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The HERON Project

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Abstract

The HERON project is an R & D effort to create a single detector suitable for real-time, high rate measurement of neutrinos from both the p-p and Be^7 reactions in the Sun using superfluid helium as the target substance. In this talk, I discuss the motivation, the particle detection mechanism in superfluid, some R & D results on low energy electron detection and a possible " third" generation, full-size detector. Future R & D plans are also presented. This work is being carried out by a collaboration of particle and condensed matter physicists at Brown University*.

1. Motivation.

There are several important questions for solar neutrino physics concerning the composition of the neutrino flux ≤ 1 MeV. We know from the SAGE and GALLEX experiments that the integrated ν_e flux above 233 keV is ~ 0.5 of the standard solar model (SSM). And, more specifically from SAGE and GALLEX, that it is measured to be 67 ± 8 and 78 ± 6 SNU, respectively. Within errors these flux measurements are equal to or below the ν_e flux to be expected for the p-p neutrinos alone in the SSM. Since the p-p flux is considered to be the most accurately predicted one, it is important to know how much of the ν_e flux is due to p-p only, how much is due to Be^7 only and how much of the total flux is made up of ν_e or $\nu_{\mu,\tau}$, separately. It is likely that experimental knowledge of these quantities will play a significant role in the full understanding of solar neutrino physics.
The HERON project seeks to answer a related, practical question: Can one make a real-time, high rate detector to measure the total flux and spectra of the p-p and Be^7 neutrinos? High rate implies the order of say 20 events per day and, for p-p and Be^7 neutrinos, energy deposition in the detector of ≥ 50 keV. To have sensitivity to the

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total flux the detection reaction would be elastic scattering,

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-,$$

thus forming a necessary complement to the flavor specific (to ν_e) detectors GALLEX, SAGE and LENS (should the latter be built).
In considering this question, there are some obvious positive and negative aspects. On the positive side, the detector need not be very large because the fluxes at these lower energies are very high and the elastic cross-section is precisely known from electroweak theory and from measurement. A mass of 10 tonnes would be sufficient for $\sim$ 15 p-p and $\sim$ 7 Be^7 events per day (SSM). On the negative side, at these low energies the backgrounds in the target material itself can be many orders of magnitude larger than the signal. The leading usual sources being long-lived cosmogenic isotopes, the primordial activities of U, Th and some of the lighter isotopes K^{40}, C^{14} and H^3.
Superfluid helium has many attractive features which make it a strong candidate as the target material for a low energy solar neutrino detector. It has no long-lived isotopes of its own and its first excited nuclear state is at 20 MeV. Liquid helium is inexpensive and standard industrial/commercial methods exist for handling. He^4 in the superfluid state has a density of 0.14 g/cc so a 10 tonne fiducial volume would occupy about a 4 meter-cube. More importantly, helium at superfluid temperatures (say, 50 mK) is self-cleaning in that all other atomic species freeze out. Consequently, superfluid helium can provide a completely radioactivity-free and compact target.
Nonetheless, to be practical it must be contained in something (the cryostat) which will be a source of external radioactivity which must be managed and discriminated against. Further, a method to extract and measure the event information from the liquid is needed.
In the HERON project so far we have developed a new method of particle detection based in bulk superfluid helium and we have made preliminary studies to test the scale of the external background problems and have explored some possible solutions.

2. Detection mechanism.

A neutrino event will consist of a single recoil electron stopping in the liquid. The Be^7 events, because the neutrinos are an energy line source, produce a flat distribution of recoils from 0 up to a 660 keV end point. The p-p recoil events, in contrast, have a slowly falling spectrum from 0 to 220 keV which reflects the two body elastic scattering kinematics convoluted with the initial p-p neutrino continuum. The recoil track in liquid helium for such events is thus less than 2 cm in length and, in a full-size detector, is essentially a point source of radiation.
As is discussed below, the detection technique we have developed depends upon measuring both phonon and uv photon radiation with the electron recoil as their source. We have carried out experiments using stopping electrons and alpha particles to test these ideas and to measure the quantities involved.

When a particle stops in the superfluid the initial energy loss is primarily by ionization which initiates a cascade of processes eventually terminating with the energy distributed among phonons/rotons, photons and a few long-lived dimers. How the energy is eventually divided among these three channels depends upon the density of primary ionization along the track. For example,a minimum ionizing electron loses 30 keV/mm while a stopping alpha loses 3×10^4 keV/mm. This difference results in a 3:1 ratio of uv radiation/keV in favor of the electron — rather different from the case in the other noble gas liquids. Conversely, the alpha particle has a 4:1 advantage in phonon/roton emission. In some applications these differences could be exploited for particle discrimination. In our method both the phonons/rotons and the uv photons are detected on the same calorimetric device.

