Dark Matter Search Projects in the Kamioka Mine

Shigetaka Moriyama,[1]
Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo, Higashi-Mozumi, Kamioka, Hida-city, Gifu 506-1205, Japan

Abstract

The motivation for dark matter searches became much stronger since recent WMAP satellite data highly prefer large amounts of dark matter in the Universe. At the Kamioka Observatory, the XMASS group is planning to build an 800 kg liquid xenon detector to improve the sensitivity for dark matter searches by more than two orders of magnitude compared with that of current experiments. The research and development for the project is currently going well and many demonstrations have been done. Activities by other institutes are also high. Kamioka Observatory will be a central site of Japanese low background experiments such as dark matter experiments.

1. Introduction

The recent data from the WMAP satellite confirm the current energy density of the Universe is comprised of about 73% dark energy and 27% matter, most of which is in the form of non-baryonic dark matter. Furthermore, the convincing evidence for the existence of dark matter involves galactic dynamics. The energy density around 0.3 GeV/cc near our solar system is needed to explain the dynamics of our galaxy. There are strong theoretical motivations to assume the dark matter is weakly interactive massive particles (WIMPs). For example, supersymmetric particles are some of the best particles which explain the dark matter in the Universe. Therefore, the motivation of this WIMPs search became much stronger because of the recent observations above.

There are several ideas on now to look for WIMPs in the galaxy. The existing and future projects of dark matter searches in the Kamioka mine utilize nuclear recoil by dark matter particles. Since the nuclear recoil cross section is very small and the energy deposit is around only a few tens of keV, background and the energy threshold should be as low as possible. Large targets with low radioactive contamination is highly favored for this kind of experiment.

The XMASS experiment is one of the future projects of Kamioka Observatory. It aims at searching for rare phenomena under a low background environment by using large-volume ultrapure liquid xenon. The main physics targets

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of the XMASS project are dark matter, neutrinoless double beta decays, and low-energy solar neutrinos. A 1 to 10-ton scale detector would be build for those purposes.

In this talk, the details of the R&D status and the future plan of the XMASS experiment are discussed. Future dark matter search activities in the Kamioka mine by other institutes are also briefly mentioned.

2. XMASS experiment

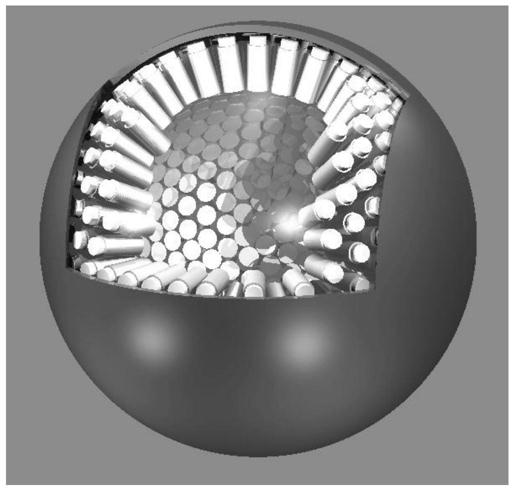

Fig. 1. XMASS detector design. This design is for an 800 kg liquid xenon detector.

The XMASS project utilizes liquid xenon as a scintillator. Fig. 1. shows the conceptual design of the XMASS detector. We put many PMT's outside the liquid xenon and observe scintillation photons to reconstruct event vertices and their energies.

Liquid xenon as a detector target for a dark matter search has many advantages which has been confirmed and demonstrated by our current R&D:

1. *High light yield as a scintillator*
   The most prominent property of liquid xenon is its light yield. It gives 42,000 photons for 1 MeV energy deposition by an electron which is comparable to that for NaI(Tl). Even for 5 keV events, intrinsic light yield is over 200 photons. This is essentially important for low energy experiments.

2. *Self-shielding effect*
   Generally speaking, PMT's give quite a large background compared with other detector parts. However, since xenon has a large atomic number, gamma rays from PMT's can be effectively shielded with just several tens

of centimeters of outer layer liquid xenon. Because event vertices can be well reconstructed based on scintillation patterns on PMT's, we can extract signals deep inside the detector with low background. This is called the self-shielding effect.

3. *Low radioactive contamination*
   As for the background due to the radioactive contamination inside the detector, we have enough prospect to realize the required background as discussed in Ref. [1]. This is mainly because xenon is a rare gas, and can be purified through its gas, liquid, and solid phases. One more important advantage is that we can purify xenon even after the experiment starts. If we use crystal scintillators or doped liquid scintillators, purification is quite difficult to perform.

