THE FIRST EXPERIMENTAL VALUES FOR THE STOPPING POWER OF Au IONS IN NICKEL*

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(Received December 18, 2007)

Stopping power of Au ions in nickel was measured using B-TOF method with accuracy of better than 1.5 % in the energy range from 0.15 to 5 MeV/u. The results are compared favourable with theoretical and semi empirical predictions. For this combination of ion and absorber there are no previously published experimental results.

PACS numbers: 34.50.Bw

1. Introduction

Reliable stopping power values of heavy ions in different media are requested in many fields of basic and applied science such as ion beam analysis, ion beam modification of materials, medical physics applications, *etc.* [1]. Since such values cannot yet be calculated with sufficient accuracy directly from the theory, most people rely on semi-empirical codes. The reliability of these codes depends directly on the availability and accuracy of the experimental data. For heavy ions the data are scarce and of uneven quality leading to significant discrepancies in the outputs of semi-empirical programs. Therefore, the stopping power measurements have to cover all accessible beam/absorbent combinations in order to provide consistent data over a large energy range and reduce the experimental and statistical errors.

* Presented at the XXX Mazurian Lakes Conference on Physics, Piaski, Poland, September 2–9, 2007.

During the past decade several measurements [2-8] have been performed. This work presents recent results for Au ions at energies below $5\,\mathrm{MeV}/u$ moving in nickel.

2. Experimental set-up

The experiment was carried out at the Accelerator Laboratory at the Department of Physics, University of Jyvaskyla, Finland. For the measurements we have used our latest B-TOF method combining a magnetic dipole with a high resolution TOF spectrometer [2-7]. The initial mono-energetic cyclotron beam with the energy of up to $5\,\mathrm{MeV}/u$ (the highest available at the time of the experiment) was directed to a beam degrader set-up. In the set-up one can choose aluminium foils with different thicknesses to be placed on the path of the beam. After the degrader, the initially mono-energetic heavy ion beam with just a single charge, becomes broadened in energy and displays wide distribution of charge states. The width and the mean value of the charge distribution depend on the velocity of the ions at the exit of the degrader and can be estimated by the well-known semi-empirical formula [9]. Our experience shows that the widest spread of energies is obtained either with a mesh of wires, or with a thin foil with slightly uneven surface positioned nearly parallel to the beam direction. A single foil of moderate thickness placed perpendicular to the beam produces less energy loss and less dispersion but the spectra are more predictable and have a Gaussian-like distribution.

Intuitively one might expect that after passing through the magnetic dipole a beam with broad energy distribution would form again a single narrow peak with the width and the mean value determined by the magnetic field and by the other key parameters of the ion optics. However, since after the degrader there are many charge states present instead of one as in the initial beam, several distinct energy peaks are observed after the magnetic dipole. This is because for each charge state a different energy is required to follow the same trajectory defined by the magnetic field, the beam pipe, and the collimators. A typical spectrum on the exit of the dipole can be seen in Fig. 3 in [8]. It is equivalent to having several distinct beam energies at the same time but with reduced intensity. When a mesh or a thick foil is used in front of the dipole, the degraded beam becomes also noticeably defocused leading to a drastic reduction of the beam current. Nevertheless, the remaining intensity is sufficient for the measurements as the particles are counted directly without the need to scatter the beam as it is the case in our previous methods [2-7].

The scheme of the B-TOF method is presented in Fig. 1. After the dipole magnet there is a rotating sample wheel with one position left intentionally empty, followed by our standard MCP-based TOF spectrometer [2-8]. Time

resolution was around 100 ps (measured FWHM of the TOF peak for the primary Au beam). The detailed description of these time detectors can be found in [2, 4]. At the end of beam line there is a Faraday Cup equipped with a semiconductor detector protected by a removable beam stopper. This detector is used only at the start of the measurement to confirm the beam purity.

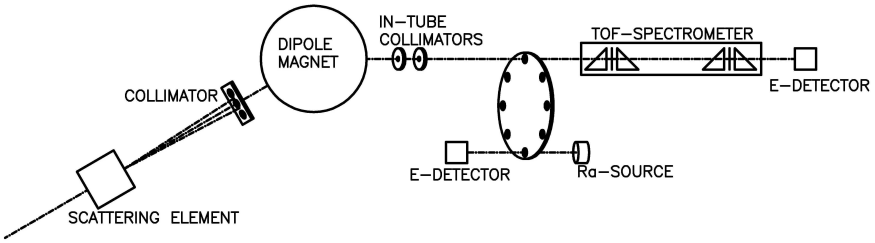

Fig. 1. Set-up for measuring of stopping power using B-TOF method. The key elements are the scattering element, magnetic dipole, motorised sample wheel and high-resolution TOF spectrometer.

