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EFFECT OF ELECTRON SCREENING ON NUCLEAR REACTION RATES*

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Recently, we performed an extensive experimental campaign, with an aim to study the electron screening in the laboratory for various nuclear reactions and involving both low and high Z targets. Contrary to the large effect observed for low Z targets, no large electron screening was observed for high Z targets. This result was quite surprising and in continuation of our campaign, we focused on the studies of low Z targets. The $^2\mathrm{H}(p,\gamma)^3\mathrm{He}$ reaction was studied at low energies, in different deuterium implanted materials. Although we were not able to deduce the value of electron screening, we report three new values for the cross section.

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1. Introduction

Reliable cross section data at low energies are crucial for precise determination of thermonuclear reaction rates in stars. However, stellar environments cannot be reproduced in a laboratory and the influence of electronic environment on nuclear reaction rates in such conditions cannot be experimentally deduced. Therefore, it is of significant importance to measure the bare cross sections as well as possible. The problem is that the nuclear reaction rates drop rapidly with decreasing beam energy, thus making the cross section measurements difficult at low energies. Extrapolations have to be used and this is faciliated by transforming the cross section σ into the astrophysical S factor [1]

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

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where $\eta = Z_1 Z_2 e^2/4\pi\epsilon_0\hbar\sqrt{2E/\mu}$ is the Sommerfeld parameter, Z_1 and Z_2 are the charge numbers of interacting nuclei, μ their reduced mass and E is the c.m.s. energy. The probability of tunneling through the Coulomb barrier depends on its height exponentially, see Eq. (1) and even small changes to the barrier caused by electrons (surrounding the reactants in almost all laboratory experiments) have a profound effect on the cross section. As a result, the measured reaction rates are enhanced compared to the reaction rates for bare nuclei, with an enhancement factor f defined as the ratio of Coulomb barrier penetrabilities in the case of screened Coulomb barrier and in the case of bare Coulomb barrier [2]

$$f(U_e) = \frac{e^{(-2\pi\eta(E+U_e))}}{e^{(-2\pi\eta(E))}} = \frac{e^{\left(-\frac{e^2}{2\epsilon_0\hbar c}Z_1 Z_2\sqrt{\frac{\mu c^2}{2(E+U_e)}}\right)}}{e^{\left(-\frac{e^2}{2\epsilon_0\hbar c}Z_1 Z_2\sqrt{\frac{\mu c^2}{2E}}\right)}}\,, \tag{2}$$

where U_e is the electron screening potential. Experimental studies of various nuclear reactions in metals have shown the expected cross section enhancement at low energies [3–7]. However, the enhancements in metallic targets were significantly larger than expected from the adiabatic limit, which provides the theoretical maximum for the magnitude of electron screening. The discrepancy between the measurements and the adiabatic limit is presently not understood under laboratory conditions, therefore, the size of electron screening has to be measured for each metallic environment and each target separately.

2. Experiment

Recently, we performed a comprehensive study of electron screening in different metallic environments [7]. Large electron screening (of a few keV) was observed for the ^{1}H(^{7}Li, α)^{4}He reaction in different metallic environments, namely hydrogen implanted Pd, Pt, Zn and Ni targets. However, surprisingly (and contrary to the large electron screening reported for ^{176}Lu(p,n)^{176}Hf and ^{50}V(p,n)^{50}Cr [6] reaction) no large electron screening was observed in the following proton capture reactions: ^{55}Mn(p,γ)^{56}Fe, ^{51}V(p,γ)^{52}Cr and charge exchange reactions: ^{55}Mn(p,n)^{55}Fe, ^{113}Cd(p,n)^{113}In, ^{115}In(p,n)^{115}Sn, ^{50}V(p,n)^{50}Cr. Furthermore, no shift in resonance energy for metallic relative to insulator environment was observed for the studied (p,n) and (p,γ) reactions, again contrary to Ref. [6]. However, it is important to note that contrary to ^{1}H(^{7}Li,α)^{4}He studies, where hydrogen implanted metallic targets were used, pure metallic targets were used in the reactions mentioned above.

Previously reported results raised a question on the validity of measurements that showed large electron screening potentials in nuclear reactions involving high Z targets and implied a dependence of the electron screening potential on the position of the target nuclei in a metallic lattice. To test the previous hypothesis and to further investigate electron screening in low Z targets, we studied the $^2\mathrm{H}(p,\gamma)^3\mathrm{He}$ reaction in deuterium implanted materials. Since the reaction $^2\mathrm{H}(p,\gamma)^3\mathrm{He}$ is of great importance to astrophysics (one of the main channels of $^4\mathrm{He}$ production) and since it has relatively low Coulomb barrier height, some measurements have been already performed with this reaction (for example, see Refs. [8–12]), even in the region of the Gamow peak. However, only gas and ice targets were used. We extended these studies to deuteron implanted targets.

The proton beams with energies E_p between 0.24 and 0.44 MeV were accelerated by the 2 MV Tandetron accelerator at Jozef Stefan Institute. The beam energy spread was about 1 keV. In order to deduce the incident proton dose, the charge deposited in the target was measured on an electrically insulated target chamber. The beam current was on average about 0.3 μA. Gamma rays were detected in an HPGe detector with a 25% efficiency relative to NaI and with a 0.5 mm thick Be entrance window, placed 4.2 cm from the target at an angle of 135° with respect to the proton beam direction. The resolution of the detector was 2.1 keV at 1.33 MeV. Deuterons were implanted at an energy of 5 keV by our Tectra IonEtch ion gun. Since no large electron screening is expected in insulators and semiconductors (see Ref. [3] for example), we chose a 250 μm thick graphite target for the reference measurement. The same target was also used in the study of the $^1\mathrm{H}(^7\mathrm{Li},\alpha)^4\mathrm{He}$ reaction, where stable thick target yields and promising results were obtained. The incident proton beam energy was significantly higher than the energy of deuterons during the implantation and the proton beam correspondingly lost only a small part of its initial energy while traversing the implanted region in C (namely, 4.3% at the lowest beam energy and 1.6% at the highest beam energy). Therefore, we considered γ-ray yields as coming from a thin target with a constant deuteron distribution. For the effective beam energy E_{eff}, we took the beam energy at one-half of the target thickness $\varDelta/2$, $E_{\mathrm{eff}} = E_p - dE/dx\,\varDelta/2$ (since the target was thin the stopping power was almost constant and was calculated using SRIM [13]).

