The underground neutron events at Tien-Shan

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Abstract: By the neutron monitor placed in the underground room of Tien-Shan mountain station is measured the spectrum of neutron multiplicities of the registered events. The spectrum has an approximately power shape with the differential slope index 3.7, its absolute intensity being 350-450 times lower than that of the events in the on-ground NM64 type neutron supermonitor.

Comparison of the intensity of underground neutron events with event intensity of the Tien-Shan NM64 supermonitor shows, that the mean absorption path of the cosmic ray component responsible for underground events is not less than 380–420 g/cm^2, which is 3–3.5 times larger than the absorption path of usual hadrons.

The slope index of the neutron multiplicities coincides with the index of the energy spectrum of bremsstrahlung gamma-quanta from energetic muons, but the observed intensity of underground events is two orders of magnitude higher than the intensity of muon-induced events should be.

Introduction

One of the constituent parts of the experimental complex *ATHLET* [1] is the installation *HADRON-M* for the study of primary cosmic ray particles in the energy range $10^{12} - 2 \cdot 10^{18}$ eV , which is now under construction at Tien-Shan mountain station (3340 m above sea level). In turn, one of the parts of this installation is the ionization-neutron calorimeter *INCA-44* with the surrounding system of neutron monitors for investigation of the hadronic component of extensive air showers. To be used with these monitors, it was designed a new registration system of neutron signals: the scheme of neutron counters feeding, electronics of signal registration channel, the system of data storage and control. These system is tested now at Tien-Shan in a new neutron monitor placed in the underground room at the depth of 20 m of water equivalent. A new materials — rubber and wood — are also tested as moderator of evaporation neutrons.

In the test experiments with underground neutron monitor was measured the dependence of the intensity of neutron events on the number (multiplic-ity) of registered neutrons M — the neutron multiplicity spectrum. These results are a subject of the current report.

The underground neutron monitor

The underground neutron monitor consists of the three separate units with 9, 9 and 7 neutron counters of the SNM15 type (see the figure 1). Internal arrangement of these units was done as similar as possible to the construction of the standard NM64 type supermonitor [2], which resides above the underground room and the data [3] of which will be used below for comparison. As an outer moderator of evaporation neutrons and reflector of background thermal neutrons in underground monitor are used the sheets of the rubber with enhanced percentage of hydrogen. As an inner moderator surrounding the neutron counters are used either the polyethylene tubes (as in NM64) or wooden boxes.

Pre-amplifiers which operate with neutron signals are mounted inside the metal caps put on the ends
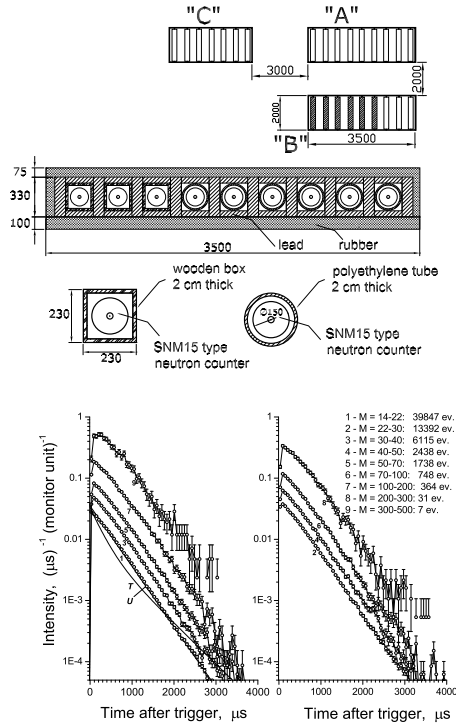
Figure 1: Mutual disposition of the three underground monitor units (above) and the internal arrangement of a single unit (below). Dimensions are shown in millimeters.

Figure 2: Temporal distributions of neutron signal in undeground events.

of the counters. Their output pulses, 1-3 μs in duration, may be transmitted without distortions via the coaxial cables of some tens of meters to the data registration center where the final amplifiers, discriminators and the shapers of standard pulses are mounted. The threshold of pulse discriminators corresponds to the amplitude of 10 mV at the neutron counter's anode, and the length of the standard rectangular pulses generated by the output shapers is 1 μs; as the previous measurements at Tien-Shan NM64 supermonitor have shown, the SNM15 counter's own dead time does not exceed this value (at least, under the usual condition of background count, 80-100 pulse per second) [4].