The stopping power values are calculated from the energy of the ions measured with the empty position on the wheel and from the energy measured after passing through the Ni foil. To receive the stopping power values in the widest possible energy range, it was necessary to carry out the measurements at 15 settings of the magnetic field and with 3 different energies of the primary beam from the cyclotron (425, 600 and 974 MeV).

The thickness of the Ni foil was monitored during each beam run using a spectroscopic quality ^{226}Ra α-source and a silicon detector. The thickness of the foil ($0.401 \pm 0.005\,\mathrm{mg/cm^2}$) was determined assuming that the dE/dx values for ^{4}He calculated with SRIM 2003 [10] are correct. The statistical error of the thickness measurement was about 1 %.

3. Results

The stopping power values for ^{197}Au ions in nickel are shown in Table I and in Fig. 2. The experimental data in this paper are the first ever measured for this combination of target and beam. The statistical error of the extracted values is below 1.5 % and the covered energy range in nearly two orders of magnitude. In Fig. 2 we compare our results (closed circles) with the values of electronic stopping power predicted by semi-empirical SRIM2003 code (solid thick line), the LET 1.24 code [11] (thin line) and with theoretical calculations made by the CASP 3.1 code [12, 13] (dashed line) and the PASS code [14, 15] (solid thin line with open circles).

TABLE I

Experimental values of electronic energy loss of ^{197}Au ions in nickel.

$E\ \left[\frac{\text{MeV}}{\text{u}}\right]$	$dE/dx\ \left[\frac{\text{MeV cm}^2}{\text{mg}}\right]$	$\Delta dE/dx\ \left[\frac{\text{MeV cm}^2}{\text{mg}}\right]$	$\Delta dE/dx\,[\%]$
0.146	14.4	0.2	1.4
0.189	17.0	0.2	1.2
0.229	19.5	0.2	1.2
0.265	21.8	0.3	1.2
0.314	24.5	0.3	1.1
0.369	27.4	0.3	1.1
0.429	30.4	0.4	1.3
0.518	34.3	0.4	1.2
0.613	38.1	0.5	1.2
0.727	42.5	0.5	1.2
0.868	47.0	0.6	1.2
1.019	51.3	0.6	1.2
1.239	56.4	0.8	1.4
1.488	60.7	0.8	1.2
1.762	65.0	0.9	1.4
2.102	68.5	0.8	1.1
2.507	71.7	0.9	1.3
3.109	74.0	0.9	1.2
4.068	75.3	0.9	1.1
4.858	74.7	0.9	1.1

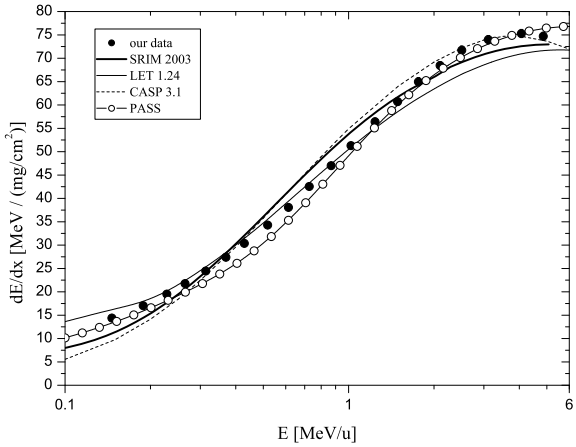

Fig. 2. Measured values of energy loss of ^{197}Au ions in nickel (closed circles). The values of electronic stopping power calculated by SRIM2003, LET 1.24 and CASP 3.1 codes are labelled by solid thick line, thin line and dashed line, respectively. The solid thin line with open circles represents prediction of the PASS code.

Predictions of the PASS code were provided directly by P. Sigmund. The dE/dx values calculated by the CASP 3.1 code were obtained for $I_{\mathrm{Bethe}} = 311\,\mathrm{eV}$, UCA (unitary convolution approximation) and a mean charge state. The shell and relativistic corrections were also applied. The indicated errors of our stopping power values are predominantly statistical. All code predictions fit quite well the experimental values. The only small differences can be noticed for energies: below 0.2 MeV/u, about 0.7 and 3.5 MeV/u.

In our opinion the B-TOF technique is a reliable and efficient method to measure energy loss of heavy ions in thin metallic foils. In the nearest future we intend to adopt our experimental setup to handle other material samples as well.

This work has been supported by the EU within the 6th framework programme Integrating Infrastructure Initiative — Transnational Access, Contract Number: 506065 (EURONS) and by the Academy of Finland under the Finnish Centre of Excellence Program 2006–2011 (Nuclear and Accelerator Based Physics Program at JYFL).

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