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Persistence of the Polarization in a Fusion Process

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Abstract

We propose an experiment to test the persistence of the polarization in a fusion process, using a terawatt laser hitting a polarized high density (HD) target. The polarized protons and deuterons heated in the plasma induced by the laser have a significant probability to fuse producing a ^{3}He and a γ-ray or a neutron in the final state. The angular distribution of the radiated γ-rays and the change in the corresponding total cross-section are related to the polarization persistence, but the resulting signal turns out to be weak. By comparison, the neutrons are produced hadronically with a larger cross-section and it is much easier to detect them. A significant reduction of the cross-section by parallel polarization of the deuterons as well as a structured angular distribution of the emitted neutrons is reliably predicted by the theory. Therefore, it is expected that the corresponding signal on the neutron counting rate could be seen experimentally. Magnetic fields, relaxation times and possibilities of local investigations are discussed.

Keywords: Fusion reactions; Magnetic fields; Neutron detector; Persistence of the polarization; Polarized targets; Relaxation times; Suppression factors; Ultra short lasers

INTRODUCTION

The polarization of deuterium (D) and tritium (T) nuclei should increase their reactivity when used as fuel material in fusion processes induced either by magnetic or by inertial confinement. The fusion reaction:

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha + \text{neutron} + 17.6\,\text{MeV}, \tag{1}$$

goes mainly through the excitation of an ^{5}He $3/2^+$ intermediate state, resulting from the coupling of the spins 1 and 1/2 of the D and T nuclei to a total spin $S = 3/2$. Without polarization of D and T, the statistical distribution of the six possible states gives four $S = 3/2$ and two $S = 1/2$ states. Only the 3/2 states can produce the intermediate 3/2 resonance. With 100% parallel polarization of D and T, all states would contribute to the fusion, increasing the reactivity by 50%. In addition, the polarization allows the control of the direction in which the reaction products are emitted, the neutron having a $\sin^2\theta$ distribution. This can be very useful to reduce damage or activation of costly equipments (Kulsrud *et al.*, 1982). The question is to know if the polarization will persist in dense and hot plasmas.

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METHOD

We propose to investigate the polarization persistency using the reactions:

$$\mathrm{P} + \mathrm{D} \rightarrow {}^3\mathrm{He} + \gamma + 5.5\,\mathrm{MeV}, \tag{2}$$

$$\mathrm{D} + \mathrm{D} \rightarrow {}^3\mathrm{He} + \mathrm{n} + 3.3\,\mathrm{MeV}, \tag{3}$$

induced by fusion of polarized protons and deuterons heated in a plasma. It is anticipated that the angular distributions of final state products as well as significant changes in the fusion rates can be measured and related to the persistence of the polarization.

MAGNETIC *VERSUS* INERTIAL CONFINEMENT

The idea of inertial confinement is to compress tiny amounts of DT — simultaneously with heating — to such an extent that sufficient fuel burn is achieved within the time interval the fuel keeps together inertially. It turns out that the plasma density n and confinement time τ required for inertial fusion are very different from those for magnetic fusion (11 orders of magnitude):

Confinement	$n(\mathrm{cm}^{-3})$	τ(s)	$n \times \tau(\mathrm{s/cm}^3)$;
Magnetic	10^{14}	10	10^{15};
Inertial	10^{26}	10^{-10}	10^{16}.

In both cases, however, the product $n \times \tau$ has to satisfy the Lawson criterion ($n \times \tau \geq 10^{15}$ s/cm^3) which is set by the DT fusion physics. In a Tokamak like International Thermonuclear Experimental Reactor, the confinement time is expected to be as large as 300 s, which makes it very difficult for the polarization to survive until the end of the cycle, while at megajoule, the whole compression time of a tiny target is on the order of 35 ns, making it much easier for the survival of the polarization. Kulsrud *et al.* (1982) has investigated several depolarization mechanisms as: (1) inhomogeneous static magnetic fields, (2) binary collisions, (3) magnetic fluctuations, (4) atomic effects, and concluded that all of them are weak. Relaxation times can become very long, when the depolarization paths are suppressed, as for example, for HD (Honig, 1967). However, in this matter, an experimental verification is always needed. In the United States, there is a project to inject polarized D and ^{3}He in the DIII-D tokamak of San Diego, in order to see a 15% increase of the reaction rate of emitted protons by the fusion reaction:

