Recent results from XMASS

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Kavli IPMU, the Univ. Of Tokyo
On behalf of XMASS collaboration
UCLA Dark Matter 2016 symposium, 19th/Feb/2016
XMASS Experiment

Multi purpose low-background experiment with single phase LXe.

- Xenon MASSive detector for Solar neutrino (pp/7Be)
- Xenon neutrino MASS detector (double beta decay)
- Xenon detector for Weakly Interacting MASSive Particles (DM)

XMASS I (FV:100kg, Total 1ton)

XMASS 1.5 (FV:3ton, Total 6ton)

XMASS II (FV:10ton, 24Ton)

2007: Project was funded.
2013〜: Data taking

3inch dome shape PMT

Solar Neutrino Dark Matter DBB

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Dark Matter

2007: Project was funded. 2013+: Data taking

- 180° field view (FISHEYE PMT)
- R10789 5.6nsec → R13111 < 3.5nsec
- goal is 1/10 of R10789 radioactivity
The XMASS collaboration:

Kamioka Observatory, ICRR, the University of Tokyo:

Kavli IPMU, the University of Tokyo:
J. Liu, K. Martens, Y. Suzuki, X. Benda

Kobe University:
R. Fujita, K. Hosokawa, K. Miuchi, Y. Ohnishi, N. Oka, Y. Takeuchi

Tokai University:
K. Nishijima

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

11 institutes 41 researchers.
• 1000m under a mountain = 2700m water equiv.
• 360m above the sea
• Horizontal access
• Experiment
  • Super-K
  • KamLAND (Tohoku U.)
  • KAGRA
  • NEWAGE

Kamioka mine
Gifu, Hida city, Ikenoyama

Kamland
super Kamiokande
- φ10m x 10m ultra pure water shield with 20 inch x 70 PMTs for muon veto
XMASS Detector

- 642 ultra low background 2 inch PMTs
- 62% photo coverage
- Largest detector: 832 kg of LXe for sensitive volume.

<table>
<thead>
<tr>
<th>RI in PMT</th>
<th>Activity per 1PMT(mBq/)</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</td>
<td>&lt;5.1</td>
</tr>
<tr>
<td>60Co</td>
<td>2.92 +/- 0.16</td>
</tr>
</tbody>
</table>
Detector calibration

- Inner calibration is for energy calibration.

<table>
<thead>
<tr>
<th>Isotopes</th>
<th>Energy [keV]</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{55}$Fe</td>
<td>5.9</td>
<td>cylinder</td>
</tr>
<tr>
<td>$^{109}$Cd</td>
<td>8 (*1), 22, 58, 88</td>
<td>cylinder</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>17.8, 59.5</td>
<td>thin cylinder</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td>59.3 (*2), 122</td>
<td>thin cylinder</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>662</td>
<td>cylinder</td>
</tr>
</tbody>
</table>

*1: $^{109}$Cd X-rays from the copper are used for source housing.

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Energy calibration

- High Photoelectron Yield $\sim 15$ PE/keV
- Good agreement between data and simulation (MC)
  (evaluated absorption length 4-11 m, scatter 52 cm)

57Co source

$57\text{Co}$
15PE/keV @122keV

PE

Relative deduced scintillation light yield

Light Yield stability 0.5%

Absorption

PE/keV

Power cut

$\sim 500$ days

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Comparison of background rate

- Background rate in the fiducial volume before separation of nuclear recoils from e/γ.

- XMASS achieved $O(10^{-4})$ event/day/kg/keVee at a few 10’s keV.

- Even modest background at low energy, XMASS has good sensitivity with a large mass (832 kg) and low energy threshold. (~ 1keVee) by annual modulation search.

Added to D.C.Malling thesis (2014) Fig.
Search by XMASS

light mass WIMP

Inelastic scattering
PTEP 2014, 063C01

Solar axion

coherent v-n scattering

Supernova

Rare decay search
Double electron capture

super-WIMPs(ALPs)

anual modulation
arXiv:1511.04807v1

Ge (solar)
HB stars
Diffused γ
XMASS

Ωh^2 = 0.1

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Search for Bosonic super-WIMPs

*Phys. Rev. Lett. 113 (2014) 121301*

- We should look for variety of candidate. Not only n-recoil signal. (NO SUSY so far.)
- Motivated by Warm Dark Matter
  - sterile neutrino, gravitino …
- However, it can be pseudoscaler or vector boson and in this case, it can be detected by absorption of the particle, which is similar to the photoelectric effect.
- Search for mono-energetic peak at the mass of the particle
- same data set as inelastic scattering
  41 kg fiducial volume cut,
  2010/12/24-2013/05/10 165.9 days data.
Bosonic super-WIMPs Search Results

- For vector boson case

  Count rate

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

  \( \alpha \): fine structure constant

- the first direct search in the 40–120 keV range.

- Our limit excludes the possibility that such particles constitute all of dark matter.

