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The effect of anomalous neutron events: new data from the scintillation neutron detectors

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Abstract: Experiments with the new generation of neutron detectors — the boron-containing scintillators placed inside a standard NM64 neutron supermonitor — have shown, that the peculiar high-multiplicity neutron events with anomalously prolonged temporal distributions of neutron intensity, which have been observed earlier in a number of neutron monitor installations, are connected with an overload of the gas ionization counters the monitors have been traditionally build on. The measured spectrum of neutron multiplicities at $M > 1000$ exceeds by several times an expected one, calculated in the framework of CORSIKA+QGSJET codes. Seemingly, the observed excess of high-multiplicity neutron events is caused by production of the multitude of low-energy neutrons in the core region of extensive air showers having the energies above the knee of primary cosmic ray spectrum.

Introduction.

Experiments with the NM64 neutron supermonitor being held since the beginning of 1990-th at the Tien-Shan mountain cosmic ray station resulted in the discovery of unusual neutron events accompanying the passages of the cores of high energy extensive air showers (EAS) through the monitor [1, 2]. These events are characterized by their extremely high neutron multiplicities (about 1000–3000 of registered neutron pulses per a standard 6-counter monitor unit) and an amazingly long temporal duration of neutron signal (3–4 usual neutron lifetimes or even longer).

The essence of considered phenomenon consists of the following. The NM64 neutron supermonitor do register in reality the evaporation neutrons from nuclear fission produced by the high energy cosmic ray hadrons inside the lead monitor's generator. Before to be detected, these evaporation neutrons, being born with energies about some MeV, must be slowed down to thermal energies. Thermalization is achieved in diffusion of evaporation neutrons inside the sheets of light, hydrogen-containing substances (moderator). As a consequence of a NM64 monitor's two-layered moderator structure (the outer and internal polyethylene layers) the typical time distribution of neutron signals is a sum of two exponents with lifetimes of about $\tau_1 = 200 - 250$ μs and $\tau_2 = 600 - 650$ μs:

$$F(t) = M[\frac{0.72}{\tau_1}exp(-\frac{t}{\tau_1}) + \frac{0.28}{\tau_2}exp(-\frac{t}{\tau_2})], \quad (1)$$

where M is the total number of registered neutrons — the neutron multiplicity.

An overwhelming majority of the registered events follows to the law (1) with a great accuracy. However, it was found, that at the energies above 3 PeV a small part — about 2–3% of the whole flux — of extensive air showers generate some strange neutron events when their cores happen to come immediately through the monitor. Typical for these events is a large neutron contents ($>$ 1000 neutron pulses obtained from a single monitor unit in a 3.5 ms time interval) and a "prolonged" shape of the temporal distribution of neutron intensity,

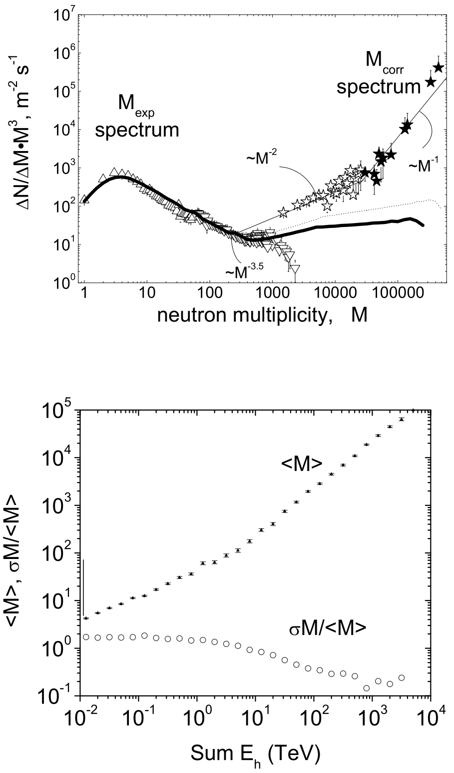

Figure 1: Above: experimental (triangles) and corrected (stars) neutron multiplicity spectra of the events in Tien-Shan NM64 supermonitor together with corresponding CORSIKA+QGSJET calculation (thick line) and the upper theoretical limit (dashed line). Below: the average neutron multiplicity in dependence on hadron energy $SumE_h$ and its fluctuations $\sigma M/\langle M\rangle$ (simulation result).

which continues up to some milliseconds after the moment of EAS passage and drastically deviates from the standard curve (1) in the range $t < 1000$ μs.

Possible explanation models.

