THE XMASS EXPERIMENT

MAR. 8TH, 2019

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CONTENTS

• XMASS project
• Physics results from XMASS
• Low background technique in XMASS
• Summary
THE XMASS PROJECT

- **XMASS**: a multi purpose experiment with liquid xenon
  - Dark matter
  - Solar neutrino (pp/7Be)
  - 0ν ββ

- Located **1,000 m underground** (2,700 m.w.e.) at the Kamioka Observatory in Japan

- Features
  - Scalability
  - Low energy threshold (~0.5keVee)
  - Sensitive to e/γ events as well as nuclear recoil
XMASS-I DETECTOR

- **Liquid xenon detector**
  - 832 kg of liquid xenon (-100 °C)
  - 642 2-inch PMTs (Photocathode coverage >62%)
  - Each PMT signal is recorded by 10-bit 1GS/s waveform digitizers

- **Water Cherenkov detector**
  - 10m diameter, 11m high
  - 72 20-inch PMTs
  - Active shield for cosmic-ray muons
  - Passive shield for n/γ
• Stable data taking from 2013 Nov. to 2019 Feb. (LT=1807.3 day)
• We achieved the objectives of XMASS-1 and shut down on Feb. 20th, 2019.
1898.4 calendar days
DAQ runtime = 1807.3 days
Good run = 1638.9 days (86.3 %)
ACHIEVEMENTS IN XMASS-I

- Dark matter searches
- Neutrino studies
- Other exotic physics (Axion, ...)
  - Solar axion, KK axion,
- Neutrino observatory
- Low background technology
DARK MATTER SEARCHES IN XMASS-I
-- ANNUAL MODULATION

• **DAMA/LIBRA’s claim** ([https://doi.org/10.15407/jnpae2018.04.307](https://doi.org/10.15407/jnpae2018.04.307))

  • The data of the new DAMA/LIBRA-phase2 confirm a peculiar annual modulation of the *single-hit* scintillation events in the (1 - 6) keV energy region satisfying all the many requirements of the DM annual modulation signature; ...

![Graph showing DAMA/LIBRA phase1 and phase2 data with residuals, cpd/kg/keV, and time, d]
• Annual modulation search with the XMASS (10.1103/PhysRevD.97.102006)

• Target volume = 800 kg, Livetime = 800 days (1.82 ton*year, 2.2 cycle)

Assuming WIMP DM, we excludes DAMA/LBRA allowed region at 3σ level by annual modulation.
In model independent analysis, we found no periodicity in data.
DARK MATTER SEARCHES IN XMASS-I -- ANALYSIS WITH EVENT RECONSTRUCTION

- **Event reconstruction in XMASS:**
  - Event energy and position can be reconstructed with numbers of P.E. in each PMTs.

\[ L(x) = \prod_{i=1}^{642} p_i(n_i) \]

\( p_i(n) \): probability that the \( i \)-th PMT detects \( n \) PE

- **Strong self-shielding** could lead small numbers of BG at the center region, \( r<20 \text{ cm} \).
RESULTS: ENERGY SPECTRUM IN THE FIDUCIAL VOLUME

- Fiducial mass 97kg (R<20cm)

- Main background in the WIMP search region
  - $^{210}$Pb in the copper
  - $\gamma$-rays from PMTs
  - Neutrons, alpha-rays are negligible

10.1016/j.physletb.2018.10.070
RESULTS: ENERGY SPECTRUM IN THE FIDUCIAL VOLUME

- Fiducial mass 97kg (R<20cm)

The energy spectrum at 2-15 keV$_{ee}$ is fitted with signal + background.

Systematic uncertainties are taken into account as nuisance parameters in the fit.

Detector surface conditions (gap, roughness) are dominant.

