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**RESEARCH & DEVELOPMENT OF A HELIUM-4
BASED SOLAR NEUTRINO DETECTOR**

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PROGRESS REPORT

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Abstract

We report on work accomplished in the first 30 months of a research and development program to investigate the feasibility of a new technique to detect solar neutrinos in superfluid helium. Accomplishments include the successful completion of design, construction and operation of the entire cryogenic, mechanical and electronic apparatus. During the last several months we have begun a series of experiments in superfluid helium to test the method. Experimental results include the first observation of the combined physical processes essential to the detection technique: ballistic roton generation by energetic charged particles, quantum evaporation of helium at a free surface and bolometric detection of the evaporated helium by physisorption on a cold silicon wafer. Additional results are also presented.

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I. INTRODUCTION

We are reporting on progress in a project to test the feasibility of detecting low energy solar neutrinos in real time, with good energy resolution and with sensitivity to both the charged and neutral weak interaction.

A particular challenge to achieve this in any detector concerns the necessity of having the intrinsic and induced radioactivity in the detecting medium itself as low as possible. This requirement becomes especially difficult because of the large mass (typically 10 tons) required.

Liquid helium at low enough temperatures (100 millikelvin) has many properties which suggest it may be the best, and perhaps unique, medium for such a solar neutrino experiment. Among these properties are its freedom from any long lived intrinsic (or induced) radioactive isotopes, its exclusion of other atomic species from its superfluid bulk and several quantum liquid features (roton stability and propagation, carrier multiplicity and quantum evaporation) promising real time energy measurement. Additionally, the price of helium is very attractive relative to any other especially refined materials.

Nonetheless, to demonstrate that these attractive features can lead to a feasible and realistic solar neutrino experiment is a significant challenge requiring, as it does, the use of sophisticated cryogenics and the uniting of diverse quantum phenomena into a functioning detection process. However, the fundamental physics to be explored by such a solar neutrino experiment is very compelling as is the need for this unique technique to carry it out. (See Section II).

Subsequent to the formulation and publication (Ref.1) of the original suggestion to this approach, we formed a group of physicists with complementary expertise in particle/nuclear, low temperature and condensed matter physics and, with Department of Energy support, initiated work. We have recently begun experimentation after an intensive period of design, construction and testing of the special purpose cryogenic equipment needed for the experiments to study feasibility of the technique. (See Section IV).

Our results so far are very promising and demonstrate for the first time that the basic processes can be made to combine in such a way that the detection of alpha particles by the proposed method has been achieved (See Section V).

In the following sections we elaborate on each of these points.

II. PHYSICS MOTIVATION

The intrinsic properties of the neutrino (mass, magnetic moment, charge radius and quantum numbers) and its interactions are of fundamental relevance to nuclear, particle and astrophysics.

For example, in double beta decay of nuclei the Majorana versus the Dirac nature of the neutrino is a crucial question. Whether or not the neutrino has a mass is of significance not only to double beta decay but to many areas of astrophysics (big bang cosmology, stellar evolution, supernovae dynamics, etc) but particularly to nuclear and particle physics because most theories of unification of the fundamental forces allow or require a mass for each of the neutrino families. Many extensions of the "standard model" (Glashow, Salam, Weinberg) of electroweak interactions suggest very small masses for them. However, it should be kept in mind that there is remarkably little theoretical guidance as to the most likely part of mass and mixing phase space to be populated.

Extensive experimental searches have been conducted terrestrially at reactors, accelerators and in beta decay (e.g., tritium and neutrinoless double beta) searches. No confirmed evidence for a finite neutrino mass has resulted. The well established limits are confined to relatively high masses (e.g. <10 eV from LANL tritium, <6 eV from double beta decay) in direct searches and to modest mass and mixing angles in neutrino oscillation searches (e.g., $\delta m^2 < 0.02 \text{ eV}^2$ and $\sin^2 \theta_\nu < 0.1$ or $\delta m^2 < 0.6 \text{ eV}^2$ and $\sin^2 \theta_\nu < 2 \times 10^{-3}$).

In light of these negative results several points should be emphasized:

- a) In spite of its successes, the "standard electroweak model" cannot be complete and at some scale its correct extension should be manifested.
- b) As an example of one of these extensions relevant to neutrino mass is the expectation via the Gell-Mann-Ramond-Slansky "seesaw" mechanism" that there should be a mass hierarchy of neutrinos such that $m_{\nu j} = (m_{ej})^2/M$ where M is the large mass scale where the electroweak and strong interactions would be unified and m_{ej} we take to be the mass of the associated charged fermion.

For example, if $M = 10^{15} \text{ GeV}$ then the masses for $\nu_e : \nu_\mu : \nu_\tau$ would be $10^{-13} : 10^{-8} : 10^{-5} \text{ eV}$.

- c) Masses this small can be tested only by neutrino oscillation experiments and we see that terrestrial capability to this level is essentially exhausted. There are cosmic rays experiments which utilize neutrinos from the upper atmosphere and these will which barely reach 10^{-5} eV ; however they are limited to essentially full mixing ($\sin^2 \theta_v = 1.0$) and have no confirmed positive results either.
- d) It therefore becomes necessary to utilize sources with source-target distances of extra terrestrial size and producing low energy neutrinos.

If these were the only arguments, the sun would recommend itself to be a source of choice for such tests. However, the historic experiment of Davis et al, begun two decades ago for reasons other than neutrino mass, and the subsequent experiments also now in progress (Kamiokande and SAGE—and soon, GALLEX) have not only proved the efficacy of the use of the sun for neutrino experiments but have provided us with exciting results possibly suggesting new physics. A proof of new physics or an understanding of the origin of the present “solar neutrino puzzle” will require further experimentation with the existing techniques as well as the development of new ones—particularly those which will allow detection of the neutrinos from the reaction

$$p + p \rightarrow d + e^+ + \nu_e$$

in real time, with energy resolution and with sensitivity to both charged and neutral current. Our proposed technique utilizing superfluid helium is designed to do just that. (Section III).

The present status of the “puzzle”, its understanding and relevance to our experiment is essentially as follows. The Davis et al (or Homestake) radiochemical (Ref.2) experiment utilizing the reaction

$$\nu_e + {}^{37}\text{Cl} \rightarrow e^- + {}^{37}\text{A}$$

measures a rate of $2.1 \pm 0.3 \text{ SNU}$ when the expected rate (with appropriate threshold

and spectra folded-in) according to the "standard solar model" (Ref.3) is 7.9 ± 2.6 SNU.

The Kamiokande experiment (Ref.4) which is a real time, Cherenkov detector experiment measures a ratio (signal/std model) of 0.46 ± 0.05 (stat) ± 0.06 (syst). The reaction used is neutrino-electron scattering

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

whose kinematics provide unambiguous evidence that the detected neutrinos originate in the sun. In addition, the recoil electron energy spectrum reflects their origin.

