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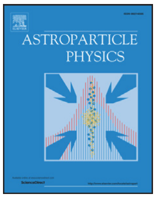

Novel measurement method of heat and light detection for neutrinoless double beta decay

G.B. Kim[a,b], J.H. Choi[a,b], H.S. Jo[a], C.S. Kang[a,b], H.L. Kim[a], I. Kim[a,b], S.R. Kim[a,b], Y.H. Kim[a,b,*], C. Lee[a], H.J. Lee[a,b], M.K. Lee[b], J. Li[a], S.Y. Oh[a,b], J.H. So[a,b]

[a] Center for Underground Physics, Institute for Basic Science (IBS), Daejeon 34047, Republic of Korea
[b] Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, Republic of Korea

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ABSTRACT

We developed a cryogenic phonon-scintillation detector to search for $0\nu\beta\beta$ decay of ^{100}Mo. The detector module, a proto-type setup of the AMoRE experiment, has a scintillating $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ absorber composed of ^{100}Mo-enriched and ^{48}Ca-depleted elements. This new detection method employs metallic magnetic calorimeters (MMCs) as the sensor technology for simultaneous detection of heat and light signals. It is designed to have high energy and timing resolutions to increase sensitivity to probe the rare event. The detector, which is composed of a 200 g $^{40}\mathrm{Ca}^{100}\mathrm{MoO}_4$ crystal and phonon/photon sensors, showed an energy resolution of 8.7 keV FWHM at 2.6 MeV, with a weak temperature dependence in the range of 10-40 mK. Using rise-time and mean-time parameters and light/heat ratios, the proposed method showed a strong capability of rejecting alpha-induced events from electron events with as good as 20σ separation. Moreover, we discussed how the signal rise-time improves the rejection efficiency for random coincidence signals.

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1. Introduction

Neutrinos are one of the elementary particles that compose the universe. In the standard model (SM) of particle physics, they are considered to be massless and electric-chargeless and to have half-integer spin. However, a series of observations on neutrino oscillation phenomena suggest that neutrinos have non-zero mass, and oscillate from one flavor state to others [1]. The flavor states can be expressed by a neutrino mixing matrix with mass eigenstates. Although the mixing angles in the matrix and square mass differences of the three mass eigenstates have been obtained recently [2], neutrino oscillation experiments do not provide the absolute mass scale of neutrinos. Moreover, their fundamental particle type (Dirac or Majorana) remains unanswered [3].

Double beta ($\beta\beta$) decay is an allowed nuclear transition for the isotopes for that the mass of the initial nucleus (A, Z) is larger than that of the final state nucleus (A, Z+2), but smaller than that of the intermediate state (A, Z+1). According to the SM, a $\beta\beta$ decay process is always accompanied by emission of two electrons and two neutrinos expressed as $2\nu\beta\beta$,

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e. \tag{1}$$

However, for the case where a neutrino is both massive and is its own anti-particle (i.e., a Majorana particle), the following $\beta\beta$ decay process without neutrino emission is allowed:

$$(A,Z) \rightarrow (A,Z+2) + 2e^-. \tag{2}$$

Observation of this neutrinoless double beta ($0\nu\beta\beta$) decay would provide an unambiguous answer to the Dirac-or-Majorana question. Allowing the physical process violating lepton number conservation would be a strong clue for matter-antimatter asymmetry in the present universe. Moreover, the absolute mass scale of neutrinos can be confined based on observation of $0\nu\beta\beta$ decay.

The half-life of the $0\nu\beta\beta$ process can be expressed as

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2 m_{\beta\beta}^2, \tag{3}$$

where $G^{0\nu}$ is a phase space factor, $M^{0\nu}$ is a nuclear matrix element, and $m_{\beta\beta}$ is the effective Majorana neutrino mass defined as

$$m_{\beta\beta} \equiv \left|\sum_{i=1}^{3} m_i U_{ei}^2\right|, \tag{4}$$

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[*] Corresponding author.
E-mail addresses: yhk@ibs.re.kr, yhkim@kriss.re.kr (Y.H. Kim).

