Large Diameter Cryogenic Germanium Detectors for Dark Matter Direct Detection Experiments

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Jun 11th 2011
WIMP ($\chi^0$) direct detection

Background is millions of times higher than desired signal!

$\alpha, \beta, \gamma, n, \chi^0$

$v/c \approx 7 \times 10^{-4} = 210 \text{ km/s}$

Electron

Nucleus

$E_r \approx 10\text{'s KeV}$

$v/c \approx 0.3$
Why cryogenic Ge Detectors?

- Employ a robust and powerful recoil-event discrimination technique
  - Measure charge-carriers (ionization signal) and phonons generated by an event.
  - Most of the energy is in the phonon signal (small quanta) which are not statistically limited and give good energy resolution.
  - The signal in the charge carriers: holes + electrons gives event location in crystal and the recoil type – nuclear vs electron.

![Cryogenic Ge detectors for DM experiments](image)

- Dark Matter (mass ~ GeV – TeV)
- $\chi^0$
- Recoil Energy (tens of keV)
SuperCDMS – Moore’s Law if zero bkgd

WIMP mass = 60 GeV/c²

- Tower 1
- Tower 1–2
- CDMSII Feb 2008
- CDMSII Dec 2009

4 kg

15 kg

SuperCDMS Soudan

150 kg

SuperCDMS SNOLAB

Cross section on nucleon (cm²) 90% CL

Raw Exposure MT kg days

Number of events/kg/day

Cryogenic Ge detectors for DM experiments
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Ge iZIP detector: phonon sensors

- Athermal phonon sensors operated at 80 mK.
  - Aluminum fins look white.
  - Tungsten transition edge sensor thin grey line.
  - aSi substrate (also) grey/green color.
CDMS Phonon sensor operation

- Recoil event occurs in Germanium substrates, 76 mm diameter, 25 mm thick.
- Aluminum fins 300 nm thick absorb phonons arriving from substrate underneath.
- Fins connect to Tungsten transition edge sensors (W TESs).

- \( W_T \approx 80 \text{ mK} \)
- Read out with SQUID array

Cryogenic Ge detectors for DM experiments
Ge iZIP detector production

• All CDMS II and SuperCDMS Ge detectors fabricated in Stanford Nanofabrication Facility (SNF)
  – Double-sided optical photolithography (90% time)
  – Manual packaging and wire-bonding (10% time)
SuperCDMS: 1-inch thick substrates

Photolithography for the 1-inch thick Ge and Si substrates required equipment modifications for the thin film depositions, photoresist coatings, U.V. exposures and plasma etching.
Ge substrates cleaned. Thin films deposited [Balzers] on both sides (the A and B trilayer depositions), amorphous Si, Al, W. Then both sides coated in photoresist.

Both sides patterned simultaneously: exposed [EV-Align], developed, wet-etched (H2O2 for W, Al-etch for Al), photoresist stripped. Both sides receive W TES film deposition.
Geom Fabrication – photolithography (2)

TES patterned for both sides: exposed [EV-Align], developed, W wet-etched, photoresist stripped. Both sides recoated and patterned for amorphous Si dry-etch.

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New SuperCDMS EV-Align

Rapid change in substrate thickness (2 inch max). Uniform line-width for TESs and grid.

Used for veto detectors for SuperCDMS at Soudan and first 3 Ge 1-inch detectors of SuperTower 1.

1.6um TES mask (80X, C4)
Scalability of Ge Detectors

- Qualify vendors and procure high-quality large diameter Ge crystals
- Develop larger detector fabrication recipe
- Optimize design for cost and performance (backgrounds rejection)

100 kg ~ 80 crystals of large diameter and thickness (100 mm by 33 mm)

100 kg ~ 180 crystals of small diameter and thickness (76 mm by 25 mm)

Detectors recently deployed by SuperCDMS at the Soudan mine

In development at SLAC
Charge signals give a fiducial volume

- Require 3D Fiducial Volume Definition
  - Outer charge electrodes separately measured for radial information
  - Complex E-fields produced by interleaving +2V/0V electrodes encode Position Information

Cryogenic Ge detectors for DM experiments Page 14

Symmetric Events = Bulk
Assymmetric Events = Surface
Electron/Nuclear Discrimination by Yield

- Electron/Nuclear Recoils well separated $E > 6\text{ keV}_{\text{ne}}$
  - $\sigma_q \sim 300\text{ eV}_{\text{ee}}$ (measured)
  - $\sigma_p \sim 192\text{ eV}_{\text{ee}}$ (measured)
- Long thermal tails from (surface) muons dominate our sensitivity
- Expect underground $\sigma_p \sim 72\text{ eV}_{\text{ee}}$ (x3 improvement)
- Tungsten Tc $\sim 100\text{ mK}$ higher than necessary and degraded phonon resolution
- Ion implantation of W with Fe-56 reduces W Tc (CDMS II)

