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Time of Flight Measurements for Neutrons Produced in Reactions Driven by Laser-Target Interactions at Petawatt level

S. Kisyov[a,b,*], F. Negoita[a], M. M. Gugiu[a], D. P. Higginson[c], L. Vassura[c], M. Borghesi[d], L. Bernstein[e], D. L. Bleuel[e], F. Gobet[f], B. L. Goldblum[g], A. Green[d], F. Hannachi[f], S. Kar[d], H. Petrascu[a], D. Pietreanu[a], L. Quentin[c], A.-M. Schroer[h], M. Tarisien[f], M. Versteegen[f], O. Willi[h], P. Antici[i], J. Fuchs[c]

[a]*Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), P.O.BOX MG-6, Bucharest - Magurele, Romania*
[b]*Atomic Physics Department, Faculty of Physics, University of Sofia, 5 James Bourchier Blvd., 1164 Sofia, Bulgaria*
[c]*Laboratoire pour l'Utilisation des Lasers Intenses, UMR 7605 CNRS-CEA-Ecolé Polytechnique-Université Paris VI, 91128 Palaiseau, France*
[d]*The Queen's University of Belfast, Belfast BT7 1NN, United Kingdom*
[e]*Lawrence Livermore National Laboratory, Livermore, California 94440, USA*
[f]*Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université Bordeaux, CNRS-IN2P3 Route du solarium, 33175 Gradignan, France*
[g]*Department of Nuclear Engineering, University of California, Berkeley, California 94720, USA*
[h]*Institut für Laser und Plasmaphysik, Heinrich Heine Universität Düsseldorf, D-40225 Düsseldorf, Germany*
[i]*INRS-EMT, Varennes, Québec, Canada*

Abstract

Short intense pulses of fast neutrons were produced in a two stage laser-driven experiment. Protons were accelerated by means of the Target Normal Sheath Acceleration (TNSA) method using the TITAN facility at the Lawrence Livermore National Laboratory. Neutrons were obtained following interactions of the protons with a secondary lithium fluoride (LiF) target. The properties of the neutron flux were studied using BC-400 plastic scintillation detectors and the neutron time of flight (nTOF) technique. The detector setup and the experimental conditions were simulated with the Geant4 toolkit. The effects of different components of the experimental setup on the nTOF were studied. Preliminary results from a comparison between experimental and simulated nTOF distributions are presented.

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Keywords: simulations; neutron detection; TNSA; intense neutron flux

* Corresponding author. *E-mail address:* stanimir.kisyov@nipne.ro

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1. Introduction

The present availability of high power lasers in the terawatt (TW) and petawatt (PW) regimes provides opportunities for accelerating charged particles. The different properties of such methods in comparison to conventional accelerator systems provoke interest in the laser-driven acceleration mechanisms and consequently new applications. The capability of producing short intense fluxes of particles is a characteristic of such facilities.

Laser-ion acceleration has potential applications in isotope production, nuclear physics, and particle beam therapy. Following their acceleration, TNSA protons can be used to obtain other secondary sources of radiation. Additional applications have been demonstrated not only for the primary particles accelerated in high power laser beam mechanisms but also for secondary particles produced by proton-induced nuclear reactions. In the present work, an experiment for generating short intense fluxes of fast neutrons using (p,n) reactions on LiF was performed at the Lawrence Livermore National Laboratory. The time of flight of the neutrons was measured to study these secondary particles for a range of potential innovative applications.

2. Experimental Setup and Results

2.1. Experimental Setup

The PW-Class laser TITAN was used in the present work. The pulses, provided by the facility had a wavelength of λ=1054 nm, τ = 0.65 ps and an intensity of 10^{19} -10^{20} W/cm^2 . They were focused on solid targets, giving rise to the production of plasma and high gradient fields [1].

Targets of aluminized polyethylene terephtalate (PET) with a thickness of 23 μm and aluminized polypropylene (PolyP) with a thickness of 12.5 μm were used in more than 70 laser shots. Protons from the rear surface of the targets were accelerated using the Target Normal Sheath Acceleration (TNSA) method [2-4]. The energy distribution of the produced protons was measured using Gafchromic Radiochromic Films (RCF). Protons with energies up to 30 MeV were obtained. Further, these protons were directed into a LiF target. Neutrons were produced due to the (^{7}Li(p,n)^{7}Be, ^{6}Li(p,n)^{6}Be, ^{19}F(p,n)^{19}Ne) nuclear reactions. The interactions with the primary and the secondary targets took place inside a cylindrical Al laser interaction chamber with a wall thickness of 9.53 cm.

