

Development of 14-MeV Neutron Measurement with Nuclear Emulsion for DT Burning Plasma Diagnostics^{*})

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A method for the measurement of energetic DT neutron tails resulting from knock-on alpha particles is needed to study plasma physics in a fusion reactor. A nuclear emulsion offers satisfactory performance for the detection of fast neutrons and measures their energies using three-dimensional tracking information. However, the time required for analysis forms a bottleneck in the implementation of this measurement technique. Recently, the analysis speed of nuclear emulsion has dramatically increased because of our development. In this report, we propose the use of nuclear emulsion for DT burning plasma diagnostics using the latest analysis technology and the validation of the methodology. In addition, we discuss the prospects of improving nuclear emulsion technologies for fusion plasma diagnostics.

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1. Introduction

A method of measuring energetic DT neutron tails resulting from knock-on alpha particles is needed for the study of plasma physics in fusion reactors. Figure 1 shows the estimated energy spectrum of neutrons from a DT burning plasma [1]. To detect and identify neutrons resulting from knock-on alpha particles, we must measure an enormous number of neutrons and their energies. The number of signals from knock-on alpha particles is less than 10^{-5} of the total number of neutron events. Thus, to detect 100 knock-on alpha neutrons, we must treat more than 10^7 neutrons.

To measure such a magnitude of neutron signals, some methods have already been proposed [2]. These methods include nuclear emulsion. However, analyzing 10^7 nuclear emulsion tracks by human scanning using only a high-magnitude optical microscope is impossible.

We have developed an optical-microscope-based automated nuclear emulsion high-speed scanning system “S-UTS” [3, 4], which can readout 10^5 tracks/cm² at a speed of 72 cm²/h to facilitate the largest-scale nuclear emulsion neutrino oscillation experiment, OPERA [5]. S-UTS overcame the readout bottleneck of the tracks recorded in the nuclear emulsion and enabled large-scale statistical analysis.

In this report, we propose the use of nuclear emulsion accompanied by the latest high-speed nuclear emul-

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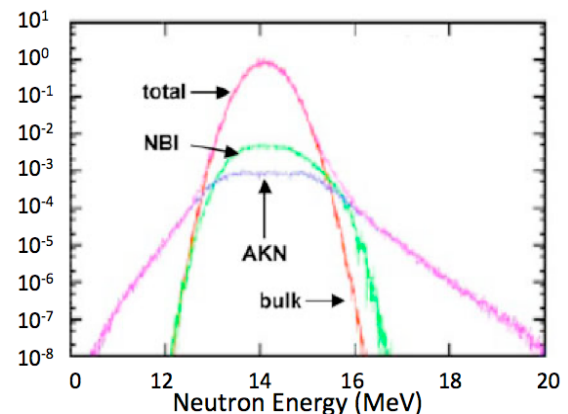


Fig. 1 Estimated neutron energy spectrum from ITER plasmas.

sion analysis for obtaining the measurements.

2. Principle of Measurement of Fast Neutrons in Nuclear Emulsion

A nuclear emulsion is a highly sensitive photographic film used for the detection of three-dimensional trajectories of charged particles. The principle of detection of fast neutrons within a nuclear emulsion depends on the detection of a proton recoiled by a neutron, as shown in Fig. 2(a). The trajectory of the recoiled proton is recorded as a three-dimensional track, as shown in Fig. 2(b). The track consists of numerous silver grains. The size of each grain is approximately 1 micron. Because a nuclear emulsion

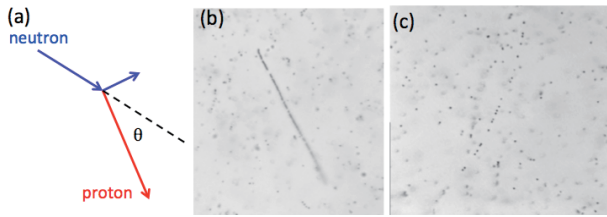


Fig. 2 (a). Illustration of the principle of neutron detection. (b). Microscopic image of a proton track recoiled by a neutron. (c). Microscopic image of an electron track scattered by a gamma ray. As shown, protons provide a higher ionization loss than electrons.

