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Micro-source development for XMASS experiment

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ABSTRACT

XMASS is a multipurpose liquid-xenon detector that currently aims to directly detect dark matter. In this paper, we describe the fabrication and characterization of reference sources used for the energy calibration and position reconstruction of the present XMASS detector. Several gamma-ray sources were produced in the form of a sealed needle-source. A thin-wall tube with a diameter of approximately 0.2 mm was sealed at both ends, with the ^{241}Am or ^{57}Co source material contained inside. The active region of the source was observed to be 1–2 mm long, close to the tip of the needle. These sources were tested in the XMASS detector, and the results were compared with Monte-Carlo simulations.

1. Introduction

The XMASS experiment is designed for multiple science goals to detect dark matter, pp and ^{7}Be solar-neutrinos, and neutrinoless double-beta decay by using highly purified liquid-xenon in an ultra-low radioactivity environment [1]. Currently, the XMASS experiment has been focused on the direct detection of dark matter. Many astronomical observations provide strong evidence for a large amount of dark matter in the universe [2–5]. However, its nature remains unknown. Weakly interacting massive particles (WIMPs) are one of the strong dark-matter candidates motivated by theories beyond the Standard Model [6–10]. The XMASS project aims to measure nuclear recoils in liquid xenon caused by WIMP-nucleon elastic scatterings. The detector is installed at the Kamioka Observatory of the Institute for Cosmic Ray Research (ICRR) at the University of Tokyo, Japan. The detector is located in the Kamioka mine 1000 m underneath (i.e., 2700 m water equivalent overburden) the top of Mt. Ikenoyama.

The XMASS detector is a single-phase liquid xenon scintillator detector containing 1050 kg of Xe in an Oxygen-Free High thermal Conductivity (OFHC) copper vessel. Using liquid xenon as the target materials has several advantages. Liquid xenon yields a large amount of scintillation light, which is comparable to the yield of a NaI(Tl) scintillator. Because xenon has a high atomic number ($Z=54$) and liquid xenon has a high density (~ 2.9 g/cm^3), external-background gamma-rays are strongly attenuated a short distance from the detector surface.

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The detector is composed of two groups of components, the inner and outer detectors (ID and OD, respectively). The ID is equipped with 630 hexagonal and 12 cylinder inward-facing photomultiplier tubes (PMTs) arranged on an approximately 80-cm-diameter spherical-type structure using a pentakis-dodecahedron shape supporter. The ID is completely immersed in pure liquid xenon inside the OFHC copper vessel. The amount of liquid xenon in the sensitive region is 835 kg. The OD is a large cylindrical water-tank with 72 20-in. PMTs. The OD is used as an active shield for cosmic-ray muons and a passive shield for low-energy gamma-rays and neutrons. The ID is installed at the center of the OD. Detailed descriptions of the XMASS detector were presented in a previous report [11].

XMASS requires a method to reconstruct the vertex position and to calibrate the energy from an event measurement with 642 PMTs of the ID. Reference events in the sensitive region can be generated by radioactive sources mounted on a source driving system that is able to change the source location in the liquid xenon. The size of the sources should be small to minimize the interference (i.e., shadow cast of scintillation light) by the source itself and its driving system. We produced several reference sources containing ^{241}Am or ^{57}Co. This paper describes the fabrication and characterization of the reference sources used for the energy calibration and position reconstruction of the present XMASS detector.

2. Micro-calibration sources for XMASS detector

2.1. Source requirements

The calibration measurement can be performed with a reference source placed in the sensitive region of liquid xenon. A conceptual design of the ID and a reference source is presented in Fig. 1. A radioactive source was mounted on the end of an OFHC copper rod which could be inserted directly into the liquid-xenon target. The rod was hung by a thin stainless-steel wire that was controlled by a stepping motor, which is not shown in the figure for simplicity. This calibration system made it possible to drive a source along the central vertical z-axis. The topmost PMT of the ID was designed to be remotely removable to insert the source rod into the sensitive region during the calibration procedure. The source driving system also had a load lock system to permit removal or replacement of the source without venting the ID chamber and breaking the vacuum of the cryostat.

