A SCATTERED-NEUTRON DETECTOR FOR AREAL DENSITY MEASUREMENT

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Abstract. Experimental results are presented on the neutron scintillating properties of a custom-designed Praseodymium-doped Lithium-6 glass for a new deuterium-deuterium (DD) fusion scattered-neutron detector. Luminescence was observed at 278 nm-wavelength, and time-resolved measurement yielded ~5.4 ns decay time for neutron excitation. Actual time-of-flight data in laser fusion experiments at the GEKKO XII facility at the Institute of Laser Engineering (ILE), Osaka University reveal that it can clearly discriminate fusion primary-neutrons from the x-ray signals. This material promises the realization of more accurate DD fusion scattered-neutron diagnostics. Design work for a scattered-neutron detector is being conducted for the Fast Ignition Realization Experiment (FIRE-X) at ILE.

1. Introduction

In both for direct and indirect drive approaches, a high-density implosion is an essential issue. Implosion experiments with deuterium fuel areal densities (ρR, g/cm^2) over 0.2 g/cm^2 have been successfully achieved [1], and over 1 g/cm^2 implosion in ignition experiments are expected to be achieved soon at the National Ignition Facility. In this research area, the scattered-neutron method promises a way to accurately measure ρR. Primary neutrons having 2.45 MeV energy and down-scattered-neutrons in the plasma core having energies down to 0.27 MeV are generated in DD fusion reactions. The calculated neutron spectrum for single neutron elastic scattering normalized with respect to the total number of neutrons is shown in Figure 1. Additionally, the case for multiple neutron scattering has been previously reported in [2]. The ratio of the primary-neutrons (around 2.45 MeV energy) and scattered-neutrons around back scattering edge (0.27 – 0.6 MeV energy) shows a nearly linear response to the ρR [2]. This linearity will not be affected so much by the multiple scattering. Experimentally, scattered-neutron measurements have some technical difficulties and

currently, a gated neutron imaging detector using a Lithium-6 glass scintillation fiber has been proposed as a promising option [2]. The advantages of Lithium-6 as a scintillator material are as follows: (1) The ^{6}Li(n,t)α reaction, with Q = 4.8 MeV, produces enough light output for scattered-neutrons having lower energy than the primary and (2) the resonant peak of the reaction cross section coincides with the back scattering edge of the neutron spectrum as shown in Figure 1; thereby allowing for increased detection efficiency. However the conventional Cerium (Ce^{3+})-doped Lithium-6 glass scintillator has an inherent problem. It has a relatively long decay profile; with its scintillation fall time from 90% to 10% of the peak value equal to 120 ns. Moreover, it has a significantly intense "after glow" [3]. This long decay time translates into a technical problem should it be used as a diagnostics tool in the GEKKO XII target chamber at ILE. With the chamber's radius at 85 cm, the scintillator must be positioned at about 30 cm away from the target in order to avoid the unwanted interference signals from the primary-neutrons scattered from the target chamber wall. This configuration entails the scintillator to have a response time of ~20 ns or better. In this work, experimental results are presented on the custom-developed, fast response Praseodymium (Pr^{3+})-doped lithium glass as a scintillator material. The detailed description about glass manufacturing process and basic characteristics are discussed elsewhere [4]. Furthermore, we also report on-going designing works of the scattered-neutron detector for the FIRE-X in ILE using this newly-developed material.
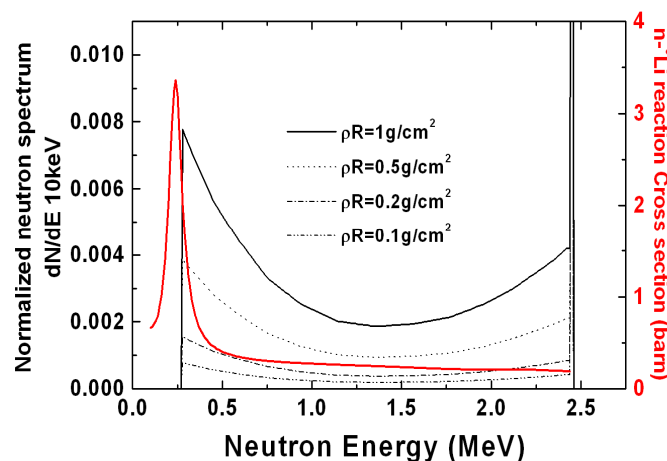

Figure 1 Calculated neutron spectrum originating from DD fusion implosion.

