Measurement of Light and Heat Signal Yields in Superfluid ^{4}He With Calorimetric Readout

Instrumentation Research Proposal

By: Vetri Velan

1. Introduction

The existence of non-luminous *dark matter (DM)* in our universe is one of the most important problems in modern physics. A common technique for understanding the particle nature of dark matter is the method of *direct detection*, in which we look for recoils between standard model particles and dark matter particles with a terrestrial detector. Most current direct detection experiments use liquid heavy noble elements, semiconductors, or scintillating crystals for their target material, and these have set the world-leading limits for dark matter-nucleus interactions. My group has shown (as I will describe below) that superfluid Helium-4 should be complementary to these efforts, offering a new and exciting approach for direct detection through calorimetric readout.

In pursuit of this goal, my proposal for the Graduate Instrumentation Research Award (GIRA) is to measure the light and heat yields of recoils in helium. Our work will begin by measuring the nuclear recoil scintillation light yield in helium down to 2 keV with photomultiplier tubes (PMTs); then, we will proceed by using calorimetry to simultaneously measure heat, light, and excitation signals. This campaign should take on the order of two years.

2. Motivation and Prior Art

Over the past 30 years, dozens of experiments have succeeded in constraining vast regions of dark matter parameter space, i.e. models with a specific dark matter mass and dark matter-nucleon scattering cross-section. Today, the leading limits are set by LUX [1], CDMS-Lite [2], CRESST-II [3], PANDAX-II [4], XENON1T [5], and the ν-nucleus prototype [6], and the most sensitive exclusions are for masses consistent with the Weakly Interacting Massive Particle (WIMP) hypothesis. At these masses, the spin-independent cross-section is excluded as low as 1 zb, an incredible 12 orders of magnitude lower than early limits published by Germanium-based experiments in 1987 and 1991 [7-8]. Still, no experiment has found a convincing dark matter signature. Simultaneously, the field is approaching the so-called *neutrino floor* [9], at which solar and atmospheric neutrinos have the potential to overwhelm any dark matter signal that might exist. It is clear, then, that in addition to Generation-2 experiments like LUX-ZEPLIN and SuperCDMS SNOLAB, the community must develop experiments which probe parameter space that is inaccessible by traditional methods.

My group, which is based at UC Berkeley/LBNL and includes collaborators at UMass Amherst, is leading the effort on one of these proposals, which would test models of dark matter with masses down to 1 MeV/c^2. This approach is motivated by the understanding that thermal production in the early universe can create dark matter at the current relic density if the dark matter mass is greater than a few keV/c^2. However, such an assumption also requires us to eliminate the assumption that we know all the mediators, since a WIMP cannot have a mass less than 2 GeV/c^2 [10].

A schematic of our detector proposal is shown in **Fig. 1**. It contains a cubic kg-scale mass of superfluid ^{4}He, cooled to about 50 mK by a ^{3}He/^{4}He dilution refrigerator. The six walls of the detector are covered by arrays of transition edge sensors (TESs). Five of the walls are in direct contact with the helium, while the sixth (top) is separated from the helium by a vacuum layer.

Our proposal relies on the simultaneous readout of photons and quasiparticles produced by a recoil in the helium. In a helium recoil, energy is partitioned into ionizations, excitations, and quasiparticles. Geminate recombination converts the ion-electron pairs into excited helium atoms at low applied fields. Meanwhile, excited helium atoms combine with nearby helium atoms to form dimer molecules. The singlet-state dimers decay within a few nanoseconds, emitting a 16 eV UV photon, while the triplet-state dimers decay with a half-life of 13 seconds. A small fraction of the excited helium atoms decay to lower-energy excited states, releasing IR photons of about 1 eV. These excitation and scintillation effects are described further in [11-12]. In our proposed detector, the UV radiation, IR radiation, and triplet molecules are all detected by the helium-adjacent TES's.

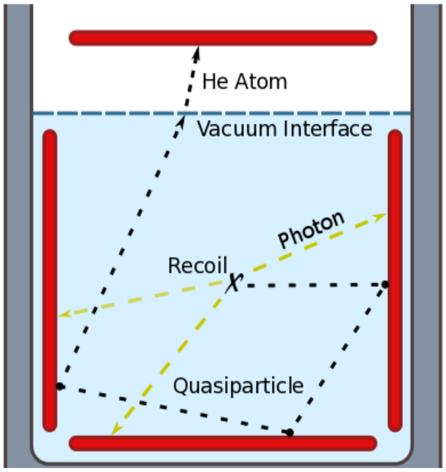

Fig. 1: Cartoon schematic of proposed dark matter detector, showing the signal from recoils in superfluid ^{4}He.

