

Scintillation and Quantum Evaporation Generated by Single Monoenergetic Electrons Stopped in Superfluid Helium

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An electron stopped in superfluid helium generates phonons and rotons in the liquid as well as uv photons via scintillation. We report recent measurements with single 364 keV electrons. A sapphire wafer with a superconducting transition-edge sensor is mounted above the liquid and can measure energy and timing information of individual events. We observe both uv photons and the quantum evaporation of helium atoms resulting from phonons and rotons generated by the ionizing particle in the liquid. The production of photons and rotons is strikingly different for an electron and for an alpha particle. The origin of the differences is associated with the different density of excitations along the tracks of an alpha particle and an electron.

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1. INTRODUCTION

For several years we have been studying the energy deposition in liquid helium at low temperatures by energetic charged particles. This work is motivated by interest in developing a detector for neutrinos emanating from the p-p reaction in the sun¹. In a detector of solar neutrinos, the recoil energy of electrons, produced as a result of the scattering of neutrinos in liquid helium, would be measured and provide a means to determine the number and spectral distribution of electron neutrinos reaching the Earth. In this paper we report on measurements obtained using electrons emitted from a radioactive source to probe the interactions in helium.

In previous work² we have discussed the nature of the energy generated by alpha particles in liquid helium. Both the uv radiation at approximately 16 eV, resulting from scintillation, and the energy associated with rotons

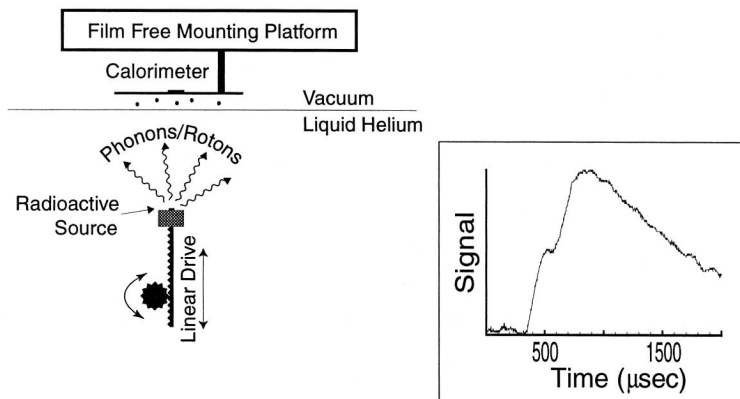


Fig. 1. Cartoon of apparatus showing wafer/calorimeter in vacuum above the liquid and movable source of electrons in the liquid. Inset: – the trace of a signal from a single 364 keV electron as recorded by the transition edge sensor on the wafer.

have been measured. We find the distribution of energy between electromagnetic radiation and collective excitations of the liquid is very different for an electron and for an alpha particle. A microscopic description of the energy deposition along the track of the particles provides a qualitative explanation of these differences.

2. EXPERIMENT

The energy generated by a charged particle in liquid helium is detected calorimetrically using a thin, large-area, sapphire wafer placed in vacuum a few mm above the liquid bath in a 15 cm diameter cell at 40 mK, see Fig. 1. The wafer, 5 cm in diameter, is mounted such that it can be maintained free of superfluid film³. A thin bilayer of iridium and gold⁴ is deposited on the wafer to serve as a superconducting transition-edge sensor. A SQUID is used to monitor the sensor, which is operated in the electrothermal-feedback mode⁵ to maintain it at its transition temperature of 50 mK. The energy threshold of the calorimeter with a 10^4 Hz bandwidth is 500 eV.

The liquid helium, on being introduced into the cell, is passed through a heat-flush purifier⁶ to reduce the ^3He concentration to a level that scattering of rotons is unimportant over path lengths comparable to the dimensions of the cell.

Monoenergetic 364 keV electrons are produced by a radioactive ^{113}Sn

source. One-third of the time the isomeric transition of the ^{113}Sn nucleus occurs by internal conversion, emitting an electron of well defined energy from the K shell. The source, with an activity of about 10 Bq, is placed in the liquid and with a stepper motor can be moved vertically from 1 cm to 5 cm below the liquid surface.

