Journal of Physics: Conference Series

The nuclear reaction polarimeter for a polarized-fusion project

To cite this article: Léonard Kröll 2011 *J. Phys.: Conf. Ser.* **295** 012138

19th International Spin Physics Symposium (SPIN2010) IOP Publishing
Journal of Physics: Conference Series **295** (2011) 012138 doi:10.1088/1742-6596/295/1/012138

The $\vec{d}d$ nuclear reaction polarimeter for a polarized-fusion project

Léonard Kröll

Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany

E-mail: `leonardkroell@web.de`

Abstract. The fusion reactions $\vec{d}+\vec{d}\to t+p$ and $\vec{d}+\vec{d}\to ^3He+n$ with both deuteron beams polarized will be studied experimentally by a collaboration between the Institut für Kernphysik of Forschungszentrum Jülich (FZJ), Germany, the Laboratory of Cryogenic Techniques, St. Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia, and the St. Petersburg State University of Information Technologies, Mechanics and Optics (ITMO) in order to analyze the influence of the vector and tensor polarization on the total fusion cross section and the branching to the two reaction channels. The results shall allow to solve the discrepancy between different theoretical predictions. Moreover, the investigation of the reaction rate is of high interest, since it may lead to an increase of the efficiency of the energy generation in fusion power plants. A change of the branching ratio of the two fusion channels, i.e., suppression of neutron production as predicted by a number of theoretical papers, would decrease the radiation damage by neutrons and would allow prolongation of the operation time of a future fusion-reactor generation. The measurements request the knowledge of the polarization of both the deuteron beam and the jet target. With an unpolarized solid-state target, the beam polarization can be determined by studying the angular distributions of the outgoing ions $\left(^3He,p,t\right)$ with use of the known analyzing powers. Vice versa, additional data for the analyzing powers can be obtained, when the beam polarization is known. This is achieved by an additional (Lamb-shift) polarimeter. The setup of the polarimeter and results of detector tests are described.

1. Introduction

The study of processes like the dd fusion is of high relevance for the understanding of few-body systems. Up to now, a description of the N(ucleon)-N(ucleon) interaction, based on the Quantum Chromo Dynamics (QCD), has not been achieved. Chiral Pertubation Theory (χPT) is closest to this aim. There, the basic assumption is the chiral limit of vanishing masses of the three lightest quarks ($m_u = m_d = m_s \to 0$). They play the role of the mediators between two particles, an anologue of the three-gluon degree of freedom in QCD. To describe a three-nucleon system, Fadeev derived a system of coupled integral equations, starting with three N-N potentials, one particle under the influence of the other two particles ($V_1 = V_{23}$ etc.) [1]. In general, however, this leads to bindings energies which are too low. The established interpretation for this fact lies in the 3N force. The χPT predicts that the 3N force is by an order of magnitude weaker than the N-N force. Its sensitivity to polarization effects, however, is much higher. This relation holds in every step extending the system by an additional nucleon. Thus, a 4N system like that of the dd reactions is highly sensitive to polarization effects. A further motivation to investigate the low-energy cross sections is found in the not well understood effect by electron screening, i.e., the decrease of the Coulomb barrier due to the presence of electron(s). The electron screening affects the solar fusion processes. Moreover, the understanding of the low-energy dd reactions is of importance, because they play a role in the astrophysical processes of nucleosynthesis. The influence by polarization of the nucleons and/or the electrons is unclear at all, which demands experimental studies. An approach to take into account all the effects was made in the theoretical work of [2]. Open questions, however, remain as discussed in [3]. The dependence of the cross section of the fusion reactions

$$d + d \;\rightarrow\; \quad t \,+\, p + \;4.0\,\mathrm{MeV} \tag{1}$$

and

$$d + d \;\rightarrow {}^{3}He + n + \;3.3\,\mathrm{MeV} \tag{2}$$

on polarization was investigated in a theoretical study [4]. At a few MeV center-of-mass energy, the cross sections should be smaller than that of unpolarized deuterons. For the keV range, however, no conclusions can be drawn. Around 50 to 100 keV, the quintet suppression factor QSF, defined as the ratio of the cross section with both deuteron spins alligned (S=2 quintet state) to the unpolarized cross section, lies between 0.5 and 2.2 (suppression and enhancement, respectively, of the polarized reactions). Similar uncertainties remain for the suppression of the reaction (2) against reaction (1), which would result in suppression of neutron production for QSF(2) < QSF(1). The use of polarized reaction partners also influences the cross sections and therewith the reaction rates of other fusion reactions,

$$\begin{gathered} d + {}^{3}He \rightarrow {}^{4}He + p + 18.4\,\mathrm{MeV} \;\;\text{at}\;\; E_d = 107\,\mathrm{keV} \\ d + t \rightarrow {}^{4}He + n + 17.6\,\mathrm{MeV} \;\;\text{at}\;\; E_d = 430\,\mathrm{keV}\ . \end{gathered}$$

