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Angular Distribution of Rotons Generated by Alpha Particles in Superfluid Helium: A Possible Tool for Low Energy Particle Detection

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We report measurements of the distribution of rotons generated by α particles interacting in a bath of superfluid helium. The roton flux is found to be anisotropic; it is about 4 times larger transverse to the track direction than along it. This asymmetry may provide a powerful tool in particle and astrophysics experiments where sensitivity to low energy recoil track direction is important.

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Several experiments in astrophysics and particle physics, such as the study of the lowest energy neutrinos from the Sun or the search for elementary particle dark matter, require the detection and measurement of low energy interactions in large targets ranging in size from several kilograms to tons [1]. The purity of the target material, particularly with respect to trace amounts of natural or induced radioactivity, is a crucial consideration. Liquid helium possesses several properties which make it a desirable target medium. It can be kept pure easily, has no long-lived radioactive isotopes, and is inexpensive. A scheme for particle detection using superfluid helium as the target material has been proposed [2], and a small-scale prototype has been constructed and tested [3]. In these experiments the energy deposited into the liquid appears, in part, as roton excitations. At sufficiently low temperature these propagate ballistically through the liquid, and lead to a burst of atoms evaporated from the free surface of the liquid. These atoms can be detected calorimetrically. In using superfluid helium as a particle detector for a full-scale experiment it will be important to extract as much information as possible from each interaction event. Ideally the event location, track direction, and energy deposition would all be determined. To achieve these goals it is essential to understand the physical processes involved in roton generation by particle interactions.

In this paper we report measurements of the angular distribution and momentum spectrum of rotons emitted by α particles stopping in superfluid helium. We find a striking result. The number of rotons propagating away from the track is highly anisotropic with respect to the track direction. This discovery opens up the possibility of a helium-based detector with sensitivity to track direction.

The experiments were carried out in a cell shown schematically in Fig. 1. The cell could contain up to 3 liters of liquid helium at a temperature as low as 25 mK. A heat-flush tube and superleak were used to reduce the concentration of ^{3}He impurity in the ^{4}He to approximately 10^{-8} [4]. A capacitance level gauge established the liquid level with an accuracy of 0.5 mm. Rotons were generated in the liquid by α particles of 5.5 MeV maximum energy from nCi ^{241}Am sources, and also by pulsed thin-film heaters; these sources could be moved around the cell by small superconducting motors contained within the cell [5]. To detect the evaporated helium atoms, thin wafers of silicon or sapphire were suspended above the surface of the liquid. These wafers were connected to a "film burner" [6], which made it possible to maintain the wafer at a low temperature and free of a superfliud helium film. When atoms were adsorbed onto these wafers, the temperature increased, and this temperature change was sensed either by a neutron-transmutation-doped (NTD) germanium thermistor [7] or by an iridium-gold superconducting-transition-edge bolometer [8]. From the measured heat capacity of the wafer and the known characteristics of the bolometer it was possible to use the measured resistance change of the bolometer to determine the energy deposited into the wafer. The experiment consisted of measurements of the distribution of these energy inputs into the wafer ("pulse height spectrum") recorded for different positions of the source of the rotons.

In the first experiment the α source was an ^{241}Am film evaporated onto a glass substrate. This source was positioned 5.7 cm below the wafer and covered by 5.0 cm of helium. While the energy spectrum of the 5.5 MeV

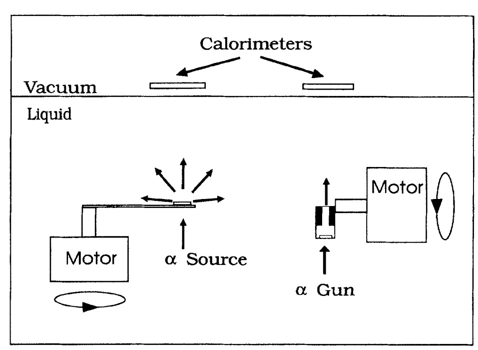

FIG. 1. Schematic diagram of the experimental cell showing collimated and uncollimated sources in liquid helium at 25 mK attached to stepper motors. The wafers (calorimeters) are in vacuum, free of helium film.

