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Simultaneous calorimetric detection of rotons and photons generated by particles in superfluid helium

J.S. Adams, S.R. Bandler, S.M. Brouër, R.E. Lanou¹, H.J. Maris, T. More, G.M. Seidel

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

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Abstract

A charged particle stopped in superfluid helium produces both excitations in the liquid (phonons and rotons) and photons by fluorescence. Using a calorimeter with a response time of 50 μ s we are able to time-resolve in a single detector signals from the photons and from the excitations of the liquid at 25 mK. The implications of this observation for the detection of low energy solar neutrinos are discussed.

Keywords: Neutrinos; Solar neutrinos; Scintillation; Rotons; Phonons; Superfluid helium

Liquid helium has many properties which make it attractive as a large-mass target material for detecting low energy particles such as neutrinos and particle dark matter. Among those properties are cleanliness with respect to radioactive contamination, low cost, and the ease with which it can be handled on an industrial scale.

In recent years we have developed a technique [1–3] for detecting small energy deposits by charged particles in superfluid helium at low temperatures. As a particle is stopped in helium it generates elementary excitations of the liquid – phonons and rotons – which propagate ballistically at low temperatures. If these excitations hit a free surface of the liquid and individually have an energy greater than the binding energy (7.16 K) of a helium atom to the liquid, they can produce quantum evaporation. The evaporated atoms can then be detected upon their adsorption on a calorimeter consisting of a large-area, low heat-capacity wafer to which a sensitive thermometer is attached. Typically,

10^4 atoms are evaporated per keV of energy deposited in the liquid.

The detection and potential identification of charged particles using liquid helium is made possible by the properties of the excitations of the superfluid liquid. A measurement of the number and spatial distribution of evaporated helium atoms using multiple wafer/calorimeters can determine the energy and location of an event in the liquid. Track direction can be identified, at least for heavily ionizing particles, because the flux of rotons from a track is highly anisotropic [3].

In this paper we report the calorimetric detection and measurement of the scintillation light from liquid helium [4] produced by α particles. The measurement of this scintillation, when combined with the observation of roton-generated signals, can provide supplemental information on particle events. The unusual feature of these measurements is the observation of separate signals arising from photons and from rotons in the same calorimetric detector, made possible by the different arrival times of the signals.

¹ E-mail: lanou@brhep1.physics.brown.edu.

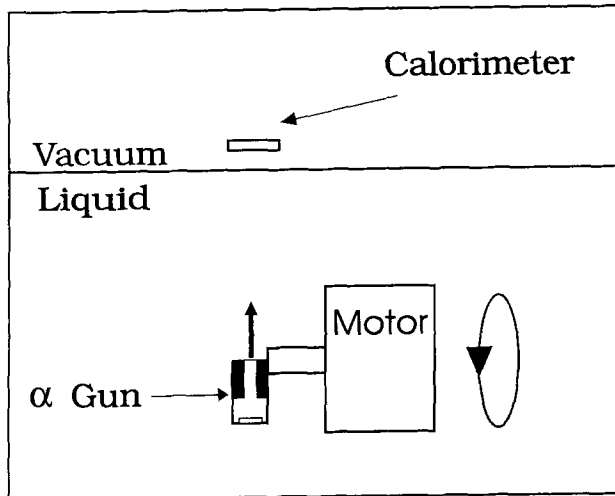


Fig. 1. Schematic diagram of the experimental cell.