At the given deuteron laboratory resonance energies, both reactions proceed via strong S-wave resonances, which are quite pure $J^P = \frac{3}{2}^+$ states. With the spins of both reaction partners oriented parallel $S = \frac{3}{2}$, the statistical weight in the cross sections lets one expect an enhancement over the unpolarized case of 1.5. The experimental determination of observables like the components of the vector and tensor analyzing powers and spin-correlation parameters is desirable for the understanding of the few-nucleon interaction. Moreover, it would be of interest for the development of future, advanced fusion power plants using polarized particles as discussed, e.g., in [5]. An enhancement of the polarized reaction cross section against the unpolarized case would allow reduced dimensions of the reaction vessel, if densities of the polarized particles would be achieved comparable to those of the unpolarized case. Reduction of the reaction rate (2) against that of reaction (1) would reduce the radiation damages by the emitted neutrons in the construction material. Furthermore, the expected anisotropy of neutron emission relative to the direction of the magnetic field direction, defining and maintaining the polarization, might enable one to get the neutrons emitted preferentially into material around the reaction vessel installed for energy degradation and heat exchange.

An important criterion for the feasibility of such reactors is the maintenance time of the polarization compared to the confinement time of particles injected into the reactor vessel. The estimates of [5] show that the possible depolarizing mechanisms, e.g., inhomogenous static magnetic fields, are too weak to destroy the polarization in the plasma during a confinement time of 300 s, assumed as a realistic value [6].

The present work is part of a common project of the Institut für Kernphysik of Forschungszentrum Jülich (FZJ), Germany, of the Laboratory of Cryogenic Techniques, St. Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia, and of the St. Petersburg State University of Information Technologies, Mechanics and Optics (ITMO), at present financially supported by Deutsche Forschungsgemeinschaft (Project no. EN 902/1-1) and by the Russian International Science and Technology Center (ISTC), Moscow (Project no. 3881). The project work aims at measuring cross sections, analyzing powers, and spin-correlation parameters in the dd reaction down to deuteron energies of 10 keV. The aim of the present work was to develop a setup with an unpolarized deuteron target and a set of detectors to measure the polarization of a deuteron beam with the use of the asymmetries in the count rates of the protons and tritons from the reaction $\vec{d} + d \to t + p$. It had been foreseen to utilize the polarized atomic beam from a polarized atomic beam source (ABS). Ionization in the sufficiently strong magnetic field by electron impact would deliver the beam of polarized deuterons.

2. The setup for the $\vec{d}\vec{d}$ fusion experiments

The experimental setup in Gatchina consists of two polarized sources, three polarimeters and a 4π-detector in the reaction chamber as shown in figure 1.

