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Energy loss of low energy Hydrogen and Helium ions in light gases

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ABSTRACT

The knowledge of stopping power in various combinations of ions and targets over a wide range of energies is necessary to extract the fundamental interaction cross section from measured yields in nuclear reactions. While, for many years, energy loss data has been measured, tabulated and incorporated in semi-empirical codes, specifically at low energies and for gaseous targets only few experiments have been performed. In this work, stopping power data of Hydrogen and Helium ions in the energy range below 25 keV traversing light gases were determined. Special emphasis was put on the energy loss of Hydrogen in Helium where a previous discrepancy between two publications was resolved and the range of measurement extended to the energies where the influence of nuclear stopping becomes apparent.

1. Introduction

Knowledge of stopping power or energy loss values is needed in the extraction of reaction cross sections or resonance strengths from experimental yields in measurements of low energy nuclear physics and astrophysics. While a significant amount of data exists for ions traversing solid targets, the lack of experiments involving gaseous targets has already previously led to significant corrections in semi-empirical stopping power codes once a new measurement was published. Additionally, the experiments in nuclear astrophysics require the energy loss information at energies far below the Bragg Peak where in static stellar burning phases light ions interact at kinetic energies of a few keV to a few 10's of keV. Measurements of the so-called electron screening effect in low energy nuclear reactions performed in the 1990's extracted with their data analysis in many cases higher screening potentials than deemed possible by atomic physics theory. One possible explanation would be that the stopping power values used (from various versions of the semi-empirical stopping power code SRIM [see SRI17]) were overestimating the real energy loss. In one case, the ^{3}He(d,p)^{4}He reaction was also used to determine stopping power at low energies from changes in the reaction yield as a function of beam energy and target pressure. The discrepant result from this method compared to a more conventional experiment measuring the velocities of H and D ions after traversing ^{4}He gas, provided an additional motivation for the work presented here. As can be seen in Fig. 1 (from Raiola et al. [28]), the stopping power in the Hydrogen on Helium system first follows the expected velocity dependent behavior at energies below the Bragg Peak. Going lower, a unique feature of this combination becomes apparent as a threshold where the single energy transfer from the energetic ion to an electron of the target is suppressed as no final state (in charge exchange) is energetically available. This threshold is seen in both previous measurements but below it the fall-off in stopping power is more significant in the Raiola data, even to the point where their result is below the expected nuclear stopping contribution (an outcome that has been deemed unlikely). Probing this system again (in a conventional stopping power experiment) provided the main motivation for this work, but, as can be seen below, the measurements were extended also to other ion/gas combinations where little or no data existed in our energy region of interest.

1.1. Theory

The energy loss of energetic ions in matter is typically tabulated and parametrized as a quantity in units of energy per distance as a so called stopping power. In order to account for different materials and densities more easily, the most commonly encountered unit is [eV/(10^{15}/cm^2)], in which some authors also term the quantity stopping cross section. In its theoretical description it was early realized that the stopping contribution from atomic electrons would, in most energy regimes, be significantly larger than the energy lost to the nucleus [7]. The so called electronic stopping power's dependence on ion energy was first described at higher velocities by Bohr exhibiting a slope decreasing with $1/v^2$ as depicted in Fig. 2. A quantum mechanical description covering the same energy regime was determined by Bethe [4] and refined by Bloch [5]. For the low energies covered in this work, Fermi and Teller [14] as well as Lindhard [21,22] and Firsov [15] described the stopping

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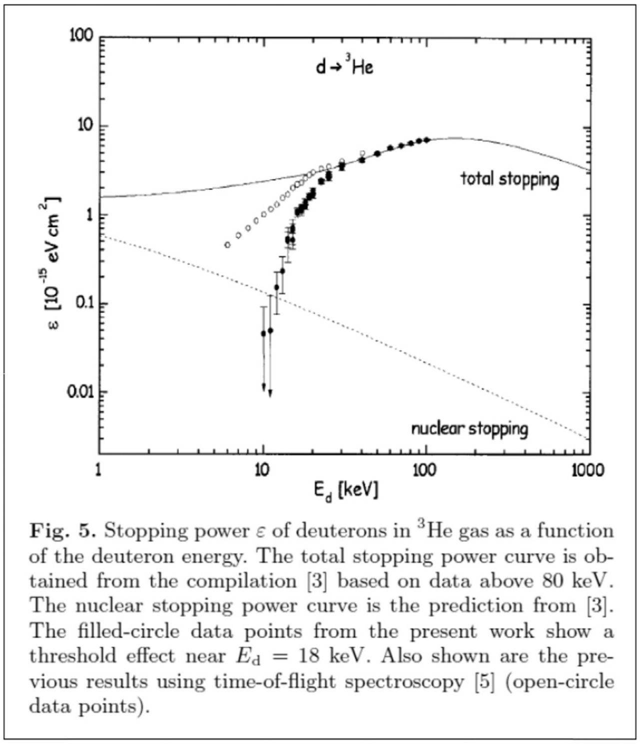

Fig. 5. Stopping power ε of deuterons in ^{3}He gas as a function of the deuteron energy. The total stopping power curve is obtained from the compilation [3] based on data above 80 keV. The nuclear stopping power curve is the prediction from [3]. The filled-circle data points from the present work show a threshold effect near $E_d = 18$ keV. Also shown are the previous results using time-of-flight spectroscopy [5] (open-circle data points).

