Walter C. Pettus
Yale University
(formerly UW–Madison)

SSGF Annual Program Review
29 June – 2 July 2015

Background Characterization and Detector Sensitivity in DM-Ice
Understanding the Universe

Visible Sky

Axel Mellinger
http://apod.nasa.gov/apod/ap010202.html
Understanding the Universe

Gamma Ray Sky

Fermi LAT Collaboration
http://fermi.gsfc.nasa.gov/ssc/Fermi_5_year.jpg
Understanding the Universe

Microwave Sky

\( \mu K_{\text{cmb}} \)

Planck Collaboration
arXiv:1502.01582
Understanding the Universe

Microwave Sky

SSGF Review: 30 June 2015

Planck Collaboration
arXiv:1502.01582
ΛCDM Universe

- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
- Dark Energy: 68.3%

Graph showing the distribution of components in the universe.
Detecting Dark Matter

*Indirect Searches*
- Identify annihilation/decay products of dark matter from extraterrestrial sources

*Direct Searches*
- Identify energy deposition from dark matter interaction in a terrestrial detector

*Collider Searches*
- Identify production signatures of dark matter in collision

![Diagram showing the distribution of Dark Matter, Ordinary Matter, and Dark Energy.](image)

Walter C. Pettus
Experiment Design – DAMA

- Monolithic detectors (up to ton-scale)
- Component radiopurity (control of radioactive backgrounds)
- Environmental stability and control (temperature, radon, …)

Performed search for dark matter annual modulation with NaI(Tl) crystal array

Bernabei et al., NIM A, (2008)
Experiment Design – DAMA

Monolithic detectors (up to ton-scale)
Component radiopurity (control of radioactive backgrounds)
Environmental stability and control (temperature, radon, …)

Low-energy (~1 keV) thresholds necessary for dark matter sensitivity (characterization and removal of noise)

Performed search for dark matter annual modulation with NaI(Tl) crystal array

Demonstrated excellent background reduction:

Bernabei et al., NIM A, (2008)

A Solitary (and Persistent) Signal
- Observed modulating signal with 9.3-sigma significance
- Matches dark matter expectation

Performed search for dark matter annual modulation with NaI(Tl) crystal array

Demonstrated excellent background reduction:

Bernabei et al., arXiv:1412.6524
Bernabei et al., NIM A, (2008)

Walter C. Pettus
SSGF Review: 30 June 2015
A Solitary (and Persistent) Signal
- Observed modulating signal with 9.3-sigma significance
- Matches dark matter expectation

Conflict with Null Results
- DAMA remains the only experiment to claim dark matter detection
- Strongly excluded by numerous other experiments

Resolution hidden in
Astrophysics?
Particle Physics?
Instrumental Effects?
Uncharacterized Background?
DM-Ice Experiments

**DM-Ice17**
(January 2011 – present)
- First dark matter experiment in South Pole ice
- Demonstrated viability and advantage of environment

**DM-Ice37**
(April 2014 – present)
- R&D testbed for NaI detectors
  - Crystal background
  - Light yield
  - PMT/lightguide configurations

**DM-Ice250**
(future)
- Science result
  - Definitive test of DAMA dark matter claim
- See also: Cherwinka et al., Astropart. Phys 35 (2012)

Walter C. Pettus
SSGF Review: 30 June 2015
A World of Dark Matter Searches

- **Homestake:**
  - LUX

- **Canfranc:**
  - ANAIS
  - ArDM
  - Rosebud

- **SNOLAB:**
  - DEAP/CLEAN
  - PICASSO
  - COUPP
  - DAMIC

- **Gran Sasso:**
  - CRESST
  - DAMA/LIBRA
  - DarkSide
  - XENON

- **Modane:**
  - EDELWEISS

- **Boulby:**
  - DRIFT

- **Kamioka:**
  - XMASS

- **YangYang:**
  - KIMS

- **Jinping:**
  - Panda-X
  - CDEX

- **STAWELL:**
  - (planned)

- **ANDES:**
  - (planned)

- **South Pole:**
  - DM-ICE
A World of Dark Matter Searches

- ANDES: (planned)
- Stawell: (planned)
- South Pole: • DM-ICE
(2x) 8.5-kg NaI(Tl) modules

- Installed Dec 2010
- Data run from June 2011 to January 2015

Goals:
- Demonstrate the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice for a dark matter search
- Study environmental stability
- *In situ* measurement of the radiopurity of the Antarctic ice / hole ice at 2450 m depth
- Study the capability of IceCube to veto muons

