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Evaluation of scintillating-fiber detector response for 14 MeV neutron measurement

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Abstract

A scintillating-fiber (Sci-Fi) detector has been employed to measure 14 MeV neutrons for the triton burnup study in the first deuterium plasma campaign of the Large Helical Device (LHD). The pulse-height spectra of the Sci-Fi detector are used to choose a suitable threshold for the discrimination of 14 MeV neutrons from a mix-radiation field of low-energy neutrons and gamma-rays. The measured pulse-height spectra of the Sci-Fi detector have two components with different decay slopes from the LHD experiment. To study the pulse-height property of the Sci-Fi detector, the pulse-height spectra on different energy neutrons have been measured by using the accelerator-based neutron source with d-D, p-Li, and d-Li reactions. Meanwhile, the simulations of the detector response have been performed by using the Particle and Heavy Ion Transport code System (PHITS). In the LHD experiment, the first decay component of the pulse-height spectra in low-pulse-height region has been found to correspond to the signals induced by 2.45 MeV neutrons and gamma-rays. In addition, the high-pulse-height region has been confirmed by both the accelerator experiment and the PHITS calculation to correspond to the recoil-proton edge induced by triton burnup 14 MeV neutrons. The detection efficiency of 14 MeV neutrons for the Sci-Fi detector calculated by the PHITS code agrees well with the detection efficiency of 14 MeV neutrons for the Sci-Fi detector evaluated in the LHD experiment. The Sci-Fi detector can work as a standard detector for the 14 MeV neutron measurement with a suitable threshold.

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The controlled nuclear fusion research is dedicated to the application of clean nuclear energy. The Large Helical Device (LHD) is a large superconducting heliotron device with a major radius of 3.9 m and averaged plasma minor radius of 0.6 m for the magnetic confinement fusion study in Japan [1]. In LHD, the first deuterium plasma operation was conducted in March 2017. In deuterium plasmas, 2.45 MeV neutrons and 1 MeV tritons are produced from d-D reactions. Production rate of 1 MeV tritons is almost the same as that of 2.45 MeV neutrons since the cross section of D(d, n)^{3}He and D(d, p)T reactions are almost the same. Energetic tritons will undergo secondary d-T reaction with background deuterons while they slow down. Therefore, the confinement of 1 MeV tritons can be studied by the measurement of secondary 14 MeV neutrons from the secondary d-T reaction. Note that the confinement of energetic particles is important for the magnetic confinement fusion study on the self-sustaining burn of the plasma.

One approach to the triton burnup study is an integral measurement of neutrons by a neutron activation system (NAS) [2 - 9] and neutron flux monitors [10, 11]. Another method is the triton burnup studied by measuring the time evolution of 14 MeV neutrons, which is useful to study the confinement change of tritons in time. Here, 14 MeV neutrons emission rate change in time, which is so called the time evolution of 14 MeV neutrons. The scintillating-fiber (Sci-Fi) detector was developed by the Los Alamos National Laboratory [12, 13], and employed on TFTR [12] and JT-60U [14, 15] to measure the time evolution of 14 MeV neutrons. The head of the Sci-Fi detector is made by 91 scintillating-fibers (BCF-10) each of 1 mm in diameter and 10 cm in length embedded in an aluminum (Al) matrix. Optical characteristics of the scintillating-fiber BCF-10 are close to a plastic scintillator such as BC-408. The Al matrix is used to stop the recoil proton and the Compton electron from one fiber to go into adjacent fibers. All the fibers are connected directly to a Hamamatsu R2490-5 magnetic field resistant photo-multiplier tube. In the first LHD deuterium plasma campaign, this Sci-Fi detector has been successfully used to measure 14 MeV neutrons for the triton burnup study by using a fast digitizer to record the pulse shapes for off-line data analysis [16]. The time evolution of 14 MeV neutron measurement and the pulse-height spectra for the Sci-Fi detector were evaluated within off-line data analysis. The pulse-height spectra of the Sci-Fi detector are used to determine the appropriate threshold for the time evolution of 14 MeV neutrons. Note that the Al matrix cannot be an effective shielding against photons. Therefore, it is important to choose a suitable threshold to discriminate 14 MeV neutrons from a mixed-radiation field of low-energy neutrons and gamma-rays. The pulse-height spectra of the Sci-Fi detector have two components with different decay slopes in the LHD experiment. To study the property of the pulse-height spectra for the Sci-Fi detector, the pulse-height spectra of different energy neutrons have been measured by using the accelerator-based neutron source with d-D, p-Li, and d-Li reactions in the fast neutron laboratory of Tohoku University [17] in August, 2017. Meanwhile, the calculations have been performed to evaluate response function of the Sci-Fi detector by using Particle and Heavy Ion Transport code System (PHITS) [18]. Finally, the detection efficiencies of the Sci-Fi detector were calculated by the PHITS code to compare with that evaluated from the LHD experiment.

