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Polarization REsearch for Fusion Experiments and Reactors - The PREFER Collaboration: Purposes and Present Status

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The PREFER (Polarization REsearch for Fusion Experiments and Reactors) collaboration aims to address the know–hows in different fields and techniques to the challenging bet on fusion with polarized fuel. The efforts on a variety of duties and goals are shared between different research groups, indicated here by underlining in the authors' list the scientific responsibles. Starting from still open questions of fusion reaction physics, as for example the study of D+D spin–dependent cross–sections (Vasilyev) to the acceleration of polarized ions from laser-induced plasmas (Büscher), there are many connections between the involved research groups. The collaboration is also tackling the production of nuclear polarized molecules, recombined from a polarized atomic beam (Engels), and its cryogenic condensation and transport (Ciullo). Other options for the production of polarized fuel are investigated in parallel, like spin separation of molecules in polarized molecular beam sources (Toporkov), or via photodissociation of molecules into polarized hydrogen/deuterium atoms (Rakitzis). The status of the different fields under investigation and the connections between these topics and the different research groups will be provided.

KEYWORDS: nuclear fusion, nuclear polarization, Laser induced phenomena

1. Introduction

Exploring the possibilities of fusion with nuclear polarized fuel involves various fields of investigations, technologies, researches and developments. The advantages of energy production by nuclear fusion of hydrogen isotopes and ^{3}He can not be ignored. The necessary fuel, especially the main element deuterium, can be extracted from water, which is world wide available and will last for many years. In parallel, this type of energy production will be CO_2 free and, therefore, will help to avoid the approaching climate change.

Starting with first ideas in the 60's, "*polarized fusion*" was mainly discussed in literature during the 80's [1], but only a few experiments were conducted [2]. In the last decades technology improvements in many fields open the door to further experiments and first applications. Promising advantages relax engineering constrains and, therefore, costs of fusion reactors and facilities, but some disadvantages have overshadowed the path of the researches. The PREFER collaboration takes the challenge of the investigation on "*polarized fusion*. The state–of–the–art on the topic has been published in a volume cured by the scientific responsibles [3]. The present status of these efforts, emphasizing in bold the **piloting group** and in brackets the groups they directly collaborate with (groups are indicated by the acronyms of the authors' affiliations).

The challenges undertaken by each group can be summarized as follows:

PNPI (IKP–FZJ/INFN–Fe/LNS–INFN): D–D spin–dependent cross–section studies and measurements.

IKP–FZJ (PNPI/INFN–Fe/LASA–INFN): Production of polarized fuel from the recombination of polarized atoms from a polarized Atomic Beam Source (pABS) and its handling.

BINP (ILPP–HHUD/IKP–FZJ): Hyper–polarized molecules from a polarized Molecular Beam Source (pMBS).

IESL–FORTH (PGI–FZJ/ILPP–HHUD): Production of polarized beams from laser quantum beat excitation and post UV photo–fragmentation.

PGI–FZJ (ILPP–HHUD): Laser–induced plasmas: production of polarized ion beams, acceleration and fusion tests.

2. Nuclear Fusion with Polarized Fuel

The exploitation of polarized fuel for nuclear fusion *a priori* can provide the following fruitful *advantages*. The **enhancement of fusion cross–sections** is theoretically well understood for spin–1+spin–1/2 interacting particles, *e. g.* deuterium+tritium (D+T), or D+^{3}He, instead for spin–1+spin–1 interacting particles (D+D) they are still unknown. The **control of angular distributions of the reaction products** allows to handle neutron wall bombardments, radioactivity activations, and degradation of materials and components in a delimited space of the surrounding of the fusion environment, *i. e.* the blanket. This can help for further fuel breading via the n+^{6}Li $\rightarrow$ ^{4}He+T reaction, or to optimize the energy extraction from the plasma. The heat load on the magnets for the confinement can be minimized, which might allow to mount them closer to the plasma and, thus, to increase the energy output due to a better confinement of the charged particles. The **possibility to design neutron lean reactors** in case of aligned spins for D+D fusion. The reaction D+D$\rightarrow$^{3}He+n might be prohibited in the pure S-wave approximation, but the reaction experiences P–, and D– partial wave and their interferences, therefore experimental data are required, which till now are still missing, in order to constrains theoretical models.

Facing the aforementioned *advantages*, there are still *disadvantages*, or open questions. **Intensity (or density), purity and high polarization** achievable for polarized fuel (following the technologies implemented for polarized targets in nuclear physics), which are still not in the range of the fusion requirements, therefore the production and the manipulation of polarized fuel for its use in fusion environment requires new technological approaches. Considering the improvements in the recent decades on the technology developed for polarized nuclear target, the engagement on this challenge could be very fruitful. **Preparation, manipulation and transportation** of polarized fuel require deep insights and R&D studies for its use in fusion test experiments. The **survival of the polarization** in fusion environments is an open question too.

