Annual modulation search by XMASS-I with 2.7 years of data

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- Introduction
- Calibration and Analysis
- Modulation Result
  - WIMP search
  - Model independent search
  - Power spectrum
- Conclusion and Summary
Modulation Searches

motivation

- DAMA/LIBRA NaI (TI) result: modulation signal (9.3σ)
- No sign for SUSY particle at LHC so far.
- No sign in direct detection for more than decade with nuclear recoil signal.
- Important to look for variety candidates.
  - WIMP-electron scattering
    - R. Bernabei et al. PRD, 77 02308 (2008),
    - B.M. Roberts et al., PRL 116, 023201 (2016)
  - Luminous dark matter
    - B. Feldstein et al., PRD 82, 075019 (2010)
  - Mirror Dark Matter
  - Plasma Dark Matter
    - J. D. Clarke at el. arXiv1512.06471v
- The search can be also used for solar related physics, for instance, Kaluza Klein Axion search (7/26 by Ichimura)
Interaction

nuclear recoil

Fast neutron

WIMP

(SUSY, KK ...)

Electronic recoil

-U/Th/40K etc background
Interaction

• If the signal is not a nuclear recoil.
  • Axial vector interaction
  • Photon emission from excited DM
    (Luminous dark matter)
  • …

• Axion like particle can not be candidate because \[ \sigma \approx 1/v, \] dm flux \( \sim v \).
• DAMA/LIBRA vs LXe
  • Energy deposit \( \sim 3 \text{ keV energy deposit} \)
    (from DAMA/LIBRA)

• Event rate is similar for Xe\( (z=54) \) and Iodine \( (z=53) \)

• Modulation analysis is not depend on the halo model.
XMASS experiment

• Kamioka Observatory in Japan (2700 m.w.e)
• Single phase LXe scintillation detector (832 kg)
• 642 low radioactive Hex PMT (R10789)
• φ10 m x 10 m Water Cherenkov active muon veto
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>1.65, 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>

Table 7: Calibration sources and energies. The 8 keV (*1) in the $^{109}$Cd and 59.3 keV (*2) in the $^{57}$Co source are Kα X-rays from the copper and tungsten, respectively, used for source housing.

Sources made by Korean group
Energy calibration and stability

- Energy calibration 1.65 - 122 keVee
- High Photoelectron Yield ~15 PE/keV @122 keV
- Low energy threshold: 1.0 keVee (4.8 keVnr) (15PE/keV)
- Evaluated absorption length 4-30 m, scatter ~52cm
- Run1: Std ± 2.4%, Run2 Std ± 0.5%

![Graph showing energy calibration and stability](image)

**Fig. 8.**

Absorption (light)

Run1 Run2

**Table:**

<table>
<thead>
<tr>
<th>Event</th>
<th>Absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013. Dec 31</td>
<td>± 2.4%</td>
</tr>
<tr>
<td>2015. Jan 01</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

**Notes:**

1. Power cut
2. Purification work
3. continuous gas recirculation
Annual Modulation search

- Run 1 was reported in Phys Lett. B (2016)272.
- Data set 2013/11/20 - 2016/07/20 (800.0 live days)
  XMASS (1.82 ton x year) ⇐ DAMA/LIBRA (1.33 ton x year)
- Quality cut + Likelihood analysis based on Sphericity, Aplanality, Maximum/Total PE

<table>
<thead>
<tr>
<th>Date</th>
<th>Live time [day]</th>
<th>Exposure [ton·year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run1 Nov/20/2013 - Mar/31/2015</td>
<td>387.8</td>
<td>0.884</td>
</tr>
<tr>
<td>Run2 Apr/1/2015 - Jul/20/2016</td>
<td>412.2</td>
<td>0.940</td>
</tr>
<tr>
<td>Total</td>
<td>800.0</td>
<td>1.82</td>
</tr>
</tbody>
</table>

~20 days live time was recovered after PLB2016 in Run1
Fitting time variation data

- 2D fitting energy and time bins with the systematic errors from PE yield stability, Decay time, Leff
- Relative efficiency differences were taken into account for each period based on PE yield.
- The efficiency was normalized @ 8 m absorption length (same as PLB2016)
- These errors are correlated with both energy and time bins and treated by pull term method.

