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Neutron fluences of the D-D fusion reaction at 10^{16} W/cm^2 laser-target interactions

S Cavallaro[1,5], **L Torrisi** [1,2], **M Cutroneo**[1,2], **J Krása**[3] **and J Ullschmied**[4]
[1]INFN-LNS, Via S. Sofia 44, 95123 Catania, Italy
[2]Dip.to di Fisica, Università di Messina, V.le F.S. D'Alcontres 31, 98166 S. Agata, Messina, Italy
[3]Institute of Physics, ASCR, v.v.i., 182 21 Prague 8, Czech Republic
[4]Institute of Plasma Physics, ASCR, v.v.i., 182 00 Prague 8, Czech Republic

E-mail: cavallaro@lns.infn.it

Abstract. In last decade many studies have been carried on deuterium-deuterium nuclear reaction induced in laser-target interactions. The relationships between neutron yields and reaction mechanisms and laser-target patterns need to be further clarified. In this contribution we investigate on fusion yields by changing the target thickness and composition and the laser energy and focal position. The experiment has been performed at PALS Laboratory in Prague. Ion yields have been measured by a Thomson spectrometer and by SiC detectors placed at suitable distances in TOF configuration. Neutron fluences have been evaluated by neutron bubble dosimeters and CR39 track detectors. Results about neutron fluences and fusion process are presented and discussed.

1. Introduction

Intense pulsed lasers have been employed to generate high plasma temperature, electron density and electric field of ion acceleration. High temperatures can result in relative velocities of deuteron ions so large as to initiate nuclear fusion. Moreover, in our experiment a high intensity laser is used to irradiate in vacuum a deuterated target producing plasma from which deuterons are accelerated at MeV energies, as recently demonstrated [1,2]. These ions could induce also nuclear fusion in the same target. The reaction has two branches that occur with equal probability [3]:

$$\mathrm{D} + \mathrm{D} \longrightarrow \mathrm{T}\,(1.01\,\mathrm{MeV}) + \mathrm{p}\,(3.03\,\mathrm{MeV}) \tag{1}$$

$$\mathrm{D} + \mathrm{D} \longrightarrow \mathrm{3He}\,(0.82\,\mathrm{MeV}) + \mathrm{n}\,(2.45\,\mathrm{MeV}) \tag{2}$$

Protons and neutrons emitted from the reaction have a characteristic energy of 3.03 MeV and 2.45 MeV, respectively.

[5] To whom correspondence should be addressed

2. Experimental setup

The measurements were carried out the Iodine PALS laser in Prague, operating at 1315 nm, 300 ps pulse duration, 70 μm laser spot diameter, and 10^{16} W/cm^2 pulse intensity [4]. Thick (3 mm thickness) and thin (10 μm thickness) targets, based on deuterated polyethylene $(CD_2)_n$ prepared at the Physics Department of Messina University, have been irradiated to generate plasma in backward and backward/forward directions, respectively. Plasmas were monitored on-line through a Thomson Parabola Spectrometer (TPS), coupled to a Multi-Channel-Plate (MCP), a phosphorous screen and a CCD camera, placed in forward direction along the normal to the target surface, and by detectors connected in time-of-flight (TOF) techniques using ion-collectors (IC) and silicon carbide (SiC) semiconductors. TOF spectra were recorded by a fast storage oscilloscope operating at 20 GS/s. Protons coming from nuclear events were recorded through the TPS, IC and SiC detectors placed in vacuum. Fusion neutrons were detected by using a plastic scintillator placed in air outside the vacuum chamber, at 2.4 m distance and angle of 30° from the target normal direction, as Fig. 1 shows. In the present work, neutron bubble dosimeter pens, with 5.2 bubbles/mrem sensitivity [5], and CR39 track detectors have been also employed to monitor and to detect neutrons. A few CR39 samples were positioned in forward direction around the laser-TPS axis, at $\theta = 4^o$, $\theta = 7.1^o$, $\theta = 7.5^o$, and in backward direction at angles of $\theta = 10.1^o$ and $\theta = 22^o$ with respect to the target normal. The efficiency of CR39 to neutron of 0.5 to 10 MeV energy has been measured with an Am-Be neutron source (34.3 10^9 Bq), 10 cm far from each CR39 frame, covered by a CH_2 film 100 μm in thickness, as proton radiator. A neutron efficiency of about 6 10^{-4} has been measured with this set-up, well taken into account by Monte Carlo simulation. Foils of CR39 have been chemically etched by a 6.25N NaOH solution at 70^o C for a time of 12h. Neutron tracks were analyzed by a photo-camera coupled to an optical microscope (4X-obj-10X ocular gain).

