High-Intensity Neutron Generation via Laser-Driven Photonuclear Reaction*)

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The generation of high-peak-intensity neutrons through a photonuclear reaction was demonstrated using the Laser for Fast Ignition Experiments (LFEX) at Osaka University. Up to 10^9 neutrons/shot were generated from a 1 mm sized gold target. Using Monte Carlo simulations, the neutron spectrum from keV to MeV was found to be independent of the γ-ray spectrum. The typical peak neutron intensity of 10^{21} neutrons /cm^2/s at the target surface was estimated, and it should be a useful tool for nuclear synthesis experiments.

Keywords: laser neutron generation, photonuclear reaction

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1. Introduction

Neutron sources have been widely studied for neutron radiography, medical applications, and nuclear synthesis experiments. The nano-second time scale short pulse neutron source combined with a fast time-gated neutron imaging system has been expected as a powerful tool for the high quality neutron radiograph diagnostics [1]. The more shorter pulsed high intense neutron source has been also desired for the study on the short lifetime nuclear reaction, such as the measurement of the lifetime of the unstable nucleus or nucleus on the isomer state [2]. Laser-driven neutron generation technique has been widely studied in the decades [3–5]. Recently, the neutron flux of the laser-driven scheme has dramatically increased. In 2013, the National Ignition Facility (NIF) succeeded in generating deuterium-tritium fusion with 5×10^{15} neutrons/shot using a laser with a photon energy of 1.9 MJ and a pulse width of 20 ns [6]. This neutron yield is presently the highest using laser in the world. However, the experimental configuration of the NIF laser facility, the largest facility in the world, cannot be widely applied to basic science problems in nuclear physics due to its complexity and cost. However, several other neutron generation schemes using short pulse lasers (tens fs to 1 ps) with hundreds of Joules have been demonstrated. Examples include 1.6×10^7 /shot at 100 J using a D_2 cluster target [7], 8×10^8 /shot with 360 J using a p-Li reaction [8], and 1×10^{10} /shot with 80 J using a p-Be reaction [9]. In this study, a new method for generating high-peak-intensity neutron pulses with a very short pulse duration and a small spot size has been studied and demonstrated using the Laser for Fast Ignition Experiments (LFEX) at the Institute of Laser Engineering, Osaka University. In this scheme, a neutron yield comparable with the previous examples and a more intense neutron pulse can be generated.

The intense, hot electron beam generated by an intense laser can generate X-rays of over 15 MeV in high-Z target materials. Here we define the γ-ray as a high-energy X-ray. This γ-ray then generates neutrons via a photo-nuclear reaction in the material. We demonstrated the generation of a short pulse intense neutron source with up to 10^9 neutrons/shot, which is equivalent to the peak intensity of 10^{21} neutrons/cm^2/s at the target surface. In the present work, we focus on the experimental neutron generation results using LFEX.

2. Laser-Driven Neutron Generation via Photonuclear Reaction

Hot electrons generated by a short pulse laser generate γ-rays via the bremsstrahlung process in high-Z targets. The resulting γ-rays above 15 MeV can create neutrons via a photonuclear reaction from the material. Figure 1 (a) shows the cross sections for the photonuclear reaction (γ, xn) in various materials. Lead and gold have

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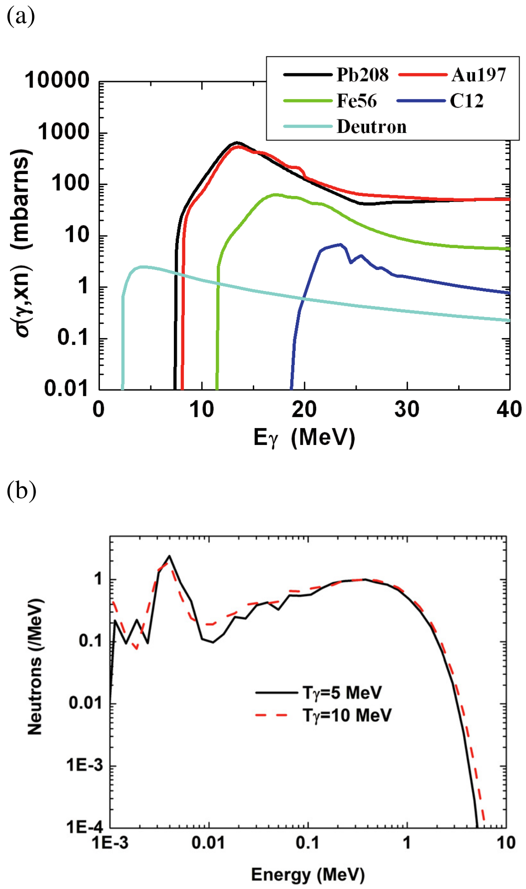

