PROCEEDINGS OF SCIENCE

Polarized Fusion

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For 90 years the advantages of polarized fuel for future fusion reactors have been discussed and are becoming more and more important. Besides the increased energy output "polarized fusion" can help to solve technological challenges like the tritium breeding within the blanket by focusing the neutrons on dedicated wall areas. In addition, the energy extraction from the plasma can be optimized, the maintenance of the blanket reduced and the lifetime of the superconducting magnets increased to reduce the costs of a future tokamak or stellarator. For laser-induced inertial fusion even the necessary laser power can be reduced for energy production.

But before polarized fuel can play an important role for fusion energy production some work needs to be done. Experiments with polarized beams and targets at accelerators have shown that nuclear polarization can be produced and stored for ^3He, D, H and, therefore, T. But for the necessary amounts of polarized fuel for energy production new techniques have to be developed. Then, in a next step, the polarization lifetime in a fusion plasma must be investigated. Here, first tests with a laser-induced plasma from a polarized ^3He gas jet have shown that the polarization survives at least partially.

The 26th international symposium on spin physics (SPIN2025)
21–26 September, 2025
Qingdao (Tsingtao), Shandong Province, China

*Speaker

PoS(SPIN2025)021

1. Introduction

In times of growing energy demands worldwide and the necessity to reduce CO_2 emissions to minimize the effects of the ongoing climate change, the spotlight for future energy production is turned again on nuclear fusion.
The idea to produce energy by fusion of two light nuclei, i.e. hydrogen isotopes, into the heavier nucleus ^4He was described in 1920 by Arthur Eddington [1] and experimentally proven by Mark Oliphant and Paul Harteck when they observed the $d + d \to t + p$ and $d + d \to ^3 He + n$ reactions in 1934 [2]. The first experiments to investigate the energy production in a magnetic confinement of a tokamak started in the 1950's and led to experiments at JET that produced nearly as much energy as it was necessary to start the fusion plasma in 1997 [3]. When ITER will start its operation with tritium in the 2030's it will be the first tokamak with an energy output 10 times the input.
In the last years, inertial-fusion experiments with laser-induced plasmas offer an alternative method. Meanwhile, the National Ignition Facility (NIF) has demonstrated that more energy was produced than it was induced by the laser beam itself. Thus, a positive Q value seems to be in range.

Only when the amount of generated energy is higher than the losses to the environment, a fusion plasma will "burn" and produce net energy. This is described by the Lawson criterion [4]:

$$\eta \cdot \tau_E > \frac{12 k_B T}{E_f < \sigma v >} \quad , \tag{1}$$

where η is the plasma density, τ_E the energy confinement time, T the plasma temperature and E_f is the energy (in eV) of the charged ejectiles in the chosen fusion reaction. The term $< \sigma v >$ is the averaged product of the Maxwellian velocity distribution at the temperature T of the particles in the plasma times the corresponding cross section σ of the fusion reaction. Thus, during the development of fusion reactors these parameters where maximized to fulfill the Lawson criterion. Magnetic-confinement machines like tokamaks and stellarators try to improve the energy confinement time τ_E, plasma temperature T and, therefore, (v), but they are limited by low plasma densities η. Inertial fusion normally optimizes the density and $T(v)$, but has to pay the price of very small τ_E.

2. Advantages of Polarized Fusion

In 1932 Maurice Goldhaber proposed to optimize another parameter of the Lawson criterion: The alignment of the nuclear spins of the plasma particles can be used to maximize the cross sections σ of the fusion reactions [5]. He realized that the main fusion reactions are spin-dependent and, therefore, their differential and even total cross sections can be influenced by the choice of the spin combinations.
For example, the $t + d \to {}^5He \to {}^4He + n$ reaction is going through a $J = 3/2^+$ resonance that is nearly completely s-wave dominated. In a naive model this means that only spin combinations of the deuteron spin of $S = 1$ and the triton spin of $S = 1/2$ can fuse if the spins are aligned to a total spin of $S = 3/2$ of the intermediate ^5He nucleus. Thus, the two antiparallel spin combinations of

