Neutrons from cosmic-ray muons underground

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***Abstract*—The results of experimental study of neutron production by cosmic ray muons at the different depths underground during more than 40 years are presented.**

I. Introduction

In passing through rock muons generate γ-quanta, electrons, neutrons, pions and long-live radioactive isotopes mainly in nuclear and electromagnetic showers. These particles are the background for all experiments deep underground. The very serious component of the background is neutrons. Underground studies of neutrons were carried out using different scintillation detectors situated at the depths of 25 m.w.e., 316 m.w.e., 570 m.w.e., 3300 m.w.e. and 5200 m.w.e. There were obtained: the dependence of number of generated neutrons per 1 muon, per 1 g/cm^2 on the depth $N_n^{tot}(H)$, on the average energy of muons at the depth $N_n^{tot}(\bar{E}_\mu)$; the dependence of neutron number, generated in nuclear and electromagnetic showers on the shower energy, $N_n^{tot}(E_{n\,sh})$, $N_n^{tot}(E_{n\,el.sh})$; energy spectrum of neutrons, produced by single muons $F_n'(E_n)$ and by showers $F_n''(E_n)$ up to $E_n \approx 500 MeV$; energy spectrum of isolated neutrons, coming from the rock, $E_n^{is}(E_n)$ and neutron multiplicity versus distance from muon track or cascade core. The comparison of the experimental data with calculations was made.

II. Depth - Intensity Curve

For the depths less than 10000 m.w.e. there are four main processes of neutron production by muon underground:

1. μ^- - capture by nucleus followed by neutron emission; this process is important at depths less than 300 m.w.e;
2. neutron generation in muon inelastic scattering on nuclei;
3. neutron production by hadrons in the muon generated nuclear showers;
4. neutron production by gammas in the muon induced electromagnetic showers.

The dependence of the contribution of neutrons born in inelastic muon interactions on the transfer energy E_t is shown in Fig.1. The first local maximum corresponds to an excitation of a giant resonance in nuclei of matter by photonuclear muon interaction with low E_t's. The second

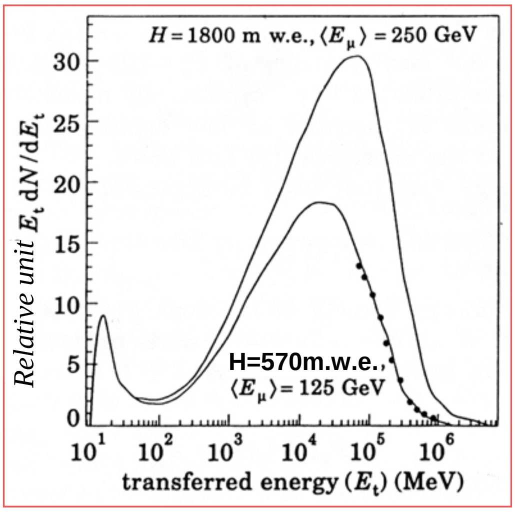

Fig.1. Dependence of the contribution of neutrons, produced in inelastic muon interactions, on the energy transfer in the interaction E_t. Points are the data from [5].

one is connected with neutron production in nuclear showers, generated by muons. The shower energy is higher than 1 GeV. The first process can be comparable with second one only for the depth less than 50 m.w.e. For larger depths the second process dominates [1, 2].

Fig.2. shows the dependence of generated neutron number per 1 muon per 1 g/cm^2 on the depth. The curves (1-3) correspond to the neutron production in electromagnetic showers initiated by muon bremsstahlung (1), by e^+e^- pair production and δ - electrons (2 and 3), correspondingly. Curve 4 is μ^-- capture and curve 5 is the neutron production in inelastic muon interactions with the account for nuclear showers. Curve 6 is the sum of all processes [1]. The points represent experimental data for the depth of 25, 316, 570 and 5200 m.w.e. The first 3 points were obtained at the Arteomovsk Scientific Station of INR (Moscow) [3, 4, 5] and the fourth one at the Mont Blanc Laboratory in collaboration with Institute of Cosmogeophysics of CNR. [6].

