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CRYOGENIC DETECTION OF NEUTRINOS?

T.O. Niinikoski and F. Udo

ABSTRACT

It is proposed to detect the gentle neutrino scattering introduced as an explanation for the apparent absence of a solar neutrino flux on earth. It should be done with a calorimeter sensitive enough to detect the heating caused by a neutrino beam traversing matter.

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1. INTRODUCTION

Davis upset the astrophysics community already a few years ago by failing to detect the flux of roughly 10^{10} neutrinos/cm² sec, which the sun is supposed to send to the earth. His latest result is compatible with a flux ten times smaller than the calculated one with an error equal to the measured value. Trimble and Reines¹⁾ gave a review of this dilemma.

Various propositions regarding the production processes in the sun have been suggested, but none is really satisfactory [cf. Bahcall and Sears²⁾]. Is it possible that these neutrinos fail to reach the earth? Instability of neutrinos has been proposed by Bahcall, Cabibbo and Yahil³⁾, but this possibility has been ruled out by an experiment of Reines⁴⁾. Recently Lubkin⁵⁾ suggested a gentle scattering of neutrinos in matter as being responsible for the failure of the solar neutrinos to trigger Davis's experiment. He estimates that an energy loss of 5×10^{-7} eV per g/cm² solar material is enough even to absorb the energy of a 10 MeV neutrino in the sun. (All neutrinos from the solar nuclear processes are below 10 MeV.)

The most direct way to detect this neutrino energy loss is to use a pulsed neutrino source like a beam from a high-energy accelerator and detect the resultant heat pulses in a calorimeter. Lubkin estimates that the most intense neutrino beams available fall short by a factor of 10^6 of producing a measurable effect. The purpose of this note is to show that a calorimeter can be made sensitive enough to detect an effect of the size suggested by Lubkin.

In Section 2 we calculate the sensitivity of a pure Si crystal as a calorimeter, when held at 5 mK in the mixing chamber of a dilution cryostat.

The most important parameters of such a detector are the specific heat and the heat contact with the ³He bath (the Kapitza resistance). Neither of these parameters have been measured anywhere near a temperature of 5 mK, but a reasonable extrapolation of data taken at higher temperatures produces results such that even a factor of 10 error in these parameters does not destroy the feasibility of carrying out the measurement.

The calorimeter can be calibrated by observing its response to the ionization energy loss of a fast charged particle traversing the Si crystal, and by measuring the Kapitza resistance independently.

Lubkin gives already one of the difficulties of a cryogenic detection method, namely the possibility that the scattering occurs recoilless in the crystal as in Mossbauer scattering. However, this effect is avoided if we consider energy transfers below 10^{-2} eV, because these small recoils would be in resonance with the phonon spectrum in the crystal, which extends to 10^{-2} eV.

An interesting correlation is suggested by the possibility that the energy transfer per collision is about 10^{-4} eV. An energy of 10^{-4} eV is about equal to the energy kT at a temperature of 3 K, so the gentle neutrino scattering might be responsible for the 3 K background found in the universe. Now, if we put the energy loss of the neutrinos at 5×10^{-7} eV per gramme hydrogen, we calculate easily that the cross-section is equal to 10^{-27} cm² for the neutrino-proton scattering. This comes near to the size of a proton!

2. DETECTOR

We describe here a fast-responding, low heat capacity calorimeter suitable both for pulsed and steady-state measurements. The calorimeter is a single crystal of Si of high purity, with a thermometer directly made on the surface by ion implanting phosphorus. This method has been developed by G. Frossati⁶⁾. The calorimeter would operate at 5 mK, a temperature readily obtainable with a dilution refrigerator in a single cycle mode. A cycle at 5 mK may last up to several hours.

Silicon has the following properties at low temperatures: specific heat $c = \beta(T/\theta_D)^3$, where $\beta = 1944$ J/(mole K), and $\theta_D = 640$ K. The thermometer may have a higher specific heat than the pure material; this may slow its response. For the Kapitza resistance of Si in ³He below 100 mK we estimate $R_K = 1400$ cm² KW⁻¹, extrapolating the high-temperature data⁷⁾ for Si according to the low-temperature data⁸⁾ for Cu.

