Eur. Phys. J. A **8**, 443–446 (2000)

The European Physical Journal A

Short note

Energy loss of deuterons in ^{3}He gas: a threshold effect

A. Formicola[1], M. Aliotta[1,a], G. Gyürky[2], F. Raiola[1], R. Bonetti[3], C. Broggini[4], L. Campajola[5], P. Corvisiero[6], H. Costantini[6], A. D'Onofrio[7], Z. Fülöp[2], G. Gervino[8], L. Gialanella[5], A. Guglielmetti[3], C. Gustavino[9], G. Imbriani[5,10], M. Junker[9], A. Ordine[5], P. Prati[6], V. Roca[5], D. Rogalla[1], C. Rolfs[1,b], M. Romano[5], F. Schümann[1], E. Somorjai[2], O. Straniero[11], F. Strieder[1], F. Terrasi[7], H.P. Trautvetter[1], and S. Zavatarelli[6]

[1] Institut für Physik mit Ionenstrahlen, Ruhr-Universität Bochum, Bochum, Germany
[2] Atomki, Debrecen, Hungary
[3] Dipartimento di Fisica, Universita di Milano and INFN, Milano, Italy
[4] INFN, Padova, Italy
[5] Dipartimento di Scienze Fisiche, Universita Federico II and INFN, Napoli, Italy
[6] Dipartimento di Fisica, Universita di Genova and INFN, Genova, Italy
[7] Dipartimento di Scienze Ambientali, Seconda Universita di Napoli, Caserta and Napoli, Italy
[8] Dipartimento di Fisica Sperimentale, Universita di Torino and INFN, Torino, Italy
[9] Laboratori Nazionali del Gran Sasso dell`INFN, Assergi, Italy
[10] Osservatorio Astronomico di Capodimonte, Napoli, Italy
[11] Osservatorio Astronomico di Collurania, Teramo, Italy

Received: 16 May 2000 / Revised version: 29 August 2000
Communicated by B. Povh

Abstract. The energy loss of deuterons in ^{3}He gas was measured at $E_{\rm d}$ = 15 to 100 keV using the ^{3}He pressure dependence of the ^{3}He(d,p)^{4}He cross-section at a given incident energy. At the highest energies, the observed energy loss is in good agreement with a standard compilation. However, with decreasing energy the experimental values drop steadily below the theoretical values and near $E_{\rm d}$ = 18 keV they drop sharply (within 1 keV) reaching the domain of nuclear stopping power. This threshold behavior is due to the minimum $1s \rightarrow 2s$ electron excitation of the He target atoms, *i.e.* it is a quantum effect. Some consequences are discussed.

PACS. 26.20.+f Hydrostatic steller nucleosynthesis – 34.50.Bw Energy loss and stopping power

Due to the Coulomb barrier of the entrance channel, the cross-section $\sigma(E)$ of a fusion reaction drops exponentially with decreasing center-of-mass energy E,

$$\sigma(E) = S(E)E^{-1}\exp(-2\pi\eta), \tag{1}$$

where η is the Sommerfeld parameter and $S(E)$ is the astrophysical S-factor [1,2]. For absolute $\sigma(E)$ measurements at sub-Coulomb energies, an accurate knowledge of the effective beam energy associated with the observed reaction yield is as important as the yield measurements themselves. In the analysis of such data, the effective energy in the target involves always energy loss corrections, which are extracted from a standard compilation [3]. The compilation is based on experimental data down to energies around the Bragg peak, while at lower energies—relevant to nuclear astrophysics—the experimental data are extrapolated with theoretical guidance. In recent studies of the d(^{3}He,p)^{4}He reaction (Q = 18.4 MeV) at the LUNA facility [4], the observed energy loss of ^{3}He ions in D_2 molecular gas was in good agreement with the extrapolated values of the compilation. For studies of the inverted reaction, *i.e.* ^{3}He(d,p)^{4}He, energy loss data are needed for hydrogen ions in He gas: measurements—using time-of-flight spectrometry—indicated [5] significantly lower values than tabulated [3], *e.g.*, a factor 3 lower at a deuteron energy $E_{\rm d}$ = 8 keV. As part of an ongoing astrophysical program, we restudied the ^{3}He(d,p)^{4}He low-energy cross-section including a measurement of the associated energy loss [6]. We report here on the latter part only.

