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Development of a low-temperature germanium detector via mechanical cooling with a compact pulse-tube refrigerator

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ABSTRACT

We have developed a new germanium (Ge) detector unit for hypernuclear γ-ray spectroscopy at J-PARC, which comprises a new Ge detector array Hyperball-J. A compact pulse-tube refrigerator is coupled to a coaxial Ge detector in order to achieve lower crystal temperatures as a means to increase radiation hardness. The obtained crystal temperature is 72 K, while an energy resolution is maintained at (FWHM) 3.1(1) keV for 1.33 MeV γ rays using a gate-integrated shaping amplifier (ORTEC 973U). Gain shifts with changing crystal temperature are also confirmed for the Ge detector.

1. Introduction

Hypernuclear γ-ray spectroscopy with high energy resolution using germanium detectors was initiated in 1998 by the construction of the Ge detector array Hyperball [1]. By that time, the use of Ge detectors had been the de facto standard for the γ-ray spectroscopy of normal nuclei. However, their application to hypernuclei had been difficult because of the severe operating conditions to which Ge detectors are subjected in those experiments using high-energy secondary hadronic beams of ~1 GeV/c pions and kaons. Despite its much lower beam intensity of $\sim 10^6$ per second than those of primary beam experiments, the secondary beam has a few cm spread (σ) at the target that is surrounded by the Ge detectors. About 10^4 charged particles originated from the beam halo hit the Ge detector where a penetrating minimum ionizing particle deposits as much as 50 MeV in energy [2]. In such a condition, a combination of Ge detector with a resistive feedback preamplifier and a shaping amplifier with pole-zero adjustment causes a several hundred μs dead time before the shaping amplifier baseline is restored. For this reason, a transistor-reset (discharge) type preamplifier combined with a gated integration type shaping amplifier is necessarily employed for the Hyperball Ge detectors resulting in dead time of only 20 to ~50 μs per reset. In order to reduce this dead time associated with the reset further, the preamplifier gain is lowered from ~150 mV/MeV to 30–50 mV/MeV; the reset threshold changes from a typical ~50 MeV to ~130 MeV. The severity of experimental conditions of hypernuclear γ-ray spectroscopy can be illustrated by around 50% dead time with 1 million beam particles per second still with the current system.

Recently, a hypernuclear γ-ray spectroscopy experiment via the (K^-, π^-) reaction has started at the K1.8 beam line of the Japanese Proton Accelerator Research Complex (J-PARC). A new dedicated Ge array, Hyperball-J (HBJ) [5], has been developed and constructed.

There are two major requirements for the Ge detectors to be used in the HBJ array: radiation hardness and compact size. Radiation damage of Ge detectors is caused by crystal lattice defects that are created via scattering of incident fast neutrons or energetic charged particles from Ge atoms. As electrons and holes produced by an incident γ ray drift toward their respective electrodes to be collected, some fraction of, predominantly, holes are trapped by these defects. This, in turn, results in incomplete charge collection within a preset collection time of pulse-shaping electronics, which shows up as a characteristic low-energy tailing

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of γ-ray photopeaks. The effect of fast-neutron damage on energy resolution is quantified by the ratio of the Full Width at Tenth Maximum (FWTM) to the Full Width at Half Maximum (FWHM). Because a closed-end coaxial n-type Ge detector has a geometry where electrons and holes are collected at the inner and the outer electrodes, respectively, the holes drift over shorter distances, on average, than the electrons. Therefore, the n-type detector is less susceptible to resolution degradation and is the choice for HBJ as it has been for the Hyperball array. The radiation damage is cumulative. It is expected that, following reactions in the target with the high-intensity hadronic beams, more neutron flux to the Ge detectors would deteriorate their energy resolution and change the γ-ray peak shapes as a function of time during a course of a single experiment.

For instance, a crude estimate of neutron flux from the past experiment using the (π^+, K^+) reaction at the K6 beam line of the KEK PS facility [3,4] gives $\sim 3 \times 10^8$ n/cm^2 by counting the peak area at 693 keV from the ^{72}Ge (n, n') reaction [6]. The total pions of 1.3×10^{12} with a momentum of 1.05 GeV/c were irradiated on a target of 18.6 g/cm^2 polyethylene; the thickness of the target is another characteristics of the hypernuclear γ-ray spectroscopy. The average distance between the Ge detector and the target was 15 cm. All in all, about 10^{10} fast neutrons per Ge detector are estimated. Energy spectra of one Ge detector at the start of the experiment and after 10^{12} pions on the target are shown in Fig. 1. The FWTM/FWHM ratio is 1.9 and 2.7, respectively. In the future J-PARC experiments, ten times higher beam intensity is anticipated and thus the same order of increase in neutron flux is naively expected.

This change in the response of Ge detectors is especially problematic for peak-shape analysis for lifetime measurements of excited states. In the worst-case scenario, detectors must be replaced or annealed during the experiment, which is impractical considering the limited number of costly Ge detectors in use.

