Vol. 49 (2018) ACTA PHYSICA POLONICA B No 3

ELECTRON SCREENING EFFECT IN NUCLEAR REACTIONS IN METALLIC AND GASEOUS TARGETS*

N. Targosz-Ślęczka[a], K. Czerski[a,b], M. Kaczmarski[a]
D. Weissbach[a,b], A.İ. Kiliç[c], G. Ruprecht[b]
A. Huke[b], S. Policastro[a]

[a]Faculty of Mathematics and Physics, University of Szczecin, Szczecin, Poland
[b]Institute for Solid-State Nuclear Physics, Berlin, Germany
[c]Department of Physics, University of Guelph, Guelph, Canada

(Received December 18, 2017)

The electron screening effect and its influence on enhanced ^{2}H$(d,p)^3$H reaction cross section was investigated based on latest metallic (Zr) target data, as well as much older gaseous target data. The enhancement can result not only from the electron screening effect but also from a suggested 0^+ resonance state in the ^{4}He compound nucleus. This resonance state allows to explain the experimental enhancement factor energy dependence.

DOI:10.5506/APhysPolB.49.675

1. Introduction

One of the unsolved problems in nuclear astrophysics is the effect of electron screening on fusion reactions, which enhances the cross section at low energies. It is extremely important for stellar processes [1, 2] and it has been experimentally confirmed by many authors [3–7]. The electron screening effect results from shielding of the Coulomb barrier between the two reacting nuclei by surrounding electrons [8]. First attempts to experimentally confirm this effect were performed on gaseous targets, *e.g.* [9]. In nuclear reactions taking place in a gaseous environment, the bound electrons of the gas form an electron cloud surrounding the interacting nuclides and act as a screening potential. The projectile sees a reduced Coulomb barrier and this leads to higher cross sections. The enhancement in the reaction cross section is compared to the same reaction with bare nuclei. However, the electron screening effect is of much greater importance in metallic media, since in metals the

* Presented at the XXXV Mazurian Lakes Conference on Physics, Piaski, Poland, September 3–9, 2017.

screening effect arises from free electrons as well as from bound electrons of reacting nuclei and metallic surroundings. Although the electron screening effect has been determined in many different gasses, metals and insulators, it is still not well-recognised, both experimentally and theoretically. Available data are tough to compare, and reported enhancements are ranging from close to expected to orders of magnitude greater [10].

Here, the ^{2}H$(d,p)^3$H reaction cross section has been analysed for data collected in a deuterated Zr target under improved ultra-high-vacuum conditions [11]. Moreover, the influence of an additional 0^+ threshold resonance state in ^{4}He compound nucleus is considered in analysis of cross-section enhancement for ^{2}H$(d,p)^3$H reaction in both, metallic target experiments, mentioned above, as well as in gaseous target experiments performed over two decades ago [12].

2. Experimental technique and data analysis

The screening energies measured by various scientists differ remarkably due to uncertainties related to the deuteron density in the target and the target's surface contamination. The experiments showed that a few monoatomic layers of carbon or oxygen contamination can reduce measured screening energy [13, 14]. For this reason, the experiments need to be performed under ultra-high-vacuum conditions. The accelerator facility used for the study has been described previously [13, 15]. The deuteron beam has been produced in the ECR ion source, magnetically analysed and focused on a deuterated zirconium target. The emitted charged particles were registered by three Si detectors. A two-step differential pumping system was applied to reduce the pressure to the order of 10^{-10} mbar in the target chamber, with the partial pressure of the water vapour and carbon below 10^{-11} mbar. The target surface purity could be verified by means of the Auger Electron Spectroscopy (AES). The deuteron density was examined, reducing systematic uncertainties [3, 15].

The experimental enhancement factor is defined by the ratio between the experimental thick target yield Y_{scr} and the theoretical one Y_{bare} [10]

$$F(E) = \frac{Y_{\mathrm{scr}}(E)}{Y_{\mathrm{bare}}(E)} = \frac{\int_0^E \sigma_{\mathrm{scr}}(E) \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1} \mathrm{d}E}{\int_0^E \sigma_{\mathrm{bare}}(E) \left(\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1} \mathrm{d}E}\,, \tag{1}$$

where the screened cross section is defined as

$$\sigma_{\mathrm{scr}} = \frac{S(E)}{\sqrt{E_{\mathrm{G}}\left(E+U_e\right)}} P\left(E+U_e\right)\,, \tag{2}$$

with $S(E)$ being the energy-dependent astrophysical $S(E)$ factor and U_e denoting the screening energy. The Gamow energy equals to $E_{\mathrm{G}} = 986$ keV for the $d + d$ reactions. The penetration probability through the Coulomb barrier in the case of a screened reaction, for $E \gg U_e$, is given by [3]

$$P\left(E+U_{e}\right)=\sqrt{\frac{E_{\mathrm{G}}}{E+U_{e}}} \exp \left(-\sqrt{\frac{E_{\mathrm{G}}}{E+U_{e}}}\right) . \tag{3}$$