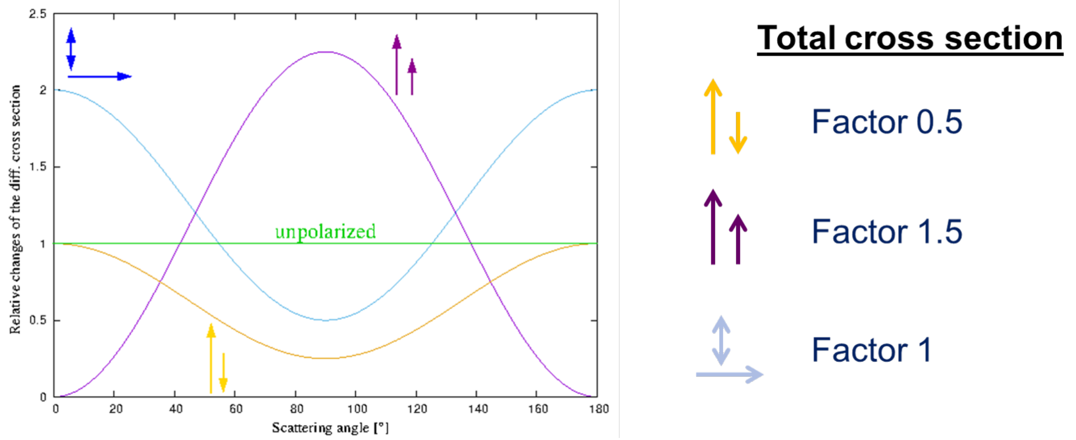

Figure 1: The modifications of the differential cross section for different spin combinations of deuteron and triton (^3He).

deuteron and triton are not allowed to build a ^5He nucleus and, therefore, only 4 of the six possible spin combinations can contribute to the fusion process. This means that a parallel alignment of both spins will increase the total cross section by a factor of about 1.5 at the low temperatures of a fusion plasma. For the neutron-free mirror reaction $^3He + d \rightarrow {^5Li} \rightarrow {^4He} + p$ this concept was experimentally proven with a polarized deuteron beam on a polarized ^3He target in 1971 [6].
Even the differential cross sections can be manipulated by the use of different spin combinations (see Fig. 1). At small plasma energies below 30 keV the differential cross section is nearly constant for every scattering angle. If now the spins of deuteron and triton (^3He ion) are parallel, the cross section is increased for 90° by more than a factor 2 and completely vanishes for 0° and 180°. Anti-parallel spins decrease the cross section at 90° by a factor 4, but do not completely suppress the fusion reactions. Nevertheless, the total cross section is decreased by a factor 2. Another option is the use of unpolarized tritium and negatively tensor-polarized deuterium only. In this case the total cross section is not changed, but now forward and backward scattering are preferred.

This effects can be used in many ways for Tokamaks, Stellarators or inertial fusion reactors:

- The enhanced total cross section will increase the energy output of a fusion reactor above average. The additional heating due to the more α particles will heat the plasma even further, which again increases $< \sigma v >$ in the Lawson criterion. Thus, it was calculated that the power output of ITER will be increased by a factor of 1.8 if the fuel is polarized [7]. For laser-induced fusion at MEGAJOULE it was shown that the heating power can be reduced by 25% and still a linear power increase is possible [8].

- Polarized fuel can help with the tritium problem, because the tritium burn efficiency is increased if it is polarized before [9]. Thus, less tritium is needed.

- Another feature is the option to focus the neutrons after the t+d reaction on dedicated parts of the blanket to breed new tritium via the $^6Li + n \rightarrow {^4He} + t$ reaction more efficiently.

- By the same effect the maintenance costs of a reactor can be suppressed when most parts of the blanket need to be exchanged less and the superconducting magnets are better shielded to increase their lifetime [10].
- If only the deuterons are negatively tensor-polarized, the forward and backward direction is preferred by the neutrons and scattering angles around 90° are suppressed. Therefore, fewer neutrons reach the inner wall of a tokamak and, thus, less cooling is needed here. This means, the magnets can come closer to the plasma which will increase the magnetic field. Due to the nonlinear dependence of the energy output of a reactor on the magnetic field ($E \sim B^{7-10}$) this effect might be the most preferable option of polarized fuel.