- For pseudoscaler case

  Count rate

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

- The most stringent direct constraint on gaee.
Double Electron Capture on $^{124}$Xe and $^{126}$Xe

Double electron capture (ECEC) is a rare nuclear decay analogue to double beta decay. Although $2\nu\beta^-\beta^-$ has been observed in more than ten isotopes, there exist only a few positive experimental results for $2\nu$ECEC so far. ($^{138}$Ca, 78Kr)

$^{124}$Xe (g.s.) +2e$^- → ^{124}$Te (g.s.) + (2$\nu_e$) ($Q_{\text{ECEC}} = 2864$ keV)

2$\nu$ mode : New reference for calculation of nuclear matrix element from the proton-rich side of the mass parabola

0$\nu$ mode : Evidence for lepton number violation, Majorana neutrino
Sensitive to right-handed weak current ($0\nu\beta^+\text{EC}$)

Searched for a peak at 64keV from two K-shell X-rays after 2$\nu$ECEC

132 live days, 41kg of natural xenon (39g of $^{124}$Xe)

$T_{1/2}^{2\nu_{2K}^{124}\text{Xe}} > 4.7 \times 10^{21}$ years (90%CL)

$T_{1/2}^{2\nu_{2K}^{126}\text{Xe}} > 4.3 \times 10^{21}$ years (90%CL)

Theoretical predictions: $T_{1/2}^{2\nu_{\text{ECEC}}^{124}\text{Xe}} = 10^{20}$-10$^{24}$ years
Annual Modulation search

- We carried out the analysis without particle ID for WIMP case and model independent case.

- Large mass (832 kg)

- Data set

  2013/11/20 - 2015/03/29 (359.2 live days)

# 1 year data of XMASS (0.82 ton x year) vs. 14 years data of DAMA/LIBRA (1.33 ton x year)

  => Current statistics is already half of DAMA/LIBRA data.

- Low energy threshold: 0.5 keV by 122 keV

  => 4.8 keVnr (estimated by Aprile et al. PRL(2011))

  1.1 keVee (15% difference from NEST, see also Baudis et al. PRD(2013))

- Systematic error due to time dependence of light yield (~ 10%) was treated by two method (pull-term, covariance matrix) as a relative efficiency difference.
WIMP case

time variation data was fitted by

\[ R_{i,j}^{\text{ex}} = \int_{t_j - \frac{1}{2} \Delta t_j}^{t_j + \frac{1}{2} \Delta t_j} \left( C_i + \sigma_X \cdot A_i(m_X) \cos 2\pi \frac{(t - t_0)}{T} \right) dt, \]

\[ t_0: 152.5 \text{ day} \]
\[ T: 1 \text{ year} \]

• assuming WIMP spectrum
• 2D fitting (time and energy bin)
• DAMA/LIBRA region is mostly excluded by annual modulation search.

\(< 4.3 \times 10^{-41} \text{ cm}^2 (90\% \text{ CL}) @ 8 \text{ GeV} \]

\[ V_0: 220.0 \text{ km/s} \]
\[ V_{\text{esc}}: 650.0 \text{ km/s} \]
\[ \rho_{\text{dm}}: 0.3 \text{ GeV/cm}^3 \]

*V_{\text{esc}} 544 \text{ km/s gives } < 5.4 \times 10^{-41} \text{ cm}^2
Model Independent Case

time variation data was fitted by

\[ R_{i,j}^{ex} = \int_{t_j - \frac{1}{2} \Delta t_j}^{t_j + \frac{1}{2} \Delta t_j} \left( C_i + A_i \cos 2\pi \frac{(t - t_0)}{T} \right) dt \]

Method 1 (pull term) free in energy bin

\[ \chi^2 = \sum_i \sum_j \left( \frac{(R_{i,j}^{data} - R_{i,j}^{ex} - \alpha K_{i,j})^2}{\sigma_{stat}^2_{i,j} + \sigma_{sys}^2_{i,j}} \right) + \alpha^2, \]

Method 2 (covariance matrix)

\[ \chi^2 = \sum_{k,l} \frac{(R_{k}^{data} - R_{k}^{ex})(V_{stat} + V_{sys})_{kl}^{-1}(R_{l}^{data} - R_{l}^{ex})}{\sigma_{stat}^2_{i,j} + \sigma_{sys}^2_{i,j}} \]

Model independent analysis:

- Annual modulation signal is searched for without any model assumption.
- \( A_i \) and \( C_i \) are free parameter.
- They are fitted by the difference of two methods are used for analysis for consistency check.
  - Slightly negative amplitude was observed.
  - Significance was evaluated with test statistic (10,000 sample) and no significant modulated signal has been observed. (1.8\( \sigma \), 1.4\( \sigma \))

- \(< \sim 3 \times 10^{-3} \) counts/day/kg/keVee in 2-6keVee (0.5keVee bin width). (90 CL, Bayesian),
  (e.g. \( \sim 0.02 \) dru by DAMA/LIBRA, closed to XENON100 sensitivity)
- Another one year cycle with more stable data set is available soon.

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Summary

- Recent Result from XMASS
- bosonic Super WIMP
  - vector-boson warm dark matter was ruled out in the 40-80 keV.
- Search for 2ν double electron capture
  - $T_{1/2}^{2\nu2K(^{124}Xe)} > 4.7 \times 10^{21}$ years (90%CL)
  - $T_{1/2}^{2\nu2K(^{126}Xe)} > 4.3 \times 10^{21}$ years (90%CL)
- Annual modulation
  - WIMP $< 4.3 \times 10^{-41}$ cm$^2$@8GeV
  - $< \sim 3e^{-3}$ counts/day/kg/keVee
    (2-6 keVee range, 0.5keVee bin width)
  - another one year cycle with more stable data will be ready soon.