The experimental data agree with calculations. The total number of neutrons produced by 1 muon in 1 g/cm^2 excluding μ^-- capture depends on the average muon energy at a given depth as [1, 5]:

$$N_n(H) = N_0 \bar{E}_\mu(H)^{0.75\pm0.05} \qquad (1)$$

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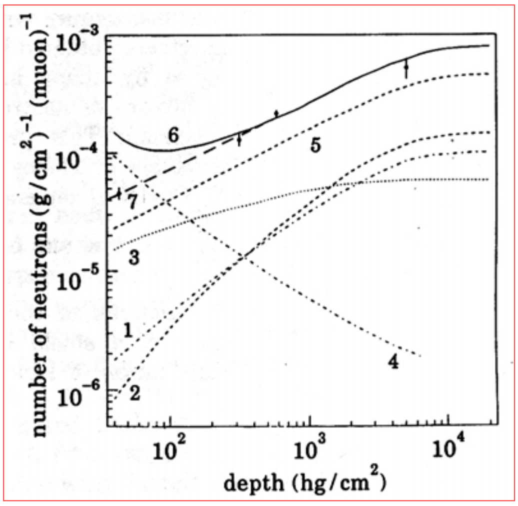

Fig.2. The number of generated neutrons per 1 muon per 1 g/cm^2 versus the depth from the top of the atmosphere [1].

Curve 1-3 are neutrons produced in electromagnetic showers initiated by bremsstrahlung, e^+e^--pair production and knock-on electrons, consequently. Curve 4 is μ^--captures, curve 5 are neutrons produced in nuclear showers. Curve 6 – the sum of all processes. Curve 7 – all processes without μ^-- captures. The points are experimental data from [3 – 6].

III. Experimental Study of Neutrons Underground

The measurements of different characteristics of neutrons underground were performed using scintillation counters: one module Arteomovsk detector (ASD) [5] having 105 tons of scintillator based on white-spirit C_nH_{2n} $(\overline{n} = 9.6)$ [7] situated at the depth of 570 m.w.e. in the salt mine (Fig.3.); Liquid Scintillation Detector (LSD) under Mt Blanc (5200 m.w.e.) consisted of 72 scintillation counters with total mass of 90 tons of the same scintillator (Fig.4.); Large Volume Detector (LVD) [8] under Gran Sasso at the depth of 3300 m.w.e. (~ 1 kt of C_nH_{2n} and ~ 1 kt of *Fe*) Fig.5.

The dependence of fluxes of hadrons (neutrons and pions) generated in nuclear and electromagnetic showers by cosmic ray muons on the shower energy and the average muon energy was obtained with ASD. This detector is able to measure about 70 % of the energy of a shower coming from the rock. A neutron, produced in the scintillator or coming from outside, slows down to thermal energies in collisions with carbon and hydrogen nuclei and after diffusion it is captured by proton creating the excited deuterium nucleus, which returns to the ground level radiating γ-quantum with energy of 2.23 MeV:

$$n + p \to d + \gamma \;\; (2.23\ MeV) \qquad (2)$$

The average lifetime of the neutron for the process is about 180 μs. The ASD has neutron detection efficiency 84±3%. Fig.6. shows the experimental dependence of the number of showers on the number of neutrons detected in them. One can distinguish two local maxima. The left one corresponds to electromagnetic showers, the right one to nuclear showers. It is seen that nuclear and electromagnetic showers are well separated by the neutron number detected in them.

