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Principles and applications of a neutral-current detector for neutrino physics and astronomy

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We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10—10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

One of the most fascinating and challenging problems of experimental physics at present is connected with the detection of low- and medium-energy neutrinos. Of the greatest interest is the nascent field of neutrino astronomy. Despite the impressive efforts of Davis and collaborators,[1] some intriguing indications,[2] and some ambitious proposals,[3] the subject is still in its infancy. The outcome of the solar neutrino problem is still unclear and the question of neutrinos from stellar collapse is completely open. Second, many important questions of particle physics revolve around the question of neutrino mass and neutrino mixing, for which studies with low- or medium-energy neutrinos are particularly suitable.

In this paper we would like to discuss the possibility of a new kind of detector for such neutrinos, using the neutral-current process of neutrino-nucleus elastic scattering for neutrino detection.

The advantages or special features of detection via the neutral-current process are as follows.

(a) Due to the coherence factor for neutrino-nucleus scattering and the E^2 increase of the total cross section, the rates are orders of magnitude greater than that for other detectors of the same weight.

(b) The neutral-current detector responds to all (known) types of neutrinos equally. For example, muon neutrinos may be studied below the energy to produce a muon. The detector should therefore also be insensitive to neutrino oscillations.

(c) The neutral-current detector responds to neutrinos of all energy, and in a known way so that the incoming neutrino spectrum may be inferred.

The central difficulty, of course, of such a neutral-current device is that detection can only take place by observation of a very-low-energy nuclear recoil. This gives both a small and, at first glance, rather unspecific signal.

In the following we will argue that nevertheless these difficulties might be overcome using a definite detector principle, that of the superconducting-grain (or -colloid) detector.[4] Many of our considerations are quite general, however, and would apply to any system proposing to use neutrino-nucleus elastic scattering.

In the superconducting colloid, metastable superconducting grains of micron dimensions are held in a dielectric filler material in a magnetic field. The field and temperature are so adjusted that a small temperature jump δT will flip the grain into the normal state. Owing to the very small value of the specific heat at low temperature the energy of a single particle, such as our recoil nucleus, can suffice to flip the grain, as we show below. As the grain goes normal, the magnetic field around the grain collapses, due to the disappearance of the Meissner effect. This in turn leads to an electromagnetic signal which can be picked up by a readout loop.[4]

As evident from the brief explanation, the method is essentially calorimetric and provides no information on direction. Thus, except for short neutrino pulses, as from supernovas, where timing from several stations might be used, it is not possible to determine the direction of the neutrinos. Such a detector, using fast electronics, will have good timing information, however.

For explanation of the detector principle and its various tests we refer to the literature. Our object in this paper is to investigate the ultimate possibilities and limitations of the device as a neutral-current neutrino detector. We shall leave for a later time a discussion of its detailed construction and instrumentation. We shall, however, attempt to identify the major advantages and disadvantages set by basic physics. Thus, in the discussion of noise and background we will leave aside instrumental noise but will attempt some estimates of particle backgrounds and their rejection. When necessary, we shall assume ideal functioning of the instrument and extrapolation or extension of its properties to theoretically possible but as-yet-untested areas. We begin by describing neutrino-nucleus elastic scattering.

NEUTRINO-NUCLEUS ELASTIC SCATTERING

Soon after the discovery of neutral-current neutrino reactions, it was pointed out that neutrino-nucleus elastic scattering should exist, and that this scattering would be coherent over the nucleons in the nucleus.[5] This leads to a cross section quadratic in the weak charge of the nucleus. In the standard model the differential cross section for neutrino-nucleus elastic scattering is

$$\frac{d\sigma}{d(\cos\theta)}=\frac{G^2}{8\pi}[Z(4\sin^2\theta_W-1)+N]^2E^2(1+\cos\theta)\ , \quad (1)$$

where Z and N are the number of protons and neutrons in the nucleus and the present value of the weak-interaction angle is $\sin^2\theta_W\simeq 0.22$. For $\sin^2\theta_W$ so near $\frac{1}{4}$, the cross section is thus essentially proportional to N^2. In arriving at Eq. (1) only the vector current for the nucleon enters. The axial-vector current leads to a small incoherent contribution (for nuclei with spin) which we neglect. It is useful to express Eq. (1) in terms of $\vec{\Delta}$, the three-momentum transfer to the nucleus, $\Delta^2=2E^2(1-\cos\theta)$:

$$\frac{d\sigma}{d\Delta^2}=\frac{G^2}{8\pi}N^2\left[1-\frac{\Delta^2}{{\Delta_{\max}}^2}\right]\ , \quad (2)$$

and we conclude by integrating over Δ^2 that the total elastic cross section is

$$\sigma=\frac{G^2}{16\pi}N^2{\Delta_{\max}}^2=\frac{G^2N^2}{4\pi}E^2\ . \quad (3)$$

Furthermore, since the kinetic energy of the nuclear recoil for a nucleus of mass number A is

$$E_A=\frac{\Delta^2}{2MA} \quad (4)$$

with M the nucleon mass, it follows that the cross section is distributed with respect to E_A as in Fig. 1.

The average value of E_A is

$$\bar{E}_A=\frac{1}{3}\frac{{\Delta_{\max}}^2}{2MA}\ . \quad (5)$$

The maximum momentum transfer depends on the neutri-

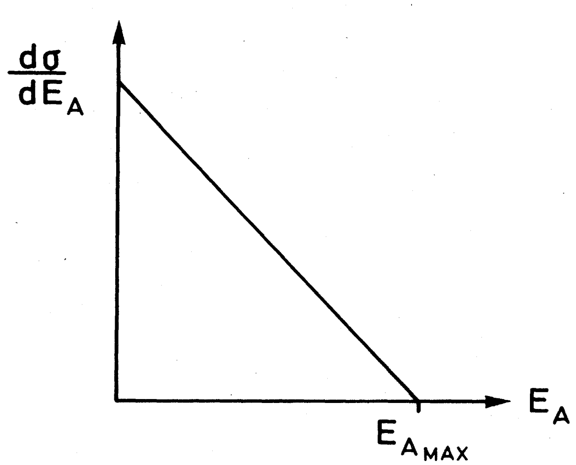

FIG. 1. Recoil-energy spectrum of the struck nucleus A in elastic neutrino scattering.

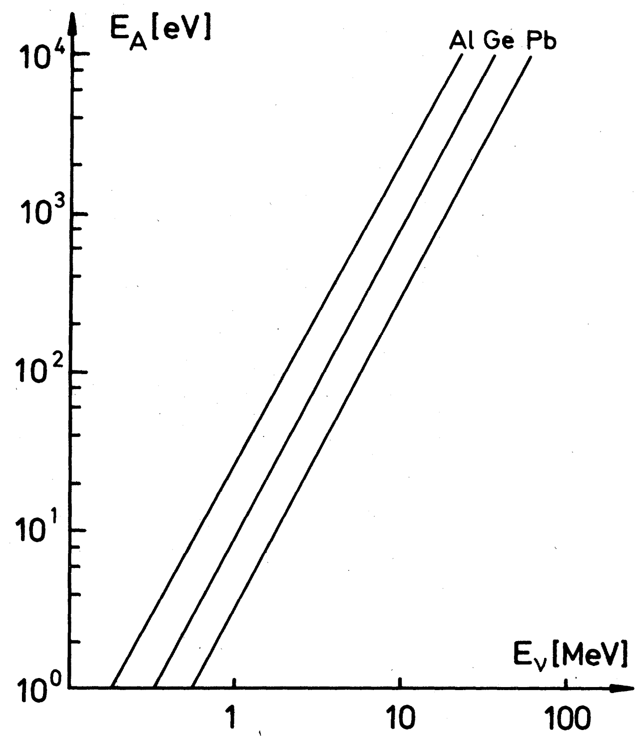

FIG. 2. Average recoil energy for various nuclei as a function of neutrino energy.

no energy:

$${\Delta_{\max}}^2=4E^2\ , \quad (6)$$

so

$$\bar{E}_A=\frac{2}{3A}(E/1\ \text{MeV})^2\ \text{keV}\ ,$$

and the cross section increases as E^2. Equation (5) leads, for heavy nuclei, to recoil energies in the 100's-of-eV range for MeV neutrinos, as seen in Fig. 2.

The range of validity of these considerations is given by the condition for coherence,

$$\Delta R_A \lesssim 1\ , \quad (7)$$

where R_A is the radius of the nucleus. For Δ much larger than $1/R_A$ the nucleus does not recoil coherently, and begins to act as an independent collection of nucleons. For Pb, for example, $1/R_A \sim 30$ MeV, and for Al, $1/R_A\sim 60$ MeV, so that according to Eq. (7), the formulas apply up to $E\sim 30$ MeV. Above this neutrino energy the coherence still applies, of course, to scattering where $\Delta R_A\lesssim 1$. Since we will never be interested in neutrinos much above 50 MeV we will always assume the above formulas are valid.