The number of holes trapped after traveling a distance Δr from the point of interaction between a γ ray and the Ge crystal is given by

$$N = n_0(1 - e^{-\Delta r/\lambda_h}) \tag{1}$$

where n_0 is the total number of holes produced and λ_h is the mean free path for holes [7]. Hull has shown that λ_h is highly sensitive to the Ge crystal temperature and exhibits a temperature hysteresis [8]. Furthermore it has been suggested that a lower Ge crystal temperature effectively prevents λ_h from decreasing and thus from increasing the probability of hole trapping. Degradation of the energy resolution can be slowed by keeping the Ge crystal temperature as low as possible. According to the experimental studies of Ref. [8], where a flux of 183 MeV neutrons at 3.2×10^8 n/cm^2 irradiated a Ge detector, the effect of neutron damage on energy resolution is negligible below ~75 K. Therefore, this crystal temperature has been set as a goal for the HBJ Ge detectors, although its effectiveness is difficult to assess until the actual experiment is performed.

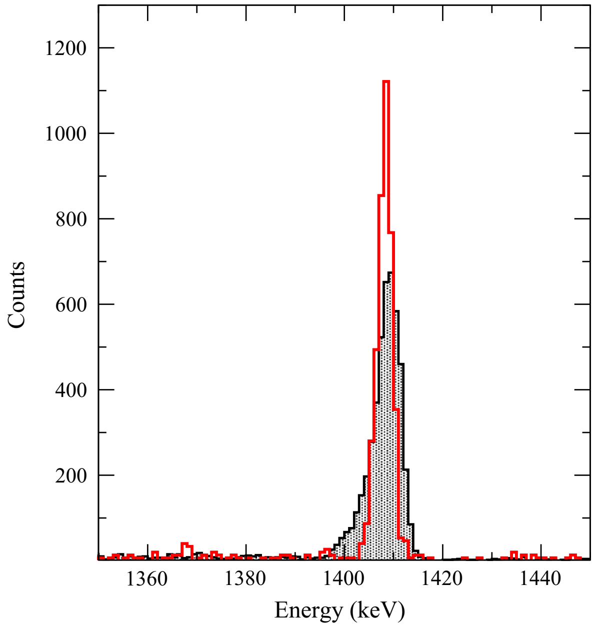

Fig. 1. Change in the shape of the 1408-keV peak from ^{152}Eu during the E566 experiment at the KEK-PS K6 beam line. Red (not shaded): right before the experiment. Black (shaded): after 10^{12} pions irradiated on the target. The peak areas are normalized for comparison. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Normally, Ge detectors are cooled with liquid nitrogen (LN$_2$) where a typical crystal temperature is ~90 K. The cold-head temperature of the LN$_2$ dewar is at 77 K, the boiling point of LN$_2$ at atmospheric pressure, unless the inner pressure of the dewar is reduced. On the contrary, mechanical cooling by a refrigerator does not have this limitation. With enough cooling power, a lower cold-head temperature and thus Ge crystal temperature can be reached. Mechanical cooling of Ge detectors had already been developed prior to this work, and such LN$_2$-free cryogenic systems are commercially available. However, there are no systems in the market intended for lower-temperature Ge detectors for increased radiation hardness. The most critical issue in mechanical cooling of Ge detectors is microphonic noise induced by vibration from a refrigerator with moving components. In our particular case, because of their low preamplifier gain requirement, our Ge detectors are more prone to the microphonic noise when coupled to a mechanical cryogenic system.

Another challenge is a constraint on the size of the mechanical cooling system. In its full scale, HBJ will have 32 Ge detectors, each with 60% relative efficiency, and will be placed in a very compact geometry. Instead of a typical spheroidal placement of detectors, parallel stacking of detectors to form a plane (wall) is adopted for a large detection efficiency of ~6% for 1-MeV γ rays. Thus, the cryogenic unit, whether it is an LN$_2$ dewar or mechanical cryo-cooler, must be slim enough to fit within a cylinder of 130 mm in diameter.

In addition to these two requirements, the mechanical cooling method reduces interruptions to beam time from refilling of the LN$_2$ dewars, during which beams must be stopped to avoid microphonic noise that leads to poor energy resolution.

We started the development of a prototype detector for HBJ in 2006. An ultra-compact pulse-tube refrigerator (PTR) manufactured by Fuji Electric Co. Ltd. was coupled to a few types of Ge detector provided by SEIKO EG&G Co. Ltd. and was tested repeatedly for performance. Based on the results of these tests and trials, modifications and improvements were made to come up with a final HBJ Ge detector unit for which specifications and performances are reported in the following sections.

2. Ge detector for HBJ

2.1. Ge sensor specifications

The prototype Ge detector consists of a Ge sensor and a cryogenic system as shown in Fig. 2. Specifications for the Ge sensor for HBJ are (1) high-purity n-type crystal for better radiation hardness, (2) transistor-reset type preamplifier with a gain of ~110 MeV/reset or above to reduce dead time caused by the reset, (3) relative photopeak detection efficiency of 60% or better at 1.33 MeV, (4) an