NEW ACCELERATOR FACILITY FOR MEASUREMENTS OF NUCLEAR REACTIONS AT ENERGIES BELOW 1 keV*

M. Kaczmarski, A.I. Kilic, K. Czerski, A. Kowalska
D. Weissbach, N. Targosz-Sleczka

Institute of Physics, University of Szczecin
Wielkopolska 15, 70-451 Szczecin, Poland

A. Huke, G. Ruprecht

Institute for Solid State Nuclear Physics
Leistikowstr. 2, 14050 Berlin, Germany

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Nuclear reactions at very low energies can be strongly enhanced due to screening of the Coulomb barrier by surrounding electrons. In the past decade, this effect was intensively studied for the $d + d$ reactions taking place in metallic environments as a model for dense astrophysical plasmas, where the reaction rates can be increased even by many orders of magnitude. The experimentally determined screening energies corresponding to the reduction of the Coulomb barrier height are, however, much larger than the theoretical predictions. New experimental data obtained under ultra high vacuum conditions additionally increases this discrepancy, the origin of which remains still unknown. One of a possible explanation is the excitation of a hypothetical threshold resonance in the ^{4}He nucleus. As the energy dependence of the resonant reaction cross section differs to that of the electron screening effect, one can distinguish between both processes expanding measurements down to the deuteron energies of 1 keV. Because of very high enhancement factors (of the order of 10^6) a new high current accelerator facility, being now under construction at the University of Szczecin, will make it possible to measure for the first time the reaction cross sections at so low energies.

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1. Introduction

Nuclear reactions induced by charged particles, studied at very low projectile energies are of special interest for nuclear astrophysics. Due to dropping of the penetrability through the Coulomb barrier with the lowering energies, the reaction cross sections at the energies corresponding to the stellar nucleosynthesis temperatures could be measured till now only in a few cases. Thus, this is the main motivation for development of new experimental systems providing high-current ion-beams and simultaneously possessing a very good energy definition of the beam.

On the other hand, at sufficiently low energies, both projectiles and target atoms cannot be treated as bare nuclei any more. The electrons surrounding the reacting nuclei screen the Coulomb barrier and lead to an exponential-like enhancement of the measured cross section compared to the bare-nuclei case. The electron screening effect owning to bound electrons was experimentally observed for the first time in gas target experiments [1] on several light nuclear fusion systems. However, to verify theory of the electron screening in astrophysical plasmas, where the electrons mainly occupy free continuum states and can increase reaction rates by many orders of magnitude, a different approach is necessary.

We studied the $^2\mathrm{H}(d,p)^3\mathrm{H}$ and $^2\mathrm{H}(d,n)^3\mathrm{He}$ reactions in metallic environments, which are very good approximation for strongly coupled astrophysical plasmas, and showed that the screening energy corresponding to the reduction of the Coulomb barrier is at least by a factor of two larger than the theoretical predictions [2, 3]. Larger screening energies in metals have been also demonstrated by other groups [4, 5] and for other reactions [6, 7]. Some differences between experimental results obtained by different groups probably result from a target surface contamination or an inhomogeneous distribution of deuterons within the target [8]. Generally, the experimental screening energies reach about 300 eV for heavier metals and are much smaller (below 50 eV) for insulating materials.

New experiments performed under ultra high vacuum (UHV) conditions with atomically clean Zr targets gave even the higher screening energy of about 400 eV [9]. The reason for discrepancy between theoretical and experimental values is still unknown. To explain it, excitation of a hypothetical 0^+ threshold resonance in the compound nucleus $^4\mathrm{He}$ has been proposed [10]. Since the energy dependence of the resonance and screening contribution is different, measurements of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ and $^2\mathrm{H}(d,n)^3\mathrm{He}$ reactions performed at energies as low as 1 keV could solve the long-standing puzzle.

Here, we present new calculations for the reaction cross sections and branching ratio for the $d+d$ reactions down to very low energies including the enhancement resulting from the electron screening effect. The details of a new accelerator system with ultra high vacuum being just under construction at the University of Szczecin and enabling measurements of nuclear reactions at energies below 1 keV will be given as well.