Since a deuteron beam is not allowed at the underground laboratory of Gran Sasso, we carried out the measurements at the 100 kV accelerator of the Ruhr-Universität Bochum [7] involving however the LUNA setup [8–10]. Briefly, the absolute incident deuteron energy, $E_{\rm d}$ = 15 to 100 keV, was known to a pre-

[a] Alexander von Humboldt Fellow
[b] e-mail: rolfs@ep3.ruhr-uni-bochum.de

cision of 5×10^{-5}. The beam entered the target chamber of a differentially pumped gas-target system through 3 apertures (A_1, A_2, and A_3) of high gas-flow impedance (respective diameters = 15, 10, and 7 mm; respective lengths = 80, 80, and 60 mm) and was stopped in a 4 W calorimeter with an active area of 3.5 cm diameter: maximum beam current $\approx 30\,\mu$A at $E_d = 30$ keV. The ^{3}He gas pressure in the target chamber, $P \leq 0.50$ mbar, was measured with a Baratron capacitance manometer to a relative accuracy of better than 0.2%. The ^{3}He gas was recirculated and cleaned using a zeolite trap; the resulting gas composition was monitored with a mass spectrometer: no contaminants could be observed ($\leq 0.1\%$). Beam-heating effects on the gas density were included by a 0.2% accidental error. For $P = 0.50$ mbar, the system reduced the pressure to 6×10^{-4}, 2×10^{-5}, and 7×10^{-7} mbar in the regions between the apertures A_3 and A_2, A_2 and A_1, and beyond A_1, respectively. The main pressure drop occurred across the entrance aperture A_3, while the extended target zone between A_3 and the calorimeter (length $d = 43.0 \pm 0.1$ cm) was characterized by a constant gas pressure. The beam diameter near the calorimeter was investigated by moving a shadowing plate into the beam envelope; at $E_d = 18$ keV and $P = 0.50$ mbar, the total beam current (more than 99.9%) had a diameter of 2.0 cm, which was consistent with visual inspection. For each run, the average power deposited by the beam on the calorimeter was deduced from the difference between transistor powers needed to keep the beam dump at the same temperature, with the beam off and on. The statistical error on the measured power difference was obtained by adding in quadrature the errors on the measured powers (typically 0.5% total error). The detector setup consisted of eight, 1 mm thick Si detectors of $5 \times 5\,\text{cm}^2$ area (each) placed around the beam axis: they formed a 12 cm long parallelepiped in the target chamber. The center of the 4 upstream detectors had a distance $z_d = 7.0 \pm 0.1$ cm from that of the 4 downstream detectors. Each detector was shielded by a 200 μm thick Al foil in order to stop the ^{4}He ejectiles, the elastic scattering products, and the light induced by the beam. In going through the gas of the target chamber, the beam experienced an energy loss to the middle of the detector setup, at a distance $z = 18.5 \pm 0.1$ cm from the middle of the entrance aperture A_3. Dead time effects in the detectors were monitored using a pulser and were kept below 3%.

At a given incident energy E_d, the reaction yield $Y(E_d, P) = N/WP$ was obtained as a function of gas pressure, where N is the number of observed protons from ^{3}He(d,p)^{4}He (in the detector setup) and W is the integrated beam power (deduced from the calorimeter). The yield is related to the cross-section $\sigma(E_d, P)$, for which one arrives—from a Taylor expansion of eq. (1) and the yield definition—at the expression

$$\alpha Y(E_d, P) = \frac{1 + \epsilon(E_d)\rho_o dP}{P_o E_d} \frac{\sigma(E_d, P)}{\sigma(E_d, P \to 0)} = \frac{1 - \epsilon(E_d)\rho_o z(\pi\eta - 1)P}{P_o E_d}, \tag{2}$$