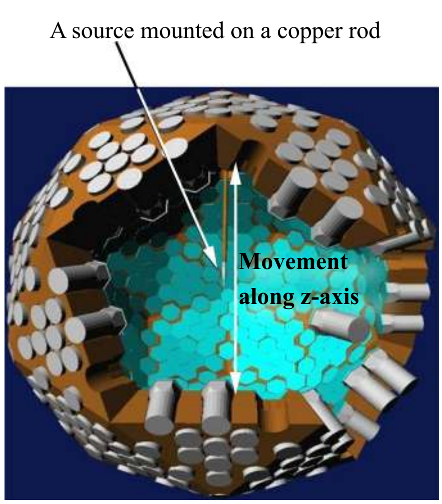

Fig. 1. A conceptual view of the inner detector. A reference source mounted on the end of a copper rod can be vertically positioned along the z-axis in the liquid xenon [11].

The calibration sources should be well constructed with a strong structure to prevent any radiation leak under the low-temperature circumstance. Their size should be sufficiently small to minimize the shadow of scintillation lights on the PMTs by the source itself. Monte Carlo simulations suggest that a cylindrical needle source with a diameter 1/3 of the attenuation length of a gamma ray dose would not block much of the propagation of the scintillation light to the PMTs.

Moreover, the count rate of the gamma-ray events should be in the range of 10–1000 Hz for a reasonable measurement time for the calibration procedure.

2.2. Fabrication details

The large gamma-ray attenuation of liquid xenon makes the source production hard for the XMASS detector. The attenuation length of gamma-rays in liquid xenon is shown in Fig. 2. For 59.5 keV and 122.1 keV gamma-rays from ^{241}Am and ^{57}Co, the attenuation lengths are 420 μm and 2829 μm, respectively [12]. We prepared a few ^{241}Am and ^{57}Co sources in a form of long fine cylinder. A cross-sectional view and an image of a completed source are presented in Fig. 3. In this design, a source material is electro-plated on a fine tungsten wire that is inserted into a thin-wall stainless steel tube with an outer diameter of 170 μm and 210 μm for the ^{241}Am and ^{57}Co sources, respectively. One of the major parts of the micro-sources for the XMASS detector is the stainless steel tube. The dimensions of the tubes used to make the sources are listed in Table 1. The tube dimension of the ^{241}Am source was slightly larger than the 1/3 attenuation length recommendation. The tube was placed in a stainless steel base that was sealed with soft solder at the both ends.

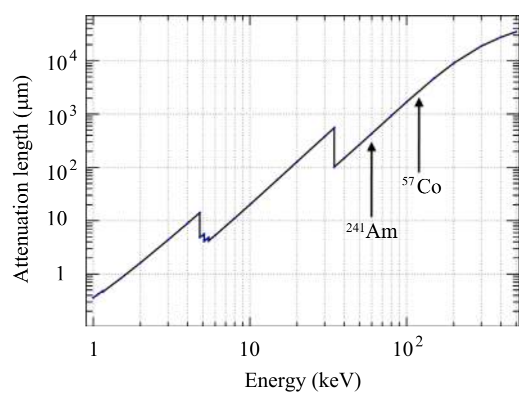

Fig. 2. Attenuation length of gamma-rays in liquid xenon [12].

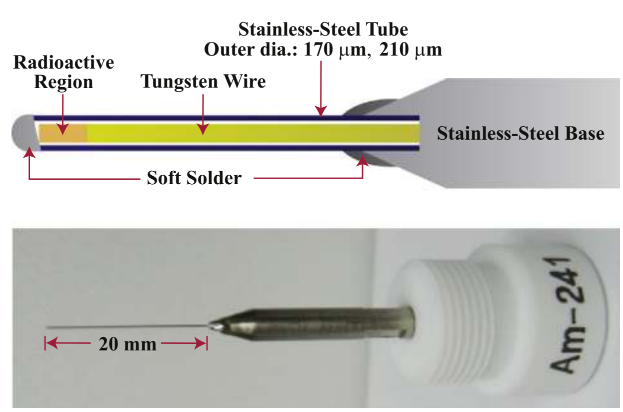

Fig. 3. The completed micro-calibration source for ^{241}Am (bottom) and its cross-section.

