AN ECRIS FACILITY FOR INVESTIGATING NUCLEAR REACTIONS IN ASTROPHYSICAL PLASMAS

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Abstract

Nuclear reactions at low energies can be strongly enhanced due to screening of the Coulomb barrier by the surrounding electrons. This effect was studied for the deuteron fusion reactions taking place in metallic environments as a model for dense astrophysical plasmas. Experimentally determined screening energies corresponding to the reduction of the Coulomb barrier height are much larger than the theoretical predictions. One 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. A novel ion accelerator was implemented at the University of Szczecin. Ions are produced by a Dresden ECRIS-2.45M as a high-current, low-Z ion source. The associated beamline designed to work on HV potential is combined with an ultra-high vacuum target chamber on ground potential. This setup enables decelerating ions below a kinetic energy of 1 keV and reduces target impurities. The ion irradiation facility as well as first experimental results are described and discussed.

INTRODUCTION

Hydrogen and Deuterium ions are used in various scientific and technical applications. An area of interest is for example the cold fusion research. Recent cold fusion experiments are based on chemonuclear Deuterium-Deuterium (D-D) and Hydrogen-Deuterium (H-D) fusion reactions in metals [1] or transition metals like palladium [2]. An important aspect for solid-state fusion is a sufficient Deuterium density [3] in the target made of palladium or other materials. Often ion implantation of Deuterium or Hydrogen is used to reach the required density [3–5].

The enhanced electron screening effect was observed for the first time in the ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H reactions preceding in metallic environments [6]. An exponential-like increase of experimental reaction cross sections for decreasing projectile energies could be explained as a result of shielding nuclear charges by surrounding electrons leading to a reduction of the Coulomb barrier in terms of a so-called screening energy U_e. The screening energies experimentally determined for the (D-D) fusion reactions in metals are about a factor of ten larger than that obtained for gas targets [7] and up to a factor of two larger than the theoretical predictions [8]. The results are particularly interesting for nuclear astrophysics since deuterized metals represent a good model for strongly coupled plasmas where the kinetic energy of plasma particles is smaller than the mean Coulomb repulsion energy. In such a case, nuclear reaction rates can be increased by many orders of magnitude as probably realized in White and Brown Dwarfs or Giant Planets [9].

Our first experimental results have been confirmed by other groups [10, 11]. Especially, the data obtained by the LUNA collaboration for almost 60 different target materials [12] allow to compare the experimental results of different groups and to look for a theoretical description of the observed target material dependence as well as for the absolute screening energy values. However, there are significant discrepancies between the data of different groups.

As discussed in previous papers [13], the strong variation of the experimental screening energy arises from the contamination of the target surfaces by Carbon and Oxygen. Even small amounts of the Oxygen contamination correlated with high deuteron densities lead to vanishing screening energies and thick contamination layers connected with low and unstable deuteron densities result in artificially high values of U_e. Thus, new experiments performed under ultrahigh vacuum (UHV) conditions at the lowest possible energies with atomically clean targets are required.

In this work we present a newly developed electron cyclotron resonance ion source (ECRIS) and demonstrate the production of Hydrogen and Deuterium ions which are used to investigate (D-D) reactions in a Zirconium environment. Zirconium as a target has been chosen because of its high affinity to form oxides so that it is of advantage to perform measurements under UHV conditions. The screening energy for Zirconium determined in our previous highvacuum experiment amounted to about 300 eV. This is in contradiction to the experimental result obtained by the LUNA collaboration with $U_e < 40$ eV [14]. The new experiment was intended to clear up this discrepancy.

EXPERIMENTAL SETUP

Ion Source

For the production of Hydrogen and Deuterium ions an electron cyclotron resonance ion source has been developed.

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ISBN 978-3-95450-186-1

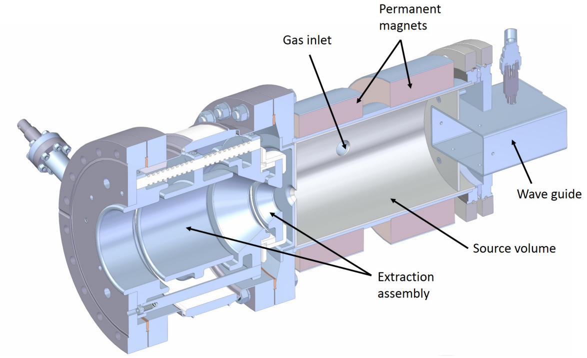

Figure 1: Schematic view of the Electron Cyclotron Resonance Ion Source (Dresden ECRIS-2.45M).

