Detection of Solar Neutrinos in Superfluid Helium

R. E. Lanou, H. J. Maris, and G. M. Seidel
Department of Physics, Brown University, Providence, Rhode Island 02912
(Received 4 March 1987)

A new method for detecting solar neutrinos and other weakly interacting particles is proposed and described. The detector consists of a large mass of superfluid helium at low temperatures (20 mK). When a neutrino is scattered off an electron, the recoil energy of the electron (10^{-6} to 10^{-7} erg) is deposited in the helium. This small amount of energy can be detected because of the unusual kinetics of rotons at low temperatures. It should be possible to construct a detector of sufficiently low background and large size to measure solar neutrino spectra.

PACS numbers: 96.60.Kx, 14.60.Gh, 29.40.−n, 67.40.Pm

The experiments of Davis and co-workers[1,2] have shown that neutrinos from the sun with energies greater than 0.814 MeV are three times fewer than predicted by the standard solar model (SSM).[3] This discrepancy between theory and experiment is commonly referred to as the solar neutrino problem (SNP). If both the experiment of Davis *et al.* and the standard solar model are correct, then what are the possible explanations of the solar neutrino problem? One interesting mechanism has been proposed by Mikheyev and Smirnov,[4] based upon earlier work by Wolfenstein[5] (MSW effect). They showed that an electron neutrino ν_e generated in the interior of the sun may be adiabatically converted into a muon neutrino ν_μ through interaction with the electron density of the sun via the charged weak current. The MSW effect can account for the observations of Davis *et al.* over a wide range of neutrino masses and mixing parameters.[6] Other possible explanations include neutrino vacuum oscillations,[7] decay of massive neutrinos,[8] the effect of a neutrino magnetic moment,[9] and modification of the solar model due to the capture of weakly interacting dark matter in the sun.[10]

Experiments using neutrinos produced on earth are at present unable to measure the neutrino parameters which enter into the different possible explanations of the SNP. More detailed measurements of the solar neutrino spectrum are needed to resolve the situation. Ideally, one would like to measure the energy spectrum, both for ν_e and ν_μ, either with a very low background, or with means to discriminate neutrino events from other processes. It could be important to have a detector that operates in real time. For example, if the MSW effect occurs, there may be a night-day variation[11] in the neutrino fluxes.

No detector proposed so far has all of these desired properties; rather, a number of different complementary detectors will be needed. Several detection methods have been discussed[12–17] based on a wide variety of techniques, and their utility is being actively pursued. Of these, only one, the radiochemical GALLEX experiment,[12] is under full construction. While each of the proposed detectors has unique and special features, most possess the common difficulty of background from residual radioactivity in the detecting medium itself or in its internal components.

The major part of the ν_e flux comes from the *pp* reaction

$$p+p \rightarrow d+e^{+}+\nu_e. \quad (1)$$

These ν_e have a continuous spectrum up to 420 keV, and an expected flux at the surface of the earth of 6.1×10^{10} $\text{cm}^{-2}\ \text{sec}^{-1}$. The reaction by which we plan to detect these neutrinos is the elastic-scattering process

$$\nu+e^{-} \rightarrow \nu+e^{-}. \quad (2)$$

For reaction (1) the maximum recoil energy of the e^- is 260 keV. We propose to use a detector consisting of a large mass of liquid helium-4. The neutrino events will be detected by means of a measurement of the energy deposited in the helium by the recoil electron. As far as radioactive background is concerned, liquid helium is the ideal detector material. At low temperatures ($T<1$ K) all impurities freeze out on the walls of the container. However, a helium detector has the difficulty that the specific heat per unit mass is very large at any reasonable temperature, and so a conventional calorimetric detection of the recoil energy of the electron is not possible. For example, below 0.5 K the specific heat of the helium is $\sim10^5$ times larger than that of crystalline silicon at the same temperature.

