Status of COSINE experiment

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Institute for Basic Science (IBS)
On behalf of the COSINE Collaboration
Current status of direct dark matter searches

- No sign of WIMP dark matter down to $4 \times 10^{-47} \text{cm}^2$ @ 30 GeV
- Exploring low-mass dark matter
- Unresolved signal from DAMA
Observation of dark matter annual modulation signal (?)

DAMA/LIBRA experiment

• Annual Modulation Searches with an array of NaI(Tl) crystals

Claimed an observation of the dark matter


Clear Modulation at 2-4 keV

DAMA/LIBRA phase 1

1.33 ton-year
Observation of dark matter annual modulation signal (?)

DAMA/LIBRA experiment

• Annual Modulation Searches with an array of NaI(Tl) crystals

Claimed an observation of the dark matter

First model independent results from DAMA/LIBRA–phase2

New result from DAMA/LIBRA

R. Bernabei$^{a,b}$, P. Belli$^{a,b}$, A. Bussolotti$^b$, F. Cappella$^{c,d}$, V. Caracciolo$^e$, R. Cerulli$^{a,b}$, C.J. Dai$^f$, A. d’Angelo$^{c,d}$, A. Di Marco$^b$, H.L. He$^f$, A. Incicchitti$^{c,d}$, X.H. Ma$^f$, A. Mattei$^d$, V. Merlo$^{a,b}$, F. Montecchia$^{b,g}$, X.D. Sheng$^f$, Z.P. Ye$^{f,h}$ arXiv:1805.10486
DAMA/LIBRA phase 2

- Energy threshold reached to 1 keV with better PMTs
- Still there is modulation
- Significance
  - 1-6 keV : $9.5 \sigma$ (phase 2)
  - 2-6 keV : $12.9 \sigma$ (phase 1+2)
- Increased modulation amplitude below 2keV
Global NaI(Tl) efforts

- KIMS/COSINE @ Yangyang
- DAMA @ LNGS
- SABRE @ LNGS
- COSINUS @ Modane
- ANAIS @ Canfranc
- SABRE @ Kamioka
- PICO-LON @ Kamioka
- DM-Ice @ South Pole
Nal(Tl) crystal developments by KIMS (since 2013)

- Understanding internal background very well
- We achieved ~2 counts/kg/day/keV level at 6keV
- Continue to reduce background of the crystal

P. Adhikari et al., EPJC 76, 185 (2016)
G. Adhikari et al., EPJC 77, 437 (2017)

K⁴⁰ ~60 days half life

I¹²⁵ L-capture

~2keV energy threshold

~ 2 dru background @ 6keV

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

- Active veto with liquid scintillator

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

Prototype design for single crystal

COSINE-100 design
Nuclear recoil data

D-D neutron generator

Quenching Factor

Am/Be source

H.S. Lee et al., JHEP 08 (2015) 093
Good discrimination due to high light yield !!

Can extract WIMP signal using PSD

arXiv:1809.10310
Surface $^{206}\text{Pb}$ recoil measurement

- Surface $^{206}\text{Pb}$ recoils are much faster than typical NaI nuclear recoils
- We will use those shapes to extract WIMP signals
Nuclear recoil event extraction using pulse shape discrimination

- 2967.4 kg days exposure from KIMS-NaI R&D (two crystals)

K.W. Kim et al., arXiv:1806.06499

Fit results (2-8 keV)  Spin Independent WIMP-nucleon interaction
DM-Ice17


Two 8.47 kg crystal
2200 m.w.e overburden

PRD 90 092005 (2014)

PRD 93 042001 (2016)

photon rate after muons, examples

5.5 ± 0.5 s
decay time
Annual modulation study with DM-Ice17

DM-Ice17 4-6 keVee (BF, 68%, 95%, 99%)

expected dark matter phase

~Jan. 1

~Apr. 1

~Jul. 1

~Oct. 1

DAMA/LIBRA, 2-4 keVee (99%)

analysis on data from arXiv:1308.5109

modulation amplitude

Proof of principle

• Continue to develop low background NaI(Tl) crystals

PRD 95 032006 (2017)
COSINE Project (Since 2015)

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

5 countries, 14 institutes, ~50 members
YangYang (Y2L) Underground Laboratory

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

Since 2003

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

KIMS (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)
Physics run started since Sept/2016

