29th International Cosmic Ray Conference Pune (2005) **9**, 239-242

The Measurement of the Total Specific Muon-Generated Neutron Yield Using LVD

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The total specific yield of neutrons generated by muons is measured with LVD (Gran Sasso, 3650 m.w.e.). The value agrees with experimental data obtained by analogous technique at the depths of 25, 316, 570 and 5200 m.w.e.

1. Introduction

The number of neutrons generated by muons in matter is an important parameter for the low-background underground experiments dedicated to the study of rare processes such as low energy neutrino interactions, detection of dark matter particles and so on.

In these cases, neutrons are the main and hardly-removable component of the background. Due to their high penetrating capability at energies higher than 100 *MeV* they can pass through the active and passive shields, degrade their energy, and via nuclear interactions simulate the signal events in a very wide energy range.

In this paper we present the measurement of the total muon-generated neutron yield. If the neutron energy spectrum is known, this allows determining their fluxes in various energy ranges.

2. The Experimental Method.

The LVD dimensions, characteristics and material composition [1] allow for a high detection efficiency of muon-generated neutrons. The average number of neutrons <*n*> (the specific neutron yield) is given as number of neutrons per muon per g/cm^2 of muon path length (L_μ). The geometric average muon path length in the whole LVD detector is $L_\mu = 536\ cm$, and $L^{in}{}_\mu = 351\ cm$ for the inner part of LVD.

Thermal neutrons are detected via their radiative capture mostly in the scintillator hydrogen ($C_nH_{2n},\ \overline{n} = 9.6$)

$$np \to D\gamma\ ,\ E_\gamma = 2.23\ MeV\ ,\ \sigma = 0.334\ barn$$

to a lesser extent in iron nuclei

$$n^{56}Fe \to {}^{57}Fe^* \to {}^{57}Fe\ (k\gamma),\ 91.7\%\ ,\ E_\gamma \le 7.64\ MeV,\ k = 1{,}2,\ \sigma = 2.55\ barn\ ,$$

$$n^{54}Fe \rightarrow {}^{55}Fe^{*} \rightarrow {}^{55}Fe\ (\gamma),\ 5.8\%,\ E_{\gamma} \le 10.2\ MeV,\quad \sigma = 2.20\ barn$$

and finally in chlorine nuclei (PVC being the main material constituting the tracking system)

$$n^{35}Cl \rightarrow {}^{36}Cl^{*} \rightarrow {}^{36}Cl\ (k\gamma),\ 75.8\%,\ E_{\gamma} \le 8.58\ MeV,\ k = 1,2;\ \sigma \approx 30\ barn$$

(the percentages represent the isotope content in the natural mixture, and the cross-sections are given for thermal neutrons).

The probability of neutron capture by ^{12}C nuclei of scintillator is two orders of magnitude lower than the probability of *np*-capture.

The energy spectrum of neutrons generated by muons varies as $\sim E^{-1}$ in the range from *keV* to 100 *MeV* and as $\sim E^{-2}$ for energies higher than 100 *MeV* [2]. Due to their collisions with scintillator protons the produced neutrons degrade their energy down to ~0.4 *eV* in a time of about 2 μs, and then thermalize down to 0.025 *eV* in about 10 μs. The lifetime of the thermal neutrons in the scintillator is $\tau_{sc} = 185\ \mu s$, in iron– $\tau_{Fe} = 22\ \mu s$, in PVC – $\tau_{PVC} = 12\ \mu s$.

A muon crossing the apparatus triggers the data acquisition. During a time interval ≤ 1000 μs the energy and time of all events with an energy deposit > 0.6 *MeV* are recorded. The time resolution is ±70 *ns* and the energy resolution is 30%.

3. Event selection

We processed data of two towers of the detector from July, 1999 to October, 2002. Each tower is divided into 4 quarters [1].
The analysis proceeds as follows:

- we select events where all 4 quarters of the tower were crossed by the muon(s), so that the low energy threshold gate was opened in the whole tower counters
- we define a neutron signal as any energy deposit greater than 0.6 *MeV* in the inner counters of the hit tower within the time interval specified above, since this signal could represent the gamma from the neutron capture.

The recorded time distribution of these events is due to an exponential component (neutron capture) and a flat component (uncorrelated background):

$$dN_n/dt = B + N_0 \cdot \exp(-t/\tau) \qquad (1)$$

By fitting the time distribution the average number of background events is determined to be ~ 0.025 per 1 counter per muon.

Relative to the *np* capture, taking into account the probability of the gamma and/or the neutron to escape undetected from the counter, the detection efficiency, for a uniform neutron distribution, is estimated to be 60%. Considering the presence of neighboring counters, the overall detection efficiency η_n rises up to ~90%.

Gammas with energies higher than 4 *MeV* (10 *MeV* being the maximum energy of gamma from nFe-capture) are detected with efficiency close to 100%.

4. Results

For this analysis 116710 muon events were selected regardless of muon multiplicity and of the presence of electromagnetic or hadronic showers. The time pulse distributions of the signals in the low energy threshold gate were analyzed for the following energy and time ranges:

- *np*-captures in scintillator, energy range 0.5 – 4 MeV, $\tau_{sc} = 185\ \mu s$, time range 40-750 μs
- *nFe,Cl* – captures, energy range 4 – 12 MeV, $\tau = 134\ \mu s$, time range 40-500 μs

The number of estimated neutrons in the first sample is $N_{<4MeV} = 30081$ and in the second one is $N_{>4MeV} = 4611$.

Taking into account the number of selected counters, the 75% detection efficiency for nFe, nCl-capture and the 90% detection efficiency for *np*-captures, the total neutron numbers are $N_n^{Fe,Cl} = 10106$, $N_n^{sc} = 54942$. So, the *nFe, nCl* –capture fraction on the total number of neutron captures is 0.155.