With a prototype detector, we have demonstrated these essential points. We also compared with expectations obtained by Monte Carlo (MC) simulations and found good agreements. This means that we have well understood the prototype detector and its behavior. These results will be shown in the following sections.

Based on the encouraging experimental results, we are now designing an 800 kg detector which aims to detect dark matter. Since its sensitivity estimation for a dark matter search is based on a similar MC which was used for the prototype detector, the dark matter detector's feasibility is now better demonstrated. The solar neutrino detector will be a future step since it needs a larger mass of xenon.

2.1. Prototype Detector

The prototype detector consists of a 31 cm cubic oxygen-free-highpurity-copper (OFHC) chamber, 54 photomultipliers (PMT's), and a heavy shield. The PMT's detect scintillation photons outside the chamber through MgF_2 windows. The heavy shield consists of 15 cm-thick polyethylene, 5 cm-thick boric acid powder, 15 cm-thick lead blocks, 30 μm EVOH sheets, and 5 cm OFHC blocks. The heavy shield reduces external gamma rays and neutrons. The EVOH sheets are important to keep a low radon level inside the shield.

The detected photons are used to estimate the event vertex and deposited energy. Since the time constant of the scintillation is around 40 ns, event reconstruction cannot be done by timing information. However, a large photon yield enables us to reconstruct events by using the photo-electron patterns of PMT's. Fig. 2. shows a typical hit pattern of a background measurement. The details of the reconstruction methods can also be found in Ref. [2].

2.2. Demonstration of the self-shielding effect

The key idea to reduce background is to utilize the self-shielding effect of xenon. Since good reconstruction performance is required to realize a low back-

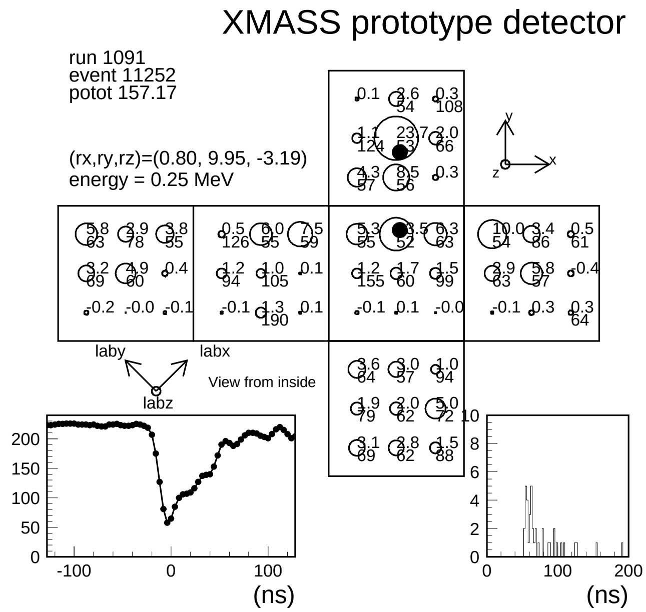

Fig. 2. Typical background event with the reconstructed information. The top center figure shows a development of the detector viewed from inside. The area of an open circle is proportional to the detected photo-electrons. By comparing these distributions with expected distributions, we can reconstruct event vertex as well as its deposited energy. The closed circles correspond to the projected position of the reconstructed vertex. The lower left figure shows FADC information of the summed signal of PMT's. The lower right figure shows hit timing distributions of each PMT.

ground deep inside the detector, we took data to demonstrate its performance. We have three small holes backside of the heavy shield. These holes can be used as collimators of gamma rays from calibration sources. We put ^{137}Cs and ^{60}Co gamma ray sources at the holes and took data. We expected exponential dumping of events towards the beam direction. Fig. 3. shows the distributions of the event vertices for ^{137}Cs and ^{60}Co gamma ray sources. The good agreement between data and MC strongly supports the validity of our simulations.

2.3. Background data of the prototype detector

We also took background data without any radioactive sources. The corresponding livetime is 3.9 days. Fig. 4. shows the real data and MC expectations. Since we have the self-shielding effect, we can expect a large reduction of background if we restrict the fiducial volume deep inside the detector. The solid histograms correspond to the innermost, 10 cm cube volume. The background at low energy is order of $10^{-2}\,\mathrm{keV}^{-1}\ \mathrm{kg}^{-1}\mathrm{day}^{-1}$ as expected by MC simulations.