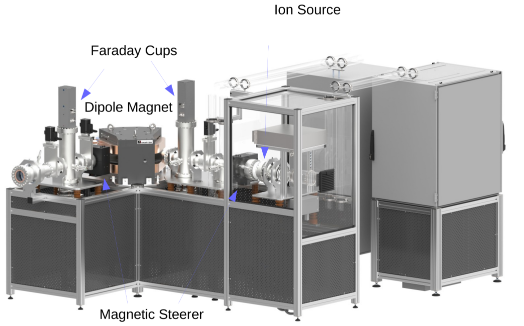

Figure 2: Schematic view of the beamline with the Dresden ECRIS-2.45M ECR ion source, the Faraday cups and the analyzing dipole magnet.

The so called Dresden ECRIS-2.45M is shown schematically in Figure 1. It is a permanent magnet electron cyclotron resonance ion source with a compact design, i.e. a length of 290 mm and a diameter of 210 mm. The axial magnetic field required for the plasma confinement is generated by two NdFeB magnet rings.

The plasma is heated by means of a solid state microwave generator with a tunable RF frequency of 2.45(15) GHz and a maximum RF power of 200 W. The rectangular wave guide, shown in Figure 1 is used to enable a stable microwave injection into the plasma and thus a stable plasma heating.

For the extraction of the ions an extraction assembly system had been designed. As shown in Figure 1 the extraction system consists of a plasma aperture, a puller electrode, and an Einzel lens for focusing the extracted ion beam. The maximum source potential amounts to 30 kV while the puller electrode can be biased up to −6 kV. The puller electrode and the first element of the Einzel lense were made of a soft magnetic material. The magnetic field lines are collected within the material. Hence, a low magnetic field is realized in the extraction system which results in an increased high voltage stability in the extraction region. Using hard magnetic materials for the puller electrode and the Einzel lens element instead lead to high voltage instabilities and plasma ignition in the extraction region.

Including extraction assembly and the corresponding high voltage feed throughs the Dresden ECRIS-2.45M has a length of 460 mm and a diameter of 340 mm.

Ion Irradiation Facility

In Figure 2 the beamline of the applied ion irradiation facility is shown. The ion source with extraction assembly is followed by a magnetic steerer which enables deflection of the extracted ion beam in horizontal and vertical direction. By means of the magnetic steerer the extracted ion beam can be optimized in the front focus point of the analyzing dipole magnet. At this position a Faraday cup (FC1) is mounted which enables the measurement of the integral ion current extracted from the Dresden ECRIS-2.45M.

In the focus point behind the analyzing dipole magnet a second Faraday cup (FC2) is positioned. The analyzing dipole magnet enables the charge to mass (q/A) separation and thus the precise selection of the ions of interest. The corresponding ion current can then be optimized by means of the second magnetic steerer and be measured in the FC2.

Vacuum Concept

From the experimental point of view, the biggest challenge is to combine a high current accelerator system with a working pressure below 10^{-10} mbar in the target chamber. The corresponding vacuum scheme is shown in n Figure 3. Differential pumping stages are used to guarantee the low vacuum pressure in the target chamber. The turbomolecular pumps in the beamline are backed with a combination of a membrane pump and a small tubomolecular pump to realize a suitable end vacuum. The turbomolecular pump of

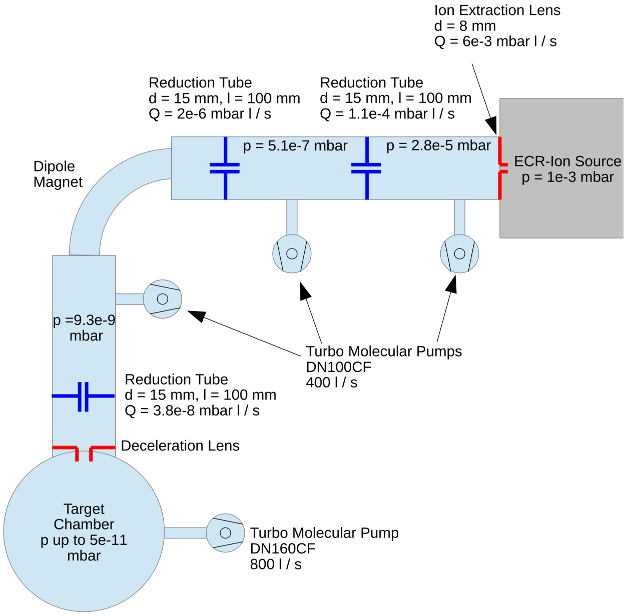

Figure 3: Schematic view of the vacuum concept including the differential pumping stages.

the ion source is backed by a multi-stage roots pump with a high pumping speed. The whole vacuum system operates on oil-free conditions.

