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DD fusion from a polarized HD target

J.-P. DIDELEZ[1] AND C. DEUTSCH[2]
[1]IPN, CNRS/IN2P3 & Université Paris-Sud (UMR-CNRS 8608), ORSAY, France
[2]LPGP, Université Paris-Sud (UMR-CNRS 8578), ORSAY, France

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Abstract

Recently, we have proposed an experiment to test the persistence of the polarization in a fusion process (D+D→^{3}He+n), using a powerful laser hitting a polarized HD target. The purpose of the present contribution is to examine in more detail the experimental constraints, to move from a principle proposal to a doable experiment. Some of the difficulties are as follows: Production of a windowless cryogenic HD target and target cryostat vacuum breakdown, identification of thermal fusion or accelerated deuterons, inducing nuclear reactions, and finally, a clear signature of the polarization persistence of the fused deuterons must be found. Those points will be reviewed and discussed in the scope of the new results presented at this conference.

Keywords: Polarized targets; Ultra short lasers; Fusion reactions; Persistence of the polarization; Acceleration processes; Particle detection; Anisotropy and asymmetry

1. INTRODUCTION

The polarization of D and 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:

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

goes mainly through the excitation of ^{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 $\text{Sin}^2\theta$ distribution. This can be very useful to reduce damage or activation of costly equipments. The question is to know if the polarization will persist in dense and hot plasmas as anticipated from theoretical considerations, both for magnetic confinement fusion (Kulsrud *et al.*, 1982) and inertial confinement fusion (More, 1983).

The persistence of the polarization in a fusion process could be tested using a powerful laser hitting a polarized HD target. The polarized deuterons heated in the plasma induced by the laser can fuse, through the reaction:

$$D + D \to {}^3\text{He} + n \tag{2}$$

The angular distribution of the emitted neutrons and the change in the corresponding total cross-section are signatures to estimate the polarization persistence (Didelez & Deutsch, 2011).

The proposal has been accepted at the ILE Osaka: The POLAF project for (POlarization in LAser Fusion Process). It uses the polarized HD targets produced at the RCNP Osaka and the powerful ILE lasers, as well as the neutron detectors existing there.

2. METHOD

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 aging technique allow getting nuclear relaxation times larger than 1 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. Since 2005, all of the IPN equipment has been transferred to RCNP Osaka, where polarized targets are

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Address correspondence and reprint requests to: J.-P. Didelez, IPN, CNRS/IN2P3 & Université Paris-Sud (UMR-CNRS 8608), Bât. 100, F-91406 ORSAY, France. E-mail: didelez@ipno.in2p3.fr

now produced for experiments at Spring-8 (Kohri & LEPS Collaboration, 2011). It is advocated that a terawatt laser hitting a piece of polarized HD ice will induce local plasma hot enough to allow the fusion reaction (2) to take place and to be measured. If D, namely the deuterons of the HD molecules, are polarized in the same direction and have kept their polarization in the fusion process, the 2.45 MeV neutrons 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 setup can be found in the previous paper (Didelez & Deutsch, 2011). The principle of this proposal is based on past observations of DD fusion induced by powerful lasers. Back in 1970, a French group of the "Commissariat à l'Energie Atomique" in France (Floux *et al.*, 1970) reported the observation of neutron emission from DD fusion, after focusing a 3 GW fast laser on a piece of space D_2 ice 1 mm^2 in cross-section. Pretzler (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 full width at half maximum, 790 nm, 10^{18} W/cm^2, 10 Hz). A total rate of 140 neutrons per shot could be produced, through the fusion reaction (2). In the present proposal, we have taken as reference this experiment, in order to estimate the whole feasibility of the project.

3. THE TARGET

The polarized HD target must be kept in a cryostat at a temperature of 4 K under a holding field of 1 T to guarantee relaxation times of the order of 1 week (Bouchigny *et al.*, 2005). As shown in Figure 1, the bottom of the target is surrounded by a holding Teflon bag. However, the copper cold finger has a bore allowing the laser beam to hit the HD without going through a window. This is possible because at this temperature, the HD vapor pressure is extremely low (5×10^{-9} mb), so that the HD ice, directly in contact with the vacuum of the cryostat, will not evaporate. On the other hand, the energy contained in a 200 mJ laser pulse is relatively small in spite of the large irradiance (10^{18} W/cm^2). Most of this energy is used to create and heat the plasma, so that a small volume of HD gas is generated by each laser pulse, keeping the cryostat vacuum within tolerable limits ($<10^{-3}$ mb for a 10 l cryostat vacuum space). Finally, at 4 K, cryostats of a cooling capacity as large as 10 W can be built, so that the heating of the target is not the limiting factor. It is anticipated that a frequency of I Hz for laser pulses of 200 mJ, limited essentially by the cryostat vacuum breakdown, should be possible.

In the present conference, it has been shown that thin cryogenic hydrogen targets could be condensed within a copper frame and used as thin targets for laser bombardments (see Bedacht *et al.*, "Laser driven ion acceleration with cryogenic Hydrogen targets", *this Conference, Book of Abstracts,* TU013, 53). This opens the possibility to use much thinner polarized HD targets, completely windowless, in configurations which in addition are favorable for the cooling by the surrounding copper. It would allow the use of much more energetic laser pulses (as those used in the above mentioned presentation), exploding the target but producing plentiful of fusion reactions (2), which could be identified by numerous appropriate detectors.

