Fast neutrons available through beam-target reactions driven by TW lasers

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Abstract

Laser accelerated deuterons with energy ranging from 0.1 to 2 MeV were exploited as drivers of the $^{7}Li(d,n)^{8}Be$ nuclear fusion reaction. Deuterons were emitted by CD_2 plasma produced with focused laser intensity of $\sim 3\times10^{16}$ W/cm^2. Deuterons accelerated upstream the laser beam impinged on a LiF catcher target producing there D-Li neutrons with energy > 13 MeV. Time-resolved signals of scintillation detectors were analysed with respect to the arrival time of fast neutrons at five scintillation detectors positioned around the target chamber. This analysis made it possible to determine energy of both the fusing deuterons and fusion neutrons. The energy spectrum of deuterons was also determined from the time-resolved charge density of ions derived from ion collector signals. Besides the neutrons produced through the $^{7}Li(d,n)^{8}Be$ fusion reaction, neutrons produced via the $^{2}H(d,n)^{3}He$ reactions driven by the laser – CD_2-plasma interaction were observed. The total dose of neutrons was determined employing high-sensitive bubble detectors (BD-PND). Since only a small fraction of generated fast deuterons were hitting the LiF catcher target, the maximum yield of neutrons from both the primary and secondary targets was $\sim 3.5\times10^{8}$ neutrons/shot, which gives a normalized yield of about 5.8×10^{5} neutrons/J. This value should still grow up when increasing the area of the catcher LiF target.

Introduction

The interaction of high fluency and intensity laser beams with matter can provide energetic ions which have been investigated being directly related to the ion implantation and laser fusion research [1-3]. Various physical processes have been clarified to generate high energy electrons, ions as well as neutrons and intense x-ray and gamma-ray radiation by using relatively small laser energy with ultra-short pulses [4].

The generation of fusion neutrons by lasers is an obvious evidence of production of high temperature plasma as demonstrated by many experiments and theoretical modelling [5]. Under these conditions the reacting ion energy is of the order of 100 keV. Fig. 1 shows fusion cross-sections of D-D and D-T fusion reactions as a function of kinetic energy of an incident deuteron on a stationary target. The D-T reaction has the largest cross-section at about 100 keV, while for the D-D reaction the peak probability occurs at much higher kinetic energy of about 2 MeV. The experimental study of emission of deuterons from the front side of a deuterated polyethylene target irradiated by a TW laser system PALS shows that the accelerated deuterons gain kinetic energy up to 2.5 MeV [6]. This result confirms the achievement that the ASTERIX iodine laser that was former located at the Max-Planck-Institut für Plasmaphysik, Garching, Germany, now at the Institute of Plasma Physics, AS CR, Prague, Czech Republic, as the PALS system belongs among facilities which were successfully constructed for investigating implosion physics [7].

The aim of this short review is to present that the laser facility PALS as an accelerator of deuterons can produce fast neutrons through $^{2}H(d;n)^{3}He$, $^{7}Li(d;n)^{8}Be$ nuclear reactions.

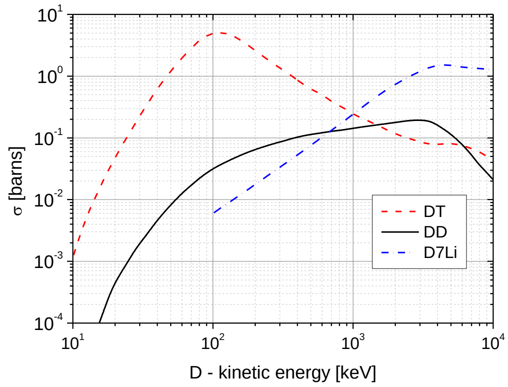

Figure 1. Fusion cross-sections of D-D and D-T fusion reactions as a function of kinetic energy of an incident D on a stationary target [Evaluated Nuclear Data File (ENDF)].

Experimental arrangement

A deuterated polyethylene target of 0.2 mm in thickness was exposed to a laser intensity of ~ 3×10^{16} W cm^{-2} with the fundamental wavelength of 1.315 μm delivered by the laser system PALS. The laser beam struck the $(CD_2)_n$ target parallel to the target surface normal. The accelerated deuterons impacted a 1-mm-thick natural LiF slab with a surface area of 17 cm^2, which was positioned 10 cm off the primary $(CD_2)_n$ target, as Fig. 2 shows [6,8]. The ion characteristics were measured with the use of ion collectors and a Thomson spectrometer. The neutron emission was observed by bubble dosimeters (BD-PND) and calibrated neutron time-of-flight (N-TOF) scintillation detectors composed of a fast plastic scintillator of BC408 type and of a photomultiplier tube. The scintillation detectors were placed around the interaction chamber to observe an angular distribution of the neutron emission. To reduce the scintillator response to the gamma rays, the scintillation detectors were mounted inside a protective housing composed of 10-cm thick interlocking lead bricks.

