CDMS Technology and Coherent Neutrino Scattering
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CDMS: interest in lower thresholds

Improvements in phonon and ionization measurements
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Same technologies could be interesting in Neutrino Coherent Scattering,
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Phonons (Matt Pyle)
CDMS Technology and Coherent Neutrino Scattering

**CDMS**: interest in lower thresholds
  Improvements in phonon and ionization measurements

Same technologies could be interesting in Neutrino Coherent Scattering, but different optimization

**Phonons (Matt Pyle)**
**Ionization (Nader Mirabolfathi)**
Speaking for

SuperCDMS Collaboration

Nader Mirabolfathi  Matt Pyle
Fantastic success of Standard Model but unstable

Why is H, W and Z at \( \approx 100 \, M_p \)?

Need for new physics at that scale

- supersymmetry
- additional dimensions, global symmetries

In order to prevent the proton to decay, a new quantum number

\[ \Rightarrow \text{Stable particles: Neutralino} \]

- Lowest Kaluza Klein excitation, little Higgs
**Standard Model of Particle Physics**

**Fantastic success of Standard Model but unstable**

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**Bringing Cosmology and Particle Physics together: a remarkable concidence**
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Bringing Cosmology and Particle Physics together: a remarkable concidence

Particles in thermal equilibrium + decoupling when nonrelativistic

Freeze out when annihilation rate $\approx$ expansion rate

$\Rightarrow \Omega x h^2 = \frac{3 \cdot 10^{-27} \, cm^3 / s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$

Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale

$\Rightarrow$ significant amount of dark matter

Weakly Interacting Massive Particles

Dark Matter could be due to TeV scale physics
Dark Matter: An Exciting Time!

Credit: Joerg Jaeckel
Dark Matter: An Exciting Time!

CRESST, EDELWEISS, CDMS, DAMA, XENON, CoGeNT, HESS, LHC, CTA, TEXONO

Credit: Joerg Jaeckel

Ohhhhh annual modulation

CDMSnix, XENONnix, modulated Muonnix

CoGeNTix, DAMAix

Credit: Joerg Jaeckel
High Mass Region
High Mass Region

CMSSM≈mSUGRA Focal point region
No threshold for Direct Detection
Ionization + Athermal Phonons
CDMS II December 2009

Ionization + Athermal Phonons

7.5 cmØ 1 cm thick ≈250g
4 phonon sensors on 1 face
2 ionization channel
Ionization + Athermal Phonons

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Ionization yield
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Ionization yield

Ionization/Recoil energy

Surface Electrons
CDMS II December 2009

Ionization + Athermal Phonons

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Ionization yield

Timing → surface discrimination

Ionization/Recoil energy

Surface Electrons

Coherent Neutrino Scattering 12/07/12
Getting rid of the surfaces
Ge: Getting rid of the surfaces

Interleaved electrodes

Reviving an idea of P. Luke (also used by EDELWEISS)

Events close to the surface seen on one side

≠ Events in the bulk seen on both sides
Ge: Getting rid of the surfaces

Interleaved electrodes
Reviving an idea of P. Luke (also used by EDELWEISS)
Events close to the surface seen on one side
Events in the bulk seen on both sides

Test with $^{210}\text{Pb}$ in low background environment

0/65,000 betas
0/15,000 $^{206}\text{Pb}$ recoils
More than sufficient for 200kg for 3 years (SNOLAB)
SuperCDMS Soudan Large Mass Region

Ø 76mm thickness
25mm
Mass 630g
SuperCDMS Soudan Large Mass Region

CDMS reach 2015
Somewhat dependent on cosmogenic neutrons + purity of our shield

CDMS reach 2019

Ø 76mm thickness
25mm
Mass 630g
Low Mass Dark Matter
Other possibilities! The Dark Matter sector could be complex or have different interactions e.g., excited states

Weiner but now dead (CDMS, Xenon 10)
Low Mass Dark Matter

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Excited states
  Weiner but now dead (CDMS, Xenon 10)

A mirror dark matter sector
  Maybe with matter-antimatter asymmetry
  Would explain naturally why $\Omega_{DM} \approx 6 \Omega_{\text{baryon}}$ if $M_{DM} \approx 6 M_p$

Could even be the origin of baryogenesis!

High cross sections within the dark matter sector?
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Sub GeV Dark Matter
Naturalness?

