

A search for energy deposition by neutrinos in matter

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An exploratory search for an anomalous energy deposition by neutrinos in a germanium crystal was performed in the CERN high energy ν_μ beam. No signal was found and a limit is set at a level of about 10^{-12} of the normal dE/dx for a minimum ionizing particle.

1 Introduction

We present here the result of a first test looking for energy deposition of neutrinos in matter, other than via weak interactions. This test consisted in exposing a high purity germanium crystal to the CERN high energy ν_μ beam. Such a device offers an easy-to-use, high-sensitivity active medium well suited for an exploratory search. With the very intense neutrino fluxes available in a beam, it is possible to achieve a meaningful limit even if each neutrino deposits only a very small amount of energy.

If detected, neutrino energy losses in matter would have important consequences in several astrophysical contexts. In particular, an energy loss of neutrinos in the interior of the Sun could explain the various deficits observed in solar neutrino experiments. The new Super-Kamiokande measurement of the solar neutrino spectrum [1] excludes a relative energy loss greater than a few per cent for 10 *MeV* neutrinos traversing 600000 *km* of matter with an average density of 1 *g/cm*³. The result discussed here reaches a limit lower by two orders of magnitude, when one assumes an energy deposition proportional to the initial neutrino energy. It is also relevant in the case of energy transfers in a supernova explosion.

2 Experimental set-up

We used a high-purity germanium (HPGe) coaxial diode from Eurisys Mesures[2] with an effective volume of 140 *cm*³ cooled at liquid nitrogen temperature.

Germanium is a semiconductor having an intrinsic band gap of 0.74 eV and a mean electron-hole pair creation work of 2.9 eV . This device gives the lowest energy threshold that can be obtained in an active target of sufficient mass without requiring heavy cryogenic environment.

The detector was installed in the CERN high-energy wide band neutrino beam on a platform between the CHORUS and NOMAD oscillation experiments, 800 m away from the primary beryllium target.

The beam is essentially composed of ν_μ of average energy 24 GeV , with a 1% contamination of ν_e . It is produced in two spills of 6 ms duration extracted at the beginning and the end of the 2.2 s so-called flat top of the SPS accelerator. The machine cycle is repeated every 14.4 s .

Synchronisation signals came from the NOMAD experiment, defining 4 gates (we keep NOMAD's nomenclature):

- Calib gate, 1 s before the first neutrino spill,
- Nu1 and Nu2 gates, covering the neutrino spills,
- Mu gate, during the flat-top in between the neutrino spills.

If the neutrino energy loss was caused by rare but individually detectable effects (i.e. releasing more than a few keV per 'interaction'), it would be impossible to disentangle them from ordinary background (such as charged particles correlated with the neutrino beam or neutrinos weak interactions). Thus, for this first test, we concentrated on hypothetical processes where neutrinos would each leave a tiny amount of energy, the neutrino flux resulting in a global increase of the leakage current during the 6 ms accelerator extraction duration.

As a consequence, the read-out was carried out by an infinite time constant charge-preamplifier, dc-coupled to the HPGe diode. The output of the preamplifier was sampled and digitized by a Sigma-Delta ADC. On each gate, the Sigma-Delta loop was reset, and sampling points were accumulated during 13.1 ms , constituting a 'row'. This arrangement allowed to integrate the energy deposition during the spill, whilst keeping a sufficient resolution on impulsional energy deposition (6 keV FWHM on the 1.33 MeV ^{60}Co line), thus allowing rough spectrometric monitoring and identification of photon or charged particle interactions in the crystal.

A P-type Ge crystal was chosen, the peripheric Li-doped zone giving some protection against alphas and low-energy beta and gamma radiations from natural radioactivity. This protection was enforced by a 3 cm thick lead shield surrounding the detector. The whole set-up was supported by 4 pneumatic

insulators. Special care was taken to enforce ElectroMagnetic Compatibility (EMC).