The heat signal is detected by means of quantum evaporation. Quasiparticle excitations, namely phonons and rotons, are long-lived and ballistic in a superfluid, propagating at speeds of about 200 m/s [13]. At a solid interface, transmission of the quasiparticles is suppressed by acoustic mismatch and Kapitza resistance, so they are reflected nearly 100% of the time [14]. After bouncing around the detector stochastically for a few milliseconds, the rotons and phonons might hit the helium-vacuum interface and evaporate a helium atom. Finally, this atom is adsorbed onto the wafer that supports the top TES array, and it deposits its energy; this energy is amplified by a factor of 10-40 due to the binding energy of helium with the wafer material [15-16].

Our group has calculated that this technique could allow us to be sensitive to new sub-GeV parameter space (**Fig. 2**). See caption for details.

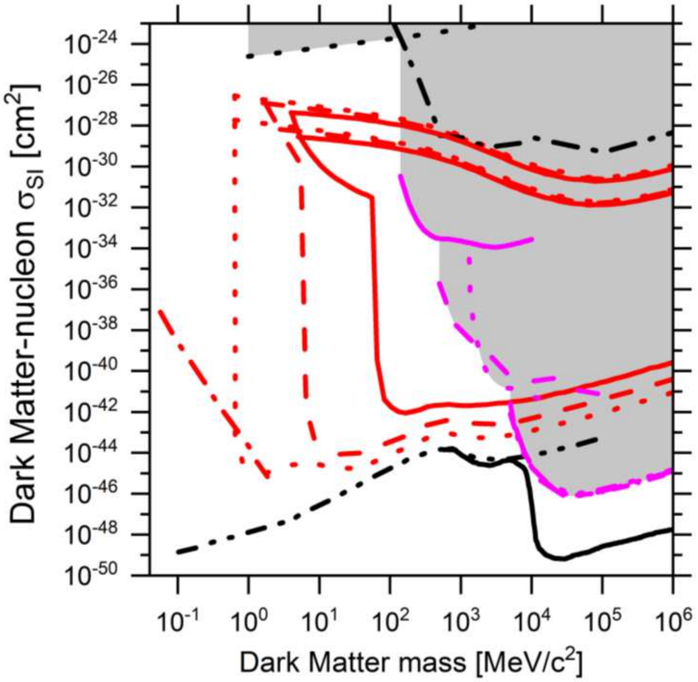

Fig. 2: Projected sensitivity of the superfluid helium DM detector to spin-independent elastic scattering at 90% confidence. Three different combinations of exposure and energy threshold are shown: 1 kg-yr with 10 eV (solid red), 10 kg-yr with 0.1 eV (dashed red), and 100 kg-yr with 1 meV (dotted red). The sensitivities are supplemented at low masses with the inelastic nuclear bremsstrahlung signal [17-18], and they are cut off at high cross-sections by Earth shielding [19], simulated for 100 m and 1478 m depths. The latter sensitivity is extended with the off-shell phonon excitation signal (dashed dotted red) [20]. The neutrino floor is shown for xenon (solid black) [9] and calculated for helium (dashed dotted dotted black). Models that have been excluded by existing results are shaded grey; these results are from Cosmic Microwave Background anisotropy and large-scale structure (dotted black) [21], the XQC experiment (dashed dotted black) [22], and existing nuclear recoil experiments (magenta) [1-6].

Most of the required R&D to build a first-generation experiment with this technology has already been developed. In a 2017 paper, Carter et al. (the authors include two of my collaborators, Professors Dan McKinsey and Scott Hertel) [23] demonstrated simultaneous calorimetric readout of singlet and triplet energy deposits in superfluid ^{4}He using TES's. In addition, the HERON collaboration developed similar technology for a proposed *pp* neutrino detector nearly two decades ago; they observed simultaneous photons and quasiparticles from 364 keV electron-induced recoils [13]. The HERON collaboration also successfully operated a film-burner to remove the ^{4}He film aggregated on the vacuum-adjacent wafer, in order to decrease the heat capacity of the wafer and maximize the signal amplification provided by the He-wafer binding energy [24].

Much additional work remains, however, which underlies the subject of my proposal. The focus of our group for the next 1.5 - 2 years will be to measure the partitioning of energy in helium from electron and nuclear recoils. We will begin by using PMTs to measure the light yield, and transition to TES's for measuring lower-energy light signals as well as quasiparticle signals. Eventually, we hope to use the results to set a new limit on DM-nucleus scattering, and to serve as a prototype for the aforementioned kg-scale detector.

