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Particle Detection by Evaporation from Superfluid Helium

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We report the first experiments in which 5-MeV alpha particles are detected via evaporation from a bath of superfluid helium. The α excites phonons and rotons in the liquid helium, and these excitations are sufficiently energetic to evaporate helium atoms when they reach the free surface of the liquid. The approximate overall efficiency of this process has been determined, and we compare this with expectations. We have also been able to detect evaporation induced by a flux of γ's from a ^{137}Cs source.

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The detection of low-energy neutrinos from the Sun remains a challenging experimental problem [1]. In a recent paper [2] we have proposed a new technique for the detection of solar neutrinos (and other weakly interacting low-energy particles) based upon evaporation from superfluid ^{4}He at low temperatures. The proposed detection scheme is shown schematically in Fig. 1. A cell contains a target mass of liquid ^{4}He at a temperature $T < 0.1$ K. When a neutrino scatters off an atomic electron, the electron will recoil through the liquid and produce further ionization. A significant fraction of the energy is likely to appear as phonons and rotons, the elementary excitations of the superfluid. At low temperatures these excitations have the remarkable property of being able to propagate very long distances through the liquid without attenuation or scattering. When they reach the free surface of the liquid, the excitations are able to evaporate helium atoms. This is because in a highly quantum system such as helium the energy of the excitations can exceed the binding energy of the particles in the system. Above the surface of the liquid a thin silicon wafer is suspended. The helium atoms evaporated from the liquid adsorb onto this wafer and raise its temperature. Thus, the neutrino-electron scattering event in the liquid leads to a sudden temperature rise of the wafer, and the magnitude of this temperature rise can be used to determine the amount of energy that was transferred to the recoil electron. This type of detector has two very important potential advantages. The first is that the heat capacity of the large mass of target material (superfluid helium) does not limit the sensitivity since the deposited energy is transferred through the helium into the silicon wafer, an object whose heat capacity can be made extremely small. This gives a low threshold of energy detection. The second advantage is that, because of its superfluidity, helium can be made much purer [3] than any other substance; consequently, the internal radioactive background can be made very small. These features are very important since any neutrino detector must have a large mass to achieve a reasonable counting rate [4]. In this Letter we report on the first tests of a detector of this type and discuss some of the results that we have obtained.

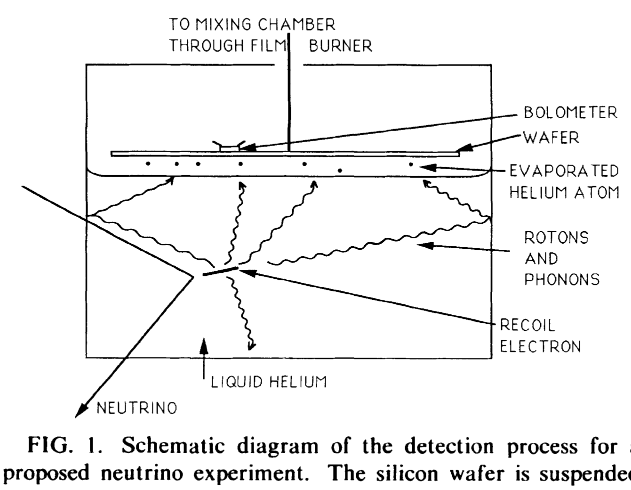

FIG. 1. Schematic diagram of the detection process for a proposed neutrino experiment. The silicon wafer is suspended from a "film-burner" which is able to prevent the superfluid film from reaching the wafer, while maintaining the wafer at a low temperature.

The experimental prototype cell we have constructed has an internal diameter of 10 cm and a height of 25 cm. The helium in the cell was normally kept at a temperature of ~70 mK. At this temperature the rate of thermal evaporation of helium atoms from the liquid bath is negligibly small. A silicon wafer (diameter 7 cm, thickness 0.02 cm) was suspended above the helium bath. Attached to the wafer was an NTD germanium bolometer chip [5]. The bolometer resistance was measured using a dc bias current together with a room-temperature amplifier. To increase the sensitivity of the experiment the silicon wafer was supported in such a way such that it could remain bare, i.e., not covered by the usual superfluid film. This is important for two reasons. At the temperatures of interest the heat capacity of the ripplons (quantized capillary waves) in the film is much larger than that of the silicon wafer itself, and so the film would decrease the temperature rise of the wafer due to the arriving helium atoms. Second, for a bare wafer the adsorption energy liberated per atom is around 100 K [6], whereas for condensation of an atom into a film the energy is only 7 K. To keep the film off the wafer we incorporated a "film burner" into the support structure for the silicon wafer [7]. This device intercepts the superfluid helium film that would normally flow up the walls of the

