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Electron screening effect in nuclear reactions and radioactive decays

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Recently, the electron screening effect in metallic environments has been experimentally investigated by many groups in low-energy nuclear reactions. The similar effect is expected in radioactive decays where the decay constant should be dependent on the valence electron density of the host material. Since metals represents a very good model for dense astrophysical plasmas, comparison of both effects can deliver new information about mechanism of the enhanced electron screening and consequences for nuclear processes taking place in stellar interior.
Here, we present a new experimental investigation of screening effect in the $d+d$ nuclear reactions under UHV conditions. Based on those experimental results a host material dependence of the alpha decay probability has been predicted.

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1. Introduction

The enhanced electron screening effect observed for the first time in deuteron fusion reactions in metallic environments [1], is of fundamental importance for astrophysical processes. Conduction electrons moving in deuterated metals represent the model of a strongly coupled plasma where nuclear reaction rates can be increased by many orders of magnitude. That concerns especially the nuclear reactions occurring in White and Brown Dwarfs or Giant Planets [2]. To understand the nuclear processes taking place in that case, the uncertainty of the experimental cross section of a few percent is not so important as the uncertainty resulted from the determination of the strength of the screening effect. This effect is also significant for modelling the Type 1a Supernova explosions with regard to specification of the ignition conditions.

Although the screening effect has been recently demonstrated by many groups in experimental investigations of low-energy nuclear reactions and radioactive decays both in gaseous and metallic environments [1, 3, 4, 5, 6], the comparison between the experimental data is highly difficult because of the experimental uncertainties. In order to minimize that, the first ultra-high vacuum (UHV) experiment was performed [7]. Since the experimental results were very sensitive even for the smallest contamination of the target surface, in this work we present new experimental data obtained under improved UHV conditions.

In addition, the discrepancies between the theoretical predictions and the experimental results have been found [8]. The absolute values of experimental screening energies are by a factor of two smaller than those calculated in the framework of the self-consistent dielectric function theory. Still, the host material dependence can be described rather well, indicating importance of the valence electron density in target materials [9]. Similar effects are also expected for alpha decays for which one should observe an environmental influence on the decay constants. The largest differences should be noticeable between insulating and metallic host materials.

2. UHV experiment

Comparison between the experimental data obtained by different groups is difficult because of some systematic errors in experiments caused by contamination of the target surface and high mobility of the implanted deuterons, which result in unstable deuteron density in the target material [9].

In the first ultra-high vacuum experiment the total cross sections and angular distributions of the $^{2}\mathrm{H}(d,p)^{3}\mathrm{H}$ and $^{2}\mathrm{H}(d,n)^{3}\mathrm{He}$ reactions in thin foils of Zirconium have been measured with special attention to the atomic cleanness of the target [7]. The ultra-high vacuum has been achieved by a differential pumping system allowing to reduce the gas pressure to a value of 5×10^{-9} mbar in the target chamber. Despite the low pressure value, the target contamination still resulted in large systematic uncertainties. Thus, in the present experiment we have applied a liquid N_2 cooling improving the vacuum pressure in the target chamber to the value of 5×10^{-10} mbar. That resulted in lowering the systematic errors induced by oxidation layers. During the measurements the contamination of the target surface has been controlled every 8 hours using the Auger Electron Spectroscopy. Except the additional cooling, the experimental set-up as well as the procedure remained unchanged, as shown in [7].

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The electron screening effect reduces the Coulomb barrier by the screening energy U_e. Thus, the screened reaction cross section reads as follows [8]:

$$\sigma_{scr}(E) = \frac{1}{\sqrt{E(E+U_e)}} S(E)\ \exp\left(-\sqrt{\frac{E_G}{E+U_e}}\right), \tag{2.1}$$

where

$$E_G = \left(\frac{2\pi\, Z_1\, Z_2\, e^2}{\hbar}\right)^2 \frac{\mu}{2}$$

is the Gamow energy, E denotes CM energy for the $d+d$ system and μ is the reduced mass of the reacting system. 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 angle-integrated thick-target yields for screened and bare nuclei [1]

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

Here, σ and ε are the cross section for bare nuclei, and the stopping power taken at the beam energy E, respectively. The bare nuclei cross section is known from the precision measurements performed with the gas target [10].

Normalized enhancement factor is the yield ratio of measured reaction to the value of the monitor measurement

$$F_{norm}(E) = \frac{F(E)}{F(E_0)} = \frac{y(E)}{y(E_0)}, \tag{2.3}$$

where the reduced yield function [1] obtained from the experiental thick-target yield $Y_{scr}(E)$ is given by

$$y(E) = \frac{Y_{scr}(E)}{\int_0^E E^{-2/3}\ S(E)\ \exp\left(-\sqrt{\frac{E_G}{E}}\right) dE}. \tag{2.4}$$

The new result of UHV investigations for Zirconium target is presented in Fig. 1. The enhancement factors are normalized to $E_0 = 14\,\mathrm{keV}$. A one-parameter fit to experimental results give a screening energy value of $U_e = 497 \pm 7\,\mathrm{eV}$ which is much higher compared to the previous one $U_e = 319 \pm 3\,\mathrm{eV}$.