The bare cross sections are obtained from precise gaseous target experiments [16]. To explain the experimental cross-section enhancement, it was proposed that the screening energies determined in the $d+d$ reactions might be influenced by a high-energy tail of a single-particle resonance state close to the reaction threshold [17]. The resonant cross section is expressed as

$$\sigma_{\mathrm{res}}(E)=\frac{\pi}{k^{2}} \frac{\Gamma_{d} \Gamma_{p}}{\left(E-E_{\mathrm{res}}\right)^{2}+\frac{1}{4} \Gamma_{\mathrm{tot}}^{2}} \approx \frac{\pi}{k^{2}} \frac{\Gamma_{d} \Gamma_{p}}{E^{2}}, \tag{4}$$

with the entrance channel width given by

$$\Gamma_{d}=2 k a P(E) \frac{\hbar^{2}}{\mu a^{2}}|\theta|^{2}, \tag{5}$$

where a and μ stay for the channel radius and the reduced mass, respectively, k is the wave number and dimensionless, reduced width $|\theta|^2$ is equal to 1 for a single-particle resonance.

The total cross section, including the interference effects with broad overlapping resonances, for which the phase shift can be kept constant, is given by [11]

$$\sigma\left(0^{+}\right)=\frac{\pi}{k^{2}} k a P(E)\left(\frac{1}{9}\left|\breve{\alpha}_{0}\right|^{2}+\frac{2 \frac{\hbar^{2}}{\mu a^{2}} \Gamma_{p}}{E^{2}}+\sqrt{\frac{8}{9}\left|\breve{\alpha}_{0}\right|^{2} \frac{\hbar^{2}}{\mu a^{2}} \Gamma_{p}} \frac{\cos \varphi_{\alpha_{0}}}{E}\right) . \tag{6}$$

Here, φ_{α_0} is the phase shift and $|\breve{\alpha}_0|^2$ is the transition matrix element for $l = 0$, the second term is the resonant contribution to the cross section, and the third term is responsible for interference effects.

3. Metallic and gaseous environments

The enhancement of the ^{2}H$(d,p)^3$H reaction cross section was experimentally determined at energies ranging from 6 to 25 keV in Zr under ultra-high-vacuum conditions. The experimental data are normalised to the value obtained at deuteron energy of 20 keV. The error bars include statistical as well as systematic uncertainties related to the deuteron density changes in the Zr target. The theoretical chi-square fits to the enhancement factors are presented in Fig. 1.

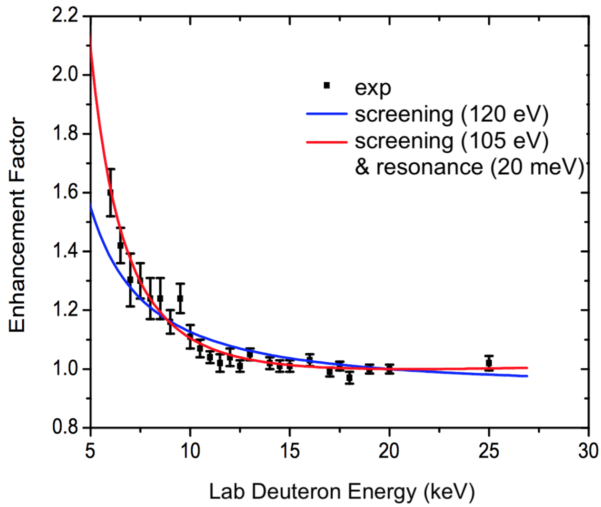

Fig. 1. (Colour on-line) Experimental enhancement factors with theoretical curves fitted to the metallic target experimental data [11].

Using the screening energy U_e as a single parameter in the fit, the value of (120 ± 7) eV was obtained. This value is much smaller than that determined previously for Zr and closer to the theoretical expectation of 80 eV [11]. However, precise data analysis shows that the energy dependence of the experimental enhancement factors is not well-described by a simple screening curve. The low-energy points are underestimated, whereas high-energy points are overestimated. The lighter/red fit provides a χ^2 value of 1.6 per data point, at the confidence level of above 95%, which is two times smaller than 3.2 obtained for the darker/blue fit, without the resonance contribution [11].

The developed analysis method allows to implement the screening energy U_e, proton resonance width Γ_p and the phase shift φ_{α_0} as free parameters to fit the experimental enhancement factors (Fig. 1). To reduce the uncertainties of the fitted parameters, the phase shift equal to 110° from [18] was used. This allowed for fitting only two parameters, that are $\Gamma_p = (20 \pm 10)$ meV and $U_e = (105 \pm 15)$ eV [11].

Gas targets, as opposed to a metallic environment, do not have free electrons to screen the Coulomb barrier between the two reacting nuclei. This highly influences the screening energy which is much lower and experimentally estimated as (25 ± 5) eV [12] compared to the theoretical value of 14 eV [12]. The necessity of including the resonant effect also in the gas target can be seen in Fig. 2, where the experimental points for energy lower than 4 keV are systematically below the theoretical curve describing the screening effect, and the points for energies higher than 4 keV are systematically above.

