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Polarization REsearch for Fusion Experiments and Reactors – The PREFER collaboration: aims, goals and present status

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The PREFER (Polarization REsearch for Fusion Experiments and Reactors) collaboration was created to improve the know–how in different fields and techniques and to address the challenging bet on fusion energy production with polarized fuel. Efforts are focused on a variety of tasks and objectives, which are under the responsibility of different institutes. Starting from open questions in the fusion reaction physics, such as the study of D+D spin–dependent cross–sections to measurements of nuclear polarization conservation in laser–induced fusion plasmas, there is still unexplored territory to discover. The collaboration aims to produce nuclear–spin polarized molecules, recombined from polarized atomic beams, and their condensation and transport, or explore a resonance ("Sona") transition technique, which promises sufficient intensity for the feeding of fusion reactors. Other options of production are investigated, like nuclear–spin polarization of molecules by laser or microwave excitation. The presentation provides the status of proposals and investigations in the European community.

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1. Introduction

Exploring the possibilities of fusion with nuclear polarized fuel involves various fields of investigation, technology, and research and development. The technology improvements in many fields during the last forty years, since the 80's when the idea of using spin–polarized fuel for fusion has been debated in literature [1], rekindled hope of pursuing the challenging task of its use for the social, climate and peaceful project of energy production from nuclear fusion. Deuterium, which is the main element for the most accessible fusion reactions, can be extracted from water which is worldwide available [2].

Promising advantages relax engineering constrains and therefore costs of fusion reactors and facilities, but some disadvantages have overshadowed the path of the research. The PREFER collaboration takes the challenge of the investigation on the topics and was founded after workshops in Trento (2013) and Ferrara (2015), whose contributions have been published[3].

The challenges that the collaboration aimed to take on can be briefly described as follows:

- D+D spin–dependent cross–section studies and measurements.
- Production of polarized fuel from the recombination of polarized atoms and its handling.
- Hyper–polarized molecules from a polarized Molecular Beam Source (pMBS).
- Production of polarized beams from laser quantum beat excitation and UV photo–dissociation.
- Acceleration of polarized ion beams and fusion tests with Laser–Induced–Plasmas (LIPs).

In this contribution the present status of the aforementioned challenges will be provided, focusing on the most recent results and publications.

2. Nuclear Fusion with Polarized Fuel

The exploitation of polarized fuel for nuclear fusion *a priori* can provide the **following fruitful advantages**:

1. The **enhancement of fusion cross–section** is theoretically well understood for spin–1+spin–1/2 interacting particles, *e.g.* deuterium+tritium (D+T), or D+^{3}He and is well proven experimentally. On the contrary, experimental data on spin–dependent cross–sections for the fusion of two spin–1 particles (D+D) are not fully understood and in addition experimental data is still missing. Various predictions based on different models allow a ratio of the polarized to the unpolarized total cross–section between zero and three.
2. The **control of angular distributions of the reaction products** allows to handle neutron wall bombardments, activations, and degradation of materials and components, in a delimited space in the area surrounding the fusion environment. This can help for further fuel breading via the n+^{6}Li→^{4}He+T reaction. A better confinement of charged particles in the plasma will heat it further, due to additional collisions of *e.g.* the ^{4}He$^+$ ions with the fuel particles, requiring less energy for maintaining the fusion.

3. The **possibility to design neutron lean reactors** in the case of aligned spins for D+D fusion. The D+D→^{3}He+n reaction might be suppressed for parallel aligned spins and pure S–wave. Nevertheless, even the unpolarized measurements showed the existence of P– and D–partial wave contributions, but again there are no data available to constrain theoretical models.

Facing the aforementioned advantages, there are still **disadvantages**, or open questions:

1. The **intensity (or density), purity and high polarization** achievable for polarized fuel, following the technologies implemented for polarized targets in nuclear physics, are still not in the range required for fusion. Therefore, the production and the manipulation of polarized fuel for its use in fusion environment will require new approaches. Considering the improvements in the recent decades on the technology developed for polarized nuclear targets, the engagement on this challenge could be very fruitful.
2. The **preparation, manipulation and transportation** of polarized fuel require deep insight and R&D for its use in a fusion test experiments.
3. The **survival of the polarization** in fusion environments is an open question too.

Schematically, the influence of the nuclear spin for the fusion reaction *generations*, sorted according to the relative energy of the interacting particles, can be summarized as in the 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 experimentally proven in 1971 on D+^{3}He [5]. Theoretical descriptions of its use in the D+T reaction has been reviewed in the past and also recently [6].

Interacting particles with spins oriented in the same direction have shown a cross–section enhanced by a factor 1.5, and the D+T reaction (same spin configuration of D+^{3}He) follows the same behavior.

