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Enhanced electron screening in nuclear reactions: a plasma or solid-state effect?

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The experimental study of low-energy deuteron fusion reactions in metallic environments shows the importance of the electron screening effect. Experimentally determined screening energies are remarkably higher than predicted theoretically. This discrepancy becomes even larger for the first ultra-high vacuum (UHV) experiment. Thus, a question arises whether the strongly enhanced electron screening originates from plasma or solid-state physics. Here, we present a possible explanation of exceptionally high experimental screening energies based on an additional contribution coming from a narrow resonance state placed close to the reaction threshold.

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1. Introduction

Study of the electron screening effect in deuterized metals is crucial for determination of ignition conditions in modelling Type 1a Supernova explosions, as well as for comprehension of stellar processes, like reactions occurring in White and Brown Dwarfs or Giant Planets [1]. In nuclear reactions between charged particles the presence of surrounding electrons reduces the Coulomb barrier by so-called screening energy U_e. This leads to an exponential-like enhancement of the experimental cross sections for decreasing projectile energies.

It has been found that the screening energy experimentally determined for deuterons fusion reactions in metallic environments being a very good model for a strongly coupled plasma is significantly higher compared to the theoretical predictions [2]. The enhanced screening effect has been confirmed by other groups [3, 4, 5]. However, the comparison between experimental and theoretical data is difficult because of some systematic errors in experiments, resulting especially from oxidation of the target surface during the measurements.

New experimental values [6, 7] for the screening energy obtained under ultra-high vacuum (UHV) conditions are even larger than the previous results, further increasing the discrepancy to the theoretical values. The question of the source of this discrepancy, very important for nuclear astrophysics, still remains unanswered. Thus, we discuss here an alternative explanation of the experimentally measured enhanced screening effect resulting from a narrow resonance close to the reaction threshold.

2. Experimental Research

For the d+d reactions in metals the cross section σ as well as the target nuclei density n are unknown. Thus, a specially adapted data analysis method is required [8]. Our differential data analysis extract all the details from the raw data by the use of the charge differentiated counting number N for the calculation of the experimental reaction yield function:

$$Y_{scr}(E;q) = \frac{ze}{\varepsilon}\frac{dN}{dq} \tag{2.1}$$

where ε is the detector efficiency and z is the charge state of the projectile. The yield needs to be set in relation to the known cross sections from a precise measurement on gaseous target [9]. Together with low-energy dependence of the stopping power $dE \propto \sqrt{E}$ [10] one can present a possible screening enhancement by the thick target enhancement factor [11, 12]:

$$F(E) = \frac{Y_{scr}(E)}{Y_{bare}(E)} = \frac{\int_0^E \frac{\sigma_{scr}(E)}{\sqrt{E}} dE}{\int_0^E \frac{\sigma_{bare}(E)}{\sqrt{E}} dE} \tag{2.2}$$

The electron screening effect in $^2H(d,p)^3H$ and $^2H(d,n)^3He$ has been experimentally studied for many different metals and insulators. For metallic environments, the experimentally determined screening energies are much larger than the theoretical predictions [2, 13]. New measurements performed under UHV conditions show that this discrepancy is even larger. The screening energy determined for Zr host material reached the value of 497 ± 7 eV [7] compared to the previous one 297 ± 8 eV obtained in the high vacuum experiment [11] and the theoretical value of 112.4 eV

