DEUTERON–DEUTERON REACTION CROSS SECTIONS AT VERY LOW ENERGIES*

K. Czerski[a,b], N. Targosz-Ślęczka[a], M. Kaczmarski[a]

[a]Institute of Physics, University of Szczecin, Szczecin, Poland
[b]Institute for Solid-State Nuclear Physics, Berlin, Germany

(Received January 14, 2020)

Recent studies of the deuteron–deuteron nuclear reactions in metallic targets, at projectile energies below the Coulomb barrier, show a significant enhancement of cross sections due to the electron screening effect and the threshold resonance contribution. Both effects are sensitive to the crystal lattice defects of the target material which increases the effective electron mass. Based on experimental results and the atomic deuteron–deuteron potential, we could calculate here the cross section of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction down to energies corresponding to room temperature where the enhancement effects are of crucial importance.

DOI:10.5506/APhysPolB.51.649

1. Introduction

The Coulomb barrier between reacting nuclei can be shielded by surrounding electrons, which leads to an exponential-like enhancement of reaction cross sections for lowering projectile energies. Thus, the so-called electron screening effect is especially important for nuclear reactions taking place in astrophysical and terrestrial plasmas [1], which can be experimentally studied using metallic targets. In the last years, the deuteron–deuteron fusion reactions were intensively exploited for this kind of investigations [2–5] due to the low Coulomb barrier and relatively high cross sections. However, the experimentally determined screening energies corresponding to the reduction of the height of the Coulomb barrier exceeded the theoretical expectations by a factor of about three [6].

Only the last precise measurements [7] performed for the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction in Zr under ultra-high vacuum conditions enable to understand previous discrepancies and the role of target lattice defects induced by irradiation. In the present work, the experimental parameters describing the

* Presented at the XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 1–7, 2019.

excitation function of the deuteron–deuteron reactions will be applied to calculate the cross-section contributions, resulting from the screening effect and the threshold resonance, down to energies corresponding to room temperature. In addition, an interplay of both effects will be demonstrated.

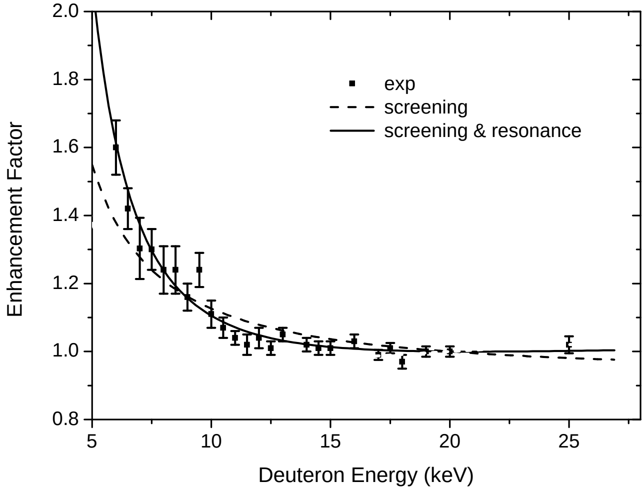

Fig. 1. Experimental enhancement factors together with theoretical curves describing the electron screening itself and screening with the resonant contribution for projectile energies between 6 and 25 keV.

2. Experimental procedure and results

The experimental setup used here, as well as the main results obtained for Zr, have already been reported previously [7]. The research has been performed at an electrostatic accelerator with a highly stable power supply adapted to low-energy ions and high beam intensity. The long-term energy stability, which is very important in this kind of experiments, was of the order of a few eV. The ion beam was analyzed magnetically and focused to a 5 mm spot on the deuteron saturated target (ZrD_2). The charged ejectiles of the deuteron–deuteron reactions, *i.e.* protons, tritons and ^{3}He particles were detected by three Si detectors placed at fixed backward angles. During the measurement, the target surface was controlled by means of the Auger Electron Spectroscopy (AES), because every contamination that leads to energy losses reduces the electron screening effect. The troublesome contaminations in the experimental study were oxidations and carbon layers. To restrain this undesirable process, the ultra-high vacuum conditions were used in the target chamber. The pressure of 10^{-11} mbar was achieved due to additional LN_2 cooling [8].

The experimental results are presented in Fig. 1 using enhancement factors which are estimated by a ratio between the experimental and theoretical reaction yields. The theoretical reaction yield [9] does not include any screening effect. Therefore, the enhancement factors normalized for the deuteron energy of 15 keV show a characteristic increase for lowering projectile energies. The fitted enhancement curve was calculated as a coherent sum of the known cross section and the 0^+ threshold resonance contributions [7]. The threshold resonance placed at the excitation energy of about 23.85 MeV in the compound nucleus ^{4}He has a single-particle $(d+d)$ structure, and the proton partial width is very small, equal to about 40 meV. The screening energy was determined to be $U_\mathrm{e} = 105 \pm 15$ eV, which is very close to the theoretical prediction of 112 eV, obtained within the self-consisting dielectric function theory [6].

