COSINE dark matter search experiment

Hyun Su Lee
Center for Underground Physics (CUP)
Institute for Basic Science (IBS)
On behalf of the COSINE Collaboration
Observation (?) of dark matter annual modulation signal

DAMA/LIBRA experiment

- Annual Modulation Searches with NaI(Tl) crystal detectors

Claim dark matter observation

\[ 9.3 \sigma \text{ significance} \]


Clear Modulation at 2-4keV
Observation (?) of dark matter annual modulation signal

**DAMA/LIBRA experiment**

- Annual Modulation Searches with NaI(Tl) crystal detectors

**Claim dark matter observation**

C. Savage et al., JCAP 04 (2009) 010
Null signals in DAMA regions

- DAMA signal regions have been ruled out by many direct detection experiments
  - Liquid Xe, Cryogenic Ge, Cryogenic CaWO₄ so on..
- It has also been ruled out by annual modulation analyses of liquid Xe electron recoil data

**XENON100, PRL 118, 101101 (2017)**

**XMASS, PLB 759, 272 (2016)**
What DAMA people thought

About interpretation

See e.g.: Riv.N.Cim.26 n.1 (2003) 1, IJMPD13 (2004) 2127,
PRD84 (2011) 055014, JMPA28 (2013) 1330022

...models...

- Which particle?
- Which interaction coupling?
- Which EFT operators contribute?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?

...and experimental aspects...

- Exposures
- Energy threshold
- Detector response (pke/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA
Best way to prove/refute DAMA/LIBRA’s result

- Exactly same experiment!!
- Need to understand why DAMA/LIBRA shows modulation (WIMP?)
  - It is possible that underline cause of DAMA signals might be due to another exciting physics.
Global NaI(Tl) efforts

- DAMA/LIBRA @ LNGS
- SABRE @ LNGS
- COSINE -100 @ Y2L
- KIMS
- PICO-LON @ Kamioka
- ANAIS @ Canfranc
- SABRE @ Stawell
- DM-Ice17 @ South Pole
YangYang(Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant
Center for Underground Physics
IBS (Institute for Basic Science)

Minimum depth: 700 m / Access to the lab by car (~2km)

KIMS (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)

Since 2003
Since 2014
KIMS (Korea Invisible Mass Search) CsI experiment

- 12 low-background CsI crystals (104.4 kg)
- 2.5 year data (2009-2012)
- Background: 2~3 count/kg/day/keV (dru)
- Model-independent rejection of DAMA signals interpreted as WIMP-Iodine interaction

PRL 108 181301 (2012)
PRD 90 052006 (2014)
JHEP 06 011 (2016)
Nal(Tl) crystal developments by KIMS (since 2013)

P. Adhikari et al., EPJC 76, 185 (2016)

- Understanding internal background very well
- We achieved ~2 counts/kg/day/keV level at 6keV

Developed crystals are used for COSINE-100

$^{40}$K and $^{210}$Pb are main background at low energy

~ 2keV energy threshold
~ 2 dru background @ 6keV
DM-Ice experiment

• Two NaI crystals in South pole (Jun.2011 – Jan.2015)

PRD 90 092005 (2014)

From R. Maruyama

PRD 90 092005 (2014)

PRD 93 042001 (2016)

photon rate after muons, examples

5.5 ± 0.5 s decay time

PRD 95 032006 (2017)

Annual modulation analysis

• Active R&D on low background NaI(Tl) crystal developments → used for COSINE-100

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KIMS and DM-Ice joint effort to search for dark matter interactions in NaI(Tl) scintillating crystals. (Goal to reproduce DAMA/LIBRA)