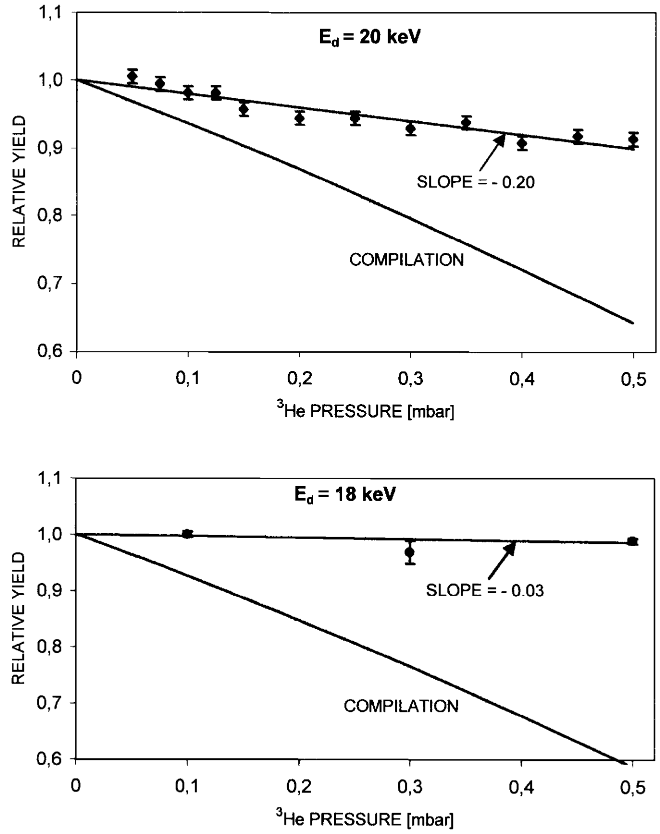

Fig. 1. Relative yield of ^{3}He(d,p)^{4}He as function of ^{3}He gas pressure at $E_d = 20$ and 18 keV, *i.e.* around the calculated 18.2 keV threshold. The solid lines through the data points are fits assuming a linear pressure dependence, where the resulting slopes are given. The expected pressure dependence according to the energy loss values from the compilation [3] is also shown.

where α is a normalisation constant, $\epsilon(E_d)$ is the energy loss of deuterons in the atomic ^{3}He gas, ρ_o and P_o are the density and pressure of the ^{3}He gas at STP, respectively, and the symbol $P \to 0$ indicates the limit of zero pressure. The term $(1 + \epsilon(E_d)\rho_o dP/P_o E_d)$ corrects for the energy loss of the beam arriving at the calorimeter. Equation (2) assumes a negligible energy dependence of $S(E)$ and $\epsilon(E)$ over the energy range of the target thickness, which is well fulfilled. Since relative values of the cross-section are involved here, only statistical errors have to be included in the analysis. The examples shown in fig. 1 led to $\epsilon(E_d) = 1.2 \pm 0.2$ and 0.11 ± 0.07 (10^{-15} eVcm^2) at $E_d = 20$ and 18 keV, respectively. An alternative way of data analysis consisted in taking solely the ratio of number of counts between the downstream and upstream detectors, which is described by eq. (2) with $z = 18.5$ cm replaced by $z_d = 7.0$ cm; the analysis provided consistent results within experimental uncertainties. The derived results were checked using Monte Carlo simulations [6,8–10]. The deduced average energy loss values are compared in fig. 2 with the values from the compilation [3].

The present energy loss values and their energy dependence are significantly different from those reported [5]; this discrepancy is not understood. The present data

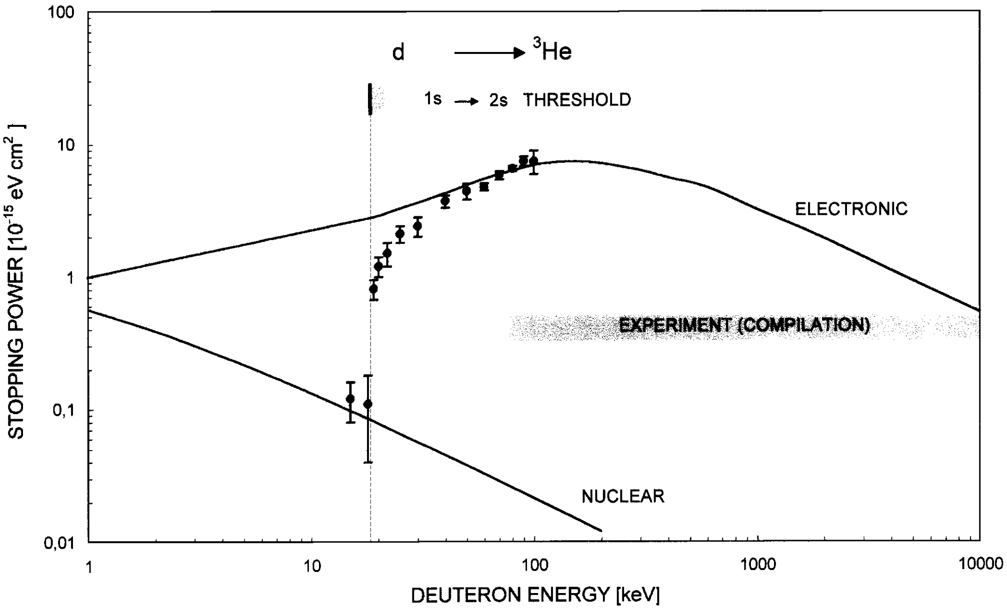

Fig. 2. Energy loss of deuterons in ^{3}He gas as function of deuteron energy. The "electronic" curve represents the electronic stopping power from the compilation [3] based on data above 80 keV (shadowed box) and the "nuclear" curve is the expected nuclear stopping power [3]. The present data show a threshold effect in the electronic stopping power at $E_\mathrm{d} = 18\,\mathrm{keV}$.

