The neutron ‘thunder’ accompanying the extensive air shower

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Abstract

Simulations show that neutrons are the most abundant component among extensive air shower hadrons. However, multiple neutrons which appear with long delays in neutron monitors nearby the EAS core (‘neutron thunder’) are mostly not the neutrons of the shower, but have a secondary origin. The bulk of them is produced by high energy EAS hadrons hitting the monitors. The delays are due to the thermalization and diffusion of neutrons in the moderator and reflector of the monitor accompanied by the production of secondary gamma-quanta. This conclusion raises the important problem of the interaction of EAS with the ground, the stuff of the detectors and their environment since they have often hydrogen containing materials like polyethylene in neutron monitors. Such interaction can give an additional contribution to the signal in the EAS detectors. It can be particularly important for the signals from scintillator or water tank detectors at km-long distances from the EAS core where neutrons of the shower become the dominant component after a few µs behind the EAS front.

1 Introduction

The dispute on the role of low energy neutrons as the possible origin of delayed (‘sub-luminal’) pulses in neutron counters and scintillator extensive air shower (EAS) detectors started long ago [1, 2, 3, 4]. In those early works people observed single pulses delayed with respect to the main shower front and concluded that they are produced by neutrons accompanying EAS without specifying their origin in more detail. The observed delays in these detectors were not dramatic, however, and did not exceed a few µs.

The present work has been inspired by the observation of the multiple neutrons which followed EAS with delays as long as hundreds of µs [5, 6, 7, 8, 9]. Such delays have been observed with the Tien-Shan neutron monitor for EAS in the PeV energy region. Later this finding has been confirmed by other experiments [10, 11, 12, 13, 14] and the existence of the effect is now beyond any doubts. There is, however, no agreement about its origin [13, 15, 16]. Briefly the essence of the effect is the appearance of the numerous neutrons delayed by hundreds of microseconds after the passage of the main shower disk in the vicinity of the EAS core. In the spectacular

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scenario of 'the thunderstorm model' this phenomenon has been compared with the thunder which appears with a delay after a strike of the lightning during the thunderstorm [17].

In the detailed study [8] of the effect it has been claimed that the process has a threshold and the delayed neutrons appear at PeV primary energies, i.e. in the region of the 'knee' observed in the primary cosmic-ray (CR) energy spectrum. Another observation is that these neutrons are concentrated within a few meters around an EAS core and accompanied by delayed \( \gamma \)-quanta. The neutron multiplicity spectrum changes its slope at high energies and becomes flatter than at low energies. All these features let the authors assume that this phenomenon is connected with the properties of high energy (PeV) interactions and it 'distinctly conflicts with the modern EAS development models of a quasi-scaling type' [16].

The other groups [14, 15] argued that the delayed neutrons appeared not in the process of EAS development in air. They attributed the effect mostly to the low energy physics and explained it by neutrons which are produced inside the neutron monitor by numerous nuclear scatterings and disintegrations, caused by hadrons in the EAS core, and which then propagate outside the core region. Some of them appear also as albedo neutrons from the nuclear cascade developing in the ground underlying the neutron detectors after EAS propagate from the air into the ground. That explanation has been based on their own experimental data.

Below we present our viewpoint on the origin of observed effects. We shall also discuss possible consequences of our explanation for the experimental observation of EAS at higher energies, viz. in the EeV energy range.

2 The PeV energy range

2.1 The change of the temporal distribution

In our paper [17] we showed that the pure geometrical approach based on an assumption that all neutrons are produced in the EAS core and propagate outside by the spherical diffusion cannot give an explanation of the distorted temporal distributions at high energies and the longitude of the delay.