WIMP case:

$$\chi^2 = \sum_i \sum_j \left( \frac{(R^\text{data}_{i,j} - R^\text{ex}_{i,j}(\alpha, \beta))^2}{\sigma(\text{stat})_{i,j}^2 + \sigma(\text{sys})_{i,j}^2} \right) + \alpha^2 + \sum_{N_{sys}} \beta_i^2$$

$$R^\text{ex}_{i,j}(\alpha, \beta) = \int_{t_j - \frac{1}{2} \Delta t}^{t_j + \frac{1}{2} \Delta t} \left( \frac{\epsilon_i^b(\alpha)}{\epsilon_i^s(\beta)} \cdot (B_i t + C_i^b) \right) dt + \sigma_{\chi n} \cdot \epsilon_i^s \cdot \left( C_i^s(\beta) + A_i^s(\beta) \cos \frac{2\pi(t - t_0)}{T} \right)$$

Model Independent case:

$$\chi^2 = \sum_i \sum_j \left( \frac{(R^\text{data}_{i,j} - R^\text{ex}_{i,j})^2}{\sigma(\text{stat})_{i,j}^2 + \sigma(\text{sys})_{i,j}^2} \right) + \alpha^2$$

$$R^\text{ex}_{i,j} = \int_{t_j - \frac{1}{2} \Delta t}^{t_j + \frac{1}{2} \Delta t} \left( \frac{\epsilon_i^b A_i^s \cos \frac{2\pi(t - t_0)}{T}}{\epsilon_i^t(\alpha)(B_i t + C_i^b)} \right) dt$$
WIMP case

- Assuming WIMP (standard halo model)
- Lewin and Smith (1996, APP)
- $T = 1\text{ year}$, $t_0 = 152.5\text{ day}$ (fixed)
- $V_0 = 232\text{ km/sec}$, $V_{\text{esc}} = 544\text{ km/s}$
- $\rho_{\text{DM}} = 0.3\text{ GeV/cm}^3$
- 2D fitting (time and energy bin)
- DAMA/LIBRA region is excluded by annual modulation search.

$<1.9 \times 10^{-41}\text{ cm}^2\ (90\%\ CL)\ @\ 8\text{ GeV}$
Model Independent Case

- Searching for without any model assumption.
- Fixed parameter: $t_0 = 152.5$ day (Jun. 2nd), $T = 365.24$. day
- Null hypotheses $p$-value: 0.11 (1.6$\sigma$), previous work (2.5$\sigma$).
- $\Rightarrow$ Upper limit. Most stringent amplitude for modulation search.

(when models assumed, the relation btw NaI and Xe might be changed)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Amplitude $10^{-3}$ (counts/day/kg/keVee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMA/LIBRA(2013)</td>
<td>25@2.75 keVee</td>
</tr>
<tr>
<td>XENON100(2017)</td>
<td>1.67$\pm$0.73 (2.0-5.8 keVee), &lt;3.1 90CL</td>
</tr>
<tr>
<td>XMASS-I (2017)</td>
<td>&lt; 1.3-3.2 (2-6 keVee) 90CL</td>
</tr>
</tbody>
</table>
Power Spectrum

• To find any period in the data in the energy range of 1-6 keVee.
• Phase $t_0$ is a free parameter.
• $\Delta \chi^2 = \chi^2(\text{null}) - \chi^2(\text{periodic hypotheses})$
• Test statistic to evaluate significance.
• Global significance: the maximum $\Delta \chi^2$ in the range to take into account ‘look elsewhere effect’.
• No significant period was found between 20 and 600 days.
Conclusion and Summary

• It is important to look for any signal (not only nuclear recoil) for dark matter search.

• XMASS-I carried out annual modulation search with 2.7 years of data. (800 live days x 832 kg)

• We did not find any modulation signals
  - $<1.9 \times 10^{-41}\text{cm}^2$ (90% CL) @ 8GeV
  - $< 1.3-3.2 \times 10^{-3}$ counts/day/kg/days (2-6 keVee) 90CL

• We did not find any particular period between 20 - 600 days in the energy region of 1-6keVee.