Spin Physics (SPIN2014)
International Journal of Modern Physics: Conference Series
Vol. 40 (2016) 1660112 (6 pages)

DOI: 10.1142/S2010194516601125

Polarized Fusion.
Can Polarization Help to Increase the Energy Output of Fusion Reactors?

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Published 29 February 2016

Keywords: Polarized Fusion; Polarized Molecules; Polarized Plasmas.

PACS numbers: 28.52.−s, 29.25.Pj, 32.10.Dk, 33.15.Kr

1. Introduction

Since more than 60 years scientists are working on the idea to produce energy from nuclear fusion of light particles like the Hydrogen isotopes. In the meantime, the energy output of e.g. tokamak reactors was increased by five orders and modern experiments like JET are approaching the border for energy production. The international ITER collaboration is preparing the first fusion reactor that will produce about ten times more energy, compared to the energy that is needed to run the experiment. Today, the laser-induced inertial fusion reached the same level and experiments at the National Ignition Facility (NIF) in California, USA, demonstrate a ratio between produced and induced energy about one at the end of 2013.[1]

In parallel, it is discussed since 1970 to use nuclear polarized fuel to increase the total cross sections of the different fusion reactions.[2] The energy gain of fusion reactors does not depend linearly on the total cross section. Depending on the different concepts for nuclear fusion, magnetic confinement or inertial fusion, the energy gain is improved above average. M. Temporal *et al.* have shown, e.g., that the energy gain of laser-induced inertial fusion might be increased by a factor four, or that the necessary laser power can be reduced by 20 %, if the nuclear fuel was polarized before.[3] The downsized laser power will reduce the costs of the corresponding project by a reasonable amount. In addition, the differential cross sections can be modified so that it will be possible to focus the ejectiles, e.g. the neutrons, on special wall areas. In a tokamak this can be used to concentrate the neutron flux to special outer parts of the blanket, where the cooling can be improved and the neutrons be used for Tritium production via the exothermic reaction $^6Li + n \rightarrow {}^4He + t$.[4] At the same time, less cooling is needed for the inner parts of the blanket that allows to bring the magnetic field coils closer to the fusion plasma. The increased magnetic field in the plasma will increase the energy gain additionally. Another option of polarized fuel is a new kind of plasma diagnostic inside a tokamak. In combination with modern Nuclear Magnetic Resonance technologies (NMR) anisotropies in the plasma can be measured to learn more about the different plasma modes.[5]

2. Open Questions

In contradiction to all this advantages of polarized fuel in nuclear fusion reactors it was never used up to now. Before the profit of polarization is an option for energy production a long list of questions must be answered.

2.1. *The polarized differential and total cross sections*

When a Triton and a Deuteron will fuse a ^5He nucleus is build for a short time, before the intermediate nucleus will decay into ^4He and a neutron. The decay is exothermic and a kinetic energy of 17.6 MeV is given to the ejectiles. This reaction is dominated by a $J = 3/2^+$ resonance, i.e. the nuclear spin of the ^5He nucleon must be 3/2. At low energies mostly s-waves contribute (96 %) and, therefore, the spins of the Triton ($S = 1/2$) and the Deuteron ($S = 1$) cannot be anti-parallel to allow the fusion process. This means that two out of six possible permutations of both spins are not contributing to the fusion process. If the spins of both projectiles are aligned right from the beginning, the total cross section is increased by a factor 1.5. In addition, the differential cross section is modified too. In the low energy regime ($\leq$ 100 keV) of a fusion plasma the differential cross section is constant for different scattering angles. If both spins are parallel to the external magnetic field the cross sections around $\theta = 90^{\circ}$ are increased and for 0° and 180° it is decreased. Other spin combinations will allow different modifications.[6] For the mirror reaction $^3He + d \rightarrow {}^4He + p$ the situation is very similar. Again, the intermediate ^5Li nucleus must have a spin of 3/2. In this case, the predictions for the differential cross sections were experimentally proved with a polarized deuteron beam on a polarized ^3He target in 1970.[7] Another option are the DD-reactions: $d + d \rightarrow {}^3He + n$ or $d + d \rightarrow t + p$. Even if these reactions are not used by themselves for energy production due to the smaller cross sections and the lower energy output, these reactions will run in

