The XMASS experiment

Kamioka observatory, ICRR, University of Tokyo
Byeongsu Yang

Oct. 6th, 2014 DBD2014 at Hawaii
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Introduction to the XMASS
XMASS experiment

What is XMASS?
Multi purpose, low-background and low-energy threshold experiment with large volume of liquid Xenon

- Xenon detector for Weakly Interacting MASSive Particles (DM search)
- Xenon MASSive detector for solar neutrino (pp/\(^7\)Be)
- Xenon neutrino MASS detector (ββ decay)
XMASS Collaborator

11 institutes
~40 physicists

Kavli IPMU, the University of Tokyo: J. Liu, K. Martens, Y. Suzuki
Kobe University: R. Fujita, K. Hosokawa, K. Miuchi, Y. Ohnishi, N. Oka, Y. Takeuchi
Tokai University: K. Nishijima
Gifu University: S. Tasaka
Yokohama National University: S. Nakamura
Miyagi University of Education: Y. Fukuda
STEL, Nagoya University: Y. Itow, R. Kegasa, K. Kobayashi, K. Masuda, H. Takiya
Sejong University: N. Y. Kim, Y. D. Kim
KRISS: Y. H. Kim, M. K. Lee, K. B. Lee, J. S. Lee
Tokushima University: K. Fushimi

Collaboration meeting at Kobe Univ. in June 2014
XMASS detector: site

Japan

Kamioka Mine

~230km

Mt. Ikenoyama

Mine entrance

~2km

Kamioka observatory
XMASS experiment

**XMASS-I**
- 835kg, 100kg FV
- 80cmφ
- 2010Nov
- DM search

**XMASS-1.5**
- 5ton, 1ton FV (x 10 of XMASS-I)
- 1.5mφ, ~1800 PMTs
- DM search

**XMASS-II**
- 25ton, 10ton FV
- 2.5mφ
- Multi purpose
- DM search
- pp solar neutrino
- 0ν2β decay

Y. Suzuki, hep-ph/0008296
XMASS-I detector

- Single phase (scintillation only) liquid Xenon detector: sensitive to e/γ events with very low backgrounds as well as nuclear recoil events
- Operated at -100°C and ~0.065MPa
- Large 100 kg fid. mass, [835 kg inner mass (0.8 mφ)]
- Pentakis-dodecahedron ← 12 pentagonal pyramids: Each pyramid ← 5 triangle
- 630 hexagonal & 12 round PMTs with 28-39% Q.E.
- High light yields (13.9 pe/keV) & Large photon coverage
  - photocathode coverage: > 62% inner surface
  - Low energy threshold: < 5 keVee (~ 25 keV_{NR}) for fiducial volume and 0.3 keVee for full volume

1.2m diameter
History of XMASS-I

- **2010**: Installation
- **2011**: Commissioning
- **2012**: Refurbishment
- **2013**: Data taking resumed
- **2014**:

- **Sep. 2010**: Image of installation
- **Aug. 2013**: Image of refurbishment
Results from XMASS commissioning run
Low mass WIMPs search

- Search for elastic WIMP nucleus scattering without discriminating between nuclear-recoil and electron events
- **Threshold is 0.3keVee** and Full volume analysis.
- Set absolute maxima of the cross section.
- With just $6.70 \text{ days} \times 835\text{kg}$ data, excluded most of the parameter space favored by DAMA.

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**Observed spectrum**

**Expected spectrum by simulation**

**WIMP cross section on nucleon (cm$^2$)**

**Expected spectrum by simulation**
Solar axion search

- Axions can be produced in the sun by bremsstrahlung or Compton effect, and detected by axio-electric effect in XMASS.
- Our detector is suitable to see these events, especially because of a large mass, low background, and sensitivity to electron recoil.
- The same data set as the low mass WIMPs search.
- No indication of signals. Set maximum of $g_{aee}$ for each mass.
- In 10-40keV, stringent constraint

Bremsstrahlung and Compton effect

Observed and expected energy spectrum.

Axio-electric effect (like photo-electric)
Bosonic super-WIMPs search

- The latest results in XMASS (Published in PRL 113, 121301(2014), in Sep. 18, 2014)
- Due to the followings, search for lighter and more weakly interacting particles is attracting attention.
  - Expectation on the structure on galactic scales of the CDM scenario is richer than observed.
  - So far no evidence of supersymmetric particles at the LHC.
  - LUX excluded parameter space $\sigma_{\text{SI}}<10^{-45}\text{cm}^2$ around 30GeV, also low mass WIMP regions.