3. Electron screening in alpha decay

Alpha particles have to tunnel the Coulomb barrier in opposite direction compared to low-energy reactions. The probability of alpha decay depends on the electronic structure of both decaying atom and the host material. The alpha decay enhancement factor f can be described by the ratio of penetration factors through the Coulomb barrier for screened and bare nuclei corresponding to an increase of the alpha decay probability in the given environment. Assuming that the reduction

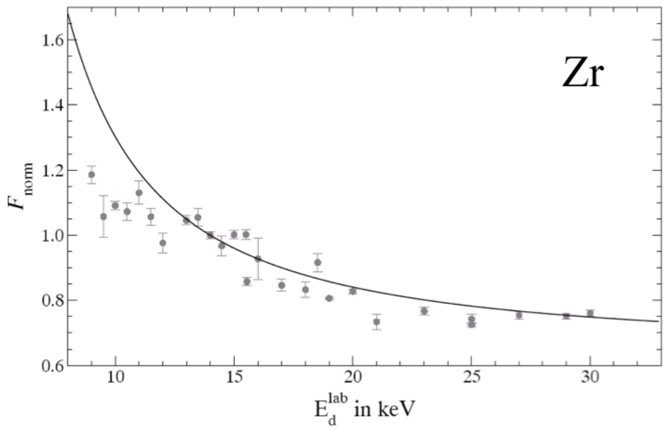

Figure 1: Experimental normalized enhancement factor obtained for $^2H(d,p)^3H$ reaction in Zirconium applying the liquid N_2 cooling. The screening energy value amounts to $U_e = 497 \pm 7\,\text{eV}$.

of the Coulomb barrier due to screening effect can be described by screening energy U_e and that the binding energy of decaying nucleus remains unchanged, one can express the enhancement factor as follows:

$$f = \frac{P(E+U_e)}{P(E)} = \frac{\sqrt{\frac{E_G}{E+U_e}}\exp\left(-\sqrt{\frac{E_G}{E+U_e}}\right)}{\sqrt{\frac{E_G}{E}}\exp\left(-\sqrt{\frac{E_G}{E}}\right)}. \tag{3.1}$$

Applying U_e values found for deuterons fusion reactions and taking into account that the screening energy scales as a product of charges of particles involved in the process, the resulting enhancement factors reach unrealistically high values [11]. Nevertheless, the alpha particle energies of a few MeV are much larger than their Fermi energy in metallic environment. In this case the screening energy should be reduced compared to the adiabatic limit even by one order of magnitude, as described in [9].

The results calculated for the alpha decay of Uranium in different host materials are presented in Fig. 2. The alpha decay of Uranium proceeds at the energy about 4.27 MeV. Comparing the predicted environmental influence of metals and the insulator on the enhancement factor one can expect a difference of $3-4\%$ in the decay constants.

4. Conclusions and discussion

The ultra-high vacuum allowed to improve the accuracy of the electron screening effect measurement. However, the lowest energy measurements deviate form the theoretical curve owing to the long target irradiation time. For those low energy values we have still observed oxygen and carbon contamination accumulation using the Auger Electron Spectroscopy.

The experimental data obtained in UHV experiment for the $d+d$ reactions revealed significantly higher U_e value increasing the discrepancy to the theoretical predictions. Understanding that issue is of fundamental importance for astrophysics, and the reason for it remains unknown.

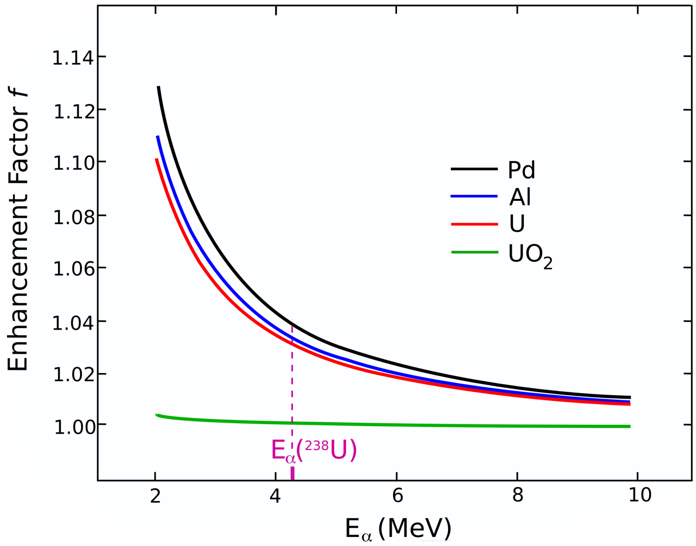

Figure 2: Enhancement factor as a function of alpha particle energy for different host materials. Alpha decay of Uranium occurs at energy $E_\alpha(^{238}U) = 4.27\,\mathrm{MeV}$. The enhancement of alpha decay in metallic surroundings is about $3-4\%$ compared to an insulator.

We presented theoretical predictions for enhancement of alpha decay probability in metallic environment of a few percent compared to an insulator. The predicted increase is of the same order as lately experimentally found for ^{221}Fr [5]. The alpha decay experiments can provide an independent test of large screening energies determined for deuterons fusion reactions.

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