One of the possible explanations of the effect is to suppose, that the above-the-knee EAS cores contain something, which is capable to initiate a self-sustaining chain reaction of nuclear disintegrations inside the lead absorber of neutron monitor. Assuming for these reactions a typical time duration of the order of some milliseconds we could explain distortion of exponential time distributions by the neutrons, being born *continuously* all the time while fission processes are going on inside the monitor. But it is well known, that in the lead are absent any conditions for initiation of nuclear reactions by usual *hadrons*; if such reactions still take place, they should be triggered by some non-hadronic component capable to change the mechanism of nuclear fission and on this explanation way we face to the necessity of a highly exotic assumptions.

Another principal possibility is to suppose, that the hadron flows in the core region above the knee are so intensive and the number of the evaporation neutrons born *simultaneously* in the moment of EAS passage is so high, that the proportional ionization counters used in the standard NM64 supermonitor for neutron detection sink into a saturation and loose their temporal resolution of the order of 1-2 μs (very limited, indeed), which is typical for their operation under normal conditions. In [3] a ”corrected” neutron multiplicity M_{corr} was obtained for the every event with $M_{exp} > 300$ as an integral of the function (1) normalized to the observed neutron intensity at 2.5-3 ms, where the counters saturation should be negligible. The spectrum of ”corrected” multiplicities is shown in the upper panel of figure 1 by the stars. One can see a sharp difference between the slope of ”corrected” and experimental multiplicity spectra.

In our work [4] it was shown, that in the low-multiplicity range $M < 100$, connected with the passages of the *single* hadrons through monitor, the experimental spectrum corresponds to a power energy dependence of neutron production: $M \sim E_h^{0.5}$, in agreement with theoretical calculations at high energies.

In the range of higher multiplicities ($M > 100-300$) where the spectrum is coupled with the passages of hadron *groups* from the EAS cores [2], neutron multiplicity should be proportional to the hadrons number: $M \sim N_h\langle E_h\rangle$. In turn, the latter is approximately proportional to the primary EAS energy E_0, while the average hadron energy $\langle E_h\rangle$ practically does not depend on E_0. Hence, the neutron multiplicity spectrum should have the slope of the primary E_0 spectrum, i.e. 2.7-3, in contradiction with the slope of the ”corrected” spectrum, which is of the order of 2.0 or even 1.0-1.5.

We have performed a series of EAS simulations in the framework of the CORSIKA+QGSJET01/QGSJET0102 codes to calculate the expected spectrum of neutron multiplicities. Calculation was based on the energy spectrum of the EAS core hadrons $F(SumE_h)$ measured with the big ionization calorimeter at Tien-Shan in a wide energy range 0.3-600 TeV [5]. At the high energies $SumE_h$ is a hadron energy summed up over the whole calorimeter area (6 × 6 m^2) with EAS axes being within the radius 3.5 m, at smaller energies this is the energy of a single hadron. The spectrum has a power shape with the slope $\gamma_h^1 \sim 2.55$ up to $SumE_h \sim 100 - 150$ TeV and a clearly seen change of the slope above 100 TeV: $\gamma_h^2 \sim 2.9 - 3.0$. This latter spectrum may be fitted well if one supposes a knee in proton spectrum around 4 PeV [7].

In figure 1b are shown the calculated theoretical dependence $\langle M \rangle - SumE_h$ and fluctuations of neutron multiplicity in a neutron monitor at the fixed value of EAS core $SumE_h$. The $\langle M \rangle - SumE_h$ distribution practically does not depend on the sort of primary EAS particle and on the chosen interaction model. In both considered models this dependence sharply changes from $\langle M \rangle \sim SumE_h^{0.53}$ to $\langle M \rangle \sim SumE_h^{1.03}$ at $SumE_h \sim 4$ TeV. Up to 4 TeV fluctuations of M are about 180%, which is close to fluctuations typical for a single hadron, above 4 TeV they begin to decrease as $\sim N_h^{-0.5}$. We have also calculated an upper limit of the contribution of neutrons generated by electron-photon component of EAS cores. (The uncertainty here is connected with the uncertainty of the power index in dependence $M \sim E_\gamma^\alpha$; so the value $\alpha = 1$ has been chosen as it's upper limit). In the figure 1a are shown an upper limit and the normal variant of the expected spectra of neutron multiplicity, both of which comes much lower, than the spectrum M_{corr}.

Hence, the "corrected" multiplicity spectrum can not be explained by the existing theoretical models, because any expected spectrum can not be flatter than the primary one. Consequently, the second assumption about the origin of "prolonged" events in a neutron monitor — an overfloating of it's neutron detectors — must have behind a some non-trivial nature too.

Experiment.

