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To cite this article: K Grigoryev *et al* 2011 *J. Phys.: Conf. Ser.* **295** 012168

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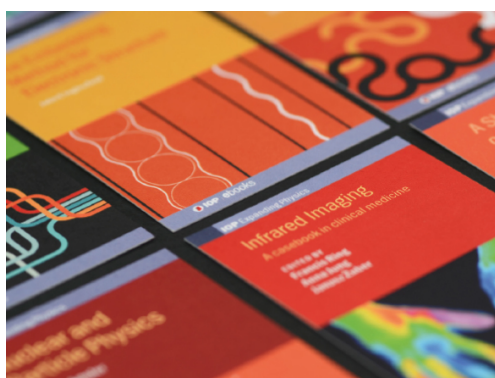
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## Double polarized dd-fusion experiment

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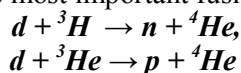
**Abstract.** We present an experiment to measure the spin-correlation coefficients for double-polarized deuteron-fusion in the energy range of 10-100 keV to determine the quintet suppression factor. The experiment setup and the future upgrade plans are described. The possible gain for future thermonuclear fusion reactors is discussed as well.

### 1. Introduction

The thermonuclear fusion problem includes the understanding of the nuclear physics aspects of the fundamental fusion reactions at low energies. For practical use at the fusion reactors one needs to know the nuclear cross-sections of the nuclear interactions of light nuclei. These cross-sections have been extensively studied but not all of them are well known. This is especially true for the polarized case, where the spin effects in few-body reactions can be gigantic.

One of the classical examples is the bound state in the nucleon-nucleon system. It exists only in the spin-triplet channel, and the spin-singlet scattering length is about four times larger and has an opposite sign. The second example is a broad  $0^+$  resonance in the  $^4\text{He}$  nucleus. It causes a gigantic cross-section of the neutron –  $^3\text{He}$  scattering in the spin-singlet channel which leads to an almost 100% spin filtering of neutrons with an excellent transmission rate of 50% in the polarized  $^3\text{He}$  target [1]. This technique is used to generate intense polarized neutron beams [2].

The fact, that the amplitudes of the most important fusion reactions



are a  $J=3/2^+$  resonance, which is S-wave dominated, simplifies the calculation of the double-polarization effects. Counting of the different spin state combinations of the projectiles implies that only 2/3 of nuclei can undergo the fusion in unpolarized plasma. Alternatively, a full polarization of the deuteron and  $^3\text{He}$  would enhance the fusion cross-section by 50%. It has been confirmed experimentally to a good accuracy [3] and seems to be an interesting option to increase the fusion rates in a thermonuclear reactor.

A substantial step forward was made in 1982 in a theoretical study of depolarization of nuclei in magnetically confined plasma [4]. The principal conclusion was that the depolarization time greatly exceeds the fusion reaction time. Presently, it is considered feasible to confine polarized  $^3\text{He}$  with a nuclear polarization of 0.55 and to inject polarized deuterium with a polarization of about 0.55, too. The experiment is planned at the DIII-D Tokamak at San Diego [5]. The estimated enhancement of the fusion should be around 15%. If retention of the deuterium polarization will be confirmed, it is planned to continue these measurements with tritium.

The alternative approach to the experimental confirmation of persistence of nuclear polarization in a fusion process in plasma, generated by a petawatt laser hitting a polarized frozen  $HD$  target, has been suggested at Orsay [6]. Detecting the count rate of the final state gamma's and neutrons as a function of the target polarization one would have an experimental access to the reactions  $p + d \rightarrow ^3\text{He} + \gamma$  and  $d + d \rightarrow ^3\text{He} + n$ . In parallel to the main reactions the dd-reactions

$$\begin{aligned} d + d &\rightarrow t + p, \\ d + d &\rightarrow ^3\text{He} + n \end{aligned}$$

will appear in a fusion reactor. On the other hand, the neutrons will reduce the lifetime of the reactor walls too. Based on the available experimental data on the deuteron-deuteron interactions, in 1969 Ad'yasevich and Fomenko suggested a possible polarization enhancement of the  $dd$ -fusion rate by a factor of two [7]. The first experimental proposal to study the polarization coefficients in double-polarized fusion [8] for the dd-reactions was not completed because the polarized atomic and ion beams technique at that time did not allow to produce beams of enough intensity.