3 Analysis

Electron-hole pairs are produced when energy is deposited in the crystal, thus creating a current through the diode. The leakage current was measured to be 4 pA after a 24-hour warm-up period. When an ionizing particle crosses the crystal, it gives a fast pulse of $1\text{ }\mu\text{s}$ duration. Typically, a minimum ionizing particle crossing the whole thickness of the diode (5 cm) deposits 30 MeV . As explained in the previous section, the expected signal behaves very differently : we are looking for a continuous current excess, building up during the neutrino spill and proportional to the neutrino flux (see Figure 1).

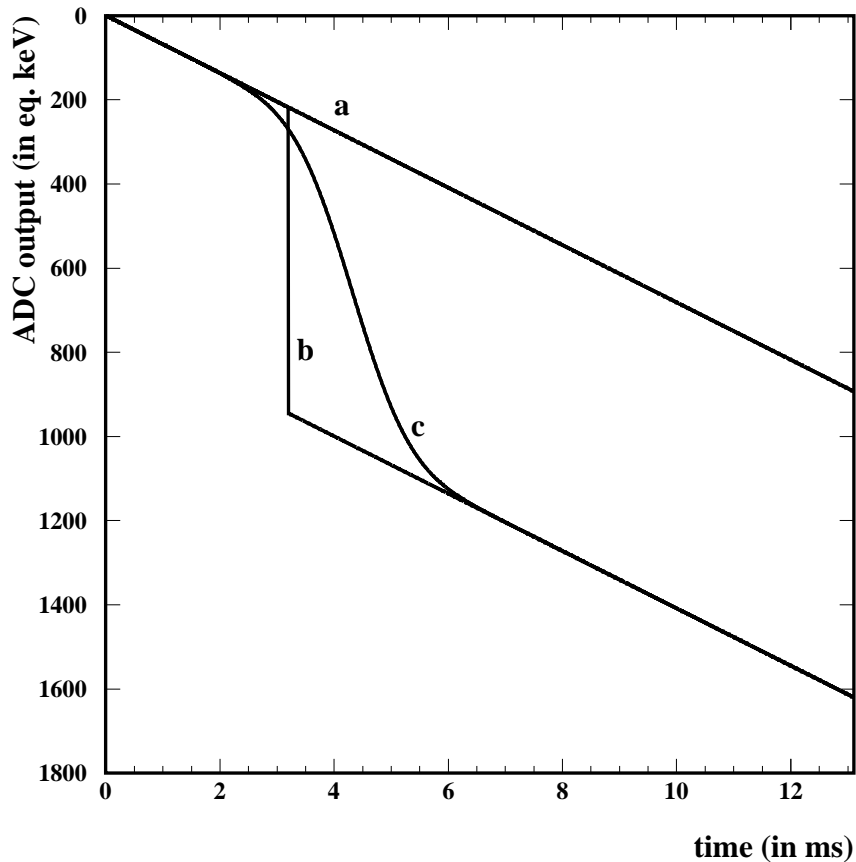


Fig. 1. Charge sampling during a 13 ms gate for 3 different cases : in the row (a), only the leakage current of the Ge crystal is present; row (b) shows the sudden energy deposition (800 keV in this example) due to a muon across the detector; row (c) is a simulation of a 800 keV “signal” during the neutrino spill.

The first step in the analysis is to identify and reject rows contaminated by photons or charged particles in the crystal. The discriminating cut is set to $250 \text{ eV}/\mu\text{s}$ over at least two sampling points. This results in rejecting 41% of the rows in the Nu1 gate, 38% in the Nu2 gate and 12% in the Calib and Mu gates. The time distribution of these rejected energy depositions inside the 13 ms Nu1 or Nu2 gates clearly exhibits the neutrino pulse time structure (Figure 2).