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where U_{ei} are the PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix elements. In the $0\nu\beta\beta$ process, the total decay energy (Q) is mostly carried by two electrons with a negligible amount carried by a recoiled daughter nuclide. Hence, the $0\nu\beta\beta$ process will result in a peak at the end point of the $\beta\beta$ spectrum.

Neutrinoless double beta decay is expected to be an extremely rare process. A Majorana neutrino mass of 50 meV corresponds to a half-life of about 10^{26} years in ^{100}Mo $0\nu\beta\beta$ decay with some model dependance of the nuclear matrix element [4]. One $0\nu\beta\beta$ event of 1 kg ^{100}Mo would occur in about 20 years. One of the strategies to enhance the sensitivity is to increase the detector mass because a larger number of source elements provides a higher $0\nu\beta\beta$ decay event rate. Reducing background events in the energy region of interest (ROI) is another key factor that increases the detection sensitivity for this rare process. Moreover, the energy resolution of the detector that defines the ROI can be an efficient and crucial parameter. High resolution measurement increases the accuracy of energy detection, and narrows the width of the ROI. It results in a reduction in the number of background events in the ROI, particularly from irreducible $2\nu\beta\beta$ background events.

For a non-negligible background condition, the experimental sensitivity to the Majorana neutrino mass can be written as,

$$m_{\beta\beta} \propto \left(\frac{B\Delta E}{Mt}\right)^{1/4} \tag{5}$$

where B is the background rate, ΔE is the energy resolution of the detector, M is the mass of the detector, and t is the measurement time. It is noted that the experimental sensitivity for Majorana neutrino mass is proportional to the 1/4 power of the quantities. On the other hand, in the case that the expected background of the detector in the ROI is less than one event during the measurement period, so-called *zero-background* case, the sensitivity for the Majorana neutrino mass can be expressed as

$$m_{\beta\beta} \propto \left(\frac{1}{Mt}\right)^{1/2}. \tag{6}$$

In this zero-background case, the mass sensitivity is inversely proportional to the square root of the mass and measurement time.

The advanced Mo-based rare process experiment (AMoRE) is an international effort to search for $0\nu\beta\beta$ of ^{100}Mo [5–7]. AMoRE employs ^{40}Ca^{100}MoO$_4$ as the target material of the ^{100}Mo decay in the source-equal-to-detector concept. In order to increase the rate of $0\nu\beta\beta$ events, isotopically enriched ^{100}Mo is used to fabricate CaMoO$_4$ crystals. Moreover, enriched ^{40}Ca from ^{48}Ca depletion is used to minimize interference from $2\nu\beta\beta$ signals of ^{48}Ca. Consequently, doubly enriched ^{40}Ca^{100}MoO$_4$ crystals are used.

The choice of ^{100}Mo as a $0\nu\beta\beta$ candidate is advantageous. The Q-value of the ^{100}Mo decay is 3034.40(17) keV [8] which is sufficiently high to prevent interference from most of the environmental γ-ray backgrounds. The expected half-life of the ^{100}Mo $0\nu\beta\beta$ process is relatively short compared with other candidates [4,9]. Moreover, the high natural abundance of ^{100}Mo of about 9.6% does not require extraordinary enrichment cost.

Metallic magnetic calorimeters (MMCs) are used as the sensor technology for simultaneous measurement of heat and scintillation-light signals. MMCs have demonstrated high energy resolutions in X-ray and alpha-particle detections [10–13]. The simultaneous measurement technique makes it possible to separate out background alpha signals in an event by event manner. Moreover, the fast response time of MMC signals can minimize possible background from random coincidences of two $2\nu\beta\beta$ events.