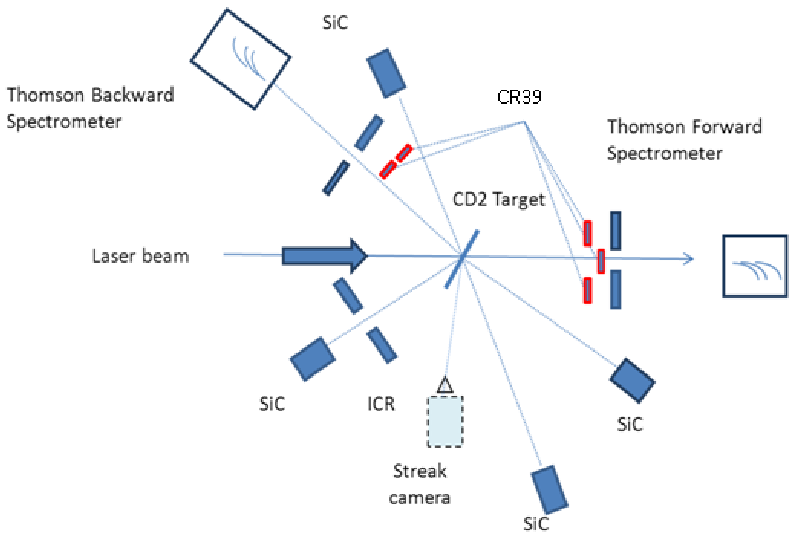

Figure 1. Scheme of the experimental set-up. The horizontal plane defined by the laser direction and the normal to target at 30^o with beam axis, is seen from the top of the interaction chamber.

3. Results

The energy of the deuterons accelerated at irradiation of thick and thin CD2 targets. was obtained from TOF measurements. Fig. 2 shows a typical example of SiC-TOF spectrum, measured at 30° forward angle and 60 cm target distance, when irradiating 14-μm thin CD_2 with 606 J of laser energy at a focal position of +50 μm (inside the target surface). The spectrum shows a photopeak caused by photons coming from the plasma (start signal), and high and large slower peaks induced by ions. The front ion peak, located at 25 ns, is probably due to protons with a kinetic energy of 3.0 MeV. The second ion peak located at 40 ns may be associated with fusing deuterons, which produce the second peak of 2.4 MeV neutrons observed with a scintillation detector (Fig. 4). The presence of 3.0 MeV protons can be due to fusion events occurring during the plasma generation. The TPS ion mass analysis is shown in

Fig.3 for the forward detection. The TPS spectra acquired during thin CD2 laser irradiation show very well the deuteron and carbon parabolas being overlapped due to the same charge/mass ratio. We note that the SiC signal is affected by the Schottky contact, which decreases the energy of detected ions and thus strongly modifies the TOF signal, the latter being proportional to the ion energy deposited in the epitaxial layer [6].

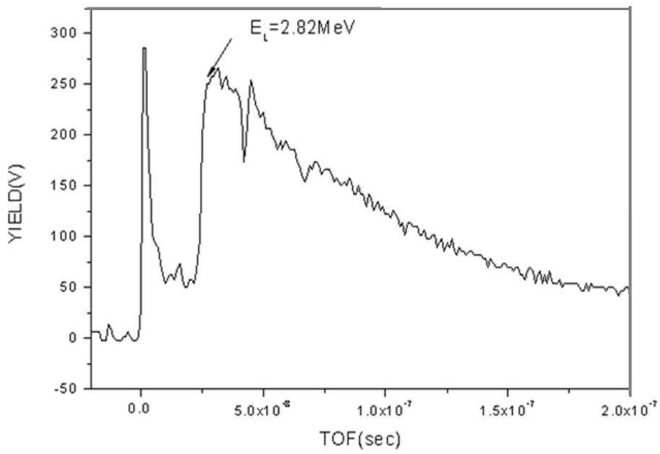

Figure 2. Typical signal of SiC detector obtained during a thin CD_2 laser irradiation.