$$D + {}^3He \rightarrow {}^4He + p + 18.35\,\text{MeV}. \quad (4)$$

However, the injection of 55% polarized D and ^{3}He into a tokamak is a problem in itself, requiring technical innovations which may take some time.

TENTATIVE SET-UP

At IPN Orsay, we have developed the static polarization of HD molecules for samples as large as 25 cm^3 (Bouchigny *et al.*, 2005). It has been demonstrated that the distillation and the ageing technique allow getting nuclear relaxation times larger than one week, even at 1.5 K and 1 T (Bouchigny *et al.*, 2009). Proton polarization in excess of 60% and deuteron vector polarization higher than 14% have been achieved. It is advocated that a terawatt laser hitting a piece of polarized HD ice will induce nearby plasma hot enough to allow the fusion reactions (2) and (3) to take place and to be measured. If both H and D, namely the proton and the deuteron of the HD molecules are polarized in the same direction and have kept their polarization in the fusion process, the 5.5 Mev γ-rays will be emitted with some angular distribution relative to the polarization axis, also the fusion rates will depend drastically on the initial state polarizations. A tentative sketch of the experimental set-up is displayed in Figure 1. It should be mentioned that with a power of 200 mJ/shot, the laser repetition rate can be adjusted to prevent melting of the target. Without cooling power provided by the holding cryostat, 1,000 such laser shots would be necessary to melt completely 25 cm^3 of solid HD. The overall polarization will decrease with time, but is continuously monitored by the NMR coils.

Back in 1970, a French group from the "*Commissariat à l'Energie Atomique*" (Floux *et al.*, 1970) reported the observation of neutron emission from DD fusion, after focusing a 3 GW fast laser on a piece of D_2 ice 1 mm^2 in cross-section. At that time, a rise time of 5 ns was considered as fast. Since then terawatt lasers have been developed using the chirped pulse amplification, able to deliver several tens of J within 20 fs to 1 ps. Those lasers can be used for fast ignition in

