Nuclear Instruments and Methods in Physics Research A 623 (2010) 448–450

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

XMASS experiment, dark matter search with liquid xenon detector

Akihiro Minamino *,1

Kamioka Observatory, Institute for Cosmic Ray Research, The University of Tokyo, Kamioka, Hida, Gifu 506-1205, Japan

For the XMASS Collaboration

ARTICLE INFO

Available online 18 March 2010

Keywords:
Liquid xenon
WIMPs
Dark matter

ABSTRACT

The XMASS Collaboration is developing liquid xenon detector for the purpose of direct detection of dark matter in the universe. A prototype detector was developed at Kamioka Observatory to test the basic performance of single phase liquid xenon detector. With the detector, the physical properties of liquid xenon were measured, and the performance of vertex and energy reconstruction and the self-shielding power of liquid xenon for background $\gamma-$rays were confirmed.

1. Introduction

Recent results from Cosmic Microwave Background, Large Scale Structure and Type Ia supernovae observations have yielded a standard model of cosmology: a flat universe consisting of more than 70% dark energy and about 23% dark matter, and the remainder of ordinary (baryonic) matter [1–3]. The widely discussed (nonbaryonic) dark-matter candidate is Weakly Interacting Massive Particle, WIMPs. Supersymmetry (SUSY), a well-motivated extension to the Standard Model of particle physics, implies WIMPs [4].

The WIMPs from the halo of our Galaxy can elastically scatter off the target nucleus of a terrestrial detector, and transfer a small amount of energy to the recoil nucleus. The main challenge of the direct detection of WIMPs is the identification of a WIMP recoil event from a background event. Recent results to a WIMP-nucleon cross-section in spin independent case are limited by CDMSII [5] and Xenon10 [6] experiments with excluding DAMA allowed region [7].

The XMASS Collaboration is developing liquid xenon detector for the purpose of direct detection of WIMPs. Liquid xenon has a large light yield, comparable to that of NaI(Tl), so we can set a low energy threshold and achieve good sensitivity for the dark matter search. Because of the large atomic number of xenon ($Z=54$) and its high density in liquid form ($\sim 3\,g/cm^3$), background $\gamma-$rays are strongly attenuated in a short distance near the surface of the liquid xenon volume, allowing us to make a low background environment at the center of the detector for a dark matter search.

2. Experimental set-up

2.1. Prototype design

The prototype detector is a cubic vessel of liquid xenon made with OFHC copper, and the inner volume of it is 27 L. High purity 5N ($>99.999\%$) aluminum and 4N ($>99.99\%$) MgF_2 were evaporated on the inner surface as a reflective mirror for the scintillation light. The reflectance of the mirror was measured with the prototype detector as discussed in Section 5.1. Nine PMTs are attached on each face of the vessel, and scintillation photons are detected by a total of 54 PMTs through MgF_2 windows. Photocoverage of the detector is about 16%. The achieved light yields for 164 keV (^{131m}Xe) and 662 keV (^{137}Cs) $\gamma-$rays are 2.1 and 1.9 photoelectron/keV, respectively. (There is a non-linear scintillation yield.) The energy threshold of the detector is 5 keV electron equivalent. A schematic view of the prototype detector is shown in Fig. 1.

3. Detector simulation

The detector simulator program has been developed base on the GEANT3 package [8]. In the simulation code, tracks of particles, scintillation processes, propagation of scintillation photons and the response of PMTs are simulated.

In connection with the propagation of charged particles, scintillation photons are generated according to LET dependence of the scintillation yield [9].

For the propagation of scintillation photons in liquid xenon, Rayleigh scattering and absorption are considered in our simulation code. Light yield and absorption length of liquid xenon, and reflectance at the mirror on the inner wall were tuned to reproduce $\gamma-$ray calibration data, as discussed in Section 5.1.

* Tel.: +81 75 753 3849; fax: +81 75 753 3795.
E-mail address: minamino@scphys.kyoto-u.ac.jp
[1] Present address: High Energy Physics Group, Department of Physics, Faculty of Science, Kyoto University, Kitashirakawa, Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan.