Experimental Chamber and Procedure

The beams of D^+ and $D_2{}^+$ ions produced in the ECRIS were magnetically analyzed by the double focusing 90° analyzing dipole magnet and directed on a Zirconium target to a spot of 5 mm diameter by adjusting the magnetic beam steerers, Einzel lenses and a series of apertures. The long-term stability achieved for the deuteron energy was about a few eV. The charged products of the (D-D) reactions (protons, tritium ions and ionized ^{3}He particles) were detected by Si-detectors located in the reaction plane at backward angles 90°, 125° and 150° with respect to the beam at 8 cm distance from the target as it is shown in Figure 4.

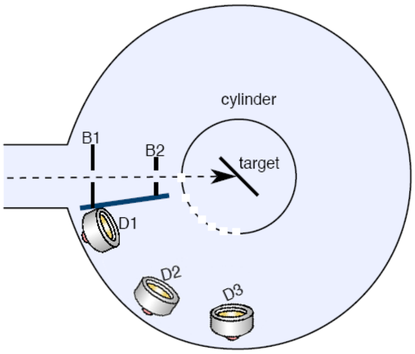

Figure 4: Schematical view of the target and detector positions.

Aluminum foils with a thickness of 150 µg cm^{-2} in front of the detectors prevented elastically scattered deuterons from entering the detectors. The beam charge collected by the target was determined by a measurement of the electric current on the target holder. A negative voltage of about −150 V was applied to a ring surrounding the target for suppression of secondary electrons. The Zirconium target (foil, 1 mm thick) was implanted up to the saturation level close to the chemical stoichiometric ratio of about two (two Deuterium atoms per one metal atom).

Before the yield measurements started, the target surface was cleaned by means of surface sputtering using 10 keV Ar^+ ions. Atomic cleanness of the target surface was controlled by applying Auger electron spectroscopy which is sensitive for a surface contamination down to one monolayer. The experimental chamber including the residual gas analyzer for vacuum characterization, the energy analyzer, the sample manipulator, the target exchange system and the detector manipulator are shown in Figure 5. A detailed experimental procedure is presented in [13].

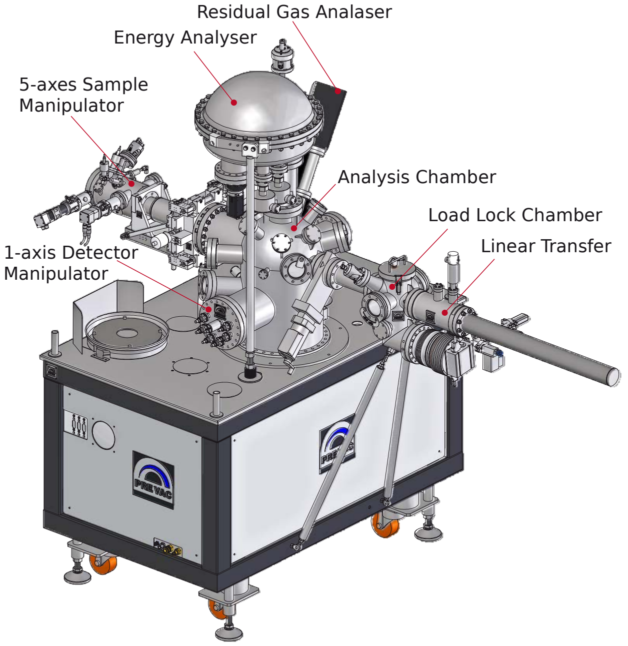

Figure 5: Schematic view of the target chamber. The ion beamline is connected to the backside of the analysis chamber.

RESULTS

Extracted Ions

Experiments with different gases were performed for ion source characterization. In addition to the irradiation experiments with Deuterium, Hydrogen, argon, helium and neon was injected into the Dresden ECRIS-2.45M. Example of the extracted ions are shown in Figure 6. The ion beams have been produced with a source potential of 20 kV and an extraction voltage of −1.8 kV. The optimum microwave power was found to be 200 W.