We have devised an approach which avoids the problem of the large specific heat. The experiment is shown schematically in Fig. 1. The large mass of superfluid helium is held at a temperature of $\simeq 20$ mK. In neutrino scattering off an atomic electron in the helium, a fraction f of the electron recoil energy E_{rec} is converted within a short time into low-energy elementary excitations of the helium, i.e., phonons and rotons.[18] The dispersion curve for phonons and rotons is shown in Fig. 2. The volume element of phase space goes as p^2dp. Because of the much larger phase space for rotons compared to phonons (see Fig. 2), we will make the approximation that the energy appears exclusively as rotons. The number of ro-

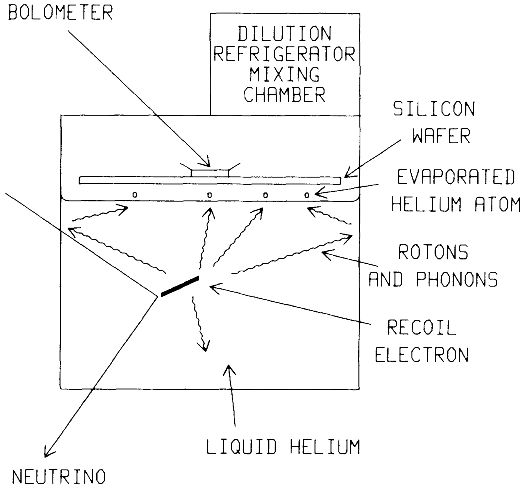

FIG. 1. Schematic design of the simplest version of the experiment. A neutrino is elastically scattered in liquid helium, and the recoil electron produces rotons and phonons. At the free surface of the liquid helium, the rotons induce evaporation of helium atoms, which are then captured by the silicon wafer. The rise in temperature of the silicon is measured by a bolometer.

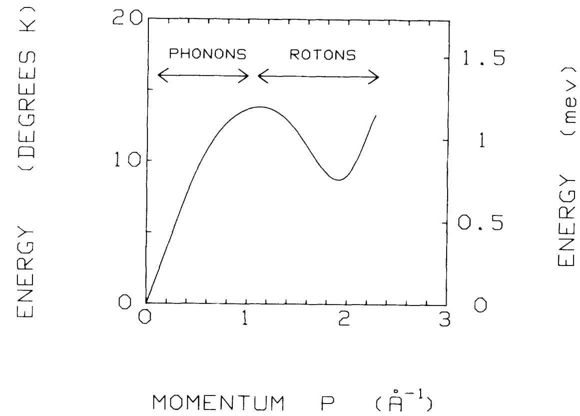

FIG. 2. Dispersion curve for elementary excitations in superfluid helium, showing the phonon and roton parts of the spectrum.

tons produced is thus approximately

$$N_r = fE_{\rm rec}/\Delta, \quad (3)$$

where Δ is the energy at the roton minimum (8.6 K). As an example, for a typical energy deposit of 200 keV, N_r is $3\times10^8 f$. The detection of these rotons within the helium appears to be an extremely difficult problem, since the volume of the helium is large. However, rotons in superfluid helium have two remarkable properties which make the detection of their energy possible. At temperatures below $\simeq 0.1$ K where the density of thermal excitations is negligible, rotons are *stable* excitations. Thus, the rotons which are produced will propagate ballistically through the liquid without decay.[19] Second, rotons induce evaporation of helium atoms when they reach the free surface of the liquid. Measurements show that a roton incident on the liquid surface has a probability of $\simeq \frac{1}{3}$ of inducing the evaporation of a helium atom.[20] Thus, the number of atoms evaporated is roughly

$$N_a \cong fE_{\rm rec}/3\Delta. \quad (4)$$

N_a could be larger than this estimate because a roton which does not cause an atom to be evaporated the first time it reaches the surface may still be able to cause evaporation if it returns to the surface. N_a may be less than (4) because some rotons will be absorbed at the container walls[21] and never reach the surface. The evaporated atoms can be detected by silicon wafers[22] suspended a few millimeters above the helium surface.[23] The helium atoms will be physisorbed onto the Si surface, and each adsorbed atom generates an amount of heat equal to the binding energy ϕ of roughly 100 K.[24] Thus, the total energy δE deposited in the Si is

$$\delta E = (\phi f/3\Delta)E_{\rm rec}. \quad (5)$$

Because ϕ/Δ is ~ 12, δE may even be larger than $E_{\rm rec}$, in which case the energy transfer via the rotons actually provides some amplification. The heat capacity of the Si wafer is

$$C = 6.25AdT^3 \text{ erg K}^{-1}, \quad (6)$$

where A is the area and d is the thickness. As an illustration of the order of magnitude of the effect, note that if $T=20$ mK, $A=200$ cm^2, $d=0.025$ cm, $E_{\rm rec}=200$ keV, and $f=0.5$, the temperature rise of the Si wafer would be 2.6 mK, which is easily measurable. We believe that by standard techniques, such as superconducting bolometers, it should be straightforward to make the noise in a measurement of δT at 20 mK at least as small as 0.02 mK. This would give a determination of the electron energy with an uncertainty of $\simeq 1.5$ keV, if we assume a well-defined relation between energy received by the bolometer and the recoil energy of the electron. The time resolution τ of the detection is determined by the linear dimensions l of the helium and the group velocity of the generated rotons ($\sim 10^4$ cm sec^{-1}). Thus, for l of 30 cm, for example, $\tau \simeq 3$ msec.