2. Nuclear reactions at very low energies

The $d+d$ reaction threshold in the compound nucleus ^{4}He lies at the excitation energy of about 23.8 MeV in the region where many broad resonances overlap. Hereby, two twin, isospin mixed resonances with spin and parity 1^- play an important role leading two a small p-wave contribution to the reaction cross section even at the lowest deuteron energy and consequently to an anisotropic angular distribution. From the theoretical point of view, the $d+d$ reactions have been described using direct reaction formalism in the frame of the DWBA calculations [11] as well as within the multi-channel R-matrix theory [12]. The latter reproduces the experimental angular distributions, total cross sections and branching ratio of the ^{2}H$(d,p)^3$H and ^{2}H$(d,n)^3$He reactions very successfully. Here, we are only interested in a small deuteron energy region ranging between 0 and 50 keV, therefore, the contribution arising from the broad resonances that can be assumed to be energy independent, and an approach based on a coherent superposition of sixteen constant transition matrix elements can be applied [13]. The energy dependence results only from the penetration through the Coulomb barrier. The values of the matrix elements are relatively well known and were obtained by fitting experimental cross sections, vector and tensor analyzing powers measured in gas target experiments. Following the notation of Ref. [13], the actual T-matrix element can be factorized into an energy-independent inner matrix element and the penetrability function C_L

$$T_{\beta\alpha}(E) = C_{L\alpha}(E)\,\hat{T}_{\beta\alpha}$$

with

$$\begin{aligned} C_{L\alpha}(E) &= \sqrt{P_{L\alpha}(E)}\,\exp\left[\,i\left(\delta_{L\alpha}+\phi_{L\alpha}\right)\right]\,, \\ P_{L\alpha}(E) &= \frac{1}{F^2_{L\alpha}(E)+G^2_{L\alpha}(E)}\,. \end{aligned} \tag{2.1}$$

Here, F_L and G_L are the regular and irregular Coulomb wave functions taken at the center-of-mass energy E and the channel radius $a = 7\,\mathrm{fm}$. P_L stays for the penetration factor of the angular momentum L. The phases δ_L and ϕ_L denote the Coulomb and nuclear phase shifts, respectively. Angular distribution of emitted protons and neutrons can be described by the following formula

$$\frac{d\sigma}{d\omega}(\theta) = a_0 + a_2\cos^2(\theta) + a_4\cos^4(\theta)\,, \tag{2.2}$$

where coefficient a_2 is small compared to a_0, and the coefficient a_4 related to the d-wave contribution can be neglected for deuteron energies below 50 keV. Thus, the anisotropy coefficient of the angular distribution can be defined as the ratio a_2/a_0 . The results of calculations are depicted in Figs. 1 and 2.

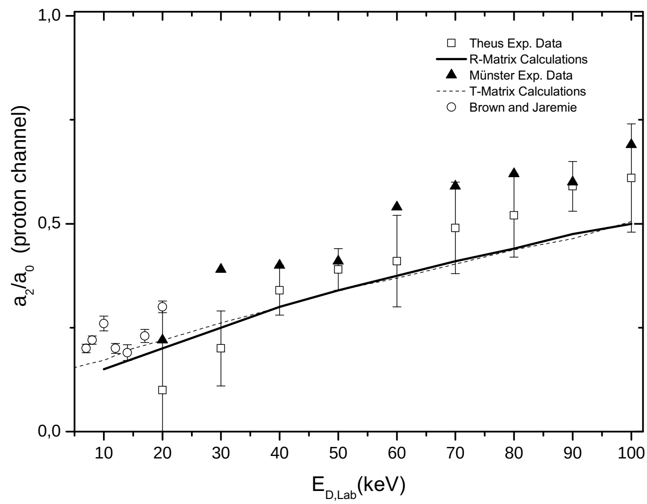

Fig. 1. T-matrix and R-matrix [12] calculations of the anisotropy coefficient for the ^{2}H$(d,p)^3$H reaction compared to the experimental data of Theus [14], Münster [15], Brown and Jarmie [16].