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.03.032

4. Vertex and energy reconstruction

The vertex and energy of each event in the prototype detector is reconstructed with the charge distribution of the 54 PMTs. Charge patterns of the PMTs are made with the detector simulation in a 30 cm cubic lattice with 3 mm step size (1 030 301 points). The charge patterns are defined as $F_i(x, y, z)$. Here $F_i(x, y, z)$ is the expected number of photoelectrons of PMT no. i for 1 photon which was generated at vertex (x, y, z).

The vertex is reconstructed with the following likelihood of a Poisson distribution by comparing the detected charge distribution of the PMTs with $F_i(x, y, z)$:

$$\log(L) = \sum_{i=1}^{54} \log\left(\frac{\exp^{-\mu_i}\mu_i^{n_i}}{n_i!}\right). \quad (1)$$

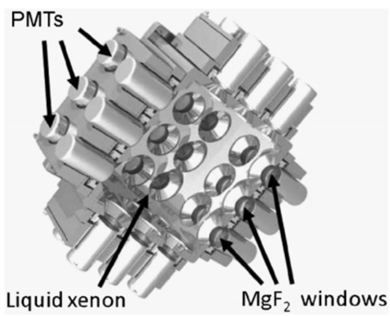

Fig. 1. Schematic view of the prototype detector. The cubic vessel of liquid xenon is made with OFHC copper, and the inner volume of it is 27 L with reflectors on the wall. Scintillation photons are detected by a total of 54 PMTs through MgF_2 windows.

Here n_i is observed number of p.e. with PMT no. i, and μ_i is

$$\mu_i = F_i(x,y,z) \times \text{“ num. of generated photons”} \quad (2)$$

$$\text{“ num. of generated photons”} = \frac{\sum_{i=1}^{54} n_i}{\sum_{i=1}^{54} F_i}. \quad (3)$$

The vertex with maximum likelihood is selected as the reconstructed vertex, then the reconstructed energy is calculated as

$$E(\text{keV}) = \frac{\text{“ num. of generated photons”}}{N_{photon}}. \quad (4)$$

Here N_{photon} is the number of generated photons per 1 keV measured with 662 keV γ−ray from ^{137}Cs source.

5. Results

5.1. Measurement of simulation parameters

Detector simulation is important for understanding the detector performance. The simulation parameters related to the scintillation photon tracking were measured with γ−ray calibration data, ^{137}Cs and ^{60}Co from the collimators. Charge distributions of the real data were compared with that of the simulation by using the χ^2 method, and the best fit parameter sets with systematic errors are as follows:

- Absorption length = 66(± 10) cm.
- Reflectance of the mirror = 52(+4 −6)%.
- Light yield = 80.6(± 4.0) photons/keV (at LET = ∞).

These simulation parameters are used for the following analysis.