The best fit BG MC

1 σ error for the best fit

WIMP

60 GeV/c$^2$, $2.2 \times 10^{-44}$ (90% CL)
- 97kg x 706 days exposure
- 90% CL upper limit on SI WIMP-nucleon cross section
- $\sigma_{\text{SI}} < 2.2 \times 10^{-44}$ cm$^2$ @ 60 GeV/c$^2$
- First stringent constraint by a single-phase LXe detector.
DARK MATTER SEARCHES IN XMASS-I
-- HIDDEN PHOTONS & AXION-LIKE PARTICLES DARK MATTER

- **Hidden photon (HP):** gauge boson of hidden U(1)
- **Axion-like particles (ALPs):** pseudo-Nambu-Goldstone boson

- Both bosons can be absorbed in the detector medium with emission of an electron. \( \Rightarrow \) analogue to photoelectric effect

- Event rate \( \propto \frac{(a'/a)}{m_{HP}} \) or \( g_{Ae}^2 \times m_{ALP} \)

Both are the cold dark matter candidates.
THE RESULTS

- 800 live days of data (Nov. 2013 – Jul. 2016)
- Fiducial volume was extended to R<30cm (327 kg of LXe)
- Fitting energy range 30-180 keV

A peak search by fitting the energy spectrum with the signal + background model.

Scanning mass every 2.5 keV/c² in 40-120 keV/c²

https://doi.org/10.1016/j.physletb.2018.10.050
No significant signal was observed.

- Axion-like particles DM
  - $g_{\text{Ae}} < 4 \times 10^{-13}$ (90% CL) for 40-120 keV/c²
  - Cover higher mass region than LUX and PandaX-II
- Hidden photon DM
  - $\alpha'/\alpha < 6 \times 10^{-26}$ (90% CL) for 40-120 keV/c²
  - Cover a region where indirect searches are weak

- The best constraint in 40-120 keV/c² for both cases.
- For HP, no possibility for thermal production mechanism for the first time in the world in the previous work in 2014. (DOI: 10.1103/PhysRevLett.113.121301)
STUDIES ON NEUTRINO PROPERTIES WITH XMASS
-- DOUBLE ELECTRON CAPTURE

- Natural xenon contains $^{124}\text{Xe}$ (N.A.=0.095%) and $^{126}\text{Xe}$ (N.A.=0.089%) which can undergo double electron capture.

- $^{124}\text{Xe} \ (\text{g.s., } 0^+) + 2e^- \rightarrow 124\text{Te} \ (\text{g.s., } 0^+) + (2\nu_e) + 2864\text{keV}$

- 0ν mode $\rightarrow$ Evidence of lepton number violation
- 2ν mode $\rightarrow$ New input for nuclear matrix element calculation
- None of the modes are overserved yet.
• $^{124}$Xe 2ν double electron capture from K-shell (2ν2K)
  • Total deposit energy of 63.6 keV by X-rays/Auger electrons
  • Expected half-life is $10^{20}$-10$^{24}$ years.
  • It may be possible to find out the 2ν2K.

• Main BG: $^{125}$I
  • $^{125}$I + e$^-$ $\rightarrow$ $^{125}$Te + ν + 185.77 keV, $T_{1/2}$=59.4 day
  • It is created by thermal neutron capture of $^{124}$Xe outside the water shield.
  • It gives a peak at 67.5 keV$_{ee}$. 
We divided the data into 4 by operation modes. In each operation modes, thermal neutron flux is measured by independent measurement.

- No significant signal was observed.
Excluded

Note on theoretical predictions:

• $g_A = 1.26$ (lower) – 1 (upper)
• Probability of 2K-capture = 0.767

The most stringent limit to date

- $T_{1/2}^{2
u 2K}(^{124}\text{Xe}) > 2.1 \times 10^{22}$ yrs
- $T_{1/2}^{2
u 2K}(^{126}\text{Xe}) > 1.9 \times 10^{22}$ yrs

The result ruled out some theoretical predictions.

