IL NUOVO CIMENTO Vol. 29 C, N. 3 Maggio-Giugno 2006
DOI 10.1393/ncc/i2005-10236-8

Study of muon-induced neutron production, propagation and energy spectrum with the LVD detector at LNGS

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(ricevuto il 20 Dicembre 2005; approvato il 10 Aprile 2006; pubblicato online il 9 Giugno 2006)

Summary. — High-energy neutrons, generated as a product of cosmic muon interactions in the rock or in the detector materials, represent the most dangerous background for a large list of research topics such as reactor neutrino studies, the search for SN relic neutrinos, solar antineutrinos, dark matter, etc. (see Khalchukov F. F. *et al.*, *Nuovo Cimento C*, **6** (1983) 320.) A high-energy neutron can be detected through a double signature: the first pulse is due to the recoil protons from n-p elastic scattering, while the second pulse is due to the thermalized neutron capture by a proton. Up to now there are few measurements of the muon-produced neutron flux at large depth underground. Moreover it is difficult to reproduce the measured data with Monte Carlo simulation because of the large uncertainties in the neutron production and propagation models. The LVD detector, situated at LNGS, has an ideal configuration for studying this kind of events because it is possible to detect both the muon track, using the high-acceptance tracking system, and the neutron interactions in the liquid scintillation detectors. We present here the results of the measurement, reporting the neutron flux at various distances from the muon track and for different neutron energies. Moreover, the analysis of the neutron yield as a function of the muon track length in the detector is described.

PACS 28.20.-v – Neutron physics.
PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles, cosmic rays.

1. – Detector description

LVD, located in Hall A of the INFN Gran Sasso National Laboratory, is a large volume liquid scintillator detector whose main purpose is the search for neutrinos from Gravitational Stellar Collapses (GSC) in our Galaxy [1]. The LVD experiment has been in operation since 1992, under different increasing configurations. During 2001 the final upgrade took place: LVD became fully operational, with an active scintillator mass $M = 1000$ tons (C_nH_{2n} with $\langle n \rangle = 9.6$). LVD now consists of an array of 840 scintillator stainless still counters, 1.5 m^3 each, and 4 mm thick, arranged in a compact and modular geometry. The detector is also equipped with a tracking system made of limited streamer

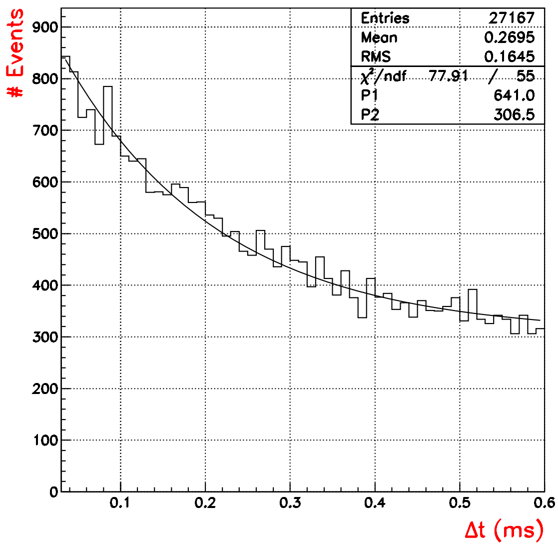

Fig. 1. – Time delay distribution between the high-energy signals and the following low-energy one detected in the same counter of the detector. From the distribution we can separate the neutron interaction from the accidental coincidences (see text).

tubes, interleaved to the scintillator counters, which allows to reconstruct muons; the depth of the LVD site corresponds to a mean muon energy of about 270 GeV.

The observation of neutrinos is made mainly trough the inverse beta-decay reaction of electron antineutrinos on protons:

$$\overline{\nu_{\rm e}} + {\rm p} \rightarrow {\rm n} + {\rm e}^+ \,, \tag{1}$$

$$ {\rm n} + {\rm p} \rightarrow {\rm d} + \gamma \,. \tag{2}$$

The prompt signal from the positron and the delayed signal from the 2.2 MeV gamma from the neutron capture (mean lifetime $\tau \sim 185\ \mu$s) constitute the double signature for this reaction. The positron signal is detected with a high-energy threshold level (HET), set at 7 MeV for the external counters and 4 MeV for the "core" counters, while the 2.2 MeV gamma is detected with a 1 MeV low-energy threshold level (LET), activated by the high-energy signal for a time duration of about 1 ms.

2. – Neutron signature

The LVD apparatus can detect neutrons with the same signature of the inverse beta-decay reaction. High-energy neutrons could cause a liquid scintillator proton to recoil (prompt HET signal) and are then thermalized and finally captured by the liquid scintillator protons with the emission of the 2.2 MeV gamma (delayed LET signal). Taking into account the energy transfer in the interaction between neutron and proton, the proton quenching and the value of the high-energy threshold in the core of the detector, we estimate that the neutrons detected in this way have energies greater than about 20 MeV.

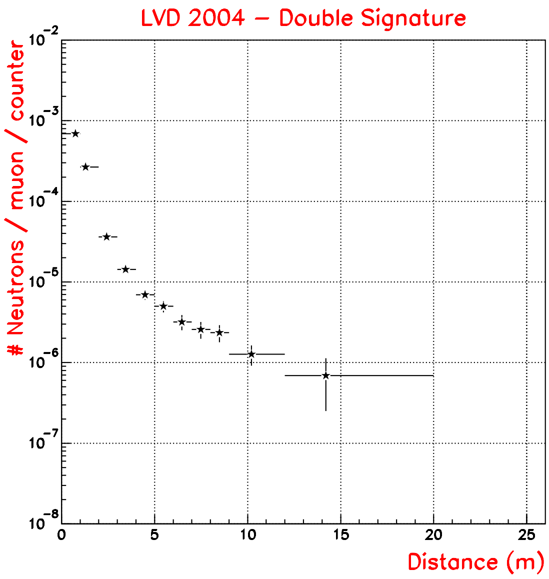

Fig. 2. – Number of neutrons detected per muon per counters as a function of the distance from the muon track.

