown in figure 3.8. The ToF-detector measures the energy (E_1) of the projectiles before the target foil and the Si SBD energy detector measures the energy (E_2) of the projectile on exiting the foil. The energy loss through the foil is then given by:

$$\Delta E = E_1 - E_2 \quad (3.8)$$

The Si SBDs are known to have a non-linear response when detecting heavy ions, this is due to the detector dead layer and the pulse height defect in the detector [11]. This results in a non-linear calibration of the energy detector. The ToF spectrometer is therefore used to provide a 1-1 channel-to-energy calibration of the SBD, for each atomic species. That is, a measurement carried out without the energy loss target foil inserted in the particle path means that the energy determined from the ToF is the same as that measured by the SBD. Therefore, two measurement runs are actually carried out; with and without the target foil in place – from which the incident energy $E_1(t_1)$ and the residual energy $E_2(t_2)$ are obtained, respectively. Energy loss in the thin film is then given by:

$$\Delta E = \frac{m}{2} \left[\left(\frac{l}{t_1} \right)^2 - \left(\frac{l}{t_2} \right)^2 \right] \quad (3.9)$$

The stopping force across the target foil is then given by:

$$[s] = \frac{\Delta E}{\Delta x} \quad (3.10)$$

where: Δx is the thickness of the foil, see figure 3.12 for a cross-sectional view of the thin film and energy loss process.

To determine energy loss from the raw data, the exit energy is determined from a ToF–E measurement without any stopper foil between timing detector t_2 and the SBD. The energy signal from the SBD is simply used to tag events of a similar energy on two ToF curves; before and after the stopper foil is inserted, and the corresponding ToF then used to calculate the energy in each instance using the known atomic mass and flight length. The procedure is then repeated for a series of different energies along the energy axis to generate a continuous energy loss curve. Figure 3.11, below, is an example showing a schematic diagram of typical results from a ToF vs Energy 2D scatter plot. Two measurement run results, with and without a stopper foil are illustrated, with the coincidence measurement of the ToF and Energy for each detected particle generating the 2-D ToF vs Energy scatter plot shown. From this plot, projections onto the ToF axis give the values that were used as t_1 and t_2 [11, 61].

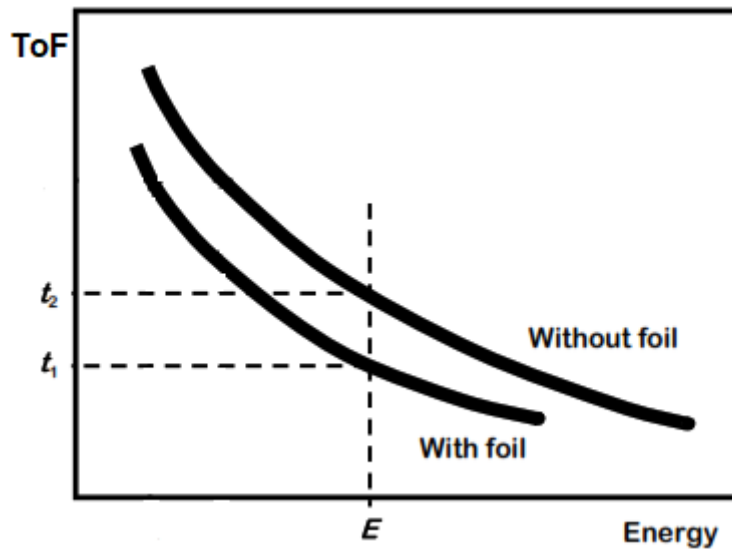


Figure 3.11: A schematic diagram showing an example of a 2D scatter plot illustrating the data reduction process from the raw measurement results from ref [11].

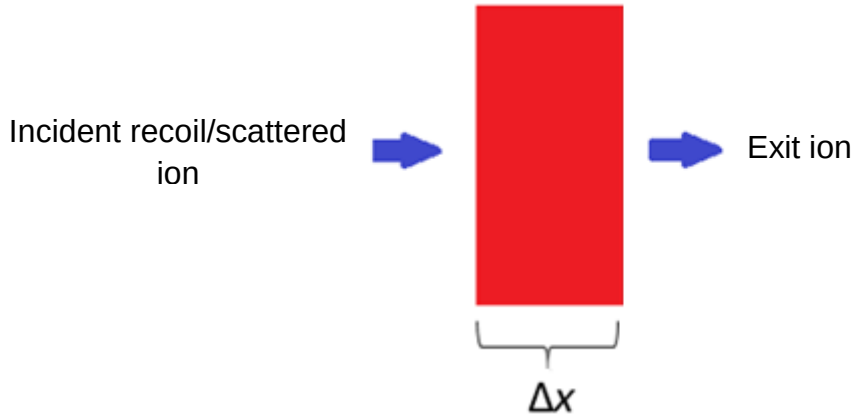


Figure 3.12: Cross-sectional view of the entire target foil energy loss process

3.3.6. Uncertainty Analysis in Stopping Force Measurements

Uncertainties in the measurement of heavy ion stopping force arise from the raw quantities used to calculate stopping force of heavy ions in thin films i.e. energy loss measurements of heavy ions as they traverse through the thin foils and, the measurement of the thickness of the thin foils themselves. As a result analysis of all uncertainties needs to start with the raw measured variables that define heavy ion energy loss and thin foil thickness. The various quantities used in the stopping force evaluation are assumed to be independent quantities and so the combined uncertainty is obtained as the square root of the sum of squares of the contributing uncertainties.

For the measurements presented in this work, uncertainties in the energy loss measurement are due to the $\pm 0.5^\circ$ uncertainty in the scatter angle, this results in a 2.3% error in the (ϕ) term in equation 3.6 which is used in the calibration of the ToF spectrometer. The energy spread of the incident ion beam is in the order of 10^{-3} , the energy lost by the ions in the carbon foils (ΔE_{T1}) in the timing detectors has an uncertainty that equates to 1.1%. The uncertainty in the flight length, l , in equation 3.4, is considered to be negligible. When the above terms are combined they yield a total uncertainty of 3.4% in the energy E_f , which results in a total error of 1.7% for t_i values used for calibration. Energy loss, from equation 3.8, then has an uncertainty of approximately 4.8%.

Uncertainties in foil thickness measurements arise from; the detector resolution of 15 keV at 2 MeV or 0.75% error for the for alpha particles; the uncertainty of SRIM stopping force used in SIMNRA software used for RBS analysis of approximately 3.3%; an incident beam energy spread of 10 keV at 2 MeV or 0.5%; the accuracy SIMNRA of 1% and the statistical uncertainty due to the number of counts under the RBS peak of 0.5%. The surface roughness of the thin Co, Pd and Pt foils is assumed to be negligible when compared to the overall thickness of the thin foil. The total error in thickness measurements amounts to a total of 3.6%. When the propagation of all the error terms associated with the determination of the stopping force is done, the end result is that the stopping force results presented here have an uncertainty of about 6.0%, with the Time of Flight and SRIM accuracy being the major contributors to uncertainty [3, 63, 66]

Chapter 4

Results and Discussion

The RBS results of foil thickness measurement and stopping force data analysis together with the energy calibration of the detectors, and experimental set up used for the measurements are presented below. It is important to point out that stopping force data was measured for an energy range of circa 0.1 MeV/u – 0.5 MeV/u. This is the typical energy range of ion beam applications of such stopping force data, such as ion beam analysis and ion beam modification of materials, etc.

4.1. Foil Thickness Analysis: Calibration

As mentioned in previous chapters, prior to running energy loss measurements and calculating stopping force it is important to characterise the target foils and ascertain elemental composition. The Co, Pd, and Pt foils used in this work were analysed using RBS. The starting point of data analysis is the calibration of the RBS detector.

RBS calibration requires a standard sample composed of different elements, which are known, be used for the calibration process. The standard in this case was a thin film made of platinum, silicon and nickel. The standard returns a spectrum which can be used to calibrate the energy detector. Figure 4.1 for the spectrum that was used for the calibration. Only incident ions backscattered right from the surface atoms of the film are considered for the calibration, therefore the actual film thickness is not critical.

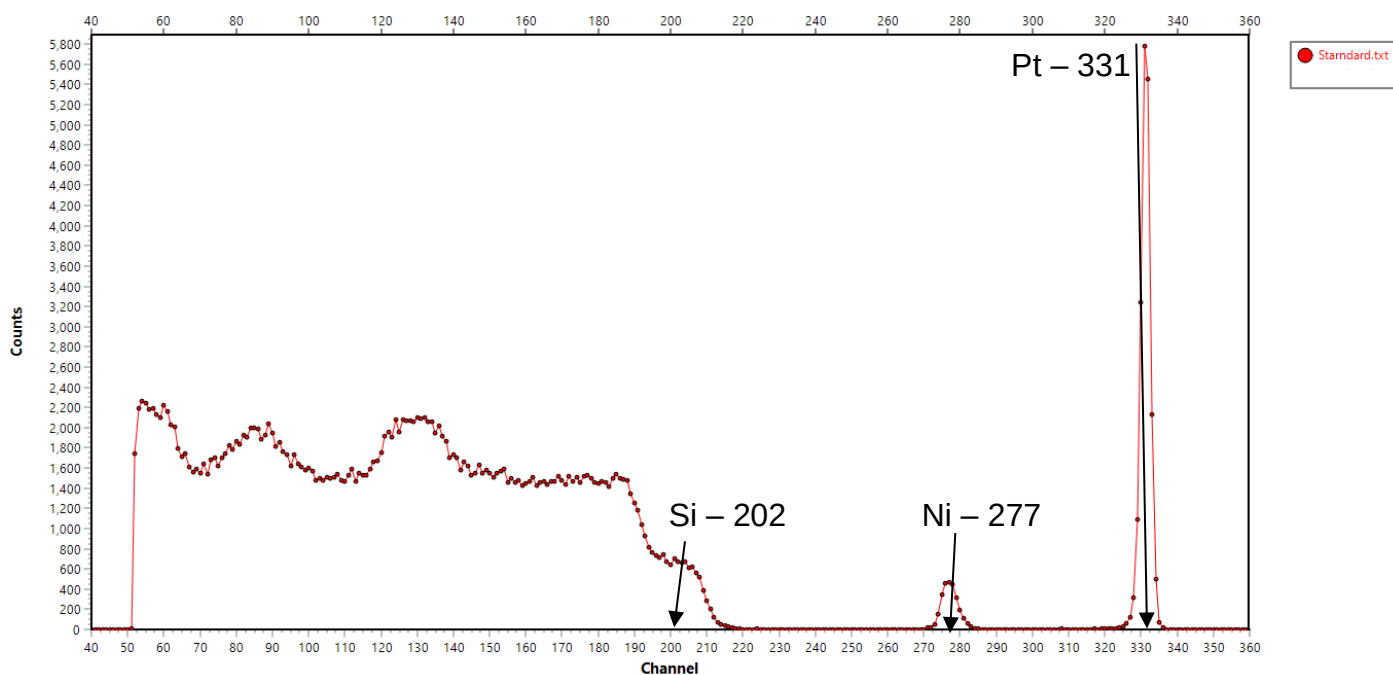


Figure 4.1: RBS spectrum of the standard sample used for calibration.

With the spectrum obtained, it is then possible to associate the channel number with the expected (theoretical) energy of the backscattered He^+ ions using equation 3.1. Calculated recoil energies are cross-checked with values obtained from SIMNRA, whether the calculations are done correctly. Backscattering energies together with the surface channel numbers of the respective elements shown in figure 4.1 are shown in Table 1.

recoil	Channel number	surface energy (keV)
Pt	331	1852.49
Ni	277	1549.947
Si	202	1170.474

Table 4.1: RBS calibration data.

The channel numbers together with the energies were plotted in Origin® version 2019b (9.65) (this version was used throughout the project) in order to establish the relationship between them. Figure 4. 2 shows that there is a linear relationship between the He^+ ion energy and the MCA channel numbers. A linear fit to the plotted data yields a slope of 5.27 keV/channel number and an intercept of 100.67 keV.

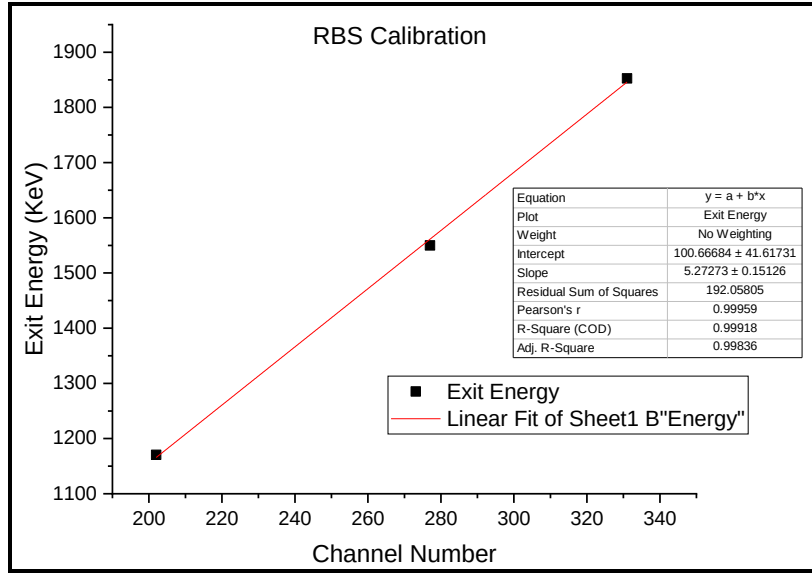


Figure 64.2: RBS energy detector calibration plot used for this work.

The calibration equation is therefore given by:

$$y = 5.27X \text{ keV/channel number} + 100.67 \text{ keV} \quad (4.1)$$

Where X is the channel number and has no units.

The slope and intercept were then used as input parameters to the SIMNRA programme used to simulate the measured RBS spectra for the actual target foils.

4.1.1. RBS Spectra Simulation

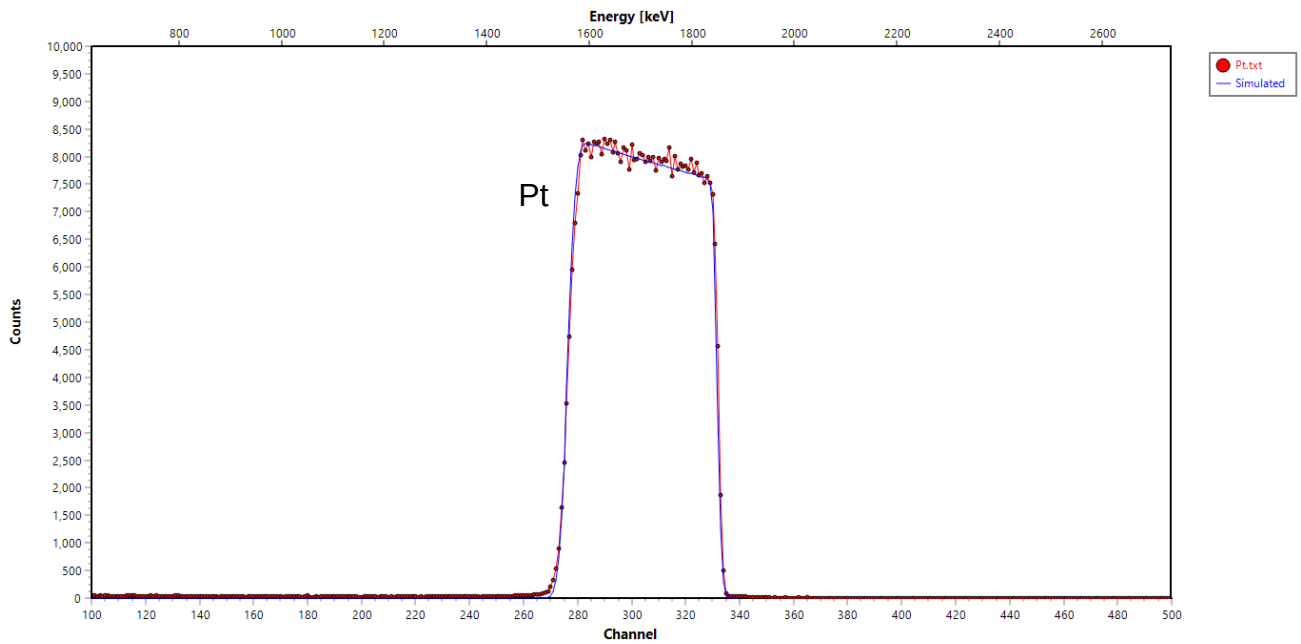


Figure 4.3: Plot of the experimental (red) and simulated (blue) RBS spectrum of the freestanding Pt thin foil used in this work

Figure 4.3 shows the RBS spectrum obtained from analysis of the Pt foil. It is clear that the simulated spectrum is in good accordance with the experimental spectrum. This theoretical fit was obtained by assuming a thickness of 1303×10^{15} atoms/cm² for the Pt foil. This is equal to 196 nm, obtained by dividing this areal density with atomic density and converting from cm to nm. When considering the 3.6% thickness uncertainty discussed in Section 3.3.6, the thickness of the Pt foil can be quoted as $(1303 \pm 47) \times 10^{15}$ atoms/cm².

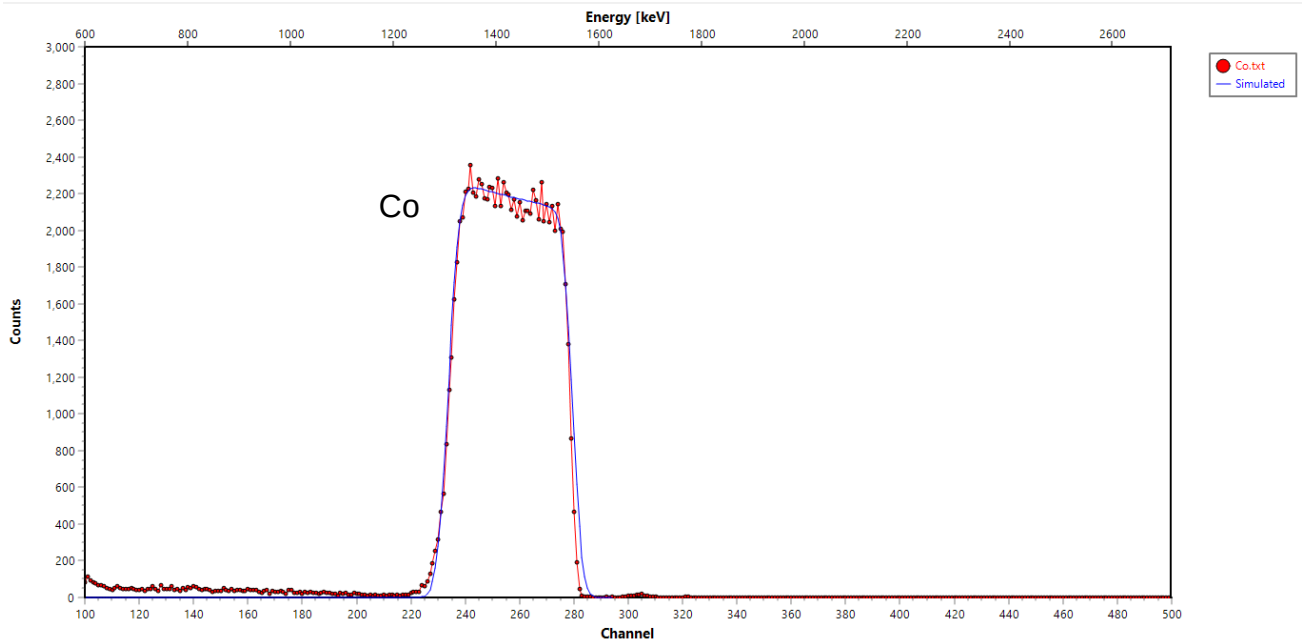


Figure 4.4: Plot of the experimental (red) and simulated (blue) RBS spectrum of the freestanding Co thin foil used in this work

Figure 4.4 shows the RBS spectrum of the cobalt foil. The simulated spectrum is in good agreement with the experimental spectrum. The simulated Co foil spectrum was obtained with an assumed thickness of $(1723 \pm 62) \times 10^{15}$ atoms/cm² or (189.40 ± 6.8) nm.

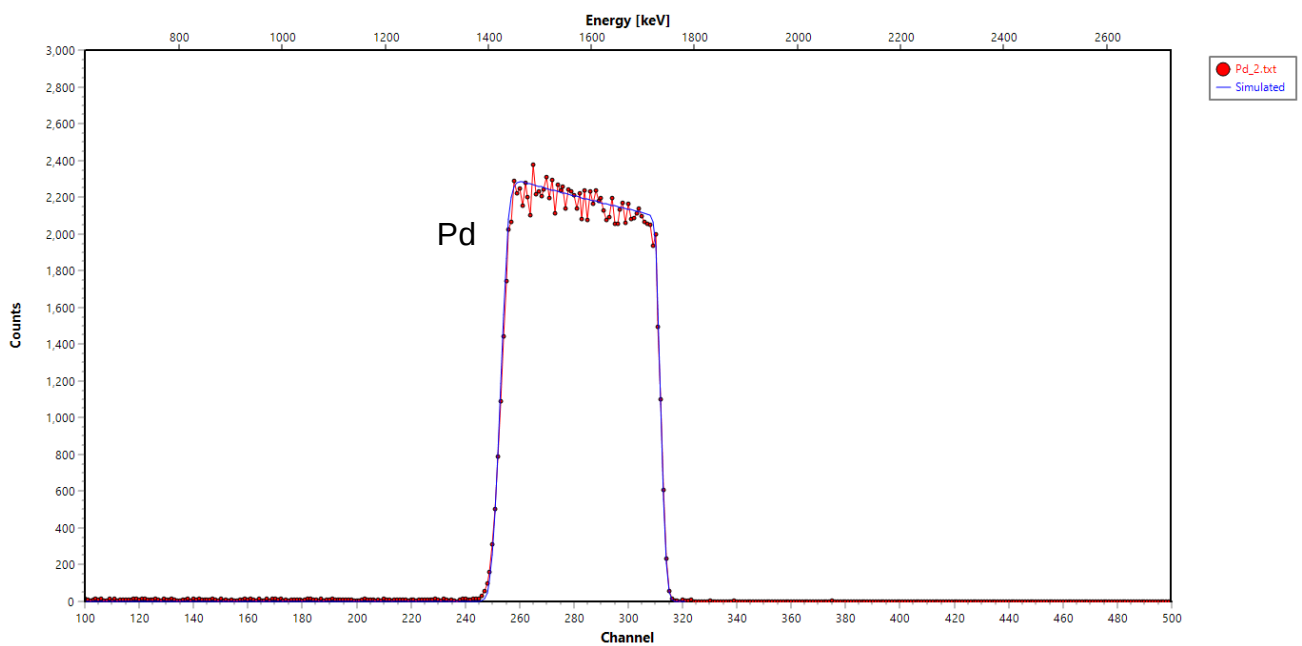


Figure 4.5: Plot of the experimental (red) and simulated (blue) RBS spectrum of the freestanding Pd thin foil used in this work

The RBS spectrum of the palladium thin film is presented above in, Figure 4.5. It is also clear in this case as well that the simulated and experimental spectrum agree with each other. The Pd thin foil was assumed to have a thickness of $(1519 \pm 55) \times 10^{15}$ atoms/cm² or (223.24 ± 8.0) nm to get the best fit shown.