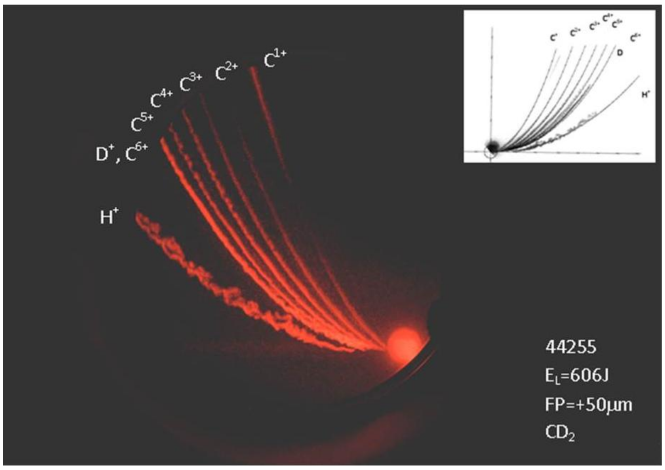

Figure 3. Typical TPS spectrum obtained by laser irradiation of thin CD_2 target.

The proton and neutron emissions from fusion events with the characteristic energy of 3.0 MeV and 2.45 MeV, respectively, were observed by SiC detectors and plastic scintillators in TOF approach when irradiating thick deuterated polyethylene targets. A typical spectrum of neutrons is seen in Fig. 4 showing the presence of a fast photopeak, due mainly to electron Bremsstrahlung in the primary target, and a broad peak centered at about 110 ns and corresponding to the 2.45 MeV neutrons thermally emitted from the targets. The (d, n) channel from the (D+D) fusion reaction with thick targets has been monitored by neutron dosimetric bubble pens (inset), and analyzed by means of CR39 detectors (inset). A direct and clear evidence of nuclear events is shown in spite of small efficiency of detection and high background noise. Table I shows the results obtained by cumulating ten laser shots. By assuming an isotropic neutron emission a value of about 4.5×10^8 neutrons per shot is obtained in good correlation with the values obtained in previous experiments [7,8].

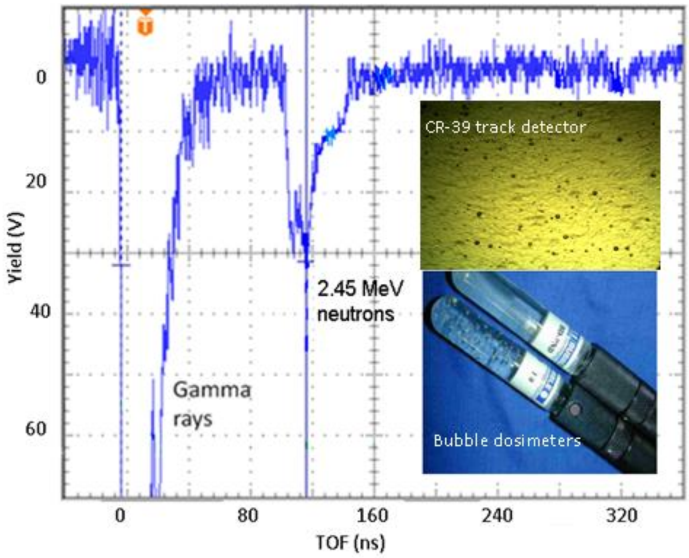

Figure 4. Typical TOF scintillator spectrum, neutron bubble dosimeters and CR-39 track detector.

Table 1. Cumulative values for 10 laser shots.

Detector	Theta (°)	Neutrons/cm^2	Solid angle (sr)	Neutrons/sr
		Forwards		
13	7.1	2.6×10^5	5.67×10^{-4}	4.7×10^8
15	7.5	2.9×10^5	5.67×10^{-4}	5.2×10^8
Stack-CR39	4.1	2.1×10^5	5.67×10^{-4}	3.6×10^8
		Backwards		
16	10.6	1.1×10^6	4.00×10^{-3}	2.6×10^8
17	22.0	4.3×10^5	2.63×10^{-3}	1.6×10^8

4. Conclusions

Deutered polyethylene targets can be irradiated by laser to study nuclear physics aspects in hot plasmas. D-D fusion can be induced in plasmas generated at sub-nanosecond regimes at laser intensities of the order of 10^{16} W/cm^2. Both the accelerated and thermal components of deuterons seem to contribute to the fusion process. An average number of about 4.5×10^8 neutrons per laser shot has been found.

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