2. Material development

The Pr^{3+} ion with a higher emission cross section in the deep ultraviolet region (~270 nm) was chosen as the dopant material [3] over the slower, albeit more widely-used Ce^{3+} ion [4, 5]. Additionally, high Li-density fluoro-Lithium glass was preferred as the host material over UV-transparent, Li-doped fluoride crystals such as LiCAF[6], primarily due to its ease-of-preparation and design flexibility. The newly developed glass sample, which was named as APLF80+3Pr, has a composition of 20Al(PO$_3$)$_3$-80LiF+PrF$_3$ (in mol) as starting materials; with 95.5 % ^{6}Li for the enriched material. The Lithium concentration (including residual ^{7}Li) of the finished glass sample was measured using an atomic absorption photometer to be 7.98 w%, 31.6 mmol/cc. This is the highest reported value for conventional ^{6}Li glass scintillators such as KG2 [5].

3. Scintillation characteristics

Figure 2 shows the photoluminescence spectra of the sample, compared with a KG2 conventional scintillator. Strong emission was observed at the design wavelength of ~ 278 nm. Furthermore, the host material was found to have good transmission in the vacuum ultraviolet region down to 180 nm

and no absorption at the luminescence region was observed. Moreover, photon yield from a Cf-252 neutron source (broad energy spectrum around 1 MeV) was measured to be 310 photons for all solid angle at the peak of the charge distribution. Gamma rays from Cf-252 spontaneous fission was shielded with 3 cm thick lead, and we assumed the dominant pulse distribution were from thermal neutron since ^{6}Li(n,T)He has much higher cross section for thermal neutrons. The fluorescence lifetime using a Cf-252 neutron source was measured to be 5.4 ns as shown in Fig. 3 where the profile of a GS2, conventional lithium glass scintillator, is also shown for comparison. The APLF80+3Pr lifetime is shown to be sufficiently fast for our requirements.
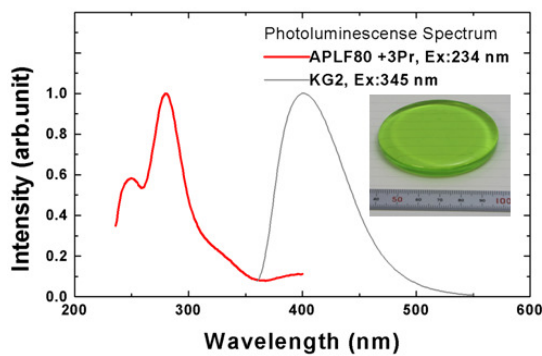

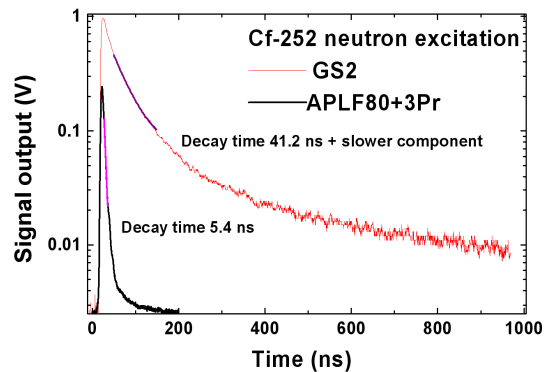Figure 2 Photoluminescence spectra of the APLF80 + 3Pr and KG2

Figure 3 The scintillation decay profiles of the APLF80 + 3Pr and GS2 using Cf-252 neutron excitation.

