Underground neutron events at Tien Shan

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Abstract. The events of multiple neutron production under a 2000 g/cm² thick rock absorber were studied at the Tien Shan mountain cosmic ray station, at an altitude of 3340 m above the sea level. From comparison of the experimental and Geant4 simulated neutron multiplicity spectra it follows that the great bulk of these events can be explained by interaction of cosmic ray muons with internal material of neutron detector. In synchronous operation of the underground neutron monitor with the Tien Shan shower detector system it was found that the characteristics of the muonic component of extensive air showers which is seemingly responsible for generation of neutron events underground do change noticeably within the energy range of the knee of primary cosmic ray spectrum. Some peculiar shower events were detected when the neutron signal reveals itself only ~100–1000 µs after the passage of the front of shower particles which probably means an existence of corresponding delay of the muon flux in such events.

1. Introduction

Investigation of the events of multiple neutron production in underground detectors of the Tien Shan mountain cosmic ray station was started about a decade ago. Phenomenological results which have been obtained then on the properties of these events were reported in [1, 2, 3]; in these publications it was stated that the original nature of neutron events observed underground still remains unclear. After completion of modification period of the complex detector system for cosmic ray studies at the Tien Shan station [4] and systematic introduction of the Geant4 package based simulation methods for determination of the properties of its particle detectors it became possible to return to the problem of underground neutron events at a new stage of experimental technique. In particular, the detection of neutron events in strict synchronization with shower installation now permits to study precisely the neutron bearing properties and temporal characteristics of the penetrative component of extensive air showers (EAS). An overview of the results newly obtained in simultaneous operation of the Tien Shan shower detector system with underground neutron detector is the subject of the present message.
2. The underground neutron monitor

Presently, the underground neutron detector at the Tien Shan station consists of a pair of separated units which have been made resembling the standard NM64 type neutron supermonitor [5], and were placed one above the other as it is shown in the left picture of figure 1. Both units include the layers of a heavy target absorber where the penetrative particles of cosmic radiation can experience nuclear interaction with lead nuclei. Evaporation neutrons which originate as a result of this interaction can be detected by the big $150 \times 2000$ mm$^2$ neutron counters with enriched $^{10}$BF$_3$ gas filling, so the detection of low-energy neutrons is possible there due to reaction $n(^{10}$B,$^7$Li)$\alpha$. Before the detection, the neutrons lose their initial MeV-order kinetic energy down to thermal level in multiple interactions with light nuclei within the sheets of internal moderator material which consists of wooden boxes surrounding the counters. Another sheets of the hydrogen enriched rubber ($C_2H_2$) which cover all the unit from outside play the role of external shielding to prevent the influence of environmental low energy neutron background on the measurement of the cosmic ray connected neutron signal.

Hence, the response of a neutron monitor unit to interaction of a nuclear-active cosmic ray particle is connected with a number of electric pulse signals obtained from its counters during some fixed time gate period after this interaction. Hereafter, sum number of such signals will be designated as the neutron multiplicity $M$. In [6] it was shown experimentally that for a monitor unit of considered construction the multiplicity $M$ is nearly proportional to a square root of the energy deposit in primary interaction (in GeV order energy range), and typical duration of the gate time can be of the order of a few milliseconds. More precisely, the energy dependence $M(E)$ can be defined through detailed simulation both of the primary interaction and of the subsequent moderation and diffusion processes of originating neutrons within the monitor material which can be made on the basis of modern Geant4 toolkit [7]. The results of such calculations for hadronic (neutron) and muonic type primaries are presented in the right plot of the figure 1.