3. Problems to solve

Nevertheless, before polarized fuel can be used to enhance the energy output and reduce the costs of a fusion reactor some questions have to be answered in advance:

3.1 What about the double-polarized $d + d$ cross sections?

The polarized cross sections of the $d + t$ and $d + {}^3He$ reactions are well understood for more than 50 years, but the cross sections of the $d + d \rightarrow t + p$ and $d + d \rightarrow {}^3He + n$ reactions are not known at energies below 500 keV [11]. Nevertheless, the analyzing powers for $d + d \rightarrow t + p$ are measured at energies down to 28 keV for an incoming polarized deuteron and are relatively large and nearly constant up to 100 keV [12, 13]. Therefore, it can be expected that even the spin-correlation parameters to describe the differential and total cross sections should be rather sensitive for the double-polarized case. A corresponding measurement has been discussed for several decades and is now under preparation at the PNPI in St. Petersburg, Russia [14]. A polarized deuteron beam from a polarized ion source interacts with a polarized atomic deuterium jet from an ABS (see Fig. 2). A Lamb-shift polarimeter and a nuclear-reaction polarimeter are used to control the polarization values of beam and target. The fusion products are measured with a 4π detector made from photodiodes for all possible spin combinations.

3.2 Does nuclear polarization survive long enough in a fusion plasma?

If the polarization does not survive in the fusion plasma long enough, the advantages of polarized fuel cannot be used. Of course, in thermal equilibrium in a hot plasma no polarization can be expected. Due to the tiny energy differences between the hyperfine substates the Boltzmann distribution will be responsible for equal occupation numbers of the different spin substates. But angular momentum conservation allows just a few decay channels for the nuclear polarization. Kulsrud et al. [15] discussed this idea and showed that the known depolarization channels are blocked due to the strong magnetic fields decoupling the electron and the nuclear spins. Other options like RF-induced transitions between hyperfine substates by different plasma modes [16] or wall interactions can be avoided [17].

Nevertheless, an experimental proof is still missing for magnetic confinement reactors. Such an investigation is now foreseen at the DIII tokamak in San Diego, USA [18]. Here, the reactor will be fed with polarized ${}^3He$ and HD ice and then the changes of the blanket irradiation and the total

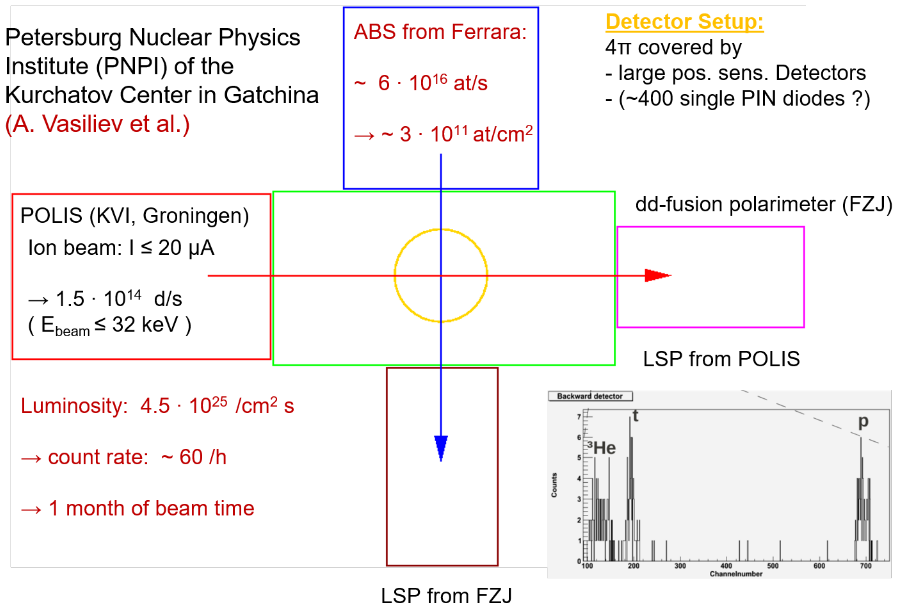

Figure 2: The experimental setup to measure the double-polarized cross sections at PNPI.

energy production can be observed as function of time to measure the polarization lifetime directly. For laser-induced inertial fusion it is expected that the process is so fast that depolarization cannot happen [19]. Even a first experimental proof with the 1 PW Laser PHELIX shooting on a polarized ^3He gas jet was successful [20]. Here, the polarization of the accelerated $^3He^{2+}$ ions at beam energies below 5 MeV was measured due to the known analyzing powers of the $^3He + d \rightarrow {}^4He + p$ reaction at these energies. The produced α particles are detected by CR39 plates (see Fig. 3) and the corresponding asymmetries are determined by counting the induced spots. It was clearly seen that the observed asymmetries changed their sign when the polarization direction was reversed. Therefore, the nuclear polarization survived the laser plasma at least partially. A more quantitative measurement is in preparation.