The distributions presented in [8] indicate that their distortions have most likely a methodical explanation connected with the 'saturation' of neutron counting rate at the high neutron intensities. The arguments for that conclusion are the following: (i) the maximum 'saturation' counting rate of the standard neutron monitor unit with 6 counters of SNM15 type (the dead time \( \tau \approx 2\mu s \)) is expected as \( 6/\tau \approx 3\mu s^{-1} \); (ii) this saturation is expected to start close to the observed neutron multiplicity \( M = 3\mu s^{-1}/f(0) \), where \( f(t) = \frac{0.72}{\tau_1}\exp(-t/\tau_1) + \frac{0.28}{\tau_2}\exp(-t/\tau_2) \) is the standard temporal distribution function for neutrons produced instantly inside the neutron monitor and detected by its counters. For \( \tau_1 = 250 - 300\mu s \) and \( \tau_2 = 600 - 650\mu s \) the saturation level at \( 3\mu s^{-1} \) can be reached at \( \log M = 2.9 - 3.0 \).
These expected values are exactly what is observed in the experiment [8]. Both arguments as well as the experimental study of the phenomenon made with neutron detectors which have better time resolution [10, 11, 15] give strong support to the methodical explanation of the observed distortions of the time distributions which are caused by the high neutron intensity inside the monitor and the saturation of the counting rate due to the finite time resolution of neutron counters.

The appearance of the minimum in the neutron temporal distributions at delays of 200 - 300 µs at high neutron intensity seen in SNM18 counters and not seen in SNM15 counters evidences also in favor of the internal, probably methodical origin of this effect, not connected with EAS. The similar explanation is proposed by authors themselves [9].

2.2 The concentration of the effect in the region near the EAS core

If the distortions of the neutron temporal distribution are due to the saturation of the counting rate this effect should be observed in the region with the highest density of neutrons, i.e. near the EAS core. Indeed distortions are observed only in one module of the neutron monitor closest to the EAS core. Remarkable is a very high counting rate in this module. The distortion starts to be seen at the recorded multiplicity (in 0 - 3400 ns interval) of $M \approx 630-1000$. The measured efficiency of the monitor is 5-6% [8], so that the total number of neutrons produced in the module is $N \approx (1 - 2) \cdot 10^4$. This number is produced by EAS of an approximately PeV energy. For showers in which the counting rate achieves the saturation level at the end of the measurement interval, i.e. at 3400 ns, the produced number of neutrons can be higher by the factor of 2000 (!). Similar estimates have been made in [9].

It will be shown later that the spatial distribution of neutrons associated with a shower is rather wide. The high concentration of the observed neutron density around the EAS core indicates that these neutrons are mostly of secondary origin, i.e. produced inside the neutron monitor and do not arrive from outside.

In order to understand the phenomenon we have made calculations. In contrast with [17] where we used an analytical approach, we have made here more adequate Monte Carlo simulations. Even with the Monte Carlo approach it is complicated to reproduce precisely the conditions of the experiment [8]. Just to get an estimate of the phenomenon we simulated showers from 1 PeV primary protons with the vertical incidence upon the atmosphere observed at the Tien-Shan altitude of 3340 m a.s.l. (687 g cm$^{-2}$). We used CORSIKA6500 code [18] with QGSJET-II high energy interaction model [19] and Gheisha 2002d for low energy interactions below 80 GeV [20]. NKG version has been used for the electromagnetic component, energy thresholds were taken as minimum recommended by [18], i.e. 0.05, 0.05, 0.001 and 0.001 GeV for hadrons, muons, electrons and photons respectively. We determined characteristics of particles both for the total shower and for those which hit the
monitor of $3 \times 2 m^2$ area at its center.

The lateral distribution of neutrons compared with that of main other hadron components - protons and pions, is shown in Figure 1a and the relevant total number of particles - in Table 1. The energy spectrum of neutrons in the whole shower and those which hit the monitor is shown in Figure 1b. I underline again that these neutrons and hadrons are shower neutrons and hadrons, which are produced in the air, but not in the monitor or in the ground.

Figure 1: Characteristics of hadrons in EAS from 1 PeV primary proton incident vertically on the level of 3340 m a.s.l.: (a) Lateral distribution of protons, neutrons and pions with energies above 50 MeV; (b) Energy spectrum of neutrons in the total shower and of those hitting the neutron monitor of $3 \times 2 m^2$ area.

