First Data from DM-Ice17, Prospects for DM-Ice

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on behalf of the DM-Ice Collaboration

IBS Mini Workshop on Direct Search of Dark Matter
July 7, 2015
Daejeon, Korea
Dark Matter Signal or Background?

DAMA

dam:1308.5109

CDMS-Si

CoGeNT

dam:1304.4279

dam:1401.3295

dam:1304.4279

dam:1401.3295

CRESST


Reina Maruyama

July 7, 2016
A World of Dark Matter Searches

- Homestake: LUX
- SNOLAB: DEAP/CLEAN, PICASSO, COUPP, DAMIC
- Canfranc: ANAIS, ArDM, Rosebud
- Boulby: DRIFT
- Modane: EDELWEISS
- Gran Sasso: CRESST, DAMA/LIBRA, DarkSide, XENON
- Kamioka: XMASS
- YangYang: KIMS
- Jinping: Panda-X, CDEX
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- Kamioka: XMASS
- YangYang: KIMS
- Jinping: Panda-X, CDEX
- Modane: EDELWEISS
- South Pole: DM-ICE
- ANDES: (planned)
- Stawell: (planned)
### Annual Modulation Dark Matter Searches with NaI Detectors

<table>
<thead>
<tr>
<th>Northern Hemisphere</th>
<th>Southern Hemisphere</th>
<th>Y2L KIMS ~200kg</th>
<th>Gran Sasso SaBRE R&amp;D</th>
<th>Canfranc ANAIS 250 kg</th>
<th>Kamioka KamLAND-PICO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gran Sasso DAMA/Libra 250kg running</td>
<td>South Pole DM-Ice 17 kg running R&amp;D for 250 kg</td>
<td>Gran Sasso SaBRE R&amp;D</td>
<td>Canfranc ANAIS 250 kg</td>
<td>Kamioka KamLAND-PICO</td>
<td></td>
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#### Several Groups conducting ultra-pure crystal with several vendors to go to the full scale DM-Ice:

- Nal dark matter search in an entirely different environment
- South Pole offers:
  - Ultra-clean and ultra-stable environment
  - Seasonal variation unambiguously different from dark matter modulation
  - IceCube offers muon monitoring and veto as well as experience
  - NSF-run South Pole Station for logistical support
**Phased Program for DM-Ice**

Directly test DAMA’s assertion that the observed annual modulation is due to dark matter & understand its origin

- probes longest-standing dark matter claim
- NaI(Tl) target
- aims to understand origin of DAMA’s signal
- only experiment with access to both Northern & Southern Hemispheres

**A Phased Experimental Program**

DM-Ice17

*Operating since 2011*

17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North

*Northern Hemisphere Run*

portable 250 kg NaI(Tl) detector, first deployment in the Northern Hemisphere

DM-Ice 250 South

*Deployment at South Pole*

if modulation seen in North & ice drilling becomes available

see also Cherwinka et al.

Astroparticle Physics **35** (2012) 749
Science and Facilities at the South Pole

- South Pole
- Amundsen-Scott South Pole Station
- IceCube
- AMANDA
- ARA
- SPT, BICEP II
- runway
- IceCube Control Lab

1 km
Advantages of South Pole

- Same dark matter signal in both hemispheres
- Seasonal variation reversed in phase
  - Muon tagging with IceCube/DeepCore
  - Spallation neutrons moderated by ice
- Overburden: 2450 m ice (2200 m.w.e.)
  - Clean Ice
    - ppt $^{238}$U/$^{232}$Th, ppb $^{40}$K
  - Enclosed space
- Stable environment under ice
- Support infrastructure of Amundsen-Scott South Pole Station

*see also* Cherwinka *et al.*  
Astroparticle Physics *35* (2012) 749
DM-Ice17: An NaI Detector in IceCube/DeepCore

Deployed at the South Pole in December 2010
- A 17 kg NaI detector
- Operation since Feb. 2011
- Data run from June 2011

Demonstrated:
- Feasibility of deploying a remotely-operable dark matter detector in the Antarctic Ice
- Stability of the environment
- Radiopurity of the antarctic ice / hole ice
- Explore the capability of IceCube to veto muons
DM-Ice-17 Detector

- 2 IceCube mainboards + HV control boards
- PMTs: 5” ETL 9390UKB
- NAIAD NaI Crystal (5”x5”, 8.5 kg)
- quartz light guides
- PTFE light reflectors
- Stainless Steel Pressure Vessel
- 1.0 m, 36 cm (14”)
- IceCube DOM 59
- IceCube DOM 60
- 7 m
DM-Ice-17 Construction & Deployment

