Measurement of the Neutron Flux Produced by Cosmic-Ray Muons with LVD at Gran Sasso

LVD Collaboration
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Abstract

The flux of muon-produced neutrons far away from the muon track may constitute a background for the underground detectors searching for rare events. The muon events collected by the first LVD tower from March, 1996, to February, 1998, (1.56 years of live time) were used to estimate the neutron flux at various distances from the muon track or muon-produced cascade.

1 Introduction:

It is well known that neutrons produced by cosmic-ray muons can move far away from the muon tracks or muon-initiated cascades and contribute to the background for large underground experiments searching for rare events such as neutrino interactions, proton decay etc. (see, for example, Khalchukov et al., 1983). At present there are few measurements of the muon-produced neutron flux at large depths underground (Bezrukov et al., 1973, Enikeev et al., 1987, Aglietta et al., 1989). In these experiments the detection of both muon and neutron was required but the distance between them was not measured. In this work we analyse the most general case, when both muon and neutron are detected by LVD (Large Volume Detector at the underground Gran Sasso Laboratory) and the distance between them (or between neutron and muon-initiated cascade) is known. The present experiment is carried out with the same scintillator (C_nH_{2n}, $< n > \approx 9.6$) as used in aforementioned earlier experiments.

2 Detector and Data Analysis:

The data presented here were collected with the 1st LVD tower during 13639 hours of live time. The 1st LVD tower contains 38 identical modules. Each module consists of 8 scintillation counters, each 1.5 m $\times$ 1.0 m $\times$ 1.0 m, and 4 layers of limited streamer tubes (tracking detector) attached to the bottom and to one vertical side of the metallic supporting structure. Each counter is viewed by 3 photomultiplier tubes (PMT) on top of the counter. A detailed description of the detector was given in Aglietta et al. (1992). The depth of the LVD site averaged over the muon flux is about 3650 hg/cm^2 which corresponds to mean muon energy underground of about 270 GeV. Each scintillation counter is self triggered by the three-fold coincidence of the PMT signals after discrimination. The high-energy threshold (HET) is set at 4-5 MeV for inner counters. During the 1 ms time period following an HET trigger, a low-energy threshold (LET) is enabled for counters belonging to the same quarter of the tower which allows the detection of the 2.2 MeV photons from neutron capture by protons. Further on we will consider only the signals induced by neutrons in the inner counters, where the LET is low enough (0.8 MeV) to allow high neutron detection efficiency, while the background rate is quite small. 138 counters were considered as inner ones.

All muon events were divided into two classes: i) 'muons' – single muon events, where a single muon track is reconstructed (small cascades cannot be excluded), and ii) 'cascades' – there is no clear single muon track but the energy release is high enough to indicate that at least one muon is present; such events may be due to either muon-induced cascades or multiple muons.

Each neutron ideally should generate two pulses: the first pulse above the HET is due to the recoil protons from $n-p$ elastic scattering (its amplitude is proportional to and even close to the neutron energy); the second pulse, above the LET in the time gate of about 1 ms is due to the 2.2 MeV gamma from neutron capture by a proton. The sequence of two pulses (one above the HET and one above the LET) was the signature of neutron

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detection. The energy of the first pulse (above HET) was measured and attributed to the neutron energy. Note that really this is not a neutron energy but the energy transferred to protons in the scintillator and measured by the counter. The distance between the counter in which a neutron was detected, and the muon track was calculated. For single muons this was the minimal distance between the center of the counter which detected a neutron and the centers of counters traversed by the muon. The precision (about 1 m) is really restricted by the fact that neither the point of neutron production nor the point of neutron capture are known with better accuracy. If the neutron is detected in a counter crossed by the muon (distance is less than 1 m) the energy cannot be attributed to the neutron alone but includes the muon energy loss. For cascade events we calculated the minimal distance between the center of counter where the neutron was detected and the centers of the counters struck by the cascade excluding that with the neutron.

Pairs of seemingly time-correlated pulses might also be produced by random coincidences of high-energy pulses (above HET) due to muon or cascade energy release and low-energy pulses (above LET) due to local radioactivity. The counting rate of such random coincidences per muon event is determined by the counting rate of background pulses in the time gate. To evaluate this background the counting rate of low-energy pulses in the counters in the absence of high-energy pulses was measured. The true neutron flux per unit energy and unit distance was calculated as a difference between the total number of correlated pairs observed and the number of pairs expected due to random coincidences.

