

"HERON" AS A DARK MATTER DETECTOR?

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Abstract

"HERON", which is the acronym for **"Helium: Roton detection of Neutrinos"**, is a project whose principal goal is a next generation detector of solar neutrinos from the p-p and ⁷Be branches. It will utilize superfluid helium as the target material and employ event energy transport out of the target by phonon and roton processes unique to helium. Many of the challenges presented for dark matter detection are very similar to those for low energy solar neutrinos. We present new results from our feasibility studies for **HERON** which indicate an asymmetry in the roton emission distribution from stopping particles and the ability to detect simultaneously the ultra violet fluorescence photons also emitted. These features are potentially valuable for solar neutrino detection and the question is explored as to whether or not the same helium technique could be valuable for WIMP dark matter detection.

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Measurements of the recoil energy spectrum from low energy solar neutrinos place many of the same demands on any detector, designed to do so, as they do in the case of measurements for WIMP dark matter. Both require an effective mix of several features. Among them are: a) an extremely low radioactivity in the target material and its container, b) good event signature discrimination, c) modest energy resolution, d) real time detection and e) relatively massive targets. Many avenues for event signature discrimination can be valuable; such as event position in the detector by taking advantage of differing mean free paths for interaction by background entering from the exterior, directionality of the recoil to take advantage of sidereal effects or source location, and particle identification to distinguish between nuclear and electron recoils.

We have been developing a particle detection technique based upon the use of superfluid helium as the target material for detecting neutrinos from the p-p and ${}^7\text{Be}$ branches of the sun's principal fusion cycle. The project is referred to as **HERON** (for **Helium: Roton** detection of **Neutrinos**) which, if the present R&D shows it to be feasible, is intended to be a "next generation" solar neutrino detector detecting > 20 events per day in real time. Such a full scale detector would utilize roughly 10 tons (fiducial volume) of liquid helium in the 100 milli-Kelvin temperature range and the events would consist of elastic scattering of neutrinos by electrons in which the recoiling electron energies are in a continuum up to 660 keV. Liquid helium is a very attractive material for this type of application for many reasons. It is the purest material known since nothing is soluble in it, foreign elements freeze out on the walls (it is self-cleaning), its first nuclear excited state is ~ 20 MeV and it has no long-lived isotopes. It is very inexpensive even in these quantities and industrial/commercial handling on this scale is standard and routine. Additionally, some of the materials suitable for containment cryostats, such as OFHC copper, tend to have few long-lived cosmogenically induced activities. In spite of this attractiveness, the traditional methods for extracting a signal from a fluid target such as drifting ions, reconstruction from scintillation, or calorimetry do not prove adequate to obtaining useful information. The primary problems, respectively, are due to too low drift velocity, too long lifetime for the fluorescing state and too large a heat capacity. However, there are a sequence of phonon and roton processes in superfluid helium which, when taken together, have been suggested ¹⁾ as a means for extracting the energy and other information from a large detector²⁾ of just this type. In recent years we have been carrying

out experiments³⁾ which have established the basic properties of particle detection by this method.

These experiments have been carried out in prototype cells (typically containing 3 liters of liquid helium) attached to a $^3\text{He} - ^4\text{He}$ dilution refrigerator. The interior of the cell contains an array of instrumentation which can be readily re-configured to suit the goals of a particular test. Radioactive sources of alpha particles ($< 6 \text{ MeV}$), gamma rays (662 keV) and electrons (364 keV) as well as pulsed heaters are utilized to study the sequence of processes which permit particle detection via phonons. Small superconducting motors are used to move the sources within the liquid which is typically at 30 mK.

While the principal interest for possible application of this technique for WIMP dark matter centers upon our recent experimental results which suggest a sensitivity to recoil track spatial orientation⁴⁾ and simultaneous detection of a fast fluorescence signal calorimetrically⁵⁾, it is instructive to first describe the sequence of processes which are the basis of the detection method. The following steps occur.

- a) A recoil particle $> 100 \text{ eV}$ generates mainly secondary ions and electrons.
- b) The secondary electrons lose energy by further ionization or atomic excitation until they fall below $\sim 20 \text{ eV}$ whereupon they scatter from the atom as a whole.
- c) recombination of the ionization then occurs resulting in the formation of dimers which subsequently fluoresce primarily $\sim 16 \text{ eV}$ photons to which helium is transparent.
- d) The energy received by atoms scattered from secondary electron collisions appears as phonons and rotons.
- e) The rotons (which are a class of phonons distinguished by their position in the non-linear, higher energy portion of the dispersion curve for superfluid helium) dominate the available phase space, are stable against interaction or decay and propagate at $\sim 150 \text{ m-s}^{-1}$.
- f) The energy of the rotons is greater than the binding energy of a helium atom to the liquid (0.65 meV) and those satisfying certain kinematic conditions undergo a process referred to as quantum evaporation in which a single roton ejects a single helium atom.
- g) A consequence of this kinematic condition is that the ejected atoms arise from those rotons contained within a cone (with axis normal to the free surface of the liquid). In our experiments the cone half-angle is $\sim 17^\circ$ and corresponds to about 1% of the recoil energy.
- h) The number of ejected atoms is very large ($\sim 10^5/\text{keV}$ of recoil energy) and these are positioned just above the liquid. The binding energy to the low heat capacity wafers is

~ 9 meV/atom thus producing an energy deposit in the wafer roughly ten times that of the original roton or, for the complete deposition, $\sim 10\%$ of the recoil particle's energy. Additionally, the ultra violet radiation (5 photons/keV) is absorbed in the wafer as a fast pulse.

i) In the final step, tiny thermometers (thin, superconducting films or thermistors) attached to the wafers record the resulting temperature pulse induced.