The dependence of the average number of neutrons ($\overline{N}_n$)

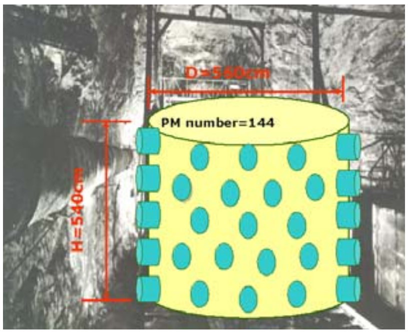

Fig.3.Arteomovsk Scintillation Detector (ASD)

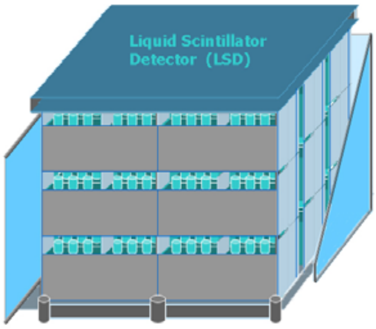

Fig.4.Liquid Scintillation Detector (LSD).

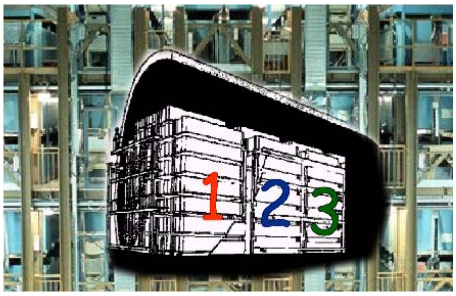

Fig.5.Large Volume Detector (LVD).

on the shower energy release is shown in Fig.7. Curves 1 and 2 are calculations for electromagnetic and nuclear showers, consequently. Fig.8. shows the dependence of average number of $\pi \to \mu \to e$ decays in electromagnetic and nuclear showers on the shower energy release in detector.

The $\overline{N}_n$ in nuclear ($\overline{N}_n^{nucl}$) and electromagnetic ($\overline{N}_n^{e.m.}$) showers depends on the energy releases in the detector and on the muon energy as

$$\begin{cases} \overline{N}_n^{e.m.} = k_1 E^{0.92\pm0.04}, & \overline{N}_n^{e.m.} = k_2 E_\mu^{1.03\pm0.05} \\ \overline{N}_n^{nucl} = k_3 E^{0.69\pm0.04}, & \overline{N}_n^{nucl} = k_4 E_\mu^{0.78\pm0.05} \end{cases} \qquad (3)$$

With Arteomovsk detector we studied the showers, their characteristics and secondary particles generated by muons. But with Mt Blanc and Gran Sasso apparata we search for rare processes predicted or non predicted by the theory.

The possibility to observe rare processes strongly depends on background conditions. Important source of the background is neutrons, their energy spectrum, their spatial

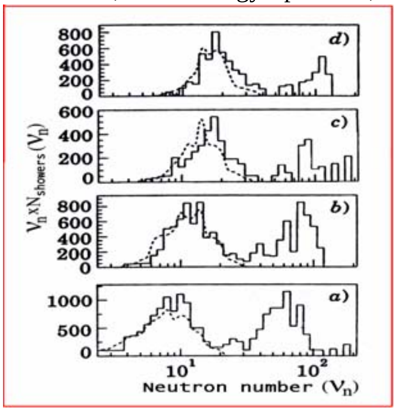

Fig.6. Dependence of the number of showers on the number of neutrons detected in them. The histograms are the experimental data for the following energy ranges: a) 90 – 115 GeV; b) 145 – 178 GeV; c) 212 – 250 GeV: d) 250 – 344 GeV.

distribution. These characteristics were studied also with LVD, consisting of 3 towers having size 13×20×10 m^3 [8]. Each tower has size 13×6×10 m^3.

