Direct Detection: Low Masses

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• What do we mean by “low mass” dark matter?

• Kinematic limitations at low mass: electronic versus nuclear recoils

• Limitations from backgrounds (why go underground)

• Current and future low threshold experiments:
  • DAMIC, CRESST, & SuperCDMS

• SuperCDMS SNOLAB Design and Prospects

• Experimental Outlook
Direct Detection Limits and Reach

WIMP–nucleon cross section $[\text{cm}^2]$ vs. WIMP Mass $[\text{GeV}/c^2]$
Direct Detection Limits and Reach
How do we Design Low-Mass Detectors?

- WIMP mass determines two quantities: local WIMP number density and recoil energy distribution
  - Mass density set by astrophysical constraints

- For low mass, sensitivity is limited by your energy threshold; lighter particles will transfer less energy to your target, and heavier nuclei will further suppress this transfer

- For high mass, increasing mass decreases number density; heavier target provides larger cross-section and therefore more exposure

- Low mass detectors can be small, as long as they have low energy thresholds!
Collision Kinematics

• Recoil energy for a typical WIMP velocity depends on target mass and recoil type

• Electron and nuclear recoils have different kinematics; nuclear recoils are simple elastic collisions, electron recoils are largely inelastic and depend on electron orbital and kinematics within the bound electron-atom system

• In addition to momentum transfer for a fixed velocity, using a velocity and angular distribution yields an expected energy spectrum

\[
\Delta E_{NR} \leq \frac{1}{2m_N} q_{max}^2 = \frac{m_N v^2}{2} \left( \frac{2m_X}{m_X + m_N} \right)^2
\]

\[
\Delta E_{ER} \leq \frac{1}{2} \mu_{N\chi} v^2 = \frac{m_N v^2}{2} \left( \frac{m_X}{m_X + m_N} \right)
\]

\[
m_{\chi, NR} \geq \sqrt{2m_T \sigma_E v}
\]

\[
m_{\chi, ER} \geq \frac{2\sigma_E}{v^2}
\]
For example, the SuperCDMS target substrates produce different rates and spectral shapes due primarily to mass differences between the Nuclei:

- Si is more preferential for low-mass WIMPS
- Ge produces higher high-mass WIMP event rate
Ultra-sensitive detectors will also suffer from additional susceptibility to low energy backgrounds.

Predominant limitations for all G2 experiments will come first from radioactive backgrounds surrounding the detectors, and then from cosmogenic activation and detector bulk contamination.

- In Ge & CaWO, leading irreducible background is cosmogenic tritium.
- Si also will have some level of Si-32 from natural abundance (150 year half-life), which is dependent on where the Si is sourced and the level of contamination in initial production steps.

Large amount of R&D shared between collaborations focused on reducing activation of detectors and contamination of detector housings and cryostats.
Low-Mass Dark Matter: Detection Strategies

- A particle deposits some of its kinetic energy in a target mass; how then do we measure it?
  - Calorimetry - detectors which simply integrate that energy
  - Charge-based - in semiconductors, there is a conversion of energy to ionization which can then be measured
  - Scintillation - energy can be converted to light and then we can use photodetectors to measure the total energy
  - Integrated rate detectors (e.g. crystal defect measurements) - not covered in this talk

- Dual mode detectors can help discriminate signals from backgrounds at higher energies
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- Dual mode detectors can help discriminate signals from backgrounds at higher energies
  - For low mass secondary phases start to be statistics limited with conventional detectors; when energy deposits drop below ~100 eV, quantization noise dominates
Low-Mass Landscape

- Calorimeters (Phonons Only)
  - SuperCDMS HV (Si & Ge, e.g. CDMSlite)

- Charge Only:
  - DAMIC (Si ‘Skipper’ CCDs)

- Charge + Phonons:
  - SuperCDMS iZIP (Si & Ge)
  - EDELWEISS (Ge)

- Charge + Light:
  - CRESST II/III (CaW0 + Scintillating Housing)
Calorimeter energy resolution is fundamentally limited by thermal fluctuations between the sensing volume and the bath regardless of detector geometry; this minimum resolution follows

\[ \sigma_E^2 = \frac{G k_b T^2}{\epsilon^2} \frac{1}{\tau} = \frac{C k_b T^2}{\epsilon^2} \approx cV \frac{k_b T^3}{\epsilon^2} \]

One way around the volume limitation is by collecting the energy before thermalization; the volume is thus the sensor volume, not the target volume.