Fig. 1 (a) Cross sections for photonuclear reactions (γ, xn) in various materials. (b) The photoneutron spectrum from a gold target. The black solid line and red dotted line show the neutron spectrum from a 5 MeV slope γ-ray and 10 MeV slope γ-ray, respectively. Where $T\gamma$ is the slope temperature of γ-ray with the energy distribution of $f(E) = \exp(-E/T\gamma)$.

very high photon cross sections of up to 1 barn with which highly efficient neutron generation can be achieved.

Figure 1 (b) shows the calculated neutron spectrums generated from a gold target via a photonuclear reaction using the Monte Carlo simulation code PHITS [10]. γ-rays for two different slope temperature the energy spectrum functions of $f(E) = \exp(-E/T\gamma)$ for $T\gamma = 5$ MeV and $T\gamma = 10$ MeV are injected into a 1 mm thick, 2 mm diameter gold plate. As shown in Fig. 1 (b), the neutron spectrum is independent of the γ-ray spectrum, in particular for high-Z materials because the photoneutron energy is determined by the gaps of the energy levels between the initial and final nucleus. Thus, the neutron energy spectrum is only dependent on the material. A very stable neutron spectrum is a highly preferable characteristic of neutron sources for the study of nuclear reaction cross sections.

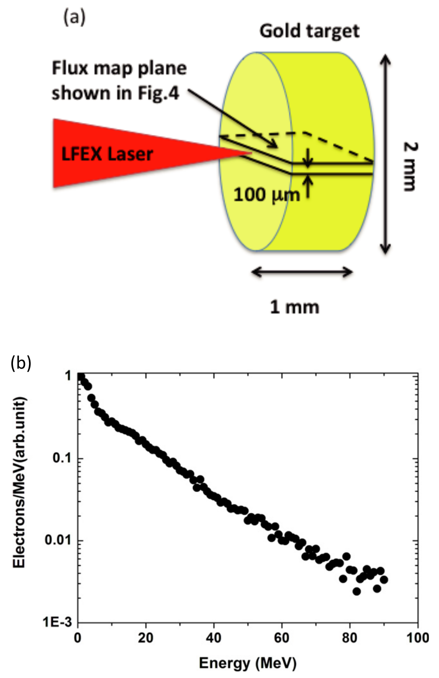

Fig. 2 (a) The configuration of the target used in the experiment. (b) The escaped electron spectrum observed by using electron spectrometer.

3. Demonstration of Laser Photoneutron Generation using LFEX

An experiment was conducted using a gold target and the LFEX laser. Several LFEX laser shots were conducted with the various pulse energy from 300 J to 1.6 kJ on the target with a 1.2 ps pulse duration. The focal spot size was estimated to be around 60 µm in diameter using X-ray pinhole camera measurements. The intensity of the laser was estimated to be 1.2×10^{19} W/cm^2 for a 1675 J shot. The target size used in the experiment was 1 mm thick and 2 mm in diameter as shown in Fig. 2 (a). An X-ray spectrometer with a LAUE transmission grating was also used to measure the absolute photon number of the gold k-α line to measure the energy transfer efficiency from the LFEX laser to the hot electrons. The detected signal implied a 35% energy transfer efficiency [11, 12]. Electrons ejected from the rear surface were measured using a magnet-based electron spectrometer [12] as shown in Fig. 2 (b). The neutrons were measured by using a bubble neutron counter BDS-1000 [13] which has a sensitivity for neutrons above 1 MeV located at 13 cm from the target. The generation of the photoneutron is isotropic, thus the neutron yield was estimated by integrating over 4π from the neutron counter. The bubble detector signal included the neutrons from non-target materials, such as the target chamber walls, the diagnostic instruments surrounding the target, and the bubble detector insertion port. In order to determine the neutron yield from the target, the neutrons generated from non-target materials were simulated by the Monte Carlo simu-

