XMASS experiment

What is XMASS?

- Multi purpose low-background and low-energy threshold experiment with liquid Xenon
- Xenon detector for Weakly Interacting MASSive Particles (DM search)
- Xenon MASSive detector for solar neutrino (pp/\(^7\)Be)
- Xenon neutrino MASS detector (\(\beta\beta\) decay)
Current status of WIMP dark matter search

WIMP-nucleon (SI) cross section (pb)

$10^{-44}$ cm$^2$

10GeV  100GeV  1TeV

R. Gatitskell@dm2012
goal of XMASS-I

- sensitivity: $\sigma_\text{sI} < 2 \times 10^{-45} \text{cm}^2$
- 5 years measurement
- 100kg fiducial mass
- $E_{\text{threshold}} = 5 \text{keV}$
<table>
<thead>
<tr>
<th>Institution</th>
<th>Collaborators</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPMU, University of Tokyo</td>
<td>J. Liu, K. Martens</td>
</tr>
<tr>
<td>Kobe University</td>
<td>K. Hosokawa, K. Miuchi, A. Murata, Y. Ohnishi, Y. Takeuchi</td>
</tr>
<tr>
<td>Tokai University</td>
<td>F. Kusaba, K. Nishijima</td>
</tr>
<tr>
<td>Gifu University</td>
<td>S. Tasaka</td>
</tr>
<tr>
<td>Yokohama National University</td>
<td>K. Fujii, I. Murayama, S. Nakamura</td>
</tr>
<tr>
<td>Miyagi University of Education</td>
<td>Y. Fukuda</td>
</tr>
<tr>
<td>STEL, Nagoya University</td>
<td>Y. Itow, K. Masuda, H. Takiya, H. Uchida</td>
</tr>
<tr>
<td>Kobe University</td>
<td>K. Ohtsuka, Y. Takeuchi</td>
</tr>
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<td>Seoul National University</td>
<td>S. B. Kim</td>
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<td>Sejong University</td>
<td>N.Y. Kim, Y. D. Kim</td>
</tr>
<tr>
<td>KRISS</td>
<td>Y. H. Kim, M. K. Lee, K. B. Lee, J. S. Lee</td>
</tr>
</tbody>
</table>
Direct Detection Principle

WIMPs elastically scatter off nuclei in targets, producing nuclear recoils.

- From the density of dark matter in the galaxy:
- Every liter of space: $10^{-100}$ WIMPs,
- Moving at $1/1000$ the speed of light
- Less than 1 WIMP/week will collide with an atom in 1kg material

\[ \frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \cdot \frac{1}{k} \cdot \frac{1}{2\pi v_0} \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{1}{v} f(v, v_E) d^3v \]

- $R_0$: Event rate
- $F$: Form Factor
- Should be calculated in each nuclei

Maxwellian distribution for DM velocity is assumed.
- $v_0$: dispersion
- $v_E$: Earth’s motion around the Sun

Spin independent case:

\[ \sigma_0 = A^2 \frac{\mu^2}{\mu_p^2} \sigma_{\chi-p} \]

Larger $A$ is higher event rate

Xe ($A=131$) is one of the best target.
Why Liquid Xenon?

- High Atomic mass Xe (A~131)
  - good for SI case (cross section \( \propto A^2 \))
- Odd Isotope (Nat. abun: 48%, 129,131) with large SD enhancement factors
- High atomic number (Z=54) and density (\( \rho=3\text{g/cm}^3 \))
  - compact, flexible and large mass detector.
- High photon yield (~ 42 UV photons/keV at zero field)
- No long life radioactive isotope
- Easy to purify for both electro-negative and radioactive purity
  - by circulating Xe with getter for electro-negative
  - Distillation for Kr removal
External gamma-ray MC

Blue: track
Pink: self-shield (liquid xenon)
Deep pink: fiducial volume (liquid xenon)
In Mar. 2008, excavation is finished.

