WIMP search from XMASS-I fiducial volume data with background prediction

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Abstract. XMASS-I is a single-phase liquid xenon detector located underground in Kamioka Observatory mainly aiming direct detection of dark matter. We performed a WIMP search in a fiducial volume containing 96.5 kg liquid xenon using 705.9 live days of data between November 2013 and March 2016. All events remaining in the fiducial volume after data reduction were consistent with only background prediction from careful evaluation of it. In conclusion, a 90% confidence level upper limit on the spin-independent WIMP-nucleon cross section of $2.2 \times 10^{-44}$ cm$^2$ for a WIMP mass of 60 GeV/c$^2$ was derived.

1. Introduction

XMASS-I mainly aiming direct detection of dark matter particles at the Kamioka Observatory (2,700 m water equivalent) in Japan is a single phase detector using ultra pure liquid xenon (LXe). We assume Weakly Interacting Massive Particles (WIMPs) as dark matter candidate in this work. XMASS-I [1] consists of inner detector (ID) and outer detector (OD). The ID holds 832 kg LXe as an active scintillator target and 642 low background PMTs (Hamamatsu R10789) mounted on the pentakis-dodecahedral-shaped support structure made of Oxygen Free High Conductivity (OFHC) copper denoted as PMT holder. To prevent background from radioactive isotope (RI) impurities in aluminum material used for sealing between PMT window and body, OFHC rings are installed around the aluminum. In addition, thin OFHC copper plates are installed on these rings to make surface structure simple. The signals from each PMT are recorded by CAEN V1751 waveform digitizers with a sampling rate of 1 GHz. The waveform information is used to identify kinds of particles in background events among beta, gamma, and alpha particles. The OD is a cylindrical water tank with 10 m diameter and 11 m height containing 72 20-inch PMTs (Hamamatsu R3600) and ultra pure water. It serves as a shield against fast neutrons and external gamma-rays as well as an active muon veto.

Most of the observed events in the low energy region were coming from beta and gamma-rays from RI contamination in PMTs, rings, and plates, and RIs attached to the surface of rings and plates. Their vertex positions were concentrated in the volume near the surface of ring and plates. To reduce these background, a dedicated event reduction was applied based on vertex reconstruction and the clean inner region of the volume was used as fiducial volume. After event reduction, origins of remaining
background events were evaluated by using a Monte Carlo (MC) simulation including systematic errors, and WIMP signals were searched by subtracting background contributions. In this paper, we will describe physics results of WIMP search using the fiducial volume of XMASS-I detector.

2. Event reduction
The data used for this analysis were taken between Nov. 2013 and Mar. 2016, and amount to a total live time of 705.9 days, excluding scheduled calibration data taking and detector maintenance work. After data quality checks rejecting data periods with unstable temperature and pressure, PMT noise, unstable pedestal levels, or abnormal trigger rates, a dedicated data reduction consisting of standard cut, timing based reconstruction cut (R(T) cut), and observed photo-electron (PE) based reconstruction cut (R(PE) cut) were applied.

In the standard cut, events caused mainly by PMT after-pulse, electronic noise, and Cherenkov lights emitted from $^{40}$K contamination in the PMT photocathode were rejected. The most effective reduction in the standard cut is Cherenkov cut which is rejecting of events whose number of PMT hits in the first 20 ns divided by the total number of hits is larger than 0.6 and total number of PEs (NPEs) are less than 200 PEs. After applying standard cut, R(T) cut was applied. R(T) means distance from the detector center to vertex positions reconstructed by using timing distributions of each PMT. Probably density functions (PDFs) for points inside the detector sensitive volume were calculated by using the MC. Vertex position of each event is estimated from the PDFs with likelihood method. The requirement of R(T) < 38 cm is effectively eliminating surface events. R(PE) is calculated based on PE based vertex reconstruction. PDFs for points are calculated from expected NPE distributions in each PMT by using MC and vertex position and energy of each event are estimated with likelihood method. The selected fiducial volume is a spherical volume of 20 cm radius (R(PE) < 20 cm) containing 96.5 kg LXe. The left panel of Fig. 1 shows the observed NPE distributions of the data after different reduction steps. The NPE is converted to keVee incorporating all the gamma-ray calibration in the energy range between 5.9 keV and 2.6 MeV from $^{55}$Fe, $^{109}$Cd, $^{241}$Am, $^{57}$Co, $^{137}$Cs, $^{60}$Co, and $^{232}$Th sources with a consideration of non-linearity of the energy scale. The right panel of Fig. 1 shows reconstructed energy distribution of the final data sample.