Experiments are carried out in a cylindrical cell which can contain up to 3 liters of liquid helium. The cell is attached to a dilution refrigerator capable of achieving temperatures down to 25 mK. The instrumentation within the cell is sufficiently flexible to allow a number of different types of experiments to be performed. Fig. 1 illustrates a typical configuration used in the experiments reported here. A collimated α source is formed by placing ^{241}Am at the bottom of a hole in a brass rod. The end of the hole is sealed by a $12\ \mu\text{m}$ Kapton sheet to exclude superfluid helium, and the hole is evacuated. The α 's emerging from the Kapton have an energy of $3.3 \pm 0.6\ \text{MeV}$, as measured by a surface barrier detector, and a collimation of $\pm 14^\circ$. This source is mounted in the liquid on the arm of a small superconducting stepper motor [5] and can be rotated through 120° in 7° steps. The liquid level in the cell is adjustable and is measured by a capacitance gauge. A $1\ \text{cm} \times 2\ \text{cm}$ sapphire wafer/calorimeter is positioned in the vacuum directly above the source and equipped with a thin-film, iridium-gold, proximity-effect, superconducting transition-edge thermometer [6]. This low-impedance thermometer has a transition temperature of $\sim 70\ \text{mK}$ and its resistance is measured using SQUID electronics. The spacing between the source and the wafer as well as the liquid level relative to each can be changed. The wafer, whose temperature can be varied independently of that of the liquid helium, is kept free of helium film by means of a "film burner" [7]. In a separate experiment the calorimeter

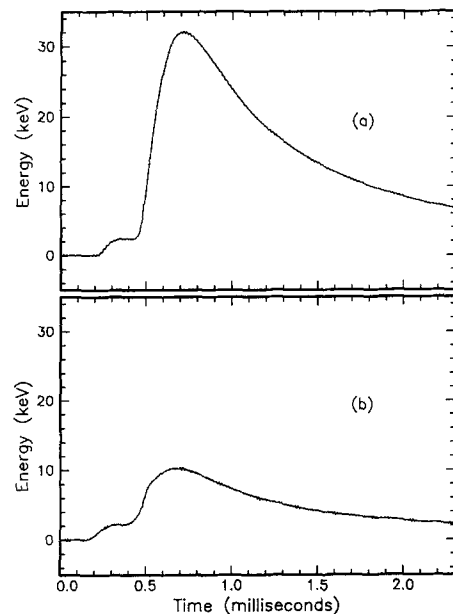


Fig. 2. The thermal response of the calorimeter when an α particle is stopped in the liquid helium. The traces are averages of about 100 single events. The calorimeter is 0.5 cm above and the source 4.5 cm below the liquid surface. a) The collimated α tracks are parallel to the liquid surface. b) The α tracks are perpendicular the surface of the liquid.

is calibrated by measuring the temperature rise produced by the 5.9 keV line from an ^{55}Fe source absorbed directly in the wafer. The cell is filled with helium through a heat flush system [8] which reduces the concentration of ^3He to less than 10^{-8} . ^3He at its natural concentration in ^4He scatters the rotons excessively. The entire apparatus is enclosed in a screened room, and the data is transferred by fiber-optic links to a computerized collection and analysis system.

The response of the calorimeter positioned 0.3 cm above the liquid surface is shown in Fig. 2a for an α particle stopped in the helium a distance of 4.5 cm below the surface. The track length of a 3 MeV α particle is approximately $200\ \mu\text{m}$ in helium. The trace is an average of about 100 single events for which the collimated α tracks are parallel to the liquid surface. The calorimeter has a response time of $\sim 50\ \mu\text{s}$ to an energy input, while its relaxation time to the thermal reservoir is $\sim 0.5\ \text{ms}$. Our interpretation of the observed signal is as follows. We believe that the calorimeter responds initially to a pulse of heat produced by scintillation light absorbed in the sapphire

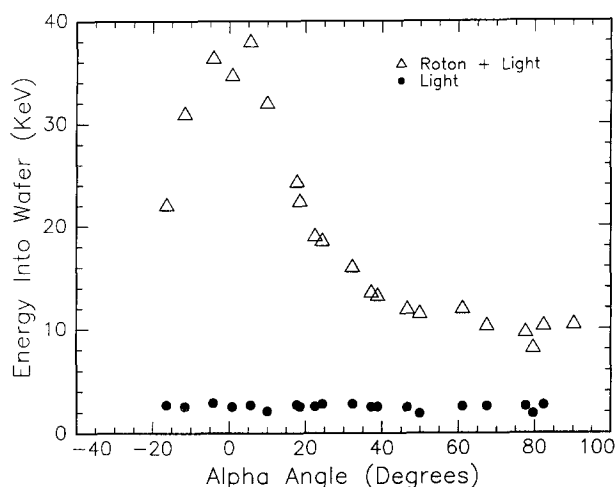


Fig. 3. The amplitudes of the photon and roton signals as a function of the orientation of the collimated α source. An α with $\theta = 0^\circ$ is directed normal to the liquid surface.