Schematically the influence of the nuclear spin in the fusion reaction *generations*, sorted according to the relative energy of the interacting particles, can be summarized as in following [4].

The 1^{st} *generation* fusion reaction, D+T→^{4}He+n, involves spin–1+spin–1/2 particles respectively. The spin–dependent behavior of the reaction has been proven in 1971 [2] on D+^{3}He and theoretical descriptions of spin–dependent reactions are available [5]. Interacting particles with spin oriented in the same direction shown a cross–section enhanced by a factor 1.5. The D+T reaction (same spin configuration like D+^{3}He) is expected to behave in the same way.

The 2^{nd} *generation* reaction has two branches: D+D→T+p and D+D →^{3}He+n. The description of this reaction is very complicated, S–, P– and D–wave scattering and the relative interferences contribute. There are various contradictory theoretical models which require data constrains.

The 3^{rd} *generation* reaction, D+^{3}He→^{4}He+ p, from the point of view of spin–dependent cross–sections, is equivalent to D+T, with in addiction the possibility of "neutron lean" reactors in the case of both interacting particles aligned parallel to the magnetic field: the reaction, in the S-wave approximation, is prohibited and the neutron production might be suppressed. The ratio of the aforementioned cross–section and the unpolarized one is known as Quintet Suppression Factor (QSF). Some models predict an enhancement of this ratio up to 2.5, against other ones estimating a decrease till to zero [6]. The D+D spin–dependent cross-section measurements are mandatory for the future exploitation of the polarized fuel for fusion, and provides deep insight on few–body systems for nuclear physics and astrophysics.

The electron screening also contributes to the enhancement of cross–sections in the energy range of fusion reactors, and with the spin–dependent enhancement of the cross–section, will play a role for energy production, reducing the power required for ignition and maintenance of the fusion processes. This might decrease the costs of the design and the operation of fusion reactors and facilities even further.

3. The PREFER Challenges: Study, Production and Test of Polarized Fuel

Deuterium is a keystone for fusion with polarized fuel, and, therefore, the PREFER collaboration will deal with: studies and investigations on D+D spin–dependent cross–sections, production of polarized fuel for feasibility studies and tests of nuclear fusion, manipulation and transportation of the fuel for dedicated studies in proper facilities with *ad hoc* diagnostics, in order to test it in fusion environments.

D+D spin dependent cross–sections at the **PNPI** (IKP–FZJ, INFN-Fe, LNS-INFN)

For the case of D+D spin–dependent cross–sections there are still missing data. The first proposal of measurements dates back to 1969 (see in Ref. [6]), in which, due to small cross–sections and low intensity of atomic beams, in the order of 10^{11} atoms s^{-1}, there was not enough sensitivity on measuring the spin correlation coefficients and the analysing powers involved.

Polarized atomic beams reach intensity of 10^{17} atoms s^{-1} and high polarization. At the PNPI an experiment is under commissioning for double spin polarized D–D cross–section studies [7].

In a crossed beam scheme a polarized deuteron beam collides orthogonally with a polarized atomic beam. The experiment will operate at a luminosity, that was never in hand in experiments on colliding polarized atomic beams, allowing measurements in any combination of spin orientation of projectiles and targets. The ion beam energy can be set in the range of 10 – 100 keV, that is of interest for fusion and astrophysics. The measurement of the angular distributions of the reaction products is fully covered by a 4π–solid angle detector around the D+D interaction point with a typical angular resolution of 10°–15°. The detector has a cubic structure with the inner surface covered with 576 Hamamatsu S3590 silicon PIN diodes (51 % coverage of the solid angle). A partial number of PIN diodes were installed and the measurements of the reaction products were performed using unpolarized targets [7].

A Lamb–shift polarimeter is installed and under commissioning for the monitoring of the polarization of both the polarized ion beam, and the polarized atomic beam [8].

Production of polarized fuel from the pABS at the **IKP–FZJ** (PNPI, INFN-Fe)
The recombination of polarized atoms, produced by a polarized Atomic Beam Source (pABS), in molecules which maintain the nuclear spin orientation (hyper–polarized molecules) is under investigation. The hyper–polarized H_2, D_2, or HD molecules can be frozen on a cold surface to collect and store enough fuel for further fusion tests. Instead atomic hydrogen, or deuterium, are strongly reactive and are not easy to handle.