- Design begin Feb. 2010
- Revive NAIAD xtals
  - July 2010
- Detector assembly
  - Sep - Oct. 2010
- Shipment to Antarctica
  - Dec. 1, 2010
- Deployment
  - Dec. 11, 2010
- Detector in the hole
DM-ICE17 Assembly
Pressure Vessel Testing

Integrity of steel pressure vessel tested against >7000 psi (freeze-in test)
DM-ICE17 Assembly

Final assembly and wiring. Lower volume purged with nitrogen and sealed from electronics.
Data from DM-Ice17

IceCube Lab

IceTop

IceCube Below

SPT/BICEP-II

DM-Ice17 Below
DM-Ice17: Detector Operations

- **Physics data taking since June 2011**

- Monitored quantities:
  - Temperature of the boards
    - ~10°C above surrounding ice
    - Fast (2-3 weeks) decrease during freeze-in
    - slower decrease over a few months after freeze-in
  - Pressure follows similar trend as temperature (ADC resolution limited)
  - Values recorded every 2 sec. before March 2012. Every 60 sec. since March 2012.
Low Energy Spectrum

- Spectrum below 10 keV dominated by “thin” pulses.
- Below 2 keV: combination of single-photoelectrons & electronics noise.

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Counts / day / keV / kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin Pulse Model</td>
<td>Data (no cuts)</td>
</tr>
<tr>
<td>EMI Noise Model</td>
<td>Data (cuts applied)</td>
</tr>
<tr>
<td>SPE Noise Model</td>
<td>Thin Pulse Model</td>
</tr>
</tbody>
</table>

DM-Ice Collaboration
arXiv:1401.4804v1

Signal: < 100 keV

SPE

Reina Maruyama
IBS, Korea - July 7, 2015
Event Selection: “Thin” pulses

- Characteristics:
  - high pulse-height relative to charge
  - asymmetric between two PMTs
- 90% of events between 5-10 keV are “thin”
- Current cut effective above 7 keV

Energy spectrum: before & after thin pulse cut

Before cut

After cut

pulse height vs. charge

Energy (keV)

charge: PMT1 vs. PMT2

Charge: PMT-1

Charge: PMT-2
Low Energy Background Model

Largest contamination from NaI(Tl) and PMTs

$^{210}\text{Pb}$

$^{125}\text{I}$ X-rays

$^{40}\text{K}$

$^{125}\text{I}$

$^{210}\text{Pb}$

$^{212}\text{Pb}$

7.9±0.4 dru

DM-Ice 2014
Spectrum vs. Simulation

- Good agreement with simulation
- Simulation based on:
  - NaI from alphas and K from data
  - radioassay of spare parts

alphas in DM-Ice17 NaI (5 mBq/kg)

Pulse-shape discrimination (1 - 9 MeVee)
Cosmogenic Activation for DM-Ice17

<table>
<thead>
<tr>
<th>Location</th>
<th>Relative Neutron Rate (to sea level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Madison, WI</td>
<td>1.38</td>
</tr>
<tr>
<td>South Pole</td>
<td>11.1</td>
</tr>
<tr>
<td>Commercial Flight</td>
<td>100 – 600</td>
</tr>
</tbody>
</table>

Commercial flights at ~36,000+ ft

Polar program flights

Storage at 9,301 ft

Low geomagnetic rigidity
Confirm identity of cosmogenic peaks:
Match simulated spectral features
Expect 65.3 keV full-energy and 37.6 keV L-shell capture peaks for $^{125}$I
Measuring decay time
Expect 59.4 day half-life for $^{125}$I

DM-Ice17 Det-1 Data and Residual

$^{113}$Sn, $^{121m}$Te X-rays

$^{125}$I L-capture, full-energy

Count Rate for $^{125}$I Peak

Det-1 $t_{1/2} = 59.2 \pm 1.8$ days
Det-2 $t_{1/2} = 60.9 \pm 2.6$ days
Lit. $t_{1/2} = 59.400 \pm 0.010$ days
Looking Ahead: Activation for DM-Ice

- Transport by sea/overland
  - Polar program flights remain
  - Reduce storage time at 9,301 ft
  - Low geomagnetic rigidity
Simulated Activation Event Rate

