Electronic Stopping Force of ^{16}O and ^{28}Si Heavy Ions in Tantalum Nitride by Time of Flight Spectroscopy

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Abstract. Accurate stopping force data of energetic ions in matter is important not just in the study of fundamental ion-matter interactions but also in practical applications that depend on particle-matter interactions. The work presented here describes the measurement of energy loss of heavy ions (O and Si) through a thin metallic film (TaN) using a Time of Flight – Energy spectrometer (ToF-E). Energy loss measurements are then used to calculate the stopping force. It is shown from the results, that the experimental and theoretical stopping force show the same trend of variation with energy, although there is a clear discrepancy between the experimental and theoretical data. The difference between the experimental results and theory is explained in terms of possible ion-atom interaction mechanisms.

1. Introduction

Knowledge of stopping force in matter is important for applications that are dependent on ion transport in matter. These applications include ion beam materials analysis, materials modification and ion implantation, ionization radiation dosimetry and tumour suppression in medicine, and validation of theoretical and experimental data [1, 2, 3, 4].

Electronic stopping force of ions in matter has been studied extensively over the years [5, 6, 7]. Although a lot of research on light ion ($Z<3$) stopping has been done in this field, not much work has been done on heavy ions [1, 8]. This has led to the need for further research in the stopping of heavy ions in matter, especially in the Bragg peak region, where the maximum stopping force lies. The Bragg peak region is of special importance in ion beam analysis work, because it corresponds to the energy region in which most measurements are carried out. This work presents measurements carried out to determine energy lost by an ion beam while moving through a thin film by using a Time of Flight – spectrometer and a silicon surface barrier detector (SBD). The energy lost and the thickness of the film were used to calculate the stopping force of heavy ions through the film.

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2. Stopping Force

When an ion beam penetrates solid matter, a series of collisions occur between the incident ions and the atoms' nuclei and/or electrons of the target material. Once the ion beam enters the target material, energy and momentum is transferred from the projectiles to the target material [1, 5, 9]. The projectiles interact with the target nuclei or electrons in one of two general mechanisms at a time: nuclear energy loss or electronic energy loss [9]. Nuclear energy loss is dominant for low energy heavy ions (stopping force in the eV/Å range) [9]. Nuclear energy losses occur due to elastic collisions where energy is imparted from the projectile to the target atom by momentum transfer [10]. Electronic energy loss is dominant for light ions at any energy and high energy heavy ions (stopping force in the KeV/Å range) [9]. Electronic energy loss occurs due to inelastic scattering, where the electrons of the projectile interact with the electrons of the target atom [10].

Energetic ions penetrating a material collide with target atoms, thus losing a fraction of their energy with each and every successive collision. The ions will eventually lose all their energy and come to a complete stop [9]. The stopping force is defined as the rate at which ions lose energy in a target material and is given by dE/dx [5].

3. Experimental Method

Figure 1 is a schematic of the experimental set up used in this work. The incident ion beam, bombards a suitable target sample film that contains elements of interest. The incident beam ejects or recoils target atoms of different masses and energies, from the target sample, and some travel towards the detector system. In other instances, depending on the mass of the target atoms, some of the incident ions are forward scattered towards the detector system. Energy lost by each detected projectile that passes through the target foil as shown in Fig 1, is measured with the aid of a Time of Flight (ToF) spectrometer and a silicon Surface Barrier Detector (SBD). The ToF spectrometer measures the energy of the particle *before* it enters the stopping foil. After passing through the foil, the particle comes to a complete stop in the SBD energy detector where it deposits all of its residual energy. The particle's residual energy is measured by the SBD.

The energy lost, ΔE, is given by:

$$\Delta E = E_1 - E_2 \qquad [1]$$

Where E_1 is the energy of the projectile before interaction with the foil (measured by the ToF spectrometer) and E_2 is the energy of the projectile after passing through the foil (tagged by the SBD).

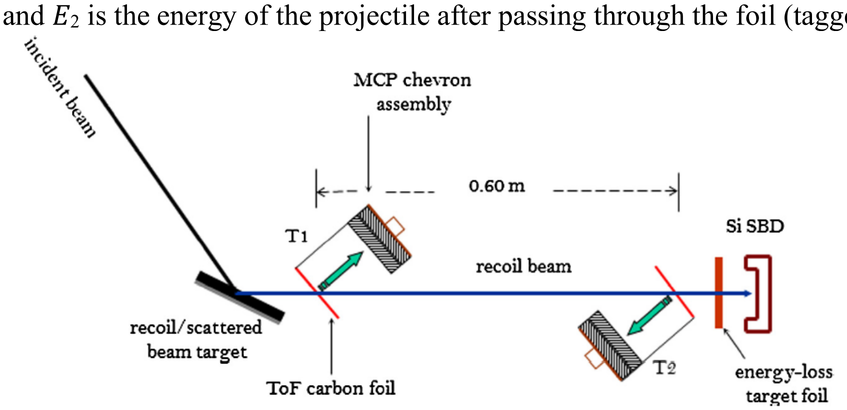

***Figure 1**: schematic representation of the experimental setup [7]*

The ToF spectrometer is an energy spectrometer that uses two detectors, to measure the time of flight of the particle of choice. Both detectors should be transparent and not alter the energy and/or trajectory of the particle of interest [13, 14]. Knowing the distance between the two detectors ($l = 0.6$

