ELSEVIER

Physica B 219&220 (1996) 727–729

PHYSICA B

Phonon physics and the detection of solar neutrinos

J.S. Adams[a], S.R. Bandler[a, b], R.E. Lanou[a], H.J. Maris[a, *], T. More[a], G.M. Seidel[a]

[a] *Department of Physics, Brown University, Providence, RI 02912, USA*
[b] *University of Heidelberg, Heidelberg, Germany*

Abstract

We present a summary of recent progress towards the development of a solar neutrino detector in which superfluid helium is used as a target material. In this detector phonons and rotons generated in the liquid by a recoiling particle propagate through the liquid and then cause a shower of atoms to be quantum evaporated from the liquid surface. We describe recent results which indicate that roton–roton interactions close to the track of the recoiling particle may make it possible to obtain information about the track direction.

The sun derives its energy from fusion processes that occur in its core [1]. In a number of these nuclear reactions neutrinos are produced. The different nuclear reactions produce neutrinos having characteristically different energy spectra (line or continuous), and this provides a way to identify neutrinos coming from different reactions. Hence, if the flux of these neutrinos and their energy spectrum could be measured, it would be possible to determine the rate at which the nuclear reactions are taking place, and to test the theory of the inner workings of the sun. It is predicted [1] that the vast majority (99.75%) of the solar neutrinos are produced by the pp reaction $p + p \to d + e^+ + \nu_e$. These neutrinos have a continuous energy spectrum extending up to 420 keV and a flux at earth of 6×10^{10} cm^{-2}. These low energy neutrinos have extremely small scattering cross sections on both electrons and nuclei. As a consequence, although the flux of neutrinos at the earth is large, it is necessary to have a very large detector (on the scale of tons) in order to be able to have a reasonable event rate, such as 10 events per day, in the detector. There are two essential difficulties in the design of a detector. Even though the detector has to be very large it must still be sensitive to the deposition of very small energies. For example, when a neutrino of energy 420 keV scatters off an electron in the target, the maximum recoil energy deposited into the target is 260 keV, i.e. only 4×10^{-7} ergs. Secondly, it must be possible to tell that the events observed do indeed arise from neutrinos and not from the internal radioactivity of the detector itself. For a detector composed of many tons of material it is very difficult to eliminate radioactive impurities to the degree required.

Because of this purity requirement it is natural to consider the use of superfluid helium as a material for a neutrino detector. It is well known that at low temperatures all impurities freeze out of the liquid. However, helium is undoubtedly the worst possible material to use if the detector is to work through a measurement of the temperature rise induced by the neutrino event. An energy deposit of 260 keV into 10 tons of helium at 10 mK will give a temperature rise of 2×10^{-13} K, which is much too small to measure. We have been working [2–5] on the development of a detector which avoids this difficulty and the design is shown schematically in Fig. 1. Superfluid helium at a temperature of 30 mK or lower is contained in a large cell. Above the surface of the liquid an array of silicon wafers is suspended. When a neutrino scatters off an atomic electron in the liquid, the electron recoils and phonons and rotons are excited along the electron recoil track. At the low temperature of the experiment, phonons and rotons propagate very large distances in the liquid without scattering. Excitations arriving at the free surface of the liquid are able, with some probability, to evaporate helium atoms. These atoms are adsorbed onto the silicon wafers. The energy released when the atoms adsorb is measured by means of bolometers attached to each of the silicon wafers. This design of the detector manages to

---

[*] Corresponding author.

SSDI 0921-4526(95)00867-5

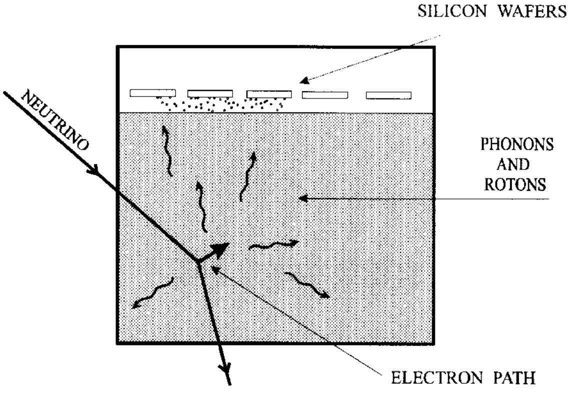

Fig. 1. Schematic diagram of the experiment.

avoid the problem of the large specific heat of helium; the helium acts solely as a conduit to channel some fraction of the energy deposited by the neutrino into the silicon wafers which have a very low heat capacity.

