HeRALD: Direct Detection with Superfluid 4He
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arXiv:1810.06283v1
HeRALD: Helium Roton Apparatus for Light Dark matter

- Superfluid 4He as a target material
  - Favorable recoil kinematics
  - Recoil energy can be fully reconstructed with TES calorimetry
  - Zero bulk radiogenic backgrounds
  - No Compton backgrounds below 20 eV
- HERON experiment at Brown (Seidel, Maris), proof of concept work
Excitations in Superfluid 4He

- Singlet UV (16 eV) Photons
- Triplet Kinetic Excitations
- ~meV Vibrations (phonons, rotons)

DM $\rightarrow$ O(ns) $\rightarrow$ He
Excitations in Superfluid $^4$He

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**Detection Method**
- Absorbed in calorimeters on 10 ns timescale

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He$^*$ $\rightarrow$ He

$\gamma$
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O(ns)

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He*
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Energy Partitioning

• Nuclear and electron recoils have different energy partitioning!

• Estimated from measured excitation/ionization cross sections

• Compared to other noble elements, lots of energy goes into atomic excitations

• Distinguishable with signal timing

Active veto for recoils less than 20 eV
Activities at Berkeley

• Measuring the light yield for nuclear recoils in 4He

• Neutron scattering experiment at room and cryogenic temperatures (red curve)

  • Room temperature on arXiv: 1907.03985

From V. Velan

Blue = quasiparticle
Red = Singlet
Green = Triplet
Grey = IR photon
Background Simulations

- Radon surface backgrounds not yet considered
Sensitivity Projections

- Solid red curve, 1 kg-day @ 40 eV threshold
- 3.5 eV (sigma) calorimeter resolution
- 9x “adhesion gain”
- 5% quasiparticle detection efficiency
Low Energy Neutron Calibration

• Coincidence at 24 keV:
  • Energy of convenient photoneutron source (124SbBe)
  • Energy of ‘notch’ in cross section of Fe (~100 m interaction length)
  • Result: can surround a photoneutron source in material opaque to gammas but transparent to 24 keV neutrons

• Endpoint in He: 14 keV

• 1 GBq 124 Sb source (practical) results in a few n/s collimated neutrons

• Also looking into pulsed source based on pulsed filtered neutron generator, DD or DT
Activity at UMass

- Characterizing dilution refrigerator

- Uncertainty in how quasiparticles, triplet excitations interact at surfaces

- Adhesion gain: use materials with higher van der waals attraction, keep calorimeter dry
  
  - Adapting the HERON film burner design, demonstrated but **heat load problematic**
Heat Load Free Film Stopping: Cesium

• Cesium coated surfaces, demonstrated but technically difficult

  • Nacher and Dupont-Roc, PRL 67, 2966 (1991)
  
  • Rutledge and Taborek, PRL 69, 937 (1992)
Heat Load Free Film Stopping: Geometry

- Atomically sharp knife edges, used by x-ray satellites at higher temperatures, has yet to be conclusively demonstrated

[Y. Ezoe et al. J. Astron. Telesc. Instrum. Syst. 4(1) 011203 (27 October 2017)]
Next Steps

UMass
- Dilution Refrigerator Characterization
- keV-scale neutron calibration

Berkeley
- Scintillation yield measurements
- Commissioning a dilution refrigerator (calorimetry)

Quasiparticle Reflection
- He Film Stopping
- Adhesion Gain
Extras
From Scott Hertel

quasiparticle  free atom  van der Waals binding

LHe  vacuum  Cal.

~1 meV  0.62 meV  10s of meV
Film Burner Model

Experimental film stoppage area

Condenser Surface

Evaporator Surface

Condenser Surface
Excitations in Superfluid 4He

DM

He

Vibrations (phonons, rotons)

Excitations

He*

He*

Dimer Excimers

He* + He

He*

e-

Ionization

He+

Detected State

Vibrations (phonons, rotons)

Singlet UV Photons

Triplet Kinetic Excitations

(IR Photons)

He

He*
### Sensitivity Projections Cont.

<table>
<thead>
<tr>
<th>Curve</th>
<th>Exposure</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Red</td>
<td>1 kg-day</td>
<td>40 eV</td>
</tr>
<tr>
<td>Dashed Red</td>
<td>1 kg-yr</td>
<td>10 eV</td>
</tr>
<tr>
<td>Dotted Red</td>
<td>10 kg-yr</td>
<td>0.1 eV</td>
</tr>
<tr>
<td>Dashed-Dotted Red</td>
<td>100 kg-yr</td>
<td>1 meV</td>
</tr>
<tr>
<td>Dashed-Dotted-Dotted Red</td>
<td>100 kg-yr</td>
<td>1 meV + off shell phonon sensitivity</td>
</tr>
</tbody>
</table>

**Diagram:**
- **Neutrino Floor**
- **Dark Matter-nucleon cross-section [$\sigma_{SI}$] [cm$^2$]**
- **Dark Matter mass [MeV/c$^2$]**

Graphs and curves showing sensitivity projections with different exposures and thresholds.
Extending Sensitivity with Off Shell Interactions

• The 0.6 meV evaporation threshold limits nuclear recoil DM search to $m_{\text{DM}} \sim 1 \text{ MeV}$

• Can be avoided if we find an excitation with an effective mass closer to the DM mass, allow DM to deposit more energy in the detector

• In helium this could be recoiling off the bulk fluid and creating off shell quasiparticles
Detecting Vibrations: Vibrations in Helium

- The vibrational ("quasiparticle", "QP") excitations we expect to see are phonons and rotons

- Velocity is slope of dispersion relation

- Rotons ~ "high momentum phonons"

  - Just another part of the same dispersion relation

- R- propagates in opposite direction to momentum vector
Distinguishing Quasiparticles and Excitations

- Use signal timing
  - Singlet signal expected to have $O(10 \text{ ns})$ fall time, delta function in calorimeter
  - Triplets have $O(1 \text{ m/s})$ velocity, observed as a delta function mostly in immersed calorimetry
  - Quasiparticles signal expected to have $O(10-100 \text{ ms})$ fall time, mostly observed on surface calorimeter spread out
Example Waveform

- Based on HERON R&D
- Can distinguish scintillation and evaporation based on timing

Annotations from Vetri Velan
Another Example Waveform

- Distinguish between different phonon distributions by arrival time in detector
  - R+ arrive first
  - P travel at a mix of slower speeds and arrive next
  - R- can’t evaporate directly, need reflection on bottom to convert into R+ or P
FIG. 3. Several fundamental characteristics of superfluid $^4$He quasiparticles are here illustrated. TOP: the dispersion relation. MIDDLE: the group velocity. BOTTOM: transmission probabilities at normal incidence in two cases, incident on a $^4$He-solid interface with solid phonon outgoing state (red dashed) and incident on a $^4$He-vacuum interface with outgoing state a $^4$He atom (blue solid). At both high and low momentum quasiparticles are of finite lifetime, and unlikely to reach an interface before decay.