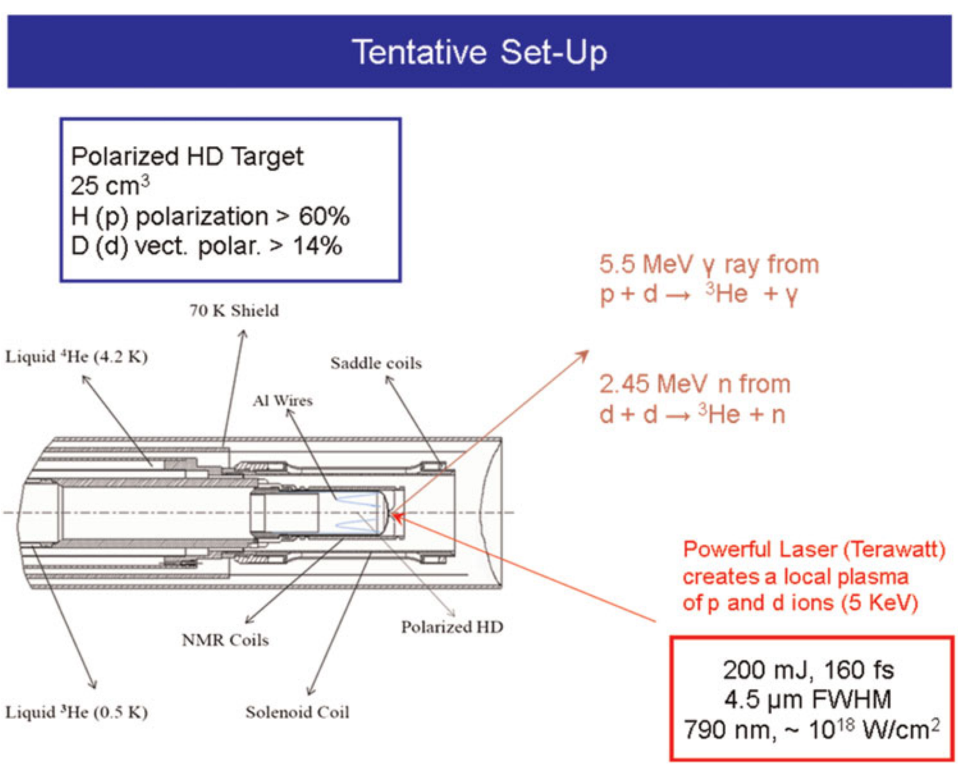

Fig. 1. (Color online) Tentative set-up showing a typical arrangement of a polarized HD target in a cryostat maintaining the target temperature below 1 K under a holding field of 1 T. The target is bombarded by a terawatt laser producing a localized plasma. Neutrons and γ-rays are produced in the plasma, by fusion reactions between polarized *protons* and *deuterons*.

inertial confinement fusion (Zepf *et al.*, 1996) or to accelerate particles (Snavely *et al.*, 2000).

Pretzler *et al.* (1998) reports quantitative data resulting from the irradiation of C_2D_4 targets with laser pulses (200 mJ, 160 fs, 4.5 μm FWHM, 790 nm, 10^{18} W/cm^2, 10 Hz). A total rate of 140 neutrons per shot could be produced, through the fusion reaction (3).

The technique to produce ion beams with ultra high power lasers starts to be well documented (Schollmeier *et al.*, 2007): scaling laws and models exist that can predict the number and energy distribution of accelerated particles. This in turn, allows to tentatively optimizing experimental conditions, although in this field, large uncertainties remain concerning the details of the processes. In particular, it is not at all sure that in a block of ice, ion acceleration will take place: acceleration of particles have been reported only with thin targets.

From the quantitative data of Prezler, given the measured cross-sections of reaction (2): σ (10 keV) = 18 μb (Schmid *et al.*, 1995); σ (10 MeV) = 1 mb (Skopic *et al.*, 1979), 0.1–1 (radiative captures/laser shot) could be expected. The detection of the corresponding γ-rays is a serious experimental problem. Conventional Ge detectors cannot be used, because of the large number of energetic electrons and Bremsstrahlung γ-rays emitted in an extremely short time, which will pile-up in the Ge detector. Pair spectrometers would perform better, in spite of their lower efficiency.

THE "FEW-BODY" PROBLEMS

For the radiative capture (2), the experiment is essentially based on the angular distribution. Assuming that *P* and *D* nuclei collide from all directions in a hot plasma, with a total spin $S = 3/2$ (quartet transitions: σ_4, namely 100% polarization), while an un-polarized plasma involves also transitions from a total spin $S = 1/2$, (doublet transitions: σ_2), the angular dependence of the γ-rays emitted from quartet transitions has the form (Viviani *et al.*, 1996):

$$d\sigma_4/d\omega \sim (1 + \cos^2\theta_\gamma). \qquad (5)$$

Where θ_γ is the polar angle of the radiated γ-ray with respect to the polarization axis in the CM of the P-D system. Due to the very low energy of incident particles as compared to the outgoing ones, the laboratory system is very close to the CM.

At the energies of interest, tens of keV or so, the process proceeds *via* S and P wave capture, and is induced predominantly by magnetic (for S-wave) and electric (for P-wave) dipole transitions. Higher multipoles, at the low energies considered here, can be neglected. In addition, the P-wave contributions are much smaller than the S-wave one, since they involve the small D-wave component of the ^{3}He ground state. Therefore, although P-wave contributions involve isotropic and ($3\cos^2\theta_\gamma$-1) terms, one would expect a very small distortion of the ($1 + \cos^2\theta_\gamma$) angular distribution due to a pure S-wave magnetic dipole transition, as given by Eq. (5).