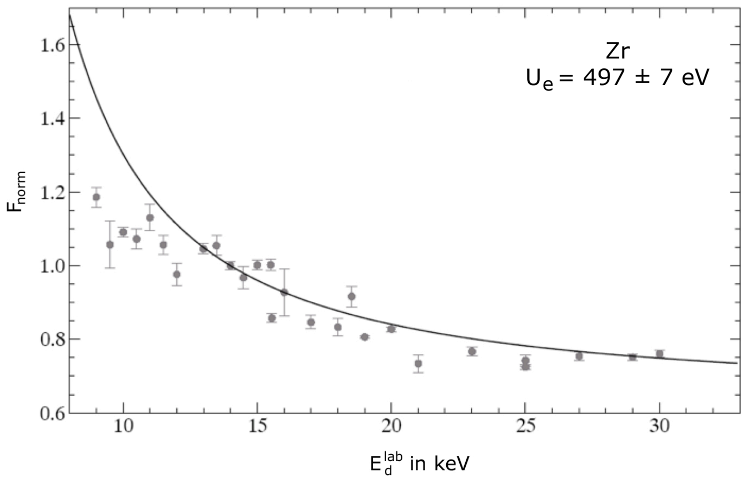

Figure 1: UHV experimental normalized enhancement factor. The fitted curve corresponds to the screening energy $U_e = 497 \pm 7$ eV.

[2]. The details of the first UHV experiment are presented in [14] and the experimental normalized enhancement factor is depicted in Fig. 1. The low-energy data are influenced by the target contamination and therefore deviate from the fitting curve. The error bars include the statistical and systematic uncertainties resulting from the differences in normalized yields measured for the deuteron energies and the monitor measurements at $E_0 = 14$ keV.

3. Single-Particle Resonance

To explain the unusually large experimental screening energy values for the deuteron fusion reactions, we assume a new hypothetical 0^+ resonance state in ^{4}He placed very close to the reaction threshold. This state should be a d+d single-particle resonance the width of which can be expressed as follows [15]:

$$\Gamma = 2P(E)\frac{\hbar^2}{\mu a^2}|\gamma|^2 \tag{3.1}$$

where P(E) denotes the penetration factor of the Coulomb barrier, $|\gamma|^2$ is the reduced width, that is dimensionless and equal to unity for a single-particle resonance, μ represents the reduced mass and a is the R-matrix channel radius. The s-wave penetration factor for screened low-energy d+d reactions is given by:

$$P(E) = \sqrt{\frac{E_G}{E+U_e}} \exp\left(-\sqrt{\frac{E_G}{E+U_e}}\right) \tag{3.2}$$

with the Gamow energy $E_G = 2\mu\left(\pi Z_1 Z_2 e^2/\hbar\right)^2$, that amounts to 986 keV, where μ is the reduced mass of the reacting system.

Applying the above formulas for a nuclear resonance state far below the Coulomb barrier, the decreasing penetration factor leads to reduction of the resonance width and simultaneously to increase of its height.

