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Stopping power, electron screening and the astrophysical $S(E)$ factor of d(^{3}He,p)^{4}He [1]

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Abstract

The d(^{3}He,p)^{4}He cross section has been measured at $E = 4.2$ to 13.8 keV using the LUNA underground accelerator facility. The experiment was performed to determine the magnitude of the atomic screening effect and to establish values for the energy loss used in data reduction. The observed stopping power of the ^{3}He ions in the D_2 target is in good agreement with the standard compilation. Using these stopping power values the data lead to an electron-screening potential energy

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$U_e = 132 \pm 9$ eV, which is significantly higher than the estimated value of 65 eV from an atomic-physics model. Published by Elsevier Science B.V.

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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,

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

where η is the Sommerfeld parameter and $S(E)$ is the astrophysical S factor. The parametrisation assumes that the Coulomb barrier is that resulting from bare nuclei. However, for nuclear reactions studied in the laboratory, the target nuclei and the projectiles are usually in the form of neutral atoms or molecules and ions, respectively. The resulting enhancement of the electron-screened cross section, $\sigma_s(E)$, over that for bare nuclei, $\sigma_b(E)$, is described by the expression [1–3]:

$$\frac{\sigma_s(E)}{\sigma_b(E)} = \frac{S_s(E)}{S_b(E)} = \frac{E}{E+U_e} \exp(\pi\eta U_e/E), \qquad (2)$$

where U_e is assumed to be a constant electron screening potential energy.

The exponential enhancement has been observed in several fusion reactions [4–10], at energies from a few keV to a few tens of keV. However, the observed enhancements were significantly larger than could be accounted for from the adiabatic limit, i.e. the difference in electron binding energies between the colliding atoms and the compound atom. The most pronounced excess has been reported for the ^{3}He(d,p)^{4}He reaction (Q = 18.4 MeV), $U_e = 186 \pm 9$ eV [7], significantly larger than the adiabatic limit $U_e = 120$ eV. In the analysis of such data, the effective energy in the target has to be known precisely and always involves energy-loss corrections. In [5], the authors used energy-loss values for deuterons in helium as tabulated [11], which were derived by extrapolation of data for deuterons above 100 keV to lower energies. However, new energy-loss measurements of low-energy protons and deuterons in a helium gas yielded [12] significantly lower values than tabulated [11], e.g. a factor 3 lower at a deuteron energy $E_d = 8$ keV. Using these lower values, a reanalysis of the ^{3}He(d,p)^{4}He data led [13] to $U_e = 134 \pm 8$ eV, in fair agreement with the adiabatic limit. It is not clear whether this solution is also applicable to other reaction studies, due to the lack of experimental energy-loss data at the relevant low energies. For example, for the inverted reaction, d(^{3}He,p)^{4}He, a value of $U_e = 123 \pm 9$ eV has been reported [7], while the united-atom model (including a Coulomb-explosion process of the D_2 target molecules) led to the estimate $U_e \approx 65$ eV [4]. More recent theoretical estimates of the screening effect on molecular targets [14] show a dependence on the molecular orientation. For the d + d system a larger screening potential energy has been found for molecular targets with respect to atomic ones, but this is not expected to hold in the general case [14].