There are several aspects of phonon physics which enter into the operation of the detector. These include (1) the electron–phonon and electron–roton interactions which govern the generation of the excitations, (2) possible interactions [6] amongst the phonons and rotons in the region where they are generated (see discussion below), (3) scattering and decay processes [6] that may occur before the excitations reach the surface, (4) the process of quantum evaporation [7] at the liquid surface, and (5) phonon transport in the silicon wafer.

In our current prototype apparatus we have a cell of volume 3 l which can be operated at temperatures as low as 25 mK. We have tested the detection scheme using radioactive α-sources to produce charged particles which recoil through the liquid and deposit energy. The source is mounted on an arm attached to a superconducting motor, and can be moved to different positions within the cell. We have also performed experiments with β and γ sources.

Here, we review briefly some interesting results which have been obtained using an α source [4, 5]. The α source is a metallic film containing ^{241}Am evaporated onto a glass substrate. It is found that with the source at a fixed position in the cell the magnitude of the signal detected at the bolometer varies from event to event, even though the energy of each α emitted from the source must be the same (see Fig. 2). The origin of this surprising result is as follows. The counts below 30 keV come from α's which enter the glass substrate. The phonons generated in the glass diffuse back to the surface of the source and then convert to rotons or phonons in the helium. The remainder of the spectrum comes from α's which go directly into liquid. We have been able to show that the variation in signal from one event to the next is associated with the variation in the track direction of the α's. This was demonstrated by experiments with an α 'gun' which generated α's travelling in a particular chosen direction. The direction could be changed through the use of another superconducting stepping motor. The large signals are produced by α's which travel in a direction parallel to the liquid surface, whereas the small signals come from α's injected close to the vertical direction. This can be understood in terms of the 'hot-rod model' shown in Fig. 3. The α track is 200 μm long, and the rotons and phonons are generated over a cylindrical volume having this length and a radius of a few hundred Å. One can show that the density of excitations within this region is so high that the excitation cloud is opaque to rotons. Consequently, the radiation perpendicular to the track direction will be larger than in the direction along the track in agreement with the observations.

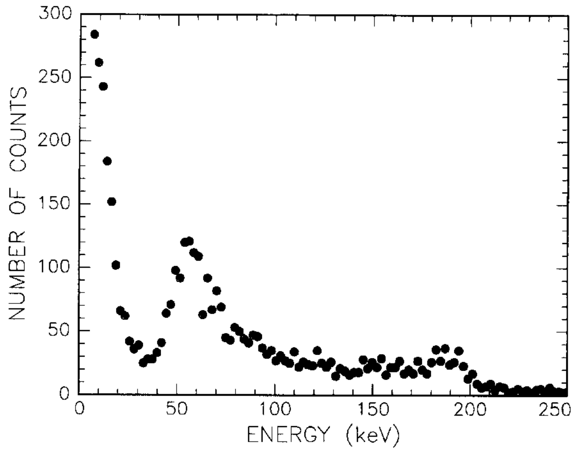

Fig. 2. Pulse-height distribution for energy deposited into the silicon wafer. For more details, see Ref. [4].

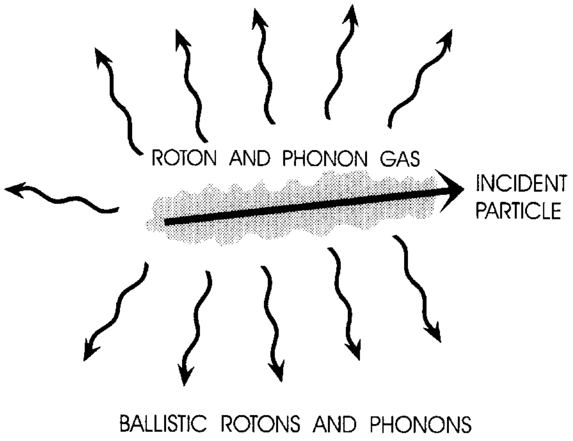

Fig. 3. Track of an α particle in liquid helium and the cloud of rotons and phonons generated around it.

