Influence of the target surface contamination on UHV screening energies

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Abstract. The $d + d$ fusion reactions have been investigated in the Zirconium environment under ultra high vacuum (UHV) conditions for projectile energies below 30 keV. The experimentally determined screening energy value of $497 \pm 7$ eV is larger than the previous results by a factor of almost two. Despite the UHV conditions a small deviation between experimental data and the theoretical curve arising from the target surface contamination could be still observed at the lowest projectile energies. Calculations made under the assumption of formation of a Zirconium oxide contamination, show that every atomic monolayer reduces the estimated screening energy significantly.

1. Introduction

The enhanced electron screening effect recently observed in $d + d$ fusion and some other nuclear reactions in metallic environments is extremely important for general understanding of stellar processes since it can strongly increase the nuclear reaction rates in dense astrophysical plasmas [1]. For this reason, the electron screening effect in metallic environments has been experimentally investigated by many research groups [2, 3, 4, 5]. Despite the large amount of data, the results obtained by various groups are inconsistent because of some systematic errors. The electron screening measurement have been performed up to now under high vacuum conditions. In those experimental studies one came across some difficulties concerning the target surface cleanness. Metal oxide or carbon deposits reduce the experimental screening energy values. In extreme case no screening is observed [6].

The screened reaction cross section reads as follows [7]:

$$
\sigma_{scr}(E_{cm}) = \frac{1}{\sqrt{E_{cm}(E_{cm} + U_e)}} S(E_{cm}) \exp \left( -\sqrt{\frac{E_G}{E_{cm} + U_e}} \right)
$$  

(1)

where $E_G = 986$ keV is the Gamow energy for the $d+d$ system, $S(E_{cm})$ is the astrophysical S-factor and $U_e$ denotes the screening energy. The strength of the screening effect can be described by means of the thick-target enhancement factor $F(E)$ defined as the ratio between the thick-target yields for screened and bare nuclei [8]:

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\[ F(E) = \frac{Y_{scr}(E)}{Y_{bare}(E)} = \frac{\int_0^E \frac{\sigma_{scr}(E)}{\sqrt{E}} \, dE}{\int_0^E \frac{\sigma_{bare}(E)}{\sqrt{E}} \, dE} \]  

(2)

The bare nuclei cross section is known from the precise measurements performed with the gas target [9]. To address the contamination layer problem and improve the accuracy of the measurements we performed the first ultra high vacuum (UHV) experiment on d+d fusion reactions in metals.

2. Experiment

We measured the \(^2\text{H}(d,p)^3\text{H}\) and \(^2\text{H}(d,n)^3\text{He}\) total cross sections and angular distributions in Zirconium foils (1 mm thick) at deuteron bombarding energies ranging from 9 to 30 keV. Details of the experimental set-up, data-taking procedure and data-analysis methods are given in our previous papers [10]. In brief, the experiment has been performed with an electrostatic UHV accelerator using an electron cyclotron resonance (ECR) ion source and a highly stabilized power supply. The ion-beam was magnetically analyzed and focused on the Zr target to a spot of 5 mm in diameter. The charged products of \(d + d\) reactions were detected at three fixed backward angles 90\(^\circ\), 125\(^\circ\) and 150\(^\circ\) with silicon detectors. Since the dominating error source of that kind of measurement comes from contamination layer formation, we cleaned the target surface by means of Argon ion sputtering. Additionally, we applied the Auger electron spectroscopy to check the target surface cleanliness. Contamination of carbon and oxygen could be clearly observed during longer measurements at the lowest projectile energies. A differential pumping system and use of \(\text{LN}_2\) cooling system allowed to reduce the gas pressure to the value of \(5 \times 10^{-10}\) mbar in the target chamber which is one order of magnitude better than in our previous UHV experiment [10].

