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Energy loss around the stopping power maximum of Ne, Mg and Na ions in hydrogen gas

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Abstract

The DRAGON (detector of recoils and gamma-rays of nuclear reactions) setup at the ISAC radioactive ion beam facility of TRIUMF, Vancouver, was used to measure the energy loss of stable neon and magnesium as well as of radioactive sodium ions (energy range 200–1150 keV/u) in hydrogen gas. Stopping power values were determined and (as no previous experimental data around the stopping power maximum existed) compared to the available semi-empirical codes SRIM 2000, SRIM 2003, ATIMA and MSTAR. The experimental data seems to favor the new SRIM 2003 approach and will hopefully provide input to a further improvement of the parameter set.
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1. Introduction

In many nuclear physics experiments, knowledge of the stopping powers and energy losses of the ion and target combinations are taken from the semi-empirical computer codes [1–4] for purposes ranging from planning the experimental setup to analyzing the final measurement. Researching the literature [5–8] that forms the basis of the various codes, one finds that often little or no experimental data exists for the ion/target combinations of interest. Especially for our application, heavy ions ($Z > 6$) with energies around the stopping power maximum impinging on gaseous hydrogen, comparison of the codes to experimental data is virtually impossible as very few measurements had

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Table 1
Measured stopping power values for heavy ions traversing hydrogen gas

Ion	Energy (keV/u)	ε_{exp} (eV/10^{15} 1/cm^2)
Ne	209	76.7 ± 6.0
Ne	270	83.1 ± 3.8
Ne	760	86.9 ± 7.9
Ne	854	78.2 ± 9.8
Ne	1156	64.5 ± 7.3
Mg	220	83.8 ± 4.5
Mg	419	109.2 ± 6.5
Mg	818	104.8 ± 5.6
Na	210.9	84.4 ± 2.8
Na	345.8	93.3 ± 6.0
Na	472.7	94.9 ± 9.0
Na	830.3	79.8 ± 8.6

been performed in the past. Of these measurements none had been done with our ion/target combinations around the stopping power maximum. With the DRAGON (detector of recoils and gamma-rays of nuclear reactions) setup [9] at the ISAC radioactive ion beam facility [10] of TRIUMF, Vancouver, we had the opportunity to measure the energy loss of stable Ne, Mg and radioactive Na ions (energy range 200–1150 keV/u) in hydrogen gas during the course of our experiments (Table 1). The extracted stopping powers were compared to the output of the computer codes, which are now used routinely for the analysis of the radiative capture experiments performed with radioactive ion beams [11,12]. It should be pointed out that the extraction of a correct nuclear resonance strength (for e.g. nuclear astrophysics tabulations) from the raw experimental yield depends linearly on the knowledge of the correct stopping power. The aim of this analysis was to study if the codes can be relied on for the use in our application.

2. Experimental setup

The DRAGON facility (Fig. 1) consists of a gas target and a recoil mass separator. Radiative capture experiments in the nuclear astrophysics program at ISAC require targets of hydrogen and helium nuclei. A gas target is preferred to a hydrocarbon solid target because it gives higher

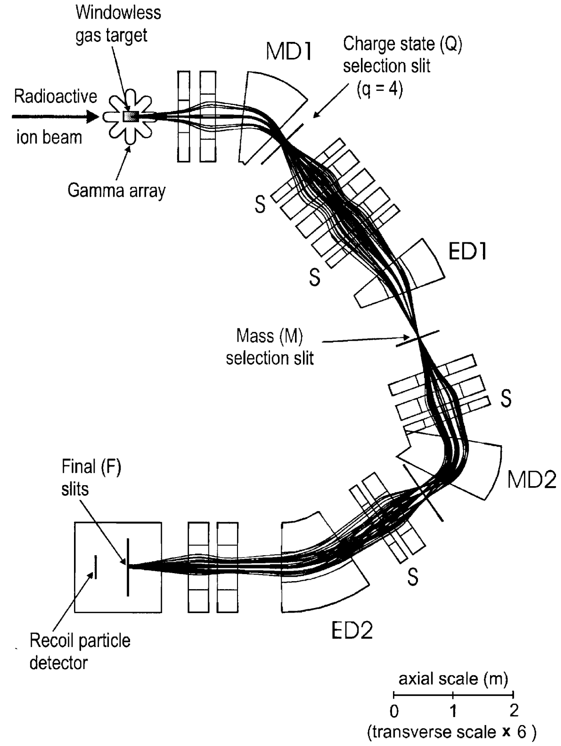

Fig. 1. Schematic representation of the DRAGON layout with typical ion trajectories.

