Review of warm scintillator detectors for Dark Matter search, the COSINE-100 project

8 low-radioactive NaI(Tl) crystals, 106 kg in total, submerged in 2 tons of liquid scintillator.

Physics run started Sept. 2016

Chang Hyon Ha
On behalf of the COSINE collaboration
Motivation: DAMA annual modulation signal, to be checked with independent measurements using the same NaI(Tl) target material.

Dark Matter Modulation
9.2 sigma

NDM15

Background:
~1 count/day/kg/keV (dru=differential rate unit) above 2 keV

Modulation between 2-6 keV
Motivation: Right thing to do

- Every scientific result should be reproducible, independently.
- Apple-to-apple comparison is necessary.
- Large crystal detector experience helps, and community supports.
Global NaI(Tl) efforts

ANAIS @ Canfranc
DAMA/LIBRA @ LNGS
SABRE @ LNGS
COSINE-100 @ Y2L
PICO-LON @ Kamioka
SABRE @ Stawell
DM-Ice17 @ South Pole

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ANAIS-112 (total of 112 kg)

TAUP17

~1 month data

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COSINE-100 experiment

Joint collaboration between KIMS and DM-Ice to search for dark matter interactions in NaI(Tl) scintillating crystals.
Shields, Vetoes, and $\mu$-counters

Plastic Scintillators for CR Muons
3-cm thick, 37 panels

20-cm thick lead shielding

40-cm active Liquid Scintillator veto

3-cm thick Cu box

5-inch PMTs

3-inch PMTs

Nal crystals

Neutron Detector

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COSINE-100 detector setup
Environmental control/monitoring

- < 0.1°C temperature fluctuation on the crystals in LS
- more than 150 environmental variables are monitored online
Very stable operation
More than 85% of physics data.
95% are good runs.
Roughly 8 months data are collected

Crystal Trigger Rate (13 Hz)
Muon Detector Rate (12 Hz)
8 NaI(Tl) Crystals

Internal background components are measured.
Average light yield ~15 PE/keV
U/Th/K contaminations are below DAMA value.
$^{210}$Po ($^{210}$Pb) is still higher than DAMA.

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<table>
<thead>
<tr>
<th>Crystal</th>
<th>Mass (kg)</th>
<th>Powder Type</th>
<th>$^{40}$K (ppb)</th>
<th>$^{238}$U (ppt)</th>
<th>$^{232}$Th (ppt)</th>
<th>$^{210}$Po (mBq/kg)</th>
<th>Light Yield (npe/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.26</td>
<td>Powder B</td>
<td>34.74±4.74</td>
<td>&lt;0.02</td>
<td>1.31±0.35</td>
<td>3.20±0.04</td>
<td>14.67±0.62</td>
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<tr>
<td>2</td>
<td>9.15</td>
<td>Powder C</td>
<td>60.64±4.64</td>
<td>&lt;0.12</td>
<td>&lt;0.63</td>
<td>2.06±0.03</td>
<td>14.56±0.54</td>
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<tr>
<td>3</td>
<td>9.16</td>
<td>WIMPSscint-II</td>
<td>34.34±3.10</td>
<td>&lt;0.04</td>
<td>0.44±0.19</td>
<td>0.76±0.02</td>
<td>15.75±0.76</td>
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<tr>
<td>4</td>
<td>18.01</td>
<td>WIMPSscint-II</td>
<td>33.32±3.50</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>0.74±0.02</td>
<td>14.69±0.46</td>
</tr>
<tr>
<td>5</td>
<td>18.28</td>
<td>Powder C</td>
<td>82.33±5.49</td>
<td>2.35±0.31</td>
<td>2.06±0.03</td>
<td>6.26±0.34</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>12.5</td>
<td>WIMPSscint-III</td>
<td>16.79±2.46</td>
<td>&lt;0.018</td>
<td>0.56±0.19</td>
<td>1.52±0.02</td>
<td>14.52±0.51</td>
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<tr>
<td>7</td>
<td>12.5</td>
<td>WIMPSscint-III</td>
<td>18.69±2.79</td>
<td>&lt;0.6</td>
<td>1.54±0.02</td>
<td>14.41±0.50</td>
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<tr>
<td>8</td>
<td>18.28</td>
<td>Powder C</td>
<td>54.25±3.82</td>
<td>&lt;0.9</td>
<td>2.05±0.02</td>
<td>3.27±0.20</td>
<td></td>
</tr>
<tr>
<td>DAMA</td>
<td></td>
<td></td>
<td>&lt;20</td>
<td>0.7 - 10</td>
<td>0.5 - 7.5</td>
<td>&lt;0.5</td>
<td>5.5 - 7.5</td>
</tr>
</tbody>
</table>

