New Results from the Cryogenic Dark Matter Search

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on behalf of the CDMS Collaboration

Joint Experimental-Theoretical Physics Seminar
December 17, 2009
What is Dark Matter?

We know the Dark Matter is stable / non-baryonic / non-relativistic / interacts gravitationally.

We don’t know what it actually is:
- mass / coupling / spin / composition / distribution in the Universe …

Bullet Cluster
Rotational Curves
WMAP 5-year
Strong Lensing
Is it a Weakly Interacting Massive Particle?

particles with mass and annihilation cross section at the weak scale naturally yield correct relic density of CDM

Kolb & Turner, "The Early Universe"

Look for nuclear recoil from WIMP scatter

M. Attisha
How to Detect WIMPs

man-made production

CERN

annihilation in the cosmos

scattering of relic particles

FERMI-GLAST

CDMS

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M. Attisha
The “Low Background Frontier

pushing the limit of background rejection with novel particle detection techniques

Expected signal:
• nuclear recoil
• featureless exponential ~ few 10’s of keV
• rates <0.1 events /kg/day

Challenges:
• low energy thresholds (~10 keV)
• mitigation of natural radioactive background (1 banana ~1M decays/day)
• operation deep underground
• long exposures, scale to high mass
How are WIMPs Distributed?

- Spherical Halo Model
- Energy spectrum & rate depend on WIMP distribution in Dark Matter Halo (NFW)

\[ \rho \sim \rho_0 \left( \frac{r}{r_s} \right)^{-1} \left( 1 + \frac{r}{r_s} \right)^{-2} \]

- Assume isothermal Maxwell-Boltzmann velocity distribution
- \( V_0 = 230 \text{ km/s} \) (WIMP velocity against detector)
- \( V_{\text{esc}} = 650 \text{ km/s} \) (escape velocity of WIMP from Galactic halo)
- Local density of WIMPs = 0.3 GeV/cm\(^3\)
the Cryogenic Dark Matter Search
CDMS Experiment

CDMSII at Soudan:
Five Towers (30 ZIPS)
operating since June '06

Most sensitive to spin-independent scattering: $\sigma \propto A^2$
4.75 kg Ge($A=73$), 1.1 kg Si($A=28$)

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* new collaborators or new institutions in SuperCDMS
Experimental Setup

MINOS CDMS 780m (2090mwe)
Surface

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**Z-sensitive Ionization and Phonon Detectors**

- **Signature of a Nuclear Recoil**
  - Reduced ionization signal relative to phonon signal

**Image Details**
- 7.6 cm diameter
- 1.0 cm thick
- 4 phonon channels (each is 1036 TES sensors in parallel)
- Inner sensor + outer guard

**Diagram**
- Electron recoils
- Nuclear recoils

**Technical Details**
- **E_phonon**
- **E_charge**

**Conclusion**
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Phonon Detection

Transition Edge Sensor (quasiparticle diffusion)

1 µm tungsten fins
380 µm x 60 µm aluminum fins

Each of 4 phonon channels reads out 1036 TES in parallel

Ge or Si
Categories of Background

**ELECTRON RECOILS**
- gamma - *bulk electron recoil*
- beta - *surface event*

**NUCLEAR RECOILS**
- neutron - *nearly irreducible*
- alpha - *not a background for CDMS*
Gamma Rejection

BETTER THAN $1:10^4$ rejection of gammas based on ionization yield alone

Gamma rejection is achieved by using a specific energy ratio of ionization yield to phonon energy. The diagram illustrates the separation of electron recoils and nuclear recoils based on this ratio:

$$\text{ionization yield} = \frac{E_{\text{charge}}}{E_{\text{phonon}}}$$

The image shows data points for $^{133}\text{Ba}$ and $^{252}\text{Cf}$, indicating that only the events falling below the specified energy ratio are considered gamma events. Ultra-clean materials and careful handling, along with ancient lead shielding, are employed to enhance rejection efficiency.
Neutron Background