4.2. Heavy Ion Stopping Force Evaluation

An Au⁸⁺ primary beam of 40 MeV energy and a current of 15 nA was used. The primary ion beam was focussed onto thick targets of quartz (SiO₂), copper and titanium to produce recoil atoms of Si, O, Cu and Ti. Recoils leaving the target at an angle of 30° to the incident beam direction were used for the stopping force measurements.

4.2.1. ToF-E Calibration

The calibration process of the ToF-E spectrometer is explained in section 3.2.4. Once the theoretical energies of the surface recoils (Si, O, Cu and Ti ions) and the corresponding ToF bin numbers are obtained, the data is used to obtain a calibration fit. The calibration data and fit are presented in Table 2 and figure 4.6 below.

ToF calibration run for Si and O ions					
Ion	ToF (ch)	Recoil energy E_r (keV)	S_C (keV/ μ g/cm ²)	Recoil energy E'_r (keV)	ToF (ns)
O-16	440	8337.9	10.2	8134.3	59.8
Si-28	480	13106.6	19.7	12713.6	63.2
ToF calibration run for Ti and Cu ions					
Cu	472	22131.1	32.7	21477.2	74.3
Ti	400	18876.9	27.5	18326.4	68.8
Si	352	13106.6	19.7	12713.6	63.2
O	304	8337.9	10.2	8134.3	59.8

Table 2: Data used for the ToF calibration fit.

Where S_C is stopping force of the carbon film in the first timing detector E'_r is energy of the projectile post interaction the carbon film in the first timing detector.

The channel numbers together with the energies were plotted to obtain the linear fit to obtain the ToF calibration parameters.

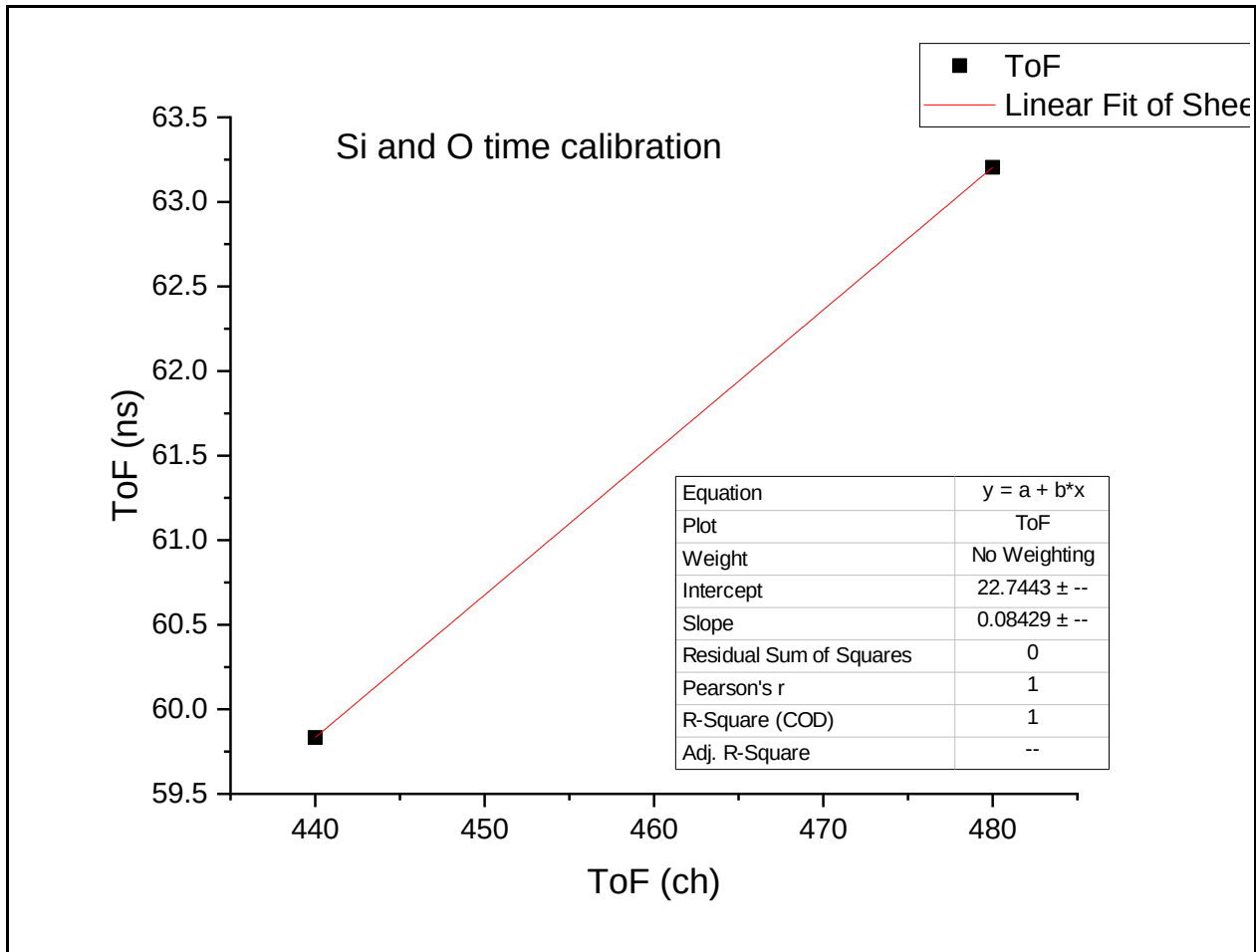


Figure 4.6: ToF linear calibration fit for Si and O projectiles used for this work.

The ToF calibration equation for silicon and oxygen projectiles was found to be:

$$ToF = 0.0843X \text{ ns/ch} + 22.744 \text{ ns} \quad (4.2)$$

Where X is the ToF channel number and has no units.

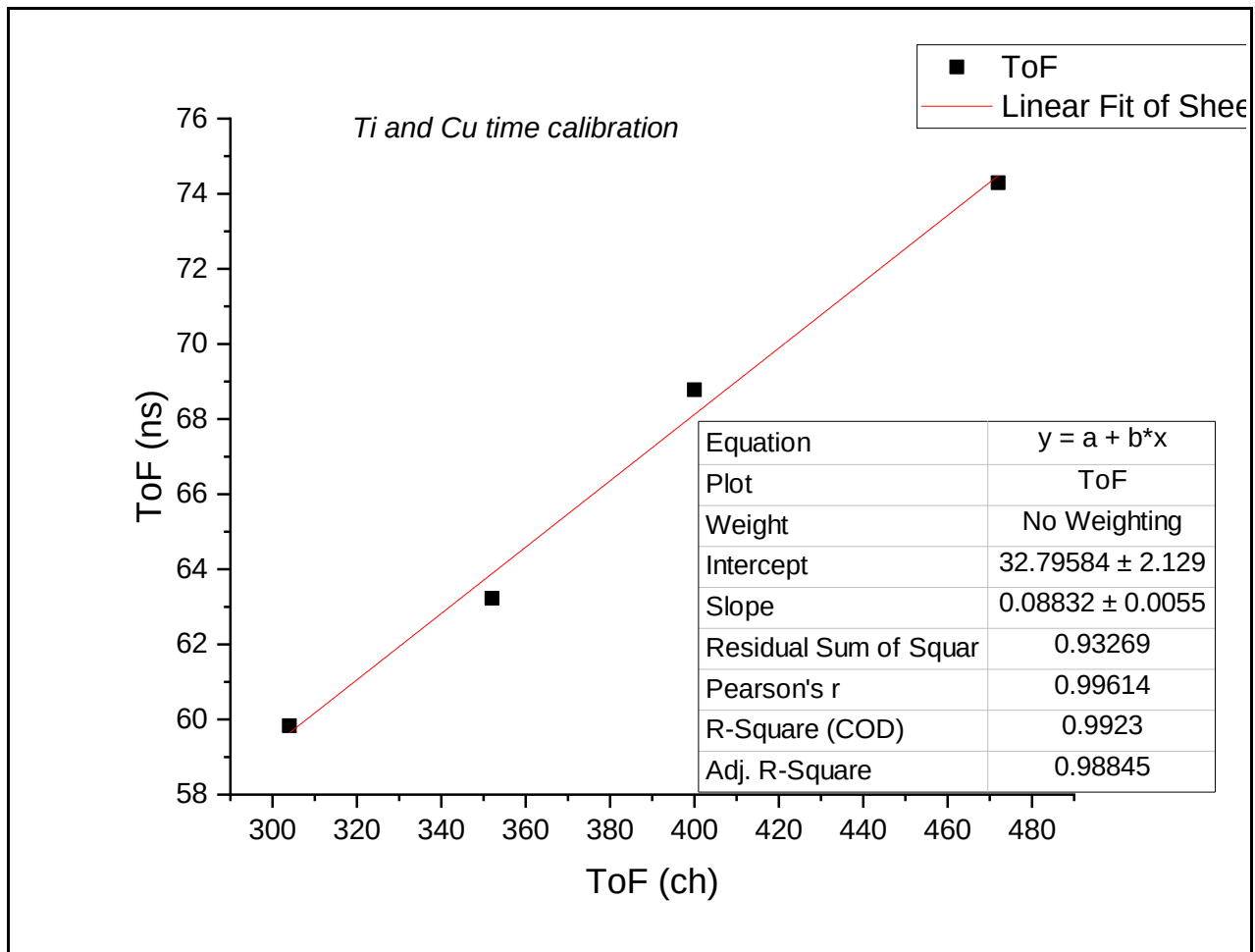


Figure 4.7: ToF linear calibration fit for Ti and Cu projectiles used for this work.

The linear calibration equation for Titanium and Copper projectile was found to be:

$$ToF = 0.0883X \text{ ns/ch} + 32.796 \text{ ns} \quad (4.3)$$

Where X is the channel number and has no units.

Due to the different electronics settings between measurements for the heavier ions, Cu and Ti, and the lighter ions, Si and O, two calibration runs were needed for the separate settings.

4.2.2. Heavy Ion Stopping Results

The scatter targets were thick enough to produce recoils of a wide range of energies. The raw 2-D ToF vs Energy scatter plots and for all the recoil ion - target stopper foil combinations are attached in Appendix 1A and all the data analysis tables in Appendix 1B. This method of stopping force measurement has been validated before in work done [46].

The total experimental stopping force data and theoretical stopping force data from SRIM-2008.04 [12], DPASS 2.05 [14] and CasP 5.2 [13] of Co, Pt and Pd are presented from Figures 4.8 to figure 4.19, for each of Si, O, Cu and Ti recoil ions. Error bars shown in each figure represent an uncertainty of 6% in the experimental stopping force data. At the time of writing no other experimental stopping force data could be found in literature for comparison for the different ion target combinations used in this work.

4.2.2.1. Data Manipulation and Calculation of Stopping Force

Time of flight and energy measurements from the SBD are measured in coincidence. This means that the ToF is tagged by a specific SBD energy response to produce a 2D ToF-E scatter plot; see Appendix 1 for all the different ion-target combinations. From the scatter plot, it is possible to determine measured energy from the ToF (in channels) by projecting onto ToF axis the section of the scatter plot corresponding to energy from the SBD. Figure 4.8 is an example of the data analysis procedure for Si and O recoils with a Pd stopper foil, where t_1 and t_2 are time of flights measured with and without the Pd foil respectively.

A gauss function is used to obtain the mean peak values of ToF in channel numbers from the raw data, this is done using ROOT 6.14/02 [67]. The move from ToF in channels to ToF in nanoseconds is done with the use of the linear calibration equation(s) 4.2 or 4.3 (equation 4.2 is used for O and Si projectiles and equation 4.3 is used for Ti and Cu projectiles). From the measured time of flight values energy loss is determined with the use of equation 3.9.

Stopping force is calculated by normalising energy loss by the foil thickness i.e. equation 3.10. It is important to note that stopping force is calculated at the effective energy (E_{av}) which is given by:

$$E_{av} = \frac{E_1 + E_2}{2} \quad (4.4)$$

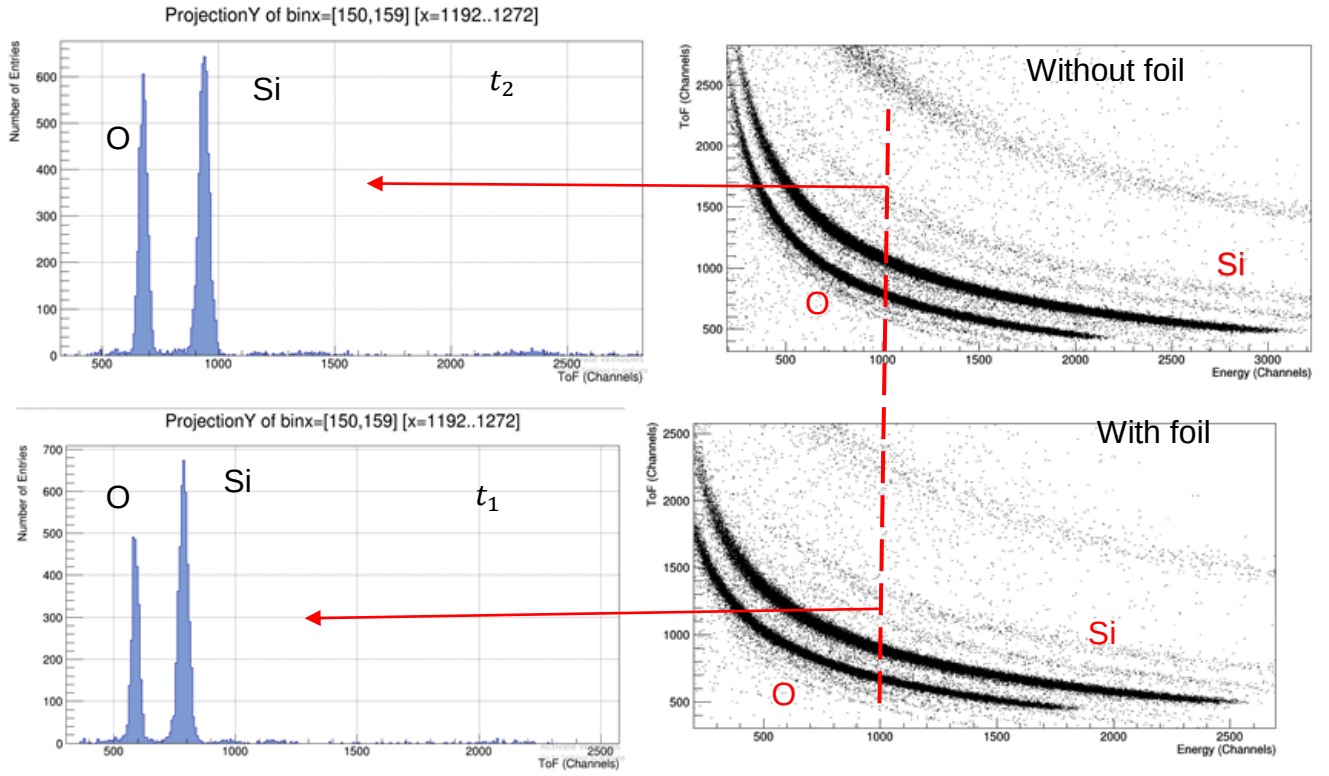


Figure 4.8: Data from the raw measurement Si and O projectiles measured with and without the Pd foil. The projections show ToF slices used to calculate energy before and after the Si and O ion travel through the thin foil.

4.2.2.2. Cobalt Stopping Results

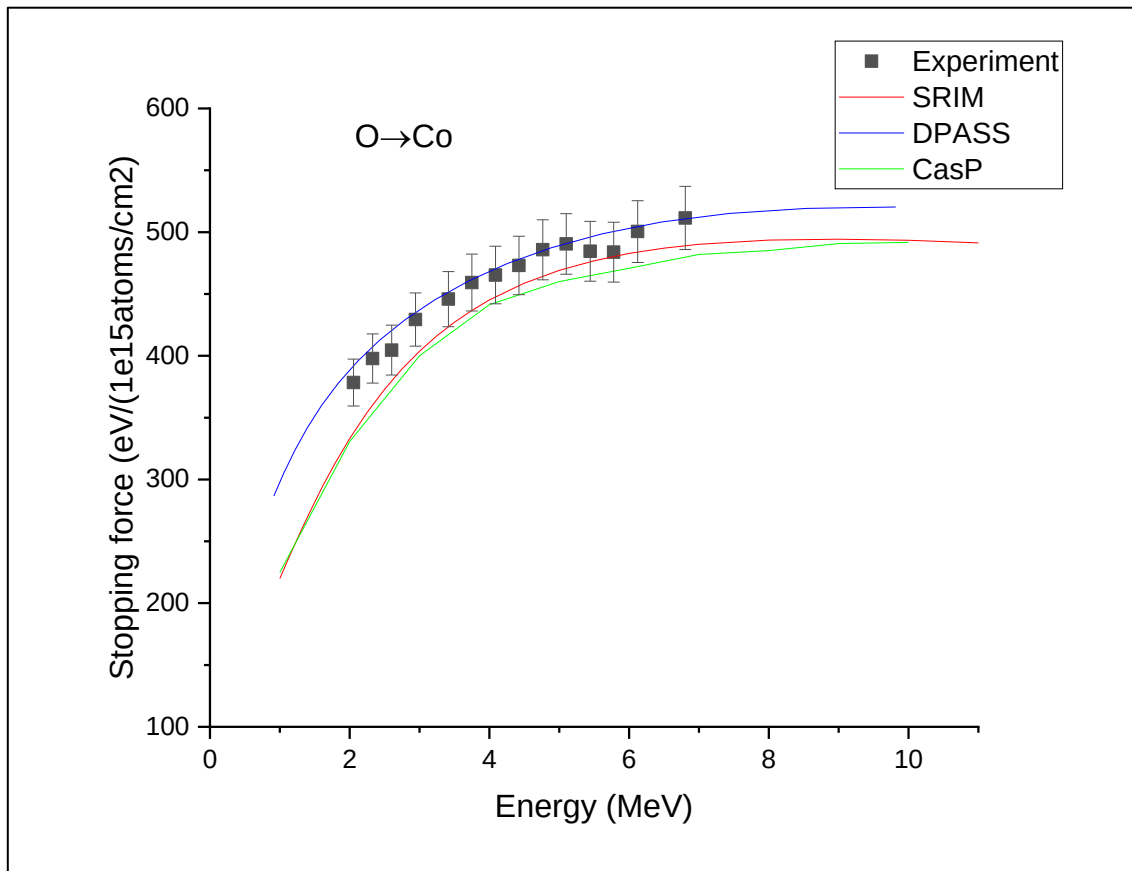


Figure 4.9: O in Co experimental stopping force data compared with data from predictive stopping force models.

The stopping force data presented in figure 4.9 above shows the stopping force of cobalt for oxygen ions, with experimental energies ranging between circa 2 – 7 MeV (0.125 MeV/u – 0.438 MeV/u). The graphs show that DPASS was able to predict the stopping force of oxygen in cobalt with a high accuracy. SRIM and CasP fell a little short at lower energies, 2 MeV – 3 MeV. They both however managed to predict stopping force within the uncertainty margin of 6% at higher ion energies, with SRIM being the better of the two predictive models.

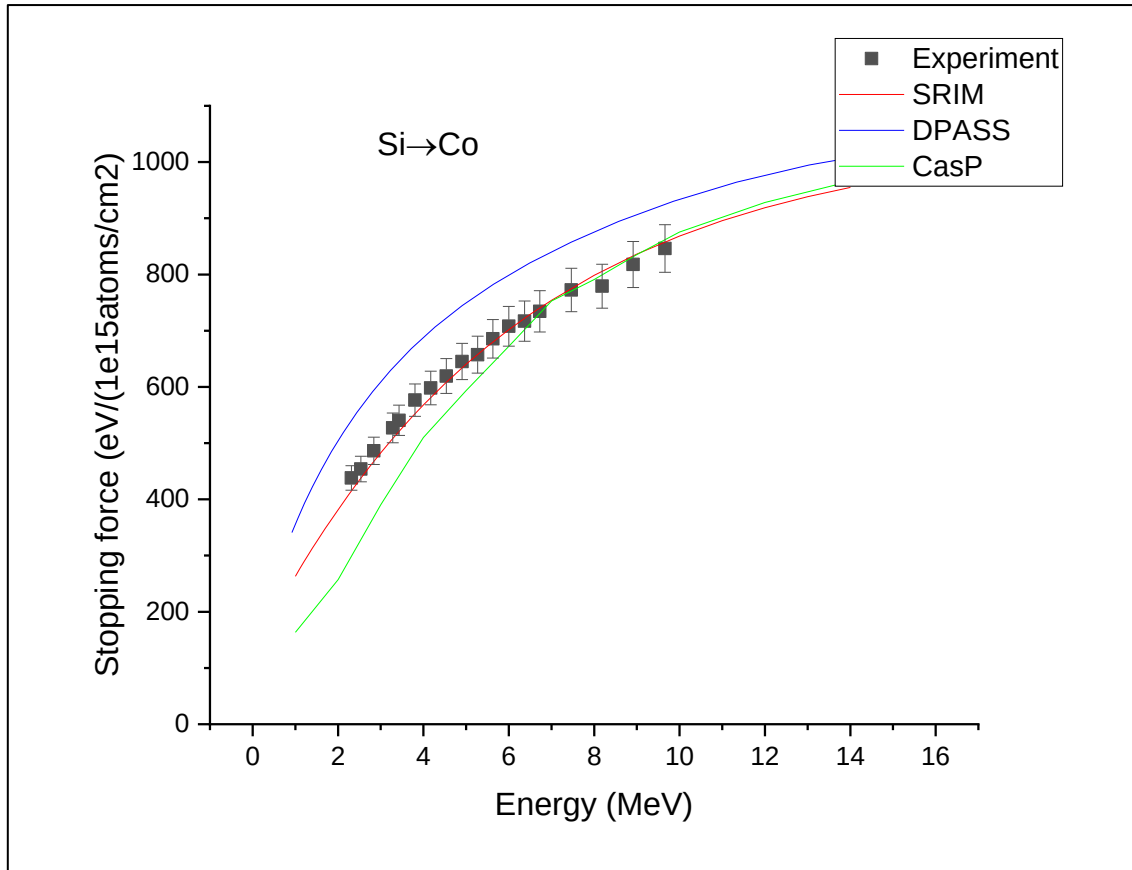


Figure 4.10: Si in Co experimental stopping force data compared with data from predictive stopping force models

The stopping force data presented in figure 4.10 above shows the stopping force of silicon in cobalt, with experimental energies ranging between 2 – 10 MeV (0.07 MeV/u – 0.36 MeV/u), and the predictive stopping force data plotted to cover an energy range of 1 MeV – 16 MeV (0.0356 MeV/u – 0.570 MeV/u). Figure 4.10 shows that SRIM was able to accurately predict the stopping force of silicon in cobalt fairly accurately. At low energies CasP underestimates stopping force but gets better as ion energy increases. The accuracy of CasP stopping prediction falls within the uncertainty margin at circa 5 MeV, and gradually increases in prediction accuracy up to the maximum ion energy at 10 MeV. DPASS overshoots the stopping force throughout the whole measured energy, with the highest deviation being 22%.