5 countries, 14 institutes, ~50 members
COSINE-100

- ~106 kg crystals running since Sept/2016

From DM-ICE

From KIMS
## COSINE-100 crystals

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Mass (kg)</th>
<th>Powder</th>
<th>Alpha rate (mBq/kg)</th>
<th>$^{40}$K (ppb)</th>
<th>$^{238}$U (ppt)</th>
<th>$^{232}$Th (ppt)</th>
<th>Light yield (p.e./keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal 1</td>
<td>8.3</td>
<td>AS-B</td>
<td>3.20 ± 0.08</td>
<td>43.4 ± 13.7</td>
<td>&lt; 0.02</td>
<td>1.31 ± 0.35</td>
<td>14.88 ± 1.49</td>
</tr>
<tr>
<td>Crystal 2</td>
<td>9.2</td>
<td>AS-C</td>
<td>2.06 ± 0.06</td>
<td>82.7 ± 12.7</td>
<td>&lt; 0.12</td>
<td>&lt; 0.63</td>
<td>14.61 ± 1.45</td>
</tr>
<tr>
<td>Crystal 3</td>
<td>9.2</td>
<td>AS-WS II</td>
<td>0.76 ± 0.02</td>
<td>41.1 ± 6.8</td>
<td>&lt; 0.04</td>
<td>0.44 ± 0.19</td>
<td>15.50 ± 1.64</td>
</tr>
<tr>
<td>Crystal 4</td>
<td>18.0</td>
<td>AS-WS II</td>
<td>0.74 ± 0.02</td>
<td>39.5 ± 8.3</td>
<td>&lt; 0.3</td>
<td>14.86 ± 1.50</td>
<td></td>
</tr>
<tr>
<td>Crystal 5</td>
<td>18.0</td>
<td>AS-C</td>
<td>2.06 ± 0.05</td>
<td>86.8 ± 10.8</td>
<td>2.35 ± 0.31</td>
<td>7.33 ± 0.70</td>
<td></td>
</tr>
<tr>
<td>Crystal 6</td>
<td>12.5</td>
<td>AS-WS III</td>
<td>1.52 ± 0.04</td>
<td>12.2 ± 4.5</td>
<td>&lt; 0.018</td>
<td>0.56 ± 0.19</td>
<td>14.56 ± 1.45</td>
</tr>
<tr>
<td>Crystal 7</td>
<td>12.5</td>
<td>AS-WS III</td>
<td>1.54 ± 0.04</td>
<td>18.8 ± 5.3</td>
<td>&lt; 0.6</td>
<td>13.97 ± 1.41</td>
<td></td>
</tr>
<tr>
<td>Crystal 8</td>
<td>18.3</td>
<td>AS-C</td>
<td>2.05 ± 0.05</td>
<td>56.15 ± 8.1</td>
<td>&lt; 1.4</td>
<td>3.50 ± 0.33</td>
<td></td>
</tr>
<tr>
<td>DAMA</td>
<td></td>
<td>&lt; 0.5</td>
<td>&lt; 20</td>
<td>0.7 - 10</td>
<td>0.5 – 7.5</td>
<td>5.5 – 7.5</td>
<td></td>
</tr>
</tbody>
</table>

- Alpha rate corresponds to $^{210}$Po ($^{210}$Pb)
- $^{210}$Pb and $^{40}$K level are still a bit higher than DAMA/LIBRA

- Hamamatsu R12669 PMTs quantum efficiency: 35% @ 420 nm

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Background simulation

G. Adhikari et al., EPJC 77, 437 (2017)

- Geant4 based MC simulation describes background of a NaI(Tl) crystal reasonably well
- Main background at low energy due to internal $^{210}$Pb, $^{40}$K, and $^{121}$Te ($\tau = 19.2$ days) cosmogenic
Internal $^{40}\text{K}$ and external background reduction

- Active veto with liquid scintillator

Prototype design for single crystal

J.S. Park et al., NIMA, 851 (2017) 103

$^{40}\text{K}$ decay

$3\text{ keV}$

$1460\text{ keV}$

$^{40}\text{K}$ tagging

~$50\%$ $^{40}\text{K}$ tagging

COSINE-100 design

Counts/kg/day/keV

Tagging efficiency (%) vs. Thickness of LS veto (cm)
Shielding design of COSINE-100

Plastic Scintillators

Filled with Liquid Scintillator (2000 L)

Lead Shielding (20 cm)

Cu Box (3 cm)

Nal(Tl) Crystals (106 kg)
Installation of COSINE-100

- Dec. 2015
- Feb. 2016
- Apr. 2016
- May. 2016
- Sep. 2016

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Monitoring of environment

Temperatures, humidity, Radon level, DAQ rates, electronics status etc. have been continuously monitored!

Overall quite stable environment & operation
COSINE-100 operation

• Stable physics run
  ❖ Excluding calibration period, more than 95% live time!!
• More than 8 months good physics data
  ❖ Physics analysis is ongoing with initial two month data
Muon detector

- Outer muon veto consists of 37 plastic scintillator panels

Muon flux has been monitored stably

Vetoing of muon correlated events in NaI(Tl) crystals was implemented

Study on muon induced events with NaI(Tl) and liquid scintillator is ongoing

Preliminary

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

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Liquid scintillator veto system

- Tagging rate of $^{40}$K is well understood with Geant4-based simulation
- Internal background of LS is well understood and low enough
- 20 keV tagging threshold is achieved

$^{40}$K of LS $\sim$300 ppb
$^{238}$U $<$ 7 ppt
$^{232}$Th $<$ 4 ppt

Fit result

Data (vetoed)
- Fit
- Subtracted $^{40}$K

>75% veto efficiency of 3keV x-ray
Crystal data

- 10 days of early data, preliminary event selection
- **Background levels** from 2 to 4 dru (counts/kg/day/keV)
- New selection criteria based on multivariable technique is on development

\[ \tau = 59.4 \text{ days} \]
Nal crystal data modeling

- Background modeling of COSINE-100 data is ongoing.