As part of an ongoing program on electron-screening effects, we have restudied at the LUNA underground accelerator facility, situated at the Laboratori Nazionali del Gran Sasso (LNGS), the d(^{3}He,p)^{4}He low-energy cross section including an estimate of the associated energy loss (stopping power). Technical details of the LUNA facility have been reported [3,7,9,15]. Briefly, the 50 kV accelerator facility consists of a duoplasmatron ion source, an extraction and acceleration system, a double-focusing 90° analysing magnet, a gas-target system, and a beam calorimeter. The whole setup is situated in the underground laboratory of the LNGS to minimize the influence of cosmic rays on the detectors. The ^{3}He beam energy ranged from $E_b = 11$ to 35 keV with a spread less than 20 eV and 60 μA maximum current. The high voltage of the accelerator was measured to a precision of 5×10^{-5} using a calibrated resistor chain. The beam entered the target chamber of the differentially pumped gas-target system through 3 apertures (A_1, A_2, and A_3) of high gas-flow impedance (respective diameters = 25, 20, and 7 mm; respective lengths = 80, 80, and 60 mm) and was stopped in the calorimeter. The D_2 gas pressure in the target chamber, $p = 0.05$ to 0.30 mbar, was measured with a Baratron capacitance manometer with a relative accuracy of 1% and an absolute accuracy of 1%. Beam-heating effects on the gas density have been included by an additional 1% accidental error. For $p = 0.30$ mbar, the system reduced the pressure to 1×10^{-6} mbar in the region of the analysing magnet. The main pressure drop occurred across the entrance aperture into the gas target cell (A_3), while the geometrically extended target zone between A_3 and the calorimeter (length $= 33.2 \pm 0.1$ cm) was characterized by a constant gas pressure. For each run, the power deposited by the beam on the calorimeter was deduced from the difference between powers needed to keep a power transistor at the same temperature as the beam dump, with the beam off and on. The statistical error on the measured power difference was obtained by adding in quadratures the errors on the measured powers (0.5% relative error each), while a systematical error of 2% on the beam power was also taken into account. Finally, the beam power was converted into beam current using the beam energy at the calorimeter, i.e. the incident energy minus the energy loss in the whole target gas; the uncertainty in the latter quantity was – for all incident energies – negligible with respect to the accuracy of the beam power.

The detector setup consisted of eight, 1 mm thick Si detectors of 5×5 cm^2 area (each) placed around the beam axis: they formed a 14 cm long parallelepiped in the target chamber. Each detector was shielded by a 27 μm thick Al foil in order to stop the ^{4}He ejectiles, the elastic scattering products, and the light induced by the beam. Since the thickness of the Si detectors was smaller than the range of the 14 MeV protons from the studied nuclear reaction, protons at normal incidence to the detectors gave rise to a continuous spectrum ranging from 5 to 14 MeV, while those incident near glancing angles exhibited a narrow peak structure near 14 MeV similar to [7]. Due to the clean spectra obtained at $E_b \geq 19$ keV, the reaction yield was derived from all counts above 4.5 MeV. The corresponding detection efficiency, $\eta = 0.259 \pm 0.005$, was calculated with a Monte Carlo simulation [16]. At $E_b < 19$ keV, the low-energy part of the spectra was contaminated by background events and electronic noise. In this case only the counts in the high-energy proton peaks were analysed using $\eta = 0.101 \pm 0.004$. The latter efficiency was calculated by the formula:

$$\eta = \sum_{i=1}^{8} \eta_i f_i , \tag{3}$$

where η_i is the total efficiency of the i-th detector as obtained by Monte Carlo simulation and f_i is the ratio between the counts in the peaks region and in the whole spectrum. The f_i coefficients where measured by high statistics runs and include several

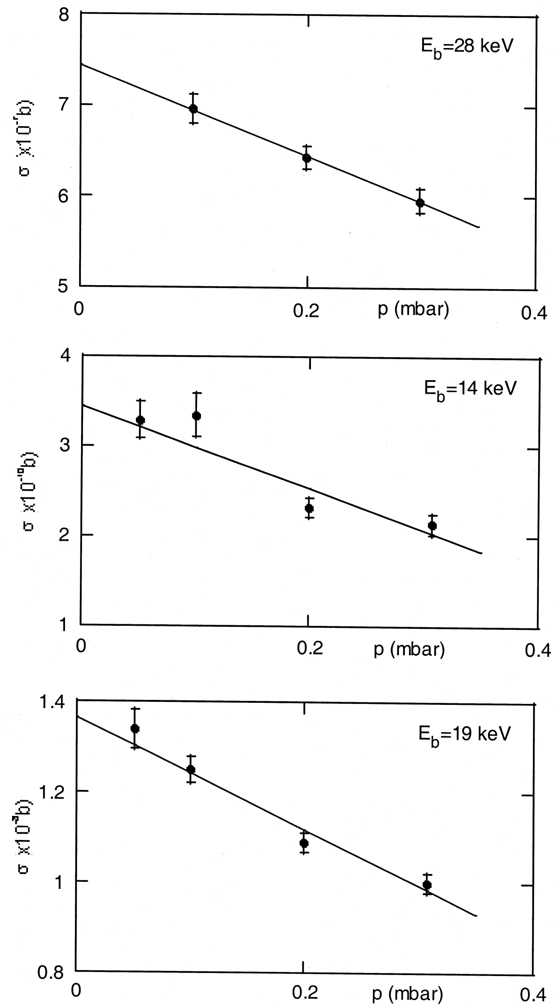

Fig. 1. Reaction yield (cross section) of d(^{3}He,p)^{4}He as a function of D_2 gas pressure p is shown for three different incident ^{3}He energies E_b. The straight lines assume a linear dependence.

