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MEASUREMENT OF FAST NEUTRON BY USING
IMAGING PLATE

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Abstract. Measurements of yield and spatial distribution of fast neutrons are of extreme importance in the inertial confinement fusion research to estimate the spatial distribution of temperature in core plasma. In experiments using an ultra intense laser light such as fast ignition research, strong electromagnetic pulses generated by the laser irradiation make it very difficult to use a detector with an electric circuit. In order to avoid this problem, we have developed several detectors to measure fast electrons, X-ray, and so on under these environments using an imaging plate (IP). Here, we demonstrate the simple fast neutron detection method by using a stack of IPs. In the experiment using a monochromatic 14MeV neutron source, the IP has linear response to quantity of incident neutrons within the fluence from $10^4$ to $10^9$. The minimum neutron yield measurable by the detector is estimated to $10^3$ or less depending on detection efficiency.

1. Introduction
In inertial confinement fusion (ICF) research, a small deuterium-tritium (DT) shell target is compressed to high density by high-power lasers. At the center of the highly compressed fuel, the ion temperature reaches several kiloelectron-Volts. Fusion reactions are then initiated in this hot spot, resulting in the production of energetic neutrons and alpha particles. Measurement of yield and spatial distribution of fast neutrons is one of key diagnostics to obtain fusion gain and heating efficiency. However in Fast ignition approach, in which an ultrashort-pulse laser is injected into highly compressed and high density core to obtain much higher fusion gain, the strong electromagnetic pulse (EMP) generated by the laser irradiation makes it very difficult to use detectors with an electric circuit such as a charge-couple device (CCD). Imaging plates (IPs) are widely used under such environments to measure fast electrons, X-ray, and so on [1,2] because IPs have less response to EMP. In addition, IPs are very cheap and are reusable, and are also easy to process as digitized data at high speeds. Here, we propose a neutron detection method using an IP stack with polyethylene as a converter from neutrons to protons. We performed a calibration experiment at OKTAVIAN, a 14MeV intense Neutron Source Facility at Osaka University. In section 2, we describe the design of the neutron measurement method. In section 3, the details of calibration experiment of this method in OKTAVIAN are explained. And section 4 is the summary.
2. Neutron detection method

A diagram of the fast neutron detection with IP stack is shown in Fig.1. The IP stack consists of a 0.3mm thick polyethylene sheet, three IP layers, and 1.4mm thick Teflon sheets. Each sheet is cut out with the size of $5 \times 5\text{cm}^2$. In the front of the stack, the polyethylene sheet is used as a neutron-proton converter because IP has little sensitive to neutrons whereas in polyethylene the incident neutron can create a recoil proton with almost same energy via elastic scattering. Then the first IP layer can record the incident recoil protons. The second and third IP layers only measure background noise of gamma ray because Teflon sheet in front of these layers contains less hydrogen, and the Teflon thickness is thicker than 14MeV recoil proton range. Background noise of gamma ray on the first IP layer is removed by substituting the back side IP layers if there are the signal in the same position with similar intensity. We use Fuji BAS-TR image plate because this image plate has no protective layer including hydrogen in order to eliminate the recoil proton signal on the later layers. This design was primarily adopted from Ref. 3, which used image plate in neutron radiography.

The sensitivity and the detection efficiency of this stack are calculated by considering the elastic scattering of fast neutrons. The polyethylene sheet is thin enough in order that a single collision with a fast neutron can be expected. The efficiency of a single collision with a fast neutron in polyethylene is given

$$
\varepsilon = \frac{N_h \sigma_h}{N_h \sigma_h + N_c \sigma_c} \left(1 - \exp \left( -\frac{N_h \sigma_h + N_c \sigma_c}{d} \right) \right)
$$

(1)

where $N_h$ and $N_c$ are the density of hydrogen and carbon atoms, $\sigma_h$ and $\sigma_c$ are the elastic scattering cross section of hydrogen and carbon, and $d$ is the thickness of the polyethylene sheet. When 0.3mm thick polyethylene is supposed, the $\varepsilon$ calculated this equation is 0.0017.

