EAS hadronic component detection by neutron monitors

YU. V. BALABIN\textsuperscript{1}, E. V. VASHENYUK\textsuperscript{1}, D. D. DZHAPPUEV\textsuperscript{2}

\textsuperscript{1}Polar geophysical institute, Apatity, Russia
\textsuperscript{2}Baksan Neutrino Observatory, Neutrino, Kabardino-Balkaria, Russia

balabina@pgia.ru

Abstract: A hadron component of EAS has been studied with the installation joining the neutron monitor (NM) and the EAS array “Carpet” at the Baksan Neutrino Observatory, North Caucasus. The NM is equipped with a new advanced registration system, which enables recording not only pulses, but time intervals between them with accuracy as high as 1 mcs. The system registers also master pulses of “Carpet”, signaling about detection of EAS events. As the NM is located in immediate proximity from the “Carpet” (∼ 15 m) we can study the NM response on the hadrons accompanying an EAS. We also studied temporal distribution of pulses from the NM after a master pulse from the “Carpet” immediately and far from it. During 1 millisecond after the “Carpet” master pulse specific distribution of time intervals between NM pulses is found. It is real evidence that energetic hadron component of EAS on the ground level is detected by a NM. Spatial size of EAS hadron core was estimated. Multiplicity events on the NM after EAS have a specific structure. The same specific structure of multiplicities was found in Barentsburg NM data, which is equipped with advanced registration system too. A multiplicity spectrum after EAS was obtained.

Keywords: neutron monitor, neutron multiplicity, extensive atmospheric shower, multiplicity spectrum

1 Introduction

Two cosmic rays detectors, the “Carpet” and the NM have been connected at the Baksan neutrino observatory located in the Northern Caucasus at an altitude of 1700 m. Due to adaptability of a new high-speed data acquiring system, it has become possible to bind the master-pulse from the “Carpet”, which indicates the arrival of a EAS, to the NM pulses with an accuracy as fine as 1 mcs. A more detailed description of the data acquiring system is in [1]. It should be pointed out that the “Carpet” responds to the EAS electron-photon component, whereas the NM detects hadrons (protons, neutrons, pions) with energy $> 50$ MeV [2]. The “Carpet” and the NM are placed in a building, being about 15 m spaced. Owing to this combination of devices with high time precision we achieve unprecedented accuracy in studying the EAS hadron component.

2 EAS influence on the NM

The NM operated at the Baksan station, consists of 6 tubes (channels). In the recording system there is the additional seventh channel, which accepts the pulses from the “Carpet”. These pulses are generated at the moment an EAS produced by the primary particle whose threshold energy is over $6 \times 10^{12}$ eV falls down on the “Carpet”. Thus, there is an opportunity to study a hadron flux produced by an EAS, which is detected in the NM. The average count rate in channel 7 is $\sim 1$ sec$^{-1}$. In the course of the subsequent processing, it is possible not only to distinguish the pulses from an EAS, also to study the sequence of the NM-detected pulses following either immediately after the EAS, or some time later. An algorithm of data processing is as follows. As soon as an EAS pulse is detected, an operating time window $T_W$ is open. The NM pulses are counted and the pulse-to-pulse intervals occurring within this time window are recorded. Then in a period of time $T_P$ (pause time) the time window of the same duration $T_W$, is open again for reference counting. The preliminary data processing ($\sim 30 - 40$ days) found that the possible influence of an EAS on the NM is not above 1 ms. Based on it, it is assumed that $T_W = 1$ ms, $T_P = 25$ ms. The first and the most important stage in data processing is a searching of a distribution of time intervals between pulses (DBP). To determine DBP means to count the number of cases when the pulse-to-pulse intervals occurring within this time window are recorded. Then in a period of time $T_P$ (pause time) the time window of the same duration $T_W$, is open again for reference counting. The preliminary data processing ($\sim 30 - 40$ days) found that the possible influence of an EAS on the NM is not above 1 ms. Based on it, it is assumed that $T_W = 1$ ms, $T_P = 25$ ms. The first and the most important stage in data processing is a searching of a distribution of time intervals between pulses (DBP). To determine DBP means to count the number of cases when the pulse-to-pulse interval was equal to t mcs. The type of DBP indicates the information on the nature of the processes occurring in the NM [3]. Figure 1a shows the different DBPs. The full 2009-10 data set has been used. The choice of the value of $T_P$ was determined by the condition that in the NM there should be no neutrons from the previous EAS. An increase of the time window $T_W$ to over 1 ms gives no sound effect: the DBP immediately after the EAS arrival (operating DBP) and the reference DBP merge. It is quite clearly seen in Figure 1a.
The DBP presented in the Figure 1a is normalized for 100 days.