Bosonic super-WIMPs search

- A lukewarm dark matter candidate, and lighter and more weakly interacting particles than WIMPs
- Experimentally interesting since their absorption in a target material would deposit an energy essentially equivalent to the super-WIMP’s rest mass.
- Search for pseudoscalar and vector boson (sometimes called as dark, para, or hidden photon)
- For vector boson, there is only astrophysical constraint.
  ➞ Need experimental search
Bosonic super-WIMPs search(2)

- Can be detected by absorption of the particle, which is similar to the photoelectric effect.
- Search for mono-energetic peak at \( m_b \) (the rest mass of a bosonic super-WIMP)
- Optimized cut for each \( m_b \)
- The remaining event rate (\( O(10^{-4})/\text{day/kg/keV}_{ee} \)), the lowest ever achieved, is in good agreement w/ expected BG from 214Pb w/ keeping > 50% signal efficiency
Bosonic

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- Search for mono-energetic peak at $m_b$ (the rest mass of a bosonic super-WIMP).
- Optimized cut for each.
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Bosonic Super WIMPs

- Can be detected by absorption of the particle, which is similar to the photoelectric effect.
- Search for mono-energetic peak at $m_b$ (the rest mass of a bosonic super-WIMP).
- Optimized cut for each $m_b$.
- The remaining event rate ($O(10^{-4})$/day/kg/keV$_{ee}$), the lowest ever achieved, is in good agreement w/ expected BG from 214Pb w/ keeping > 50% signal efficiency.
The counting rate in the detector becomes:

\[ S_a \approx \frac{1.2 \times 10^{19}}{A} g_{\text{ae}e}^2 \left( \frac{m_a}{\text{keV}} \right) \left( \frac{\sigma_{\text{photo}}}{\text{barn}} \right) \text{ kg}^{-1} \text{ day}^{-1} \]

\[ S_v \approx \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left( \frac{\text{keV}}{m_V} \right) \left( \frac{\sigma_{\text{photo}}}{\text{barn}} \right) \text{ kg}^{-1} \text{ day}^{-1} \]

where, \( \alpha' \) is the vector boson analogue to the fine structure constant.

For vector bosonic super-WIMPs, the first direct search in the 40-120keV range. The limit excludes the possibility that such particles constitute all of dark matter. The most stringent direct constraint on \( g_{\text{ae}e} \), because of the low background in this energy range.
Inelastic WIMP nucleus scattering search

\[ \chi + ^{129}\text{Xe} \rightarrow \chi + ^{129}\text{Xe}^* \]

\[ ^{129}\text{Xe}^* \rightarrow ^{129}\text{Xe} + \gamma \text{ (39.6keV)} \]

(Natural abundance of \(^{129}\text{Xe}: 26.4\%\))

(Nuclear recoil with \(\gamma\)-ray emission)

- The same data set as the bosonic super-WIMPs search was used.
- Cuts are optimized to have best S/N in 30-80keV using calibration data
- Achieved without explicit background subtraction because of low background.

Achieved \(~3\times10^{-4}\) dru @ a few 10’s keV

Published in PTEP 063C01 (2014)
Refurbishment, current status and future project
Refurbishment

- BG in the commissioning run originated from “detector surface” is dominant.
  - RI in PMT Al seal and on surface of PMT and PMT holder
  - Such events are likely to be leakage, because photons are hardly detected in neighboring PMTs.
- Refurbishment from May 2012 to Nov. 2013
  - PMT Al seal are covered by copper ring and plate, to reduce the beta and X-ray and make a simple and flat surface to reduce the mimic of inside event.
  - Also those rings, plates & PMT holders were electropolished.
**Refurbishment**

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![Diagram showing refurbishment process and scintillation photons](image)
Current status(1)

- Restarted data taking from Nov. 2013
- Quick check of energy spectrum indicates one order reduction of background from commissioning run data.
- Already accumulated 192.2 days data for WIMP search till Sep. 2014.
- Using this data, physics analyses including WIMP search with fiducialization and annual modulation are on-going.

Energy spectrum for entire volume

XMASS commissioning

XMASS refurbishment

Counts/day/keV/kg

Energy (keV)
Current status (2)

- Annual modulation analysis after the refurbishment
  - For full volume
    - World’s largest mass: 1 yr data of XMASS ~ 14 yrs data of DAMA/LIBRA
      0.8 ton*year ~ 1.33 ton*year
      Current statistics is ~ half of DAMA/LIBRA data
    - Low energy threshold: 0.3 keVee
    - Select events with simple cut w/o reconstruction
    - For several physics (DM, axion,..) w/o PID.
      The results for 1yr data will come in near future.

- To be analyzed for fiducial volume in near future.

Expected modulation in XMASS for 8GeV WIMP

- 0.3-0.4keV
  ~3 x10^-40cm^2
  1.9 x10^-41cm^2
  No modulation

Prospects after refurbishment for full volume
Future project

• XMASS-1.5 : FV 1ton, Full 5tons xenon
• New PMT:
  – More clean material (include Al seal) will be selected.
  – New PMTs being developed help to identify surface events.
• BG will be controlled by techniques of refurbishment.
• Sensitivity for DM search:
  – $\sigma_{SI} < 10^{-46}\text{cm}^2 (>5\text{keV})$ for fiducialization.

PMTs for XMASS-1.5
Scintillation light from the surface can be detected.