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cell and onto the wafer and directs it onto a heated surface above 0.5 K where it evaporates. The evaporated atoms are condensed on a series of baffles, and have an extremely small probability of reaching the wafer. It was possible to keep the wafer free of helium while maintaining it at a temperature as low as 45 mK. To evaporate the film a power of 500 μW is needed and this power has to be removed from the condensing baffle. To do this efficiently the baffle was maintained at a higher temperature than the rest of the cell and was cooled by an intermediate-temperature heat exchanger of a custom-designed dilution refrigerator.

For the experiment to work as intended, it is essential that the rotons and phonons excited in the liquid by a recoiling charged particle propagate ballistically through the liquid, i.e., without scattering. Ordinary ^{4}He from well gas has a concentration of $\sim 10^{-7}$ of ^{3}He which would give a roton mean free path of the order of 1 mm. To remove the ^{3}He we incorporated a heat-flush purifier based on the design of Hendry and McClintock [3].

In the experiments we report here we used 5-MeV α particles from a ^{241}Am source located 7 cm above the bottom of the cell. With no helium in the cell the α's could strike the silicon wafer directly, and the response of the bolometer to this process is shown in Fig. 2(a). With the wafer at 50 mK the temperature rise is roughly 1 mK and gives a signal-to-noise ratio of about 100. A pulse-height distribution for this process is shown in Fig. 3(a). The width of the distribution ($\sim 15\%$) is substantially larger than the energy distribution of the α particles, and is presumably due to α's hitting different regions of the wafer. When we installed two independent Ge bolometers on the wafer, it was found that the ratio of the signal detected by one bolometer to the other varied by about 25% from one event to the next. These variations are not unexpected since the energy is deposited at one point of the wafer and the time for heat to diffuse across the wafer is comparable to the time for heat to escape out of the wafer.

From the measured change in resistance of the bolometer and the known bolometer characteristics we can calculate the temperature rise of the wafer. When combined with the known energy of the α this can be used to determine the heat capacity C of the wafer. The result for C at 50 mK was found to be about 10 times larger than that expected from the T^3 specific heat of bulk silicon, and the variation of C with T was found to be small. This may indicate a contribution from two-level systems in the oxide layer [8] on the silicon or from the epoxy used to attach the bolometer to the wafer. When helium film was allowed to cover the wafer, the expected decrease in signal level due to the increase in heat capacity of the wafer was observed [7,9].

When bulk helium is introduced into the cell and the ^{241}Am source is covered, a smaller signal is detected on the wafer. This signal is due to evaporation of helium atoms by the phonons and rotons which were excited by the α particles in the liquid, and arises from helium ad-

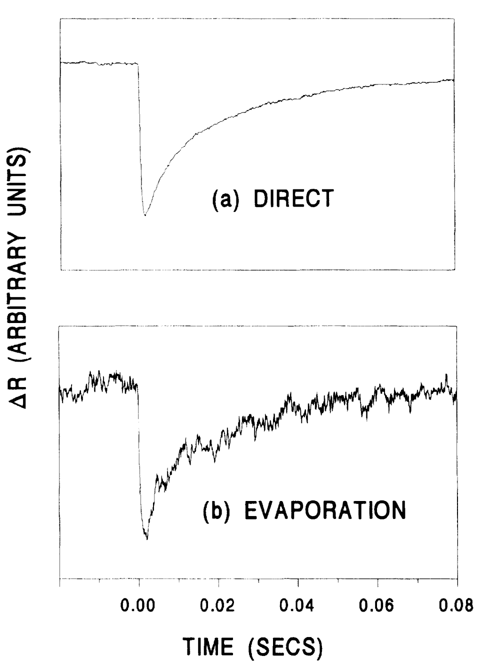

FIG. 2. Change in resistance of the bolometer detector (a) when the α hits the wafer directly and (b) when the α scatters in the superfluid helium bath and the wafer is heated by evaporated helium atoms.