3. Technical Details

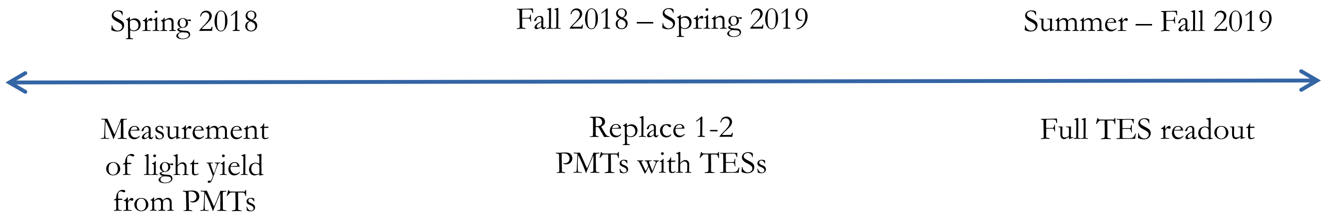

Fig. 3: Estimated timeline of proposal.

Fig. 3 shows an approximate timeline of how the work might proceed.

a) Measurement of light yield

We begin by making a measurement of the nuclear recoil light yield in superfluid helium, as shown by the schematic in **Fig. 4**. A 1-in^3 helium cell (about 2 grams of helium) at 1.5 K is covered by six Hamamatsu R8520 PMTs, which operate in conjunction with tetraphenyl butadiene (a wavelength shifter) coated on the panel surface. We generate 2.8 MeV neutrons using a Thermo Electron MP320, a deuterium-deuterium fusion neutron generator. These neutrons scatter in the helium volume, travel through air for about 50 ns, and deposit energy in a far-side detector, which is described further below. By measuring the recoil angle in coincidence with the light signal in the PMTs, we can measure the light yield (i.e. number of photons produced per unit energy deposit) down to 2 keV.

For the far-side neutron detector, we plan to use two technologies. First, we will use organic scintillator, specifically Saint Gobain BC 501-A, adjacent to a PMT. The narrow time window for neutrons to arrive at the detector allows us to get good energy resolution and identify coincidences between the far-side PMT and the helium cell PMTs. The second approach is to use the Arktis S-670 ("Arktis detector"), a commercial product developed for measurement of fast neutrons. The Arktis detector is a cylinder of ^{4}He gas operating at room temperature and 180 bar pressure; it is filled with 1.01 L of helium. It is optically separated into three sections, each of which contains eight silicon photomultipliers (SiPMs) summed pairwise into four output channels. As a neutron passes through the detector, it causes the helium atoms to scintillate, and the resulting signal can be read out from the SiPMs.

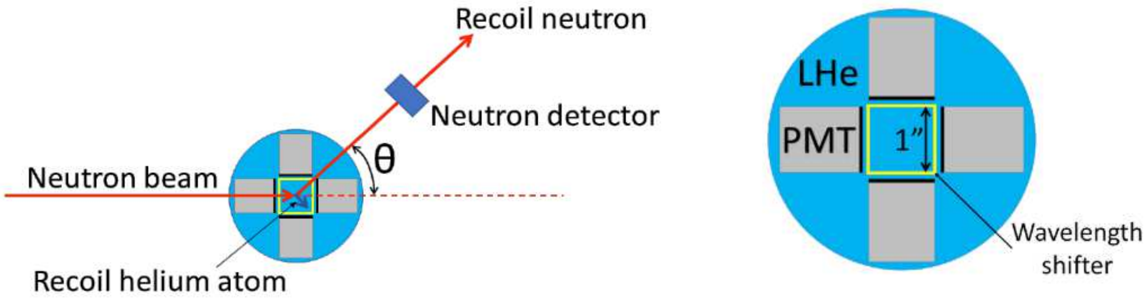

Fig. 4: Schematic of experiment to measure scintillation light yield.

In addition to using the Arktis detector as our neutron detector, we hope to use it to measure the scintillation yield for nuclear recoils in gaseous helium.

This phase of our program should take 6-12 months. Our current progress is in the setup of the experiment; we have purchased all of the relevant equipment, including the PMTs, organic scintillator, neutron generator, and Arktis detector. At the time of writing (February 2018), we are building the cryostat to contain the helium cell, the gas handling system, and testing our data acquisition system. We should begin running the experiment and measuring light yield in the next 2-4 months.

b) Calorimetric Readout Detector

The next phase is to gradually begin replacing PMTs with TESs. A TES is sensitive not only to the UV photons from singlet de-excitations, but also the triplet ballistic molecules and the phonons and rotons via quantum evaporation. In the most basic setup, we will begin by installing 1 cm^2 wafers with just one readout channel each. Replacing 1-2 PMTs at first will allow us to characterize the operation of the TESs in vacuum and in superfluid helium. By replacing the top TES, we will be able to understand the response to quantum evaporation; by replacing one of the other TESs, we can study the signal from UV, IR, and triplet sources.