Table 1
Dimensions of stainless steel tubes used for the ^{241}Am and ^{57}Co sources.

Source	E_γ (keV)	Attenuation length in liquid xenon (μm)	Outer diameter (μm)	Wall thickness (μm)
^{241}Am	59.5	420	170	35
^{57}Co	122.1 136.5	2829 3740	210	65

The electrodeposition procedure was performed in a small beaker. A gold-plated tungsten wire with 50-μm diameter was used as the anode, and a platinum wire was used as the cathode. The two wire electrodes were parallelly placed in an electrolyte containing the ^{241}Am or ^{57}Co source materials. Only a few mm of the anode was dipped in the solution. The source material was deposited on a short length at the end of the tungsten wire.

After the deposition procedure, the tungsten wire was cleaned with distilled water and ethanol several times. Then, the radioactivity of the tungsten wire was measured with a coaxial low-energy high-purity germanium (HPGe) detector containing germanium with 13 mm height and 25 mm diameter. If a sufficiently high rate was measured, the end of the wire was cut to have only approximately 1–2 mm active length. The wire was threaded through the stainless steel tube with a length of approximately 22 mm. The wire was pulled to set the active region, that is, the end of the wire at one end of the tube, as illustrated in Fig. 3. The wire was cut out at the other end. This tube with the wire was then put in a base made of stainless steel. Both ends were soldered carefully to seal the source inside.

After source fabrication, leakage tests were performed with several cooling cycles. The source was put in and removed from liquid nitrogen several times and left inside liquid nitrogen for 48 h. The solder seals were checked by eye, and it was confirmed that the gamma activities of the source before and after the cooling cycles were not different. Moreover, any possible alpha particle leakage was tested with a low background multi-wire proportional counter. A 16-h measurement observed no excess counts from the background of the detector, which was approximately 0.03 counts/s.

2.3. Activity measurement

The gamma radioactivity of the completed source was tested with the HPGe detector and a lead collimator. A 2-mm-thick lead plate with a 1-mm-diameter hole was placed 1 cm above the window of the HPGe detector. A small apparatus to move the source horizontally, aligning the body of the source tube on the collimator hole, was installed on the lead plate. A set of the source distribution measurements along the tube direction was obtained for all of the sources. In addition, the angular uniformity of the source distribution was tested for the ^{241}Am source by rotating the source with respect to the detector.

A typical gamma-ray spectrum measured for each of the sources is presented in Fig. 4. The dominant peaks were identified as the major gamma lines from the sources, as marked with arrows in the figures. Some tungsten X-ray florescence lines, including dominant ones near 60 keV, appeared in the spectrum measured with the ^{57}Co source.

The gamma intensities of the ^{241}Am and ^{57}Co sources were calculated on the basis of the detection efficiency estimation using a Geant4 simulation [13] for the geometry of the source, the detector, and the collimator. The gamma activities emitting out of the source tube were in the range of 200–1000 Hz for the ^{241}Am and ^{57}Co sources.