m), the ToF of the projectile particle of interest (t_1), and the mass of the projectile (m), the incident energy (E_1) of the particle is then given by the non-relativistic formula:

$$E_1 = \frac{m}{2}\left\{\frac{l}{t_1}\right\}^2 \qquad [2]$$

Due to the known non-linearities of silicon SBDs in the detection of heavy charged particles, the ToF spectrometer is 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 stopper 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 stopper foil in place – from which the incident energy E_1 and the residual energy E_2 are obtained, respectively. Equation 1 then becomes

$$\Delta E = \frac{m}{2}\left\{\left(\frac{l}{t_1}\right)^2 - \left(\frac{l}{t_2}\right)^2\right\} \qquad [3],$$

And the stopping force, the energy loss per unit depth, is given by

$$S = \frac{\Delta E}{\Delta x} \qquad [4],$$

Where Δx is the thickness of the target foil.

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 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 [6]. Figure 2 is an example showing results from a measurement set up where the target sample was a film of Al_2O_3 [11]. Two measurement runs, with and without a stopper foil were carried out and the coincidence measurement of the ToF and Energy for each detected particle generated the 2-D ToF vs Energy scatter plot shown. From this plot, projections on to the ToF axis gave t_1 and t_2 values used in Eq. 3, for both ^{27}Al and ^{16}O species.

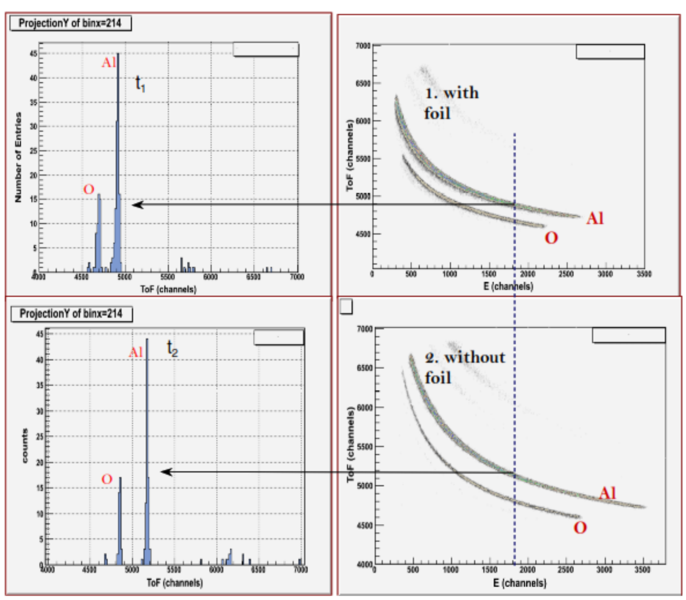

Figure 2. An example of raw data from measurements carried out with and without a stopper foil. The projections show ToF slices used to calculate energy before and after the Al ion passes through the foil

4. Results and Discussion

In this work the initial energy of the projectile was 26 MeV Cu^{7+}, and the target was a thick quartz (SiO_2) sample, from which recoils of ^{28}Si and ^{16}O were obtained. The stopper foil consisted of a thin film of TaN on a Si_3N_4 backing membrane. The energy loss measured, E_1-E_2, was therefore across the entire foil. In order to calculate stopping force across the TaN film, it was important to use the stopping force (S_M) of the backing membrane for ^{28}Si and ^{16}O ions, to account for the energy loss in the membrane. For this work, previous experimental data was used for the stopping force of Si_3N_4 for ^{28}Si and ^{16}O ions [7]

Correcting for energy loss in the Si_3N_4, the stopping force (S_F) in the TaN was then given by:

$$S_F = \frac{E_1 - (S_M \times \Delta x_M + E_2)}{\Delta x_F}$$

Where Δx_F is the thickness of the film of interest and Δx_M is the thickness of the backing membrane.