Table 1
Excitation function of d(^{3}He,p)^{4}He

E_b [a] (keV)	p [b] (mbar)	E [c] (keV)	$S(E)$ (MeV b)	$\Delta S(E)$ [d] (MeV b)	$\Delta S(E)$ [e] (MeV b)
10.98	0.30	4.22	9.70	1,65	0,79
11.92	0.30	4.59	9.00	0.67	0.69
11.93	0.10	4.71	8.09	0.62	0.41
12.90	0.30	5.00	8.95	0.70	0.60
12.89	0.10	5.09	9.82	1.01	0.49
13.94	0.30	5.37	8.86	0.48	0.64
13.95	0.20	5.44	8.01	0.39	0.47
13.95	0.10	5.51	9.68	0.70	0.48
13.94	0.05	5.54	8.87	0.55	0.42
14.94	0.30	5.77	8.99	0.31	0.62
14.93	0.20	5.83	8.93	0.36	0.52
14.93	0.10	5.90	8.74	0.25	0.44
14.93	0.05	5.93	8.31	0.55	0.39
15.96	0.20	6.23	8.15	0.29	0.46
15.93	0.10	6.31	8.10	0.23	0.39
16.91	0.30	6.52	8.26	0.48	0.55
16.97	0.30	6.57	8.03	0.26	0.51
16.94	0.10	6.72	8.32	0.16	0.40
17.92	0.30	7.00	7.90	0.27	0.44
17.88	0.20	7.07	8.32	0.28	0.40
18.92	0.30	7.34	7.70	0.16	0.37
18.87	0.20	7.40	7.69	0.15	0.30
18.85	0.10	7.46	7.90	0.18	0.26
18.90	0.05	7.52	7.83	0.26	0.24
20.90	0.30	8.12	7.31	0.11	0.33
20.89	0.20	8.19	7.31	0.25	0.28
20.94	0.20	8.22	7.43	0.24	0.28
20.93	0.10	8.29	7.85	0.24	0.25
20.94	0.05	8.34	7.51	0.22	0.23
21.90	0.30	8.51	7.38	0.22	0.33
21.91	0.20	8.60	7.65	0.23	0.28
21.96	0.10	8.71	7.82	0.28	0.25
22.87	0.20	8.98	7.36	0.19	0.27
22.91	0.10	9.08	7.66	0.17	0.25
22.96	0.05	9.14	7.60	0.24	0.23
23.87	0.30	9.29	7.54	0.23	0.33
23.89	0.20	9.38	7.47	0.14	0.27
23.90	0.10	9.48	7.59	0.13	0.24
24.90	0.20	9.78	7.32	0.22	0.26
24.88	0.10	9.87	7.52	0.19	0.24
24.89	0.05	9.91	7.24	0.18	0.22
25.88	0.30	10.07	7.39	0.19	0.31
25.91	0.20	10.18	7.35	0.14	0.26
25.94	0.10	10.29	7.44	0.17	0.23
27.90	0.30	10.87	7.38	0.16	0.30
27.89	0.20	10.96	7.35	0.13	0.26
27.87	0.10	11.05	7.41	0.17	0.23
29.86	0.30	11.65	7.24	0.14	0.28
29.95	0.20	11.78	7.21	0.12	0.25
29.88	0.10	11.85	7.35	0.11	0.23
31.91	0.30	12.41	7.58	0.14	0.30
31.88	0.20	12.55	7.31	0.13	0.25

Table 1 (continued)

E_b [a] (keV)	p [b] (mbar)	E [c] (keV)	$S(E)$ (MeV b)	$\Delta S(E)$ [d] (MeV b)	$\Delta S(E)$ [e] (MeV b)
31.87	0.10	12.65	7.31	0.14	0.23
32.93	0.10	13.07	7.36	0.13	0.23
34.84	0.10	13.83	7.23	0.13	0.22

[a] Incident ^{3}He energy.
[b] D_2 gas pressure in the target chamber.
[c] Effective energy within the target (center-of-mass system).
[d] Accidental error.
[e] Systematical error.

effects such as dead layers, thickness inhomogeneity, etc. hardly to be realistically simulated.