yield with less background for resonance reactions. As windows would significantly hinder detection of reaction recoils, DRAGON has a windowless gas target with multiple stages of differential pumping to achieve the necessary quality of vacuum at the entrance to the target and the exit from it to the mass separator. The target is in the form of an extended cell, 11 cm long, with beam entrance and exit holes of 0.6 and 0.8 cm, respectively (Fig. 2). Typical pressure in the center of the cell is 4.5 Torr (measured via a baratron, Leybold CMH 10, temperature controlled with accuracy 0.15% of measured value) for these apertures with a resultant flow of about 0.3 atm l/s through the holes. The vacuum box, which encloses the cell, is pumped by a series of Roots blowers, resulting in a manifold pressure of 0.35 Torr when the cell pressure is 4.5 Torr. The vacuum box is connected to other stages of differential pumping by small diameter pumping tubes, which also allow unobstructed passage of the incident ion beam and the

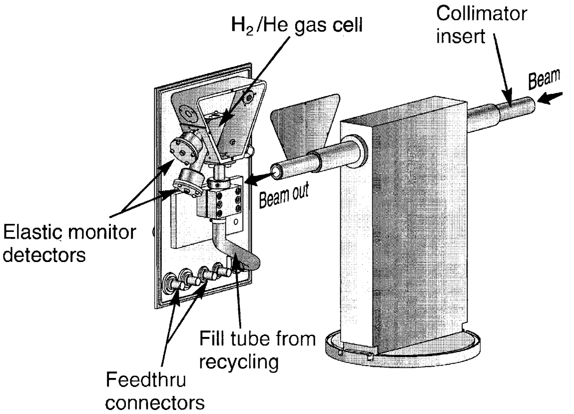

Fig. 2. Schematic representation of the inner gas target cell embedded in the first pumping stage of the DRAGON windowless gas target.

exit of the beam and the heavy reaction products. Turbomolecular pumps on the differential stages reduce the end pressures to about 10^{-6} Torr. The gas is recirculated through a cryo-trap to ensure gas cleaning. Efficient removal of possible heavier gas contaminations was monitored via the elastic scattering detectors situated in the gas cell for beam current monitoring purposes. In the case of gas contamination additional scattering peaks would have shown up in these detector spectra.

The recoil mass separator consists of a magnetic dipole (MD)–electrostatic dipole (ED) – MD–ED combination with magnetic quadrupole and sextupole elements inserted to ensure proper beam or recoil focussing. A first focus is achieved at the so-called charge slits after the first MD (equipped with an NMR probe), which allows, with knowledge of the ion mass and charge state, a determination of the energy of the ions focussed through the slits. The NMR readings were calibrated at well-known nuclear resonances using the reactions $H(^{15}N,\alpha\gamma)^{12}C$, $H(^{21}Ne,\gamma)^{22}Na$, $H(^{20}Ne,\gamma)^{21}Na$ and $H(^{24}Mg,\gamma)^{25}Al$ [9,13].