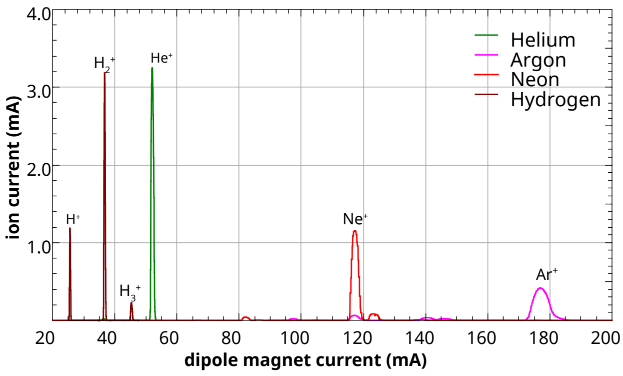

Figure 6: Extracted ion currents in the Dresden ECRIS-2.45M. The ion current measured in FC2 in dependence on the dipole magnet current is plotted.

Significant high ion currents in the mA range of Hydrogen, Helium, Neon and Argon are measured in Faraday

ISBN 978-3-95450-186-1

cup 2 behind the differential pumping stage having a diameter of 15 mm.

The ion source parameters were optimized for ionization of Deuterium. The q/A measurement results shown in Figure 7 revealed that additional to the expected Deuterium ions also Hydrogen ions and charged molecules are present. The detected Hydrogen may be residual gas from the previous Hydrogen ionization but also might be a part of the injected Deuterium gas. This aspect will be part of future studies.

A D^+ ion current of 650 µA is measured. Here must be noted that this peak may be overlapped by simultaneously extracted $H_2{}^+$ ions. Nevertheless, from the H^+ peak with an ion current of 30 µA and the $H_3{}^+$ peak with an ion current of 70 µA a maximum ion current of about 50 µA for $H_2{}^+$ ions can be deduced. Therefore, a minimum D^+ ion current of 600 µA can be assumed.

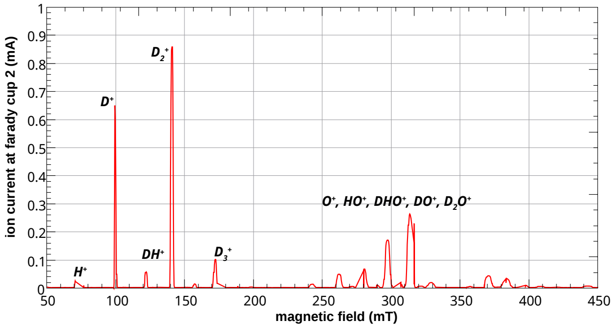

Figure 7: Deuterium ionization in the Dresden ECRIS-2.45M. The ion current measured in FC2 in dependence on the dipole magnetic field is plotted. The ion beam current peaks between dipole magnet currents of 230 mT and 400 mT are assigned to residual gas as water, hydrocarbons, Oxygen and Nitrogen.

Additional to the charged ions charged molecules are observed for Deuterium injection. In particular, a $D_2{}^+$ ion current of 850 µA and a $D_3{}^+$ ion current of 100 µA is measured.

The observed ion species, the corresponding dipole magnet current as well as the measured ion current in FC2 are listed in Table 1.

Table 1: Ion Species and Corresponding Dipole Magnet Current and Measured Ion Current in the FC2

Ion species	Dipole magnet current (A)	Ion current in FC2 (µA)
H^+	20.60	30
D^+ (and H_2^+)	29.60	650
H_3^+	36.60	70
D_2^+	42.30	850
D_3^+	52.20	100

Enhancement Factor

The experimental results are presented as a total, angle integrated, thick-target yield Y_{scr} which is compared to the theoretical value Y_{bare} based on the gas target experiments for which the screening contribution can be neglected [15]. The ratio of both determines the enhancement factor $F(E)$ at different deuteron energies (see Fig. 8) in the central mass (CM) system, given by:

$$F(E) = \frac{Y_{\text{scr}}(E)}{Y_{\text{bare}}(E)} = \frac{\int_E^0 \sigma_{\text{scr}}(E)\left(\frac{dE}{dx}\right)^{-1} dE}{\int_E^0 \sigma_{\text{bare}}(E)\left(\frac{dE}{dx}\right)^{-1} dE} \tag{1}$$

The enhancement factor can be also calculated theoretically using the expression for the screened cross section σ_{scr} [8]

$$\sigma_{\text{scr}}(E) = \frac{1}{\sqrt{E(E+U_e)}} \cdot \exp\left\{-\sqrt{\frac{E_G}{E+U_E}}\right\} \tag{2}$$

$$= \frac{1}{\sqrt{(E \cdot E_G)}} \cdot P(E+U_e) \cdot S(E) \tag{3}$$

The relation above results from the definition of the astrophysical S-factor $S(E)$ and takes into account that the electron screening effect reduces the height of the Coulomb barrier by the screening energy U_e. It can be added to the center mass energy E in the expression for the S-wave penetration $P(E)$. The Gamow energy E_G reaches the value of 986 keV for the (D-D) system.