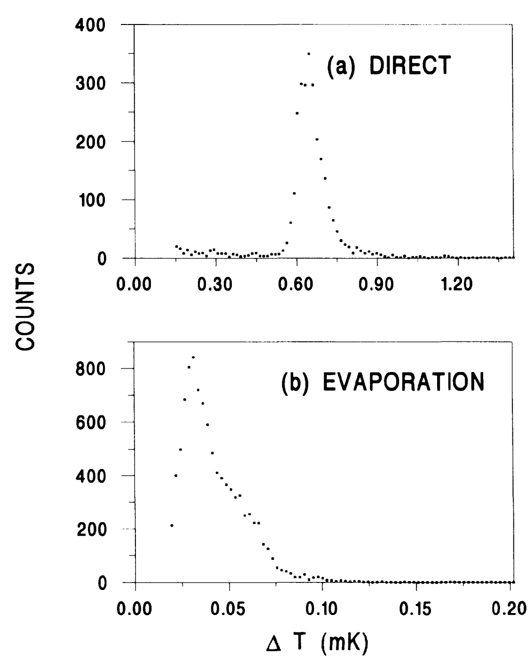

FIG. 3. Pulse-height distribution, expressed in terms of temperature rise, (a) for α particles hitting the bare wafer directly ($T_{\rm wafer}=84$ mK) and (b) for α particles stopped in the superfluid helium bath ($T_{\rm wafer}=50$ mK).

sorption over the entire face of the wafer in contrast to the energy deposit at a point characteristic of α's hitting the wafer directly. The rate of detected events is increased to 16/sec, compared to 1.5/sec with the empty cell, because all α's entering the liquid now give a signal, whereas with the empty cell the α's had to lie in the small solid angle subtended by the wafer. The bolometer response is shown in Fig. 2(b), and the pulse-height distribution is shown in Fig. 3(b). The origin of the unusual shape of the pulse-height distribution is not clear, although some contribution is likely to arise from the limited ratio of the signal-to-noise ratio. It is possible that the distribution is associated with the short range of the α track (~ 250 μm). This short range gives a dense distribution of rotons close to the solid surface of the source, and some of the rotons may be converted to low-energy phonons at the wall. Alpha particles coming out of the source at closer to normal incidence will generate rotons at a greater distance from the wall than will α's emerging at oblique incidence, and so fewer rotons will be lost. If this is the origin of the effect, it will not be relevant to a full-scale neutrino experiment because then the vast majority of interactions will occur in the bulk of the liquid far from any walls.

With the α source 7 cm below the surface of the liquid the size of the measured signal is 20 times smaller than for α's hitting the wafer directly in the empty cell at the same temperature. To consider the significance of this result it is necessary to take into account the various processes occurring between the scattering event and the energy deposited into the wafer. Let $f_{\alpha\text{-roton}}$ be the fraction of the α energy that is converted into rotons, and let the average energy of these rotons be E_{roton}. Let $p_{\text{roton-atom}}$ be the probability that a roton will evaporate a helium atom which then strikes the wafer, and p_{stick} be the sticking probability for helium atoms incident on the wafer. The binding energy on the bare wafer is E_{bind}. Using these parameters the ratio of the signal S_{full} due to evaporation in the full cell to the value S_{empty} due to α's hitting the silicon directly in the empty cell is

$$\frac{S_{\text{full}}}{S_{\text{empty}}} = \frac{f_{\alpha\text{-roton}} p_{\text{roton-atom}} p_{\text{stick}} E_{\text{bind}}}{E_{\text{roton}}} = \frac{1}{20} . \qquad (1)$$

To determine approximate values of some of these parameters we performed a separate experiment. We used a pulsed heater below the surface of the liquid to generate phonons and rotons. These excitations evaporated a burst of helium atoms from the liquid surface. We compared the signal on the bolometer when the wafer was bare to when it was covered with a helium film. Because the sticking coefficient for a helium atom incident onto a saturated helium film is known to be close to unity [10] this experiment can be used to give an approximate value for $p_{\text{stick}} E_{\text{bind}}/E_{\text{roton}}$. The experimental result for this combination of quantities is ~ 10. Using this in Eq. (1) gives

