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Stopping power measurements with the Time-of-Flight (ToF) technique

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ABSTRACT

A review of measurements of the stopping power of ions in matter is presented along with new measurements of the stopping powers of O, Si, Ti, and Au ions in self-supporting thin foils of SiO_2, Nb_2O_5, and Ta_2O_5. A Time-of-Flight system at the Ion Beam Materials Laboratory at the University of Tennessee, Knoxville, was used in transmission geometry in order to reduce experimental uncertainties. The resulting stopping powers show good precision and accuracy and corroborate previously quoted values in the literature. New stopping data are determined.

1. Introduction

The measurement of the energy loss of ions in materials is of crucial importance in a number of academic and industrial fields [1–5]. For example, an accurate knowledge of the stopping power is essential for compositional and structural analysis of thin films and surfaces utilizing Ion Beam Analysis (IBA) techniques [6–9], in computational and experimental studies of radiation effects and radiation damage in materials and electronics under extreme conditions [10], in electronic device fabrication [11], nuclear physics [12], astrophysics [13], and medical physics [14]. Despite the fundamental importance of measured stopping power data to these fields, there are still numerical disagreements between energy loss models and measured values for various combinations of ion and target [15,16].

2. Methods

There are two main classes of methods for measuring stopping powers. The first class relies on back-scattering ions from materials [7,17–20]; while in the second case, ions are transmitted through a thin foil [21–24]. Back-scattering methods are ideally suited to measure the stopping powers of light ions in heavy materials (materials with high-Z elements). In addition of being able to measure stopping powers in random incident ion directions, this technique has also been adapted to measurements along ion channeling directions [18,20]. On the other hand, the transmission method is the more versatile of the two because it can be used both for light and heavy ions in light or heavy matrices. However, the need for uniform, free-standing thin films and the potential for film contamination pose additional challenges [25]. It has been shown that the two approaches can be complementary [25].

2.1. Back-scattering techniques

Backscattering techniques rely on measuring the energies of ions directly backscattered off the target material. If the sample composition, density, and layer structure is known, the stopping power can be inferred from the energy spectrum of the backscattered particles. Accuracy better than 2% error has been achieved with monochromatic He ions in the MeV range on a silicon target [18]. In this study, the thickness ($\sim$1 μg) of the sample was determined by Near-InfraRed (NIR) spectrometry. Similar accuracies were obtained for C, O, and Cl ions, of several MeV, in Si and Ta_2O_5 targets by carefully fitting a model to the Rutherford Back-Scattering (RBS) spectra [7,19]. Stopping powers of He and Li were both measured in the 0.1 to 10 MeV range in Si, and the sample structure was characterized by Transmission Electron Microscopy (TEM) and Atomic Force Microscopy (AFM) [20]. The TEM was employed to measure the sample thickness, and the AFM to measure the surface roughness.

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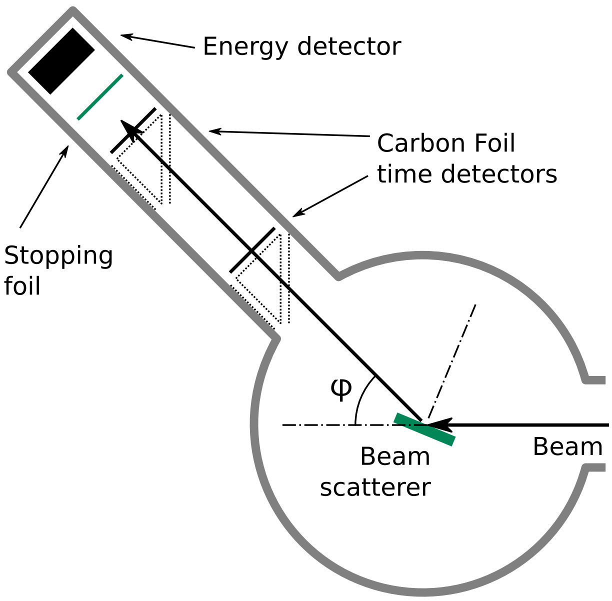

Fig. 1. Typical experimental system for stopping power measurements. Two carbon foil time detectors are used to measure the Time-of-Flight (ToF) of the ions, and a silicon energy detector is used to measure the total energy after the stopping foil.

2.2. Transmission techniques

Transmission techniques rely on the measurement of an ion energy loss through a stopping foil. An ion beam is transmitted through a stopping foil, and its energy is measured before and after the foil. The foil is thin enough to keep the fractional energy loss small. Consequently, the precision of transmission techniques depends largely on the resolution and linearity of the energy measurement. Typically, the beam currents are small, thus sputtering is negligible [23]. In early experiments, an attenuated beam was transmitted through an insertable sample and its energy spectrum

