Charge Transport in Liquid Helium at Low Temperatures

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Abstract. In an experiment to investigate the possibility of using superfluid helium as a detection medium for low energy solar neutrinos, we have studied the currents produced by a radioactive source in a helium cell having a liquid/vacuum interface at 50 mK. A number of phenomena have been observed that appear not to have been described in the literature. These include the following: 1) The current at very low voltages in a cell having a free surface can be 100 times greater than in a filled cell. This additional current is associated with Penning ionization of metastable triplet dimers in surface states. 2) There is a large amplification of current in modest electric fields with a free surface present in the cell. This is the result of charges accelerated across the vacuum having sufficient energy to produce ionization and additional free charges upon hitting a liquid surface. The amplification becomes sufficiently large that breakdown occurs at potential differences across the vacuum of less than 1000 V. The dependence on ^{3}He concentration of these phenomena has been studied.

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INTRODUCTION

A single electron, extracted from liquid helium and accelerated by a field to an energy of several hundred eV, can be detected calorimetrically at low temperatures on striking a reasonably sized wafer [1]. In a preliminary experiment to study if such a process could be used to detect electrons that are produced by the scattering of low energy p–p neutrinos from the Sun, we have investigated the current resulting from the presence of a radioactive source in a cell partially filled with helium at 50 mK.

EXPERIMENT AND DISCUSSION

A 1 mCi radioactive beta source, ^{63}Ni, the mean energy of the emitted electrons being 17 keV, was placed at the bottom of a 2.5 cm diameter, 0.4 cm high cell. The helium level in the cell was adjustable and its position could be measured with a capacitance gauge. The current was measured upon applying a potential between a source electrode at the bottom of the cell and a collector electrode at the top. The range of a 17 keV electron in liquid helium is less than 100 microns.

It takes 43 eV, on average, for an energetic electron to produce an ionizing event in liquid helium. The ions and electrons, for the most part, rapidly undergo geminate recombination to atoms in either singlet or triplet excited states. The excited state atoms form He_2^* dimers with ground state helium atoms. The singlets radiatively decay to the dissociated ground state with the emission of EUV photons of 16 eV energy in less than 10^{-9}s. The triplet dimers have a long radiative lifetime of about 13 s.

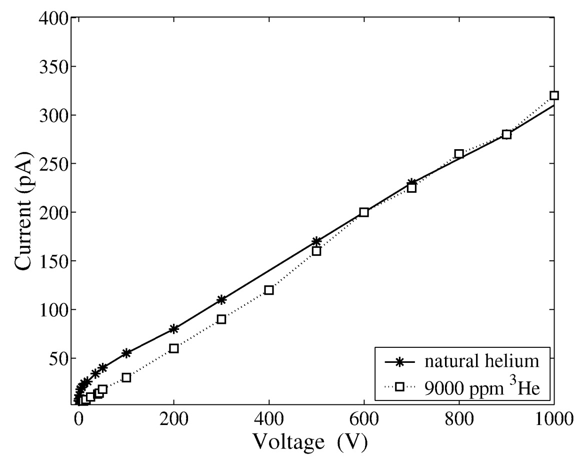

FIGURE 1. Current as a function of potential applied across the cell filled with natural helium and ^{4}He with 0.9% ^{3}He.

The current in the completely filled cell is small. The field dependence is shown in Fig. 1. At very low voltages there is a component, depending on the sign of the voltage, that is due to the primary electrons. As the voltage rises a small but increasing number of the electron/ion pairs are separated by the field and do not recombine. The manner in which the current varies with field depends on the initial spatial distribution of electron/ion pairs and upon the nature of the motion of the electron bubble and ion snowball in the combined Coulomb and applied field. The addition of ^{3}He atoms at 50 mK produces scattering of the moving charges, affects the formation of vortices and decreases the current, as shown in Fig. 1. To obtain a significant change in current, ^{3}He

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concentrations of greater than 0.1% are required. A quantitative analysis and discussion of these results will be presented in a more comprehensive paper.