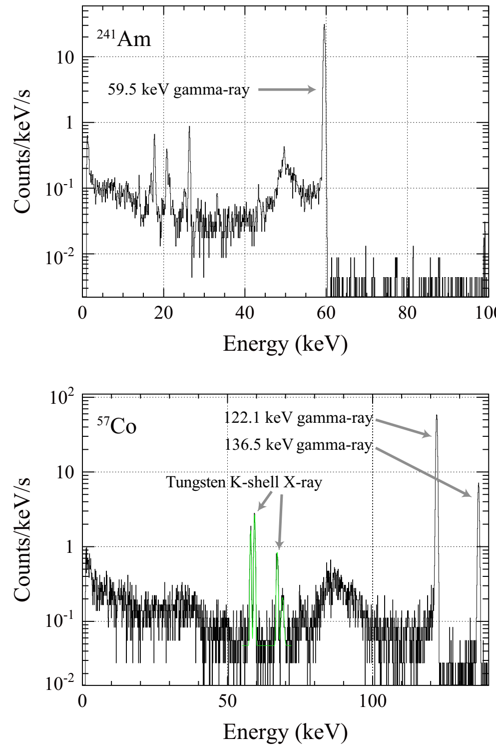

Fig. 4. Gamma-ray energy spectra of micro-calibration sources acquired with the HPGe detector. The major gamma lines are at 59.5 keV for ^{241}Am and 122.1 keV and 136.5 keV for ^{57}Co. Noticeable peaks appear near 60 keV in the ^{57}Co spectrum which are attribute to X-ray florescence from the tungsten wire.

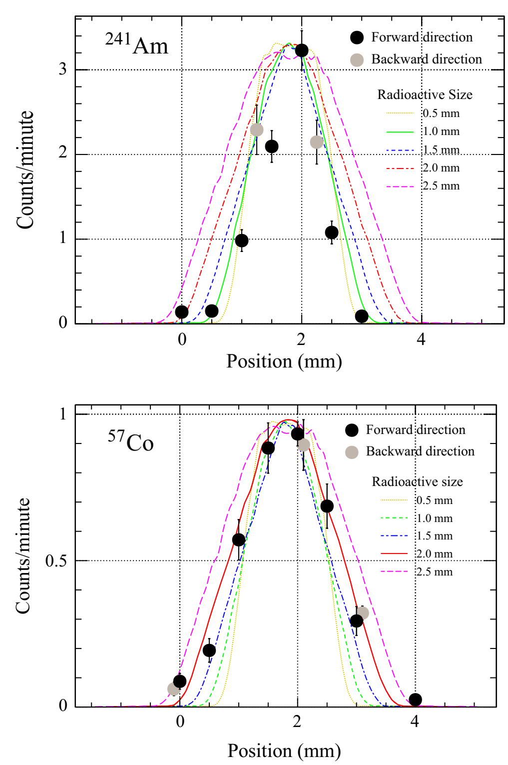

Fig. 5. The measurement results of the radioactive length on the micro-calibration source and simulation results with different radioactive sizes for (top) ^{241}Am and (bottom) ^{57}Co.

Fig. 5 presents the source distribution measurements of the ^{241}Am and ^{57}Co sources along the tube direction. Several measurements in different tube positions with respect to the collimator

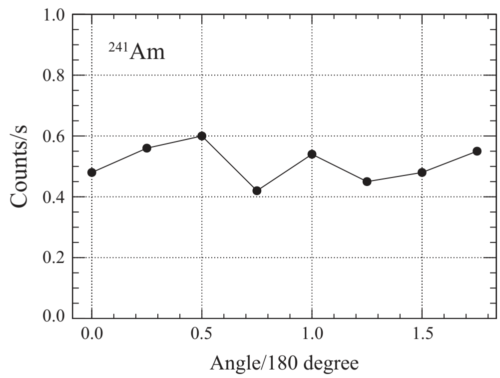

Fig. 6. The angular distribution measurement of an ^{241}Am source in 45° rotation steps.

hole were made in the forward and backward directions. A microscope was used to ensure a 0.5-mm increase of the relative position of the source tube to the hole in the forward direction. The zero position indicates that the edge of the collimator hole and the end of the solder seal at the tube end are in alignment. The solid lines represent the results of Geant4 simulations with 5 different active lengths of the source having the same maximum count rate. In comparison with the measurement and simulation for the ^{241}Am source, the simulation with the active length of 1 mm showed the best fit to the measurement. An approximately 2-mm-long active region was suggested for the ^{57}Co source. The comparison also suggested that the maximum activity was observed at approximately 1.8 mm from the end of the sources.

At the source position that resulted in the highest count rate, an ^{241}Am source was rotated to test the angular distribution of gamma-ray emission. It was a test of whether the source material was uniformly electrodeposited in the angular direction on the surface of the tungsten wire. As shown in Fig. 6, it was clear that the activity rates for the 8 different angles did not exhibit a tendency to a certain direction. However, the values were scattered with large deviation. Because the rotation axis and the tube direction were slightly different, the position of the active region relative to the 1 mm collimator hole varied slightly with different angles.

