Bolometric Detection of Neutrinos

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(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (<0.41MeV) *pp* ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of *pp*, ^{7}Be, and ^{8}B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).

PACS numbers: 13.10.+q, 14.60.Gh, 29.40.−n

The problems associated with the detection of low-energy neutrinos are both well known and numerous. For example, in spite of its clear scientific importance and after two decades of heroic efforts, the ν spectrum from the sun has still not been measured. Traditionally, low-energy neutrino detection has involved measurement of induced nuclear transmutations.[1-3] In this Letter we explore a new, bolometric method. This method can provide a new practical detector for making more sensitive measurements of reactor ν's, and can lead to a detector for measuring the spectrum of neutrinos emitted from the solar core.

The differential cross section for a ν or $\bar{\nu}$ with energy E to scatter elastically off an electron with recoil energy T is given by[4]

$$d\sigma/dT = (G_F^2 m_e/2\pi)\{(C_v + C_a)^2 + (C_v - C_a)^2[1 - T/E]^2 - (C_v^2 - C_a^2) m_e T/E^2\}, \qquad (1)$$

where, for ν_e $\{\bar{\nu}_e\}$, $C_v = 2\sin^2\theta + \frac{1}{2}$ and $C_a = \frac{1}{2}$ $\{-\frac{1}{2}\}$, and for ν_μ $\{\bar{\nu}_\mu\}$, $C_v = 2\sin^2\theta - \frac{1}{2}$ and $C_a = \frac{1}{2}$ $\{-\frac{1}{2}\}$. The difference between ν_e and ν_μ scattering arises because charged and neutral currents contribute to the former, but only neutral currents to the latter. The total cross section is then given by integration of Eq. (1) from $T=0$ to $T_{\max} = 2E^2/(2E+m)$.

In order to determine rates for solar-ν interactions, we calculate cross sections for production of electrons in a given energy range weighted over solar-ν spectra. Rates are then calculated with use of the integrated fluxes of Bahcall,[5] and with use of the fact that there are fourteen electrons per Si atom (with $\sin^2\theta_w \approx 0.25$). Our results are presented in Table I and Fig. 1.

As seen from Table I, a detector of recoil electrons is most sensitive to the *pp* and ^{7}Be solar ν's. The *pp* neutrinos produce recoil electrons with a frequency of ~ 1 ton^{-1} d^{-1} for silicon, about 500 times the total rate currently achieved with the ^{37}Cl detector.[1] As shown in Fig. 1, they produce recoil energies below 260 keV. The ^{7}Be neutrinos interact about half as often, and produce recoil electrons with energies up to 660 keV. As a result of the relatively flat differential cross section [Eq. (1)] and the monochromatic nature of the electron-capture ^{7}Be ν's, their recoil electron spectrum has a sharp cutoff at its upper energy, making signal detection easier. In fact, the width of the ^{7}Be ν energy (~ 1 keV) is determined by the solar-core temperature ($\sim 10^7$ K). Measurement of the resultant rounding of the recoil electron-energy cutoff could directly determine the solar-core temperature. The electron events produced by ^{8}B ν's have a higher weighted average cross section with energies up to 13 MeV, but do not appear in Fig. 1 because of the substantially reduced flux.

However, coherent scattering off nuclei for these highest energy ν's produces energy transfers up to about 10 keV with large rates, resulting in a peak below the significant energy range for the *pp* electrons (see Fig. 1). The coherent cross section for vector neutral-current scattering off nuclei is given by

$$\sigma_{\text{tot}} = G_F^2 E^2 (Z[1 - 4\sin^2\theta_w] - N)^2/4\pi$$

(independent of ν type), where N is the number of neutrons in nucleus, and Z is the nuclear charge.[6]

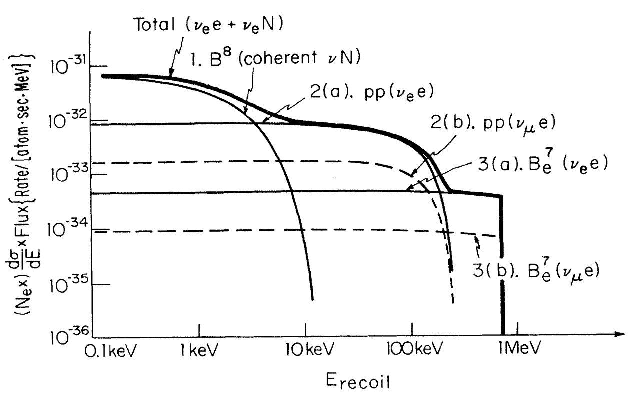

FIG. 1. Event rate vs recoil energy for solar-ν spectra.

TABLE I. Weighted total neutrino cross sections and rates.