1. Go Deep:
   - Soudan Mine: 2090 mwe
     (muon rate reduced by \(>10^4\))

2. Use Active Shielding:
   - Muon veto \(~98\%\) efficient
   - \(<< 1\) unvetoed single scatter neutron / kg /year

3. Use Passive Shielding:
   - 2 layers polyethylene - shields from cosmogenic and radiogenic neutrons

4. Use Event Topology:
   - Neutrons may double scatter or be accompanied by EM shower

5. Run Extensive Simulations:
   - GEANT4
   - FLUKA+MCNPX
   - MUSIC

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Surface Event Rejection

10 μm “dead layer” results in reduced ionization collection

Phonon pulse shape (timing) distinguishes surface events

Both yield and “timing” rejects these events

133Ba
252Cf

approximate signal region

rising edge slope

surface event
nuclear recoil

bulk electron recoils
surface electron recoils
nuclear recoils

ionization yield

10 µm “dead layer” results in reduced ionization collection.
CDMS II 2008: 1st Five Tower Result

398 raw kg-d
121 kg-d (for 60 GeV/c² WIMP)
10 - 100 keV analysis range

Expected Surface Events:
$0.6^{+0.5}_{-0.3} \text{(stat.)}^{+0.3}_{-0.2} \text{(syst.)}$

Expected Neutrons:
$(\alpha,n): < 0.03$
(fission): $< 0.1$
Cosmogenic: $< 0.1$ (MC 0.03-0.05)

ZERO Events Observed in Signal Region!
2009 analysis
Continuation of 5-Tower Running

Operations:
Stable operation from July 2007 - until end of CDMS II (March 2009). 4 periods of warmup for cryogenic maintenance.

New Data “Pipeline”:
Complete revamp of data reconstruction software - streamlined, modular, migrated to ROOT and ready for SuperCDMS!

Refined Analysis:
Necessary to maintain background < 1 event without cutting harder on exposure.

30 ZIPs (5 Towers)
~4.4 kg Ge, ~1.1 kg Si

processed ~8TB of data on FermiGrid in ~1 month -Thanks Steve Timm & FermiGrid management!
WIMP Search Exposure

4 runs separated by partial warmups of cryostat

Total raw exposure is 612 kg-days

Data taken from 9/08-3/09: primarily an engineering run

2008 result

2008 result

some detectors not analyzed for WIMP scatters

periods of poor data quality removed

recorded data

raw exposure

this work

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Analysis Overview

Candidate Criteria:
• Data Quality + Fiducial Volume Cuts
• Muon-veto anticoincident
• Single Scatter (only 1 zip w/ signal)
• Ionization yield within $2\sigma$ nuclear recoil band
• Phonon “timing” cut

All cuts established before unblinding!
(sidebands and calibration data are used for cut development)

Low yield singles masked
**Calibration Data**

*Two Sources:*

133Ba: $\gamma$-lines at 303, 356 & 384 keV

252Cf: neutrons ~few MeV, neutron activation of Ge $\rightarrow$ 10.4 keV $\gamma$-line

Many Uses:

In-situ measurement of energy scale resolution and linearity position correction set cuts & measure selection efficiencies develop surface event rejection ($^{133}$Ba ~40X the number of WS events)
Event Reconstruction

No tracks or showers? Event reconstruction is trivial right?

No, not really

Sophisticated signal processing algorithms enable a low energy threshold.

Features in phonon pulse shape provide surface event discrimination

Fitting the phonon pulses in the time domain (5 parameter fit) also implemented
Phonon Position Correction

Timing and energy response vary across the detector.

Construct a lookup table from $^{133}\text{Ba}$ data to correct the variation.

Position Dependence of Timing Parameter (measured with e-recoils)

Events near and outside fiducial volume

2009 Improvement:

Include events just outside the fiducial volume to better correct events at high radius.

$\rightarrow$ Significantly reduces timing outliers (we cut on the tails)

Neither partition nor arrival time provide a unique measurement of position at high radius. Together, they unfold the degeneracy.
Data Quality Monitoring
sounds mundane, but it's important!

Regular flashing with LED's “neutralizes” ion trapping centers.

Checking data consistency against 7 reconstructed parameters

Data quality checks ensure the data was taken during good periods of neutralization.

Visual representation of KS-tests
expected background
Estimated Neutron Background

Cosmogenic Neutron Estimate:

\[
\frac{N_{\text{MC}}^{\text{unvetoed, single NR}}}{N_{\text{MC}}^{\text{vetoed, single NR}}} \times N_{\text{data}}^{\text{vetoed, single NR}} \times \epsilon_{\text{neutron}} = 0.04^{+0.04}_{-0.03} \text{(stat) events}
\]

From GEANT4 and FLUKA simulations

3 vetoed, single NR (in Soudan dataset) correct for efficiency and exposure

Radiogenic Neutron Estimate:

0.03 - 0.06 events

Detector contamination measured with HP Ge detector + global gamma simulation

→ GEANT4 simulation of U/Th chains in detector materials

- fission, (α, n) in Cu, Poly, Pb

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Surface Event Background

$^{133}$Ba provides surface events for tuning the surface event rejection cut.

