DOUBLE POLARIZED DD-FUSION*

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A double-polarized *dd*-fusion experiment is under preparation at PNPI, Gatchina. The experimental program includes the measurements of the asymmetry in the differential cross section of the reactions $d + d \to {}^3He + n$ and $d + d \to t + p$. The total cross section modification for polarized *dd*-fusion will also be investigated. Increase by a factor of 1.5 was already deduced for the $d + {}^3He$ and the $d + t$ reactions. The spin-correlation coefficients $C_{z,z}$ and $C_{zz,zz}$ will be measured to determine the quintet-state suppression factor for both reactions, which has quite different theoretical predictions and is very important for the building of neutron-lean fusion reactor. In addition, more spin-correlation coefficients can be measured at different energies with this experimental setup, to get more information about the *dd*-fusion process. The screening effect due to atomic electrons which shows up in the astrophysical S-factor may also be investigated in this experiment for different spin combinations of the electron and nucleus.

1. Introduction

The principal aspects of the thermonuclear fusion problem includes understanding of the nuclear physics aspects of the fundamental fusion reactions at low energies; confinement of the hot and dense plasma; and energy extraction from plasma. Standard candidates for the fusion fuel include the hydrogen isotopes (deuterium and tritium) and the light Helium isotope – ^{3}He. For practical use at the fusion reactors one needs to know the nuclear cross-sections of nuclear interactions of light nuclei. These cross-sections have been extensively studied but not all of them are well known. This is also true for the spin sector, where the spin effects in few-body reactions are 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}He nucleus. It causes a gigantic cross-section of the neutron – ^{3}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}He target [1]. This technique is used to generate intense polarized neutron beams [2]. The fact that the amplitudes of important fusion reactions

$$D + {}^3H \to n + {}^4He,$$

$$D + {}^3He \to p + {}^4He$$

are *S*-wave $J = 3/2^+$ resonance dominated significantly simplifies the double-polarization effects handling. Simple counting of the spin states implies that only 2/3 of nuclei can undergo the fusion in unpolarized plasma. Alternatively, a full polarization of the deuteron and ^{3}He would enhance the fusion cross-section

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by 50 %. It has been confirmed experimentally to a good accuracy [3].

Based on the available experimental data on the deuteron-deuteron interactions, in 1969 Ad'yasevich and Fomenko suggested a possibility of the polarization enhancement of the *DD*-fusion rate by a factor of two [4]. The first experimental proposal to study of the polarization coefficients in double-polarized fusion [5] was not completed because the polarized atomic and ion beams technique at that time does not allow to produce the beams of enough intensity.

A substantial step forward was made in 1982 in a theoretical study of depolarization of nuclei in magnetically confined plasma [6]. The principal conclusion was that the depolarization time greatly exceeds the fusion reaction time. Presently, it is considered feasible to confine ^{3}He with nuclear polarization reaching 55 % and to inject neutral deuterium with nuclear polarization of about 55 %. The experiment is planned at the DIII-D Tokamak at San Diego [7]. 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 [8]. Detecting the final state gamma's and neutrons one would have an experimental access to both reactions $p + D \rightarrow {}^3He + \gamma$ and $D + D \rightarrow {}^3He + n$.

2. Cross-section measurement of the polarized fusion reactions

The reactions $\vec{d} + \vec{t}$ and $\vec{d} + {}^3\vec{He}$ with initially polarized particles have been already investigated [3]. Spin-correlation components of the basic fusion reaction $\vec{d} + \vec{d}$ in the energy range of 10-100 keV are not measured yet. For the practical use of the polarized fuel in the fusion reactor, there are only two spin combinations are important: when the deuteron spins are parallel or antiparallel to each other. Theoretical predictions for a change of the reaction cross-section are shown in Figure 1.

Here a quintet state suppression factor (QSF) is defined as a ratio of the reaction cross-section for the parallel spins of the initial particles to the total unpolarized reaction cross-section. The value of the QSF = 1 means that polarization of the initial particles does not affect the total reaction cross-section. Large discrepancy in predictions illustrates a strong demand

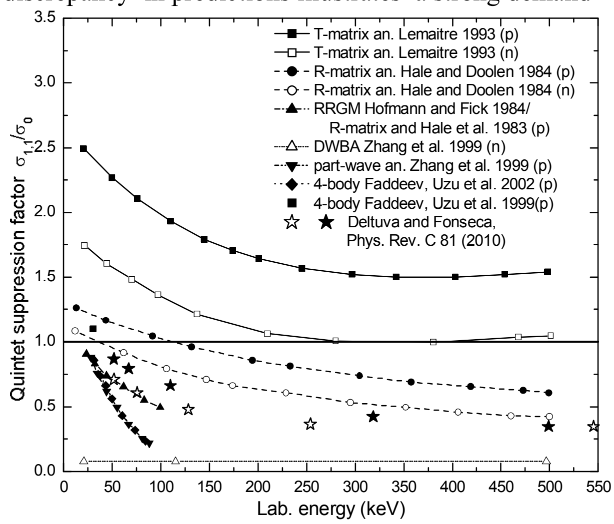

Figure 1. Theoretical predictions of the quintet suppression factor.

for the direct measurements of this observable to check theoretical models. In addition it will allow to measure the asymmetry of differential cross-sections, to determine of the total cross-section change for the polarized initial particles, and measure of the spin-correlation factors Cz,z and Czz,zz for investigation of the quintet suppression factor.