Standard pulses come to the scaler schemes whose outputs are connected to a random access stor-age with a ring organization. Each scaler counts the number of pulses during a fixed time interval (60 μs), pulse numbers being stored in the buffer storage. The buffer's capacity is enough for memorizing of 85 subsequent counts from 25 neutron detectors; after the buffer is exhausted, its filling renews from the first address. When a signal comes which marks the beginning of a neutron event inside the monitor — the trigger — the system makes another 67 counts and terminates operation waiting until a control computer reads the stored data. Hence, in every event 67 intensity measurements after the trigger and 18 measurements before this moment are available.

The system of trigger generation selects the cases, when just a number of neutron pulses appear in a monitor unit during a short time period. To achieve that, all the signals from neutron counters of a monitor unit are summed by a logical *OR* scheme and the number of resulting united pulses is counted by a separate pulse scaler: every next of united pulses starts the time gate with a fixed 600 μs duration; if at the end of this gate the total number of succeeding pulses happens to be above a pre-defined threshold (1, 2, 4, 8, ...), the scaler scheme generates a trigger signal; if otherwise, it simply resets itself. The overwhelming part of exposition was held with the threshold value "8"; when the spectrum of neutron events was measured in the range of low multiplicities, the trigger scheme had been tuned to the threshold "1", i.e. to the starting by the single signal from the every of neutron monitor counters.

Experimental data

The temporal distributions of neutron intensity. In the measurements of temporal distributions of neutron signals the three underground monitor units were considered separately, the data of only one of them — that with the highest multiplicity of the registered neutron pulses M — being included into statistics. The same condition had been applied earlier in the measurements of temporal distributions in the three units of Tien-Shan NM64 supermonitor [4].

The averaged temporal distributions of the neutron intensity are shown in figure 2. Intensity of back-

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ground counts for a 9-counters underground monitor unit is 4.5 p.p.s; the lower threshold of the considered multiplicity range, 14, was selected so as to exclude the influence of the background neutrons on the shape of temporal distribution in the whole time period up to 4000 μs. The considered distributions may be approximated by a simple exponent function with lifetime 400-430 μs (line U in figure 2) and their shape practically does not depend on neutron multiplicity. The temporal distributions of the neutrons in NM64 supermonitor have quite another form: they correspond to the sum of two exponential functions with lifetimes about 240 μs and 650 μs (line T) [4]. The reason of this difference is, apparently, in the worse characteristics concerning the capture of thermal neutrons the materials of the underground monitor (rubber and wood) have in comparison with the NM64 supermonitor's standard polyethylene moderator. The difference in temporal distributions between both installations means that the registration efficiency of evaporation neutrons in the underground monitor is rather lower than that of the NM64 supermonitor (which has a value about 5% [2]). Consequently, with the same number of evaporation neutrons the multiplicities measured underground must be underestimated comparatively with the multiplicities of NM64 supermonitor to $20\% - 30\%$.

The neutron multiplicity spectrum. Differential neutron multiplicity spectrum of the events observed in the underground monitor is shown in figure 3 together with the spectrum of the on-ground NM64 supermonitor events. The slanted dot lines mark the levels of equal intensity of primary cosmic radiation, while the thin smooth curves indicate the positions of the "upper" supermonitor's spectrum re-calculated to the depth of underground room (accordingly to the usual exponential absorption law) for a set of mean absorption path values (shown near these curves).

The differential multiplicity spectrum underground may be described by a power function $dN/dM = 0.3 \cdot M^{-3.7}$ m^{-2}s^{-1}, which is similar to the shape of the spectrum of NM64 supermonitor in the range $M > 5$ (the difference in power indexes does not exceed 0.3), though the nature of the particles responsible for the events in both installations must be quite different. Indeed, the events of

NM64 supermonitor are generated by the cosmic ray hadrons which are totally absorbed on the way to underground room because their mean absorption path is $120-130$ g/cm^2 [5] and the 2000 g/cm^2 thick ground layer reduces the hadron flux by 10^6 times. Since the experimental intensities of multiplicity spectra differ only by $350 - 450$ times, the events registered by underground monitor must be generated by some another particles having the penetrative properties like those of the muons. (Because of the mentioned difference in registration efficiency of evaporation neutrons, the last value must be considered only as an upper limit for the relation of absolute intensities, which may be much lower in reality).