As opposed to inverse β decay or neutrino-electron reactions we see that the cross section Eq. (3),

$$\sigma\simeq 0.42\times 10^{-44}N^2(E/1\ \text{MeV})^2\ \text{cm}^2\ , \quad (8)$$

is enhanced by the N^2 factor and has a quadratic increase with energy.

We can conveniently express this as an approximate cross section for a kilogram of detecting material of mass

TABLE I. Properties of some elements that might be used for grains. The nonsuperconductors Si and Ge are included for the possibility of making a coated grain, where the bulk of the grain is a nonmetal. The quantity N^2/A in the last column is the factor determining the effective cross section per kilogram of detecting material.

	T_c (K)	Z	A	N^2/A
Al	1.2	13	27.0	9.5%
Si		14	28.0	9.2%
Ga	1.1	31	69.7	27%
Ge		32	72.6	29%
Cd	0.52	48	112.4	48%
Sn	3.3	50	118.7	53%
La	6.0	57	138.9	63%
Pb	7.2	82	207.8	100%

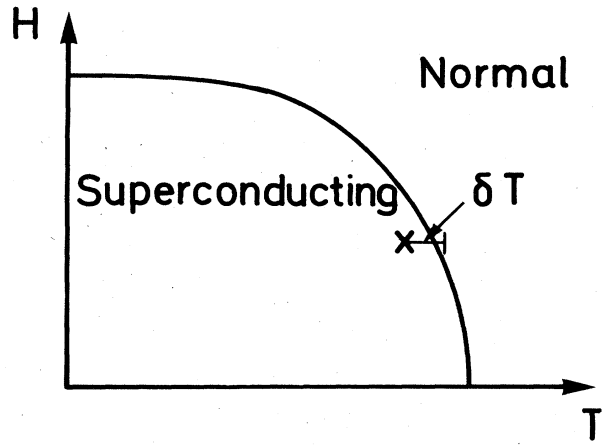

FIG. 3. Schematic phase diagram for the superconducting material, with grains at operating point × requiring a temperature jump δT to become normal.

number A,

$$\sigma \simeq 2.5\times 10^{-18}\frac{N^2}{A}(E/1\text{ MeV})^2\ \frac{\text{cm}^2}{\text{kg}} . \qquad (9)$$

In Table I we show the variation of the (cross section)/(kg) factor N^2/A for various materials. Its maximum value, for Pb, is 76; the range from Al to Pb is a factor of 10.

To appreciate the size of this cross section, we can compare the rate to be expected with that in the ^{37}Cl solar-neutrino experiment.[1] For the average neutrino energy (8 MeV) and flux (10^8/sec) expected there, Eq. (9) would yield 10^3 solar-neutrino units (SNU) instead of the 7 SNU or so expected for ^{37}Cl. If we suppose it possible to use the superconducting-grain detector to observe the much more intense flux of *pp*-cycle neutrinos ($E\simeq 0.4$ MeV, $F\simeq 6\times 10^{10}/\text{cm}^2\text{sec}$), then the rate becomes 10^4 SNU. Or if we consider an experiment at a large reactor ($F\simeq 10^{13}/\text{cm}^2\text{sec}$) then Eq. (9) yields a rate of 30/h for only a kilogram of detecting material (Pb grains). We stress that on the basis of present understanding the cross-section formulas apply to all kinds of neutrinos equally. Thus, oscillations from one kind to another will not affect the detector. Similarly, the detector responds to the total flux from, say, a supernova or a spallation source.

Such rates make it conceivable that a true neutrino observatory can be built, should it be possible to master the various technical problems involved in making a workable detector and to control and understand backgrounds.

RECOIL ENERGY AND GRAIN RESPONSE

The point where the basic physics of the neutrino scattering process contacts the questions of detector technology is the recoil energy of the nucleus. In the "uniform-heating model" of the grain-flip process, the recoil energy must be large enough to cause a temperature jump δT in the superconducting grain, where δT is the difference between the temperature of the grain and the transition temperature. This temperature jump can be set, knowing the phase diagram of metal, to the desired value by adjusting the magnetic field or temperature (Fig. 3).

If the recoil is large (keV), relatively large (10 μm) grains can be "flipped" at pumped liquid-helium-4 temperatures. If the recoil energy is very small, then smaller grains and/or lower temperatures are necessary in order that the energy deposited gives a temperature increase adequate to change the state of the grain. A smaller grain implies less mass to heat up, a lower temperature implies a smaller heat capacity for the metal. For a given superconducting metal and temperature jump δT, then, the neutrino energy E, the mass of the nucleus MA [through Eq. (5)], and the heat capacity of the metal are the relevant factors determining the grain size to be used.

In Table II we show in the uniform-heating model the radius of the largest grains which will be flipped by the average recoil energy [Eq. (5)] induced by a neutrino of energy E. The temperature jump δT has been taken as 10 mK at all temperatures. This seems a reasonable value for stability requirements.

The entry in the table for a nonsuperconducting material, Ge, concerns the possibility of "coated grains." In this idea a nonmetal like Si or Ge would be covered with a thin (perhaps 0.5 μm) layer of superconductor. Since the heat capacity of the Ge or Si is extremely small, essentially the entire heat capacity is in the metal covering. Thus, the heat produced in the Ge by a scattering will be absorbed by the metal shell. Since the amount of metal is small the object has the sensitivity of a small grain to the energy deposit, but a large geometric size, implying large readout signals. Since the main technical difficulty at present is the weakness of the readout signal, this seems a very promising idea. Furthermore, materials like Si and Ge can be produced in extremely high purity, which may be important for background suppression. At the moment, the coated grain must be regarded as speculative, however, since it has not been investigated experimentally, and studies must be made as to which materials might have suitable characteristics. In the example shown, the coating dominates the total heat capacity of the grain.

In our discussion of the grain-flipping process we shall

TABLE II. Maximum sizes of grains that will be flipped in the uniform heating model for various temperatures and materials by an energy deposit E_A. E_A is chosen as the average nuclear recoil energy corresponding to the neutrino energy E indicated. The temperature jump δT has been taken as 10 mK. For example, taking the first line of the table: to heat an Al grain by 10 mK at 50 mK by the $E_A = 55$ eV deposited by the solar ^{7}Be neutrino (1.44 MeV), the grain must be 3.1 μm radius or smaller. In the uniform heating model (Ref. 6) it is assumed the whole grain must be heated by the given amount, using the heat capacity of the normal state.

Material	T (mK)	C_v (eV μm^{-3}K^{-1})	Neutrino energy, recoil energy, and radius			
Al			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=55.0 eV	E_A=240.0 eV	E_A= 1.7 keV	E_A=24.0 keV
	50	42.0	R = 3.1 μm	5.1 μm	9.9 μm	24.0 μm
	400	340.0	1.6	2.6	4.9	12.0
	1000	860.0	1.2	1.9	3.6	8.7
Ga			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=21.0 eV	E_A= 93.0 eV	E_A=660.0 eV	E_A= 9.3 keV
	50	16.0	R = 3.2 μm	5.2 μm	10.0 μm	25.0 μm
	400	130.0	1.6	2.6	5.0	12.0
	1000	350.0	1.1	1.8	3.6	8.6
Ge (grain coated with 0.5 μm Ga)			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=20.0 eV	E_A= 89.0 eV	E_A=630.0 eV	E_A= 8.9 keV
	50	(16.0)	R = 4.5 μm	9.4 μm	25.0 μm	95.0 μm
	400	(130.0)	1.6	3.3	8.8	33.0
	1000	(350.0)	0.9	2.0	5.3	20.0
Cd			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=13.0 eV	E_A= 58.0 eV	E_A=410.0 eV	E_A= 5.8 keV
	50	15.0	R = 2.7 μm	4.5 μm	8.8 μm	21.0 μm
	400	120.0	1.4	2.3	4.4	11.0
Sn			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=12.0 eV	E_A= 54.0 eV	E_A=390.0 eV	E_A= 5.4 keV
	50	34.0	R = 2.1 μm	3.4 μm	6.5 μm	16.0 μm
	400	280.0	1.0	1.7	3.2	7.8
	1000	790.0	0.7	1.2	2.3	5.5
La			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A=10.0 eV	E_A= 47.0 eV	E_A=330.0 eV	E_A= 4.7 keV
	50	140.0	R = 1.2 μm	2.0 μm	3.9 μm	9.4 μm
	400	1100.0	0.6	1.0	1.9	4.7
	1000	2900.0	0.4	0.7	1.4	3.4
Pb			E = 1.44 MeV	E = 3.0 MeV	E = 8.0 MeV	E = 30.0 MeV
			E_A= 6.9 eV	E_A= 31.0 eV	E_A=220.0 eV	E_A= 3.1 keV
	50	52.0	R = 1.5 μm	2.4 μm	4.6 μm	11.0 μm
	400	470.0	0.7	1.2	2.2	5.4
	1000	1800.0	0.5	0.7	1.4	3.5

always use the "uniform-heating picture" where it is assumed that the whole grain is heated by the deposited energy to give the temperature jump δT. This picture probably gives a conservative estimate of the energy deposit necessary, since it may be that if the normal zone created by the energy deposit reaches the surface of the grain where the magnetic field is strong, the flipping process will start without the whole grain heating up.[6] Unfortunately, the detailed mechanism of the grain-flipping process is not fully understood at the present time.