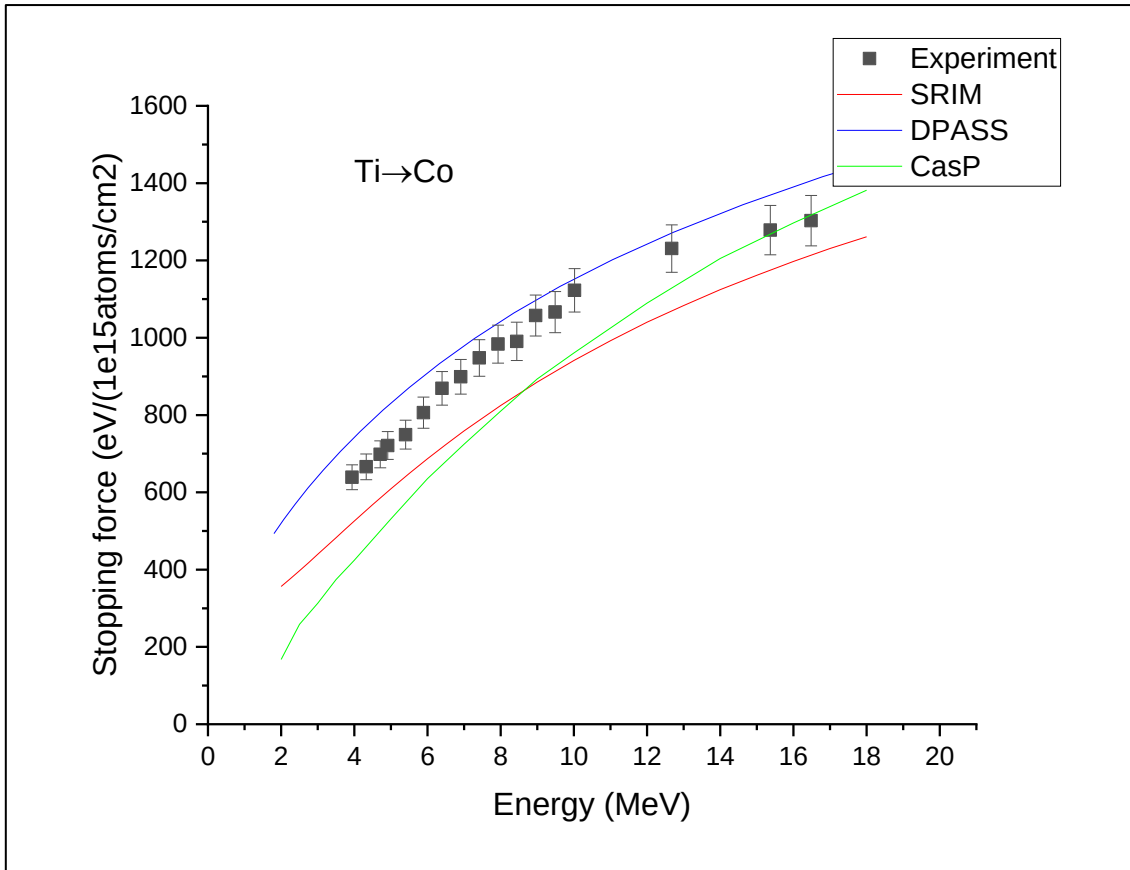


Figure 4.11: Experimental stopping force data of Ti on Co compared with data from predictive stopping force models

Figure 4.11 shows experimental and simulated stopping force data of titanium in cobalt. The stopping force data presented above covers a wide range of energies, from circa 4 – 18 MeV (0.08MeV/u – 0.3 MeV/u) for the experimental stopping data and 2 – 20 MeV (0.04 MeV/u – 0.4 MeV/u) for the predictive stopping data. DPASS slightly overshoots stopping force, but moves within the uncertainty region at energies 8 MeV – 10 MeV. Both SRIM and CasP undershoot stopping force of titanium in cobalt, with CasP being able to accurately estimate stopping only at higher energies.

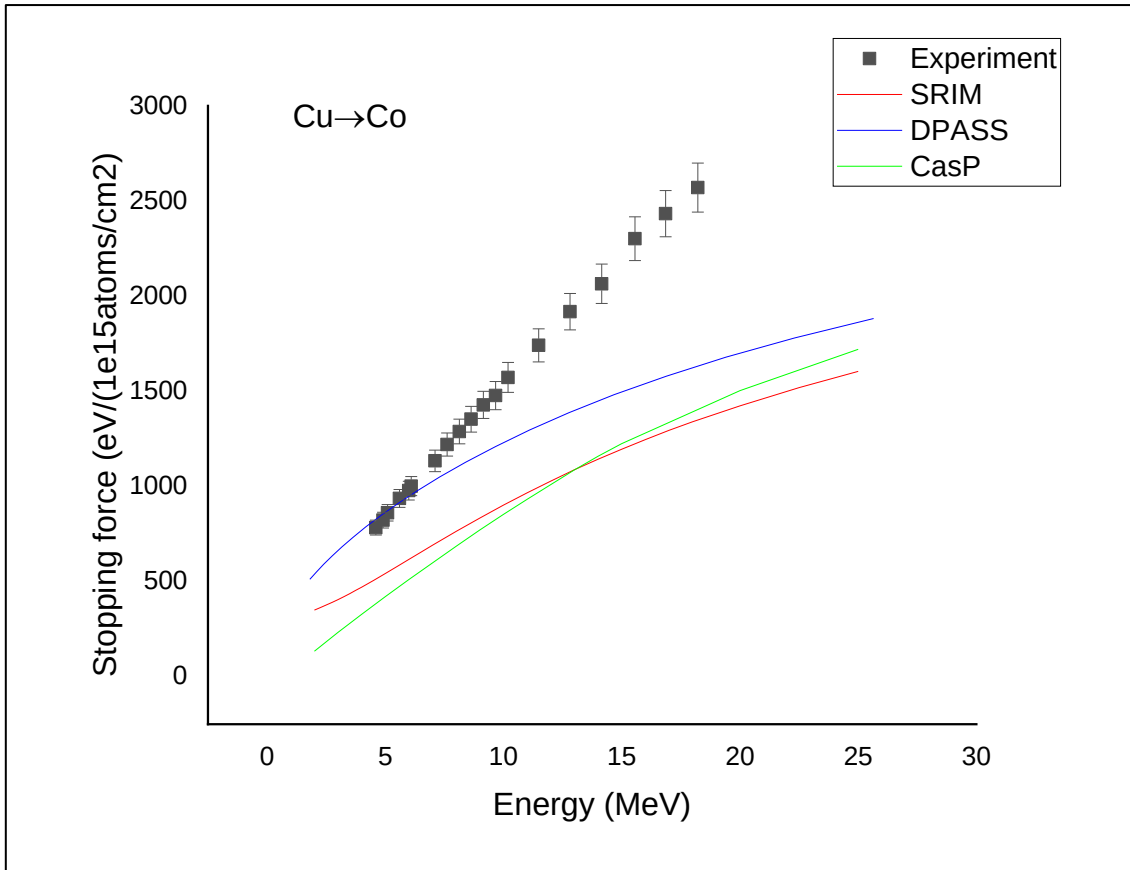


Figure 4.12: Cu in Co experimental stopping force data compared with data from predictive stopping force models

Figure 4.12 shows experimental and simulated stopping force data of copper in cobalt. The stopping force data presented above covers a wide range of energies, from 4 MeV – 18 MeV (0.06 MeV/u – 0.28 MeV/u) for the experimental data and 2.5 MeV – 25 MeV (0.04 MeV/u – 0.4 MeV/u) for the theoretical data. It is clear from figure 4.12 that none of the predictive models (SRIM, DPASS and CasP) were able to predict the trend and indeed the stopping force of copper in cobalt. DPASS, however, manages to predict stopping force around 5 MeV, but this is thought to be a fortuitous coincidence.

4.2.2.3. Platinum Stopping Results

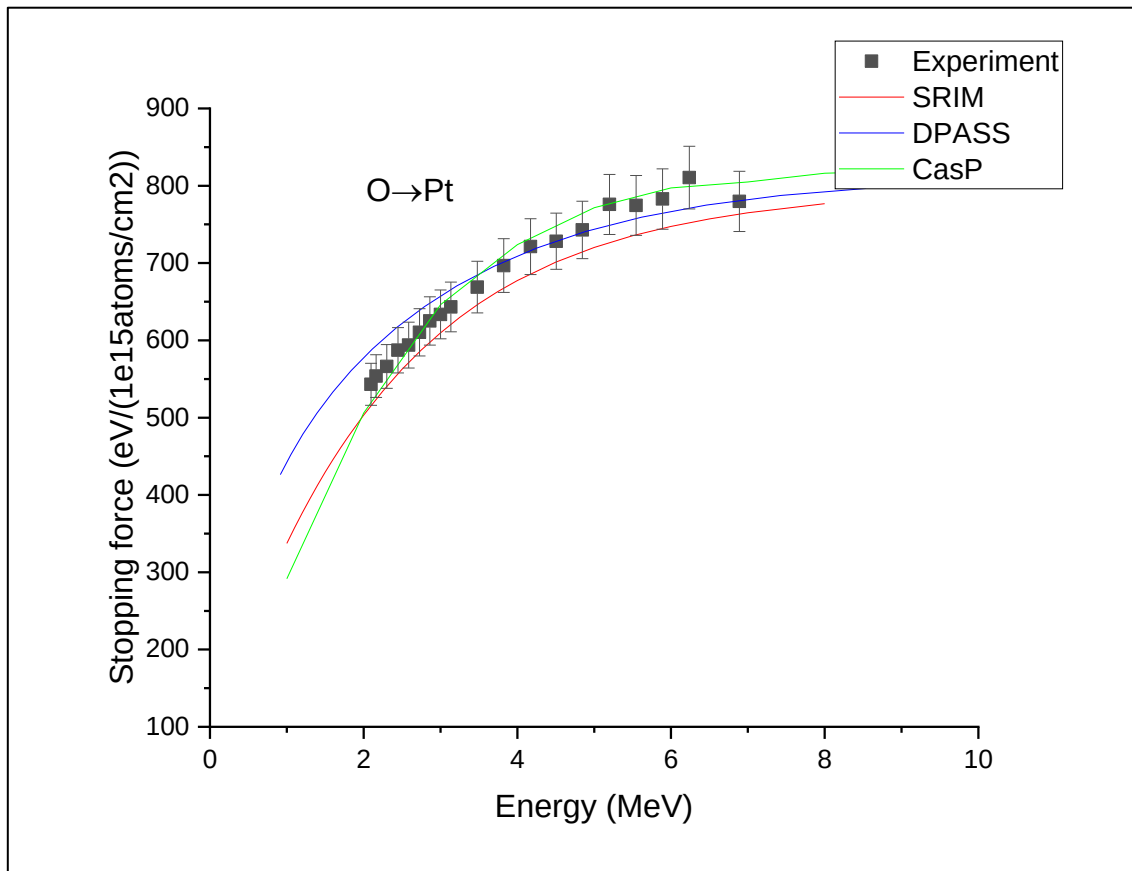


Figure 4.13: O in Pt experimental stopping force data compared with data from predictive stopping force models

Figure 4.13 shows experimental and theoretical stopping force data of oxygen in platinum. The stopping force data presented above energies, from 2 MeV – 7 MeV (0.13 MeV/u – 0.44 MeV/u) for the experimental data extends from 1 MeV– 9 MeV (0.06 MeV/u – 0.56 MeV/u) for the simulated data. The comparison reveals that all the stopping force predictive models were able to estimate stopping with a fairly relative accuracy, albeit that SRIM is right on the lower edge of the uncertainty margin and DPASS improves accuracy at circa 4 MeV and above.

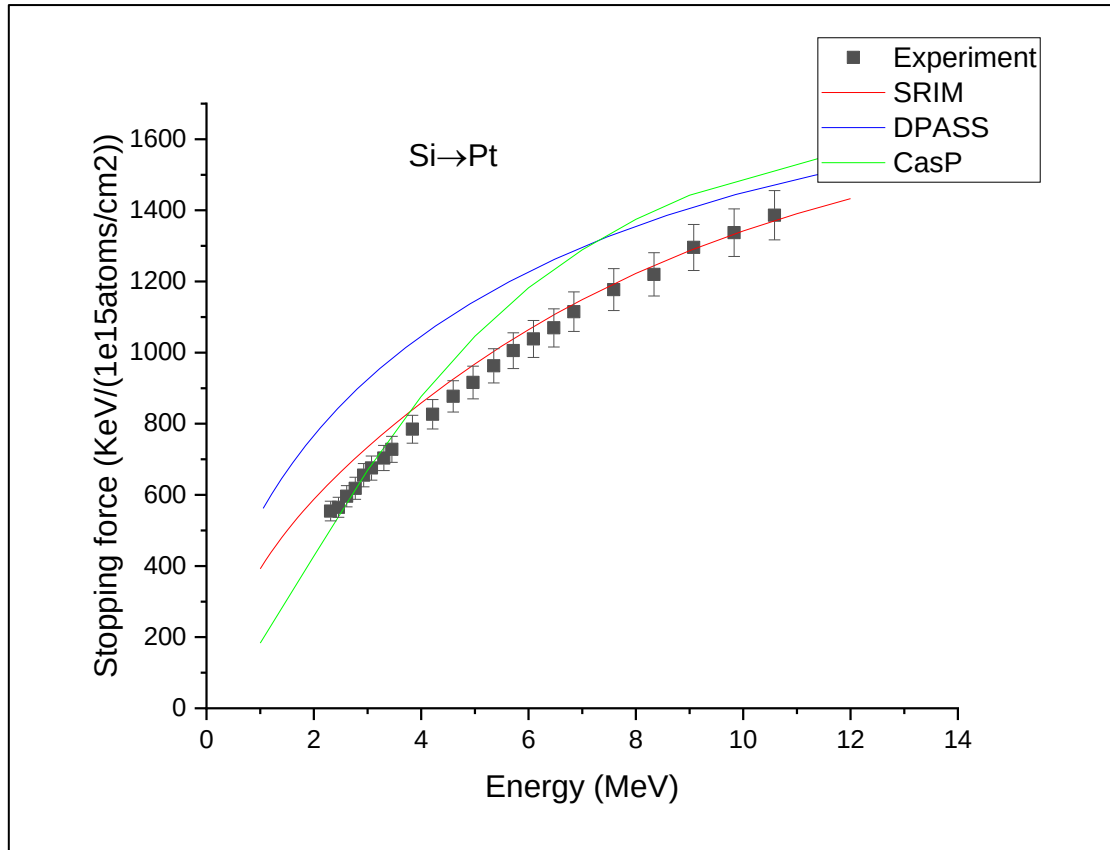


Figure 4.14: *Si in Pt experimental stopping force data compared with data from predictive stopping force models*

Figure 4.14 shows experimental and theoretical stopping force data of silicon in platinum. Experimental and theoretical stopping force is presented from 2 MeV – 11 MeV (0.07 MeV/u – 0.40 MeV/u) and 1 MeV – 13 MeV (0.04 MeV/u – 0.46 MeV/u) respectively. SRIM was able to predict stopping from approximately 5 MeV and gradually increase accuracy with increasing ion energy. CasP managed to predict stopping at low energies (2 MeV – 3 MeV) and overshoot experimental values for energies greater than 3 MeV. DPASS overestimated stopping altogether.

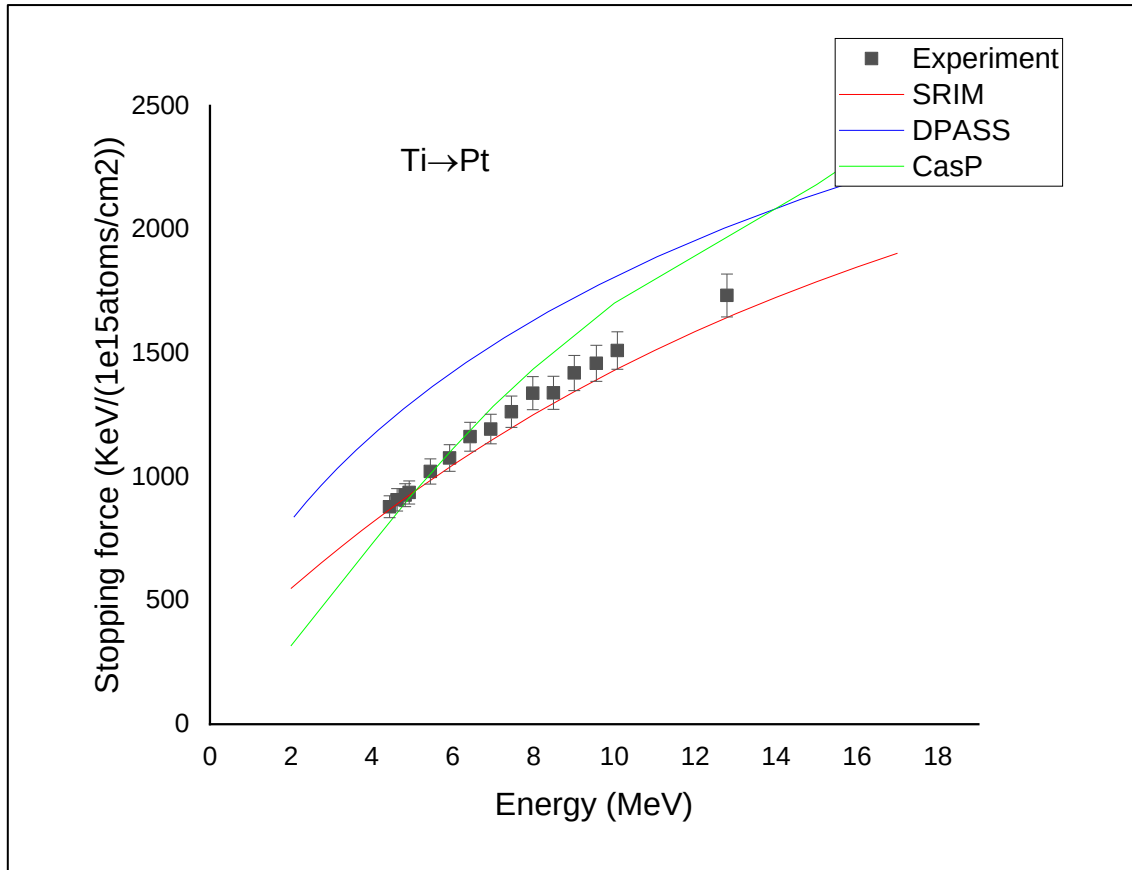


Figure 4.15: Ti in Pt Experimental stopping force data compared with data from predictive stopping force models

Fig 4.15 shows the stopping force from experimental data and predictive models of titanium on platinum. SRIM Managed to predict the stopping force of Ti in Pt reasonably well, SRIM predicted stopping well at lower energies, around the 4 MeV region. The accuracy of SRIM prediction decreased with increasing ion energy, although it managed to stay on the lower edge of the uncertainty margin. CasP predicts stopping fairly well between 4 MeV – 7 MeV, and gradually loses accuracy with increasing ion energy. DPASS completely over shoots stopping, with the 50% being the highest deviation.

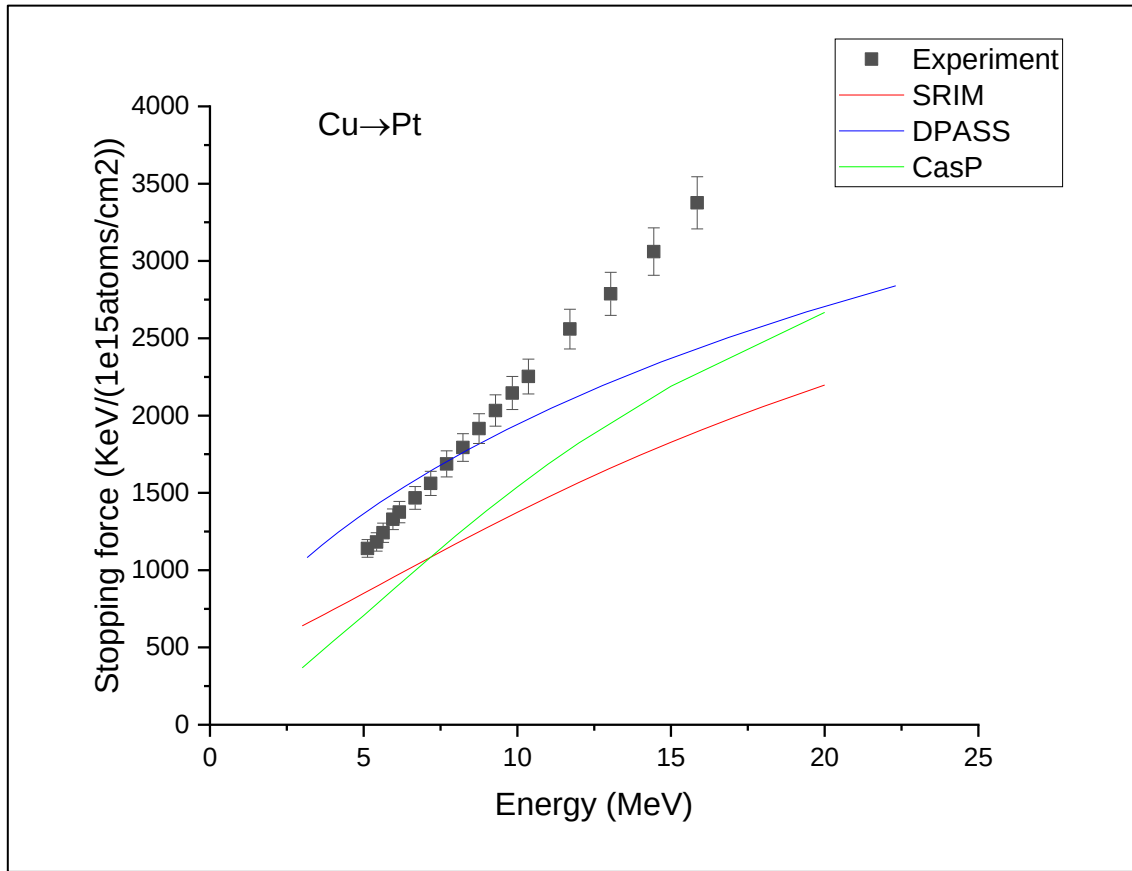


Figure 4.16: Cu in Pt experimental stopping force data compared with data from predictive stopping force models

Figure 4.16 shows experimental and theoretical stopping force data, between 2.5 MeV and 22.5 MeV, of copper in platinum. None of the stopping force predictive models used was able to predict the stopping force or the stopping force trend. DPASS manages to predict the stopping force around the 7 MeV mark, this is thought to be a coincidence.