3-inch PMT 35% QE
Crystal-LS Coincidence

- $^{40}$K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal

- Tagging 1460 keV events with LS enables to veto 3 keV background events (70% tagging efficiency)
Liquid Scintillator for COSINE-100

Linear alkylbenzene (LAB) : Good optical/radioactive properties
2,5-Diphenyloxazole (PPO) : fluor, scintillator/wavelength shifter
p-bis-(o-methylstyryl)-benzene (bis-MSB) : wavelength shifter

This background of the liquid scintillator contributes negligible amount to the crystal (<0.01 dru)
CR Muon detector system

CR muon induced crystal events are vetoed when muon pass through it.

$4 \times 10^{-7}/\text{cm}^2/\text{s}$

Muon flux monitor.

 gamma background

COSINE-100 Preliminary
High Energy Spectrum

$U/Th/K/Cosmogenics$

Counts/day/keV/kg

Energy (keV)

$100-2000$ keV

--- data

--- sim
Low Energy Spectrum ($^{210}$Pb bkg.)

Internal components (crystal growing/raw material) : $^{210}$Pb ($t_{1/2}=22$yr), U/Th

External components (handling of crystal/material assay) $^{210}$Pb on the surface of crystal and reflector directly in contact.

Cosmogenic components (excitation) : $^{125}$I (59d), $^{109}$Cd(460d), $^3$H (12yr)

2-4 dru (counts/day/kg/keV) between 2-6 keV

2-20 keV

2-100 keV

$^{210}$Pb gammas (bulk + surface)

$^{210}$Pb beta decay

Slopes indicate level of surface contamination

DAMA 1 dru
Understanding single-site event spectrum

Currently, 10-15% discrepancy at the ROI
Goal <5%

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Event selection efficiency measured with $^{60}$Co Compton beta events

Above 2 keV, more than 90% selection efficiency

Hardware trigger threshold (0.14 keV)
Expected Sensitivity for COSINE-100

*Assumed 2 dru or 4 dru flat backgrounds depending on crystals.

The sensitivity should be comparable with the DAMA allowed region.
COSINE-200 (Phase-II)

Goal: Reaching background lower than DAMA (1 dru). A factor two or more improvement is needed.

Powder purification (Recrystallization)

<table>
<thead>
<tr>
<th>Powder</th>
<th>$^{39}$K (ppb)</th>
<th>$^{208}$Pb (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astro grade</td>
<td>4.5</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Crystal grade</td>
<td>45.1</td>
<td>6.0</td>
</tr>
<tr>
<td>Cian (99.5%)</td>
<td>180000</td>
<td>1305</td>
</tr>
</tbody>
</table>

$^{39}$K (ppb) | $^{208}$Pb (ppb) |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>After</td>
</tr>
<tr>
<td>Initial</td>
<td>After</td>
</tr>
<tr>
<td>0.9</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>3.3</td>
<td>0.8</td>
</tr>
<tr>
<td>5.7</td>
<td>&lt;0.4</td>
</tr>
</tbody>
</table>

Crystal growing & Handling

Established a facility at our center

Powder purification

(mass production facility for purification under construction)
Expected sensitivity for COSINE-200 (Phase-II)

*Assumed 1 dru flat backgrounds
Conclusion & Outlook

- KIMS and DM-Ice join forces (the COSINE-100 collaboration) to reproduce DAMA annual modulation using the same NaI(Tl) target material.

- COSINE-100 (Phase-I) is running with 106 kg of NaI(Tl) crystals.
  - CR muon tagging and liquid scintillator tagging.

- Physics run started on September 2016

- Initial performance of COSINE-100 is promising. 2 keV thres., 2-4 dru at ROI

- Expect to have DAMA-comparable sensitivity in ~2 years

- Continued R&D on higher purity crystals for COSINE-200 (Phase-II)
You Bet!

July 18, 2017

Within 5 years from today,
Frank Wilczek bets
that the DAMA signal
will not be confirmed.

"Bet is against
Katie Freese.
Frank Wilczek bets
1000 to 1 odds
I.e. To be precise
$1000 vs. $1
I.e. Katie loses $1 max.

Referee is Lars Bergstrom.

Frank Wilczek

https://twitter.com/ktfreese/status/888730718477713408

I have a bet with Frank Wilczek on status of DAMA dark matter detector in 5 years - Katie Freese

tweet on 7/22/2017