First results published:
Sources of downtime understood (DAQ, characterization data, satellite issues)

- Uptime has improved over physics data run

DM-Ice17 Uptime

> 99% uptime

PRELIMINARY
Temperature Stability

- Ice environment provides stable temperature
  - 0.3°C cooling over 3.5 years measured at mainboard
  - < 0.025°C daily RMS

Changing PMT HV setting affects MB temperature

Power outages affect MB temp, not crystal temp
**Betas & Gammas:**
- Internal contamination lines allow calibration
- Well matched by *a priori* background model
  - Only crystal background unconstrained

**Alphas**
- Crystal contaminants only
- Constrains $^{232}$Th-, $^{235}$U-, $^{238}$U- and chain levels

Detector backgrounds dominate at all energies;
Negligible contributions from environmental background

Cosmic Ray Air Showers

High energy particles, ‘cosmic rays’ penetrating through Earth’s atmosphere produce cascades of secondary particles following interaction:

- cosmic ray intensity varies with position on Earth
- shower intensity varies with altitude
- secondary particles are a source of both prompt and delayed background

Louis et al., Los Alamos Science (1997)
Cosmic Ray Air Showers

10 TeV Proton Shower (millions of secondaries)
CORSIKA Simulation, https://www.ikp.kit.edu/corsika/

* shower greatly simplified

Louis et al., Los Alamos Science (1997)
Cosmic ray muons passing directly through DM-Ice detectors

- Highest energy signals measured
  - Unambiguous identification of muons with IceCube detector demonstrated
- Induces seconds-long afterpulsing
Cosmic ray hadrons interact with nuclei in detector components

- Transmutation of nucleus to radioisotope via spallation or capture processes
- Decay over days or years governed by radioactive half-life

\[
^{127}\text{I} \ (n, 3n) \ ^{125}\text{I}
\]
Cosmic ray hadrons interact with nuclei in detector components

- Transmutation of nucleus to radioisotope via spallation or capture processes
- Decay over days or years governed by radioactive half-life

$^{127}\text{I} \ (n,3n) \ ^{125}\text{I}$

- Neutrons dominate cosmogenic activation rates
- Activation cross section peaked for 10 – 100 MeV neutrons
- Activation rates scale with cosmic ray rate
  - Dependence on altitude, position, ...
Cosmogenic Activation Hazards

<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
- Madison, WI, USA
- South Pole Station
- McMurdo Station
- Christchurch, NZL
- Sandviken, SWE
- Boulby, GBR
- Storage at 9,301 ft

Polar program flights

Low geomagnetic rigidity

SSGF Review: 30 June 2015
Cosmic Ray Exposure Timeline

$F_{tot}$ – Relative cosmic ray neutron flux (scaling from sea level)
- Long periods of low-level exposure during storage and construction
- Punctuated exposure from flight shipment

"Cumulative Activation" – Time-integrated neutron flux scaling
- Different detector components have different exposure histories
- Two DM-Ice17 detectors have different deployment times
But decay not included: \[ N = R \times (1 - e^{-lt}) \]
Most cosmogenic features arise from NaI activation
- Rates simulated for start of dataset (6 months of decay)
- Five peaks (four isotopes) with > 1 dru rate
  - All of which have been identified in data
Confirm identity of cosmogenic peaks:
- Match simulated spectral features
  - Expect 65.3 keV full-energy and 37.6 keV L-shell capture peaks
- Measuring decay time
  - Expect 59.4 day half-life

\[ \text{Det-1 } t_{1/2} = 59.2 \pm 1.8 \text{ days} \]
\[ \text{Det-2 } t_{1/2} = 60.9 \pm 2.6 \text{ days} \]
\[ \text{Lit. } t_{1/2} = 59.400 \pm 0.010 \text{ days} \]
Simulation can reproduce changing spectral features

- Requires 6 cosmogenic isotopes
- Improved total background model via broken chains ($^{232}$Th in pressure vessel)
- Independent measurement of $^{60}$Co ($t_{1/2} = 5.3$ yr)
- Improvement in energy resolution modeling
  - Mismatch of 65 keV peak width

- Region of interest rates constrained indirectly
  - All 3 keV cosmogenic components have higher-energy peaks
DM-Ice17 Cosmogenics