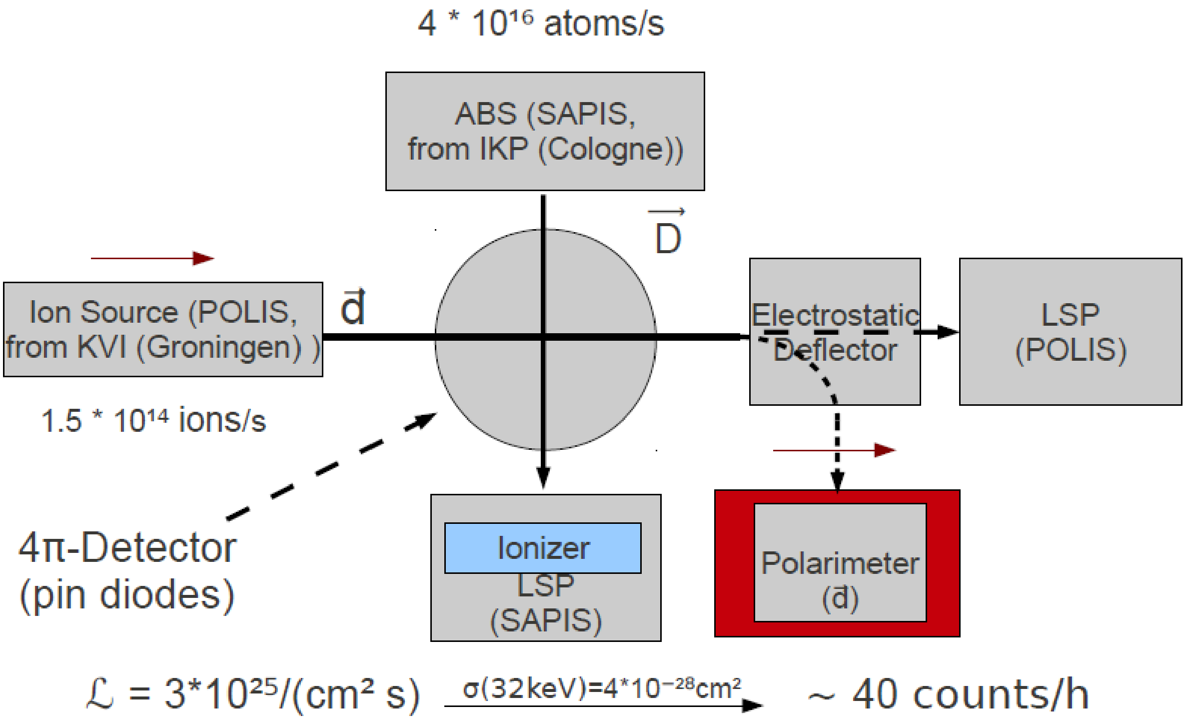

Figure 1. Setup of the future experiments in Gatchina.

The ABS of the former SAPIS project of Universität zu Köln [7] after an upgrade will deliver a polarized atomic deuteron beam of a few meV with an areal density of $2 \cdot 10^{11}$ atoms/cm^2. The beam will be the target for the 32 keV ion beam from the POLIS source, formerly used at KVI Groningen [8]. With the ion-beam intensity of $1.5 \cdot 10^{14}$/s, a luminosity of $L = 25 \cdot 10^{25}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ can be achieved. This corresponds to a reaction rate of 40/h for the dd fusion reactions at 32 keV ion energy. An acceleration cavity with a longitudinal electric field will be implemented in order to reach energies up to 100 keV, where a reaction rate of 1/s can be obtained. The 4π-detector will consist of PIN diodes, arranged in a cubic structure. Tuning of the ABS and the ion source will be performed with the use of the POLIS Lamb-shift polarimeter (LSP) and behind an ionizer with the SAPIS LSP. Whereas short-term measurements of the polarization are performed with these polarimeters, long-term measurements and monitoring of the ion beam are done with the $\vec{d}d$ polarimeter with the use of an unpolarized target. This target is developed in the framework of the present work. The POLIS ion source delivers longitudinal polarized particles only, whereas the polarimeter requests transverse-polarized ions to allow determination of both the vector and tensor polarization components p_z and p_{zz}. This is achieved by the electrostatic deflector.

3. The $\vec{d}d$ nuclear reaction polarimeter

3.1. Layout

The polarimeter setup within the vacuum chamber, made from aluminum, is shown in figure 2.

