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Particle Detection in Superfluid Helium: R&D for Low Energy Solar Neutrinos

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Introduction:

This report presents a condensed summary of the R&D carried out by the Brown group under this grant. Its goal has been to test the feasibility of using superfluid helium as a real-time detection medium for low energy PP and ^{7}Be solar neutrinos via neutrino elastic scattering from electrons. As was well known at the start of the project, and remains so at the present writing, PP neutrinos have never been detected in real time. The scientific motivation for doing so is very strong as has been attested to by many studies --- most recently in 2004-5 by the American Physical Society's multi-divisional study entitled: "*The Neutrino Matrix*" [http://arxiv.org/abs/physics/0411216]. A precise real-time experimental measurement of both the PP and ^{7}Be fluxes will provide crucial tests of stellar models, could also make new measurements of additional neutrino properties and, by virtue of opening a new energy window, offer discovery potential. The principal challenges in constructing and carrying out a full scale PP and ^{7}Be real-time experiment by means of the elastic scattering of solar neutrinos come from the low energies of the recoil electrons (< 264 and <661 keV, respectively), from the very low signal rate (typically, ~ 2 events/ton/day) and the requirement to detect this low energy in the presence of backgrounds in a large detector.

Superfluid helium was proposed by us [1] and adopted for this project principally for three important features: a) the superfluid is self-cleaning of all other substances, b) it was expected to provide multiple mechanisms for particle detection and c) it was an inexpensive material amenable to, and scalable for, particle detection in the bulk without segmentation. The first two properties are crucial for reasons of background control and establishing a signal signature; the third is important for cost, availability and flexibility of design. The advantages provided by the helium superfluidity; however, come with the attendant challenges of working with milli-Kelvin cryogenic techniques and augmenting the limited radiation self-shielding of helium. Our original conception of a full size solar neutrino detector (called HERON) is outlined in [5]; later versions in its evolution described in later publications [16, 19, 21, 28].

Broadly, the R&D work carried out has consisted of experiments and studies on several diverse topics. A list of these generic topics includes: establishing the particle detection properties of the superfluid, developing the apparatus to do so, developing devices to detect the several detection channels (scintillation, phonons/rotons, drifted e-bubbles), experiments and studies of low radioactivity materials, conceptual design of a method to extract precision data from a large detector and simulations to test the expected performance based upon our experimental results on sensitivity to particle detection and the properties of the detection devices developed.

As should be apparent from the nature of the topics listed, new ground has been broken in this work. In addition to the thirty papers already published or in press, it should be noted that the original works of seven graduate students have been detailed in the seven PhD dissertations also noted at the end of this report [D1-D7]. In what follows we provide a summary of the work accomplished.

Development of facilities for this R&D at Brown:

Most of the work was carried out in the existing cryogenic laboratories of the Seidel Group in the Barus-Holley Laboratory of the Department of Physics. Two dilution refrigerator systems with sub-50mK capability were acquired: a large (500mW) one was specially built to our design in the Brown Physics Department shops and the other smaller one was a custom-retrofitted existing one. The former was designed to permit attachment of various prototype helium cells with several liter volumes for testing scintillation/roton/e-bubble devices ("wafer calorimeters") and to study the scintillation/roton emission from electrons, alpha particles and gamma rays. The other fridge, more amenable to the fast turn-around of experiments, was used for wafer calorimeter testing and for e-bubble experiments. Two unique features of some of the apparatus (e.g.,"film burners", radioactive sources movable in superfluid) used in the prototype cells are described in [2, 3, 4, 7]. A large electromagnetically shielded room was constructed and two data acquisition systems built. In other areas, such as micro-electronics, wafer calorimetry and fabrication, gamma and mass spectrometry, and large scale computing), we have supplemented our own facilities with those of collaborators at University of Heidelberg, Harvard-Smithsonian, Lawrence Berkeley National Laboratory and the State of Rhode Island Nuclear Reactor.