Fig. 1. Photograph showing the polarized HD target in its original geometry. The HD ice is contained in a Teflon bag, surrounded by the NMR coils and maintained at a temperature of 4 K under a holding field of 1 T. The copper cold finger has a central bore allowing a windowless access to the HD for the laser beam.

4. THE FUSION PROCESS

The initial idea behind this proposal is that in the plasma created by the laser, polarized deuterons would be heated enough to undergo mutual thermal fusions. However, it is unlikely that thermal fusion alone could account for the observed rate of neutron production as seen in previous experiments. More likely, some deuterons are accelerated in the plasma by the laser–plasma interaction and those accelerated ions act as a beam to generate nuclear reactions with colder deuterons in the plasma. This mechanism has been recognized since a while, although no significant forward–backward asymmetry of the neutron counting rates could be established (Norreys *et al.*, 1998). A significant fraction of the laser energy can be transferred to the ions (Fews *et al.*, 1994). Since then, ion acceleration by laser pulses has been investigated showing two main mechanisms: The Target Normal Sheath Acceleration for ion acceleration behind the target (Perego, 2013) and Radiation Pressure Acceleration for ion acceleration in front of the target (see Schmidt *et al.*, "Radiation pressure acceleration and advanced transport methods" *this Conference, Book of Abstracts,* TUP2-26, 135). However, the acceleration process has been demonstrated and studied essentially for thin targets. A polarized HD target cannot be thin in the sense considered for laser particle acceleration, but ion acceleration definitively plays the dominant role in the DD fusion considered in the present proposal. Referring to Pretzlers's experiment, performed on a thick support (Pretzler *et al.*, 1998), one can get a more precise idea on the detail of the fusion process: "According to the PIC simulations, the major part of the absorbed energy is contained in the electrons within and around the high-intensity light channel. The high electron temperature generates strong space charge fields which accelerate the deuterium ions from the plasma channel radially outwards in a kind of a radial explosion. The accelerated deuterium ions collide with cold deuterium ions in the surrounding preplasma leading to the release of neutrons via the fusion reaction (2)". The corresponding deuterons energy spectrum extends to 0.5 MeV, with the typical exponential shape of laser accelerated particles, so that the main contribution comes from deuterons with energies below 100 keV. Considering the relatively high energy of the emitted neutrons (2.45 MeV), the lab system is close to the CM system, which explains qualitatively, the lack of anisotropy observed by Norreys (Norreys *et al.*, 1998).

5. SIGNATURE OF THE POLARIZATION PERSISTENCY

We have seen that the neutrons coming from reaction (2) initiated by laser interaction with matter are emitted isotropically in the laboratory. It is anticipated 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, therefore, the so-called Quintet Suppression Factor (QSF)]. Figure 2 shows the QSF factors as predicted in (Deltuva *et al.*, 2008).

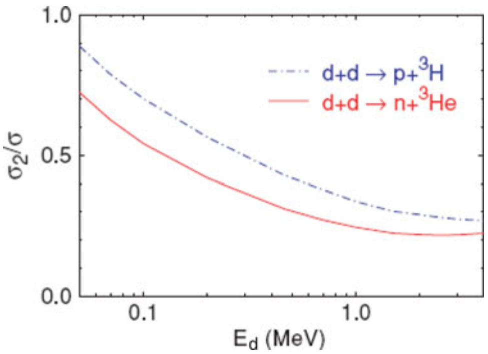

Fig. 2. Predictions of the σ_2/σ (*total spin 2 cross-section/un-polarized cross-section*) from (Deltuva *et al.*, 2008), shows that at the fusion energies, there is less suppression coming from the parallel polarization of the deuteron spins than in the MeV energy region.

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. The ongoing direct experimental measurement of the QSF by the Jülich–Gatchina collaboration (Grigoryev *et al.*, 2011) will definitively stop the dispute concerning the size of the QSF as discussed in detail by Didelez & Deutsch (2011). In any case, the neutrons produced by quintet transitions are preferentially emitted perpendicular to the polarization axis according to a $\text{Sin}^2\theta$ angular distribution (Paetz gen. Schieck, 2010). This behavior is further confirmed by a calculation of Deltuva (Deltuva & Fonseca, 2010) for the reaction (2) 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 $\text{Sin}^2\theta$ shape. This means that in the direction parallel to the polarization axis, where θ equals zero, the persistence of the polarization will create a hole in the counting rate, as compared with the results obtained with a an unpolarized target. It should be noted that for a polarized HD targets, it is possible to increase the D vector polarization above 50% at the expense of the H one, by transfer of the H polarization to D, using adiabatic fast passage (Didelez, 1994). Vector polarization of the deuterons in excess of 40% have been achieved by our US colleagues (Sandorfi, 2013), meaning that 16% of the reactions (2) would be double polarized, creating a hole with a signal/noise ratio of the same order of magnitude in the counting rate parallel to the polarization axis.

6. 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 the fusion reaction: $D+D \rightarrow {}^3He+n$. A signal as large as 10–20% on the neutron counting rates, produced by a favorable angular distribution of the neutrons emitted by quintet transitions can be expected. 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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