## 2. Theoretical predictions

The reactions  $\vec{d} + \vec{t}$  and  $\vec{d} + ^3\vec{\text{He}}$  with initial polarized particles have been already investigated [3] and, therefore, it seems possible to increase the fusion rates in a thermonuclear reactor with polarized fuel. The spin-correlation components of the fusion reactions  $\vec{d} + \vec{d}$  in the energy range of 10-100 keV are not measured yet and predictions are complicated due to the fact, that the dd-reactions are not S-wave dominated. Even at these small energies the contribution of P- and D-waves cannot be neglected. The best example is the so called quintet state suppression factor (QSF) shown in figure 1 [9]. The QSF is defined as the ratio of the cross-sections for the dd reactions with parallel spins of the initial particles to the total unpolarized cross-section. A value of QSF=1 means that polarization of the initial particles does not affect the total cross-section and if the total cross section is increased the QSF will be bigger than 1. Large discrepancy in the different predictions illustrates a strong demand for the direct measurement of this observable to check the theoretical models. To get the QSF the asymmetry of the differential cross-sections have to be determined to calculate the different spin-correlation

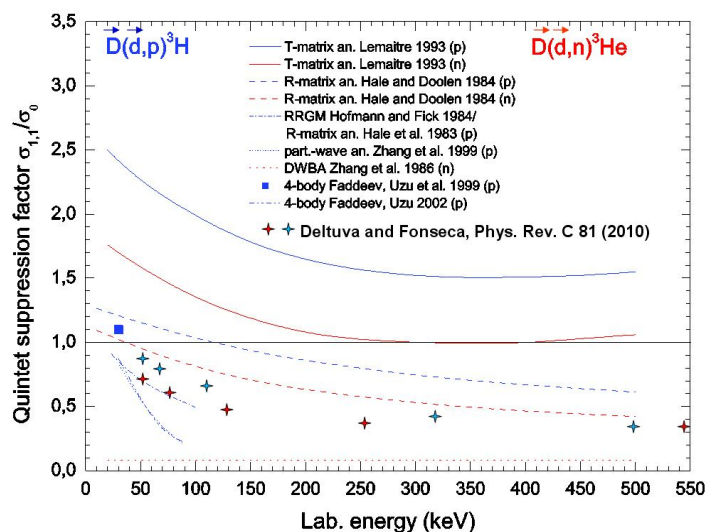


Figure 1. Theoretical predictions of the quintet suppression factor.

coefficients like  $C_{z,z}$  and  $C_{zz,zz}$ , from which the QSF is deduced. In addition, many other spin-correlation coefficients can be measured to test the predictions by theory.

For a coming fusion reactor the lifetime of the reactor walls is dominated by the neutron flux on the walls. For this reason, a suppression of the n-channel would increase the lifetime of the complete reactor and, therefore, it would help to make energy production from fusion more profitable. On the other hand it might be possible to modify the differential cross sections for different scattering angles, so that the neutrons from the dd-reaction can be concentrated on special parts of the reactor walls, which are better shielded like the rest.

### 3. The experiment

In a common project it was proposed to investigate the angular distribution of the ejectiles at various energies (between 10 and 100 keV) for both double-polarized dd-reactions:

$$\vec{d} + \vec{d} \rightarrow t + p$$

$$\vec{d} + \vec{d} \rightarrow {}^3\text{He} + n$$

The energy of the initial particles is very low and the penetrating depth is exceedingly small. Therefore, an experiment with a polarized jet target from an Atomic Beam Source (ABS) is the only possibility to measure the spin-correlation coefficients directly. A polarized solid state target would not allow to cover a  $4\pi$ -sphere with detectors which are necessary to measure these coefficients for all scattering angles. In addition, a deuterium beam of an ABS will not interact with the ejectiles because of the small density. The price one has to pay is the small count rate due to this thin target.

The ABS for this experiment (see figure 2) is created on the basis of the Cologne University source that was used in the SAPIs project [10]. It produces a beam of polarized atoms with vector and/or tensor polarization. Polarized atoms in the beam have thermal velocity with energy of about 0.1 eV. The achieved beam intensity at the Cologne University of  $10^{15}$  at/s is not sufficient for the measurements and there are plans to upgrade and increase the intensity up to a few times  $10^{16}$  at/s [11].