The two experiments have somewhat different thresholds, 0.8 MeV for Homestake and 7.5 MeV for Kamiokande. Thus Kamiokande detects dominantly the 8B neutrinos while Homestake has not only 8B but also sensitivity to the 7Be , pep and CNO reaction neutrinos.

A very instructive direct comparison can be made of these data. Using the Kamiokande data the rate it would predict for 8B alone in Homestake would be 2.8 ± 0.3 SNU. To this rate must be added 1.1 SNU for 7Be and 0.2 SNU for pep for a total rate of about 4 SNU. This would appear to be about the maximum rate established by experiment. It does not appear that reasonable alternative models of the sun itself based upon known physics can give fluxes this low (Ref.5). Several authors have attempted to make analyses consistent with both experiments. They are all based upon neutrino oscillation phenomena either with or without MSW effects (Ref.5,6).

A particularly interesting one is the analysis of Bethe and Bahcall. (Ref.5) From this analysis they conclude that a solution to the "puzzle" can be found if the non-adiabatic MSW effect with a neutrino mass parameter of $\delta m^2 = 1 \times 10^{-8} \sin^{-2} \theta_V$ as the cause. This indeed would be new physics implying a finite, non-degenerate neutrino mass as well as lepton flavor non-conservation. This solution then permits predictions for the rates to be found for the $p-p$ and 7Be neutrinos. For the radiochemical experiments with gallium, which are sensitive only via the charged weak

current, only 0.03 of the "standard solar model" rate is to be expected. Indeed, the preliminary results from SAGE (Ref.7) based upon four months data give a best fit of 0 SNU and < 72 SNU at 68% C.L. with 132 SNU expected in the "standard solar model".

If this or almost any other solution is to be tested or proved correct at least four more things are required:

- a) Confirmation of the SAGE results by GALLEX.
- b) Observation of the $p-p$ and ${}^7\text{Be}$ spectrum.
- c) Observation of the neutral current interaction for the $p-p$ and ${}^7\text{Be}$ neutrinos.
- d) Observation of the neutral current for the ${}^8\text{B}$ neutrinos (the Sudbury Neutrino Observatory is expected to achieve this as part of its extensive program).

Currently, there exists no technique to carry out (b) and (c) for $p-p$ neutrinos. It is the aim of the work discussed here to establish the feasibility of accomplishing this as well as for ${}^7\text{Be}$ neutrinos. Because this technique is sensitive to both the charged and neutral current, the expected rate it would see in the Bethe-Bahcall scenario should be 0.14 of the "standard model" - still several events a day in a 10 ton detector - and thus would provide an essential, major part of the full experimental test for new physics. Several authors (Ref.5,8) have made this point concerning the need for seeing the $p-p$ and ${}^7\text{Be}$ neutrinos by the cryogenic technique with superfluid helium.

In what follows we discuss the progress we have made so far in testing the feasibility of solar neutrino detection in superfluid helium.

III. PRINCIPLES OF THE SUPERFLUID HELIUM TECHNIQUE

The limitations associated with the existing detection techniques for $p-p$ and Be solar neutrinos as discussed in the previous section have led us to consider another approach. We believe that liquid helium can be used as the major component of a very sensitive calorimetric detector, with the major advantage of being able to achieve very low background levels.

From the point of view of the elimination of background, the ideal detector material is certainly liquid helium. Helium is the only element which remains a liquid down to $T = 0K$. Consequently all other elements freeze out on the walls of the container of the liquid. For example, a H_2 molecule in liquid 4He has an energy approximately 80 K greater than in solid hydrogen. Thus, the solubility of H_2 in helium is proportional to $\exp(-80/T)$, and is totally negligible below 1 K. If by some process an impurity is introduced into the interior of the liquid, it moves very rapidly through the superfluid liquid and quickly absorbs onto the container wall. Thus, in contrast to solids, helium may be considered to be a self-cleaning system.

The idea of our experiment is shown in the cartoon of Fig. 1. A solar neutrino of energy E_μ scatters elastically off an electron, and transfers energy

$$E_{rec} = \frac{2m_e c^2 E_\mu^2 \cos^2 \theta}{E_\mu^2 (1 - \cos^2 \theta) + 2m_e c^2 E_\mu + (m_e c^2)^2}$$

where θ is the propagation direction of the electron relative to the direction of the incident neutrino. The energy of the recoil electron is transferred to the liquid helium in a few mm by a number of processes, secondary ionizations, the generation of elementary excitations in the helium (phonons and rotons) and the creation of other entities such as metastable He_2 molecules in excited states. Much of the energy that initially goes into producing positive ions and electrons is most likely to end up as rotons, when the He^+ ions form He_2^+ complexes and the electrons create bubbles (Ref.9). Some significant fraction of the total energy appears ultimately on de-excitation and recombination as photons, principally in the ultraviolet, since liquid

helium is known to function as an effective scintillator (Ref.10). Nonetheless, another substantial fraction of the energy must appear finally as elementary excitations of liquid ^4He , the dispersion curve for which is shown in Fig. 2a. Because of the large phase space associated with rotons, as seen in Fig. 2b, almost all this energy will be at large momenta in rotons and high frequency phonons. No comprehensive measurements have yet been made on the division of the kinetic energy of an electron in liquid helium, and we assume by way of illustration that the fraction f of that energy appearing as rotons is 0.5. If this fraction turns out to be appreciably smaller, say 0.1, the design of the proposed detector is still valid albeit the minimum energy that can be detected is somewhat increased.

In superfluid helium at $T = 0\text{K}$ a roton is a stable excitation because, for kinematic reasons, there are no decay modes. At finite temperatures there is a thermal distribution of phonons and rotons in the liquid, and a roton is scattered by collisions with these thermal excitations. However, at 0.1K the density of the thermal excitations is so low that the rate of scattering of a roton is negligible (Ref.11). Rotons can also scatter from ^3He impurities in the liquid, but it is easy to reduce the ^3He concentration to a level such that this scattering is unimportant.

At the free surface of the liquid, rotons can induce evaporation of helium atoms. This has been studied experimentally by Wyatt et al (Ref.12). Their conclusion is that a roton (or a high energy phonon) incident on the liquid surface has a probability of roughly 1/3 of inducing the evaporation of 1 helium atom. For an electron recoil energy, E_{rec} of 200 keV, the number of rotons produced is $\sim fE_{rec}/\Delta \sim 1.4 \times 10^8$. (We make the approximation that all rotons have an energy close to the minimum roton energy $\Delta = 8.6\text{K}$.) The number of helium atoms evaporated from the surface of the liquid is thus $\sim 5 \times 10^7$. (This assumes that rotons which leave the electron track in the direction of the sides or bottom of the helium container will be reflected elastically at these surfaces, and eventually find their way to the free surface of the helium. We will discuss this question further in our renewal proposal).

To detect these ^4He atoms we suspend thin plates of a high purity, high Debye temperature, crystalline, dielectric material such as silicon 1cm above the surface.