Note on theoretical predictions:

- $g_A = 1.26$ (lower) – 1 (upper)
- Probability of 2K-capture = 0.767
NEUTRINO OBSERVATORY, XMASS

- XMASS has the sensitivity to detect neutrino burst from a supernova around 10 kpc via neutrino coherent scattering

\[ \nu + A \rightarrow \nu + A \]

<table>
<thead>
<tr>
<th>Supernova model</th>
<th>d=10 kpc</th>
<th>d=196 pc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livermore</td>
<td>15</td>
<td>3.9x10^4</td>
</tr>
<tr>
<td>Nakazato (20M_{solar}, Z=0.02, t_{rev}=100ms)</td>
<td>3.5</td>
<td>0.9x10^4</td>
</tr>
<tr>
<td>Nakazato (30M_{solar}, Z=0.02, t_{rev}=300ms)</td>
<td>8.7</td>
<td>2.3x10^4</td>
</tr>
<tr>
<td>Nakazato (black hole)</td>
<td>21</td>
<td>5.5x10^4</td>
</tr>
</tbody>
</table>

K. Abe et al. (XMASS Collaboration), Astropart. Phys. 89 (2017) 51-56
• Especially for nearby-supernova case,
  • KL can measure pre-SN ν to distribute SN alert.
  • XMASS can measure $10^4$ events
• We established SN monitoring network in Kamioka.
  • Monitor SN alert provided by KL in 24 hours.
The result:

- We are *not* lucky enough to observe any SN ν in this 30 years.
- But it is shown by XMASS that a large scale DM detector is potentially utilized as SN ν observatory.
• Other astrophysical object:

• We searched for event bursts related to GW170817.

- Around GW170817 (Aug. 17 2017 12:41:04 UTC) in [-400, +10,000] sec
- Simple data reduction:
  - Full volume
  - No OD trigger
  - Removing PMT after pulses
  - Remove Cherenkov events
- Four event regions
  - <~30 keV: 0.22 event/s
  - 30-300 keV: 0.56 event/s
  - 300-3000 keV: 0.99 event/s
  - >~3000 keV: 0.02 event/s
- Analysis Window
  - Vary from 20 ms to 10 s to find bursts.
No bursts were found.
LOW BG TECHNOLOGY

• Introduction:
  • The main backgrounds of the XMASS detector are
    • $^{210}$Pb from cupper and
    • RI’s from the PMT.
  • We have lots of efforts.
  • Three topics in this talk:
    • New 3” round-shape PMTs
    • Particle ID by Xe scintillation property
    • Ultra low level $\alpha$ counter
LOW BG TECHNOLOGY
-- PARTICLE ID BY XE SCINTILLATION LIGHT

• Nuclear scattering from electron scattering
  • With neutron source, scintillation time profile are measured.

\[ f(t) = \frac{F_S}{\tau_S} \cdot \exp \left( -\frac{t}{\tau_S} \right) + \frac{1 - F_S}{\tau_T} \cdot \exp \left( -\frac{t}{\tau_T} \right) \]

https://doi.org/10.1088/1748-0221/13/12/P12032
• Log likelihood ratio

![Log likelihood ratio graph](image1)

• Acceptance of electron recoil events assuming 50% acceptance of 100 GeV WIMPs.

![Acceptance graph](image2)

It is not easy to distinguish NR from ER at lower energy region.
• Electron event from gamma event
  • Gamma ray interacts with electrons and loses the energy.
  • This reads the time profile difference between gamma and electron.

\[ \beta_{CL} = P \times \sum_{i=0}^{n-1} \frac{(-\ln P)^i}{i!} \]
\[ P = \prod_{i=1}^{n} CL_i \]

\[ ^{241}\text{Am} \ 60\text{keV } \gamma\text{-ray} \]
\[ ^{214}\text{Bi} \ \beta\text{-ray (30-200 keV}_{ee}) \]

This method is applied to the \(^{124}\text{Xe} \ 2\nu2\text{K analysis.} \)

\( S/N \) is improved by factor 5.
LOW BG TECHNOLOGY
-- ULTRA-LOW ALPHA-RAY COUNTER

• XIA Ultra-Lo-1800
  • Measure ionization signal of Ar by induction.
  • Wall event rejection by pulse shape
  • Installed in Kamioka mine in 2015.
  • It was the first time installation into the underground experimental lab.