A single muon passing trough the detector (average distance is about 3.5 m) produces $<n>=0.155$ neutrons. The value for muon bundle is 0.55. Per one muon in the bundle <*n*> is the same as for single muon. Per one shower with

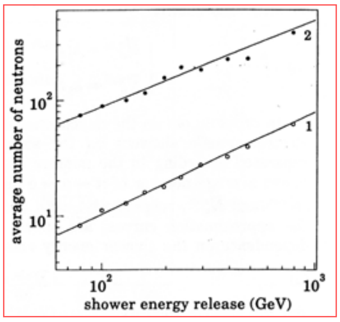

Fig.7. Dependence of the average number of neutrons on the energy release of the shower in the detector. The points O and ● represent the experimental data for electromagnetic and nuclear showers, respectively.

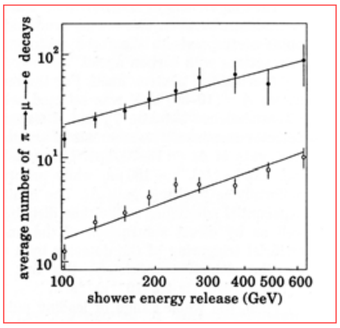

Fig.8. Average number of π→μ→e decays in electromagnetic (O) and nuclear (●) showers as functions of the shower energy release in the detector.

energy higher than 1 GeV $<n>\approx 2$.

The average number of neutrons produced by a muon per 1 g/cm^2 of scintillator is equal to $4.38\cdot 10^{-4}$ at the depth of 3300 m.w.e. [9]. It is interesting that for the large apparata having the height of about h=20 m of scintillator the total number of neutrons at the similar depth is more or less equal to the total number of producing them muons. For LVD the corresponding value of h is equal to 10 m, because LVD is the

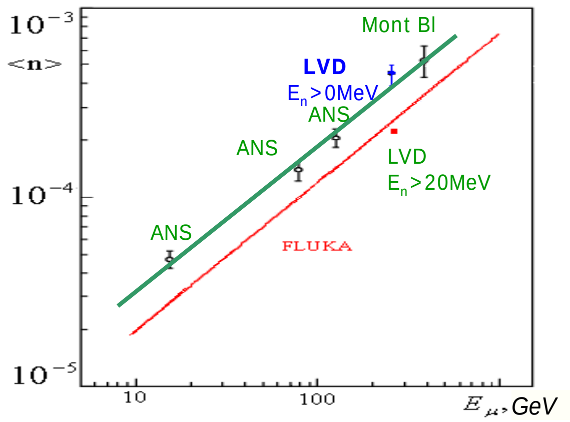

Fig.9. Dependence of neutron number produced by one muon in 1 g/cm^2 on the average energy of muons at the corresponding depth; $<n>=N_0<E_\mu>^{0.75}$ (R.Z.,1965) [1]. The lower curve is the calculation using FLUKA. The points are experimental data from [3-6, 9].

iron - scintillation detector.

The dependence of the neutron number generated by one muon in 1 g/cm^2 on the average energy of muons at the corresponding depth is shown in Fig.9. The experimental data are in accord with the calculation of 1965 [1] rather well.

IV. Neutron Energy Spectrum Underground

The knowledge of energy spectrum of neutrons as during their generation, as during their transport through the rock is very important for many reasons. First of all the spectrum is strongly connected with processes of neutron production in the showers. And the understanding of neutron transport gives us the possibility to calculate the neutron background for the detection of rare processes.

Neutron energy spectrum was measured with ASD up to energy about 100 MeV [10] and the energy spectrum of neutron induced events with LVD up to energy 300 MeV [11 - 12]. In the first case flux and energy spectrum of isolated neutrons coming from the rock was studied. In the second one the analyses of the experimental data was done when both muon and neutron were detected with LVD and the distance between them (or between neutron and muon initiated shower) was known.