- Hall-C facility was completed in Mar. 2009.
- Urethane resin for radon shield on the wall and floor.
- Air from the outside the mine (8m$^3$/min, ~20Bq/m$^3$)
- Water tank construction is completed in Mar. 2009.
• 72 20-inch PMTs will be installed to veto cosmic-ray muon ($<10^{-6}$ for thr-mu, $10^{-4}$ for stop-mu).
• Water is active shield for muon induced neutron and also passive shield for gamma-ray and neutron from rock/wall.
• IVC and OVC are made of OFHC (Oxygen-free high thermal conductivity) copper.
More than 200cm water is needed to reduce the BG to the PMT BG level.
Water Shield for fast neutron background

- Fast n flux @Kamioka mine:
  $(1.15 \pm 0.12) \times 10^{-5} \text{ /cm}^2\text{/sec}$

- Assuming all neutron’s energies are 10 MeV very conservatively

- Water shield:
  - 200 cm of water
  - Energy: 10 MeV

- Fast n flux @Kamioka mine:
  $(1.15 \pm 0.12) \times 10^{-5} \text{ /cm}^2\text{/sec}$

- Generat: $10^7$ MC events, no event in Liquid Xe volume

- $< 2 \times 10^{-4}$ counts/day/kg

- 200 cm of water is enough to reduce the fast neutron background

2012/7/19
K. Kobayashi, XMASS, ppp2012, Kyoto
Detector design detail

- Total: 642 PMTs
- Photo coverage: 62%
- Diameter: ~800mm

Hexagonal PMT
Hamamatsu R10789

- 60 triangles

231.5mm
310.3mm
## PMT history

<table>
<thead>
<tr>
<th>YEAR</th>
<th>2000</th>
<th>2002</th>
<th>2009</th>
</tr>
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<tbody>
<tr>
<td>Model</td>
<td>Prototype</td>
<td>R8778</td>
<td>R10789</td>
</tr>
<tr>
<td>Material:Body</td>
<td>glass</td>
<td>Kovar</td>
<td>Kovar</td>
</tr>
<tr>
<td>QE</td>
<td>25%</td>
<td>25%</td>
<td>27-39%</td>
</tr>
<tr>
<td>RI:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U $[^{235}\text{U}]$ [mBq/PMT]</td>
<td>50</td>
<td>$18\pm2$</td>
<td>$0.7\pm0.28$</td>
</tr>
<tr>
<td>Th $[^{232}\text{Th}]$ [mBq/PMT]</td>
<td>13</td>
<td>$6.9\pm1.3$</td>
<td>$1.5\pm0.31$</td>
</tr>
<tr>
<td>$^{40}\text{K}$ [mBq/PMT]</td>
<td>610</td>
<td>$140\pm20$</td>
<td>$&lt;5.1$</td>
</tr>
<tr>
<td>$^{60}\text{Co}$ [mBq/PMT]</td>
<td>$&lt;1.8$</td>
<td>$5.5\pm0.9$</td>
<td>$2.9\pm0.16$</td>
</tr>
</tbody>
</table>

- Developed with Hamamatsu Photonics K.K.
- Mass production of the PMTs was completed in Oct. 2009.

**With base**
PMT, holder, and filler installation

- Dust and radon in the air could be background source.
- Dust from mine is shielded by two shutters.
- Water tank is closed and is filled with radon-free air.
- Clean booth is made in the water tank for the installation.
- During the installation, radon concentration is \(~200\text{mBq/m}^3\).
- Dust level is \(<1000/\text{ft}^3\).
Clean booth in the water tank

Air shower room

Clean wear

Base with clean booth
For the detector assembly

• No smoking two hours before the work
• No beard
• No make up

2012/7/19
K.Kobayashi, XMASS, ppp2012, Kyoto
PMT/holder installation

PMT installation was done from Dec. 2009 to Feb. 2010.
PMT holder

OFHC Filler to reduce the amount of liquid xenon
chamber, OD installation and water filing

IVC/OVC installation

OD PMT installation

water filling

fall, 2010
Xe filling

- Evacuation and Baking
- 2010.10.16 Test filing 100kg
- 2010.10.16 Xe Collection
- 2010.10.24 1st Filling 1129kg
- 2010.10.26 Xe Collection
- 2010.10.31 2nd filling 1065kg

![Diagram of Xe filling setup]

- 2011.01.21 Xe Collection
  - for the work to fix the stacked calibration rod
- 2011.01.31 3rd filling 1085kg

液体のまま回収することで、測定器内部をきれいにする。
commissioning run

- calibration
  - source rod (57Co, 241Am, 137Cs, 109Cd, 55Fe)
  - external source (60Co, 137Cs, 232Th, neutron)
- normal run data taking
- develop software
- change of the xenon quality
  - high/low pressure run
    (change of Xe refractive index)
  - O2 injected run
    (change of absorption length)
  - boiling run
    (make convection flow)
- Xe gas run
  - important to identify the surface background.
- measurement of the background candidate material
  - Al, goretex, Cu, Ni plate (measured at calibration source rod)
commissioning run history

