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X Li[1], D H Kwon[2], K Tetsuno[3], I Kim[2,4], H L Kim[2], H J Lee[2], S Yoshida[1], Y H Kim[2,5], M K Lee[5], S Umehara[3], T Kishimoto[3]

[1] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[2] Center for Underground Physics, Institute for Basic Science, Daejeon 34047, Republic of Korea
[3] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[4] Los Alamos National Laboratory, Los Alamos, NM 87545, The United States of America
[5] Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea

E-mail: ps.lixiaolong@gmail.com

Abstract. Scintillating bolometer is a powerful tool to search neutrinoless double beta decay. We established a large scintillating bolometer using a 312 g CaF_2(Eu) crystal with a readout technology of metallic magnetic calorimeters. A set of successful measurements were carried out for simultaneous detection for heat and light signals at 10-40 mK in an above-ground laboratory. We found large light signals with clear difference in scintillation yields between electron- and alpha-induced events. The comparison of relative amplitudes of heat and light signals obtained about 10 σ discrimination power. We also found the heat signals experiencing strong position dependence from the event location. This position dependence can be interpreted by the spin-lattice interaction of paramagnetic Eu ions in the CaF_2 crystal.

1. Introduction

Neutrinoless double beta decay ($0\nu\beta\beta$) is a way to prove fundamental properties of neutrinos such as Majorana nature, mass hierarchy and absolute mass scale. We developed a scintillating bolometer with a CaF_2(Eu) crystal to search for $0\nu\beta\beta$ of ^{48}Ca

Several low-temperature experiments were previously carried out using CaF_2(Eu) crystals. None of the measurement showed a promising result to realize for a $0\nu\beta\beta$ search experiment [1,2]. CaF_2(Eu) has a light yield of $\sim$23000 photons/MeV, independent of the temperature between 1 K and 300 K [3]. One can expect a good discrimination power between α background and β/γ events when a sensitive light detector is adopted. However, although a 0.3 g CaF_2(Eu) crystal was used in an R&D setup for a dark matter detection, a resolution of 0.41% (FWHM) was found for 5.5 MeV α particles [4]. Moreover, the heat capacity of the Eu doped crystal has never been studied at low temperatures.

We present our recent measurement of using a large scintillating bolometer made of a 312 g CaF_2(Eu) crystal at 20 mK. This work was motivated to test phonon and scintillation properties at low temperatures as a possible use of the crystal to search for $0\nu\beta\beta$ of ^{48}Ca.

2. Detector development of the CaF_2(Eu) scintillating bolometer

A 312 g CaF_2(Eu) crystal in weight percent of 0.17% Eu is employed as a target of this R&D detector configuration (Fig.$\sim$1). Heat signals from the crystal are read by a metallic magnetic calorimeter (MMC) that is thermally connected to a multi-layer phonon collector film evaporated on the surface of the crystal. A light detector composed of a 2 inch Ge wafer and an MMC sensor is placed just above the crystal [5,6]. A silicon heater is attached to the crystal to generate periodic reference signals in the heat channel.

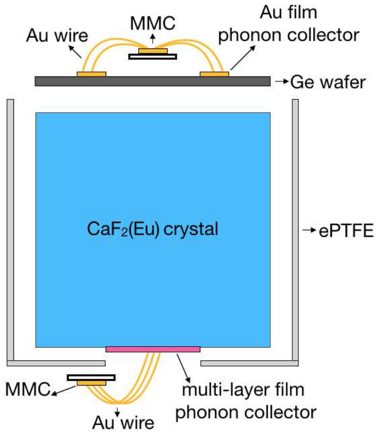

Figure 1. The schematics of phonon-scintillation detection using a CaF_2(Eu) crystal and MMC readouts. A Ag-Au phonon collector film was deposited on a 50 mm $\Phi \times$ 50 mm H CaF_2(Eu) crystal. The Ag layer can reflect 99.9% of 425 nm scintillation light of the crystal and the gold layer prevents the silver's oxidation. An expanded PTFE reflector is surrounded around the crystal to increase the light collection efficiency. The detector was installed in a dilution refrigerator to cool down to 10-40 mK. The measurement was carried out in an above-ground laboratory. (Refer [7] for the details of the detection scheme.)

3. Scintillation and phonon studies at low temperature

The result of this simultaneous detection for phonon and scintillation signals is shown in Fig.2 (left). The signal amplitudes showed several groups of events identified for beta/gamma band and internal alpha decays. The alpha decays are mainly from ^{226}Ra decay series that are confirmed by 3-minute decay coincidence of ^{222}Rn$\rightarrow^{218}$Po$\rightarrow^{214}$Pb and energy ratio between ^{218}Po and ^{222}Rn.

The double readout system showed an anti-correlation between light and heat signals as seen in a similar detection system [8]. With the anti-correlation correction, three groups of α events can be notable in the α spectrum measured with the light channel as shown in Fig.2 (middle). The resolution of the 4.9 MeV ^{226}Ra events is $\Delta E_\sigma = 3.2\%$.

