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Polarized Fusion on a Table Top
Test of the 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 *HD* target. The polarized protons and deuterons heated in the plasma induced by the laser have a significant probability to fuse producing a ^3He 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.

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:

$$D + T \rightarrow \alpha + n + 17.6\ MeV \tag{1}$$

goes mainly through the excitation of an $^5He\ 3/2^+$ 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 [1]. The question is to know if the polarization will persist in dense and hot plasmas.

2. Method
We propose to investigate the polarization persistency using the reactions:

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

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

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.

3. 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.

Confinement	$n\ (cm^{-3})$	$\tau\ (sec)$	$n \cdot \tau\ (sec/cm^3)$
Magnetic	10^{14}	10	10^{15}
Inertial	10^{26}	10^{-10}	10^{16}

In both cases, however, the product $n \cdot \tau$ has to satisfy the Lawson criterion $(n \cdot \tau \geq 10^{15}\ sec/cm^3)$ which is set by the *DT* fusion physics. In a Tokamak like ITER, the confinement time is expected to be as large as 300 s, which makes it very difficult for the polarization to survive till the end of the cycle, while at MEGAJOULE, the whole compression time of a tiny target is of the order of 35 ns, making it much easier for the survival of the polarization. Kulsrud [1] 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* [2]. However, in this matter, an experimental verification is always needed. In the US, there is a project to inject polarized *D* (in *HD* molecules) and ^3He 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:

$$D + {}^3He \rightarrow {}^4He + p + 18.35\ MeV \tag{4}$$

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

4. Tentative set-up

At IPN Orsay, we have developed the static polarization of *HD* molecules for samples as large as 25 cm^3 [3]. It has been demonstrated, that the distillation and the ageing technique allow one to obtain nuclear relaxation times larger than one week, even at 1.5 K and 1 T [4]. 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 locally a plasma hot enough to allow for 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 ray 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 of the "*Commissariat à l'Energie Atomique*" in France [5] 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 inertial confinement fusion [6] or to accelerate particles [7]. Pretzler [8] 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 hadronic fusion reaction [Eq. (3)].

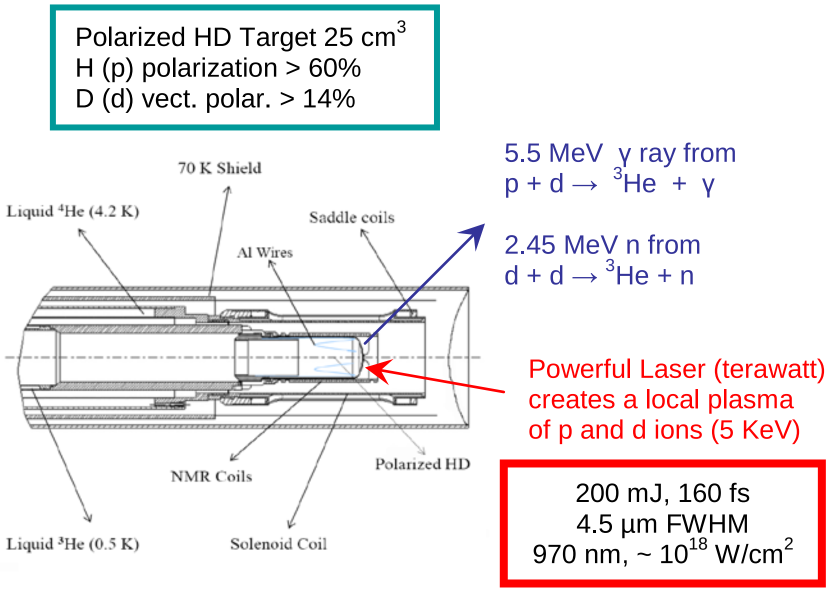

Figure 1. Tentative set-up showing a typical arrangement of a polarized *HD* target in a cryostat maintaining the target temperature below 1 K under a holding field of 1 T. The target bombarded by a terawatt laser producing a localized plasma. Neutrons and γ rays are produced in the plasma, by fusion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

From the quantitative data of Prezler, given the measured cross sections of the radiative capture reaction [Eq. (2)]: σ (10 keV) = 18 µb [9]; σ (10 MeV) = 1 mb [10], 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.

5. The "Few-Body" problems

For the radiative capture reaction [Eq. (2)], the experiment is essentially based on the angular distribution of the radiated γ ray with respect to the polarization axis. 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 has the form [11]:

$$d\sigma_4 \,/\, d\omega \sim (1 + \cos^2\theta) \qquad (5)$$

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. A detailed discussion on the respective contributions can be found in [12]. 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 [13], 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 for the polarization of *H* and *D* in an anti-parallel configuration [14] 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 [Eq. (3)] producing 2.45 MeV neutrons which are much easier to be detected than γ rays in a surrounding background. It has been argued [12] 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). Large QSF (Quintet Suppression Factors : $\sigma_5 / \sigma_{unpol}$) are confirmed by recent calculations, with QSF going from 0.5 at 100 keV to 0.2 at 4 MeV [15]. In a recent review paper concerning "The status of polarized fusion" [16], Paetz gen. Schieck shows that the QSF is not at all well predicted in the fusion energy range, with variations of the order of five. Therefore, the project of direct experimental measurement of the QSF by a Jülich-Gatchina collaboration is very well come [17]. Corresponding total cross sections are in the range of 100 mb, to be compared to 100 μb for the electromagnetic reaction [Eq. (2)]. 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 [14]. A decrease of the emitted neutron counting rate of 10-20% going from an 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 [15, 16].

6. Local possibilities

In practice the IPN Orsay has moved the *HD* target technology to RCNP Osaka [18, 19]. The final experiment should be done there. However, locally we have at the LOA (*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 by the project. A positive point is that all the necessary technological tools are available, including neutron detectors and data acquisition systems.

7. 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 wether the polarization will persist in the 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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