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Fine structure of neutron multiplicity on neutron monitors

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Abstract. Based on a huge data set acquired with a unique recording system, multiplicity events $M = 4 - 50$ on a neutron monitor have been analyzed in detail. The multiplicity events are recorded in detail for the first time, their structure being examined. The multiplicity processes in a neutron monitor have been numerically simulated by a toolkit GEANT4. Analysis of neutron monitor data with high temporal and spatial resolution reveals that most multiplicity events involving more than three adjacent counter tubes are due to local hadronic air showers with characteristic dimensions of size $1 - 3$ m and duration of ~ 1 ms.

1 Introduction

A neutron monitor (NM) is used to continuously record a neutron component of secondary cosmic rays. A conventional NM (like a 18-NM-64 type) consists of 18 tubes SNM-15 (it is analog of a BP-28 tube) filled with $B^{10}F_3$. A polyethylene layer and a lead one surround each tube as shown in Fig. 1. An additional outer polyethylene layer surrounds the NM-unit too. The outer polyethylene layer reflects back neutrons produced inside the NM. Lead is a producer of neutrons and at the same time it protects tubes from gamma-radiation and electrons. The inner polyethylene layer moderates neutrons. With SNM-15 being sensitive only to thermal neutrons, it is necessary to moderate energetic neutrons. When a neutron is captured by a B^{10}, the reaction $B^{10}(n,\alpha)Li^7$ takes place. As a result of this reaction some energy (~ 2.5 MeV) (Dorman, 1975) releases and then is fully spent for gas ionization inside a tube. Thus, having been recorded, a neutron disappears, with one pulse corresponding to one neutron. In this case, there are various neutron interactions in the NM. (It should be noted that these interactions mainly occur in lead because of its thickness (of $\sim 58\,\mathrm{g\,cm^{-2}}$), which is by an order of magnitude greater than the two polyethylene layers.

1) Passing through polyethylene and lead layers, a neutron undergoes only elastic interactions, becoming less energetic. If its energy has sufficiently decreased when it gets into a tube, it will be recorded as a single pulse.

2) As a result of non-elastic interaction with neutron, the lead nucleus becomes excited. The excitement is eliminated by some neutrons emission. These are referred to as evaporating neutrons. Their life-time is: $\tau_{ev} = 370\,\mu s$ (Dorman, 1975).

3) Getting into the lead nucleus, a high-energy neutron can split it. Alongside with nucleus fragmentation, several neutrons, called instantaneous, are being emitted. The average detection time of such neutrons is $\tau_f = 130\,\mu s$ (Dorman, 1975). The scheme of Process 3 is shown in Fig. 1.

Neutrons produced in Processes 2 and 3, are called multiple (Dorman, 1975). Having lost some energy in lead and in the inner polyethylene layer, neutrons can be detected by tubes, giving a cluster of pulses spaced by small time intervals. The number of neutrons produced in Processes 2 and 3, depends on the energy of the primary nucleon coming on NM. It has been assumed that there are no other sources of multiplicity in the NM. Well, the multiplicity event (ME) number M is a cluster of M pulses spaced by short intervals.

Earlier there were systems developed to detect MEs. These systems were based on a certain circuit, with which a continuous flux of pulses from a NM could be processed, and the advent of a multiplicity event could be determined. In this case, a time window T was opened and all the pulses M detected within the time window were taken as multiplicity events M. This way has a number of drawbacks. Its main drawback is that it does not inform us what multiplicity will be, so at a fixed value T the events of large multiplicity are cut off, and at a small M additional background pulses come.

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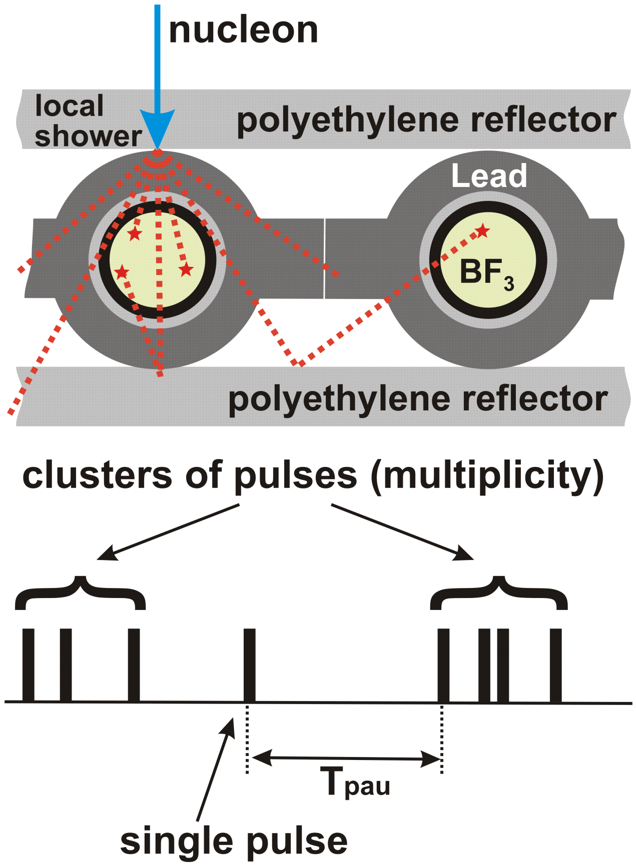