In a scintillating bolometer, the relative ratio of heat and light signals provide a high discrimination power between electron and alpha events. Since there is no quenching in the heat signals for different types of particles, we compared the ^{226}Ra events with the β/γ events in the same pulse height (Fig.2 (right)). A Gaussian function is used to fit the distribution of Light/Heat ratios of each α and β/γ events. Using the mean values (μ_α, $\mu_{\beta/\gamma}$) and the sigma values (σ_α, $\sigma_{\beta/\gamma}$), we obtain a discrimination power of 10 σ. This strong discrimination power originates from the high light yield of the CaF_2(Eu) crystal and a large quenching in scintillation mechanism. A quenching factor $\mu_\alpha/\mu_{\beta/\gamma}$ of about 17% is found for the events in 4.9 MeV region.

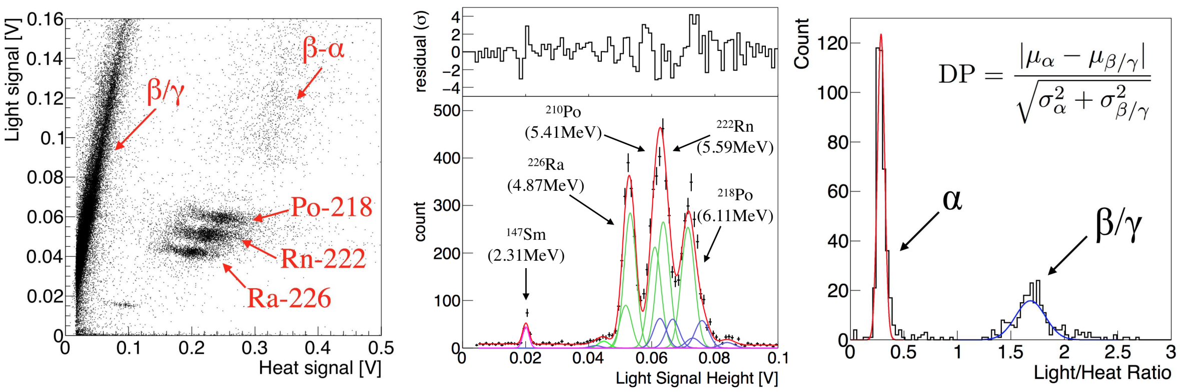

Figure 2. Left: Pulse height distribution of heat and light signals. Middle: α histogram fit with decay chains from ^{226}Ra and ^{228}Th and ^{147}Sm impurities. Right: discrimination power (DP) between β/γ and α events near 4.9 MeV region.

Fig.$\sim$3 shows the signal amplitudes of ^{226}Ra events and their following signals within 3 minutes. The events show a wide distribution of their amplitudes. However, the consecutive pairs also characterize a clear correlation line with the amplitudes proportional to each other likely originating from a series of two α decays of ^{222}Rn$\rightarrow^{218}$Po$\rightarrow^{214}$Pb in the crystal. It indicates the position dependence exists in the heat signals.

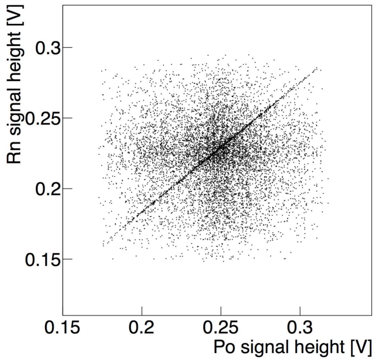

Figure 3. Evidence of position dependence. A clear correlation line can be seen in the figure. Its slop is consistent with the energy ratio of ^{222}Rn/^{218}Po. The resolution of the correlation line is 0.42% which is comparable to that of the heater events. (The heat channel shows a 0.3% energy resolution for heater signals of alpha equivalent energy of about 4 MeV while the alpha events have much worse energy resolution. The resolution difference is another indication of the position dependence in the heat channel.)

We interpret that the strong position dependence is attributed to the spin-lattice interaction of paramagnetic Eu ions in CaF_2 crystal [9]. In cryogenic particle detection with a crystal absorber, athermal phonons are initially generated near the vortex of an event in the crystal, and down-covert to lower energy phonons becoming a thermal phonon distribution. In general, the series of down-conversion processes last in an order of ms depending on the crystal quality. In this case of using a CaF_2(Eu) absorber, a significant portion of initial athermal phonons can interact with paramagnetic Eu ions. The mean life of athermal phonons can be much shorter than that in a pure crystal. The excitation of paramagnetic ions from athermal phonons takes place near the event location. However, the relaxation mechanism of the stored energy in the paramagnetic system to the crystal lattice has strong temperature dependent characteristics. The energy release from the spin system becomes very inefficient at the temperatures of the detector operation. Therefore, events near the phonon collector film experience less inelastic scattering of athermal phonons to the paramagnetic ions providing larger heat signals while those further from the film result in smaller and slower signals in the heat channel.

4. Conclusion

We studied a scintillating bolometer with a 312 g CaF_2(Eu) crystal that is two orders of magnitude larger than those in the previous experiments. The light/heat ratios showed a promising particle identification capability of 10 σ discrimination power. The light yield of alpha events is found as 17% of that of electron events in the CaF_2(Eu) crystal. Strong position dependence in heat channel can be interpreted as the effect from the spin-lattice interaction of paramagnetic Eu ions in the CaF_2 crystal.

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