The high energy neutron was found in investigation [10] of delayed coincidence between two pulses produced by neutron

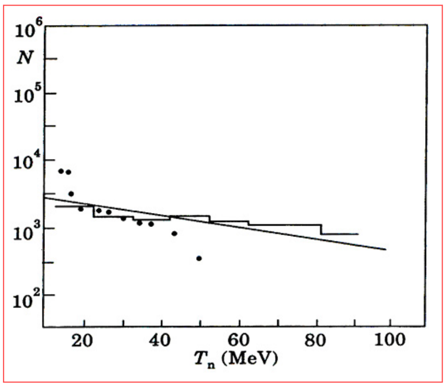

Fig.10. Energy spectrum of isolated neutrons underground

with $T_n > 18 MeV$. $T_n \approx 18 MeV$ corresponds to energy loss of relativistic particle of $A \approx 10 MeV$. The first pulse corresponds to the recoil protons and neutron energy losses due to inelastic

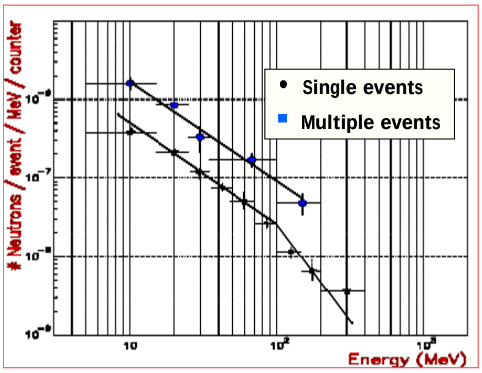

Fig.11a) Energy spectra of neutron – produced events till 300 MeV

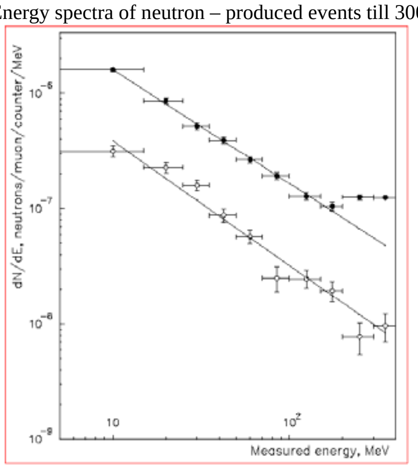

Fig.11 b) Neutron flux versus energy loss pulses at R> 1 m (filled circles) and R> 2 m (open circles)

interactions with carbon nuclei and the second one to the radioactive capture of low energy neutron. The correspondence between T_n and A was obtained in Monte Carlo calculations of the detector response. The flux of isolated neutrons, coming from rock, at the depth of 570 m.w.e. is equal to $2.3 \cdot 10^{-4} m^{-2} s^{-1}$. Fig.10. presents the neutron energy spectrum together with the spectrum measured by Barton at the depth of 60 m.w.e. [13]. μ^-- captures by nuclei are seen in the Barton spectrum because the process is important at low depth, see Fig.1. The approximation of the spectrum obtained at the depth of 570 m.w.e. is

$$F_n(T_n) = cT_n^{-0.5\pm0.1} \tag{4}$$

The energy spectrum of neutron - produced events till 300 MeV was detected at the depth of 3300 m.w.e. with 1 tower of LVD (13×6×10) [11] and with 3 tower of LVD [12].

Fig.11 shows the spectrum.

The neutron space distribution till 22 m from muon track was also measured. The results are represented in Fig. 12 a) and b). First one shows the distribution for neutrons generated by single and multiple muons in 3 towers; second one for neutrons, produced by single muons and showers in 1 tower. The neutrons from showers have higher energy and can

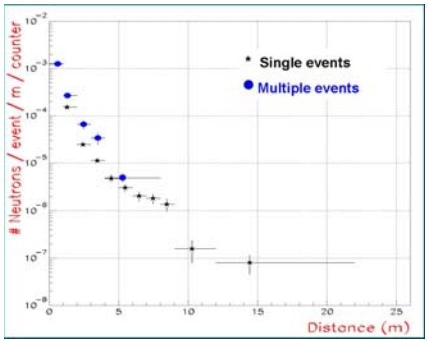

Fig.12 a) Neutron space distribution till 22 m from muon track.