The study of the properties of the neutrons was done in several ways - in neutron activation measurements, with bubble detectors, with CR-39 plastics [1], and by using the neutron time of flight (nTOF) technique. 11 plastic scintillators BC-400 with a size of 4x4x12 cm were coupled to photomultipliers tubes type XP2972 and were placed at different angles relative to the proton beam direction. Since they respond not only to neutrons, but also to X-rays and γ-rays, shielding was necessary. Otherwise, the strong photon flash that follows the interaction of the laser beam with the primary target would saturate the detectors and they would not be active for the period of arrival of the neutrons. In order to minimize the detection of X-rays and γ-rays, Pb bricks were placed around the scintillators. The largest amount of Pb was set in the direction towards the Al laser interaction chamber, ranging between 20 – 40 cm for the different detectors. A schematic representation of the configurations of Pb bricks around the detectors is shown on Fig. 1 (a).

2.2. Experimental nTOF

The neutron time of flight (nTOF) was measured to deduce the neutron energy distribution. Unlike the conventional scheme of processing the signal from every neutron interaction event through a discriminator, an alternative approach was employed. The waveforms of the signals for each shot were directly digitized, recorded and the nTOF distributions were obtained by summation of all neutron interactions with a detector during a laser

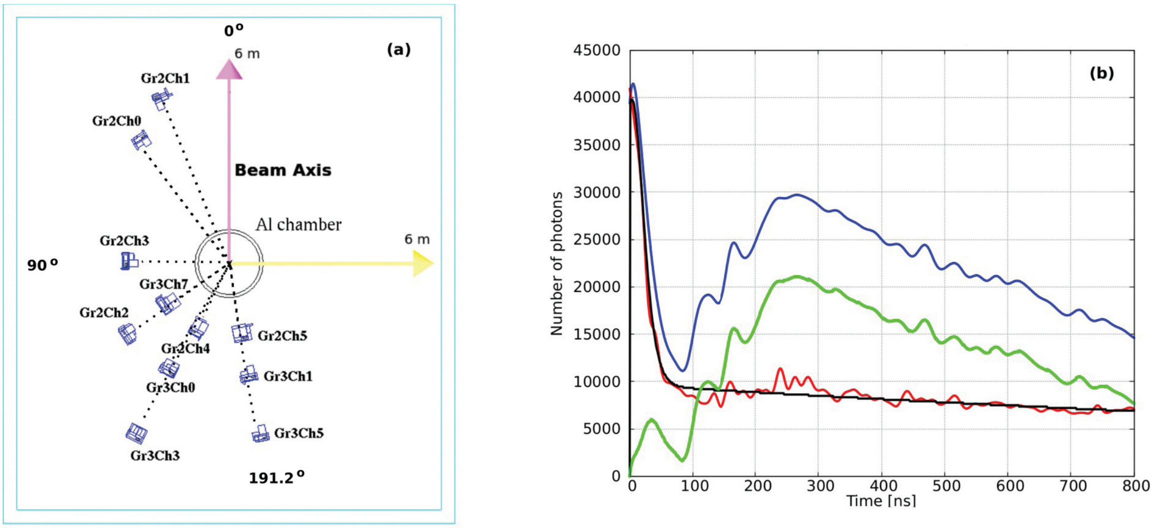

Fig. 1. (a) Schematic representation of the position of the scintillators and their Pb shields in the experimentall hall. The 11 volumes presented on the figure correspond to the configurations of Pb bricks around every scintillator; (b) nTOF distribution and background subtraction procedure for detector Gr3Ch5: (blue) nTOF in the shot of interest, (red) nTOF in a background shot, (black) fit of the background nTOF, (green) nTOF after the subtraction of the background fit.

shot. Due to the Pb shielding, the signal from the X-rays and γ-rays was significantly reduced but still present in the distributions, and was used for calibration of the different detectors in time. The time corresponding to the value of 20% of the γ-peak amplitude was chosen as reference for every detector. A correction for the nTOF of the X-rays and γ-rays was also applied, as the detectors were placed at different distances between 2 – 6 m from the secondary target.

Given that the response of the BC-400 scintillator for protons and electrons is known [5,6], the amplitude of the experimental signal was converted to number of scintillation photons. For this purpose, a calibration with ^{60}Co and ^{137}Cs sources was performed within the present study. Fig. 1 (b) presents the nTOF distribution for a detector placed at 5.14 m from the LiF target, 191.2° relative to the proton beam axis, with 30 cm of Pb in front of it (labeled Gr3Ch5 in Fig. 1 (a)). The data were collected in a laser shot with an energy of 114.8 J, focused on a 23 μm aluminized PET target. A background subtraction was performed with data from a shot, in which the secondary LiF target was removed, with the assumptions that other differences in the experimental conditions do not significantly affect the results for the background. The signal from the background shot was fit with a multicomponent exponential, and the fit was subtracted from the shot of interest. The slope of the obtained distributions suggests that either a large amount of low energy neutrons were produced, or a lot of neutrons were scattered prior to detection. Both cases correspond to the observed significant number of events at high values of nTOF. Another possible explanation of this effect is an alteration of the detector response in the intense neutron flux.

3. Simulations

The analysis of the experimental nTOF distributions requires consideration of many phenomena. Simulations of the experimental setup and the interactions that take place were performed using the Geant4 toolkit [7].

