Snowmass2021 - Letter of Interest

Calorimetric readout of a superfluid ^{4}He target mass

Thematic Areas:
(IF1) Quantum Sensors
(IF8) Noble Elements
(CF1) Dark Matter: Particle-like

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Abstract:
This letter describes an upcoming detector technology in which low-temperature ($\sim$10mK) calorimetry is paired with a superfluid ^{4}He target mass. At low energies ($<$20 eV) the energy of a particle recoil is entirely converted into phonon-like quasiparticle excitations of the superfluid medium, which can readily be sensed. This technology would be sensitive to nuclear recoils of galactic dark matter (DM) down to DM masses of order 1 MeV, and sensitive to lower DM masses via direct excitation of quasiparticles (bypassing the nuclear recoil). The calorimetry development is general to many possible targets and uses and is discussed elsewhere; in this letter we describe those aspects of this technology that are specific to the ^{4}He target response.

Introduction: Despite technological progress in recent decades, the particle nature of dark matter (DM) remains unknown. Direct detection searches have largely been confined to DM masses greater than ∼2 GeV (the Lee-Weinberg bound [1]), motivated by an assumption that DM interacts through some extended version of the weak force. However, if new low-mass mediators are hypothesized, then a keV-to-GeV ('light DM') window is newly interesting. Light DM models include freeze-out DM [2, 3, 4, 5, 6, 7, 8, 9], asymmetric DM [10, 11], and freeze-in DM [12]. Direct detection sensitivity in this mass range is aided by the correspondingly high DM number flux, meaning a given cross section can be probed using surprisingly small active target masses and exposure. The dominating experimental challenge is instead the requirement of extremely low energy thresholds at the eV scale and below (while retaining some particle ID ability). Two DOE Basic Research Needs (BRN) reports have recently emphasized this DM window and these thresholds: a dedicated BRN on light DM [13], and a BRN on on HEP Instrumentation [14].

The transfer of kinetic energy from the incident DM to the target nucleus is made inefficient in this regime, where the incident DM is lighter than the target nucleus. This has motivated electron-recoil experimental approaches [15, 16, 17, 18, 19, 20, 18], however NR approaches are still strongly motivated: 1) NR experimental backgrounds are greatly reduced. 2) Many DM models predict suppressed leptonic interactions, making NR experiments a required element of a broad search.

Superfluid ^{4}He: Superfluid ^{4}He has received recent attention as a potential target material for light DM detection [21, 22, 23, 24, 25, 26, 27] due to several key advantages over other candidate target materials. These advantages include:

- A low nuclear mass, enabling comparatively efficient transfer of energy from sub-GeV DM particles.
- Extreme radiopurity, because helium has no long-lived radioisotopes, can be purified using getters, and when condensed induces impurity freeze-out.
- A liquid phase to zero temperature, thereby compatible with mK-scale calorimetry (Transition Edge Sensors [TESs], Metallic Magnetic Calorimeters [MMCs], Kinetic Inductance Detectors [KIDs], etc.).
- Multiple observable and distinguishable signal channels, each detectable via identical calorimetry, and in sum expressing the total recoil energy:
  1. Short-lived singlet atomic excitations, observable as VUV (∼16 eV) photons [28].
  2. Long-lived triplet atomic excitations, observable directly in molecular form [29] or upon 'quenching' at an interface [30] after ballistic propagation from the recoil site.
  3. Phonon and roton ('quasiparticle', or QP) excitations, observable either directly using immersed calorimetry or as ^{4}He atoms ejected at the liquid/vacuum interface ('quantum evaporation') [31].
- A large band gap energy of 19.8 eV (the energy needed to excite the ground state to the first excited state), inhibiting all electronic energy depositions (backgrounds) below this energy.
- Significant isolation of the target mass from environmental vibration and phonons, due to the superfluid material's distinct sound velocity (aka acoustic Kapitza resistance).
- Complete isolation of the target mass from vacuum calorimetry. The vacuum gap between target and sensor allows only strongly athermal QP excitations to be communicated (via quantum evaporation).

These numerous attributes enable superfluid ^{4}He to provide both a low background rate and a robust signal at sub-keV energies, or even sub-eV energies. Some of these attributes have been experimentally demonstrated by the HERON solar neutrino program [32, 28, 33].