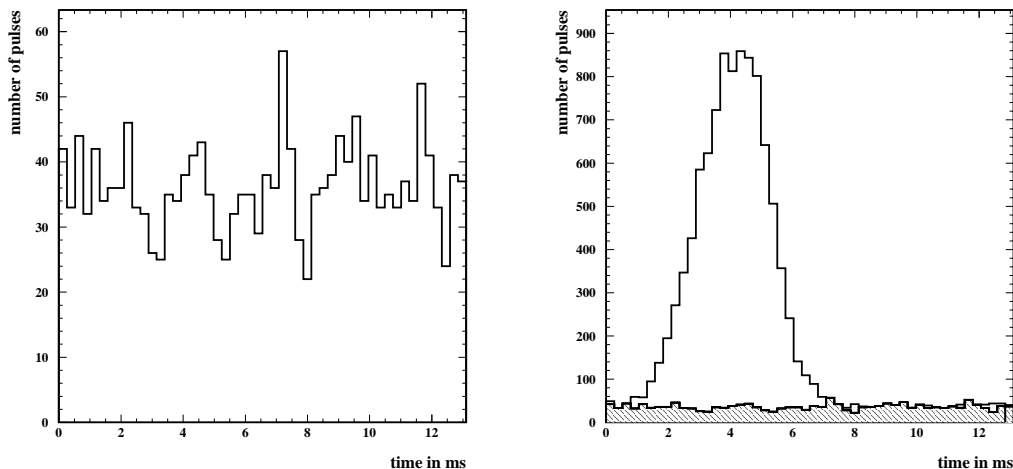


Fig. 2. time distribution (inside the gates) of impulsional energy depositions in the crystal (above threshold : $250 \text{ eV}/\mu\text{s}$; see text) for the Calib (left) and Nu1 (right) gates. The neutrino pulse time structure (revealed by the energy deposited by the associated muons) is clearly visible above a flat distribution, compatible with the one in the Calib gate (reported on the same plot as a shaded area for the sake of comparison).

In the remaining rows, a systematic departure to the straight line is observed and may be attributed to the periodic reset of the ADC. These systematic effects prohibit the use of time-correlation related methods. Furthermore, the charge-per-row versus time distribution shows a semi-periodic pattern over 24 hours, indicating a perceptible temperature sensibility.

To minimize these systematic effects, two 5ms long windows are defined in each row : ‘in-burst’ and ‘out-burst’. The mean current in each window (I_{in} , I_{out}) is then computed, and the sensitive variable S is defined as the difference between the current in- and out-burst ($S = I_{in} - I_{out}$).

The next step should be to compare S in neutrino gates (S_{Nu1} , S_{Nu2}) versus reference gates (S_{Calib} , S_{Mu}) as a function of the beam intensity. The analysis is then restricted to accelerator cycles with all beam informations available¹.

¹ as taken from the NOMAD experiment.

However, as the experiment was performed during a start-up period of the accelerator, the beam intensity was strongly correlated with time. The risk is then to confuse beam intensity and time dependant effects. A series of tests using S_{Calib} and S_{Mu} as control samples showed indeed such time dependences ($> 1\sigma$). In spite of a cost in sensitivity and statistics, we have thus decided to use the difference $S_{Nu1} - S_{Nu2}$ as a function of the beam intensity difference $pot_{Nu1} - pot_{Nu2}$, which is much less time-correlated (pot stands for Protons On Target)². In the end only 38% of the data in the $Nu1$ and $Nu2$ gates were used.

If we write

$$S_{Nu1} - S_{Nu2} = A(pot_{Nu1} - pot_{Nu2}) + B$$

the parameter A is intended to describe the searched-for neutrino-induced current excess per pot unit, whilst B regroups all the non beam-correlated effects. A linear fit on our data gives

$$\hat{A} = 2.5 \times 10^{-4} \text{ keV}/10^{10} \text{ pot}, \hat{\sigma}_A \simeq 1.5 \times 10^{-3}$$

Figure 3(a) confirms that the residuals to the fit are normally distributed. Thus under the normal assumption, figure 3(b) shows the conditional distribution of the slope A using the Jeffreys' prior [3].