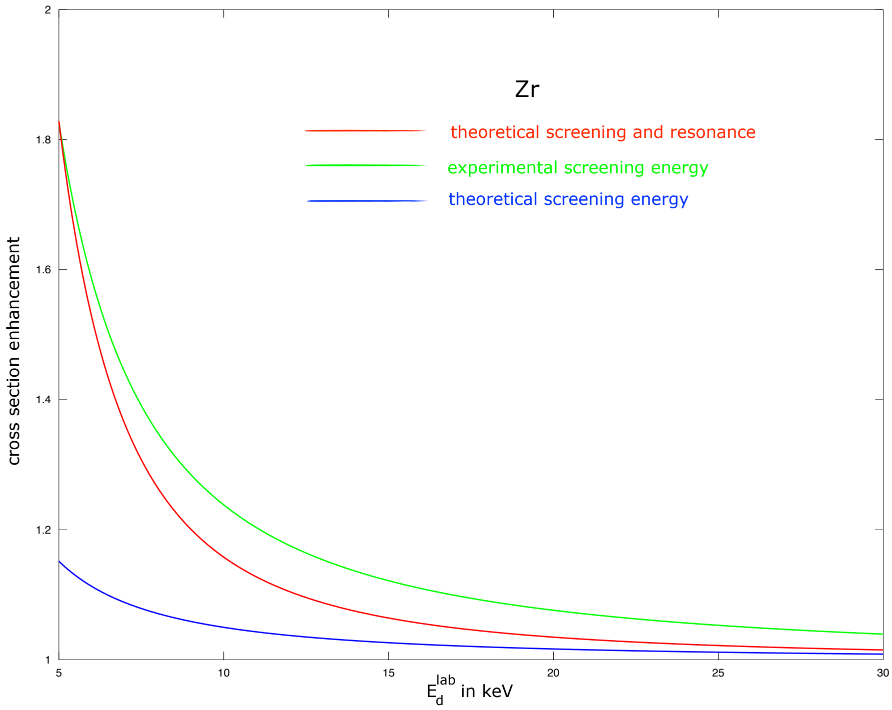

Figure 2: Postulated resonance contribution to the experimental cross section enhancement.

Calculations of the possible resonance contribution explaining observed exponential-like increase of experimental cross sections are presented in Fig. 2. The resonance energy was assumed to 10 eV and its total width amounted to 10 eV, as well. To fulfill the hypothesis of a single-particle resonance the proton width was set to a very small value of 33×10^{-9} keV. For the S-factor the value from [9] was used. The blue curve represents theoretically predicted enhancement in d+d reaction cross section resulting from the electron screening ($U_e = 112$ eV) in Zirconium target. The green curve shows the enhancement determined in our UHV experiment, corresponding to the screening energy value of about 497 eV. The red line illustrate the enhancement coming from the theoretical screening energy mentioned above, together with the hypothetical resonance contribution.

4. Conclusions

The cross section enhancement arising not only from the electron screening but also from the resonance has been shown. Such a resonance could explain the exceptionally high experimental results. As the energy dependence of the resonance curve (see Fig. 2) is slightly different from that of the screening, future UHV experiments of improved accuracy could in principle confirm our resonance hypothesis.

On the other hand the resonance position is difficult to determine based only on the direct experimental data since the cross section energy dependence of the distant resonances is not sensitive for its value explicitly $\sigma(E) \backsim \frac{1}{E^3}$.

Nevertheless, new experiments carried out at energies lower than 5 keV could contribute to solving the enhanced screening problem.

References

[1] S. Ichimaru and H. Kitamura *Phys. Plasmas* **6** 2649 (1999)

[2] K. Czerski, A. Huke, P. Heide and G. Ruprecht *Europhys. Lett.* **68** 363 (2004)

[3] F. Raiola et al. *Eur. Phys. J.* A **19** 283 (2004)

[4] C. Bonomo et al. *Nucl. Phys.* A **719** 37c (2003)

[5] J. Kasagi, H. Yuki, T. Baba, T. Noda, T. Ohtsuki and A.G. Lipson *J. Phys. Soc. Jpn.* **71** 2281 (2002)

[6] K. Czerski et al. *J. Phys.* G **35** 014012 (2008)

[7] N. Targosz-Ślęczka et al. *J. Phys. Conference Series* **202** 012041 (2010)

[8] A. Huke, K. Czerski and P. Heide *Nucl. Instrum. and Meth. in Phys. Res.* B **256** 599 (2007)

[9] R. E. Brown and N. Jarmie *Phys. Rev.* C **41** 1391 (1990)

[10] F. Ziegler et al., *The Stopping and Ranges of Ion in Matter*, Pergamon Press, NY (1985)

[11] K. Czerski, A. Huke, A. Biller, P. Heide, M. Hoeft and G. Ruprecht *Europhys. Lett.* **54** 449 (2001)

[12] K. Czerski, A. Huke, P. Heide, G. Ruprecht *Eur. Phys. J.* A **27** 83 (2006)

[13] A. Huke, K. Czerski, G. Ruprecht, N. Targosz, W. Żebrowski and P. Heide *Phys. Rev.* C **78** 015803 (2008)

[14] K. Czerski et al., *J. Phys.* G **35** 014012 (2008)

[15] A.M. Lane and R.G. Thomas, *Rev. Mod. Phys.* **30** 257 (1959)