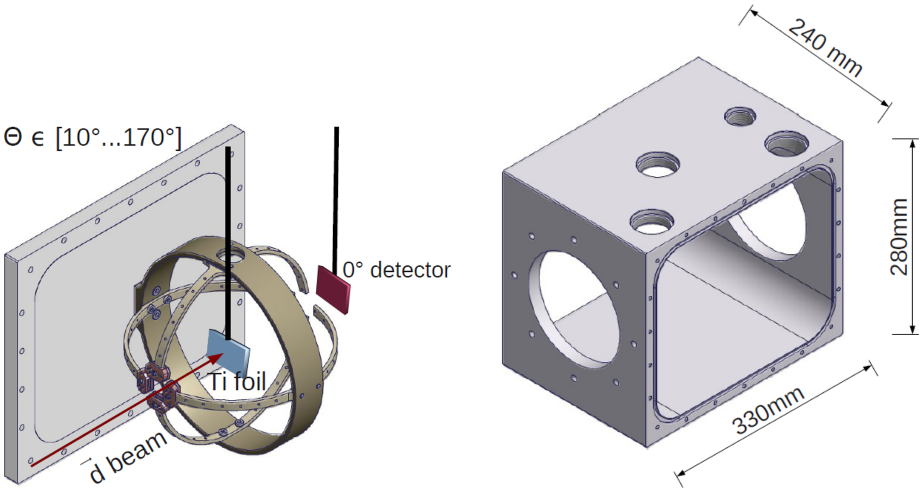

Figure 2. Left: 3D drawing of the polarimeter setup, which is fixed to one of the chamber flanges; at a distance of 10 cm from the titanium-foil target, the PIN diodes can be placed at polar angles between 10 ° and 170 ° relative to the direction of the incoming $\vec{d}$ beam. Right: central part of the vacuum chamber.

The polarized ion beam from the electrostatic deflector is directed to unpolarized deuterium atoms embedded in a metallic foil. The ejectiles from the $\vec{d}d$ reaction are measured by PIN diodes (type Hamamatsu S3590 with $10 \times 10\,\mathrm{mm}^2$ active area), placed in two orthogonal ring-shaped supports. Series of holes allow to choose appropriate positions. The way of mounting the diodes is explained in figure 3. The count-number asymmetries between the detectors allow to determine the polarization components, when the vector and tensor analyzing powers of the reaction are known.

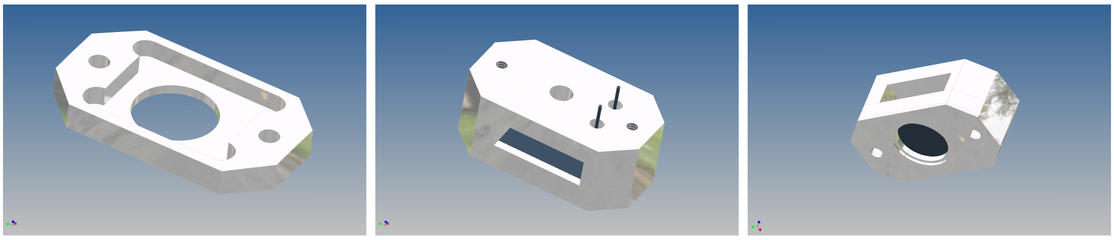

Figure 3. PIN-diode holdering. Left: frame with 9 mm diameter aperture and groove for the diode, which is electrically insulated from the frame by a plastic foil. Middle: outer frame with two holes for the signal pins and a threaded hole for mounting on the support ring; in the figure the inner frame is inserted and fixed from below. Right: the whole assembly, the side openings allow pumping.

3.2. Titanium foil as deuterium storage medium

The ring-shaped target-foil holder, made from stainless steel, has an outer radius of 25 mm and an inner radius of 11.5 mm (figure 4). Connected by a ceramic insulator, it is carried by a linear feed-through, which allows vertical adjustment. To minimize the energy loss and energy straggling of the reaction products, the titanium foil has to be thin ($d = 1\,\mu$m). It has to be loaded with deuterium, which can be done in three different ways.

(i) The incoming beam provides the deuterons. But an ion current of a few 100 nA, as expected in the present work by ionization of an ABS beam, leads to an equilibrium between feeding and reaction rate after some 1000 h only, which obviously is a too long time. This method can be and has been applied with higher currents ($I \geq 10\,\mu$m).

(ii) The foil is heated in vacuum for outgassing and during its cooling down the vacuum chamber is vented with deuterium, which is captured in the atomic lattice of the titanium.

(iii) The molecules from deuterated polyethylene, heated and vapourized in vacuum, create a layer on the surface of the titanium foil, or a foil of another appropriate material.

Figure 4. 3D drawing of the target holder with the titanium foil.

In the present work it is planned to investigate the applicability of the second and third method. From the ionizer, the created ions get extracted and accelerated to ~1 keV. At this energy the $\vec{d}d$ reaction cross section is by far to small for the planned measurements. Therefore, the target is set to -20 kV, which yields a deuteron energy of T_{d}=21 keV. The resulting experimental situation is depicted in figure 5. The target foil gets heated by the energy losses of the incoming and outgoing particles.