A key question in the problem of "prolonged" neutron events is, if we have to deal with a momentary or continuous generation of secondary neutrons inside the monitor. It is obvious, that the problem may be settled by a principal improvement of the temporal resolution of applied neutron detectors, which was a main purpose in development of the boron-enriched scintillators capable to register the thermal neutrons due to reaction with ^{10}B nuclei [6]. In contrast to ionization counters, the radiation decay times of these scintillators are about some nanoseconds and there is no problem with light output's linearity up to a very high intensities of registered neutron pulses. In 2005 year a set of 24 boron scintillators was installed inside the Tien-Shan NM64 supermonitor; the data obtained since that time during a 18000 h long operation period are presented in this section.

The signals from scintillation detectors are registered in two separate channels: scintillation amplitude from the interaction products of the thermal neutrons with ^{10}B nuclei being 3-5 times lower than that of the minimum ionizing particles peak, the same detector may be used for simultaneous registering both the neutrons and accompanying γ-radiation. Correspondingly, analogue pulses from the PMT are transmitted to a pair of amplitude discriminators having the thresholds below and above the range of the peak from thermal neutrons in scintillation spectrum. Temporal distributions of the shaped discriminator pulses are registered by a special system of time scanning [2].

The averaged temporal distributions of scintillation pulses for the low- and high-multiplicity neutron events are shown in figure 2 together with distributions of the signals from ionization neutron counters (as before, neutron multiplicity M is calculated as a sum of pulse numbers from all 6 neutron ionization counters of the NM64 unit). The curve F presents a best fit of the low-amplitude (neutron) points in the low-multiplicity range by a sum of two exponents like (1); on the high-multiplicity plot this curve is normalized to coincide with the points on the tail of experimental distribution.

It may be seen, that distributions of scintillation pulses continue to follow to exponential function (1) up to the highest values of neutron mul-

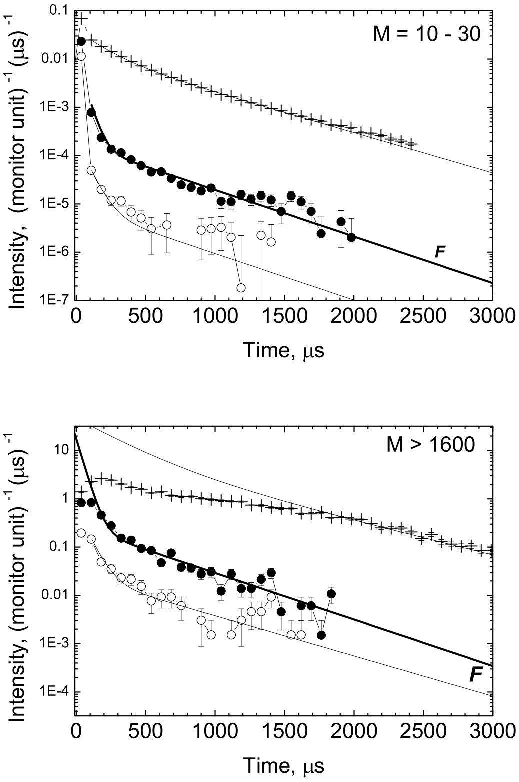

Figure 2: Time distributions of scintillation pulses in the two extreme ranges of neutron multiplicity. Filled circles — low-amplitude signals (neutrons), open circles — high-amplitude signals (γ-radiation); crosses — the signals of ionization neutron counters.

tiplicity. Lifetime parameters of the exponential fit of lower-amplitude points in the range $M = 10-30$ (curve F) are $\tau_1 = 45$ μs and $\tau_2 = 520$ μs. The shorter lifetime of the "fast" exponent in comparison with the corresponding τ_1 value in (1) reflects the much smaller size of the ⊘105x300 mm scintillation detector and its surrounding moderator casing, than the polyethylene tubes around the 2 m long neutron ionization counters are. The lifetime of the "slow" exponent is much closer to that of ionization counters (after 700–1000 μs the curve F comes nearly parallel to the counters points), because at large delays after beginning of a neutron event both detectors register the same flux of neutrons diffusing in the monitor's outer moderator. As for the high-amplitude distributions, their behavior generally repeats the behavior of the lower-amplitude ones, since the high-amplitude signals are caused by γ-radiation which is genetically connected with the captures of the same thermal neutrons by the light moderator nuclei.

Conclusion.

Presented figures does not demonstrate such a drastic difference in temporal dependencies of neutron scintillation signals between the low- and high-multiplicity ranges, as the ionization neutron counters do. This fact is a *direct* evidence, that the second model of anomalous neutron events with a *momentary* generation of an enormous number of hadrons in EAS is realized in practice. Hence, according to the results of Tien-Shan supermonitor experiments, the models of EAS development in the above-the-knee energy range are to be modified in direction of an enhanced production of a low-energy hadron component.

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