Even with target decoupling, the tradeoff between sensor volume and energy efficiency requires temperatures below \(~50\) mK for sub-GeV dark matter.
Electron recoils liberate an electron, creating an electron-hole (eh) pair, which in turn down-converts to free more eh pairs producing 1 eh pair per ~2.9 eV in Ge, ~3.6 eV in Si
- Compare to ~13 eV in LXe

This is the mean number of electron-hole pairs; we use Fano statistics to determine the range of possible electron numbers for a given recoil energy

Nuclear recoils are more complicated, as the nucleus produces both free electron-hole pairs and phonons as it recoils through the lattice, in addition to the relaxation phonons produced during both electron and nuclear recoils

The Lindhard scaling law predicts the mean energy partitioned into the charge system as a fraction of input recoil energy
Charge Resolution in Practice: DAMIC

- Charge resolution roughly proportional to detector capacitance, but historically dominated by charge amplifier noise.

- DAMIC, which uses science-grade CCDs, has leading sensitivity to charge at a noise level of ~30 eVee, but suffers from low exposure.

- Even ultra-pure crystals suffer from limited charge collection efficiency; scaling a pure charge collection experiment to larger exposure is prohibitively expensive.

- Size limitations also restrict ability to reject backgrounds.
CRESST II/III: Phonons + Light

• Dual-phase phonons+light, which follows a yield model similar to charge

• Can separate electronic and nuclear recoils based on yield, and use light as an additional energy measure

• Light and energy resolution very competitive, TES sensors operate around 15-30 mK

• No fiducialization ability, so analysis is background limited at all masses
SuperCDMS iZIP: Phonons + Charge 1

• Interleaved electrode design allows for collection of charge and phonons on the same crystal and clear surface reconstruction

• In any recoil event, all energy eventually returns to the phonon system
  • Prompt phonons produced by interaction with nuclei
  • Indirect-gap phonons produced by charge carriers reaching band minima
  • Recombination phonons produced when charge carriers drop back below the band-gap

• Phonons are also produced when charges are drifted in an electric field; makes sense by energy conservation alone

• Total phonon energy is initial recoil energy plus Luke phonon energy, as shown at right

• Athermal phonons collected in superconducting aluminum fins and channeled into Tungsten TES, effectively decoupling crystal heat capacity from calorimeter (TES) heat capacity
Charge lines biased to opposite voltages creating a bulk drift field for charges, and a larger fringing field at the surfaces.

Charge yield/symmetry allows for rejection of surface events and separation of electronic and nuclear recoils.

Additionally, bulk field contributes to Luke phonon production, yielding a small energy gain in addition to the initial phonon energy.

Fiducialization ability of iZIP detectors allows for much cleaner signal region, and exposure limited search rather than background limited search.
• CRESST and SuperCDMS iZIP results show limitations of the yield discriminant below ~1 keV; instead of using charge as a discriminant, CDMSlite used charge to amplify the signal by increasing detector voltage to convert charge energy into phonon energy:

\[
E_{\text{phonon}} = E_{\text{recoil}} + V \times n_{\text{eh}}
\]

\[
= E_{\text{recoil}} \left[ 1 + V \times \left( \frac{y(E_{\text{recoil}})}{\varepsilon_{\text{eh}}} \right) \right]
\]

• CDMSlite Runs 1&2 pushed low-mass limits below 5 GeV/c^2 for the first time using iZIP detectors operated in single-sided mode, running at 75V single-sided

• This experiment elucidated design challenges for dedicated ‘HV’ detectors
• Go for ultimate in phonon energy resolution, and operate at 100V bias:
  • Ge: 10 eV resolution
  • Si: 5 eV resolution

• With voltage bias, one electron-hole pair produces ~100 eV of phonon energy for a gain of ~30. This translates to:
  • Ge: ~0.3 eVee
  • Si: ~0.15 eVee
  • Single electron-hole pair resolution

• Maintain 15-20% energy efficiency with
  • Faster, more position dependent pulses - better phonon-only position reconstruction
  • Lower device Tc: 40-45 mK
  • Larger detectors (x2 more volume, proportionally more of it fiducial)
SuperCDMS SNOLAB (2000 MWE)

Detector Tower

Detector Housings

- MiniCLEAN
- Cryopit
- Workshop
- DAMIC
- PICO
- Low Background Counting
- Showers
- Entrance
- Lunch area
- Meeting room
- SNO+
- DEAP
- HALO
- SuperCDMS