Remarkable is that the neutron component is the most abundant among all nuclear-active particles. The total number of neutrons above 50 MeV in such showers is about 2000, while protons amount as much as 750 and pions 600. The energy spectrum presented in Figure 1b, shows that the bulk of neutrons are low energy neutrons. Their differential energy spectrum is of $E^{-2}$ type, but it continues up to a few tens of TeV (!) This spectrum shape gives a possibility that if the energy threshold of 50 MeV could be reduced to, say, 1 MeV, the total number of neutrons will be substantially higher. However these low energy neutrons populate mostly the periphery of the shower at distances up to kilometers from the axis. As it is seen from the Table 1 in the EAS core $\sim$1.6% of all hadrons including neutrons carry $\sim$50% of the whole energy of hadrons in the shower. Since most of neutrons recorded by the monitor have the thermal energy of 0.02 eV even such a huge total number of them as $(1 - 2) \cdot 10^4$ carry the total energy no more than 0.2-0.4 KeV, which is incomparably small with $\sim$40 TeV provided by EAS hadrons in the core and should not create ‘the energy crisis’ during their cascading with the subsequent
production and thermalization of neutrons. Simulations of neutrons in EAS have been also made in [21].

As it can be seen from Table 1, if such a shower hits the neutron monitor at the centre of one of its module with $3 \times 2 m^2$ area the mean number of hadrons inside this module is about 55 and their total energy is about 40 TeV. The lead in the monitor is a neutron rich element and it is poor absorber of fast neutrons. Interactions of hadrons with lead are followed by emission of recoil and evaporation neutrons with their subsequent moderation and thermalization inside the polyethylene reflector. This process leads to an accumulation of multiple neutrons inside the monitor. If to take the results of calibration for this neutron monitor connecting the hadron energy $E_h$ and the multiplicity of produced neutrons $N$ as $N = 35 \cdot E_h^{0.5}$ with $E_h$ in GeV [6], then 40 TeV of hadron energy, which hit the monitor, give $0.7 \cdot 10^4$ neutrons. This estimate is in good agreement with an estimate for the number of neutrons $\sim (1-2) \cdot 10^4$ created inside the monitor by EAS of PeV energy for which the saturation of the counting rate has just started to be seen.

|     | total in EAS | monitor at $R=0$ | monitor at $R=4m$ |
|-----|--------------|------------------|------------------|
| $N_h$ | 3445         | 55               | 9.3              |
| $E_h$, GeV | 72610       | 37680            | 823.5            |
| $N_n$ | 1994         | 2.1              | 0.6              |
| $E_n$, GeV | 3389        | 1115             | 25.1             |

Table 1. The number and the energy content of hadrons with the energy above 50 MeV in the EAS from the 1 PeV primary proton incident vertically on the observation level of 3340 m a.s.l.. $N_h$, $E_h$ and $N_n$, $E_n$ are the number and the energy in GeV for all hadrons and neutrons respectively for the whole shower and for those hitting the neutron monitor of $3 \times 2 m^2$ area located at the EAS axis or 4m apart.

Table 1 demonstrates also the strong concentration of energy in the core region: if the monitor is at 4m from the shower axis the energy of hadrons and neutrons hitting it decreases by the factor of 40.

These estimates show that the numerous neutrons which are detected in the neutron monitor after the passage of EAS are not the EAS neutrons which are produced in the air and follow the main shower disk with delays no longer than a few $\mu s$, but neutrons produced in the lead inside the monitor during the process of inelastic scattering of high energy EAS hadrons with their subsequent attenuation and thermalization within a polyethylene moderator and reflector which is a relatively long process lasting hundreds of $\mu s$.

### 2.3 Delayed $\gamma$-quanta

As for the existence of gamma-quanta delayed by hundreds $\mu s$ their intrinsic connection and an origin from neutron induced reactions seem to be apparent. The authors of [8, 16] notice themselves the similarity of gamma-quanta temporal distribution with that of neutrons. The rapid rise of their integral number with the neutron
multiplicity $M$ at $M > 630$, mentioned in [8], is most likely not due to the real fast rise, but on the opposite - with a slower rise of recorded $M$ compared with the rise of the true corrected multiplicity $N$ due to the saturation effect mentioned above. The small counting rate at the beginning of the measurement time interval and its maximum at about hundred $\mu s$, observed at large $M$ is most likely connected with the long recovery time of gas counters after a passage of high fluxes of particles in large EAS.