3. Investigations of methods of increasing the intensity of polarized sources

An atomic beam source (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 [9]. Building of the polarized atomic beam source is possible only in the framework of high-expenditure accelerator experiments due to a 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 full 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. Thus, it is necessary to research a new source of polarized deuterons. One of the possible directions of this search is use of the molecular deuterium with nuclear polarization.

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4. The experiment

It was proposed to investigate the angular distribution of the reaction products at various energies (between 10 and 100 keV) for different reactions:

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

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

The energy of the initial particles is very low and the penetrating depth is exceedingly small but the solid target experiments would have a large error bars because of an unknown surface polarization and influence of the multiple scattering on the energy of the reaction products. To make this factor small one can use a direct interaction of the polarized deuteron beam with the polarized neutral deuterium atoms in vacuum (Figure 2).

The ABS for this experiment is created on the basis of the Cologne University source that was used in the SAPIS project [10]. It produces a beam of neutral polarized atoms with given vector 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 10^{16} at/s.

Using the neutral atoms for the target allows significantly increase the target density (no space charge restriction), 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 thermonuclear reactor. An electron screening effect (so-called astrophysical S-factor) is well known and measured experimentally [11]. This effect has considerable influence at the energies below 10 keV and not important at the higher energies. Reversing the arguments, the direct experimental investigation of this effect with allowance for the polarization of both incident nucleus and target atomic electron would be very interesting on its own. Neither the experimental data nor theoretical calculations were done in this field at the moment.

The neutral atoms of the target will be bombarded by the positive deuterium ions (deuterons) that are produced by the 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 the ion beam of 20 uA and energies up to 35 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 then 100 keV). It is planned to use linear ion accelerator to increase the energy from 35 keV up to the desired range of 35-100 keV. This upgrade will change the constant beam into the bunched one with a certain intensity losses.

Production and use of the polarized ion and atomic beams require accurate measurements of the polarization. It is planned to use four polarimeters in the experiment: two Lamb-shift polarimeters (LSP) for initial tuning of the beams and two nuclear reaction polarimeters for constant monitoring of the beam polarization during the production runs.

The LSP has substantially better precision and

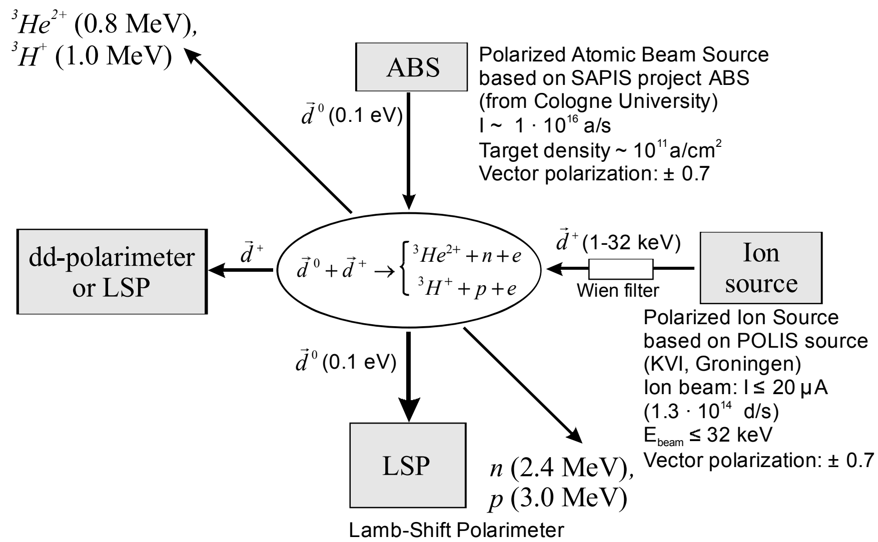

Figure 2. Layout of the experiment.

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allows to measure more 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.

One of the crucial tasks of the experiment is the detection of the fusion reaction products – protons, tritium and ^3He ions (neutrons could not be detected in this experiment). The calculated count rate at energy of 20 keV will be about 13 events per hour. 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.

5. 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: 4π solid angle), with typical angular resolution of 10-15º. The prototype of the detector system will consist of two Elementary Detector Cells (EDC) located at 180º to each other (see Figure 3). 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. The prototype will also 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 quite active substance, lifetime of the detector in the experimental conditions etc. The final detector system should cover 4π solid angle. It is supposed to be built in a cubic shape construction with 80 % covering of the area around the interaction point (Figure 4).

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.

6. Conclusion

This experiment on the investigation of the cross-section of the polarized deuterium fusion reaction will provide first in the world direct measurements of the spin-correlation coefficients in the energy range of 10-100 keV and finally will give a systematic ground for the practical use of the polarized deuterons in the thermo-nuclear fusion with estimation of possible benefits from the polarization.

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