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ASTROPHYSICAL $^{3}\mathrm{He(d,p)}^{4}\mathrm{He}$ CROSS SECTION AND THE ELECTRON SCREENING WITH LOSSES OF ENERGY

DHARMESH KHARE

Research Scholar, Jodhpur Natioanl University,

Jodhpur, INDIA

Abstract:

We reanalyze the low-energy $^{3}\mathrm{He(d,p)}^{4}\mathrm{He}$ cross section measurements of Engstler et al. using recently measured energy loss data for proton and deuteron beams in a helium gas. Although the new $^{3}\mathrm{He(d,p)}^{4}\mathrm{He}$ astrophysical S-factors are significantly lower than those reported by Engstler et al., they clearly show the presence of electron screening effects. From the new astrophysical S-factors we find an electron screening energy in agreement with the adiabatic limit.

OVERVIEW

The penetration through the Coulomb barrier forces the (non-resonant) cross section $\sigma(E)$ between charged particles to drop exponentially with decreasing energy E. (Energies are in the center-of-mass system throughout this paper.) As a consequence, the cross section at the very low energies at which stellar hydrostatic burning takes place is in most cases too small to be measured directly in the laboratory. It is therefore customary in nuclear astrophysics to measure cross sections to energies as low as possible and then to extrapolate the data to the energy appropriate

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for the astrophysical application. Conventionally this extrapolation is performed in terms of the astrophysical S-factor defined (in a model-independent way) by

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

where $\eta(E) = Z_1 Z_2 e^2 \sqrt{\mu/E}$ is the Sommerfeld parameter for initial nuclei of charges Z1; Z2 and reduced mass μ. The exponential Gamow-factor in Eq. (1) describes the s-wave penetration through the Coulomb barrier of point-like charges and thus accounts for the dominant energy dependence of the cross section at energies far below the Coulomb barrier. Additional energy dependences due to nuclear structure, strong interaction, phase space, finite nuclear size, etc. are expected to leave the S(E)-factor a slowly varying function of energy for non-resonant reactions.

It is common strategy in nuclear astrophysics to reduce the uncertainties related to the extrapolation of the S(E)-factor by pushing laboratory measurements to even lower energies. However, as has been pointed out by Assenbaum et al. [1], there is a potential problem with this strategy as, at the lowest energies now accessible in laboratory experiments, the electrons present in the target (and possibly also in the projectile) may lead to an enhancement of the measured cross section over the desired cross section for bare nuclei by partially screening the Coulomb barrier between projectile and target. As discussed in [1], the screening effect is equivalent to giving the colliding nuclei an extra attraction (described by an energy increment Ue). Thus, the nuclei may be considered as tunneling the Coulomb barrier at an effective incident energy $E_{\rm eff} = E + U_e$. The resulting enhancement of the measured cross section $\sigma_{\rm exp}(E)$ over the cross section for bare nuclei $\sigma_{\rm bn}(E)$ can then be defined as

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$$f(E) = \sigma_{\text{exp}}(E)/\sigma_{\text{bn}}(E) = \sigma(E + U_e)/\sigma(E). \qquad (2)$$

Considering that $U_e << E$ at those energies currently accessible in experiments and approximating $S(E)/E = S(E_{\text{eff}})/E_{\text{eff}}$ one finds [1]

$$f(E) \approx \exp\left\{\pi\eta(E)\frac{U_e}{E}\right\}. \qquad (3)$$

In general, the screening energy Ue is a function of energy. However, it has become customary to express the enhancement of measured cross sections due to electron screening in terms of a constant screening energy [2]. For atomic (deuteron and helium) targets this assumption has been justified in [3] for the energies at which screening effects are relevant.

