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# Detection of a single electron produced inside bulk superfluid helium☆

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**Abstract**

The HERON project is an effort to develop a detector for low-energy solar neutrinos in real time by observing their elastic scattering from electrons using superfluid helium as the target material. By applying appropriate electric fields, the recoil electron can be separated from the positive ion, drifted upward to the liquid–vacuum interface, transmitted through the surface with the aid of a vortex ring, and detected using a calorimeter. By studying the correlation of the 16 eV photon signal produced by scintillation and the single-electron signal, we can locate a neutrino event in a large detector and distinguish it from the background events involving multiple Compton scattering.


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## 1. Introduction

The goal of the HERON project is to measure in real time the low-energy neutrino spectra from the p–p reaction in the Sun [1]. Superfluid liquid helium is used as the target material. In the proposed detector, having a fiducial volume of 70 m$^3$, 20 events per day are to be expected according to the standard solar model. In a neutrino event, a recoil electron is produced by elastic scattering. The recoil electron propagates in the helium and deposits its energy by the ionization of helium atoms and by the generation of elementary excitations in the liquid, phonons and rotons. The helium ions and electrons recombine and immediately form helium dimers in excited states, which radiatively dissociate emitting 16 eV photons. Roughly, 35% of the initial energy of the recoil electron is emitted as photons [2]. In our previous work, we investigated the possibility of locating where in the detector a neutrino event occurs by measuring both the photon and roton signals using a calorimeter array above the bulk helium surface, arranged in the pattern of coded aperture [3]. The location of an event in the detector is essential in order to separate neutrino events from signals arising from the dominant multiple Compton scatters which constitute the principal background.

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An alternative event selection method involves the use of the photon signal in conjunction with extracted recoil electrons. A recoil electron travels a very short distance in helium before it loses all its kinetic energy to the liquid. By drifting an electron upward and pulling it out of the liquid with an electric field, an electron can be detected with the calorimeter array above the liquid. The horizontal position of an event can be determined from the location of the pixel detecting the drifted electron, while the vertical position is deduced from relative arrival times of the photon and electron signals.

## 2. Movement of free electron in superfluid helium

Several conditions must be satisfied in order to drift a recoil electron upward and pull it out of the liquid helium. First, the electron must be separated sufficiently from the positive ion so that recombination does not occur. Second, the electron must drift through the liquid fast enough that a correlation between the photon and electron signals is possible. Third, the electron must be sufficiently energetic to penetrate the barrier at the surface of the bulk liquid and enter the vacuum. We discuss these issues below.

### 2.1. Drifting electrons in helium

A recoil electron loses its kinetic energy in the liquid by ionization and scattering from atoms. When its kinetic energy is less than 1 eV, it forms a bubble with a radius of 18 $\mathring{A}$. The bubble displaces roughly 500 helium atoms whereas its hydrodynamic mass is 243 $m_{He}$ [4]. Buoyancy alone gives the electron bubble an acceleration of $2g$ (the gravitational mass being twice the hydrodynamic mass), which is equivalent to that produced by an electric field of $1\times10^{-4}$ V/m. At a working temperature of 40 mK, an electron bubble is scattered by the phonons and rotons inside helium. Since the mobility of an electron bubble at this temperature is $1.73\times10^{3}$ m$^2$/V s [5], the drift velocity of the bubble due to the buoyancy force is 0.17 m/s. To be able to associate unambiguously an electron signal with a photon signal in a 5 m deep detector, it is desirable to sweep electron bubbles to the surface with a velocity greater than 10 m/s. However, when the velocity of a bubble exceeds 40 m/s, it creates and remains attached to a vortex ring. The velocity of the bubble/ring pair then decreases as the energy increases [6]. The energy that an electron gains in moving in an electric field results in the expansion of the diameter of the ring. The velocity of the ring is proportional to (apart from logarithmic corrections) the inverse of its diameter or energy. The maximum electric field that can be applied to a bubble in pure liquid $^4$He at 40 mK and not create a vortex ring is 0.02 V/m.

