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PARTICLE DETECTION USING SUPERFLUID HELIUM

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Abstract

We have observed 5 MeV α particles stopped in volumes up to two liters of liquid helium at 70 mK. A fraction of the kinetic energy of an α particle is converted to elementary excitations (rotons and phonons), which propagate ballistically in isotopically pure ^{4}He below 0.1 K. Most of these excitations have sufficient energy to evaporate helium atoms on hitting a free surface. The evaporated helium atoms can be detected calorimetrically when adsorbed on a thin silicon wafer ($\sim$1.7 g, 35 cm^2) suspended above the liquid. Temperature changes of the silicon are measured with a NTD germanium bolometer. For the geometry studied the observed temperature change of the silicon resulting from an α event in the liquid is approximately 5% of the temperature rise from an α hitting the silicon directly. The implications of these measurements will be discussed as they relate to the possible construction of a large scale detector of solar neutrinos.

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1 Introduction

We are pleased to have the opportunity to discuss in this forum our current results on studies of the use of superfluid helium for particle detection. It was at the first of these workshops on low temperature particle detectors that we originally presented [1] some of the experimental considerations related to our proposed method [2] to detect low energy solar neutrinos using a large volume of superfluid helium below 0.1 K. Since that time we have been engaged in constructing a large dilution refrigerator and test cell to investigate the physics of the processes important for converting a low-energy particle event in helium to a detectable signal. Some preliminary results of this study are described below.

This paper is divided into four parts. First, we very briefly review the reasons for and the principles behind the use of helium for particle detection. Second, the important components of the apparatus are described. Third, our initial results using α particles stopped in helium are discussed. And finally, we comment on the implication of these results for the design of a full scale detector of solar neutrinos.

2 Principles

In considering the cryogenic detection of solar neutrinos one of the principal concerns is the problem of background. The neutrino event rate is so low that under most circumstances natural radioactivity in the detecting medium and its immediate surroundings will overwhelm calorimetric detection schemes unable to distinguish the origin of the heat inputs. The exception to this may be helium because of its phenomenal purity in the superfluid state.

The process by which solar p–p neutrinos may be observed in liquid helium involves the following sequence of events. In scattering a neutrino, an electron typically acquires a recoil energy of 100 keV. This kinetic energy is converted to various excitations in the liquid such as atoms in excited states, ions, and collective excitations, in particular elementary excitations

of the liquid, phonons and rotons. At low temperatures rotons and high energy phonons are stable and propagate ballistically for long distances. If an individual excitation strikes a free surface of the liquid and has an energy higher than the binding energy of a helium atom to the liquid (7.16 K), then it has a significant probability of evaporating an atom. Thus, the observation of a neutrino event is transformed into the detection of helium atoms evaporated from a liquid surface. We have estimated [1,2] that for a recoil energy of 100 keV approximately 10^7 atoms would be evaporated.

Estimating the response of a detector to a particle being stopped in helium is extremely difficult given our lack of quantitative understanding of the physics by which energetic charged particles produce excitations in the liquid. There are no measurements or calculations of many of the relevant processes in the literature. The dynamics of rotons and phonons are not known in several important aspects. The quantum evaporation process has been studied in considerable detail [3], but quantitative measurements are lacking on how the probability of evaporation depends on the energy and angle of incidence of the excitation. There is no information currently available on reflection of rotons by solid surfaces. The number of rotons ultimately incident on the free surface is dependent on scattering from walls and needs to be understood. These and other problems must be investigated in order to assess properly the utility of helium as a detector of neutrinos and other particles.

3 Apparatus

A schematic diagram of the apparatus constructed to study the interaction of particles in liquid helium is illustrated in Fig. 1. The two principal components are 1) the helium cell, at the top of which is a wafer with thermistor attached for calorimetrically detecting the evaporated helium atoms, and 2) a dilution refrigerator, thermally connected to the cell at several different points for reasons discussed below.