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α source had a width of less than 25 keV as measured by a surface-barrier detector, the pulse height distribution measured using the wafer (calorimeters) is given by the points in Fig. 2(a). The distribution above 30 keV consists of two maxima, one at $\sim$60 keV and a less pronounced one at $\sim$190 keV, together with a continuous distribution between the two. The counts below 30 keV but above the threshold of 8 keV are not associated with α's being stopped in the liquid, as discussed below. When a heater was used as the roton source, however, the response of the bolometer on the wafer was the same to within 5% for each electrical pulse applied to the heater [9]. Thus, the peculiar pulse height spectrum shown in Fig. 2(a) must be attributed to some characteristic of the α source.

In order to investigate the pulse height spectrum in more detail we constructed an α source (α gun) that produced a beam of collimated α's in the liquid. An ^{241}Am source was placed at the bottom of an evacuated hole in a brass rod. The end of the hole was permanently sealed by a 12 μm Kapton sheet to exclude superfluid helium. The energy of the α's exiting through the Kapton sheet was measured with a surface-barrier detector to be 3.3 $\pm$ 0.6 MeV, collimated to $\pm 14°$, as governed by the geometry of the gun. The α gun was mounted on the shaft of a stepper motor and the particle direction could be rotated by 120° without shadowing the α track from the detector by the gun or its holder. The distances of the source and the wafer relative to the liquid surface were approximately the same as stated earlier. The source was rotated in 7° steps, and the pulse height spectrum was measured at each angular setting. A typical spectrum at one angle is shown in Fig. 2(b). The spectrum now consists of a structureless peak. The energy at which the peak occurs varies with the direction of the α gun, and this variation is shown in Fig. 3. It is found that the signal for an α with track parallel to the liquid surface (90° in Fig. 3) is close to 4 times larger than for an α directed normal to the liquid surface. The observed width of the peak is consistent with the spread in energy of the α source, the variation of track direction of the α particles and the resolution of the detector.

The dependence of signal size on track direction can be used to calculate the spectrum for an α source that emits particles isotropically in a hemisphere. The smooth curve through the data points in Fig. 3 is used to characterize the angular dependence, and a Gaussian broadening (σ = 3 keV) is applied to the distribution to account for the resolution of the detector. The computed spectrum, scaled to account for the difference in areas of the detectors and energies of the α's used in the two experiments, is given by the solid curve in Fig. 2(a). The curve is in good agreement with the measured spectrum above 40 keV, with a peak at 60 keV and a shoulder extending

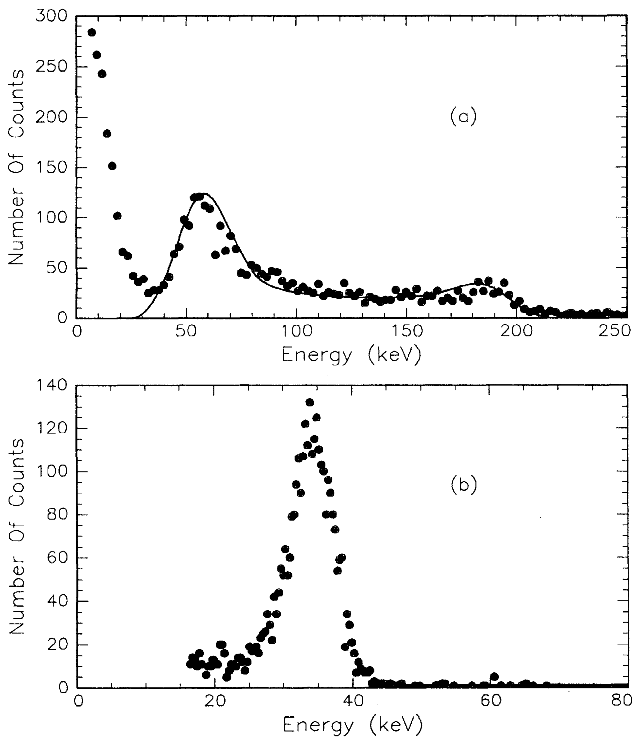

FIG. 2. Pulse height distribution for energy deposited into a wafer (calorimeter). (a) The points represent the distribution recorded with a 9 cm^2 wafer using an ^{241}Am source consisting of a film deposited on a substrate. The solid curve is a computed spectrum (see text). (b) Distribution recorded with a 2 cm^2 wafer and a collimated α source (α gun) producing α's at an angle of 90° with respect to the normal to the liquid surface. The large difference in energy scales of the two graphs is related to the difference in areas of the wafers and to a difference in energies of the α's.