3. Background evaluation
A Geant4 based XMASS MC has been developed for background evaluation. The MC covers the generation of scintillation photons, the tracing of each scintillation photon taking into account the optical properties of all the components in contact with the LXe, angle dependent reflection and absorption at the PMT photo-cathode, and response of all the data acquisition devices. It is verified against all available detector calibrations [2]. Three kinds of data set were used for background
prediction; (1) 15 days data (a subset of the 705.9 days data sample in this analysis) without any fiducial cuts denoted as “full volume data”, (2) selection of alpha events from data set of (1), and (3) 705.9 days data (same data sample in this analysis) with some kinds of fiducial volume cut.

(1) Amount of RI in all the detector materials except for OFHC copper and LXe were evaluated from 15 days full volume data with NPEs > 400 PEs. Since events in full volume of the ID with NPEs > 400 PEs mainly caused by external beta and gamma-rays from the detector materials surrounding LXe, contribution from WIMP signals is negligible. Therefore, full volume data was used for evaluation of amount of RI without affection from WIMP signal. The amount of RIs were extracted from observed NPE spectrum by fitting with MC. Initial values and errors of RIs of all detector components except for the OFHC copper and the LXe needed for fitting were obtained from measurement with high purity germanium (HPGe) detectors. Fig. 2 shows comparison of the 15 days full volume spectrum and the BG spectrum corresponding to the best fit. The thick black line is data and stacked colored spectra are various RI contributions.

(2) The $^{210}$Pb contaminations in the OFHC copper used for rings and plates were evaluated by extracting alpha events from 15 days data. Alpha events were selected based on their shorter scintillation decay time recorded with the waveform digitizer. The estimated concentration of $^{210}$Pb in the OFHC copper rings and plates is $24.8 \pm 4.8$ mBq/kg. It was consistent with the value of 17~40 mBq/kg independently measured with low background alpha counter [3].

(3) The amount of RIs in LXe were evaluated using all 705.9 days of data. The activities of $^{222}$Rn and $^{85}$Kr were obtained from coincidence events of $^{214}$Bi-$^{214}$Po in full volume and beta-gamma decay with R(PE) < 38 cm cut for 1st beta, respectively. The concentrations were $10.0 \pm 0.2$ µBq/kg for $^{222}$Rn and $0.4 \pm 0.1$ µBq/kg for $^{85}$Kr. Argon and carbon concentrations were evaluated by fitting of R(PE) < 30 cm spectrum above 30 keVee events. After evaluation of amount of all the RIs in all the detector materials, back ground MC with same live time of 705.9 days were generated with consideration of natural decay of each RI and time variation of optical parameters of LXe obtained from biweekly $^{57}$Co calibration. Same event reduction described in section 2 was applied to MC data set. Fig. 3 shows the energy distribution applying standard cut, R(T) and R(PE) cut for background MC. The main origins of remaining background events were $^{210}$Pb in OFHC copper rings and plates. They generated events happened on the surface of rings and plates with less sensitive angle of closest PMT and these events were wrongly reconstructed as inside the fiducial volume denoted as “miss-reconstructed events”. Miss-reconstructed events were also made by gamma-ray from PMT and aluminum seal. Only LXe internal background were actually happened inside the fiducial volume.

Systematic errors for background prediction were evaluated. Table 1 shows the list of systematic errors and their relative values. Uncertainties related to detector geometry corresponding from (1) to (4) in Table 1 resulted in large contributions to systematic errors.

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Figure 2: NPE spectra for the 15 days data and MC. Black line is data. Each color histogram is a different background RI. One bin corresponding to 400 PE.
Table 1: The list of the averaged systematic errors on the total event rate in background MC.

| Categories        | Contents                                      | Systematic errors  |
|-------------------|-----------------------------------------------|--------------------|
| Detector geometry | (1) Plate gap                                 | 2 – 15 keV$_{ee}$  |
|                   | (2) Ring roughness                             | +6.2/-22.8%        |
|                   | (3) Copper reflectivity                        | +6.6/-7.0%         |
|                   | (4) Plate floating                             | +5.2/-0.0%         |
|                   | (5) PMT aluminum seal                          | +0.0/-4.6%         |
| Detector response | (6) Reconstruction                             | +0.7/-0.7%         |
|                   | (7) Timing (decay time, PMT jitter)            | -                  |
|                   | (8) Timing (response near detector surface)    | -                  |
|                   | (9) Dead PMT                                   | -                  |
| Xenon property    | (10) LXe absorption and scattering             | 15 – 30 keV$_{ee}$ |
|                   | (11) Response for 206Pb nuclear recoil         | +6.7/-6.7%         |