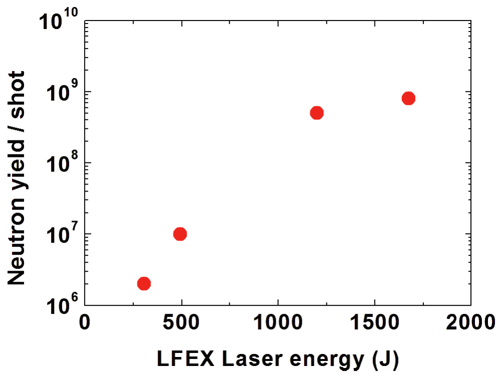

Fig. 3 The neutron yield observed from a 1 mm thick gold disc target irradiated with the LFEX laser.

lation code PHITS. In the simulation the neutrons coming from (i) the target, (ii) the electron spectrometer, (iii) the target chamber, and (iv) the bubble detector insertion tube were evaluated. The electron beam with the experimentally observed energy spectrum and the angular distribution was injected into the target. The electron angular distribution was measured to be 100 (±10) degree in full width half maximum by using glass badge dosimeters attached on the target chamber outer surface. About 47 (±3)% of the signal was confirmed to be from the target. The error in the analysis comes from the ±10 degree error of the angular distribution measurement of the electron beam. Finally, up to a maximum of 8×10^8 neutrons resulted from a 1675 J laser energy. The neutron yields obtained in the experiment with the function of laser energy is shown in Fig. 3.

In order to estimate the neutron or γ-ray yield and the peak intensities inside of the target material or at the target surface, a series of PHITS simulations were performed. The target and the electron configuration were same as described in Fig. 2 (a). The fluxes at the central horizontal area with 100 μm thickness are shown in Figs. 4 (a) and (b). The color scale shows particle track for every 100 μm cubic region in units of neutrons/cm^2/source. The total energy in the electron beam was assumed to be 586 J, which is 35% of the 1675 J laser pulse. The number of electrons injected into the gold then becomes 2.7×10^{14}. The total number of neutrons with energy larger than 1 MeV was calculated to be 7.5×10^9, while experimental value was 8×10^8. This difference might be originated from the discrepancy of the real electron spectrum or absolute number in the target of experiment and the simulation.

A summary of the simulation results is listed in Table 1. The energy transfer efficiency from the laser to electrons, laser to γ-rays, and finally laser to neutrons was 35%, 9.4%, and 2.6×10^{-4}%, respectively. The neutron yield can be further improved by optimizing the target size. With a 10 mm long target, the neutron yield can be increased 10 times because most of the γ-rays escape from the target. Furthermore, in this calculation γ-rays