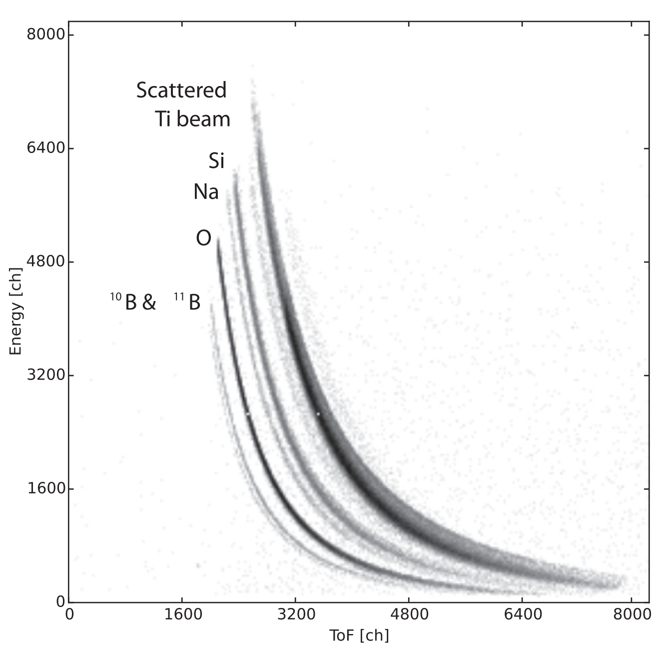

Fig. 2. Recoils from an 18 MeV Ti beam on a glass slide. The color scale is logarithmic. The mass lines from top to bottom correspond to: the forward scattered titanium beam, silicon, sodium, oxygen and the two isotopes of boron (^{10}B and ^{11}B).

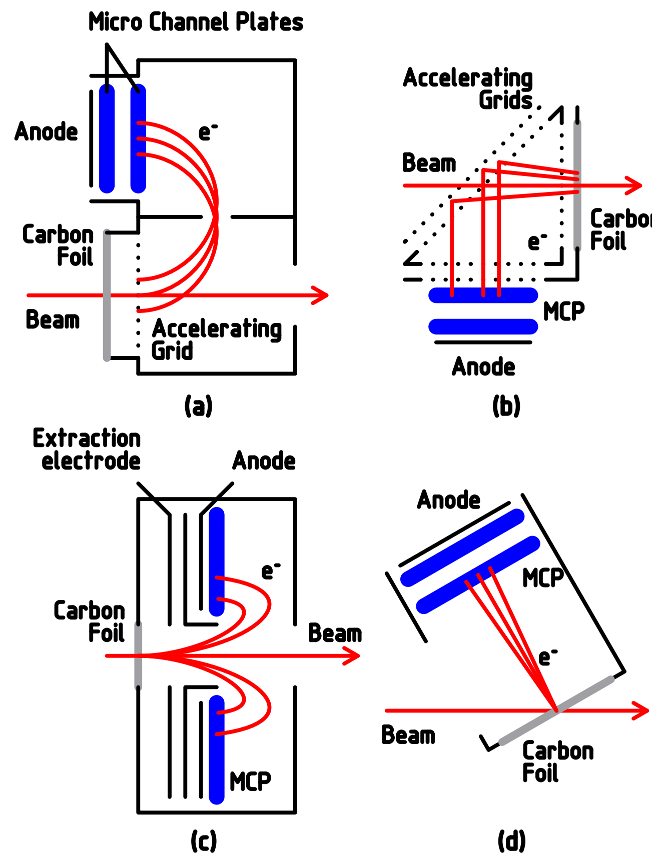

Fig. 3. Schematic representations of the electron transport in different carbon foil time detector designs: (a) magnetic field deflector, (b) electrostatic mirror, (c) annular electrostatic mirror, (d) direct transport.

was measured by means of a silicon detector [12,22]. The energy loss was determined by comparing the spectra with and without the foil between the ion source and the detector. Measurements of the stopping powers over a range of energies were obtained by changing the energy of the ion beam in discrete intervals, and using Time-of-Flight (ToF) techniques to accurately measure the energy spectra. The thicknesses of the samples were also determined by an ion transmission technique. Energy loss measurements, similar to the stopping power measurements themselves, were performed using alpha particles emitted by ^{241}Am and ^{212}Bi sources. The stopping powers were given as ratios of the alpha particle energy loss.

A faster and more comprehensive approach uses a beam with a continuous energy spectrum, rather than a series of monochromatic beams. By scattering the main beam off a scattering target and orienting the detector at an angle away from the beam line, ions travelling toward the detector are scattered into a broad range of energies. The beam scatterer can be: a bulk sample containing light atoms, which are emitted as recoiled ions when hit with a grazing beam [26,27], or a bulk sample containing heavy atoms (like Au) that scatters the main beam [21,28–31].

Energy measurements can be performed using conventional silicon detectors (having 4–5% uncertainties) [12,22], or by combining ToF and silicon detector systems ($<$3% uncertainties) [21,28,29]. The former has the advantage of simplicity in that it comprises only one detector. However, the incident ion beam must be monochromatic. The ToF & Si detection system is more complex, but it permits the use of a continuous energy ion source [32]. There are also examples of energy measurements by ToF with bunched beams, in which the main beam is pulsed and the time of flight