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A Time of Flight–Energy spectrometer for stopping power measurements in Heavy Ion–ERD analysis at iThemba LABS

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ABSTRACT

The quantitative analysis of thin layers using Heavy Ion–Elastic Recoil Detection (HI–ERD) can be reliably performed if the stopping powers of the probing ions and recoils in a given target matrix are known accurately. Unfortunately for many projectile/target combinations experimental data is limited and where available, deviations of up to 50% between experiment and theory have been reported. This presentation describes the assembly of a Time of Flight–Energy (*ToF–E*) detector system developed for HI–ERD analysis and adapted for stopping power measurements at iThemba LABS. First results from energy loss measurements of 0.1–0.5 MeV/nucleon ^{28}Si and ^{84}Kr ions in ZrO_2 are presented and compared with predictions of the widely used SRIM2003 (Stopping Range of Ions in Matter).

1. Introduction

Accurate and quantitative depth analysis of thin layers using Heavy Ion–Elastic Recoil Detection Analysis (HI–ERDA) requires that among other factors, the stopping powers of the probing ions and recoils in a given target matrix be known accurately [1]. Most of the available experimental stopping power data is for light ions, particularly hydrogen and helium, in elemental targets [2]. For a vast range of elements as well as compound targets, experiment and theory agree quite well for these light ions. Data on compound targets and heavier ions is, however, limited [3–6] and where available, deviations of up to 50% between experiment and semi-empirical predictions have been reported. More experimental data is needed to validate and improve current theories and predictive models.

A Time of Flight–Energy (*ToF–E*) spectrometer has been recently developed and assembled for HI–ERD analysis and further adapted for stopping power measurements at iThemba LABS. This article gives a brief description of the set up of the spectrometer and a sample of results from first measurements of stopping powers of ^{28}Si and ^{84}Kr ions in the oxide ceramic ZrO_2.

2. Experimental

2.1. The ToF–E detector system

The HI–ERDA set up at iThemba LABS is installed on a beam line connected to a solid-pole injector cyclotron (SPC2), where a range of low energy ($\leqslant$0.34 MeV/nucleon) light and Heavy Ions is available. The *ToF–E* spectrometer consists of a Time of Flight detector, built from two timing detectors, T1 and T2, a *flight* distance of 0.584 m apart and a silicon surface barrier detector (SBD) positioned 6.5 cm behind the second time detector for energy measurement. The configuration of the spectrometer, sitting at an angle of 30° to the incident beam direction, is illustrated in the schematic in Fig. 1. Each timing detector consists of a 9.0 μg cm^{-2} thin carbon foil placed about 5 cm from a microchannel plate (MCP) chevron configuration. Each foil is mounted on a steel frame with a circular aperture of 8 mm in diameter. Recoil and/or scattered ions passing through the carbon foil eject electrons from the foil and an electric field, which was applied between the carbon foil and a grid, accelerates and guides the electrons to the MCP assembly where the electron signal is multiplied to give a fast (<1.0 ns rise time) timing signal. A particle passing through the

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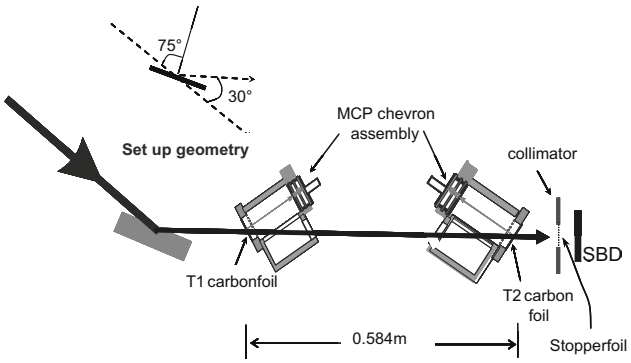

Fig. 1. A schematic of the construction of the *ToF–E* spectrometer showing the recoil/scattered ion axis through the carbon-foil based timing detectors T1 and T2 to the stopper foil and the Si SBD. (Not drawn to scale.)

detector system, depending on the detection efficiency for that particular ion species, is detected by the two timing detectors to give the Time of Flight and the SBD signal provides both the energy signal and the coincidence trigger between the two timing detectors and the SBD. For the present measurements the coincidence window was set at 300 ns.

2.2. Stopper foils

Freestanding ZrO_2 stopper foils produced by physical vapour deposition were purchased from ACF-Metals [Arizona, USA] for our first test measurements. The foils were mounted on steel frames each with a circular aperture of 0.8 cm in diameter. The thickness of the foil used in the measurements described here, nominally 300 $\mu g\,cm^{-2}$ from the manufacturer, was measured from the energy loss measurement of ^{241}Am alpha particles to be 345 $\mu g\,cm^{-2}$. Given that the thickness of vapour deposited foils is prone to significant lateral variation on the micrometer scale [4], this measured value is effectively an average thickness since the spot size of the alpha beam from the ^{241}Am source is virtually limited to the size of the frame aperture.