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Event</th>
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<tbody>
<tr>
<td>2010</td>
<td>12</td>
<td>3rd filling</td>
</tr>
<tr>
<td>2011</td>
<td>01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>02</td>
<td>Xe collection</td>
</tr>
<tr>
<td></td>
<td>03</td>
<td>4th filling</td>
</tr>
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<td></td>
<td>04</td>
<td>Xe collection</td>
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<td></td>
<td>05</td>
<td>Xe collection</td>
</tr>
<tr>
<td>2012</td>
<td>01</td>
<td>5th filling</td>
</tr>
<tr>
<td></td>
<td>02</td>
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<td></td>
<td>04</td>
<td></td>
</tr>
<tr>
<td></td>
<td>05</td>
<td></td>
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</tbody>
</table>

- Special runs:
  - 3rd filling: Low pressure run, High pressure run
  - 4th filling: Gas run
  - 5th filling: Boiling run

- Electronics
  - ATM: (ADC+TDC, old SK elec.)
  - +FADC: (60ch, 10-11 PMTsum)
  - +FADC: (642 individual channels)
# Calibration system

## RI sources

<table>
<thead>
<tr>
<th></th>
<th>energy [keV]</th>
<th>RI</th>
<th>φ [mm]</th>
<th>package</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Fe-55</td>
<td>5.9</td>
<td>350</td>
<td>5</td>
<td>brass</td>
</tr>
<tr>
<td>(2) Cd-109</td>
<td>22, 25, 88</td>
<td>800</td>
<td>5</td>
<td>brass</td>
</tr>
<tr>
<td>(3) Am-241</td>
<td>59.5</td>
<td>485</td>
<td>0.15</td>
<td>SUS</td>
</tr>
<tr>
<td>(4) Co-57</td>
<td>122</td>
<td>100</td>
<td>0.21</td>
<td>SUS</td>
</tr>
</tbody>
</table>

- Source rod
- RI source with holder
- adaptor (SUS304)
- OFHC

Source introduce machine

Top PMT moving machine

Gate valve

Xenon gas area

~5m

Top PMT (removed between calibration)
Detector response for a point-like source (~WIMPs)

- $^{57}$Co source @ center gives a typical response of the detector.
- 14.7 p.e./keV$_{ee}$ (↔ 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.
Background and its understanding

• Major origin of BG was considered to be $\gamma$ from PMTs. But the observed data seemed to have additional surface BG.
• Detector parts which touch liquid xenon were carefully evaluated again:
  – Aluminum sealing parts for the PMT (btw metal body and quartz glass) contains U238 and Pb210 (secular equiv. broken).
  – GORE-TEX between PMT and holder contains modern carbon (C14) 0~6+/−3%.
background contribution to NPE spectrum

- Three contributions to the NPE spectrum
  1. High energy (0.1-3MeV): PMT $\gamma$ rays: Measured by Ge detectors and well understood.
  2. Mid. energy (5keV-1MeV): Aluminum and radon daughters: Measured by Ge det. and consistent with observed $\alpha$-ray events (61/64mcps in data/MC). Rn daughters on the inner wall identified by $\alpha$ events.
3. Low energy (0-5keV): Under study. Prediction based on some assumptions on GORE-TEX gives a similar shape. But assumption dependent. Confirmation possible only by removing the GORE-TEX.

BG >5keV (the design energy thre.) is well understood!
Low background even with the surface BG

- Our BG is still quite low, even with the extra surface BG!
- In principle, the surface BG can be eliminated by vertex reconstruction. Optimization of the reconstruction program is on going to minimize a possible leakage to the inner volume.
- Our sensitivity for the low mass WIMP signals at low energy without reconstruction will be shown.

E. Aprile, 2010 Princeton
Low energy, full volume analysis for low mass WIMPs

- The dark matter signal rapidly increase toward low energy end. The large p.e. yield enables us to see light WIMPs. Try to set absolute maxima of the cross section (predicted spectrum must not exceed the observed spectrum).
- The largest BG at the low energy end is the Cherekov emission from $^{40}$K in the photo cathodes.
- Selection criteria
  - Triggered by the inner detector only (no water tank trigger)
  - RMS of hit timing <100ns (rejection of after pulses of PMTs)
  - Cherenkov rejection
  - Time difference to the previous/next event >10ms
Detail of the Cherenkov rejection

• Basically, separation between scintillation lights and Cherenkov lights can be done using timing profile.