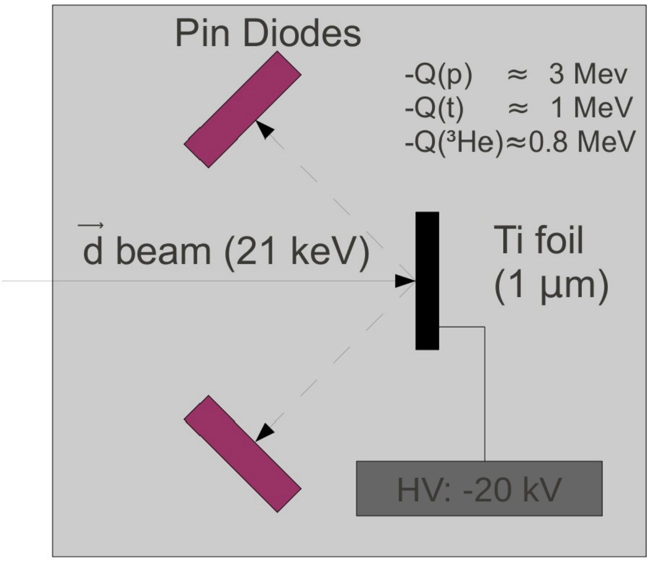

Figure 5. Kinematics of the $\vec{d}d$ reactions of equations 1 and 2 with the kinetic energies of the charged particles resulting from the energy-mass balances, the Q values of the reactions.

For deuterons stopped in the Ti foil and neglecting the energy losses by the ejectiles, the heat-deposition rate is P=$T_\mathrm{d} \cdot I_\mathrm{d}$, where I_d $[s^{-1}]$ is the deuteron ion-beam intensity. With T_d=21 keV and $I_\mathrm{d} = 2 \cdot 10^{12} s^{-1}$ P is 6 mW. Since the foil is as thin, it gets rid of the heat by radiation according to the Stefan-Boltzmann law. When all the incoming power is radiated from the foil surface, the equilibrium temperature results as ∼300 K, far below the Ti melting temperature of 1941 K.

3.3. PIN diodes

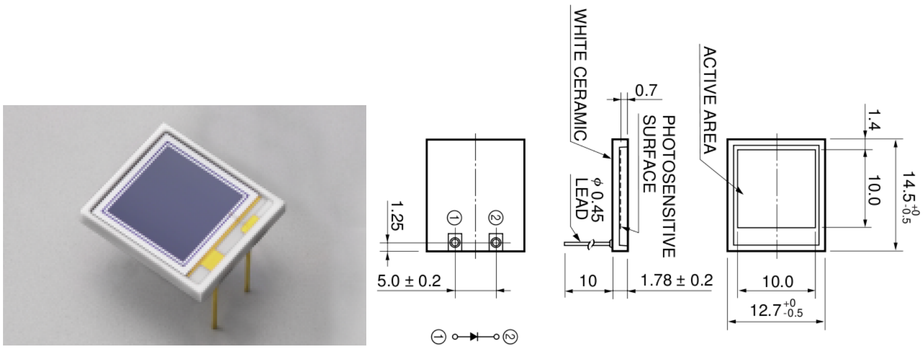

Figure 6. PIN Diode S3590-09, Photograph and dimensions [mm] of the Hamamatsu PIN Diode S3590-09. The thickness of the sensitive layer is 0.3 mm.

The detectors are Hamamatsu PIN diodes of the type S3590-09 (figure 6). They can be used in the temperature range of $-20... + 60\,^\circ$C, and a maximum reverse voltage of 100 V can be applied.

For a number of diodes, the energy resolution was measured as function of the applied voltage with the use of a ^{244}Cm α-particle source, positioned about 3 cm from the detector. ^{244}Cm has a half-life of 18.1 years and decays via the emission of 5.902 MeV α particles to ^{240}Pu. The detectors were connected to a Hamamatsu H-4083 preamplifier. Both the detector and the preamplifier were installed in a chamber, pumped by a rotary vane pump. An example of the

