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The XMASS Experimental Program and its Current Implementation

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XMASS is an experimental program at the Kamioka Observatory in Japan designed for low energy, low background dark matter searches and neutrino physics. The core technology is a self-shielding single-phase liquid Xenon detector optimized for maximum scintillation light collection. In this talk we describe its current implementation and discuss its general performance after its 2013 refurbishment.

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1. Introduction

XMASS is a low background, self-shielding, single phase liquid xenon (LXe) detector. More precisely, the name refers to an experimental program at the Kamioka Observatory in Japan that is built around this detector technology [1]. High photocathode coverage on the inner detector (ID) inner surface optimizes the photoelectron yield and gives our technology an edge in low energy searches. The ID inner surface in our current design is a pentakis-dedecahedron, a close approximation to a spherical inner surface made from triangles. This allows to define a fiducial volume (FV) that itself is spherical and centered in the detector. Self-shielding for the FV is provided by the radio-pure LXe buffer between the radius defining the FV's outer limit and the inner wall of the ID. The detector's total active volume comprises both, the FV and that shielding LXe buffer - in other words: the active volume is the whole, homogeneous LXe volume inside the ID.

The XMASS experimental program aims for a final detector size that allows to address three of the most fundamental challenges in contemporary particle and astroparticle physics:

- the direct search for dark matter
- the search for neutrinoless double beta decay
- measuring the low energy pp-neutrino flux from the Sun

The acronym XMASS reflects these main physics objectives of the program:

- Xe detector for weakly interacting MASSive particles
- Xe neutrino MASS detector
- Xe MASSive neutrino detector

The final step in this program is projected to contain 24 tons of LXe, with 10 tons of this total active LXe mass comprising the fiducial volume. Assuming standard fluxes this future detector will record 14 pp and 6 ^{7}Be solar neutrino events per day, which also are an irreducible background to our dark matter searches.

2. XMASS at the Kamioka Observatory

The first step in this program was a 100 kg, proof of principle experiment that concluded successfully [2] and paved the way for a dedicated experimental hall to be excavated for the program. The current implementation of XMASS contains more than 830 kg of LXe inside the ID's active volume, making it the largest LXe detector in operation. The photocathodes of 642 low background, hexagonal, high quantum efficiency 2-inch Hamamatsu R10789 photomultiplier tubes (PMTs) line this active volume.

The PMTs are held in place by oxygen free, high conductivity (OFHC) copper triangles that the pentakis-dodecaheral structure of the ID is constructed from. During the commissioning phase, which lasted from December 2010 through May 2012, the PMTs' metal bodies were pulled back into holes in those copper triangles, with their flat entrance windows protruding into the ID's LXe volume. This detector configuration is referred to as XMASS-1 and a detailed description is given in [3].

During 2013 the detector was refurbished. Among other things a thin copper layer with cutouts for the PMTs' photocathode areas was added that effectively moved the PMT entrance windows below the ID's copper surface. At the same time the inner surface of the detector's structural triangles was taken a little further out in radius to keep the total active volume as close to that of the original XMASS-1 configuration as possible. The total mass of LXe in our active volume did therefore not change by much: it was 835 kg for XMASS-1, and is 832 kg now. This new detector configuration is referred to as XMASS-RFB and has been taking data continuously since November 2013.

XMASS physics results so far were largely obtained with the XMASS-1 detector used in the commissioning phase [4][5][6][7]. First results obtained from XMASS-RFB data will be presented at this conference.

The ID is contained in an OFHC copper vacuum vessel that holds the LXe. Thermal insulation against the surrounding active water shield is provided by another OFHC vacuum vessel surrounding this inner vessel and maintaining the vacuum between the two vessels.

XMASS was the first Dark Matter (DM) experiment to use an active water shield, building on the Kamioka expertise with water Cherenkov detectors. This active shield vetos cosmic ray muons, and both moderates fast neutrons and attenuates the external gamma ray flux from the surrounding rock. It thus provides another important layer of shielding the FV and in fact the whole ID from external BG radiation. Inside the tank the air above the water is scrubbed of ^{222}Rn in chilled active charcoal traps. Outside of this tank the experimental hall is provided with outside air low in ^{222}Rn and lined with a retardant to suppress the injection of ^{222}Rn from the surrounding rock. The layout of the experimental hall and the current dimensions of this water tank can accommodate the program's ultimate envisioned detector size with the 10 ton FV.