The energy of recoiled proton is given as a function of a scattering angle of recoil in the following equation:

$$
E_R = E_n \cos^2 \theta
$$

(2)

where $E_R$, $E_n$ and $\theta$ are recoiled proton kinetic energy, incident neutron kinetic energy and scattering angle of the recoiled proton in the laboratory coordinate system. Recoil proton energy distribution is almost constant from zero to incident neutron energy because hydrogen scattering is isotropic in laboratory system. The energy of recoil protons scattered by a single collision with the fast neutrons decreased in polyethylene via small angle scatterings. According to the calculation of SRIM 2008, only 70% of recoil protons reach the first later of IP because low energy proton is stopped in polyethylene. From this calculation and the efficiency of a single collision with a fast neutron, about 0.1% of incident neutron number is detected in IP as the signal of protons.
3. Calibration experiment

We calibrated this method using an intense neutron source, OKTAVIAN at Osaka University. At the OKTAVIAN facility, the 14MeV neutrons are produced via the T(d, n)$^4$He reaction by bombarding a Ti-T rotating target with a d$^+$ beam of about 5mA and 300kV. The yield of 14MeV neutrons is measured by a NE213 liquid scintillator [4], which is calibrated by the $^{24}$Al(n, $\alpha$)$^{24}$Na activation foil method.

The experimental setup is shown Fig. 2. Four sets of IP stack are used at different distance from the neutron source in order to measure the signal linearity to neutron number because the neutrons are a point source. After IP stacks were exposed for about 660 seconds, IPs were read out using an IP reader (Model BAS 1800: Fuji Photo Film Co. Ltd.) with the spatial resolution of 50μm in 16 bit data depth. The fast neutron yield of $2.0 \times 10^7$/s was measured by NE213. IPs have $10^6$ pixels for the IP size of $5 \times 5$cm$^2$ and a spatial resolution of 50μm. The number of IP pixel is much larger than the recoil proton number detected with IP. Therefore, counting the signal of protons can estimate the incident neutron numbers like single photon counting technique [5]. Fig. 3 shows histogram of IP signals for the first (solid line), second (dotted lines), and third layers (dashed lines). In the figure, the horizontal and vertical axes represent PSL value in each pixel and the number of pixels, respectively. The first IP layer has larger number of pixels with high PSL value compared with that in second and third IP layers. On the other hand, there is not so much difference between the signals of second and third IP layers. It clearly shows that the recoil protons are detected only in the first IP layer whereas the backside IP layers detect only background gamma noise. Taking into account of the neutron numbers from 4 sets of stacks with different distances from the source, the integrated signal count exceeding background PSL level shows a linear response to the number of incident neutrons as shown in Fig. 4. From the detection efficiency by equation (1) and SRIM results, one incident proton into IP may spread into around 20 pixels, which well agrees with the previous measurement using heavier ions [6]. And the average PSL value per one 14MeV neutron is...
calculated to $1.2 \pm 0.1 \times 10^{-3}$ PSL/neutron, which shows good agreement to all of detected neutron number in the experiment.

Figure 3 (a), (b) Signal of IP set in the place of the distance 32cm, 62cm, respectively

Figure 4 Dependence of number of incident neutron to signal count

4. Conclusion
A new neutron detection technique has been demonstrated using a stack of imaging plates (IP). Detection efficiency is estimated about 0.001 by SRIM simulation for our experimental conditions. Dynamic range to the incident neutron number is ideally from $10^4$ to $10^9$ when using IP of the $5 \times 5\text{cm}^2$ size. In addition IP signal has linear response to number of neutrons. Neutron detection system which is less influenced to EMP has been established using IP. It is useful in experiments using an ultra intense laser light such as fast ignition research.

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