Fig. 1. Fig. 5 from [28] showing the discrepancy in results between the conventional time-of-flight energy loss determination ([5] corresponds to Ref. [18]) and the reaction yield approach. The cited compilation is Ref. [1].

power with a linear velocity proportionality leaving the so called Bragg peak with the maximum in energy loss at energies of app. 100–200 keV/u for the light ion/gas combinations involved here.

Fermi and Teller had already noted that the linear dependence on velocity would not hold if there were a minimum energy required for energy exchange between the projectile and its target [14]. This energy gap would lead to a reduction in stopping power below a so termed threshold energy [14,23,20,33]. An example of a system in which a threshold effect should be apparent is the interaction of protons in noble gases like Helium and Neon. The proton (H^+) has an unfilled electron orbital with a potential of −13.6 eV, while the light noble gases have first ionization energies of −24.6 eV (He) and −21.6 eV (Ne). With the target atoms (in low ion beam power experiments) being neutral noble gas atoms, these energy values are the lowest that can be transferred via ionization. At the low energies covered here, the most probable method of energy loss is not ionization or excitation, but charge exchange [9,19]. This process, where in this case an electron transfers from a neutral noble gas atom (leaving it ionized) to a proton (producing a neutral Hydrogen projectile), is possible when the energy to overcome the energy gap (11 eV in He; 8 eV in Ne) is provided from the kinetic energy of the proton in collision with an atomic electron. In a simple classical description, the largest amount of energy (ΔK_{max}) that can be lost by a heavy particle (proton m_p) in a collision with a less massive partner (electron m_e) is given by the relation:

$$\Delta K_{max}/K_i = m_e/(m_e + m_p) = 1/1836 \text{ with } K_i \text{ the initial proton energy.} \tag{1}$$

This means in the case of H on He a threshold energy of app. 20 keV and for H on Ne of app. 15 keV would be expected. This approach appears to be confirmed by the previous experiments in the H on He case (Fig. 1) and was therefore included in the parametrizations of the widely used stopping power code SRIM [SRI17]. Fig. 3 shows the stopping cross section predicted by SRIM (version SRIM 12.03) for the H ion projectile measurements in this work. As can be seen, SRIM predicts a much weaker threshold effect in H on Ne based on the data points measured by Schiefermueller et al. [32] where, however, only one data point appears to be lower than the previous predictions. Additionally, due to the strong threshold effect in H on He, this is the only case where at keV energies the nuclear stopping component becomes competitive with electronic stopping and enticed this work to attempt a measurement into this nuclear stopping regime.

2. Experimental setup

2.1. Ion accelerator and pulse generator

The ion beams in this experiment were generated in the Colorado

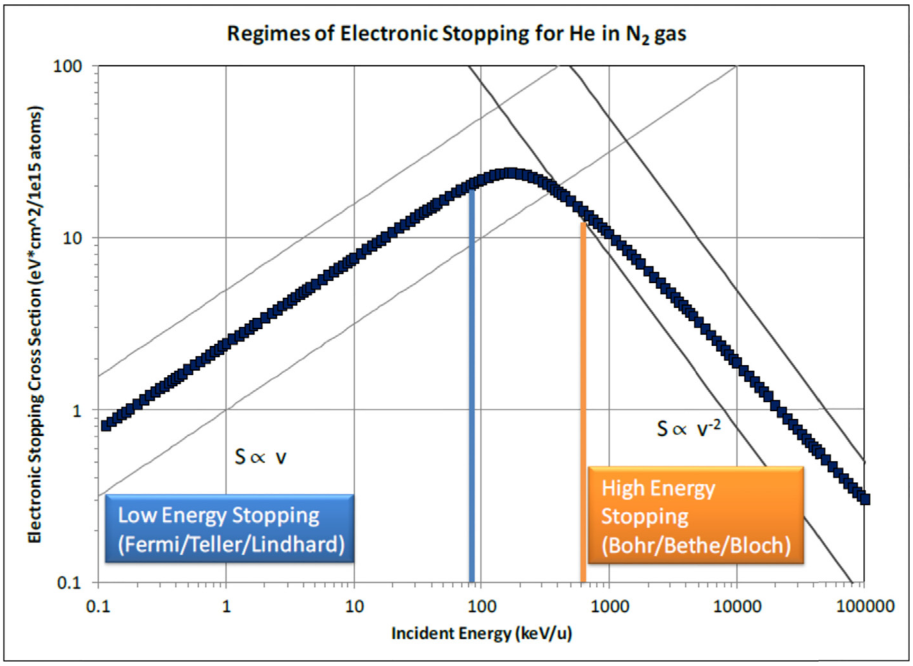

Fig. 2. Different velocity dependence regimes in the electronic stopping of He ions in nitrogen gas.