Fig. 1. A part of a neutron monitor and a sketch of the process in which multiplicity M is produced. A high-energy nucleon produces in lead several neutrons whose tracks are shown in dotted lines. The asterisks placed at the ends of the tracks, indicate the neutron absorption by boron in the tube. The example shows multiplicity $M=4$. Given below is a fragment of time sequence of NM pulses.

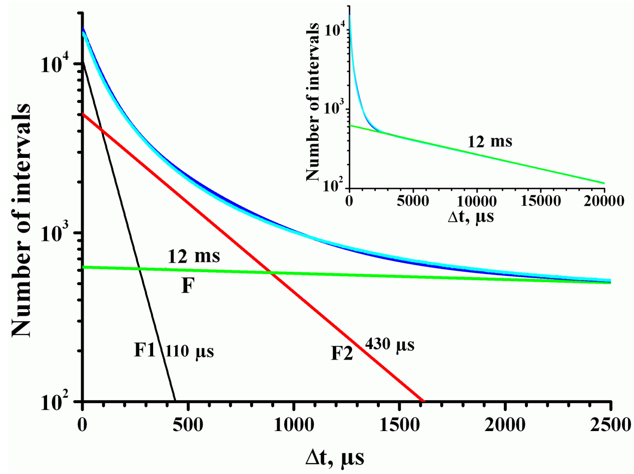

Fig. 2. The distribution of the time intervals (DOTI) for the NM data at the Barentsburg station (navy line). With $\Delta t > 2000\,\mu s$, it is quite well fit by function $F(\Delta t) \sim \exp(-\Delta t/\tau_0)$ (see setting-in, green line). The value τ_0 is close to the one calculated by Eq. (3). Within the range $\Delta t < 1500\,\mu s$, there is an excessive number of intervals compared with that calculated by Eq. (2). Two additional exponents $F1$ and $F2$ (in red and black lines) exhaust this excess, their characteristic times are τ_1 and τ_2. The sum of the three components is in blue line. It should be noted that the exponential function in the semilogarithmic scale is a straight line.

In addition the duration of the time window is determined by the electrical circuit. Due to this reason, it is impossible to change the duration of time window T in the course of experiment.

2 A new recording system and preliminary measurements

Using a new system developed in PGI, it is possible to continuously make measurements of time intervals between NM pulses to accuracy as fine as 1 µs, the tube number being recorded either. The detailed description of the system is given in (Balabin et al., 2008, 2009). The system is open, which allows an additional equipment to be used, and signals from new equipment are locked to the NM pulses to accuracy as fine as 1 µs. The system is arranged at the Barentsburg station on Spitzbergen (18-HM-64), and at the Baksan station on Northern Caucasus (6-HM-64). In (Bieber et al., 2004) there is a description of the similar recording system but it is designed for one tube only with the time resolution accounting for 95 µs.

The pulse number distribution per time unit is given by Poisson's law (Gol'dansky et al., 1959)

$$p(\Delta t) = \frac{(N_0 \cdot \Delta t)^k}{k!} \exp(-N_0 \cdot \Delta t) \tag{1}$$

where Δt is the time interval, N_0 is an average number of pulses per time unit, k is a number of pulses, $p(\Delta t)_k$ is the probability of getting of k pulses during the interval Δt. An important feature of the Poisson distribution is that (Gol'dansky et al., 1959) 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

$$w(\Delta t) = N_0 \cdot \exp\left(-\frac{\Delta t}{\tau_0}\right) \tag{2}$$

where $w(\Delta t)$is the probability to get an interval Δt between pulses, τ_0 is a characteristic time and according to Eq. (3) (Gol'dansky et al., 1959)