wafer. The plateau in the signal roughly $100 \mu\text{s}$ long corresponds to an energy input of 2.5 keV. At about $250 \mu\text{s}$ after the initial appearance of a signal, heating begins as a result of the adsorption on the wafer of roton-evaporated helium atoms. The average arrival time of the atoms is approximately $300 \mu\text{s}$ after the light pulse so that the calculated velocity of the rotons is centered about $1.5 \times 10^4 \text{ cm s}^{-1}$. This value is consistent with the velocity of rotons near the minimum in the dispersion curve. This signal generated by rotons has been investigated previously [2,3], and the rotons produced by an α particle are known to thermalize about the dispersion minimum.

Four experiments have been performed which support this interpretation of the structure in the signal from an α event.

(1) The magnitude of the roton signal was varied by changing the direction of the collimated α source with respect to the normal to the liquid surface. We have shown that the roton flux propagating away from an α track is anisotropic [3]. The roton signal produced by an α travelling perpendicular to the surface, shown in Fig. 2b, is approximately four times smaller than for an α travelling in a plane parallel to the surface, Fig. 2a. Fig. 3 shows the variation of the amplitudes of the photon and roton signals as the collimated α source is rotated in a plane perpendicular to the surface. The distances between source, wafer and

liquid surface all remain fixed. At all track orientations the photon signal is unchanged while the roton signal varies as expected [3].

(2) In a separate experiment the level of the liquid was lowered so that the α source was 3.5 cm below the free surface and the calorimeter 1.3 cm above the surface. To the accuracy of the measurements the photon signal is unchanged in magnitude. This is to be expected since the solid angle subtended by the wafer is constant and refraction of the light is negligible. However, the roton signal is observed to be substantially smaller. This is a consequence of the kinematics of the quantum evaporation process. A roton near the minimum of the dispersion curve can only evaporate an atom if its angle of incidence on the surface is less than about 17° . The velocity vector of an evaporated atom makes a much larger angle with respect to the normal to the surface than the angle of incidence of the roton that produced the evaporation. Consequently, the number of helium atoms intercepted by the wafer from an event directly below it decreases as the distance between the liquid surface and the wafer increases. The calculated ratio of the size of the roton signals for the two geometries used is 0.60 to which the measured ratio of 0.55 compares well.

(3) When the source-to-wafer distance was decreased to 1 cm with the liquid level equidistant between the two, no structure in the response of the calorimeter could be resolved. In this case the time delay in the arrival of the roton signal is small. The jitter in the timing of the trigger resulting from the noise on the signal produces a smooth, structureless response upon averaging.

(4) With the source-to-wafer distance of 1 cm, ^3He was added to the cell to produce a concentration of 1 part in 10^5 . The mean free path for rotons is less than 1 mm at this concentration of ^3He . The response of the calorimeter to α 's was small, corresponding to the expected photon signal alone with no roton contribution.

In comparison to work on other noble liquids, liquid helium has not been widely used or studied as a medium for particle detection principally because of its poor drift velocity for charged particles. However, the nature of its scintillation spectrum is of considerable interest and has been studied for its own sake [9]. The spectrum of liquid helium at 1.4 K is very strongly concentrated in the ultraviolet and arises from the radiative dissociation of neutral He_2^* dimers in ex-

cited states which are formed along the particle path. The emission extends from 13 to 19 eV with a broad maximum centered at 15.5 eV. Helium is transparent below 20 eV, the energy of the 2^3S excited state of the He atom. Scintillation has been observed for both electrons and α particles [4,9] stopped in helium. For an electron the amount of energy emitted as photons is estimated to be 8% of the incident particle energy. For an α the ratio of the two energies is not as well known but is of the same order. Sapphire is strongly absorbing in the uv above 10 eV. When account is taken of the solid angle subtended by the wafer/calorimeter in this experiment, we find that the detected photon energy of 2.5 keV corresponds to about 10% of the 3.3 MeV energy of the α particle.