3.3 How to produce enough polarized fuel?

To feed a fusion power station in the order of 1 GW about 10^{23} fuel particles/s are needed. Until now, this amount can be produced for ^3He with optical pumping only. Spin-exchange optical pumping is even working for the polarized H^- source at RHIC [21] and should, therefore, work for T too, because the hyperfine structure of both isotopes is identical. But what is still missing is the production of macroscopic amounts of D. An atomic beam source (ABS) can produce large polarization values up to 0.9, but is limited in intensity to 10^{17} atoms/s. Dynamic nuclear polarization (DNP) delivers smaller polarization values and cannot be done for pure materials. The extremely expensive "brute force" method can produce enough HD (TD) ice, but is again limited in polarization values about 0.2. Thus, new ideas are needed.
One option to feed a tokamak at least for a few seconds is to produce polarized HD (TD) ice by recombination of polarized atoms from an ABS on a cold fomblin surface inside a strong magnetic field to preserve the nuclear polarization and collect these molecules as ice for one day [22]. Another

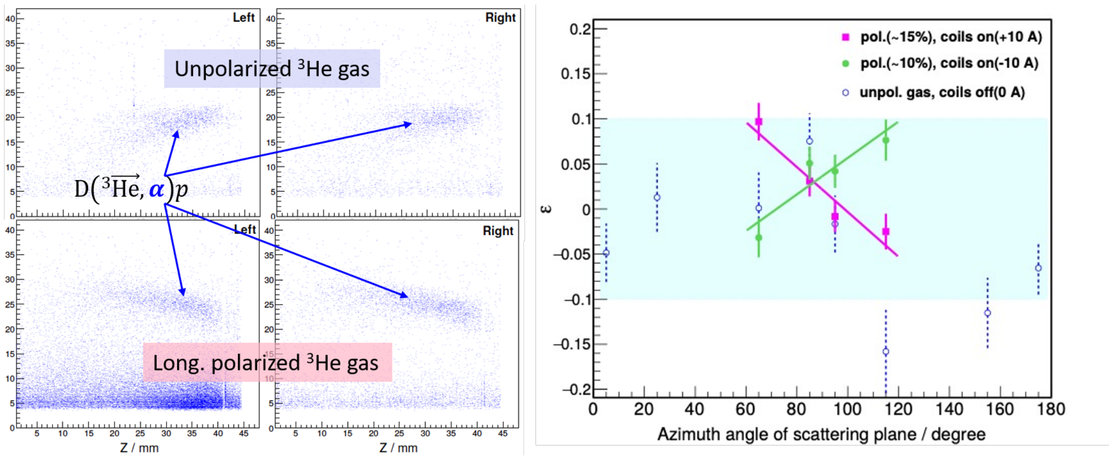

Figure 3: Left side: The spots on nuclear track plates produced by polarized and unpolarized α particles. Right side: The measured asymmetry for positive and negative polarization of the ^3He gas.

option seems to be a new technique of optical pumping of the ro-vibrational states of HD (TD) molecules with an IR laser and then to transfer the induced polarization of the rotational magnetic moment to the nucleons. By repeating this process large polarization values are possible and even the intensity of the neutral molecular beam can be very large [23].

4. Conclusion

The advantages for all types of fusion reactors by the use of polarized fuel to manipulate the differential and total cross sections are very promising. On one hand the energy output can be increased in different ways and on the other hand it can help to solve technological problems and reduce the costs of a power plant. For example, it can help to reduce the necessary amount of tritium and to breed new tritium more effectively, to extract the energy from the plasma, to reduce the maintenance of the blanket or to increase the lifetime of the superconducting magnets due to the focusing of the neutrons on dedicated wall areas. Therefore, the option of "polarized fusion" cannot be ignored for future magnetic confinement or inertial fusion reactors.

But before, some general questions have to be answered by actual investigations. That the nuclear polarization can survive a laser-induced plasma has been shown at least partially, but more quantitative measurements are necessary and are underway. For the much longer plasma lifetimes in magnetic confinement corresponding measurements are foreseen at the DIII tokamak. The last, but most important problem, is the production of reasonable amounts of polarized fuel, i.e. D and T with large polarization values of 0.8 and above. Current methods can reach this polarization level, but are limited in intensity. Nevertheless, a new optical-pumping technique gives hope that even this problem will be solved in the near future.

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