Event rate one month after deployment

Event rate vs. time

Cosmogenic contribution to ROI:
- $^{126}$I ($t_{1/2} = 13$ days)
- lead contribution at deployment
- $^{113}$Sn ($t_{1/2} = 115$ days)
- dominates rate over physics run

- Multiple strong cosmogenic lines
- Significant contributions to 2 – 6 keV region of interest & must be minimized
Cosmogenic Mitigation

“Exposure budget” for $^{113}$Sn in DM-Ice250S:

- After “easy” 40% reduction
- Major contributions remain from NZL-McM flight and South Pole

Further reductions:
- 50% reduction in low-altitude NZL-McM cargo flight (15% of total)
- 90% reduction in South Pole activation from under-ice storage:
Antarctic Ice: Overburden at -2500 m (2200 m.w.e.)

- ~85 muons/m$^2$/day at bottom of IceCube (2/day for DM-Ice17)
- IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude.

Preliminary
Identifying Muons in DM-Ice

Muons are identified with their high energy depositions and pulse shape variable using the pulse height ($h_i$) at time ($t_i$):

$$
\tau = \frac{\sum h_i t_i}{\sum h_i}
$$

Expect 0 $\alpha$, 3 $\gamma$ in muon sample/year
IceCube - DM-Ice Coincidence

Events that trigger both DM-Ice and IceCube Found!

Muon rate in DM-Ice (appear as mip): 2/day

81 events in 11 months pass IceCube’s muon trigger. (expect more events in less stringent triggers)

Muon events result in elevated event rate at low energies in DM-Ice17 persisting for > 10 sec.

December 2012 – Event #14
2012-12-21 RunID: 121431, EventID 79868923
Seasonal Muon Rate Modulation

The muon rate at the South Pole well measured by IceCube

Temperature of the stratosphere in pressure layers, $T^p$ [K]

IceCube muon rate [Hz] (K)

Muon rate modulation with a single IceCube DOM

IceCube Collaboration, arXiv:1108.0171
Muon Rate in DM-Ice and IceCube

- The muon rate observed in DM-Ice tracks IceCube’s rate

![Graph showing muon rate comparison between DM-Ice and IceCube](graph.png)

**DM-Ice**
- DM-Ice Fit
- DM-Ice17: 14±3% mod.

**IceCube**
- IceCube: 8.6±1.2% mod.
Muon Energy Distribution

- Energy & direction of the muons measured by IceCube
- DM-Ice anchors muons in IceCube to 13 cm
- Studies underway to help improve IceCube reconstruction
DM-Ice250 Simulations

Close-Packed Detector Array

inner crystal

outer crystal

Sensitivity to DAMA Modulation Signal

DM-Ice250 Background

2-6 keV region: 3 dru w/o xtal-xtal veto, 1.75 dru average with veto

DM-Ice250

DM-Ice250  Background

DAMA
New Low-Background NaI(Tl) Crystals

Development of NaI(Tl) detectors with Alpha Spectra, Inc (ASI) in CO, USA
Three groups work with Alpha Spectra: DM-Ice, ANAIS, KIMS.
Communication and sharing of R&D results

- 2 x 18 kg crystals from Alpha Spectra, first ran at Fermilab MINOS near hall for testing, then moved to Boulby

Backgrounds are within acceptable levels for an experiment with 2 counts/day/keV/kg.
DM-Ice37 Contamination

• Collective NaI(Tl) effort (DM-Ice, ANAIS, KIMS)
  • Goal set by DAMA: 1 dru in ROI
  • Currently: 3 dru above noise energies
    • Noise removal in progress
    • DM-Ice17: 8 dru
  • 2 mBq/kg alphas
What do we need to test DAMA?

• 500 kg-yr, 1 cnt/keV/kg/day at various thresholds
What do we need to test DAMA?

- 500 kg-yr, 1, 2 & 5 cnt/keV/kg/day, 2 - 20 keV
What If...

- 1000 kg-yr, 0.1 cnt/keV/kg/day
Summary

Directly test DAMA’s assertion that the observed annual modulation is due to dark matter & understand its origin

- Successful installation and running of DM-Ice17 at the South Pole
- IceCube gives additional information on muons in DM-Ice, DM-Ice may help IceCube’s reconstruction
- DM-Ice37 at Boulby, crystal R&D going forward
- 11x reduction in 40K, 8x in 210Pb
- DM-Ice250: unique position in global effort to definitively test DAMA
DM-Ice Collaboration

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