Experimentally, electron screening effects have been established and studied intensively by the Münster/Bochum group [2,4{7]. By fitting the expression for the enhancement factor $f(E)$, as given in Eq. (3), to the ratio of measured cross section over the expected barenuclear cross section (σ_{bn} is usually derived by extrapolating cross sections from higher energies where screening effects are negligible), electron screening energies Ue have been derived for several nuclear reactions [4{7]. Surprisingly, these screening energies have been reported to be larger than the adiabatic limit in which the electrons adjust instantaneously to the change in nuclear configuration, and in which it is assumed that the associated gain in electron binding energy is entirely transferred to the relative motion of the colliding nuclei. As long as it is justified to treat the nuclei

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as infinitely heavy, which appears to be a valid approximation at the energies involved, the adiabatic limit should constitute the maximum screening energy possible.

The most pronounced excess of the experimentally derived screening energy over the adiabatic limit has been reported for the $^{3}\mathrm{He(d,p)}^{4}\mathrm{He}$ reaction [7]. With an atomic $^{3}\mathrm{He}$ gas target, cross sections were measured down to E = 5:88 keV. At this energy, the observed cross section exceeds the extrapolated bare nuclear cross section by about 50%. Furthermore, the enhancement of the data over the bare nuclear cross section _ts the expected exponential energy dependence with a screening energy of $U_e = 186 \pm 9$ eV [7]. This value is significantly larger than the adiabatic limit of $U_e = 120$ eV [3]. Note that one possible source of uncertainty is the extrapolation of the bare-nuclei cross section. For $^{3}\mathrm{He(d,p)}^{4}\mathrm{He}$, the extrapolation appears to be su_ciently well under control. For example, the parametrization of the available data for energies E = 40 keV to 10 MeV predicts an astrophysical S-factor in the relevant energy regime E = 5−40 keV which agrees very well with the one calculated in a microscopic cluster model [8].

Obviously the determination of electron screening effects require high-precision measurements. In particular, the effective energy in the target or, equivalently, the energy loss in any matter upstream of the target has to be known very precisely. In [4,7], the authors used the stopping power data for deuterons in helium as tabulated in [9]. These tables were derived by extrapolation of the stopping power for deuterons above 100 keV to lower energies, assuming a linear dependence on the projectile velocity [10,11]. As noted by Lindhard [12] and by Bang [13], this extrapolation can contain substantial errors. In fact, recent measurements of the stopping power of low-energy protons and deuterons $(\leq 25$ keV$)$ in a helium gas [14] found significantly lower values than tabulated in [9]. These smaller stopping powers are in good agreement with a more recent calculation, based on a coupled-channel solution for the time-dependent

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Schrödinger equation for a hydrogen beam traversing a helium gas [15]. In this calculation, Grande and Schiwietz show that the stopping power at low energies is dominated by electron capture by the projectile. This process, however, requires a substantial minimum energy transfer which results in a considerably reduced stopping power at lower energies than would be expected from a velocity-proportional extrapolation of data from higher energies.

We now re-derive the low-energy $^3He(d,p)^4He$ astrophysical S-factors for the Engstler et al. measurements [4] using the stopping power data of [14] rather than the tabulated values of [9]; the latter values were adopted in [4] and in the recent reanalysis of the data by Prati et al. [7]. We translated the stopping power data of [14] into energy losses as a function of deuteron $+^3He$ (c.m.) energies E and then fitted these data by a smooth curve. The resulting energy loss functions are shown in Fig. 1 for the two different pressures (0.1 Torr and 0.2 Torr) at which the experiment [4] has been performed. For comparison, the energy loss function as derived from the Ziegler-Andersen table [9] is also shown. From Fig. 1 we observe that at the lowest energy (E = 5:88 keV), at which Engstler et al. report 3He(d,p)4He astrophysical S-factors (0.2 Torr), the measured energy loss [14] is about 80 eV less than the tabulated value. At E = 10 keV, the difference is still 48 eV. Note that these differences are significant compared with of the energy previously attributed to electron screening (Ue = 186 eV). In fact, using the reduced energy losses will result in reduced astrophysical S-factors. Correspondingly we expect the electron screening energy deduced from the data to decrease.

