Background from Cosmogenic Activation in the DM-ICE Dark Matter Experiment

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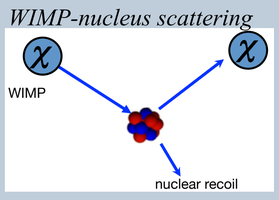
Program Year 2

Abstract:
DM-ICE is a quarter-ton-scale dark matter experiment planned for deployment deep in the ice at the South Pole. This experiment will search for the expected annual modulation signature in the dark matter signal using low-background NaI(Tl) scintillating crystals. Cosmogenic activation of the detectors during transport to and storage at the South Pole (altitude 9,301 feet) has the potential to produce long-lived radioisotopes which will add a significant source of background and threaten the discovery potential of this experiment. In data from the presently operating DM-ICE17 detectors, we examine decaying regions of the spectrum to identify activated isotopes and estimate activation effects. We compare these activation estimates to our simulation for the DM-ICE17 detectors and discuss the effects on the full-scale DM-ICE experiment.

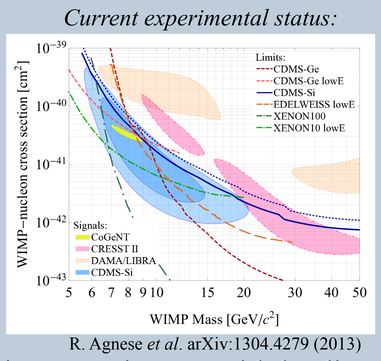
Dark Matter Direct Detection:

Seek to measure energy from nuclear recoil of WIMP scattering
- Look for distinctive dark matter signal features to enable background reduction
  - Discriminate between recoil type (electron vs. nuclear)
    - CDMS, CRESST, EDELWEISS, XENON
  - Annual modulation
    - DAMA, CoGeNT, CDMS
  - Diurnal modulation
  - Directional sensitivity

WIMP-nucleus scattering

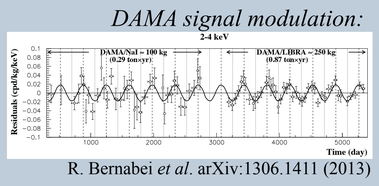


Current experimental status:

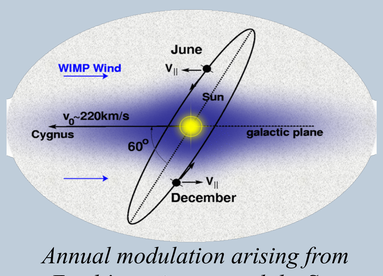


R. Agnese *et al.* arXiv:1304.4279 (2013)

DAMA signal modulation:



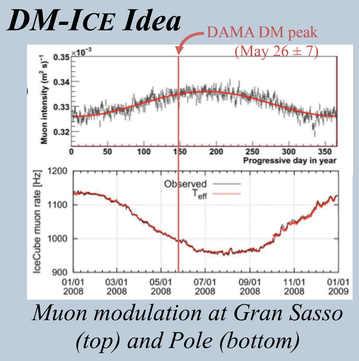
R. Bernabei *et al.* arXiv:1306.1411 (2013)



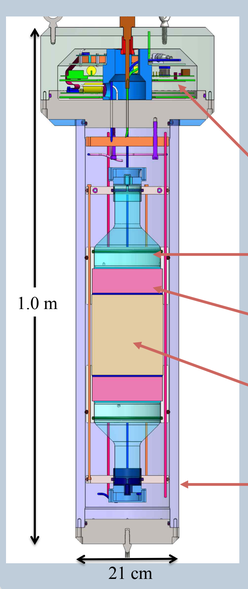
Annual modulation arising from Earth's motion around the Sun

Tension between direct detection experiments with leading exclusion limits and detection hints
- DAMA: >8σ modulation over 15+ annual cycles
  - Interpreted as dark matter detection

What will it take to unambiguously test the DAMA claim? ***The DM-ICE Idea***
- Run an experiment with the same target material (NaI(Tl))
  - Inherit identical detector effects, particle interaction
- Go to the South Pole to alter the experimental systematics
  - Experience opposite (*e.g.* muons) or absent (*e.g.* temperature) seasonal effects
    - DM-ICE is the only planned or operating dark matter detector in the Southern Hemisphere

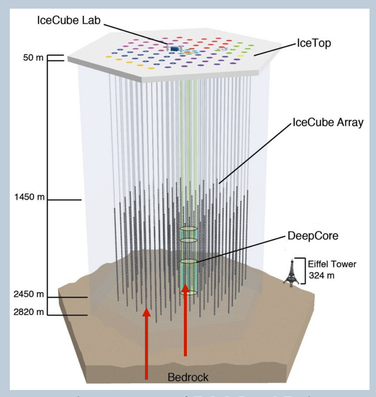


Muon modulation at Gran Sasso (top) and Pole (bottom)



