

Difference of particle populations in neutron multiplicity

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Abstract: High-speed data acquisition system for a neutron monitor (NM), developed in PGI, to the present moment is installed at the four stations: in Moscow, Barentsburg, Apatity and Baksan. Multiplicity events of M from $M = 4$ up to $M = 100$ from the Polar cycle to high mountain middle latitude zone were studied due to the system. In this paper we carry out the result of study and comparison of transient phenomena on NMs.

Keywords: neutron, multiplicity, Poisson distribution.

1 Introduction

The high-speed data acquisition system has been described some times in our paper, for example [1, 2, 3]. It is briefly said the system registers the arrival of each pulse from 18 count tubes of NM with $1 \mu\text{s}$ accuracy. Now the system are installed on four stations: Moscow (cutoff rigidity 2.4 GV), Barentsburg (Spitzbergen, 0 GV), Apatity (0.6 GV) and Baksan (North Caucasus, 5.4 GV). The special software processing of the gathered data in accordance with established algorithms is further used. With this system, the fast processes in NM are investigated, including the multiplicity. In this paper investigation and comparison of the observed fast processes at different NM stations are presented.

2 Indicator of transient phenomena in neutron monitor

High-speed data acquisition system installed at these stations collects unique information: it records all the time intervals between the electrical pulses coming from the NM detectors. It is known that random process, like the number of particles caught by NM, is described by Poisson's law [4].

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

where Δt is the gathering interval, N_0 is an average number of pulses per time unit, k is a number of pulses, $p(\Delta t)$ is the probability to get k pulses during the interval Δt . An important feature of the Poisson distribution is that if the probability of the pulse number is described by Equation (1), the probability of the interval mean between pulses is given by expression [4]

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

where $w(\Delta t)$ is the probability to get interval Δt between pulses, τ_0 is a characteristic time according to Equation (3) [4]

$$\tau_0 = 1/N_0 \quad (3)$$

The Equation (2) can be called the time interval distribution (TID). The TIDs $w(\Delta t)$ were derived from the ex-

perimental data acquired by the our recording system installed at the stations. The total number of pulses gathered during this period is at least $2 \cdot 10^{10}$ at Baksan and Barentsburg stations, $2 \cdot 10^9$ at Moscow and Apatity stations, so the statistic accuracy of $w(\Delta t)$ is considered to be good. The TIDs of four stations are shown on the Figure 1a. Within a wide range of the interval values, the TIDs are described by one exponent F according to (2). τ_0 is determined by average count rate according to (3) on each station. However one can see an excess of short intervals. The excess profiles have similar shapes and the same upper interval values $\sim 2000 \mu\text{s}$ on all stations. The excesses of short intervals are managed to fit only by a sum of two additional exponents F_1 and F_2 like it is shown on Figure 1b and 1c. Characteristic times (in μs) of all stations are given in Table 1. Total fitting function is

$$N(\Delta t) = N_0 \cdot \exp(-\Delta t/\tau_0) + N_1 \cdot \exp(-\Delta t/\tau_1) + N_2 \cdot \exp(-\Delta t/\tau_2) \quad (4)$$

where N_0, N_1, N_2 is normalizing factors, $N(\Delta t)$ is number of interval Δt duration (μs) per day. When the fitting function (4) is used, experimental and derived TIDs are very close on the range from $10 \mu\text{s}$ up to 150 ms and more. The presence in the TIDs of such excesses with the same shape and length on the different stations NM (different design types, cut-off rigidity and altitude above sea level) points to the cause of this phenomenon out of NM.

Station	τ_0	τ_1	τ_2
Apatity	114650	1379	165
Baksan	12648	537	152
Barentsburg	23268	472	146
Moscow	31063	475	142

Table 1: The characteristic times of the Poisson process for the different NMs.

