Recent Results from the COSINE-100 Experiment

Jay Hyun Jo
on behalf of the COSINE-100 Collaboration

Yale University

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Current Status of Direct Dark Matter Searches

- No sign of WIMPs down to $>10^{-46}$ cm$^2$ @ 30 GeV
- New experiments exploring low-mass dark matter
- DAMA’s signal remains unresolved
• DAMA/LIBRA-phase2 result with 1 keV threshold
  - (2-6) keV: $12.9 \sigma$ from 2.46 ton-year
  - (1-6) keV: $9.5 \sigma$ from 1.13 ton-year
• Modulation amplitude:
  (0.0103±0.0008) cpd/kg/keV in (2-6) keV
• Phase: (145±5) days
• Period: (0.999±0.001) year
• Long-standing conflict with other experiments using different target material
Global NaI Efforts

- **DAMA**
- **SABRE**
- **COSINUS**
- **KIMS (+ DM-Ice)**
- **COSINE-100**
- **PICOLON**
- **ANAIS**

**Publications**:
- JINST 13 T02007 (2018)
- Phys. Rev. D 90 052006 (2014) (CsI)
- Phys. Rev. D 93 042001 (2016)
- Astropart. Phys. 35 (2012) 749

**Locations**:
- Gran Sasso + Australia
- Kamioka
- Yangyang
- Canfranc
- Boulby
- South Pole
- Canfranc
- South Pole
- Canfranc
- South Pole
A joint effort between DM-Ice and KIMS collaborations

- 8 NaI(Tl) crystals with 106 kg in total
- Located at Yangyang underground laboratory (Y2L), South Korea, with ~700 m rock overburden
- Physics run started September 2016
COSINE-100 Detector Configuration

Plastic Scintillator Panels

2-inch PMT

Lead (20 cm)

Copper Box (3 cm)

5-inch PMTs

Copper box

Liquid Scintillator Filled

Encapsulated Crystals

3-inch PMT
COSINE-100 Construction Timeline

Dec. 2015

Mar. 2016


Sep. 2016
COSINE-100 Operation

- Data taking since Sep. 2016
  - Stable operation
  - ~95% live time
  - Near 100% uptime outside of calibration
- 21.6 months of data accumulation
  - SET1 data (59.5 days) - Background modeling, detector understanding, and WIMP analysis
  - SET2+SET3 data (585 days) - Annual modulation analysis

COSINE-100 Accumulated Data

Calibration

- COSINE-100 Preliminary
- Total Livetime: 622.2 days (94.9%)
- Good Data: 610.8 days (93.1%)

Livetime (day)

0 100 200 300 400 500 600

12/31, 04h 12/31, 10h

2018/7/18 14h:40m

SET1

SET2+SET3
• Monitoring stability of temperature, humidity, current/voltage, etc.

• < 0.5 °C temperature and < 2% humidity fluctuation inside the shielding structure

• Current and voltage of detectors very stable

See William Thompson’s Thursday talk
COSINE-100 NaI(Tl) Crystals

- 8 Crystals, total 106 kg
- Culmination of R&D program with Alpha Spectra
- U/Th/K below DAMA, $^{210}$Po very close
- High light yield
  - Crystal-5 & 8 used primarily for veto due to low light yield

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Mass (kg)</th>
<th>Size (inches diameter x length)</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 (PEs/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal-1</td>
<td>8.3</td>
<td>5.0 x 7.0</td>
<td>AS-B</td>
<td>3.20 ± 0.08</td>
<td>43.4 ± 13.7</td>
<td>&lt;0.02</td>
<td>1.3 ± 0.4</td>
<td>14.9 ± 1.5</td>
</tr>
<tr>
<td>Crystal-2</td>
<td>9.2</td>
<td>4.2 x 11.0</td>
<td>AS-C</td>
<td>2.06 ± 0.06</td>
<td>82.7 ± 12.7</td>
<td>&lt;0.12</td>
<td>&lt;0.6</td>
<td>14.6 ± 1.5</td>
</tr>
<tr>
<td>Crystal-3</td>
<td>9.2</td>
<td>4.2 x 11.0</td>
<td>AS-WSII</td>
<td>0.76 ± 0.02</td>
<td>41.1 ± 6.8</td>
<td>&lt;0.04</td>
<td>0.4 ± 0.2</td>
<td>15.5 ± 1.6</td>
</tr>
<tr>
<td>Crystal-4</td>
<td>18.0</td>
<td>5.0 x 15.3</td>
<td>AS-WSII</td>
<td>0.74 ± 0.02</td>
<td>39.5 ± 8.3</td>
<td>&lt;0.3</td>
<td>14.9 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>Crystal-5</td>
<td>18.3</td>
<td>5.0 x 15.5</td>
<td>AS-C</td>
<td>2.06 ± 0.05</td>
<td>86.8 ± 10.8</td>
<td>2.4 ± 0.3</td>
<td>7.3 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>Crystal-6</td>
<td>12.5</td>
<td>4.8 x 11.8</td>
<td>AS-WSIII</td>
<td>1.52 ± 0.04</td>
<td>12.2 ± 4.5</td>
<td>&lt;0.02</td>
<td>0.6 ± 0.2</td>
<td>14.6 ± 1.5</td>
</tr>
<tr>
<td>Crystal-7</td>
<td>12.5</td>
<td>4.8 x 11.8</td>
<td>AS-WSIII</td>
<td>1.54 ± 0.04</td>
<td>18.8 ± 5.3</td>
<td>&lt;0.6</td>
<td>14.0 ± 1.4</td>
<td></td>
</tr>
<tr>
<td>Crystal-8</td>
<td>18.3</td>
<td>5.0 x 15.5</td>
<td>AS-C</td>
<td>2.05 ± 0.05</td>
<td>56.2 ± 8.1</td>
<td>&lt;1.4</td>
<td>3.5 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>DAMA</td>
<td></td>
<td></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>
</tr>
</tbody>
</table>
• Dominant source of noise events comes from PMT noise
• Boosted Decision Tree (BDT) was utilized to reject such noise events
Selection Efficiency/Low Energy Spectrum