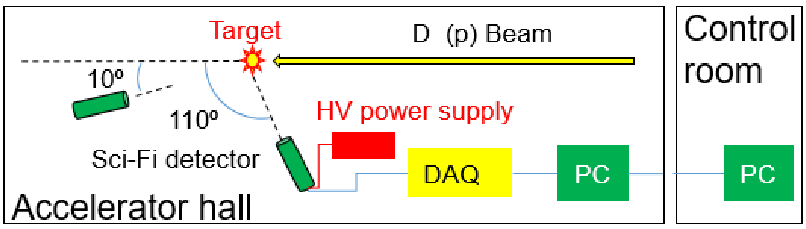

Figure 1. Overall arrangement of accelerator experiment in the fast neutron laboratory of Tohoku University.

The fast neutron laboratory of Tohoku University is an accelerator-based neutron source facility using a Dynamitron accelerator with the maximum acceleration voltage of 4.5 MV and the maximum beam current of 3 mA [17]. The accelerator experiment has been performed for the Sci-Fi detectors by different energy neutrons in the fast neutron laboratory. The experiment setup and the Sci-Fi detector arrangement are shown in Fig. 1. The Sci-Fi detector, a power supply, a data acquisition system (DAQ), and a PC for the data acquisition were located in the experiment hall of the fast neutron laboratory, while the data can be read in the control room via a network. The 2.45 MeV neutrons at 110° and higher-energy neutrons at 10° against the D^+ beam direction were generated by the d-D reaction. The low-energy neutrons were generated by the p-Li reaction. By a misuse of Li target for D target, 13 MeV neutrons were generated by ^{7}Li(d, n)^{8}Be reaction to simulate 14 MeV neutron response of Sci-Fi detector in LHD experiment.