3 Results and Discussion:

A typical time distribution of the LET pulses after an HET pulse is shown in Figure 1. The plot includes single muon events with all HET energies and distances (1–2) m from the muon track. Although the expected background has already been subtracted, as described in Section 2, the figure shows an exponential superimposed on a flat distribution of background pulses. This implies that the real level of background of LET pulses is higher in the counters with HET pulses than without HET pulses. The measured distribution was fitted with the following formula: $dN/dT = B + N_n/\tau \cdot exp(-t/\tau)$, where $B = 92^{+13}_{-15}$ is the constant term (residual background) per bin, $N_n = 2746^{+273}_{-218}$ is the total number of neutrons, and $\tau = 187^{+24}_{-19}$ μs is the mean time of neutron capture. The value of τ is in good agreement with previous measurements (Aglietta et al., 1989, and references therein). To obtain the numbers of neutrons at various distances from the muon track, similar distributions were fitted to the above equation with fixed value of $\tau = 190$ μs. The average neutron multiplicity per event (whether single muon or cascade) per counter is plotted against distance from the muon track or cascade core in Figure 2 (single muons - open circles, cascades - open squares). Only the statistical errors from the fits are shown. Horizontal bars show the range of distances for each point. The total contributions to the neutron flux of single muons and cascades are found to be roughly comparable. As the number of reconstructed single muon events exceeds that of 'cascade' events by an order of magnitude, the number of neutrons per cascade is several times higher than the number of neutrons per single muon event. This supports the results of previous measurements (Bezrukov et al., 1973, Enikeev et al., 1987, Aglietta et al., 1989) and early estimations (Ryazhskaya & Zatsepin, 1966). The results of combined treatment of single muons and cascades are shown by filled circles. Only upper limits to the neutron multiplicity can be obtained for last three bins. The exponential fit to the all-event distribution is shown by the solid curve: $F = A \cdot exp(-R/ < R >)$ where $A = (4.17 \pm 0.17) \cdot 10^{-3}$ neutrons/(muon event)/counter and $< R >= (0.634 \pm 0.012)$ m.

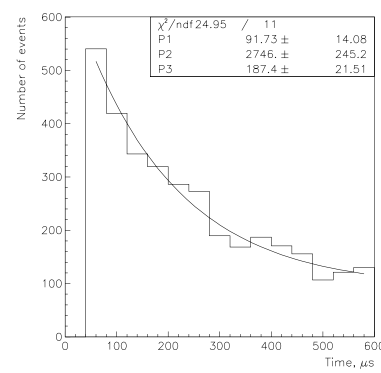

Figure 1: Time distribution of pulses of 2.2 MeV gammas from neutron capture by protons.

Note that the LVD is not a uniform detector, and there are several ten-centimeter air gaps between modules and several centimeter gaps between the counters in a module. This means that the neutrons, as well as

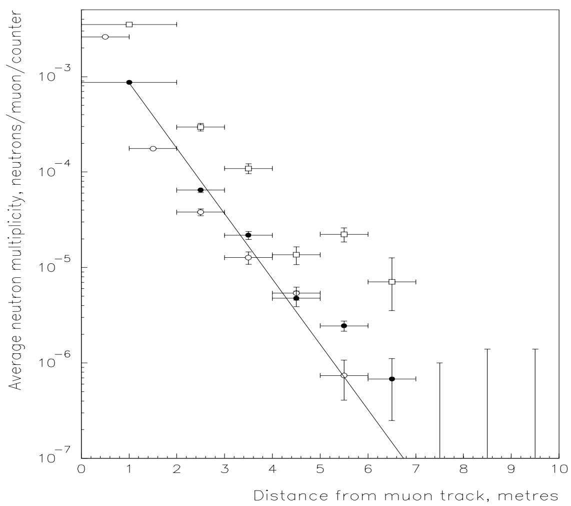

Figure 2: Neutron multiplicity versus distance from the muon track or cascade core. *Open circles* – single muons; *open squares* – cascades; *filled circles* and *solid curve* – all events and exponential fit (upper limits are shown at $R > 7$ m.

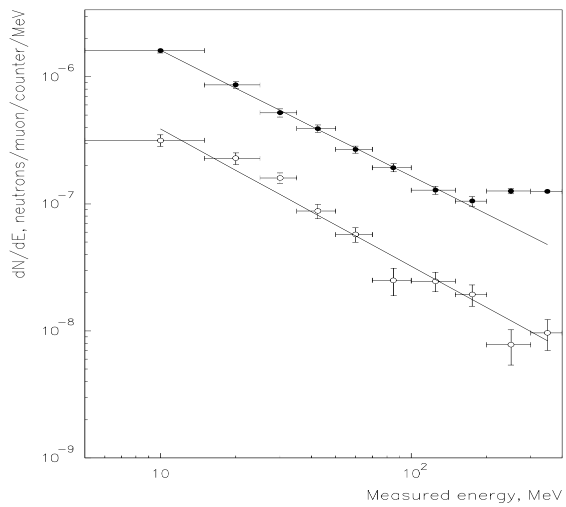

Figure 3: Neutron flux versus energy of HET pulses at $R > 1$ m (*filled circles*) and $R > 2$ m (*open circles*).

other secondary particles, can escape from the counters where they were produced and reach another counter (possibly quite far from the original one) by way of low density air gaps.