Same Geant4 simulation model can be of use to answer the question which was put in [1] on the nature of the underground neutron events. Taking into consideration the spectrum of energy deposits from penetrative cosmic ray particles which has been measured earlier in the

**Figure 1.** Left: internal arrangement of the underground neutron monitor installation in the present time: 1 – neutron counter, 2 – moderator, 3 – lead target, 4 – rubber (outer moderator and shielding), 5 – iron absorber, 6 – plastic scintillators. Dimensions are shown in millimeters. Right: Geant4 simulation results for multiplicity of the signals from neutron counters of a single monitor unit in dependence on the energy of incident neutrons and muons; continuous straight line beside the neutron data indicates the approximation of corresponding experimental results from the work [6].
same underground room of Tien Shan station with ionization calorimeter [8], and using it as an input for Geant4 simulation series with \( \mu^\pm \) type primaries one can obtain the expected neutron multiplicity spectrum of underground events. A comparison of such simulated and experimentally measured multiplicity spectra is made in the plot of figure 2 where it is seen that both spectra do agree rather well with each other. From this fact a conclusion can be drawn that in the case of underground monitor we deal mostly with the products of nuclear interaction caused by cosmic ray muons, so this monitor as a whole can be used as a specific detector of the cosmic ray muonic component, and particularly of the muons which accompany the passage of extensive air showers.

3. Underground neutron events and extensive air showers

During operation periods of the Tien Shan shower installation [4] in the years 2015-2018 the data taking process at the underground neutron monitor was fulfilled under the control of external trigger signal which was generated in the moments when an extensive air shower has been detected above the surface of Tien Shan station. The multiplicity spectra of the neutron events of muonic origin which have been registered simultaneously with an EAS are presented in figure 3, in comparison with analogous spectra calculated over the whole set of underground events. It is seen there that generally the intensity of EAS accompanied events occurs being 2–3 order of magnitude below the total flux of \( M \lesssim 100 \) events, but tends to match with the latter in the range of extremely high multiplicities. Seemingly, this difference can be explained by particulars of the shower trigger elaboration threshold and their influence on registration probability of the EAS connected neutron events underground.

To clarify more precisely what are the favorable conditions for detection of the muonic EAS component by the neutron signal from its nuclear interaction a correlation plot can be built between the multiplicity of underground neutron events \( M \), and the core distance \( R \) and size \( N_e \) (total number of the charged particles) of accompanying showers. An example of such correlation is presented in the left plot of figure 4. The range of distance values here is limited from above with geometrical sizes of the central detector “carpet” of Tien Shan shower installation \( (R_{\text{max}} \simeq 36 \) m, see [4]) which was used for precise location of EAS axis in the measurement series when the considered experimental data have been obtained. From correlation plots of figure 4 it

![Figure 2. Experimental (circles) and Geant4 simulated (squares) multiplicity spectra of neutron events in the underground monitor.](image)

![Figure 3. Multiplicity spectra of all neutron events seen underground (above), and of the events with EAS accompaniment only (below).](image)
Figure 4. Left: correlation plots between the multiplicity of underground neutron events $M$, the shower size $N_e$, and the core distance $R$ of accompanying EAS. Right: relative share of EAS with detected neutron signal from muonic interactions underground. (Here, there are plotted only the data obtained for the lower unit of the underground monitor; those for its upper unit are quite analogous to presented ones).

is seen that the events with non-zero multiplicity values were observed mostly in the cases when a shower axis has passed in relative vicinity ($R \lesssim 20 - 25$ m) to projection of the position of neutron detector to the surface of the ground, but the distance between EAS core and location of the monitor in such events can be somewhat bigger for the showers with $N_e \gtrsim 10^6$. As well, the events with comparatively high values of detected neutron multiplicity ($M \gtrsim 10^{-30}$) were met only amongst EAS with $N_e \gtrsim 10^6$.

The dependence between the mean relative amount of EAS events with non-zero multiplicity of the underground neutron signal (which is normalized to the total statistics of registered extensive air showers $N_{EAS}$) and the average size of accompanying shower $N_e$ is illustrated by the right plot of figure 4. It follows from this picture that for all EAS with $N_e \lesssim 10^6$ the share of $M \geq 1$ events remains at an approximately one and the same low level which statistically nearly fits zero, and generally can be explained by random coincidences of shower trigger with background neutron events in the monitor. Contrary to this, in the range of shower sizes $N_e \approx 10^6$ the relation $N_{M \geq 1}/N_{EAS}$ starts to grow, and evidently can not be put into any agreement with its previous behaviour.

