HeRALD: Direct Detection with Superfluid 4He

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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

Excitation

~meV Vibrations (phonons, rotons)

Singlet UV (16 eV) Photons

Triplet Kinetic Excitations

Detection Method

Adsorption of quantum evaporated He atoms on upper calorimeter + adhesion gain, 10-100 ms timescale

Absorbed in calorimeters on 10 ns timescale

Ballistic, travel at O(1 m/s), deposit energy in immersed calorimeters
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

Blue = quasiparticle
Red = Singlet
Green = Triplet
Grey = IR photon
Activities at Berkeley

• Measuring the light yield for nuclear recoils in 4He (red curve)

• Neutron scattering experiment at room and cryogenic temperatures

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

From V. Velan
Background Simulations

- Uncertainty in neutron flux spectrum low energy
- 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
Activity at UMass

- Uncertainty in how quasiparticles, triplet excitations interact at surfaces
- 24 keV neutron calibration source
- Adhesion gain: keep calorimeter dry and use materials with higher van der waals attraction
  - Adapting the HERON film burner design, demonstrated but **heat load problematic**
Heat Load Free Film Stopping

- Cesium coated surfaces, demonstrated but technically difficult

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

UMass

Dilution Refrigerator Arrives ~1 month

24 keV neutron calibration source

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 $^4$He

- DM
- Vibrations (phonons, rotons)
- Excitations
- Dimer Excimers
- Detected State
  - Vibrations (phonons, rotons)
  - Singlet UV Photons
  - Triplet Kinetic Excitations
    (IR Photons)
- He
- $\text{He}^+$
- Ionization
- He$^+$ and e$^-$
Sensitivity Projections Cont.

<table>
<thead>
<tr>
<th>Curve</th>
<th>Exposure</th>
<th>Threshold</th>
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</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>
Extending Sensitivity with Off Shell Interactions

• The 0.6 meV evaporation threshold limits nuclear recoil DM search to $m_{\text{DM}} > \sim 1$ 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 ns) fall time, delta function in calorimeter

  • Triplets have O(1 m/s) velocity, observed as a delta function mostly in immersed calorimetry

  • Quasiparticles signal expected to have O(10-100 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.