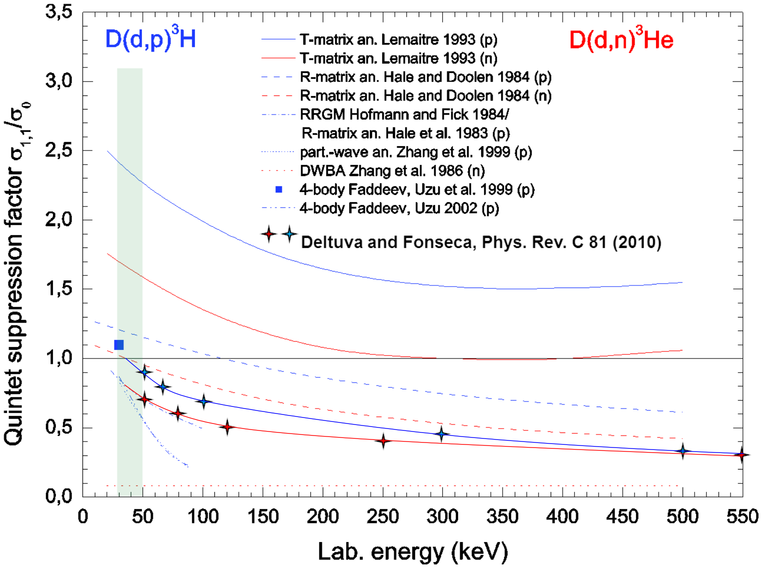

Fig. 1. The different predictions for the quintet-suppression factor of the DD reactions, i.e. the ratio of the total cross sections when both deuteron spins are parallel to the quantization axis ($\sigma_{1,1}$), and the unpolarized case (σ_0).

parallel to the other fusion reactions. Therefore, the dependence of the cross sections on the polarization of the projectiles must be known before polarized deuterons are used for energy production. For these spin $S = 1$ on $S = 1$ fusion reactions the predictions are much more complicated (see Fig.1) and must be verified by a precise measurement with a polarized deuteron beam on a polarized Deuterium target. In this case, several spin-correlation coefficients can be measured for different spin combinations as a function of the beam energy and the influence on the differential and total cross sections can be calculated. This measurement is under construction at the Petersburg Nuclear Physics Institute in Gatchina in a collaboration with the Institute for Nuclear Physics of the research center Jülich, Germany, and the University of Ferrara, Italy. The polarized deuteron source, formerly used at the KVI in Groningen, the Netherlands, will produce a vector- or tensor- polarized beam of up to 50 μA and polarization values about 70 % of the maximum values.[8] For the polarized jet target a polarized atomic beam source (ABS) is rebuilt that was used at the University of Ferrara before. The atomic flux of this source is about 6×10^{16} atoms s^{-1} and the corresponding target thickness is 3×10^{11} atoms cm^{-2}. The luminosity is therefore 4.5×10^{25} cm^{-2} s^{-1} and the following count rate will be about 60 counts h^{-1} at a beam energy of 30 keV. This count rate is rather low, but for a stand-alone experiment without an accelerator absolutely reasonable. The polarization of the Deuterium target beam will be measured with a Lamb-shift polarimeter[9,10] and, in addition, the polarization of the deuteron beam will be registered with a nuclear-reaction polarimeter.[11]

2.2. *Polarisation conservation in the different types of plasma*

Polarized fuel is useless, if the polarization will not survive in the fusion plasma. First calculations showed that the polarization might be preserved long enough in a magnetic confinement plasma[12] and during the interaction with the blanket of a tokamak reactor.[13] Other depolarizing effects are possible,[14] but can be overcome. Nevertheless, a test under real conditions is necessary and suggested for the DIII tokamak in San Diego.[6]

For inertial fusion the situation seems to be relaxed due to the very short duration of the fusion process.[15] For laser-induced fusion the extreme amplitudes of the oscillating magnetic field up to 10^4 T might be able to influence the polarization.[16] An experiment to investigate the conservation of the polarization at these conditions is foreseen by a collaboration of the University of Düsseldorf and the Research Center Jülich in 2015 at the PHELIX-laser in Darmstadt, Germany. Laser-acceleration of $^4He^{2+}$ ions from a ^4He gas jet up to 1 MeV was made successfully. If now polarized $^3He^{2+}$ ions from a polarized ^3He gas jet target will be registered with a nuclear-reaction polarimeter, based on the known analyzing powers of the $d+\overrightarrow{^3He} \rightarrow {}^4He+p$ reaction, it is shown that the polarization will survive in a laser-induced plasma.

2.3. *How to produce and handle polarized fuel*

At least for the possible energy production with polarized fuel, but even for the supposed experiments at a tokamak a reasonable amount of polarized fuel is needed. Due to "laser-pumping" macroscopic amounts of polarized ^3He gas are produced and stored in special glass bottles to be used for several applications, e.g. NMR spectroscopy of the lounge after inhaling. Laser-pumping is useful for Hydrogen atoms and, therefore, must be possible for Tritium, because the hyperfine structure of both isotopes is very similar. The polarized Tritium atoms cannot be stored for a long time, because it is a radical that attacks more or less any kind of surface. But "online" production close to a tokamak is a possible option.

For Deuterium exists two methods to produce polarized nucleons: with a polarized atomic beam source[17] a large polarization up to $P_z = +/-0.9$ or $P_{zz} = +0.9/-1.8$ is achieved, but the intensity with less than 10^{17} atoms s^{-1} is at least four orders to low to feed a tokamak. Frozen-spin targets of HD ice are produced at extreme magnetic fields of 15 T and temperatures below 100 mK.[6] The Deuterium polarization is limited to $P = 0.25$ and the Hydrogen atoms are an unwanted contribution for the fusion plasma. In principle, frozen DT ice is possible, but to reach the very low temperatures during the continuous decay of the tritons needs a larger amount of cooling power.