Discussion

Without drawing any exotics for explanation of underground neutron events, we must conclude that these events descend from interactions of energetic ($E_\mu > 1$ TeV) muons inside the lead monitor's generator. Indeed, the slope index of the neutron multiplicity spectrum practically coincides with the slope of energy spectrum of bremsstrahlung gamma-quanta which had been measured by X-ray emulsion chambers [6]. The mechanisms of the muon interactions with a large energy transfer are well known, these are photo-nuclear interactions and the emission of bremsstrahlung gamma-quanta.

Both our accelerator measurements and simulations according to the GEANT code give a linear dependence of the mean neutron production ν on the energy of electron-photon cascade: $\nu = 3 \cdot E_{e,\gamma}$/GeV [7]. Since the neutron registration efficiency in underground monitor is about 3.5%, the mean number of registered neutrons may be defined according to the simple formula $M = M_0 \cdot E_{e,\gamma}$/TeV, where $M_0 = 10$.

The energy spectrum of bremsstrahlung gamma-quanta in the lead was measured in [6] and [8]. Absolute intensities of the spectra presented in both articles coincide at the gamma-ray energy 1 TeV but their power indexes differ by $0.5 - 0.6$ ($\gamma = 3.65 - 3.7$ in [6] and $\gamma=3.13$ in [8]). Our differential spectrum of neutron multiplicity has the slope index 3.7, in agreement with [6]. Using
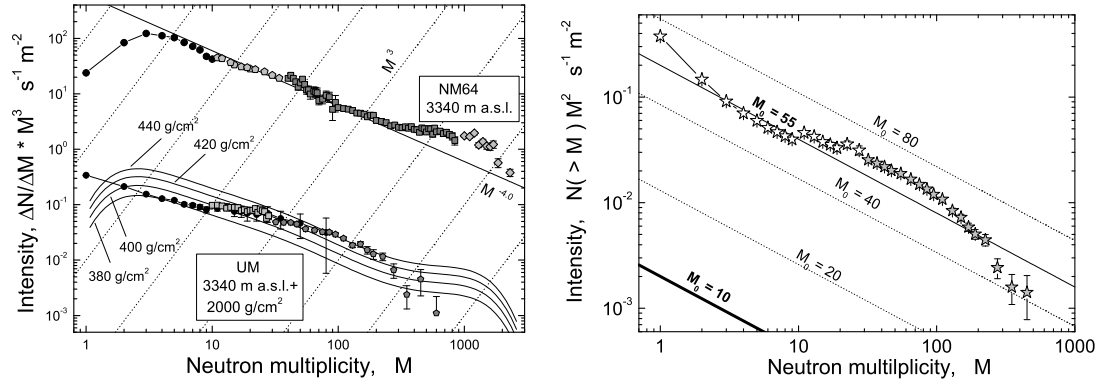
Figure 3: Neutron multiplicity spectra of the events in Tien-Shan NM64 and underground neutron monitors (left panel); the underground spectrum in an integral form (right panel).

the linear dependence of the neutron multiplicity M on the gamma-quanta energy and integrating the differential spectrum from [6], we have calculated the expected multiplicity spectrum of neutron events which is shown by a bold straight line in the right panel of figure 3. (Our experimental data, re-calculated from the differential spectrum, are shown there by the stars).

As it is seen, intensity of the expected spectrum is two orders of magnitude lower than that of experimental one. For agreement of both spectra it is necessary to consider the factor M_0 in the above formula as a free parameter. In the figure 3 is shown a set of straight lines for a number of M_0 values. The intensity of experimental spectrum agrees with $M_0 \sim 55$, correspondingly to a 5 times more abundant neutron production in electromagnetic cascades, than expected.

As for the nuclear interactions of the muons, since the energy losses in the lead due to these interactions do not exceed 5% of the bremsstrahlung losses, intensity of nuclear cascades also can not be higher than 5% of the gamma-quanta intensity. Energy dependence of neutron production in nuclear cascades is non-linear: $\nu = C \cdot E^\alpha$ (in our case of a thin absorber $\alpha \simeq 0.5$ [3]). Despite an order of magnitude higher neutron production in nuclear cascades [7], the neutron multiplicity spectrum of the events from them should always have a slope index $5.0 - 5.4$ and can not match the observed spectrum.

Hence, an interpretation attempt of the experimental neutron multiplicity spectrum of underground events in the framework of their muonic origin meets a large difficulties.

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