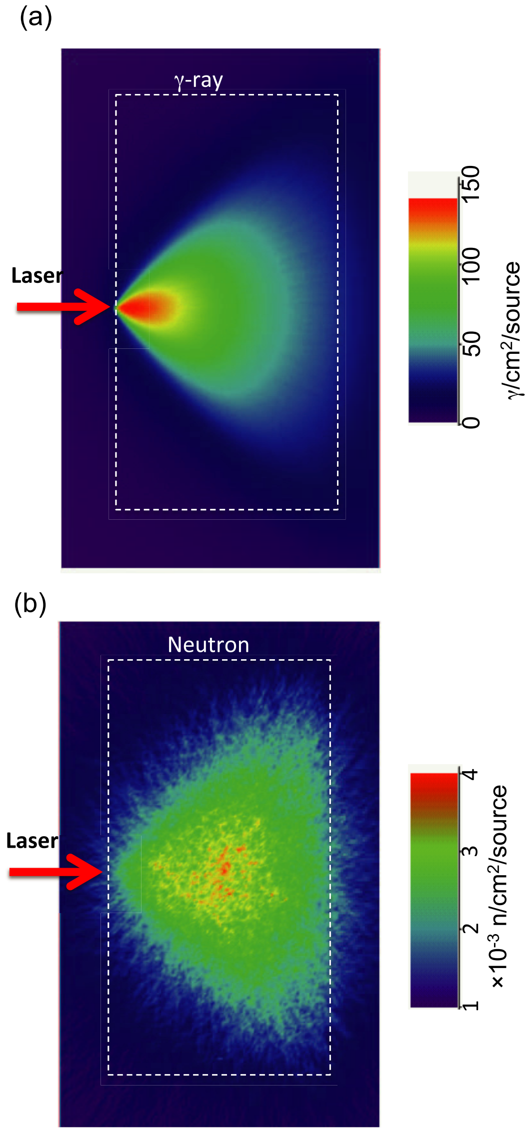

Fig. 4 (a) Simulated flux map of γ-rays and (b) neutron by using PHITS code. All units are in 1/cm^2/source (electron injection).

Table 1 The simulated values of the particle number of electrons, γ-rays, neutrons, and the energy transfer efficiencies with the assumption of electron energy is 35% of the incident laser energy.

	Electron	γ-ray	Neutron
Yield	2.7×10^{14}	3.2×10^{14}	1.7×10^{10}
Yield (>1 MeV)	2.4×10^{14}	1.5×10^{14}	7.5×10^{9}
Energy transfer efficiency (%)	35(assumed)	9.4	2.6×10^{-4}

originated only from bremsstrahlung radiation in the solid gold target. Thus, the efficiency from electrons to γ-rays is fixed. However, under realistic conditions, the interac-

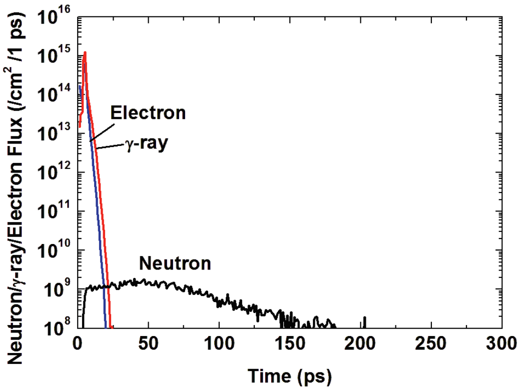

Fig. 5 Time history of the neutron, γ-ray, and electron at all target surfaces.

tion between an ultra-high intense laser field and electrons can result in a strong bremsstrahlung γ-rays from electrons that are directly excited by the electric field of the laser. High efficiency γ-ray generation, for example up to 30% using high-intensity lasers, has been reported previously [14]. Thus, a much higher yield for γ-ray or neutron generation can be expected.

The peak γ-ray flux was over 100 γ-rays/cm^2/source in the simulation at the laser focal point. A flux of over 2.7×10^{16} γ-rays/cm^2 at the peak was estimated with a source electron number of 2.7×10^{14}. In the same way, the peak neutron flux was about 3×10^{-3} neutrons/cm^2/source in the simulation, and 8.1×10^{11} neutrons/cm^2 was estimated. The time history of a neutron and γ-ray at the target surface was also calculated and shown in Fig. 5. The γ-ray flux at the target surface exceeds 10^{15}/cm^2/ps. With the definition of the peak intensity as γ-rays/cm^2/s, the resulting flux was 10^{27} /cm^2/s. In the same way, neutron flux and peak intensity were 10^9/cm^2/ps and 10^{21}/cm^2/s, respectively.

Since a high-energy γ-ray can be easily created from any ultra-high intensity laser with a few Joules, such as Ti: Sapphire-based lasers and simple solid targets, this method can be used for high-repetition neutron generation, suitable for industrial applications such as neutron radiography. In addition, high-energy ultra-intense laser facilities such as OMEGA-EP [15], PETAL [16], and NIF-ARC [17], could become more widely applicable to nuclear science questions using this method.

4. Conclusions

A new method for generating high-peak-intensity neutrons was demonstrated using the LFEX laser. Up to a 10^9 neutron yield from a 1.6 kJ / 1.2 ps laser pulse and a 1 mm thick gold target was obtained. The neutron peak intensity estimated by experimental data and Monte Carlo simulations was 10^{21}neutron /cm^2/s. This level of intensity is useful for a number of nuclear synthesis experiments.

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