The activity measurement by moving and rotating the sources confirmed that the source material was confined to a short length near the end of the tube. The uniformity and localization of the source material in the reference sources would help us to minimize systematic errors for vertex reconstruction procedures in the XMASS detector.

3. Calibration measurement with a micro-source in the XMASS detector

The reference sources described in the present report have been used for the vertex and energy reconstruction of the XMASS detector [11]. With the ^{57}Co source, the light yield of the ID of the XMASS detector was measured to be 14.7 ± 1.2 photoelectron/keV[2]. The vertex positions and energies of events were reconstructed using the number and the pattern of photoelectron (PE) information from the ID PMTs [11]. Fig. 7 presents the measured energy spectrum with the ^{57}Co source at the position $z=0$ cm. The energy resolution for 122.1 keV gamma-rays is 4% (rms). The bottom figure of Fig. 7 shows the reconstructed vertices for different positions of the ^{57}Co source [11].

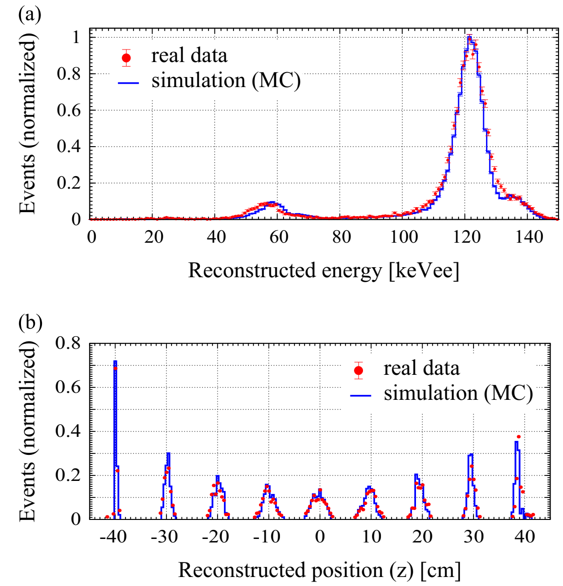

Fig. 7. (a) Energy spectrum measurement with the ^{57}Co source compared with the Monte-Carlo simulation at $z=0$ cm [11]. (b) Vertex distributions reconstructed by the measurement and the simulation using the same source at the source position between −40 and 40 cm in the ID.

The position resolution (rms) was determined to be 1.4 cm at $z=0$ cm and 1.0 cm at $z=\pm 20$ cm for 122.1 keV gamma-rays. The distributions of the reconstructed energies and vertices for 122.1 keV gamma-ray events are reproduced in good agreement with the Monte-Carlo simulations.

Moreover, the calibration measurements along the z-axis have been regularly performed with the reference sources. The threshold of the current XMASS detector was found as low as 0.3 keVee (electron-equivalent) [14]. Recently, a series of physics results on the detection limits of light WIMP search [14], solar axion search[15], search for inelastic WIMP nucleus scattering on ^{129}Xe [16] and search for bosonic superweakly interacting massive dark matter particles [17] were reported based on the regular calibration measurement.

4. Conclusions

Using highly purified liquid-xenon as a target material, the XMASS acts as a multipurpose detector system for a dark matter, pp and ^{7}Be solar neutrinos, and neutrinoless double-beta decay research. We have fabricated reference gamma-ray sources for the energy calibration and position reconstruction of the present XMASS detector. A micro-source structure that consisted of radioactive materials deposited on a tungsten wire in a fine stainless steel tube was successfully realized. The active length and uniformity of the source distribution were suitable for the use of the sources as a calibration source for position and energy reconstruction of the events measured in the XMASS detector.

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[2] The different photoelectron yield was reported in Ref. [11, 14–17] since we changed a correction on the charge observed in the electronics. The correction is within the uncertainty, ±1.2 p.e/keV.

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