Atmospheric hadronic shower characteristics derived from observation of a multiplicity in neutron monitors

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Abstract: In this paper we present results of multiplicity studying on a neutron monitor. It was found that 1) large multiplicities (M > 10) can’t be produced by one particle inside NM and 2) a large multiplicity is composed of two particle populations. The first population consists of evaporation neutrons emitted by excited lead nuclei within NM. The second population is particles of ‘local atmospheric hadronic shower’ falling to NM. Cross-section of a shower and longitudinal size were derived.

Keywords: hadronic showers, EAS, multiplicity.

1 Introduction

There have been installed an advanced data acquisition system on neutron monitors (NMs) in Apatity, Barentsburg, Baksan and Moscow. The system registers each NM pulse: which tube produced the pulse and how many microseconds elapsed since the previous pulse. Thus it has been recorded information about fast and transient events into NM. After the installation of this collection system for NM, the opportunity to examine individual neutron cascades (showers) arising in the atmosphere above the HM and in the monitor itself has offered. Such cascades of neutrons generate on NM neutron multiplicity phenomenon with numbers M, which represents a series (cluster) of the M pulses, separated by small intervals. The possibilities of our collection system and results, derived with its help, were presented in some our works, for example [1,2]. In these works, the algorithm of detection and searching of multiplicity events M in the data stream has described. In [3] the following quantities: the spectrum of multiplicity J(M) ∼ M−4 (i.e., the frequency of event occurrence) and the average multiplicity event length D(M) ∼ M1/2, depending on the number of multiplicity M has defined. In the same work probability estimates of accidental events of multiplicity, which turned out to be negligible, has carried out.

The NM feature would be noted: one electrical pulse of the detector is corresponds to one registered neutron. When a free neutron is registered, it is absorbed causing an electrical pulse in the tube.

Observations of multiplicity have been held for a long time, however, neither previous system did not provide a detailed record (saving the entire data about the channel number of pulse, and the time intervals between the previous one) of all events. Availability of detailed and huge database of multiplicity events provide to find out a characteristic processes related to the origin, development and decay of multiplicity. It was shown [3] that the multiplicity events with M ≥ 10 only occur from neutron cascades generated in the atmosphere over NM. These cascades are known as local air hadronic showers (LAHS). They are produced by high-energy cosmic ray particles. Events M from the LAHS are distinguished by the presence of two phases (body and tail phases), very different to each other. At the initial (or body) phase the neutron flux density is kept constant. At the final (or tail) phase it steeply decreases. Features of these phases, as well as the events themselves M ≥ 10 is not much different for different stations as Barentsburg (Spitzbergen), Moscow and Baksan (Northern Caucasus).

2 Evaluation of transverse dimensions of local atmospheric hadronic shower

Barentsburg NM has a design feature that helps to better understand and explore the multiplicity. The fact that a standard NM (18-HM-64) in Barentsburg consists of three sections 6-HM-64 arranged in a row with the spacing between adjacent sections is about 5 m. In addition, each section consists of two subsections with three counters, i.e. 3-NM-64. These subsections are arranged as shown in Figure 1a. Subsections contact each other only by one verge. Such design of the neutron monitor (with the division on sections and subsections) provides a “neutron” independence of each unit. In other words, the neutrons are born from nuclear interactions in one subsection, have no chances to pass to the other subsection and be registered there. First, it follows from geometrical considerations: the solid angle subtended by adjacent subsection is small. Therefore the probability of the neutrons leaving one subsection and getting into other is low. Second, secondary neutrons born in lead have an energy of no more than 20-30 MeV [4] and the outer polyethylene layer effectively reflects such neutrons. Hence, the appearance of multiplicity events simultaneously in two subsections of one section clearly points to a common external source of neutrons. Note that NM is sensitive to neutrons with energies above 50 MeV [4]. At ground level, the main source of such neutrons is the cosmic rays. In this paper, an additional study based on the design features of the minorities is conducted.

At the beginning we study the distribution of events in different channels. The internal layout of the section is shown in Figure 1a. Secondary neutrons from one subsection can’t get into the other. Consequently by the nature of the channel numbers distribution in events M we can conclude about the size of local showers. Note that since the start of the new collection system in Barentsburg in 2006 a large database of events was accumulated. Now we can study the channel numbers distribution up to values of M = 50 with good statistical accuracy.
To do this from all given \( M \) events those were selected which started with a fixed channel number \( K \). In these selected events the total number of counted pulses from each channel has been counted. On Figure 1 the result of the channel numbers distribution with the condition that the events beginning at the channel \( K = 2 \) (the first sub-section) is shows. Channels multiplicity distributions \( M = 10, 20, 25 \) and 30 are normalized to 1. If the event \( (M = 10 \) and 20) started in the first subsection, then all others impulses, that formed the event, are likely to be of the same subsection. In our case it is channels number 1, 2 and 3. A small (less than 0.05) “tail” in channels distribution extending at \( K = 4 - 6 \) to the second subsection, corresponds to the case when both subsection covered a shower, i.e. it falls at their edges, as it is shown in Figure 1. At a value \( M = 25 \) the distribution significantly is flat, however, still remains the prevalence of the subsection, in which the event started. With \( M = 30 \) and more distribution becomes flat along the section. In the Figure 1 schematically shows the location of the LAHS and its transverse dimensions to affect both subsections in founded proportion. The numbers 0.1, 0.2, 0.6, and 1.0 above schematic view of sections are correspond to the approximate proportions of the number of channels from the second to the first subsection. Figure 1 shows the size (diameter) of showers for these values of \( M \), which could provide the observed ratio. They are \( \sim 0.5m \) for \( M = 10 \), \( \sim 1.5m \) for \( M = 20 \), \( \sim 2.5m \) for \( M = 25 \) and \( \sim 5m \) for \( M = 30 \).