3. Gas target thickness

For both the measurement of radiative capture reactions and stopping power determinations, it is important to know the total target thickness of the DRAGON gas target. In order to determine the thickness with our standard gas cell apertures of 6 and 8 mm diameter, we replaced these by apertures of only 1.5 mm diameter. This way a well-defined profile was created, where gas flows are low ($\sim$0.015 atm l/s) and, due to high pumping speeds in the first pumping stage ($\sim$1000 l/s), a negligible (for purposes of contributing to energy losses) gas pressure can be maintained directly outside the gas cell (for details see [9]). Pressure measurements and gas flow calculations (using standard gas flow equations, see e.g. [20]) set an upper limit of 1% of the gas intercepting the beam outside of the geometrically (length 11 cm) confined cell. This upper limit was included as a possible systematical error in our error budget. The ratio of energy loss per unit of central cell pressure in both aperture setups times the geometrical length gave the effective target length of the larger aperture setup. With a ^{21}Ne beam of 275 keV/u, this ratio was measured to be 1.109, which translates into an effective target of 12.3 ± 0.4 cm for the 6 mm/8 mm apertures. This error in the effective target length was treated as a possible systematic error and thus added (not in quadrature) to our random errors. Pressure measurements and gas flow calculations for this larger aperture setup agreed with the result of the ratio measurement. Energy loss measurements with both aperture setups were used for the stopping power determinations presented here with the majority stemming from the larger aperture configuration.

4. Experimental procedure

Standard procedure during the course of our experiments with the gas target and the DRAGON separator is to first measure the beam energy of the ion beam as delivered by the ISAC facility operations team. For this purpose the gas target is pumped out to levels of residual gas in the gas cell below a few millitorr. Quadrupole magnets and sextupole magnets are set according to the mass, selected charge states and nominal energy of the beam. These settings were determined in extensive tests using a deflection magnet in the target position and also by running numerous stable ion beams as "pilot" beams through the facility. The incoming ion beam axis is given by the apertures of the gas cell, as well as by the preceding and following gas flow limiting tubes of the windowless gas target. Usually a 5^+ or 6^+ charge state ion beam is accelerated through the ISAC accelerator. The charge-selection slits, which are used for energy determination in this case, are usually set to be 25 mm wide in both the horizontal and vertical plane to ensure full reaction recoil transmission. For the energy determination, the horizontal slits are closed to 2 mm width. This setting in all cases still allowed for more than 40% beam transmission with the beam centered on the slits. The dipole magnetic field, monitored by the NMR probe, was varied to achieve this centering. In order to estimate the error introduced by the experimenter in centering the beam, in several cases two experimenters went through the above procedure. In this way a relative error for the determined NMR setting (usually between 2700 and 5300 G) of ±1.5 G was estimated. The absolute error from the energy calibration becomes negligible when calculating the energy loss by subtraction of the gas-in from the gas-out value.

After this step gas was allowed to flow into the gas cell by adjusting a gas flow valve, until the desired cell pressure (up to 10 Torr) was reached. Cell pressure was routinely constant to better than 1% without adjustment of the gas flow valve. An absolute error of 0.1 Torr (1% of full scale) in the pressure reading was included in the error analysis presented here to account for the given accuracy of the baratron (0.15%) and possible shifts in cell pressure as well as zero point shifts. The temperature in the gas was measured with a J-type thermocouple to be 27 ± 1 °C. This value agreed with other temperature measurements around our gas cell and, as beam induced gas heating was not expected [14] at the low beam currents used in this experiment, this temperature value was included in the target density determinations.

After selecting a charge state (between 4^+ and 9^+, usually the most abundant) all beam transport elements were adjusted using the new charge state and an approximate transmitted beam energy value estimated with the SRIM program. This was followed by a renewed beam energy determination following the procedure described above.

5. Results and discussion

The difference in beam energies measured with and without gas constitutes the energy lost in the hydrogen gas. From the pressure readings and the known target length the areal target density was calculated for the extraction of the stopping power values. The above mentioned experimental errors were propagated. The total target thickness range used was between 3×10^{17} and 8×10^{18} hydrogen atoms/cm^2. Different measurements at the same energy were combined into one value. These results are depicted in Figs. 3–5 in comparison to the different calculations and previous measurements where they existed at higher or lower energies [15,16]. Data where several measurements existed from different beam times (sometimes several months apart) showed the good reproducibility of our results. The results of this experiment are generally in better agreement with the newer version of the SRIM code. In some cases energy losses were determined for more than one charge state of the transmitted ions. No charge state dependence was observed here in agreement with expectations [17,18], as our target thickness range was sufficient to reach charge state equilibrium in the first 20–30% of our target [19].