We optimized for the best sensitivity (results in < 1 expected background).

Challenges (!)

Setting the cut on the tails of the distribution

Accounting for systematic differences between surface events in $^{133}$Ba and WIMP-search datasets
Surface Event “Leakage” Estimate

Expected surface leakage = \frac{N_{\text{sideband passing cut}}}{N_{\text{sideband failing cut}}} \times N_{\text{data failing cut}}

3 independent sidebands for estimating the passing/failing ratio

SIDEBAND 1
Use multiple-scatters in NR band

SIDEBAND 2
Use singles and multiples just outside NR band

SIDEBAND 3
Use singles and multiples from Ba calibration in wide region

Correct for systematic effects due to different distributions in energy and yield

All 3 consistent, blind estimate = 0.6 ± 0.1 (stat) events

WIMP Search Data
Total exposure after all cuts: 194.1 kg-days

Sensitivity Based on Expected BG:

Estimated Surface Events: $0.6 \pm 0.1$

Estimated Cosmogenic Neutrons: $0.04^{+0.04}_{-0.03}$

Estimated Radiogenic Neutrons: $0.03-0.06$
unblinding
Unblinding

We unblinded the signal region November 5, 2009

masked signal region (2σ NR band)

All WIMP search data
Unblind Events Failing Timing Cut

All WIMP search data failing the timing cut

150 events in the NR band fail the timing cut, consistency checks deemed ok

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Unblind Events Passing Timing Cut

2 events in the NR band pass the timing cut!

Event 1:
Tower 1, ZIP 5 (T1Z5)
Sat. Oct. 27, 2007
8:48pm CDT

Event 2:
Tower 3, ZIP 4 (T3Z4)
2:41 pm CDT

All WIMP search data passing the timing cut
Alternate View w/ Timing

bulk electron recoils

All (10-100 keV) WIMP search data

outside NR

1

2

signal region

timing cut

Normalized yield ($\sigma$ from NR hand mean)

Normalized Timing parameter

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Alternate View w/ Timing w/ Calibration Data

All (10-100 keV) WIMP search data

\( { }^{252}\text{Cf} \) neutrons

Outside NR
post-unblinding studies
Are These Events Signal or Background?

Statistical analysis tells us that the likelihood of observing 2 background events based on 0.6 expected surface events is non-negligible (12%).

In addition to a statistical analysis, we scrutinized these 2 events to see what more we could learn.

Does the open dataset provide a means to rule out the possibility of one or both events being a nuclear recoil?

Post-unblinding studies (as much as can be done in 5 weeks time):

- Data quality (re-checks)
- Reconstruction quality (re-checks)
- Cut varying studies
- Likelihood analysis (still under development)
At the recorded time of both events, the experimental performance was excellent.

<table>
<thead>
<tr>
<th>Data Quality Item</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon veto performance</td>
<td>✔ good</td>
</tr>
<tr>
<td>neutralization</td>
<td>✔ good</td>
</tr>
<tr>
<td>KS tests</td>
<td>✔ normal</td>
</tr>
<tr>
<td>noise levels</td>
<td>✔ typical</td>
</tr>
<tr>
<td>pre-pulse baseline rms</td>
<td>✔ typical</td>
</tr>
<tr>
<td>background electron-recoil rate</td>
<td>✔ typical</td>
</tr>
<tr>
<td>surface event rate</td>
<td>✔ typical</td>
</tr>
<tr>
<td>radial position</td>
<td>✔ well-contained</td>
</tr>
<tr>
<td>single-scatter identification</td>
<td>✔ good</td>
</tr>
<tr>
<td>special running conditions</td>
<td>✔ no</td>
</tr>
<tr>
<td>operator recorded issues</td>
<td>✔ no</td>
</tr>
</tbody>
</table>
Reconstruction Checks

ionization and phonon energies look good, phonon timing looks good...

Could there be a problem with the start time of the charge pulse?
(affects timing parameter)

This effect is strongly correlated with the ionization energy (affects ~1% of events with < 6 keV ionization energy) and was mostly accounted for in the pre-unblinding leakage estimate.