From experimental point of view, this angular distribution means that 1/3 of the γ-rays due to quartet transitions will be preferentially emitted in the direction of polarization, namely in the direction of the laser beam. However, it is out of question to put a γ-ray detector in the direction of the laser beam, because of the large number of energetic electrons produced at forward angles. A transverse position, typically 90 degrees, is the most convenient. There the effect of the polarization on the quartet γ-rays counting rate is reduced to 25% to be compared to values approaching 100% at forward angles. Taking into account the highest achievable *P* and *D* polarization rates of, respectively, 80% and 30% in HD by the static polarization method and the dominant γ-ray contribution coming from doublet transitions for un-polarized nuclei: typically $\sigma_4/\sigma_{unpol} \sim 0.2$ from theoretical estimates and even much smaller from experimental results at low energies (Konijnenberg, 1990), one cannot expect a signal larger than 3% on the counting rates between polarized and un-polarized targets. This makes the radiative capture experiment fairly difficult to exploit. It should be mentioned here, that the HD polarization technology allows the polarization of H and D in an anti-parallel configuration (Didelez, 1994) in order to enhance the dominant σ_2 contribution. So doing, an increase $\sigma_{pol}/\sigma_{unpol} \sim 1.07$, namely 7% could be expected and eventually measured.

There is an alternative possibility offered by the hadronic fusion *reaction* (3) producing 2.45 MeV neutrons which are much easier to be detected than γ-rays in a surrounding background. From a partial wave analysis (Ad'yasevich *et al.*, 1969), it has been argued that the cross-section should be significantly reduced if the interacting deuterons have parallel vector polarizations (i.e., with total spin $S = 2$, namely quintet transitions: σ_5 (Kulsrud *et al.*, 1982), but resonating-group calculations (Hofmann & Fick, 1984) found that polarized fusions are not suppressed. However, it is known that resonating-group calculations are not very reliable for weakly bound nuclei as deuterons. On the other hand, DWBA calculations give a large Quintet Suppression Factor (QSF): $\sigma_5/\sigma_{unpol} \sim 0.08$ in the range $E_d =$ 20–150 keV (Zhang *et al.*, 1985). Large reduction factors are confirmed by recent calculations (Deltuva *et al.*, 2008; Deltuva & Fonseca, 2010), with QSF going from 0.5 at 100 KeV to 0.2 at 4 MeV. Figure 2 shows the QSF factors as predicted (Deltuva & Fonseca, 2010). Identification of the persistence of the polarization by the suppression of the reaction may not be that easy at the low fusion energies, because there, the QSF is small. However, the total cross-sections are in the range of 100 mb, to be compared to 100 μb for the electromagnetic reaction (2) (Schmid *et al.*, 1995). In view of those considerations, the $D + D \rightarrow {}^3He + n$ fusion reaction is the way to go. It should be noted that for a polarized HD target, it is possible to increase the D polarization above 50% at the expense of the H one, by transfer of the H polarization to D, using adiabatic fast passage

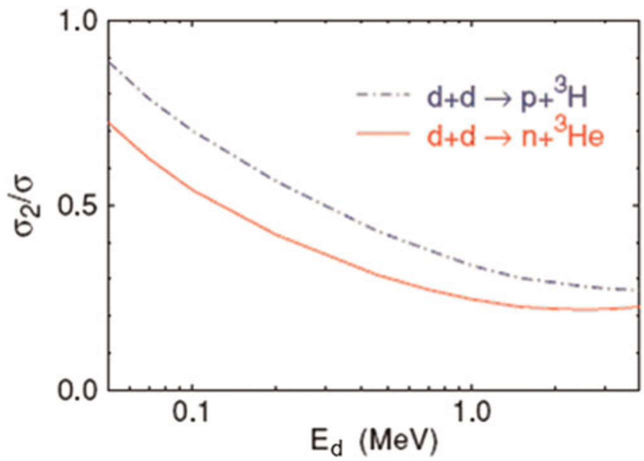

Fig. 2. (Color online) Predictions of the σ_2/σ (total spin 2 cross-section/unpolarized cross-section) from Deltuva and Fonseca (2010), showing that at the fusion energies, there is less suppression coming from the parallel polarization of the deuteron spins than in the MeV energy region.