Eventually, we will modify our helium cell so that it is fully covered by TESs, and so that the top TES is separated from the helium by vacuum. As described above, this allows us to measure all the signals, which can be distinguished based on timing; the UV and IR will arrive promptly, while the triplet molecules and evaporated helium atoms will hit the TESs after a few milliseconds. In particular, my group has modeled the pulse shape that we expect to see from quantum evaporation, and this is shown in **Fig. 5**. It is also important to note that the performance of our experiment will depend on the energy

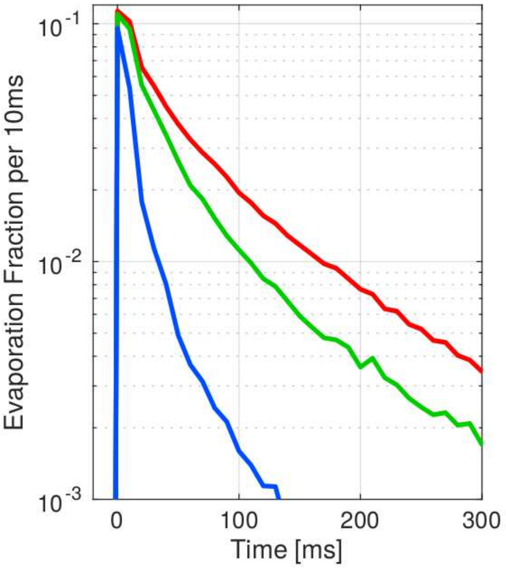

Fig. 5: Simulated pulses from the helium evaporation channel, showing the pulse decay timescales. We vary the quasiparticle loss probability per surface interaction: 0.001 (red), 0.01 (green), and 0.1 (blue).

threshold we are able to achieve; optimistically, we believe we can measure recoil energies down to 10 eV, but even a conservative 100 eV threshold would still be useful for measuring the roton/phonon yield. This corresponds to an energy threshold in the wafer of 100 eV or 1 keV, respectively, as a result of the ~10x amplification from the helium atom binding energy.

In preparation for this goal, which will likely take 1.5 – 2 years to realize, there are two main tasks my group is focusing on in the short term. First, we have acquired a wet dilution refrigerator, the Leiden Cryogenics MNK 126-500, which will be operated at around 50 mK. This allows us to minimize vibrations on the TES and do calorimetric readout. Second, we are building a film burner, based on the HERON design. This will allow us to operate the top TES wafer without worrying about the helium sticking onto the wafer.

c) Dark Matter Limit

As described in **Section 2**, the eventual goal (perhaps 5-10 years away) is to build a kg-scale dark matter detector from superfluid helium. However, this does not preclude us from making physics advancements in the short term. By the final phase of the program described in **Sections 3a-b**, we will have a 2-gram prototype of the detector, and this prototype might be sufficient to set a new limit on dark matter parameter space. Such an objective depends on factors like energy threshold and background rate, so we are currently working to estimate the latter and analyze potential event pileup. An especially useful feature of a result from a surface detector is the absence of shielding from the Earth's crust [19], so any limits would constrain dark matter scattering nearly up to infinity (technically, up to the cross-section where the building becomes a source of shielding).

4. Qualifications and Collaboration

The work I have outlined in this proposal will be done by a collaboration of scientists at UC Berkeley, Lawrence Berkeley National Lab, and UMass Amherst. At UC Berkeley and LBNL, my collaboration includes professor Daniel McKinsey, postdocs Junsong Lin and Scott Kravitz, assistant researcher Raul Hennings-Yeomans, and graduate student Andreas Biekert. At UMass Amherst, we work with professor Scott Hertel and postdoc Alessandro Serafin.

Although the physical experiments will be located at UC Berkeley, we plan to make use of the resources available at the national labs in terms of engineering and detector fabrication. At LBNL, these include machine shops and dedicated staff with expertise in electronics, chip fabrication, and detector development. One particular issue that we anticipate is electronic filtering. Existing detectors at UCB have shown low-frequency noise associated with cell phones and warm electronics, so we will need to improve our RF shielding. Thus, as the project progresses, we will consult with Maurice Garcia-Sciveres (Senior Scientist at LBNL) on how we can use artificially injected noise to determine a filtering and shielding strategy. In addition, we plan to collaborate with other scientists on TES fabrication; Matt Pyle (Professor at UC Berkeley) and Clarence Chang (Staff Scientist at Argonne) have expressed interest.

If awarded the GIRA fellowship, there are several papers that I will likely write. My group and I are currently working on a manuscript in preparation, titled *"A Path to the Direct Detection of sub-GeV Dark Matter Using Calorimetric Readout of a Superfluid* ^{4}*He Target"*. Some other papers that will be written might include:

- *"Measurement of scintillation yield in superfluid* ^{4}*He from neutrons"*
- *"Simultaneous measurement of scintillation, excitation, and heat in superfluid* ^{4}*He"*
- *"Scintillation yield of high-pressure* ^{4}*He gas from a commercial neutron detector"*
- *"Discrimination between electron and nuclear recoils in superfluid* ^{4}*He through light and heat energy partitioning"*

5. References

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