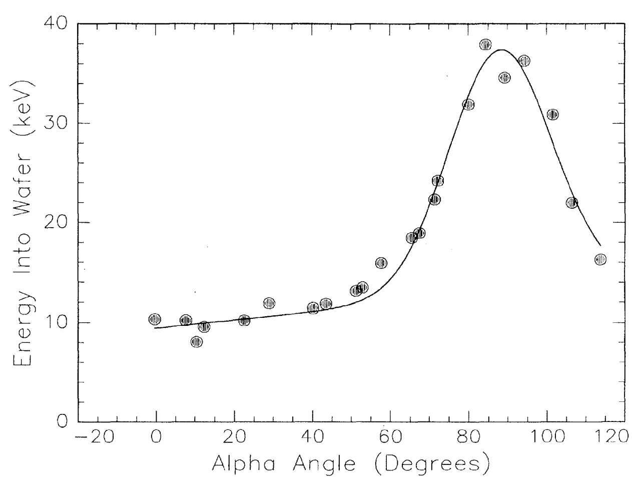

FIG. 3. Energy deposited into the wafer by α's from the collimated α source as a function of the angle θ specifying the α direction. An α with $\theta = 0$ has a direction normal to the liquid surface.

to about 4 times that energy. The signals below 30 keV in Fig. 2(a), not accounted for by the computed spectrum, are the result of α particles that go into the glass substrate on which the source is deposited. The α's heat the glass locally to such an extent that rotons are generated in the liquid in sufficient numbers to produce detectable evaporation signals [10].

Why should there be more rotons emitted perpendicular to the α track than there are parallel to it? It appears that this anisotropy comes about because of the very high density of rotons produced along the α track. The range of a 3.3 MeV α in liquid helium is $L = 200\ \mu$m. The secondary electrons produced along the track have a range r of several hundred angstroms [11]. Thus, the primary roton production occurs in a volume $\pi r_0^2 L \approx 6 \times 10^{-13}$ cm^3. If we assume that one roton is generated for every 10 K of energy deposited by the α, the total number of rotons is 4×10^9, and so the initial roton density is of the order of 10^{22} cm^{-3}. This density is higher than occurs in helium at the lambda transition. The roton-roton scattering cross section is of the order of 10^{-14} cm^2 [12], and so at this density rotons will have a very short mean free path Λ, much less than the radius r_0 of the excited region. The cloud will be opaque and, from geometrical considerations, will radiate more strongly perpendicular to the track than along it. However, the extent of the anisotropy of the roton flux must depend on the initial roton density and on the strength and nature of the roton-roton interaction. We have not attempted a quantitative theory of the effect.