(Didelez, 1994). A decrease of the emitted neutron counting rate of 10–20% going from a un-polarized target to a polarized one, namely $\sigma_{pol}/\sigma_{unpol} \sim 0.85$ should be easily measurable. The corresponding effect is further increased by the fact that the neutrons produced by quintet transitions are preferentially emitted perpendicular to the polarization axis according to a $\sin^2\theta_n$ angular distribution, where θ_n is the polar angle of the neutrons with respect to the polarization axis in the CM of the D-D system (Paetz gen, 2010). This behavior is further confirmed by a calculation of Deltuva (Private Communication, 2009) for the reaction (3) at 1.5 MeV, in which he shows that the neutrons from the quintet transitions are preferentially emitted perpendicularly to the polarization axis. The corresponding angular distribution is again suggestive of a $\sin^2\theta_n$ shape. In a recent review paper concerning "The status of polarized fusion," Paetz gen. Schieck shows that the QSF is not at all well predicted in the fusion energy range, with variations on the order of five depending on the authors. Therefore, the project of direct experimental measurement of the QSF by a Jülich-Gatchina collaboration is very well come (Engels *et al.*, 2010).

MAGNETIC FIELDS AND TEMPERATURE

In the laser plasma interaction, very high magnetic fields are created. The maximum amplitude of self generated quasistatic magnetic field is roughly one-third of the laser electromagnetic field (Kato *et al.*, 2004). The magnetic field associated with an intense laser of intensity I_L is extremely large:

$$B_L = 290 \times (I_L/10^{19})\text{MGauss}. \quad (6)$$

Where I_L is the laser irradiance in W/cm^2.

In our case, with I_L on the order of 10^{18} W/cm^2, magnetic fields as high as 10^3 Tesla can be generated in the laser-plasma interaction, which is a thousand times larger than the initial holding field of 1 Tesla (see for instance, Eliezer (2002)). However, those fields have a very short live time on the order of the laser pulse duration and at most of the plasma live time itself. They could destroy the polarization or change the polarization direction. In this connection, it should be appreciated that even for I_L values of relevance to inertial confinement fusion fast ignition, the possible hundred MGauss magnetic fields (Sudan, 1993) advocated in Eq. (6) last only a laser oscillation time about fs and remain confined to a skin depth penetration length about 10 Å.

More has discussed the possibility to use polarized fuel in inertial fusion (More, 1983), and concluded that collisional depolarization cross-sections are not large enough to give significant depolarization, and that the short duration of inertial-fusion implosion precludes spin resonance for magnetic fields that can be reasonably expected in the target fuel (More, 1983). In other words, the field duration is too short to depolarize the target. Similar arguments hold for a rotation of the polarization direction. It should be noted however that the signature of the persistence of the polarization is the occurrence of some anisotropy in the distribution of emitted neutrons; a rotation of the polarization axis would not ruin the experiment.

The temperature in plasma can also become very high. For 1 keV mean energy, the plasma temperature is estimated to be on the order of 10^7 K. Even if in a plasma the depolarization mechanisms are weak (Kulsrud *et al.*, 1982; More, 1983) such temperatures are risky because they shorten drastically the relaxation times. A simple way to estimate relaxation times is to compare similar systems at the same values of $\mu B/kT$, where μ is the magnetic moment of the nuclear species and k is the Boltzmann constant (Didelez, 1994). Polarized ^{3}He can be transported far away at room temperature (300 K) and holding fields of a few hundred Gauss (3×10^{-2} Tesla). The B/T value for the transported ^{3}He (hours of relaxation time) *is* on the order of 10^{-4} Tesla/Kelvin. If we assume that the depolarization mechanisms in a gas that can be roughly compared to those in a plasma at the same B/T, we find that for a 10^3 Tesla field, a plasma could handle a temperature of 10^7 K.