A full-scale detector of solar neutrinos based upon these physical principles could consist of an underground volume of 10 tons of liquid ^{4}He ($\simeq 70$ m^3), approximately $\frac{2}{3}$ being used as a fiducial volume, and the remaining outer section used to establish background (expected to be low-energy γ rays and neutrons) entering the helium from the outside. The helium would be divided into 10^3–10^4 cells each with its own silicon wafer (or wafers). To prevent rotons from passing from one cell to the next, it is sufficient to use very thin plastic sheets as dividers; thus, apart from the silicon wafers no large mass other than helium need be in the fiducial volume. The cross sections for reaction (2) are now well measured,[25,26] and are in agreement with the electroweak unified model of Glashow, Weinberg, and Salam.[27] If we assume a fiducial volume of 7 tons and the SSM for the solar neutrino flux, the total event rate is 14 per day.[16] The rate from *pp* neutrinos alone is 8 per day. In this method only the distribution of energy of the recoiling electrons is measured; hence the distribution of E_ν is not directly determined. Nevertheless, if one uses the known cross sections, a comparison of the distribution of recoil energies with that expected on the basis of the SSM can be made. If other information is available, such as independent measurement of the ν_e flux (from GALLEX, for example), then additional tests of the origin of the SNP can be made.

Preliminary studies of acceptable levels of neutron and γ-ray backgrounds (which can in the experiment be monitored by use of the outer helium volume to establish rate, energy, and attenuation length) indicate that construction materials with radioactive content control less stringent than those already achieved for double-β-decay experiments[28] would be adequate at the expected neutrino rate. Surveys[29] of background emanating from rock surrounding existing underground laboratories also indicate acceptable levels.

In summary, we have described a new method of low-temperature calorimetry which uses the unique kinetics of roton excitations in superfluid helium at low temperatures. Because of the extremely high purity of helium-4, this method is ideally suited for studies of the solar neutrino flux and spectrum. The method also has applications to dark-matter searches.

We acknowledge helpful discussions with F. Guerin. This work was supported in part by the U.S. Department of Energy, and the National Science Foundation through Grants No. DMR 8501858 and No. DMR 8304224.

---

[1]R. Davis, D. S. Harmer, and K. C. Hoffman, Phys. Rev. Lett. **20**, 1205 (1968).

[2]J. K. Rowley, B. T. Cleveland, and R. Davis, in *Solar Neutrinos and Neutrino Astronomy—1984,* edited by N. Cherry, W. Fowler, and K. Lande, AIP Conference Proceedings No. 126 (American Institute of Physics, New York, 1985), p. 1.

[3]J. N. Bahcall *et al.*, Rev. Mod. Phys. **54**, 767 (1982); J. N. Bahcall, Rev. Mod. Phys. **50**, 881 (1978).

[4]S. P. Mikheyev and A. Y. Smirnov, in *Massive Neutrinos in Astrophysics, Proceedings of Sixth Moriond Workshop, Tigne, France, 1986,* edited by O. Fackler and J. Tran Than Van (Editions Frontières, Gif-sur-Yvette, France, 1986), p. 355; S. P. Mikheyev and A. Y. Smirnov, Nuovo Cimento C **9**, 17 (1986).

[5]L. Wolfenstein, Phys. Rev. D **20**, 2634 (1979), and **17**, 2369 (1979).

[6]H. A. Bethe, Phys. Rev. Lett. **56**, 1305 (1986); S. P. Rosen and J. M. Gelb, Phys. Rev. D **34**, 969 (1986); S. J. Parke, Phys. Rev. Lett. **57**, 1275 (1986); V. Barger *et al.*, Phys. Rev. D **34**, 980 (1986); E. W. Kolb *et al.*, Phys. Lett. B **175**, 478 (1986); J. N. Bahcall, J. M. Gelb, and S. P. Rosen, Phys. Rev. D **35**, 2976 (1987).

[7]V. Gribov and B. Pontecorvo, Phys. Lett. **28B**, 495 (1969); J. N. Bahcall and S. C. Frautschi, Phys. Lett. **29B**, 263 (1969).