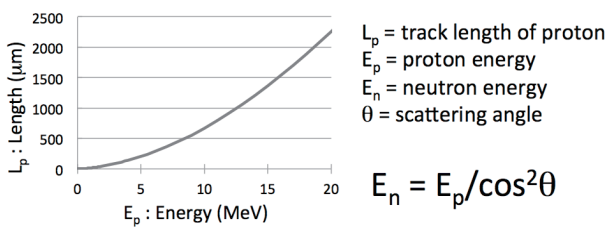


Fig. 3 Plot represents the relation between proton energy (E_p) and track length (L_p) in the nuclear emulsion (OPERA film [6]). The equation represents the relation between neutron energy (E_n), proton energy, and scattering angle (θ), which is defined in Fig. 2 (a).

has high sensitivity, electrons scattered by gamma rays are also recorded, as shown in Fig. 2 (c). However, these two tracks can be separated by the density of silver grains along the tracks due to the differences in ionizing energy loss in the emulsion and by analyzing the differences in the track forms.

Furthermore, in the nuclear emulsion, we can measure the proton and neutron energies by measuring the three-dimensional track length and angle with an accuracy of 1 micron. The proton energy is measured using the track length, as shown in Fig. 3. The neutron energy is calculated using the equation shown in Fig. 3. Thus, the energy of incoming neutrons can be reconstructed by measuring the three-dimensional recoil proton tracks.

3. Nuclear Emulsion Detector

3.1 Nuclear emulsion “OPERA films”

The Nagoya University group and Fujifilm Corporation jointly developed an advanced nuclear emulsion, OPERA film [6], for the OPERA experiment. Figure 4 shows an image and a cross-sectional schematic of the nuclear emulsion. This structure consists of a 44- μm emulsion layer attached onto both sides of a 205- μm plastic supporting layer. The recoil proton production probability of a 14-MeV neutron is approximately 10^{-4} in a 44- μm emulsion layer and approximately 10^{-3} in a 205- μm plastic layer. Thus, the recoil probability of the plastic layer is one order of magnitude higher than that of the emulsion

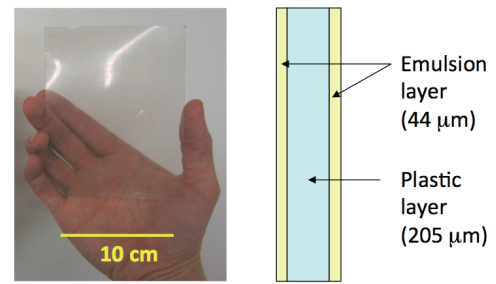


Fig. 4 Photograph and cross-sectional schematic of the OPERA film.

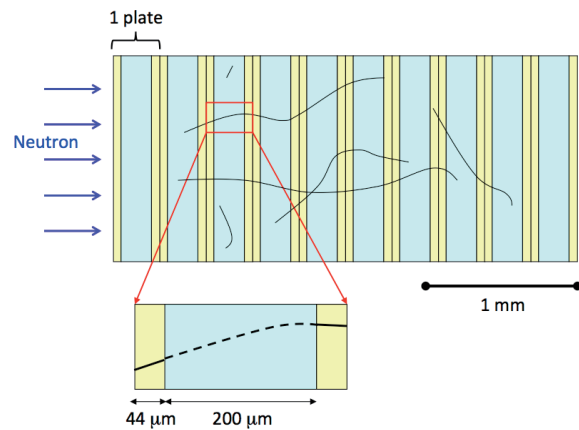


Fig. 5 Cross-sectional schematic of the ECC structure. The yellow regions represent the nuclear emulsion, and the blue regions represent the plastic layers. Proton trajectories are recorded as tracks in the yellow regions, as shown in the magnified view. The black lines represent tracks recorded in the nuclear emulsion, while the dotted line represents the unrecorded trajectory through the plastic layer.

layer. In the case of fast neutron detection, the plastic layer also functions as a good converter.

3.2 Emulsion cloud chamber

The track length of 14-MeV protons in a nuclear emulsion is over 1 mm, as shown in Fig. 3. To obtain the total track image from the scattering point to the stopping point in the emulsion detector, these films are stacked in the structure, as shown in Fig. 5. The emulsion stacking detector is called the emulsion cloud chamber (ECC). In this figure, the neutron parallel beam irradiates the left side of the ECC and some protons in the neutron emulsion are scattered (indicated by black lines). As shown in this figure, we can measure the total recoil proton tracks in the ECC.

4. Measurement of 14-MeV Neutrons

4.1 Experiment

We conducted experiments using the DT (14.8 MeV) neutron standard source at the National Advanced Indus-

trial Science and Technology to validate this method. We built an ECC comprising 10 OPERA films and placed it 2.2 m from the neutron source. DT neutrons irradiated in the vertical direction were incident on the emulsion detector surface. The total irradiation was approximately 10^7 neutrons/cm². After irradiation, we unpacked and developed the exposed films in a dark room.

