

Energy loss of energetic ^{40}Ar , ^{84}Kr , ^{197}Au and ^{238}U ions in mylar, aluminum and isobutane

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The BigSol Superconducting Solenoid Beam Line at the Texas A&M Superconducting Cyclotron was used to measure the stopping power of ^{40}Ar , ^{84}Kr , ^{197}Au and ^{238}U in mylar, aluminum and isobutane in the energy range from below 1 AMeV up to 15 AMeV.

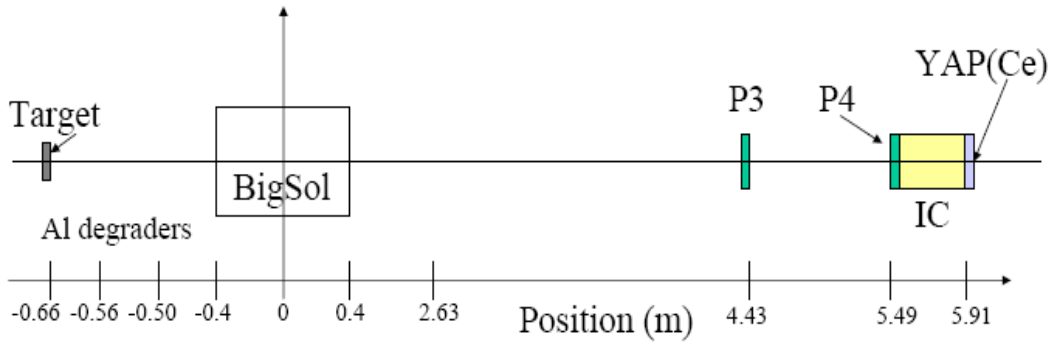


FIG. 1. Schematic lay-out of the BigSol beam line as used for this work.

A schematic lay-out of the experimental set-up is shown in Fig. 1 for more details see Ref.1. Two position sensitive PPAC detectors (P3 and P4) are used to measure the time of flight and to reconstruct the trajectory of the particles. A multi-anode Ionization Chamber (IC) is used either as a stopping detector or as a transmission detector for fragments that are stopped in an array of YAP(Ce) scintillators. The IC has an active area of $6.5 \times 6.5 \text{ cm}^2$ and is equipped with 8 parallel anodes, each having a width of 4.65 cm along the beam direction. The IC is filled with isobutane gas at the pressure of 30 mbar. Consequently, the time-of-flight (tof) between P3 and P4, the entrance position in P4, the energy loss in P4 and energy loss in each of the IC segments are measured. For some calibration runs P3 was also removed.

The calibration of the energy loss in the IC was performed using the direct 14.85 AMeV ^{40}Ar and ^{84}Kr beams data (without the Al degrader) and the SRIM predictions for those beams [2]. Ppac P3 was removed from the beam line in order to reduce the material budget before the IC. Consequently, the absolute values of the energy loss presented in this work are normalized to the SRIM predictions for the 14.85 AMeV ^{40}Ar and ^{84}Kr .

The P3-P4 time of flight calibration was performed by using known delays to obtain the slope of the time to channel relationship. The time zero was determined for each ion using the time of flight measured for the direct beam without an Al degrader.

The calibration of the P4 energy signal was performed in two steps. For the particles stopped in the IC the energy loss in P4 was determined from the difference between the energy before P4 (calculated from the measured time of flight) and the measured energy in the IC. For the particles not stopped inside the IC, the direct beam data for runs in which P3 was removed from the line were used. For these the SRIM code was used to calculate the energy loss of the different beam particles in P4.

Al degraders having thicknesses in the range of 5-150 μm were placed at the target position to lower the incident energies. The thickness of the aluminum foils was measured in a separate run using a 6.27 AMeV $^4\text{He}^2\text{H}$ molecular beam, assuming that the SRIM stopping power for alpha particles in aluminum is correct. The statistical error on the aluminum degrader thicknesses is about 0.05% for all the layers. An average systematic error of about 4% was found comparing the thicknesses obtained using both the alpha particles and the deuterons resulting from the breakup of the molecular beam.

The experimental stopping power data for ^{40}Ar , ^{84}Kr , ^{197}Au and ^{238}U in mylar, aluminum and isobutane are shown in Figs 2-4 respectively and compared with the stopping power values predicted by the SRIM code.