(fig. 2) show a threshold behavior near $E_\mathrm{d} = 18\,\mathrm{keV}$, where the values reach the domain of nuclear stopping power. The threshold in the electronic stopping power arises from the minimum energy transfer $E_\mathrm{e,min}$ in the $1s \to 2s$ electron excitation of the He target atoms, $E_\mathrm{e,min} = 19.8\,\mathrm{eV}$, which translates into a minimum deuteron energy $E_\mathrm{d,min} = (m_\mathrm{d}/4m_\mathrm{e})(1 + m_\mathrm{e}/m_\mathrm{d})^2 E_\mathrm{e,min} = 18.2\,\mathrm{keV}$ (m_d = deuteron mass, m_e = electron mass). Below this energy, the electron cloud of the He atom cannot be excited *via* an ion-electron interaction and thus the electronic energy loss vanishes leaving solely the nuclear stopping power. Between $E_\mathrm{e,min}$ and the ionisation energy $E_\mathrm{i} = 24.6\,\mathrm{eV}$ (corresponding to $E_\mathrm{d} = 22.6\,\mathrm{keV}$) many electronic states in the He atom can be excited leading to the steep rise in the electronic stopping power near these deuteron energies. To our knowledge, a sharp threshold effect in the energy loss behavior—as seen in fig. 2—has not been predicted. A threshold effect has been discussed for the energy loss of protons in Ne gas [11], however these theoretical studies led to an electronic energy loss which depended on the square of the projectile velocity, *i.e.* no sharp threshold was predicted. The threshold behavior seen in fig. 2 is a quantum effect and may be compared in a way with superconductivity.

In principle, the observed threshold behavior should occur in many ion-target combinations. For the case of ^{3}He ions in D_2 molecular gas, the D_2 molecule can be dissociated involving an energy of about 0.6 eV with a corresponding threshold energy near $E_{^3\mathrm{He}} = 0.8\,\mathrm{keV}$; above this energy one may expect no significant deviation from the compilation, as observed [4]. In metallic targets, there should be no threshold effect at all since the electrons can be excited continuously within overlapping or partially filled energy bands. However, in insulators or semiconductors with separated band gaps, *e.g.*, about 10 eV for diamond, the threshold effect should exist and is—for Al implantation in diamond—at $E_\mathrm{Al} = 120\,\mathrm{keV}$. Indeed, the range of low-energy ion implantation has been observed to be larger than expected and was suggested as arising from channeling effects; the present work offers an alternative explanation.

Below a given threshold energy, one has the possibility to measure directly—and to our knowledge for the first time—the nuclear stopping power (fig. 2), which may help to improve the quantitative understanding of this process. In turn, the process is the basis of many ion-beam applications in materials science such as sputtering and angle-straggling effects in implantation. Precise measurements require however a dedicated setup, such as the availability of a low-energy accelerator (*i.e.* 20 kV) with high beam transmission and a different detector geometry. Alternative experimental techniques as well as some interesting ion-target combinations are discussed elsewhere [6].

The observed threshold behavior may have important consequences in nuclear astrophysics, *i.e.* the properties of a stellar plasma, where the chemical elements are present in form of atoms and assumed to be nearly fully ionized, with thermal energies of $kT = 1.3\,\mathrm{keV}$ at the solar center. However, rigorous consequences have to await the results of detailed calculations.

The paper has been Supported in part by BMBF (06BO812), DFG (436UNG113-127) and OTKA (T025465).

References

1. W.A. Fowler, Rev. Mod. Phys. **56**, 149 (1984).

2. C. Rolfs, W.S. Rodney, *Cauldrons in the Cosmos* (University of Chicago Press, 1988).
3. H. Andersen, J.F. Ziegler, *The Stopping and Ranges of Ions in Matter* (Pergamon, New York, 1977) and SRIM-2000.
4. H. Costantini *et al.*, Phys. Lett. B, **482**, 43 (2000).
5. R. Golser, D. Semrad, Phys. Rev. Lett. **66**, 1831 (1991).
6. A. Formicola *et al.*, to be published.
7. A. Krauss *et al.*, Nucl. Phys. A **465**, 150 (1987).
8. C. Arpesella *et al.*, Nucl. Instrum. Meth. A **360**, 607 (1995).
9. M. Junker *et al.*, Phys. Rev. C **57**, 2700 (1998).
10. R. Bonetti *et al.*, Phys. Rev. Lett. **82**, 5205 (1999).
11. D. Semrad, Phys. Rev. A **33**, 1646 (1986).