The recombination apparatus, built at the PNPI and moved to the FZJ, allows to use different materials for the coating and for the recombination cell. The cell is immersed in a longitudinal magnetic field, generated by a superconducting solenoid (up to 1 T), keeping the recombined molecules in a defined quantum state. When these molecules reach a cold surface below 10 K they might be stored for fusion tests.

Big progresses have been done on the diagnosis of the phenomena [9], and as a result it has been proven that it is possible to produce hyper–polarized molecules of H_2, D_2, and HD. For the latter a large nuclear polarization ($\approx$ 80 % for both nuclei) has been preserved and HD is a perfect training ground for the studies of DT molecules [10].

The possibility of using a freezing surface in a magnetic field inside a MgB_2 cylinder without any power supply, open the door to transport the polarized ice for further tests in fusion facilities [11].

Hyper–polarized molecules from pMBS at **BINP** (ILPP–HHUD, IKP–FZJ)
The idea of filtering molecules according to the total nuclear spin follows the technique of the Stern–Gerlach separation in an inhomogeneous magnetic field, providing then polarized Molecular Beam Sources (pMBS). The strength of the combined nuclear magnetic moment of a molecule compared to the one of an atom, is $\approx$600 less, therefore higher magnetic field and gradient are required. The available technology nowadays relies on superconducting magnets. The group of BINP adapted a superconducting pABS for its feasibility studies of spin separation of molecular beams. The geometry of the system is pushed in order to exploit higher magnetic field with a nozzle of an annular geometry, injecting a molecular beam in proximity of the cylindrical boundary of the sextupole superconducting magnetic systems. The molecules are separated according to their nuclear spin projections [12].

Cooling down the annular nozzle to 6.5 K the results confirm the MonteCarlo simulation of an expected flow in the order of 3×10^{12} molecules s^{-1} in the case of hyper–polarized H_2 molecules. The measured maximum intensity of the polarized D_2 jet was 5×10^{11} molecules s^{-1}, that lower intensity is due to the lower nuclear magnetic moment of D_2 in comparison with that of the H_2 molecules. The test on the existing adapted source is promising and allows to refine the parameters required for designing a proper polarized molecular beam source. Polarized molecules can be condensed on a cryo–surface, *i. e.* the technology under development for the recombined molecules at the IKP-FZJ. It is expected that such a source could provide an intensity of polarized molecules comparable with the intensity of the best atomic beam sources 10^{17} molecules s^{-1}. Molecules with the projection of magnetic moment along the beam axis having the value m_I = -1 are focused towards the beam axis.

Laser induced plasma: production, acceleration and fusion at the **PGI-FZJ/ILPP–HHUD** (IESL–FORTH)
Laser technology can be exploited for polarized ion acceleration, polarization survival and fusion tests. It is a very promising tool which matches properly in the effort of the production of polarized D_2 molecules. Meanwhile the involved groups are tuning the tools, theories and devices for the pro-

duction, preparation and manipulation, the piloting group of this topic already is gaining deep insights from polarized proton beams laser–induced plasmas [14].

They already exploited these techniques in the production of unpolarized He–ion beams from unpolarized He–jets [13].

Nowadays it is possible to have polarized ^{3}He gas transportable and easily manageable. The challenge to test the survival of the polarization in picosecond shots of high power lasers on solid or gaseous high intense polarized beams is on the way and it is possible to get as a result polarized ions accelerated at energies till the order of MeV. Tests on polarized ^{3}He have been performed in summer 2021, the data are under analysis for publication [15].

Laser Quantum beat excitation and post UV –dissociation IESL-FORTH (FZJ/ILPP–HHUD). The photo–dissociation of hydrogen halides (HCl, HBr) and deuterium iodide (DI), with circularly polarized UV laser pulses, has been shown to produce ultrahigh density spin–polarized H and D atoms [16, 17], and opens the way for the production of very intense polarized proton and deuteron beams. The expected density has been shown to be at least in the order of 10^{19} cm^{-3} [18], which is then very promising for the fusion research, or for the polarized ion beams in accelerator physics, which involves also the group of HHUD and FZJ.

Studies on the measurements of the polarization of the photo–fragments can be performed by the Lamb-shift polarimeter [8], a tool already used, or in plan to be used, in the different activities of the PREFER collaboration.

Recently a new proposal was published which predicts a production of 10^{20} hyper–polarized molecules s^{-1}, from the IR rovibrational excitation of molecular beams, thanks to the availability of a laser which provides 10^{21} IR-photons s^{-1} [19].

The cooperation between the groups mentioned, and the tools and knowledge in their hand, will yield fruitful results in the exploitation of this new ultrahigh–density regime of spin–polarized H and D atoms.

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