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Section A

Scintillation and anisotropic roton generation by charged particles in superfluid helium

S.R. Bandler*[,1], J.S. Adams, S.M. Brouër[2], C. Enss[1], R.E. Lanou, H.J. Maris, T. More, F.S. Porter[3], G.M. Seidel

Department of Physics, Brown University, Providence, RI 02912, USA

Abstract

The physical processes of a superfluid helium-based particle detector are outlined. In particular, we discuss the fluorescent production of UV photons and the generation of an anisotropic roton flux by α particles. These two observed phenomena have potential use in the development of a full-scale helium particle detector.

Because of the deficiency in the measured number of neutrinos from the sun compared to the number predicted by the standard solar model, a measurement of the spectrum of solar neutrinos remains an important and challenging experimental problem. Ideally a detector should be able to measure solar neutrinos in real time, with good energy resolution, with good discrimination from background and with a threshold sufficiently low to observe the most abundant component of the spectrum, namely, neutrinos resulting from the p–p reaction forming a continuous distribution below 420 keV. A detection scheme using superfluid helium as a target material has been proposed [1] which has the potential to satisfy the criteria for a useful detector. A neutrino would be detected when it is elastically scattered off an atomic electron in superfluid helium. The recoil energy given to the electron results in the evaporation of a cloud of helium atoms which are calorimetrically detected when they are adsorbed onto thin wafer/calorimeters suspended above the liquid. In addition, the helium fluoresces, and the photons can also be observed calorimetrically.

We have constructed a small-scale prototype of this detector [2] in order to investigate the physical processes that take place between the scattering event and the measurement of energy in the calorimeters. In the experiments reported here we use monoenergetic alpha particles stopped in helium to study the sequence of physical processes following a nuclear event that lead to its calorimetric detection. These processes can be separated into the following steps:

1) A charged particle moving in the liquid with an energy above a hundred eV loses its energy principally by ionizing helium atoms with the generation of secondary electrons.

2) If a secondary electron has sufficient kinetic energy, it can lose energy through excitation or ionization (24.6 eV) of other atoms. Once the energy falls below 20 eV it no longer has sufficient energy to excite an atom, and an electron can only lose energy through elastic scattering with entire atoms. The rate of energy loss for the electrons and their range in liquid helium has been calculated by Tenner [3].

3) Recombination of ions and electrons occurs. Excited helium atoms are known to form He_2^* dimers in the liquid. Transitions from high lying excited states produce radiation in the infrared and visible [4,5]. The radiative dissociation of the dimers undergoing a transition from the first excited state is the principal source of electromagnetic radiation. These transitions produce a band of radiation in the ultraviolet from 13 to 19 eV peaking at about 16 eV [6,7]. Since helium is transparent below 20 eV, the energy of the 2^3S state, this radiation is not readsorbed.

4) The recoil energy of the helium atoms imparted by the scattering electrons is transformed into elementary excitations in the liquid, i.e., phonons and rotons. The spectrum of excitations in superfluid helium extending to about 1.5 meV (≈ 17 K) is well known. Electrons with energies above ~1 eV can transfer to an atom sufficient energy to produce rotons whose minimum energy is 0.75 meV (8.6 K). Because of the large phase space associated with rotons as compared to phonons, a large

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* Corresponding author. Tel. +1 6221 549295, fax +1 6221 549262, e-mail ih7@urz.uni-heidelberg.de.

[1] Present address: Universität Heidelberg, Germany.

[2] Present address: Universität Karlsruhe, Germany.

[3] Present address: Naval Research Laboratory, Washington, DC, USA.

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fraction of the initial energy of the alpha particle (or neutrino) ultimately appears as rotons.

5) Rotons are stable quasiparticles in that they cannot decay. Below ~0.1 K the density of thermal excitations is low, and phonons and rotons can propagate long distances in the liquid without scattering. If the concentration of isotope ^{3}He, the only impurity which can exist in ^{4}He at low temperatures, is reduced to sufficiently low levels [8], ballistic propagation can extend for meters [2].

6) Elementary excitations within the liquid having energies greater than the binding energy of a helium atom to the fluid of 1.2 meV (7.2 K) can lead to quantum evaporation [9]. Because of kinematic constraints (the conservation of energy and of momentum parallel to the surface) only rotons incident on a surface within a specified cone can evaporate atoms. Those processes that are kinematically allowed have a probability of evaporation of less than unity so that the overall efficiency of transforming the energy of excitations in the liquid into the energy of gas atoms is low [2], of the order of 1%.

7) Thin, low heat capacity wafers with attached thermistors are placed above the liquid surface. Helium atoms adsorb on a bare silicon or sapphire surface of the wafer with a binding energy per atom of ~8 meV (100 K) and a sticking probability of ~0.7. The large binding energy of a helium on a bare solid surface as compared to the condensation energy of an atom in the liquid results in an amplification of ~10. A shower of atoms can be detected calorimetrically. The UV photons produced by fluorescence are absorbed by the wafer and result in a thermal signal as well.

A schematic diagram of the experimental arrangement to investigate the energy deposition into a wafer/calorimeter is shown in Fig. 1. A 1 cm × 2 cm sapphire wafer with an attached iridium–gold transition-edge thermometer is suspended above the surface of liquid helium. A collimated alpha source (3.3 MeV into the liquid) can be rotated about a horizontal axis 4.5 cm below the liquid surface [10]. The response of the calorimeter when an α particle is stopped in the liquid is shown in Fig. 2 for two different track directions of the particle. The traces are averages of about 100 events so as to be able to show clearly the initial rise on the leading edge of the pulse. The response time of the calorimeter to an energy input is ~50 μs while the relaxation time to the thermal reservoir is ~500 μs.