The assumption that the entire recoil energy is contained within the grain seems reasonable as far as the recoil nucleus itself is concerned since it moves slowly and only travels a microscopic distance. Furthermore, due to the low velocity, it also has a small probability of losing an inner-shell electron which might lead to radiation leaving the grain.

Probably more important than the loss of energy from the grain is the energy used up by the recoil atom or ion in producing permanent dislocations of various kinds in the crystal lattice. This means that a part of the recoil energy does not finally end up as heat and so does not contribute to flipping the grain. At low enough energy ($E_A = 20$ eV for Al) the recoil atom does not leave its lattice position. Therefore, this effect does not occur and all the energy goes into phonons, i.e., heat. As the recoil energy increases and the atom moves through the material the fraction of the energy going into heat declines from 100% becoming on the order of 60—70% for various materials.[7] Hence, this is an effect which must be taken into account for the larger recoils, but it does not qualitatively alter our conclusions. We shall call the fraction of the energy E_A going into heat η.

The converse of the production of lattice defects by the recoil is the possibility that at very low temperatures the release of strains already presented in the crystal may set free energy which is large enough to flip a grain. Since the energies for such interatomic processes are in the eV range this problem only becomes relevant when we consider the very smallest recoils, as for *pp*-cycle solar neutrinos.

A further point in connection with the crystalline structure of the material is the binding of the struck atom in the crystal and its effect on the cross section and energy transfer characteristics of the reaction. Strictly speaking, the atom finds itself in a potential well, coupled to the lattice, and when the momentum transfer is small enough, it is not correct to treat the atom as obeying free particle kinematics. The condition for the validity of the free particle assumption can be expressed as

$$\Delta l \gg 1 , \tag{10}$$

where l is the width of the potential confining the atom. Since l is of angstrom dimensions and $1\ \text{Å}^{-1} \simeq 2$ keV, however, such effects should not be significant for the present considerations. The smallest *momentum* transfers we consider are ~ 100 keV. At low E, say in the tens of keV, however, such considerations would become important. We note that the validity of (10) and the free particle assumption is independent of the question of whether the atom leaves the potential well; the atom should merely be able to move about in the well approximately as a free particle.

ENERGY THRESHOLDS AND ENERGY RESOLUTION

The setting of a temperature jump δT means that a certain minimum deposited energy $E_{\min}$ is necessary to flip a grain. This means, in turn, that the very-small-angle, small-momentum-transfer neutrino scattering will not contribute to the rate. By integrating the theoretical cross section [Eq. (2)] we find that there is therefore a reduction of the theoretical cross section [Eq. (3)] so that

$$\sigma \to \left[1 - \frac{E_{\min}}{E_{\max}}\right]^2 \sigma , \tag{11}$$

where $E_{\max}$ is the maximum recoil energy at the given incident neutrino energy, i.e., $E_{\max} = 2E^2/MA$.

Furthermore there is the dislocation effect discussed above, when not all the energy appears as heat. There is then a further shift of the effective threshold to flip the grain so that $E_{\min} \to \eta^{-1} E_{\min}$ and

$$\sigma \to \left[1 - \frac{E_{\min}}{\eta E_{\max}}\right]^2 \sigma \tag{12}$$

as a first approximation. In a more detailed analysis fluctuations in η may have to be considered.

With a "neutral-current detector" the recoil-energy spectrum provides information on the incoming neutrino spectrum. Owing to the simple forms of Eq. (2) there is in principle a relatively direct relation between the two. In practice, instrumental and other effects such as the η parameter must be folded in.

With superconducting grains there appear to be two methods for studying the recoil energy. First by adjusting δT and therefore $E_{\min}$ it should be possible to "sweep" through the energy spectrum (see Figs. 8—10).

In addition to the possibility of adjusting the grain energy threshold, another speculative extension of the superconducting grain principle, the "flip-flop effect" suggests the possibility of directly measuring the energy deposited in a single grain and therefore the recoil spectrum. For the flip-flop effect one envisions working with grains so that after the grain is heated and flips to the normal state, it will lose its heat to the surroundings and "flop" back to the superconducting state, giving a second signal. The time for this flip-flop will depend on the heat or energy deposited. Thus, a measurement of the flip-flop time is a measurement of the energy deposited. Owing to the Kapitza resistance effect, where the mismatch in the phonon spectrum inhibits heat transfer across the boundary between different materials, the cooling time for the grain may be long for certain materials compared to the flip time. If this condition obtains and the material has a very small difference between superheating and supercooling fields, the flip-flop effect may be realizable.

Since all previous work has been with "superheated" grains which simply flip and stay flipped, the flip-flop effect would have to be explored and calibrated. It would, however, be extremely valuable in rejecting backgrounds, as we discuss below. This applies particularly to backgrounds which might flip only one grain, but which deposit a different energy than the sought for neutrino scattering.

GRAIN EFFICIENCY

Another important question touching upon the energy resolution and performance of the grains has to do with their mutual separation in the filler material. Since a superconducting grain pushes out the magnetic flux, a nearby grain will feel a higher magnetic field than the external applied field. In general the local field will therefore vary from grain to grain, smearing out the position of the grains on the phase diagram (Fig. 3) in the vertical direction. In general, a grain will feel a field greater than the applied field, and if we are very close to the phase boundary (δT small) then a large fraction of the grains will be over the boundary and no longer superconducting, giving a situation of low efficiency.

In a two-dimensional Monte Carlo study[8] of this effect 10—20% uncertainties of the local fields were found for a volume-filling factor of 10%. This diamagnetic inefficiency may prove to be one of the fundamental experimental problems. It could be attacked by techniques for regular spacing of the grains or by using low-filling factors. Improvements can also come from more sensitive readout systems, allowing us to move farther away from the boundary of the phase diagram.

Other causes of insensitive grains or grains with shifted or poorly defined thresholds include surface defects and size and shape irregularities. It is hoped that present research in the field[9] will clarify these problems and delineate their relative importance.

GRAIN SIZE AND READOUT SIGNALS

Although other methods may be contemplated, the only way in which individual grain flips have been observed thus far is through the emf induced by the changing flux in a readout loop. Low-noise charge-sensitive preamplifiers and SQUID's (superconducting quantum-interference devices) have been used to sense the few-microvolt pulses induced when the grain changes the state. Such individual flips have been seen in a transition radiation experiment[4] with 15-μm grains and a 1-mm-diam readout loop and with 5-μm grains and 0.3-mm-width and 20-cm-long loop with hard x rays.[6] Signal-to-noise ratios on the order of 5 to 10 were achieved using room-temperature charge-sensitive devices. The signals involved in these cases are on the order of 10's of μV.

If R is the grain size, the superconducting sphere is equivalent to a magnetic dipole of strength $\sim HR^3$. The signal is proportional to this dipole strength and the amount of flux it creates outside the readout line, so that the signal strength for a given magnetic field is proportional to R^3, the volume of the grain, and inversely proportional to the distance to the readout line.

Now it is evident from Table II that small grains and correspondingly smaller volumes than have been so far used are necessary for low-energy neutrino detection, at least in the uniform-heating model. However, detection of neutrinos with $E \gtrsim 15$ MeV may be possible with grains of size comparable to or larger than those used in previous work.

For lower-energy neutrinos two possible directions of development suggest themselves. One is more sensitive electronics with smaller, miniaturized readout lines. It may be possible by such improvements to gain an order of magnitude in sensitivity, bringing the grain size down to 2 or 3 μm.

A great improvement in signal sensitivity and therefore the detectability of small grains may follow from the use of SQUID's. While the flux sensitivity with field-effect-transistor (FET) preamplifiers was measured as[10]

$$\varphi \simeq 2\times 10^{-6}\ \mathrm{G\,cm^2}\ , \tag{13a}$$

SQUID's can be orders of magnitude more sensitive:[11]

$$\varphi \simeq 10^{-11}\ \mathrm{G\,cm^2 Hz^{-1/2}}\ , \tag{13b}$$

where Hz refers to the frequency of sampling in seconds. However, when fast readout ($t \sim 1$ μsec) is required SQUID operation becomes difficult. Recently, it was shown[12] that SQUID's can be used for detection of extremely rare events where the flux change is even smaller than that expected here. In our examples and tables we include cases of R smaller than can be read by present FET technique for reference and possible future developments.

The other possible direction for improvement is the as yet undeveloped but interesting idea of coated grains, as mentioned in the last section. In this case quite large grains can result even for low energies. This is shown in the tables for the various experimental projects.