A typical signal pulse from a single electron, as measured by the calorimeter, is shown in the insert in Fig. 1. The initial signal rise is associated with the absorption of uv photons that results from scintillation by He_2 dimers⁷ in undergoing transitions from the first excited state, $\text{He}_2(A^1\Sigma_u^+)$, to the ground state, $\text{He}_2(X^1\Sigma_g^+)$. The subsequent structure in the signal, appearing 200 μs later, is due to the adsorption of helium atoms on the wafer.

These atoms are produced by quantum evaporation when rotons and phonons with energy greater than 7.16 K strike the free surface of the liquid. The time delay in the arrival of the phonon-generated signal is principally the transit time for the phonons, traveling ballistically, to reach the surface from their point of origin on the electron track. The time for return of the wafer to its equilibrium temperature is determined by the thermal coupling to its reservoir. The energy sensitivity of the wafer is calibrated by the direct absorption of x-rays from the Sn source (K_α of 25.2 keV) and from an auxiliary Fe source (K_α of 5.9 keV). A pulse height distribution showing the total signal from the 364 keV electrons stopped in helium as well as the calibration signals at 6 and 25 keV is presented in Fig. 2.

The dependence of the uv signal upon the vertical position of the electron source is shown in Fig. 3(a). The position dependence of the phonon/roton generated signal is shown in Fig. 3(b). Pulse-shape analysis is used to distinguish the signals from the electrons and from the 25 keV K_α line at depths where their energies overlap.

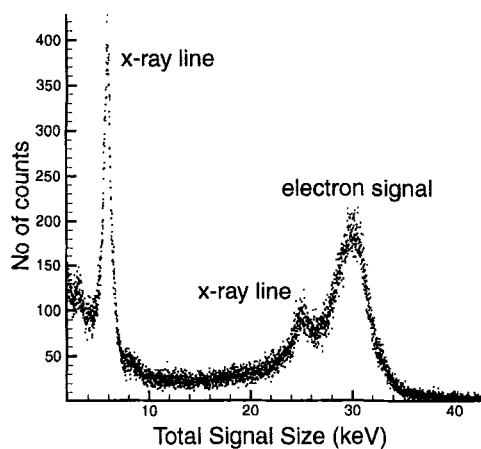


Fig. 2. Pulse-height distribution showing the signal from electrons and from calibration x-rays at 5.9 keV and 25 keV.

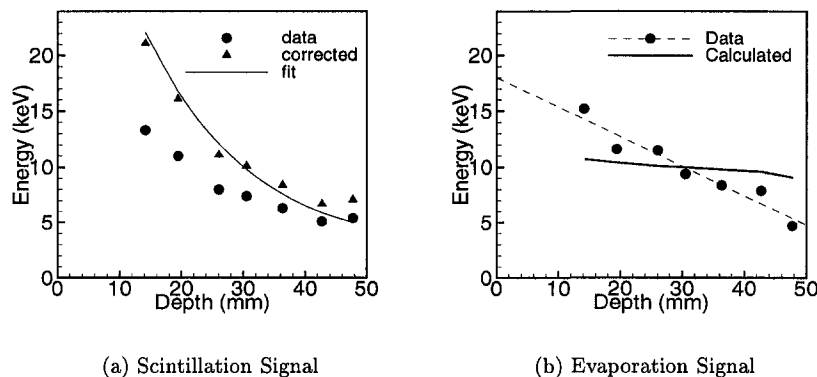


Fig. 3. 3(a): Measured uv energy received by wafer as a function of depth of the electron source. The uv energy incident on wafer is corrected for reflection of sapphire at 16 eV. The fit is to dependence on depth of solid angle subtended by wafer. 3(b): Measured adsorption energy received by wafer as a function of depth of the electron source. The calculated depth dependence of signal assumes the excitations in the liquid are produced with a uniform density in phase space and have evaporation probabilities as calculated in Ref. [9].

3. DISCUSSION

To obtain the energy emitted as uv radiation we correct the measured data for the reflectivity of sapphire⁸ at 16 eV. A reflectivity averaged for angle of incidence is calculated for each particular geometry of source and wafer. A least squares fit of the data to the solid angle subtended by the wafer is shown in Fig. 3(a). From the fit, the energy emitted into a solid angle of 4π steradians is 87 keV, or 24% of the total energy of the 364 keV electron. In contrast, for an alpha particle stopped in helium we found², upon correcting for reflectivity, that only 10% of the initial energy of the particle is emitted as uv radiation.