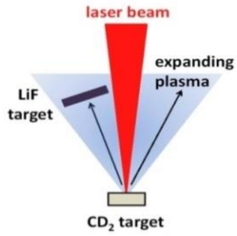

Figure 2. Diagram of the CD_2 target and LiF target configuration. Fast deuterons emitted from the CD_2 target bombard the LiF target.

Results and discussion

2.45-MeV neutrons

Average time-of-flight signals of scintillation detectors operated in current mode revealed broad energy spectra of fusion neutrons with dominating energy of about 2.45 MeV [6]. The energy dependence of the neutron yield from deuterated targets shown a consistency in results of nanosecond, picosecond and sub-picosecond experiments performed in other laboratories. We achieved a maximum yield of 2×10^{8} neutrons per laser shot for the average laser energy of 550 J [6].

Although a D-T reaction has not been performed in the PALS laboratory, the knowledge of the cross-sections, σ_{DD} and σ_{DT}, allows us to compare neutron yields from D-T reaction obtained at various laser facilities with the yield from D-D reaction by the PALS facility, where the kinetic energy of deuterons ranges up to 2.5MeV [8]. Over the deuteron energy range from 100 to 1000 keV the value of ratio of σ_{DT}/σ_{DD} decreases from ~150 to ~1.5. The achieved value of the neutron yield of D-T reaction for the energy distribution of deuterons at the laser energy of ~600 J is $Y_{DT} \cong 70 \times Y_{DD\text{-}PALS}$. The value of a probable yield estimated by this way for the laser system PALS is compared with values from different experiments with laser driven neutron sources employing specific targets and laser systems, as Fig. 3 shows. Neutrons were produced via different physical processes such as cluster/Coulomb explosion, by laser accelerated particle, target heating or implosion by laser, as reported in [2].

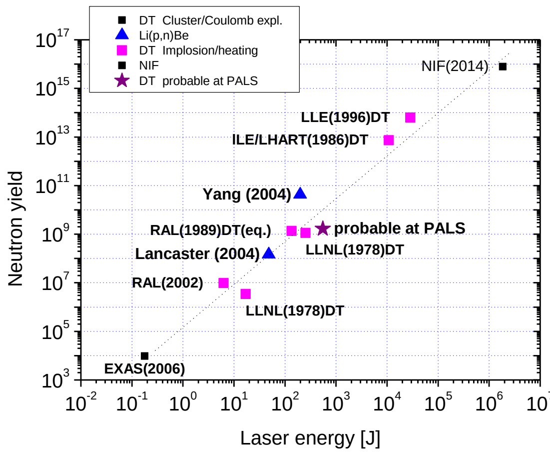

Figure 3. Laser energy scaling of neutron production per laser shot. Plot symbol star represents a probable yield of neutrons estimated for the PALS laboratory.

It is obvious that the varying efficiency of different physical processes leading to the ion acceleration causes fluctuations in the neutron production, as Fig. 3 demonstrates. Furthermore, due to the instabilities occurred during the laser-matter interaction and instability mechanisms of expansion of the plasma into the vacuum at the initial phase of plasma formation cause significant shot-to-shot fluctuations in acceleration and production of fast ions [6]. Since the energy of fusion neutrons depends on the energy distribution of fusing ions [9], we can obtain basic characteristics of fusing ions from time-of-flight spectra of observed fusion neutrons. This method is well applicable to the beam-target fusion experiments, see Fig. 2, as it was shown for ^{7}Li(d,n)^{8}Be fusion reaction with high amount of energy released by this reaction Q = 15.03 MeV [8].

14-MeV neutrons

The zero TOF time coordinate for neutrons from the primary ^{2}H(d,n)^{3}He reaction is related to the TOF of gamma radiation, while the determination of the start time of neutrons produced through the ^{7}Li(d,n)^{8}Be reaction is encumbered by uncertainty caused by the broad-band TOF spectrum of deuterons impinging on the LiF catcher target.
The arrival time of neutrons, t_N, related to the time of the beam-target interaction, is the sum of the TOF_D of deuterons to the catcher LiF target and the $N\text{–}TOF$ of ^{7}Li(d,n)^{8}Be neutrons from the LiF catcher target to the scintillation detectors:

$$t_N = TOF_D + N\text{–}TOF_{D\text{–}Li}. \qquad (1)$$

The values of TOF_D and $TOF_{D\text{–}Li}$ depend on energy of deuterons, E_D, and neutrons, E_n. The energy of neutrons is given by:

$$E_n = \left[\frac{m_D m_n}{(m_m + m_4)^2} + \frac{m_2 m_4}{(m_D + m_2)(m_n + m_4)}\right] E_D + \frac{m_4}{m_n + m_4} Q$$

$$+2\sqrt{\left(E_D^2 + Q E_D \frac{m_D+m_2}{m_2}\right)\frac{m_D m_2 m_n m_4}{(m_D+m_2)(m_n+m_4)^3}} \times \cos\theta\,, \qquad (2)$$

where m_D, m_2, m_n, and m_4 are masses of the incident deuteron, target atom (^{7}Li), neutron and the other product (^{8}Be), respectively, and θ is the angle of the emitted neutron relative to the direction of the incident deuteron [9].

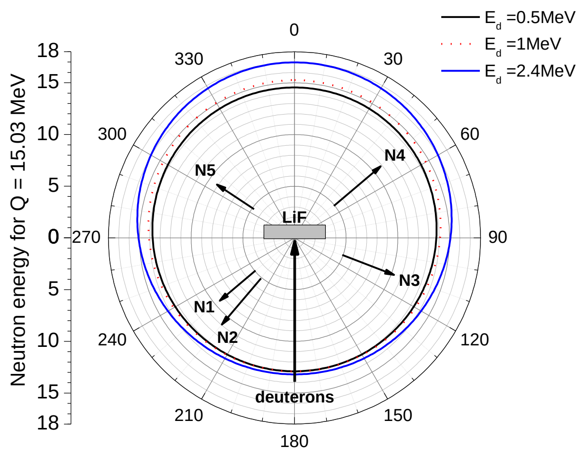

Figure 4. Angular dependence of arrival time of neutrons calculated for various values of deuteron energy. Arrows indicate directions of neutron observation in our experiment.

Equations (1) and (2) allow us to calculate the arrival time of neutrons from a beam-target fusion reaction for the actual experimental arrangement and chosen values of deuteron energy, as Fig. 4 shows. The calculated arrival time makes it possible to evaluate the energy of both the projectile and produced neutron from the observed scintillation detector signal. Fig. 5 shows an example a double peak signal induced by neutrons originating from two bursts of deuterons emitted from the primary target [8]. The peak energy of the 1st burst of deuterons is ~400 keV and of the 2nd one is ~200 keV. The energy of both the corresponding peaks of neutrons reaches nearly the same value of 13.08 MeV because the detector N1 detected neutrons emitted in the backward direction with respect to the direction of the deuteron beam. The bursts of neutrons emitted in the forward direction N4 reached energy of 14.11 and 14.37 MeV. Since only a small fraction of fast deuterons were hitting the LiF catcher target used, the maximum number of d-Li neutrons reached a value of $\sim 5\times10^7$ neutrons per laser shot. The maximum number of neutrons produced through all the fusion reactions was 2×10^8 n/shot.

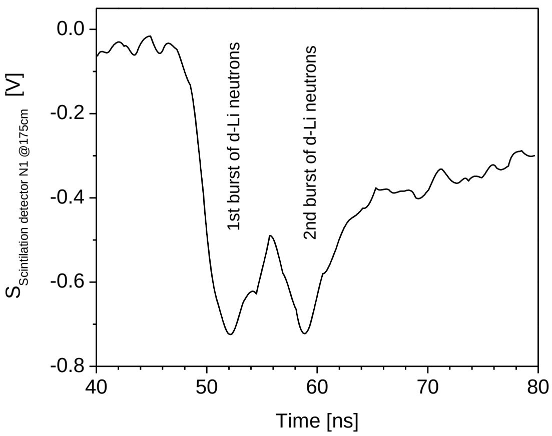

Figure 5. Scintillation detector signal observed in the direction N1 (see Fig. 4) and at a distance of 175 cm from the target.

Conclusions

The deuterons generated on the front side of a thick $(CD_2)_n$ foil exposed to the intensity of 3×10^{16} W/cm^2 with the use of the PALS laser system were exploited as drivers of the ^{7}Li(d,n)^{8}Be nuclear reaction. Two bursts of deuterons with energy of 200 and 400 keV produced bursts of d-Li neutrons with energy > 13 MeV which, thus, arrived at scintillation detectors at different times. When we consider the full angular distribution of the expanding plasma, then the possible maximum yield of the beam-target neutrons with mean energy of ~13.5 MeV could be $\sim 1\times10^9$ n/shot.

Acknowledgements

The research leading to these results has received funding from the Czech Science Foundation (Grant No. P205/12/0454), the Czech Republic's Ministry of Education, Youth and Sports (grant for the PALS RI - Project LM2010014, and for the OPVK 3. - CZ.1.07/2.3.00/20.0279).

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