4.2 Emulsion scanning and reconstruction

We scanned all films by using S-UTS [3, 4]. S-UTS captures 16 tomographic images of the nuclear emulsion layer, detects linearly aligned silver grains across these images, and outputs the reconstructed track data at a speed of 72 cm²/h. The track data consists of three-dimensional position, angle, pulse height (PH), and volume pulse height (VPH). PH is the number of tomographic images that include silver grains along a single track, and VPH is the number of pixels of silver grain images along a single track. VPH is strongly correlated with the ionization loss of a charged particle. Thus, VPH is an effective parameter for the identification of proton tracks by discriminating them from electron tracks.

The number of total readout tracks for this scanning condition was approximately 10^6 tracks/cm². The main component of these tracks was the electron tracks resulting from gamma rays. The tracks recognized on each emulsion layer were connected across the plastic layer to adjacent plates using the nuclear emulsion data reconstruction software “NETSCAN” [7]. Then, we selected the recoil proton tracks by applying a VPH threshold to discriminate these from electron tracks. The VPH distribution of this data is shown in Fig. 6, and we discriminated proton and electron tracks by applying a VPH threshold value of 200. Figure 7 (a) shows all tracks readout by the scanning system, and Fig. 7 (b) shows tracks selected under the connection condition of more than six plates after reconstruction with VPH discrimination. The magnified view of

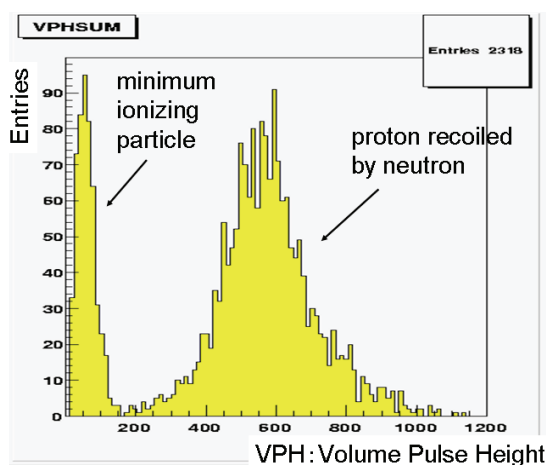


Fig. 6 VPH distribution of reconstructed tracks illustrating the VPH threshold selection.

each two-dimensional projection of five reconstructed proton tracks is shown in Fig. 8. The yellow lines in the figure represent tracks recognized in a given plate. Thus, track number 1 including four yellow lines shows that the track was connected through four emulsion plates. In these figures, the z-axis is parallel to the neutron irradiation direction and the x–y plane is parallel to the emulsion surface.

As shown in Fig. 7 and Fig. 8, some proton tracks were selected from numerous background tracks, enabling the measurement of the track position, length, and angle. The track angle θ , as defined in Fig. 2 (a), is given by $\theta^2 = \theta_x^2 + \theta_y^2$ in the coordinate system shown in Fig. 8, because the neutron irradiation direction was chosen parallel to the z-axis. Thus, we can measure the neutron energy using this reconstructed track dataset.

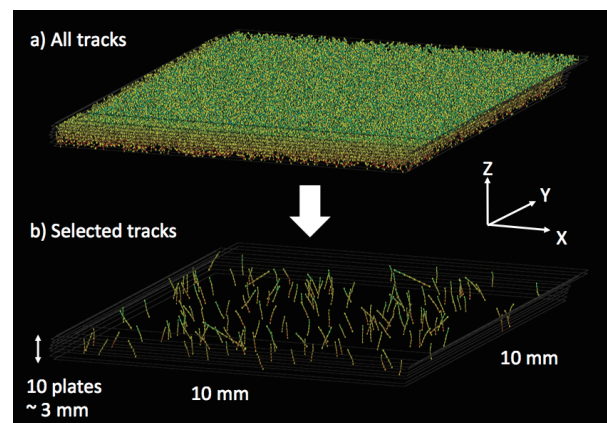


Fig. 7 Three-dimensional display of track data over an area of 1 cm². Data (a) before and (b) after selection.

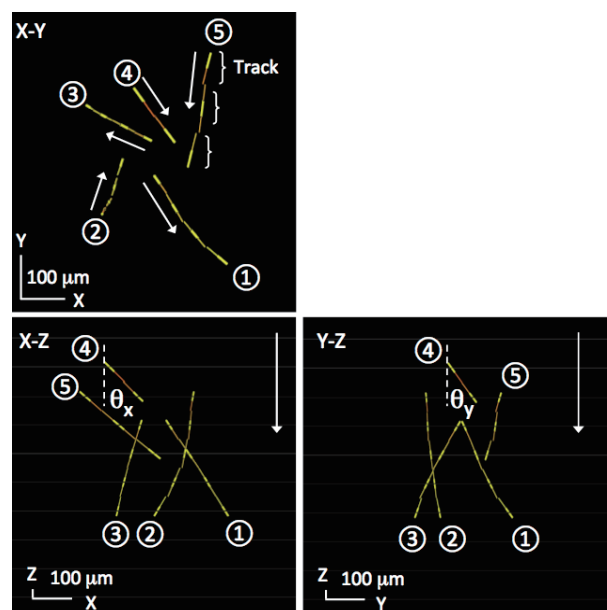


Fig. 8 Projected diagram of five tracks. White arrows show the positive to negative direction along the z-axis.