It is seen from the Figure 1a that the number of short intervals (to 200-300 mcs) recorded in operating window is several times as many as the number of such intervals in the reference window. However, with \( t \sim 1000 \) mcs, their number is becoming equal. One can see that the total time of an EAS influence on the NM does not exceed 1 ms. This value disagrees with that obtained in many works, for instance, in [4, 5]. The matter is that consideration is given to the different energy ranges. The NM detects hadrons of at least 50 MeV in energy, [4, 5] studied EAS thermal neutrons. So we see that EAS hadronic component has various duration in different energies.

It is quite real suggestion both the background NM count rate (from cosmic rays (CR)) and the during EAS events are incidental, obeying Poisson’s law:

\[
p_k(\Delta t) = \frac{N_0 \cdot \Delta t}{k!} \exp(-N_0 \cdot \Delta t) \quad (1)
\]

where \( \Delta t \) is the time interval, \( N_0 \) is an average number of pulses per time unit, \( k \) is a number of pulses, \( p_k(\Delta t) \) is the probability of getting exactly \( k \) pulses during the \( \Delta t \). An important feature of the Poisson distribution is that [3] if the probability of the pulse number is described by Eq. (1), the probability of the interval mean between pulses is given by an expression

\[
w(\Delta t) = N_0 \exp \left( -\frac{\Delta t}{\tau_0} \right) \quad (2)
\]

where \( w(\Delta t) \) is the probability to get an interval \( \Delta t \) between pulses, \( \tau_0 \) is a characteristic time \( \tau_0 = 1/N_0 \).

We called earlier this function as DBP. Poisson’s distributions also have another feature [3]: the sum of two Poisson’s processes with the average intensity \( N_1 \) and \( N_2 \) respectively, will be the Poisson’s distribution with intensity \( N_{\text{tot}} = N_1 + N_2 \) and characteristic time \( \tau_{\text{tot}} = 1/N_{\text{tot}} \).

Hence, the DBP function \( w_{\text{tot}}(\Delta t) \) for the sum of two processes will be described as (2) where \( \tau_{\text{tot}} = 1/N_{\text{tot}} \), rather than the sum of two exponentials with characteristic times \( \tau_1 = 1/N_1 \) and \( \tau_2 = 1/N_2 \). However, while the probability of two Poisson’s processes’ contributions to the total flow is different (for our case background cosmic ray flux is continuous, EAS influence to NM is occasional for a short time) in the DBP the true exponential dependences \( w_1(t) \) and \( w_2(t) \) will be observed separately, which correspond to the initial processes \( N_1 \) and \( N_2 \) and characteristic times \( \tau_1 = 1/N_1 \) and \( \tau_2 = 1/N_2 \). It is called the complicated sum. This is a very important feature of Poisson’s distribution. As Figure 1 shows the DBPs in a semi-log scale, the exponential curve is shown as a line. The DBP nonlinearity in the chosen scale indicates that process under study is the complicated sum of Poisson’s processes [3].

The reference DBP is calculated only on the background CR flows, whereas the operating DBP are the sum of the CR flows and the EAS proper (because while EAS was occurring, the background CR flow was occurring either).