4.2.2.4. Palladium Stopping Results

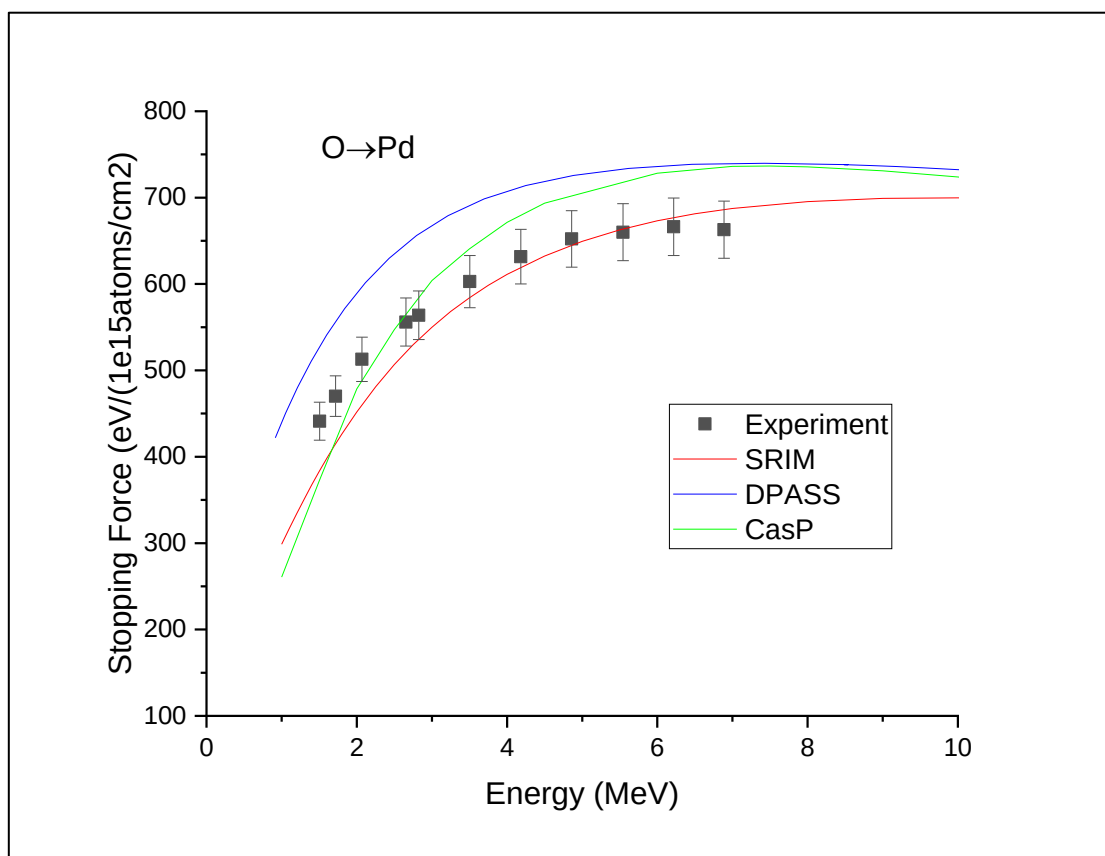


Figure 4.17: O in Pd experimental stopping force data compared with data from predictive stopping force models

Figure 4.17 shows the stopping force of oxygen in palladium. The stopping force is compared with stopping predictive models. SRIM manages to predict stopping accurately at ion energies greater than 3 MeV, with not so good accuracy at ion energies below 3 MeV. CasP is accurate around the 3 MeV region and loses prediction accuracy as the ion energy moves away from the 3 MeV mark. DPASS overshoots stopping force altogether.

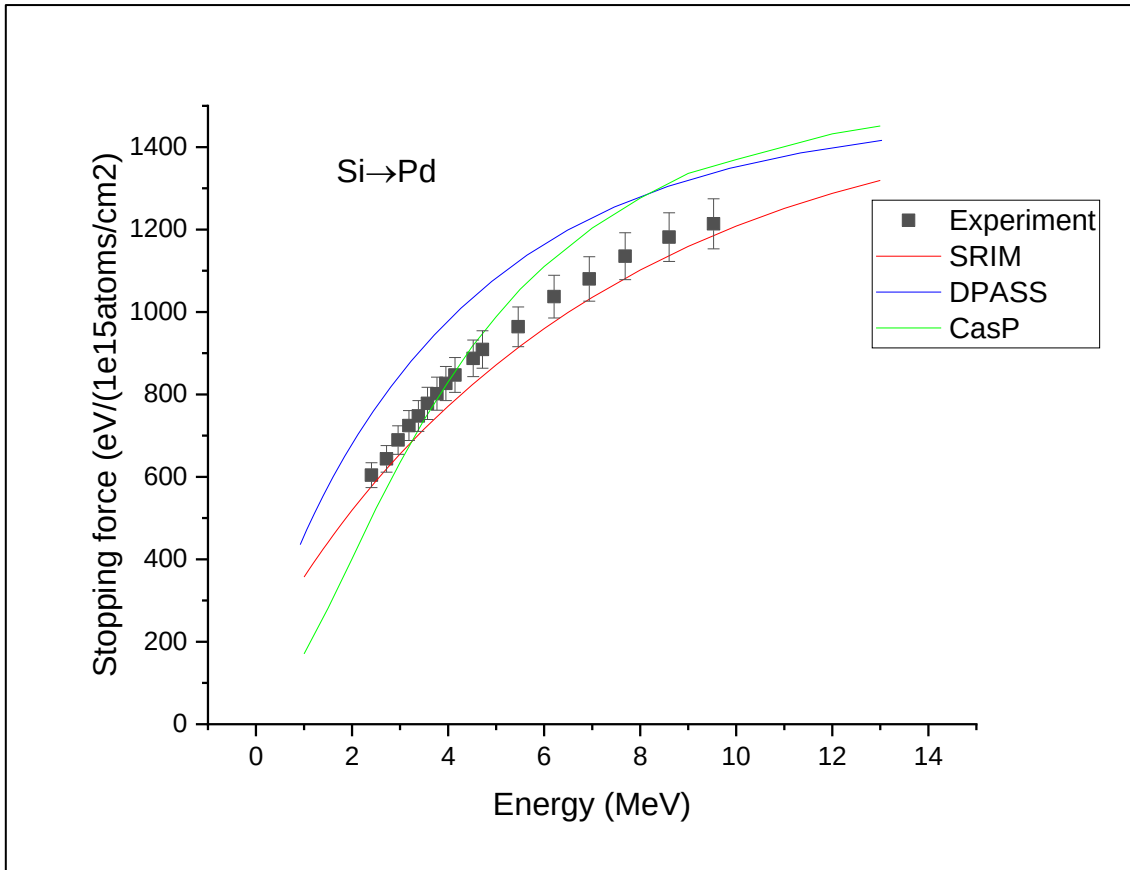


Figure 4.18: Si in Pd experimental stopping force data compared with data from predictive stopping force models.

Figure 4.18 shows experimental and simulated stopping force data of Silicon in Palladium, from circa 2 MeV – 11 MeV (0.11 MeV/u – 0.39 MeV/u) and 1 MeV – 14 MeV (0.04 MeV/u – 0.5 MeV/u) with respect. SRIM has estimated stopping fairly well, with the predictions laying around the bottom edge of the uncertainty margin. CasP estimates stopping relatively accurately between 3 MeV and 4.5 MeV. DPASS overshoots the stopping force of Si in Pd.

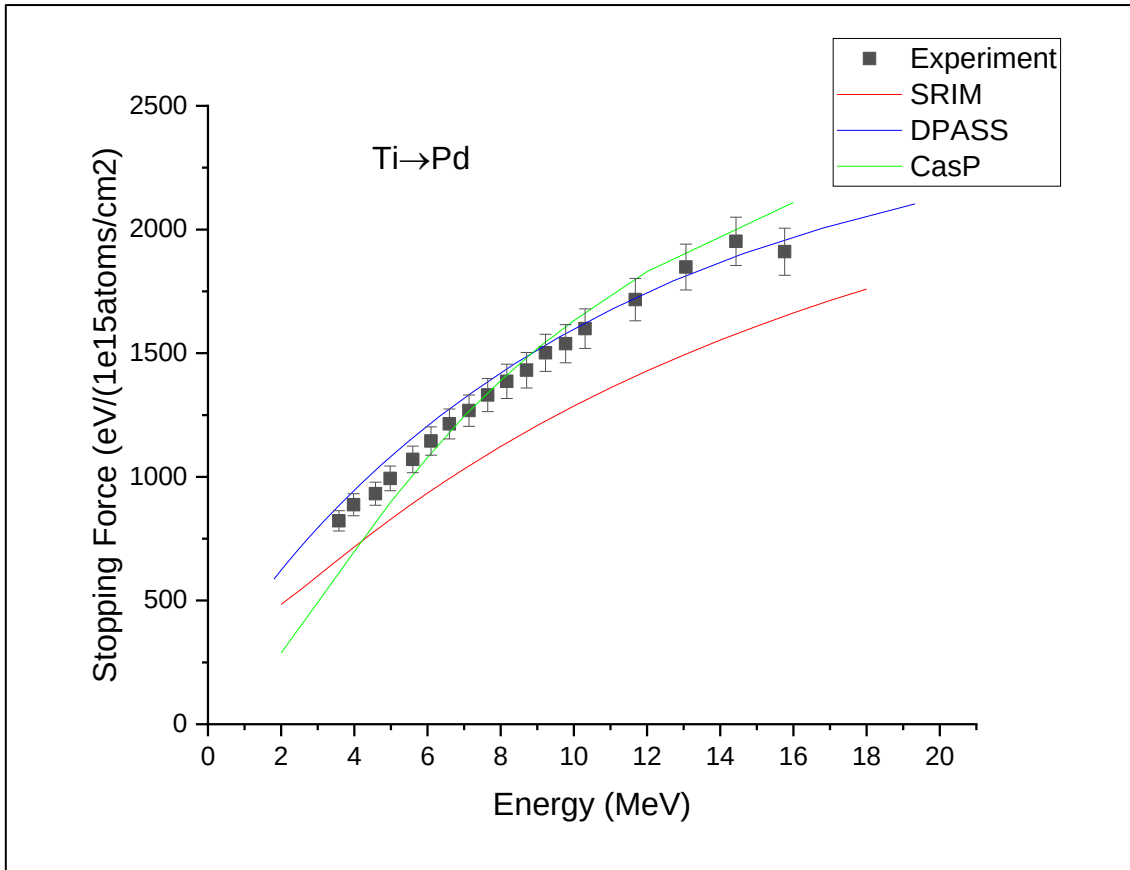


Figure 4.18: Ti in Pd experimental stopping force data compared with data from predictive stopping force models

Figure 4.19 shows experimental and theoretical stopping force data of titanium in palladium, from circa 4 MeV– 18 MeV (0.08 MeV/u – 0.38 MeV/u) for the experimental data and 2 MeV – 21 MeV (0.04 MeV/u – 0.44 MeV/u) for all the theoretical data. DPASS and CasP managed to estimate stopping relatively well from ion energies of 7 MeV and above, with DPASS increasing in accuracy with increasing ion energy and CasP with highest accuracy between 7 MeV – 9 MeV and gradually losing predictive accuracy from 9 MeV as ion energy increases. SRIM under estimates stopping force of Ti in Pd.

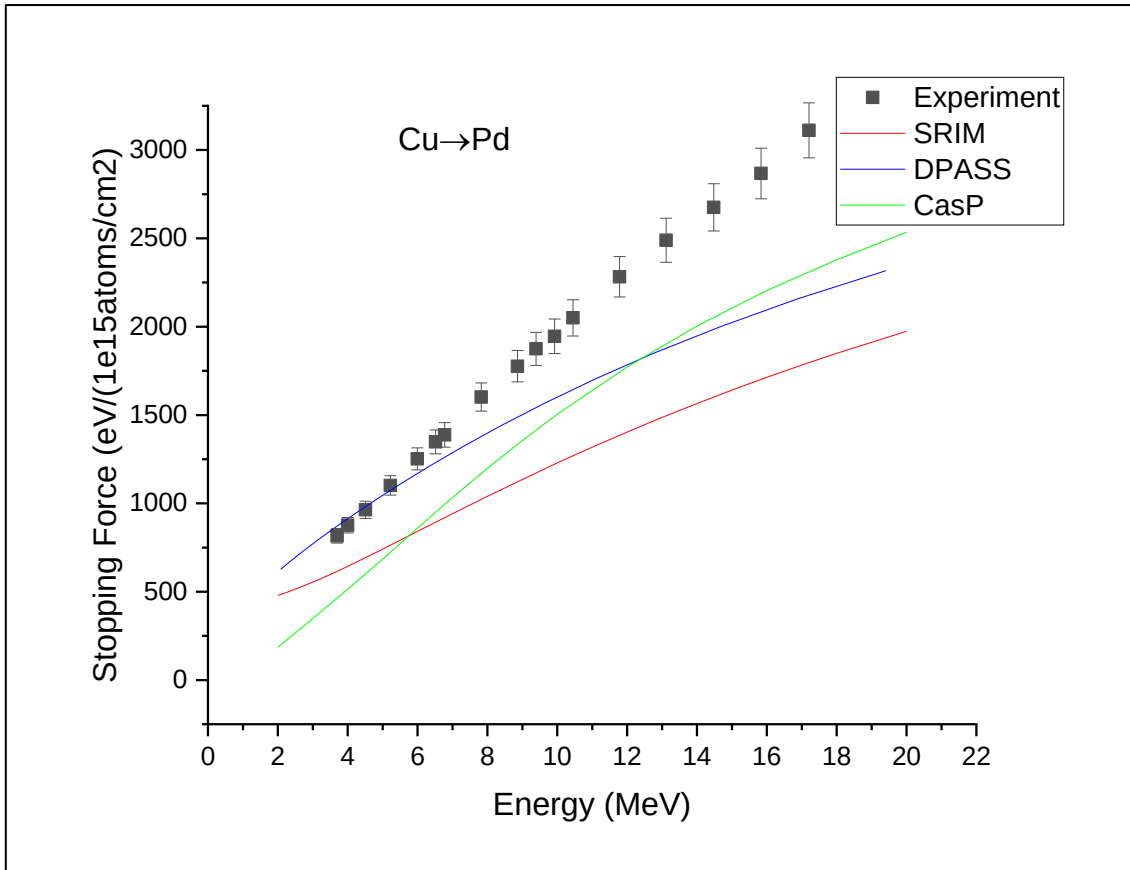


Figure 4.20: Cu on Pd experimental stopping force data compared with data from predictive stopping force models

Figure 4.20 shows experimental and simulated stopping force data of Copper in palladium. The predictive stopping force models fail at estimating the stopping force of copper in palladium, however DPASS manages to predict stopping around the 4 MeV or 0.0629 MeV/u mark, like with all other measurements with copper, it is assumed to be anomaly.

4.2.3. Stopping Force Predictive Models Data vs. Experimental Data

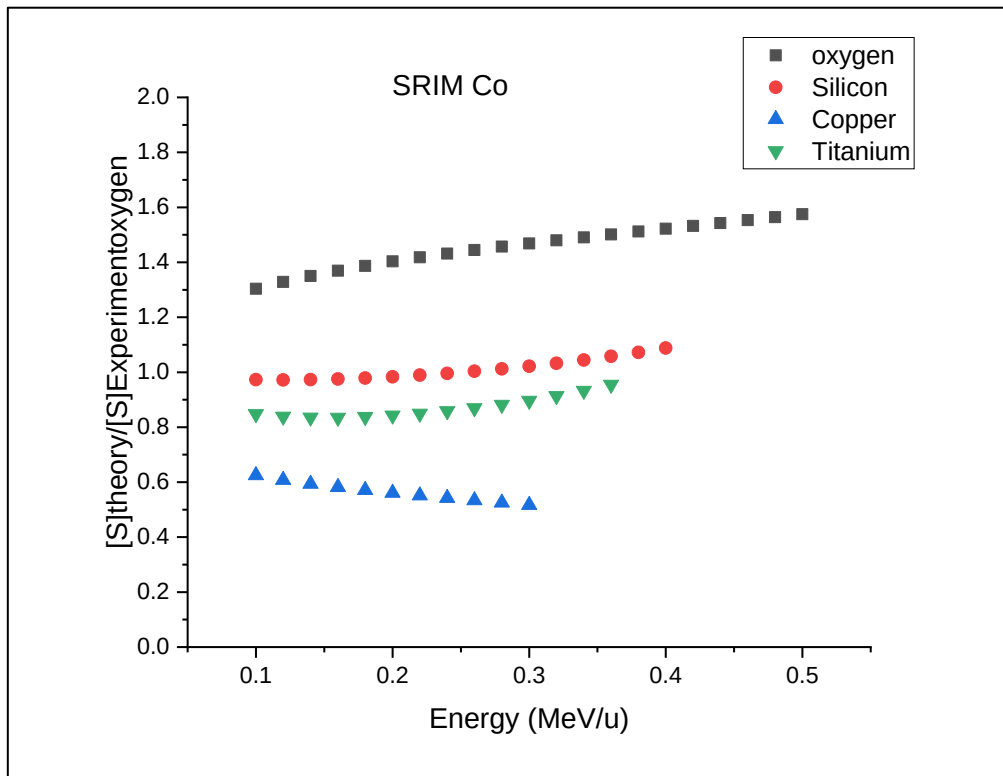


Figure 4.21: Variation of the SRIM $[S]_{theory}/[S]_{experiment}$ ratio in Co for different ions.

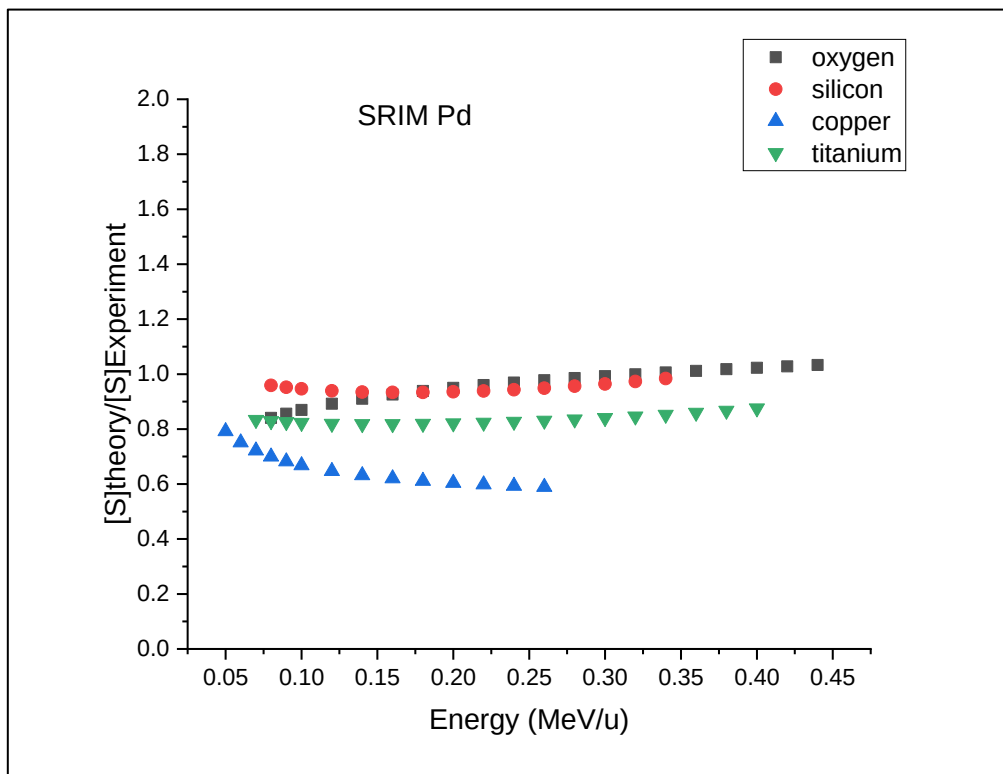


Figure 4.22: Variation of the SRIM $[S]_{theory}/[S]_{experiment}$ ratio in Pd for different ions.

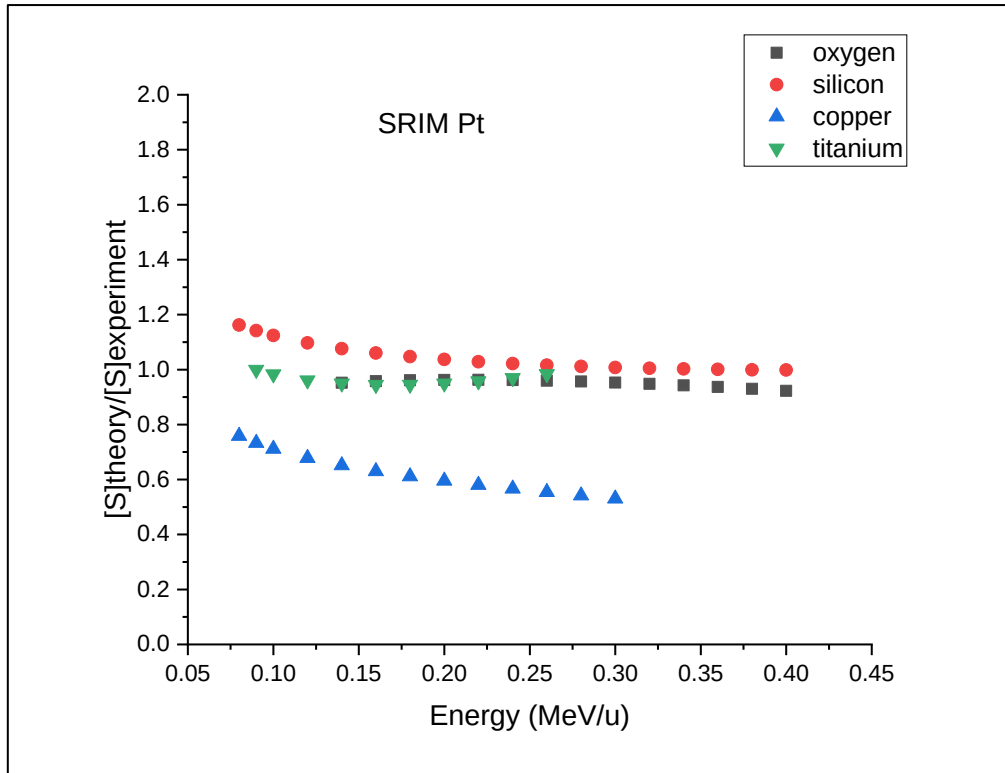


Figure 4.23: Variation of the SRIM $[S]_{theory}/[S]_{experiment}$ ratio in Pd for different ions

Figures 4.21 – 4.23 show the predictive accuracy of the semi-empirical stopping force model SRIM for oxygen, silicon, copper and titanium ions in cobalt, palladium and platinum foils respectively as a function of ion energy. As mentioned in **section 2.2.6**, SRIM is probably the most widely used stopping force predictive model, as a result the bulk of the discussion is based on SRIM. From Figures 4.9-4.20 it can be seen that there are considerable disagreements between the theoretical models themselves so the discussion between experiment and theory will be limited to the semi-empirical SRIM. Figures 4.21 shows that SRIM was able to accurately predict the stopping of silicon relatively well, with titanium and oxygen not being accurately predicted. In Pd, SRIM predicted the stopping of oxygen and silicon very well, with a discrepancy of approximately 20% in the accuracy of stopping titanium. SRIM managed to predict the stopping force of titanium and oxygen, with silicon improving with stopping force predictions as ion energy increases. From figure 4.21 – figure 4.23 it is clear that SRIM could not predict the stopping force of copper. In fact, except for anomalies from DPASS, none stopping force predicted the stopping of copper in all the foils. See appendix 3 for the remaining models predictive models. SRIM uses the effective charge concept to predict stopping of heavy ions, which might be the cause of the discrepancy between the experimental and theoretical stopping force data for copper.