A more careful accounting revised the surface event leakage from 0.6 to 0.8 events

(Note: event 1 does not appear to be affected by this issue)
Cut Varying Study

Tightening the cut to yield ~1/2 the expected surface events, removes both events from the signal region and reduces the exposure by ~28%.

Additional events appear in the signal region after loosening the cut to ~2X the expected leakage.

The calculated limit doesn’t depend strongly on chosen surface-event rejection cut value.
Final Comments

After finalizing the systematic uncertainty on the surface event estimate, the final surface event background estimate is:

0.8±0.1(stat)±0.2(sys) events

The probability to observe 2 or more surface events based on the estimated background is 20%

After including the neutron background, the probability to observe 2 or more events is 23%

These values indicate that the results of this analysis cannot be interpreted as significant evidence for WIMP interactions, but we cannot reject either event as signal.
limits
90% C.L. Spin-Independent Limit

In the presence of 2 events (no bg subtraction):

CDMS 2009
@WIMP mass 70 GeV
$\sigma = 7.0 \times 10^{-44} \text{ cm}^2 \ (90\% \ C.L.)$

CDMS Combined Soudan Data
@WIMP mass 70 GeV
$\sigma = 3.8 \times 10^{-44} \text{ cm}^2 \ (90\% \ C.L.)$

Sensitivity curve based on revised bg estimate:
0.8±0.1(stat.)±0.2(sys.) surface events
0.04+0.04 -0.03 cosmogenic neutrons
0.04 - 0.06 radiogenic neutrons

*a similar figure will available on the arXiv tonight*
Inelastic Dark Matter

Has been invoked by Weiner et al. to explain DAMA/LIBRA data, among other things. [Phys. Rev. D 64, 043502 (2001)]

Scattering occurs via transition of WIMP to excited state (with mass splitting $\delta$)

$spectrum peaks at higher recoil energies$

DAMA, allowed regions (at 90% C.L.) computed from $\chi^2$ goodness-of-fit and standard truncated halo-model [JCAP 04 (2009) 010]
the future
SuperCDMS

15 kg of Ge at Soudan, arranged as 5 SuperTowers

<table>
<thead>
<tr>
<th>SuperTower</th>
<th>CDMSII Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>• modified Al fin layout, improves phonon collection efficiency</td>
<td></td>
</tr>
<tr>
<td>• cleaner, simplified, and streamlined production</td>
<td></td>
</tr>
<tr>
<td>• “mercedes” phonon sensor layout, outer phonon “guard”</td>
<td></td>
</tr>
<tr>
<td>• 2.5X thicker (1-inch) Ge crystals</td>
<td></td>
</tr>
<tr>
<td>• “endcap” Ge veto detectors in each tower</td>
<td></td>
</tr>
</tbody>
</table>

“mercedes” zip
First SuperTower Installation

CDMS II data-taking ended March 2009

First SuperTower installation is now complete!

Preliminary background assessment done

Currently collecting data for surface event estimate!

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Surface Events a Thing of the Past?

\[ iZIP = \text{interleavened charge and phonon channels} \]

1/3000 rejection of surface events in NR band based only on charge collection

- rejection of surface events X10 better than CDMSII style detectors!
- efficiency for neutrons passing charge cut is ~55%

Charge near surface is collected by electrodes on only one side

Surface and bulk events experience different electric fields
CDMS Future Projections

**CDMS II**
- 4 kg Ge
- ~ 2 yrs operation

**SuperCDMS @ Soudan**
- 15 kg Ge
- ~ 2 yrs operation

**SuperCDMS @ Snolab**
- 100 kg Ge
- ~ 3 yrs operation

**DUSEL/GEODM**
- 1.5T

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summary

We report results from a blind analysis of 612 (raw) kg-days

2 events were observed in the signal region
(0.8 surface events and < 0.1 neutrons were expected)

We cannot interpret this result as a statistically significant signal
but, within the blind analysis, we cannot exclude either event as signal.

We establish a world-leading limit on the spin-independent
WIMP-nucleon cross section:

3.8x10^{-44} cm^2 at 90% CL (for 70 GeV/c^2 WIMP mass)

...and place constraints on alternate models

Stay tuned: 15-kg of SuperCDMS detectors operating in 2010,
results from other dark matter experiments may be coming soon!
Thank You!

arXiv: 0912.3320