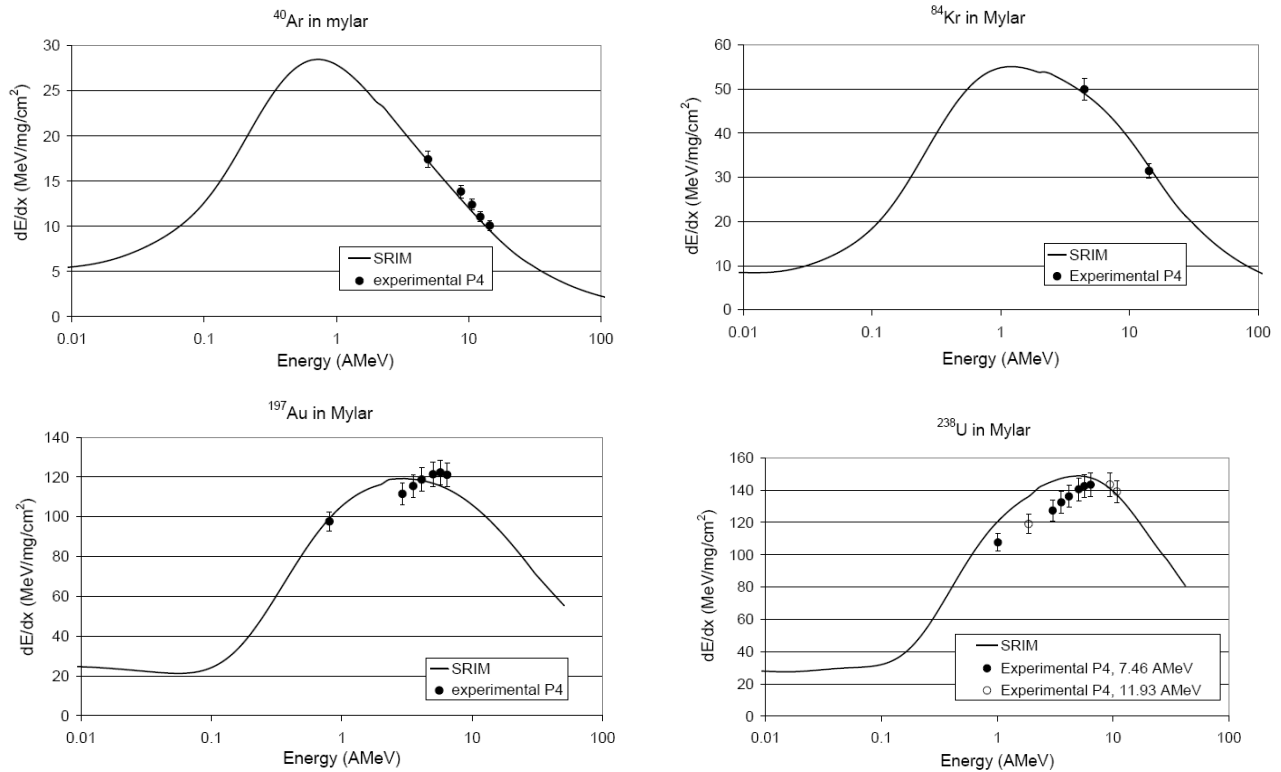


FIG. 2. Stopping powers of ^{40}Ar , ^{84}Kr , ^{197}Au and ^{238}U measured in mylar as a function of the ion energy. The black line shows the SRIM prediction for the stopping power. For the ^{238}U beams, the full and the open circles indicate the 7.46 AMeV and 11.93 AMeV beams, respectively. For details see the text.

The stopping powers $\Delta E/\Delta x$ for ions in mylar were obtained dividing the calibrated energy signal from the ppac P4 by its equivalent mylar thickness.

The results reported in Fig. 2 for ^{40}Ar , ^{84}Kr and ^{197}Au ions in mylar agree with the SRIM prediction to within 4%. The stopping power for the ^{238}U beam in the energy range from 7 to 0.8 AMeV seems to be overestimated by SRIM by about 9%, whereas for energies larger than 10 AMeV the agreement is good to within 1%.

The stopping power ($\Delta E/\Delta x$) in aluminum was determined from the experimental range-energy curves. The results are reported in Fig. 3 as a function of the ion energies. The experimental stopping power for ^{40}Ar and ^{84}Kr particles in aluminum in the energy range from 14 to 10 AMeV is in very good agreement with the SRIM stopping power, being the average difference between the measured values and the SRIM prediction about 0.3%.

The measured stopping power points for ^{197}Au and ^{238}U particles in aluminum lie at the top of the Bragg peak region where no other experimental points are so far available [3-4]. The measured stopping power for ^{197}Au particles in aluminum indicates that SRIM underestimate the Bragg peak height by 10%, whereas the measured stopping power for ^{238}U in aluminum is on average a 4% higher than the SRIM prediction.