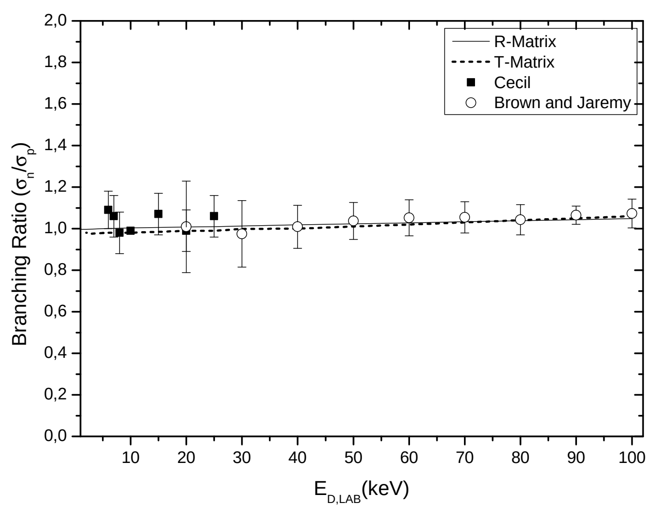

Fig. 2. Experimental and theoretical neutron-to-proton branching ratio. The experimental data are from Ref. [17] and [16].

Enhancement of the $d+d$ reaction cross sections due to the electron screening effect takes place below 15 keV where the contribution from the partial s-wave dominates. The penetration factor for the s-wave reads as follows

$$P = \sqrt{\frac{E_{\rm G}}{E}}\ \exp\left(-\sqrt{\frac{E_{\rm G}}{E}}\right), \tag{2.3}$$

where $E_{\rm G} = 986,3$ keV is the Gamow energy for the $d+d$ reactions. The total cross section can be then expressed by

$$\sigma(E) = \frac{1}{E}\ S(E)\ \exp\left(-\sqrt{\frac{E_{\rm G}}{E}}\right) = \frac{1}{\sqrt{E_{\rm G}E}}S(E)P(E)\,, \tag{2.4}$$

where $S(E)$ represents the astrophysical S-factor. Usually, the electron screening effect can be taken into account by increasing the energy in the expression for the s-wave penetration factor (Eq. (2.3)) by the screening energy U_e corresponding to reduction of the Coulomb barrier height. Here, we can rather use Eq. (2.1), exchanging $E \to E + U_e$ in expression for penetration factors for $L = 0, 1, \ldots$ and, finally, we calculate the screening enhancement factor as a cross section ratio for the screened and the bare nuclei case

$$f(E) = \frac{\sigma_{\rm scr}(E)}{\sigma_{\rm bare}(E)}\,. \tag{2.5}$$

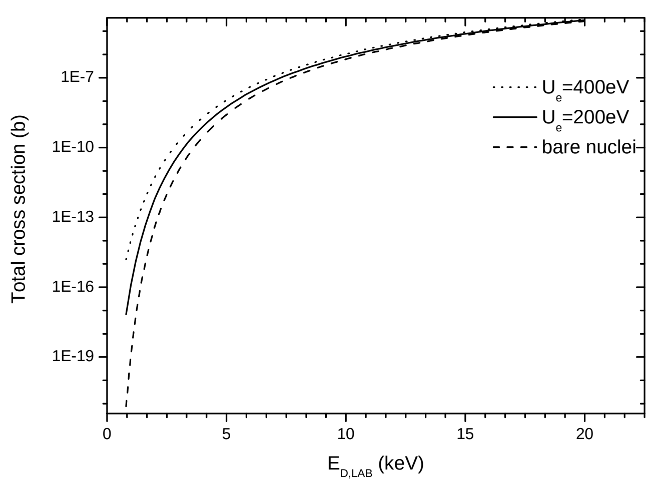

Fig. 3. Total cross section for the ^{2}H$(d,p)^3$H reaction including the screening energies of 200 eV and 400 eV.

The results of calculations for different screening energies are presented in Figs. 3 and 4. The cross section drops very rapidly with decreasing deuteron energies. However, due to very large enhancement factors, the excitation function for the $d + d$ reactions can be measured down to the deuteron energy of 1 keV (0.5 keV in the center mass system) assuming the deuteron beam current of 10 mA and close detection geometry. For the screening energy of 400 eV and enhancement factor 3×10^6, we get a counting rate of about one event per day which is a limit because of the natural background. Thus, using our new accelerator system it will be possible for the first time to reach the so-called pycnoreaction region where the particle energies are comparable with the screening energy.

