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Development of a pixel detector for ultra-cold neutrons

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ABSTRACT

A pixel detector with high spatial resolution and temporal information for ultra-cold neutrons is developed based on a commercial CCD on which a neutron converter is attached. ^{10}B and ^{6}Li are tested for the neutron converter and ^{10}B is found to be more suitable based on efficiency and spatial resolution. The pixel detector has an efficiency of $44.1 \pm 1.1\%$ and a spatial resolution of $2.9 \pm 0.1\,\mu$m (1 sigma).

1. Introduction

When ultra-cold neutrons (UCNs) are trapped in the earth's gravitational field, their energy is quantized. In consequence, their probability density distribution exhibits their vertical modulation. The scale of this density modulation is calculated to be $(\hbar^2/2m_n^2 g)^{1/3} \sim 6\,\mu$m. Observations of such quantum states have been presented in Refs. [1–3]. We have proposed a more precise measurement using a pixel detector with an image magnification system [4]. Another pixel detectors for UCN have been developed recently, such as that reported in Ref. [5]. In this article we present the development of a pixel detector based on a commercial charge coupled device (CCD) covered with a neutron converter. By comparing ^{10}B and ^{6}Li as converter materials, we find that a ^{6}Li converter produces energetic tritons which penetrate deep into the CCD in various directions, degrading the spatial resolution. Hence we conclude that ^{10}B is an appropriate material for a neutron converter.

2. Detector design

The developed detector consists essentially of a CCD covered by a neutron converter. Charged particles produced via nuclear reaction in the converter are detected with the CCD. The choices of converter material and CCD are key for this detector.

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2.1. Neutron converter

^{10}B and ^{6}Li are chosen as test materials for the neutron converter, because of their large cross-sections with neutrons. The neutron absorption cross-sections for ^{10}B and ^{6}Li are 4.01×10^3 and 0.95×10^3 barn, respectively, for thermal neutrons ($v = 2224$ m/s).

Neutrons react with ^{10}B and ^{6}Li in the following processes:

$$n + {}^{10}\mathrm{B} \rightarrow \alpha(1.47\,\mathrm{MeV}) + {}^{7}\mathrm{Li}\ (0.84\,\mathrm{MeV}) + \gamma\ (0.48\,\mathrm{MeV}) \quad 93.9\% \tag{1}$$
$$\rightarrow \alpha\ (1.78\,\mathrm{MeV}) + {}^{7}\mathrm{Li}\ (1.01\,\mathrm{MeV}) \quad 6.1\%$$

$$n + {}^{6}\mathrm{Li} \rightarrow \alpha(2.05\,\mathrm{MeV}) + {}^{3}\mathrm{H}\ (2.73\,\mathrm{MeV}) \quad 100\%. \tag{2}$$

^{10}B has advantages over ^{6}Li in that it has a larger cross-section and a shorter range for converted charged particles in the CCD; ^{10}B emits only short range particles. The ranges of α(1.47 MeV), α(1.78 MeV) and ^{7}Li(0.84 MeV, 1.01 MeV) in Si are 5, 6 and 2 μm, respectively. In contrast, ^{6}Li emits α particles and tritons with ranges of 7 and 40 μm. Long range tritons degrade the spatial resolution, as discussed in Ref. [4].

2.2. CCD sensor

A CCD is an ideal device for UCN detection because of its high spatial resolution and its ability to capture data in real time. Since a CCD cannot directly detect neutral particles, a neutron converter to create charged particles must be attached to the front of the device. A back-thinned type CCD is chosen to avoid a large insensitive volume in front of the active volume of the CCD, which would

Table 1
Specifications of the HAMAMATSU S7170-0909 ($T_a = 25\,^{\circ}$C).

Parameter	
Active area	12.288 × 12.288 mm
Number of pixels	512 × 512
Pixel size	24 × 24 μm
Frame rate	0.9 frames/s
Full well capacity (vertical)	300 ke⁻
Full well capacity (horizontal)	600 ke⁻
Dark current max. 0 °C	600 e⁻/pixel/s
Readout noise	8 e⁻rms

prevent converted charged particles entering the active volume or degrade the spatial resolution. We use a commercial CCD detector, HAMAMATSU S7170-0909, in the low dark current read out mode. The specifications are shown in Table 1. Generally, CCD might have white-spot pixels induced by radiation damage. Only 2 pixels have become noisy after 60 million neutron irradiation per 512 × 512 pixels during the neutron beam tests mentioned below.

2.3. Fabrication of a converter layer

The neutron converter is attached directly to the surface of a CCD to minimize the distance between the positions of an incident neutron and a detected charged particle [4]. The converter layer is mounted on the CCD surface by vacuum evaporation at Kyoto University Research Reactor Institute. The pressure of the evaporation chamber is around 10^{-3} Pa and the evaporation rate is about 1 Å/s for each material. The facility used is described in Ref. [6].