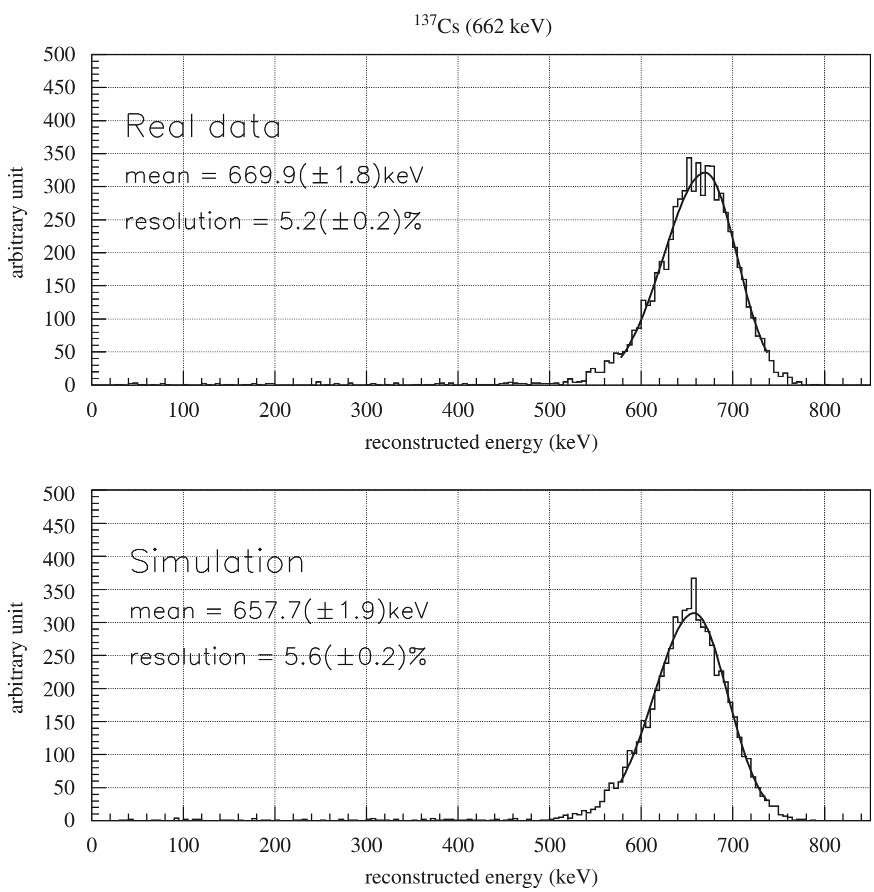

Fig. 2. Reconstructed energy spectrum for 662 keV γ−ray (^{137}Cs) reconstructed in 10 cm cubic from the center of the detector. Photoelectric absorption peaks are fitted with an asymmetric Gaussian (heavy line), and the energy resolutions of the real data (top) and the detector simulation (bottom) are 5.2 ± 0.2% and 5.6 ± 0.2%.

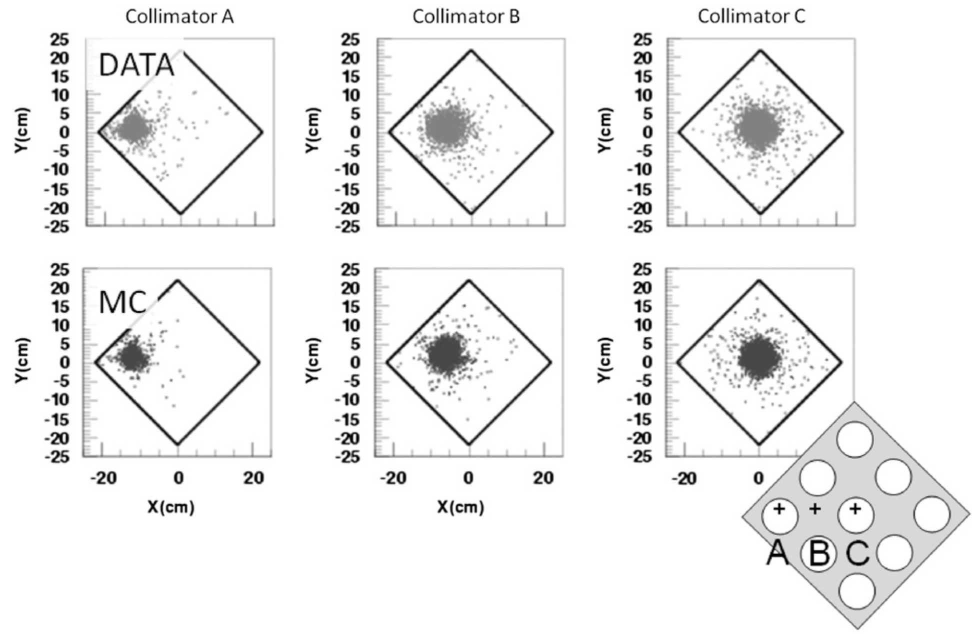

Fig. 3. The *X–Y* projection of the reconstructed vertices of ^{137}Cs from Collimator A, B and C. The injection positions of the $\gamma-$rays are shown by the right-bottom drawing.