The experiments have been carried out in a test cell which contains ~3 liters of superfluid held at, typically, 30 mK by a dilution refrigerator for most of the tests. The interior of the cell is instrumented with a variety of devices which can be reconfigured appropriately for each experiment. Besides thermometers, heat pulsers and liquid level sensors there are small, superconducting stepper motors for positioning and moving radioactive sources within the liquid volume. The sources were low activity Am^{241} for 3-5 MeV alphas and Sn^{113} for 364 keV electrons. X-rays from Fe^{55} as well as from the Sn and Am sources were used for calibrations. For the calorimetric detection method we mount, just above the liquid surface by 2 mm, thin silicon or sapphire wafers ranging in size from 5 cm diameter to 1 by 2 cm. Temperature pulses in the wafers are measured by Ir-Au thin-film superconducting transition edge sensors[1] (TES) which are read out with SQUID electronics. The wafers are kept free of superfluid film by a "film burning" device[2].

When the phonons and rotons are radiated from the particle track they propagate ballistically at speeds typically of 150-200 m/sec. Those which reach the free surface of the liquid and whose energy is greater than the binding energy of helium to itself can cause quantum evaporation. The latter is a process in which one phonon or roton can evaporate one helium atom and does so in about 30 % of the cases. Particularly for rotons, energy and momentum conservation at the evaporation surface place constraints on the range of incident roton angles which can cause evaporation[3]. The helium binding energy is 0.7 meV (milli-electron volt) and the typical phonon/roton energies involved are ≥ 0.8 meV; thus for a particle recoil in the 50 keV range a very large population of atoms is involved in the resulting evaporation burst. The evaporated atoms are adsorbed to the wafer and their deposited binding energy produces a heat pulse in the TES.

The scintillation uv photons result from the radiative decay of helium dimers formed along the track and have energies in the range of 14-20 eV but peaked at 16 eV. Since the first excited state of atomic helium is at 21 eV the liquid is transparent to these photons. The silicon and sapphire wafers are highly absorbent for photons at these energies and thus create a prompt heat pulse. The two contributions, photons and phonons, can be distinguished by their relative times of arrival on the wafer. In the results described here the thresholds for energy transferred to the wafers was 300 eV

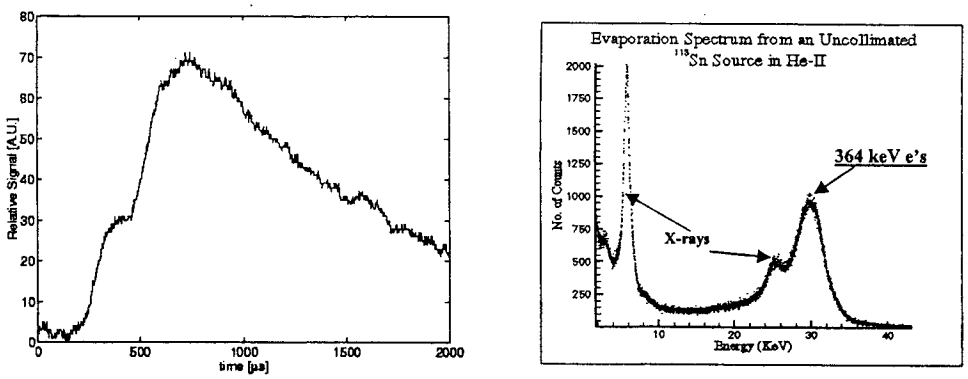

Figure 1: On the left: a typical 364 keV electron pulse from superfluid helium; the initial rise is due to photons and the later one to evaporation by phonons/rotons. On the right, is the energy spectrum for 364 keV electrons in superfluid helium; also shown are the 6 and 25 keV x-ray calibrations.

so single photons were not detectable.

To understand the mechanisms involved, we have carried out extensive studies using comparisons of alpha particles and electrons. The principal results for alpha particles, including evidence for particle directionality, are discussed elsewhere[4]. Briefly presented here are some results with 364 keV electrons and a description of our current understanding of the detection mechanisms for both particle types — sparsely vs. densely ionizing.

The Sn^{113} had an activity of a few nano-curie so that single electrons could be distinguished. A 364 keV electron is produced by isomeric transition in In^{113} following electron capture; a 25 keV x-ray is also produced and is used as one of the calibration points for the wafers. For the data illustrated in Figure 1 the source was 5 cm below the wafer and the time delay difference can be clearly seen in the pulse shape even for that very short distance. Also shown in the figure is the measured single electron spectrum.