3. XMASS-1: Lessons from the commissioning phase

Two main sources of background were identified during the analysis of the XMASS-1 data. The first stems from to a radio-isotope (RI) contamination in the aluminum seal between the PMT entrance window and the metal body of the PMT. The second originates from RI embedded in or attached to the copper surfaces of the detector's structural oxigen free high conductivity (OFHC) copper that had accumulated during detector assembly.

While the materials for PMT production were carefully screened, the minimal amount of aluminum needed to seal the PMT's entrance window to its Kovar body was not properly appreciated in this process. In XMASS-1 this seal was facing the inside of the ID as well as being immersed in the detectors active LXe target. This allowed its ^{210}Pb and ^{238}U chain contamination to give rise to low energy scintillation light events: beta particles may deposit only a minimal fraction of their energy in the LXe as their paths straddle the boundary between the opaque Al and the scintillator. Confounding this problem is the fact that the PMTs currently in use have a flat photocathode: Light emitted to the side of the PMT in or below the photocathode plane will not intersect the photocathode and not be detected. As neighboring PMTs in the pentakis-dodecahedral layout of the ID's inner surface often find themselves in the same geometric plane (on the same triangle surface), this systematically prevents a signal originating on the inner surface of our detector from being registered on the PMTs nearest to the signal's place of origin, throwing off our photoelectron count based vertex reconstruction.

This problem afflicts both RI contamination on the inner surfaces of the copper structure as well as that in the Al seal. Before assembly the XMASS-1 copper surfaces where chemically etched to remove such contamination, but during assembly new RI deposits by ambient ^{222}Rn decays and RI decays in dust particles partially reversed this effort.

4. Solutions implemented during refurbishment

Based on our experience with XMASS-1 various improvements were made during the 2013 refurbishment of the detector. These improvements start with the surface treatment and protection prior to and during assembly and extend to configuration changes at the detector's innermost surface. They resulted in significantly reduced background in the refurbished detector. The refurbished detector is referred to as XMASS-RFB.

The first of the procedural improvements was to electropolish rather than chemically etch the copper surfaces after machining. Re-using the original XMASS-1 copper triangles we machined their inner surface to retract the PMTs a little bit, which allowed us to cover the contaminated Al seal on each individual PMT with an electropolished OFHC copper ring around the PMT window's edge and to add an electropolished OFHC copper plate to cover the resulting gaps between the copper rings on the detector's inner surface. This new structure is shown in figure 4. To avoid scintillation light from LXe filling the new copper rings reaching the inner detector through the PMT window, a high purity, ultra low RI aluminum light seal was evaporated onto the sides of the PMT windows.

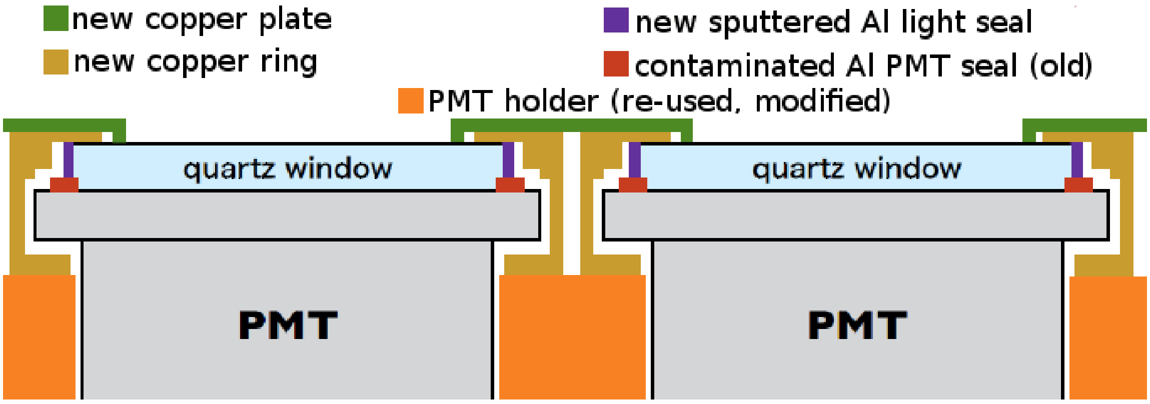

Figure 1: XMASS-RFB cross section of the detector's inner surface structure. Set screws keep the new copper rings flush with the PMT entrance window. As in XMASS-1 each PMT - now with its copper ring - is pulled back against the inner surface of the now electropolished OFHC copper PMT holder. A new copper plate covers the new copper rings and the gaps between them. All new copper parts also were electropolished before installation.