Chapter 5

Conclusion and Summary

The aim of this work was to measure the stopping force of low MeV heavy ions and compare the experimental results obtained with theoretical and semi-empirical models of stopping force.

Stopping force measurements of Co, Pt and Pd were carried out using a 40 MeV Au⁸⁺ primary ion beam. Various scatter or recoil targets were used to produce a variety of poly-energetic ions; quartz or SiO₂ was used to produce ions of silicon and oxygen, and pure copper and titanium was used to produce Cu and Ti ions respectively. The experimental data obtained from the experimental work was compared to that of semi-empirical codes; SRIM and CasP and that of a purely theoretical code DPASS. The comparisons of experimental, theoretical, and semi-empirical target-ion combinations were separated for each ion species.

Data from the plots in section 4.2.3 and in Appendix 3 show a clear discrepancy in some of the comparisons of the experimental data and the data obtained from the semi-empirical and theoretical stopping force models used for this work. This is due to the complex nature of energy loss of heavy ions in matter, this means that the stopping force predictive models cannot describe heavy ion stopping in matter accurately, as explained in section 2.1.2. The discrepancies exist due to the failure of the model to correctly account for some of the energy loss mechanisms that occur during heavy ion stopping, these effects include: excitation and ionisation of the target atoms, excitation and electron capture of the incident ion itself, direct energy transfer from the ion to the target atoms to name a few.

From the data presented in section 4.2.3 and Appendix 3, it is clear that none of the predictive models were able to accurately predict the stopping force of copper in any of the target foils used in this work. This is either due to the inability of the predictive models to properly describe stopping force of heavy ions or there may be a flaw in the measurement data of the copper ions. Whatever the reason the issue needs to be investigated further.

SRIM uses the effective charge concept, by scaling the stopping power of protons at a certain energy, to predict the stopping power of heavy ions at energies used for this work. This assumption is incorrect, because at these energies the ion is stripped of its electrons, and the charge exchange occurs as the ion traverse through the target, this is not considered by SRIM. This might be the reason there is an observable discrepancy between the theoretical and experimental stopping force data [3, 46].

In conclusion, as discussed in section 1.2, the semi-empirical and theoretical models were used to predict stopping force and the data was compared to experimental stopping force data. The data obtained shows variations in agreement between predictive and experimental stopping force data for the different ion-target combinations. On the whole, for O, Si and Ti the disagreements between experiment and SRIM predictions is within experimental uncertainty. It is the Cu data that shows huge discrepancies. The data collected from this work will be added to databases to further assist researchers to develop and improve predictive models of stopping force. SRIM, DPASS and CasP need to make the necessary adjustments to improve stopping force predictions of heavy ions used in this work.

Heavy ion stopping force research needs to continue and more data is needed due the importance of stopping force in research and industry. In future work associated with this thesis it is planned that surface topography be measured in order to account for uncertainties due to sample roughness. Further work will also look at using even heavier ions than Cu to check if the Cu data is not due to experimental artefacts.

References

- [1] N. M. Denkin, Stopping Power of Gases for Heavy Ions, California, 1976.
- [2] J. F. Zeigler, J. P. Biersack and U. Littnark, The stopping and range of ions in solids, New York: Pergamon Press, 1985.
- [3] M. Msimanga, C. Pineda-Vargas, T. Hlatshwayo, C. Comrie, H. Ammi and M. Nkosi, "Electronic stopping force of C¹², Si²⁸ and Cu⁶³ in HfO₂ and SiO₂ dielectric films," *Nuclear Instruments and Methods in Physics Research B*, no. 322, pp. 54-58, 2014.
- [4] R. Mikšová, V. Hnatowicz, A. Macková, P. Malinsky and P. Slepíčka, "The stopping power and energy straggling of heavy ions in silicon nitride," *Nuclear instruments and Methods in Physics Research B*, vol. 354, pp. 205-209, 2015.
- [5] R. Hellborg, H. J. Whitlow and Y. Zhang, Ion Beam in Nanoscienc and Technology, Heidelberg: Springer, 2009.
- [6] R. C. Brundle, C. A. Evans, Jr and S. Wilson, ENCYCLOPEDIA OF MLATERIALS CHARACTERIZATION, Greenwich: Manning Publications Co, 1992.
- [7] M. Mayer, SIMNRA User's Guide, Garching: Max-Planck-Institut für Plasmaphysik, 1997.
- [8] K. Gärtner, "Ion-Solid Interaction," in *Ion Beam Modification of Solids: Ion-Solid Interaction and Radiation Damage*, Switzerland, Springer, 2016, pp. 3-60.
- [9] C. Jeynes, R. Webb and A. Lohstroh, "Ion Beam Analysis: A Century of Exploiting the Electronic and Nuclear Structure of the Atom for Materials Characterisation," *Reviews of Accelerator Science and Technology*, vol. 4, pp. 41-82, 2011.
- [10] University of Surrey, "Ion Beam Analysis," [Online]. Available: <https://www.surrey.ac.uk/ion-beam-centre/research/ion-beam-analysis>. [Accessed 01 July 2020].
- [11] International Atomic Energy Agency, "Improvement of the Reliability and Accuracy of Heavy Ion Beam Analysis," International Atomic Energy Agency, Austria, 2019.
- [12] J. F. Ziegler, M. D. Ziegler and J. P. Biersack, "SRIM - The stopping and range of ions in matter (2010)," *Nuclear Instruments and Methods in Physics Research Section B*, vol. 268, no. 11-12, pp. 1818-1823, 2010.
- [13] G. Schiwietz and P. L. Grande, "Electronic stopping-power program CasP," January 2014. [Online]. Available: https://www.helmholtz-berlin.de/people/gregor-schiwietz/casp_en.html. [Accessed 2020 June 2020].
- [14] A. Schinner and P. Sigmund, "Expanded PASS stopping code," *Nuclear Inst. and Methods in Physics Research B: Beam Interactions with Materials and Atoms*, vol. 460, pp. 19-26, 2019.
- [15] D. Fink and L. T. Chadderton, "Ion-Solid Interaction: Status and Perspectives," *Brazilian Journal of Physics*, vol. 35, no. 3B, pp. 735-740, 2005.
- [16] J. Tirira, Y. Serruys and P. Trocellier, Forward Recoil Spectrometry: Applications to Hydrogen Determination in Solids, New York: Plenum Press, 1996.
- [17] H. Bethe, "The theory of the passage of fast corpuscular rays through matter," *Ann. Phys.*, vol. 397, no. 3, 1930.
- [18] K. Nordlund, "Energy loss of energetic ions," 30 September 1996. [Online]. Available: <http://beam.helsinki.fi/~knordlun/mdh/rangetext.html>. [Accessed 05 March 2020].

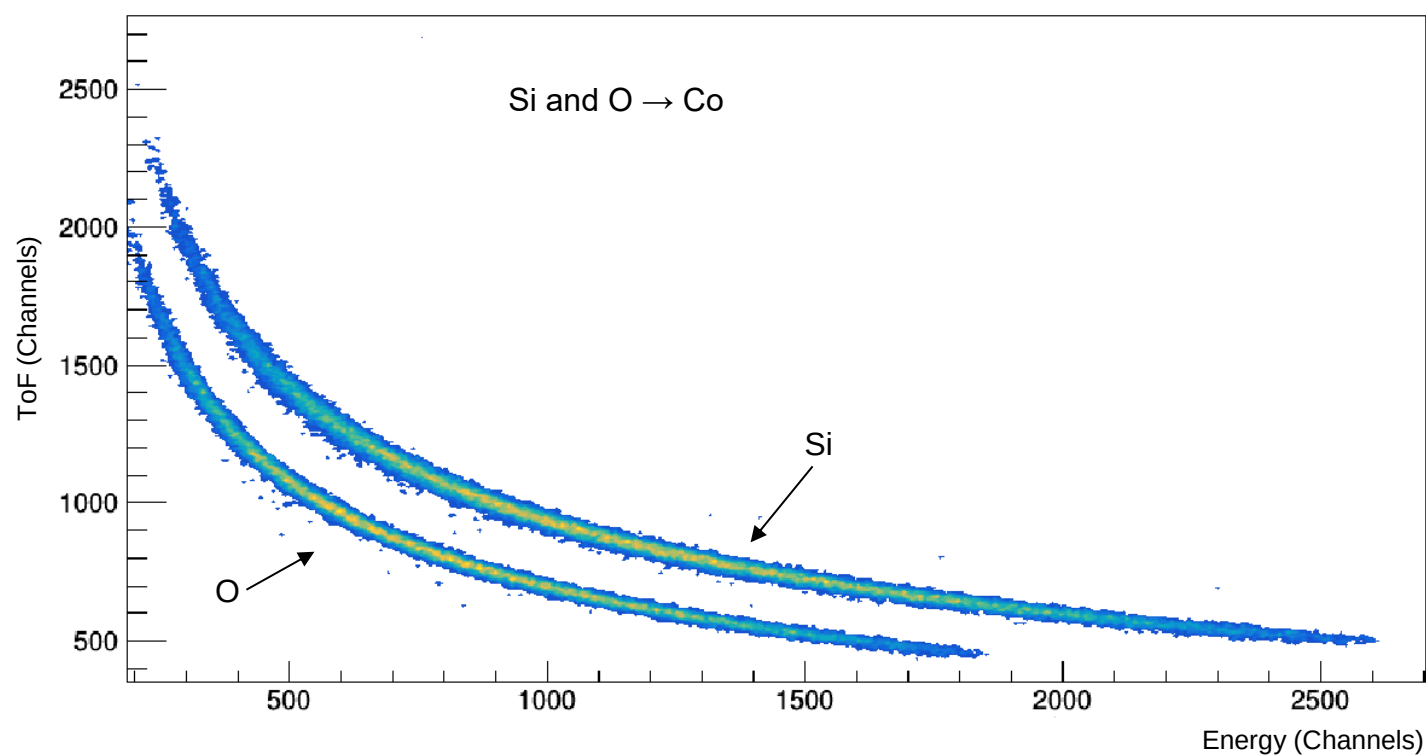
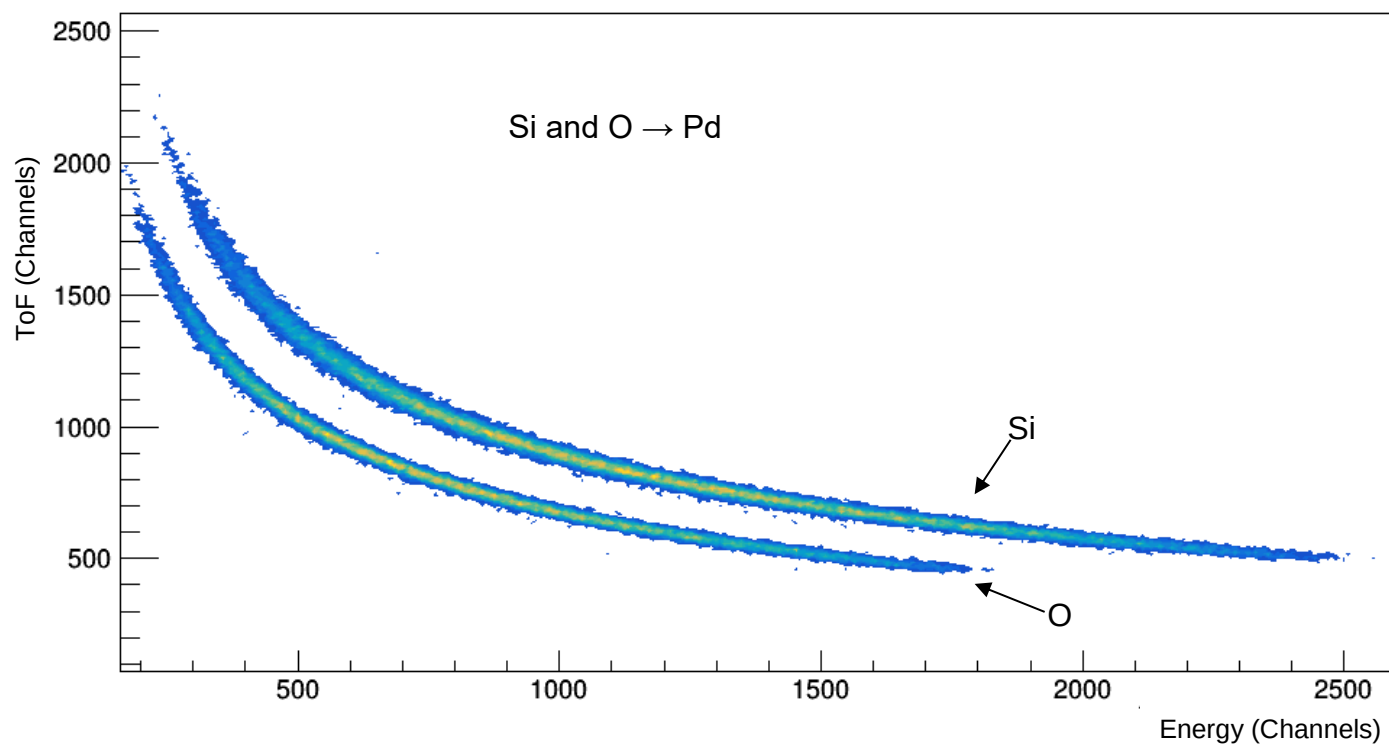
- [19] M. Backman, "Effects of nuclear and electronic stopping power on ion irradiation of silicon-based compounds," Helsinki, 2012.
- [20] E. Rauhala and J. F. Ziegler, "Energy Loss AND Energy Straggling," in *Handbook of Modern Ion Beam Materials Analysis*, Pennsylvania, Materials Research Society, 2009, pp. 5-26.
- [21] International Commission on Radiation Units and Measurements, "Stopping Powers and Ranges for Protons and Alpha Particles," International Commission on Radiation Units and Measurements, Maryland, 1993.
- [22] A. Mozumder and M. Burton, "Encyclopædia Britannica," Encyclopædia Britannica, inc., 14 April 2017. [Online]. Available: <https://www.britannica.com/science/radiation/Stopping-power>. [Accessed 25 May 2020].
- [23] J. F. Ziegler, "The Stopping of Energetic Light Ions in Elemental Matter," *Journal of Applied Physics*, no. 85, pp. 1249-1272, 1999.
- [24] P. Sigmund, *Particle Penetration and Radiation Effects Volume 2: Penetration of atomic and molecular ions*, Springer, 2014.
- [25] P. Sigmund, *Particle Penetration and Radiation effects: General Aspects and Stopping of swift Point Charges*, Springer, 2006.
- [26] A. Guesmia, H. Ammi, S. Mammeri, A. Dib, C. Pineda-Vargas, M. Msimanga and M. Hedibel, "Semi empirical formula for electronic stopping power determination of Mg24, Al 27 and Si28 ions crossing Formvar foil in the ion energy domain of LSS theory," *Radiation Physics and Chemistry*, vol. 96, pp. 205-210, 2014.
- [27] J. Lindhard and M. Scharff, "Energy Dissipation by Ions in the kev Region," *Physical Review*, vol. 124, no. 1, pp. 128-130, 1961.
- [28] P. Sigmund, "LSS and the Integral Equations of Transport Theory," *Physica Scripta*, vol. 28, pp. 257-267, 1983.
- [29] Y. Wang and M. Nastasi, *Handbook of modern Ion Materials Analysis* 2nd edition, Warrendale: Materials Research Society, 2009.
- [30] A. Sharma, A. Fettouhi, A. Schinner and P. Sigmund, "Stopping of Swift Ions in Compounds," *Nuclear Instruments and Methods in Physics Research*, vol. B, no. 218, pp. 19-28, 2004.
- [31] CasP, "CasP," December 2013. [Online]. Available: <http://www.casp-program.org/>. [Accessed 6 June 2020].
- [32] P. Sigmund, "The University of Southern Denmark Research," 18 February 2020. [Online]. Available: <https://www.sdu.dk/en/dpass>. [Accessed 06 June 2020].
- [33] International Commission on Radiation Units and Measurements, "Stopping powers for electrons and positrons," International Commission on Radiation Units and Measurements, Bethesda, Maryland, 1984.
- [34] International commission on Radiological Units and Measurements, "Stopping of Ions Heavier Than Helium," International commission on Radiological Units and Measurements, Maryland, 2005.
- [35] C. C. Montanari and P. Dimitriou, "The IAEA stopping power database, following the trends in stopping power of ions in matter," *Nuclear Instruments and Methods in Physics Research B*, vol. 408, pp. 50-55, 2017.

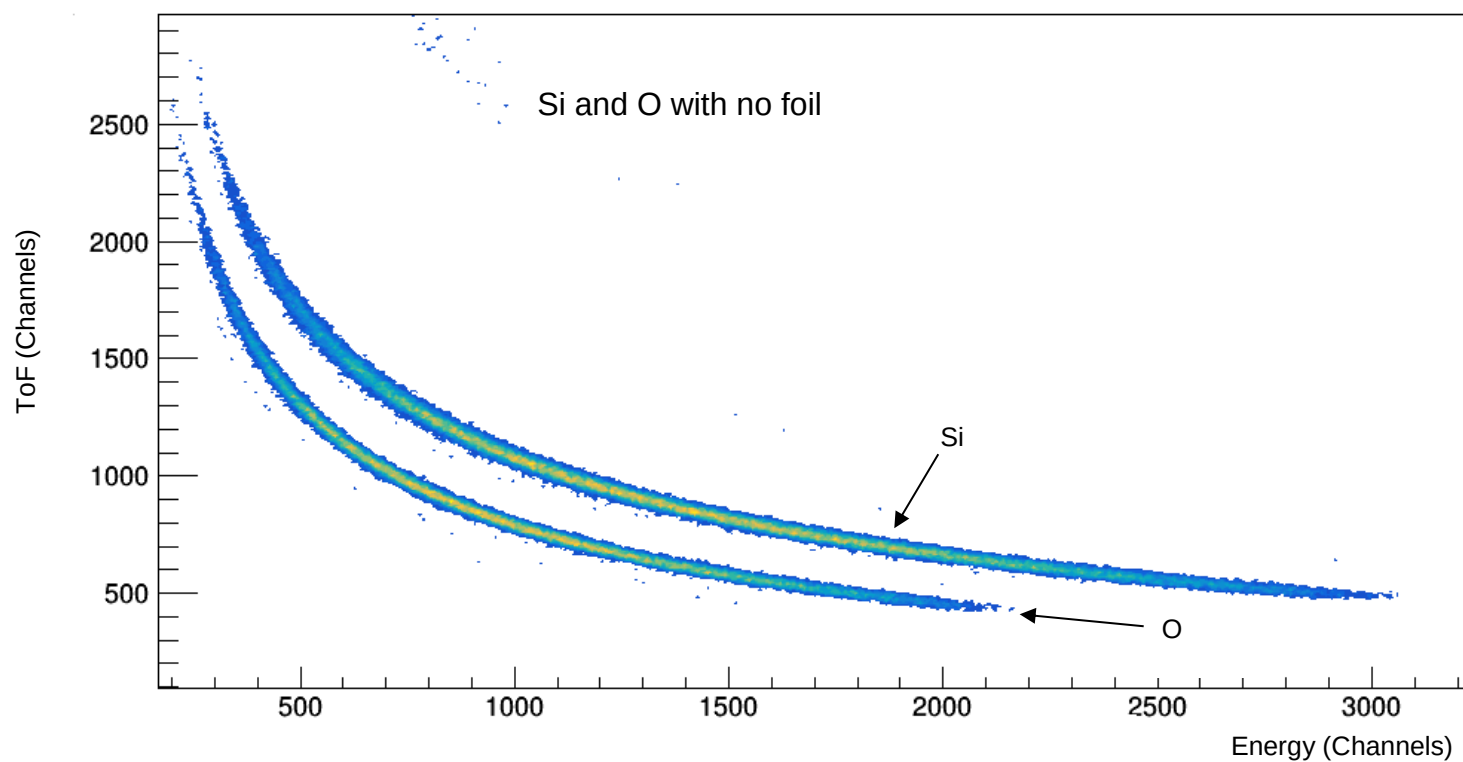
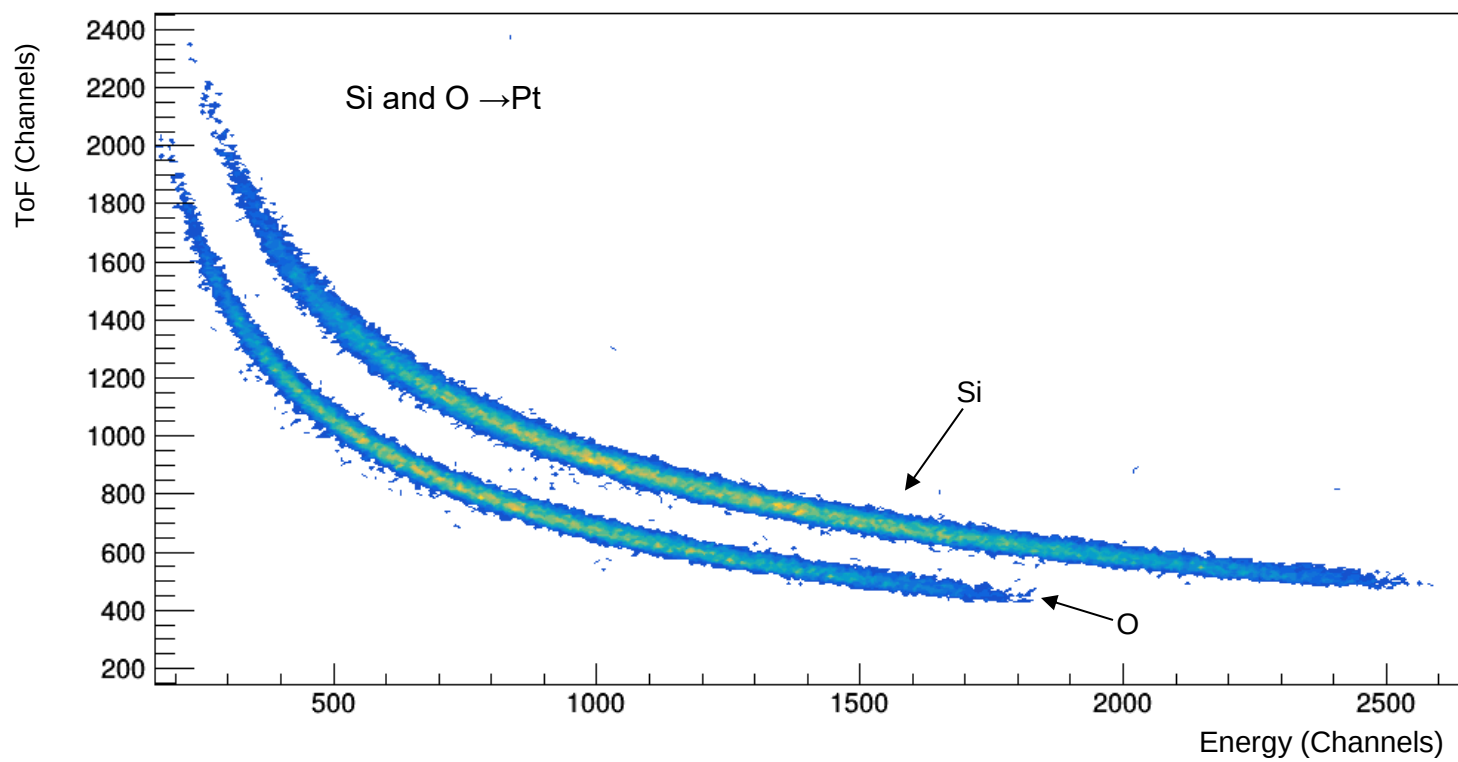
- [36] E. D. Cantero, C. C. Montanari, M. Behar, R. C. Fadanelli, G. H. Lantschner, J. E. Miraglia and N. R. Arista, "Stopping power of Zn for heavy ions," *Journal of Physics: Conference Series*, vol. 388, no. 13, 2009.
- [37] H. Paul, "New results about stopping power for positive ions: Experiment and theory," *AIP Conference Proceedings*, vol. 265, pp. 295-299, 2013.
- [38] R. Liguori Neto, N. Added and F. A. Coutinho, "A new experimental method for precise energy loss measurements," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 161–163, pp. 159-163, 2000.
- [39] H. Timmers, K. Stenstrom, M. Graczyk and H. J. Whitlow, "Energy loss measurements for mass-14 ions using a patterned stopping medium on a PIN diode," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Vols. 219-220, pp. 263-267, 2004.
- [40] R. V. Ribas, N. H. Medina, N. Added, J. R. Oliveira, E. W. Cybulska, M. N. Rao, W. A. Seale, F. Brandolini, M. A. Rizzutto and J. A. Alcántara-Núñez, "Stopping power of Au for silver ions at low velocities," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 211, no. 4, pp. 453-459, 2003.
- [41] M. Bergsmann, P. Hörlsberger, F. Kastner and P. Bauer, "Evaluation of energy loss from DUAL-TOF spectra," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, Vols. 136-138, pp. 1218-1222, 1998.
- [42] W. N. Lennard, H. Xia and J. K. Kim, "Revisiting the stopping powers of Si and SiO₂ for 4He ions: 0.5–2.0 MeV," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 215, pp. 297-307, 2004.
- [43] W. K. Lin, S. Matteson and D. Powers, "α-particle stopping cross section of gold and silver as measured from thick targets," *Phys Rev, B*, vol. 10, pp. 3746-3755, 1974.
- [44] U. Hauser, W. Neuwirth, W. Pietsch and K. Richter, "On the determination of collision cross sections by nuclear Doppler shift," *Zeitschrift für Physik*, vol. 269, no. 2, pp. 181-188, 1974.
- [45] K. ARSTILA, "An experimental method for precise determination of electronic stopping powers for heavy ions," *Nuclear Instrumentation and Methods in Physics Research B*, vol. 168, pp. 473-483, 2000.
- [46] M. Msimanga, Development of a Time of Flight – Energy spectrometer for applications in Heavy Ion – Elastic Recoil Detection thin film analysis, PhD, Cape Town: University of Cape Town, Department of Physics, 2010.
- [47] iThemba LABS, "TAMS-Infrastructure," 24 October 2019. [Online]. Available: <https://tlabs.ac.za/tams/infrastructure/>. [Accessed 15 July 2020].
- [48] LEBOW COMPANY, "Lebow Company Hoame Page," [Online]. Available: <https://lebowcompany.com/>. [Accessed 11 January 2021].
- [49] B. Schmidt and K. Wetzig, *Ion Beams in Materials processing and Analysis*, Springer, 2012.
- [50] F. Pászti and A. Kótai, "Instrumentation for PIXE and RBS," Vienna, 2000.
- [51] V. Peřina and A. Mackova, "Laboratory of Nuclear Analytical Methods," [Online]. Available: http://neutron.ujf.cas.cz/vdg/methods_rbs.html. [Accessed 26 April 2019].