The detected energy division of the electron's initial energy is 25% into photons (or 15 photons/keV)and 10% into phonons/rotons (or 10^5 phonons/keV). This contrasts with the 8% and 40%, respectively, for alpha particles. These results agree well with a model in which the formation of excited helium dimers in the close vicinity of the track and then their subsequent de-excitation by radiation or collision plays a central role[5]. In the model, the sequence of events is briefly as follows. The incident electron loses it energy principally in primary ionization but also to excitation and elastic scattering from helium atoms. The latter create phonons/rotons via their recoils. The secondary electrons also undergo the same processes but their average energies are only $\sim$ 100 eV and they rapidly ($\sim 10^{-10}$ sec) recombine with the positive ions. In the superfluid environment the excited, recombined atoms form a molecular dimer

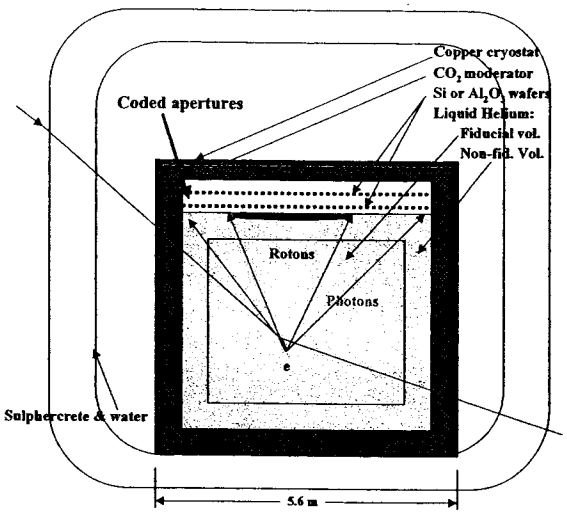

Figure 2: A possible full-size configuration.

(He_2^*). The lifetime for the singlet $A^1\Sigma_u$ to decay to the dissociated ground state is 10^{-8} sec and is the origin of the $\sim$ 16 eV photon. A competing reaction leading to dimer dissociation is Penning ionization resulting from dimer-dimer collisions:

$$He_2^* + He_2^* \rightarrow He + He + He_2^+ + e^-$$

. Most of this energy then appears as phonons and rotons. Which of the two processes dominates is governed by the density of initial ionization along the particle path. Since the stopping electron has a factor 10^{-3} less primary ionization density the mean-free-path for dimer-dimer collisions is sufficiently long to favor the uv radiative decay. We feel confident that the detection method is well understood.

3. Requirements in a full-size detector.

To illustrate the requirements and constraints in a full-size detector, Figure 2 presents a schematic view of a possible HERON configuration with total helium dimensions of a 5 meter-cube.

It is essential to measure the neutrino event position for both background discrimination and for energy reconstruction. In order to do this, the wafers would be arranged into two planes separated from each other vertically. In the upper plane the wafers would be arranged in a uniform array covering $\sim$ 90% of the area; beneath it the other plane would have the wafers in a patterned array covering $\sim$ 50% of the area. The event position would be reconstructed from the associated hit patterns in the two planes. The technique will be recognized as that which is referred to as coded-aperture arrays[6] long in use for x-ray astronomy except that in this application all elements in both planes are active. (The position resolution can be tested in-situ