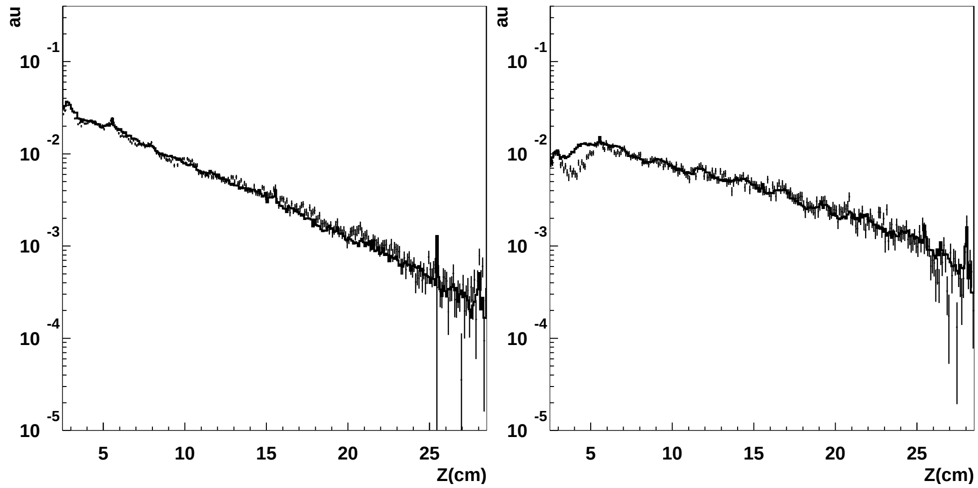

Fig. 3. The reconstructed event vertex distributions for ^{137}Cs (left) and ^{60}Co (right) gamma rays. The crosses show real data and solid histograms show Monte Carlo simulations. The horizontal axis corresponds to the depth of the event measured from the injection point. The exponential dumping toward the beam direction can be seen. The discrepancy at 2-5 cm in the right hand figure is due to an incomplete treatment of PMT saturation effect. Good agreement between real data and Monte Carlo simulations demonstrates the self shielding effect.

This agreement strongly supports the validity of our MC simulations, analysis method, and the background study for the next 800 kg detector.

The MC simulation is based on the measured radioactive contamination of PMT's and other parts which are used in the detector. The discrepancy in the resolution between data and MC is due to an incomplete understanding of photon absorption and scattering in liquid xenon as well as the reflection coefficient of the inner surface of the detector. We are now tuning those parameters in MC.

The increase of the event rate towards low energy is due to misreconstruction of events. Since the PMT's are outside the detector, there are some dead angles from the PMT's due to total reflection at the detector window. This causes misreconstruction of the events near the wall as if their interaction points are deep inside the detector. The misreconstruction is well reproduced in MC simulations and understood. In the 800 kg detector we will immerse PMT's inside the liquid xenon. Therefore this misreconstruction will be negligible compared with real background.

However, if we can reduce background at low energy with the prototype detector, this will serve as a satisfactory demonstration for the 800 kg detector. We will take data to overcome this weak point of the prototype detector. We will put teflon cones to reduce dead angles as shown in Fig. 5. Six cones will connect PMT's which occupy the center of each face to the central volume. With these cones, the central volume will be viewed only by these six PMT's without