The neutral atoms of the target will be bombarded by the positive deuterium ions (deuterons) that are produced by a polarized ion source (POLIS). This source has been utilized as an injector of the cyclotron accelerator at the KVI institute, Groningen, Netherland. This source is producing an ion beam of 20  $\mu\text{A}$  and energies up to 32 keV [12]. A substantial upgrade of this source to increase the beam energy up to 100 keV is required. At this energy one can crosscheck the experimental results with the existing data (available for the energies higher than 100 keV). It is planned to use a linear ion accelerator to increase the energy from 32 keV up to the desired range of 32-100 keV. This upgrade will change the constant beam into the bunched one with a certain intensity losses.

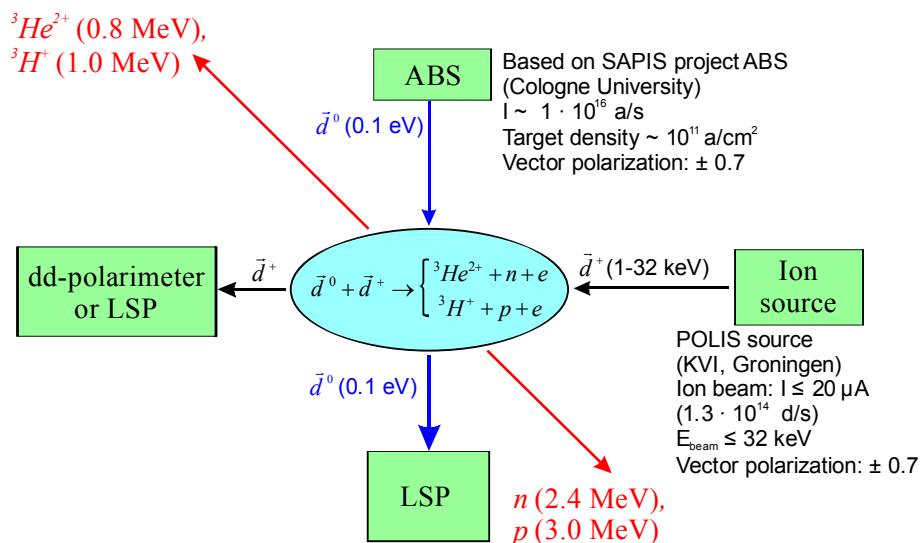


Figure 2. Layout of the experiment.

Production and use of the polarized ion and atomic beams requires accurate measurements of the polarization. It is planned to use three polarimeters in the experiment: two Lamb-shift polarimeters (LSP) for initial tuning of the beams and one nuclear reaction polarimeter for constant monitoring of the ion beam polarization during the production runs. The LSP has substantially better precision and allows to measure all spin states of the beam, but its operation is more complicated compared to the nuclear reaction polarimeter. Therefore, this polarimeter will be used only for the tuning of the beam sources and periodic checking of the polarization. The nuclear reaction polarimeter makes use of the asymmetry of the nuclear fusion reaction products which can be detected with semiconductor detectors. The necessary analyzing powers in this energy range are well known [13, 14].

One of the crucial tasks of the experiment is the detection of the fusion reaction products – protons, tritium and  $^3\text{He}$  ions (neutrons could not be detected in this experiment). The calculated count rate at an energy of 20 keV will be about 13 events per hour and will increase to more than 500 counts/h for 100 keV. Therefore, the detector system should have low background and noise to distinguish these rare events. Problems of the cosmic radiation and the natural radioactivity of construction materials have to be carefully investigated.