Signal Channel 1, Atomic Excitations: The minimum atomic excitation energy, 19.8 eV, divides ^{4}He response into two distinct energy regimes: **>19.8 eV** The atomic:QP ratio provides robust particle ID, distinguishing electron and nuclear recoils with high fidelity [26]. **<19.8 eV** No electron recoil process is possible. This regime can be thought of as 'NR-only' on the interaction side or 'QP-only' on the signal side. While the $<$19.8 eV window serves as the primary motivation for the ^{4}He technology, atomic excitations will provide essential information in understanding backgrounds and rejecting higher-energy recoils. The production yield of singlet and triplet excimers down to their production threshold is a high-priority task.

Signal Channel 2, Quasiparticles: Superfluid ^{4}He QPs are comparable to phonons in a crystal lattice, but are unique in two ways. 1) QPs propagate away from the recoil site entirely ballistically, provided the ^{4}He is sufficiently cold ($\lesssim$ 100 mK) and sufficiently pure isotopically (^{3}He fraction: $\lesssim 10^{-9}$, easily achieved [34]). 2) For a significant momentum window (1.10 $<$ p $<$ 4.54 keV/c), spontaneous 1→n downconversion is forbidden due to conservation of energy and momentum [35, 36]. Taken together, the lack of scattering and the lack of decay enable ^{4}He QPs to preserve more information than phonons in a lattice.

The momentum distribution of QPs escaping a recoil site can be measured, thanks to strongly momentum-dependent QP characteristics including group velocity and quantum evaporation efficiency. The distribution of QP direction leaving the production site is also preserved (and has been demonstrated experimentally to carry recoil orientation information [37]). In superfluid ^{4}He, the the outgoing QPs encode an energy deposition's position, its track orientation, and through its momentum spectrum its nature as either NR, ER, or some instrumental non-particle background.

QP Sensing via Quantum Evaporation and ^{4}He Adsorption: A single QP ($\sim$1 meV) can liberate a single ^{4}He atom at the liquid/vacuum interface through a process called 'quantum evaporation' (threshold: 0.62 meV). This occurs at a significant probability of 10s of percent (per QP arrival at the interface), consistent between both theoretical treatments [38, 39, 40, 41, 42, 43] and experimental observations [44, 31]. An energy deposition in the ^{4}He target is thus expressed as a pulse of evaporated ^{4}He atoms, and this evaporation pulse can be sensed via large-area calorimetry. The energy received by the calorimeter is dominated not by the kinetic energy of the liberated atoms, but by the atoms' adsorption energy onto the calorimeter surface (from the van der Waals attractive potential).

The mass reach of the ^{4}He technology is set by the energy threshold of the evaporation channel, and the key R&D goal of minimizing this threshold can be accomplished by 1) reducing calorimeter threshold, the topic of a separate LOI, 2) boosting QP reflectivity at solid interfaces [45] to increase the fraction of QPs which result in evaporation[1], 3) boosting the adsorption gain per atom at the calorimeter surface by adding a surface treatment of unusually high adsoprtion energy.[2]

If the adsorption gain were increased to 43 meV/atom, then a calorimeter of $\sim$1 eV threshold could sense the evaporation/adsorption of ($\sim$1 eV)/(0.043 eV)$\approx$23 evaporated atoms. And if the evaporation efficiency were increased to $\sim$50%, then a $\sim$23-atom signal would represent $\sim$46 QPs each of $\sim$1 meV energy, a $\sim$46 meV recoil threshold. The adsorption gain has a clear benefit, enabling sensitivity to recoil energies below the calorimeter threshold. A future calorimeter threshold of $\sim$50 meV would enable the detection of single evaporated atoms or single $\sim$1 meV QPs.

Conclusions: Superfluid ^{4}He is a unique material, offering an exceptionally low energy threshold with a large and accessible information content per energy deposit. Near-term R&D goals include 1) measurement of atomic excitation yields to their production threshold, 2) improved sensing methods of triplet excimer quenches on surfaces (perhaps conversion to photons), 3) improved isolation of immersed calorimetry or testing of alternative photon sensors, 4) enhanced QP reflectivity at interfaces, and 5) enhanced adsorption gain. Calorimetric readout of ^{4}He offers a plausible path towards recoil thresholds of the meV scale, and complementarity with electron-recoil and crystal-based detection methods.

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[1] The evaporation efficiency is currently only $\sim$5% [46].

[2] A monolayer of fluoro-graphene, for example, could increase this energy per atom from $\sim$10 meV to 43 meV [47].

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