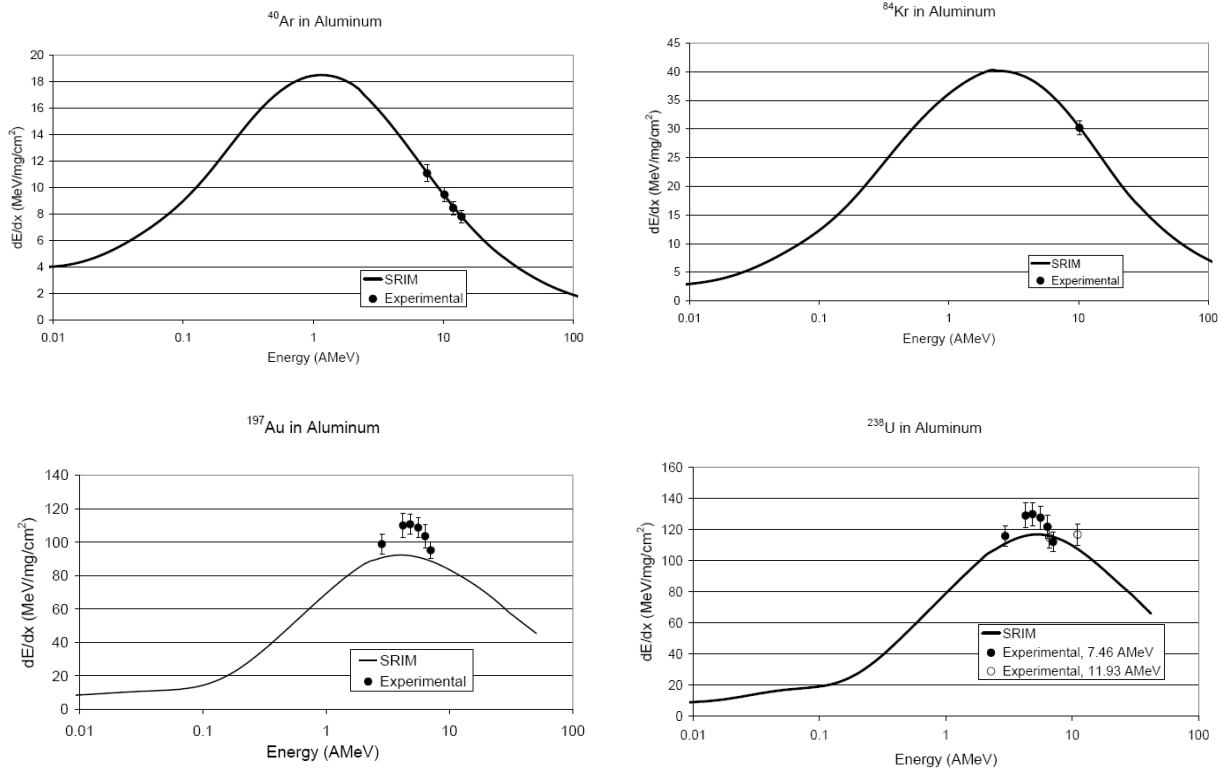


FIG. 3. Stopping powers of ^{40}Ar , ^{84}Kr , ^{197}Au and ^{238}U measured in aluminum as a function of the ion energy. The black line shows the SRIM prediction for the stopping power. For the ^{238}U beams, the full and the open circles indicate the 7.46 AMeV and 11.93 AMeV beams, respectively. For details see the text.

The energy loss for ions in isobutane was determined using the pulse height data for each anode on the IC. For each anode the stopping power $\Delta E/\Delta x$ was obtained simply by dividing the measured energy in the i^{th} anode (MeV) by the anode thickness (mg/cm^2). Fig. 4 reports results the experimental stopping powers in isobutane gas as a function of the ion energies. The energy of an ion in the i^{th} anode ($i=1$ to 8) was obtained by subtraction of half of the measured energy loss in the i^{th} anode from the energy incident on that anode. These were divided by the mass A to obtain the energy per mass unit. For ions which are not stopped in the IC, the energy of the ion is obtained from the incident energy, determined from the tof, corrected by the energy loss in P4 and the total energy loss in the preceding anodes. In the case of ions stopping in the IC, the total energy measured in the IC is directly used instead of the energy derived from the tof measure. In Fig.4 the measured values are compared with the electronic stopping powers predicted by SRIM. For this comparison we have assumed that the part of the energy lost by nuclear stopping does not produce a signal in the counting gas. Thus the experimental data are compared with the electronic part of the stopping power.