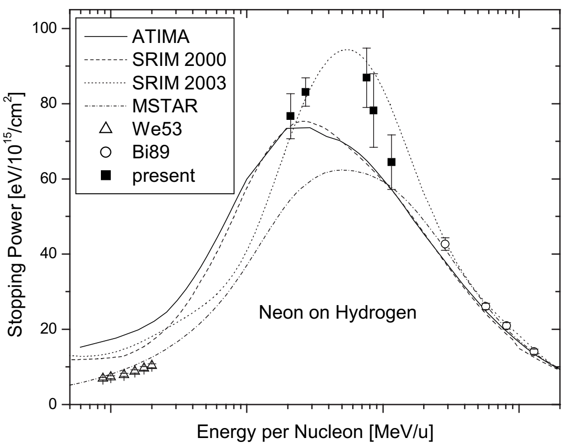

Fig. 3. Measured stopping power values for neon ions on gaseous hydrogen compared to values calculated with the various codes [1–4] and experimental data of [15,16].

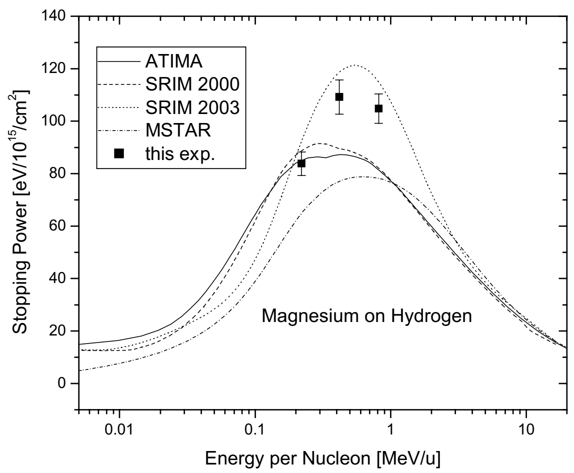

Fig. 4. Measured stopping power values for magnesium ions on gaseous hydrogen compared to values calculated with the various codes [1–4].

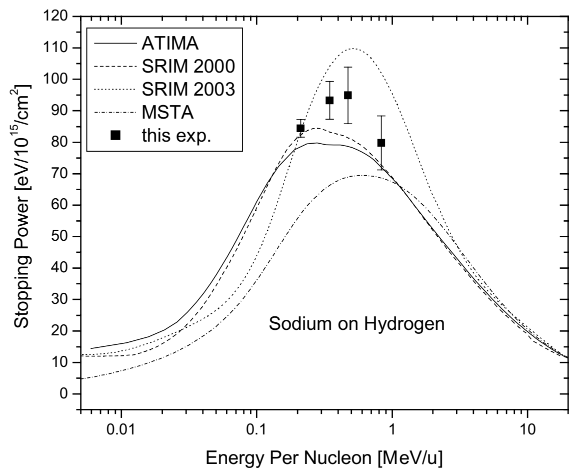

Fig. 5. Measured stopping power values for sodium ions on gaseous hydrogen compared to values calculated with the various codes [1–4].

6. Conclusion

Within the course of commissioning and radiative capture experiments with stable and radioactive ion beams (energy range 200–1150 keV/u), stopping power values for several heavy ion isotopes impinging on gaseous hydrogen were determined. The measured values were compared with four semi-empirical stopping power codes and favor the description given by the new SRIM 2003 version. Nevertheless, for the purposes of measuring resonance strengths relevant to nuclear astrophysics with gaseous hydrogen targets even the SRIM 2003 code deviates up to 20% from our measured values and constitutes the dominant error in this type of experiment if stopping power codes are used. This measurement constituted the first determination of stopping powers around the stopping power maximum for the ion/hydrogen target combinations presented. The stated precision and estimated accuracy is comparable to previous experiments with light gaseous targets [8].

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