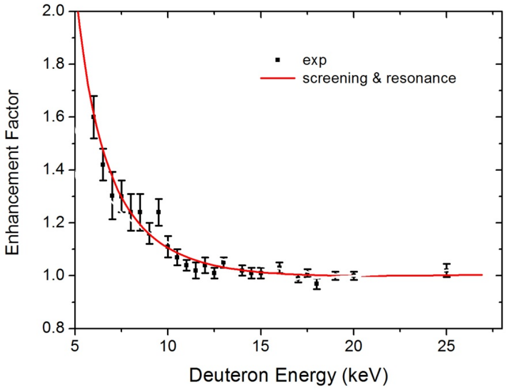

Figure 8: Enhancement Factor.

CONCLUSION

A newly developed electron cyclotron resonance ion source has been introduced and first results on Hydrogen and Deuterium ionization have been presented. Thereby, a D^+ ion current of 600 µA was measured. It was also observed that charged molecules of Hydrogen and Deuterium are generated and can be easily extracted and transported.

The measurement of the enhancement factor provides new experimental data that are much more precise than

ISBN 978-3-95450-186-1

those obtained previously due to better vacuum conditions and higher deuteron currents. They could not be fitted by a simple screening curve using only the screening energy U_e as a free parameter. In agreement to the (D-D) threshold resonance hypothesis [16], a contribution resulting from the single-particle resonance in the compound nucleus ^{4}He, placed close to the (D-D) reaction threshold at the excitation energy of about 24 MeV had to be included. The resonance component considerably reduced the fitted value of the screening energy $U_\mathrm{e} = 105(15)$ eV which is now very close to the theoretical one of about 80 eV [8]. As the (D-D) threshold resonance is of great importance for nuclear astrophysics and applied studies concerning the future energy sources based on the fusion reactions, further experiments performed at even lower deuteron energies are highly required. This is the future task of the new accelerator system at the University of Szczecin, Poland [17].

REFERENCES

[1] V. F. Zelensky, ISSN 1562-6016, *Problems of Atomic Science and Technology* N3(85), Series: Nuclear Physics Investigations (60) p.76-118, (2013).

[2] S. N. Hosseinimotlagh and N. Tavallaee, *International Journal of Modern Theoretical Physics*, 3(2), 114-134, (2014).

[3] Han S. Uhm and W. M. Lee, *Fusion Science and Technology*, Vol. 21, NO. 1, p. 75-81, (1992).

[4] J. Roth, R. Behrisch, W. Möller, and W. Ottenberger, *Nucl. Fusion* 30, 441, (1991).

[5] F. Raiola *et al.*, ”Enhanced d(d,p)t fusion reaction in metals”, *Eur. Phys. J.* A 27, s01, 79-82, (2006).

[6] K. Czerski, A. Huke, A. Biller, P. Heide, M. Hoeft, and G. Ruprecht, *Europhys. Lett.* 54 449, (1998).

[7] U. Greife *et al.*, *Z. Phys.* A 351 107, (1995).

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

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

[10] J. Kasagi *et al.*, *J Phys. Soc. Japan* 71 2281,(2002).

[11] F. Raiola *et al.*, *Phys. Lett.* B 547 193, (2002).

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

[13] A. Huke, K. Czerski, and P. Heide, *Nucl. Instrum. Methods* B 256 599, (2007).

[14] F. Raiola *et al.*, *J. Phys.* G: Nucl. Part. Phys. 31 1141, (2005).

[15] R. E. Brown and N. Jarmie, *Phys. Rev.* C 41 1391

[16] N. Targosz-Ślęczka, K. Czerski, A. Huke, L. Martin, P. Heide, A. i. Kilic, D. Blauth, and H. Winter, *J. Phys.* CS 202, (2010).

[17] M. Kaczmarski, A. i. Kilic, K. Czerski, A. Kowalska. D. Weissbach, and N. Targosz-Ślęczka, *Acta Phys. Pol.* B 45, (2014).