The ^4He atoms which evaporate will be absorbed (physisorbed) onto the Si surface (Ref.13). Each atom generates in the Si an amount of heat equal to the binding energy ϕ between ^4He and a Si surface (Ref.14). This binding energy is roughly 100K, and originates in the van der Waals attraction between a helium atom and the silicon surface. Notice that the energy deposited in the Si is

$$E_{Si} \simeq \frac{1}{3} f \frac{\phi}{\Delta} E_{rec}.$$

Thus, with $f = \frac{1}{2}$, E_{Si} may be two times larger than the kinetic energy of the electron, and so for a 200 keV electron E_{Si} is 6×10^{-7} ergs. Hence, this design not only efficiently collects the energy deposited by the electron, but actually provides some amplification.

If the area of the Si plate is $A \text{ cm}^2$ and the thickness is $d \text{ cm}$, the heat capacity is

$$C = 6.25 \times 10^{-7} A d T^3 \text{ joule/K}$$

As representative numbers we might take $A = 100 \text{ cm}^2$, $d = 0.02 \text{ cm}$. and $T = 20 \text{ mK}$. Then the temperature rise δT_d of the Si wafer caused by an electron recoil of 200 keV is 3mK, which is very easy to measure.

It is precisely this sequence of processes which has been the goal of the research discussed below. We have constructed a small-scale prototype apparatus to carry out the initial investigations.

IV. APPARATUS

The apparatus to test the principles of the proposed neutrino detector is rather complex owing to the need to satisfy several conditions. A large working volume at very low temperatures is needed. Heat extraction rates at low temperatures are fairly high. The nature of bolometric detection is such that the system is likely to be extremely sensitive to mechanical vibration and electrical noise. Because of this complexity and the difficulty in making changes once the basic construction has been started, we have adopted a conservative approach to the design. This conservatism has led to a rather longer building phase than we had originally anticipated, but it has already been shown to be justified in that we have had to make no major, time consuming changes from the original design.

We have broken down the apparatus into its major component systems and discuss them separately in the following sections. Some of the subsystems are large and costly while others are small but essential to the overall success of the project.

A. Dilution Refrigerator

The essential component of any experiment being conducted in the millikelvin region is its refrigeration system. Dilution refrigerators are normally the method of choice for achieving temperatures in this region and several models may be purchased commercially. However design considerations, which could not be satisfied inexpensively or easily with commercial units because of cost and delivery times, led us to construct our own. The unusual features of our design that prompted this conclusion were the following. 1) The need to extract reasonably large amounts of heat at two different stages, 100mK and 200mK. 2) The desire to have a large working volume at 100mK, potentially 10 liters of liquid helium). 3) The importance of having the bolometer/detector at as low a temperature as possible, certainly below 50mK and preferably below 20mK.

We have built a relatively high circulation rate dilution refrigerator. It is capable of circulating in excess of 1 mmole/sec, but for our current experiments it has been operating at 0.5 mmole/sec. It uses the usual counterflow heat exchangers

plus a discrete exchanger of the Frossati (Ref.15) type just above the mixing chamber. Between sections of the counterflow exchanger are inserted two special sintered exchangers, one at 200mK and the other at 100mK. These provide the coupling to remove the large heats from the experimental cell at these temperatures. The design of the refrigerator is illustrated in Fig. 3 along with other of the low temperature parts of the apparatus.

The pumping system for the still of the dilution refrigerator consists of an Edwards model EH1200 roots pump backed by an Alcatel model 2063H rotary pump. The gas handling system for the refrigerator is fairly standard.

The mixing chamber of the dilution refrigerator is capable of reaching 16mK under conditions of no heat load. With high recirculation rates and heat inputs to the 100mK and 200mK plates the base temperature of the mixing chamber is 30mK.

B. Cryostat

The liquid helium/liquid nitrogen dewar was a special order based on conventional design. The only mildly unusual feature of the cryostat configuration was the use with a dilution refrigeration of a design in which the vacuum surrounding the refrigerator is common with that of the liquid nitrogen and liquid helium reservoirs. The 1K helium pot and the dilution refrigerator are suspended below the bottom plate of the helium reservoir. This makes access to the low temperature components extremely easy, requiring only one O-ring vacuum seal at room temperature. It does mean one added complexity, however. In order to cool initially from room temperature to 4K a special system is required in which first liquid nitrogen and then, in turn, cold helium gas can be circulated.

The principal reason for choosing a design with the cell hanging well below the main components of the cryostat and refrigerator in a common vacuum is that shielding from background radiation is simplified. The only materials between the experimental cell and the outside world are copper thermal radiation shields and the outer vacuum jacket of the tail section of the dewar.

C. Mechanical Support

With a goal of constructing a calorimetric detector having an energy sensitivity the order of 1 keV or less one must be very concerned about mechanical effects. Since the mass of the wafer may be several grams and it must be suspended with little support above a helium bath, we have taken the trouble to mount the dewar/cryostat system on a massive table which is supported by air mounts. All vacuum lines, including the 8 inch pumping line connecting the mechanical pumps to the still of the dilution refrigerator, contain special bellows assemblies to reduce the transmission of vibrations to the cryostat/detector.

The allocation of time and resources to this problem in the early stages of construction has proved to have been well worth the investment.

D. Electrical Shielding

Electrical pick-up presents a problem comparable to mechanical vibrations in potentially degrading the sensitivity of the detector. To provide as electrically quiet an environment as possible a double screened room was constructed surrounding the cryostat, parts of the gas handling system and the electronics. All pumping lines passing into the screened room are electrically isolated from each of the two layers of separately grounded shielding. Power lines into the room are specially filtered. All sensitive leads leading to the bolometers are shielded coax. Even so, the best results are obtained with all power to the screened room disconnected and essential equipment, e.g. low noise amplifiers, operated from batteries.

E. Helium Purification System

The presence of small amounts of the isotope ^3He can have a substantial influence on the propagation of rotons in superfluid ^4He at low temperature. The cross section for roton scattering from ^3He is the order of 10^{-14}cm^2 so that even the naturally occurring concentration of ^3He in ^4He of 1 part in 10^7 can limit the roton mean free path to less than 0.1cm and thereby make neutrino scattering in the liquid undetectable.

Fortunately ^3He can be separated from superfluid ^4He in a relatively simple manner by using of a heat current to drag the ^3He to one end of a tube. We have

constructed such a heat flush purifier based on the design of Hendry and McClintock (Ref.16) who were successful in reducing the concentration of ^3He to less than a part in 10^{13} . The configuration of the helium fill system containing the purifier is illustrated in Fig. 4. In addition to the heat flush tube, the fill line contains a superleak consisting of fine packed carbon black, which can be used as valve. If heated above the superfluid transition the viscosity of liquid helium in the normal state is sufficiently high to shut off the flow effectively.

Filling of the cell is monitored using a capacitance gauge consisting of a pair of vertical coaxial cylindrical plates the liquid helium being able to occupy the space between them. The sensitivity of the capacitance bridge is such that the level in the experimental cell can be monitored to 0.1cm.