The detection of particles interacting in liquid helium by observing the evaporation of

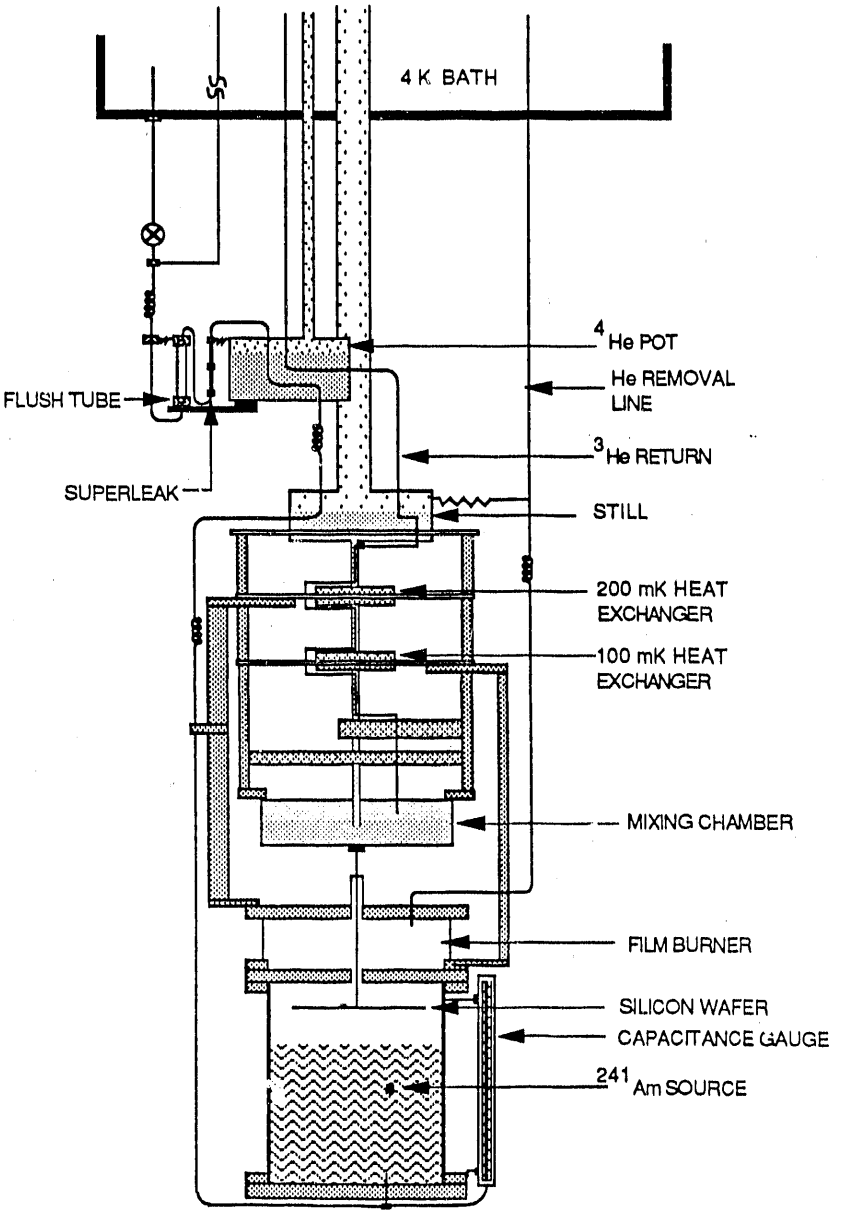

Figure 1: Diagram of the apparatus, not to scale, showing the principal components. Details of the film burner are omitted. A 4 K shield, which surrounds the apparatus, is 100 cm long and 30 cm diameter.

atoms requires that the liquid be at low temperatures for two reasons. Firstly, the equilibrium vapor density must be low so as not to obscure the small number of atoms evaporated as the result of a particle interacting in the liquid. This condition is easily met below 0.15 K since

at low temperature the saturated vapor pressure decreases exponentially with temperature ($p \sim \exp(-7.16/T)$). And secondly, for rotons and phonons to propagate ballistically the density of thermal excitations in the liquid, from which they can scatter, must be low. This condition is satisfied for $T < 0.1K$.

To ensure ballistic propagation it is also necessary to remove the naturally occurring concentration of the ^{3}He isotope from the liquid. Helium from wells has a ^{3}He concentration of 10^{-7} so that with a scattering cross section of $\sim 10^{-14}$ cm^2 rotons would have a mean free path of less than 1 cm. To remove the ^{3}He we have incorporated a heat-flush purifier based on the design of Hendry and McClintock [4], who achieve ^{3}He impurity concentrations of less than 10^{-13}. Our present system is such that we can transfer 1 liter of purified liquid ^{4}He from the main bath into the cell in about 10 hours.