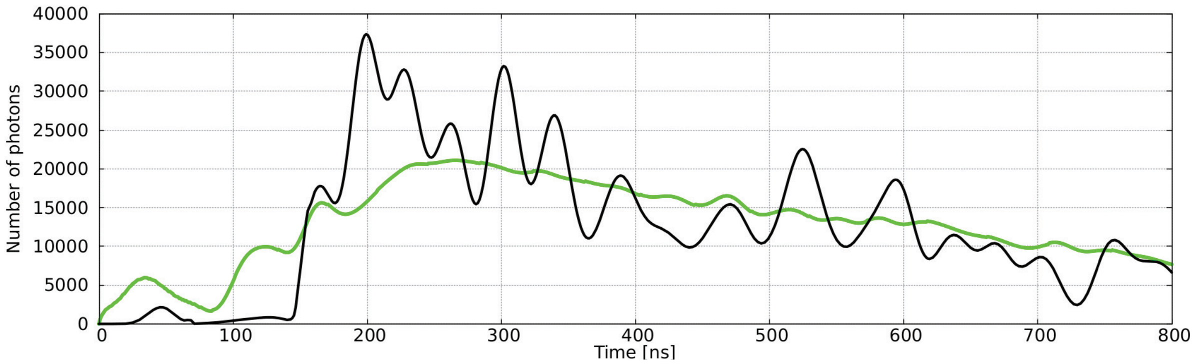

Fig. 2. Comparison between the experimental and simulated nTOF for detector Gr3Ch5: (green) experimental nTOF distribution, (black) nTOF from a Geant4 simulation.

3.1. Conditions

The geometry of the experimental setup was simulated according to the position and configuration of the detectors, their Pb shields and the Al laser interaction chamber. The experimental hall 40-cm-thick concrete walls were also taken into account. The response of the BC-400 plastic scintillators was set according to [6] and [8]. The modeling of the interactions within the volumes in the experimental hall was done using the QGSP_BIC_HP physics list. QGSP_BIC_HP models the transport of neutrons with energies down to thermal with good precision [7].

Simulations with different initial neutron energy distributions were performed. The response of the detectors was studied with a uniform energy distribution. For a real representation of the experimental conditions, the neutron energy distribution was simulated with MCNP6 [9]. A fit of the measured proton spectrum was used as an input for the MCNP6 calculations [1]. The simulated nTOF spectra were convolved with a Gaussian function with a Full Width at Half Maximum (FWHM) of 10 ns, representing the response function of the detectors to a single photon interaction. The data from the simulations were stored and analyzed using the ROOT platform [10].

3.2. Simulated nTOF

A set of different configurations of the volumes in the experimental hall was used in order to study their individual contribution to the nTOF spectra. Separate runs were performed with a number of initial neutrons sufficient to observe the shape of the nTOF distribution in the chosen case. Simulations in which only the concrete walls of the experimental room and the Al interaction chamber were included show that they do not have a big impact on the shape of the nTOF. On the contrary, the Pb shielding has a more important role in the present configuration. A large amount of neutrons are scattered from the Pb structures, thereby decreasing the number of neutrons that arrive at the detectors directly. This effectively increases the traveled distance and respectively the nTOF of the detected neutrons.

A simulation with the full configuration of the volumes in the experimental hall was performed with $4.3\text{x}10^8$ initial neutrons. A smoothing procedure [10] was applied to the simulated nTOF distributions because of the presence of large statistical fluctuations. The simulated smoothed nTOF distribution for the Gr3Ch5 detector, with a height scaled according to the experimental nTOF, is shown by the black line in Fig. 2. The experimental nTOF for the detector is superposed on the same figure and represented by the green line. An agreement in the shape of both distributions is observed. Similar comparisons for the other detectors show that the simulated nTOF distributions are in a better agreement with the experimental data for detectors placed at larger distances from the Al laser interaction chamber.

An estimation of the total neutron number was performed based on the Geant4 simulations. The comparison of the absolute height of the experimental and simulated nTOF distributions suggests a total number of $\sim 1.6 \times 10^9$ neutrons in a laser shot. Future work is required to determine the total neutron yield with associated uncertainty.

4. Conclusion

An experiment on the production of fast neutrons using ultra-short high power laser pulses was performed. Protons were accelerated via the TNSA method and were focused on a secondary LiF target, where neutrons were obtained due to nuclear reactions. The time of flight of the neutrons was measured with BC-400 plastic scintillators. A set of Geant4 simulations was performed reproducing the experimental conditions. The preliminary results suggest that most of the neutrons were scattered mainly from the Pb shields. This effect produces a shape similar to the experimentally observed one. A possible alteration of the detector response in the intense neutron flux is also not excluded as a another possible contributing explanation of the slope of the experimental nTOF. Tests with different intense pulsed light sources will be performed in order to study this effect. The comparison of the experimental data and the simulated nTOF in the present experiment was used to estimate the number of neutrons produced in a single laser shot. Analysis of the experimental and simulated nTOF distributions for all of the scintillators will be performed in future studies and an estimation of the total number of neutrons produced will be based on data from all of the detectors.

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