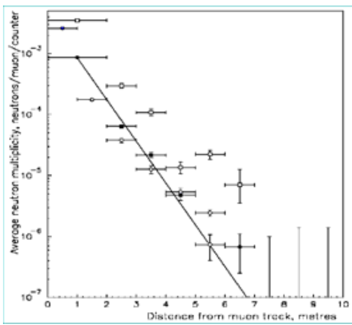

Fig.12 b) Neutron multiplicity vs distance from the muon track or cascade core. o– single muons, □ – cascades; • and curve – all events and exponential fit (upper limits are shown at R>7 m)

transport to the larger distance.

Calculations of the energy spectra of neutrons born in showers and passed through a shield of a different thickness were performed in [14] and [15]. The calculation [14] was made for incident neutrons having energy spectrum of neutrons produced in nuclear showers.

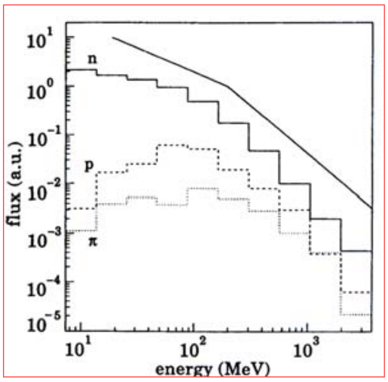

Fig.13. Energy spectrum of neutrons passed through the shield of 250 g/cm^2 together with the spectra of secondary protons and pions at the same distance.

$$F_n(T_n)dT \sim \frac{dT_n}{T_n} \qquad (T_n < 200MeV)$$
$$F_n(T_n)dT_n \sim \frac{dT_n}{T_n^2} \qquad (T_n > 200MeV) \qquad (5)$$

The spectrum of neutrons passed through the thickness of 250 g/cm^2 is shown in Fig.13. The energy spectra of secondary pions and protons produced in the shield by the neutrons are shown also in this figure. Behind the shield, neutron contribution is about 91%, proton 7% and pion 2% of the total particle flux. The neutron spectrum in Fig.13 has the shape in the range of T_n = (20 - 100) MeV as (4). After the passing through matter the spectrum dT_n / T_n (T_n <200) changes to $dT_n / T_n^{0.5}$, due to the dependence of neutron interaction cross-section on energy.

Monte Carlo calculation of differential distributions of hadrons going into LVD experimental hall from rock was performed in [15].

TABLE I
The sum of the results on neutron yield measurements at the different depths

Publication years	Location	Depth, m.w.e	Muon intensity, $sr^{-1}cm^{-2}s^{-1}$	Average muon energy , GeV	N. det. eff. %	Neutron yield 10^{-4}
1969-73	Gypsum mine	25	$2.7\cdot10^{-3}$	16.7	60	0.47
1969-72	Salt mine	316	$3.3\cdot10^{-5}$	86.0	60	1.21
1985-87	Salt mine	570	$7.3\cdot10^{-6}$	125.0	84	2.04
2004-5	Rock	3650	$1.7\cdot10^{-8}$	270.0	70	4.38
1989	Rock	5200	$1.5\cdot10^{-9}$	385.0	60	5.30

The dependence of total number of hadrons with energy above 200 MeV on the thickness of the rock is presented in Fig.14. As one can see the neutrons come in the detector from the distance up to 5 m of the rock.

The total number of neutrons with E_n > 200 MeV is about

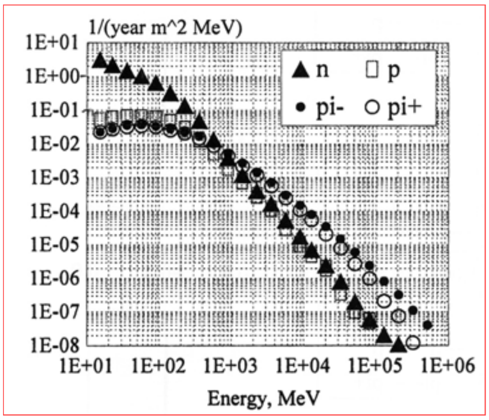

Fig.14. Spectra of particles going into the LVD hall from the rock.

