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THRESHOLD RESONANCE CONTRIBUTION TO THE THICK TARGET ^{2}H$(d,p)^{3}$H REACTION YIELD[*]

M. Kaczmarski, K. Czerski, D. Weissbach, A.I. Kilic

Institute of Physics, University of Szczecin
Wielkopolska 15, 70-451 Szczecin, Poland

G. Ruprecht, A. Huke

Institute for Solid-State Nuclear Physics
Leistikowstr. 2, 14053 Berlin, Germany

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Thick target yield of the ^{2}H$(d,p)^{3}$H reaction has been measured at very low energies under ultra-high vacuum conditions using deuteron-implanted Zr targets. Increase of enhancement factors observed for lowering deuteron energies could not be explained only by the electron screening effect. Assuming an additional contribution resulting from a single-particle threshold resonance, we are able to describe the energy dependence of the experimental reaction yield correctly. The theoretical calculations performed within the T-matrix approach allows also to study interference effects between different reaction amplitudes and predict a saturation of the threshold resonance strength at deuteron energies below 5 keV.

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1. Introduction

Nuclear reactions at very low energies are studied mainly for their astrophysical importance. Cross sections of those reactions can be strongly enhanced due to electron screening of the Coulomb barrier by the surrounding electrons [1]. For the last decade, this effect has been investigated for the ^{2}H$(d,p)^{3}$H and ^{2}H$(d,n)^{3}$He reactions taking place in metallic environments which represents a unique model for dense astrophysical plasmas [2]. The screening energies determined experimentally as a reduction of the height of

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the Coulomb barrier turn out to be by a factor of two larger than the theoretical predictions based on the self-consistent dielectric function model. This model includes polarization of bound and valence electrons as well as a contribution coming from positive ions of the crystal lattice and correctly describes the target material dependence of the screening energies [3]. To provide precise measurements, atomic cleanness of the target surface is required due to significant energy deposition in even few monoatomic layers of carbon or oxygen. This can be obtained with Ar sputtering in ultra-high vacuum (UHV) environment (10^{-9}–10^{-10} mbar). Screening energy determined previously on the deuteron-implanted Zr target in UHV conditions [4] amounted to 490 eV compared to HV value 300 eV, whereas theory predicts 80 eV. Measurements performed by other groups under HV conditions gave results of 205 ± 35 eV and 205 ± 70 eV [5, 6]. Here, we present new experimental data obtained under improved vacuum conditions (10^{-10} mbar) and strongly reduced water vapour pressure which is responsible for target surface oxydation. Enhancement of the reaction cross section observed at low energies will be discussed in terms of the hypothetical 0^+ threshold resonance in the compound nucleus ^{4}He.

2. Experimental results

The experimentally determined enhancement factor at different deuteron energies is given by the ratio between the experimental thick-target yield Y_{scr} and the theoretical one Y_{bare} at the center-of-mass system

$$F(E)=\frac{Y_{\mathrm{scr}}(E)}{Y_{\mathrm{bare}}(E)}=\frac{\int_E^0 \sigma_{\mathrm{scr}}(E)\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1}\mathrm{d}E}{\int_E^0 \sigma_{\mathrm{bare}}(E)\left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1}\mathrm{d}E}\,, \tag{1}$$

where σ_{bare} corresponds to the theoretical cross section calculated using the T-matrix approach [7]. Y_{scr} can be also determined using the expression for the screened cross section σ_{scr}

$$\begin{aligned}\sigma_{\mathrm{scr}}(E) &= \frac{1}{\sqrt{E(E+U_e)}}S(E)\exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E+U_e}}\right)\\ &= \frac{1}{\sqrt{EE_{\mathrm{G}}}}P(E+U_e)S(E)\,, \end{aligned}\tag{2}$$

where E_{G} and U_e stay for Gamov energy and screening energy, respectively. The experimental enhancement factors normalized to the value determined at the deuteron energy of 15 keV are presented in Fig. 1 and compared to the theoretical calculations.

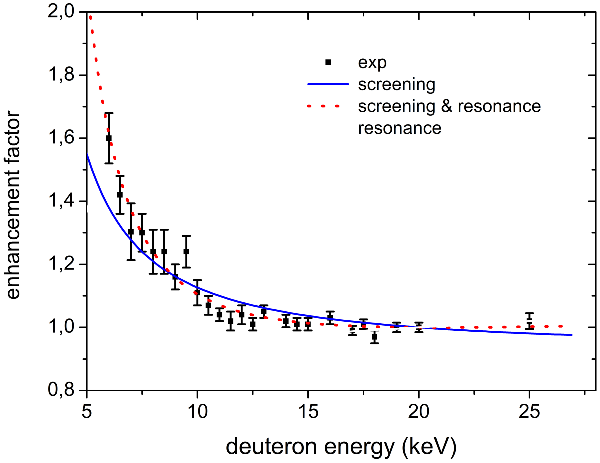

Fig. 1. Experimentally determined enhancement factors compared with theoretical fit curves including the screening effect and the threshold resonance [8].