$$\tau_0 = \frac{1}{N_0} \tag{3}$$

Equation (2) can be called the distribution of time intervals (DOTI). The DOTI $w(\Delta t)$ were calculated using the experimental data acquired by a new recording system placed at the Baksan and Barentsburg stations in 2009. For the Barentsburg station it is shown on the Fig. 2. The total number of pulses recorded during this period accounted for at least $3 \cdot 10^9$ at each station, so the statistic accuracy of $w(\Delta t)$ is considered to be good. Within a wide range of the interval values, the DOTI is described by one exponent F. The excess of short intervals is managed to fit only by a sum of two additional exponents $F1$ and $F2$ with $\tau_1 = 110\,\mu$s and $\tau_2 = 430\,\mu$s. It is this excess that represents the neutrons additionally produced in lead. If three exponents F, $F1$ and $F2$ are used, the DOTI is excellently fit within the wide range from 0 to 50 ms and more. The similar results are acquired at the Baksan station, with the characteristic time for functions $F1$ and $F2$ turning out close to those acquired at the Barentsburg station: 125 µs and 465 µs. Having studied the time intervals distribution, we can conclude that in an NM there are some additional fast processes with the times mentioned, which produce secondary neutrons. The absolute share of these processes in the total number of NM pulses accounts for less than 5%, because of this reason it was difficult to detect them earlier.

3 The study of multiplicity

A new system only records the tube number and the time interval of each NM pulse. As the files are processed, one can select different events. To do that it is necessary to develop an algorithm and make software to hunt for the events like these. The above mentioned drawbacks of the ME detection by systems with the fixed time window are absent in our system. The authors have developed an approach to be applied in hunting for MEs. Given below are the conditions (the algorithm of hunting):
1) before a ME there should be a time interval of at least $T_{\rm pau}$, during which there are no pulses;
2) the intervals between the pulses following each other (after $T_{\rm pau}$) should not exceed the value T_0. The total duration of the clusters of pulses depends on the number of multiplicity. The first interval of more than T_0 duration finalizes an event.

The average interval between the background particles is 12 ms (value τ_0, Eq. (3)), while the average time between the secondary neutrons is (τ_1 and τ_2) $\ll \tau_0$. If the value $T_0 \sim \tau_2$ is chosen, the probability of appearance of a background pulse is small. The purpose of $T_{\rm pau}$ is to have all the multiple neutrons produced in an NM from the preceding primary particle, leave the NM or be absorbed by tubes, and to provide a consistency in that the event M, which has come, is a new one. The means $T_{\rm pau} = 3000$ and 5000 µs, and $T_0 = 300$ and 500 µs were used first. It is likely to be as

$$T_{\rm pau} \gg (\tau_1 \;\text{ and }\; \tau_2) \;\text{ and }\; T_{\rm pau} \ll \tau_0 \qquad (4)$$

The preliminary studies have shown that the results practically do not depend on $T_{\rm pau}$, and in all the later calculations the authors used only one value $T_{\rm pau} = 3000$ µs. When

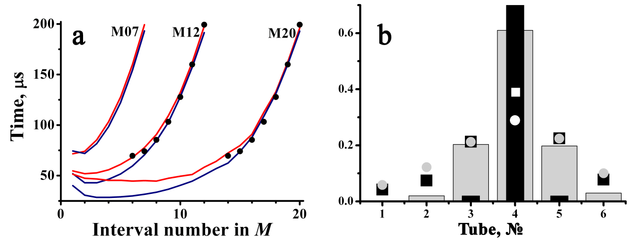

Fig. 3. (a) the dependence of interval values between neighbouring pulses (IVBNP) in events $M = 7$, 12 and 20, at the Baksan station (black line), at the Barentsburg station (red line). To visualize the identical part of IVBNPs for $M = 12$ and 20, the dependence for $M = 7$ is shown near $M = 12$ and 20 with the corresponding shift (circles); **(b)** the dependence of relative frequencies for $M = 12$ and 20 (black squares and grey circles, respectively) on the number of the tube at the Baksan station. The histograms show relative frequencies calculated using a toolkit GEANT-4. A grey histogram corresponds to $M = 1$, a black one to $M = 3$.

$T_0 = 300$ µs, the processes with the characteristic time 430 µs are not involved into the study, therefore $T_0 = 500$ µs has been used.

As a result of NM data processing of two years data array, large sets of MEs in the range $M = 4 - 50$ have been accumulated. The events are selected primarily by the value M. Having a large set of MEs of a given value M one can examine different processes inside multiplicity.