Several Mo-containing crystals, such as Li$_2$MoO$_4$, CaMoO$_4$, MgMoO$_4$, and ZnMoO$_4$, have been used for suitability tests of large-scale $0\nu\beta\beta$ search experiments [14–18]. Using semiconductor-based neutron transmutation doped (NTD) Ge thermistors as their thermal sensors of phonon and scintillation measurement, 6.3 keV FWHM resolution for the 2615 keV γ-line of ^{208}Tl was found with a 330 g ZnMoO$_4$ detector, where 18σ and 19σ event discrimination capability were found from heat/light ratios and pulse shape parameters of β/γ and α signals, respectively [15]. Although the phonon-scintillation detector with NTD Ge readout provides high energy resolution and discrimination power, it showed limited timing resolution where the rise-times of the phonon and light signals were 12 ms and 3.2 ms, respectively. This limit on the rise-time of the signals originates from inefficient thermal coupling between phonons in the absorber crystal and conduction electrons in the thermistor. Recently, another type of phonon-scintillation detector was tested for a CaMoO$_4$ crystal with a NTD Ge sensor for heat signals and a millikelvin photomultiplier tube (PMT) readout for light signals where extreme timing resolution of the light signals was achieved [19], and two decay constants of 41 μs and 3.4 ms were found for CaMoO$_4$ scintillation below 100 mK [20].

The present experiment aims to develop a cryogenic phonon-scintillation detector based on a CaMoO$_4$ crystal with MMC readout as the detector technology of the AMoRE project. Taking advantage of the high energy and timing resolution of MMCs, simultaneous measurement of heat and light signals has been conducted using a 200 g ^{40}Ca^{100}MoO$_4$ crystal in an above-ground laboratory. This paper focuses on detector performances and characteristics, such as energy and timing resolutions as well as event discriminations by pulse shapes and heat/light ratios. These characteristics are empirically studied under various temperature conditions in an above-ground laboratory. Other aspects of the AMoRE experiments are discussed elsewhere (e.g. Monte Carlo background simulation [21], radioactive contamination of ^{40}Ca^{100}MoO$_4$ crystals [22], and the overall status of the AMoRE project [7]) (Fig. 1).

2. Detector setup

The detector module is designed for simultaneous measurement of heat (phonon) and scintillation-light (photon) signals from a CaMoO$_4$ crystal. In this present experiment, a doubly enriched ^{40}Ca^{100}MoO$_4$ was used as the target absorber. The internal background of the crystal, named *SB28*, was previously studied with room-temperature scintillation measurements at the YangYang Underground Laboratory (Y2L) [23]. The module was structured using oxygen-free high conductivity (OFHC) copper for high thermal conductivity at low temperatures. The crystal, with a mass of about 200 g, as an oval cylinder, was held by phosphor-bronze springs that were firmly attached to the copper holder. A patterned gold film of 2 cm diameter and 400 nm total thickness was evaporated on the bottom surface of the crystal. This film collects phonons generated by particle detection in the crystal. The phonon signals are read by a temperature sensor (i.e., an MMC sensor) placed on a copper plate with a superconducting quantum interference device (SQUID). The thermal connection between the gold phonon collector and the MMC sensor was made with annealed gold bonding wires. The majority of the energy absorbed in the crystals is converted into heat signals in the form of phonons. The excess phonons make net heat flow from the absorber crystal through the gold phonon collector film, gold wires and the MMC sensor. The heat eventually releases to a thermal bath through a weak thermal link made of a couple of gold bonding wires connecting the MMC sensor and the copper sample holder. The MMC, together with the SQUID read-out, measures the temperature change at the MMC sensor in the heat flow sequence. The details of the phonon sensing system are described in our previous reports [24,25].

A light detector composed of a 2 in Ge wafer and an MMC sensor was used to detect scintillation light from the CaMoO$_4$ crystal. This light detector was constructed in a manner similar to how the phonon sensor was made. It has three circular gold films, 5 mm in

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