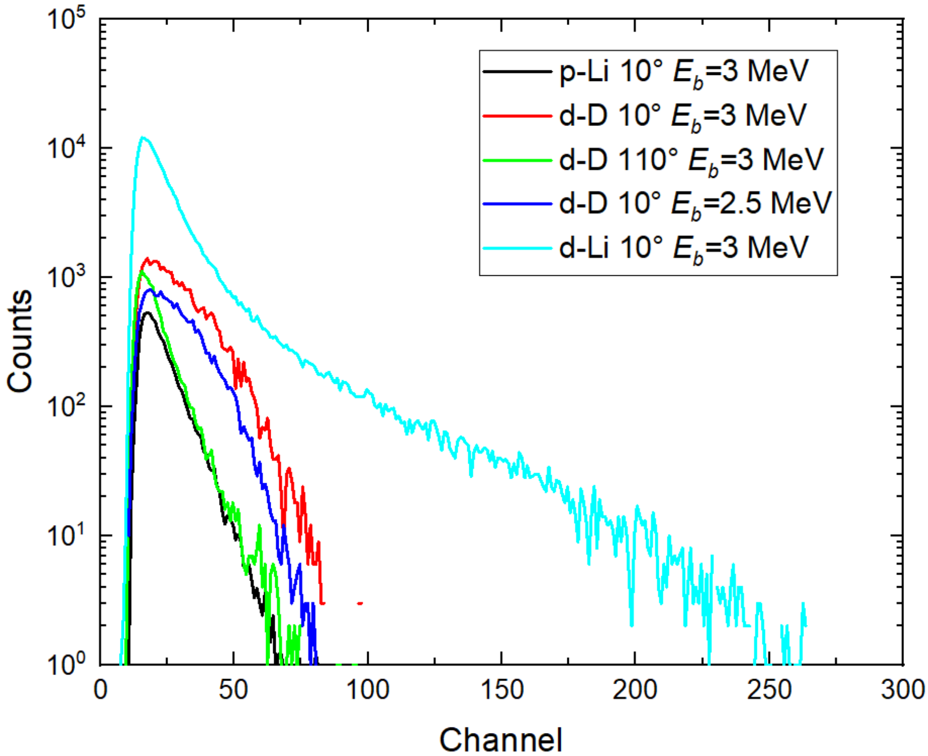

Figure 2. The pulse height spectra of the Sci-Fi detector measured by p-Li, d-Li, and d-D reaction in the accelerator experiment.

In the accelerator experiment, tritium target can not be used in order to avoid the tritium contamination of the beam line. Instead of the 14 MeV neutrons from d-T reaction, 13 MeV neutrons generated by d-Li reaction were used to test the response of the Sci-Fi. The pulse-height spectra of the Sci-Fi detector were measured with neutrons in different energies and gamma-rays as showen in Fig. 2. The pulse-height spectrum of the Sci-Fi detector for p-Li reaction is almost the same as that of the d-D reaction at 110°. The pulse-height response of d-D reaction at 10° was found to be larger than the one at 110°. The much larger pulse-height response has been found by neutrons generated by d-Li reaction at 10°, which is the same as the second decay slope in the LHD experiment.

The neutron responses of Sci-Fi detector were calculated by the PHITS code. The electron-equivalent energy (E_{ee}) of proton in a plastic scintillator BC-408 is cited in J. Zhang [19] and the data sheet of Organic Scintillation Materials from Saint-Gobain Crystals [20].

The head of the Sci-Fi detector was modeled for the response calcuation as shown in Fig. 3. The 91 fibers of 1 mm in diameter and 10 cm in length are embedded in an Al matrix of 3.5 cm in diameter and 10 cm in length as a real head of the Sci-Fi detector. The density of fibers is 1.05 g/cm^3. Also, the atomic composition of the fiber is hydrogen (H) and carbon (C) with ratio H/C of 1.

