ENHANCED PYCNONUCLEAR REACTIONS IN METALLIC ENVIRONMENTS*

N. Targosz-Ślęczka[a], K. Czerski[a,b,c], A. Huke[b,c], G. Ruprecht[c]
L. Martin[d], D. Blauth[e], H. Winter[e]

[a]Institute of Physics, University of Szczecin, Szczecin, Poland
[b]Institut für Optik und Atomare Physik, Technische Universität Berlin, Germany
[c]Institute for Solid-State Nuclear Physics, Berlin, Germany
[d]TRIUMF, Vancouver, Canada
[e]Institut für Physik, Humboldt-Universität zu Berlin, Berlin, Germany

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Study of the deuteron fusion reactions at very low energies in metallic environments enables us to determine the strength of the astrophysical electron screening effect in the terrestrial laboratories. Experiments performed under high and ultra high vacuum conditions showed that the experimentally determined screening energies corresponding to the reduction of the Coulomb barrier were significantly larger than the theoretical values calculated in terms of the dielectric function theory. As the origin of the so-called enhanced screening effect observed in nuclear reactions taking place in metals is unexplained we discuss here the interplay between a strong plasma screening and a narrow resonance placed close to the reaction threshold, which leads to the target material dependence of the reaction cross-section.

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1. Introduction

Pycnonuclear reactions taking place in dense astrophysical plasmas at very low temperatures are enhanced due to electron screening of the Coulomb barrier even by many orders of magnitude. The low energy $d + d$ reactions in metals, being a very good model for the strongly coupled plasma, investigated first under high vacuum (HV) conditions, showed that the experimentally determined screening energies corresponding to the reduction of the Coulomb barrier height were by at least a factor of two larger than the theoretical values calculated in terms of the dielectric function theory [1, 2, 3]. The enhanced screening effect in metals has been experimentally confirmed by many groups [4, 5, 6].

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Since contamination of the target surface plays a crucial role in the screening experiments we performed a series of new experiments dealing with atomically clean targets under ultra-high vacuum (UHV) conditions [7, 8]. The resulting screening energies turned to be remarkably larger than the previous experimental values, stepping up the discrepancy to the theoretical data. Since reasons for the enhanced screening effect still remain unknown, we examine the influence of a narrow resonance placed close to the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction threshold, on the screening energies and increased cross-section.

2. Screening in nuclear reactions

In low-energy nuclear reaction the reacting particle has to tunnel the Coulomb barrier. If the reaction takes place in metallic environment, the electrons of the host material screen the charges of reacting particles which results in Coulomb barrier reduction corresponding to the screening energy U_e. Related cross-section enhancement can be calculated as a ratio of the screened to bare nuclei cross-section [1]

$$f(E) = \frac{\sigma_{\mathrm{scr}}(E)}{\sigma_{\mathrm{bare}}(E)} \approx \frac{P(E+U_e)}{P(E)} \,. \tag{1}$$

The s-wave penetration factor $P(E)$ for a nuclear reaction influenced by the screening effect can be expressed as follows

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

with the Gamow energy $E_{\mathrm{G}} = (\pi\alpha Z_1 Z_2)^2\, 2\mu c^2$ that amounts to 986 keV for deuteron fusion reactions. Here α is the fine-structure constant, Z_1 and Z_2 are the charges of reacting particles and μ is the reduced mass.

The screening energy values, obtained earlier under HV conditions, reported in [2] and that obtained under UHV conditions [8] together with the theoretical calculations are presented in Table I. Those, astonishingly large discrepancies provide grounds to expect a resonance contribution to the reaction cross-section.

TABLE I

Electron screening energies determined for various target materials.

Target material	U_{theo} (eV)	$U_{\mathrm{exp}}^{\mathrm{HV}}$ (eV)	$U_{\mathrm{exp}}^{\mathrm{UHV}}$ (eV)
Al	96.6	191±12	
Zr	112.4	295±7	497±7
Pd	133.8	296±15	
Ta	135.7	302±13	

3. Resonance contribution

The experimental deuteron fusion cross-section may be significantly enhanced by a resonance state placed near the reaction threshold in ^{4}He. One can assume a 0^+ single particle resonance (of the $d \oplus d$ structure) with the width [9]

$$\Gamma_d = 2P(E)\frac{\hbar^2}{\mu a^2}|\theta|^2 \,. \tag{3}$$

Here, a denotes the R-matrix channel radius. $|\theta|^2$ is the dimensionless reduced width, which is equal to unity for a single particle resonance.