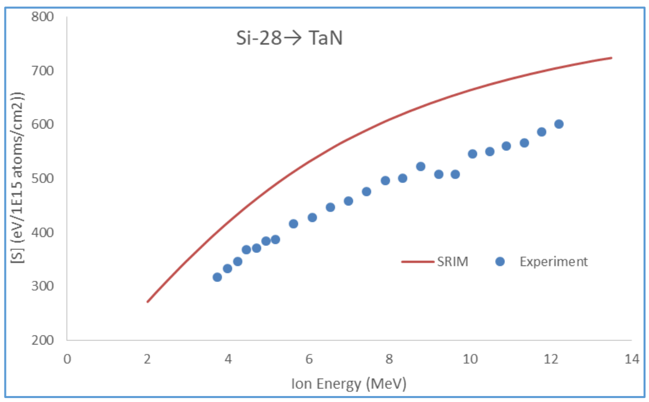

Figure 3

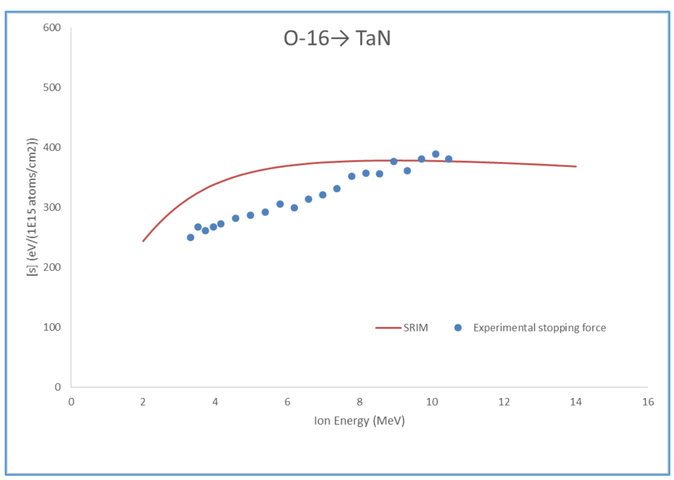

Figure 4

Figures 3 and 4 show the stopping force of Silicon and oxygen across a wide range of energies. Experimental data is compared to predictions of the semi-empirical code *Stopping and Range of Ions in Matter* (SRIM) [5]. Both plots show that SRIM overestimates experimental data around the Bragg peak region. The deviation between the experimental and theoretical data is about 24% for ^{28}Si in TaN and 22% for ^{16}O in TaN. This may be due to a lack of experimental data for the O-TaN and Si-TaN collision systems and/or a lack of proper accounting for charge-exchange of the projectile ion as it traverses the target. Incidentally no other experimental data could be found in the literature for these collision systems.

5. Conclusion

The electronic stopping force of silicon and oxygen in TaN have been determined as described above. The measurement method and data analysis procedure facilitate spanning a wide range of energies in one measurement run. Results obtained show clear discrepancies between experiment and theory and point to a need for more measurements to validate our data for further testing of theoretical predictions.

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References

[1] R. Miksova, V. Hnatowicz, A. Mackova, P. Malinsky and P. Selpicka, "The Stopping power and Energy Straggling of Heavy Ions In Silicone," *Nuclear Instruments and Methods in Physics Research B,* vol. 354, pp. 205-209, 2015.

[2] R. Mikšová, V. Hnatowicz, A. Macková, P. Malinsky and P. Slepicˇka, "The stopping power and energy straggling of heavy ions in silicon nitride," *struments and Methods in Physics Research B,* vol. 354, pp. 205-209, 2015.

[3] R. Hellborg, H. J. Whitlow and Y. Zhang, Ion Beam in Nanoscienc and Technology, Heidelberg: Springer, 2009.

[4] R. C. Brundle, C. A. Evans, Jr and S. Wilson, ENCYCLOPEDIA OF MLATERIALS CHARACTERIZATION, Greenwich: Manning Publications Co, 1992.

[5] 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.

[6] M. Msimanga, C. Pineda-Vargas, T. Hlatshwayo, C. Comrie, H. Ammi and M. Nkosi, "Electronic stopping force of C^12, Si^28 and Cu^63 in HfO2 and SiO2 dielectric films," *Nuclear Instruments and Methods in Physics Research B ,* no. 322, pp. 54-58, 2014.

[7] 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.

[8] M. Mayer, SIMNRA User's Guide, Garching: Max-Planck-Institut für Plasmaphysik, 1997.

[9] D. Fink and L. T. Chadderton, "Ion-Solid Interaction: Status and Perspectives," *Brazilan Journal of Physics,* vol. 35, no. 3B, pp. 735-740, 2005.

[10] L. A. Giannuzzi, B. I. Prenitzer and B. W. Kempshall, ION - Solid Interactions, Hillsboro: Nanospective inc, 200.

[11] M. Msimanga, Development of a Time of Flight – Energy spectrometer for applications in Heavy Ion – Elastic Recoil Detection thin film analysis, Cape Town, 2010.