One option to overcome these problems is to recombine the Deuterium atoms of an ABS into molecules and to store them. To optimize this process a collaboration was built between the University of Cologne, the Petersburg Nuclear Physics Institute and the research center Jülich. In T-shaped storage cells with a selected surface material the polarized atoms, Hydrogen or Deuterium, recombine at temperatures between 40 to 120 K and magnetic fields up to 1 T. The cooled surface of the superconducting solenoid is even used for pumping to achieve a vacuum about 10^{-9} mbar. The atoms and molecules are ionized by a through going electron beam at about 150 eV and the produced protons and H_2^+ ions are accelerated into a Lamb-shift polarimeter. This device is able to measure the polarization of both types of ions online with a precision of 1 % in few seconds. In addition, the recombination on different surfaces and the amount of wall collisions of the molecules inside the storage cell are measured in parallel.[18] On several materials, especially metals, the polarization of the molecules is about 50 % of the original atomic polarization. In Fig. 2 a measurement is shown for the recombination of polarized Hydrogen atoms on a cold Fomblin[19] surface. Depending of the external magnetic field close to 100 % of the initial polarization is conserved in the molecules. The storage cell is fed with Hydrogen atoms in the hyperfine state 3. The polarization of the protons produced from these atoms is independent from the magnetic field. Due to the measured function it can be deduced that most protons stem from the molecules and, therefore, 99.3 % of the atoms are recombined inside the cell. Even the number of wall collisions n can be measured from the proton behavior. The result $n = 174 \pm 19$ fits nicely to the expected value from Monte-Carlo simulations based on the assumption that the molecules will stay for a short time on the surface, forget where they have come from, and leave the surface with a cos θ distribution. The H_2^+ ions, which are produced in the center, cannot leave the cell, because the mean

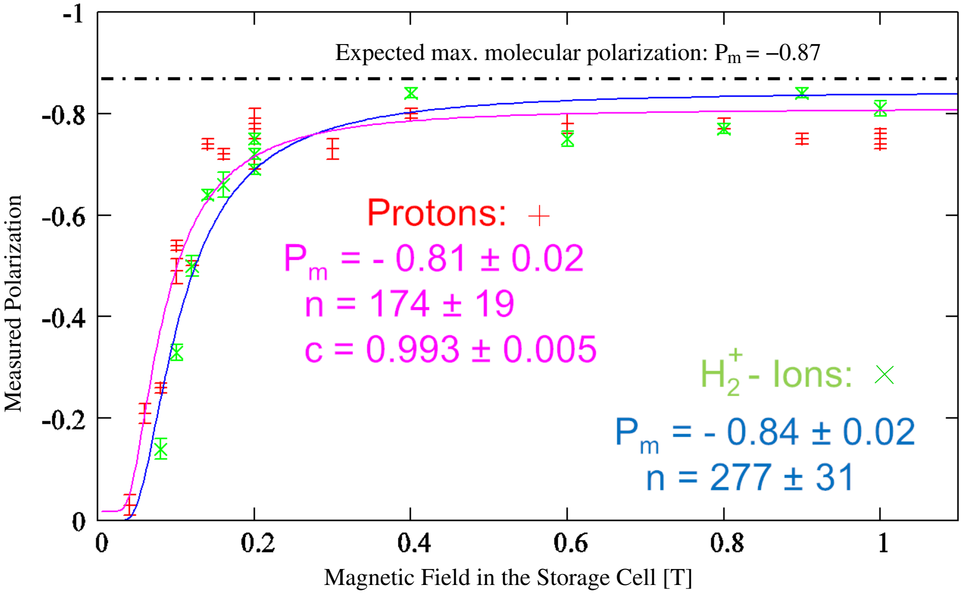

Fig. 2. The measured polarization of the protons (red +) and H_2^+ ions (green ×) as a function of the magnetic field in a storage cell with a Fomblin surface. At large magnetic fields the measured molecular polarization is at most 100 % of the expected maximum polarization.

free path of this large ions at a cell pressure of about 10^{-4} mbar is shorter than the length of the cell. Thus, all of these ions are built close to the exit of the storage cell, where the average amount of wall collisions is larger.

This method should be useful for Deuterium too. In this case, the polarized D_2 molecules can be collected by freezing them at the end of the cell. If now the atomic flux of an ABS is stored for one day the amount of polarized D_2 ice will be enough to feed a tokamak for one second.

3. Discussion

Before polarized fuel might be useful for nuclear fusion these questions must be answered. The necessary tools we already have in hand within our community.

Acknowledgments

This work was supported by the International Science and Technology Center (ISTC No. 1861 and 3881) and the Deutsche Forschungsgemeinschaft (DFG Project 436 RUS 113/977/0-1 and 436 RUS EN 902/1-1).

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