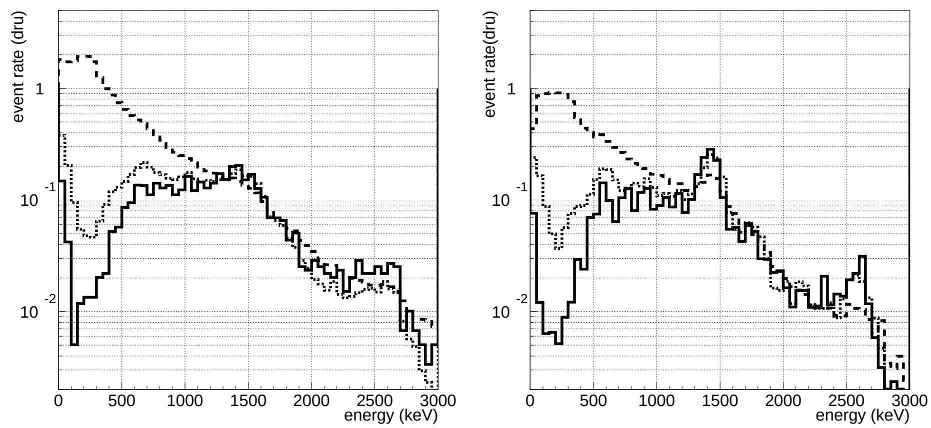

Fig. 4. Background spectrum for real data (left) and MC simulations (right). The horizontal axis is the reconstructed energy and the vertical axis is the event rate in unit keV^{-1} $kg^{-1}day^{-1}$ (DRU). The thick dotted line, thin dotted line, and solid line correspond to all volume (31 cm cube), inside 20 cm cube, and the most inside 10 cm cube volume, respectively. One can see a large reduction of background around 100-500 keV region due to the self shielding effect. One can see the reduction factor is as expected by MC simulations. See text for the peak below 100 keV in the 10 cm cube volume data.

any dead angles. A background estimation based on another MC simulations suggests $10^{-2}keV^{-1}kg^{-1}day^{-1}$ level background which is two orders of magnitude lower than that of DAMA experiment. We are preparing this experimental setup and will take data in Feb. 2005.

2.4. Radioactive contamination and reduction in xenon

Radioactive contamination in xenon is another issue. For U and Th chains, we can select the Bi-Po events in each chain by using FADC information. As a result, we found ^{238}U is $33 \pm 7 \times 10^{-14}$g/g and ^{232}Th is less than 23×10^{-14}g/g if we assume equilibrium of U and Th chains. Those values are a factor of 30 larger than the target values for the 800 kg detector. However, since we did not use any filter except for a simple getter, we have prospects to reduce these contaminations by using more specialized filters we are now developing.

As for the Kr contamination, we independently developed a distillation system which reduces Kr contamination in xenon. The principle is based on the difference of boiling points of xenon and krypton. We built this distillation system, processed our xenon, and confirmed the reduction factor is as expected; it is almost a factor of 1000 since the raw xenon gas has 3 ppb Kr and the processed xenon gas has 3.3±1.1 ppt Kr(mol/mol). Though this value is a factor of 3 larger than the target value, we can modify our system to achieve the target value easily

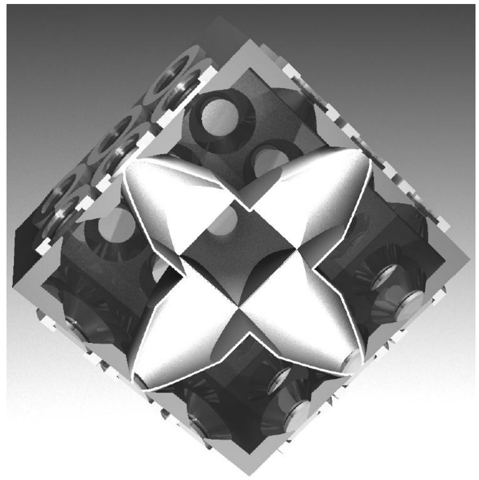

Fig. 5. Configuration for the light guides. See text.

by just increasing the height of the distillation tower.

The method to measure 3.3 ppt Kr in xenon gas is also an interesting technique. We enriched the Kr concentration by a factor of 100 by using a liquid nitrogen trap and measured it with an API-MS. Further improvement is possible by increasing this enrichment.

2.5. Expected sensitivity of the 800 kg detector

Based on these encouraging experimental results, we are now designing the 800 kg detector. The schematic view of the detector is already shown in Fig. 1. Its sensitivity for spin-independent interactions will be two orders of magnitude higher than the current experimental results. This detector would reveal the nature of dark matter.

For estimation, we assume 5 years data taking and expected a background of $10^{-4}\mathrm{keV}^{-1}\mathrm{kg}^{-1}\mathrm{day}^{-1}$. We are now developing further low background PMT's whose radioactive contamination is an order of magnitude lower than present PMT's. Since we already know high radioactive parts in the current PMT's, we have enough prospect to achieve this improvement.