We have not measured the degree to which the ^3He concentration has been reduced by our heat flush purifier, but nonetheless we have ample evidence that it is functioning satisfactorily. As discussed in section V E the introduction of ^3He into the purified ^4He at the naturally occurring level of a part in 10^7 has a profound effect on the signals we detect from the liquid.

F. Film Burner

The sensitivity of our detector to a change in temperature is inversely proportional to its heat capacity.

$$\Delta T = \Delta E / C.$$

In this experiment involving the calorimetric detection of helium atoms evaporated from a bath of liquid helium at very low temperature a problem arises in that a superfluid film covers all surfaces within a closed container. This film formed because of the van der Waals interaction of the helium with the solid surfaces is the order of 300 Angstroms thick and has a heat capacity principally due to surface excitations, ripplons, with magnitude given by

$$C_{rip} = 2.1 \times 10^{-9} T^{4/3} \text{ joule/Kcm}^2.$$

By way of comparison the heat capacity of the dielectric wafer itself, which serves

to collect the evaporated helium atoms, can be made quite small. For example, the lattice heat capacity of silicon is

$$C_{Si} = 6.2 \times 10^{-7} T^3 \text{ joule/Kcm}^3$$

For a 0.02cm thick silicon wafer the ratio of surface (2 sides) to volume is 100 cm^{-1} . Then the ratio of ripplon to silicon heat capacities is

$$C_{rip}/C_{Si} = 0.34 T^{-5/3},$$

which at 50mK is 50 and increases to 250 at 20mK. Obviously, to increase the sensitivity it is important to remove the superfluid film from the detector.

The removal of the film must be a continuous process. The detector from which the film is to be removed has to be maintained at low temperature and at the same time the superfluid film cannot be allowed to flow over the support structure back onto the detector. This is accomplished by heating a region of the support to a temperature sufficient to evaporate the film completely. The film in flowing towards the bare region is continuously evaporated (burned off) before reaching the detector. The geometry and materials of the structure are chosen so that the detector can be maintained below 30mK while the burner can be heated as high as 3K if need be. The evaporated helium is condensed back onto the surfaces from whence the film originally came. In addition, baffling ensures that the gas atoms from the burner cannot make their way to the detector.

The design of our film burner is shown in Fig. 5. The silicon wafer/detector is attached to a support plate with a weak thermal link. The plate, in turn, is connected to a 0.15cm diameter OFHC copper rod, which runs through a 0.5cm diameter stainless steel tube and then through a vacuum seal at the end of a stainless stand-off. The end of the rod is attached to the mixing chamber of the dilution refrigerator. The film is prevented from reaching this copper rod and hence the detector by forcing the film to flow from the surrounding walls onto the outside of

the 0.5cm diameter tube and then onto the heated section of the evaporator. The heated portion can be held well above 1K with only the order of 10^{-5} watts being transferred by conduction to the top plate of the chamber. In contrast, the order of 5×10^{-4} watts is required to evaporate the helium, a power that must be removed from the top and side walls upon which the gas recondenses. The temperature of the post and detector is essentially unaffected by heating the burner since the thermal contact of the post to the mixing chamber is two orders of magnitude better than through the stainless steel stand-off to the top of the chamber.

The amount of film flowing onto the burner is limited by the cylindrical section of the top of the chamber where the film is required to flow vertically upward before flowing down the 0.5cm tube. The limiting flow velocity of 50 cm/sec together with the thickness of the film of 2.5×10^{-6} cm and constricting perimeter of 2cm yields a volume flow rate of 2.5×10^{-4} cm³/sec, a value requiring 5×10^{-4} watts to evaporate. This value agrees well with the measured performance of the film burner illustrated in Fig. 6. At low power the temperature of the burner rises rapidly until evaporation begins. Once the temperature reaches approximately 0.40K almost all the heat goes into evaporation, but the film is not completely evaporated until a power level of 4.7×10^{-4} watts is reached. At higher power levels, since there is no more film to evaporate, the temperature rises rapidly, determined by the conduction of the stainless tubing. The calculated temperature dependence illustrated by the solid curve in Fig. 6 using one adjustable parameter, the film flow rate. The agreement of the experimental results with theory is certainly satisfactory for the purposes of this apparatus.

The elaborate baffling section, which physically forms the largest part of the burner, is required for the following reason. An energy input of 1 keV to the detector represents the condensation of only 10^5 helium atoms on a bare silicon surface. However, the burner evaporates 5×10^{18} atoms per second. Even if the sticking coefficient of a helium atom on a helium-coated surface were 0.99, many collisions with walls are required to ensure that a significant number of atoms do not make it through the maze.

To conclude this section we note that the film burner can be maintained above 1K, the chamber walls on which the helium recondense at 200mK, the experimental helium cell below 100mK, and the detector below 30mK.

G. Helium Cell

The experimental cell for testing the concepts of the proposed neutrino detector is illustrated in Fig. 7. The cell has an inner diameter of 10cm and a depth of 25cm. A silicon wafer (wafer A in Fig. 7) 0.02cm thick having a surface area per side of approximately 35cm^2 is suspended from the copper post 2cm below the top of the cell. The wafer has attached to it by epoxy a neutron transmutation doped (NTD) germanium resistance bolometer. The germanium bolometer was provided to us by E. Haller of LBL (Ref.17) and is from the same batch as used by Wang et al (Ref.18) in their work on low temperature calorimetry for a detector of dark matter.

Also, for diagnostic purposes a second smaller silicon wafer (wafer B in Fig. 7) with its own germanium bolometer is located 5cm below and to the side of the first principal detector.

Two separate ^{241}Am alpha sources have been used. One is positioned 2cm directly below the principal detector and has an activity of approximately 1 Bq. About 0.6 alphas per second hit the principal detector if no helium is above the source. A second ^{241}Am source is contained within a small metal cylindrical collimator having a hole such that approximately 3 alphas per second emerge to strike the secondary silicon wafer. In addition a ^{113}Sn source providing monoenergetic 364keV electrons is positioned as shown in Fig. 7. It has an activity of 2 Bq.

We also employed in the early testing of the apparatus, a small electrical heater consisting of a coil of tungsten wire, which can be pulsed to provide a synchronous roton pulse for diagnostic purposes. Its location within the cell is indicated in Fig. 7. Attached to the outside of the cell is the capacitance level sensor.

The cell itself is attached in such a manner that it can be easily removed and replaced by another of different size or configuration should the need arise.

H. Data Acquisition System

In designing the data acquisition system for this experiment we adopted a conservative approach. Since the scale and dynamic range of the data in which we are interested can vary over many orders of magnitude, we chose components and developed software adaptable to these varying circumstances. For the center point of this system we chose a DEC Micro VAX II since Brown's campus-wide software license to all of Digital's products allowed us to acquire many powerful software development tools. This powerful machine has been very successful in meeting our present needs. Other components of the system include a Stanford SR-560 low-noise preamplifier, and a LeCroy 9400A 100 mega-sample/second digital oscilloscope. The main communication link is via an IEEE-488 (HP-IB) bus anchored by a National Instruments controller card for the MicroVax II. The easiest way to describe how this system functions is to follow the data path from the detector to the storage system, see Fig. 8.