Channel distribution of the multiplicity in the current design NM section in Barentsburg confirms the earlier conclusion made by [1, 3] that the observed events with \( M \geq 10 \) are produced not a single energetic particles inside the lead (neutron multiplication process is described in [4]) but local atmospheric hadron shower occurring in the atmosphere over NM. However, the transverse sizes of these LAHS are less than hadron cores of extensive atmospheric showers (EAS) [6]. We assume that the small size of the showers are due to the fact that they are produced by primary cosmic ray particles with energies less than the EAS threshold. At the same time, as we can see in Figure 1, with the increase \( M \) the transverse size of the hadron shower is increasing, so that when \( (M > 30) \), it corresponds to the EAS hadron showers. Such studies have been carried out in [7].

3 The longitudinal size of the local air showers

Figure 2 shows the average time profiles and the average duration of multiplicity events. In [3] it was shown that the time profiles of the multiplicities in \((M > 10)\) are composed of two parts: body and tail. The body part is characterized by average time interval constancy between pulses, which is not more than 50\(\mu s\). In the second tail part the intervals between pulses increases monotonically toward the end of the event. It can be observed in Figure 2. It just indicates the presence of two different processes operating in NM during multiplicity. The arguments given above are based on measurements on the distribution channels for high multiplicity events. Such events are only produced by LAHS in the atmosphere over NM. In this case, the length of body phase is determined by the difference in arrival time of neutrons with different energies on NM. High-energy neutrons (\(\sim 1\)GeV and higher) with a velocity close to the light speed reach the NM first. Then a lower energy neutron down to NM threshold energy is arrived.

In [3] there is evidence that the tail phase in all \( M > 10 \) has the same temporal profile and the equal time length. Therefore, to calculate the space length of body phase \( L_{BM} \) of multiplicity \( M \), one needs deduct its total duration \( T_M \) and total time length of \( M = 10 \) \( (T_{10}) \). At Figure 2, \( T_{70} \approx 2500\mu s \), \( T_{10} \approx 900\mu s \), respectively, \( T_{70} \approx 1600\mu s \). It is known [4] that the lower energy sensitivity threshold NM is about 50MeV. Neutrons with such energy have a speed \( V_N \approx 0.05\cdot c \). Such neutrons will pass for the time \( T_{BM} \) the distance \( L_M \)

\[
L_M = V_N \cdot T_{BM} \tag{1}
\]

By substituting the values we get \( L_{70} \approx 22km \). This is the average altitude at which the interaction of primary cosmic rays in the Earth’s atmosphere is usually occurred [4, 5]. It may be noted that the dependence of the average duration of multiplicity events reaches a constant value about 2500\(\mu s \) (Figure 2). It will be quite clear when we take into account that 22 – 25km higher the interaction of cosmic rays with the atmosphere does not occur. Events with lower values of \( M \) can be produced either from showers in the atmosphere depth or from showers at 22-25 km, which include only the high-energy neutrons. The second condition is artificial: it is hard to imagine that in a cascade of nuclear reactions in
the atmosphere only high-energy neutrons were produced. Consequently, the first is true.

The overall picture is as follows. At moderate values of $M$ ($\approx 20$) place of LAHS origin is in the atmosphere depth at altitudes of several kilometers from the Earth surface. By increasing $M$ the altitude of shower starting places rises and with $M \approx 60 - 70$ it reaches a altitude limit by $20 - 22$km. On Figure 2, there is a clear trend to the fact that the average length of $M$ has reached a plateau. Our proposed explanation of the plateau is the most simple and natural. On Barentsburg station, located at sea level, the events of $M > 70$ are so rare that it’s not possible to determine with reasonable accuracy the average duration of events.

4 Two sections multiplicity on the NM

The new collection system allows revealing and investigating pulse appearance events (neutrons) in two different sections with an accuracy of $1\mu$s. We are selected sections 1 and 3, which are spaced by a distance about 15m (see Figure 2). First of all, let us determine the events, which should be looked for. On the basis of the algorithm, described previously in [11], we set a new one of finding two sections multiplicity (TSM):

1. Before any multiplicity event should be an interval of at least $T_{pau} = 5$ms.
2. The interval between pulses in the TSM should not exceed the value of $T_0 = 500\mu$s.
3. TSM event comes when each section put into event at least $N_0$ pulses. The sequence of pulses from each section is not limited.