One of the more complicated subcomponents of the apparatus is that labeled the "film burner" in Fig. 1. The design, construction and performance of the film burner is discussed in detail by Torii *et al.* [5]. Its function is to keep the wafer/calorimeter, suspended above the liquid, free of superfluid film. Normally any surface below 2.2 K in contact but above a bath of helium liquid will be covered by a superfluid film, which is held there by van der Waals' forces. The presence of the film on the bolometer exacts a serious penalty in calorimetrically detecting evaporated atoms since the heat capacity of the film may be many orders of magnitude larger than that of the underlying wafer. The burner maintains the wafer free of helium by intercepting the film as it flows toward the wafer and forcing it onto a large heated surface from which it evaporates. This evaporation process must be kept completely separate from the main section of the helium cell, and the wafer must be cooled well below the temperature of the evaporation surface. In our design roughly 500 μW is required to evaporate the film. This power is removed from the location at which the helium recondenses by a thermal connection to a special stage of the dilution refrigerator.

The main section of the test cell has a diameter of 10 cm and a length of 25 cm. An

electrical heater was placed at the bottom of the cell for use as a diagnostic source of phonons and rotons. An ^{241}Am α source of 60 Bq activity was located 7 cm above the bottom, and a 0.020 cm thick silicon wafer with attached NTD germanium thermistor [6] was placed 15 cm above the bottom. The area of the silicon was 35 cm^2, slightly less than half the area of the liquid surface. A capacitance level sensor was used to measure the height of the liquid in the cell.

In steady state the helium and the cell could be maintained at 70 mK. When the film burner was not in operation the wafer/calorimeter could be cooled to 20 mK, but with the burner functioning, the lowest achievable temperature of the wafer is presently 45 mK. This performance can be improved by correcting a heat transfer problem in one of the heat exchangers of the refrigerator.

4 Results

If the liquid helium level in the cell is below the ^{241}Am source, or if there is no helium in the cell, α particles strike the silicon wafer directly. The resulting temperature rise of the wafer free of helium film at 50 mK is approximately 1 mK with a time constant for return to equilibrium of 12 msec. At this temperature the α signal is roughly 100 times the noise. At lower temperatures, obtained with no helium in the cell so that the film burner does not have to be operated, the signal to noise ratio increases by another factor of three. A distribution of pulse heights is shown in Fig. 2 where it can be observed that the width of the distribution ($\sim$15%) is substantially larger than that of the incident α particles. This increased width is presumably due to a dependence of the size of the signal on the position at which the α hits the wafer. When two germanium thermistors were attached to the wafer, one at the center and the other near the edge, it was found that the ratio of the size of the two signals varied by about 25% from one α pulse to the next. This is not an unreasonable result given the dimensions of the wafer. Heat transport is limited by phonon scattering

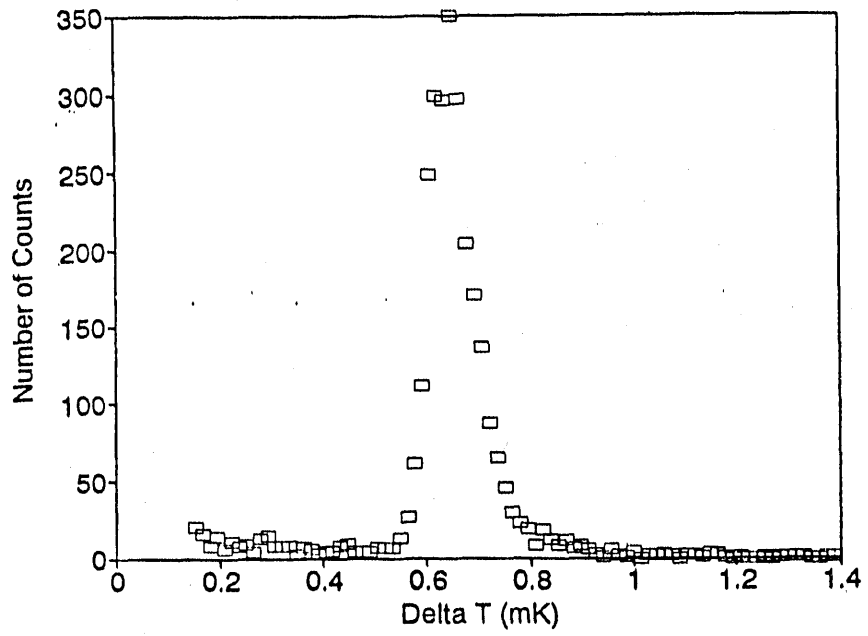

Figure 2: Pulse height distribution (3000 counts), expressed in terms of a temperature rise, for α particles incident directly on the wafer. The wafer temperature is 84 mK.

from the surfaces; the time constant for phonon diffusion across the wafer is comparable to the time for heat to flow out of the wafer through the leads.