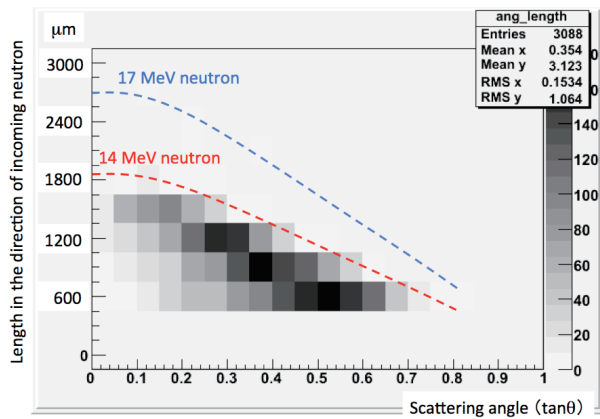


Fig. 9 Two-dimensional histogram of the relation between track length and scattering angle ($\tan\theta$) from the reconstructed data. The red line is that expected from 14-MeV neutrons and blue line is that expected from 17-MeV neutrons.

4.3 Result

Figure 9 shows the relation between track length and scattering angle ($\tan\theta$) for each proton track from the reconstructed data. The distribution shape is consistent with expected results from 14-MeV neutrons. The width of the two-dimensional histogram distribution results from the nonsensitive plastic layer region of the OPERA film.

In the measurement of neutrons resulting from knock-on alpha particles, the region over 17 MeV is determined as the signal region. In the experiment, there are no candidates in this region.

5. Further Improvement

5.1 Improvement of energy resolution

The improvement of neutron energy resolution is essential for the separation of knock-on alpha neutrons and other components. Hence, improvements in the detector structure are needed by enlarging the volume of the sensitive emulsion layer. This can be accomplished by using only the emulsion without the plastic layer, which is called pellicle, or by reducing the plastic layer thickness.

5.2 Improvement of gamma discrimination performance

In the experiment, electron tracks were not a bottleneck for scanning and analysis because the source was environmental gamma rays. However, in the environment of fusion plasma diagnostics, there is a significant amount of gamma rays. Thus, we must improve the discrimination performance while maintaining sensitivity for detection of

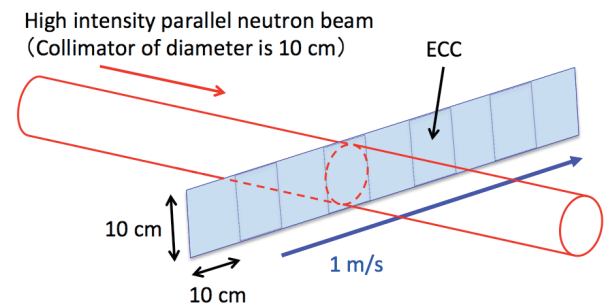


Fig. 10 Schematic conceptualization of the incorporation of time resolution to the nuclear emulsion in a high-intensity neutron field.

recoil protons by optimization of nuclear emulsion sensitivity.

5.3 Addition of time resolution

In the measurement of plasma diagnostics, time variation information is very important. For the measurement of high-intensity neutron fields such as ITER, time resolution can be incorporated to nuclear emulsion measurements by moving the plates continuously, similar to that in a motion picture film camera, as shown in Fig. 10. In this mechanism, the moving speed defines the irradiation time and time resolution. Here we discuss the neutron field for a collimator diameter of 10 cm and a total neutron flux of 10^9 neutrons/cm²/s. Under this situation, for an emulsion moving speed of 1 m/s, the irradiation time is 10 ms. Under conditions equivalent to the detector used in the test experiment, the number of over 17-MeV neutrons resulting from knock-on alpha particles is estimated to be approximately 100 events/10 ms/100 cm².

6. Conclusions

In this study, we propose a novel DT burning plasma diagnostic method with a nuclear emulsion using advanced high-speed, large-scale statistical analysis. The experiment conducted for 14-MeV neutron measurement validates the fundamental ideas of the methodology.

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