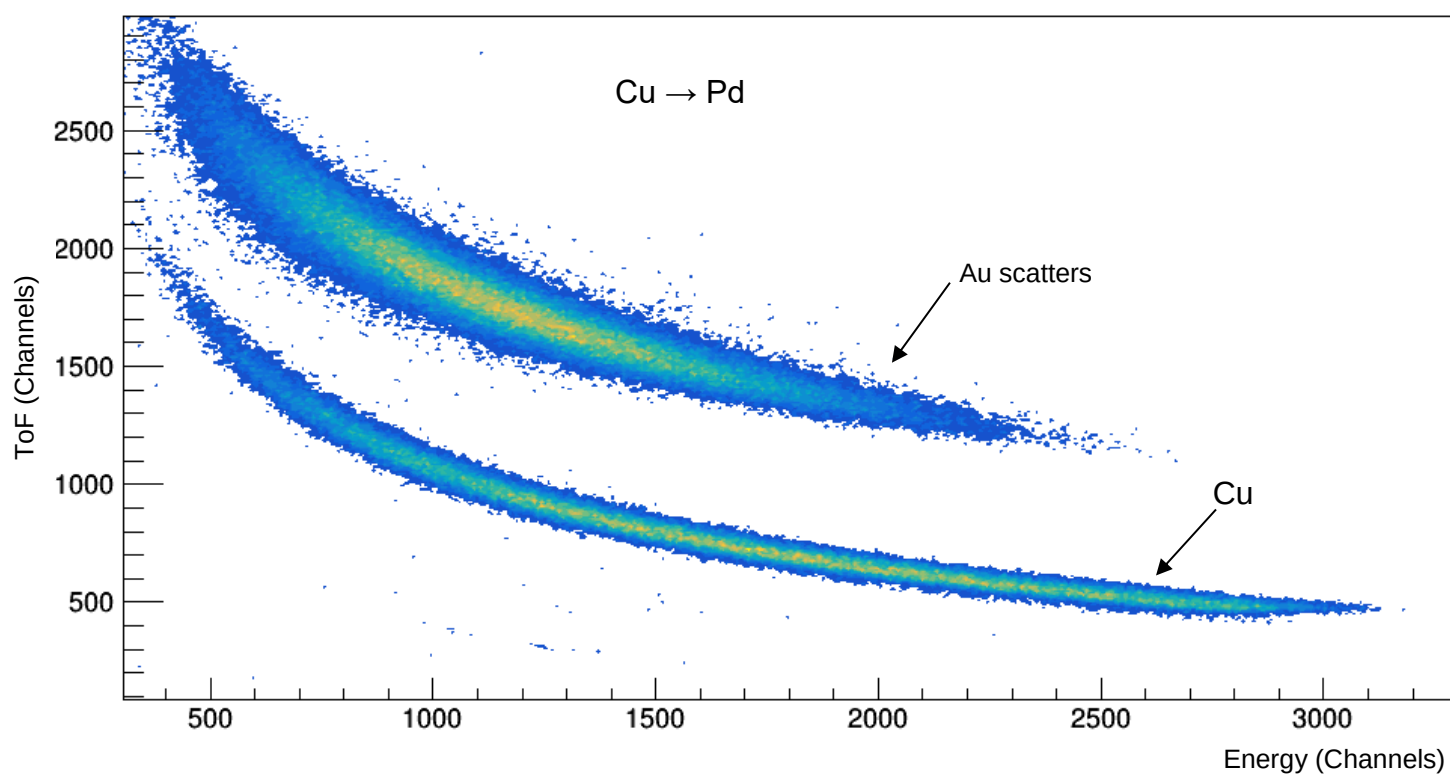
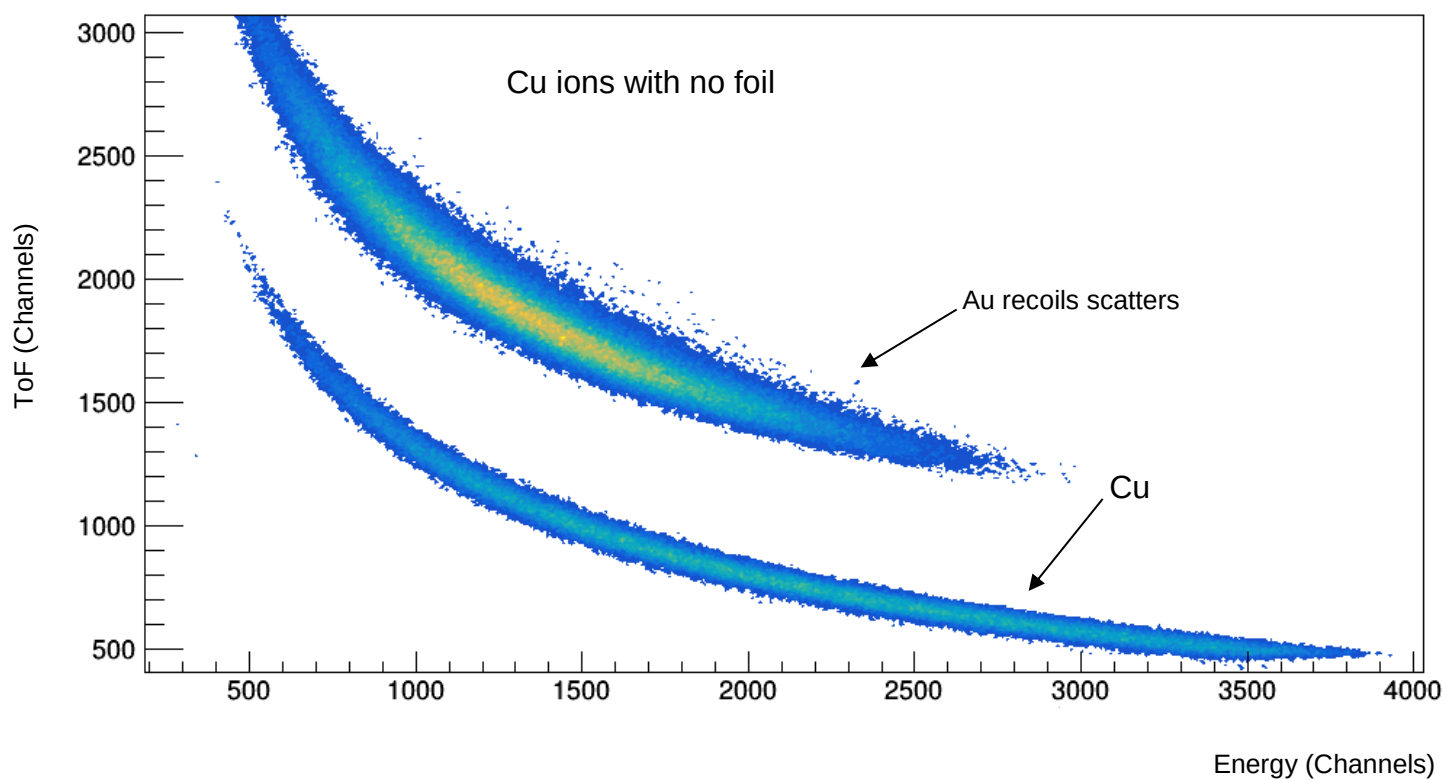
- [52] M. Mayer, "SIMNRA Introduction," 5 November 2020. [Online]. Available: <https://www2.ipp.mpg.de/~mam/>. [Accessed 17 June 2021].
- [53] Max-Planck Innovation, "SIMNRA 7 software," 2019 12 05. [Online]. Available: <https://www.max-planck-innovation.com/technology-offers/technology-offer/simnra-7-software.html>. [Accessed 16 June 2021].
- [54] M. Mayer, SIMNRA User's Guide, Garching: Max-Planck-Institut für Plasmaphysik, 2019.
- [55] R. Hellborg, Electrostatic Accelerators: Fundamentals and applications, Berlin: Springer, 2005.
- [56] M. R. Jana, "Inter-university accelerator center," 2008 August 2014. [Online]. Available: <http://www.iuac.res.in/atmol/~safvan/mridulathesis/node14.html>. [Accessed 11 September 2019].
- [57] L. Lamm, 2008. [Online]. Available: <https://www3.nd.xn.edu>urlsPDF> Ion Sources. [Accessed 09 07 2019].
- [58] National Electronics Corp., [Online]. Available: <http://www.pelletron.com/products/snics/>. [Accessed 09 September 2019].
- [59] V. K. Mittal, R. C. Verma and S. C. Gupta, Introduction to Nuclear and Particle Physics, New Delhi: PHI Learning Private Limited, 2013.
- [60] F. Hinterberger, "CERN Document Server," [Online]. Available: <http://cds.cern.ch/record/1005042/files/p95.pdf>. [Accessed 26 February 2020].
- [61] M. Msimanga, D. Wamwangi, C. M. Comrie, C. A. Pineda-Vargas, M. Nkosi and T. Hlatshwayo, "The New Heavy Ion ERDA Set Up at iThemba LABS Gauteng: Multilayer Thin Film Depth Profiling Using Monte Carlo Simulation Codes," *Nuclear Instruments and Methods in Physics Research B*, vol. 296, pp. 54-60, 2014.
- [62] MIDAS, "MIDAS Main Page," MediaWiki, 08 September 2019. [Online]. Available: https://midas.triumf.ca/MidasWiki/index.php/Main_Page. [Accessed 04 April 2020].
- [63] M. Msimanga, C. M. Comrie, C. A. Pineda-Vargas, S. Murray, R. Bark and G. Dollinger, "A Time of Flight-Energy spectrometer for stopping power measurements in Heavy Ion-ERD analysis at iThemba LABS," *Nuclear Instruments and Methods in Physics Research*, vol. 267, pp. 2671-2674, 2009.
- [64] Y. Uehara, T. Ushiroku, S. Ushioda and Y. Murata, "High Resolution Time-of-Flight Electron Spectrometer," *Japanese Journal of Applied Physics*, vol. 29, no. 12, pp. 2858-2863, 1990.
- [65] J. Bocan, The Development of Time-of-Flight for Elastic Recoil Detection Analysis, MSc, Prague: Czech Technical University, Department of Physics, 2001.
- [66] M. Msimanga, C. Comrie, C. A. Pineda-Vargas and S. Murray, "Experimental stopping powers of Al, Mg, F and O ions in ZrO₂ in the 0.1–0.6 MeV/u energy range," *Nuclear Instruments and Methods in Physics Research B*, vol. 208, pp. 1772-1775, 2010.
- [67] ROOT Team, "About ROOT," 2021. [Online]. Available: <https://root.cern/about/>. [Accessed 2021 December 1].
- [68] J. Ziegler, "SRIM/TRIM Introduction," [Online]. Available: <http://www.srim.org/SRIM/SRIMINTRO.htm>. [Accessed 24 June 2020].

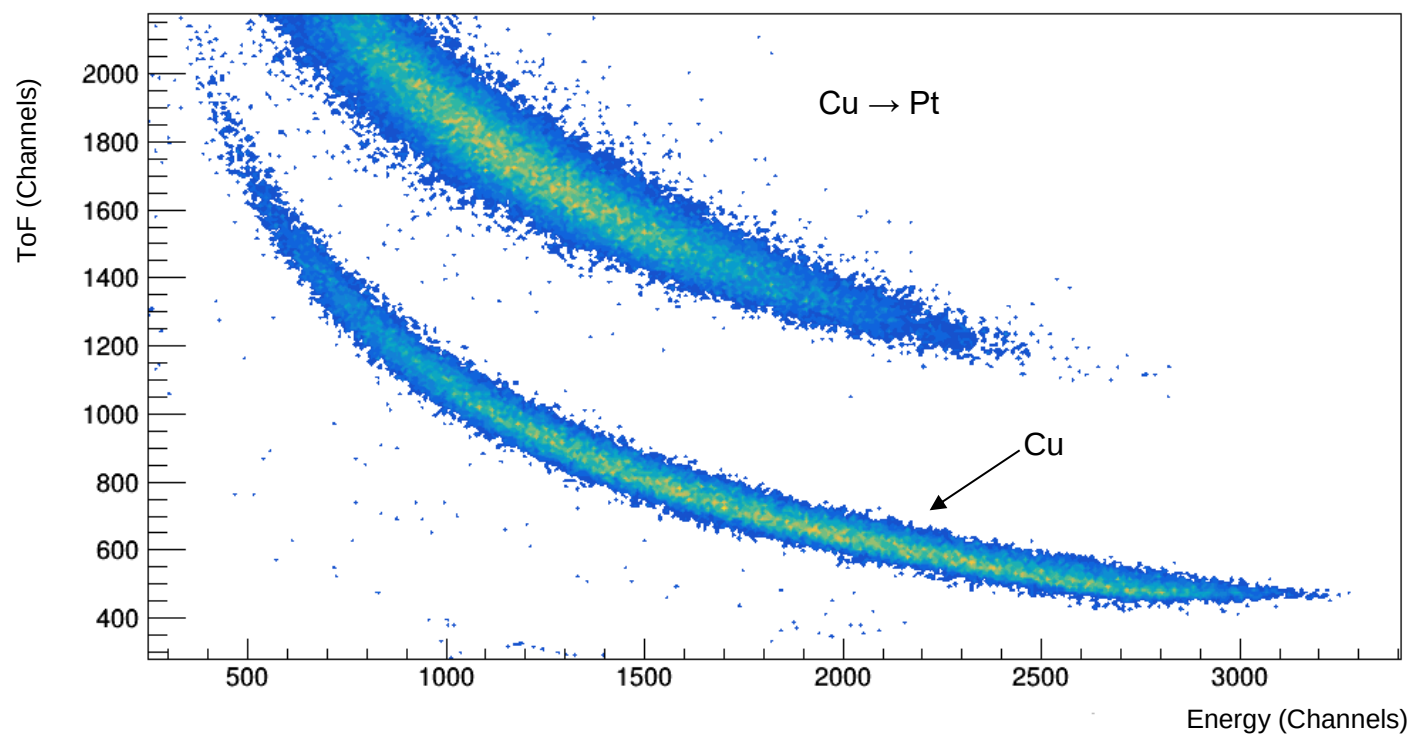
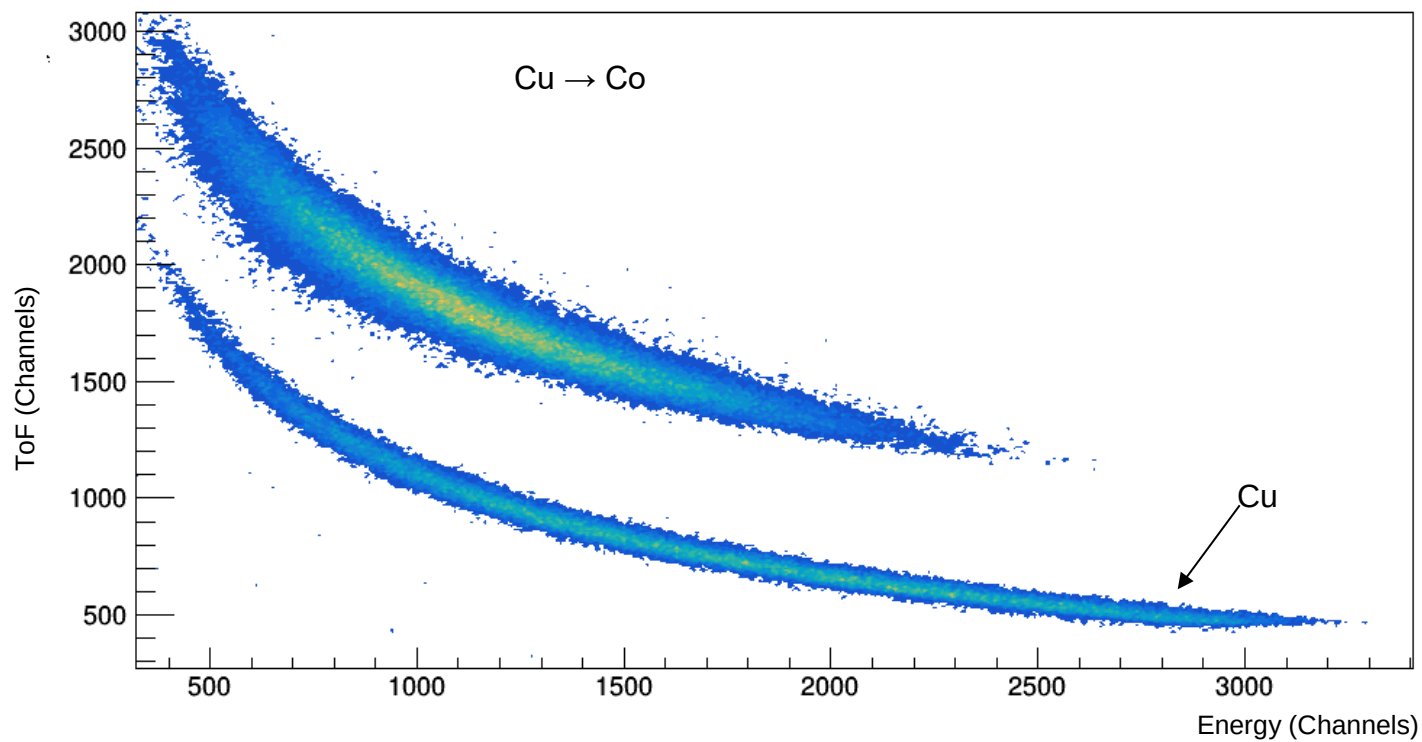
Appendix 1