[8]J. N. Bahcall, N. Cabibbo, and Y. Yahil, Phys. Rev. Lett. **28**, 316 (1972); J. N. Bahcall, S. T. Petcov, S. Toshev, and J. W. F. Valle, to be published.

[9]L. B. Okun, M. Voloshin, and M. Vysolsky, Institute for Theoretical and Experimental Physics Report No. 86-82, 1986 (to be published); J. A. Grifols and J. Sola, Phys. Lett. B **182**, 53 (1986); D. B. Cline, University of Wisconsin Report No. WISC-EX-86-283, 1986 (to be published).

[10]D. N. Spergel and W. H. Press, Astrophys. J. **294**, 663 (1985), and **296**, 679 (1985); G. Steigman, C. Sarazin, H. Quintana, and J. Faulkner, Astrophys. J. **83**, 1050 (1978); A. De Rújula, S. L. Glashow, and L. Hall, Nature (London) **320**, 38 (1986).

[11]M. Cribier, W. Hampel, J. Rick, and D. Vignaud, Phys. Lett. B **182**, 89 (1986); A. J. Baltz and J. Weneser, Brookhaven National Laboratory Report No. 38528, 1986 (to be published).

[12]W. Hampel, in Ref. 2; T. Kirsten, in *Massive Neutrinos in Astrophysics, the Sixth Proceedings of Moriond Workshop, Tigne, France, 1986,* edited by O. Fackler and J. Tran Than Van (Editions Frontières, Gif-sur-Yvette, France, 1986), p. 119. The articles describe what has become known as the GALLEX detector.

[13]Sudbury Neutrino Observatory Feasibility Study Reports No. SNO-85-3, 1985 (to be published), and No. SNO-86-6, 1986 (to be published); G. Aardsma *et al.*, University of California, Irvine, Report No. 86-47 (also Report No. SNO-86-7) (to be published).

[14]A. Suzuki, University of Tokyo Report No. UT-ICEPP-86-07, 1986 (to be published). This discussion concerns the attempts to detect reaction (2) with the existing Kamiokande proton-decay detector.

[15]J. M. Bahcall, M. Baldo-Ceolin, D. B. Cline, and C. Rubbia, Phys. Lett. B **178**, 324 (1986); this proposed detector is called ICARUS. R. S. Raghavan, S. Pakvasa, and B. A. Brown, Phys. Rev. Lett. **57**, 1801 (1986).

[16]B. Cabrera, L. M. Krauss, and F. Wilczek, Phys. Rev. Lett. **55**, 25 (1985).

[17]A. Drukier and L. Stodolsky, Phys. Rev. D **30**, 2295 (1984).

[18]Some energy may appear as photons which can be transmitted through the helium and be absorbed at the walls of the container. It is also possible that on the time scale of the experiment some helium atoms will remain ionized, and so energy will remain stored in this way.

[19]S. Balibar, J. Buechner, B. Castaing, C. Laroche, and A. Libchaber, Phys. Rev. B **18**, 3096 (1978). See also H. J. Maris and R. W. Cline, Phys. Rev. B **23**, 3308 (1981).

[20]A. F. G. Wyatt, Physica (Amsterdam) **126B**, 392 (1984).

[21]This probability is not known from experiment and is clearly an important parameter for a more quantitative analysis of the proposed detector.

[22]Silicon is suggested because of its high Debye temperature

(low specific heat), and availability with high purity. Other materials may prove to be suitable.

[23]The Si wafers must be supported by a mount incorporating a superfluid "film burner" so that the Si surface remains bare.

[24]This is an average value (of different crystallographic orientations) provided to us by M. J. Cardillo based on a variety of experimental data. Unless special precautions are taken, the silicon surfce will have an oxide layer which will change ϕ somewhat.

[25]L. A. Ahrens *et al.*, Phys. Rev. Lett. **51**, 1514 (1983); L. A. Ahrens *et al.*, Phys. Rev. Lett. **54**, 18 (1985).

[26]R. C. Allen *et al.*, Phys. Rev. Lett. **55**, 2401 (1985).

[27]S. Glashow, Nucl. Phys. **22**, 579 (1961); S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, in *Elementary Particle Theory,* edited by N. Svartholm (Almqvist and Wiksells, Stockholm, 1968), p. 367.

[28]F. T. Avignone *et al.*, Phys. Rev. Lett. **54**, 2309 (1985).

[29]A. Rindi *et al.*, Istituto Nazionale di Fisica Nucleare, Frascati, Report No. LNF-86/16R, 1986 (to be published), and Report No. SNO-85-3 in Ref. 13.