If the total kinetic energy of the α particle is assumed to be transformed to heat, the estimated heat capacity (see Ref. [5]) of the bare wafer is substantially larger than that of bulk silicon, which has been measured at these temperatures[7]. At 50 mK the wafer has a heat capacity 10 times larger than silicon. The origin of this excess heat capacity is not understood [5]. It may be associated with the surface of the wafer. Its existence, however, decreases the present sensitivity of the detector.

When helium film is allowed to cover the wafer, the dominant contribution to the heat capacity results from the surface excitations (ripplons) of the film. The measured heat capacity of the film-covered wafer is in reasonable agreement with the sum of the ripplon contribution [8] and the measured heat capacity of the bare wafer. The ratio of the heat capacities of the film-covered wafer to bare wafer is approximately 6 at 50 mK.

With liquid helium in the cell the evaporated helium atoms resulting from a pulse of energy to the electrical heater can be measured by the wafer/calorimeter. Because the number and energies of the excitations produced by the heater is not known, the magnitude of the signal is of little value. However, the ratio of the response of the bare wafer to the film-covered wafer for a pulse of a given size is useful. That ratio for evaporated helium atoms is 60 at 50 mK; i.e., the temperature rise of the bare wafer is 60 times larger than that of the film-covered wafer for the same heat input to the liquid. Since the ratio of heat capacities is only 6, the other factor of 10 must come from the binding energy of helium atoms to the surface of the wafer. The sticking coefficient of a helium atom to a liquid surface [9] is close to 1, and the atom gives to the liquid not only its kinetic energy but its condensation energy of 7.16 K as well. The energy imparted to the film-covered wafer is the same as the energy given to the helium atoms in the process of evaporation from the bulk liquid. On the other hand, the binding energy of a helium atom to silicon [10] is in the range of 100 K. Thus, even though the sticking coefficient on the bare wafer [11] may be considerably less than 1, an amplification in energy of 10 can result, as predicted [1].

When the surface of the liquid helium is above the ^{241}Am source, the signals associated with α particles hitting the wafer directly disappear. In their place smaller signals arise that are the result of the α particles being stopped in the helium. The measured rates are very different but are consistent with the different geometries, 1.5 per sec for α hitting the wafer directly compared to 16 per sec for α being stopped in the helium. With the α source 7 cm below the surface of the liquid the signal is 20 times smaller than in the case of a direct hit. Taking into account the energy amplification of 10 this means that only 0.5%, ($\frac{1}{20\times10}$), of the kinetic energy of the α particle stopped in the helium is converted into the energy of the evaporated helium atoms that strike the wafer. With the present sensitivity the shape of the signal resulting from an α particle being stopped in the liquid is not observably different that when the wafer is hit directly by an α.

