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Observation of neutrons in the interaction of high intensity laser pulses with solid targets

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Abstract. We report an experimental study on fusion neutron generation from deuterated polyethylene $(CD_2)_n$ target irradiated by 400 mJ, 45 femtosecond laser pulses focused to an intensity $>10^{18}$ W/cm^2. The fusion neutron signal has been detected using a CR-39 detector, a bubble detector, and also confirmed by a neutron time of flight detector. In addition, substantial bremsstrahlung X-ray radiation of MeV energy was also observed. These MeV X-rays have been used to trigger (γ, n) reaction in Be and Cu targets and the resulting photo-neutrons were detected on a BF_3 and a bubble detector.

1. INTRODUCTION

Exciting new fields of research have emerged in high intensity laser matter interactions as a result of the rapid advancements in the laser technology. At intensities above 10^{18} W/cm^2, relativistic plasmas are created as the quiver velocity of the generated electrons approaches the velocity of light. The laser energy is primarily transferred to the plasma electrons and they are accelerated to very high energies [1]. The rapid exit of these hot electrons from the target creates a space-charge field which accelerates protons and ions [2]. Further, the propagation of the hot electrons inside the target generates high energy bremsstrahlung X-rays which can induce nuclear processes [3]. Laser induced nuclear reactions that produce neutrons have interesting applications. For example, the nuclear activation technique i.e. production of neutrons through (γ-xn) reaction has now become a well established technique for determining the radiation temperature of the bremsstrahlung photons and the plasma electron temperature [4]. The neutrons, due to their neutral charge and large mean free path, readily carry information from the plasma, without any influence of the electric and / or magnetic fields inside the plasma. The neutrons produced by the D(d, n)^{3}He reaction in ultra-short laser produced plasma have some unique features like: a) they are emitted in very short duration pulses (few picoseconds), b) they have characteristic energy around 2.45 MeV at the threshold energy, and c) they have very small source size (of the order of the laser focal spot). The production of a burst of fusion neutrons could be useful in the study of radiation induced damage in materials [5]. In addition, the short duration inherent in laser driven neutron sources could allow time resolved studies of neutron damage [6]. A laser driven source of neutrons might also serve as a source for fast neutron radiography, where the small source size could lead to high spatial resolution.

Neutron production by irradiating targets containing deuterium with ultra-short laser at different intensities has been experimentally observed. Pretzler *et al* [7] have observed more than 140 neutrons per laser shot with a laser of 200 mJ pulse energy and 160 fs time duration. Similar type of experiment was also performed by Hilscher *et al* [8]. They observed a maximum of 10^4 neutrons in a single laser shot. Norreys *et al* [9] have observed about 10^8 neutrons/sr with a relatively long pulse of duration

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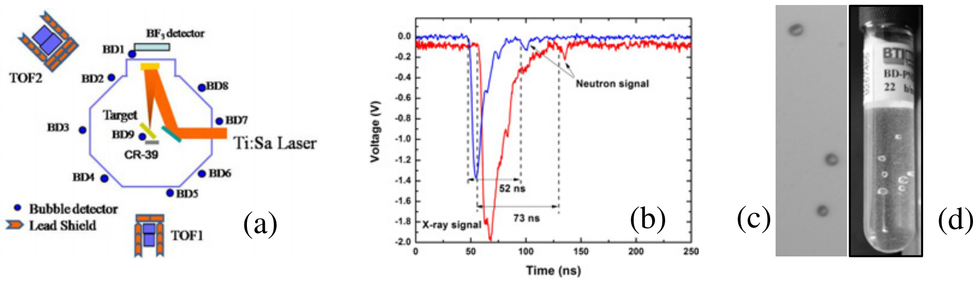

Figure 1. a) Experimental setup, b) the neutron time of flight signal observed in TOF1 (blue line) and TOF2 (red line), the vertical scale of red line is slightly shifted for clarity c) neutron tracks in the CR-39 detector, and d) observed bubbles in a bubble detector.

~1.3 ps focused to an intensity approaching 10^{19} W/cm^2 on deuterated polystyrene target. Neutrons produced in the interaction of a laser beam with clusters have also been observed by several groups. Notably, Ditmire *et al* [10] have demonstrated neutron generation from cryogenically cooled large D_2 clusters at peak intensities of 10^{16} W/cm^2. More than 10^4 neutrons per shot were reported by them.

In this paper, we present our results on neutron generation in the interaction of high intensity laser pulses with deuterated polyethylene $(CD_2)_n$. The interaction of high intensity laser pulse generates substantial number of high-energy electrons that give rise to intense bremsstrahlung X-rays when stopped in a high Z target. The high-energy bremsstrahlung X-rays have been used to trigger the (γ-n) reaction in beryllium and copper targets. A neutrons flux of $\sim 9 \times 10^3$ has been measured on CR-39 detector in the case of D-D reactions, whereas a flux of ~ 70 neutrons per shot in the (γ, n) reaction.