3.1 The intervals duration depending on their place within multiplicity

The dependence of interval values between neighboring pulses (IVBNP) on their place within a ME contains important information about the processes producing ME. To calculate IVBNP, it is necessary to calculate the average mean of the time interval between pulses 1 and 2, using all the events of the given multiplicity M and then between pulses 2 and 3 etc. Figure 3 shows IVBNPs acquired at Baksan and Barentsburg stations for $M = 7,\ 12,\ 20$. Along the lines corresponding to $M = 12$ there is a line for $M = 7$ which is shifted along the axis OX so that their ends coincide with each other. One can see that at the beginning of ME intervals are approximate constant and they increase only at the end of ME. The approximate constancy (about 750 µs for $M = 20$) of intervals at the beginning of ME indicates the neutron density constancy within NM in spite of the fact that they are absorbed during recording or they leave NM. Hence, there should be a process implementing replenishment with new neutrons during some time. Close coincidence between the right-hand parts of the plots for $M = 12$ and 20, with the dependence for $M = 7$, means that around the last 7 pulses with any M are stipulated by some physical process finalizing the multiplicity process with $M > 7$. This conclusion is also confirmed by that IVBNPs of multiplicities $M = 12$ and 20 at different stations coincides at the last $6-7$ points (intervals). It can be naturally and simple explained by NM relaxation after an external action: the influx of new neutrons is exhausted, with the rest being either absorbed by the tubes or leaving NM. In this case, the time intervals between the pulses will steadily increase, which is observed in Fig. 3.

3.2 Pulse distribution within multiplicity events through NM tubes

It is supposed that if the primary neutron producing secondary neutron, gets into lead near a tube L, the first pulse is sure to be detected in the same tube L. A study has been carried out regarding the relative frequency at which pulses are detected in different tubes in all the MEs with the given M, with ME beginning from the pulse in tube L. As a result, one can obtain the value indicating the probability to meet a pulse from tube J within ME of M if ME starts from a pulse in tube L. Relative frequencies have been studied for all the tubes and MEs with $M=5-40$. Figure 3**(b)** shows the results of this study at the Baksan station with $M=12$ and 20, Tube $L=4$. The distribution width covers approximately three tubes, it increasing as M increases. ME is also simulated by a toolkit GEANT-4. Neutrons and protons of 0.3, 1, 3, 10 GeV (10^4 particles per kind and value of energy) were released to NM at random angles and to any place, but the target was within the lead surrounding Tube 4. The tracks of all the nuclear-active particles produced in the interaction with the lead nuclei have been calculated before they have been absorbed, decayed, or left NM. When the secondary neutron has been captured by boron nucleus, the tube where it occurred was recorded. It should be noted that for neutrons of 10 GeV, the probability to pass through NM without interaction is essential, that is why higher energies have not been simulated. The ME simulation results are shown in Fig. 3**(b)**. In spite of that the particles of energy 3 GeV and over can produce in NM more than two tens of secondary neutrons, only a small part of these is detected. The events of multiplicity more than $M=7$ were not observed in simulation at all. There is also a difference in the form of distribution. Being calculated even for $M=1$, the distribution turns out to be narrower than that for $M=12$, with it becoming narrower as M increases, turning into $\delta-$function just at $M=3$ (Fig. 3).

Having compared the observations and calculations (see Sect. 3.1, and Fig. 3) one can conclude that the events of multiplicity $M>7$ can not be produced by one energetic particle. One particle, however highly-energetic, can produce ME not more than 7 in number, the pulse distribution function is $\delta-$type. To produce an actually observed ME, it is necessary for multiple energetic particles to fall down during a short period of time, which will produce many secondary particles in the various parts of an NM. In the first approximation, the size of this cloud of particles can be estimated by the width of the dependence of relative frequencies (Fig. 3): the cross-section of three tubes accounts for about 2 m.

4 Conclusions

Using a new high-precision recording system installed in neutron monitors at the Barentsburg and Baksan stations, high resolution study of events of multiplicity have been carried out for the first time. It has been found that all the events $M>7$ at both stations have a “tail” part, which is in fact a relaxation of NM after the effect of a flux of cosmic rays. On the basis of these studies, and simulations with the GEANT4 package, it is shown that multiplicity events in a neutron monitor can arise both from neutron multiplication within the lead in the NM, and also from local hadrons induced air showers. The size of such cloud is approximately equal to $2-3$ m.

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