When the cell is partially filled with natural helium, the current is dramatically different as shown in Fig. 2. At very low fields the current rises to a plateau where it is 100 or more times larger than in the filled cell. Since the primary ionizing electrons are stopped with 100 microns or less of the bottom electrode, the production of electron/ion pairs cannot be influenced by the presence of a free surface, approximately 2 mm higher. The origin of this large excess current is due to the metastable triplet dimers in the $a^3\Sigma_u^+$ state. At low temperatures the triplet dimers travel ballistically and, in the filled cell, upon encountering a solid surface, nonradiatively decay. In the partially-filled cell having the geometry of a thin disc, roughly half of the dimers reach the free surface to which they become bound. Because of their large diameter outer electron orbits, these neutral dimers form bubbles in the liquid and have a lower energy on the surface. When two dimers interact, they are known to undergo a thresholdless Penning ionization process

$$\mathrm{He}_2(a^3\Sigma_u^+) + \mathrm{He}_2(a^3\Sigma_u^+) \rightarrow 3\,\mathrm{He}(1^1S) + \mathrm{He}^+ + e^- \quad (1)$$

or

$$\mathrm{He}_2(a^3\Sigma_u^+) + \mathrm{He}_2(a^3\Sigma_u^+) \rightarrow 2\,\mathrm{He}(1^1S) + \mathrm{He}_2^+ + e^-. \quad (2)$$

This process occurs in the bulk, but the probability of occurrence is small since the concentration of dimers is low. Also, upon ionization in the bulk the separation of the electron and ion is small, and the charges tend to recombine immediately producing no contribution to the current. However, on the free surface the density builds up to the point where one dimer is likely to encounter another. When Penning ionization does occur, one of the two charged particles is likely to enter the vacuum, and depending on the polarity of the applied potential, either is accelerated across the vacuum or is returned to the bulk liquid at a substantial distance from where it originated. In either case the Penning process at the free surface results in a current. The magnitude of this current is consistent with estimates of the number of triplet dimers formed by electrons stopped in liquid helium[2] and will be discussed in detail elsewhere.

This explanation of the large excess current is supported by the observed influence of small amounts of ^{3}He. The introduction of less than 10 ppm of ^{3}He reduces the current in the partly filled cell to approximately that observed in the filled cell. The ^{3}He scatters the triplet dimers sufficiently often that in undergoing a random walk from their origin very close to the bottom electrode, they are much more likely to encounter the bottom surface and be destroyed rather than to reach the free surface.

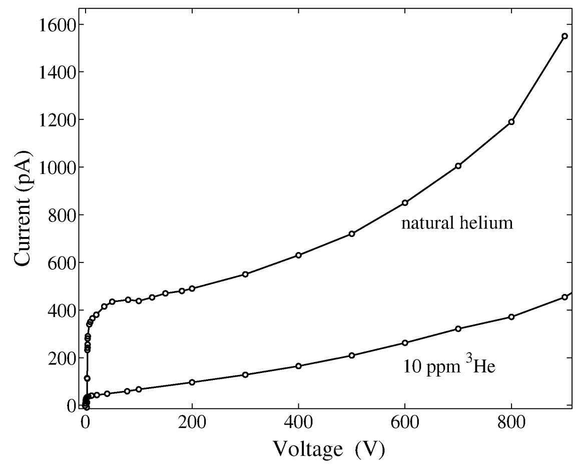

FIGURE 2. Current as a function of potential applied across the cell half full of helium. The sign of the potential is such that electrons travel upwards through the liquid and vacuum to the electrode on the top of the cell.

At higher voltages the total current is not simply the sum of the current from charge separation of secondaries in the bulk plus the current from surface Penning ionization. The current is a nonlinear function of field and, at potentials of less than 1000 V across the vacuum, electrical breakdown occurs. This amplification phenomenon must be the result of charged particles, accelerated across the vacuum gap, producing additional ionization events and dimers upon striking the film on the top electrode or the bulk liquid depending on sign of the charge. The helium atom density in the vacuum at 50 mK is far too small to be of significance. Amplification and breakdown occur for either sign of the potential applied to the cell, but there are differences that do depend on polarity. These details are presumed to be associated with the mechanisms by which electron bubbles and positive ion snowballs escape through the liquid surface. These pheonomena are still being explored with the aid of a ring electrode, which has been added to the cell.

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