- Drift B3: SuperCDMS Utilities
- Water Cooling
- Radiation Suppression
- Drift C3: SuperCDMS Experiment

- Outer Water/Poly Shielding
- Lead Shielding
- Snobox (6 cans w/towers)
- Inner Poly Shielding
- E-tank
- Dilution Refrigerator
- C-Stem
- E-Stem
- Bottom Solid HDPE Plates
- Seismic Platform

15 mK
SuperCDMS SNOLAB (2000 MWE)

Detector Tower

iZIP (Ge)

HV (Si)

Detector Housings

15 mK
Projected G2 Low-Mass Reach

http://cdms.berkeley.edu/limitplots/mm/WIMP_limit_plotter.html
Dark Sectors: MeV-Scale Dark Matter Now and Future

• Dark sectors easily accommodate sub-GeV dark matter, and the coupling to standard model particles through dark-photon mediator naturally suppressed the interaction cross-section

• The upcoming SuperCDMS SNOLAB nuclear recoil analysis will definitively constrain this parameter space down to ~300 MeV

• Our detectors are designed with the goal of achieving sensitivity comparable to these electron recoil limits
Looking Forward: Detection Media for Lower Mass

- Looking at current/future technologies, we have a mix of materials with small but non-zero bandgaps, to limit dark counts and maximize energy to carrier conversion

- Extent of these arrows driven by fundamental limitations from kinematics and material properties, and assumes large current hurdles can be overcome in energy and charge noise across all experiments

SuperCDMS Collaboration

California Inst. of Tech., CNRS-LPN, Durham University, FNAL, NISER, NIST, Northwestern, PNNL, Queen's University

* Associate members
References

  • See references therein for more detail on dark-sectors and light dark matter projections


• 3rd Berkeley Workshop on Direct Detection (https://indico.physics.lbl.gov/indico/event/311/timetable/#all)
  • See talks by Eureca Collaboration (CRESST and EDELWEISS) and CDMS

• Projected Sensitivity of the SuperCDMS SNOLAB Experiment (https://arxiv.org/abs/1610.00006)

• DAMIC Experiment (https://arxiv.org/abs/1510.02126)

• CDMSlite Long Paper (In Prep)
Backup Slides
Optimized HV Detector Design
Optimized iZIP Detector Design
Detector Readout - Measuring Phonons (CDMS)

- QET -
  - Quasiparticle assisted
  - Electrothermal feedback
  - Transition edge sensors

- Energy transport follows the following chain:
  - Phonon breaks cooper pair in superconducting aluminum fin
  - Quasiparticles (free charges in the superconducting ‘conduction band’) drift to the tungsten trap
  - The tungsten, with a lower bandgap, traps the quasiparticles, and channels their energy to the TES
  - The TES heats up, changing resistance, which is seen as a change in current, and produces a pulse

- The integral of the current pulse is proportional to the absorbed energy

- Limitations include energy transport efficiency limits at each interface, and a reflection probability of around 40% at the aluminum interface
Optimizing Sensitivity: Sensor Efficiency

• A sensor unit cell consists of an absorber (superconducting aluminum) and a TES sensor. The length and geometry of the aluminum fins, and tungsten ‘traps’, affects the collection efficiency of the device.

• Increasing film thickness increases the diffusion length of quasiparticles in aluminum; adding slots makes diffusion more ‘1D’, also increasing collection efficiency.

• Increasing overlap length increases trap surface area, causing more QPs to be collected.

• Unclear how far we can carry this overlap improvement before diffusion in the tungsten begins to reduce collection efficiency again.

• Not quite sure how to optimize connectors from fins to QETs.
Optimizing Sensitivity: Sensor Energy Resolution

- Increasing fin length increases total phonon collection while decreasing efficiency; tradeoff produces optimum

- Sensors wired in parallel in a single channel, with 12 channels per device; increasing TES length increases number of QETs, and therefore collection efficiency

- Increasing collection time reduces amount of noise that is included in the signal integral, improving energy resolution

- With too many QETs, efficiency limited by interfaces, and more interfaces reduce overall efficiency

- Noise sources dependent on quality of SQUIDs and temperature of detector/wiring components; the colder the better
Optimizing Sensitivity: Rejecting Residual Backgrounds

- Channel configuration chosen to maximize position reconstruction ability
- Truth information from detector Monte Carlo simulation
- Full simulation of detector readout run, analysis quantities constructed, and potential channel layouts contrasted by fiducialization ability