Hence, it is possible to describe:

\[
w(\Delta t) = w_{\text{EAS}}(\Delta t) + w_{\text{CR}}(\Delta t) \quad (3)
\]

where \( w(t) \) is the function presenting the operating DBP, \( w_{\text{EAS}}(t) \) is the function of the DBP properly from EAS, \( w_{\text{CR}}(t) \) is the reference DBP. We see that the operating DBP is made of the sum of two functions presenting the EAS proper and the reference one. One can gives the \( w_{\text{EAS}}(t) \) as the difference between \( w(t) \) and \( w_{\text{CR}}(t) \). In Figure 1a, the difference is shown as a green line, marked as (3) and a deviation of the DBP from the linearity is clearly seen, which univocally evidences about the complicated sum of the Poisson’s processes taking part in the process caused by EAS proper. In Figure 1b DBP approximation is shown as the sum of two exponentials. The values of the characteristic times are \( \tau_1 = 45 \) and \( \tau_2 = 230 \) mcs.
and the approximating function is
\[ w_{\text{EAS}}(\Delta t) = A \cdot \exp(-\Delta t/\tau_1) + B \cdot \exp(-\Delta t/\tau_2) \] (4)

In Figure 1b the function (4) is shown and it agrees closely with experimental DBP and is lost on it.

3 Multiplicity structure

The papers [6, 7] have a detailed survey of all the multiplicity events detected in an NM in general. As for the present study, it deals with the multiplicities related to EAS only. It is well known that the multiplicity event (ME) is the number \( M \) of neutrons detected in the NM over a short period of time. Given below are the conditions for search and selection of multiplicity events.

- a) before a ME there should be a time interval of at least \( T_{\text{pau}} \), during which there are no pulses;
- b) the intervals between pulses following each other (after \( T_{\text{pau}} \)) should not exceed the value \( o \). Total number of pulses in such cluster is ME of \( M \). The total duration of the clusters depends on the number \( M \). The first interval of more than \( T_0 \) duration finalizes an event.
- c) it is necessary that during the multiplicity event the pulse from the “Carpet” be recorded.

Usually algorithm of multiplicity searching is realized by fixed duration of time window. All pulses, which come from NM during the time window, are ME. Our algorithm a)-c) is more suitable for multiplicity searching because it has not a fixed time window. Till a multiplicity lasts, nobody knows its duration. Our algorithm is adaptive to each ME. The condition c) is optional. If it omits one gets total ME on the NM.

In [7] optimal values to be used in search of MEs have been found: \( o = 500 \) and \( T_{\text{pau}} = 5000 \) mcs. The same values are used in the present study. In data processing, both the search of all MEs (without c)) and the MEs accompanied by EAS were used.

Amount of MEs up to \( M = 30 \) is enough for the DBP to be calculated with a small statistical error for any given \( M \). The procedure is simple. In all the events of the given \( M \), the number of intervals duration \( t \) mcs is counted. Figure 2c shows that the DBP is quite different from the exponential which was calculated for the Poisson’s process (2). The DBP for all ME can be fitted only by the sum of two exponentials, like in (4), with characteristic times \( \tau_3 \) and \( \tau_4 \). Its values some vary. A study has been carried out to determine in what particular part of ME the processes \( N_3 \) and \( N_4 \) occur. It has been found in [7] that time intervals in ME vary at the initial phase of events insignificantly, but closer to the end (final phase) of the events these steadily increase. Delimitation between initial and final phases is on around 8-9 pulses before end. Based on these results, we have calculated DBP for first 10 and for last 7 intervals separately. All three DBP for \( M = 25 \) are shown in Figure 2. The DBP based on the full set of events is a sum of exponentials with \( \tau_3 = 35 \) mcs and with \( \tau_4 = 165 \) mcs (Figure 2c), whereas the DBP based on the first 10 and the last 7 intervals consist of practically one exponential with each (Figure 2a, b) having characteristic times \( \tau_3 = 35 \) mcs and \( \tau_4 = 165 \) mcs respectively. This is the direct prove of the presence of two different processes: in one and the same ME with one of these forming the initial phase, the other - the final or relaxation phase. The similar result is also obtained with \( M < 15 \). However, while the DBP for the relaxation part preserves its linearity, the DBP for the initial part, as \( M \) decreases, increasingly gets the shape like in Figure 2c, i.e. loses its specificity. What’s more, it makes no difference whether the MEs-based DBP have been found immediately after the EAS arrival or based on the whole set of MEs. The property detected is specific for all MEs. It could be called the dual structure of ME. This structure points to different physics processes forming any large ME.