THERMAL FLUCTUATIONS

In addition to the usual sources of noise at finite temperature such as readout lines, amplifiers, and so forth, the effect of thermal fluctuations specific to the superconducting grain detector must be examined. In particular, a large mass detector will have very many grains; for grains of 5 μm there are 4×10^{16} grains in a ton. Since our signal is the flipping of one grain, the possibility of a flip due to random temperature fluctuations must be considered. On the other hand, since the temperature jump T necessary to flip a grain is set to a substantial value, perhaps

$$\frac{\delta T}{T} \geq 0.01\ , \tag{14}$$

and since μm dimensions are still macroscopic on an atomic scale, the probability due to random, purely thermodynamic fluctuations turns out to be small. According to general principles[13] the probability of a temperature fluctuation δT for an object of heat capacity C is

$$\exp\left[-C\left[\frac{\delta T}{T}\right]^2\right]. \tag{15}$$

Since $C\,\delta T$ is $E_{\min}$, the energy to flip a grain, we can also write this as

$$\exp\left[-\frac{E_{\min}}{T}\frac{\delta T}{T}\right]. \tag{16}$$

For, say, $E_{\min}=100$ eV, $T=1$ K$=10^{-4}$ eV, this factor is $e^{-10^4}=10^{-4000}$. Since the time scale is presumably set by the thermal relaxation time, say, μsec, this is a negligible flipping rate even compared to the 10^{16} grains in a ton.

It is this factor which sets the ideal limit for the size and sensitivity of the detector as far as thermal effects are concerned. For example, if the temperature stability of the apparatus could be made perfect one might consider achieving increased sensitivity to small recoils by reducing δT. Looking at Eq. (16) we see that the exponent might be envisioned to be a factor of 100 smaller. Thus, $\delta T/T$ might be set a factor of 10 smaller, but not much more. This shows that the limitation set by this kind of argument is not entirely academic. Sensitivity to smaller energies can of course also be achieved by lowering T, for given δT.

Of probably much more practical importance than the theoretical thermodynamic limitation will be thermal fluctuations due to various imperfections and instabilities. Here the potentially high spatial resolution of the detector becomes important. It is difficult to imagine temperature fluctuations due to drifts, leaks, currents, etc., which will occur only over the spatial dimensions of the distance of ~ 10 μm, the distance around one grain. Such instabilities would seem necessarily to be over much larger areas, encompassing many grains. With sensitivity to single flips, such events would be rejected since the neutrino signal is the flipping of one and only one grain.

A variant on this idea would be to introduce a small admixture of a substantially larger grain, a "gauge grain." Such grains, having a big volume can absorb a large energy and could be made so as not to be flipped by particle reactions. On the other hand, by, say, alloying, they could be made to have a slightly lower transition temperature so as to be flipped by local temperature fluctuations. Since the readout signal is proportional to the grain size these grains would give a distinctive signal, thus providing a direct measurement of these fluctuations.

BACKGROUNDS: INTRODUCTION

Our proposed detector would have two characteristic advantages in background suppression. One is that due to the relatively high rates it produces, the detector may be relatively small and compact, making shielding or anticoincidence methods more effective. The second is that due to good spatial and time resolution a high level of background rejection is potentially possible. The essential point here is that the *signal of a neutrino event is the flipping of one and only one isolated grain.*

The passage of charged particles, for example, will typically involve the flipping of many grains along the particle trajectory, and this leads to a strong background rejection. A 0.5-MeV electron with a range ~ 0.5 g/cm^2 must pass through ~ 100 grains (10-μm grains) to lose its energy (the majority of the weight of the detector is in the grains) and will be rejected. A further level of background rejection would theoretically be possible through functioning of the flip-flop effect, discussed above, giving a degree of energy resolution in the individual grains.

Background may originate from cosmic rays, radioactivity in the vicinity of the detector, and radioactivity in the active part of the detector itself. Cosmic-ray fluxes are known and can be handled by a combination of passive and anticoincidence shielding. For very low counting the detector may be envisioned underground in a deep mine where very low cosmic-ray fluxes obtain, for example, less than 1 muon/m^{2}day.[14] Since the detector is relatively small it appears that cosmic rays will not be the limiting factor.

Radioactivity in the surroundings of the detector can be reduced by careful shielding, and in the low-counting experiments of the Milano group,[15] for example, rates as low as counts/keV h have been reached for a cm-dimensions detector. When very low backgrounds are required, however, the rejection capabilities of the detector itself must be used.

For the multiton neutrino observatory, for example, we might imagine the detector as a solid block with a wire-chamber-like array of readout lines embedded in the material. In this case, an outer layer of the detector may be used as a protective region, defining a "fiducial volume" inside. Then flips in the protective layer are used to reject background from the outside coming in as well as radioactive backgrounds starting near the edge of the detector and going out. For a 0.1-g/cm^2 layer the chance that a charged particle passes through the layer without causing a single flip is small, typically 10^{-4}.

The main background from the surroundings will presumably be photons around 1 MeV and below coming from various radioactive processes with subsequent down scattering of the photons. Around 100 keV (for Pb) the 0.1 g/cm^2 corresponds to about one absorption length and so below this energy the outer layer provides considerable protection, in view of the steeply rising photon cross section. It is possible, however, that a photon of many keV enters the fiducial region, Compton scatters with a small energy transfer so that the recoil electron flips a single grain, and then the photon leaves the detector without further interaction. This would seem to be the most dangerous case for external backgrounds. It is difficult, however, for the photon to both reverse its direction and leave a small energy; preliminary calculations indicate a few 0.1 g/cm^2 should provide adequate protection. Naturally, with spatial localization information and a thick detector, significant background from outside the detector will be recognized by the concentration of events near the edges, as opposed to the uniform distribution expected from neutrino scatterings. Finally, neutrons from spontaneous fission in the vicinity must be considered, but this does not seem to be as great a problem as photons.

RADIOACTIVITY IN THE DETECTOR

The most difficult background question and probably ultimate limiting factor as a whole is natural radioactivity in the detector itself. Radioactivity coming from outside the sensitive region of the detector may be shielded or identified, but radioactivity of the detector material is unavoidable. This must be controlled by the use of high-purity materials and the intrinsic rejection capabilities of the detector. The ultimate potential of the detector for background rejection in this respect is good since most sources of radioactivity will lead to multigrain flips.

Radioactivity in the detector can be in the form of the very-slowly-decaying primeval nuclides such as the U, Th families and ^{40}K, or in the form of trace elements such as tritium or ^{14}C present in very small amounts but with relatively high decay rates. For the purposes of a preliminary orientation in this paper we will take the cases of ^{40}K and tritium as examples. Potassium is an ubiquitous contaminant, and the activity in nature due to ^{40}K and the U,Th families are roughly on the same level. Furthermore, ^{40}K decays by both β decay ($^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}$)

TABLE III. Estimates of the background due to the β decay of ^{40}K in the detector. The first column gives the fraction (by weight) of the element potassium in the detector. The remaining columns give the rates/kg day with no rejection by the detector (second column), with the assumption that all β rays with energy above 30 keV can be rejected (rejection A), and that all β's above 3 keV can be rejected (rejection B).

Purity of K	Decays/kg day	Rejection A (Rate/kg day)	Rejection B (Rate/kg day)
10^{-4}	2.4×10^5	10^3	10
10^{-6}	2.4×10^3	10	10^{-1}
10^{-8}	24	10^{-1}	10^{-3}

and electron capture ($^{40}K \rightarrow ^{40}A + \nu$) furnishing a good example of both β-decay and electron-capture backgrounds.

We first examine the example of ^{40}K β^- decay. Using the abundance of 1.2×10^{-4} of ^{40}K in the element potassium, the half life of 1.3×10^{9} yr, and the branching ratio of 89% into β^- decay, we arrive at the decay rate $p\times10^{8}$ decays/kg h, where p is the purity of the element potassium assumed in the detector. This is shown in Table III.

It is clear that except for observations with short neutrino pulses, or the use of highly purified materials, the rejection capabilities of the detector itself must be brought into play. Typically the 1.5-MeV electron will flip many grains. The dangerous case is when the neutrino from the β decay carries away most of the energy, leaving a very-low-energy electron. In the last columns of Table III we show the rates remaining when two types of rejection by the detector are assumed. In rejection A it is assumed that all electrons with energy more than 20 keV, crossing about ten grains can be rejected. By integrating over the β spectrum (simple Coulomb correction) we find this brings a rejection factor of 10^{-2}. In rejection B we assume the functioning of the flip-flop effect, allowing the rejection even of single grain flips with a high-energy deposit, namely, that all electrons with more than 3 keV are rejected. This results in a rejection factor of 10^{-4}.

A more subtle and probably most difficult background is the electron-capture process.[16] ^{40}K decays 11% of the time by this process. In electron capture an inner-shell electron is absorbed by the nucleus, leading to the emission of a neutrino (1.5 MeV for ^{40}K) and a recoiling daughter nucleus. Thus, the processes appear dangerously similar to an elastic neutrino scattering at this stage. However, there are a number of subsequent steps to the process.