In order to study the influence of the surface contamination on the resulting screening energies, a series of measurements was performed determining the enhancement factors for a specific deuteron energy over time (Fig. 2). The increase of enhancement factor during the first hours of experiment is clearly visible, as well as the following decrease reaching the state where no screening effect is observed anymore. The "weakening" of the effect is caused by a thick contamination that covered the target surface. On the other hand, during the first hours of irradiation, the target contamination is small enough (below 1 atomic monolayer) not to cause any energy losses of projectiles, but results in crystal lattice defects, locally changing the band structure of the target. This leads to increase of the effective electron mass and the related screening energy which is, according to the Thomas–Fermi

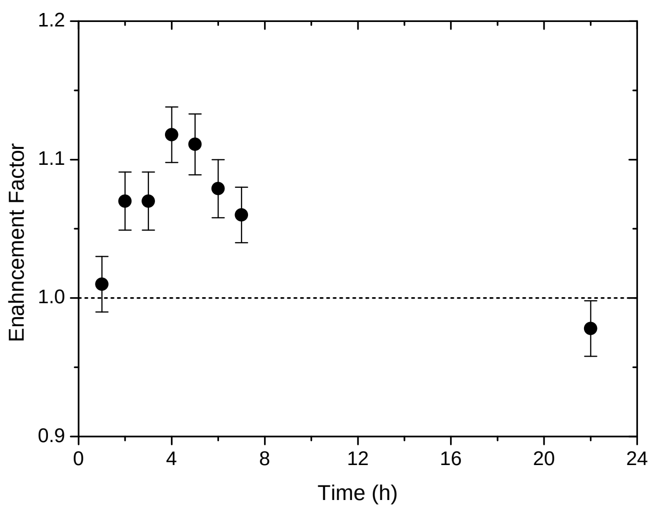

Fig. 2. Enhancement factors measured over time for deuteron energy of 15 keV.

model, proportional to the square root of the effective electron mass. The measured enhancement factor already after the first 4 hours reached its maximum that corresponds to the screening energy of about 300 eV and the connected increase of the effective electron mass by a factor of about 9.

Indications for importance of crystal lattice defects were also found in different proton-induced reactions studied by means of the inverse kinematics method [10]. The authors reported that the large screening energies determined experimentally can be consistently explained by pulling the implanted protons in the target lattice regions of a high electron density, which agrees, in fact, with our finding.

3. Extrapolation of cross section to room temperature

In the data analysis, the enhancement of the total yield for lowering projectile energies is described by the so-called electron screening energy U_{e}, which causes reduction of the Coulomb barrier. It can be taken into account, as a first order approximation, by increase of the kinetic energy of the projectile in the expression for the barrier penetration factor $P(E_{\mathrm{cm}})$ [7]. The screened cross section can be then calculated from

$$\sigma_{\mathrm{scr}}(E_{\mathrm{cm}}) = \frac{1}{\sqrt{E_{\mathrm{cm}}E_{\mathrm{G}}}} P(E_{\mathrm{cm}}+U_{\mathrm{e}})S(E_{\mathrm{cm}})\,, \tag{1}$$

where

$$P(E_{\mathrm{cm}}) = \sqrt{\frac{E_{\mathrm{G}}}{E_{\mathrm{cm}}}}\exp\left(-\sqrt{\frac{E_{\mathrm{G}}}{E_{\mathrm{cm}}}}\right). \tag{2}$$

Here, $S(E_{\mathrm{cm}})$ is the astrophysical S-factor, well known from the precise gaseous target experimental study [9], and $E_{\mathrm{G}} = 986$ keV is the Gamow energy. The approximation above can be, however, used only when the screening energy is much lower than the projectile energy. Otherwise, the screening energy slightly decreases with decreasing projectile energy in dependence of the atomic potential between deuterons embedded in the metallic hosting material. Therefore, an energy-dependent effective screening energy U_{eff} can be calculated if the penetration factor is expressed by the WKB approximation, according to the equation

$$\sqrt{\frac{E_{\mathrm{G}}}{E_{\mathrm{cm}}+U_{\mathrm{eff}}}}\exp\left[-\sqrt{\frac{E_{\mathrm{G}}}{E_{\mathrm{cm}}+U_{\mathrm{eff}}}}\right] = \exp\left[-\frac{2\sqrt{M}}{\hbar}\int\limits_{R_1}^{R_2}\sqrt{V(r)-E_{\mathrm{cm}}}\mathrm{d}r\right], \tag{3}$$

where R_1 and R_2 are the classical turning points in the WKB expression for a specific deuteron–deuteron potential $V(r)$, and M is the deuteron mass.

As shown in [6], the effective screening energy reaches at energies of about 1 eV its low-energy limit which is about 78 percent of the value U_e determined in the accelerator experiments. Now, the screened cross section can be determined at very low energies for different U_e assuming the known S-factor (Fig. 3).