This result is compatible with 0 and can be translated into a limit of $\sim 3 \text{ keV}$ (90% C.L.) on the average energy deposited by high-energy neutrinos for a typical extraction of 10^{13} pot . Such an extraction corresponds to 8×10^7 neutrinos of type ν_μ and $\bar{\nu}_\mu$ crossing the crystal. It is then possible to extract a limit on the maximum continuous energy deposited by a single neutrino.

4 Conclusion

We performed a first test to search for a continuous energy loss of neutrinos in matter. This was done by exposing a high-sensitivity germanium crystal to the CERN high-energy ν_μ beam. It was found that a neutrino of type ν_μ loses less than 10^{-5} eV per cm of germanium (about 10^{-12} of the normal dE/dx characterizing a minimum ionizing particle). Incidentally, this would mean an energy loss of 10 keV for ν_μ traversing the whole diameter of the earth; thus

² During the start-up period, the neutrino beam intensity changes often and independently in the two spills as a result of beam steering.

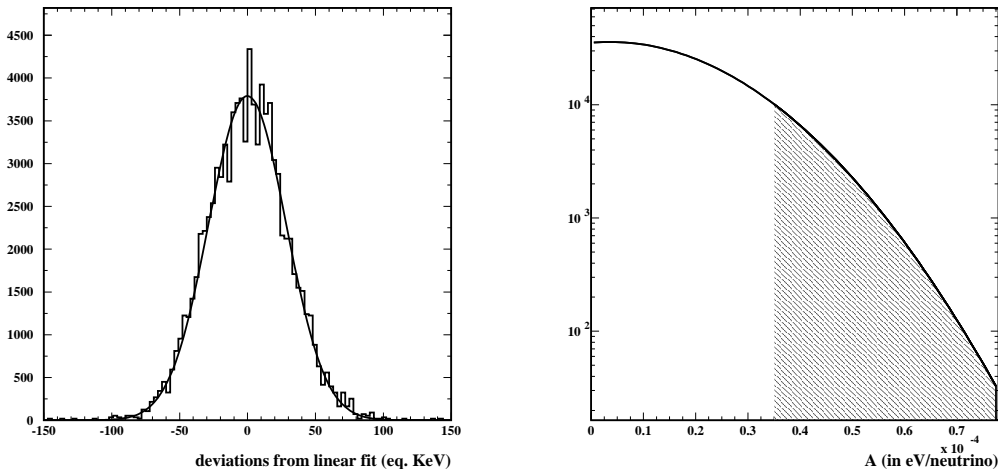


Fig. 3. distribution of the residuals to a linear fit on the current excess in function of beam intensity (left), and the corresponding *a posteriori* probability (right) for the energy deposited by a single neutrino across the detector. The white area covers the 90% C.L. region.

an anomalous energy loss of ν_μ cannot explain the deficit of upgoing neutrinos seen by the SuperKamiokande detector [4]. For the sake of comparison, the energy loss due to weak interactions amounts to $10^{-2}eV$ per *cm* of germanium for neutrinos of the energy considered here³. If the loss is predominantly attributed to ν_e 's (which could be more probable for an interaction of electromagnetic origin), then the limit is $10^{-3}eV$ per *cm* of germanium and per ν_e . This result applies to a continuous interaction having an energy quantum in the range $1 eV$ to $1 keV$.

To improve the significance of this result we should carry out the search again in better experimental conditions (improved mechanical stability, enlarged statistics ...). We are also planning to continue the search at a nuclear reactor where the neutrino flux is higher and the energies are more relevant for astrophysical considerations. Finally, we should investigate the use of other devices (bolometers, RF cavities, etc.) in order to alleviate the limitation on the minimum interaction quantum, which is intrinsic to the present technique.

Acknowledgement

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³ This figure is obtained by assuming that a weak interacting neutrino deposits all its energy over one “weak interaction length”.

the necessary interfaces with the accelerator informations. Special thanks to the ICARUS 50l group who kindly shared their already-crowded platform.

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