Energy deposition by electrons and alphas in superfluid helium:

In order to study the particle energy deposition process in superfluid helium we carried out a series of experiments using cells of ~4 liters equipped with wafer calorimeters (see below) as radiation detectors. Our primary goal was to directly measure the principal mechanisms involved in the generation of scintillation light and of rotons/phonons. The scintillation is in the UV with peak energy at 16eV.The wafer calorimeters were of sapphire which could absorb the full photon energy. The deposited energy was detected by the wafer's temperature pulse sensed in an attached thermal read-out. In these experiments typically 20-200 photons were detected at once on a single wafer. In separate runs, they were calibrated absolutely by direct injection into the wafer of charged particles of known energy. The rotons, a type of bulk excitation propagating ballistically (~200m/s) in the superfluid at low temperature, were detected through a secondary process known as quantum evaporation. In this latter process a single roton (or high energy phonon) upon reaching the free liquid surface can eject a single helium atom into the vacuum with a ~30% efficiency and well known kinematic constraints. The evaporated helium atom is adsorbed by the wafer and gives up its binding energy which also appears as a thermal pulse. Interestingly, an energy gain takes place because although a single roton may carry and transfer to the atom a few meV, the binding energy to the wafer is a factor ~10 greater. Typically, a few thousand helium atoms were detected in a pulse. Rotons can be scattered by ^{3}He atoms so in filling the cell ^{3}He was removed to an acceptable level by a thermal flush in the fill line. The photons and rotons have very different propagation times to the wafer and so can be differentiated by timing. Mono-energetic 330keV electrons were provided from both collimated and un-collimated sources of ^{113}Sn. Similar mono-energetic 5.4MeV alpha sources of ^{241}Am were also used. The x-rays from ^{55}Fe and ^{241}Am were also used for calibration purposes. The respective ranges in the liquid for the electrons and alphas used are 7mm and 200 microns.

As a result of these experiments we now have a satisfactory understanding of these processes. A key point in this understanding concerns the nature and behavior of the (He^{*}_{2}) excimers formed. They are formed when an atom, either ionized or in an excited state, created by the stopping particle, binds with another atom in the liquid forming both spin-singlet and spin-triplet states. These species have decay lifetimes of 1nano-sec and 15 sec, resp.; however, they can also undergo radiationless collisional annihilation with Penning ionization. The scintillation we detect is from the short-lived singlet state while that from the triplet is lost. The energy deposited from the recoil of un-ionized atoms and from the Penning process appears as bulk excitations in the liquid and provides the source of rotons. In an individual event both scintillation and roton evaporation signals are measured. For stopping electrons, we find that 35% of the energy appears as scintillation (~29,000 photons/MeV) from singlets and 41% into rotons; the remaining 24% is presumed to be carried off by the triplets. For more energetic alphas, for which the ion density along the track is much higher, the energy distribution is quite different: 10% in scintillation, 87% in rotons and 3% in triplets.

The high density of ions, excimers and thermal excitations long an alpha track has other consequences as well. The scattering of rotons within the dense cloud is such that more rotons emerge into the cold liquid traveling perpendicular to the track than parallel to it. This asymmetry, which carries over to the detected signal from quantum evaporation, could, in principle, be used to determine track direction of an alpha particle.

The data gathered in these experiments have been essential in our subsequent work on neutrino detection feasibility.

[More details on this section can be found in1, 6, 8, 10-15, 17, 18, dissertations D1-D4]

Wafers and Metallic Magnetic Calorimeters:

The requirement of being able to detect calorimetrically single 16 eV photons absorbed in a 12 x 12 cm wafer necessitates the development of extremely sensitive thermometers. We have studied the properties of paramagnetic sensors to serve in this capacity and have shown that the energy resolution of a calorimeter consisting of a wafer and magnetic sensor is given by $E_{rms} = (4kT^2C)^{1/2}(4\tau_0/\tau_1)^{1/4}$, where k is Boltzmann's constant, T is the temperature, C is the heat capacity of the wafer, τ_0 is the time constant for achieving internal thermal equilibrium, and τ_1 is the thermal time constant with the thermal reservoir. The lattice heat capacity of a silicon wafer having an area of 150 cm^2 and 0.05 cm thick at 30 mK is 1.1×10^{-10} J/K. A time constant to the reservoir of 0.1 s should be sufficient to be able to handle a possible background rate of 1 per second without pile-up. Then the internal time constant must be 5×10^{-3} s to achieve an energy resolution and threshold of 5 eV, well below 16 eV to have close to 100% confidence of being able to identify scintillation photons. Given the constraints imposed by heat capacity and time constants it would appear that it would be difficult to operate at temperatures above 40 mK and obtain the required performance of the calorimeter/wafers.

