Development of high spatial resolution cold/ultra-cold neutron detector using fine-grained nuclear emulsion

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Abstract

We have been developing neutron detectors with spatial resolution of submicron to several tens of nanometers using fine-grained nuclear emulsion with nuclides with large neutron absorption cross sections such as ^{6}Li and ^{10}B. Those detectors were demonstrated their ability to detect cold and ultra-cold neutrons.

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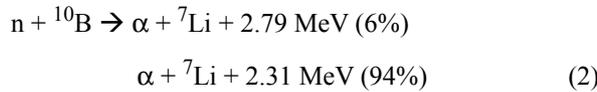
1. Introduction

Neutron detectors with spatial resolution of submicron or less are required for experiments to search for displacement from the inverse square law in the position distribution of ultra-cold neutrons under the earth's gravitational field[1][2][3]. We have been developing such detectors by using fine-grained nuclear emulsion and nuclides with large neutron absorption cross sections emitting charged particles.

2. Fine-grained nuclear emulsion

Fine-grained nuclear emulsion is a kind of photographic film and works as a high spatial resolution 3 dimensional tracking detector. It consists of a substrate coated with nuclear emulsion gel containing silver bromide crystals with diameter of about 40 nm dispersed in gelatin[4]. When a charged particle passes through crystals in emulsion, latent images are formed in crystals. The latent images turn into aligned silver grains with diameter of about 100 nm by procedure of development. After the development, they can be observed by an optical microscope and recognized as a track. The fine-grained emulsion is studied and produced at Nagoya University[5]. This emulsion has no sensitivity to minimum ionizing particles, so that it has low sensitivity to gamma ray backgrounds. By using nuclides emitting large dE/dx particles after neutron absorption, it works as a neutron detector with high S/N ratio.

3. Detection principle

We used ^{6}Li and ^{10}B as neutron absorbers. Their absorption cross sections to neutrons with velocity of 10 m/s are large as about 2×10^5 barn and 8×10^5 barn, respectively. After absorption, they emit charged particles with large dE/dx as equations (1) and (2).

$$n + {}^6\text{Li} \rightarrow \alpha + t + 4.78 \text{ MeV} \qquad (1)$$

$$n + {}^{10}\text{B} \rightarrow \alpha + {}^7\text{Li} + 2.79 \text{ MeV (6\%)}$$

$$\alpha + {}^7\text{Li} + 2.31 \text{ MeV (94\%)} \qquad (2)$$

Tracks of these charged particles are detected by fine-grained nuclear emulsion. Therefore, the high spatial resolution is realized.

4. Types of detectors

We have been developing two types of detectors. One is called "doping type", which is nuclear emulsion gel with a chemical compound of neutron absorber doped in it. The other is "thin layer type", which consists of a thin layer of neutron absorber and a nuclear emulsion layer coated on it. In this section, we explain the principles of the two types of detectors and show the results of demonstration experiments of neutron detection.

4.1.1. Doping type

This type is fabricated by doping neutron absorbing nuclide into nuclear emulsion. We doped LiNO_3 with natural isotope abundance of Li into melted gel of fine-grained nuclear emulsion up to 1.6×10^{-2} mol/cm^3, and coated 1 mm-thick glass plate. Thickness of the gel after drying was 27 μm (Figure 1). When a neutron is absorbed by ^{6}Li in the emulsion, the reaction of equation (1) occurs. An α particle and a triton are emitted back-to-back and both of their tracks will be detected in the emulsion layer. Ranges of the α particle and the triton are calculated to be 7.8 μm and 44 μm, respectively, by SRIM 2008.04. Those tracks have different dE/dx at the starting point, therefore have different linear density of silver grains (grain density, GD). Tracks can be identified by the difference so that the starting point of tracks, i.e. neutron absorption point can be determined.

4.1.2. Demonstration experiment with neutrons

During exposure, the detector was packed with a light-tight and airtight package made of a foil consisting of nylon (15 µm), polyethylene (13 µm), aluminum (7 µm), polyethylene (13 µm), and black polyethylene (80 µm), to avoid light, since the detector being photosensitive. It was exposed to cold neutron at CN-3 beam line at Kyoto University Reactor Research Institute. After development, tracks in the detector were observed under an optical microscope with epi-illumination system. One of neutron absorption events is shown in Figure 2. A pair of tracks of an α particle and a triton forming a back-to-back topology is seen. From GDs of α particles and tritons, spatial resolution of absorption points was estimated to be 0.4 µm[6]. Detection efficiency to cold neutron was measured at the Low Divergence Beam Branch of BL05 in MLF/J-PARC[7, 8]. It turned out to be consistent to the doped amount of Li into the detector[6].
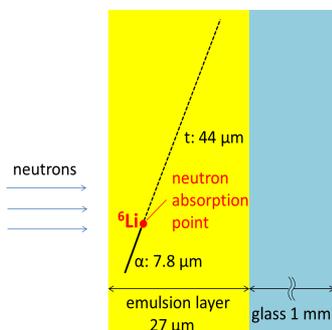