There are means to predict the magnitude and the direction of the magnetic fields in a laser-plasma interaction. Several parameters of the laser beam, in particular its polarization can influence the direction of the magnetic field in the plasma (Kato *et al.*, 2004). On the other hand, the direction of the target polarization can be oriented in almost any direction. For example, the HD polarized target of RCNP in Osaka (Khori, 2010) is equipped with Helmholtz coils allowing the rotation of the polarization axis at will. It should be therefore possible to use a configuration in which the magnetic field generated in the plasma could be aligned with the polarization and help to maintain the polarization in spite of the fast rising temperature.

The present discussion is qualitative and based on field simulations performed for inertial fusion (Mima *et al.*, 1978; Deutsch *et al.*, 1997; Deutsch, 2004) or laser beams

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Fig. 3. (Color online) Prototype of a neutron detector under development at IPN Orsay, from (Bettane, 2010). There are three layers of plastic scintillator detectors, each 3 cm thick. The final version will cover 360° in Φ, with a bore of 60 cm.

hitting a thin target (Sudan, 1993). One should run similar simulations for the present case of a laser hitting a massive bloc of 25 cm^3 of HD ice. This is out of the scope of the present proposal, but expectations are encouraging.

LOCAL POSSIBILITIES

In practice, the IPN Orsay has exported the HD target technology to RCNP Osaka (Khori, 2010; Tanaka *et al.*, 2010). The final experiment should be done there. However, locally we have at the *Laboratoire d'Optique Appliquée*, on the *Ecole Polytechnique* campus, a terawatt laser able to deliver laser pulses similar to the one mentioned in Figure 1. Simulations and experiments have to be done to optimize the neutron production rate with low energy laser pulses, for example, by keeping the same power with a reduction of the pulse duration and of the energy/pulse. Also the focalization of the laser on an HD ice sample is not a trivial problem and could be studied with a D_2 ice target. We have started discussions with the LOA physicists who are interested in the project. A positive point is that all the necessary technological tools are available, including neutron detectors and data acquisition systems. Figure 3 shows the prototype of a neutron detector under development at IPN Orsay. The final version should have a 4π configuration. The demonstration of the persistence of the polarization in a fusion process is of fundamental interest for future fusion reactor plants and should be pursued in any case.

CONCLUSION

A considerable effort is under way to produce energy using controlled fusion either by magnetic or by inertial confinement. Polarized fusion fuel is of great interest, both to increase the fuel reactivity and to control the direction in which the reaction products are emitted. The question is to know if the polarization will persist in a fusion process. We propose a possibility to investigate this point using high power laser beams on polarized HD samples through fusion reactions like: $P + D \rightarrow {}^3He + \gamma$ or $D + D \rightarrow {}^3He + n$. Before undertaking the corresponding experimental venture, precise predictions of the cross-sections and polarization observables at low and moderate energies were needed. It turns out that the radiative capture, which was initially considered to demonstrate the persistence of the polarization in a fusion process is not the preferred way to go, because the γ-rays, not only are difficult to select, but they are emitted preferentially along the polarization axis, in a region of high electromagnetic background. In addition, the low cross-sections attached to an electromagnetic process, make it very difficult to pin down a signal smaller than 3% on the counting rates, although significant change in the total cross-section (7%) could be exploited in a different polarization scheme: P and D in an anti-parallel configuration.

By comparison, the hadronic fusion seems much better, having a cross-section larger by 3 orders of magnitude and producing a signal as large as 10–20% on the neutron counting rates, further increased by a favorable angular distribution of the neutrons emitted by quintet transitions. Neutron counters can be shielded and can work in a high background environment. Polarized target preparation is more difficult, requiring high deuteron polarization, but the relevant techniques are now well established.

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