DM-ICE17 Detector:
- Deployed: December 2010
- Data Run: since June 2011

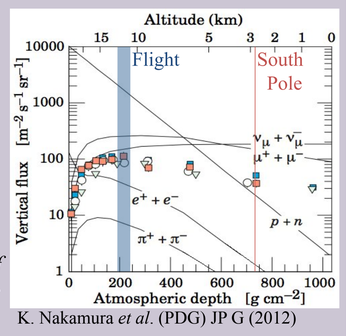
Each unit (2 deployed) contains:
- Electronics housed in endcaps
- 5" ETL 9390 PMTs (x2/crystal)
  - Noise reduction with coincidence cut
- 5 cm quartz lightguide (x2/crystal)
  - Attenuates PMT radioactivity
- 8.5 kg NaI(Tl) scintillating crystal
  - Sensitive volume
- 191.3 kg steel pressure vessel
  - Capable of withstanding >6000 psi freeze-in pressure



Deployment locations of DM-ICE17 devices within the IceCube array at 2450m depth

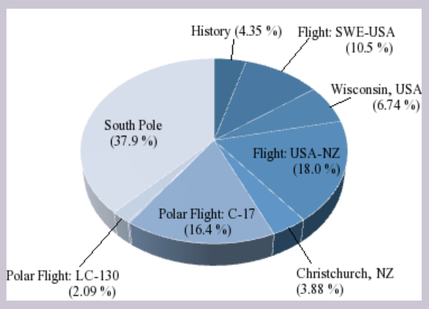
South Pole Deployment Challenge – Cosmogenic Activation:

- Cosmic ray particles can activate radioactive isotopes through spallation and capture processes (neutron-dominated)
  - Increased cosmic ray flux with altitude
    - South Pole (9,186 ft.) and flight altitude
  - Decreased shielding at lower geomagnetic rigidity
    - Minimized at polar latitudes around Earth B-field poles



Altitude dependence of cosmic ray flux:

K. Nakamura *et al.* (PDG) JP G (2012)



Activation contribution in steel pressure vessel by stage of journey

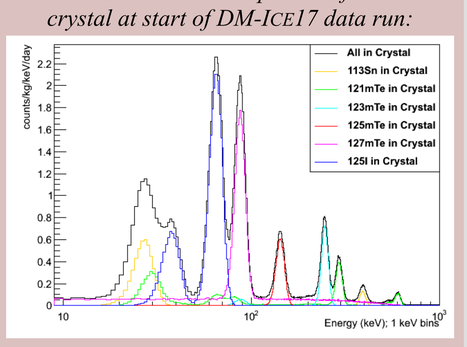
DM-ICE17 Activation Timeline
- Surface history (~1 year for steel pressure vessel)
- Trans-Atlantic flight (~10 hours at 40,000 ft)
- Detector construction on surface (~2 months)
- Flight from USA – New Zealand (16 hours at 40,000 ft)
- Storage in Christchurch, NZ (3.5 weeks)
- Flight from NZ – McMurdo (5 hours at 35,000 ft)
- Flight from McMurdo – Pole (3 hours at 21,000 ft)
- South Pole testing and storage (2 weeks at 9,186 ft)

For more information on DM-ICE, please see:
J. Cherwinka *A search for the dark matter annual modulation at the South Pole*, Astroparticle Physics, **35** (2012) 749-754

Cosmogenic Activation in NaI Crystals:

Activation rates simulated using ACTIVIA code
- Based on Silberberg & Tsao semi-empirical formulae
  - * Overestimates production of metastable isotopes
- Expect numerous cosmogenic isotopes to persist into data run (began June 2011, 6 months after deployment)
  - Look for regions of spectra with decaying rate

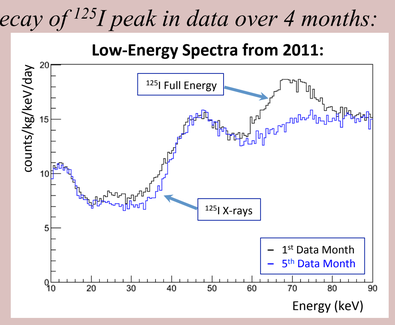
Simulated activation spectrum from crystal at start of DM-ICE17 data run:



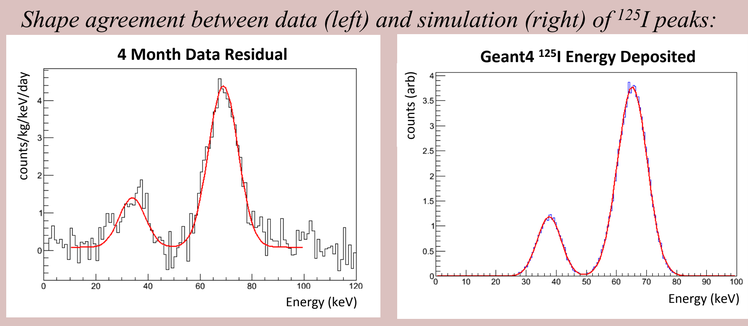
^{125}I – An Absolute Calibration Point

- Highest production rate of all crystal cosmogenics
  - via ^{127}I(n,3n)^{125}I and ^{127}I(n,3n)^{125}Xe interactions
- Half-life ($t_{1/2}$ = 59.41 days) is long to survive into data run, but short enough to provide noticeable monthly decay

