Results from the fiducial volume analysis of the XASS-RFB dark matter data

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30th of Jul. 2015
A. Takeda for the XMASS Collaboration
XMASS I detector


- Single phase liquid xenon detector (832 kg liquid xenon for sensitive region).
- 642 low background PMTs (HAMIAMATSU R10789).
- 10 m x 10 m water tank with 72 PMTs (20 inch ) for muon veto.
- High light yield 14.7pe/keV.
- After detector refurbishment, data taking resumed since Nov. 2013.
  - Fiducial volume analysis (This talk)
  - Annual modulation analysis using full volume of the detector.

(ID: 950 K. Hiraide 14:00 31st of Jul.)
Fiducial volume analysis: data set and reduction

- Total live time is **292.7 days** taken from Nov. 2013 to Jan. 2015.

- Data reduction
  
  **(1) pre-selection**
  
  - Events only inside the liquid xenon detector (Cosmic ray events are vetoed by outer detector)
  - # of PMT hits $\geq 4$
  - RMS of hit timing $< 100$ ns (Removing electric noise and after pulses)
  - Time from the previous event $> 10$ ms (Removing events after cosmic rays or high charge events)
  - $(\# \text{ of hits within } 20 \text{ ns})/(\text{total } \# \text{ of hits}) < 0.6$ (Removing Cherenkov events generated in PMT windows)

  **(2) PE based position reconstruction: R(PE) [cm]**
  
  Events whose distance from center of the detector (R(PE)) < 20cm are selected.

  **(3) Timing based position reconstruction: R(T) [cm]**
  
  Removing remaining events after selection of (2) although they occurred near detector wall.

  **(4) Decay constant**
  
  Nuclear recoil events are selected.
PE based positron reconstruction: \( R(PE) \)

**Position reconstruction**

1. Making acceptance map: the detector is based on grid points throughout the volume and on the surface for which the expected photo-electrons (pe) in each PMT are calculated in our MC.
2. From measured photo-electrons (pe) and scaled acceptance map (\( \mu \)) in (1), position is calculated where following likelihood is maximum.

\[
\log(L) = - \sum_{\text{PMT}} \log \left( \frac{\exp(-\mu)\mu^{pe}}{\Gamma(pe + 1)} \right)
\]

\( \Gamma(x) \): Gamma function
\( \Gamma(n) = (n-1)! \), \( n>0 \)

\( R(PE) < 20 \text{cm} \) was selected as fiducial volume.

Reconstructed position distribution of \(^{57}\text{Co} \) events (122 keV)

\[ \rightarrow \text{R(PE)<20cm was selected as fiducial volume. (effective mass: 97kg)} \]
Timing based position reconstruction: R(T)

- Using FADC hit timing of each PMT.
- Timing constant for 2–10 keV events: $25 \pm 2\text{ns}$.
- Position reconstruction is done by using likelihood method from probability density function for each PMT.

$$L(\vec{X}, T) = \prod_{i=1}^{N_{\text{hits}}} \left( P(t_i - \frac{\vec{x}_i - \vec{X}}{v_g} - T) \right)$$

$P(\tau)$ : probability density function
$x_i$, $t_i$ : PMT position and hit time
$v_g$ : group velocity in Lxe (110mm/ns)

$
\text{Rate \,[/\text{sec/cm}\,]}$

$z = 0\text{cm}$
$z = 20\text{cm}$
$z = 40\text{cm}$

To remove surface events ($R>40\text{cm}$) effectively with keeping efficiency high, $R(T)<38\text{cm}$ is selected.
Event selection using decay time

The left figure shows an example of wave form measured in $^{252}$Cf calibration data taking (sum of all PMT’s FADC channel) The decay time ($\tau$) is calculated by fitting with single exponential (black curve)

The bottom figure shows distribution of decay time. The real data (gray hatched) has longer value than expected one (blue histogram).

Real data (gray hatched) after applying R(PE) and R(T) cut
- WIMP MC (100GeV)
- Electron recoil generated at detector center in MC.
- Electron recoil generated at detector wall (narrow valley) in MC

$\rightarrow$ Events in right side from blue dotted-line are rejected. (50% WIMP signal is survived in MC)
Systematic error for decay time cut

Difference between data and MC in decay time distribution from $^{252}$Cf calibration was taken into account as a systematic error. MC (red) has good agreement with data (black).

In real data, nuclear recoil events were selected from the trigger time information taken by plastic scintillator.

Real data (Cf-252)
Neutron MC
Neutron MC (single)
Data reduction and efficiency

- Energy spectrum of real data

Event rate after applying all cuts (4) in 2-2.5 keV region (just above energy threshold) is \( \sim 3 \times 10^{-3} \) /day/keV/kg.