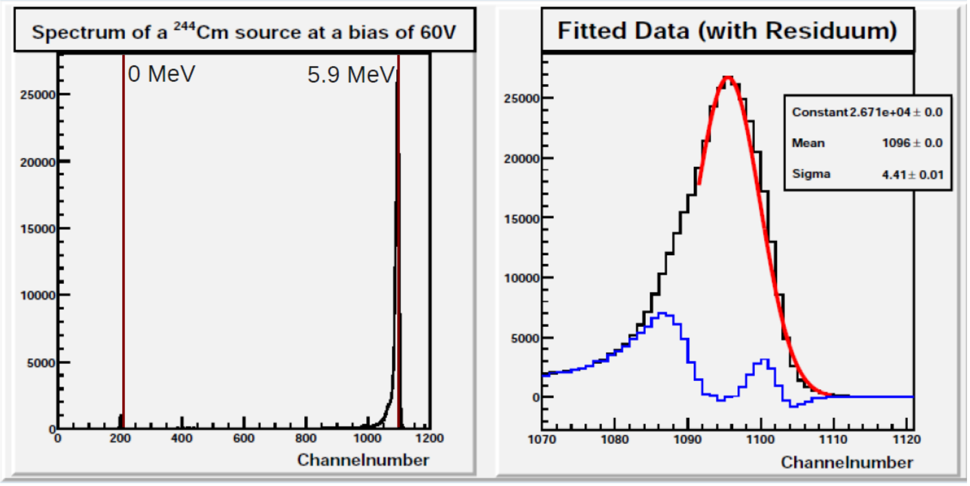

Figure 7. Left: ^{244}Cm α-particle spectrum taken with one of the PIN diodes taken with 60 V bias voltage. Right: Gaussian-fit (red) to the 5.902 Mev peak and the residuum (blue).

observed spectra and the fit of the 5.902 MeV peak by a Gaussian distribution are shown in figure 7. Further measurements concern the detector energy resolution as function of the bias voltage. As one can see from figure 8, the measured standard deviations are 28 ± 2 keV for bias voltages beween 10 and 60 V. The scattering around the mean value outside the fit errors possibly occur because of electronic instabilities and requests further studies. The achieved resolution is by far sufficient to separate the ejectile peaks from the $\vec{d}d$ reaction, which are at least 200 keV apart.

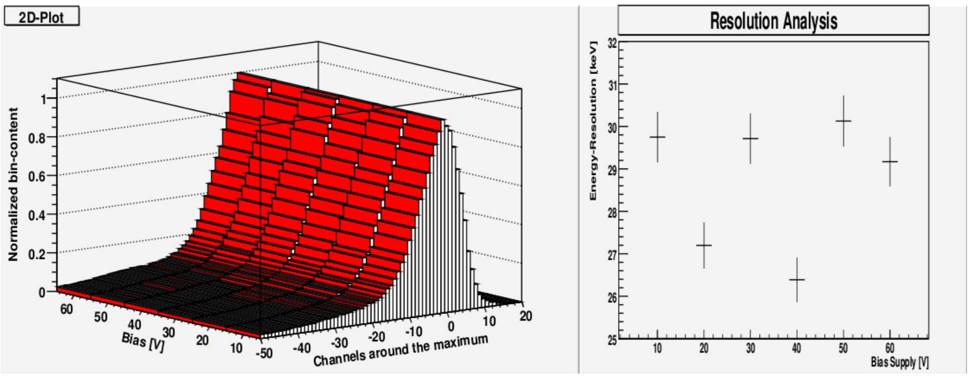

Figure 8. Example of measured energy resolutions of the PIN diodes. Left: normalized 5.902 MeV peak distributions around the peak maximum as function of the bias voltage. Right: the energy resolutions (σ), resulting from the Gaussian fit to the 6 peaks in the left-side part of the figure, versus the bias voltage.

References

[1] Fadeev L D 1961 *Scattering theory for a three particle system Sov. Phys. JETP* **12** 1014
[2] Deltuva A and Fonseca A C 2007 *Four-nucleon scattering: Ab initio calculations in momentum space Phys. Rev.* C **75** 014005
[3] Paetz gen. Schieck H 2010 *The status of polarized fusion Eur. Phys. J.* **44** 321
[4] Deltuva A and Fonseca A C 2010 *Polarization observables and spin-aligned fusion rates in* $H(d,p)H$ *and* $H(d,n)He$ *reactions Phys. Rev.* C **81** 054002
[5] Kulsrud R and Goldhaber M 1982 *Fusion Reactor Plasmas with Polarized Nuclei Phys. Rev. Lett.* **49** 1248
[6] Didelez J P and Deutsch C 2010 *Persistence of the Polarization in a Fusion Process Eur. Phys. J. Web of Conferences* **3** 04018
[7] Emmerich R and Paetz gen. Schieck H 2008 *Proof of principle of SAPIS, a new type of polarized ion source Nucl. Instr. Meth.* A **586** 387
[8] Drentje A 1998 *Ion sources at the KVI Rev. Sci. Instr.* **69** 728