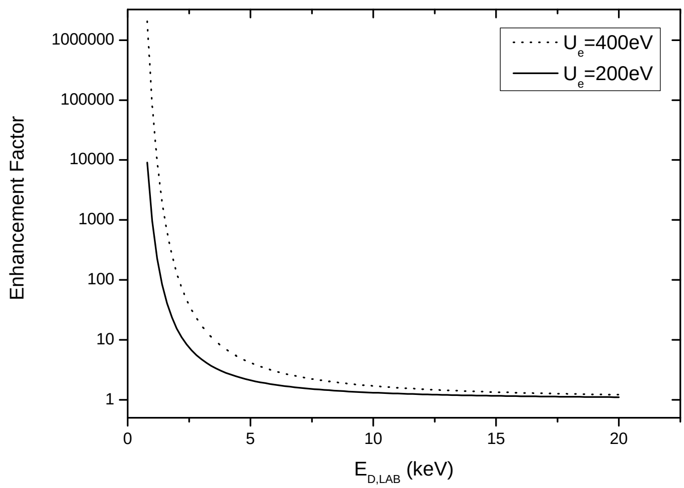

Fig. 4. Enhancement factor for screening energies of 200 eV and 400 eV.

3. New accelerator facility

The future UHV accelerator facility at the University of Szczecin (see Fig. 5) will allow for investigation of nuclear reactions in metallic environments at energies even lower than 1 keV applying high current beams of light ions focused at the cooled down targets. The system will operate under UHV conditions which are necessary to prevent the target contamination, which has been already proven in previous experiments [8–10]. Combining nuclear and solid state physics methods will enable deeper understanding of nuclear reaction mechanism at very low energies.

The system consists of two independent parts manufactured by different companies: the accelerator and beam transport system (Dreebit GmbH, Germany) and the UHV target chamber with diagnostic equipment (PREVAC, Poland). The 2.7 GHz ECR ion source with permanent magnets was

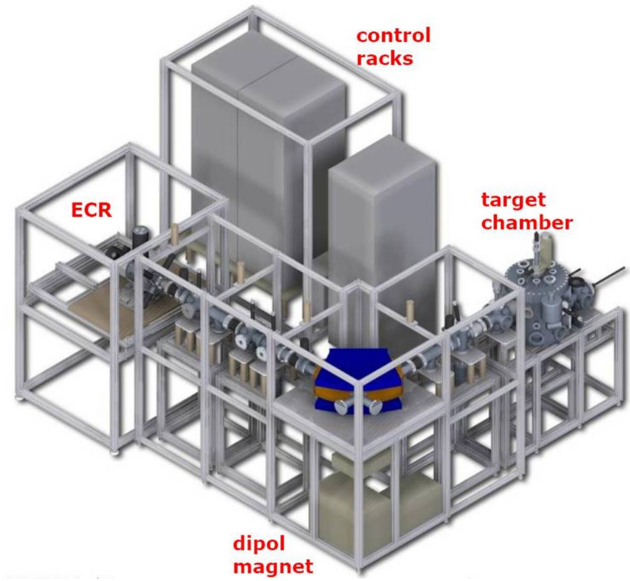

Fig. 5. New accelerator facility with UHV at the University of Szczecin.

chosen because of its reliability, low emittance and very good long term stability. It can provide light ion beams (till Xe) of high currents (up to 10 mA deuteron beam at the target) with energy resolution of a few eV that can be sustained for very long time with a low energy consumption. The accelerator system will be additionally equipped with a deceleration/acceleration unit allowing for operation with high currents in the energy range between 0.5 and 100 keV for different research fields. A 90° double focusing analyzing magnet and system of magnetic and electrostatic focusing elements delivers the ion beam through the units of differential pumping system to the target chamber.