In any large scale application of this technique a close-spaced, regular array of wafers would be placed just above the liquid and, from the wafer hit pattern as well as pulse magnitude and timing distributions, the coordinates and energy of the event would be derived.

In order to investigate further the possibility of obtaining directional information on the recoil as well as to make measurements of the presence of detectable fluorescence photons, we have performed the following test. A collimated source of alpha particles was constructed; the average energy of the emerging alpha particles was 3.3 MeV with a 15% FWHM determined by the geometry and Kapton window thickness. The source (4.5 cm. below the surface) was mounted on the drive shaft of a small superconducting stepper motor oriented so that the direction of the alpha particles could be rotated in a plane perpendicular to the helium liquid surface (see Figure 1). A 1cm. by 2 cm. silicon wafer with an Ir-Au superconducting transition edge thermometer attached was placed just above the liquid and readout by a SQUID. Data were taken as the track direction was stepped at 6.5° intervals through a full 180° . In Figure 2 are shown traces (100 event averaged to illustrate detail) taken with the track orientation a) horizontal and b) vertical. The rise time of the wafer is ~ 50 μ -s and the relaxation time to the reservoir is ~ 500 μ -s. The fast, small step at the start is due to the arrival of the UV photons and the large subsequent rise is due to the slower rotons and is consistent with their known speed of propagation. The value of the pulse heights for both portions of the pulse at all of the track angles is shown in Figure 3. As can be seen, the roton pulses range a factor ~ 3.5 between a direction parallel and normal to the surface while the photon pulses are independent of track direction as would be expected for photon emission. In contrast, the large difference in energy collection due to rotons suggests a commensurate asymmetry in the radiation of rotons from the track itself. This asymmetry is believed to arise due to the very high density of rotons in the volume swept out by the stopping track and by the large roton-

roton scattering cross section (10^{-14} cm²). For these alpha particles there are $\sim 10^9$ rotons in $\sim 10^{-13}$ cm³ resulting in the down conversion of the original rotons to lower energy and then radiating the resulting thermal distribution whose directional intensity reflects the geometrical aspect ratio of the track volume. We have confirmed this thermalization effect in separate experiments previously reported³). This picture is also supported by our detection of the fluorescence photons. Experiments⁵) have established that the fluorescence results due to collisional de-excitation of helium dimers which requires a region of high energy density. Additionally, the photon intensity we measure (5 photons/keV) is consistent with that measured in these same experiments.

How could either of these effects be used in a real detector of WIMPS or solar neutrinos? Differences in the ratio of scintillation light relative to roton signal strength for electron or ⁴He recoils may provide a useful particle I.D. Should these observations of roton emission asymmetry survive to lower energy recoils and to other particle types (e.g., electrons) then, with the known distribution of emission versus track orientation and the differential pulse height distribution on the wafers, both the track orientation and the event energy could be found. This would be a very powerful addition to event signature discrimination by correlation of the sun's position with solar neutrino events or to observe the sidereal direction change of WIMP dark matter due to the Earth's motion through the dark matter distribution.

Much work remains before the feasibility of these applications is known. We are now beginning a new set of experiments which will attempt to address some of the issues involved. Among them are experiments on the following. We need to improve the sensitivity of our wafer calorimeters and their attached thermometers in order to build detectors large enough for solar neutrinos and at the same time bring our knowledge of the energy deposition by low energy electrons up to the same level we have for alpha particles (particularly with respect to directionality). In order to get a measure of the potential for energy, position and directional resolution we are planning to construct a new prototype roughly ten times larger than our present one. It would be 30 liters (~ 4 kg.) and be instrumented with eight wafer channels. The prototype will also be useful for other

test of a more structural sort such as the use of cesium films for superfluid film flow control and test of construction materials. On this scale, it is not inconceivable that the prototype could itself serve a useful purpose for dark matter detection.

On any scale, however, we must take into account what the weaknesses and strengths of helium are as a target material for WIMP dark matter. Among its weaknesses must be counted its poor cross section for supersymmetric particles (a well motivated candidate for WIMP dark matter); further it is a spin-0 nucleus. Its low nuclear mass is both a weakness and a strength in that although that makes the visible recoil energy greater at the same time it is most effective when the dark matter mass is also low. On the strength side, we can count its extreme purity, the potential for event directionality and position, the absence of form factors at low collision energies and the ease of making very large targets. We will have to wait and see whether our future tests and Mother Nature together can answer our original question.

(See text for figure discussion)

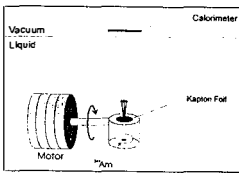


Figure 1

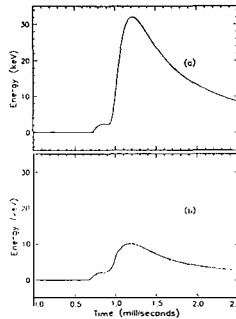


Figure 2

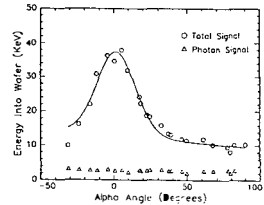


Figure 3

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- 4) We are indebted to Dr. Susan Cooper of the Max Planck Institute for Physics (Munich) and Prof. F. v. Feilitzsch of the Technical University (Munich) for providing us with this device.
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