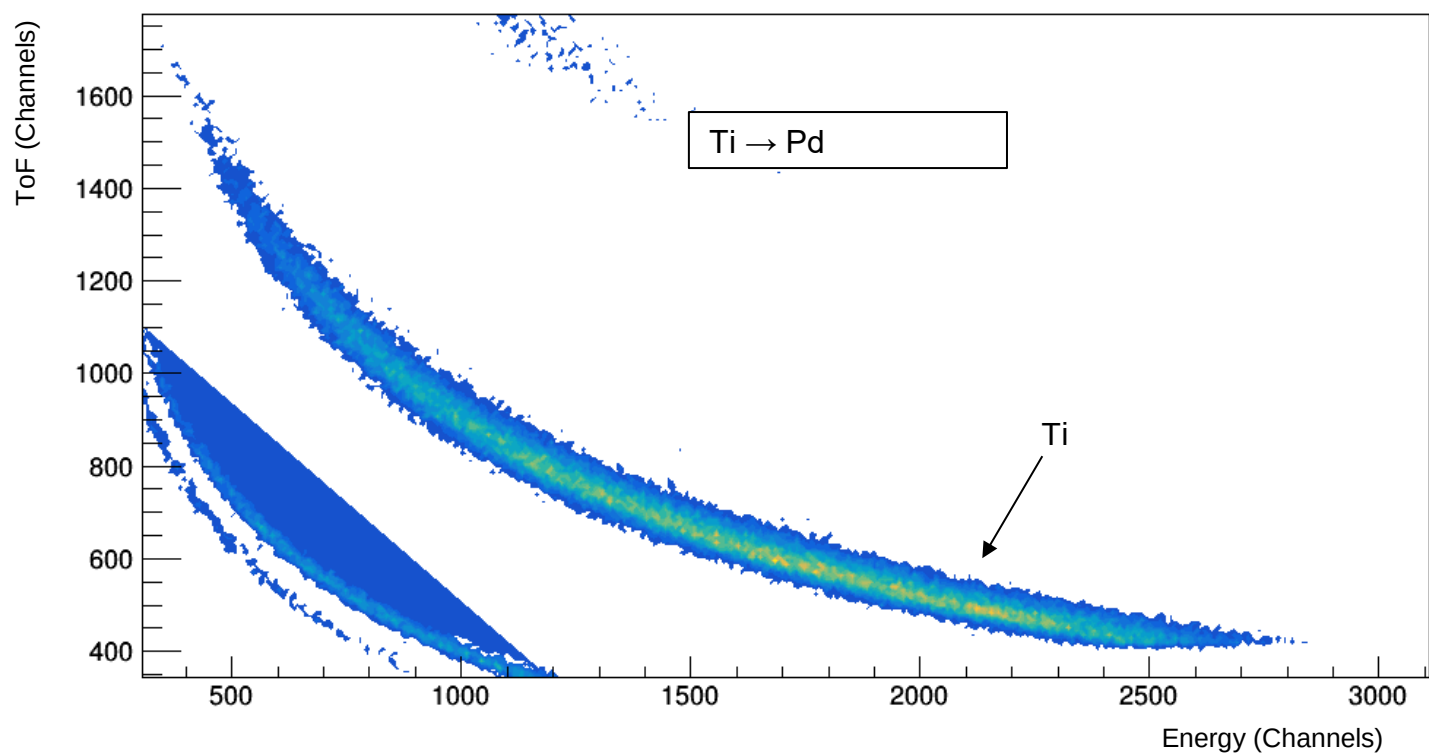
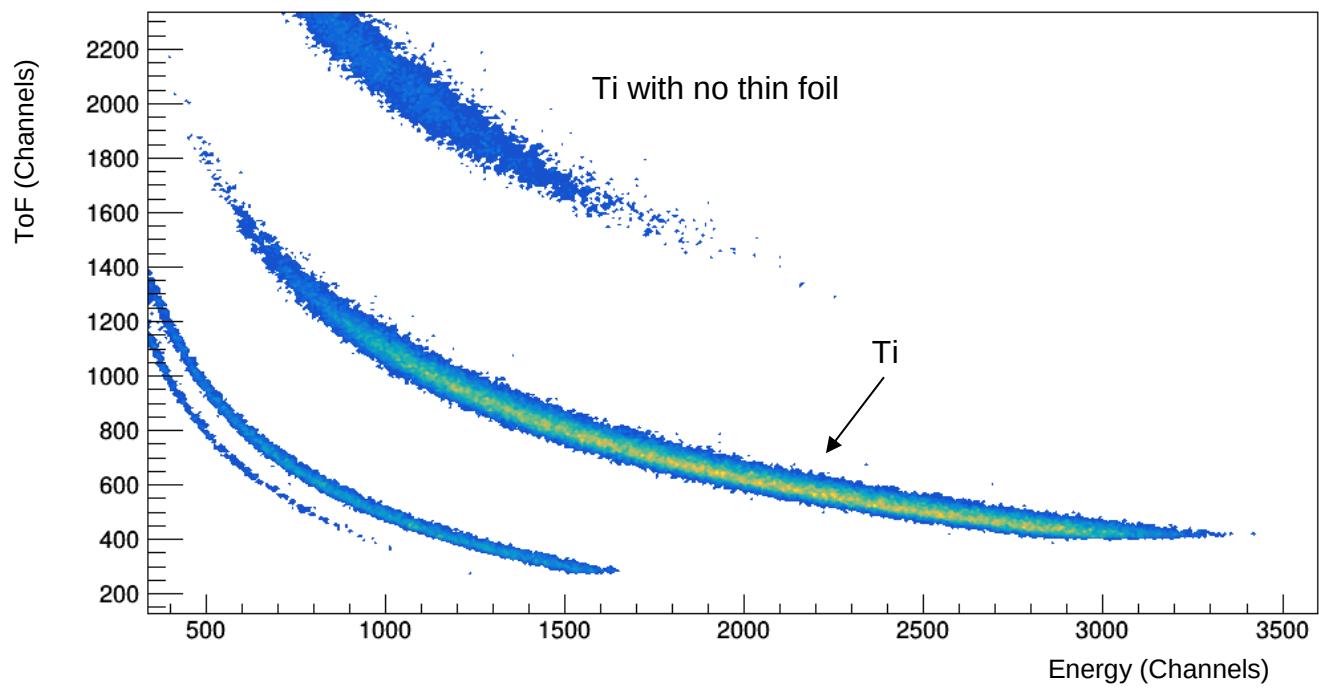
The figures below, in appendix 1, are 2D scatter plots of ToF (Channels) vs Energy (Channels) of all target-ion combinations, together with runs where there was no thin foil.

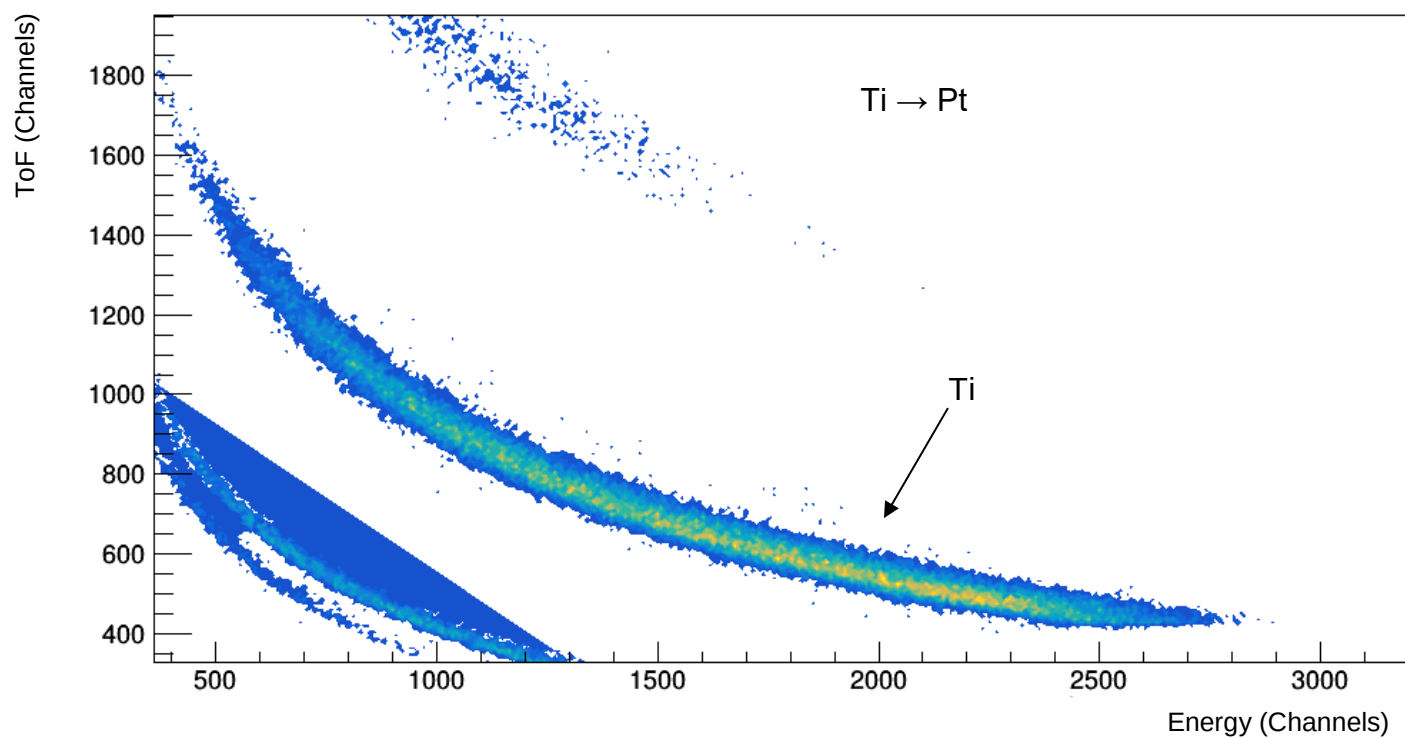
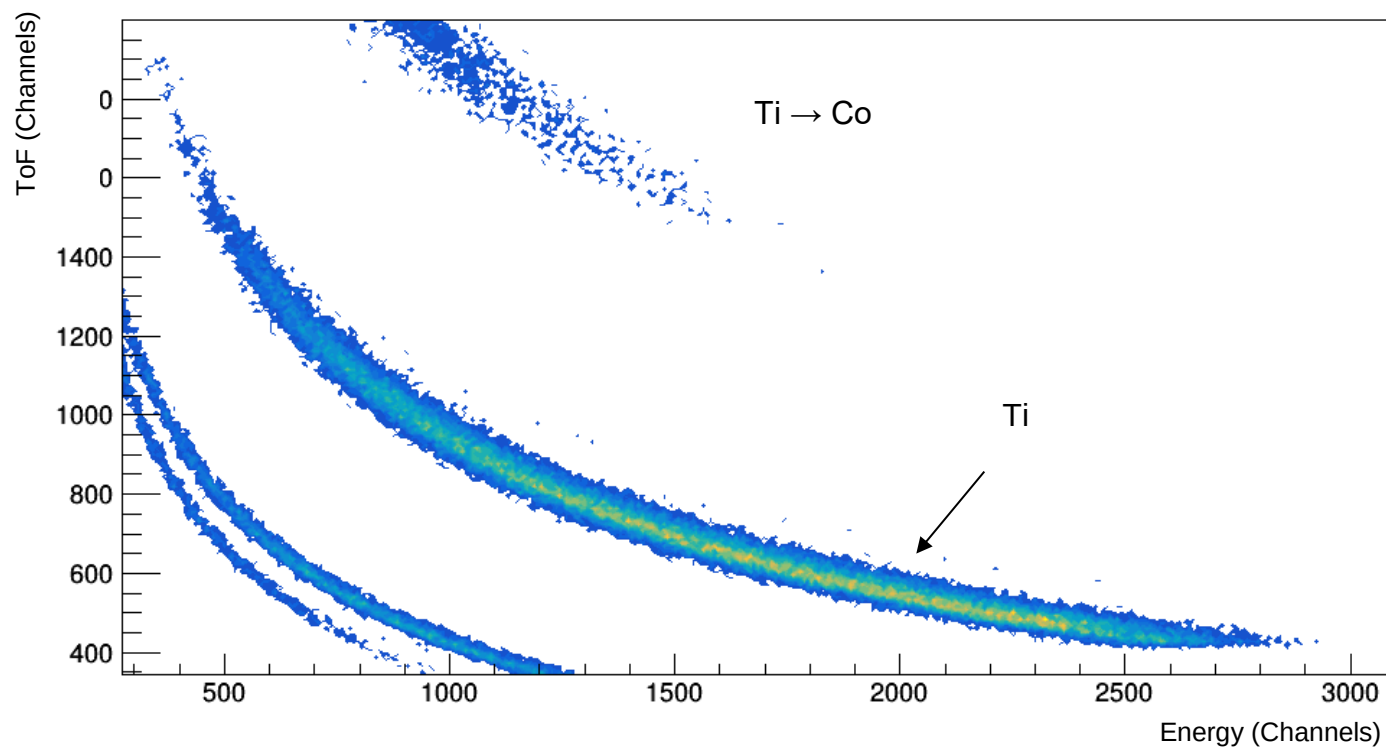












Appendix 2

The tables under appendix 2 show the data analysis of the raw data from the raw 2D scatter plot as explained in section 3.3.5

Data analysis of stopping force of Si in Pt									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (keV)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
62.00	1368.70	1641.66	138.13	161.14	2746.24	2017.91	7.28E+05	2.38	558.87
64.00	1344.91	1607.78	136.12	158.28	2827.76	2091.39	7.36E+05	2.46	565.04
68.00	1297.40	1550.52	132.11	153.45	3001.81	2225.03	7.77E+05	2.61	596.04
70.00	1273.82	1521.64	130.13	151.02	3094.22	2297.35	7.97E+05	2.70	611.46
72.00	1253.73	1493.85	128.43	148.68	3176.36	2370.32	8.06E+05	2.77	618.50
74.00	1232.08	1469.72	126.61	146.64	3268.59	2436.53	8.32E+05	2.85	638.46
76.00	1212.67	1447.27	124.97	144.75	3354.75	2500.66	8.54E+05	2.93	655.36
78.00	1195.00	1425.32	123.48	142.90	3436.17	2565.85	8.70E+05	3.00	667.83
80.00	1178.62	1403.21	122.10	141.03	3514.33	2634.11	8.80E+05	3.07	675.42
84.00	1145.64	1359.30	119.32	137.33	3680.01	2778.02	9.02E+05	3.23	692.12
86.00	1130.12	1340.02	118.01	135.71	3762.05	2844.96	9.17E+05	3.30	703.71
88.00	1115.66	1321.17	116.79	134.12	3840.99	2912.78	9.28E+05	3.38	712.24
90.00	1100.08	1303.10	115.48	132.60	3928.86	2980.09	9.49E+05	3.45	728.02
100.00	1032.43	1219.28	109.78	125.53	4347.67	3325.03	1.02E+06	3.84	784.70
110.00	975.60	1146.43	104.99	119.39	4753.47	3675.90	1.08E+06	4.21	826.85
120.00	924.68	1083.70	100.69	114.10	5167.44	4024.53	1.14E+06	4.60	876.99
130.00	881.45	1029.23	97.05	109.51	5562.80	4369.11	1.19E+06	4.97	915.95
140.00	840.51	979.25	93.60	105.29	5980.63	4725.79	1.25E+06	5.35	962.88
150.00	805.88	937.13	90.68	101.74	6371.91	5061.34	1.31E+06	5.72	1005.64
160.00	773.86	897.01	87.98	98.36	6768.86	5415.41	1.35E+06	6.09	1038.54
170.00	744.31	860.08	85.49	95.25	7169.00	5775.24	1.39E+06	6.47	1069.47
180.00	717.05	828.03	83.19	92.55	7570.54	6117.33	1.45E+06	6.84	1115.09
200.00	669.47	769.71	79.18	87.63	8356.96	6822.95	1.53E+06	7.59	1177.09
220.00	628.68	718.85	75.74	83.34	9133.06	7543.11	1.59E+06	8.34	1220.01
240.00	592.20	676.47	72.67	79.77	9922.42	8233.81	1.69E+06	9.08	1295.72
260.00	560.20	637.33	69.97	76.47	10702.40	8959.73	1.74E+06	9.83	1337.20
280.00	531.35	602.90	67.54	73.57	11486.98	9680.64	1.81E+06	10.58	1386.05
300.00	511.41	571.34	65.86	70.91	12080.74	10420.57	1.66E+06	11.25	1273.89

Data analysis of stopping force of O in Pt									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
62.00	1020.15	1256.71	108.74	128.68	2524.09	1802.40	7.22E+05	2.16	553.77
64.00	1001.43	1230.93	107.16	126.51	2598.97	1864.85	7.34E+05	2.23	563.31
66.00	984.22	1204.28	105.71	124.26	2670.80	1932.89	7.38E+05	2.30	566.22
68.00	967.79	1180.02	104.33	122.22	2742.20	1998.12	7.44E+05	2.37	570.95
70.00	948.58	1156.66	102.71	120.25	2829.35	2064.10	7.65E+05	2.45	587.20
72.00	933.80	1134.20	101.46	118.36	2899.24	2130.67	7.69E+05	2.51	589.75
74.00	918.98	1112.53	100.21	116.53	2972.01	2197.99	7.74E+05	2.59	593.93
76.00	904.94	1091.53	99.03	114.76	3043.48	2266.33	7.77E+05	2.65	596.33
78.00	889.53	1072.97	97.73	113.20	3124.90	2329.41	7.95E+05	2.73	610.40
80.00	875.71	1054.37	96.57	111.63	3200.78	2395.31	8.05E+05	2.80	618.05
82.00	863.82	1038.54	95.56	110.29	3268.26	2453.63	8.15E+05	2.86	625.09
84.00	851.51	1020.97	94.53	108.81	3340.40	2520.88	8.20E+05	2.93	628.84
86.00	839.48	1004.24	93.51	107.40	3413.22	2587.52	8.26E+05	3.00	633.58
88.00	828.24	988.43	92.56	106.07	3483.50	2652.96	8.31E+05	3.07	637.29
90.00	817.09	973.50	91.62	104.81	3555.35	2717.07	8.38E+05	3.14	643.24
100.00	765.97	904.97	87.31	99.03	3914.96	3043.29	8.72E+05	3.48	668.86
110.00	721.22	846.83	83.54	94.13	4276.51	3368.48	9.08E+05	3.82	696.76
120.00	681.46	795.42	80.19	89.80	4641.45	3701.45	9.40E+05	4.17	721.29
130.00	648.40	750.73	77.40	86.03	4981.73	4032.72	9.49E+05	4.51	728.21
140.00	617.87	711.43	74.83	82.72	5330.22	4362.26	9.68E+05	4.85	742.75
150.00	588.28	676.21	72.34	79.75	5704.22	4693.09	1.01E+06	5.20	775.87
160.00	563.34	642.95	70.23	76.94	6050.87	5041.33	1.01E+06	5.55	774.65
170.00	540.35	613.85	68.30	74.49	6399.11	5378.91	1.02E+06	5.89	782.83
180.00	518.11	587.92	66.42	72.31	6765.50	5709.02	1.06E+06	6.24	810.67
200.00	483.68	541.46	63.52	68.39	7397.84	6381.60	1.02E+06	6.89	779.79

Data analysis of stopping force of Cu in Pt									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
102.00	1221.36	1471.75	140.64	162.75	5993.34	4475.58	1.52E+06	5.23	1164.61
104.00	1208.97	1453.69	139.55	161.16	6087.68	4564.59	1.52E+06	5.33	1168.70
106.00	1195.43	1436.41	138.35	159.63	6193.35	4652.27	1.54E+06	5.42	1182.50
108.00	1181.71	1421.07	137.14	158.28	6303.25	4732.24	1.57E+06	5.52	1205.48
110.00	1164.89	1404.02	135.66	156.77	6442.03	4823.57	1.62E+06	5.63	1241.88
112.00	1151.34	1403.89	134.46	156.76	6557.19	4824.27	1.73E+06	5.69	1329.71
114.00	1136.05	1372.78	133.11	154.01	6690.88	4997.90	1.69E+06	5.84	1299.06
116.00	1122.04	1357.79	131.87	152.69	6817.00	5084.93	1.73E+06	5.95	1329.06
118.00	1108.33	1341.40	130.66	151.24	6943.91	5182.71	1.76E+06	6.06	1351.41
120.00	1096.41	1328.07	129.61	150.06	7057.15	5264.33	1.79E+06	6.16	1375.67
130.00	1040.26	1259.28	124.65	143.99	7629.71	5717.84	1.91E+06	6.67	1467.02
140.00	990.13	1198.74	120.22	138.64	8201.85	6167.27	2.03E+06	7.18	1561.18
150.00	942.84	1145.93	116.05	133.98	8802.72	6604.03	2.20E+06	7.70	1687.11
160.00	900.40	1095.84	112.30	129.56	9400.04	7062.63	2.34E+06	8.23	1793.55
170.00	861.34	1051.60	108.85	125.65	10005.09	7508.59	2.50E+06	8.76	1915.62
180.00	825.30	1009.99	105.67	121.98	10616.95	7967.75	2.65E+06	9.29	2032.79
190.00	791.82	970.77	102.71	118.52	11236.82	8440.18	2.80E+06	9.84	2145.93
200.00	762.40	936.27	100.12	115.47	11827.55	8891.46	2.94E+06	10.36	2252.92
250.00	640.24	792.50	89.33	102.77	14856.45	11223.69	3.63E+06	13.04	2787.50
300.00	546.34	683.92	81.04	93.19	18051.90	13652.07	4.40E+06	15.85	3376.09
350.00	484.92	600.69	75.61	85.84	20734.28	16089.95	4.64E+06	18.41	3563.70

Data analysis of stopping force of Ti in Pt									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
92.00	1124.42	1330.17	132.08	150.25	5118.68	3955.65	1.16E+06	4.54	892.42
94.00	1110.10	1313.24	130.82	148.76	5218.11	4035.56	1.18E+06	4.63	907.40
96.00	1095.21	1293.49	129.50	147.01	5324.61	4131.87	1.19E+06	4.73	915.21
98.00	1080.93	1275.40	128.24	145.41	5429.83	4223.15	1.21E+06	4.83	925.91
100.00	1066.96	1257.84	127.01	143.86	5535.81	4314.67	1.22E+06	4.93	937.01
110.00	997.20	1176.05	120.85	136.64	6114.51	4782.82	1.33E+06	5.45	1021.84
120.00	943.25	1109.24	116.08	130.74	6626.72	5224.18	1.40E+06	5.93	1076.20
130.00	890.71	1049.20	111.45	125.44	7189.88	5675.09	1.51E+06	6.43	1162.33
140.00	846.45	991.39	107.54	120.34	7721.90	6166.78	1.56E+06	6.94	1193.28
150.00	804.90	942.85	103.87	116.05	8277.17	6630.72	1.65E+06	7.45	1263.36
160.00	765.83	897.62	100.42	112.06	8855.67	7111.76	1.74E+06	7.98	1338.14
170.00	734.49	854.68	97.65	108.26	9364.68	7618.67	1.75E+06	8.49	1339.75
180.00	702.39	818.99	94.82	105.11	9932.96	8082.35	1.85E+06	9.01	1420.02
190.00	672.71	782.31	92.20	101.87	10505.65	8604.44	1.90E+06	9.56	1458.85
200.00	646.31	751.16	89.87	99.12	11057.63	9088.52	1.97E+06	10.07	1510.94
250.00	535.87	619.91	80.11	87.53	13913.61	11654.52	2.26E+06	12.78	1733.46
300.00	461.37	523.30	73.53	79.00	16514.48	14307.31	2.21E+06	15.41	1693.61