A metallic magnetic sensor consists of a metal (gold) containing a dilute concentration of paramagnetic ions (erbium) the magnetization of which is measured by a highly sensitive SQUID magnetometer. The Au:Er material, a few microns thick, is vapor-deposited on top of a superconducting niobium in the form of a meander. The niobium meander functions as the pick-up loop for the magnetization of the Au:Er sensor. The meander and sensor cover a significant fraction of the Si wafer to achieve a fast response of the calorimeter to the absorption of a photon. The meander is inductively coupled to the SQUID, which is located off the wafer. This type of detector is being developed in several laboratories for other applications, *e.g.*, calorimetric detection of neutrinoless double beta decay, so that they should be available in a timely fashion for use in a helium-based neutrino detector.

[More details on this section 4, 22, 24, theses D1-D5]

Background Studies:

The signature for a PP or ^{7}Be neutrino event by elastic scattering from electrons is a single recoil electron with energies below 264 keV (PP) or 661 keV (^{7}Be). A detection threshold of 45 keV has been assumed in all our studies. Given the short range in liquid He, and the scale of the detector fiducial volume (>55 m^3), the track is effectively a point source of radiation. The background events arise from gamma rays entering from materials external to the He. These background sources can be from cosmogenic and primordial activities in the containment vessel materials, primordial activity in the environment housing the detector, from cosmic rays and from cosmic ray induced activity in the environmental shielding material. We have studied a number of methods to reduce the amount of radiation entering the He from these sources; additionally, we have devised a system combining the use of a moderator material and a coded aperture array internal to the cryostat with which to give the entering background a distinctive signature. (This system is discussed in the next section.)

We have completed a study to shield the detector from cosmic radiation. It involves siting the detector underground at a depth of 6000 m.w.e. in a pit configuration with 3 m of water as shielding surrounding the detector in the pit. At this depth there are < 0.4 muons/m^2-day. We have done a simulation of this configuration for the Homestake, SD site using appropriate fluxes, interaction cross-sections, and attenuation processes for muons, neutrons and gammas. Punch-through from interactions in the shield itself would produce < 0.2 gammas/day into the He which would be reduced to < 0.002 events/day after signature cuts. Attenuation factors of $>10^9$ and of $>10^6$ were found for 2.61 MeV and 8.5 MeV gammas, respectively. (Similar results hold for neutrons. Muons entering the He itself produce negligible background since the only long-lived activity they produce is ^3H whose 18.7 keV decay is well below threshold and the muon capture lifetime is essentially equal to the free lifetime.

The dominant background is expected to be due to cosmogenic activity in the copper cryostat, e.g., ^{54}Mn, ^{58}Co and ^{60}Co with a lesser contribution from U/Th/K.. Extensive data exists on copper principally from double beta decay and other low background experiments. In practice, two approaches have been used to reduce this source. One approach is to produce OFHC copper commercially and immediately move it to storage underground for a period of a few years. Another approach consists of electroforming underground using high purity copper sulphate and ultra-pure reagents. Depending on application both methods have proved effective. To use the latter method for the several ton scale of the HERON cryostat has never been attempted although it is technically feasible. Instead, for our simulations we have adopted the rapid commercial surface production and storage approach. In our model (2 months above ground and 3 years below ground) we would expect ~50μBq from cosmogenics. (Recently the EXO Collaboration has carried out a similar production/storage cycle on a large amount of copper and they find a residual activity consistent with our calculation.) Experience has shown that much of the remaining U/Th is superficial and can be removed by electro-polishing. In our work we assume that the U/Th contribution to the total copper rate of gammas is 10% of the cosmogenic rate. To test this we obtained a sample of electroformed copper and tested it by isotope dilution mass spectrometry (ID-MS) and found an upper limit for U of $<10^{-12}$g/g .