4. WIMP search

We performed a WIMP DM search in final data set considering BG evaluation. Events induced by WIMP-nucleon elastic scattering were simulated for WIMP masses from 10 GeV/c$^2$ to 10 TeV/c$^2$ denoted as WIMP MC. We assume a standard spherical isothermal galactic halo model with the most probable speed of $v_0 = 220$ km/s, escape velocity of $v_{esc} = 544$ km/s, and a local dark matter density of 0.3 GeV/cm$^3$, following [4]. The same event reduction that was applied to the data and background MC was also applied to the WIMP MC. The systematic errors for WIMP MC come from the uncertainty of absorption and scattering length of LXe including time variation, scintillation decay time, efficiency for event reduction evaluated and scintillation efficiency for nuclear recoils. The largest systematic error for 60 GeV/c$^2$ WIMPs is coming from the uncertainty in the scintillation decay time and its relative values to total event rate are -10.4+3.3%, -8.0+4.9%, and -2.5+8.4% averaged in the 2–5, 5–10, and 10–15 keV$_{ee}$ ranges.

The energy spectrum of real data was fitted with background MC and WIMP MC in the energy range of 2–15 keV$_{ee}$. The best fit result was obtained with a WIMP contribution = 0. Fig. 4 shows the energy spectrum of the data as filled dots and the background estimate as a solid histogram reflecting this best fit. The 90% C.L. upper limit for 60 GeV/c$^2$ WIMP are also shown as the dotted histogram. The shaded band in Fig. 4 shows the sum of the 1σ errors for the background estimate which is smaller than the initial error estimate shown in the right panel of Fig. 3 because the largest component of the systematic error from the plate gap dependence was strongly constraint by the shape of the energy spectrum in the fitting process. The size of WIMP signal shown as the dotted histogram is
consistent with the size of shaded band. Fig. 5 shows the 90% C.L. upper limits for different WIMP masses. Our lowest limit is $2.2 \times 10^{-44}$ cm$^2$ for a 60 GeV/c$^2$ WIMP.

Figure 4: Data spectrum with statistic error (filled dots), background estimate (blue thick histogram) with 1 $\sigma$ error from the best fit shown as a shaded band, and WIMP MC expectation for 60 GeV/c$^2$ and a $2.2 \times 10^{-44}$ cm$^2$ cross section at 90% C.L. level (red broken histogram).

Figure 5: The spin-independent WIMP-nucleon cross section limit as a function of WIMP mass at 90% C.L. confidence level for this work (red thick line) Limits as well as allowed regions from other experimental results are also shown [5-14].

References
[1] K. Abe, et al., XMASS Collaboration, Nucl. Instr. and Meth. A716 (2013).
[2] N.Y. Kim, et al., XMASS Collaboration, Nucl. Instr. and Meth. A784 (2015) 499.
[3] K. Abe, et al., XMASS Collaboration, submitted to Nucl. Instr. and Meth., arXiv:1707.06413.
[4] J.D. Lewin and P.F. Smith, Astropart. Phys. 6 (1996) 87.
[5] K. Abe, et al., XMASS Collaboration, Phys. Lett. B 719 (2013) 78.
[6] K. Abe, et al., XMASS Collaboration, in preparation.
[7] J. Kopp et al., JCAP 03 (2012) 001.
[8] C.E. Aalseth, et al., CoGeNT Collaboration, Phys. Rev. D 88 (2013) 012002
[9] R. Agnese, et al., CDMS Collaboration, Phys. Rev. Lett. 111 (2013) 251301.
[10] R. Agnese, et al., SuperCDMS Collaboration, arXiv:1708.08869.
[11] P.-A. Amaudruz, et al., DEAP-3600 Collaboration, arXiv:1707.08042v2.
[12] A. Tan, et al., PandaX-II Collaboration, Phys. Rev. Lett. 117 (2016) 121303; X. Cui, et al., PandaX-II Collaboration, arXiv:1708.06917v1.
[13] D.S. Akerib, et al., LUX Collaboration, Phys. Rev. Lett. 118 (2017) 021303.
[14] E. Aprile, et al., XENON Collaboration, arXiv:1705.06655v2.