Since the total resonance width Γ is dominated by the deuteron partial width Γ_d ($\Gamma \approx \Gamma_d$) the resonance strength for the ^{2}H$(d,p)^3$H reaction related to the resonance integrated cross-section can be expressed as follows

$$\gamma = \frac{\Gamma_d \Gamma_p}{\Gamma} \approx \frac{\Gamma_d \Gamma_p}{\Gamma_d} = \Gamma_p \,. \tag{4}$$

Due to high proton energies (the Q value of the $d(d,p)t$ reaction amounts to 4.03 MeV) the penetration factor is close to unity, and consequently the partial proton width Γ_p remains approximately constant. Thus, the resonance strength γ (see Eq. (4)) of the $d \oplus d$ single-particle resonance is equal to the partial proton width Γ_p and independent of the resonance energy. On the other hand, the total resonance width ($\Gamma \approx \Gamma_d$) strongly decreases for lower energies due to penetration factor for deuterons (see Eq. (3)). Therefore, neglecting the energy dependence of the partial proton width, the narrowing of the single-particle resonance for low resonance energies is accompanied by an increase of its height (Fig. 1).

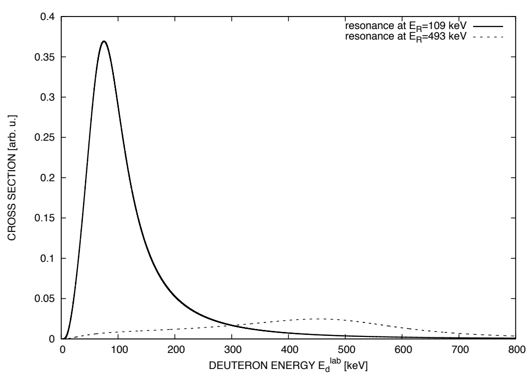

Fig. 1. The narrowing process of the resonance: as the strength of the resonance has to remain constant, disregarding the energy dependence of the partial proton width, with reducing its width, the height of the resonance increases.

As already shown in Ref. [10] a 0^+ single-particle resonance in ^{4}He assumed at $E_{\rm R} = 10$ eV with the width of 10 eV could explain the experimental cross-section enhancement at low energies with a theoretical screening energy U_e in Zirconium as presented in Fig. 2. However, the calculated energy dependence related to the resonance (solid line) does not agree exactly with the experimental data (dotted line). More precise experimental data could allow us to distinguish between the screening and resonance effects.

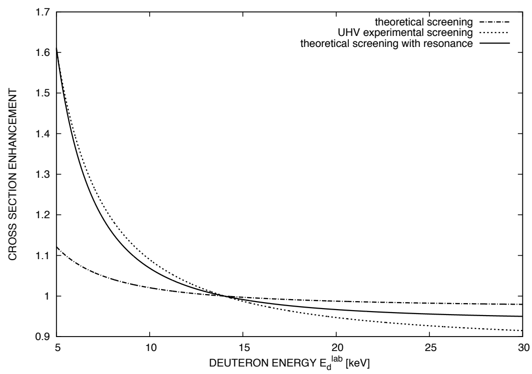

Fig. 2. Cross-section enhancement for $d(d,p)t$ reaction in Zr resulting from the theoretical screening, UHV experimental screening and the theoretical screening together with the resonance at $E_{\rm R} = 10$ eV.

The screening effect, besides of a direct change of the penetration factor and thus the resonance width, can lead to a resonance energy shift [11] resulting in strong host material dependence of the reaction cross-section. The latter effect has to be studied separately.

REFERENCES

[1] K. Czerski *et al.*, *Europhys. Lett.* **54**, 449 (2001).
[2] K. Czerski, A. Huke, P. Heide, G. Ruprecht, *Europhys. Lett.* **68**, 363 (2004).
[3] A. Huke *et al.*, *Phys. Rev.* **C78**, 015803 (2008).
[4] J. Kasagi *et al.*, *J. Phys. Soc. Jpn.* **71**, 2281 (2002).
[5] C. Bonomo *et al.*, *Nucl. Phys.* **A719**, 37c (2003).
[6] F. Raiola *et al.*, *Eur. Phys. J.* **A19**, 283 (2004).
[7] K. Czerski *et al.*, *J. Phys. G* **35**, 014012 (2008).
[8] N. Targosz-Ślęczka *et al.*, *PoS* **(NIC-X)**, 220 (2008).
[9] A.M. Lane, R.G. Thomas, *Rev. Mod. Phys.* **30**, 257 (1959).
[10] N. Targosz-Ślęczka *et al.*, *PoS* **(NIC-XI)**, 133 (2011), to be published .
[11] K. Czerski *et al.*, *Acta Phys. Pol. B* **40**, 903 (2009).