Process	σ (cm^2)	E_{max} (MeV)	Rate (ton^{-1} d^{-1})
$\nu_e e$	8.1×10^{-46} [a]	0.26	1.2
	5.3×10^{-45} [b]	0.66	0.75
$\nu_\mu e$	2.1×10^{-46} [a]	0.26	0.3
	1.0×10^{-45} [b]	0.66	0.13
νN	3.3×10^{-41} [c]	0.014	0.16
$\bar{\nu}_e e$	5.3×10^{-45} [d]	9.6	4500
$\bar{\nu}_\mu e$	1.9×10^{-45} [d]	9.6	1600
$\bar{\nu} N$	2.5×10^{-45} [d]	0.007	161 000

[a]For *pp* neutrinos.
[b]For ^{7}Be neutrinos.
[c]For ^{8}B neutrinos.
[d]For reactor neutrinos.

Because of the N^2 factor for coherent scattering, but mostly because of the E^2 dependence of the cross section (compared to $\sigma\sim E$ for the ν-e cross section), the reaction rate for ^{8}B neutrinos is about 15% of that for *pp* ν-e scattering. Detection of these events could be compared directly with the Davis *et al.* ^{37}Cl result. Their result is sensitive to these same ν's with the important distinction that the coherent process is unaltered by possible oscillations which would reduce the ^{37}Cl rate. Neutrinos of energies less than about 3 MeV produce coherent energy transfers which are probably too small to be detectable amidst other noise, as we discuss later. (The processes $\nu n\rightarrow pe^-$ and $\nu p\rightarrow ne^+$ are not significant, because of both suppressed nuclear matrix elements and high thresholds for silicon.)

Since the *pp* neutrino flux is a direct consequence of the primary reaction responsible for the luminosity of the sun, any significant deviation from predicted rates would be important, and might be ascribed to ν oscillations. By exploiting this together with the monochromatic nature of the ^{7}Be ν's, much information regarding ν masses greater than 10^{-6} eV and their mixing angles can be extracted. Oscillations could change the overall rate and the energy dependence of the recoil spectrum (see Fig. 1). A full analysis, treating variations of the Earth-sun distance, thermal broadening, and finite core size, will be presented elsewhere.[7]

Nuclear reactors are an excellent source of antineutrinos with energies in the range 0.25–10 MeV and fluxes of $\sim2\times10^{13}$ cm^{-2} sec^{-1} at distances of ~10 m.[2] Weighting over their spectrum[4] we find coherent scattering of $\bar{\nu}$'s in this range should result in energy deposits of ≤6 keV. Events with recoil energy >0.5 keV occur with a rate ~40 kg^{-1} d^{-1} (see Table I and Fig. 2), several orders of magnitude greater than rates in present charged-current detectors.[3] Detection of coherent scattering is of considerable intrinsic interest since it plays an important role in supernova dynamics.[4,6] Yet it has never been observed in the laboratory. Scattering of these $\bar{\nu}$'s off electrons results in much greater energy deposits, up to ~10 MeV, at a rate of ~4 kg^{-1} d^{-1}. Detection of these recoil electrons would permit a small movable detector to be sensitive to ν oscillations, by a reduction in the overall signal and by a different energy dependence at the upper end of the recoil spectrum (see Fig. 2), for (mass)^2 differences $>10^{-4}$ $(eV/c^2)^2$. Particularly important in this regard, coherent scattering events simultaneously provide an oscillation-independent measurement of the incident $\bar{\nu}$ flux.

Finally, supernovae in the center of the galaxy are estimated to occur at a rate of $\sim10^{-1}$ y^{-1}, and produce pulses on Earth lasting a few seconds which contain $\sim10^{12}$ ν's and $\bar{\nu}$'s per square centimeter of average energy ~10 MeV.[8] Such a pulse would result in about ten simultaneous events in a 10-ton detector. Also, some dark-halo candidates (e.g., photinos or scalar neutrinos) could produce measurable event rates even in kilogram-size detectors.[9]

Detectors.—To observe these ν interaction rates through low-energy recoil electrons and nuclei, large detector masses are required; however, at present no effective detector exists. We propose here the use of large quantities of silicon. This elemental material is especially well suited for thermometric detection both of recoil electrons and of lower-energy recoil nuclei from ν interactions. Moreover, because of its large-scale use in the semiconductor industry, Si is readily available with extremely high purity in large amounts. Equally important are the nearly total absence of radioactive impurities and the simple radiochemistry of its isotopes, which greatly limit the level of induced radioactivity.

