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Energy deposition by electrons in superfluid helium and design of a detector for solar neutrinos

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Abstract

We report recent progress in the development of HERON, a detector of low-energy solar neutrinos that will use as a target material 10 tons of liquid helium. The HERON detector is intended to detect p–p neutrinos from the sun in real time with a an energy threshold of approximately 50 keV. The recoil energy of electrons resulting from the elastic scattering of neutrinos is measured with calorimetric wafers above the free surface of the liquid at 40 mK. Both the EUV scintillation and the helium atoms produced by quantum evaporation, which result from phonos and rotons hitting the free surface, are detected by the wafers. Background rejection is achieved statistically by a determination of event location with respect to the walls of the helium containment. The wafers will be used to form a coded aperture array. If the wafers have an energy threshold such that they can detect single 16 eV photons, a neutrino event having a recoil electron with an energy greater than 50 keV could be located to within 10 cm or better anywhere in the 10 tons of helium.

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1. Introduction

The fundamental properties of the neutrinos and their role in nature continue to be central issues in nuclear physics, particle physics, astrophysics and cosmology. There are now strong indications from experiments with atmospheric and solar neutrinos that neutrinos possess small but significant masses [1], an observation that has profound implications for our understanding of the fundamental laws of nature.

No detector of solar neutrinos now built or under construction is capable of measuring in real time the energy spectrum of low-energy neutrinos produced by the p–p reaction in the sun. Our present research has as its goal the development of technology to make possible the design of a detector with this capability. Our detector (HERON) is based on the use of superfluid helium as the target material. The elastic scattering of a neutrino off of an electron produces a recoil electron with sufficient energy to detected. Liquid helium may be the only material sufficiently pure that the very low-energy neutrino events are not completely masked by internal radioactive background.

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A full-scale detector of 10 tons would detect 25 p–p and ^{7}Be events per day based on the standard solar model. Large backgrounds due to the Compton scattering of γ-rays from the containment vessel can be suppressed by event signature and spatial distribution. This paper describes a new design of a full-scale detector based upon recent experimental results of electrons stopped in liquid helium.

2. Energy deposition in liquid helium by electrons

We have used a test cell containing 3 L of ^{4}He at $\sim$ 30 mK to study the energy deposition by electrons in the liquid. A calorimeter, consisting of a 5 cm diameter sapphire wafer with an Ir–Au bilayer used as a superconducting transition edge thermometer[1] is placed a few millimetres above the liquid surface.

Neutrino events are simulated experimentally by placing in the liquid a radioactive source that emits single monoenergetic 364 keV electrons. An energetic charged particle passing through liquid helium will generate ionized helium atoms, secondary electrons, excited helium atoms, and quasiparticles in the liquid. Both ionized and excited helium atoms can combine into He_2 dimers, of which the singlets decay radiatively in $\sim 10^{-9}$ s emitting EUV photons in a band centred around 16 eV. Liquid helium is transparent to this radiation, so the EUV photons can be measured directly by the calorimetric wafer, suspended above the liquid surface.

The large numbers of quasiparticles (phonos and rotons) produced in the liquid propagate ballistically at low temperatures. Upon hitting the free surface, it is possible for a single quasiparticle to evaporate a single helium atom in a process known as quantum evaporation [2]. If the evaporated atoms then strike the calorimeter, they adsorb onto the surface depositing their binding energy in the wafer. Since the binding energy of the helium atom to a wafer is $\sim$ 10 times greater than that of a helium atom to the liquid surface, the evaporation process amplifies the quasiparticle signal. We have reported elsewhere the measured calorimetric signal obtained when an electron is stopped in liquid helium, as well as a model that accounts for the strikingly different signals obtained for electrons and alpha particles [3]. The model takes into account the large difference in density of energy deposited along the tracks of an electron and an alpha particle. It involves a set of coupled rate equations for the singlet and triplet dimers that includes lifetimes, diffusion away from the track, and non-radiative bimolecular decay. A sample pulse from an electron is shown in Fig. 1. This model necessitates a new design for a large-scale detector [4] to take into account the larger scintillation signal as well as the smaller evaporation signal.

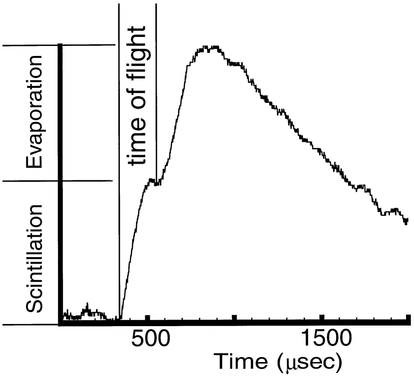

Fig. 1. Sample pulse from a 360 keV electron stopped in helium. The two components of the signal can be seen separated in time. The time separation is due to the different propagation velocities of the two signal components.