<table>
<thead>
<tr>
<th>Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>efficiency</td>
<td>&gt;90% of 2π</td>
</tr>
<tr>
<td>ΔE</td>
<td>&lt;9% FWHM at 4.6MeV</td>
</tr>
<tr>
<td>E range</td>
<td>1-10MeV</td>
</tr>
<tr>
<td>Max. sample size</td>
<td>707cm² (φ30cm disk), 1800cm² (42cm*42cm)</td>
</tr>
<tr>
<td>Max. sample weight</td>
<td>9kg</td>
</tr>
<tr>
<td>Max. sample thickness</td>
<td>6.3mm</td>
</tr>
</tbody>
</table>
| Sensitivity         | $10^{-4}\alpha/cm²/hr$  
  ~ 0.56 mBq of $^{210}$Po on 1 m² surface |
We found that the alpha counter is also sensitive for α-rays from bulk.

According to MC, α-ray comes from d=2～6 μm can be measured at E=2.5～4.8 MeV under some conditions:

• An α counter must be low-BG itself.
• Sample surface must be low-BG.
• Sample roughness << 10 μm
• Ris other than 210Po can be ignorable.

• Measure $^{210}\text{Po}$ count rate several times.
\[ N_{\text{Pb}}(t) = N_{\text{Pb}}(0)e^{-k_{\text{Pb}}t} \]
\[ N_{\text{Po}}(t) = N_{\text{Pb}}(0)\frac{k_{\text{Pb}}}{k_{\text{Po}} - k_{\text{Pb}}} \left( e^{-k_{\text{Pb}}t} - e^{-k_{\text{Po}}t} \right) + N_{\text{Po}}(0)e^{-k_{\text{Po}}t} \]

- Calculate \(^{210}\text{Pb}\) and \(^{210}\text{Po}\) in the material.

\[^{210}\text{Pb}\] in copper is measured with high sensitivity.
This technique is applicable to other conductive material. (Non-conductor? \(\Rightarrow\) Future R&D item)
LOW BG TECHNOLOGY
-- 3” ROUND SHAPE PMT FOR FUTURE DETECTOR

- We have developed a new low PMT, R13111, for a future detector with Hamamatsu.
  - Low RIs
  - Round shape
  - Larger photo-cathode
• Why round shape?
  • The BG from detector wall can be removed

2 < E < 5 keV

99.95% of BG is rejected.
• **Low BG**
  
  • We screened materials with Ge-detectors, GD-MS, and ICP-MS.
  
  • A low BG PMT, R113111, is developed successfully.

**Table:**

<table>
<thead>
<tr>
<th>(Unit: mBq)</th>
<th>$^{226}\text{Ra}$</th>
<th>$^{238}\text{U}$</th>
<th>$^{210}\text{Pb}$</th>
<th>$^{228}\text{Ra}$ ($^{232}\text{Th}$)</th>
<th>$^{40}\text{K}$</th>
<th>$^{60}\text{Co}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced in 2015</td>
<td>0.38 (0.07)</td>
<td>&lt;1.6</td>
<td>&lt;32</td>
<td>0.29 (0.06)</td>
<td>&lt;1.4</td>
<td>0.22 (0.05)</td>
</tr>
<tr>
<td>Produced in 2016</td>
<td>0.44 (0.06)</td>
<td>&lt;1.4</td>
<td>&lt;24</td>
<td>0.20 (0.06)</td>
<td>2.0 (0.5)</td>
<td>0.13 (0.04)</td>
</tr>
<tr>
<td>XMASS-I PMT (R10789)</td>
<td>1.2 (0.3)</td>
<td>-</td>
<td>-</td>
<td>&lt;0.78</td>
<td>9.1 (2.2)</td>
<td>2.8 (0.2)</td>
</tr>
</tbody>
</table>

Paper will be published soon.
SUMMARY

• XMASS project
• Physics results from XMASS
• Low background technique in XMASS

Thank you for your supports to XMASS-I.