Passing through the gas of the target chamber, the beam experienced a mean energy loss ΔE to the middle of the detector setup (at a distance of $z_{av} = 12.0 \pm 0.1$ cm from the middle of the entrance aperture A_3). This was taken into account by introducing an effective energy $E_{eff} = E$ corresponding to the mean value of the beam energy distribution in the detector setup, evaluated by Monte Carlo simulations for each accelerating voltage. Values for ΔE were derived from [11], where a 5% uncertainty of ΔE was propagated to derive the systematic error of E_{eff}. At subcoulomb energies the assumed ΔE values influence strongly the final results: for example, at $E = 8$ keV the above uncertainty in ΔE translates into an uncertainty in E of 0.3%, which in turn contributes a 3.5% error to the $S(E)$ value.

If one measures, at a given incident energy E_b, the reaction yield or, equivalently, the cross section $\sigma(E_b, p)$ as a function of gas pressure p, one arrives from a Taylor expansion of Eq. (1) to the expression

$$\sigma(E_b, p) = \sigma(E_b, p=0) \times \left[1 - \frac{\varepsilon(E_b)\,\rho_0\, z_{av}}{p_0 E_b} (\pi\eta - 1)\, p + \dots \right], \tag{4}$$

where $\varepsilon(E_b)$ is the energy loss (stopping power) of ^{3}He ions in the D_2 gas, and ρ_0 and p_0 are the density and pressure of the D_2 gas at STP, respectively. Eq. (4) assumes a negligible energy dependence of the $S(E)$ factor and of the energy loss $\varepsilon(E)$ over the energy range of the target thickness, which is well fulfilled. Using for $\sigma(E_b, p = 0)$ the intercept a of the experimental $\sigma(E_b, p)$ data and for $d\sigma/dp$ the slope b of these data, one arrives at the energy loss value

$$\varepsilon(E_b) = \frac{b}{a} E_b \frac{RT}{M z_{av} (\pi\eta - 1)}, \tag{5}$$

where R, T, and M are the gas constant, absolute gas temperature, and molecular weight of the D_2 gas, respectively. The values for a and b have been extracted from a linear fit of the $\sigma(E_b, p)$ data. Since only relative values of the cross section are involved here, only statistical errors have to be included in this analysis. The examples shown in Fig. 1 led to energy loss values $\varepsilon(E_b) = 0.89 \pm 0.10$, 0.94 ± 0.11, and 1.28 ± 0.37 keV/μg/cm^2 at $E_b = 14$, 19, and 28 keV, respectively, in good agreement with the respective values 0.85, 0.99, and 1.19 keV/μg/cm^2 from the compilation [11]. These and other results (see below) give confidence that the deduced $S(E)$ factors are not seriously affected by systematic errors arising from an incomplete knowledge of the relevant energy-loss data.

The cross section values measured at $E = 4.2$ to 13.8 keV ($\sigma(E) = 6.7$ pb to 4.9 μb) are summarized in form of the $S(E)$ factor in Table 1 and displayed in Fig. 2. The data include measurements at the same incident energy and different gas pressures, which were corrected for the associated energy loss using the compiled values [11]. Within statistical errors, the $S(E)$ factors are independent of gas pressure and this again indicates that the used energy loss values are correct within our experimental accuracy.