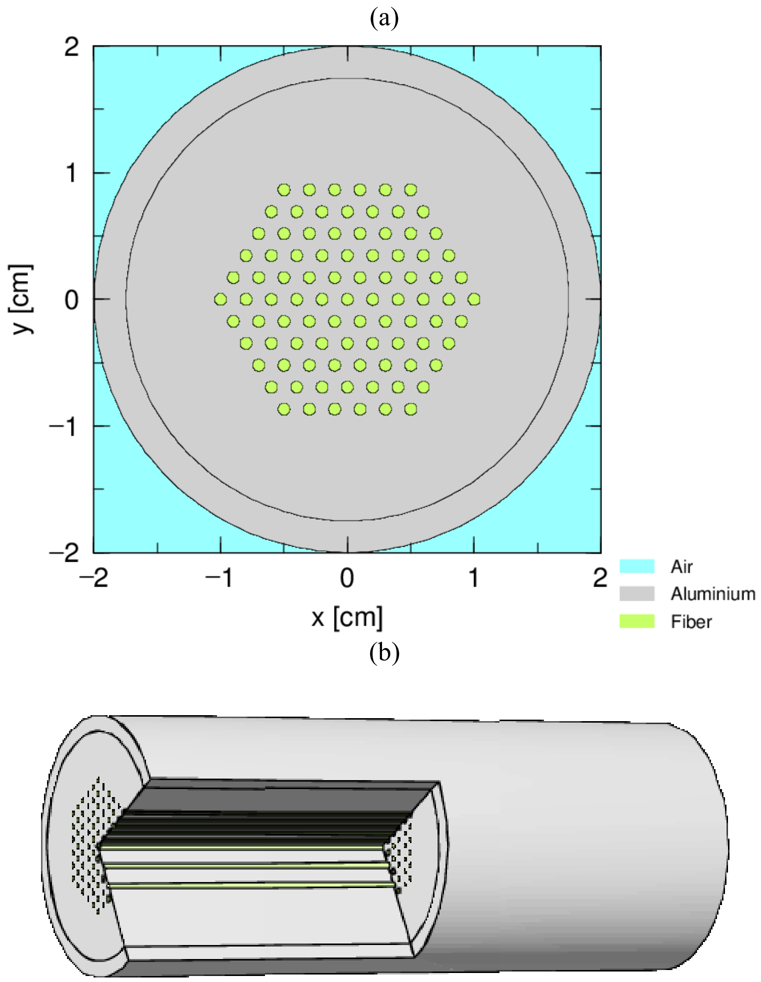

Figure 3. Model of the Sci-Fi detector on (a) the x-y plane, and (b) 3 D angle cutting model.

The neutron response of the Sci-Fi detector for d-Li reaction is analyzed as follows. The energy spectrum of neutrons from d-Li reaction with D^+ beam energy of 2.9 MeV was measured by an activation method in K. V. Mitrofanov's paper. [21] This neutron energy spectrum was used to calculate the neutron response for d-Li reaction in the accelerator experiment. This neutron response has been calculated with and without an energy resolution of 20% Gaussian broadening as shown in Fig. 4, where the target hard X-rays and induced gamma-rays were not taken into account in this calculation. The neutron response in high-energy parts agree well with a measurement in the accelerator experiment. Therefore, the measured pulse-height spectrum can be calibrated by the response calculation. It is found from the calculation that the inconspicuous recoil-proton edge around E_{ee} of 6 MeVee corresponds to the response of 13 MeV neutron peak as measured in Mitrofanov's work.

After this calibration, the measured pulse-height of p-Li reaction and d-D reaction at 110° in Fig. 2 were close to E_{ee} of 3 MeVee. Since the 2.45 MeV neutrons response is lower than 1 MeVee electron response in fiber. [19, 20] It can be said that the responses of the Sci-Fi detector for d-D reaction at 110° and p-Li reaction are dominant by gamma-ray response. On the other hand, the recoil-proton edge was found on the pulse-height spectrum of d-D reaction at 10° as shown in Fig. 2. This is because the E_{ee} is about 2.5 MeVee for the proton recoiled by 6.2 MeV neutrons of d-D reaction at 10°. The recoil-proton edge overlaps with the gamma-ray response. Note that the X-axes of Fig. 2 and Fig. 4 are the same.

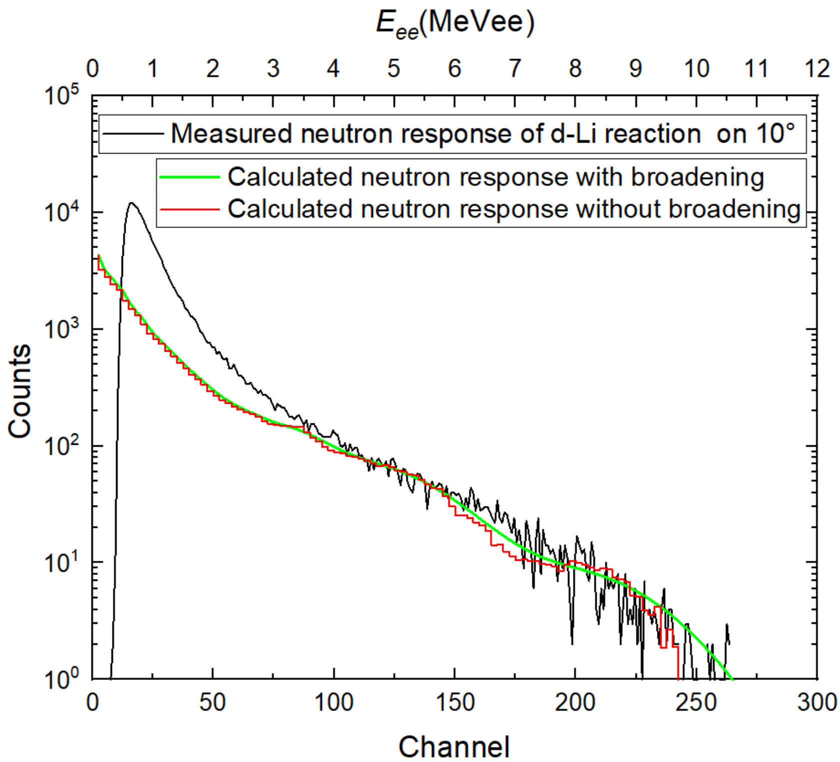

Figure 4. Measured pulse height spectrum and calculated neutron response for d-Li reaction in the accelerator experiment.