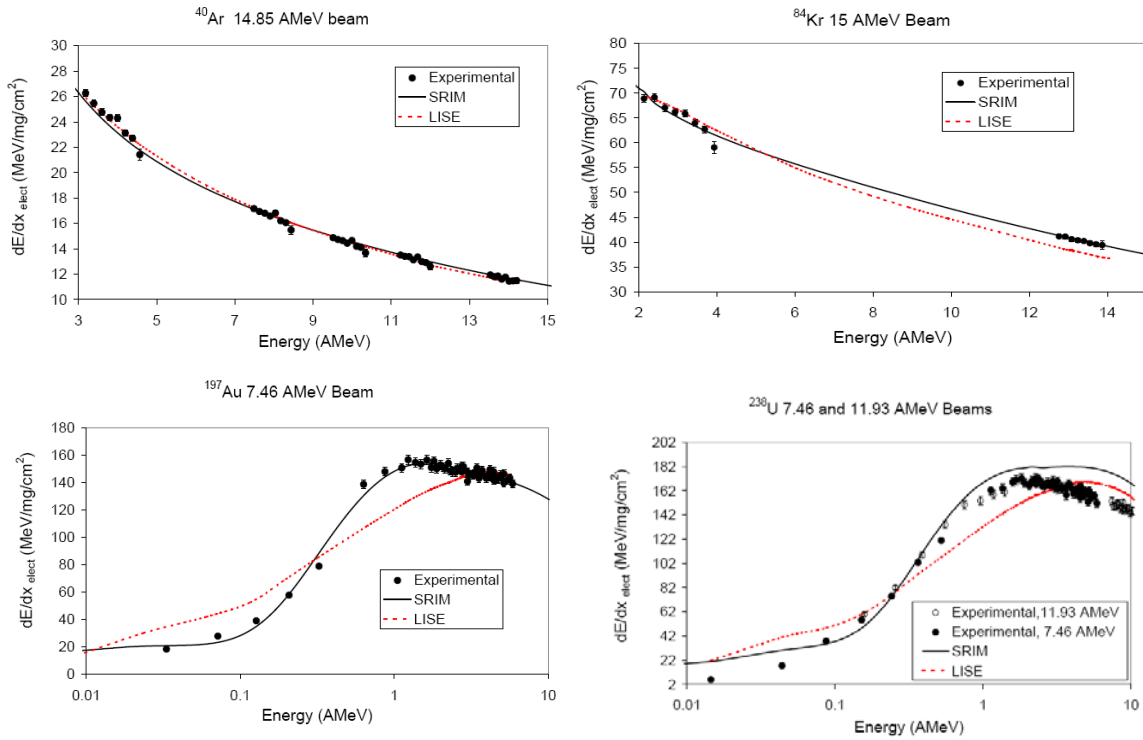


FIG. 4. Stopping powers of ⁴⁰Ar, ⁸⁴Kr, ¹⁹⁷Au and ²³⁸U measured in the IC anodes. The black line shows the SRIM prediction for the electronic stopping power. The red dotted line shows the LISE prediction. For the ²³⁸U beams, the open and full dots indicate the 11.93 AMeV and 7.46 AMeV beams, respectively. For details see the text.

Recalling that the absolute energy scale has been calibrated using the SRIM predictions for 14.85 AMeV Ar and Kr beams, the results for ⁴⁰Ar, ⁸⁴Kr and ¹⁹⁷Au show a very good agreement over the whole

energy range studied. Deviations between the experimental data and predicted values are, on average, within 3%. Larger deviations, on average about 10%, are evident in the case of ^{238}U projectiles.

For ^{40}Ar and ^{84}Kr the LISE [5] calculations are in a reasonable agreement with the data. Large deviations are seen in the case of the ^{197}Au and ^{238}U ions.

[1] M. Barbui *et al.*, Nucl. Instrum. Methods. Phys. Res. **B265**, 605 (2007).

[2] J. F. Ziegler, SRIM-2003, Nucl. Instrum. Methods Phys. Res. B219, 1027 (2004).

[3] H. Paul, Nucl. Instrum. Methods Phys. Res. **B261**, 1176 (2007); and references therein

[4] the collection of experimental data are available at the H. Paul web page (<http://www.exphys.unilinz.ac.at/stopping/>) or at the SRIM site (<http://www.srim.org/>).

[5] O. Tarasov, D. Bazin, M. Lewitowicz and O. Sorlin Nucl. Phys. **A701**, 661 (2002).