Support for this interpretation is provided by another experiment we performed in which the angular dependence of the evaporation by rotons was studied. When a roton is incident on the liquid surface and an atom evaporates, the energy and the momentum parallel to the liquid surface are conserved. As a consequence, it is straightforward to show that a roton of momentum p can only lead to evaporation if it is incident on the liquid surface at an angle Θ, measured from the normal, less than some critical value Θ_c which depends on p. For rotons close to the roton minimum p_0, $\Theta_c \approx 17°$, whereas for rotons of higher energy away from the minimum Θ_c increases. Thus, by means of a measurement of the range of incident angles over which the rotons are able to cause evaporation, one can obtain information about the energy spectrum of the rotons. Based on phase space considerations, one would expect the *primary* rotons produced by the α to be distributed over the entire range of possible momenta. However, if the rotons interact strongly in the cloud before leaving the vicinity of the track, one can expect that the roton distribution will be closer to a thermal distribution and therefore concentrated in the momentum range near to the roton minimum. In the experiment an ^{241}Am film source was mounted on the end of the arm of a stepper motor, as shown in Fig. 1, at a depth of 1.6 cm below the liquid surface. The source was moved in 2 mm steps on an arc at constant depth below a 1 cm square silicon wafer which was located 1.5 cm above the liquid surface. Figure 4 shows the upper end point of the pulse height spectrum as a function of the source position. The signal is largest with the source directly beneath the wafer. The data are compared with two simulations. In the first of these it is assumed that excitations (both phonons and rotons) are generated uniformly in momentum space across the entire spectrum from $p = 0$ to 2.3 Å^{-1}. This simulation gives a variation of signal with source position considerably less rapid than experimentally observed. The results are in much better agreement with a simulation in which the excitations are assumed to be restricted to a narrow momentum range ($1.95 \geq p \geq 1.85$ Å^{-1}) around the roton minimum. This agreement suggests that as a result of the strong interactions between the excitations in the expanding roton cloud the rotons have thermalized to the region near the roton minimum. We tested this idea by making measurements in which a heater source is moved in the same manner that is described above. The variation of the signal with heater position was found to be almost identical to that found with the α source. This is expected because it is known that a thin-film heater driven by a small-amplitude electrical pulse generates only rotons close to the roton minimum [13].

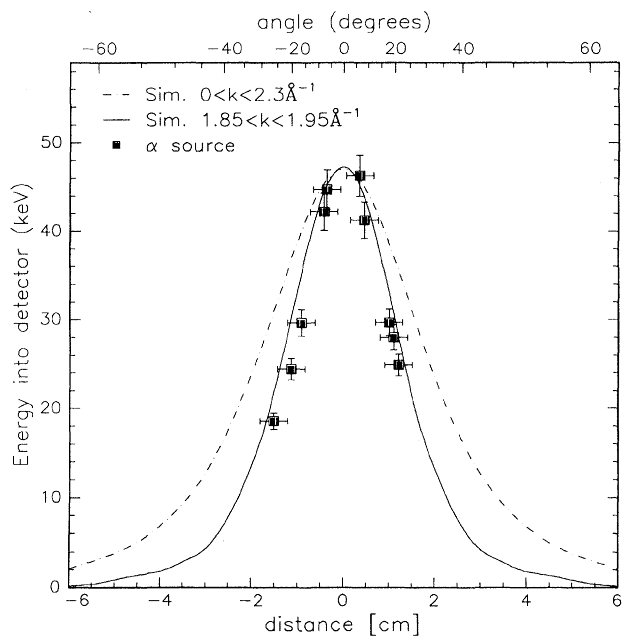

FIG. 4. Evaporation signal from an α source as a function of distance from the position directly beneath the detector wafer. The solid curve is the result of a simulation based on the assumption that the rotons are distributed over the entire momentum range up to 2.3 Å^{-1}, and the dashed curve is for rotons restricted to a narrow range near to the roton minimum.

In summary, we have measured the characteristics of the rotons generated by α particles in superfluid helium. The width in energy of signals from a collimated α source is dominated by the spread in energies of the source and by the detector resolution rather than by the inherent statistical nature of the detection process. The angular distribution of the roton flux generated by the α particles is strongly asymmetric with respect to the parent particle direction. Rotons propagating away from the particle path are narrowly concentrated into a momenta band giving a small critical angle for evaporation. These measured properties of roton generation by particles in superfluid helium suggest that detailed information on position, energy, and track direction of particle events can be determined in very large volumes of helium by measuring the number and spatial distribution of atoms evaporated from the surface using an array of calorimeters (detectors).

It is not yet known whether recoiling electrons, such as would be produced by the scattering of neutrinos in a low energy solar neutrino experiment, exhibit an asymmetry of roton flux with respect to track direction. We are planning experiments to investigate this. However, the present results do have direct relevance to possible experiments using nuclear recoil in liquid helium to measure the neutral current coherent scattering of neutrinos or to search for particle dark matter in the galaxy.

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