The size of the target does not affect a transient measurement, in principle, as the heating is uniform in the material. However, a minimum volume is prescribed by the fact that the thermometric area has to be very small compared with the total size to allow one to neglect the heat capacity due to the doping of the material there. A maximum size is given by considerations of charged particle background. We choose a size of 1 cm³ for the crystal as a compromise between the two limits. This has a time constant for reaching internal thermal equilibrium $\tau' = Ls^{-1} = 10$ μsec, where s is the speed of sound (10^5 cm/sec). The time constant for reaching thermal equilibrium with surrounding helium is $\tau = R_K A^{-1} C = 150$ μsec, where A is the area of the cube and C its heat capacity. If the heating burst length $t < \tau$, the calorimeter integrates the heat and the observable temperature pulse height is determined entirely by the heat capacity C ; this we call a 'pulse' measurement. For $t > \tau$ the Kapitza resistance determines the temperature rise. This is called a 'steady state' measurement.

The resistance of the thermometer in a pulse measurement would be obtained by biasing it with constant current and measuring the voltage. A suitably shaped and doped thermometer might have $R = 1$ MΩ value at 5 mK and 2 mK/MΩ sensitivity. A voltage drop, $U = 100$ μV, across the resistor gives a dissipation of 10^{-14} W and raises the temperature of the cube 20 μK above that of the helium.

A good FET amplifier has a noise voltage $e_n = 1 \text{ nV(Hz)}^{-1/2}$ above 100 Hz. For pulse measurement we suggest a bandwidth Δf of about 40 kHz, taking into account the two time constants τ and τ' , which roughly correspond to the decay- and rise-times of a fast burst.

Using the parameters given above we find the pulse energy resolution

$$E = C \frac{dT}{dR} \frac{R}{U} e_n (\Delta f)^{1/2} = 2 \text{ eV} , \quad (1)$$

for a single pulse, by equating the r.m.s. temperature fluctuation to minimum observable heating.

In contrast to pulse measurement, where the total amount of heat is integrated, the steady-state measurement yields the heat flux through the surface of the silicon crystal. This flux is determined by the steady temperature difference $\Delta T = \dot{Q} R_K A^{-1}$ after a few τ . The steady-state measurements are further divided into two classes: (i) fast varying beam and (ii) slowly varying beam. In the first case the power resolution is

$$\dot{Q} = A R_K^{-1} \frac{dT}{dR} \frac{R}{U} e_n (\Delta f)^{1/2} = 2 \times 10^{-15} \text{ W} , \quad (2)$$

using the parameters mentioned above, in particular the 40 kHz bandwidth, which is necessary for seeing the temperature rise in detail and for rejecting background particle events.

In a slowly varying beam one needs to record both the target and liquid temperatures with two highly reproducible thermometers. The liquid temperature is best recorded also with a doped silicon thermometer which has a large surface-to-volume ratio; this recovers quickly from background particles. For high reproducibility an a.c. resistance measurement is necessary. For the electronics to recover quickly from charged particle heating one might choose a measuring frequency of 10 kHz, with a lock-in time constant of about 1 msec. For further hastening of recovery one needs to use non-linear components in the amplifying chain. The temperatures would thus be recorded with about 1 kHz bandwidth, which can possibly be reduced to 10^{-1} Hz by statistical handling of the recorded data. An unwanted systematic source of error is the variation of ΔT due to variation of the measuring voltage. A 10 μV voltage over a 1 M Ω resistor causes 10^{-16} W dissipation and 0.2 μK temperature increase; this may be stable enough to allow one to achieve the temperature resolution of $\Delta T = (dT/dR)(R/U) e_n (\Delta f)^{1/2} = 0.063 \text{ } \mu\text{K}$. Here Δf is taken to be 10^{-1} Hz. The power resolution now is

$$\dot{Q} = A R_K^{-1} \Delta T = 3 \times 10^{-17} \text{ W} . \quad (3)$$

In the first five columns of Table 1 we give data of some neutrino beams already functioning or expected to be functioning in the near future. In the sixth column we have given our predicted resolution of the neutrino energy loss per g cm^{-2} assuming a noise suppression of a factor of 100 by signal averaging. Lubkin's estimate $5 \times 10^{-7} \text{ eV}/(\text{g cm}^{-2})$ could thus be measured with high precision at different energies at the CERN PS, CERN SPS and any high-flux reactor. With some effort to achieve a short intense burst at a meson factory, one might be able to improve the energy resolution at Los Alamos. In the last column we give the estimated experimental time for collecting the required amount of data, obtained by assuming that 50% of the data is good.

