Snowmass2021 LOI: Quantum Sensing of ^{3}He for Low-Mass Dark Matter Detection

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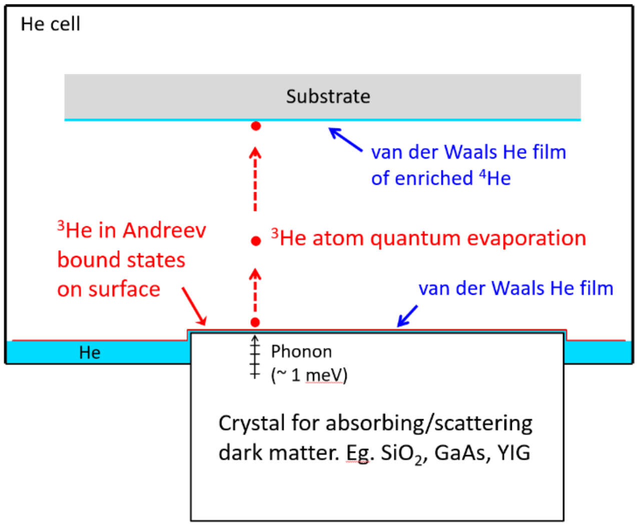
Detecting low-mass dark matter particles is a difficult challenge. The interactions are rare and the energy deposited in the detector is small, requiring high-sensitivity with low background. Here we consider a concept based upon the quantum evaporation of ^{3}He from the surface of liquid helium, and then sensing the ^{3}He atoms by using their nuclear spin to decohere the spin state of an entangled pair of electron spin qubits. This quantum sensing concept promises the possibility of detecting single ^{3}He atoms, and can thus extend sensitivity into the milli-electron volt (meV) range. This approach is also compatible with large magnetic fields for probing potential spin dependent interactions, and it can be scaled to large absorber volumes.

A schematic diagram of this concept is shown in the figure. We assume that the dark matter will interact with a solid, through optical phonons,[1] magnons,[2] spins,[3,4] or other excitations.[5] These excitations can eventually decay to phonons, and low energy phonons are able to travel ballistically in high quality crystals.[6] Rare events in the volume of a large crystal are difficult to detect, but the ballistic phonons can travel to the surfaces for sensing. However, these phonons are now typically ~meV energy, which is again a challenging detection problem, requiring high efficiency and low background. An efficient physical process with that energy scale is the quantum evaporation of He atoms from the surface of liquid helium, and it has been studied in the context of a large mass of helium for detecting neutrinos,[7] and dark matter.[8] However, the efficient detection of helium atoms is again quite challenging at the single-atom level.



At low temperature (below ~100mK) ^{3}He atoms in liquid helium reside at the surface in Andreev bound states.[9] It has been demonstrated that phonons in liquid helium quantum evaporate the surface ^{3}He atoms with the same efficiency as ^{4}He atoms[10] (the threshold energy for evaporation of ^{3}He is about 5K, and about 7K for ^{4}He). After being evaporated, the ^{3}He can be collected on another surface covered with a van der Waals film of isotopically enriched ^{4}He. The advantage of evaporating and collecting ^{3}He is that sensitive quantum sensing though the nuclear spin becomes possible.

On the upper helium film the ^{3}He will rapidly diffuse across the surface,[11] and detecting the atoms will be most efficient if they are localized. It is well known that electrons can be bound to the surface of liquid helium,[12] and if the electric field holding an electron there is strong, it dimples the helium surface.[13] We have calculated that these dimples will bind ^{3}He atoms because the ^{3}He locally lowers the surface tension of the liquid.[9] The calculations indicate that a binding energy of a few Kelvin/atom is possible, which will localize the ^{3}He at mK temperatures. Electrons and their dimples can also be used to "getter" residual ^{3}He on the upper surface, and sequester arriving atoms after they have been detected.

With the ^{3}He atoms localized on the upper ^{4}He van der Waals film, there may be variety of approaches to detecting them. One, which promises single-atom sensitivity, is to use the ^{3}He nuclear spin to decohere electron spin qubits bound to the helium.[14] In a magnetic field an electron can be prepared in the ground state, and then put in a superposition of up and down spin with a microwave pulse. If a ^{3}He atom is trapped in a dimple below that electron, the magnetic dipole-dipole interaction will decohere the electron within a few milliseconds, much shorter than the expected electron spin coherence time.[14] Without a magnetic field, a pair of electron spin qubits can be entangled (in a singlet state, for example) and the ^{3}He atom will decohere the entangled pair (changing the singlet to a triplet). Detecting these electron spin states has not been demonstrated on helium, but there is work along these lines aimed at using these qubits for quantum information processing.

Understanding the physical processes underlying this quantum sensing concept will require fundamental research, and there are at least three research areas which can be identified: (1) quantum evaporation from phonons in a solid supporting a van der Waals helium film, or "phonoatomics";[15] (2) trapping ^{3}He atoms with electron dimples; and (3) measuring quantum states of individual electron spin qubits on a helium surface. Phonoatomics was identified and studied in the 1980s, but there remains much that is not understood. Surface roughness at the atomic scale will likely have an important influence on the phonons in the helium film[16] and the efficiency of the quantum evaporation process. However, the experimental tools to study those properties have largely been developed since the early phonoatomics work was done. To the best of our knowledge, trapping ^{3}He in electron dimples has not been considered previously. Demonstrating the trapping of ^{3}He atoms, and controlling their transport across the surface by moving the electron and its dimple will be important for establishing the feasibility of the concept. Isolating individual[17] and pairs[18] of electrons on a helium surface has been demonstrated, but experiments accessing the spin states of the electrons have not yet been performed. Gate-defined quantum dots for electrons on a helium surface (much like their semiconductor counterparts) appear feasible, though other approaches to sensing an electron's spin are also promising.[19,20]

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