3. Electron screening versus threshold resonance

The theoretical curve corresponding to the electron screening effect cannot describe the experimental data correctly (see Fig. 1). Whereas the theoretical values for deuteron energies below 10 keV underestimate the experimental results systematically, the data for higher energies lay below the theoretical curve. These differences support the hypothesis of the single-particle 0^+ resonance state located very close to the reaction threshold [8]. Its high-energy tail could contribute to the increase of the enhancement factor at lower projectile energies and moreover, a destructive interference with other resonances could explain the flat energy dependence of the enhancement factor observed at higher energies. The total cross section of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction is well-known and can be described by T-matrix elements [7] representing the broad overlapping resonances of the compound nucleus ^{4}He. Thus, the coherent contribution to the reaction amplitude resulting from the postulated narrow threshold resonance can be easily calculated using the Breit–Wigner formula

$$\sigma_{\mathrm{R}} = \frac{\pi}{k^2}\frac{\mathit{\Gamma}_d\mathit{\Gamma}_p}{(E-E_{\mathrm{R}})^2+\frac{\mathit{\Gamma}^2}{4}}\,. \tag{3}$$

Assuming a single-particle $d\oplus d$ structure of the resonance with the deuteron partial width

$$\mathit{\Gamma}_d = 2P(E+U_e)ka|\gamma|^2\,. \tag{4}$$

It strongly depends on the penetration factor $P(E)$, which is influenced by screening energy U_e. Here, k is the wave number, a and $|\gamma|^2$ stand for the channel radius and the reduced resonance width, respectively [8]. The total resonance width is a sum of partial widths for all open channels, *i.e.* also for protons, neutrons and electromagnetic transitions which are energy independent (see Fig. 2). The total cross section for 0^+ resonances including the interference effect between the flat part of the cross section $\sigma_{\rm F}$ (known broad 0^+ resonances) and the threshold resonance can be calculated as follows:

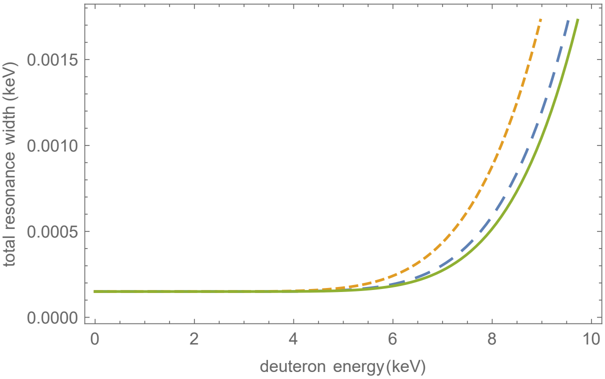

Fig. 2. Screening energy dependence of the total resonance width, full line $U_e = 0$, long dashed line $U_e = 100$ eV and dashed line $U_e = 400$ eV.

$$\sigma(0^+) = \sigma_{\rm F} + \sigma_{\rm R} + 2\sqrt{\sigma_{\rm F}}\sqrt{\sigma_{\rm R}}\cos(\varphi_{\rm F} - \varphi_{\rm R})\,, \tag{5}$$

where $\varphi_{\rm R}$ and $\varphi_{\rm F}$ stand for phase shifts of the resonance and the flat part of the reaction amplitudes, respectively. The resonance phase shift equal to $\arctan(\Gamma/2/(E-E_{\rm R}))$ is very small since the deuteron energies studied are much higher than resonance width and, therefore, can be neglected in the above formula. As illustrated in Fig. 3, the resonance strength of the single particle resonance and its width strongly depend on the resonance energy. Only below the deuteron energy of 5 keV, they do not change any more since the deuteron partial width is smaller than the energy-independent part of the resonance width of 150 meV. It is in agreement with the calculations performed previously [8] in frame of which the deuteron width dominates the total resonance width even for deuteron energies below 10 keV. Additionally, the electron screening effect can increase the single particle resonance width considerably (see Fig. 2).

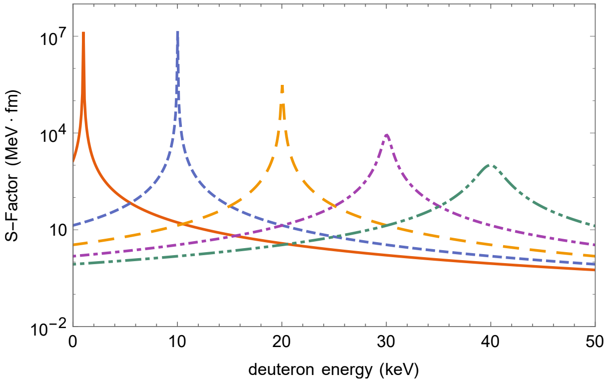

Fig. 3. Resonant S-Factor for different resonance energies.

4. Conclusions

The screening energy determined for the ^{2}H$(d,p)^3$H reaction using the concept of the threshold resonance ($U_e = 105$ eV $\pm$ 15 eV) is considerably smaller than the values obtained previously and much closer to the theoretical prediction of 80 eV. Furthermore, the experimental enhancement factors can be described more accurately. However, calculations presented here show that the deuteron width dominates the total resonance width only for deuteron energies larger than 5 keV which confirms the assumption used in the previous calculations. Below this energy, the contribution of other partial resonance widths can be visible and leads both to a constant resonance width and resonance strength. This result might be confirmed in future experiments in which we plan to measure the DD fusion cross section at deuteron energies as low as 1 keV. The enhancement curve will allow to determine the resonance contribution and the resonance width much more precisely.

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