The resulting new inner surface structure eliminates surface area that is directly facing the ID, but "below" the photocathodes. Yet again scintillation light from the new innermost copper surface

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has no direct path to the nearest photocathodes. To fundamentally solve this problem XMASS and Hamamatsu Photonics developed a new PMT with a domed photocathode. The first batch of these new 3-inch round PMTs are currently being tested at Kamioka for future deployment in an upgraded detector. This development is described in a separate presentation at this conference.

Environmental improvements were also important during the assembly of the refurbished detector. Making the XMASS experimental hall itself a clean room with its own clean room provisions and installing new HEPA filters improved the cleanliness of the innermost cleanroom environment where the ID was re-assembled inside the water tank. Both assembled and yet-to-assemble detector parts were kept under both electrostatic and radon shields throughout construction. The volume inside these shields was continually flushed with pure nitrogen, requiring extra safety procedures to protect the scientific staff working on the installation.

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5. Performance of the refurbished detector

As a consequence of these efforts the background situation in XMASS-RFB is significantly improved, validating our understanding of detector backgrounds. There are two major thrusts in our analysis: At low energy deposits we can capitalize on our detector's exceptional photon yield - the highest among operating LXe detectors. On the other hand the low photon counts even in our detector makes position reconstruction unreliable, and we have to take events from all of the active volume inside the detector. As can be seen in figure 5, overall event rate in the refurbished detector is reduced by one order of magnitude from XMASS-1.

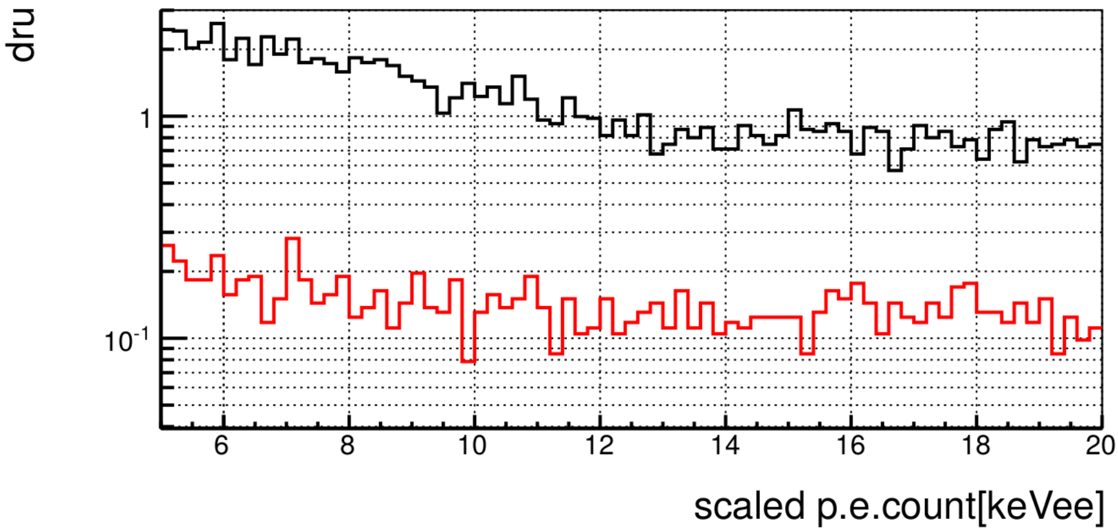

Figure 2: Low energy event rates: Event rate in the whole active volume before and after refurbishment: black is XMASS-1, red is XMASS-RFB.

At energies greater 5 keV$_{ee}$ event reconstruction is done using a likelihood fit to the measured charge distribution over the ID PMTs, and background from external gamma rays attenuated in the LXe outside of the fiducial volume can be discarded. Note that our detector is a single phase detector in which pulse shape discrimination between nuclear and electron recoils can only be used at energies that are too high for standard DM analyses. With standard cuts [7] the event rate inside a fiducial volume of 15 cm radius at the center of the detector was of $O(10^{-4})$/kg/day/keV$_{ee}$ for energy deposits of around 100 keV$_{ee}$ in XMASS-1 already, lower than any other DM experiment operating in that energy region. The fiducial volume analysis for XMASS-RFB is currently being finalized.

6. Conclusions

Refurbishing XMASS-1 in 2013 with minimal changes keeping its fundamental design allowed us to reduce the remaining background in the detector by one order of magnitude. This was achieved by improving our procedures as we re-assembled it using its original components, adding only some specific solutions to address the major problem with the existing PMTs. Since November 2013 XMASS-RFB is steadily and reliably taking new, high quality dark matter data again.

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