The 2^{nd} *generation* reaction has two branches: D+D→T+p and D+D→^{3}He+n. The description of the mechanism of this reaction is quite complicated: S–, P– and D–wave scattering and the relative interference between them will contribute in different amounts. There are various contradictory theoretical models, which require data constraints.

The 3^{rd} *generation* reaction, D+^{3}He→^{4}He+ p, is equivalent to D+T from the point of view of spin–dependent cross–section. The possibility of "neutron lean" reactors relies upon the knowledge of the spin–dependent cross–section of the D+D→^{3}He+n reaction that runs in parallel. The ratio of the polarized total cross–section and the unpolarized one is known as the Quintet Suppression Factor (QSF). There are models which predict an enhancement of this ratio up to 2.5, and models which estimate it to be close to zero [7].

The D+D spin–dependent cross–section measurements are mandatory for the future exploitation of polarized fuel for fusion, and provides deep insight on few–body systems for nuclear and astrophysics [8].

The D+^{3}He might be useful for first test experiments for the following motivations:

- enhancement of cross–sections,
- no neutrons,

- ^{3}He (not radioactive, can be polarized at room temperature) is easier than T to handle.

Electron screening also contributes to the enhancement of cross–sections in the energy range of coming fusion reactors that will be below 50 keV. In addition to the spin–dependent enhancement of the cross–section, it might play a role for energy production. An enhanced screening effect due to polarized electrons might be able to reduce the power, required for ignition and maintenance of the fusion processes, and the costs of the design and the operation of fusion reactors and facilities.

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

Deuterium is a keystone for fusion with polarized fuel. Therefore the PREFER collaboration was and still is dealing with studies and investigations of D+D spin–dependent cross–sections, production of polarized fuel for feasibility studies and tests of nuclear fusion, manipulation and transport of the fuel for dedicated studies in proper facilities with *ad hoc* diagnostics, in order to test it in fusion environments.

Studies and investigations on D+D spin–dependent cross–sections

As described earlier the spin–correlation coefficients of the D+D reactions, to determine their polarization dependence, are not known so far. The first proposal of measurements dates back to 1969 [7], in which, due to small cross–sections and low intensity of atomic beams, on the order of 10^{11} atoms s^{-1}, there was not enough sensitivity to measure these parameters in a reasonable time with an adequate precision.

Nowadays polarized atomic beams reach intensities of 10^{17} atoms s^{-1} and high polarization, up to P∼0.9, is reached in polarized nuclear targets. The Petersburg Nuclear Physics Institute (PNPI) in Gatchina (Russia) is behind studies of the double spin polarized D+D cross–section studies [9], in the mainframe of the PREFER collaboration.

In 2022 the start of the Russia–Ukraine conflict, the collaboration between european and Russian groups was broken. However we have literature evidence that the project is still in progress [10].

In a crossed–beam scheme a polarized ion beam collides orthogonally with a polarized atomic beam. The experiment will operate at a luminosity, that was never available in experiments on colliding polarized atomic beams, allowing measurements in any combination of spin orientations of projectiles and targets. A polarized ion beam of 15 μA can be tuned in the energy range of 30–100 keV, which is of interest for nuclear fusion and astrophysics. The ion beam collides with a neutral atomic polarized deuterium target with an attainable intensity of 4 10^{16} atoms s^{-1}.

The angular distribution of the reaction products is fully covered by a 4π–solid angle detector, surrounding 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 Lamb–Shift Polarimeter (LSP) and a Nuclear Reaction Polarimeter (NRP) are installed and under commissioning for the monitoring of the polarization of both the polarized atomic beam, and the polarized ion beam. The answer to the open question of QSF (Quintet Suppression Factor) can be easily accessed in near future with this facility.

Production of polarized fuel from the pABS and quantum manipulation of molecules

The recombination of polarized atoms, produced by a polarized Atomic Beam Source (pABS), into molecules, which maintain the nuclear–spin orientation during the recombination process (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 of atomic hydrogen, or deuterium, that are strongly reactive and are not easy to handle.

The recombination apparatus, built in collaboration with PNPI and operated at the FZJ, allows to investigate different materials for the cell coating, or temperature of the surface. 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 frozen and collected as polarized ice for further fusion tests.

Significant progress has been made on the diagnosis of the spin phenomena[11], by upgrading the LSP for its use with molecules[12]. As a result it has been proven that it is possible to produce hyper–polarized molecules of H_2, D_2, and HD with polarization value above 0.8. In particular the HD molecules, a perfect training ground for DT, can be produced in several spin combinations of the proton and the deuteron [13].