To derive $^3He(d,p)^4He$ astrophysical S-factors for the new energy loss data, we first transformed the S(E)-factors into cross sections, using the S(E) data and energies E as given in Table 1 of Ref. [4]; a 3:8% intrinsic error has been added in quadrature to the data, in accordance with Ref. [7]. Then we derived new effective energies $E' = E + \Delta E_{\rm loss}$, where $\Delta E_{\rm loss}$ is the

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excess of the tabulated energy [9] losses over the recently measured values [14]. The cross section data, now attributed to the effective energy E', are then transformed into astrophysical S-factors $S(E')$.

For the exponent in the Gamow factor we used $2\pi\eta(E) = 68.75/\sqrt{(E)}$ (with E in keV), in accordance with [4,16]. As expected, the new astrophysical S-factors are significantly smaller than those reported in [4,7] (Fig. 2).

Following Refs. [4,7] we then determined the electron screening energy Ue by fitting expression (3) to the ratio of the new S(E) data to the bare-nuclei astrophysical S-factors. As in [7] we used the 3-rd order polynomial (n = 3) parametrization given in [16] for the bare-nuclei cross section. We find $U_e = 117 \pm 7$ eV with a χ^2-value of 0.5 per degree of freedom. To roughly estimate the uncertainty of the extrapolated bare-nuclei cross section on Ue we have repeated the _t for the 4-th order polynomial (n = 4) parametrization of [16]. We then find $U_e = 134 \pm 8$ eV $(\chi^2 = 0.4)$. Both values are in agreement within uncertainties with the adiabatic limit, which has been shown to apply at the low collision energies studied here [3]. Thus, the $^3He(d,p)^4He$ astrophysical S-factors derived with the recently measured energy loss data do not show the excess of screening energy reported in [7]. We stress that the uncertainties related to the extrapolation of the bare-nuclei cross sections are significantly larger than the statistical errors of the experimental data, even in a case where the extrapolation appears to be reasonably well under control.

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Note that the approximation $S(E_{\rm eff})/E_{\rm eff} = S(E)/E$, used to derive Eq. (3) from the definition of the enhancement factor (2), is incorrect by about 3% at the lowest energies studied here, leading to an approximately 10% underestimation of the screening energy. We have therefore repeated the determination of the screening energy, now using Eq. (2). We then find $U_e = 130 \pm 8$ eV and 149 ± 9 eV for the n = 3 and n = 4 parametrization of the bare-nuclei cross sections, respectively. Although these values are slightly larger than the adiabatic screening limit, they do not provide evidence for an excess of screening beyond the uncertainties in the experiments involved, as deduced in [7].

In summary, we have shown that conclusions drawn previously about electron screening effects on low-energy fusion data depend very sensitively on the assumed energy loss in the target and in matter up-stream of the target, for which only rather scarce data exist at such low collision energies. Recent measurements [14] and theoretical work [15] indicate that the energy loss of a hydrogen beam transversing a helium gas is significantly less than given by the standard tables. If these reduced energy losses are applied to the $^{3}\text{He}(\text{d,p})^{4}\text{He}$ astrophysical S-factors, we have found an electron screening energy in agreement with the theoretically expected adiabatic limit $(U_e = 120 \text{ eV})$, within uncertainties, that no longer requires an unexplained screening excess. Our work clearly stresses the need for improved low-energy stopping power data for this and other reactions in which an excess of the screening energy over the adiabatic limit has been reported [2]. Further work on low-energy stopping powers in gas and solid targets has already been initiated [17]. If this work conforms the reduced stopping powers at very low energy, it will also validate the general strategy in nuclear astrophysics to achieve more reliable astrophysical nuclear cross sections by steadily lowering the energies at which the cross sections are measured in the laboratory, as the electron screening effects, at least for atomic targets, can then be considered to be understood.

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