The detection scheme is based on observation of the temperature rise caused by the recoil energy[10] throughout a macroscopic silicon mass. After a ν scattering event, the recoil electrons at energies below 1 MeV will lose energy by ionization within a range of $\sim10^{-1}$ cm, while recoil nuclei, with energies below 10 keV, will lose their energy in a much smaller distance by production of phonons. These energies cause

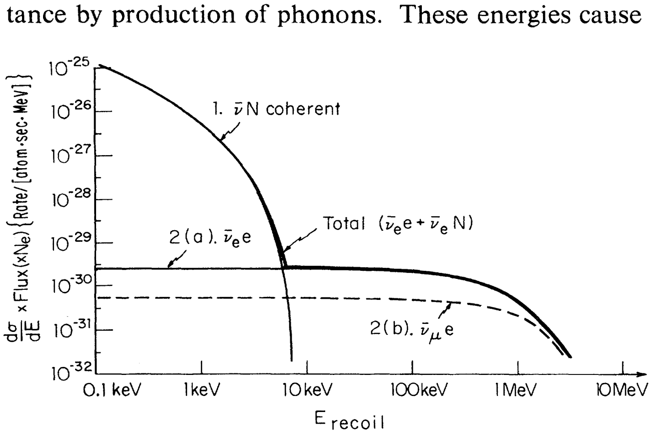

FIG. 2. Event rate vs recoil energy for reactor-$\bar{\nu}$ spectrum.

a detectable thermal signal. Silicon has one of the highest Debye temperatures, $\Theta - 636$ K, because of its low atomic number ($A = 28$) and high lattice stiffness. As a result, at low temperatures its specific heat, given by $C_V = 1941(T/\Theta)^3$ J mol^{-1} K^{-1},[11,12] is extremely small. Hence, *small energy transfers result in measurable temperature changes in macroscopic masses.* For example, an energy transfer of 100 keV will raise the temperature of 1 kg of Si initially at 1 mK to about 4 mK. This temperature change scales inversely as the fourth root of the mass when the T_{initial} is small compared to T_{final}. McCammon *et al.*[12] have demonstrated this technique for the recoil energy range of interest utilizing a small Si detector ($\sim 10^{-5}$ g) at 100 mK as a photon calorimeter for x rays. Their data convincingly demonstrate high efficiency ($> 70\%$) for the conversion of recoil energy into thermal heating.

Equally important for timing information and coincidence detection is the fast thermal response of silicon at millikelvin temperatures. Each recoil event will generate a ballistic phonon pulse which travels at a velocity of $\sim 5 \times 10^5$ cm sec^{-1} throughout the crystal and scatters or is absorbed at the walls. For $a \sim 1$-kg silicon block (with characteristic dimensions ~ 10 cm) the energy deposited would approach a spatially uniform phonon distribution after several transit times $\tau_T \approx 20$ μsec, although the phonon spectrum may not be thermalized until longer times.[12] The uniform phonon energy can be measured with use of one or more thermal sensors located on the crystal surface. With the Si block submerged in the mixing chamber of a continuously operating ^{3}He-^{4}He dilution refrigerator, the recovery-time constant $\tau_R = R_K C_V M/A$ is determined by the Kapitza boundary resistance R_K (between the He and the Si), where A is the boundary area and M the molar mass. Estimation of $R_K T^3 \sim 500$ cm^2 K^4 W^{-1} ($R_K \propto T^{-3}$ below 100 mK) by extrapolation of higher temperature data[13] gives a $\tau_R \sim 100$ μsec (independent of T). Thus, event response times < 100 μsec and recovery times < 1 msec are expected for a ~ 1-kg mass.

The only remaining component necessary for a detector is a method for observation of the thermal pulses associated with an event. Thermometers have been made directly on the surface of single-crystal silicon wafers by ion implantation. This technique has been used by McCammon *et al.*[12] to measure x rays with an energy resolution better than 0.2 keV at 100 mK. However, at a few millikelvins, the heat capacity of such a sensor would dominate over that of 1 kg of Si (note that a sensor with heat capacity approaching that of a metal must be $\leqslant 10^{-8}$ G if it is not to dominate over 1 kg of silicon at these temperatures). It may be possible to extend the parameters of such a thermometer to reduce its heat capacity within the desired range; however, there are other techniques. An attractive possibility is to use the transition temperature T_c of a superconducting thin film as the sensor. Tungsten ($T_c = 15$ mK) or an alloy ($T_c \sim 5$–10 mK) would be deposited onto the Si block and could be monitored by a four-terminal resistance measurement (bandwidth ~ 1 MHz). A broad transition is expected which would provide a linear T versus resistance region and avoid supercooling and superheating effects often seen at these temperatures.[14] If heat leaks through the leads prove prohibitive, one can inductively measure the resistance of a thin-film ring with a SQUID magnetometer at some loss of bandwidth (~ 1 kHz). By use of different modulation frequencies for each sensor, many sensors could be monitored by a single SQUID. For either technique, we estimate that for ~ 1-kg Si blocks an energy resolution of ~ 10 keV could be achieved within the range 10 keV to 2 MeV. As a result of the nonlinear response of the system, the resolution at lower energies is better. For the reactor experiments, where event rates are high, smaller blocks could be used to optimize sensitivities for the low-energy signals from coherent nuclear scattering versus high-energy signals from electron scattering. Finally, no thermal process, including activated relaxation of defects, should produce noise greater than 1 keV.