• \[
\frac{\text{(# of hits in 20ns window)}}{\text{(total # of hits)}} = \text{“head total ratio”}
\]
   is a good parameter for the separation.
“head total ratio” distribution

• Cherenkov events peaks around 1 ⇐⇒ scintillation ~ 0.5
• Low energy events observed in Fe55 calibration source as well as DM simulation (t=25ns) show similar distributions.
• Efficiency ranges from 40% to 70% depending on the p.e. range.
p.e. distribution after each cut

• 6.64 days data
• The Cherenkov events are efficiently reduced by the cut.

![Graph showing energy distribution for different cuts]

- cut0: trigId == 1
- cut1: +dT_Pre(10msec)
- cut2: +tdcRMS<100
- cut3: +Cherenkov

Counts vs. energy [keVee]
exclusion region

- Sensitive to the allowed region of DAMA/CoGeNT.
- Some part of the allowed regions can be excluded.
Uncertainties

- Major uncertainty is the scintillation efficiency of nuclear recoil in liquid xenon.
- Uncertainties of the trigger thre. (hard trig. 4hits), cut eff., and energy scale are also taken into account.

![Scintillation efficiency as a function of energy](image)

Note: our “energy” = keVnr \times L_{eff}
Sensitivity on the axio-electric dark matter coupling

- The DAMA signal may be due to electromagnetic interaction of WIMPs to the NaI detectors by such as a non-relativistic axion dark matter. See J. Collar, arXiv: 0903.5068

Non relativistic axion deposits its total energy similarly to the photo-electric effect.

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**Graphical Illustration:**

- **DAMA allowed:**
  - CoGeNT
  - CDMS
  - XMASS

**Observed spectrum Expectation for \( m_a = 3 \text{keV} \)**

**Events/keV/kg/day**

**Axion mass (keV)**

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**Diagram Elements:**
- \( g_{a e e} \) (axion-electric coupling)
- \( Z^+ e^- \) (positron annihilation)
- Total Energy Deposition Similar to Photo-Electric Effect.

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**Equation:**

\[ g_{a e e} \]
Solar axion search

Bremsstrahlung + Compton: gaee only

- Large flux can be expected for DFSZ axions.
- $m_A=0$ by Derbin gaee=1
- Analytical expression for $m_A=0$ is in PRD 83, 023505 (2011)

![Graph showing the flux of axions with different masses and energies.](Image)

- Photo electric xsec
- Axio electric xsec for relativistic axions

![Graph showing the cross-sections for Xe and other elements.](Image)
Expected signals and MC simulation

- Left: analytical spectrum
- Right: simulated spectrum overlaid with observed spectrum

Black: w/o efficiency
Red: w/ Cherenkov cut eff

DRU
For $g_{aee} = 1e^{-11}$

MC axion signals
Abs upper limit
$g_{aee} = 4.5e^{-11}$
solar axion sensitivity

XMASS Limit by solar axion 4.5e-11

Solar limit 2.8e-11

Original figure from Derbin, 1206.4142

Allowed mass < 200eV for KSVZ
<2eV for DFSZ
Plan: Refurbishment work

• Tuning of reconstruction/reduction is on going but for better sensitivity, removing the origins of BG must be done.
• To reduce the BG caused by Aluminum, we are planning to cover the part and surfaces by copper rings and plates:

• BG > 5keV must be reduced significantly.
• Schedule: latter half of this fiscal year
Expected sensitivity with fiducialization

**Spin Independent**

Initial target of the energy threshold was $\sim$5keVee. Because we have factor $\sim$3 better photoelectron yield, lower threshold = smaller mass dark matter may be looked for.

Expected energy spec.

$\sigma_{\chi p} = 10^{-44}$ cm$^2$

50GeV WIMP

**WIMP Mass [GeV/c$^2$]**

- **Black**: signal+BG
- **Red**: BG

DATA listed top to bottom on plot
- DAMA/LIBRA 2008 3-sigma, no ion channeling
- WARP 2.5L, 96.5 kg-days 55 keV threshold
- CRESST 2007 60 kg-day CaWO4
- Edelweiss II first result, 144 kg-days interleaved Ge
- ZEPLIN III (Dec 2008) result
- XENON10 2007, measured Left from Xe cube
- CDMS: Soudan 2004-2009 Ge
- Trotta et al 2008, CMSSM Bayesian: 68% contour
- Trotta et al 2008, CMSSM Bayesian: 95% contour
- Ellis et. al Theory region post-LEP benchmark points
- Baltz and Gondolo 2003
- Baltz and Gondolo, 2004, Markov Chain Monte Carlos

1 year exposure