Probing Sub-GeV Dark Matter with Superfluid Helium

Daniel McKinsey
UC Berkeley and LBNL

(with Scott Hertel (UMass Amherst), Andreas Biekert, Junsong Lin, Vetri Velan)
Dark Matter Nuclear Recoils: Current Landscape

![Graph showing the current landscape of dark matter nuclear recoils with various experimental constraints and the neutrino floor.](image-url)
Dark Matter Nuclear Recoils: Future Directions

- Lighter target/ lower threshold
- Neutrino Floor
- Increase exposure

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Helium for light dark matter detection

Light baryonic target with multiple signal channels, including light, charge, triplet excimers, phonons, and rotons. (W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).)

\[ m_x = 1 \text{ GeV/c}^2 \]
Why Superfluid Helium-4?

• Liquid down to 0 K, allowing 10-100 mK-scale TES readout.
  – Take advantage of the great advances in TES technology
  – Take advantage of possible ~ 100% detection efficiency for photons, triplet excimers
  – Take advantage of the extremely low vapor pressure of superfluid helium at low temperatures, enabling quantum evaporation-based heat signal amplification.

• Helium is expected to have robust electronic excitation production efficiency, with a forgiving Lindhard factor, so nuclear recoil scintillation signals should be relatively large.

• Negligible target cost

• Low nuclear mass and charge -> low backgrounds from neutrino-nucleus scattering and gamma-nucleus scattering.

• Low vibration sensitivity: As a superfluid, small velocities don’t generate excitations.

• Large ionization gap -> less signal quanta per keV than in super-, semiconductors. But no electron recoil background below 16 eV.

• Impurities easily removed from helium using cold traps and getters, and will literally fall out of the superfluid.
Anatomy of a Recoil

- UV and IR photons detectable as scintillation
- Triplet molecules directly detectable with TES
- Phonons and rotons can be detected with TESs, with some extra work
Superfluid Helium Detector Concept

(S. Hertel, U. Massachusetts, Amherst
Junsong Lin, Andreas Biekert, Vetri Velan, DNM, UC Berkeley)

Initial sensitivity studies, taking neutrino and gamma ray backgrounds into account:

Signal channels:
  1) Scintillation
  2) Ballistic Triplet Excimers
  3) Phonons/Rotons

No drift field, and no S2 signal
• No worry of few-electron background
• (Though could apply drift field to detect single electrons via roton/phonon production.)

Discrimination using signal ratios

Event position via signal hit patterns
Superfluid helium-4 as a detector material


Two signal channels, heat and light. Both measured with a bolometer array.

Concept Demonstrated

- HERON: proposed $pp$ neutrino observatory
- Pulse at the right shows simultaneous detection of photons and rotons

Sample pulse from 364 keV electron

**Signal in Si/Al$_2$O$_3$ wafer**

- Evaporation
- Scintillation

**Time [μs]**

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Reading Out Singlet Excitations (16 eV Photons)

Detecting photons is a simple calorimetry application. Operating calorimetry in LHe: less standard. Possible thanks to:
- Huge LHe-solid Kapitza resistance
- Fast conversion of photon energy to non-phonon excitations (e.g. Al quasiparticles)

Triplet excimers may also be read out using the same calorimetry!

Phonons and Rotons

Superfluid supports vibrational modes (some non-intuitive).

Ballistic, \( \sim 150 \) m/s.

Enormous Kapitza resistance, i.e. tiny probability of crossing into solid.

Few downconversion pathways.

Most signal expected in R- and R+ rotons, with absorption probability on walls measured to be \( 2.8 \times 10^{-3} \). See Brown and Wyatt, J. Phys.: Condens. Matter 15, 4717 (2003).
Quantum evaporation from superfluid helium – vacuum interface

Heat amplification from desorption – adsorption process
Adsorption gives 10-40 meV depending on surface

~10x signal energy enhancement!
Phonons and rotons can change type when reflecting from surfaces

Calculations based on Tanatarov et al., arXiv:1004.3497

direct reflection mode-change probabilities
(blue=0, red=1)

upper three: solid interface
lower three: vacuum interface

D. McKinsey
Expected Backgrounds

Backgrounds included:
- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017))

Arguments for low “detector” backgrounds:
- Low-mass calorimeter, easy to hold
- Target mass highly isolated from environment (superfluid: friction-free interfaces)
Electron recoil / nuclear recoil discrimination

Toy Monte Carlo detection efficiencies:
- singlet UV photons: 0.95 (4pi coverage by calorimetry)
- Triplet excimers: 5/6 (only solid surfaces)
- IR photons: 0.95 (similar to UV photons)

Excellent predicted discrimination at sub-keV energies
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Phonon and Roton Monte Carlo Studies

Below are shown Monte-Carlo-determined efficiencies of detecting quasiparticles (phonons or rotons) as a function of quasiparticle momentum, for varying surface absorption probabilities (0.001 to 0.1)
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Heat-only Readout?

Signal channels:
- Phonons
- Rotons

Energies in principle down to \(~ 1\) meV.

Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/phonon distributions, with resulting differences in signal timing.

Position reconstruction using signal hit patterns
Background vs Signal Discrimination with Phonon/Roton Timing?

D. McKinsey  Superfluid helium  20
Possible stages of a superfluid helium program

**Generation 1:** “shovel ready”
10 eVr threshold, 1 kg-yr
Assuming 40 meV per He atom (graphene-fluorine)
20 eV calorimeter threshold w/ 5% evap. efficiency

**Generation 2:** “feasible after R&D”
100 meVr threshold, 10 kg-yr
Assuming 40 meV per He atom (graphene-fluorine)
1 eV calorimeter threshold w/ 25% evap. Efficiency

**Generation 3:** “theoretically possible”
1 meVr threshold, 100 kg-yr
Limit of single-atom counting
(~40 meV calorimeter threshold)
Higher Order Phonon Processes

- Virtual phonons not limited to dispersion relation.
- Process allows sensitivity to keV-scale warm DM
- Two-phonon process experimentally observed in neutron scattering (below)


Next Steps

Now: Measure scintillation light yield from low energy nuclear recoils in superfluid helium

Also: Dilution refrigerator instrumentation studies (UCB + UMass)

Right: Successful cool down to 1.5 K!
Superfluid Helium Detector

Leiden (wet, low-vibration) dilution fridge being set up in McKinsey lab at UCB

First tests being designed, with TES, SQUIDs, helium film burner, shielding
Summary

- Preliminary studies on limits for a dark matter search using superfluid helium are very promising.
- Basic technology has been demonstrated.
- Future generations aided by current R&D in TES technology by CDMS, CRESST, many others.
- Paper imminent!
- Also stay tuned for instrumentation studies out of UCB and UMass.
Ballistic Triplets

- 22Na gamma source
- Titanium TES in 100 mK 4He bath
- Singlets from TES coincident with PMT; triplets from only TES

LHe reach at the surface

2g LHe on surface. Zero background
Projected Sensitivity – dark matter, with heavy dark photon mediator
Superfluid helium-4 as a detector material