2. EXPERIMENTAL DETAILS

The experiments were carried out using a 10 TW Ti:sapphire laser system delivering 45 fs (FWHM), 400 mJ pulses, at 10 Hz repetition rate, at a central wavelength of 800 nm. Figure 1a shows a schematic diagram of the experimental setup. The p-polarized laser beam was focused to a focal spot of 10 μm diameter (FWHM) with a gold coated f/7.5 off-axis parabolic mirror, giving a peak intensity of the order of $\sim 3 \times 10^{18}$ W/cm^2. The angle of incidence of the laser on the target was set to 45° for efficient absorption of the laser into the deuterated plasma. The laser pulse had an amplified spontaneous emission (ASE) pedestal for about 2 ns before the main pulse. The intensity contrast ratio between the main pulse and the pedestal was about 10^6. The target was a 1 mm thick sheet of deuterated polyethylene (D enrichment over 99%) and mounted at the centre of an octagonal experimental chamber on a 3D motorized translation stage. In order to expose a fresh target surface, the target was moved by 200 μm after each laser shot. The neutron diagnostics consisted of 1) CR-39 track detector, 2) neutron time of flight (n-TOF) detectors, 3) bubble detectors, and 4) BF_3 detector. Unlike the scintillator based n-TOF detector, the CR-39 and bubble detectors have the advantage of being insensitive to the high energy X-rays and electrons. All the above detectors recorded neutrons during the experiment. Bubble detectors were placed at different locations with respect to the target. A piece of CR-39 detector was placed close to the target for measuring the neutron yield. Two UPS-91F plastic scintillators (BC422Q analogs), with diameters of 5 cm and 12.5 cm and thickness of 13 cm, were used as n-TOF detector. These detectors were positioned at 1.2 m and 1.7 m from the target at an angle of 0° (TOF1) and 135°(TOF2) relative to the incident laser beam respectively. Intense bremsstrahlung X-rays are also generated along with neutrons. As the n-TOF detector is quite sensitive to the X-ray radiation, the large X-ray signal saturates the detector for some time, making it difficult to detect the signal of the 2.45 MeV energy neutrons from D-D reaction. To overcome this problem, the n-TOF detectors were shielded with a 20 cm thick lead on the front side and 4 cm lead on all other sides. Even with this thick shielding, a detectable bremsstrahlung signal was always present in the initial n-TOF signal along with the neutron signal.

3. RESULTS AND DISCUSSION

Figure 1b shows the time of flight trace recorded for TOF1 (blue color) and TOF2 (red color) detectors. The first broad peak corresponds to the MeV X-ray (bremsstrahlung) flash generated by the fast electrons inside the target and the second peak (low amplitude) is of neutron arriving from the D-D reaction. The second peak appears after 52 ns and 73 ns for the TOF1 and TOF2 detectors respectively, from the start of the bremsstrahlung flash. For the detectors located at 1.2 m and 1.7 m from the plasma source, this corresponds to neutrons of 2.45 MeV energy, which is the energy expected for D-D fusion neutrons. Due to the large bremsstrahlung signal, the TOF detectors were kept at large distances to record the neutron signal. However, at the large detector distance from the source, the neutron flux also reduces at the detector solid angle resulting in detection of neutron signal only once in $\sim 25 - 30$ laser shots. To measure the neutron yield, the CR-39 detector was kept at a distance of 12 mm from the target. The CR-39 was wrapped in aluminum foil (thickness 0.5 mm) to ensure no exposure to the protons and exposed for about 1600 laser shots on the $(CD_2)_n$ target. The exposed CR-39 was developed for 8 hours in 6 N NaOH solution kept at 70 °C. Figure 1c shows the observed neutron tracks in CR-39. The tracks were counted with an optical microscope for the neutron yield. Assuming an isotropic neutron emission, the neutron yield is calculated to be 9×10^3 per shot in 4π sr, which is very close to the maximum reported neutron yield of 10^4 per shot [8] under similar experimental conditions as in the present case. The generation of neutrons from the CD_2 target was also registered in the bubble detector kept at 20 mm distance from the target. Like the CR-39 track detector, the bubble detector is also insensitive to the X-rays, ions, and electrons. It gives an instant and visible signal in the forms of bubbles. Figure 1d shows a picture of the bubbles recorded in a bubble detector. In order to confirm the fusion neutron signal, the $(CD_2)_n$ target was replaced with a plastic target (CH_2) in the plasma chamber and more than 600 shots were fired. In this case, no time of flight signal was observed in any n-TOF detector, and no bubbles were observed in the bubble detector. This confirms that the observed neutron signal is due to the presence of deuterium atoms in the $(CD_2)_n$ target. The other source of neutrons e.g. electro disintegration of D atoms or photo dissociation of D or C atoms as well as other beam target reaction are expected to have negligible contribution in our relatively low intensity laser irradiation condition [11, 12]. Here it is also important to note that for the low contrast laser, as in our case, deuterium ions are essentially accelerated in radial direction and it is observed that neutrons are emitted isotropically (or with weak anisotropy) [7]. In contrast, for a high contrast laser pulses, the deuterons are mainly accelerated in forward direction and in this case the neutron anisotropy will be large [11, 12].