In the actual case of ^{40}K electron capture the daughter ^{40}Ar nucleus is left in an excited state and immediately decays with emission of a 1.46-MeV γ ray. Since we wish to treat ^{40}K as a general example and since the absorption length for such a γ ray is rather long (10 cm for Pb grains, 10% filling factor) we ignore in the following the extra rejection that observation of the 1.46-MeV γ ray could provide. It should be kept in mind, however, that with a thick detector or a suitable active shielding this signal will improve the rejection of ^{40}K electron capture considerably.

In any case electron capture is always followed by an atomic deexcitation cascade of x rays and Auger electrons involving many keV.

In Table IV we show rates from ^{40}K electron capture taking place in a grain. In rejection A the K-shell x ray is used, assuming that there is either a two-grain flip (parent grain and grain absorbing the x ray) or that the x ray is rejected by depositing too much energy via the flip-flop effect. The rejection is weak since the x ray occurs only 14% of the time. In rejection B the energy left in the grain from the Auger electrons is used in addition, assuming for example that energies 300 eV or greater (the L-shell transition energy) can be rejected. Thus, we see that the energy resolutions hoped for via the flip-flop effect is important in rejecting this background.

Another aspect of the electron-capture background concerns capture processes taking place in inactive material, in the filler or in dead grains. In this case the Auger electrons, being very short ranged, are not likely to flip a grain, but an x ray will most likely be absorbed in a grain, which might then simulate a neutrino scattering. Table V shows estimates of this background, again using ^{40}K, assuming the inactive material to be 50% by weight. If the inner-shell x ray can be eliminated by energy resolution in the grain then this background can be greatly reduced since the probability of radiative as opposed to Auger transitions goes down sharply for the outer shells (last column of Table V).

Finally, consider the case of tritium β decay ($^{3}H \rightarrow ^{3}He + e^- + \bar{\nu}$) as an example of the problem of trace elements. Tritium has a high specific activity ($t_{1/2} = 12$ yr) and is particularly dangerous since the maximum electron energy is only 18 keV, implying that the electron will often stay in the grain where the decay occurs. Tritium is, of course, extremely rare, being measured in units of 10^{-18} of the hydrogen content.[17] Assuming, then, tritium at the level of 5×10^{-18} of hydrogen, we find the rates in Table VI for various purities (by weight) of hydrogen in the grains. In column 3 of Table VI we show the results of using the flip-flop effect to re-

TABLE IV. Similar to Table III for ^{40}K electron capture. In rejection A it is assumed that only the K-shell x ray, which follows the capture 14% of the time is used to reject the process, while in rejection B it is assumed that in addition, energy deposit in the grain itself of more than 300 eV can be rejected, allowing the Auger electrons following the capture to be used for rejection. Since we treat ^{40}K here only as an example, we have not included the substantial extra rejection which would result from identification of the 1.5-MeV nuclear γ ray which follows ^{40}K electron capture.

Purity of K	Decays/kg day	Rejection A (Rate/kg day)	Rejection B (Rate/kg day)
10^{-4}	2.9×10^{4}	2.5×10^{4}	10
10^{-6}	2.9×10^{2}	2.5×10^{2}	10^{-1}
10^{-8}	2.9	2.5	10^{-3}

TABLE V. Background due to ^{40}K electron capture in the inactive material (taken to be 50% by weight), followed by absorption of a subsequent atomic x ray in an active grain. The third column gives the rate resulting from the K-shell x rays (3–4 keV) and the last column gives the rate resulting if these can be eliminated by rejecting energy deposits over 3 keV, thus leaving the L-shell x rays ($\sim$300 eV) as background. Here again possible extra rejection from the prompt nuclear 1.5-MeV γ is not taken into account.

Purity of K	Decays/kg day	K-shell x rays (Rate/kg day)	L-shell x rays (Rate/kg day)
10^{-4}	1.5×10^{4}	2×10^{3}	1
10^{-6}	1.5×10^{2}	20	10^{-2}
10^{-8}	1.5	0.2	10^{-4}

TABLE VI. Background estimate for tritium, as an example of a trace contaminant. Tritium is taken to be present at the 5×10^{-18} level in hydrogen, which is taken to be in the detector according to the fraction by weight given in the first column, resulting in the tritium decay rates in the third column. In rejections A, B, and C it is assumed that β's from the tritium decay with energy over 3.0, 1.0, and 0.33 keV, respectively, can be rejected.

Purity of H	Atoms/kg	Decays/kg day	Rejection A (Rate/kg day)	Rejection B (Rate/kg day)	Rejection C (Rate/kg day)
10^{-4}	3×10^{5}	70	45	0.26	0.02
10^{-6}	3×10^{3}	0.7	0.45	2.6×10^{-3}	2×10^{-4}
10^{-8}	30	7×10^{-3}	4.5×10^{-3}	2.6×10^{-5}	2×10^{-6}

ject electrons with energy above 2 keV. It seems that tritium is not as severe a problem as ^{40}K.

EXPERIMENTS AND OBSERVATIONS

We turn now to a brief sketch of some projects possible with the detector. We indicate the rates and the physical or astronomical points of interest in each case, and try to estimate the level of background suppression necessary. We arrange them in order of decreasing neutrino energy, that is, of decreasing energy deposit by the recoil nucleus.

Spallation-source neutrinos

The spallation source provides a high intensity of neutrinos, from $\pi^+\rightarrow\mu^+ +\nu_\mu$ and $\mu^+\rightarrow e^+ +\nu_e+\bar{\nu}_\mu$, in short bursts. We base our estimates on the planned Jülich spallation source.[18]

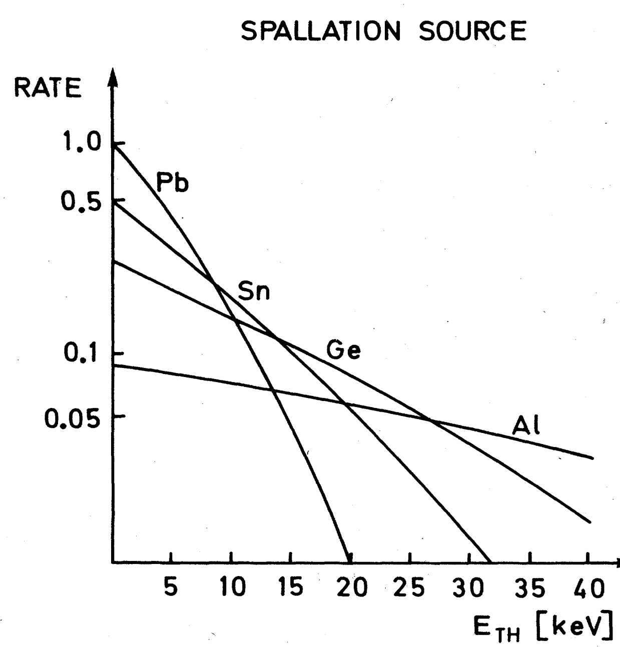

FIG. 4. Variation of the counting rate with grain energy threshold for a spallation-source neutrino spectrum, normalized to Pb. Because of their smaller recoil energy heavier nuclei are more strongly affected by raising the threshold energy.

The total count rate for all species on Pb grains with zero energy threshold and a distance of 6 meters is 40/kg day. In Fig. 4, we show, normalized to this figure, the rates for various materials and grain energy thresholds. Typical energy deposits here are in the keV range (Fig. 2). Note that the advantage of heavier materials falls off rapidly with increasing energy threshold, because of the small recoil energy of heavy nuclei.

A point of physics interest with the spallation source is the possibility of a check on the coherent behavior [Eq. (1)] predicted by the "standard model" of weak interactions. The low-energy phenomenology of the model appears to be well established, of course, but there has never been a direct measurement of the coherent elastic scattering, as used here in the detector. This coherent scattering is also important in supernova mechanisms.[5]

By using different materials in the detector, one could, by comparing the rates, check this prediction of the standard model. An elegant way to do this would be to have grains with two kinds of nuclei, one heavy and one light, and to examine the recoil energy distribution. Since the heavy nucleus' recoil spectrum (Fig. 1) cuts off before that of the light nucleus, there should be a break in the spectrum. This is shown for the monoenergetic ν_μ from the spallation source in Fig. 5 for a (coated) grain of GeO_2, where the theoretical count rate as a function of the grain threshold has been calculated. Curves for different values of $\sin^2\theta_W$ are also shown in Fig. 5(a).

In Table VII we show some possible configurations of parameters applicable to a spallation-source experiment. The two rates shown in the last two columns refer to the material dependence parameter η which measures the amount of recoil energy not appearing as heat [Eq. (12)]. The rate in the last column is simply arrived at by assuming the threshold is shifted $(1/0.7)\simeq30\%$ higher, as compared to $\eta=0$.

