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Development of a Dark Matter Detector that Uses Liquid He and Field Ionization

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Abstract. We describe a new detector capable of directly measuring dark matter particles with masses as low as 1 MeV/c^2. The detector is based on the quantum evaporation of helium atoms from the surface of liquid helium and their detection using field ionization. When a dark matter particle collides with an atom in liquid helium, the deposited energy results in the evaporation of helium atoms from the liquid surface. A dense array of sharp, positively charged metal tips, known as the field ionization detector array, creates a strong electric field that ionizes the helium atoms and accelerates them into a calorimeter, which detects the impact. We studied field ionization from single tips and investigated the dependence of the ionization rate on the applied voltage. We discuss the results of these single tip field ionization experiments, as well as upcoming experiments, which will focus on studying the temperature dependence of field ionization of gaseous helium at low temperatures.

1. Background

Recent theoretical models propose dark matter particles with masses below $\sim$ 10 GeV/c^2 [1, 2]. However, current direct detection experiments cannot detect particles with masses $\lesssim$ 2 GeV/c^2 because the high mass of the target atom, typically xenon, limits the maximum amount of kinetic energy that can be transferred in a collision with a light dark matter particle.

The HERON detector [3], which was designed to detect solar neutrinos with a liquid helium target, offered two distinct advantages over other detection methods. First, the low mass of the target helium atom allows the target to recoil with more kinetic energy in a collision with a light particle. Second, the low binding energy (0.62 meV) of a helium atom to the surface of liquid helium offers a method to detect small energy deposits. A helium atom can be released from the surface by a phonon or roton, which are the fundamental excitations of superfluid helium, by a process called quantum evaporation. The evaporated helium atoms are in turn detected by binding to a silicon wafer and bolometer above the liquid helium. A schematic of HERON is shown in Figure 1a. The increase in depositable kinetic energy and the sensitivity to low energy deposits could enable the detection of low-mass dark matter particles. However, the minimum energy deposit that HERON could detect was limited by the large number of helium atoms that needed to adsorb onto the silicon wafer to cause a detectable rise in temperature. To detect light particles, a more sensitive method of capturing evaporated helium atoms is needed.

1.1. Field Ionization

Three of us recently proposed a method of measuring energy deposits as low as 1 meV through employing field ionization to detect single helium atoms evaporated from the surface of liquid helium [4]. Figure 2 schematically illustrates the field ionization of a helium atom by a charged tip and the corresponding potential energy landscape experienced by the bound electron. A potential difference of a few kilovolts applied between a sharp nanotip and a cathode results in a strong electric field near the tip. This electric field raises the ionization energy of a helium atom to the level of the work function of the tungsten tip, allowing one of the electrons to tunnel to the tip with a probability dependent on the size of the potential barrier and leave behind a helium ion.

1.2. The Proposed Detector

The new detector will employ a field ionization detector array (Figure 1b), a dense array of sharp, positively charged metal tips, to detect single free helium atoms. The array will provide a strong electric field that will capture and ionize helium atoms. The electric field then accelerates the helium ion across a potential difference. A calorimeter with a low heat capacity can detect the impact of even one of these helium ions, each of which has a kinetic energy of a few kiloelectronvolts. The energy deposited in the detector by a dark matter particle is measured by counting the number of captured helium atoms. The single helium atom sensitivity of the proposed detector could enable the detection of weakly interacting massive particles (WIMPS) as light as 1 MeV/c^2.

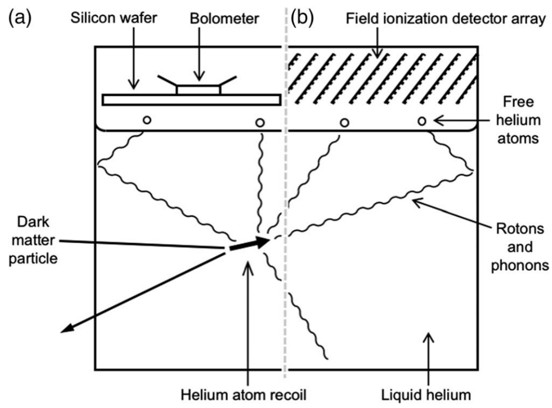


Figure 1. Schematic diagram of (a) The HERON detector and (b) the proposed detector. In both cases the collision between a dark matter particle and a helium nucleus results in phonons and rotons which, upon arriving at the surface, eject helium atoms by quantum evaporation. [4]

2. Preliminary Field Ionization Experiments

We studied field ionization from a single tip by measuring the dependence of ionization rate on voltage in the presence of a background pressure of gas. When the tip is supplied with a background of gas, the ionization rate, which depends on the tunneling probability of the electron, can be measured as a current of captured electrons. Figure 3 presents data taken by O'Donnell [5] of field ionization of helium from a tungsten tip. In the field limited region, the tunnelling probability is strongly dependent on the potential barrier height and width (Figure 2), which are determined by the applied voltage. In the supply limited region, the potential barrier drops below the tungsten work function and the tunnelling probability is unity, thus the observed current is limited only by the amount of gas supplied to the tip.

2.1. Experimental Design

An electrochemical etching technique created nanotips from 0.25 mm-diameter tungsten wire. A tip and cathode were suspended from the roof of a metal can (Figure 4b). The can was attached to the end of two long, stainless steel tubes that carry electrical feedthroughs to the tip and cathode and allow the can to be pumped down to vacuum and for helium gas to be introduced into the can through a leak valve at the top (Figure 4a). The can can be submerged in liquid helium to study field ionization at low temperatures.