25 n per m^2 per year. The value is in very good agreement with previous experimental data [10, 11].

A comparison of energy spectra of neutrons, protons and pions going into the experimental hall is presented in Fig.15.

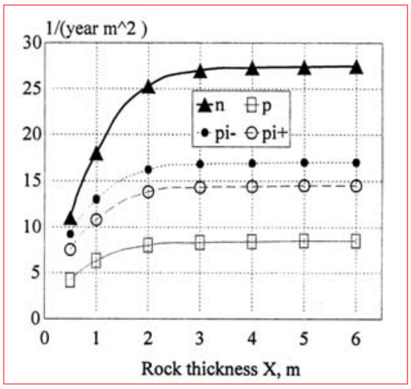

Fig.15. Number of particles (with E>200 MeV) going into the hall as a function of the rock thickness

The total number of neutrons is much higher than the number of other particles (p,$\pi^{\pm}$-mesons) if their energy is less than 600 MeV. The energy spectrum of neutrons in the range of 20 – 300 MeV is close to the spectrum measured with ANS and LVD.

At the high energies all spectra are asymptotically coincident. Charged pion spectra are hardened then neutron and proton ones.

The sum of the results on neutron yield measurements at the different depths is presented in the table I. The study of neutron production by muons was carried out up to the depth of 5200 m.w.e. At the depths higher than 12 000 m.w.e. the same processes of neutron generation as mentioned above exist, but they connect with neutrino produced muons. There the main process is the neutrino produced μ^-- capture following by neutron emission. The Fig.16 shows the

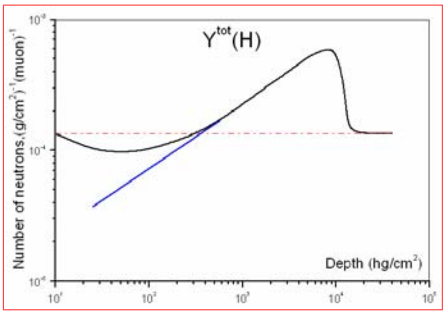

Fig.16. Dependence of the total specific muon generated neutron yield on the depth.

dependence of the total specific muon generated neutron yield on the depth. It is interesting that the number of neutrons born by one muon in g/cm^2 at the depth higher than 12 000 m.w.e. is close to the number of neutrons generated by one muon at the depth of about 25 m.w.e. The maximum of the curve is situated at the depth of about 7000 m.w.e.

The experimental data of neutron production in nuclear and electromagnetic showers can be used in study of extensive air showers (EAS):

1. The energy of EAS can be estimated by measurements of

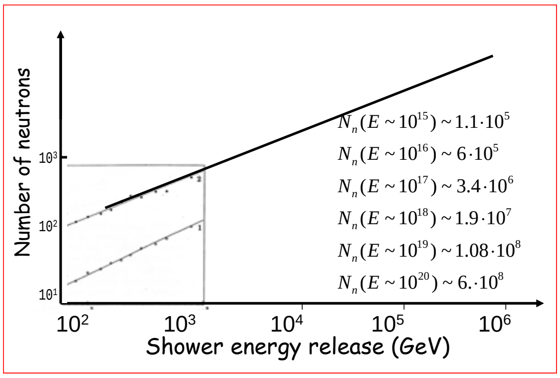

Fig.17. E_{sn} can be estimated by measurements of N_n

the neutron number. The dependence of neutron number on the energy of EAS obtained by extrapolation of the experimental data [5], see Fig.7, to the higher energy of showers is presented in Fig.17.

2. The shower generated by proton or nuclei can be separated from EAS initiated by gammas or electrons, see the Fig.6. and Fig. 17. So, the particle initiating EAS can be distinguished with using the neutron number, produced in the shower.

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