Electric/Dipole moment
Graham, Kaplan, Rajendran, & Walters (arXiv 1203.2531)
Claim: Pretty Natural
CDMS II

**Limited by ionization below 7 keVnr**

To go down to 2 KeVnr; use phonon only and assume nr yield to compute Enr

Incompatible with original CoGeNT claim

CDMS not incompatible with $2 \times 10^{-41}$ cm$^2$/nucleon signal

In latest paper, CoGeNT collaboration does not claim any WIMP signal
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Collar & Fields: a signal in CDMS?

Maximum likelihood very sensitive to assumptions about background analytic shape

Doing our own analysis

No significant difference between singles and multiples
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What we are doing for SuperCDMS Soudan
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2 modes

• “Low Threshold”: we measure the phonon energy and correct for the phonon emission from carrier drift in the electric field (Luke Neganov Effect) with the ionization yield of a nuclear recoil (15% correction)

• “CDMS Lite”: take one or two detectors, apply $\approx 60\text{V} \Rightarrow$ measure the ionization with the phonon $\Rightarrow 100\text{eV}$ threshold
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in either case, no discrimination

rapidly background limited

=> result in coming year
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**Working on phonons**

Optimization with new SQUIDS (lower $L \rightarrow$ lower $R_{TES}$)
Possibly working at lower $T_c$ (sensitivity increase as $T_c^3$—See below)
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**Working on phonons**
- Optimization with new SQUIDS (lower L => lower $R_{\text{TES}}$)
- Possibly working at lower Tc (sensitivity increase as $T_c^3$—See below)

**Working on ionization**
- FET-> HEMT: 4K instead of 100K, 100$\mu$W instead of 5mW
- + lower white and 1/f noise: theoretically could reach 200eV FWHM if detector leakage current is $10^{-13}$
- better system engineering (≠pick up) + may be local amplification
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better system engineering ($\neq$ pick up) + may be local amplification
How to improve the phonons for coherent neutrino scattering?

Matt Pyle
Transition Edge Sensor
with electro thermal feedback

- Superconducting film artificially held within it’s transition through voltage biasing
- Resistance incredibly sensitive to temperature change

\[ P = \sum \left( T_{TES}^n - T_{bath}^n \right) \Rightarrow \frac{P}{GT} = \frac{1}{n^6} \]
Athermal Phonon Detection Principles

\[ \frac{V_W}{V_{abs}} \approx 10^9 \]
Athermal Phonon Detection Principles

Become insensitive to $C_{\text{absorber}}$ by collection and concentration of Phonons.

$V_{W}/V_{\text{absb}} \sim 10^9$
Athermal Phonon Detection Principles

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More Complex

$V_W/V_{\text{absb}} \approx 10^9$
Athermal Phonon Detection Principles

Become insensitive to $C_{\text{absorber}}$ by collection and concentration of Phonons

More Complex Phonon Collection efficiencies ($\varepsilon$)

- Theoretical Max: $\sim 40\%$
- Best Measured: $20\pm 4\%$
- CDMS II: 1-4%
- SuperCDMS $<\varepsilon>$: $\sim 12\pm 3\%$

Active Research Area for Stanford SuperCDMS
Athermal Phonon Detection Principles

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Active Research Area for Stanford SuperCDMS

Not New $\rightarrow$ CDMS technology (10+ yrs)
CDMSII resolution

Measured CDMS II Phonon Resolution

T1  T2  T3  T4  T5

\[ x: \text{Si} \]
\[ o: \text{Ge} \]

Zip

D. Moore
$E_{\text{trigger}} \sim 6\sigma_E$: early CDMS II Si detectors good enough for reactor CNS
$\sim 12$evt/kgday
$0\% < \varepsilon < 4\%$
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CDMSII resolution

\[ E_{\text{trigger}} \approx 6\sigma_E \]: early CDMS II Si detectors good enough for reactor CNS
\[ \sim 12\text{evt/kgday} \]
\[ 0\% < \varepsilon < 4\% \]
Detailed analysis of SUF data

Top plot is combined Ge (upper panel) and Si (bottom panel) WIMP candidate event rates as a function of recoil energy.

Bottom plot is ionization yield vs recoil energy for unvetoed single scatters for Ge (top panel, Z5 6 V) and Si (bottom panel, Z4 3 V) WIMP searches.

From PHYSICAL REVIEW D 82, 122004 (2010)

Nearly good enough!
Background a bit high!
Can We Do Better?

- **Johnson Noise**
  - \(4k_B T R\)
- **Thermal Fluctuation Noise**
  - \(4k_B T^2 G\)

- Optimal Filter
  \[\sigma_E^2 = \frac{4kT^2 C}{\alpha} \sqrt{n} \implies \sigma_E \propto T_c^{1.5}\]
Can We Do Better?