Dotted line = photo cathode
Dotted curve = photo cathode
Red arrows: track of scintillation photon
PMTs for XMASS-I
High probability to miss catching the photons from the surface.
Summary

- Physics results from commissioning data
  - Taking the full advantage of sensitivity to $e/\gamma$ events as well as nuclear recoil, large volume, low threshold and low background at a few 10's keV at a level of $10^{-4}$/day/kg/keV$_{ee}$
    - Low mass WIMPs: with just 6.70 days ($\times$ 835kg) data, excluded most of the parameter space favored by DAMA. (Phys. Lett. B 719 78 (2013))
    - Bosonic super-WIMPs: For vector boson, the first direct search in the 40-120keV range. The limit excludes the possibility that such particles constitute all of dark matter. For pseudoscalar, the most stringent direct constraint on $g_{ae}$. (Phys. Rev. Lett. 113, 121301(2014))
    - Inelastic WIMP nucleus scattering: Achieved the limit without explicit background subtraction (PTEP 063C01 (2014))

- Current status
  - The refurbishment of detector completed and data-taking resumed in Nov. 2013.
  - Succeeded one order reduction of background from commissioning run data. Using these data, physics analyses including WIMP search with fiducialization and annual modulation are on-going. Its results will come in near future.

- Future
  - Designing of XMASS-1.5 is on-going.
  - Aim to $\sigma_{SI} < 10^{-46}$cm$^2(>5$keV) for fiducialization.
Characteristics of XMASS

- **XMASS**: single phase detector
  - Large volume and simple structure, operation.
    - 1 ton scale xenon detector, 100kg for fiducial volume.
  - Background reduction technique:
    - Self shielding
    - Reconstruction by hit pattern of PMTs
  - High light yields & Large photon coverage (15 pe/keV)
    - Low energy threshold (< 5 keVee ~ 25 keVNR) for fiducial volume
    - Lower energy threshold: 0.3 keV for whole volume
  - Large Scalability, simple to construct.
Low background technique

(1) BG from detector materials

- 642 PMTs: We developed new ultra low RI PMT with Hamamatsu. (1/100 of ordinary one).
- OFHC copper: Bring in the mine < 1 month after electrorefining (Mitsubishi Material Co.).
- Other materials: All the components were selected with HPGe and ICP-MS. (>250 samples were measured) The total RI level is much lower than PMT BG.

(2) External BG

- Gamma and n from rock are sufficiently reduced by a >4m thickness pure water tank : $\gamma < \gamma$ from PMT, $n << 10^{-4}$/day/kg
- 72 20” PMTs for active veto for $\mu$

PMT HPGe meas. result

<table>
<thead>
<tr>
<th>RI in PMT</th>
<th>Activity per 1 PMT (mBq/PMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>238U-chain</td>
<td>0.70 +/- 0.28</td>
</tr>
<tr>
<td>232Th-chain</td>
<td>1.51 +/- 0.31</td>
</tr>
<tr>
<td>40K-chain</td>
<td>9.10 +/- 2.15</td>
</tr>
<tr>
<td>60Co-chain</td>
<td>2.92 +/- 0.16</td>
</tr>
</tbody>
</table>
(3) Internal BG (in Xenon)

- **Radon**: Our goal \(<10^{-5} \text{ /day/keV/kg}\) => 222Rn \(< 0.6\) mBq/detector
  - Radon emanation from detector material was measured with material selection. <15mBq/detector was estimated.
  - Radon concentration in XMASS by Bi-Po coincidence analysis : 8.2+/−0.5mBq.
  - The radon removal system from xenon gas are prepared.

  *K. Abe et al. for XMASS collab., NIMA661, 50-57 (2012)*

- **Kr**: Our goal \(<10^{-5} \text{ /day/keV/kg}\) => 1ppt
  - 5 order of magnitude reduction with 4.7kg/hr processing time was achieved by distillation system.
    - <2.7ppt (API-MS measurement of sample gas) was achieved.

  *K. Abe et al. for XMASS collab., Astropart. Phys. 31 (2009) 290*

- **Water, H2, O2 etc**:
  - Worse the optical property of xenon and probability of BG (3T)
  - Xenon gas was passed to hot and room temperature getter to remove these.

1st event \(^{214}\text{Bi}\) β
2nd event \(^{214}\text{Po}\) α

Distillation tower

total number of PEs x10^3

4m
Detector response for a point-like source (~WIMPs)

• $^{57}$Co source @ center gives a typical response of the detector.
• 14.7 p.e./keV$_{ee}$ ($\cong$ 2.2 for S1 in XENON100)
• The pe dist. well as vertex dist. were reproduced by a simulation well.
• Signals would be <150 p.e. exp shape.
Unexpected BG in XMASS commissioning run:

- BG was 2 order larger than PMT gamma BG which was assumed as main BG.
- (BG level is nearly with DAMA and CoGent.)
- The origin of BG for >5keV were confirmed. (1) BG from PMT Al seal (238U-230Th and 210Pb-206Pb). (2) 210Pb-206Pb in Copper surface.
- BG origin from “detector surface” is dominant. Leakage event in FV region is introduced by worse of PMT response. Need to remove these.
Current status (2) maxpe/totPE

- The event in small Maxpe (maximum NPE for one PMT)/totalPE region are reduced rapidly.
- It suggest that the event near of “blind of PMT” are reduced and mimic of inside event are reduced.
- Dark matter search with fiducial volume analysis is ongoing.