Previous data [4,7,17,18], normalized as described in the following, are also shown in Fig. 2. For the analysis of electron screening effects, one must ex-

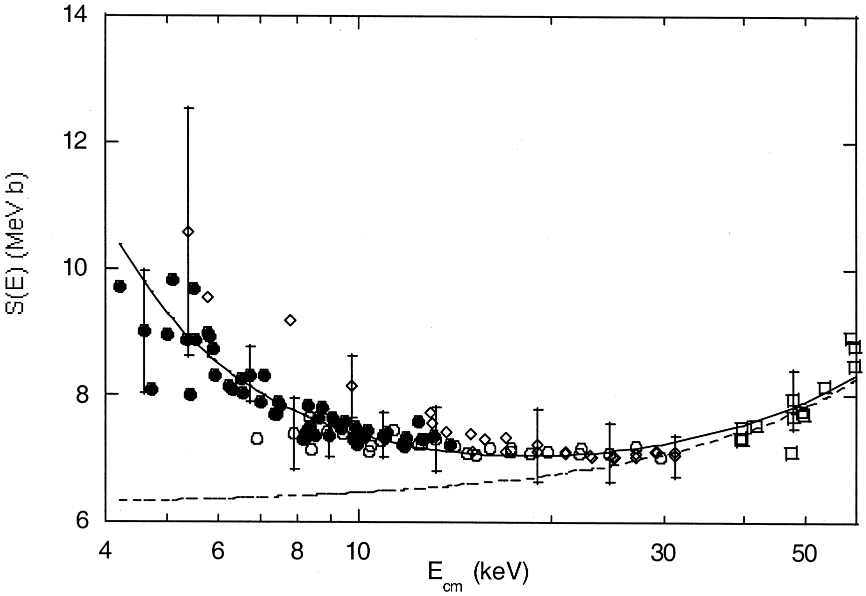

Fig. 2. $S(E)$ factor data for the d(^{3}He,p)^{4}He reaction from previous work ([4]: open points; [7] : open diamonds; [18] : open squares), normalized by a fitting procedure, and present work (filled-in points). Accidental and systematical errors, added in quadratures, are shown only for a few points. The dashed curve represents the $S(E)$ factor for bare nuclei and the solid curve that for shielded nuclei with U_e = 132 eV.

trapolate the bare cross section $\sigma_b(E)$ at high energies ($E > 30$ keV) to low energies. This extrapolation appears to be sufficiently under control. For example, the parametrisation [19] of the available data for energies E = 40 keV to 10 MeV predicts an $S_b(E)$ factor at low energies, which agrees well with the one calculated in a microscopic cluster model [20]. Recent measurements at E = 36 to 385 keV included also a polarized deuteron beam [21] and led to a consistent $S_b(E)$ energy dependence at low energies, which we have adopted: $S_b(E) = 6.70 + 2.43 \times 10^{-2} E + 2.06 \times 10 - 4E^2$ MeV b (with E in keV). With this $S_b(E)$ function (including a free normalisation factor N) and Eq. (2), the resulting fit of the data at $E \leq 60$ keV (Fig. 2) led to U_e = 132 eV $\pm$ 0.3 eV (statistical) $\pm$9 eV (systematical), $N =$ 0.93 $\pm$ 0.01 (statistical) $\pm$0.07 (systematical) and a reduced χ^2 = 2.07. In the fit, present data and those in [4,7] were considered, together with the subset in [18] with $30 < E <$ 60 keV. Statistical errors only were taken into account in the fit. Each data set has been normalized with a proper constant determined by the χ^2 minimization procedure. In this way, the effects of systematical uncertainties on the four data sets on U_e are reduced. Normalization constants turned out to be within the systematical errors quoted by each author [4,7,18]. The corresponding $S(E)$ factor curves for bare and shielded nuclei are shown in Fig. 2 as dashed and solid curves, respectively. The experimental U_e value is much larger than the expected value of 65 eV predicted with inclusion of the Coulomb explosion effect, but in agreement with the value calculated for the atomic case. Calculations reported in [14] lead to a small momentum transfer to the spectator nucleus, so that the decrease in screening energy due to the breaking of a molecular bond should be negligible. According to the same calculations, such a decrease for a molecular target with respect to the atomic case could derive from the angle dependence of the screening energy and the subsequent angle-averaging procedure. The latter effect has not been investigated experimentally in detail so far. A similar experiment of ^{3}He(d,p)^{4}He, where Coulomb explosions effects are not present, including energy-loss measurements, is in progress.

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