Examples of data taken with the α gun are shown in Fig. 4. The ratio of the magnitude of the signal for α's parallel and perpendicular to the helium surface is approximately 3. To

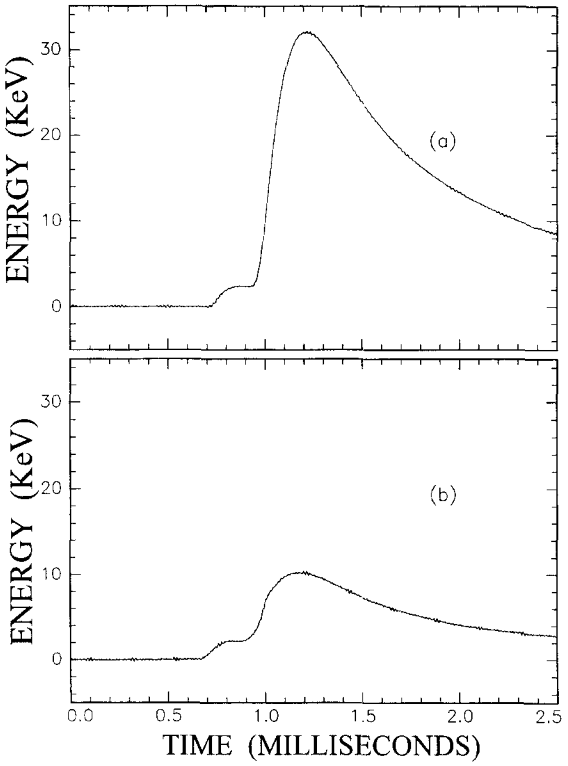

Fig. 4. Energy deposit into the silicon wafer versus time for α tracks (a) parallel to the liquid surface and (b) normal to the surface.

improve the signal to noise ratio in this figure the traces for 100 events have been averaged. In this way it is possible to resolve a small step at the beginning of the waveform. This step comes from the small part (~ 5%) of the energy of the α-particle that goes into the production of photons in the ultraviolet. Some of these photons are absorbed in the detection wafer giving a signal which appears before the arrival of the evaporated atoms. As can be seen from Fig. 4, the size of this photon signal is the same regardless of the direction of the α track. This is to be expected since the photon radiation should be isotropic.

The magnitude of the signal is found to vary rapidly as the location of the α-source is changed. Analysis of this variation indicates that the signal must come mainly from rotons, rather than phonons, and that these rotons are concentrated close to the roton minimum [8]. This result is again consistent with the idea that strong interactions occur between the excitations before they leave the region near to the track. The dense cloud of interacting rotons that is initially produced expands and the average roton energy decreases before the rotons become free to propagate.

In summary, these results indicate that a neutrino detector based on this technique may be feasible. More work is required to improve the sensitivity so that smaller energy depositions can be detected. The observation of the dependence of the signal on the track direction is important because it opens up the possibility of a detector with the ability to determine track direction. Such a detector would be a primitive form of neutrino telescope. However, at this point we do not know whether this directionality also exists for the recoiling electrons which will be produced by neutrino–electron scattering.

This work was supported in part by the Department of Energy under Grant No. DE-FG02-88ER40452 and by the National Science Foundation through the Center for Particle Astrophysics.

References

[1] J.N. Bahcall, Neutrino Astrophysics (Cambridge, New York, 1989).
[2] R.E. Lanou, H.J. Maris and G.M. Seidel, Phys. Rev. Lett. 58 (1987) 2498.
[3] S.R. Bandler, R.E. Lanou, H.J. Maris, T. More, F.S. Porter, G.M. Seidel and R.H. Torii, Phys. Rev. Lett. 68 (1992) 2429.
[4] S.R. Bandler, S.M. Brouër, C. Enss, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, Phys. Rev. Lett. 74 (1995) 3169.
[5] J.S. Adams, S.R. Bandler, S.M. Brouër, R.E. Lanou, H.J. Maris, T. More and G.M. Seidel, Phys. Lett. B 341 (1995) 431.
[6] See: I.M. Khalatnikov, Theory of Superfluidity (Benjamin, New York, 1965).
[7] A.F.G. Wyatt, Physica B 126 (1984) 392; F.R. Hope, M.J. Baird and A.F.G. Wyatt, Phys. Rev. Lett. 52 (1984) 1528; M. Brown and A.F.G Wyatt, J. Phys. Condens. Matter 2 (1990) 5025.
[8] C. Enss, S.R. Bandler, R.E. Lanou, H.J. Maris, T. More, F.S. Porter and G.M. Seidel, in: Proc. 20th Internat. Conf. on Low Temperature Physics, Eugene, Oregon, Physica B 194–196 (1994) 515.