If the effect is as large as Lubkin estimates, the CERN neutrino beam would deposit 5 eV/burst in the calorimeter. The energy resolution for a single burst is 2 eV according to our estimate, Eq. (1); the effect would thus be visible on an oscilloscope screen, and clearly distinguished from minimum ionizing particles which leave 5 MeV/particle.

3. BACKGROUND

We discuss here the background in the CERN PS neutrino facility, because reliable data were made available to us⁹⁾. The typical dose rate behind the neutrino dike is 1.1 mrem/h normalized to 10^{13} protons per burst. Neutrons below 14 MeV are responsible for 80% of this dose, the rest is mainly muons. These numbers translate approximately to 2 muons $\text{cm}^{-2} \text{ sec}^{-1}$ and 9 neutrons $\text{cm}^{-2} \text{ sec}^{-1}$. The total cross-section of neutron-silicon scattering around 14 MeV is 0.5 b, so only 3% of the neutrons traversing the target of 2 g give a collision. Besides that, a shielding of 50 cm of paraffin takes away most of these neutrons, and many of them are delayed.

The spectrum of the muons centres around 100 MeV; a shielding of 1 m of iron is certainly sufficient to stop them. It is clear that an experiment to confirm these propositions is needed before we can embark in a serious attempt to measure the effect in the PS neutrino beam.

4. CONCLUSIONS

Table 1 shows that under ideal conditions one should be capable of reaching a sensitivity far below the value of the effect proposed by Lubkin. We have shown in Section 3 that background is a problem to be taken seriously, but the situation is far from hopeless here. A first step would be to measure background, Kapitza resistance and specific heat of a calorimeter as proposed in Section 2. This relatively small effort seems more than justified in view of the importance of detecting this new neutrino interaction.

REFERENCES

- 1) V. Trimble and F. Reines, Rev. Mod. Phys. 45, 1 (1970).
- 2) J.N. Bahcall and R.L. Sears, Annu. Rev. Astrophys. 25 (1972).
- 3) J.N. Bahcall, N. Cabibbo and A. Yahil, Phys. Rev. Letters 28, 316 (1972).
- 4) F. Reines, Phys. Rev. Letters 32, 180 (1974).
- 5) E. Lubkin, Phys. Letters 46 A, 431 (1974).
- 6) G. Frossati, Proc. EPS Low Temp. Conf., Freudenstadt, 1972, abstract only published.
- 7) R.C. Johnson and W.A. Little, Phys. Rev. 130, 569 (1963).
- 8) W.L. Johnson and A.C. Anderson, Phys. Letters 37 A, 101 (1971).
- 9) M. Nielsen, Health Physics Group, CERN, private communication.

Table 1

The estimated resolution of the measurement of the neutrino energy loss in a 1 cm³ Si calorimeter, based on averaging 10⁴ signals, with 50% rejection. Lubkin's predicted energy loss is 5×10^{-7} eV/(neutrino g cm⁻²).

Machine	Neutrinos (burst cm ²)	Burst length (μsec)	Repetition rate (sec ⁻¹)	Neutrino energy		Energy loss resolution [eV/(neutrino g cm ⁻²)]	Running time
				Typical	Max.		
CERN PS ^{a)}	5×10^6	2	0.5	2 GeV	12 GeV	1.7×10^{-9}	11 h
CERN SPS ^{a)}	2×10^6	24	0.13	20 GeV	120 GeV	4.1×10^{-9}	40 h
Los Alamos ^{b)}	4×10^5	500	120	20 MeV	100 MeV	6.7×10^{-8}	3 min
Reactor ^{c)}	10^{11} sec ⁻¹	continuous		0.5 MeV	5 MeV	8.5×10^{-10}	1 min

a) Pulse measurement, Eq. (1).

b) Steady-state measurement with fast varying beam intensity, Eq. (2).

c) Steady-state measurement with slowly varying beam intensity, Eq. (3).