In addition, fusion-originated neutrons were successfully observed at the GEKKO XII fusion experiment using the scintillator, as shown in Fig. 4. A deuterated polystyrene spherical shell target was irradiated by the GEKKO XII laser facility. Initially, a conventional plastic scintillator was used to establish a baseline for the number of primary neutrons and this was measured to be 5×10^5. In this experiment, a 24 mm-diameter, 10 mm-thick APLF80+3Pr sample was positioned at about 10 cm from the target and fluorescence was transmitted to the radiation shielded PMT using a UV fiberoptic bundle. Although scattered-neutrons were not observed since the neutron yield was too low (we estimated 6 primary-neutrons in this signal by ^{6}Li density and cross section), the scintillator's sufficiently fast response characteristics were evident. A dashed- line box in figure figure 4 also indicates the expected temporal location of the scattered neutron signal for a sufficiently intense neutron yield.
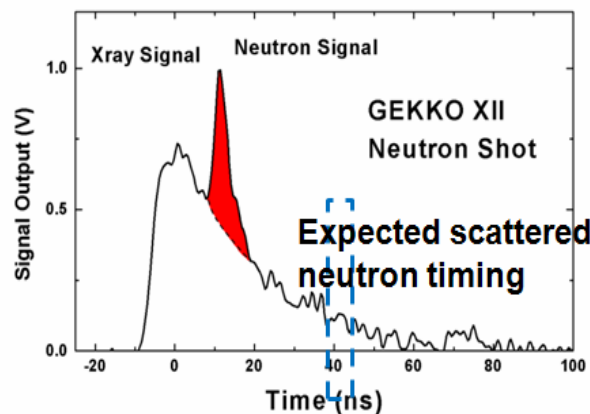

Figure 4 Detected primary neutron signal from the fusion- neutron observation experiment at the GEKKO XII facility using the APLF80+3Pr scinitllator..

4. Detector designing works

A scattered-neutron detector, based on the conventional design constructed with a multi channel scintillation array and a time-gated image intensified CCD camera [2, 6] for the FIRE-X system has been designed at ILE. The neutron yield (Ny) of the first phase of the fast ignition experiment is expected to be about 10^7 - 10^8, and ρR is expected to be the same as Refs. [7, 8] for a ~0.15 g/cm^2 CD target, which is equivalent to 0.021 g/cm^2 for a pure deuterium target. The scintillator array having a total size of 4 cm×4 cm×4cm is designed to be positioned at a distance of 30 cm from the target. The predicted scattered-neutron count is about 3 for a fusion shot with an Ny of 10^7 and ρR value of 0.021 g/cm^2, and about 30 counts for Ny of 10^8. The scintillator is composed of 400 channels; each having a pixel size of 2mm×2mm×40mm, to reduce strong unwanted signals from the x-ray or primary-neutrons. The signal to noise ratio (S/N) of this design is estimated by scaling the S/N values derived from the results in Fig. 4 at the 40 ns region. With the assumption that the signal from a scattered-neutron is 70%, that of a primary-neutron, the estimated S/N in intensity at the 40 ns region is 8.75 for Ny of 10^7 and 0.875 for Ny of 10^8. As such, it can be deduced that this design is feasible to be used for initial testing at the FIREX facility. In the future, the objective is to develop smaller structure scintillation fiber array designs using this new material to further improve the dynamic range of future scintillation systems.

5. Summary

We have succeeded in developing a fast-response ^{6}Li glass scintillator material suitable for scattered-neutron diagnostics of the inertial confinement fusion plasma experiments at the ILE, Osaka University. The scintillator exhibited a decay time of 5.4 ns for neutron excitation. Fusion-originated neutrons were successfully observed using the GEKKO XII laser at the Institute of Laser Engineering, Osaka University, and these results could pave the way for more accurate scattered-neutron detector systems for DD fusion experiments. In this regard, actual detector design and development for this new material, has commenced.

Acknowledgement

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