The energy deposited into the wafer resulting by the adsorption of atoms is dependent upon a number of properties that are not well known. These include 1) the adsorption energy and sticking probability, 2) the dependence of the probability of quantum evaporation by an excitation in the liquid with a particular momentum and angle of incidence on the surface, and 3) the distribution in momentum space of the excitations produced along the track of the energetic electron. Information about some of these properties can

be obtained from the dependence of the measured energy on depth of the source, shown in Fig. 3(b).

If an excitation in the liquid is to evaporate a helium atom in a two-body process in which no third excitation (e.g. a ripplon) is involved, it must be incident upon the surface at an angle less than a critical angle, θ_c . The existence of a critical angle is the result of the conservation of energy and the conservation of momentum parallel to the surface. The dependence of θ_c on quasiparticle momentum is shown in Fig. 4. The probability as a function of momentum that an excitation with angle of incidence less than θ_c will evaporate an atom has been calculated by Dalfovo et al.⁹ The data on the depth dependence does not fit a model in which the excitations are assumed to be produced with a uniform density in phase space up to an arbitrary cutoff of 2.5 \AA^{-1} (the number of excitations with wavevector q is taken to be proportional to q^2 for $q < 2.5 \text{ \AA}^{-1}$), and have evaporation probabilities given by Dalfovo et al. A predicted depth dependence of this model for our geometry is shown in Fig. 3(b) where one adjustable parameter has been used for normalization. In contrast with the measurements, the calculations show little dependence on depth. In this model the predominant contribution to the evaporations signal is due to excitations above the roton minimum. For these excitations the critical angle is always less than 30° . However, the angle subtended by the wafer with the source at its greatest depth is 28° . Thus in the model, the wafer collects most of the atoms evaporated independent of depth, and little increase occurs as the source is moved closer to the surface.

Extending the range in phase space over which excitations are produced from 2.5 to 3.6 \AA^{-1} does not improve the agreement of the model with experiment, even allowing for decay of the unstable quasiparticles above 2.5 \AA^{-1} .

The experimentally measured depth dependence of the signal indicates that a substantial fraction of the helium atoms must be evaporated by excitations with large angles of incidence to the surface. For two-body evaporation processes, excitations with this property are limited to the phonon branch with energies between 7.2 K and the maxon energy. Therefore, either phonons are preferentially produced by the passage of an energetic electron through liquid helium or a large fraction of events leading to the evaporation of a helium atom involve the creation of a third excitation (ripplon), thereby loosening the restriction on critical angle. Given the extensive evidence by Wyatt and coworkers¹⁰ that quantum evaporation at low temperatures is a two-body process, it appears that phonons are created preferentially.

The distribution of excitations in the liquid produced by an electron is strikingly different from that produced by an alpha particle. The number of excitations that propagate away from the track of an alpha particle exhibits

a spatial anisotropy with respect to track direction². For electrons this is not the case¹¹. The excitations from an alpha particle also exhibit² a critical angle for evaporation of approximately 17° indicating they are mainly rotons near the minimum in the dispersion curve. On the other hand, the excitations from an electron appear to be primarily phonons.

The number of helium atoms evaporated by the two types of particles is also quite different. Assuming equal evaporation probabilities for excitations produced by an alpha particle and by an electron, we can compare the fraction of the initial kinetic energy of the particles that appears as quasiparticles in the liquid. This fraction for an electron is only about 20% of that for an alpha particle.

The differences in the energy produced by an electron and an alpha particle in liquid helium are due to the different rates of energy loss for the two particles. In our experiments, an alpha particle deposits energy in the liquid at a rate of approximately 3×10^4 keV/mm whereas for an electron the average deposition along the track is about 30 keV/mm.