Due to very large experimental uncertainties as well as similar shapes of the fitted curves, it was possible to fit only one parameter at a time, with the confidence level of 68%. The fitted values are $\Gamma_p = (19 \pm 6)$ meV and $U_e = (23 \pm 5)$ eV [19].

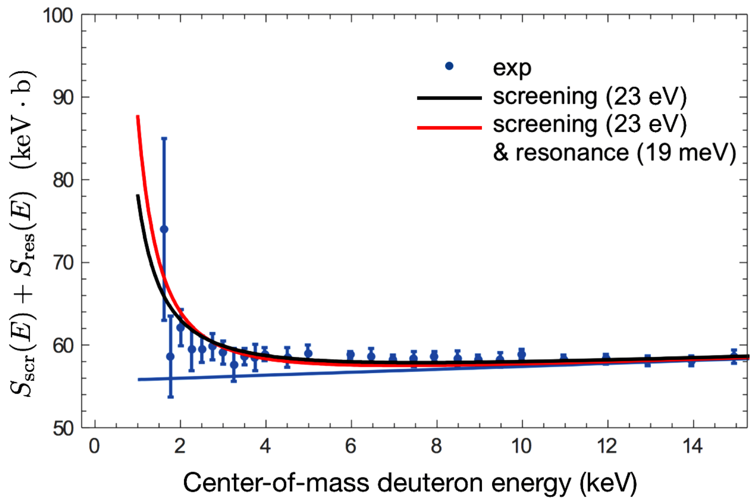

Fig. 2. (Colour on-line) Theoretical $S(E)$ factors connected with screening energy only (black line), as well as together with the resonance contribution (light grey/red line) fitted to gaseous experimental data of Greife *et al.* [12, 19]. The dark grey/blue line has been proposed by the authors of the experiment as the linear parametrisation of $S(E)$ factor.

Contribution of a hypothetical resonance to the value of the astrophysical $S(E)$ factor changes the shape of fitted curve and gives a better fit to obtained values. However, for simplicity, the interference effects, which flatten the theoretical curve for energies below 4 keV, were not included here. Calculating their impact will be the next step of the analysis.

Further experiments allowing high current beam at energies down to 1 keV are required to provide reliable experimental data proving existence of a 0^+ resonance.

4. Conclusions

A 0^+ resonance contribution reduces the screening energy to the value of 105 eV in Zr and allows for much better description of deuteron energy dependence of the enhancement factor. Further experimental investigation should be focused on reaching lower projectile energies, for which the resonance contribution could be more evident.

The contribution of such a resonance was also taken into account in data analysis for a gaseous target measurement performed in 1995 by Greife *et al.* Although the uncertainties of the data were extremely large especially at low energies, the authors could conclude on the screening energy of 25 eV. However, the fitted curve did not describe the data properly. The analysis performed in the present work showed that the resonance contribution causes a flatter energy dependence of the astrophysical $S(E)$ factor. Additional effort is needed if one wants to take into account the interference effect between the reaction amplitudes. In this case, the analysis is more complicated and is still in progress. Only more precise experimental data can support the occurrence of such a threshold resonance.

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

REFERENCES

[1] S. Ichimaru, H. Kitamura, *Phys. Plasmas* **6**, 2649 (1999).
[2] A.C. Calder *et al.*, *Astrophys. J.* **656**, 313 (2007).
[3] K. Czerski *et al.*, *Europhys. Lett.* **54**, 449 (2001).
[4] J. Kasagi *et al.*, *J. Phys. Soc. Jap.* **71**, 2881 (2002).
[5] F. Raiola *et al.*, *Eur. Phys. J. A* **13**, 377 (2002).
[6] C. Bonomo *et al.*, *Nucl. Phys. A* **719**, 37c (2003).
[7] S. Ichimaru, *Rev. Mod. Phys.* **65**, 255 (1993).
[8] H.J. Assenbaum, K. Langanke, C. Rolfs, *Z. Phys. A* **327**, 461 (1987).
[9] C. Rolfs, E. Somorjai, *Nucl. Instrum. Methods Phys. Res. B* **99**, 297 (1995).
[10] A. Huke *et al.*, *Phys. Rev. C* **78**, 015803 (2008).
[11] K. Czerski *et al.*, *Europhys. Lett.* **113**, 22001 (2016).
[12] U. Greife *et al.*, *Z. Phys. A* **351**, 107 (1995).
[13] K. Czerski *et al.*, *J. Phys. G* **35**, 014012 (2008).
[14] N. Targosz-Ślęczka *et al.*, *J. Phys.: Conf. Ser.* **202**, 012041 (2010).
[15] A. Huke *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **256**, 599 (2007).
[16] R.E. Brown, N. Jarmie, *Phys. Rev. C* **41**, 1391 (1990).
[17] N. Targosz-Ślęczka *et al.*, *Acta Phys. Pol. B* **42**, 795 (2011).
[18] H. Paetz gen. Schieck, *Eur. Phys. J. A* **44**, 321 (2010).
[19] S. Policastro, M.Sc. Thesis, University of Szczecin, 2017.