The background to the neutron detection is due to the accidental coincidences between the high-energy signals and the low-energy ones. This background, however, has a flat distribution of the delay between the two signals and can be estimated by fitting the time delay distribution. An example of this distribution is shown in fig. 1; we can fit the data with the curve

$$\frac{\mathrm{d}N}{\mathrm{d}t} = P1 \cdot e^{-t/\tau} + P2\,,$$

where $\tau = 185\,\mu$s. From the first parameter we obtain the number of neutron interactions, while the second takes into account the number of accidental coincidences.

3. – Analysis and results

We have analyzed the neutron production in association to single muon events, that is events with only one reconstructed track, from 1994 to 2002, for a total sample of more than 7 millions of single muons events.

First we have evaluated the production of neutrons per counter per event at various distances from the muon track; the distance is defined as the distance between the reconstructed muon track and the center of the counter where the neutron is detected. Notice that in the counters traversed by the muon track we require, in addition to the high-energy signal associated to the muon, a second one associated to the recoiling proton. Neutron candidates are selected with the procedure described in the previous section; at each distance the background contribution has been evaluated by fitting the time delay distribution between the HET signal and the LET ones. The result obtained is shown in fig. 2; we were able to evaluate the neutron production up to about 20 m from the muon track. Due to the non-homogeneous distribution of the scintillator in the LVD detector

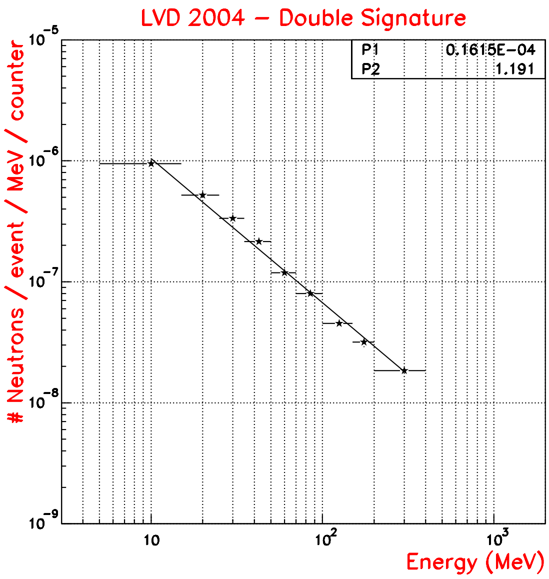

Fig. 3. – Number of neutrons detected per muon per counters as a function of the proton recoil energy.

the behavior observed in fig. 2 has to be studied with a detailed Monte Carlo simulation which is under development.

To estimate the neutron energy spectrum, we studied the number of neutrons detected as a function of the energy released in the scintillator from the recoiling proton. The result is shown in fig. 3; the data are well fitted by the power law spectrum:

$$\frac{\mathrm{d}N}{\mathrm{d}E} = A \times E^{-\alpha},$$

where $A = (1.6 \pm 0.1) \cdot 10^{-5}$ and $\alpha = (1.19 \pm 0.02)$; the errors are statistical only.

Finally we evaluate the neutron production as a function of the muon track length in scintillator (L). The preliminary result is shown in fig. 4.

The data are well fitted by

$$y = 0.14 \cdot 10^{-3} + 0.13 \cdot 10^{-2} \cdot L,$$

where the first parameter takes into account the neutron production in the rock, as it is independent of the muon track length inside the liquid scintillator, while the second parameter takes into account the increase in the neutron production with the muon track length in scintillator. Comparing the two values we can conclude that the neutron production in the core of the experiment is mostly due to the interaction of muons with the detector nuclei (Fe,C).

4. – Conclusion

We report the neutron production from muon interaction in the LVD detector for single muon events and selecting neutrons with a double signature, that is neutrons of

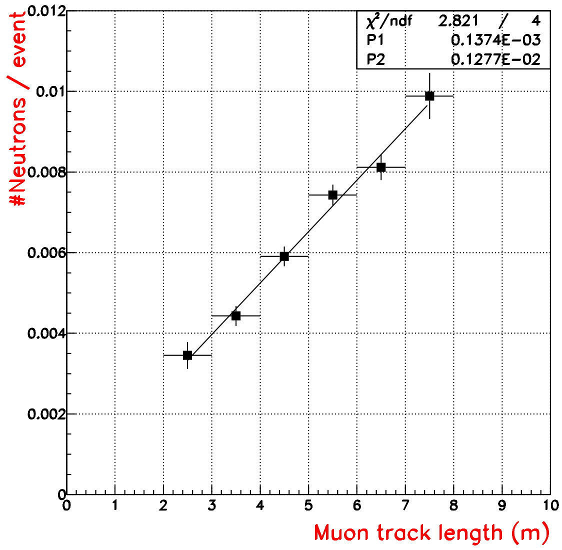

Fig. 4. – Number of neutrons per events detected as a function of the muon track length in scintillator; the main production of neutron is due to the muon interaction with the detector nuclei.

energies larger than about 20 MeV. For this sample of events we were able to measure the neutron flux up to about 20 meter from the muon track and the neutron energy spectrum. We also find out that the neutrons selected are produced in the muon interaction with the detector material.

REFERENCES

[1] Aglietta M. *et al.*, *Nuovo Cimento A*, **105** (1992) 1793.