To calculate the specific neutron yield value the formula

$$< n >= N_n^{tot} / < l_\mu > \cdot N_\mu^{ev} \tag{2}$$

is used, where $N_n^{tot} = N_n^{sc} + N_n^{Fe,Cl} = 65048$; the average muon path length $< l_\mu >$ in the inner volume of the detector is $< l_\mu >= L_\mu^{in} \cdot \bar{\rho} = 505\ g/cm^2$, where $L^{in}{}_\mu = 351\ cm$ and the average detector material density $\bar{\rho} = 1.44\ g/cm^3$, including scintillator and structure materials ($\bar{A} = 8.7$); the total number of muon events including single muons, muon groups, electromagnetic (*e.m.*) and hadronic (*h.*) cascades and stopping muons, is $N_\mu^{event} = 116710$.

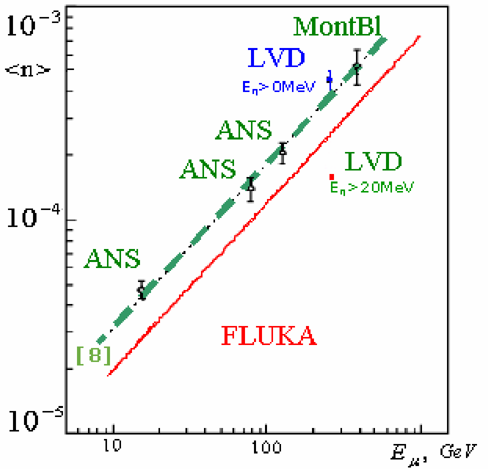
Finally we find $< n >= 11 \cdot 10^{-4} (\mu - event)^{-1} (g/cm^2)^{-1}$, in this value ~1.5% contribution of neutrons from $\mu^- Fe$-captures is present.

The accuracy of <*n*> depends mainly on the uncertainties of the *np*-capture exponent, $\tau_{sc} = 185 \pm 15\ \mu s$, and the detection efficiency $\eta_n = 0.90 \pm 0.04$, that gives the accuracy for < *n* > $\delta = 0.07$ and hence $< n >= (11 \pm 0.8) \cdot 10^{-4} (\mu - event)^{-1} (g/cm^2)^{-1}$. The fraction of neutrons Q_{sc}, generated only in the scintillator is determined analogously to [3], and is equal to $Q_{sc} = 0.60 \pm 0.06$. In this case $< n_{sc} >=< n > \cdot Q_{sc} = (6.6 \pm 0.8) \cdot 10^{-4} (\mu - event)^{-1} (g/cm^2)^{-1}$.

We have reconstructed as single muons 62% of a total amount of muon events, 20% of muon events as muon groups. The contribution of *e.m.* and/or *h.* cascades and stopping muons are 17% and 1%, consequently. The event was regarded as a cascade if it was not possible to reconstruct a track and if there were energy losses released in more than 16 scintillation counters. The muon group multiplicity turned out to be from 2 to 26, the average multiplicity is 3.54. For each type of muon event the neutron number by fitting data in two energy ranges (for *np*-captures in scintillator and *nFe, Cl* - captures) was determined.
For single muons we obtained the specific neutron yield for scintillator as $1.8 \cdot 10^{-4} (g/cm^2)^{-1}$.
We got the same yield value for muon groups, if we take into account the mean number of muon in the

bundle. To obtain the values $< n >$ and $< n_{sc} >$ per one event the muon group has been considered as one muon event. For cascades we find 2.03 neutrons per cascade in average.
Comparing the values of table 1 we can conclude that the greater part of neutrons (>60%) is generated in hadronic and electromagnetic cascades produced by muons.
As is customary, the calculations are performed for single muons [4]. If the multiplicity of the muon groups is taken into account, then the value of neutron yield decreases: $< n_{sc} >= (4.38 \pm 0.53) \cdot 10^{-4}\ (one\_\mu)^{-1} (g/cm^2)^{-1}$.

	$\bar{N}_n$/events	$\bar{n}_{Fe,sc}$ $(cm^2/g)\pm\delta$	$\bar{n}_{,sc}$ $(cm^2/g)\pm\delta$
Single μ	0.155	$3.06\cdot10^{-4}$	$1.84\cdot10^{-4}$
Muon Bundle	0.547	$10.85\cdot10^{-4}$	$6.51\cdot10^{-4}$
kμ (k=3.54)	0.154	$3.06\cdot10^{-4}$	$1.84\cdot10^{-4}$
cascade	2.03	-	$2.41\cdot10^{-4}$
μ - events	0.557	$11\cdot10^{-4}$	$6.6\cdot10^{-4}$
Per 1 μ all processes with μstop			$4.38\cdot10^{-4}$



The value $< n_{sc} >$ is obtained for depth of 3650 m.w.e. and for $\overline{E_\mu} = 270\ GeV$. It is in agreement with experimental results, obtained with the analogous technique at depths of 25 [5], 316 [5], 570 [6] m.w.e. and 5200 m.w.e. [3]. As shown in Fig.1 the values exceed calculation with the FLUKA program, as was pointed out in [4]. The result presented in [7] $< n_{sc} >= 1.5 \cdot 10^{-4} (one\_\mu)^{-1} \left(g/cm^2\right)^{-1}$ is related to neutrons with energies higher than 20 *MeV*, because an additional signal with a threshold of 5 *MeV* was required in the analysis. The upper curve is the calculation [8].
This work is made with the RFFI financial support (grants 03-02-16414, SSchool-1782.2003.2) and Program for Fundamental Research of Presidium of RAS "Neutrino Physics" 2005.

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