3. Other Projects in the Kamioka Mine

At present, there are four more experiments projected in the Kamioka mine:

1. *Waseda University dark matter experiment: XMASS-DP*
   Waseda group also belongs to the XMASS group. They are developing a particle identification technique using liquid xenon. By applying an electric field, one can extract and detect ionization electrons outside the liquid

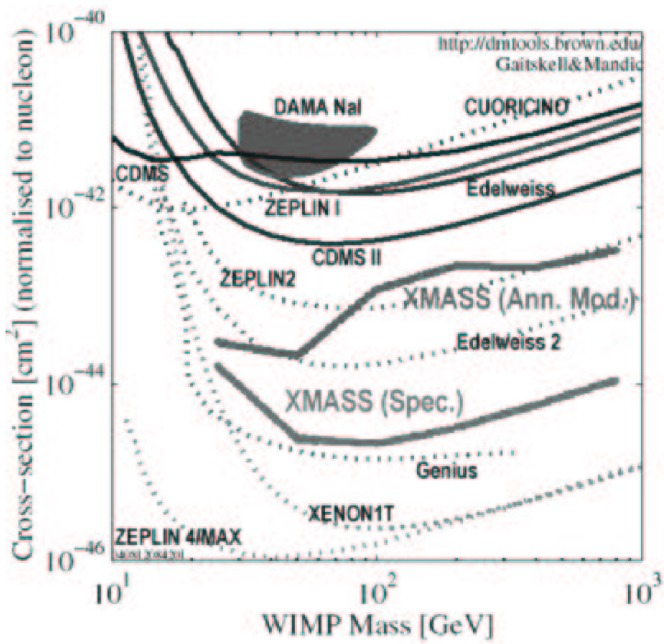

Fig. 6. Expected sensitivity for the 800 kg detector. Lower thick curve corresponds to an analysis to find an increase of number of events due to a dark matter signal in a spectrum. Upper thick curve corresponds to an analysis to look for an annual modulation. Both analysis can give large improvements compared with existing experiments.

xenon. However, due to different ionization densities which lead to different recombination probabilities, gamma rays and electron events give an ionization signal but the nuclear recoil events do not. By utilizing this difference, major background coming from gamma rays and beta rays can be reduced significantly. They are developing a 15 kg gas-liquid (double phase) detector.

2. *Kyoto University dark matter experiment: NEWAGE*
Since the solar system and the earth are moving in the galaxy, the average velocity of dark matter particles on a target varies as a function of time. If we can identify tracks of the recoil nucleon and correlation to the variation, it will be definitive evidence for the existence of dark matter. The Kyoto group is developing a fine gas tracking technique. An advanced technology μ-PIC read-out system is used in a gas TPC system. This system is being developed for astronomical applications which can be also used for a dark matter search. It also has particle identification since nuclear recoil gives large dE/dx along its track. They are going to put a prototype detector in the Kamioka mine within a few years.

3. *University of Tokyo dark matter experiment*
   Tokyo group is studying achievable low background levels at low energy. They are using low background CaF_2(Eu) crystal which uses pure Ca and F material developed by Osaka group. Modified XMASS PMT's are attached to the crystal and measure its background. Its background is around $7\,keV^{-1}kg^{-1}day^{-1}$. They already obtained an improvement for the sensitivity of dark matter search. They will continue to improve its background.

4. *Osaka University double beta experiment: CANDLES*
   CANDLES is a double beta decay experiment. A large number of CaF_2 crystals are immersed in a large volume of liquid scintillator. PMT's will be located outside the volume. Since ^{48}Ca has a large Q value, $0\nu\beta\beta$ probability is high and only a limited number of sources can contribute as background. It is expected to make significant improvements for double beta decay experiments. Although scintillation yield is not large, the group is considering to lower its energy threshold. Since fluorine is sensitive for spin-dependent interactions of dark matter, it would give interesting results also for a dark matter search.

R&D for these experiments are on-going and expected to be set up within several years. All of them are going to improve the sensitivity for a dark matter search. The Kamioka Observatory is expected to be a central site for Japanese dark matter search experiments.

4. Summary

The motivation for searching for dark matter became much stronger since recent WMAP satellite data highly preferred a large amount of dark matter in the Universe. At Kamioka Observatory, the XMASS group is planning to build the 800 kg liquid xenon detector to improve sensitivity with more than two orders of magnitude compared with that of the current best dark matter search experiments. The R&D for the project is going well and many demonstrations have been done. Activities by other institute are also high. Kamioka Observatory will be a central site for Japanese low background experiments such as dark matter experiments.

5. References

1. Y. Suzuki, hep-ph/008296.
2. S. Moriyama, *In the proceedings of BEYOND 2003,* Springer Verlag, pp 385-396, Castle Ringberg, Tegernsee, Germany, 9-14 June, 2003.