Both types of particles lose energy principally by ionizing He atoms and by promoting them to excited electronic states. These processes account for the transfer of more than 80% of the initial energy of an electron to the helium¹². Presumably the percentage is similar for an alpha particle. The range of the secondary electrons, which are responsible for a significant portion of the energy deposition, is typically 200 Å. The ions and electrons recombine in a time on the order of 3×10^{-10} s to form atoms in excited states¹². Most atoms in excited electronic states quickly form He_2^* dimers. Dimers in spin singlet states can cascade to the lowest excited state, $\text{He}_2(A^1\Sigma_u^+)$, and radiatively decay to the unbound ground state in less than 10^{-8} s¹³. Dimers in the lowest spin triplet state, $\text{He}_2(a^3\Sigma_u^+)$, are extremely long lived against radiative decay; in solid helium their lifetime has been measured¹⁴ to be ~ 15 s. However, a dimer can nonradiatively dissociate and decay to the ground state by interacting with another dimer in a process of Penning ionization. Two alternate routes for this process are possible. $\text{He}_2^* + \text{He}_2^* \rightarrow 3\text{He} + \text{He}^+ + e^-$ or $\text{He}_2^* + \text{He}_2^* \rightarrow 2\text{He} + \text{He}_2^+ + e^-$. In either case, upon the recombination of

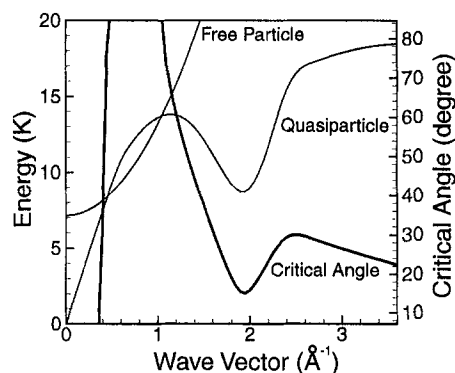


Fig. 4. The critical angle for evaporation as a function of wave vector shown in relation to the dispersion curve for quasiparticles in the liquid and free helium atoms.

ion and electron, there is a net reduction in the number of dimers by one.

The rate of change in the density of dimers, n , by this bimolecular process is $dn/dt = -\alpha n^2$, where α is found to be^{15,16} $\alpha \approx 2 \times 10^{-10} \text{ cm}^3\text{s}^{-1}$. The density of excited atoms and dimers within a distance of 200 Å from an alpha track is $\sim 5 \times 10^{17} \text{ cm}^{-3}$ while along the track of an electron the density is $\sim 5 \times 10^{14} \text{ cm}^{-3}$. At a uniform density of $\sim 5 \times 10^{14} \text{ cm}^{-3}$, the lifetime of a triplet dimer is $\tau = 1/\alpha n = 10^{-5} \text{ s}$. However, at this density the mean free path of the dimers is large compared to the dimensions of the spatial region of high density near the track. Consequently the dimers are unlikely to interact. The energy which they carry will remain in the liquid for times long compared to the pulse duration and therefore will not contribute to the signal. At a density along an alpha particle track of $\sim 5 \times 10^{17} \text{ cm}^{-3}$ the initial lifetime of a dimer is 10^{-8} s . While some of the triplet dimers will travel out of the region of high density near the track, most will interact and nonradiatively decay. Many of the singlet dimers will also nonradiatively decay, and therefore the uv light output from alpha particles is lower than from electrons.

Collective excitations of the liquid are produced by 1) the scattering of secondary electrons with energies principally below the electronic excitation threshold of 20 eV, 2) the dissociation of dimers in the ground state, $\text{He}_2(X^1\Sigma_g^+)$, 3) the transfer of rotational and vibrational energies of dimers to the liquid, and 4) the kinetic energy of the products of the Penning ionization process. As discussed previously², the excitations along the track of an alpha particle are sufficiently dense to form a cloud in which the interacting excitations thermalize via multiple scatterings. When the cloud expands to the extent that the mean free path of the excitations is comparable to its radius, the excitations travel ballistically away from the cloud, with a larger number propagating in a direction perpendicular to that of the track. For an electron track the density of excitations is more than 10^3 times smaller. A phonon or roton produced along the track will propagate with low probability of scattering from another excitation. For an electron stopped in helium the momentum distribution of the liquid excitations reaching the surface is that which was created originally. The distribution is not modified by interactions among the excitations. Hence the evaporation signals from alpha particles and electrons are different.

A more quantitative discussion of the the interaction of energetic charged particles in liquid helium will be presented elsewhere¹¹.

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