It should be noted that at the altitude of the Tien Shan mountain station the range of EAS sizes $N_e \approx 10^6$ corresponds to the primary energy of a cosmic ray particle $E_0 \approx 3 \cdot 10^{15}$ eV [9], i.e. to position of the well-known knee in the energy spectrum of cosmic rays. Since the revealed sharp increase in the relative share of the showers which were accompanied by the underground neutron events (and consequently, a corresponding increase in the average multiplicity or in the energy of EAS connected muons which are the original source for generation of these events) occurs nearly at the same point on energy scale, probably it could be added to a wide list of various peculiar effects which have been met up to date within the energy range around the knee of primary spectrum by many research groups, and particularly in the experiments which have been held previously at the Tien Shan cosmic ray station [4].

Another peculiarity found in behaviour of the underground neutron events concerns their temporal characteristics. Since the shower trigger provides a rather strict binding to the EAS passage it is possible to trace precisely the time distribution of subsequent neutron signals with regard to initial moment of nuclear interactions caused by the EAS muons in underground
Figure 5. Top: a sample of normal (left) and delayed (right) time distributions of neutron signal in EAS connected events of underground monitor. Zero point of time axis in both plots corresponds to the moment of EAS trigger; vertical axis is graduated in the units of neutron counter pulses which have come during a single 60 µs long time interval. Neutron counters 1 . . . 9 correspond to the upper monitor unit, 10 . . . 18—to the lower one. Bottom: distribution of the time delay values between the shower front and the beginning of the neutron signal development in underground events with sum multiplicity $M \geq 3$ and $M \geq 5$.

It is natural to expect that generally this distribution must be of the exponent type which results from diffusion of the newly born evaporation neutrons within the monitor material. In fact, most part of detected events do have such exponential shape, like a sample event shown in the top left panel of the figure 5. At the same time, among all EAS connected events it was found a noticeable amount of cases when the beginning of exponential intensity decrease has been too late by a some considerable time $T$ in relation to the moment of shower trigger, so that $T$ can be of up to a few hundreds of microseconds order. An example of a such “delayed” event is presented in the top right panel of figure 5.

Of course, a certain part of uncommon delays seen underground can be explained by an arbitrary overlapping between the moments of EAS trigger and the background neutron events in monitor. To elucidate the role of random coincidences in the discussed effect a distribution can be built over observed values of the delay time $T$. Such distribution (normalized to the total amount of registered EAS cases with a neutron accompaniment underground) is presented in two bottom plots of the figure 5 which are drawn for the events with detected neutron multiplicity $M \geq 3$ and $M \geq 5$ correspondingly. As it is seen in these plots the probability to find an overtaking signal from neutron detector in the negative range of delay times $T < 0$ is
about \((2 - 4) \cdot 10^{-4} \, \mu \text{s}^{-1} \cdot \text{event}^{-1}\). Since obviously such pulses must be causally independent on the succeeding EAS it is this level which can be accepted as a background which owes to the random coincidences between the extensive air showers and the neutron events underground. Nevertheless, an evident and statistically reliable excess of events is seen in the plots of figure 5 in the range of delay times between \(T = 0\) and \(T \approx 500 - 800 \, \mu \text{s}\) which means that some noticeable part of the observed delays can not be completely due to the accidental background but must have some physical reason in the EAS passage. Since the primary source of underground neutron events is the interaction of the muons same conclusion on existence of a considerable delay time relates as well to the flux of the muonic component in extensive air showers.

4. Conclusion

Presently, the investigation results of neutron generation in the underground monitor at the Tien Shan station can be summarized as the following. The comparison of the experimental and Geant4 simulated neutron multiplicity spectra has shown that the great bulk of the events observed underground can be rather convincingly explained by the interaction of the cosmic ray muons with internal material of the neutron detector. In synchronous operation of the underground neutron monitor with the Tien Shan shower installation it was found that the origination frequency of neutron events (and consequently either the average energy of EAS connected muons which are the primary source of neutron generation, or the mean muon multiplicity in EAS, or both these characteristics) starts to grow significantly around the knee of primary cosmic ray spectrum. Some peculiar EAS events were detected when the neutron signal underground reveals itself only a few hundreds of microseconds after shower trigger which circumstance means an existence of the corresponding delay of EAS connected muon flux in relation to the main front of shower particles in these events.

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