The detector is connected to the outside world via stainless steel, twin-twisted conductor, coax cable, which runs from the low temperature area of the apparatus to hermetically sealed tri-axial connectors at the top of the cryostat. Tri-axial cable is used to connect the top of the cryostat to the input stage of a Stanford Research SR-560 low-noise preamplifier. The special cabling is necessary to eliminate both electrical and magnetic environmental noise. The preamplifier provides movable filtering over a 1 MHz bandwidth and up to 50000 gain, and is battery powered. The signals we are currently observing are of the order of a few microvolts and are thus easily contaminated before they are boosted by the amplifier.

After amplification the signal is then digitized by a LeCroy 9400A digital oscilloscope. The oscilloscope has a flash analog to digital converter which is capable of 100 mega-samples per second into a 32000 point memory. The oscilloscope is capable of performing fast digitization from the nanosecond to the 100 second time scale with very fine time resolution and has proven faster and much easier to use than most computer-based analog to digital converters (ADC's). The oscilloscope does most of the work in computing the sample rate and appropriate preamplifier gain to get the

most performance out of the ADC. Our chief worry in choosing this system over an ADC computer board was in through-put speed from digitization to disk storage. We have, however, been able to achieve over 150 kilobytes per second sustained data transfer from digitization to disk storage.

The central processor for this system is a DEC MicroVAX II with 11 MBytes of main memory, 660 MBytes of disk storage, and a 90 MByte cartridge tape drive. The data is transferred over an IEEE-488 (HPIB) bus using a National Instruments controller card capable of transferring 250 kbytes/sec. The Brown software license has provided us with compilers, graphics packages and interface libraries, which we have used to develop our controlling software.

The data acquisition software we developed was specifically designed to transfer data quickly and easily from the oscilloscope to permanent storage. To do this we have invented a special file format which stores multiple events in native VAX disk format, and is optimized for extremely quick transfer rates. The data is also multiply buffered and then written to disk asynchronously with data transfers from the oscilloscope. This allows us to move data virtually simultaneously from the digitizer and to the storage system, yielding a 50% increase in our sustained transfer rate. We have also developed many software tools to complement our acquisition software. These include graphical display, pulse height analysis, fast fourier transforms, smoothing, and averaging.

The design goal throughout this systems development was that it be easily adaptable. Both the software and the hardware are constructed in such a way as to be modular. Any component of the system, either hardware or software, can be replaced or modified with only a minimum effect on the other components.

V. EXPERIMENTAL RESULTS

Since the design and construction phase of our proposed research program consumed most of the first two years of the three year grant period, we have been able to make diagnostic measurements and take data for considerably less than a year now. The dilution refrigerator was operated for the first time in March 1990. Since that time we have been engaged in testing and calibrating the various subsystems, optimizing their performance and correcting problems that invariably arise in the shake-down of any low temperature apparatus, such as leaks, poor thermal contacts, improper impedance to fluid flow, etc. We now have made substantial progress in demonstrating the successful performance of all the components of the apparatus. In the past few months we have been able to complete three cool-downs of the refrigerator which resulted in the measurements described below. The turn-around time between cool-down depends on the extent of the modifications to the apparatus but is typically about a month.

A. Bolometers

The need for very sensitive, low heat capacity bolometers operating below 100mK is certainly not unique to this experiment. Much work has been performed over the past two decades in developing such devices. In this many-faceted experiment we have chosen so far to devote our development effort to those parts of the equipment for which we could not rely on the work of others and wherever possible have used existing technology developed for other purposes.

We were very kindly supplied by E. Haller of LBL (Ref.17) with neutron transmutation doped germanium bolometers, which are very sensitive in the temperature region below 50mK. Careful measurements of the properties of this type of bolometer have been carried out by Wang et al (Ref.18). Our measurements of the temperature dependence of the resistance of a $1 \times 0.2 \times 0.5$ mm chip of this material mounted on a silicon wafer are substantially the same as found by the Berkeley group. The resistance vs. temperature in the limit of very low measuring current is shown in Fig.9 and is given by the equation

$$R = 1.0 \exp(6.7/T)^{\frac{1}{2}}$$

The voltage versus current profiles for different temperatures is shown in Fig. 10. Again, the results are in general agreement with Wang et al.

The limitation in measuring small temperature changes is obviously related to the noise level of the bolometer and the measuring system. The noise in our system is primarily that resulting from the room temperature amplifier used to detect the voltage from the bolometer. Contributions from electrical pick-up and heating from mechanical vibrations have been largely, but not completely, eliminated. We are currently using a Stanford SR-560 for the amplifier but have under construction a low temperature amplifier based on the designs of Lee and of Stanton (Ref.19).

B. Bare Silicon Wafer

In the absence of any helium in the experimental cell, alpha particles from the ^{241}Am source can readily be observed hitting the silicon wafer(A). Fig. 11 shows a trace of a single α event of approximately 5 MeV. The signal to noise ratio is the order of 100. The measured distribution of pulse heights of alpha particles hitting the silicon is shown in Fig. 12. This distribution is in part due to the energy loss of the α 's in the gold coating of the source (the measured α spectrum using a silicon surface barrier spectrometer peaks at 4.7 MeV and has a width of approximately 15%). This spectral width of the source is not sufficient, however, to account for the pulse height distribution of Fig. 12. We do not, at present, have a definitive explanation of the observed variation in apparent energy deposited in the wafer, although we are currently investigating several possibilities.

The return of the bolometer to a constant temperature after the wafer is hit by an alpha cannot be described well as a single exponential decay (see Fig.11). Initially the pulse decays with an apparent time constant of $\sim 20\text{msec}$, but a tail of the signal persists with a constant of $\sim 90\text{msec}$. This non-exponential decay is related to the nature of the thermal coupling of the wafer to its support. This is not a problem of particular relevance to the discussion here.

We have also observed the energy loss of electrons as they pass through the 0.02cm thick wafer. A trace of a single electron event is shown in Fig. 13. Since the energy loss is expected to be approximately 80keV, or slightly higher depending on the angle at which the electron traverses the wafer, the noise level expressed in keV with the present detector free of helium under the conditions of Fig. 13 is less than 20keV.

The measured temperature rise due to the α particles being stopped in the wafer is used to calculate the heat capacity of the silicon and its addenda. We assume that all the kinetic energy of an α particle is converted to heat, this assumption is possibly in error by 20%, an uncertainty which does not alter the nature of the results. As shown in Fig. 14, the measured heat capacity of the wafer is much higher than the lattice heat capacity of the silicon from 25mK to 110mK. At 25mK the measured heat capacity is a factor of 10 larger than the expected lattice contribution. We are not yet certain of the origin of this excess heat capacity. It may be due to the epoxy used to attach the bolometer and leads. Or it may result from the thermal contact between leads and wafer being better than intended, so that a portion of the gold leads contribute to the heat capacity. Another possibility is that it could result from two level systems associated with the oxide layer on the silicon surface. Whatever its origin, the sensitivity of the detector is diminished because of it. This question of the additional heat capacity is discussed further in the Renewal Proposal.