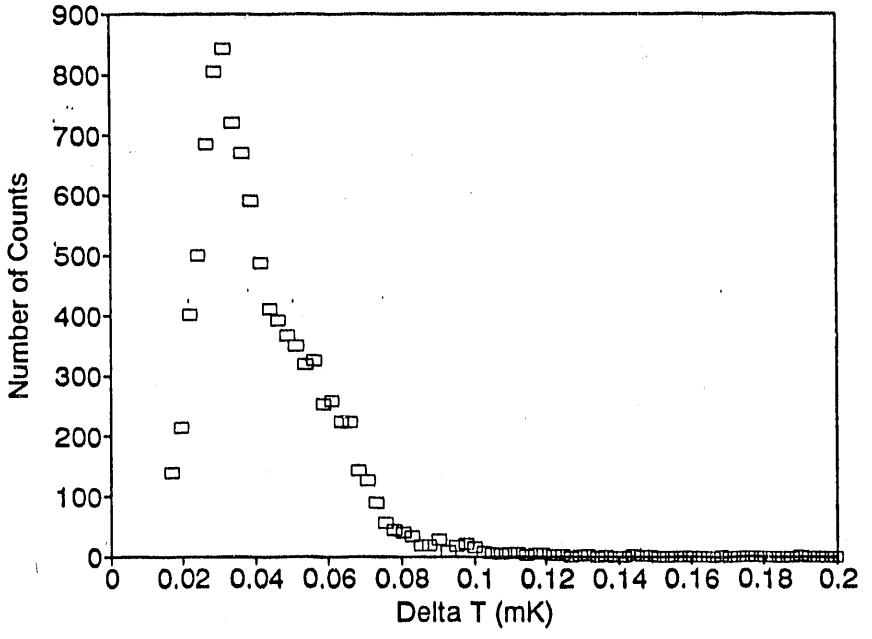

Figure 3: Pulse height distribution (10^4 counts), expressed in terms of a temperature rise, for α particles stopped 7 cm below the surface of liquid helium. The temperature of the wafer is 50 mK.

A plot of the pulse height distribution for α's stopped in helium is shown in Fig. 3. The reason for the peculiar shape of the distribution is not understood. The noise is certainly contributing to the increased width since the signal to noise is now only about 5; however, the assymetry to larger temperatures (energies) is unexplained. We can only speculate that this feature is related to the short range of the α particle (250 μm in helium) resulting in a dense cloud of rotons close to the solid surface from which the α's are emitted. The variation in track direction together with roton-roton and roton-surface interactions may lead to differences in the amount of energy that ultimately ends up as rotons.

To gain some preliminary understanding of the dependence of signal size on depth in the liquid at which the particles interact, a separate experiment was conducted using a collimated beam of γ rays from a 5 mCi ^{137}Cs source external to the dewar. The beam width in the vertical direction was limited to 1 cm at the location of the cell, and its position could be

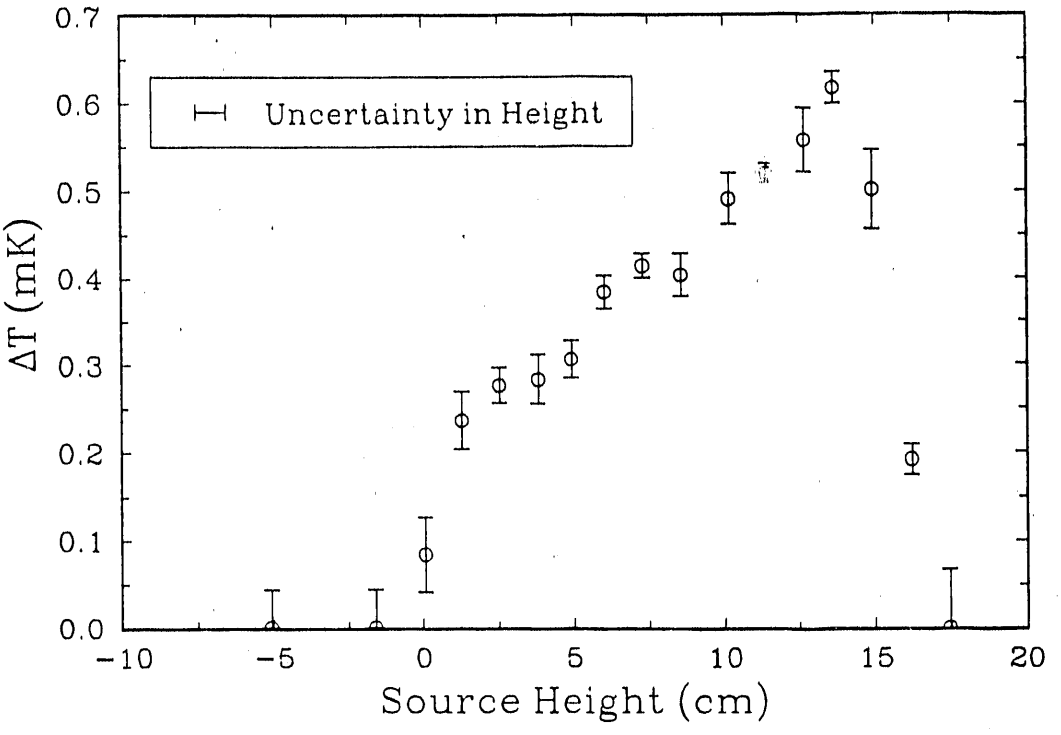

Figure 4: Dependence of the temperature rise of the wafer/calorimeter on the position of Compton scattering of γ rays from a ^{137}Cs source. The bottom of the helium cell is at 0 cm, the liquid level is at 14 cm, and the wafer is at 15 cm.