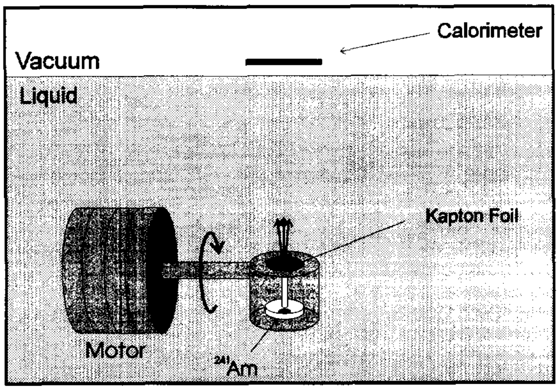

Fig. 1. Schematic diagram of apparatus. The collimated α source is mounted on a stepper motor.

The structure in the response of the calorimeter is the result of the two separate heat inputs that arrive at different times. The UV light reaches the wafer first, while the heat from adsorbing helium atoms is delayed because of the low velocity of the rotons. The average delay in arrival of the atoms is ≈300 μs and is consistent with a roton velocity of 1.5×10^4 cm s^{-1}. The initial energy of 2.5 keV arising from the absorption of the UV photons by the sapphire corresponds to approximately 10% of the initial alpha energy of 3.3 MeV being emitted in the full 4π steradians. This is consistent with the measurement of 8% as the fraction of the energy emitted in the UV when a beam of 150 keV electrons is stopped in liquid helium [7].

While the distribution of UV photons does not depend upon direction of the track of the α particle, the signal from the evaporated helium atoms varies with the orientation of the track relative to the surface, as can be seen by the differences recorded in Figs. 2a and 2b. The measured angular dependence of the evaporation signal is shown in Fig. 3. The evaporation signal for an α with track parallel

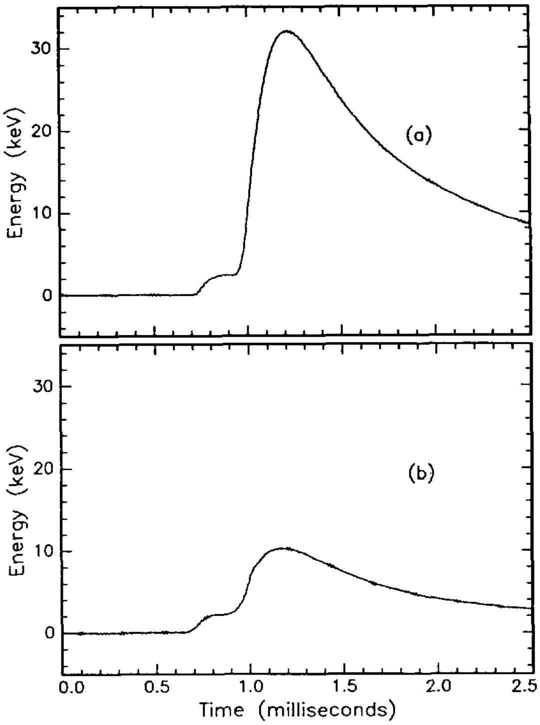

Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

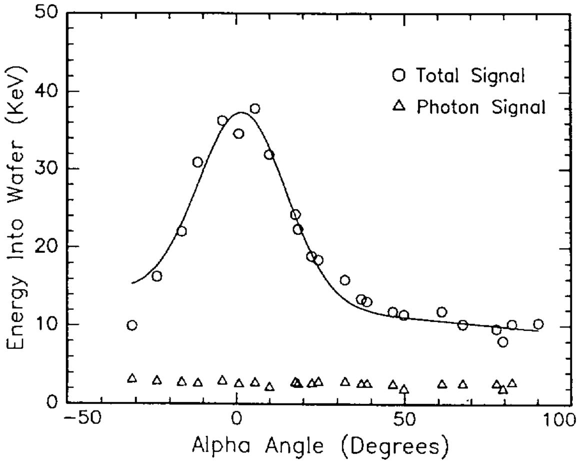

Fig. 3. Dependence of the roton and photon signals upon track direction. The line through the roton data points are to help guide the eye.

to the liquid surface is close to four times larger than for an α directed normal to the surface [11]. The reason for this orientational dependence has to do with the production of rotons along the α track. The track length of a 3 MeV α particle in liquid helium is $\approx 200\,\mu m$ while the secondary electrons travel only ≈ 20 nm. The $\sim 10^9$ rotons are created in a long, thin cylindrical cloud with a very high density. The roton–roton scattering cross-section is $\sim 10^{-14}\,cm^2$. Initially the rotons have a mean-free-path that is shorter than the radial dimension of the cylinder. As a consequence of the interactions the rotons thermalized about the roton minimum in the dispersion relation [12]. As the cloud expands more rotons propagate away perpendicular to the cylinder axis than parallel to it [11].

Both the scintillation and the anisotropic roton generation in superfluid helium could be of significance for the development of helium-based detectors. However, it is not yet known to what extent, if any, the roton flux from an electron track, such as produced by neutrino–electron scattering, carries information about its direction. The present results are directly relevant to experiments involving nuclear recoils in liquid helium.

Although the calorimetric signal from UV photons is substantially smaller than that from evaporated atoms, the timing information available from the photons may be very useful in a large-scale detector. In a large detector having dimensions of meters and involving hundreds of calorimeters [13], the difference in arrival times of the roton signal on the wafers could be the order of 10 ms. These signals cannot be summed easily. In contrast, summing the outputs of the wafers would enhance the simultaneous photon signals with respect to noise and provide timing information for use in event location. The sensitivity of large area calorimeters needs to be improved by an order of magnitude to make this technology practical.

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