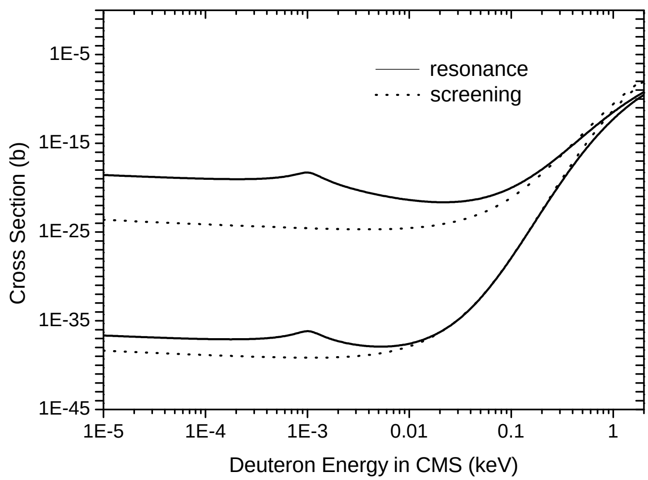

Fig. 3. Nonresonant (dotted line) and resonant (solid line) cross sections for $U_\mathrm{e} =$ 110 eV (lower part of diagram) and $U_\mathrm{e} = 300$ eV (upper part).

The threshold resonance contribution can be calculated using the standard Breit–Wigner formula for an isolated resonance state

$$\sigma_\mathrm{res}(E_\mathrm{cm}) = \frac{\pi}{k^2}\frac{\Gamma_d \Gamma_p}{(E_\mathrm{cm} - E_\mathrm{R})^2 + \frac{1}{4}\Gamma^2}\,, \tag{4}$$

where Γ_d and Γ_p are partial deuteron and proton widths, respectively. The wave number is denoted by k. E_R and Γ stand for the resonance energy (set to 1 eV) and the total resonance width, which is assumed to be energy-independent and equal to 0.5 eV. It is because of a very small deuteron width, which is strongly reduced at low energies by the penetration factor

$$\Gamma_d(E_\mathrm{cm}) = 2kaP(E_\mathrm{cm})\frac{\hbar^2}{\mu a^2}|\theta|^2\,, \tag{5}$$

where a is the channel radius of 7 fm [11], μ is the reduced mass and $|\theta|^2$ is the reduced width set to unity to include the single-particle resonance structure. In order to take into account the electron screening effect, the effective screening energy should be added to E_cm in the expression for the penetration factor. The resonance cross sections calculated for the screening energies of 110 eV and 300 eV are shown in Fig. 3.

4. Discussion and conclusion

The cross section for the ^{2}H$(d,p)^3$H reaction has been calculated down to energies corresponding to room temperature using the effective screening energy approach and the parameters determined in the accelerator experiment performed at a few keV. The both, resonance and screened (nonresonant) cross-section contributions drop with the decreasing deuteron energies due to lowering penetration factors. At room temperature, the cross sections slightly increase due to the wave length dependence. Absolute values of the cross sections at this limit strongly depend on the screening energy — they increase by 15 and 18 orders of magnitude for the screened and resonance cross sections, respectively, while the screening energy changes from 110 eV to 300 eV. The resonance curves have a local maximum at the resonance energy and significantly exceed the corresponding screened cross sections (stronger for the higher U_{e}). Oppositely, at energies of a few keV, the resonance contribution is smaller compared to the screened cross section. Our calculations lead to the conclusion that the resonance cross-section contribution reaching the value of 10^{-18} b in the case of $U_{\mathrm{e}} = 300$ eV should result in measurable effects at room temperature. On the other hand, the accelerator experiments performed at higher energies are not able to unambiguously determine the resonance energy which can be slightly shifted in dependence of the screening energy.

This work was supported by the National Science Centre, Poland (NCN) grant No. 2011/03/N/ST2/03627.

REFERENCES

[1] S. Ichimaru, *Rev. Mod. Phys.* **65**, 255 (1993).
[2] K. Czerski *et al.*, *Europhys. Lett.* **54**, 449 (2001).
[3] J. Kasagi *et al.*, *J. Phys. Soc. Jpn.* **71**, 2881 (2002).
[4] F. Raiola *et al.*, *Phys. Lett. B* **547**, 193 (2002).
[5] A. Huke *et al.*, *Phys. Rev. C* **78**, 015803 (2008).
[6] K. Czerski *et al.*, *Europhys. Lett.* **68**, 323 (2004).
[7] K. Czerski *et al.*, *Europhys. Lett.* **113**, 22001 (2016).
[8] K. Czerski *et al.*, *J. Phys. G* **35**, 014012 (2008).
[9] R.E. Brown, N. Jarmie, *Phys. Rev. C* **41**, 1391 (1990).
[10] A. Cvetinovic *et al.*, *Phys. Rev. C* **92**, 065801 (2015).
[11] H. Paetz gen. Schieck, *Eur. Phys. J. A* **44**, 321 (2010).