As will be discussed in more detail below, the inner cryostat needs to be lined with a material we refer to as the “moderator” whose purpose is to enhance the rejection of externally entering background partially by attenuation but principally to reduce the gamma mean-free-path for showering or scattering in itself and in the He. Consequently, very high radiogenic purity, ease of containment in the He environment and reasonable density are desirable. One of the candidates we considered was high purity graphite. We obtained several samples of commercial high purity graphite and tested them by neutron activation analysis (NAA) for a variety of activities but principally for U/Th/K. None proved adequate. We then, in discussions with industry, looked into fabricating graphite bricks from highly purified naphthalene samples tested for U/Th/K by ICP-MS. We concluded that while it might be possible to achieve purities of 10^{-15}g/g the cost (driven largely by the labor intensive graphitification processes) would be prohibitive. (an group internal note summarizes these NAA and ICP-MS data.) Instead, for purposes of modeling potential performance, chose to utilize frozen nitrogen enclosed in an acrylic cell structure as part of the inner cryostat. Nitrogen of the requisite purity can be obtained commercially and good data exists on acrylic from the SNO group tests. [24]

Coded Apertures and Conceptual Design:

The size and shape of a superfluid helium-based solar neutrino detector is governed by several constraints. The temperature range must be well below the superfluid transition temperature of 2.1 K. We have chosen the range of 25-40 mK in order to keep the phonon equilibrium density low and to provide a sufficiently low temperature that the heat capacity of the wafer calorimeters is low enough to ensure high sensitivity to small energy input. For purposes of event and background discrimination it is important to have good position resolution for point sources (signal), a measure of the non-point-like nature of some sources (backgrounds) and a measurement of the event energy. In order to achieve these latter three goals we have introduced the idea of a coded aperture array of wafer calorimeters located in the vacuum space above the liquid. Coded aperture arrays have been in use for many years in astronomy where low light flux and inability to focus radiation prevail. For astronomy, a coded aperture array ordinarily consists of two closely spaced planes of pixels: a uniform image plane and a patterned semi-transparent mask plane between image and source(s), with only the image pixels active. The normal astronomical task is to resolve faint point sources at infinity by angular dispersion, the image having been reconstructed by a variety of transformation methods. Our application has a very different goal and realization. Instead, we have more flux but need to resolve events in real-time, our sources are near-by, need to have their position in 3-space determined and we need to distinguish point sources from distributed ones. Neutrino events, besides being point sources, are uniformly distributed through-out the detector volume; in contrast the background events have multiple conversion sites and/or a structured, non-uniform spatial distribution. To achieve these goals we have determined that an array of 2400 wafer calorimeters (1600 in the image plane and 800 in the mask plane) separated by one meter can be used. The wafers, in order not to cool too rapidly after a hit, must not be in the superfluid hence the array is above the liquid. As will be discussed in more detail below, instead of an image reconstruction we adopt a maximum likelihood technique for event position and discrimination. The lateral extent of array and the size of the pixel wafers are driven by the size of the helium volume and practicalities of instrumenting wafer control and readout. The required amount of helium is governed by the event rate (~2 neutrino events/tonne-day), required statistical power and the size of the non-fiducial buffer region.