The tip chosen for the experiments had a radius of 55 nm. The can was pumped to vacuum and then flushed with helium, and air was allowed to reenter up to 1 atm. Varying voltages were applied between the tip and cathode, field ionizing the mixture of air and helium and resulting in a current that depends on the applied voltage.

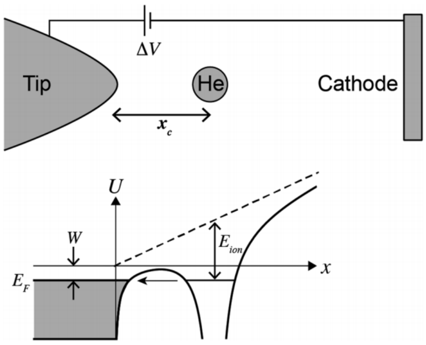


Figure 2. Illustration of a He atom near a positively charged metal tip and the potential energy U seen by the bound electron. [4]

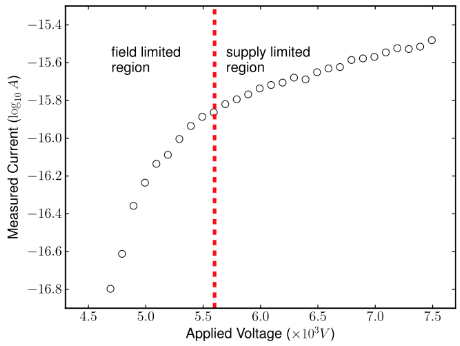


Figure 3. Field ionization data of He from a W tip taken by O'Donnell [5]. The field limited and supply limited regions are highlighted.

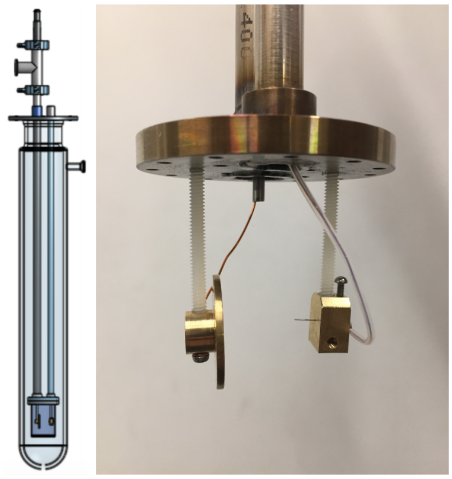
2.2. Results

Figure 5 presents the dependence of the field ionization current on the applied voltage in the presence of air at room temperature. Two distinct humps are visible between 1 and 3 kV.

Different species of gas have different ionization energies and are thus ionized at different applied voltages. This suggests that the humps may be due to the field ionization of different species of gas in air. To explore this possibility, we employed a theoretical model of field ionization by O'Donnell [5] to predict the theoretical I-V curves for Nitrogen and Helium based on the applied voltage, the properties of the gas and the properties of the tip. The helium and nitrogen curves matched with the two humps in the data (Figure 6), indicating that the humps could in fact be due to nitrogen and helium.

3. Upcoming Experiments on Single Tips and Nanotip Arrays

We will replace the cathode with a Channeltron to study field ionization from a single tip at low pressures and temperatures. The Channeltron detects the impact of individual ions and outputs a current pulse for each. This removes the lower limit on measurable currents. Once the behavior of single tip field ionization is well understood, we will create nanotip arrays and measure the capture cross section of free helium atoms down to temperatures of 100 mK. We will also investigate the migration of helium atoms along the surface of a tip, which could help or hinder the detection process, and we will search for sources of dark counts in order to have a better understanding of background in the detection experiment.



(a) (b)

Figure 4. (a) The experimental can susupended in a glass dewar and (b) the brass cathode and tungsten nanotip susupended from the roof of the can by threaded nylon rods.

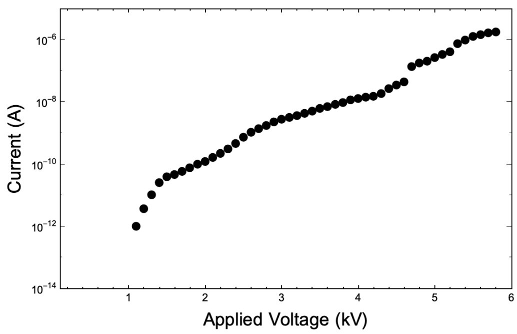


Figure 5. I-V curve for air mixed with helium at room temp. and 1 atm.

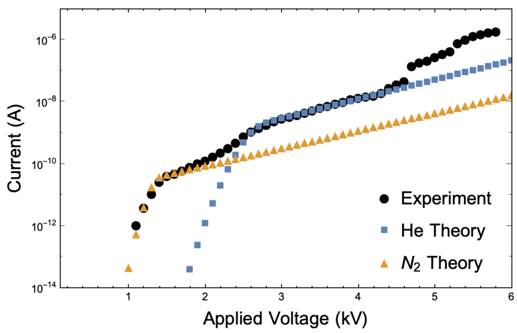


Figure 6. Fit of theoretical nitrogen and helium I-V curves to data.

4. Conclusion

We have described the development of instrumentation offering a path to detect dark matter particles with masses down to 1 MeV/c^2. The unique properties of a liquid helium target and the single atom sensitivity of a field ionization detector make this possible. This detector technology is not limited to the search for dark matter, but can also be used to detect other particles including neutrinos. It could also prove to be a technological advance with broader applications in imaging and spectroscopy.

References

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