#### 4. Detector setup

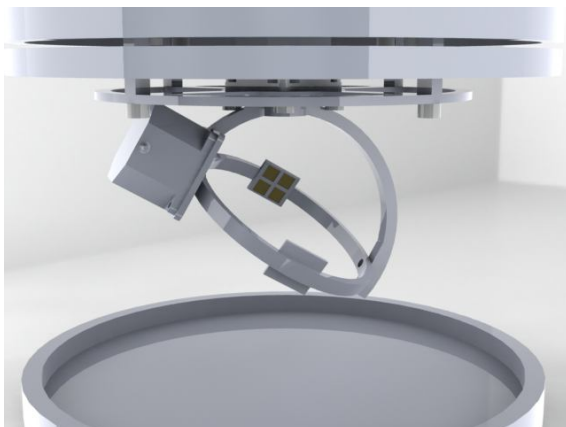
The main goal of the experiment is a direct measurement of the angular distributions of the reaction products. Therefore, the detector system should cover the maximum solid angle around the interaction point (ideal case:  $4\pi$  solid angle), with typical angular resolution of 10-15 degree. The prototype of the detector system will consist of two Elementary Detector Cells (EDC) located at 180 degree to each other (see figure 3). These EDC will be made from PIN photodiodes from Hamamatsu [15] with an energy resolution of about 10 keV [16].

This setup will be used to measure the energy resolution of the detectors, preliminary angular distributions with small statistics and also to determine the necessary angular resolution for the final detector system. In addition, the prototype will help to investigate the technical questions to the detectors: degradation time of the semiconductors in the vacuum with some traces of atomic deuterium, which is a quite active substance, lifetime of the detector in the experimental conditions etc. The final detector system should cover the  $4\pi$  solid angle. It is supposed to be built in a cubic shape construction with 80% covering of the area around the interaction point (see figure 4).

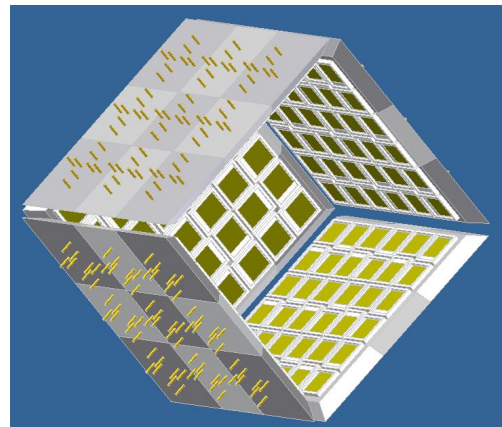
The readout electronics for the detector system should be designed, including electronic signal conditioning and processing with dedicated software. All information from the detector system will be acquired, accumulated and analyzed off-line to calculate the differential cross-sections.

#### 5. Polarized electron screening effect

Using the neutral atoms for the target allows significantly to increase the target density (no space charge restriction, slower beam velocity) compared to ion beams, but it requires to take into account an impact of the atomic electron on the reaction rate, which does not exist in the ionized plasma of the



**Figure 3.** Prototype of the detector system.



**Figure 4.** Final detector system structure.

thermonuclear reactor. An electron screening effect (so-called astrophysical S-factor) is well known and measured experimentally [17]. This effect has considerable influence at energies below 10 keV and is not important at higher energies. Reversing the arguments, the direct experimental investigation of this effect with different polarization of both incident nucleons and the target electron would be very interesting on its own. Neither experimental data nor theoretical calculations were done in this field at the moment.

## 6. Investigation of methods to increase the intensity of polarized sources

The ABS is presently the main method for the production of polarized deuterium. These sources are used at accelerator injectors (with subsequent ionization) or for the internal targets at the storage rings of the accelerators [11]. The construction of a polarized atomic beam source is possible only in the framework of high-expenditure accelerator experiments due to the high cost of the ABS equipment. The intensity of the world-best polarized sources do not exceed  $10^{17}$  at/s. At the same time the feeding flux of polarized deuterons for the 100 MW fully fledged polarized thermonuclear reactors have to be  $10^{21}$ - $10^{22}$  at/s. An intensity increase by 4-5 orders of magnitude is not feasible with the atomic beam sources. Even the production of laser-pumped polarized deuterium is not possible up to now due to the very small energy difference of the single hyperfine substates of deuterium. Thus, it is necessary to research a new source of polarized deuterons. One of the possible directions of this search is the use of an ABS for molecular deuterium with nuclear polarization.

## 7. Conclusion

This experiment on the investigation of the spin-correlation coefficients of the double-polarized deuterium fusion reactions will provide the first direct measurements of the quintet suppression factor in the energy range of 10-100 keV and finally it will give a systematic ground for the practical use of polarized deuterons in the thermonuclear fusion with estimation of possible benefits from the polarization.

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