using a small, movable Fe^{55} x-ray source.)
The prompt photon pulse would serve as trigger and the principal means for establishing the event position. The delayed evaporation pulse height would then be combined with the photon information to give the event energy. As an example of the energies involved, a 100 keV electron recoil at a median depth of a 4 meter-cube fiducial volume will produce 4 keV of photon signal on the two planes with the phonon evaporation signal contributing in addition about an equal amount. In order to reach the lowest event energies possible in a large detector we are aiming to improve our wafer sensitivity so that single, 16 eV photons can be detected (see below). Also, in the case of the very lowest energy events, the trigger time and known phonon speed would be used as a consistency check on position and as an aid in enhancing the signal to noise of the wafers.
As was mentioned, the backgrounds are external and arise predominantly from activities in the cryostat materials producing gamma rays which then Compton scatter in the helium. OFHC copper is a convenient material from which to construct the cryostat. It has a minimum of long-lived cosmogenic activities (Mn^{54}, Co^{57} and Co^{60}) and when electroformed can have much reduced U and Th content. If the copper is kept to a regime of only two months above ground followed by two years below ground the cosmogenic activity can be 47μBq/kg or less[7]. In what follows a U,Th activity one tenth of that is assumed and corresponds to 10^{-13} g/g. The majority of gammas entering the liquid are $\sim$ 1MeV or less.
A single, Compton scatter is indistinguishable from a neutrino event. Consequently, background events with just a single Compton must be kept to an absolute minimum. However, such a large volume of liquid helium provides essentially hermetic containment for most of the gammas in this energy range; that is, an individual gamma creates multiple Comptons. To enhance this effect we envision lining the inner cryostat with 25 cm of moderator made from low activity acrylic or a frozen non-polar liquid. We have conducted a monte carlo study of background rejection based on these assumptions and configuration. We find that the average Compton multiplicity is 10, they are distributed over $\sim$ 60 cm and have a strong depth dependence with the energies strongly peaked below 100 keV. Using cuts based upon achieving $\pm$5 cm position resolution and only a single energy deposit $\leq$ 800 keV, we divide the liquid volume into a fiducial (4 meter-cube) and non-fiducial volume. These cuts produce a signal to background ratio of 1:1 before making use of the non-fiducial events to perform a background subtraction. An example of what such cuts would produce in a monte carlo-simulated, 6 month (70% duty factor) run is shown in Figure 3. The need to distinguish single recoil electron events from multiple ones emphasizes the requirements for event position determination.

4. Summary & Future R & D Plans.

We believe we have established understanding of a new, particle detection method which is particularly suited to low energy solar neutrino experimentation due to su-

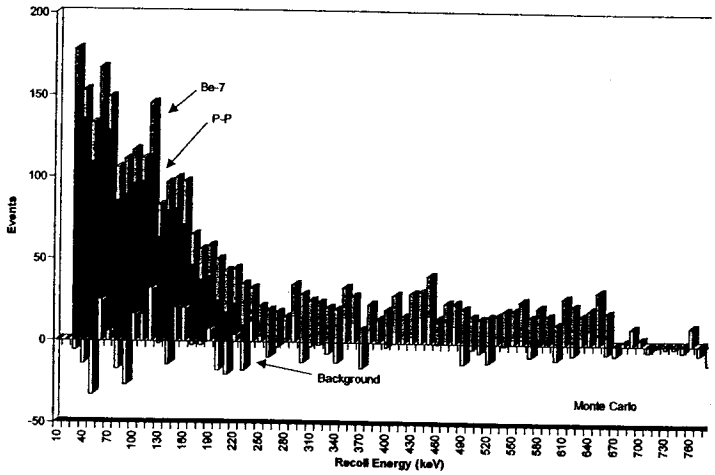

Figure 3: A monte carlo simulation of a background subtracted 6 mo. run in HERON.

perfluid helium's freedom from radioactivity. The method is based on the detection of both photons and phonons radiated by the particle. Preliminary studies of backgrounds indicate that with careful selection and treatment of materials the rates appear controllable. However, to achieve that control we must successfully demonstrate single photon sensitivity for individual wafers and adequate position resolution with the coded aperture method.

Over the duration of the project there have been several technological developments in the sensor thermometry on the wafers which have allowed us to improve the sensitivity from 5 keV down to the present 300 eV. A particularly useful one was a shift from NTD thermistors to TES films with electrothermal feedback. We are now pursuing a promising new sensor — the fast, magnetic micro-calorimeter. Under development at Brown and in Heidelberg[8] for x-ray astronomy, these devices make use of temperature dependent magnetization in dilute systems of atomic spins in a metal, e.g. Er-Au. The sensors operate into SQUID electronics similar to our current method. These groups have made impressive progress showing 90 eV resolution at 6 keV in samples whose heat capacity is as large or larger than the largest wafers we contemplate using in a full size solar neutrino detector. Several avenues look promising for trying to adapt these devices to our application and to push the limit to $\sim$ 10 eV and we have begun an attempt to do so. At the same time, we have begun computer modeling of a large coded aperture array of 1000-2000 wafers on the scale of a full-size HERON. The principal aim being to establish the minimum event energy for which it is still possible to achieve sufficient position resolution for controlling the external background.

The construction of a full-scale superfluid helium solar neutrino detector presents significant engineering challenges; however, they do not appear to require any new technologies for their solution and do not exceed what is currently done in the cryogenics industry. We are not yet in the position of designing full scale systems (cryostats, cryogen handling, wafer fabrication, trigger electronics, data acquisition, shielding

management, site requirements, etc.). We are focused on demonstrating feasibility and look forward to the opportunity to have a HERON-like detector be a major contributor to the resolution of the solar neutrino "puzzles".

5. References

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