- Good agreement with other NaI activation measurements
  - Validation of scaling model
- Identification of one new activated radioisotope ($^{113}\text{Sn}$)
  - Implications for low-energy region of interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$t_{1/2}$ (days)</th>
<th>DM-Ice17 (#/kg/day)</th>
<th>Literature (#/kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Na}$</td>
<td>951</td>
<td>-</td>
<td>45.1 ± 1.9</td>
</tr>
<tr>
<td>$^{113}\text{Sn}$</td>
<td>115.1</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>$^{121}\text{Te}$</td>
<td>19.2</td>
<td>-</td>
<td>9.9 ± 3.7</td>
</tr>
<tr>
<td>$^{121m}\text{Te}$</td>
<td>164.2</td>
<td>25</td>
<td>23.5 ± 0.8</td>
</tr>
<tr>
<td>$^{123m}\text{Te}$</td>
<td>119.2</td>
<td>21</td>
<td>31.6 ± 1.1</td>
</tr>
<tr>
<td>$^{125m}\text{Te}$</td>
<td>57.4</td>
<td>27</td>
<td>28.2 ± 1.3</td>
</tr>
<tr>
<td>$^{127m}\text{Te}$</td>
<td>106.1</td>
<td>&lt; 9</td>
<td>10.2 ± 0.4</td>
</tr>
<tr>
<td>$^{125}\text{I}$</td>
<td>59.4</td>
<td>230</td>
<td>220 ± 10</td>
</tr>
<tr>
<td>$^{126}\text{I}$</td>
<td>12.9</td>
<td>-</td>
<td>283 ± 36</td>
</tr>
</tbody>
</table>

Walter C. Pettus
SSGF Review: 30 June 2015
DM-Ice250 Experimental Program

Modular detector supporting deployment in both hemispheres

- 125 kg NaI(Tl) / module
- 7-crystal array
  - Coincidence between PMTs
  - Anti-coincidence between crystals

**DM-Ice250N**

**DM-Ice250S**

local muon veto

150 cm
Background Simulation

- Crystal array geometry allows for coincidence studies
  - Reduction in total background rate via anti-coincidence
  - Stronger constraint on background model via MC comparison
- Crystal backgrounds dominate at all energies

Outer Crystal Spectrum
(after veto)
- $^{40}$K 3 keV peak complicates ROI
  - Veto reduction of 37-67%
- $^{210}$Pb flat background is remaining low-energy background
  - Minimal improvement with veto
- High light yield imperative for resolution and noise reduction
  - 15 pe/keV demonstrated in alternate geometry
DM-Ice250S Activation

relative to DM-Ice17:

- Flight Reduction
- South Pole Reduction
- Remaining

Maintain polar program flights
Minimize storage time

Overland (sea) shipment to replace flights

Madison, WI, USA

Christchurch, NZL
McMurdo Station
South Pole Station
(vendors)

Walter C. Pettus

SSGF Review: 30 June 2015
Event rate one month after deployment

- Multiple strong cosmogenic calibration lines
- Significant contributions to 2 – 6 keV region of interest

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

L-shell X-ray or Auger $e^{-}$  
K-shell X-ray or Auger $e^{-}$  
$^{126}$I, $^{113}$Sn, $^{121m}$Te
Cosmogenic Mitigation

“Exposure budget” for $^{113}\text{Sn}$ 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
Sensitivity Projection

Null Hypothesis:
(90% CL contours, 500 kg*yr exposure)

Signal Hypothesis:
(250 kg detector)

DAMA dark matter claim can be definitively tested with 500 kg*yr exposure

- 5-sigma test possible with background of 2 dru
  - cf. DAMA background of ~1 dru
- DM-ICE17 has completed a successful 3.5-yr data run
  - 1 concept paper and 1 results paper published
  - +4 more papers by year end
- NaI(Tl) continues to have a promising future as a detector for dark matter searches
  - Verification or refutation of DAMA within few years
  - Still learning about activation products, phosphorescence,…
- DM-ICE250 uniquely poised as planned Southern Hemisphere experiment
- Four detector built and operated
  - 3 NaI(Tl) and 1 plastic scintillator
    - (last R&D detector has been deconstructed and rebuilt 2 more times)
  - Uncountably many tons of lead moved
Some parting thanks:
To the NNSA for their sponsorship of this fellowship program
To Krell for four great years of support and coordination
To you for stimulating discussions at these conferences