C. Helium-Covered Wafer

With helium in the experimental cell and saturated superfluid film covering the wafer, the amplitude of the signal associated with an α particle striking the silicon is diminished substantially, by a factor of five to 10 depending on temperature, from the response of the bare silicon. As seen in Fig. 15 where such an event is recorded, not only is the amplitude decreased but the time constant for return to equilibrium is increased by a corresponding amount, as it should be due to the increased heat capacity. The measured heat capacity of the film-covered wafer is illustrated in Fig. 14. Also shown is the theoretical heat capacity of ripplons added to the measured heat capacity of the bare wafer. The good agreement between the measurements and the predicted heat capacity is perhaps fortuitous given the uncertainty in the

energy deposition and an expected loss of energy from the wafer through desorption of helium atoms by high energy phonons created in the α event. Nonetheless, the general agreement for the helium covered wafer does provide confidence in the measurements. This is of some importance given the factor of ten discrepancy in the results for the bare wafer.

To investigate more directly the desorption of atoms from helium-covered silicon we have made use of the secondary wafer(B) hit by α particles from the collimated source. Small heat pulses are observed in the primary wafer(A) coincident with the secondary wafer being struck by an α particle. An average of signals from 332 such events is shown in Fig. 16. The trigger provided by the pulse on the secondary wafer(B) is essential since the amplitude of a single event on the primary wafer(A) is below the noise level. No such coincident signal is observed when the wafers are bare, confirming the role of helium evaporation in its origin. The magnitude of the coincident signal due to recondensation of the evaporated helium atoms represents 15% of the energy of the α particle. When geometrical factors are taken into account, this appears reasonable in comparison with related experiments.

D. Alpha Particles Stopped in Liquid Helium

When the free surface of the liquid helium is raised above the secondary wafer(B), thereby covering it, the bolometer on that wafer ceases to show any indication of α events. Since the range of 5 Mev α particles in liquid helium is ~ 0.2 mm, the α 's are stopped before reaching the covered wafer. The sensitivity of the bolometer immersed in the helium is insufficient to detect the energy imparted to the liquid by the α 's. The sensitivity to heat pulses is known to be very poor for bolometers immersed in liquid helium. However, in this configuration with the liquid level above the secondary wafer(B), the primary wafer(A) exhibits an increased rate of energetic events. With the level of the liquid below the secondary wafer(B) the counting rate of the primary wafer(A) is approximately 0.5/sec, the α 's coming from the ^{241}Am source directly beneath the wafer(A). With the helium surface above the secondary wafer(B) the rate of events with energies comparable to 5MeV rises to about 3/sec. This is close to the measured rate of α 's arriving at the secondary wafer(B) (when

uncovered by liquid) from the collimated source above it. This is a clear demonstration that a major fraction of the energy of α particles when stopped below the surface of liquid helium goes into the evaporation of atoms from the surface. We have not yet made a systematic study of the phenomenon and can only put a rough estimate that in excess of 50% of the energy of the particle ends up in the evaporation process. This is discussed further in the Renewal Proposal.

When the level of the liquid helium is raised further to just below the primary wafer(A), covering both of the ^{241}Am sources, the event rate seen by the primary wafer drops to the order of 1.0/sec. In this configuration the α 's emitted by the source beneath wafer must be generating rotons which on travelling to the surface evaporate helium atoms. However, when the collimated source is immersed in liquid helium, the rotons created by the α 's from that source are mostly contained within the metal enclosure; only a few of them escape and then, by design, not in a direction to hit the free surface directly.

The signal produced on the primary wafer(A) by an α particle being stopped in the liquid helium 1cm below the surface (see Fig. 17) is only slightly smaller in magnitude than when the wafer is hit directly by the α under comparable conditions.

The importance of ballistic propagation of rotons in the liquid helium in producing the observed signal is evidenced by the influence of ^3He . We have tested for ballistic propagation by the controlled addition of ^3He to the cell when the cell is filled as in the previous paragraph. When 5 parts in 10^8 are introduced into the purified ^4He the signal from the α particles is no longer identifiable. A more quantitative measure of the effect of the ^3He is illustrated in Fig. 18. A 0.4 μsec pulse of heat is generated in the tungsten wire. The amplitude of the signal received at the wafer is 50 times smaller with the ^3He present than when it is not.

VI. DISCUSSION AND CONCLUSIONS

The data resulting from the experiments described in the previous section is admittedly preliminary. Nonetheless, we believe the results provide conclusive evidence of the validity of the principles and processes upon which the proposed solar neutrino detector is based. Further, we believe that the sensitivity required for a practical detector is achievable. The processes involved are the generation of rotons by an energetic particle in liquid helium, ballistic propagation of the rotons to a free surface, quantum evaporation at that surface and physisorption of the evaporated atoms resulting in a detectable temperature rise of the absorbing material. The sensitivity required for a solar neutrino experiment is the order of 1 keV.

From the preliminary results so far we believe we can provide answers to the following questions.

1. Can a large area silicon wafer at 30 mK equipped with a NTD Ge bolometer have sensitivity in the few keV region when not covered by a superfluid film?

Prior to filling the cell but with the silicon wafer at 30 mK, we have observed the deposition of energy directly by 5 MeV alpha particles stopping and 364 keV electrons traversing the wafer. The electrons deposit roughly 80 keV by dE/dx . The measured counting rates agree with estimates from the known geometry and activity of the sources determined separately. The signal to noise for the α particles is roughly 100 to 1 and roughly 4 to 1 for the electrons. The noise corresponds to about 20 keV. The signal to noise can be improved in at least two ways. By developing a low temperature amplifier and reducing the electrical pick-up the noise can be reduced substantially. Also the heat capacity is a factor of ten larger than expected theoretically. The signal can be increased in proportion to a reduction in this heat capacity. Plans for increasing the signal to noise are discussed in the Renewal Proposal.

2. Can superfluid helium film be kept from covering the silicon wafer?

The performance of the film burner, its thermal isolation from other components of the detector and the ability of the refrigerator to accommodate the large heat input from the burner are the key issues. As discussed in Section IV F, the

experimentally observed performance of the film burner agrees with our theoretical expectations. Also, the dilution refrigerator satisfactorily handles the additional heat load of the burner while maintaining the wafer/detector below 30mK. An obvious check on whether the silicon wafer remains free of superfluid film is to measure its heat capacity. We have done this and found the heat capacity to be less than that of the wafer covered with a saturated film but more than that of the bare wafer. In a second test we applied a pulse of heat to the primary wafer and observed the signal on the secondary wafer due to recondensation on it of helium atoms evaporated by the pulse on the primary. The size of the observed signal depended on the pulse repetition frequency allowing us to measure the rate at which film flowed back on to the wafer. We discovered that in assembling the detector the support frame for the wafer unfortunately made contact with the side wall of the helium cell. This allowed the film to short circuit the film burner and flow directly to the wafer, but at a rate considerably less than with the film burner off. This aspect of the experiment clearly needs further work; however, we are confident of the eventual successful performance of this part of the apparatus.