The neutron response of the Sci-Fi detector on the LHD deuterium plasma experiment is analyzed. The energy spectrum of neutrons just outside the 8-O horizontal ports of LHD was calculated by MCNP6 [22] assuming the triton burnup ratio of 0.5% as shown in Fig. 5. [23] Here triton burnup ratio is defined as the ratio of 14 MeV neutron yield to 2.45 MeV neutron yield. Based on this neutron spectrum, the neutron response and the induced gamma-ray response were calculated by the PHITS code to calibrate the measured spectrum in the LHD experiment as shown in Fig. 6. Here the gamma-rays were only induced by neutrons in the head of the Sci-Fi detector.

The recoil-proton edge in high pulse-height part of the spectrum from 0.5 V to 0.67 V corresponds to 14 MeV neutrons as shown in Fig. 6. The calculated E_{ee} of around 6.5 MeV for this edge is slightly larger than the calculated E_{ee} of around 6 MeVee for 13 MeV neutrons from d-Li reaction as shown in Fig. 4. The pulse-height of 0.7 V equal to E_{ee} of 7 MeVee as shown in the up and down x-axis of Fig. 6. Therefore, the pulse-height in voltage is calibrated by calculated response to be a conversion coefficient E_{ee}/V of 10, where the high voltage for the Sci-Fi detector on the LHD experiment was -1700

V. The discrepancy in low pulse-height might come from a large number of gamma-rays from device and support in LHD experiment which are not taken into account. The gamma-ray response is calculated to be lower than 3 MeVee as shown in Fig. 6. The E_{ee} of 3 MeVee corresponds to approximately the proton energy of 7 MeV. [19] Therefore, if the threshold of 300 mV (E_{ee} =3 MeVee) is applied to discriminate 14 MeV neutrons, the 2.45 MeV neutrons and gamma-rays can be eliminated in the LHD experiment as shown in Fig. 6.

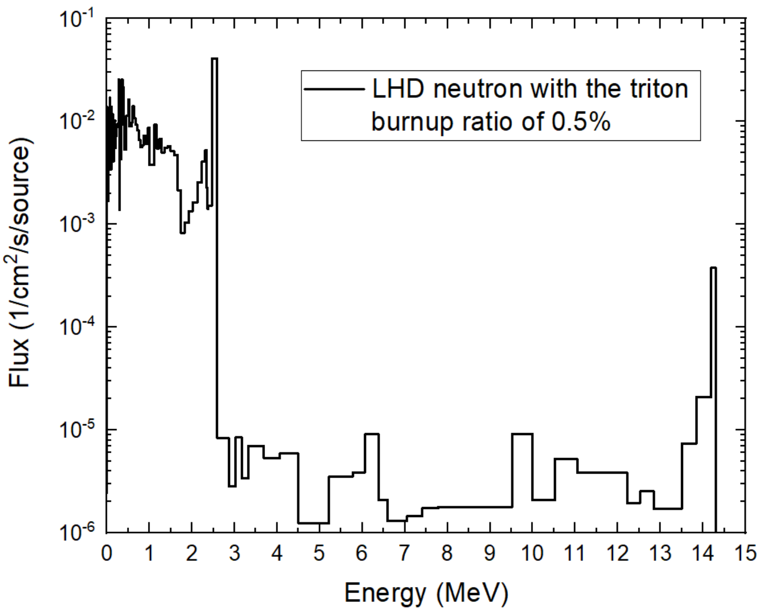

Figure 5. Neutron spectrum near the LHD horizontal port was calculated by MCNP6 assuming the triton burnup ratio of 0.5%.