The background problem for the spallation source is considerably eased by the short duty cycle. Taking the longer of the two duty cycles, 2×10^{-4}, and assuming from the rates in the background tables that we wish the background when the pulses are "on" to be below $10^{-1}-10^{-2}$/kg day, we conclude that the background must be held at the intrinsic rate of $10^{+3}-10^{+2}$/kg day. According to the tables such suppressions of natural radioactivity should be possible.

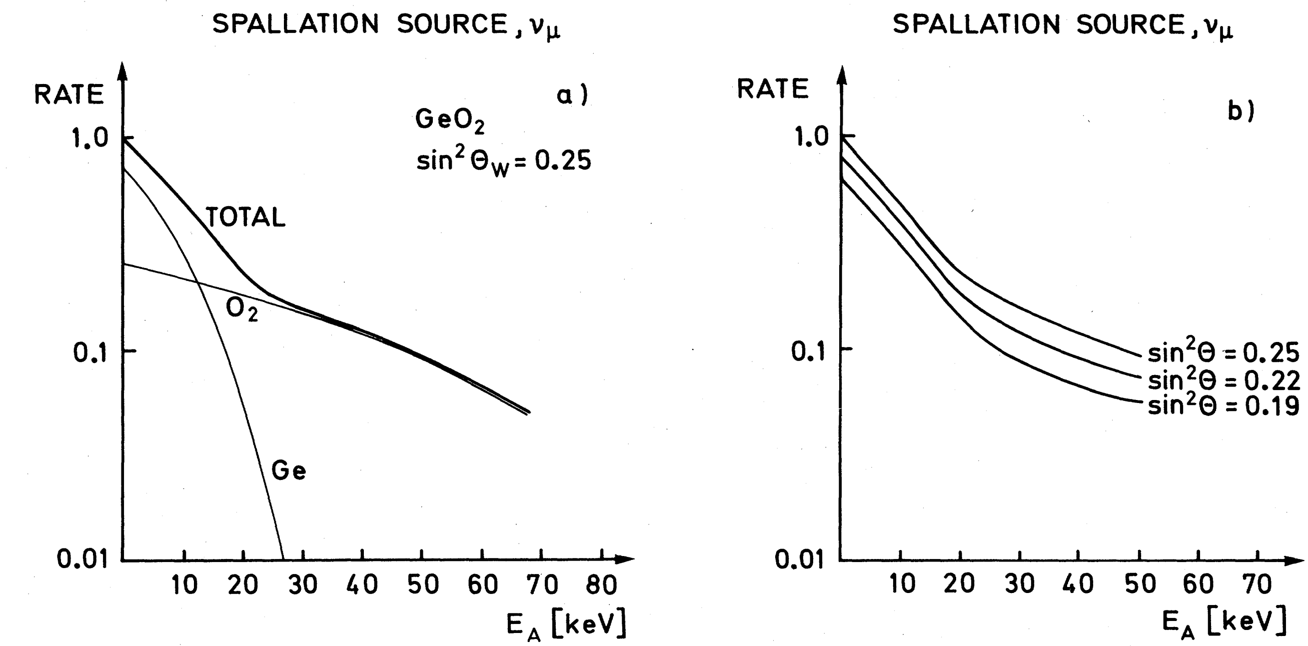

FIG. 5. (a) Recoil-energy spectrum for a target material containing two kinds of nuclei (GeO_2) for a test of the coherent scattering formula, using the monoenergetic ν_μ from a spallation source. Isotopically pure elements have been assumed. The break corresponding to the two nuclei is clearly visible. (b) Same as (a), with various values of the weak-interaction angle. Naturally occurring isotropic mixtures have been used.

Supernova bursts

Supernovas are expected to lead to very intense bursts of neutrinos, so that a supernova in the center of our galaxy (10 kpc) is expected to give $\sim 10^{12}\nu/\text{cm}^2$ at the earth, containing all types of light neutrinos.

A supernova event may have been seen[2] but the time structure was too short (1 msec) for current expectations. Recent models[5] give supernova neutrino bursts on the order of 0.1 sec in length for the neutrinos leaving the star.

Since the neutrinos are thought to be emitted with a distribution in energy around 20 or 30 MeV, a pulse of massive neutrinos will have a dispersion in velocity and spread out in arrival time at the detector. For example, a neutrino with 1 eV mass will spread about 1 msec for every kpc traveled. Furthermore, if neutrinos have a mass at all, the different neutrinos will certainly have different masses, so they arrive as separated pulses. Therefore, "pulse counting" from a supernova can provide information as to the mass and number of neutrinos. Study of the pulse shape can provide information about the supernova mechanisms, and if there are indeed separated pulses, help distinguish various possible explanations for the pulses, such as "bounces" in the explosion. In Fig. 6 we show[19] sample pulse shapes for a supernova in the galactic center with zero mass for ν_e and a 1-keV mass for ν_μ, the pulses are distinctly separated. It should also be noted, as a further check, that there should be a correlation between po-

TABLE VII. Some possible configurations of parameters for a spallation-source experiment, based on the fluxes of all neutrino types, as given by Zeitnitz (Ref. 18) for the Jülich project. The first column is the operating temperature, the second the grain material, where Ge(La) refers to germanium coated with 0.5 μm of lanthanum, and the third column the resulting threshold energy to flip the grain. The temperature jump in the uniform-heating model has been taken as $\delta T = 10$ mK. For rate 1 it is assumed that the grain flips if the recoil nucleus has the stated threshold energy or more, while for rate 2 it is assumed that $\eta = 0.7$, that is, that 30% of the energy does not contribute to heating the grain. It should be noted that a day for the spallation source corresponds to about 10 sec "on time."

T (K)	Material	R (μm)	E_{TH} (keV)	Rate 1 [(kg day)$^{-1}$]	Rate 2 [(kg day)$^{-1}$]
0.4	Ge(La)	3.8	1	1.3	1.2
0.4	Ge(La)	6.6	3	1.2	1.1
0.4	Sn	7.6	5	1.5	1.2
0.4	Pb	8.0	10	0.7	0.3
1.0	Ge(La)	7.4	10	0.8	0.6
1.0	Pb	5.1	10	0.7	0.3

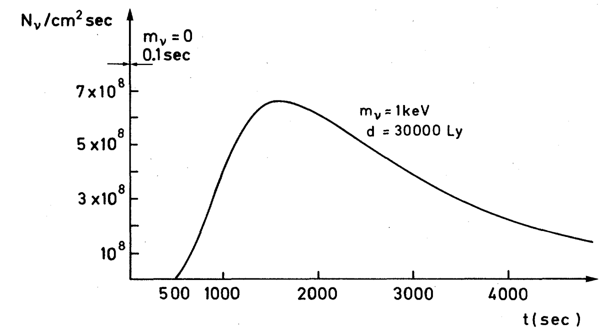

FIG. 6. Time distribution of neutrinos arriving at the Earth from a supernova at a distance of 10 kpc (galactic center). The arrival times of two neutrino types, one with $m \approx 0$, arriving at $t=0$, with a width ~ 0.1 sec containing 10^{12} neutrinos and the other with $m = 1$ keV arriving later and spread out are shown.

sition in the pulse and energy of the neutrino, the more energetic ν arriving first. Too great a spreading, of course, can become unfavorable for detection since the count rate per unit time may fall below the noise of background rate in the detector. On the other hand, arguments from the "big-bang" model[20] limit the neutrino masses to less than ~ 100 eV, and in fact an observation like Fig. 6 would create the greatest difficulties for the big-bang theory.

The special feature of the neutral current detector that it "sees" all neutrino types equally means that it will respond directly to the neutrino mass eigenstates, making the interpretation of pulse counting particularly simple. In Table VIII we show, for various values of the parameters, the number of grain flips to be expected per 100 kg of detecting material for 10^{12} neutrinos/cm^2 (supernova at 10 kpc). It appears that a ton of detecting material would be adequate to identify an event.

Since supernovas are rare, perhaps on the order of one every 30 or 60 yr in our galaxy, it is interesting to inquire if it could be possible to see supernovas in neighboring galaxies. The local galactic cluster is believed to contain more than twice the luminous mass of our galaxy (including the great Andromeda galaxy) and such an increase in the supernova expectancy would certainly be very welcome. The Andromeda galaxy is at a distance of 10^3 kpc, so the expected neutrino burst is reduced by a factor of 10^4, giving 10^8 ν/cm^2. Hence, a "local-galactic-cluster detector" would have a mass on the order of 10^4 tons. Time-spreading effects due to neutrino masses become larger at such a distance, so that the 1-h delay of the second pulse in Fig. 6 now corresponds to a muon neutrino mass of 100 eV.