3. Can a silicon wafer, even covered with helium film, detect helium atoms evaporated with the energy released by a charged particle being stopped in matter?

The proof here comes from the use of the two silicon wafers in coincidence. When the liquid level in the cell is low, the two wafers are nonetheless covered with superfluid film. The ^{241}Am source in the small, collimating cylinder is positioned such that alphas from it hit only the lower wafer(B). The uncollimated α 's from the lower source can hit only the upper wafer(A). The singles counting rates in both wafers are consistent with this configuration. However, when a signal pulse on the lower wafer(B) is taken as a trigger, a low level pulse is seen on the upper wafer(A). Electronic cross talk has been excluded as an explanation by independent checks. The pulse height and timing are consistent with evaporation of atoms from the lower wafer and the subsequent adsorption on the upper one.

4. Can the energy deposition by a recoil helium nucleus (alias, alpha particle from an ^{241}Am source) in liquid helium be detected by the silicon wafer, even if

covered by a superfluid film?

Here again, the answer is affirmative although more quantitative data is needed. When the level of the liquid helium in the cell is raised above the lower, secondary wafer(B), the alphas from the collimated source hit the liquid rather than the lower wafer. In this configuration the counting rate of energetic pulses on the upper wafer(A) increases to 3/sec. When the liquid level is raised further to cover the collimated source(thereby inactivating it due to its collimating cylinder) the rate returns 0.6/sec due to the lower alpha source.

5. Is the evaporation produced by ballistic rotons?

The mean free path for scattering of rotons is strongly reduced by the presence of ^3He in the superfluid. Using rotons generated in the liquid by a pulsed heater we can measure the time delay for the arrival of evaporated helium atoms at the silicon wafer. With isotopically pure ^4He in the cell we find a velocity for the rotons of 1.2×10^4 cm/sec. In addition to the signal from the heat pulse we can, of course, observe the pulses from the ^{241}Am source immersed in the helium. However, when ^3He is added to the cell two dramatic things happen. The ^{241}Am signal disappears. Also, the signal from the heat pulser decreases in size and is delayed in time. The propagation velocity increases to about 2.8×10^4 cm/sec suggesting diffusive phonon/roton propagation resulting from scattering by ^3He .

We are very encouraged by these results. We believe these experiments provide proof of the soundness of the ideas upon which the proposed solar neutrino detector is based. The apparatus constructed is ideally suited to carry out these experimental studies. The positive answers we have obtained relating to the necessary conditions for success of the technique are very exciting.

Although the preliminary data represent a breakthrough in low energy particle detection, much further experimental work remains to be done before we can demonstrate that a practical detector for solar neutrinos is feasible. We are confident that we know how to complete these experiments and that we have the best tools to do so as a consequence of the present grant from the Department of Energy. To this end we have submitted the accompanying Renewal Proposal for the Department's

consideration. In it we outline a research program which we feel will provide the answers to the outstanding questions concerning the feasibility a practical detector.

VII. OTHER MATTERS

Listed below are a number of publications from this group concerning the work of the project.

In addition we have in preparation two papers: one on the innovative instrumentation - the film burner and specialized cryogenic systems, designed and constructed by the group, and one on the physics results - the first detection of particles in helium as reported here. Further quantitative data to complete these papers will be taken in our next data run during January.

The graduate students, Tamar More, Simon Bandler and Scott Porter, have been an important and integral part of the successful construction and operations of the apparatus as well as discussing experiments and making measurements. They now look forward to completing their theses on the series of physics experiments, utilizing the now completed equipment, as outlined in the accompanying Renewal Proposal.

The following papers and reports were produced so far under this grant:

1. R. E. Lanou, H. J. Maris, G. M. Seidel, C. A. Smith, R. H. Torii, "Particle Detection via Rotons in Helium-4 Superfluid", in Particle Astrophysics: Forefront Issues, Ed: E. B. Norman (World Scientific, Singapore 1989) p.49 (DOE/ER/40452-2).
2. H. J. Maris, B. Cabrera, J. Wolfe, B. Sadoulet, "Phonon-mediated Detection of Particles", Proceedings of PHONON89 (Heideberg) (World Scientific, Singapore, 1989) p.175 (DOE/ER/40452-3).
3. R. E. Lanou, H. J. Maris, G. M. Seidel, Progress Report (1988) (DOE/ER/40452-1).
4. R. E. Lanou, H. J. Maris, G. M. Seidel, Progress Report (1989) (DOE/ER/40452-4).

and just prior to the initiation of this grant but integrally related:

5. R. E. Lanou, H. J. Maris, G. M. Seidel, "Detection of Solar Neutrinos in Superfluid Helium," Phys. Rev. Lett. 58, 2498, (1987).

6. R. E. Lanou, H. J. Maris, G. M. Seidel in Low Temperature Detectors for Neutrinos and Dark Matter, Ed: K. Pretzl, N. Schmidt and L. Stodolsky (Springer-Verlag Publ), 150 (1987).
7. H. J. Maris, "Design of Phonon Detectors for Neutrinos", in Phonon Scattering in Condensed Matter V, Ed: A. Anderson and J. Wolfe (Springer-Verlag, Berlin 1986) p. 404.
8. R. E. Lanou, H. J. Maris, G. M. Seidel "Superfluid Helium as a Dark Matter Detector", Proc. of XIII Rencontre de Moriond Workshop on Dark Matter, Ed: J. Tran Thanh Van and J. Audouze, (Editions Frontiers, 1988) p.75.

VIII. SCIENTIFIC PERSONNEL ASSOCIATED WITH THE PROJECT

R. E. Lanou	Professor of Physics
H. J. Maris	Professor of Physics
G. M. Seidel	Professor of Physics
R. H. Torii	Research Associate
F. S. Porter	Graduate Research Assistant
S. R. Bandler	Graduate Research Assistant
T. More	Graduate Research Assistant (not supported by this grant)
J. T. Yun	Undergraduate in Physics

Figure 1. Schematic diagram of the simplest version of the experiment. A neutrino is elastically scattered in the liquid helium. The recoil electron produces rotons and phonons in the liquid. When the rotons reach the surface, they evaporate helium atoms, which are then collected on the silicon wafer. The rise in temperature of the silicon is measured with a bolometer. Support for the silicon wafer is not shown.

Figure 2(a). Dispersion curve for elementary excitations in superfluid helium. Excitations are divided into phonons (momentum less than $1\text{\AA}^{-1}$) and rotons ($2.4\text{\AA}^{-1} > p > 1\text{\AA}^{-1}$).

Figure 2(b). Density of states of excitations in arbitrary units.