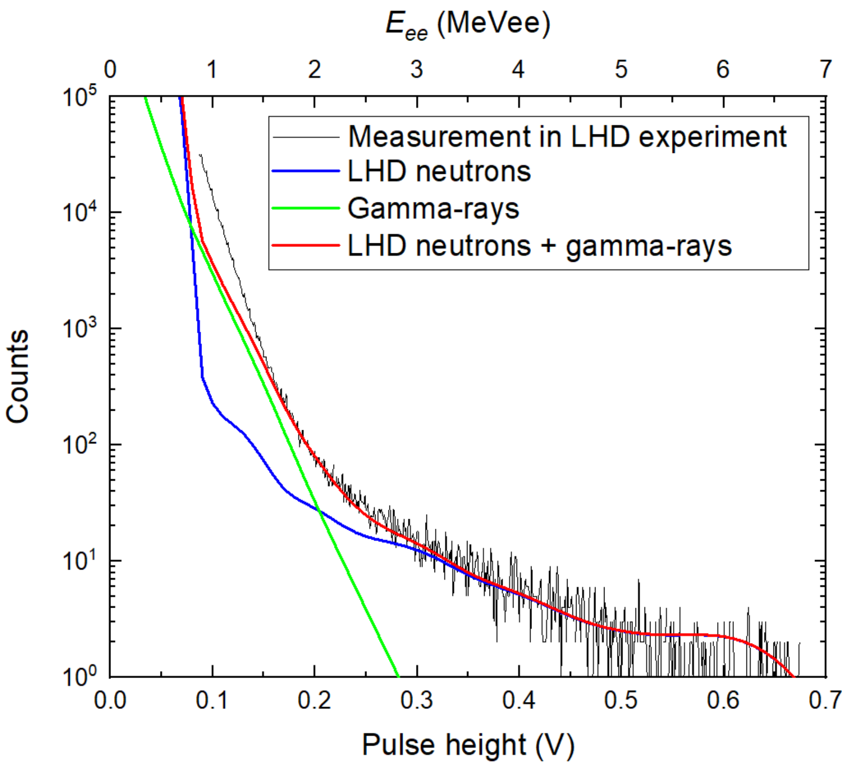

Figure 6. Measured pulse height spectrum and calculated response in LHD experiment.

Finally, the detection efficiencies of the Sci-Fi detector have been evaluated from the calculated neutron response and the LHD experiment as shown in Fig. 7. Here, the threshold is evaluated to correspond to E_{ee} by the calibration done in Fig. 6. Note that, the detection efficiency of Sci-Fi detector for 14 MeV neutrons in the LHD experiment (the experimental detection efficiency) is evaluated from the relationship among the shot-integrated 14 MeV neutron yield measured by NAS, the shot-integrated counts of Sci-Fi detector with the thresholds, and the neutron fluence in the detector position calculated by MCNP6. The uncertainty of the shot-integrated 14 MeV neutron yield measured by NAS is about 7.5%. The uncertainty of the neutron flux in the detector position calculated by MCNP6 is 5%. Therefore, the error of the experimental detection efficiencies is evaluated from those uncertainties and the standard error of the shot-integrated counts of Sci-Fi detector with the thresholds as shown in Table 1. The error of the calculated detection efficiencies is a statistical error of the calculation. The experimental detection efficiencies with the thresholds of 3 MeVee and 3.5 MeVee agree well with the calculation. The experimental detection efficiency with the threshold of 4 MeVee close to the calculation. There is a small difference which may come from statistical error of counts with such high threshold. In addition to this, the experimental detection efficiency with the threshold of 2.5 MeVee and 2 MeVee are higher than the calculations as shown in Fig. 7. This is because gamma-rays are taken into account in the low-threshold case. The higher threshold should be chosen to evaluate the triton burnup ratio by using data of Sci-Fi detector which is calibrated by the NAS measurement.