Since such a detector will be underground and the energy threshold can be set so that the grains are insensitive to the solar and terrestrial neutrinos, the limiting factor would appear to be natural radioactivity in the detector. The background tables indicate that background levels on the level of perhaps 10^{-2}—10^{-3} kg day or 1—10 ton day may be attainable. Thus, supernova pulses not spread over more than one to several days are in principle detectable from our galaxy, while from Andromeda the pulse must not be longer than seconds.

Reactor neutrinos

This is the most intense of continuous neutrino sources, reaching $10^{13}\nu$/cm^{2}sec close to the core of a power reactor. With an E^2 weighted cross section as in Eq. (1), the typical neutrino energy from a reactor is 2—3 MeV. For the Institut Laue-Langevin (ILL), Grenoble spectrum we have $\langle E^2\rangle^{1/2} = 2.3$ MeV. The "ideal" rate with the Pb grains and zero energy threshold is 30/kg h for the ILL spectrum and 10^{13}/cm^{2}sec. Figure 7 shows how the rate varies with threshold and material. The nuclear recoil energy here has become rather low, however, implying small grains and/or lower temperatures. Some sample configurations of parameters are shown in Table IX. In order to keep to grains around 5 μm or larger it appears necessary to work at 50 mK, except perhaps for coated grains.

With rates on the order of counts or tens of counts/kg h, it seems that with purified materials the background from natural radioactivity could be kept under control. Neutrons from the reactor (and from cosmic rays) can be effectively slowed and captured by a hydrogen-containing material with layers of metal to absorb the capture γ rays. Slow neutrons in the detector itself will, upon capture, lead to an energetic nuclear γ-ray cascade, giving a signal quite different from that expected from neutrino scattering.

The physics interest of a reactor experiment would include a check on the N^2 behavior of the cross section. In addition, a check on the theory of neutrino oscillations, if they are found, is possible. As mentioned earlier, a neutral current detector should see no oscillations, at least if the oscillations are among the known neutrinos. Observation of the oscillation or disappearance of neutrinos in a neutral-current detector would indicate the existence of

TABLE VIII. Some sample configurations of parameters for detecting a supernova pulse, which is taken as 10^{12} neutrinos of 20 MeV. The meaning of the entries is the same as in Table VII. The rates refer to the whole pulse however, and not per unit time.

T (K)	Material	R (μm)	E_{TH} (keV)	Rate 1 [(100 kg)$^{-1}$]	Rate 2 [(100 kg)$^{-1}$]
0.4	Sn	7.6	5	2.3	1.8
0.4	Ge(La)	7.9	3	2.1	1.4
0.4	Pb	8.0	10	1.9	0.9
1.0	Pb	5.1	10	1.9	0.9
1.0	Ge(La)	7.4	10	0.5	0.3

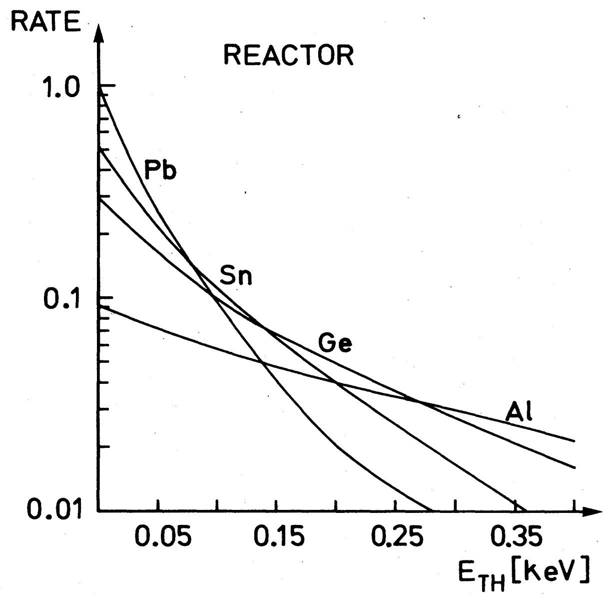

FIG. 7. Variation of the counting rate with grain energy threshold for a reactor neutrino source, normalized to Pb.

"sterile" neutrinos interacting very weakly with ordinary matter. Furthermore, the ability to alter the energy threshold of the detector can allow a measurement of the neutrino energy spectrum from the reactor, which is of interest in itself and can check the operation of the detector.

Solar neutrinos

We turn now to perhaps the most challenging problem, neutrinos from the Sun. The most intense part of the spectrum is that from the *pp* cycle, cutting off at 0.44 MeV, with a total flux thought to be $6\times10^{10}/\text{cm}^2\text{sec}$ at the Earth. Due to various other cycles and subcycles in the Sun the neutrino spectrum should also extend to higher energies, up to $\sim$12 MeV, with intensities one or two orders of magnitude below the *pp* neutrinos.

The ideal maximum rate, for *pp* neutrinos on Pb with zero-energy threshold, would be 0.1/kg day. The nuclear recoil from the *pp* neutrinos is very small, however, (a few eV even for Al) so that the grains must be quite small (2 μm for Al).

Although the grain-flipping principle should still work for such grains, they will yield a readout signal which from the standpoint of present technique seems impossibly small (with the possible exception of SQUID electronics).

Next to the *pp* neutrinos the most important, from the present point of view, are those from the ^{7}Be reaction. Although estimated to be about a factor of 20 less in flux than *pp* neutrinos, their higher typical energy roughly compensates through the E^2 behavior of the cross section. In Fig. 8 we show, on the basis of a typical solar model,[21] the rates expected for aluminum grains as a function of the grain threshold energy. Figures 9 and 10 are the same plot for Ge and Pb grains. We note that even on Al the *pp* contribution only becomes comparable to the ^{7}Be contribution when recoils of a few eV can be detected, while on Pb the *pp* contribution is very small even at 1-eV recoil energy.

From these plots it is clear that the important experimental goal is to reach grain sensitivities below 10 eV. In this case rates involving tens of thousands per ton yr could be attained from the ^{7}Be neutrinos. These plots also indicate how recoil energy information, either from the flip-flop effect or from varying the grain threshold and varying the detecting material can be used to map out the solar neutrino spectrum.

Table X shows some sample configurations of parameters. Those rates involving thresholds above 100 eV come essentially only from ^{8}B neutrinos. We note that in this case observations at 400 mK may be possible by using coated grains. To see lower-energy neutrinos it appears necessary to go to 50 mK. To reach rates on the order of many thousands/ton yr, grains at least as small as 3 μm must be detectable, with coated grains. For solid grains 1-μm dimensions are involved. We include such cases of very small grains, although it is not clear to us at present how much small grains should be read.

The solar neutrino observatory will be deep underground where cosmic rays are rare, so that given adequate anticoincidence shielding the main background will be natural radioactivity. Even with tens of events per ton day very strong background rejection must be attained. On the basis of the ^{40}K examples, this does not seem impossible, but it is clear that in addition to the use of high-purity materials the full rejection capabilities of the detector must be brought into play. In particular, we

TABLE IX. As in Tables VII and VIII, some sample configurations for a reactor experiment, with a flux of 10^{13} cm^2/sec, and the ILL spectrum.

T (mK)	Material	R (μm)	E_{TH} (eV)	Rate 1 [(kg day)$^{-1}$]	Rate 2 [(kg day)$^{-1}$]
50	Ge(Ga)	4.5	20	160	150
50	Ge(Ga)	10	100	77	56
50	Sn	4.1	100	84	50
50	Pb	2.1	20	380	320
50	Pb	3.6	100	75	42
400	Ge(Ga)	3.5	100	77	56
400	Pb	1.7	100	75	42

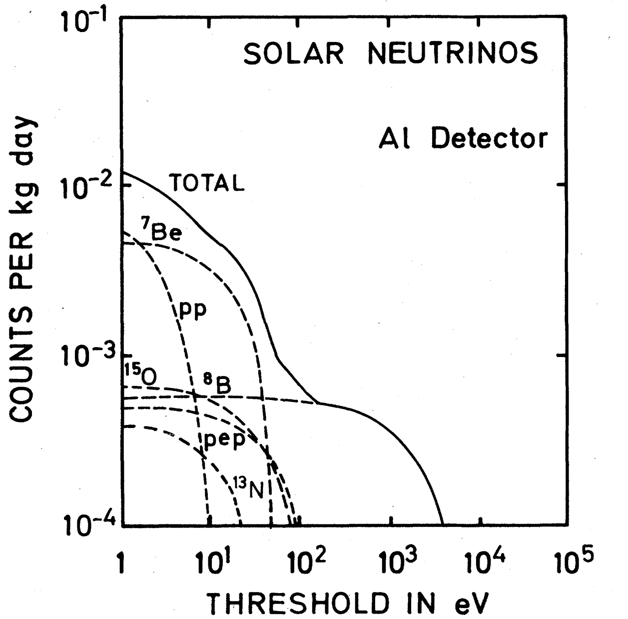

FIG. 8. Solar-neutrino counting rates as a function of grain energy threshold (assuming $\eta=0$), for Al detecting material. Curve labels refer to contributions from various solar-neutrino processes. The solar model of Ref. 21 has been used.