$$f_{\alpha\text{-roton}} p_{\text{roton-atom}} \approx 0.5\% . \qquad (2)$$

To consider the significance of this result it is necessary to take account of the kinematics of the evaporation process. If as believed [11] the evaporation is via a single-particle process, that is, if one excitation in the liquid (roton or phonon) evaporates one helium atom, then the requirements of conservation of energy and momentum parallel to the surface restrict the excitations which can cause evaporation to lie within a certain angular range from normal incidence. For rotons this range is between 15° and 25° [11], depending on the roton momentum. If we take an average angle of 20°, then we find that the requirements that energy and parallel momentum be conserved have the consequence that in the present geometry only 3% of the rotons have a *chance* to evaporate a helium atom. The difference between 3% and the experimental result of 0.5% is not surprising. In the first place not all of the energy of the α will go into roton production, i.e., the factor $f_{\alpha\text{-roton}}$ may be significantly less than unity. Second, even if an excitation is allowed by conservation laws to evaporate an atom, the probability that it will actually do so is not necessarily unity.

This discussion of the size of the signals ignores the contribution to the evaporation from rotons that are reflected from the walls of the container. However, the small solid angle in which the momentum vector of the roton must lie in order for evaporation to occur, together with the large ratio of wall area to free liquid surface in our cell, makes it unlikely that there is a major contribution to the signal from those rotons that are reflected from the cell walls.

In a separate experiment we have detected evaporation resulting from ^{137}Cs γ rays which Compton scatter in the liquid. We used a 5-mCi source external to the Dewar. The source was collimated so that it had a width of about 1 cm as it passed horizontally through the cell. Individual events were not recorded, but the steady-state temperature rise of the silicon wafer due to the adsorption of quantum-evaporated helium atoms could readily be detected. From the measured temperature rise and the known γ flux, we were able to show that the efficiency of the detector with the γ source (i.e., the ratio of the signal on the bolometer to the energy deposited in the liquid) was similar to that measured with the α source. With the movable γ source we were able to make a measurement of the signal as a function of the height of the γ source in the cell, and the results are shown in Fig. 4. These results are consistent with the general ideas about the evaporation process discussed above. When the γ source is near to the liquid surface, rotons whose momenta lie within an angle of $\sim 20° \pm 5°$ from the vertical direction can cause evaporation. As the source is lowered some of these rotons will no longer strike the liquid surface underneath the wafer, but will instead hit the walls of the cell or the outer regions of the free surface of the liquid. To study the evaporation process in more detail we have constructed a superconducting stepping motor to move the α source vertically and horizontally in the liquid. This will

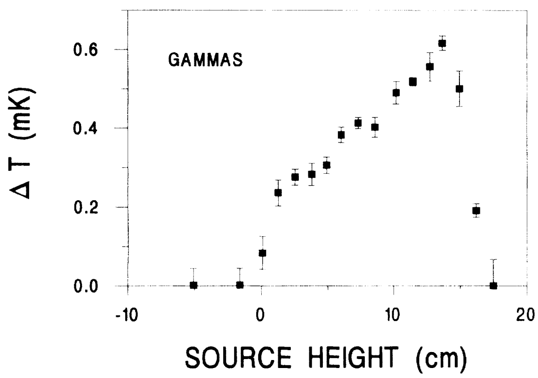

FIG. 4. The steady-state temperature rise of the bolometer on the silicon wafer as a function of height of the γ source. The bottom of the cell is at 0 cm, the liquid is at 14 cm, and the wafer is at 15 cm.

enable us to study, for example, how the number of atoms evaporated from a region of the liquid surface varies with the distance from the point directly above the α source, and to test our conclusion that the main part of the signal comes from rotons that have not been reflected from a wall.

In summary, we have detected helium atoms that have been evaporated from a superfluid bath by rotons excited by α particles and by recoil electrons from Compton scattering. We have measured the overall efficiency of this process and found it to be in reasonable agreement with expectations based on other experimental data. These results provide experimental evidence upon which to base an estimate of the energy threshold for observation of solar neutrinos in a detector of sufficient mass ($\sim$10 tons) to have useful counting rates ($\sim$20 events per day) for p-p neutrinos. Such a detector might use 10^3 to 10^4 wafers. The wafer-bolometer assembly we have used so far has a threshold of $\sim$50 keV and a mass of 1.2 g, whereas other groups [12] working with silicon or germanium have been able to achieve 2-keV resolution in as much as 60 g. Thus, it should be possible to reduce the threshold for an individual wafer to $\sim$0.1 keV. Allowing for geometric effects and for the analysis of the signals from a large number of wafers, it appears reasonable to expect a full detector threshold of $\leq$ 10 keV.

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