While under normal conditions the photon signal from the calorimeter is considerably smaller than the roton signal, it nonetheless has the potential of providing important additional information for particle detection using superfluid helium. A liquid helium detector of solar neutrinos capable of observing 20 events per day from the p-p and ^7Be reactions in the sun [10] would have a fiducial volume of 70 m³ (mass of 10 metric tons). An array of ~ 1500 , 15 cm diameter wafers positioned above the liquid surface for detecting the roton-generated signals would also intercept approximately 20% of the emitted photons. A 150 keV recoil electron produced by neutrino elastic scattering would generate more than 500 VUV photons. Those hitting the wafers would be fully absorbed, without the need for a wavelength shifter. Currently, large-area cryogenic calorimeters do not have thresholds of 15 eV that would be required for an individual wafer to detect a single photon. However, the outputs of the wafers can be summed to enhance the scintillation signal as compared to noise. The roton signals cannot be summed easily because their time delays differ depending on distance of the wafers from the event. In this manner it should be possible, with only modest improvements in present technology, to provide a trigger for timing the arrival of roton signals on the individual wafers. Timing information can supplement a measurement of the number and spatial distribution of the evaporated helium atoms in determining the position, the energy and possibly the track orientation of a particle event in the liquid.

We are planning experiments to determine if the division of energy between rotons and scintillation pho-

tons in helium is different for electrons and for heavy ionizing particles. If there is a difference, then a means will exist by which particles can be distinguished.

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References

- [1] R.E. Lanou, H.J. Maris and G.M. Seidel, *Phys. Rev. Lett.* 58 (1987) 2498.
- [2] S.R. Bandler, R.E. Lanou, H.J. Maris, T. More, F.S. Porter, G.M. Seidel and R.H. Torii, *Phys. Rev. Lett.* 68 (1992) 2429;
S.R. Bandler, C. Enss, G. Goldhaber, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, *J. Low Temp. Phys.* 93 (1993) 715;
C. Enss, S.R. Bandler, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, *Physica B* 194-196 (1994) 515.
- [3] S.R. Bandler, S.M. Brouër, C. Enss, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel (to be published).
- [4] E.H. Thorndike and W.J. Shlaer, *Rev. Sci. Instr.* 30 (1959) 838;
H. Fleishman, H. Einbinder and C.S. Wu, *Rev. Sci. Instr.* 30 (1959) 1130;
J.E. Simmons and R.B. Perkins, *Rev. Sci. Instr.* 32 (1961) 1173;
J.R. Kane, R.T. Siegel and A. Suzuki, *Rev. Sci. Instr.* 43 (1963) 817;
F.E. Moss and F.L. Hereford, *Phys. Rev. Lett.* 11 (1963) 63.
- [5] F.S. Porter, S.R. Bandler, C. Enss, R.E. Lanou, H.J. Maris, T. More and G.M. Seidel, *Physica B* 194-196 (1994) 151.
- [6] U. Nagel et al., *J. Low Temp. Phys.* 93 (1993) 543.
- [7] R. Torii, S.R. Bandler, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, *Rev. Sci. Instr.* 63 (1992) 230.
- [8] P.C. Hendry and P.V.E. McClintock, *Cryogenics* 27 (1987) 131.
- [9] M. Stockton, J.W. Keto and W.A. Fitzsimmons, *Phys. Rev. Lett.* 24 (1970) 654; *Phys. Rev. A* 5 (1972) 372;
C.M. Surko, R.E. Packard, G.J. Dick and F. Reif, *Phys. Rev. Lett.* 24 (1970) 657;
J.W. Keto, M. Stockton and W.A. Fitzsimmons, *Phys. Rev. Lett.* 28 (1972) 792.
- [10] S.R. Bandler, C. Enss, G. Goldhaber, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, *J. Low Temp. Phys.* 93 (1993) 715.