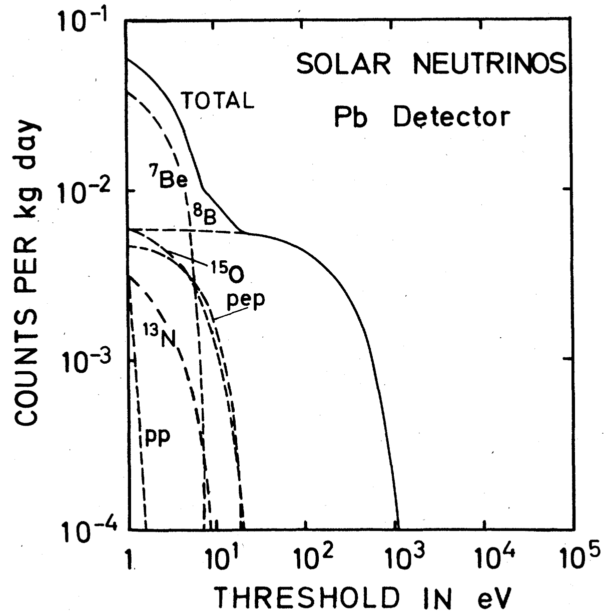

FIG. 10. Same as Fig. 8 with Pb detecting material.

note the success of the flip-flop effect in rejecting electron capture is very important.

If indeed rates on the order of tens of thousands per year can be measured, the solar origin of the signal can be verified through the flux variation (7%) due to the ellipticity of the Earth's orbit. Furthermore, although they are not generally expected, rapid variations in the solar neutrino output would be detectable in such a relatively-high-statistics detector.

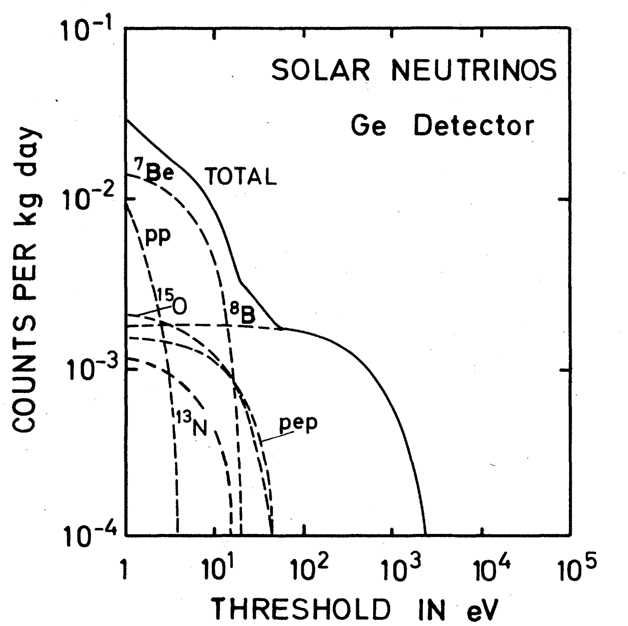

FIG. 9. Same as Fig. 8 with Ge detecting material.

We stress that the neutral current should be insensitive to neutrino oscillations, which have sometimes been proposed as the explanation for the "solar neutrino puzzle." Conversely, a comparison of the results of the neutral current detector and those detectors sensitive to neutrino oscillations could be used to establish the existence of oscillations and to give sensitive information on neutrino mass and mixing parameters.

Finally, a detector sensitive to such low-energy neutrinos would constitute a true neutrino observatory. It would detect supernova explosions in our Galaxy and perhaps beyond, as well as perhaps new and unexpected sources in this as-yet-unexplored realm of astrophysics.

Terrestrial neutrinos

Were it possible to measure the flux of neutrinos produced by the Earth, a new fundamental piece of information on the composition and history of the Earth, and in particular, its heat generation would become available.[22] The flux of neutrinos indicates the rate of energy generation at the present time, and could be compared with the heat generation estimate arrived at from the temperature gradient observed in the Earth's crust, to see if they agree. Comparison of the flux over the oceans and on the continents could check if the Earth's radioactivity is concentrated in the crust, as is now believed.[23] If it were further possible to identify the ^{40}K monoenergetic electron-capture neutrino and compare it with the continuum from β decay, it would be possible to determine the relative amounts of potassium and U,Th family elements present in the Earth, which is of importance in distinguishing different evolutionary models for the Earth.[24] Unfortunate-

TABLE X. Sample configurations for solar neutrinos, as in the preceding tables. In rate 2, η has been taken as 1 since for small recoils the struck atom does not leave its site to produce lattice defects.

T (mK)	Material	R (μm)	E_{TH} (eV)	Rate 1 [(kg day)$^{-1}$]	Rate 2 [(kg day)$^{-1}$]
50	Al	1.4	5	6×10^{-3}	6×10^{-3}
50	Ge(Ga)	1.4	2	19×10^{-3}	19×10^{-3}
50	Ge(Ga)	2.3	5	13×10^{-3}	13×10^{-3}
50	Ge(Ga)	3.2	10	8×10^{-3}	8×10^{-3}
50	Ge(Ga)	4.5	20	4×10^{-3}	4×10^{-3}
50	Ge(Ga)	22.0	500	1.5×10^{-3}	1.2×10^{-3}
400	Ge(Ga)	7.0	500	1.5×10^{-3}	1.2×10^{-3}
1000	Ge(Ga)	4.8	500	1.5×10^{-3}	1.2×10^{-3}

ly, the main branch of the electron capture is through an excited state of ^{40}Ar, giving a very-low-energy neutrino, while the small (10^{-3}) branch, giving a 1.5-MeV neutrino, is right next to the solar *pep* line.

Owing to the uncertainty of the whole subject, it is possible to entertain models[22] where the terrestrial flux varies from several times 10^8/cm^{2}sec to 10^5/cm^{2}sec, the upper values corresponding to having the radioactivity found in the crust throughout the entire volume of the Earth. In Fig. 11 we show a model[25] of the terrestrial neutrino flux plotted together with a calculation of the solar flux. The normalization of the terrestrial flux is to be taken as arbitrary in view of its uncertainty; our plot corresponds to the high estimates at the 10^8/cm^{2}sec level.

Since our plot corresponds to a high estimate of the terrestrial flux, it would seem very difficult to identify the terrestrial neutrinos below the cutoff of the solar ^{15}O neutrinos (from the CN cycle) around 2 MeV. The main hope for observing the terrestrial neutrino seems to be offered by a possible window between the cutoff of the ^{15}O and the rise of the ^{8}B neutrino, in the region, say, 2 to 5 MeV. With reliable and high-statistics operation of the detector the terrestrial origin of the flux could be verified by the absence of the annual variation of the flux expected for solar neutrinos as the sun-Earth distance changes.

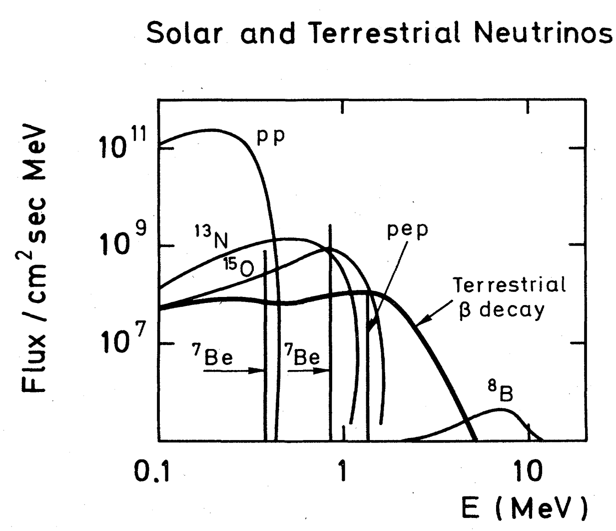

FIG. 11. Solar- and terrestrial-neutrino spectra plotted together. Line sources are in number/cm^{2}sec.

Finally, we note that given the relative lightness of the detector, it offers the possibility of being flown in space some day to study the neutrino flux of the moon and other planets.

OTHER DETECTION TECHNIQUES

In this paper we have concentrated on the superconducting-grain method for observing the nuclear recoil in neutrino-nucleus elastic scattering. It is possible, however, that in view of the many difficult and often new technical problems involved that other techniques for observing this reaction may have to be considered also. These may include, for example, superconducting tunnel junctions, where the small energy to break a Cooper pair is exploited, or very-low-temperature thermometry with pure carbon or silicon where the very low heat capacity of these materials is used. This last alternative may be quite attractive since the great purity of the silicon and the potential for high-resolution calorimetry could considerably ease the problems of background suppression. In any event, our calculations of cross sections and rates, and considerations for the various tests and applications may be directly taken over, since the basic physics and energetics of the neutrino-nucleus are always the same. Similarly, the nature of the background and the principles for suppressing it will not be essentially different in other detection methods. We may return to some of these ideas in a further publication.

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