- ~70% efficiency at 2 keV
- 2 - 4 counts/keV/kg/day in region of interest depending on the crystal
Data reproduced well with GEANT4 simulation

Background well understood from 2 keV - 2000 keV

Dominant background from $^{210}\text{Pb}$ and $^{40}\text{K}$, followed by cosmogenic $^3\text{H}$

See Estella Barbosa de Souza’s talk today
• Using 59.5 days of data: 6303.9 kg·day exposure

• Spectrum fit for 2-20 keV including WIMP model
  - Likelihood analysis to fit data using background model and WIMP signal model (SHM as described in Savage et al., JCAP 0904:010 (2009))
  - Background understanding consideration from V. Kudryavtsev et al. (Astropart. Phys. 33 (2010) 91)
Physics Analysis: WIMP Analysis

- Spectrum with known sources of backgrounds
- Excludes DAMA/LIBRA-phase1 w/ NaI(Tl) (as spin-independent WIMP with Standard Halo Model)
- Consistent with null results from other direct detect experiments with different target medium
• Crystal 1, 5, and 8 are excluded in this analysis due to low light yield and excessive PMT noise

• Sideband data fits well with exponential models built with the known cosmogenic components
Currently data in 2-6 keV is blinded, only using 9% of total data.

Full data analysis will be using 585+ days of data.

Data quality, cosmogenic component estimation, background trend understanding almost done: Stay tuned!

5 years of running can rule out DAMA.

Agreed to combine data with ANAIS.
COSINE-100: Goal is to test DAMA's claim for dark matter observation; running very smoothly since Sept. 2016

COSINE-100 confirms that DAMA's modulation signal cannot be from standard WIMP & SHM with NaI(Tl)

Model independent annual modulation analysis is ongoing

Crystal growing R&D is being developed in IBS, and looks promising

Stay tuned for more exciting results to come!

See William Thompson’s talk (yesterday): Detector Stability of COSINE-100
See Estella Barbosa de Souza’s talk (today): Background Assessment of the COSINE-100 Experiment
Backup
DAMA Experiment

- Located at LNGS, Italy
- 25 x 9.70 kg NaI (TI) detectors
  - Grown by Saint-Gobain
  - 0.85 - 1.3 cpd/kg/keV total background rate
- 2 PMTs/crystal
  - ~38.5% QE
  - Light yield of 5.5 - 7.5 pe/keV
  - 10 cm quartz lightguides attached
- DAMA/NaI (100 kg, 1996 - 2003), DAMA/LIBRA phase 1 (250 kg, 2003 - 2010), DAMA/LIBRA phase 2 (250 kg, 2010 - 2018)
“What is causing DAMA’s modulation? Could it be some backgrounds?”
Interpretation of the DAMA Result

...models...
- Which particle?
- Which interaction coupling?
- 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 (phe/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

P. Belli, IDM2016
- $^{40}\text{K}$ emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal

- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events**

- Liquid scintillator internal contamination well modeled with simulation
• Muon veto with 37 plastic scintillator panels
• Events correlated with muon tagged
• Muon-induced events in NaI(Tl) under investigation

Muon candidate

\[328\pm1\text{(stat)}\pm10\text{(syst)} \text{ muon/m}^2/\text{day}\]
Muon flux at COSINE-100 is $\sim 3.98 \times 10^{-7}$/cm$^2$/s (344.29 muons/m$^2$/day)

- Rate has been consistent throughout the physics run
- Muon selection used to veto muon-induced crystal events
From the background understanding, other interesting searches are actively on-going:

- PSD analysis: looking at different decay time between electron/nuclear recoil within NaI(Tl) crystal.

- Bosonic Super-WIMP, Solar axion, inelastic Boosted Dark Matter searches, ...
COSINE-100 Crystal growing R&D

- Needs to grow our own crystal with low(er) background and better understanding of the crystal
- Powder purification system and crystal growers are available at Korean facility
- Went through many trials and errors, found ways to reduce background contamination in powder & improve growth condition of NaI(Tl) crystals
- Current measurements show great improvements!