The target chamber (Fig. 6) is built of mu-metal ($B < 0,5\ \mu T$) in order to shield the magnetic field and to enable electron spectroscopy of the target surface. It is constructed to work under ultra high vacuum conditions with the pressure up to 10^{-11} mbar and equipped with an electron gun and an X-ray source operating together with a high-resolution electrostatic electron detector. Thus, for investigation of the cleanness and the structural contamination of the target surface the Auger electron spectroscopy (AES) and the X-ray photoelectron spectroscopy (XPS) will be used, respectively. The density of deuterons implanted into metallic targets will be tested by small angle scattering of He/Ar ions applying a pulsed ion gun and the ToF method. The ion gun will be also used for cleaning the target surface. Targets will be placed in the center of the chamber on 5-axes manipulator combined with laser positioning system. The targets mounted on a transportable target holder can be cooled down to 170°C and heat up to 1200°C, and will be moved by a linear transfer system from a load lock chamber to the main target chamber. The latter was designed for loading samples without destroying the UHV. In future, the system will be completed by a preparation chamber where thin surfaces on target samples will be produced.

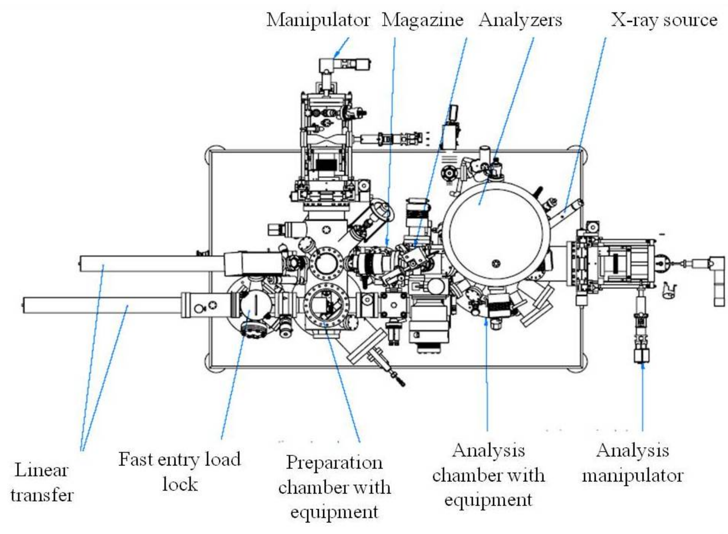

Fig. 6. UHV target chamber.

Two different detection systems of charged nuclear reaction ejectiles are expected to be used. A close geometry system is based on an Si detector telescope setup that enables to cover the largest possible detection solid angle. The second detection system is designed for a measurement of reaction angular distributions and will consist of many large area Si detectors placed at larger distances to the target. A combination of both systems depending on experimental requirements will be possible.

4. Upcoming experiments

The construction and commissioning of the new facility system will be finished in May 2014. The first experiments planned in the Nuclear and Medical Physics Laboratory at the University of Szczecin involve a wide spectrum of possible fields, starting from nuclear astrophysics experiments, through solid state physics up to biological responses for irradiation and cell repairing mechanisms. First of all, the facility will be prepared for investigating nuclear reactions at the lowest possible energies. We will be able to perform experiments with higher deuteron currents, better vacuum and lower projectile energies than it was the case in our previous experiments performed at the Humboldt University in Berlin, Germany. We will try to distinguish between different nuclear and solid-state physics mechanisms, apart from the electron screening effect, contributing to the increase of the total cross sections and the enhancement factors for lowering projectile energies. Here, the search for a hypothetical threshold resonance in ^{4}He will play a prominent role.

On the other hand, some structural effects, connecting to the number of crystal defects as well as to some target impurities can modify the reaction cross sections measured at very low energies. That is why the electron spectroscopy methods in future experiments are necessary, and preparation of targets with controlled thin layers of oxides or metallic alloys are so important.

The results of our experiments might be also very interesting for plasma physics and future thermonuclear reactors for which the so-called interaction with the first wall is still investigated, and the electron screening effect is not included. The system will allow to produce fair amount of protons, neutrons, ^{3}He and ^{3}H and other light ions which can be used to study different astrophysically relevant nuclear reactions. We also plan to use the facility for irradiating biological samples. Studies on biological response and repairing mechanisms of single cells, especially at low doses are an important field, and not yet well known. High ion currents and very stable ion source will enable precise modulation of the dose. The first irradiation experiments should apply fast neutrons resulting from the $d+d$ fusion reaction.

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