Therefore the gamma quanta delayed by hundreds of $\mu s$ do not evidence for the new processes in the development of EAS in PeV energy region. The bulk of them have a local origin from neutrons created inside the neutron monitor.

### 2.4 The flat spectrum of the 'true' neutron multiplicity

In [16] it is argued that the spectrum of the 'true' neutron multiplicity $N$ derived from the observed multiplicity $M$ by correcting it for the saturation effect is too flat to be explained by this methodical reason. Fitted by the power law it has the shape of $dI/dN \sim N^{-2}$ above $M \approx 1000$, which contradicts to the expected shape $\sim N^{-3}$ at energies above the knee. I think that on the contrary this observation supports the assumption that the distortion of the temporal distribution is due to the saturation of the counting rate.

Indeed in the case of a saturation the observed and the 'true' neutron multiplicity are connected as [22]

$$M = \frac{N}{1 + N \frac{\tau}{T}}$$  \hspace{1cm} (1)

where $\tau$ is the dead time and $T$ is the collection time during which neutrons are recorded. The differentiation of the equation (1) gives $dM = \frac{dN}{(1 + N \frac{\tau}{T})^2}$ and if $dI/dM \sim M^{-\gamma}$ then

$$\frac{dI}{dN}(N) = \frac{dI}{dM}(N) \frac{dM}{dN}(N) = \left( \frac{N}{1 + N \frac{\tau}{T}} \right)^{-\gamma} (1 + N \frac{\tau}{T})^{-2} = N^{-\gamma} (1 + N \frac{\tau}{T})^{-2} \quad (2)$$

At large $N$ when $N \frac{\tau}{T} >> 1$ $dI/dN \sim N^{-2}$ for any slope of $\gamma$.

Incidentally $N$ exceeds $M$ by the factor of 2 at $M \sim 600 - 1000$ which confirms the validity of the expression (1) for $\tau = 2 \mu s$ and $T = 3400 \mu s$, which connects $M$ and $N$ with an account for the saturation effect.

### 2.5 Pre-conclusion I

The presented analysis shows that our interpretation of the phenomenon of 'neutron thunder', based on the analysis of the experiment [8] and on our own simulations and quantitative estimates is identical to the interpretation [14, 15] based on their own experimental data. The neutrons which are observed in EAS with hundreds of $\mu s$ delay after the main shower front are not the result of a new physics, indicating
the production of a new EAS component in the air and the change in the EAS spatial and temporal development, but is a local phenomenon, which appears as a result of the EAS interaction with the stuff of detectors and their environment.

1. The distortion of the temporal distribution is caused by the saturation of the counting rate at high neutron fluxes due to the finite time resolution of counters.
2. The observed threshold of the effect is right at the energy when this saturation is achieved.
3. The concentration of the effect in the region of the EAS core is due to the steep lateral distribution of EAS hadrons and their energy.
4. The delayed gamma-quanta have the secondary origin produced by delayed neutrons.
5. The flat spectrum of 'true' neutron multiplicities is also explained by the saturation of the counting rate.

This interpretation does not understate the importance of the real discovery of the effect made by Chubenko A.P. with his colleagues. If the presented interpretation is true, the scenario of 'the neutron thunder' complements our knowledge of the EAS development and its interaction with the ground, surface detectors and their environment. Once again like in the case of the transition effect, when some part of invisible gamma-quanta is converted into electrons or electron-positron pairs in the thick scintillators or in thick water cherenkov detectors this effect indicates that our records depend on our detectors. Within this scenario another problem appears - the production and propagation of neutrons created when the EAS core hits the ground. Due to their long propagation length \cite{23} these neutrons can give observable effects both at shallow depths underground in particular at mountain altitudes where the EAS cores are more energetic, and as albedo neutrons - in surface detectors. There might be plenty of other interesting effects worth of the experimental and theoretical study.