For stopping power measurements the incident ions were obtained either as scattered ions or recoils into the *ToF–E* spectrometer. To get krypton ions, a thick layer of gold was prepared by electron beam deposition onto a silicon substrate and then used to scatter an incident Kr^{15+} ion beam into the detector system. Silicon recoils were produced from a freshly cleaned plain silicon wafer piece mounted at a grazing incidence angle to an incoming krypton beam. This configuration means that the incident ions on the stopper foil were produced with a continuous range of energies, as opposed to the traditional monoenergetic beams.

3. Results

3.1. Time calibration

The spectrometer was characterised by performing analyses on samples of known composition and layer structure. Fig. 2 is a typical 2D *ToF–E* plot obtained from a CaF_2 layer of about 750×10^{15} at cm^{-2} (222 nm) thick on a Si substrate bombarded by a 27.5 MeV $^{84}Kr^{15+}$ beam at a grazing incidence angle to the sample surface. The mass separation capabilities of the spectrometer are clearly demonstrated. The major elements in the sample Ca, F, Si are clearly separated, as well as suspected surface impurities C and O.

To calibrate the *ToF* detector the short time (high energy) edge of the recoil spectra of each of Ca and F from the surface layers of

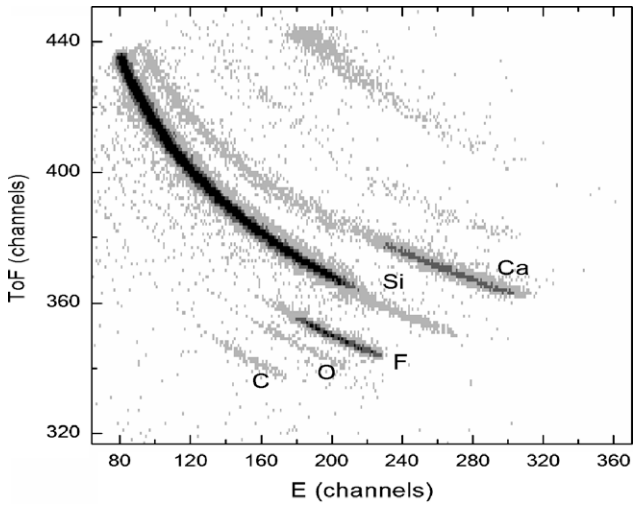

Fig. 2. A 2D Time of Flight–Energy mass contour plot showing recoil ions from a 750×10^{15} $atcm^{-2}$ (222 nm) CaF_2/Si sample bombarded by 27.5 MeV ^{84}Kr ions. The contour plot shows O and C impurities present on the sample surface.

the CaF_2/Si target was fitted using a Sigmoidal [4] fit function using the graphing and analysis software ORIGIN®. This was repeated for Si, C, O and Ti ion spectra from other sample targets with surface layers containing these ions. This gave the channel number corresponding to the shortest Time of Flight t_i for each recoil ion. The energy E_i of an ion of mass m_i was calculated from the kinematic relation

$$E_i = \frac{4m_i m_o E_o}{(m_i + m_o)^2}\cos^2\Phi - \Delta E_{T1}, \quad (1)$$

where E_o is the energy of the incident beam particles of mass m_o and Φ is the scattering angle. The ΔE_{T1} term represents the energy loss of the recoil ions through the carbon foil of the first timing detector. This quantity was evaluated using Ziegler et al.'s SRIM2003 code [7]. The Time of Flight t_i was then calculated using

$$t_i = \sqrt{\frac{m_i}{2E_i}}L, \quad (2)$$

where L is the known flight length of 0.584 m. This was done for five different recoils over a wide mass range and a correlation coefficient of 0.999 between the linear fit and data was a clear indication that the *ToF* calibration was independent of the mass of the detected particles. The time resolution estimated from the sigmoidal edge fit varied between 0.112 ns for scattered krypton ions and 0.904 ns for carbon recoils.

3.2. Measurement of stopping powers

To measure stopping power the stopper foil is mounted on a screw in–out foil holder that can be inserted between the second timing detector and the Si SBD and similarly pulled out of the way without breaking vacuum. This configuration has been successfully employed by Zhang et al. [8,9] and Trzaska et al. [10] for their stopping power measurements. The energy of the incident ion before hitting the stopper foil is determined from the *ToF* measurement and, for ions of $Z \geqslant 4$, due to the problem of non-linear response in the SBD, the exit energy is determined from a *ToF–E measurement without any stopper foil* between T2 and the Si SBD. The energy signal from the SBD is used to tag events of a similar energy on two *ToF* curves (see Fig. 3); 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