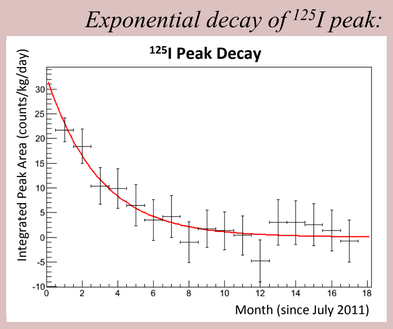
Decay of ^{125}I peak in data over 4 months:



Shape agreement between data (left) and simulation (right) of ^{125}I peaks:

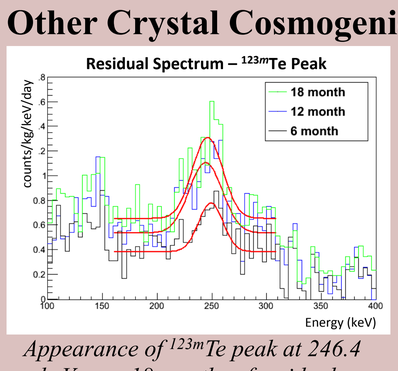


Exponential decay of ^{125}I peak:



- Identity of peak as ^{125}I confirmed by fitted half-life
  - $t_{1/2\text{-fit}}$ = 59.41 ± 2.66 days
- Activity at deployment obtained from data fit
  - 1151 ± 118 counts/kg/day
  - 407 counts/kg/day expected from simulation

Other Crystal Cosmogenics



Appearance of ^{123m}Te peak at 246.4 keV over 18 months of residuals

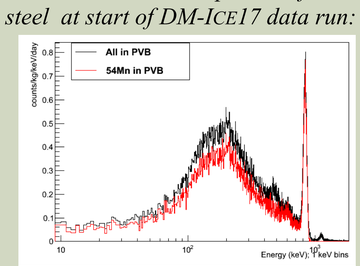
Search for other crystal cosmogenic isotopes in 2 year data set only yielded ^{123m}Te
- Lower production rates and longer half-lives make identification more challenging
- Allows quantification of overestimate of metastable tellurium isotope production
- Places limits on production expected in full-scale detector

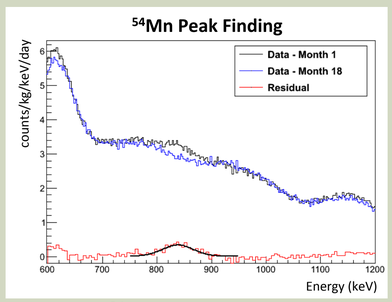
Isotope	Half-life
^{3}H	12.3 y
^{22}Na	2.60 y
^{109}Cd	461 d
^{113}Sn	115 d
^{121}Te	19.2 d
^{121m}Te	164 d
^{123m}Te	119 d
^{125m}Te	57.4 d
^{127m}Te	106 d
^{125}I	59.4 d
^{126}I	12.9 d
^{127}Xe	36.3 d

Cosmogenic Activation in Steel Pressure Vessel:

Activation rates based on scaling of steel activation measurements for GERDA
- Only significant feature expected in data is 835 keV gamma from ^{54}Mn
  - Long-lived ^{54}Mn will decay away slowly

Simulated activation spectrum from steel at start of DM-ICE17 data run:





Decay of ^{54}Mn over 17 months of data and appearance of peak in residual

^{54}Mn peak closely matches expectation:
- Peak center 836.1± 3.0 keV
  - 834.8 keV simulation
- Deploy activity = 51,700 ± 6,500 decays/day
  - 41,850 decays/day predicted

Isotope	Half-life
^{7}Be	53.2 d
^{46}Sc	83.8 d
^{48}V	16.0 d
^{51}Cr	27.7 d
^{52}Mn	5.59 d
^{54}Mn	312 d
^{56}Co	77.2 d
^{58}Co	70.9 d
^{56}Ni	6.08 d

Prospects for Future Deployments:

DM-ICE full-scale detector (~250-kg) is planned for deployment within few years

Cosmogenic activation provides calibration points for energy spectrum of detector
- At cost of raising background level (~0.1 cpd/kg/keV in region of interest < 10 keV)
  - Target rate is 1 cpd/kg/keV in ROI

Faster commissioning period will give more short-lived calibration lines
- *e.g.* ^{121}Te and ^{126}I (crystal), ^{51}Cr (steel)

Mitigation strategies are being explored as part of detector planning
- Reduction of flight timing in shipping
- Reduced time spent on Pole surface (*e.g.* tunnel storage)