raised from the bottom of the cell up to the height of the wafer. The energy produced in the liquid as a result of the recoil of electrons from Compton scattering yielded a measureable temperature rise of the wafer. Individual scattering events could not be detected given the present sensitivity and the very high event rate, but the average temperature rise from the 5 mCi source could easily be observed. From the known activity, geometry and Compton cross sections it was calculated that the measured steady-state temperature increase was consistent with 0.5% of the recoil energy of the electrons going to produce evaporated helium atoms that strike the wafer. As can be seen in Fig. 4, there is a weak dependence of the signal on depth in the liquid, the signal doubling as the source is raised from the bottom of the cell to the position of the liquid surface.

5 Discussion

The calorimetric observation of α particles stopped in liquid helium is a clear demonstration that the basic principles of the proposed detector for solar neutrinos are sound. The principal issue now is whether or not the sensitivity for the detection of scattering events in liquid helium can be improved to the degree that interactions of p–p neutrinos from the sun can be observed in a large volume of helium [1,2].

The subject of sensitivity breaks up naturally into two parts. One topic is the sensitivity of the wafer/calorimeter to a heat input. The other is the subject of energy production in the liquid and its conversion into energy of evaporated helium atoms. Our approach has been to focus on the second of these two problems, which is unique to this research, in the belief that for improvements in the sensitivity of the wafer we will be able to benefit later from the work of others concerned with the development of low temperature calorimeters. In this regard, the performance of our wafer is at present certainly not comparable to that currently achieved by other research groups [12]. The threshold level of our wafer/calorimeter is roughly 50 keV at 50 mK with 1.7 g of silicon. This is two orders of magnitude poorer than what others now report. Part of our problem is the use of a room temperature amplifier for the first stage rather than coupling the germanium thermistor into a cooled FET [13]. Also, the heat capacity of the silicon is anomalously large. The origin of the excess heat capacity needs to be investigated and its magnitude reduced.

The reasons for the small, 0.5%, conversion of kinetic energy of an α particle into energy of evaporated helium atoms are not known in detail. However, it is likely that the low conversion efficiency is do in large measure to the kinematics of the evaporation process. If the evaporation is a single particle process; i.e., the energy of an elementary excitation in the liquid is converted totally at the surface into the energy of an gas atom, then the conservation of energy and of momentum parallel to the surface put limitations on the angle

of incidence the initial excitation in the liquid may have and produce evaporation. Brown and Wyatt [14] found that rotons capable of evaporating atoms are restricted to angles of incidence less than 15° to 25°, the limit dependent on the roton energy. Since the solid angle within a cone making an angle of 20° to the normal of a surface constitutes only 3% of that of a sphere, kinematic constraints may be much of the cause of the energy loss.

One might expect that reflections of rotons from surfaces could substantially increase the number of evaporated helium atoms. It is known from thermal transport measurements that rotons do not transfer energy to solid surfaces and are therefore thought to scatter from walls. However, the restrictions on the angle of incidence for evaporation together with the large ratio of wall area to free surface area requires that the excitations undergo many reflections before producing an evaporated atom. Even a small loss of excitations on reflection could severely diminish the contribution of scattered rotons. At the present time we have no experimental measure of the effect.

In order to investigate these questions in detail we are currently incorporating a superconducting stepping motor into the helium cell. By varying the various geometries involving source, wafer, free surface, and scattering surfaces we should be able to assess the separate parameters important to the conversion efficiency. Also, with improved efficiency of the calorimeter, the time dependence of the signal should resolve the contribution of roton scattering from solid surfaces.

The present results indicate that while the conversion of particle energy to evaporation energy is small, a detector of solar neutrinos using superfliud helium appears practical. By employing currently available calorimeter sensitivities we would have the ability to detect 10 keV events in a 1 liter volume (140 g). Because the calorimeter is distinctly separate from the medium in which the particle interactions take place, the threshold sensitivity does not decrease linearly with increasing volume of helium. However, the design of a large-scale detector does require a better understanding of the physical processes taking place in the

helium and must await further experimental results.

6 Acknowledgments

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