The energy of a trigger pulse in a counter can be attributed to the neutron kinetic energy if: 1) there is no energy loss of the muon nor that of secondary particles (other than neutrons) in this particular counter; 2) all neutron kinetic energy is tranferred to protons inside this counter; 3) the energy deposited by a recoil proton is proportional to the pulse amplitude and this proportionality is the same as for electron pulses. Although these conditions are not strictly satisfied, we assume (at zero approximation) that the measured spectrum of HET pulses at large enough distances from the muon track corresponds to the neutron energy spectrum (near the point of neutron capture, within a sphere with a diameter of about 1 m). Such a spectrum is presented in Figure 3 by filled circles for distances $R > 1$ m. Only statistical errors are shown. Horizontal bars show the range of energies for each point. To check the contamination of the distribution by energy deposited by secondary particles (other than neutrons) we plotted also the energy spectrum of HET pulses at distances $R >$ 2 m (open circles). It is obvious that the contributions of secondary particles of all kinds should decrease with R. Both data samples show similar behaviour at $E < 200$ MeV. At $E > 200$ MeV the points for $R > 1$ m (filled circles) are higher than is expected from the general trend of the spectrum. This can be explained by contamination from the energy loss of muons (this is a region near the peak of muon energy release in the counter) and cascade particles. There is no such excess of events at 200-400 MeV at distances $R > 2$ m. This means that the contribution of secondary particles other than neutrons to the neutron spectrum at high energies is negligible. Both spectra were fitted with power-law functions with two free parameters: $dN/dE = A \cdot E^{-\alpha}$. The energy bins 200-300 MeV and 300-400 MeV were excluded from the analysis of data at $R > 1$ m. The results of the fits are: $A = (1.58 \pm 0.14) \cdot 10^{-5}$ neutrons/(muon event)/counter/MeV, $\alpha = 0.99 \pm 0.02$ for $R > 1$ m, and $A = (4.67 \pm 0.71) \cdot 10^{-6}$ neutrons/(muon event)/counter/MeV, $\alpha = 1.08 \pm 0.04$ for $R > 2$ m. The errors are statistical only. The slopes of the two spectra are in good agreement, a more quantitative indication that the contributions of energy losses of particles other than neutrons are not very important, if not negligible at energies less than 200 MeV or distances more than 2 meters. The slope of the spectrum is also in reasonable agreement with the results of Monte Carlo simulations (Dementyev et al., 1997). The units used in Figure 2 and 3 can be converted to more convenient ones (m^{-2}) assuming that each counter has an average area of about 1.5 m^2 orthogonal to the direction of neutron flux and dividing each value by the neutron detection efficiency (about 0.6 for MeV-neutrons uniformly distributed in the counter volume).

Finally, we calculated the average number of neutrons produced by a muon per unit path length in liquid scintillator using the formula: $< N >= N_n \cdot Q/(N_c \cdot L \cdot \epsilon)$, where $< N >$ is the average number of neutrons produced by a muon per 1 g/cm^2 of its path in scintillator, N_n is the total number of neutrons at all distances from the track (result of the fit similar to that shown in Figure 1), N_c is the number of counters crossed by muons, L is the mean path length of a muon inside the counter, ϵ is the efficiency of neutron detection in the inner LVD counters, and Q is the correction factor which takes into account the neutron production in iron of the supporting structure and counter walls. The fit of the all-data sample gives $N_n = (2.34 \pm 0.46) \cdot 10^4$ neutrons. The error includes both statistical and systematic uncertainties. The total number of counters crossed by all muons can be calculated directly only for single muon events when the muon track is well reconstructed. The estimation for all events results in the value of $N_c = (3.3 \pm 0.2) \cdot 10^6$. The mean path length of muons in the scintillation counter is equal to 65 ± 7 g/cm^2 (Aglietta et al., 1989). The efficiency of neutron detection by one scintillation counter has been measured with a source and calculated by Monte Carlo techniques (see, for example, Aglietta et al., 1989, 1992). For MeV-neutron sources uniformly distributed in the counter volume the efficiency of neutron detection is 0.6 ± 0.1. The correction factor Q takes into account the neutron production in iron which should be subtracted since we want to calculate that in scintillator only. It was obtained by Aglietta et al. (1989) for LSD, $Q = 0.61 \pm 0.04$. Similar estimation for LVD gives $Q = 0.85 \pm 0.10$. Finally, one gets $< N >= (1.5 \pm 0.4) \cdot 10^{-4}$ neutrons/(muon event)/(g/cm^2). The value of $< N >$ is 3.5 times smaller than that obtained with LSD detector at larger depth. This difference cannot be easily explained even by large systematic uncertainties and the difference of the depths of the detector sites.

4 Conclusions:

The muon events collected by the first LVD tower (1.56 years of live time) were used to estimate the neutron flux at various distances from the muon track (or from the muon-produced cascade). The neutron flux decreases by more than three orders of magnitude at distances more than 5 meters from muon track or cascade core. The average number of neutrons produced per muon per g/cm^2 of its path in the liquid scintillator is found to be $(1.5 \pm 0.4) \cdot 10^{-4}$ neutrons/(muon event)/(g/cm^2). Under the assumptions mentioned in the previous section the neutron differential energy spectrum in the kinetic energy range (5 – 400) MeV was found to follow a power law with exponent close to -1.

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