These considerations lead to a detector configuration with a fiducial volume of 10 tonnes with a surrounding buffer He mass of 22 tonnes (superfluid density = 0.145 g/cc). Outside the He buffer region are the acrylic cells (5.3 tonnes) containing 103 tonnes of frozen N_2 moderator (density 1.03 g/cc). These acrylic cells are envisioned as being engineered into the structural integrity of the inner cryostat whose overall dimensions would be R= 3.8 meter and height of 6.4 meters. The coded aperture planes, which are located in the one meter vacuum space in the upper part of the inner cryostat, are taken, for purposes of this study, to be 4.8 x 4.8 m and wafer sizes of 12 x 12 cm each. The wafers in the mask plane are arranged in a so-called 17x19 uniform redundant array ("URA"). We simulated several other mask configurations and found this one simple to implement and with a somewhat better resolution than the others. These dimensions were also seen to give excellent coverage within the fiducial volume while still providing good coverage in the buffer region. Typical spatial resolutions in the fiducial volume were 1.5 cm in x and y (horizontal plane at all depths) and 6.5 cm in z near the bottom and 0.4 cm at the top of the liquid. While this z-resolution near the bottom might prove marginally adequate when all optical effects are taken into account, a very attractive and more precise z determination (< 1 cm) is available to complement the coded aperture via the e-bubble drift time relative to the scintillation trigger. The reconstructed energy resolutions were dE/E of ~10 % at 60keV and ~3 % at 650keV. The absolute scales for energy threshold and z-positions will require calibration with a radioactive source. The reconstruction capabilities of this coded aperture model were tested both with and without various optical effects (e.g., He refractive index, multiple reflections between wafer planes) and found to be consistent. (Other uses of e-bubbles in background control and coded aperture performance are discussed further in the next two sections.)

The inner cryostat is enclosed by the conventional array of heat shields, vacuum gaps and outer cryostat (R=4m x H=8m). A commercial, large capacity dilution refrigerator with attendant pumps, gas handling, stand-by gas/liquid storage and liquifiers would complete an underground detector system.

[More details on this section can be found in 5, 19, 21, 23, 28, dissertation D7]

Detection of Single Electrons:

We have proposed a method by which it should be possible to detect a single electron in the liquid helium and determine the position of its creation. The scheme involves the use of a weak field to drift the electron to the free surface of the liquid, extracting the electron from the liquid and accelerating it in the vacuum with a larger field, and then detecting it with the wafer/calorimeters of the coded aperture. The horizontal position of the event, determined more precisely by the scintillation, is provided a check by the wafer sensing the electron, and the vertical position by the time interval between the arrival of the electron and the photon signal. The recoil electron produced by elastic scattering travels a sufficient distance in helium so that even in very low fields it will not recombine with its ionic partner. Depending on the energy of the recoil electron, there may be secondary electrons (delta rays) that are sufficiently separated from ions that they will not recombine as well. At least one electron will mark a scattering event, so that its detection can be a powerful diagnostic tool.

There are technical challenges to implementing this detection scheme, such as the fact that an electron in superfluid helium forms a bubble and if it achieves a velocity of greater than about 40 m/s generates a vortex ring to which it remains attached. The kinematics of this bubble/ring is such that its usefulness is impaired for timing. Scattering by a small amount of ^{3}He (10 ppm) can keep the velocity below the threshold for vortex creation in weak fields (2 V/cm). However, attachment to a vortex is required to carry the electron through the surface in the face of the polarization charge at the interface. A modest field of ~100 V/cm over 1 cm of the liquid just below the surface is necessary to accomplish the transmission. (A group internal note summarizes a simulation study showing that this amount of ^{3}He does not contribute any significant background from neutron capture.)

In applying fields in the vacuum above the liquid we have encountered another problem, which appears not to have been discussed in the literature. Cells partly filled with liquid helium below 0.5 K undergo electrical breakdown upon the application of very low potentials between electrodes. It has been necessary to explore and understand this phenomenon to ensure that would not be an impediment to the implementation of our technique for detecting single electrons. We have discovered that electrical breakdown in partially filled He cells whose walls are covered by a superfluid film is the result of the fact that metastable He excimers form a bound state on the surface of helium and on undergoing annihilation inject electrons into the vacuum via Penning ionization. The electrons are accelerated across the vacuum and produce additional excimers on hitting the liquid. With sufficient voltage more excimers are created than are annihilated and the current increases without limit. Since we now know the breakdown mechanism and its dependence on electrical potential and electrode design, we are able to develop means to avoid its occurrence in a detector for solar neutrinos. Basically, the accelerating potential across the vacuum must be limited to less than 100 volts. This is acceptable since the electrons are to be detected with calorimeters having a threshold of less than 10 eV.