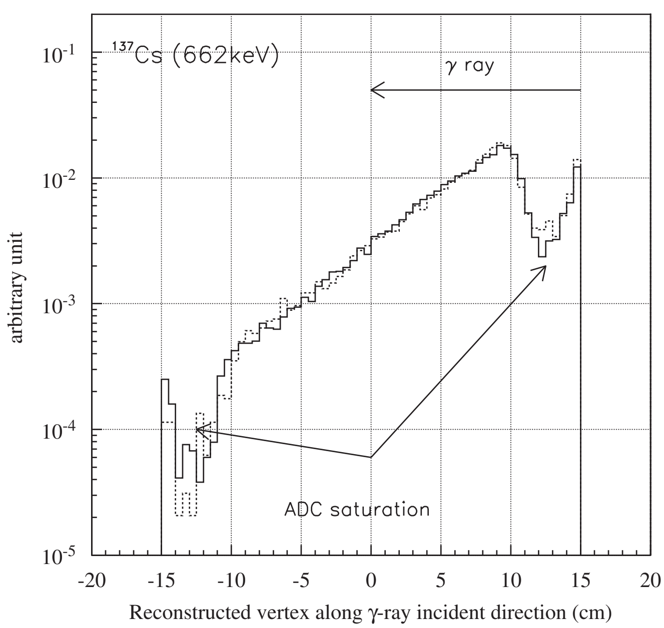

Fig. 4. Reconstructed vertex distributions along the particle incident direction for 662 keV $\gamma-$ray (^{137}Cs). The distribution of the real data (solid line) agrees well with that of the detector simulation (dotted line). Both ends of the distributions are chipped by cutting ADC saturated events.

5.2. Confirmation of detector performance

The performance of the vertex and energy reconstruction and the self-shielding power of liquid xenon was evaluated with γ- ray calibration data with ^{137}Cs (662 keV).

The reconstructed energy spectra in 10 cm cubic from the center of the detector are shown in Fig. 2. The spectrum of the real data agrees well with that of the detector simulation, so the energy reconstruction works as expected. Photoelectric absorption peaks are fitted with asymmetric Gaussian functions, and the energy resolution of the real data and the detector simulation are 5.2 $\pm$0.2% and 5.6 $\pm$0.2%.

The *X–Y* projection of the reconstructed vertices of the real data cluster around the $\gamma-$ray injection points and agree well with that of the detector simulation as shown in Fig. 3, which demonstrates that the vertex reconstruction works as expected. The reconstructed vertex distributions along the $\gamma-$ray incident direction are shown in Fig. 4. The distribution of the real data agrees well with that of the detector simulation, so the vertex reconstruction and the self-shielding power of liquid xenon for $\gamma-$rays works as expected.

6. Conclusion

A prototype single phase liquid xenon detector was developed at Kamioka Observator to check the performance of single phase liquid xenon detector. With the detector, the physical properties of liquid xenon were measured, and the performance of vertex and energy reconstruction and the self-shielding power of liquid xenon for background $\gamma-$rays were confirmed.

The XMASS Collaboration is constructing a single phase detector with 800 kg of liquid xenon for the purpose of direct detection of dark matter. The expected sensitivity of the detector to the neutralino as dark matter is about 2 orders magnitude higher than the present best limit in the world [6].

Acknowledgments

We gratefully acknowledge the cooperation of Kamioka Mining and Smelting Company. This work was supported by Grant-in-Aid for Scientific Research on Priority Areas. We are supported by Japan Society for the Promotion of Science.

References

[1] B.P. Schmidt, et al., Astrophys. J. 507 (1998) 46.
[2] D.N. Spergel, et al., Astrophys. J. Suppl. 148 (2003) 175.
[3] M. Tegmark, et al., Phys. Rev. D 69 (2004) 103501.
[4] G. Jungman, M. Kamionkowski, K. Griest, Phys. Rep. 267 (1996) 195.
[5] D.S. Akerib, et al., Phys. Rev. Lett. 96 (2006) 011302.
[6] J. Angle, et al., Phys. Rev. Lett. 100 (2008) 021303.
[7] R. Bernabei, et al., Phys. Lett. B 480 (2000) 23.
[8] GEANT, CERN Program Library Long Writeup W5013, 1994.
[9] T. Doke, et al., Jpn. J. Appl. Phys. 41 (2002) 1538.