Figure 3. Schematic diagram of the dilution refrigerator and related low temperature components from the 4°K plate down to the experimental cell.

Figure 4. Schematic diagram of the helium fill system including the heat-flush tube for purifying the helium, a superleak used as a valve, and various heat exchangers.

Figure 5. Schematic diagram of the film burner.

Film Burner

Temperature vs Heat Input 12/14/90

Figure 6. Temperature of the film burner as a function of the power applied to it. The curve through the experimental points is calculated using one adjustable parameter, the flow rate of the film.

Figure 7. Schematic diagram of the experimental cell showing the location of the various components.

Figure 8. Diagram of the data acquisition system.

Figure 9. Resistance versus temperature for the NTD germanium bolometer obtained from Berkeley. The points at low temperature scatter because of problems with thermal contact.

Voltage Vs. Current for Bolometer

12/21/90

Figure 10. Voltage versus current for the NTD bolometer at several different temperatures.

File: alphas23.hcap, Trace 201/499

Time Base = 20.0 ms/div Vertical Scale = 200.0 mV/div Coupling = DC, 1 MOhm

Figure 11. Signal from a single alpha particle striking the bare silicon wafer at 23 mK.

475 ALPHAS: PULSE HEIGHT DISTRIBUTION

T=25mK, Bias=3.75mV, DC Level=1.255V

Figure 12. Pulse height distribution of 475 alpha particles striking the bare silicon wafer at 25 mK.

File: beta23.v5, Trace 1/1

Time Base = 20.0 ms/div Vertical Scale = 50.0 mV/div Coupling = DC, 1 M Ω m

Figure 13. Signal from the energy deposition of a single electron traversing the wafer at 23 mK.

Figure 14. Heat capacity of bare silicon wafer (X, solid line is to guide the eye) and wafer covered with a saturated superfluid film (O). The vertical scale on the right applies to the bare wafer; the scale on the left to the film-covered wafer. (.....) $\rightarrow$ Lattice heat capacity of 1.74g of Si. (---) $\rightarrow$ heat capacity of ripplons. (-.-.-) $\rightarrow$ heat capacity of ripplons plus bare wafer.

File: film1.hcap, Trace 4/500

Time Base = 100.0 ms/div Vertical Scale = 10.0 mV/div Coupling = DC, 1 M Ω m

Figure 15. Signal from a single alpha particle striking the film-covered silicon wafer at 27 mK.

Figure 16. Signal on the primary wafer coincident with an alpha particle striking the secondary wafer. Average of 332 events at 41 mK. The lower trace is the same as the upper with an increase in gain of 10.

File: top_he_level4_100.dat, Trace 9/100

Time Base = 100.0 ms/div Vertical Scale = 20.0 mV/div Coupling = DC, 1 MOhm

Figure 17. The signal detected by the helium-covered silicon wafer for a single alpha particle being stopped in liquid helium at 25 mK.

Pulsed Heater without ^3He

Pulsed Heater with ^3He

Figure 18. The influence of ^3He on the response of the bolometer to rotons produced by a pulsed joule heater emersed in the liquid He . The upper trace is for pure ^4He and the lower trace is for 5 parts in 10^8 of ^3He . The gain was held constant. Note: The time scale for the lower trace is 1/5 of the upper trace.

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IX. APPENDIX

In this Appendix we include brief summaries of progress in two areas related to the experimental results just described in the Sec. IV, V and VI.

1. Simulations of Detector Response

As a guide to carrying out the experiments to be performed in the next grant period we have undertaken some Monte Carlo simulations of the pulse shapes to be expected from the bolometer on the silicon wafer. To perform these simulations we assumed that the event generates excitations which are distributed uniformly in momentum space out to a cut-off momentum of $2.3 \text{ }^\circ\text{A}^{-1}$. The group velocity of an excitation is calculated from the phonon-roton dispersion curve that has been measured by neutron scattering, and the excitations are assumed to be scattered into a random direction when they heat the walls of the cell. A simple model is used for the momentum and angle- dependence of the evaporation process. The simulation determines the rate at which helium atoms are evaporated from the free surface of the liquid as a function of the time t after the event occurs, and from this quantity the rate of heating of the Si wafer can be calculated. Some results are shown on two different time scales in Figures A and B. In each of the figures three simulation are shown, corresponding to an event occurring at heights of 5, 10 and 15 cm from the bottom of the cell (from the top to bottom in Figs. A and B). The total depth of the liquid is assumed to be 20 cm. The total amount of energy deposited as excitations in the helium is taken to be 700 keV. For long times (see Fig. B) the rate at which energy is deposited is essentially independent of the position of the event. This is because most of the evaporation is being produced by excitations that have been reflected several times at the walls of the cell. However, on the short time scale (Fig. A) the input power to the wafer has a time-dependence which is very different for the different positions of the event. Thus, it appears that a detailed study of the pulse shape appearing on the bolometer can give the position of the event within the experimental cell.

2. Radiation Studies

As a preliminary to construction of the test set-up we conducted a number of exploratory measurements using a Ge-Li detector of 100 grams.

Radioactive backgrounds in the laboratory are quite tolerable being due primarily to the ^{238}U and ^{232}Th series plus ^{40}K at the higher gamma ray energies. The rates in the Ge-Li were 1.3 hz/gm(Ge) unshielded and 3×10^{-2} hz/gm(Ge) when enclosed in 2 inches of Pb.

We then used this same detector to test for radioactive content in construction materials to be used in or near the test cell. Sensitivity to this content was set by the above quoted room background. Of particular interest was the copper to be used for the helium cell itself. The walls of the cell are made 0.5" thick to provide some self-shielding but because of this increased mass relative to the contained mass of helium it is important to keep the radioactive content of the copper itself low. Double beta decay experiments have achieved 0.1 disint./min./kg. We tested a nine kilogram sample of OFHC type 101 copper and could see nothing above background this setting a limit of approximately 0.2 disint./min./kg - very suitable for our present purposes. Similarly, no effects were seen for smaller samples of construction materials such as indium gaskets, vespel, welding rods, polystyrene, etc. Some solder fluxes were found to be less desirable than others due to ^{40}K content.

A crude test was made on a large block of polystyrene to estimate its effect on a transmitted gamma spectrum for incident energies of 660 and 1275 keV gammas. The interest in this is to use materials such as polyethelene, polypropelene or other hydrocarbons as liners to a full scale detector. The liner's purpose being to degrade the spectrum by Compton scattering thus shortening the scattering mean free path in the helium making self-shielding definition of the fiducial volume easier. The result suggests that this is a promising technique. Fig.C shows the result for 13.5 cm thickness of polystyrene. The lower curve is for no absorber and the upper for absorber. They are normalized at the photo-peak and the difference illustrates the greatly degraded spectrum. The vertical line marks 363 keV on the energy scale.

POWER (erg/sec)

POWER (erg/sec)

POWER (erg/sec)

TIME (msecs)

FIGURE A

FIGURE B

END

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