Data analysis of stopping force of Si in Co									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (kev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
62.00	1366.79	1641.66	137.96	161.14	2752.65	2017.91	7.35E+05	2.39	443.50
64.00	1344.30	1607.78	136.07	158.28	2829.90	2091.39	7.39E+05	2.46	445.77
66.00	1321.83	1578.38	134.17	155.80	2910.36	2158.45	7.52E+05	2.53	453.86
68.00	1299.36	1550.52	132.28	153.45	2994.31	2225.03	7.69E+05	2.61	464.34
70.00	1277.03	1521.64	130.40	151.02	3081.39	2297.35	7.84E+05	2.69	473.25
72.00	1257.72	1493.85	128.77	148.68	3159.79	2370.32	7.89E+05	2.77	476.53
74.00	1238.14	1469.72	127.12	146.64	3242.38	2436.53	8.06E+05	2.84	486.41
76.00	1220.34	1447.27	125.62	144.75	3320.30	2500.66	8.20E+05	2.91	494.74
78.00	1201.94	1425.32	124.07	142.90	3403.84	2565.85	8.38E+05	2.98	505.82
80.00	1185.24	1403.21	122.66	141.03	3482.42	2634.11	8.48E+05	3.06	512.04
82.00	1169.08	1379.63	121.30	139.05	3561.08	2709.96	8.51E+05	3.14	513.74
84.00	1153.12	1359.30	119.95	137.33	3641.42	2778.02	8.63E+05	3.21	521.15
86.00	1138.33	1340.02	118.71	135.71	3718.31	2844.96	8.73E+05	3.28	527.16
88.00	1124.44	1321.17	117.53	134.12	3792.77	2912.78	8.80E+05	3.35	531.16
90.00	1109.43	1303.10	116.27	132.60	3875.77	2980.09	8.96E+05	3.43	540.64
100.00	1042.65	1219.28	110.64	125.53	4280.22	3325.03	9.55E+05	3.80	576.56
110.00	987.10	1146.43	105.96	119.39	4666.96	3675.90	9.91E+05	4.17	598.20
120.00	938.42	1083.70	101.85	114.10	5050.55	4024.53	1.03E+06	4.54	619.31
130.00	894.57	1029.23	98.16	109.51	5438.14	4369.11	1.07E+06	4.90	645.27
140.00	856.23	979.25	94.92	105.29	5814.78	4725.79	1.09E+06	5.27	657.32
150.00	820.94	937.13	91.95	101.74	6197.10	5061.34	1.14E+06	5.63	685.55
160.00	788.07	897.01	89.18	98.36	6588.21	5415.41	1.17E+06	6.00	707.91
170.00	759.18	860.08	86.74	95.25	6963.29	5775.24	1.19E+06	6.37	717.11
180.00	732.84	828.03	84.52	92.55	7334.07	6117.33	1.22E+06	6.73	734.44
200.00	684.09	769.71	80.41	87.63	8102.75	6822.95	1.28E+06	7.46	772.50
220.00	643.76	718.85	77.01	83.34	8833.99	7543.11	1.29E+06	8.19	779.18
240.00	607.07	676.47	73.92	79.77	9588.68	8233.81	1.35E+06	8.91	817.80
260.00	573.73	637.33	71.11	76.47	10361.65	8959.73	1.40E+06	9.66	846.21
280.00	546.50	602.90	68.81	73.57	11064.66	9680.64	1.38E+06	10.37	835.40
300.00	521.20	571.34	66.68	70.91	11783.64	10420.57	1.36E+06	11.10	822.75

Data analysis of stopping force of O in Co									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
62.00	1041.34	1256.71	110.53	128.68	2443.16	1802.40	6.41E+05	2.12	386.77
64.00	1027.71	1230.93	109.38	126.51	2494.76	1864.85	6.30E+05	2.18	380.21
66.00	1003.37	1204.28	107.33	124.26	2591.07	1932.89	6.58E+05	2.26	397.28
68.00	987.43	1180.02	105.98	122.22	2657.19	1998.12	6.59E+05	2.33	397.82
72.00	955.16	1134.20	103.26	118.36	2799.02	2130.67	6.68E+05	2.46	403.42
76.00	926.11	1091.53	100.81	114.76	2936.68	2266.33	6.70E+05	2.60	404.63
78.00	911.45	1072.97	99.58	113.20	3009.98	2329.41	6.81E+05	2.67	410.79
80.00	897.05	1054.37	98.37	111.63	3084.73	2395.31	6.89E+05	2.74	416.14
82.00	884.06	1038.54	97.27	110.29	3154.59	2453.63	7.01E+05	2.80	423.10
84.00	870.57	1020.97	96.13	108.81	3229.67	2520.88	7.09E+05	2.88	427.83
86.00	858.57	1004.24	95.12	107.40	3298.76	2587.52	7.11E+05	2.94	429.31
88.00	847.08	988.43	94.15	106.07	3366.94	2652.96	7.14E+05	3.01	430.96
90.00	834.97	973.50	93.13	104.81	3441.19	2717.07	7.24E+05	3.08	437.09
100.00	784.03	904.97	88.84	99.03	3781.89	3043.29	7.39E+05	3.41	445.82
110.00	738.73	846.83	85.02	94.13	4129.31	3368.48	7.61E+05	3.75	459.24
120.00	699.27	795.42	81.69	89.80	4472.37	3701.45	7.71E+05	4.09	465.33
130.00	664.02	750.73	78.72	86.03	4816.38	4032.72	7.84E+05	4.42	473.02
140.00	631.78	711.43	76.00	82.72	5167.00	4362.26	8.05E+05	4.76	485.74
150.00	603.62	676.21	73.63	79.75	5505.60	4693.09	8.13E+05	5.10	490.43
160.00	577.95	642.95	71.47	76.94	5844.04	5041.33	8.03E+05	5.44	484.52
170.00	554.56	613.85	69.49	74.49	6180.37	5378.91	8.01E+05	5.78	483.77
180.00	531.69	587.92	67.57	72.31	6538.13	5709.02	8.29E+05	6.12	500.45
200.00	492.44	541.46	64.26	68.39	7228.91	6381.60	8.47E+05	6.81	511.44

Data analysis of stopping force of Cu in Co									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
92.00	1313.83	1568.53	148.81	171.30	5353.67	4040.16	1.31E+06	4.70	792.84
94.00	1296.73	1546.94	147.30	169.39	5463.99	4131.61	1.33E+06	4.80	804.23
96.00	1278.61	1526.34	145.70	167.57	5584.66	4221.80	1.36E+06	4.90	822.63
100.00	1246.03	1490.63	142.82	164.42	5811.91	4385.28	1.43E+06	5.10	861.12
102.00	1231.63	1471.75	141.55	162.75	5916.79	4475.58	1.44E+06	5.20	869.92
104.00	1215.63	1453.69	140.14	161.16	6036.69	4564.59	1.47E+06	5.30	888.57
106.00	1201.46	1436.41	138.88	159.63	6145.95	4652.27	1.49E+06	5.40	901.59
108.00	1187.59	1421.07	137.66	158.28	6255.80	4732.24	1.52E+06	5.49	919.63
110.00	1172.94	1404.02	136.37	156.77	6375.05	4823.57	1.55E+06	5.60	936.48
114.00	1147.59	1372.78	134.13	154.01	6589.60	4997.90	1.59E+06	5.79	960.76
116.00	1134.21	1357.79	132.95	152.69	6707.24	5084.93	1.62E+06	5.90	979.24
118.00	1123.64	1341.40	132.01	151.24	6802.42	5182.71	1.62E+06	5.99	977.66
120.00	1110.51	1328.07	130.85	150.06	6923.49	5264.33	1.66E+06	6.09	1001.48
130.00	1052.83	1259.28	125.76	143.99	7495.63	5717.84	1.78E+06	6.61	1073.08
140.00	1003.22	1198.74	121.38	138.64	8046.42	6167.27	1.88E+06	7.11	1134.27
150.00	956.28	1145.93	117.24	133.98	8625.38	6604.03	2.02E+06	7.61	1220.10
160.00	914.34	1095.84	113.53	129.56	9197.30	7062.63	2.13E+06	8.13	1288.50
170.00	877.35	1051.60	110.27	125.65	9750.34	7508.59	2.24E+06	8.63	1353.13
180.00	841.57	1009.99	107.11	121.98	10334.01	7967.75	2.37E+06	9.15	1428.29
190.00	810.34	970.77	104.35	118.52	10887.33	8440.18	2.45E+06	9.66	1477.11
200.00	778.60	936.27	101.55	115.47	11496.55	8891.46	2.61E+06	10.19	1572.44
250.00	656.09	792.50	90.73	102.77	14401.45	11223.69	3.18E+06	12.81	1918.11
300.00	561.62	683.92	82.39	93.19	17465.48	13652.07	3.81E+06	15.56	2301.80
350.00	493.01	600.69	76.33	85.84	20348.24	16089.95	4.26E+06	18.22	2570.32

Data analysis of stopping force of Ti in Co									
E (bin)	ToFi (Ch)	ToFe (Ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
82.00	1211.56	1441.16	139.78	160.05	4570.65	3486.05	1.08E+06	4.03	654.67
84.00	1192.30	1419.03	138.08	158.10	4683.93	3572.76	1.11E+06	4.13	670.71
86.00	1176.87	1394.29	136.71	155.91	4777.75	3673.58	1.10E+06	4.23	666.49
88.00	1161.11	1370.89	135.32	153.85	4876.53	3772.92	1.10E+06	4.32	666.14
90.00	1146.82	1349.32	134.06	151.94	4968.76	3868.10	1.10E+06	4.42	664.36
92.00	1131.64	1330.17	132.72	150.25	5069.63	3955.65	1.11E+06	4.51	672.40
94.00	1115.58	1313.24	131.30	148.76	5179.72	4035.56	1.14E+06	4.61	690.62
96.00	1100.16	1293.49	129.94	147.01	5288.84	4131.87	1.16E+06	4.71	698.36
98.00	1084.48	1275.40	128.56	145.41	5403.38	4223.15	1.18E+06	4.81	712.40
100.00	1070.43	1257.84	127.31	143.86	5509.20	4314.67	1.19E+06	4.91	721.02
110.00	1007.45	1176.05	121.75	136.64	6023.96	4782.82	1.24E+06	5.40	749.16
120.00	949.96	1109.24	116.68	130.74	6559.54	5224.18	1.34E+06	5.89	806.03
130.00	897.36	1049.20	112.03	125.44	7114.65	5675.09	1.44E+06	6.39	868.93
140.00	851.68	991.39	108.00	120.34	7656.04	6166.78	1.49E+06	6.91	898.93
150.00	810.35	942.85	104.35	116.05	8200.91	6630.72	1.57E+06	7.42	947.77
160.00	773.25	897.62	101.07	112.06	8741.20	7111.76	1.63E+06	7.93	983.54
170.00	740.73	854.68	98.20	108.26	9259.76	7618.67	1.64E+06	8.44	990.56
180.00	707.76	818.99	95.29	105.11	9834.33	8082.35	1.75E+06	8.96	1057.51
190.00	679.46	782.31	92.79	101.87	10371.16	8604.44	1.77E+06	9.49	1066.41
200.00	651.38	751.16	90.31	99.12	10948.32	9088.52	1.86E+06	10.02	1122.58
250.00	543.13	619.91	80.75	87.53	13693.41	11654.52	2.04E+06	12.67	1230.68
300.00	463.62	523.30	73.73	79.00	16425.28	14307.31	2.12E+06	15.37	1278.42
320.00	436.15	490.88	71.31	76.14	17562.03	15403.30	2.16E+06	16.48	1303.02

Data analysis of stopping force of Si in Pd									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
62.00	1308.81	1641.15	133.08	161.09	2958.57	2018.98	9.40E+05	2.49	616.75
64.00	1286.68	1607.87	131.21	158.29	3043.30	2091.19	9.52E+05	2.57	624.97
66.00	1264.97	1581.51	129.38	156.07	3130.00	2151.16	9.79E+05	2.64	642.52
68.00	1246.39	1549.86	127.81	153.40	3207.19	2226.64	9.81E+05	2.72	643.64
70.00	1223.78	1521.67	125.91	151.02	3305.02	2297.27	1.01E+06	2.80	661.50
72.00	1203.73	1493.78	124.22	148.67	3395.58	2370.51	1.03E+06	2.88	672.87
74.00	1184.55	1470.05	122.60	146.67	3485.73	2435.61	1.05E+06	2.96	689.31
76.00	1167.60	1447.23	121.17	144.75	3568.42	2500.78	1.07E+06	3.03	700.81
78.00	1150.30	1424.99	119.71	142.87	3655.89	2566.84	1.09E+06	3.11	714.86
80.00	1134.61	1403.10	118.39	141.03	3738.04	2634.46	1.10E+06	3.19	724.40
85.00	1095.97	1349.04	115.13	136.47	3952.54	2813.35	1.14E+06	3.38	747.78
90.00	1060.57	1303.10	112.15	132.60	4165.69	2980.09	1.19E+06	3.57	778.24
95.00	1027.98	1258.60	109.40	128.84	4377.53	3156.15	1.22E+06	3.77	801.73
100.00	998.38	1219.28	106.91	125.53	4584.25	3325.03	1.26E+06	3.95	826.57
105.00	971.17	1182.22	104.61	122.41	4787.50	3496.92	1.29E+06	4.14	847.15
110.00	946.20	1146.02	102.51	119.35	4986.17	3678.03	1.31E+06	4.33	858.67
115.00	921.09	1114.64	100.39	116.71	5198.65	3846.66	1.35E+06	4.52	887.46
120.00	897.69	1083.70	98.42	114.10	5409.07	4024.53	1.38E+06	4.72	908.83
140.00	821.18	979.25	91.97	105.29	6194.42	4725.79	1.47E+06	5.46	964.03
160.00	756.73	896.88	86.54	98.35	6996.57	5416.66	1.58E+06	6.21	1037.07
180.00	704.77	828.05	82.16	92.55	7762.53	6117.06	1.65E+06	6.94	1080.10
200.00	658.65	769.68	78.27	87.63	8553.01	6823.35	1.73E+06	7.69	1135.36
250.00	570.07	655.94	70.80	78.04	10452.11	8603.02	1.85E+06	9.53	1213.76

Data analysis of stopping force of O in Pd									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
42.00	1240.07	1624.70	127.28	159.71	1842.34	1170.20	6.721E+05	1.51	441.20
44.00	1209.97	1578.85	124.74	155.84	1918.06	1228.97	6.891E+05	1.57	452.33
46.00	1180.63	1530.13	122.27	151.73	1996.44	1296.40	7.000E+05	1.65	459.51
48.00	1152.67	1487.94	119.91	148.18	2075.70	1359.38	7.163E+05	1.72	470.20
50.00	1126.53	1452.52	117.71	145.19	2154.14	1415.87	7.383E+05	1.79	484.61
52.00	1101.57	1413.45	115.61	141.90	2233.27	1482.36	7.509E+05	1.86	492.91
54.00	1078.79	1377.40	113.69	138.86	2309.35	1547.95	7.614E+05	1.93	499.79
56.00	1057.47	1344.09	111.89	136.05	2384.14	1612.51	7.716E+05	2.00	506.51
58.00	1036.98	1312.21	110.16	133.36	2459.49	1678.15	7.813E+05	2.07	512.88
60.00	1018.03	1283.01	108.56	130.90	2532.40	1741.86	7.905E+05	2.14	518.92
65.00	973.32	1218.68	104.80	125.48	2717.83	1895.67	8.222E+05	2.31	539.67
70.00	934.55	1156.66	101.53	120.25	2895.65	2064.10	8.316E+05	2.48	545.84
75.00	898.31	1102.22	98.47	115.66	3078.12	2231.15	8.470E+05	2.65	555.96
80.00	866.24	1054.35	95.77	111.63	3254.32	2395.39	8.589E+05	2.82	563.81
100.00	759.76	904.83	86.79	99.02	3962.28	3044.01	9.183E+05	3.50	602.76
120.00	679.19	795.42	80.00	89.80	4663.69	3701.45	9.622E+05	4.18	631.62
140.00	615.74	711.41	74.65	82.72	5355.97	4362.40	9.936E+05	4.86	652.19
160.00	563.61	642.94	70.26	76.94	6046.88	5041.45	1.005E+06	5.54	659.97
180.00	520.52	587.89	66.62	72.30	6724.32	5709.39	1.015E+06	6.22	666.21
200.00	483.92	541.35	63.54	68.38	7393.27	6383.42	1.010E+06	6.89	662.87

Data analysis of stopping force of Cu in Pd									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
72.00	1480.87	1819.45	163.56	193.45	4431.62	3167.72	1.26E+06	3.80	829.64
74.00	1455.99	1790.51	161.36	190.90	4553.11	3253.09	1.30E+06	3.90	853.34
76.00	1433.69	1765.04	159.39	188.65	4666.30	3331.12	1.34E+06	4.00	876.43
78.00	1411.11	1736.06	157.40	186.09	4785.27	3423.36	1.36E+06	4.10	893.97
80.00	1390.93	1709.24	155.62	183.72	4895.49	3512.19	1.38E+06	4.20	908.01
82.00	1369.60	1682.27	153.73	181.34	5016.17	3605.04	1.41E+06	4.31	926.28
84.00	1350.61	1657.45	152.05	179.15	5127.42	3693.78	1.43E+06	4.41	941.05
86.00	1331.57	1635.54	150.37	177.21	5242.71	3774.87	1.47E+06	4.51	963.50
88.00	1312.78	1613.18	148.71	175.24	5360.35	3860.41	1.50E+06	4.61	984.57
90.00	1294.79	1590.80	147.13	173.26	5476.72	3948.98	1.53E+06	4.71	1002.83
95.00	1252.40	1538.36	143.38	168.63	5766.40	4168.82	1.60E+06	4.97	1048.66
100.00	1212.09	1490.63	139.82	164.42	6063.72	4385.28	1.68E+06	5.22	1101.74
105.00	1173.34	1445.12	136.40	160.40	6371.75	4607.76	1.76E+06	5.49	1157.90
110.00	1139.72	1404.02	133.43	156.77	6658.42	4823.57	1.83E+06	5.74	1204.42
115.00	1107.79	1365.14	130.61	153.34	6948.98	5041.97	1.91E+06	6.00	1251.78
120.00	1075.30	1328.07	127.74	150.06	7264.60	5264.33	2.00E+06	6.26	1313.00
125.00	1048.27	1292.73	125.36	146.94	7543.86	5490.29	2.05E+06	6.52	1347.98
130.00	1021.89	1259.28	123.03	143.99	7832.23	5717.84	2.11E+06	6.78	1387.90
140.00	969.22	1198.74	118.38	138.64	8459.76	6167.27	2.29E+06	7.31	1504.81
150.00	925.15	1145.93	114.49	133.98	9044.54	6604.03	2.44E+06	7.82	1601.97
160.00	883.49	1095.84	110.81	129.56	9655.02	7062.63	2.59E+06	8.36	1701.67
170.00	848.63	1051.59	107.73	125.65	10214.66	7508.70	2.71E+06	8.86	1776.22
180.00	813.82	1009.99	104.66	121.98	10823.45	7967.75	2.86E+06	9.40	1874.51
190.00	783.24	970.77	101.96	118.52	11404.44	8440.18	2.96E+06	9.92	1945.77
200.00	753.54	936.27	99.33	115.47	12014.61	8891.46	3.12E+06	10.45	2050.06
250.00	634.86	792.50	88.85	102.77	15015.77	11223.69	3.79E+06	13.12	2489.16
300.00	547.15	683.92	81.11	93.19	18020.16	13652.07	4.37E+06	15.84	2867.26
350.00	486.31	600.69	75.74	85.84	20667.23	16089.95	4.58E+06	18.38	3004.57

Data analysis of stopping force of Ti in Pd									
E (bin)	ToFi (ch)	ToFe (ch)	ToFi (ns)	ToFe (ns)	Ei (kev)	Ee (Kev)	ΔE (ev)	Eav (MeV)	[S]
			equation 4.2		equation 3.8		Ei-Ee	Ei+Ee/2	$\Delta E/X$
72.00	1260.23	1571.30	144.07	171.54	4302.04	3034.64	1.27E+06	3.67	831.93
74.00	1239.51	1541.79	142.24	168.94	4413.42	3128.98	1.28E+06	3.77	843.12
76.00	1218.97	1511.96	140.43	166.30	4528.15	3228.88	1.30E+06	3.88	852.86
78.00	1197.20	1490.75	138.51	164.43	4654.71	3302.85	1.35E+06	3.98	887.37
80.00	1178.82	1461.53	136.89	161.85	4765.74	3409.00	1.36E+06	4.09	890.58
82.00	1164.46	1441.16	135.62	160.05	4855.28	3486.05	1.37E+06	4.17	898.77
84.00	1147.97	1419.03	134.16	158.10	4961.24	3572.76	1.39E+06	4.27	911.41
86.00	1130.60	1394.29	132.63	155.91	5076.65	3673.58	1.40E+06	4.38	920.99
88.00	1116.13	1370.89	131.35	153.85	5175.89	3772.92	1.40E+06	4.47	920.93
90.00	1100.25	1349.32	129.95	151.94	5288.20	3868.10	1.42E+06	4.58	932.17
92.00	1084.40	1330.17	128.55	150.25	5403.97	3955.65	1.45E+06	4.68	950.69
94.00	1069.76	1313.24	127.26	148.76	5514.32	4035.56	1.48E+06	4.77	970.68
96.00	1055.97	1293.49	126.04	147.01	5621.39	4131.87	1.49E+06	4.88	977.73
98.00	1041.49	1275.40	124.76	145.41	5737.20	4223.15	1.51E+06	4.98	993.84
100.00	1026.92	1257.84	123.47	143.86	5857.38	4314.67	1.54E+06	5.09	1012.65
110.00	964.87	1176.05	117.99	136.64	6414.01	4782.82	1.63E+06	5.60	1070.73
120.00	910.61	1109.24	113.20	130.74	6968.35	5224.18	1.74E+06	6.10	1144.89
130.00	862.32	1049.20	108.94	125.44	7524.58	5675.09	1.85E+06	6.60	1214.03
140.00	817.83	991.39	105.01	120.34	8098.08	6166.78	1.93E+06	7.13	1267.73
150.00	778.74	942.85	101.56	116.05	8657.92	6630.72	2.03E+06	7.64	1330.68
160.00	742.88	897.62	98.39	112.06	9224.07	7111.76	2.11E+06	8.17	1386.55
170.00	709.70	854.68	95.46	108.26	9799.00	7618.67	2.18E+06	8.71	1431.19
180.00	679.53	818.99	92.80	105.11	10369.60	8082.35	2.29E+06	9.23	1501.38
190.00	651.40	782.31	90.31	101.87	10947.91	8604.44	2.34E+06	9.78	1538.28
200.00	625.47	751.16	88.03	99.12	11524.78	9088.52	2.44E+06	10.31	1599.19
250.00	518.24	619.91	78.56	87.53	14470.32	11654.52	2.82E+06	13.06	1848.32
300.00	444.19	523.30	72.02	79.00	17217.41	14307.31	2.91E+06	15.76	1910.22

Appendix 3

The figures below show the Variation of the $[S]_{\text{theory}}/[S]_{\text{experiment}}$ ratio of different predictive models. The $[S]_{\text{theory}}/[S]_{\text{experiment}}$ is an indication of the general predictive accuracy of each model.