Because of the real-time detection of events, background vetoing is possible. As mentioned above, recoil electrons and nuclei produced via ν scattering lose their energy in less than 1 mm. Hence, for the reactor experiments, consisting of ~ 100 isolated cells (each an ~ 1-kg silicon block), neutrino-induced events will only excite one cell, and boundary losses will be minimal. Cosmic-ray muons, however, will deposit ionization energy throughout the detector, exciting many cells. Such events can easily be vetoed, provided their rate is not too large. For a 1–10-ton detector consisting of $\sim 10^4$ cells, it is possible to go to a depth of 6000–8000 meters of water equivalent in the Homestake mine.[15] There, cosmic-ray muon events should have a frequency of $\leqslant 0.4$ ton^{-1} d^{-1},[16] so that this background is not larger than the expected solar-ν event rate even before vetoing.

A more severe background is due to radioactive impurities in the Si itself, or in the surrounding Dewar, resisitors, etc., which may result in electrons or gamma rays in the 1–700-keV range. To keep such events for the solar experiment to less than about 1 ton^{-1} d^{-1} requires a decay rate times abundance $< 10^{-33}$ sec^{-1} atom.$^{-1}$ However, Si is available at impurity levels of 1 part in 10^{12} or better (via zone-refining techniques[17]) through its commercial use in the semiconductor industry. Radioactive impurities such as ^{40}K and ^{87}Rb can be down by additional factors of 10^{-3}–10^{-5}. These isotopes have lifetimes of order 10^9–10^{10} yr. Thus we expect that impurities such as ^{40}K, ^{87}R, Th, and U can be reduced below the level required for the solar-ν experiment. Even if this were not possible, energy-spectrum measurements requiring $E < 660$ keV would rule out most such events.

Neutrons and photons from sources outside the apparatus can cause problems if they scatter just once in the fiducial volume of the detector, and in the process deposit a small amount of energy. Such events must be kept to a minimum through choice of construction materials and adequate shielding. In particular, this surface effect should be reduced for the large targets we envision. An attractive possibility, which may remove this background, is to use large amounts of silicon, perhaps more crudely monitored, surrounding the actual fiducial volume. Such an active shield, the size limited only by cost factors, could, in principle, veto these events by sensing associated activity outside the detector volume.

For the reactor experiments, the demands of radioactive purity and background rejection are less severe because of the larger signal. Background levels already achieved for $\beta\beta$ experiments[18] seem adequate for use in a reactor environment, and it is likely that these levels would themselves be reduced by going to large detector volumes. In fact, existing $\beta\beta$ experiments could be converted for use in reactor ν experiments of the type proposed here, although the cost of the high-purity germanium crystals required may prove prohibitive and they would not be sensitive to the nuclear recoil events.

In conclusion, using large amounts of Si at millikelvin temperatures to detect low-energy ν's seems practical with present technology and promises many important applications. However, some experience must be gained before optimal designs are achieved, in particular with regard to the backgrounds at the very low levels required for a solar-ν experiment. Initially, we envisage the design of a prototype single-Si-block detector of mass ~ 1 kg for use with known nonneutrino sources. Measurements of the thermodynamic properties of Si in the millikelvin regime, made for the first time, would be used to calibrate thermometry, timing, thresholds, etc. Based on this, reactor-ν experiments would be built with 10–100-kg(~ 100 cells) active detectors, followed by a solar-ν experiment requiring 10^3–10^4 kg ($\sim 10^4$ cells) of active detector, and better control of backgrounds.

We believe that major efforts to develop bolometric neutrino detectors are justified on the basis of the principles suggested here and the merit of the scientific goals that could be achieved—including possible development of the first comprehensive solar-neutrino observatory.

We thank many colleagues for discussions, notably D. Caldwell, M. Witherill, R. Schrieffer, S. Glashow, F. Goulding, R. Scace, G. Stevenson, D. Turnbull, M. Tinkham, E. Fireman, J. Bahcall, S. Dimopolous, and B. Neuhauser. One of us (B.C.) would like to thank J. Martoff for many useful discussions related to this work. Another (L.M.K.) also thanks the Aspen Center for Physics, and the Institute for Theoretical Physics at Santa Barbara. This work was supported in part by NASA, the U. S. Department of Energy under Contract No. DE-AM03-76SF00326, and National Science Foundation Grants No. DMR 84-05384, No. PHY 82-15249, and No. PHY 77-27084. L.M.K. acknowledges receipt of a Junior Fellowship from the Harvard Society of Fellows.

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