Electron Recoils ($^{133}\text{Ba}$)

- Preliminary surface results -> overly conservative

Nuclear Recoils ($^{252}\text{Cf}$ source (external) + 7evt/hr background)

- Surface Electron Recoils have suppressed Yield
- Internal $^{109}\text{Cd}$ $\beta$ rate 70Hz

Cryogenic Ge detectors for DM experiments
R&D of Charge-carrier Performance

Charge-carrier performance mask (FY10)
Test 100 mm diameter Ge crystal quality.
Test optical photolithography steps for 1.4 kg Ge substrates
This mask has 4 charge electrodes separated by 400um trench.

Fabricated Second Ionization detector (FY11)
Faster fabrication recipe: more processes conducted in 'parallel' for this double-sided geometry.
Final 100-mm-diameter-detector recipe will be based upon this double-sided recipe.
First 100 mm diameter Ge Detector

Ge detector in a copper housing

Mechanical parts to integrate with fridge

Transportation container

Experimental set-up at UMN

Cryogenic Ge detectors for DM experiments
Energy Spectrum (Am-241, Ba-133)

Cryogenic Ge detectors for DM experiments
Large detector Electrode configuration

New masks and detector housing for 100 mm diameter Ge presently being designed:

Validate electric-field configuration necessary for final detector – compare to simulations.

Interleaved electrodes are arranged simply as a spiral. Electrode spacing 1.5 mm.

The surface tangential field configuration is similar to that required by the iZIP Dark matter detector for surface-event rejection.
Monte Carlo simulations of charge propagation

Events deposited on a field line which ends on a side wall have incomplete charge collection.

Events deposited on a ‘bulk’ field line have very good charge collection.
Observed iZIP Phonon Pulse Shape Discrimination

Surface Event: side summed pulses (Pr~25keV)

- S2(-z)
- S1(+z)

25 keV electron event near top surface

Bulk NR Event: side summed pulses (Pr~25keV)

- S2(-z)
- S1(+z)

25 keV nuclear recoil event in bulk

Surface Electron vs Nuclear Recoil discrimination seen in operating iZIP detectors in both pulse shape differences and energy partition in z-direction.

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Geant4 simulations of phonons

Investigating possible new avenues for improving background rejection with Geant4

SIMULATION

Colors correspond to different phonon polarization states:
(Fast Transverse, Slow Transverse, Longitudinal)

GEANT4 phonon transport test code includes
- Crystal lattice orientation
- Anisotropic scattering (k space)
- Speed of sound (not light!) propagation for massless particles

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CDMS – Neganov/Luke phonons

- Ionization yield $Y \approx 0.2$ at these low recoil energies.

- Only $\sim 20\%$ contribution to phonon recoil energy scale if $Q_{\text{bias}} = 3$ Volts for Ge.

- Initial tests with CDMS detectors indicate $\sim 50$ eV recoil detection threshold.

- "CDMS-lite"
  $Q_{\text{bias}} \sim 30$ V
  $\Rightarrow$ WIMP mass down to sub GeV.
SuperCDMS SNOLAB (150 kg Ge)

Planning to submit proposal 2011. Expected reach 0.3 zepto-barnes ($3 \times 10^{-46} \text{ cm}^2$)

- Need deeper site than Soudan, > 4000 mwe. Need new fridge and shield.
  - New fridge and shield design work in progress at FNAL.
- Select iZIP detector technology ~ 1 kg each.
  - Detector fabrication at Stanford/SLAC (baseline).
  - Direct readout of all electrical channels, similar to CDMS II.
DUSEL design study (NSF S4) funded

- Deliver study end of 2012.
  - Cryogenic engineering
  - Electrical readout, multiplexing (NIST & MIT)
  - Detector fabrication scalability (TAMU & SLAC)
  - Material screening, background studies.

- Rapid advance on high risk items could feed into earlier programs.

**GEODM for 1.5 tonne Ge target**
Summary

- Cryogenic Ge dark matter detectors excellent track record.

- Essential to have multiple target materials – and different technologies even if the same material.

- Redundancy, redundancy, redundancy. As many handles as possible to assess the nature of any candidate events seen. Burden of proof for discovery is very high.

- Scalability: reduce costs in the fabrication and testing programs. Maintain construction phase for future experiments that is only 2 years.

- Starting a Critical Design (CD) process for CDMS detectors sited at SNOLAB for 150 kg scale experiment could start later this year.