Recently, the group has been researching a promising technique that utilizes induced coherent transitions between quantum states with very small energy differences [14]. The technique is used in several variations in different experiments to flip the nuclear spin and is known under different names such as Majorana, non-adiabatic, diabatic, Sona, or spin–flip transitions.

The possibility of using a freezing surface in a magnetic field inside a MgB_2 cylinder without a power supply opens the door to transporting the polarized substances for further tests in fusion facilities [15]. A dedicated apparatus for testing superconducting MgB_2 material was put into operation in Ferrara [16]. Several hollow MgB_2 cylinders, produced using the so–called Reactive Liquid Infiltration (RLI) technique [17], have been shown to be useful, demonstrating that there are viable products for this purpose that are capable of conserving a magnetic field of 960 mT when cooled below its critical temperature (39 K) in an external magnetic field of 970 mT. **Hyperpolarized molecules from pMBS**

The idea of filtering molecules by their total nuclear spin follows the technique of Stern–Gerlach separation in an inhomogeneous magnetic field and can thus be used as a polarized Molecular Beam Source (pMBS). The strength of the combined nuclear magnetic moment of a molecule compared to that of an atom is approximately 600 times smaller. Therefore, the required magnetic field scales by the same factor and also has steeper field gradients. The technology available today relies on very high magnetic fields that can be achieved by superconducting magnets. A group, at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk, has modified a superconducting pABS accordingly for their feasibility studies on spin separation of molecular beams.

In order to utilize the maximum gradient of the magnetic field, a nozzle with a ring–shaped geometry is used, which generates a molecular ring jet near the cylindrical boundary of the superconducting sextupole magnet system. The molecules are oriented according to their nuclear spin projections along the symmetry axis of the sextupole.[18]

By cooling this ring–shaped nozzle to 6.5 K, the measurement results confirm the Monte Carlo simulation with an expected flux on 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 beam was $5\ 10^{11}$ molecules s^{-1}.

This lower intensity is due to the lower nuclear magnetic moment of D_2 compared to that of the H_2 molecules.

The tests on the existing adapted source are promising and allow to refine the parameters required for the development of a polarized molecular beam source. Polarized molecules can be condensed through a cryogenic surface, a technology being developed for recombined molecules at the IKP-FZJ. It is expected that such a source could provide an intensity of polarized molecules comparable to the intensity of the best atomic beam sources: 10^{17} molecules s^{-1}. Molecules with the projection of the magnetic moment along the beam axis having the value m_I = -1 will be focused in the direction of the beam axis and could eventually be directed onto freezing surfaces.

Laser–Induced –Plasma acceleration and fusione tests The LIP technologies can be used to accelerate polarized ions, or even to generate energy through nuclear fusion. In both cases, however, the nuclear spin polarization must survive long enough in the plasma. It is a very promising tool and the groups involved have made efforts to develop the tools, theories and devices for production, preparation and manipulation. The pilot group on this topic has already gained deep insights into laser-induced plasmas with polarized proton beams [20].

In a first step, these techniques were investigated to generate unpolarized $^4He^{2+}$ ion beams by laser bombardment of an unpolarized He jet [19]. Subsequently, polarized ^{3}He was used to measure the polarization of the $^3He^{2+}$ ions generated in this way [21].

Nowadays, it is possible to generate and transport polarized ^{3}He gas and maintain the polarization for many hours. The challenge of testing the survival of polarization in the picosecond shots of high–power lasers is on its way, and it is possible to obtain polarized ions as a result. First tests with polarized ^{3}He were performed in summer 2021, and preliminary data were recently published. Further measurements with an improved setup will follow. However, the preliminary results are quite encouraging as they prove that polarization can survive in the inertial confinement environment of fusion [22].

Laser Quantum beat excitation and post UV–dissociation By photodissociation of hydrogen halides (HCl, HBr) and deuterium iodide (DI) with circularly polarized UV laser pulses, it was shown that ultra–high density spin–polarized H and D atoms can be generated and that the way is open to generate very intense polarized proton and deuteron beams by subsequent selective ionization [23]. The expected density is at least of the order of 10^{19} cm^{-3}, which is very promising for fusion research or for polarized ion beams in accelerator physics [24].

Studies to measure the polarization of the photofragments can be performed with a lamb-shift polarimeter [12], an instrument implemented at the IKP and used in the several activities of the PREFER collaboration. Recently, a new proposal has been published that predicts a production of 10^{20} hyper–polarized molecules s^{-1}, thanks to the availability of lasers that produce 10^{21} IR photons s^{-1} [25]. The collaboration between the aforementioned groups with their respective tools and knowledge will lead to fruitful results in the exploitation of this new ultra–high density regime of spin–polarized H and D atoms.

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