3 The EeV energy range

3.1 The role of neutrons at large EAS core distances

In the light of the possible contribution of neutrons to the signal in water and ice cherenkov detectors used in many experiments, viz. Pierre Auger Observatory (PAO), MILAGRO, NEVOD, Ice-Top and others, we have made simulations of EAS in EeV energy range similar to those made at PeV energies. The interaction model is the same QGSJET-II, but the observation level is that of PAO, i.e. 1400 m a.s.l.. The primary proton has 1 EeV energy, the electromagnetic component has been simulated using EGS4 option with the thinning level of $10^{-5}$.

The lateral distribution of electromagnetic component ($e^+ + e^- + \gamma$), muons ($\mu^+ + \mu^-$) and neutrons is shown in Figure 2. The gamma-quanta are included into the graph since the water tanks of PAO are thick enough to absorb them and to get their contribution to the signal. Both distributions of particles number and of
particles energy are shown. The separation of PAO water tanks is 1.5 km. It is seen that if neutrons are absorbed in the water and their energy is transformed into the visible light they could contribute up to 10% to the signal at such large distances.

Correlation plots of different lateral, angular, temporal and energy characteristics of EAS neutrons are shown in Figure 3.

Figure 2: Lateral distribution of particle numbers (a) and the particles energy (b) for 1 EeV primary proton incident vertically at the level of 1400 m a.s.l. It is seen that neutrons could contribute up to 10% to the signal of water tanks at 1km distance from the shower axis, if among products of their interaction with water are relativistic electrons.

It should be remarked that neutrons at large distances from the EAS core have mostly an energy below a few GeV and a very wide, nearly isotropic angular distribution. Their delays with respect to shower front spread up to tens of $\mu$s. Interestingly, neutrons create two distinct groups with energies above and below $\sim 10^2$GeV, seen clearly in Figure 3d. Apparently such separation is the consequence of different production mechanisms: neutrons above $10^2$GeV are produced as secondaries in high energy hadron collisions, lower energy neutrons appear mostly in knock-on processes. It is neutrons of the first group which together with other hadrons carry the bulk of hadron energy in the EAS core, create $\gamma$- and hadron families in X-ray films and ensure the subsequent multiplication process in the neutron monitor. The neutrons of the second group diffuse with non-relativistic speed and a wide angular distribution to the periphery of the shower where they can give delayed ‘sub-luminal’ pulses in the scintillators.

The temporal distribution of the particle number for electromagnetic, muon and neutron component at distances $R<10$m, 100 and 1000 m from the core are shown in Figure 4. It is seen that after $5\mu$s at the core distance of 1km neutrons are the
Figure 3: Correlation plots between different characteristics of EAS neutrons: (a) zenith angle $\theta$ vs. core distance $R$; (b) arrival time delay $T$ vs. core distance $R$; (c) energy of neutrons $E$ vs. core distance $R$ and (d) arrival time delay $T$ vs. energy of neutrons $E$. Interesting is the distinction of two groups of neutrons by their energy seen in the last plot.

dominant component of the shower. If they could produce relativistic electrons in the process of moderation and thermalization in water (viz. an excitation of oxygen nuclei with the subsequent emission of $\gamma$-quanta or $n + p \rightarrow d + \gamma$ reaction) they could contribute to the signal and should be taken into account in the conversion of $S(1000)$ - the characteristics used by PAO for the energy estimate, into the primary energy. The experiments on the sensitivity of water detectors to neutrons are now discussed.

3.2 Pre-conclusion II

Simulations show that low energy EAS neutrons propagate far from the shower axis and they constitute the component which has relatively long delays of their arrival time. At core distances approaching 1km and at about 5$\mu$s after the passage of the main shower front these neutrons dominate among other particles. These distances and times are typical for the detectors of Pierre Auger Observatory and principally neutrons could contribute up to 10% to the water tank signals. However, neutrons are neutral particles and at these distances they are non-relativistic, therefore they cannot emit cherenkov light directly. Only if in the process of their moderation and thermalization in water they create relativistic electrons and $\gamma$-quanta, they can be detected. The experiment at Tien-Shan showed that neutrons create such gamma-quanta in the surroundings of the neutron monitor §. As for water tanks such a
possibility has to be checked experimentally.