Figure 1. A cross sectional view of the doping type (LiNO$_3$) detector. An α particle and a triton emitted back-to-back from neutron absorption by ^6Li will be detected inside the emulsion layer.
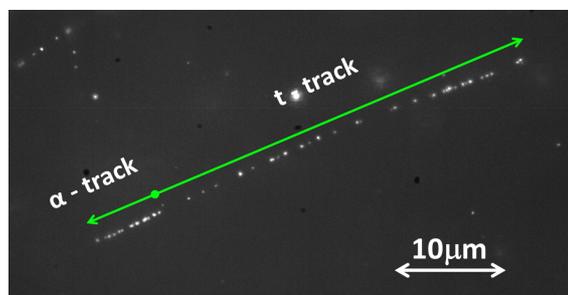

Figure 2. A microscopic view of tracks of an α particle and a triton emitted from neutron absorption by ^6Li forming a back-to-back topology. Arrows show the tracks.

4.2.1. Thin layer type

The other type of detector is a thin layer of neutron absorber on a substrate, coated with the fine-grained nuclear emulsion. A 50 nm-thick B_4C layer, whose ^{10}B is enriched, was sputtered on a 400 µm-thick Si plate. Cover layers of a 60 nm-thick NiC layer and a 30 nm-thick C layer were formed on it. Finally the plate was coated with fine-grained nuclear emulsion (Figure 3). When a ^{10}B absorbs a neutron, an α particle and a ^7Li are emitted back-to-back. One of them enters the emulsion layer and then will be detected. Ranges of the α particle and the ^7Li are calculated to be 5.1 µm and 2.6 µm, respectively, by SRIM 2008.04. By extrapolating the track detected in the emulsion to the B_4C layer, we can determine an absorption point with resolution depending on the thickness of the B_4C layer and GDs of tracks. It is expected as several tens of nanometers for this detector.

4.2.2. Demonstration experiment with neutrons

The detector was exposed to cold and ultra-cold neutron, in a package made of 20 µm-thick aluminum foil, at BL05 in MLF. Tracks from neutron absorptions by ^{10}B were observed under an optical microscope after development (Figure 4) for both cold and ultra-cold neutrons.
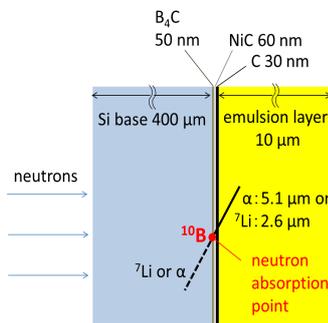
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Figure 3. A cross sectional view of the thin layer (B_4C) type detector. An α particle and a ^7Li are emitted back-to-back from neutron absorption by ^{10}B. One of them will be detected inside the emulsion layer. The absorption point will be determined by extrapolating the track to the B_4C layer.

Figure 4. A microscopic view of four tracks of α particles or ^7Li s emitted from neutron absorptions by ^{10}B. Arrows show the starting points of the tracks.

5. Conclusion

We have been developing cold/ultra-cold neutron detectors with spatial resolution of submicron to several tens of nanometers. There are two types of detectors: doping type and thin layer type. For doping type, $LiNO_3$ is doped into fine-grained nuclear emulsion. Tracks from cold neutron absorptions by ^6Li were observed. Its spatial resolution was estimated to be 0.4 µm from GDs of tracks emitted after absorptions. For thin layer type, a 50 nm-thick B_4C layer with cover layers was coated with fine-grained nuclear emulsion. Tracks from cold and ultra-cold neutron absorptions by ^{10}B were observed. The spatial resolution of several tens of nanometers is expected to be achieved from its structure and GDs of tracks.

6. Acknowledgements

References

[1] V. V. Nesvizhevsky et al., Nature, 415, (2002).

[2] H. Abele et al., Nuclear Physics A 827 (2009) 593c–595c.

[3] G. Ichikawa et al., Phys. Rev. Lett. 112, (2014) 071101.

[4] T. Asada et al., arXiv:1705.05014 (2017)

[5] T. Naka et al., Nuclear Instruments and Methods in Physics Research A 718, (2013) 519-521.

[6] N. Naganawa et al., arXiv:1612.04544 (2016)

[7] K. Mishima et al., Nuclear Instruments and Methods in Physics Research A 600, (2009) 342-345.

[8] K. Mishima, Neutron network news (Hamon) 25 (2), (2015) 156-160.