Fine tuning of Geant4-based MC simulation to describe underground data.

This study will provide a constraint for background in the ROI of WIMP signal.
Nuclear recoil data

D-D neutron generator

Quenching Factor

Am/Be source

Good PSD due to high light yield!!

JHEP 08 (2015) 093

Preliminary

Polyethylene blocks for neutron shielding

$2.42 \text{ MeV}$

$^{25}\text{Na}$

$^{25}\text{Na}$

$\text{NaI(Tl)}$ Detectors

$\text{NaI(Tl)}$ Detector

$\theta$

$\text{NaI(Tl)}$ Detectors

Good PSD due to high light yield!!

Number of events vs. $\ln MTI (\text{in} \text{MeV})$

(a) 1-2 keV

(b) 2-3 keV

(c) 3-4 keV

(d) 4-5 keV

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COSINE-100 projected sensitivity

- Assuming 4 dru flat background (no background constraints)
- 2 years live data with 1 keV energy threshold with an annual modulation analysis
- Interesting physics results will be given soon
Next phase of COSINE (COSINE-200)

- **Background** levels of COSINE-100 are 2-3 times higher than DAMA/LIBRA
  - We may not resolve all possible scenarios interpreting DAMA/LIBRA signals
  - Still need to develop better crystals

- **Issues** are internal $^{40}\text{K}$ and $^{210}\text{Pb}$
  - $^{40}\text{K}$: Powder purification
  - $^{210}\text{Pb}$: Any part of powder, crystal growing, and crystal handling can make it

- **Extremely pure crystal** development
  - From initial materials to detector assembly, we need very careful handling
  - These are very difficult jobs for a private company
  - We decide to do our own development for the entire process

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Nal powder purification

Recrystallization

1. Selection of an appropriate solvent.
2. Add just enough solvent at boiling point to dissolve solid.
3. Dissolve the every solid at boiling point.
4. Cool down slowly to get the pure crystal, leaving impurity in solution.

\[ ^{238}U \text{ and } ^{232}Th \text{ are very low even in Normal grade powder} \]

<table>
<thead>
<tr>
<th>Powder</th>
<th>(^{138}\text{Ba} \text{ (ppb)})</th>
<th>(^{88}\text{Sr} \text{ (ppb)})</th>
<th>(^{39}\text{K} \text{ (ppb)})</th>
<th>(^{208}\text{Pb} \text{ (ppb)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astro grade</td>
<td>Initial 0.6, After &lt;0.3</td>
<td>Initial &lt;0.3, After &lt;0.3</td>
<td>Initial 4.5, After &lt;1.0</td>
<td>Initial 0.9, After &lt;0.4</td>
</tr>
<tr>
<td>Crystal grade</td>
<td>7.14, 0.62</td>
<td>0.9, &lt;0.3</td>
<td>45.1, 6.0</td>
<td>3.3, 0.8</td>
</tr>
<tr>
<td>Cian (99.5%)</td>
<td>2592, 5.3</td>
<td>65.8, &lt;0.3</td>
<td>180000, 1305</td>
<td>5.7, &lt;0.4</td>
</tr>
</tbody>
</table>

Cian powder did two recrystallizations while other powders did only one.
Reduction factor for K is about factor 10. (~20 ppb of K is enough)

One recrystallization of crystal grade powder provides good enough background.
Crystal growing

• Dedicated R&D grower was built

Crucible size is $\phi = 15$ cm; 1~2 kg test crystal can be grown

3rd trial

Seeding was successful
Optimization is under development

We will prepare 4th trial in this week
Planning mass production

~ 50 kg NaI Recrystallization in one batch

~ 100 kg NaI crystal (ingot) grower concept
Crystal encapsulation

400 cm diamond saw

Normal encapsulation

Liquid scintillator

NaI encapsulation R&D with LS

Filled with Liquid Scintillator

NaI(Tl)

Idea coming from CANDLE

Surface $^{210}$Po can be tagged with LS

Humidity in LS is a problem; O(10ppm)
COSINE-200 sensitivity

- 1 dru background (same as DAMA/LIBRA)

If DAMA is right...

200 kg × 3 year

7.3 sigma observation (2-6 keV)
Summary

• **Global efforts** to verify DAMA/LIBRA’s annual modulation signals are quite active

• KIMS and DM-Ice jointly launch COSINE project

• **COSINE-100** is running with 106 kg low-background NaI(Tl) crystals at Yangyang underground laboratory **since September 2016**

• Initial performance of COSINE-100 is promising and will provide **interesting physics results within 2 years**

• Active R&D to develop **better quality NaI(Tl) crystal detector** is ongoing for next phase COSINE-200

• **COSINE-200** experiment will bring **definite conclusion about the signals from DAMA/LIBRA**