3. Requirements of full-scale detector

A solar neutrino scattering off of an atomic electron produces an electron with a maximum recoil energy of 660 and 260 keV for ^{7}Be and p-p neutrinos, respectively. In liquid helium the range of these electrons is less than 2 cm. On the scale of the detector (volume $\sim$ 60 m^3), the neutrino events are effectively point sources of photons and quasiparticles. In contrast, most of the background γ-rays make spatially extended energy depositions by multiple Compton scattering. Although there is

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[1] We are indebted to the group of F. von Feilitzsch for providing us with Ir:Au transition edge thermometers

always a small number of single Compton scatterings, the major contribution to background is from multiple depositions originating from an initial γ-ray. To suppress the background, multiple Compton scattering events must be identified and the spatial distribution of point energy depositions obtained. The background from point depositions can be determined statistically using the measured distribution of such events with respect to the walls of the container [4].

A knowledge of the position of the event in a large detector is essential not only for background rejection and diagnostics but also for the determination of the energy of the event.

A full-scale detector will have a helium surface area of $\sim 20\,\mathrm{m}^2$ with about 10^3 calorimeters suspended above it. The position of an event cannot be determined from the arrival times of the UV photons hitting the wafers, principally because of the inherent slowness of the calorimeters. Even if the detectors were fast (e.g. photomultiplier tubes), the timing of photons could not be used due to the fact that the lifetime of the singlet dimers is comparable to the transit time of a photon in the detector. Timing information of the evaporation signal could be used to locate an event, but because of the small size of that signal on an individual wafer this procedure would be difficult to implement. We prefer, instead, to use the distribution of photons hitting the wafers as the primary means of determining position and utilize the timing of the evaporation signal as a consistency check.

4. Event location

A coded aperture array [5] is a device used to determine the position of an event in circumstances where the radiation cannot be focused. Such arrays are widely used in X-ray tomography, X-ray astronomy and in other applications. A coded aperture consists of an image plane of detectors in front of which is a parallel plane of patterned masks with roughly 50% transmission. With a sufficient number of photons, the distribution of their signals on the image plane uniquely determines the source position. In simulations of a coded aperture for a neutrino detector we have used a model in which the image plane consists of 1600, $150\,\mathrm{cm}^2$, densely packed wafers, separated by 50 cm from the mask plane of 800 wafers patterned as a uniformly redundant array [6]. Unlike the coded apertures used in the X-ray tomography the wafers forming the masks are active calorimeters and are used in both position finding and energy determination. Thus, no signal is lost by the presence of the mask.

We have initiated Monte Carlo calculations in which the distribution of photons incident on the wafers is used to determine the most probable position of an event based on a maximum likelihood method. In the calculations we have assumed the wafers have an energy threshold sufficiently low to detect single 16 eV photons. The simulations suggest that is possible to determine the position of an energy deposition by an electron anywhere within a $60\,\mathrm{m}^3$ cube of liquid with a resolution of 10 cm FWHM provided about 75 photons hit the array. This corresponds to an energy of 30 keV for an event near the top of the liquid and 75 keV near the bottom. Since we have not yet optimized the parameters of the array – the size of wafers, the separation of planes, the pattern of the mask or the search algorithm – it is likely that these energy thresholds can be lowered or the resolution improved. Background events involving multiple Compton scattering events can be distinguished by the poor quality of the determination of event location.

The position of an event determined by photons can be corroborated by timing information of the evaporation signal. Since the evaporation signal is spread over the wafers, the size of the evaporation signal on an individual wafer will be on the order of 1 eV. The output of many adjacent wafers will need to be summed to extract the evaporation signal from the noise. The evaporation signal is also important for measuring the energy of an event as the limited number of photons being detected limits the accuracy with which the energy can be determined.

5. Wafer sensitivity

For the coded aperture array to work, the wafers must be able to detect with high probability a single 16 eV photon. A silicon wafer of $150\,\mathrm{cm}^2$ area and 0.2 mm thick has a heat capacity of

$\sim 1 \times 10^{-10}$ J/K at 40 mK. Currently, we have achieved a resolution of 13 eV with a magnetic calorimeter having a heat capacity of $\sim 1 \times 10^{-12}$ J/K [7], and a resolution of 135 eV with a calorimeter having a heat capacity of 4×10^{-9} J/K [8]. Since the sensitivity varies roughly as $C^{-1/3}$ for magnetic calorimeters, we require a factor of 5 improvement over present performance. Such an improvement is well within that predicted to be achievable with better calorimeter design [7].

6. Conclusion

The results of measurements on the energy deposition of electrons stopped in liquid helium point to the importance of using the EUV scintillation photons in the design of a solar neutrino detector. A coded aperture array using wafer/calorimeters capable of detecting single 16 eV photons appears capable of providing the necessary event location required for background rejection and energy determination.

Acknowledgements

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