The conditions 1 and 2 and their parameters values are exactly the one of the multiplicity detection algorithm in [13]. Condition 3 just is set the requirement for a TSM event. The value of $N_0$ in a series of studies was taken in range from 4 to 7; the results dont depend on $N_0$. The condition 3 is similar to one of the multiplicity events accompanying extensive atmospheric showers at the Baksan neutron monitor [7].

Probability calculation of multiplicity event $M$ by random coincidence background pulses was given in [1]. At the real count rate NM we found that the probability of the random coincidence of 5 pulses sequence (false event $M = 5$) within the range $T_3 = 700\mu$s (this is the average duration of the event $M = 5$) is about $5 \times 10^{-9}$. During the day such events would happen approximately $q = 0.05$, or one false event per 20 days. Actual events $M = 5$ per day on NM is $J(5) = 10^4$. Therefore, if we accept the condition 3 with a value of $N_0 = 5$, it needs to find the probability $p_5$, meaning that a real event $M = 5$ in one section overlaps the false event in another section. From the simple considerations it follows:

$$p_5 = \frac{3 \cdot I_5 \cdot J(5)}{S} \cdot q$$

where $S = 86400$ is the number of seconds in day. Numerically $p_5 = 1.2 \cdot 10^{-9}$. This is the probability that a false TSM occurs in day. The factor 3 in front of $I_5$ means that we take the worst case: a true event in one section and a false in another do not overlap and fit together, so that the total duration may be up to three event duration $M = 5$. Of course, this is not an exact calculation of the probability of false events TSM, because true event $M > 5$ in one section may be superimposed on a false event to another. But as the spectrum of multiplicities $J(M)$ is decreasing function with a power law with exponent $-4$ [1], the big $M$ events should provide only a small correction to the calculated probability.

According to the mentioned algorithm, NM data were processed with value $N_0 = 4 - 7$. When $N_0 = 4$ the minimum multiplicity $M = 8$. When $N_0 = 7$ multiplicity is 14. For each value of $N_0$ database containing TSM from the minimum value to $M = 70$ has been accumulated. However, when $M = 50$ the number of such events is not large, and they are not considered in the work. Number of TSM with $M = 8$ is $10 \times 15$ per day, which is many orders larger than the number of random coincidence. On the basis of the database, the average profile and the average duration of TSM event of each $M$ value were determined. It was made like single section multiplicity procedure [1][13]. The results are shown in Figure 2. Averag time profiles of TSM events

Figure 2: a) Time profiles of multiplicity events $M$ in Barentsburg station. Time profile means interval duration dependence on its place in multiplicity. One can easy see two phases in any $M$. Body phase is flat, tail one is gradually increasing. b) Total duration of multiplicity events $M$ depend on number $M$. Red is Baksan, blue is Barentzburg, green is Moscow. At $M \geq 70$ the duration has plateau.
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Figure 3: a) View on the Barentsburg station. Each section is in a different van. b) Common scheme of the EAS hadronic core, covering the NM sections.

Figure 4: Average time profiles of TSM events with \( M = 20 \) and \( 40 \). At comparison there is the time profile of single section multiplicity event \( M = 40 \) (black line). In the shown profiles two same phases (body and tail) are present.

do not differ from the same single section profiles. Time profile of the event \( M \) is an important characteristic because it was found that the intervals in the events of \( M \) are not accidental [1, 3]. The profile identity confirms that the TSM is a typical multiplicity event too. The form of average duration dependence doesn’t significantly differ from the same dependence on single section.

Figure 5 schematically shows TSM event in HM. It is necessary that the two sections have been covered by the hadron shower with a transverse dimension not less than \( \sim 15 \) m. These dimensions are specific for a hadronic core of the extensive atmospheric showers (EAS) [6]. Thus, with the new collection system and specific NM design we have the opportunity to detect EAS hadronic core. The differences of some parameters are from the cause that even the TSM with small \( M \) values are events with huge numbers of neutrons. Due to small section size NM intercepts a little fraction of the total number of neutrons presenting in the trunk of the EAS.

5 Conclusions

This paper presents the studies to determine the size of the local atmospheric hadron showers, causing multiplicity events in NM. Specific design features (modularity) of Barentsburg NM has been used. It was found that the shower size is grows with the multiplicity number \( M \) and approximately have the following values: cross-section \( 0.3 - 0.5 \) m in the events \( M = 10 \), 1.5 m in \( M = 20 \), 2.5 m in \( M = 25 \) and 5 m in \( M = 30 \) or more. Lengthwise dimensions of showers also increase with increasing \( M \), reaching at \( M \sim 70 \) values of about 22 km. At this height the interaction of cosmic rays with the Earth’s atmosphere is occurred. The phenomenon of two section multiplicity on NM has been studied too. The probability estimations of random realization of TSM have been made. At \( M = 8 \) the number of random events is less than \( 10^{-5} \) per day. Real number of such events is \( 10 - 15 \) per day. The time profiles of TSM are identical to those for a single section. However TSM with the distance between the sections exceeding 10m is required hadron shower with a size of 15 meters or more. Such cross-section is typical for EAS hadronic core.

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References