The energy of the capture γ rays is: $E_\gamma = Q + m_D/(m_p + m_D)\,E_{\mathrm{eff}} + E_{\mathrm{doppler}}$, where Q is the reaction Q-value (5.5 MeV), m_p and m_D, proton and deuteron mass and E_{doppler}, the Doppler correction. An example of a γ-ray energy spectrum is shown in Fig. 1. It was found that only the 6129 keV line from the $^{19}\mathrm{F}(p,\alpha)^{16}\mathrm{O}$ reaction gives rise to the high energy background. Therefore, we corrected the γ-ray yields, when necessary. We then summed the photopeak, single escape and double escape γ-ray yields and normalized

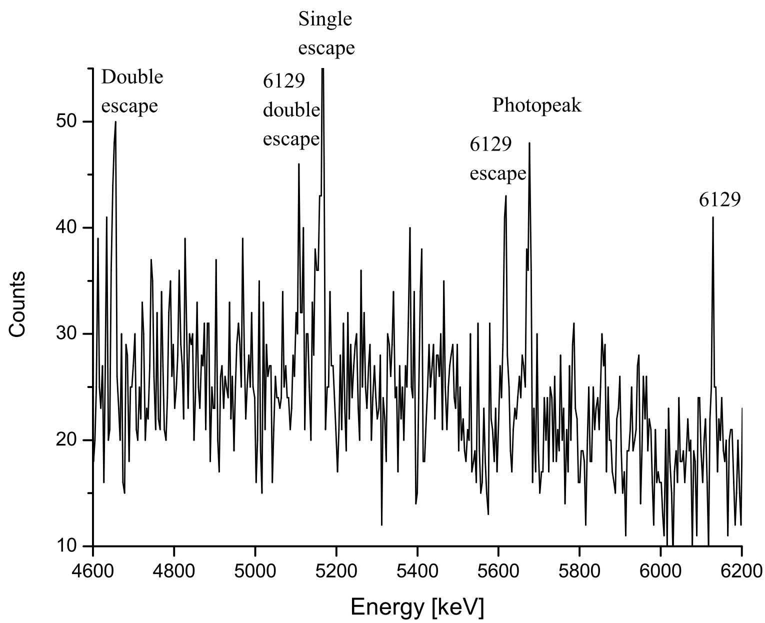

Fig. 1. The high energy part of the γ-ray spectrum at incident proton beam energy of 0.34 MeV.

them to the cross section data reported in Ref. [12] as described below. We chose the data from Ref. [12] for normalization since their data set has the closest energies to ours. The normalization was performed by firstly, finding the S-factor from data points reported in Ref. [12], then fitting them with a parabolic function. We then scaled our γ-ray yield at incident proton energy of 0.34 MeV to the cross section obtained using Eq. (1). For angular distribution, we took the form suggested in Ref. [12]: $(\sin^2\theta + b)$ and fitted the reported b values. In this way, we obtained the angular distribution values and taking into account the efficiency of the detector we were able to correct corresponding γ-ray yields at incident proton energies of 0.24 and 0.44 MeV for different angular distributions, as well. The cross section as a function of E_{eff} is shown in Fig. 2 and listed in Table I. As can be seen from

TABLE I

Effective energy *vs.* cross section.

Effective energy [keV]	Cross section [μb]
233.6 (10)	1.0(3)
336.6 (10)	1.2(1)
439.4 (10)	1.6(2)

Figs. 1, 2 we had low statistics, due to the low concentration of implanted deuterons and low detection efficiency of our detector. Therefore, we deduced that with current experimental setup the study of electron screening in the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction is not feasible.

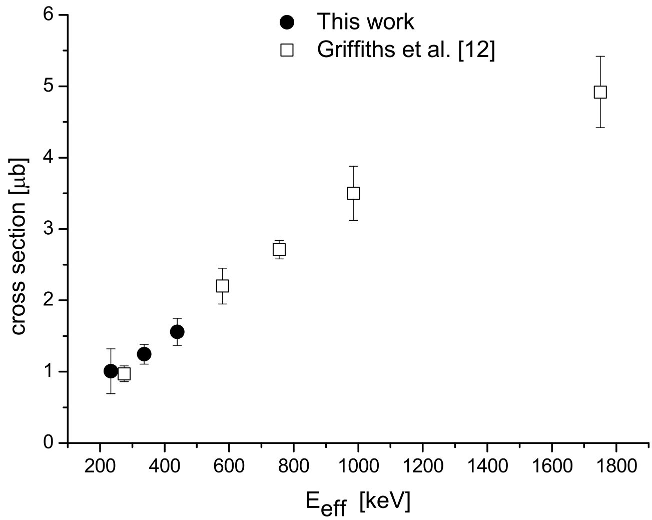

Fig. 2. The cross section as a function of incident beam energy.

3. Conclusions

Although studied for more than two decades electron screening still poses many open questions. In order to answer some of them, we studied the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction at low energies. However, due to low statistics, we were not able to deduce the value of the electron screening potential. Instead, we report on a few new data points for the cross section.

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