Improving the Energy Sensitivity of Massive Calorimeters to Search for Light Mass Dark Matter

Matt Pyle
University of California Berkeley

LTD-16 Grenoble
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Light Mass DM Limits: Why So Bad?
The low-mass WIMP Direct Detection Challenge

\[ \Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2v^2}{M_N} \]

Detector Requirement: Amazing Energy Sensitivity
Currently Published (PRL 112, 041302 (2014)):
- $\sigma_{pt} = 340 \text{ eV}_t$
- Threshold: $12 \sigma_{pt}$

SuperCDMS SNOLAB requirements:
- $\sigma_{pt} = 50 \text{ eV}_t$
- Threshold: $7 \sigma_{pt}$
Athermal Phonon Sensors

Collect and Concentrate Phonon Energy into W TES (Transition Edge Sensor)
• Pulse fall time varies with QET density.
• Phonon energy signal bandwidth limited by athermal phonon collection

\[ \nu_{signal} = 210 \text{ hz} \]
Transition Edge Sensor: Dynamics

\[ \nu_{\text{signal}} \ll \nu_{\text{sensor}} \]

\[ \nu_{\text{sensor}} \propto \frac{G}{C} = 4 \text{kHz} \]
Transition Edge Sensor: Noise

DC noise scales with $G$

$$S_{pG} = 4k_bT^2G$$

Theoretical Power Noise for TES (NEP)
Bandwidth Optimization Rule

\[ \nu_{sensor} < \nu_{signal} \]

Power Noise for various G

Phonon Power Noise \([W/\text{rtHz}]\) vs. \(\nu_{signal}\) for various G.
Phonon Sensitivity with $T_c$

Baseline Energy Resolution (sigma) [eVt]

- Ge iZIP4
- Si iZIP4
- Ge ulZIP
- Si ulZIP

- G48: Measured
- G48: 1/f subtracted
- S12C: Measured
- S12C: 1/f subtracted

$G \propto T_c^4$

$S_{ptfn} = 4k_bT_c^2G$

$\propto T_c^6$

$\sigma_E \propto T_c^3$
New: Noise of G23R Test Device

- $T_c = 52-53\, \text{mK}$
- iZIP-IV TES Geometry

Estimated Noise: TFN + Johnson Noise

Sp = $1.5 \times 10^{-17}\, \text{W/rtHz}$:
- Ge: $\sigma_{pt} \sim 50\, \text{eVt}$
- Si: $\sigma_{pt} \sim 25\, \text{eVt}$
- (15% phonon collection efficiency)
- Some things not yet understood G is $x4$ bigger than expected

Estimated Power Noise [W/rtHz]
New: G23R Sensor Bandwidth

- Sensor Bandwidth measured via voltage bias jitter
- No phase separation
- $\tau_{\text{sensor}} = 35 \ \mu s$
  $\nu_{\text{sensor}} = 4.5 \ \text{kHz}$
- 52 mK W TES is still too fast! We need to continue lowering $T_c$
Phonon Sensitivity with $T_c$

Baseline Energy Resolution (sigma) [eVt]

- Ge iZIP4
- Si iZIP4
- Ge ulZIP
- Si ulZIP

- G48: Measured
- G48: 1/f subtracted
- S12C: Measured
- S12C: 1/f subtracted
- Measured G23R

Why are we above the scaling law curve?

G: x4 larger than expected
- W TES films too thick?
- $\Sigma_{ep}$ varying with $T_c$?
Why is it taking so long?

What are the fundamental limits in phonon resolution?
Problem #1: Parasitic Power

As we lower $T_c$, we become more sensitive to nuclear recoils, but we also become more sensitive to environmental noise.

These problems have definitely been solved by other groups here at LTD!
Summary

• We’re slowly, but surely, continuing to improve our phonon energy resolution by lowering $T_c$ and improving our environmental shielding.

• Currently at $\sigma_{pt} \sim 50eV_t (\text{Ge})/25eV_t (\text{Si})$. We have met requirements for SuperCDMS using 75mm detectors, but not yet with a larger 100mm detector.

• Over the coming 5 years we hope to really explore the limits of the technology (ER/NR rejection via charge quantization)
Backup
Energy lost to ionization by 254-eV $^{73}$Ge atoms stopping in Ge

K. W. Jones and H. W. Kraner
Brookhaven National Laboratory, Upton, New York 11973
(Received 30 July 1974)

A 1-cm$^3$ Ge(Li) $\gamma$-ray detector was placed directly in a beam of thermal neutrons where the $^{72}$Ge($n,\gamma$)$^{73}$Ge reaction produced 254-eV $^{73}$Ge recoil atoms in the detector. The primary capture $\gamma$ rays from the reaction were detected in a 7.6-cm $\times$ 7.6-cm NaI(Tl) detector placed at 90$^\circ$ to the incident beam. In addition to singles measurements a coincidence between the primary capture $\gamma$ ray and the $\gamma$ ray or conversion electrons from the decay of the 68.75-keV $^{73}$Ge third excited state was used to search for directional effects in the stopping and to check the value of the recoil energy deduced from the feeding of the 68.75-keV level. The level energy was remeasured and a value of 68.755 $\pm$ 0.005 keV was found, which when combined with the results of previous work gives a value of 68.7535 $\pm$ 0.0043 keV. The amount of energy lost to ionization in the stopping of the 254-eV $^{73}$Ge atom is found from the energy shift in the peak position for the 68.75-keV level. Our measurement of this shift gives a value of 39.2 $\pm$ 5.5 eV, which is then the energy loss to ionization by the stopping of the 254-eV $^{73}$Ge recoil atom. This result is (27 $\pm$ 3)% higher than the theoretical estimate made from an extrapolation of the Lindhard theory to this energy region. An attempt to observe a dependence of the ionization loss on the recoil direction in the Ge crystal was made, but no positive effect was observed.

- Brought to us by Juan
- Photon needs to be huge!
Ge Yield and Lindhard

KSU reactor neutron calibrations: recoil sensitivity below 1 keV_{rec} demonstrated with 0.5 kg detector (a first)

Juan TAUP11
Gory details:
P.S. Barbeau Ph.D. Thesis

ionization energy (keV)

10^0

10^{-1}

recoil energy (keV)

0.4 0.7 1 4

inelastic n scattering (Jones and Kraner 71)
elastic n scattering (Messous et al. 95)
thermal n capture (Jones and Kraner 75)
elastic n scattering (this work)

Lindhard theory (k = 0.2)