**COSINE-100 operation**

- **Stable physics run**
  - More than 90% live time!! Most of data are marked as good quality data
- Operating about 2 years

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**COSINE-100 exposure**

- SET1 data: Sep/30 (2016)
- SET2 data: Jul/17 (2018)

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> 200 parameters are monitored
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

\[ 328 \pm 1 \text{(stat)} \pm 10 \text{(syst)} \text{ muon/m}^2/\text{day} \]

\[ \sim 2 \times 10^{-5} \text{ of sea level} \]

JINST 13, T02007 (2018)

Muon Modulation

Muons are detected using a NaI(Tl) crystal, and they are analyzed using a charge spectrum.

Preliminary

Muon induced events at NaI

Preliminary

The analysis shows that the number of muon events is consistent with the expected level, and no significant modulation is observed.
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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
Crystal data (initial two month – SET1)

- **Background levels** from 2 to 4 dru (counts/kg/day/keV)
  - Higher than DAMA/LIBRA crystals
  - Efficiency corrected spectra
Background understanding

Single hit event
(6-2000 keV)

Multiple hit events
(2-2000 keV)

Expected background (2-6 keV)

<table>
<thead>
<tr>
<th>Components</th>
<th>Background 2-6 keV (dru)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal $^{210}$Pb</td>
<td>1.50 +/- 0.07</td>
</tr>
<tr>
<td>Internal $^{40}$K</td>
<td>0.05 +/- 0.01</td>
</tr>
<tr>
<td>Surface $^{210}$Pb</td>
<td>0.38 +/- 0.21</td>
</tr>
<tr>
<td>$^3$H (Cosmogenic)</td>
<td>0.58 +/- 0.54</td>
</tr>
<tr>
<td>$^{109}$Cd (Cosmogenic)</td>
<td>0.09 +/- 0.09</td>
</tr>
<tr>
<td>Other cosmogenic</td>
<td>0.05 +/- 0.03</td>
</tr>
<tr>
<td>External</td>
<td>0.03 +/- 0.02</td>
</tr>
<tr>
<td><strong>Total expected</strong></td>
<td><strong>2.70 +/- 0.59</strong></td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td><strong>2.64 +/- 0.05</strong></td>
</tr>
</tbody>
</table>

Background modeling was done only using 6-2000 keV events
Fit with WIMP signals

Background modeling was done only using 6-2000 keV events
Sensitivity of COSINE-100 59.5 days data

- Generate mock data from MC modeling

Mock data generation:

1. **Total MC**
   - Generate mock data from MC modeling.
   - Sensitivity estimation is done through a pseudo experiment.

Signal probability:

- Single hit-spectra from eight crystals are fit simultaneously with an assumed WIMP signal.
- Same parameters as Savage et al. (2009).

Set 90% CL upper limit:

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No Sign of WIMP

Preliminary

Data fit (COSINE 59.5 days)
COSINE-100 excludes DAMA/LIBRA-phase1’s interpretation with the spin-independent WIMP interaction in Standard Halo Model

First time with same NaI(Tl) target

Consistent with other null experiments

Preliminary

Quenching factor
Q(Na)=0.3, Q(Tl)=0.09
Annual Modulation

- Cosmogenic components were constraint by the measurements
- Floating $^3$H and constant (internal background)

**Multiple 2-6 keV**

**Single 6-10 keV**

- C5 & C8 were excluded due to low light output
- C1 was excluded due to uncontrolled PMT induced noise
- Side bands are well explained by known background
~ 9% data opened (blinded analysis)

- Current data is blinded, only 9% of total data

Data quality, cosmogenic component subtraction, and background modeling almost done

9% data

Under evaluating systematic uncertainty

Assuming total SET2 data (error reduction only)
Solar axion search

C7 signal spectrum

Preliminary
Boosted inelastic dark matter search


- Effectively ton scale detector using 2ton of liquid scintillator

Preliminary
Analysis with 1 keV energy threshold

Understand signal-like events and noise-like events at low energy

Develop new parameter to reject noise-like events effectively

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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 in interpreting DAMA/LIBRA signals
  - Still need to develop better crystals

- **Issues are** internal $^{40}$K, $^{210}$Pb, and $^3$H
  - $^{40}$K: Powder purification
  - $^{210}$Pb: Any part of powder, crystal growing, and crystal handling can make it
  - $^3$H: Cosmogenic activation