4 Conclusion

Since the EAS discovery in thirties all the subsequent studies manifested the concept that the EAS is a complex multicomponent phenomenon. So far different detectors observe and study different EAS components: Geiger counters - charged particles, mostly electrons, thick scintillators are sensitive also to some part of gamma-quanta, gamma-telescopes - cherenkov light, ionization calorimeters - an electromagnetic and hadron component and X-rays - highest energy part of these components. Neutrons are neutral particles and so far they were not studied separately from all other hadrons. It is a merit of Chubenko A.P. and his colleagues who applied neutron monitors for the detailed study of the neutron component of EAS. The neutron monitor is the detector which includes the moderator and the reflector - the hydrogen containing materials, which increase the sensitivity of the device to neutrons. Chubenko A.P. et al. discovered the 'neutron thunder' - neutrons delayed up to $ms$ after the passage of the main shower front. Although according to our interpretation the bulk of the observed neutrons have a secondary origin, i.e. they are produced and delayed inside the monitor, the existence of the neutrons produced by EAS in air and accompanying the main shower front is now without any doubt. The true 'neutron thunder' associated only with EAS is not so long as that observed inside the

![Diagram of arrival time distribution of electromagnetic, muon and neutron component of the shower at core distances less than 10m (a), 100m (b) and 1000m (c). It is seen that at 1000m from the core neutrons dominate among other particles after 5µs.](image)
monitor - the simulations show that it can last up to hundred ns. However neutrons of EAS can definitely cause the same effects in the environment, in the ground and in the detectors as they make in the neutron monitor, like an 'echo effect', which lasts up to hundreds of µs.

It is particularly true for the studies at the mountain level where EAS cores are more energetic than at sea level and a good part of the year the ground is covered by snow (Tien-Shan, Aragats, Chacaltaya, South Pole) sometimes a few meters thick. As for the Tien-Shan station there might be an additional factor emphasizing the role of neutrons - its ground is a permafrost with a good fraction of ice inside.

As for the detector sensitivity to neutrons, water and ice tanks are particularly worth of attention. First of all water is not just an absorber, but also a moderator. Secondly, although the neutrons as neutral and mostly non-relativistic particles cannot produce cherenkov light directly, the study [8] showed that they produce gamma-quanta and electrons, which can be eventually detected by water tanks due to their emission of cherenkov light. Since water and ice filled detectors are widespread all over the world and in particular used in the Pierre Auger Observatory, the contribution of neutrons to their signals at large distances from the EAS core and at large delays from the trigger moment, can be substantial. It should be analysed and taken into account if necessary. The same remarks could be referred to hydrogen containing plastic scintillators used in many other large EAS arrays (Yakutsk, Telescope Array etc.). As has been mentioned above, signals delayed by µs (‘subluminal pulses’) have been already observed in large scintillator arrays, such as Volcano Ranch [3][4].

Presumably the effect of 'the neutron thunder' can be applied in practice for the neutron carotage of the upper layers of the ground. Instead of the artificial neutron source in this method the ordinary EAS can be used since EAS cores carry on and produce a lot of secondary neutrons. Also 'the neutron thunder' can be used for the search of water on the Moon or on the surface of other planets, like it is being made with Mars Odyssey mission [24][25].

In any case the phenomenon of 'neutron thunder' complements our knowledge of the EAS development and it is certainly worth of further experimental and theoretical analysis.

Acknowledgments

The author thanks the INFN, sez. di Napoli and di Catania, personally Professors M.Ambrosio and A.Insolia for providing the financial support for this work and their hospitality. I also thank Martirosov R., Petrukhin A., Ryazhskaya O.G., Stenkin Yu.V., Szabelski J., Ter-Antonian S., Tsarev V.A., Vankov Kh., Watson A. and Yodh G. for useful discussions and references.

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