Matt: We can indeed!

Increase raw sensitivity
Match better TES (ETF) bandwidth to collection bandwidth
Prevent phase separation (a big loss in CDMS II/ SuperCDMS Soudan)

- Johnson Noise
  - $4k_b T R$
- Thermal Fluctuation Noise
  - $4k_b T^2 G$

Optimal Filter

$$\sigma_E^2 = \frac{4kT^2 C}{\alpha} \sqrt{n} \Rightarrow \sigma_E \propto T_c^{1.5}$$
But large bandwidth mismatch

- Position and Total Energy Signals have wildly different bandwidths
- Optimization for both Impossible
- SuperCDMS: Choose Position

\[ \tau_E = 750\mu s \]
\[ \tau_{xyz} < 30\mu s \]

\[ \nu_{xyz} = \frac{1}{\tau_{xyz}} > 5\text{kHz} \]

\[ \nu_E = \frac{1}{\tau_E} = 210\text{Hz} \]
But large bandwidth mismatch

Phonon collection time $\gg$ TES time $\gg$ ETF time (phase separation)

- Position and Total Energy Signals have wildly different bandwidths
- Optimization for both Impossible
- SuperCDMS: Choose Position

\[ \tau_E = 750 \mu s \]
\[ \tau_{xyz} < 30 \mu s \]
\[ \nu_{xyz} = \frac{1}{\tau_{xyz}} > 5 \text{kHz} \]
\[ \nu_E = \frac{1}{\tau_E} = 210 \text{Hz} \]
\[
\sigma_E^2 = \frac{4 k T_c^2 G}{\tau_{\text{coll}}} \Rightarrow \sigma_E \propto T_c^3 \]

Noise$^2$ = power noise/ Collection bandwith
We gain as the cube of $T_c$!
Consequence

\[ \text{Noise}^2 = \text{power noise/ Collection bandwith} \]

We gain as the cube of \( T_c \)!

\[ \sigma_E^2 = \frac{4kT_c^2G}{\tau_{\text{coll}}} \Rightarrow \sigma_E \propto T_c^3! \]

Furthermore: Lower \( T_c \) -> less phase separation!
**Consequence**

\[ \sigma_E^2 = \frac{4kT_c^2 G}{\tau_{\text{coll}}} \Rightarrow \sigma_E \propto T_c^3 ! \]

Furthermore: Lower \( T_c \) -> less phase separation!

In addition we can decrease \( G \) (and \( C \)) by decreasing length of the TES (we can accommodate lower \( R \) with lower \( L_{\text{SQUID}} \))

- QP trapping in Al antenna
  - \( L_{\text{diff}} \approx 180 \text{um} \)
- Optimally use area near TES
- Not Possible in iZIP detectors charge signal capacitance constraints
Baseline Energy Resolution Estimates

- Low $T_c$ estimates significantly affected by $\alpha(T_c)$ & $\beta(T_c)$
- Baseline Resolution
- Position systematics?
  - SuperCDMS 3%

Resolution Scalings with $T_c$ ($l_{qp} = 255\,\mu m$)
Baseline Energy Resolution Estimates

Possible stumbling blocks

- Low $T_c$ estimates significantly effected by $\alpha(T_c)$ & $\beta(T_c)$
- Baseline Resolution
- Position systematics?
  - SuperCDMS 3%
Possible stumbling blocks
  • Film quality C if we decrease $T_c$

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Baseline Energy Resolution Estimates

Possible stumbling blocks
- Film quality C if we decrease $T_c$
- Film uniformity (How does alpha evolve)

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- Baseline Resolution
- Position systematics?
  - SuperCDMS 3%
Baseline Energy Resolution Estimates

Possible stumbling blocks

- Film quality C if we decrease $T_c$
- Film uniformity (How does alpha evolve)
- Engineering: Fridge, low frequency noise, IR loading (goes as $T^5$)

- Low $T_c$ estimates significantly effected by $\alpha(T_c)$ & $\beta(T_c)$

- Baseline Resolution

- Position systematics?
  - SuperCDMS 3%
Short Term Plans: Misfit Toys

- Si: not interesting for standard high mass WIMP search
- Ion-Implant
  - LDM?
  - $\bar{\nu}N \rightarrow \bar{\nu}N$
Short Term Plans: Misfit Toys

SuperCDMS throughput study
6 x 1” Si detectors in 3 weeks with 3FTE fab team
IMPRESSIVE!

• Si: not interesting for standard high mass WIMP search
• Ion-Implant
  • LDM?
  • $\bar{\nu} N \rightarrow \bar{\nu} N$
Can We Improve the Ionization Measurement through Phonons?