The occurrence of neutrons in the experiment implies acceleration of the deuterium ions to few tens of keV energy. The energetic electrons removed from the laser focus, build up space charge electric field in the focal region of the plasma, which accelerates deuterons which collide against each other to give rise to D-D fusion neutron production. A simplified estimation of the expected neutron yield from $(CD_2)_n$ target in our experiment can be made using the expression $0.5n^2 <\sigma v>_{DD} \tau V$ [13], where n is the deuterium concentration, $<\sigma v>_{DD}$ is the velocity averaged fusion cross section, τ is the lifetime of the plasma, and V is the plasma volume. In our case, ns ASE pedestal having a contrast ratio of 10^6 is capable of generating pre-plasma and the hydrodynamic expansion of the pre-plasma will create a density gradient in front of solid CD_2 target. The main laser pulse propagating through this preformed plasma can reach up to the critical density (1.7×10^{21} cm^{-3} for $\lambda = 0.8\,\mu$m). Hence the deuterium ion density has been calculated at critical density where the maximum laser absorption will take place and it is estimated to be $\sim 10^{21}$ cm^{-3}. The plasma volume $V \approx 5 \times 10^{-10}$ cm^{-3}, corresponding to the laser focal spot size. Assuming deuterons of tens of keV energy, which have been experimentally observed, the reaction rate $<\sigma v> \approx 2.6 \times 10^{-18}$ cm^3/s [14]. Taking plasma life time τ to be 5 ps [15], about $\sim 4 \times 10^3$ neutrons per shot is estimated from the above expression. This simple estimate on the neutron yield gives an order estimate only but for more accurate calculation the ion distribution needs to be measured.

The presence of high energy X-rays was clearly identified as an initial peak in n-TOF spectrum, which was always present even with 20 cm lead shield (transmission $\approx 10^{-5}$ at 1.5 MeV). Bremsstrahlung X-rays in MeV range with compact Ti:sapphire laser have also been observed in earlier works. Pretzler *et al* [7] have estimated 10^7 photons in the MeV range per shot into full solid angle. Using MeV energy γ photons, we have observed photo-nuclear reactions in beryllium, which has the lowest (γ, n) threshold of 1.67 MeV. For this purpose, the laser was focused on 1 mm thick copper, backed with 500 μm beryllium. The photo-neutrons were detected using bubble detectors and a BF_3 detector. The BF_3 detector (LND make, Model 202106) consisted of a cylindrical BF_3 tube surrounded by high density polyethylene (HDPE) moderator. The neutrons were discriminated against the MeV photons by the pulse height. The BF_3 detector was shielded by 4 cm thick lead bricks. About 70 photo-neutrons per shot (in 4π solid angle) resulting from the (γ, n) reactions in beryllium were estimated from the BF_3 counts. Bubble detectors were also placed around the experimental chamber to record the neutron signal. Bubble detector at locations BD1, BD2 and BD6 (in Figure 1a) formed one bubble each, and the one placed very close to the target i.e. at BD9, formed five bubbles during the laser shots. Schwoerer *et al* [16] have also demonstrated (γ, n) reaction using 250 mJ laser pulses with pulse duration 60 fs.

4. CONCLUSION

In conclusion, we have observed fusion neutrons in D-D reaction by ultra-intense laser pulse focused on $(CD_2)_n$ target. The presence of fusion neutrons of 2.45 MeV is confirmed by the n-TOF signal. About $\sim 9 \times 10^3$ neutrons per shot in 4π sr were estimated from the tracks recorded in CR-39 detector. A simple estimate shows that the observed neutron yield is in agreement with the estimated value and also consistent with the neutron yield reported by others in similar experimental conditions. Further, neutrons have been also observed by (γ, n) reaction in Be target resulting from high energy bremsstrahlung generation by ultra intense laser interaction with Cu target. Though the neutron yield from $(CD_2)_n$ target is small using 10 TW laser, however with 100 – 200 TW class intense laser, one can expect a higher neutron yield in D-D as well as in (γ, n) reactions.

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