### 2.2. Separation of an electron/ion pair

To separate an electron and the positive ion from which it originated, the applied field must be larger than the Coulomb field of one charge on the other. The distance an electron travels from the positive ion can be estimated using the ESTAR program [7]. For a 1 keV electron the distance is 300 nm while for 30 keV, it is 120 μm. The external field needed to separate an electron and positive ion depends on the angle between the field and the line formed by the electron/ion pair. The field $E$ needed to drag the pair apart is $E = e[1+\tan(\theta/2)^2]/r^2$. In a field of 300 V/m, 17% of electrons with recoil energy of 5 keV will recombine, whereas for 30 keV only 1 in 3000 will recombine. The number of secondary ionizations that do not recombine is small and can be accounted for by a statistical analysis.

It is possible to avoid the generation of vortex rings and have a field sufficient to separate the charges by adding $^3$He to the liquid. Bubbles are scattered by $^3$He atoms. Below 100 mK the mobility of a bubble is found to be, roughly, inversely proportional both to the $^3$He concentration and to $T^{1/2}$ [8]. At an operating temperature of 40 mK, a $^3$He concentration of 30 ppm is sufficient to limit the drift velocity to 20 m/s in an applied field of 300 V/m.

### 2.3. Tunneling of electron through the surface

On approaching the surface from the liquid side, an electron inside the bubble sees its repulsive image potential, and without the assistance of an electric field does not tunnel through the interface at low temperatures. The combination of an applied field normal to the surface and the field from the image charge produces a potential minimum below the surface. The probability of tunneling an electron out of its bubble, through the liquid and into the vacuum appears not to have been measured at low temperatures. The theoretically calculated tunneling rate is only $2 \times 10^{-3}$/s when the electron is 40 $\mathring{A}$ from the surface [9]. The field required to produce a potential minimum at this position is $6 \times 10^5$ V/m.

Surko and Reif [10] found that at temperatures below 1 K, working with electric fields up to $10^4$ V/m, negative charges in the liquid can emerge into the vapor above its surface. They concluded that this occurs when a bubble is attached to a vortex ring. Also, the electron emerges with little or no time delay ($<10^{-3}$s) and negligible energy ($<0.3$ eV), independent of the energy of the vortex ring arriving at the liquid surface. Thus, while in the bulk of the liquid the field should be such that no vortex ring is formed to slow the velocity of the bubble, near the free surface the opposite is required; namely, the bubble should be attached to a vortex ring to carry it through the surface. A field of $10^4$ V/m applied over the few mm of the liquid just below the surface is sufficient to extract the electron with negligible loss of timing information. Also, the drag force on the vortex ring from the $^3$He is small and of little consequence [6].

Fig. 1 contains a schematic illustration of the cell used to study the drift and detection of a single election at 40 mK. An electron, produced by a radioactive source, is drifted in the liquid through region A with the aid of a small field produced by the rings. On passing through the lower grid the bubble enters the field region B of $10^4$ V/m where it forms a vortex and is dragged through the surface. The upper grid electrode is located the order of 1 cm above the liquid surface so that an electron upon entering the vacuum is given an energy sufficient to be easily detected by the calorimeters, whose threshold is sufficiently low to be able to detect a single 16 eV photon.

In our experiment, the photons produced by the energetic electron inside helium are also detected by the same calorimeter for detecting the electron. By measuring the time delay of the electron signal the vertical position where the electron originates can be determined. With a small test array of calorimeters the horizontal position will also be fixed. The size of the photon signal is proportional to the original energy of the electron.

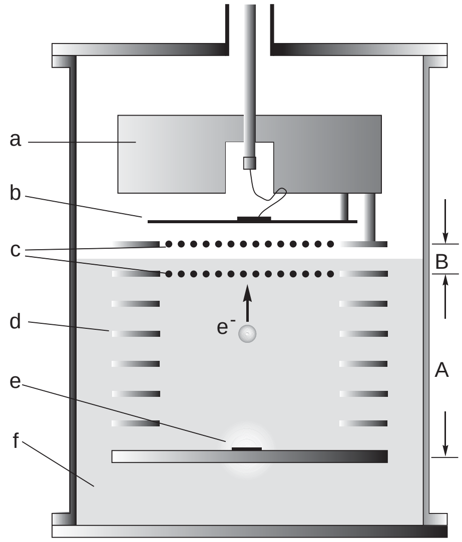


Fig. 1. Experimental setup: (a) helium free stage; (b) calorimeter; (c) grid electrodes; (d) drifting field electrode rings; (e) electron source; (f) superfluid helium.

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