The obtained result confirms the assumption stated in [7], that large MEs consist of two phases - the initial and relaxation ones, which differ in value of characteristic time. The relaxation phase is composed of the last 8-9 pulses in a ME, and the initial phase is composed of the first (M-10) pulses. For the events with \( M \leq 10 \), to separate ME into phases is impossible. Besides, the calculated values of times \( \tau_3 \) and \( \tau_4 \) are close to characteristic times \( \tau_1 \) and \( \tau_2 \), respectively, which describe the DBP immediately after the EAS arrival (Figure 1b). The differences between time intervals are explained by the fact that \( \tau_3 \) and \( \tau_4 \) are calculated for a particular value \( M \) whereas the DBP immediately after the EAS arrival is based on all \( M \) possible.

As it was mentioned above and in [7], any large ME consists of two parts. Two component structure of ME is well distinguishable on Figure 3. There are initial and final parts. An initial part of ME are short, steady and less than 50 mcs (see Figure 3). A DBP of the initial part is described by a simple exponential function with small characteristic time. Average time intervals between pulses in a final part are more than 100 mcs and steeply increase to the end. A DBP of the final part is described by a simple exponential function too, but its characteristic time is large. The assumption of local hadronic shower explains all results. A lifetime of neutrons into NM is short [1]. They are accepted by tubes or leave NM. Average time intervals between pulses can be only steady in a case of external neutron source, which feeds a cloud of neutrons into NM. Local hadronic shower above NM could be such source. When the local shower exhausts relaxation process runs into NM: neutron density decreases, intervals between pulses increases steeply. In [6] a cross-section of local hadronic shower was estimated via distribution of NM channel into ME. The cross-section is around some meters.
Figure 2: Distribution of time intervals between pulses (DBP) is made for \( M = 25 \). a) the DBP of the 10 initial intervals of MEs only, characteristic time \( \tau_3 = 35 \) mcs; b) the DBP of the 7 last intervals of MEs only, characteristic time \( \tau_4 = 165 \) mcs; c) the total DBP (all intervals of MEs are used). Fitting functions are shown as a line: they are simple exponential function for a) and b), there is the sum of them for c). Arbitrary units are normalized on a total number of pulses.

Figure 3: Average time profile of multiplicity event \( M = 40 \). OX is pulse number into ME, OY - average interval between (K-1) and K pulses. From K = 2 up to K = 20 interval values are so stable and up to K = 30 ones are less than 50 mcs.

4 Conclusion

A study has been carried out into the distribution of NM pulses calculated immediately after the EAS master-pulse arrival. The similar distribution of the reference time intervals outside EAS influence zone have been compared. It has been found that the hadron component of EAS influences on a conventional NM for not over 1 ms after the EAS arrival. The calculation of the distribution of time intervals between pulses (DBP) (within 1 ms after the EAS arrival) has shown the presence of sequence of the NM pulses produced by high-energetic hadrons detected in the NM during the EAS influence. The average lifetime of the particles population inside the NM is 45 mcs.

The calculation of the DBP separately for the initial and final parts of the MEs shows that the MEs for \( M > 10 \) consist of two different processes having their own characteristic times, with there being no difference in whether the ME is accompanied by an EAS or not.

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