Converter layers of 46 μg cm^{-2} (220 nm) and 11 μg cm^{-2} (230 nm) for ^{10}B and ^{6}Li, respectively, are attached to the CCD surface. To form a firm layer, a 9 μg cm^{-2} (20 nm) Ti layer is directly deposited on the CCD surface and the converter layer is mounted on the Ti layer. To repel moisture from the air, the outer surface of the converter layer is covered with a 9 μg cm^{-2}(20 nm) Ti layer. (Note that we incorrectly reported the amount of Ti and Li layer in our previous report [4].) Ti has good characteristics for this use, because of its chemical stability, adhesion and negative potential for neutrons. The stability of these Ti–^{10}B–Ti and Ti–^{6}Li–Ti structures have allowed our developed detector to work reliably for more than three years.

3. Performance of a CCD sensor

We investigate the CCD response to charged particles using α particles from ^{241}Am. The CCD and the α source are put in a chamber filled with dry N_2 gas, with the distance between them fixed at 123 mm. The N_2 gas pressure is varied to change the energy of the α particles at the surface of the CCD. The energy to create an electron–hole pair in Si is 3.65 eV, and hence an energy deposit of 1 MeV, for instance, creates about 300,000 electron–hole pairs.

Electrons are collected at the anode and stored in a charge capacitance. During storage, electrons spread to the adjacent pixels and make a cluster. Fig. 1 shows typical cluster shapes made by α particles of energy 1 and 4 MeV. For α particles with energy lower than 2 MeV, the created electrons diffuse isotropically in the vertical and horizontal directions. For more energetic particles, higher than 2 MeV, the cluster shapes become anisotropic. This is because so many electron–hole pairs are created that they overflow the full well capacity. As shown in Table 1, the vertical full well capacity is lower than the horizontal capacity. Overflowed electrons spread only in the vertical direction and make an anisotropic cluster.

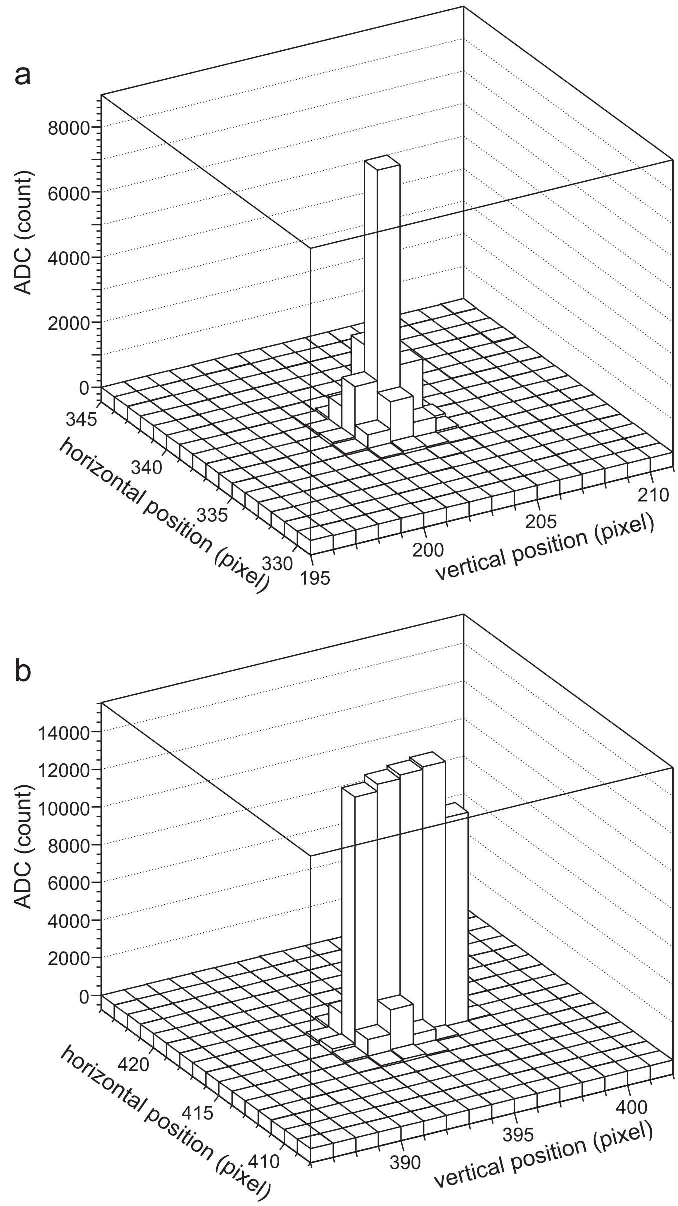

Fig. 1. Typical signals made by α particles of energy (a) 1 MeV and (b) 4 MeV. An α particle of energy lower than 2 MeV creates an isotropic cluster, while an α particle of energy higher than 2 MeV creates an anisotropic cluster spread in the vertical direction.

Considering the anisotropy of the full well capacity, the signal region is determined to be 7 pixels (horizontal) × 11 pixels (vertical) around the peak pixel, collecting all the created electrons. More than 99% of the diffused electrons are stored in this region. Fig. 2 shows the energy calibration curve of the total charge in the signal region to the energy of α particles. Linearity is confirmed below 4 MeV. α particles of energy more than 4 MeV are so energetic that they can penetrate a CCD detection volume thickness of 20 μm.

When the neutron rate is 100 events/frame, more than one event is observed inside one signal region.

4. Neutron beam test

The performance of neutron detectors with a ^{10}B converter and a ^{6}Li converter are tested with neutrons from reactors.