![Figure 1](image)

**Figure 1.** Experimental normalized enhancement factor obtained for Zr target under UHV conditions due to liquid \(\text{LN}_2\) cooling. The value of the electron screening energy \(U_e\) amounts to 497 ± 7 eV.
3. Results

3.1. Experimental screening energy

The enhancement factor $F(E)$ in equation (2) is independent of both the deuteron density in the target and the stopping power. The screening energy value has been determined by fitting an increase of $F(E)$ towards lower projectile energies to experimental results. The normalized thick-target enhancement factor is defined as the ratio between enhancement factors for a certain measurement and for the monitor measurement (here at the projectile energy $E_0 = 14$ keV):

$$F_{\text{norm}}(E) = \frac{F(E)}{F(E_0)}$$

The experimental thick target enhancement factors are shown in Figure 1. The error bars of presented data are dominated by statistical uncertainties and include also systematic uncertainties resulting from the alternating deuteron density in the target. The experimental data analysis gives the screening energy value of $U_e = 497 \pm 7$ eV. The fitted curve according to equations (2) and (3) takes on unity for the projectile energy $E_0 = 14$ keV. Low energy experimental points (below 12 keV) deviate from the fitted curve, most probably because of the contamination layer formation. Thus, we decided to study quantitatively influence of the target surface contamination on the experimentally estimated UHV screening energies.

3.2. Influence of contamination layer

We considered the proton branch of deuteron fusion reactions in the Zirconium target. Calculations assumed formation of the Zirconium dioxide layer on the target surface where the deuteron density can be neglected compared to that in the Zr target. Therefore, the ZrO$_2$ layer

![Figure 2](image_url)

**Figure 2.** Theoretical normalized enhancement factor for Zr target with $U_e = 497$ eV. The black line stands for the clean target, the red line is the case when the target is contaminated by 10 monolayers of Zirconium dioxide and the blue line is for 20 contamination layers.
reduces only the projectile energy but does not contribute to the experimental reaction yield. The theoretical normalized thick-target enhancement factors were calculated under assumption that, the stopping power of deuterium in Zirconium and in the oxidation layer are proportional to the square root of the energy \[11\]. The astrophysical S-factor for considered reaction has been taken from \[9\]. The calculations were carried out for the experimentally found screening energy value of \(U_e = 497\) eV.

Figure 2 shows the theoretical normalized enhancement factors for a different number of the contamination monolayers. The curve in black corresponds to the virgin target case. The red and the blue curves were plotted for 10 and 20 ZrO\(_2\) monolayers formed on the target surface, respectively. It can be noticed that the enhancement factor is significantly reduced toward lower projectile energies.

The calculations showed that even a single contamination monolayer can change the enhancement factor value at the deuteron energies below 12 keV. Our experimental results suggest formation of about 10 contamination monolayers during the measurement. However, the number of contamination monolayers can strongly vary for different deuteron energies. The largest number can be expected for the lowest projectile energies with the longest measurement time. Thus, the final quantitative analysis of systematic errors of the determined screening energy due to the target surface contamination remains ambiguous \[12\].

4. Conclusions
We have measured the deuteron fusion reaction cross sections and angular distributions in the Zirconium host target under UHV conditions with the additional LN\(_2\) cooling system at deuteron bombarding energies below 30 keV. The observed enhancement of the thick target yield leads to the screening energy value of 497 ± 7 eV which is much larger than our previous values measured for Zr under high vacuum conditions (5 × 10\(^{-7}\) mbar) \[7\] and ultra high vacuum conditions (without LN\(_2\) cooling, 5 × 10\(^{-9}\) mbar) \[10\], both being of about 300 eV. As we could experimentally and theoretically show, even at the vacuum pressure in the target chamber of the present experiment of 5 × 10\(^{-10}\) mbar, a small oxide contamination of the target surface observed for the deuteron energies below 12 keV and longer measurement times still decreases experimental thick target yields, significantly. Thus, our new value of the screening energy for the \(d + d\) fusion reactions in the Zr environment, although the systematic uncertainties could be strongly reduced, probably represents its lower limit. Further improvement of the experiential set-up is necessary.

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