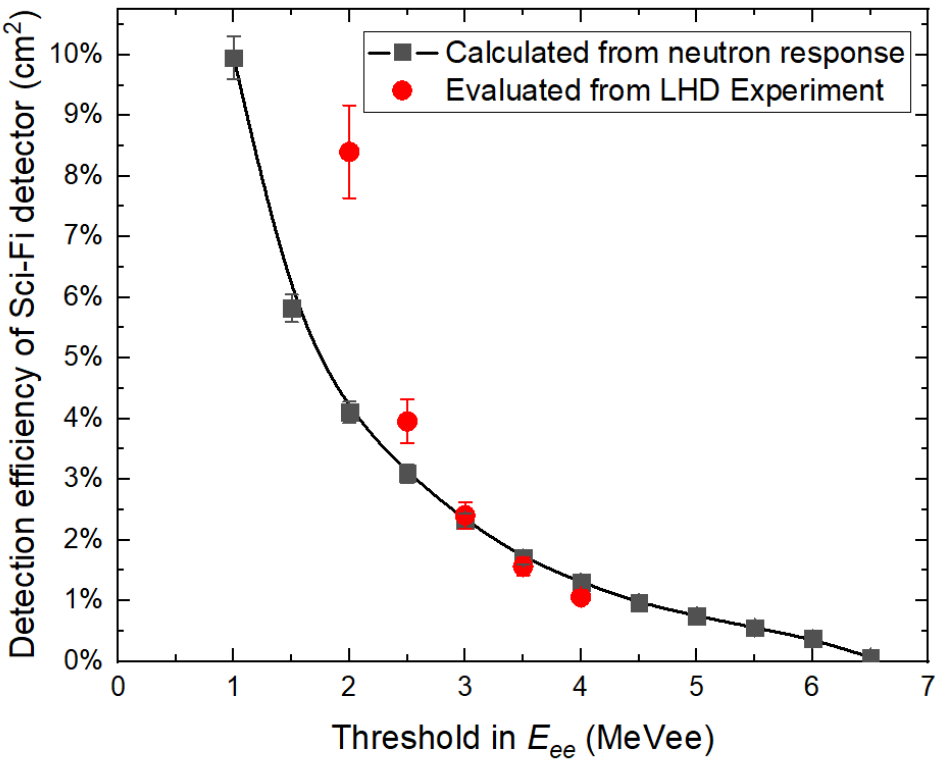

Figure 7. Comparison of calculated detection efficiencies of the Sci-Fi detector for 14 MeV neutrons with different threshold (E_{ee}) and the experimental detection efficiencies evaluated from the LHD experiment.

TABLE 1 Uncertainties of the experimental detection efficiencies and the calculated detection efficiencies

Threshold (MeVee)	*2*	*2.5*	*3*	*3.5*	*4*
Uncertainty of Experimental Detection Efficiencies	9.1%	9.2%	9.2%	9.4%	9.5%
Uncertainty of Calculated Detection Efficiencies	4.3%	4.7%	5.3%	6.0%	6.7%

The accelerator experiment has been carried out to study the different neutron response for the Sci-Fi detector. The pulse-height spectrum of d-D reaction at 110° is almost the same as that of p-Li reaction due to the pulse-height of neutrons being lower than that of gamma-rays. The recoil-proton edge was observed in high energy neutrons generated from d-D reaction. The much higher pulse-height responses were observed for 13 MeV neutrons generated by d-Li reaction, which has been confirmed by the neutron response calculated with the PHITS code. After that, the calibration was performed by calculated response for experiment.

In the LHD experiment, the first decay component of the pulse-height spectra in low-pulse-height region has been found to correspond to the signals induced by 2.45 MeV neutrons and gamma-rays by the PHITS calculation. The recoil-proton edge induced by triton burnup 14 MeV neutrons in the LHD deuterium experiment has been confirmed by both the accelerator experiment and the PHITS calculation. The threshold level of the Sci-Fi detector with a high voltage of -1700 V is evaluated to correspond to E_{ee}. The detection efficiencies of the Sci-Fi detector evaluated from the LHD experiment with higher threshold agree well with the detection efficiencies of the Sci-Fi detector calculated by PHITS code. By setting a suitable threshold, the gamma-rays and low-energy neutrons can be completely eliminated which allows to discriminate 14 MeV neutrons from a mixed-radiation field of low-energy neutrons and gamma-rays. Therefore, the Sci-Fi detector can be a standard 14 MeV neutrons detector for future d-T experiments.

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