From the MC study, events occurred near the detector wall are sometimes miss-reconstructed inside the fiducial volume and remained after applying all cuts.

Energy threshold is set as 2 keV, so that position reconstruction can be done with enough photo-electrons. The signal efficiency for events in 2–3 keV after applying all cuts is 7%.
Upper limit for WIMP signal

Remaining events after applying all cuts were considered as WIMP signal conservatively. Upper limit in cross section was calculated so that expected WIMP signal did not exceed the real data.

90% CL upper limit for 100GeV WIMP:
1.23 \times 10^{-43} \text{ cm}^2 (\text{w/o systematic errors})
1.60 \times 10^{-43} \text{ cm}^2 (\text{w/ systematic errors})
Systematic errors for signal MC

Possible all the systematic errors were taken into account.

<table>
<thead>
<tr>
<th>items</th>
<th>Relative systematic errors</th>
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<tbody>
<tr>
<td></td>
<td>2–3 keV</td>
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<tr>
<td>(1) R(PE) &lt; 20cm + R(T) cuts</td>
<td>-7.3%, +0.9%</td>
</tr>
<tr>
<td>(2) Decay time cut</td>
<td>-5%, +5%</td>
</tr>
<tr>
<td>(3) Absorption of liquid xenon (500–1100 cm)</td>
<td>-4.5%, +3.1%</td>
</tr>
<tr>
<td>(4) Time constant for nuclear recoil events (25+1-2 ns)</td>
<td>-9.5%, +2.6%</td>
</tr>
<tr>
<td>(5) Scintillation efficiency: Leff (+/- 1σ)</td>
<td>-9.3%, +6.3%</td>
</tr>
<tr>
<td>Total</td>
<td>-17%, +9%</td>
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</table>

(1) Estimates from the comparison between data and MC in $^{57}$Co calibration.
(2), (4) estimated from the comparison between data and MC in $^{252}$Cf calibration.
(3) Effect of variation of absorption length during data taking (2013/11–2015/01).
Summary

● 292.7 days (live time) data were used.
● Detector wall events were sometimes miss-reconstructed as events happened inside the FV.
● Conservative limit for spin-independent interaction assuming all remaining events were caused by WIMP without BG subtraction were derived. $\sigma_{SI} < 1.6 \times 10^{-43} \text{ cm}^2$ (100 GeV WIMPs).
● Possible all the systematic errors were taken into account.

● Main BG sources were identified.
  Results with BG subtraction is now being prepared.
Backup

Dark Matter Search
The XMASS Collaboration

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June 2014

11 institutes
~40 physicists
XMASS-I (RFB) setup

- Water tank: 11m
- Reservoir: 10m
- OFHC copper vessel: ~1.2m
- Liquid xenon: 832kg
- 642 PMTs
- 72 20inch PMTs (veto)
- Electron hut
- Refrigerator
History of XMASS-I

<table>
<thead>
<tr>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
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<tbody>
<tr>
<td>Dec.</td>
<td></td>
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<tr>
<td><strong>Constuction</strong></td>
<td><strong>Commissioning Run</strong></td>
<td><strong>Refurbishment</strong></td>
<td><strong>Data taking</strong></td>
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<tr>
<td>Sep. 2010</td>
<td>Several physics results from this term were published later</td>
<td>Main BG source was identified, and it was cover with copper ring and plate.</td>
<td>Stable and long term data taking is ongoing.</td>
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Physics results of XMASS-I

**Published**

- Bosonic Super-WIMPs, *Phys. Rev. Lett. 113 (2014) 121301* → Chosen as Editor’s suggestion
- Inelastic scattering on $^{129}$Xe, *PTEP 2014, 063C01*

**Results to come soon**

- Seasonal modulation with full volume of LXe
- Fiducial volume analysis for heavy WIMPs
- Double electron capture of $^{124}$Xe
XMASS Refurbishment work

- **Purpose of Refurbishment:**
  - Confirmation of BG reduction by shielding of scintillation light originated from PMT Al
  - Also reducing $^{210}\text{Pb}$ (2nd largest component in BG) with electro-polishing and special clean environment.
- **Expected BG level:**
  Al and surface BG are reduced to same level as PMT gamma BG. ($\sim 10^{-44}$ cm$^2$ for 100 GeV WIMP with fiducialization)
- **In next step (XMASS-1.5), it will be replaced with new PMT.**
XMASS-1.5

- Total 5 ton (FV 1 ton)
- BG reduction:
  - No dirty Al seal
  - Less surface $^{210}\text{Pb} (< 1/100)$
- New PMT with round shape window to identify surface event is being developed. MC study for evaluation of miss-reconstruction rate is on-going.

Round shape window

Red arrows: track of scintillation photons

PMTs for XMASS-I
High probability to miss catching the photons from the surface.

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