[More details on this section can be found in 26, 29, 30 dissertation D6]

Simulation and Expected Performance of a Full Scale HERON:

The criteria required for precision measurements of the low energy solar fluxes have sharpened significantly recently due to the advances made at KamLAND, SNO and SuperKamiokande and the theoretical interpretation of their results. To make significant advance in our understanding of the solar processes, which can probably only be done by direct measurement of the PP (or p-e-p) neutrinos, the flux should be measured to a precision of <3% and preferably to 1% or better. A simultaneous measurement of the ^{7}Be flux in the same experiment to 5% or better would permit a direct test of the matter-to-vacuum transition in neutrino oscillations, tighten bounds on mixing angles and search for evidence of new physics such as “mass-varying-neutrinos”, sterile neutrinos and magnetic moment effects.

We have carried out a program of testing, by computer simulation, the performance to be expected from a HERON-like detector based on the configuration outlined above. This configuration takes into consideration: the results of our experiments with particles in superfluid He (scintillation, roton, e-bubbles), experiments with wafer design and performance (assumes single 16eV photon sensitivity), formulation and testing of coded aperture algorithms and our studies of background sources.

To carry this out very large Monte Carlo samples of the expected three data channels (PP, ^{7}Be, backgrounds) must be created. This is done by making use of the CERN GEANT-3 program. A full scale version of HERON as described above is set-up in the program, the three signal and background parent channels are generated and the subsequent interactions are propagated through the detector materials and into the helium. The parent samples for PP and ^{7}Be fluxes are generated based upon the present best data for δm^2 and $\sin^2 \Theta_{12}$ and a total of $5x10^5$ events of each were created throughout the full He volume. The background events are generated according to the decay schemes and processes appropriate to the various materials and parts of HERON; a total of $\sim 10^9$ background decays were followed which would be the equivalent of ~4 years of data taking. The resulting, detailed energy depositions in the He are then processed and reconstructed through our coded aperture analysis system. Each event is then assigned fitted position (x,y,z), energy, likelihood as point-like or non-point-like photon source and the number of e-bubble candidates in that event noted. (It was decided that use of the e-bubbles, rather than rotons, in background control presented a superior second channel to that of scintillation. Although the drifting of the electrons would require the addition of a low electric field, the implementation of the roton analysis was deemed to be less attractive and less powerful.)
These reconstructed data are then used to test how well experiments of different running times could make a separation of the three channels and to measure with what precision that the PP and ^{7}Be fluxes could be established. Briefly, the procedure for extracting this separation is based upon the use of four probability distribution functions (PDF’s) in which each channel has a distinctive feature. The PDF’s quantities are the distributions for event energy, radial position, depth and point-like loglikelihood. Prior to the use of the PDF’s so-called “high-level” cuts were made and consisted of an energy threshold cut (>45keV), a fiducial volume cut and a requirement of less than 3 electrons detected on separate wafers. The less-than-3-electron cut reduces the number of background candidates by 2/3. In the radial and depth position, PDF’s the neutrino events are uniform so PP and ^{7}Be are undistinguishable from each other; however, the background is structured and its separation gives an independent measure of the total neutrino flux. In the energy and likelihood PDF’s all three differ significantly from each other. The combination of these features provides a powerful tool for separation of channels. The immediate challenge in carrying out this scheme for simulation of experiments of up to 5-year duration is the computing time required to assemble large enough samples for “data” as well as for constructing the PDF’s without building in statistical bias. We have tried to avoid this with a variety of analytical short cuts to reduce the computing load. Simulated experiments of duration 3-mo., 1-yr. and 5-yr. were carried out. Of most interest is 5-yr where data sets of 27,000, 9300 and 75,000 events, respectively for PP, ^{7}Be and background. There we find, including statistical and estimated systematic errors (e.g.,energy scale, resolutions, fiducial cut), that a one-sigma precision of <1.5% and <5% could be achieved for PP and ^{7}Be, respectively. Covariance matrices are also

constructed among channels and among PDF's. The analysis was repeated for a larger fiducial volume cut and the same result was found. In a real experiment independence of fiducial cut would be a strong indication confidence in the background model. As a side issue we also simulated a test for the eccentricity of the Earth's orbit with 5-yr data and found that, at the 90% confidence level, a non-zero eccentricity could be established from the monthly variation in the flux. [More details on this section can be found in dissertation D7, talks at PANIC2005 and at Homestake DUSEL workshop websites, paper in preparation]