- **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 decided to do our own development for the entire process

**Cosmogenic activation will be naturally reduced if we grow the crystals in Korea**
Nal powder purification (Lab experiment)

• Recrystallization

Saturated NaI solution @ 25 °C → Evaporation of 40 % of H₂O under vacuum → Crystallization: Cooling down with stirring

T↑ 110 °C → T↓ 25 °C

Purified NaI powder

Nal crystal

Drying crystal under vacuum @ 130 °C
Purification of NaI powder

- Recrystallization three times for normal grade while one times for the other pure grade powders

**ICP-MS results**

<table>
<thead>
<tr>
<th>Powder</th>
<th>$^{39}$K (ppb)</th>
<th>$^{208}$Pb (ppb)</th>
<th>$^{232}$Th (ppb)</th>
<th>$^{238}$U (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>initial After</td>
<td>Initial After</td>
<td>Initial After</td>
<td>Initial After</td>
</tr>
<tr>
<td>Astro grade</td>
<td>5 &lt; 1</td>
<td>0.9 &lt; 0.4</td>
<td>&lt;0.1 &lt;0.1</td>
<td>&lt;0.1 &lt;0.1</td>
</tr>
<tr>
<td>Crystal grade</td>
<td>45 6</td>
<td>3.3 0.8</td>
<td>&lt;0.1 &lt;0.1</td>
<td>&lt;0.1 &lt;0.1</td>
</tr>
<tr>
<td>Normal grade</td>
<td>240,000 210</td>
<td>6.9 0.2</td>
<td>&lt;0.1 &lt;0.1</td>
<td>&lt;0.1 &lt;0.1</td>
</tr>
</tbody>
</table>

- Efficiency: 40% – 50%
- Mother solution can be reused for next recrystallization.

Reduction for K and Pb after one recrystallization

- K : ~ 10 reduction
- Pb: ~ 3 reduction

**Goal**: K less than 20 ppb

Purification factory

70 kg NaI powder can be loaded

Goal: K less than 20 ppb

<table>
<thead>
<tr>
<th></th>
<th>K (ppb)</th>
<th>Pb (ppb)</th>
<th>U (ppb)</th>
<th>Th (ppb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial NaI</td>
<td>248</td>
<td>19.0</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Purified NaI</td>
<td>&lt;16</td>
<td>0.4</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Our system is more effective than lab experiment
Crystal growing

• Small crystal grower was installed at 2017

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

Sept/2017 Pure NaI

Pure NaI

~ 7.0 cm (D) x 4.5 cm (L): ~ 840 g

~ 7.0 cm (D) x 5.3 cm (L): ~ 970 g

~ 6.5 cm (D) x 5.1 cm (L): ~ 850 g
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Tl doped crystals

Feb/2018

Crystal grade

May/2018

Astro grade

~40,000 Photons/MeV

~10.4 PEs/keV

660.6 g
A full size grower

- Full size grower & annealing furnace were installed ($\phi = 60 \text{ cm}$)
  - Similar growing machine as the DAMA/LIBRA crystals
  - Maximum powder loading: 120 kg
    - About three full size detectors (12.5 kg) per ingot

- Tests on temperature control & mechanical operation were done
- Real experiments will be started soon
COSINE-200

- Current COSINE-100 shield designed to accommodate 16 of 12.5 kg crystals = 200 kg

Total 200 kg

Another 200 kg in south pole? If we have same modulation..

Under consideration

2022-2023 (IceCube upgrade)
COSINE-200 sensitivity (Modulation)

- 1 dru background (same as DAMA/LIBRA)

Model independent comparison of the modulation amplitude at 2-6 keV will be performed
Summary

• COSINE-100 detector was installed at Y2L and runs smoothly for about two years

• COSINE-100 detector is well understood
  ❖ ~ 2.7 counts/day/kg/keV with 2 keV threshold for best crystal

• COSINE-100 confirms that DAMA’s modulation signal cannot be from standard WIMP in SHM with same NaI(Tl)

• Modulation analysis of COSINE-100 is ongoing

• Preparing 1keV threshold analysis

• COSINE-200 is under preparation
  ❖ Unambiguous conclusion for the DAMA/LIBRA signals
  ❖ Goal to start ~200 kg experiment at 2019 with less than 1dru background