Nader Mirabolfathi for:

Enectali Figueroa-Feliciano (MIT),
Matt Pyle (UCB), Kai Vetter (UCB, LBNL), Paul Luke (LBNL), Marc Amman (LBNL), Ryan Martin (LBNL),
Bernard Sadoulet (UCB, LBNL)
• **Luke-Neganov Gain**

\[ E_{tot} = E_r + E_{luke} \]
\[ = E_r + n_{eh} eV_b \]
\[ = E_r \left( 1 + \frac{eV_b}{\epsilon_{eh}} \right) \]

• Phonon noise doesn’t scale with the ionization bias

=> \( S/N \uparrow \)

In theory one can increase \( \sqrt{F\epsilon E} \)

Bias to reach Poisson fluctuation limit: Ge Breakdown
• CDMSII 1 cm thick Ge detectors can’t handle much beyond 10 V/cm
• To keep ionization phonon discrimination CDMS limited to low collection fields anyways => no interest for field > V/cm
• Need to neutralize detector: All impurity levels (p or n) at neutral state to reduce trapping.
• Impact ionization on neutral states lead to breakdown?
• What if we charge all impurities like 77K depleted Ge gamma spectrometers.
• Results from latest UCB tests.
Point contact ionization detectors

- Main advantage: low electrode capacitance i.e. threshold.
- CoGeNT 440g 5mm PPC, 1 pF gate capacitance
- $\sigma_n \sim 70$ eV
- Threshold 0.4 keVee

Idea:
- Transform Ionization to Phonons:
- Use very low threshold phonon detectors
Alternative: Point contact phonon
Alternative: Point contact phonon

Use the same principle as point contact but

- Very low temperature: No Carrier generation.
- < 4K the impurity charge status will freeze.

Need to deplete the detectors at 77K and cool!

Depleted => All impurities charged.
Alternative: Point contact phonon

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Very low temperature: No Carrier generation.

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Depleted => All impurities charged.
Recent tests at Berkeley

Φ=20 mm, h=10 mm p-type Ge: $10^{10}$ cm$^{-3}$
Could deplete at 180 Volts at 77K and cool to 0.05 K
Detector maintained depleted state down to 0.05 K
Ionization calibration with Ba-133 source

Not very good resolution
baseline= 1keV (badly adapted Cconnect+CFET)
lines: problem of collection close to surface?
Next: Add phonon sensor

A tungsten ($T_c \sim 65$ mK) thermometer glued: Only sensitive to thermal phonons.
Currently running with internal $^{241}$Am source; 10 to 60 keV
Study the Neganov-Luke gain
Study near surface (dead layer)

W : 65 mK TES
Near surface events: Ionization dead-layer

• Near surface cause:
  • Back diffusion to the wrong electrode.
  • Self shielding of the initial e-h cloud
  • How bad for recoils <<1 keV ??
    • Need to be studied
    • Trapping on the surface states.

• One can engineer the size of the point contact such that:
  • Field near the phonon surface ~ Volts/cm.
  • Use the same concept as iZIP.
  • Majority of phonons released in the vicinity of the point contact.
  • Use Phonon partition to select only center events.

• Can also cover the cylindrical surface:
  • EDELWEISS FIDs.
Advantage: No Position dependence
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Majority of athermal phonon emitted from a small region around the point contact.

Fiducial volume events: Most phonons from $\sim 1 \text{ cm}^3$ around point contact where the field is strong.

The same principle can be used to identify deadlayer events.
**Advantage: No Position dependence**

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The same principle can be used to identify deadlayer evenst.

**Disadvantage:**

Basically ionization measurement.

Low ionization yield $\sim 1/10$ at the region of interest.

But very good $\sigma$ should compensate?

No event-by-event discrimination: Requires a very good understanding of the backgrounds.
Conclusions

Noise improvement:

1-100eV $E_{\text{trigger}}$ seem technically possible

$T_c^3$ scaling for athermal phonon detectors

Improved cold/warm electronics

Optimize detector design

R&D Challenges Remain

W FILM QUALITY

6 Si iZIPs -> hoping to be the first group to study CNS
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6 Si iZIPs -> hoping to be the first group to study CNS

Signal improvement:

Can deplete and operate Point contact Ge detectors at very low temperatures

Phonon response improves linearly with collection potential while phonon noise is independent.

Can reach ultimate Poisson fluctuation limit.

R&D challenges:

Near surface events.

Larger detector and the regions of low electric field.