Personnel:

Seven graduate students will have received PhD's either fully or partially supported on this grant during their research. Three, F. Scott Porter, Simon R. Bandler and Joseph R. Adams are active in physics research in permanent positions at the Goddard Space Flight Center (NASA). Tamar More is an Associate Professor of Physics conducting research in low temperature physics and teaching at the University of Portland (OR.). Yong Ham Kim is a research scientist in physics at the Korean Research Institute of Standards and Science (KRISS). Baskar Sethumadhavan and Yun Hu Huang are just starting their searches for positions as they complete the writing of their theses this Spring. There were four postdoctoral research associates: Dr. Rodney Torii is a senior research scientist at Stanford University, Dr.Weijun Yao is now at the MIT Magnet Lab, Dr. James Distel is in the Space and Remote Sensing Sciences Group at LANL and Dr.Sun-Chong Wang accepted a research position with the neutrino magnetic moment group at the Kuo-Sheng Reactor Neutrino Laboratory in Taiwan.

Summary, Conclusions and Recommendations:

In summary, we have completed R&D on the basic principles on which a superfliud helium-based detector for PP and ^{7}Be solar neutrinos could be built. These studies have involved measurements in helium of three detection mechanisms (scintillation, roton generation and electron drift) for locating and measuring energy deposited in the superfluid. Devices and methods have been developed to handle some of the special challenges in this application presented by helium at low temperature. Among these are the wafer calorimeters and the metallic magnetic calorimeters sensitive enough to detect all three channels as well as the "film burners" used to prevent superfluid film flow onto the wafers. A method was created for arranging the detector wafers into a coded aperture array suitable for event location and energy determination as well as helping to create a background rejection signature. We carried out tests and studies of materials suitable as low background materials to be used in construction of a large device. Additional studies of background control from sources external to the detector, such as environmental gammas and neutrons and the shielding materials used to reduce them, were conducted with the goal of establishing the limits necessary for obtaining a signal and background separation accurate enough to do the neutrino science. All of these data have been combined to form an input to carry out a computer simulation study of the precision which might be expected for a full scale HERON operating for several years. We have completed that simulation and find that precisions of $<1.5\%$ and $<5\%$ might be expected for the fluxes of PP and ^{7}Be solar neutrinos, respectively.

Everything we have learned so far suggests that, from the science point of view, the HERON approach is feasible and that it could achieve the precision required by the physics. While we are unaware that there could be any fundamental reason HERON could not be realized, it should be noted that an engineering design was not to be part of the deliverables from this grant. However, in developing the base-line concept for HERON we have tried to make physically reasonable choices of scope and available materials.

Therefore, to proceed to the next step, should it be desired to carry this work forward to the design of a full scale detector based on superfluid helium, further R&D primarily of a cryogenic engineering nature will be required to evaluate models and to project cost. It should also be combined with a parallel but more modest laboratory effort to flesh out the details of single photon and single electron detection by wafers/calorimeters ---- this area is one in which there is rapid progress in related fields (e.g., for x-ray astronomy and nuclear beta decay) and therefore might offer new opportunities for simplification.

Since it is likely that the cryogenic engineering work will dictate further choices to be made in the configurations affecting the physics, both areas of R&D should be prepared to proceed in parallel. With this in mind we would suggest that the first engineering be done for a prototype sufficiently large to test an integrated inner cryostat of copper, acrylic and solid nitrogen which would also be suitable for tests of an operational coded aperture array of reduced scale. The latter would permit the further definition of needs for, say, movable calibration sources in the helium for energy and position precision and could suggest choices for a different pixilation of the array. The engineering results will also provide needed information on the maximum mass of material needed for the full scale helium containment and set the final level of radioactive purity acceptable in construction materials. The electronics and data acquisition are likely to be quite routine and in some ways simpler than current practice in the neutrino field; however, they will nonetheless need to be designed and built for such a prototype detector.

Published Papers:

Group website: http://www.physics.brown.edu/physics/researchpages/cme/heron/LTD_home.html

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