Distribution of Apatity NM is outstanding (Figure 1b) due to its leadless design 4-NM-64. τ_0 is huge because the count rate of this NM is low. But there is similar excess with two additional exponents too. On the other station characteristic times τ_1 and τ_2 are close instead the differences of station location. If three exponents F, F_1, F_2

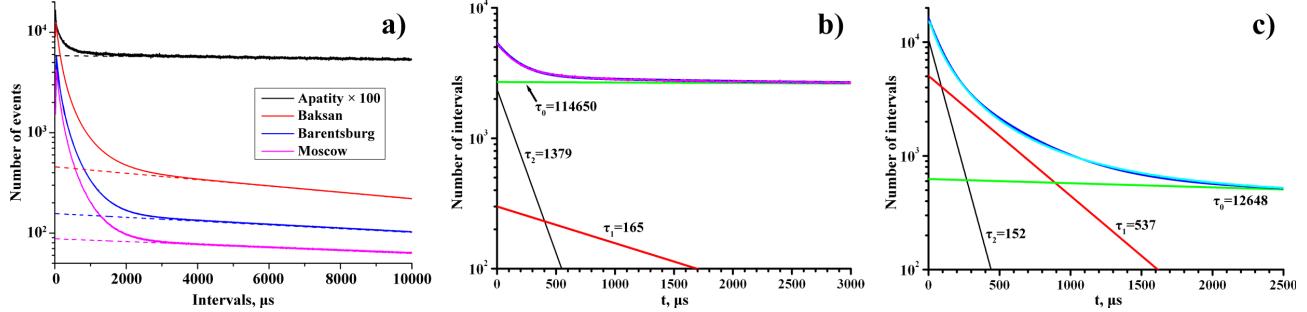


Figure 1: Time interval distributions and its fitting functions. **a)** TIDs of Apatity, Baksan, Barentsburg and Moscow stations on wide range. The dot lines correspond to approximation function F . **b)** Apatity. Fitting function as a sum of three exponents (magenta) covers exactly experimental (blue) line. Green, red and black lines are the three exponents (F, F_1, F_2 correspondently) shown separately. **c)** Baksan. Fitting function as a sum of three exponents (blue) covers experimental (navy) one. Green, red and black lines are the three exponents (F, F_1, F_2 correspondently) shown separately.

are used, the TID is excellently fit within the wide range from $10 \mu\text{s}$ to 150 ms . Out TIDs are normalized and integral over t 0 to infinity (really it is $\sim 10^6 \mu\text{s}$) gives total amount of intervals per day. Consequently integral of each exponent gives its part of the total. Amount of intervals in the excesses is about $20 - 23\%$ of total number of intervals. It means the processes with τ_1 and τ_2 not operate continuously, but only a short period time to time.

Observed distinction of characteristic times on a station is the result of complex sum of three independent Poisson processes in NM [4]. Having studied the TID, we have concluded that in NM there are some additional transient processes with the characteristic times mentioned, which produce secondary neutrons [5]. The process with time τ_2 is close to the so-called "fast multiplication" of neutrons in NM, and the process with τ_1 corresponds to the "evaporated" neutrons [5, 6].

It is the wonderful result. This is the especially important result of Apatity NM, since this monitor design is leadless (the lead shield is as a neutron multiplier). This means that the neutrons including in the fast processes with τ_1 and τ_1 can be not only associated with a generation in the lead, but be produced in the atmosphere above the unit.

3 Two particle populations in multiplicity

In this paper, we are focusing on statistical study of time intervals in multiplicity. The algorithm of multiplicity M event detection in the data stream and the properties of these multiplicities are detailed described in [1, 2, 3, 8]. It would be mentioned these studies have carried out the presence in events ($M > 10$) of two phases (body and tail), which differ in the average value of the interval between the pulses. The body phase is on the first ($M - 10$) intervals, the tail one is on the last 10 intervals of event M (see Figure 2b). During time operating the new system has accumulated huge amount of data, containing millions of multiplicity events that has allowed to do event separation of various kinds having good statistic accuracy. In this case we are interested in the distribution of time intervals in given M .

We calculated the time intervals distribution, using only the events of multiplicity given M . It could be called differential time interval distribution (DTID). It is shown in Figure 3. DTID in Figure 3c was based on the array of events $M = 35$ without separation. Figure 3a shows DTID, which is calculated on the basis of the first ($M - 10$)

intervals only (body phase) in the array of events $M = 35$, Figure 3b - DTID of the last 10 intervals (tail phase) of the same array. In Figure 3c the presence of two characteristic times is clearly observed. In this case the fitting function is

$$n(\Delta t) = n_3 \cdot \exp(-\Delta t / \tau_3) + n_4 \cdot \exp(-\Delta t / \tau_4) \quad (5)$$

where n_3 and n_4 is normalizing per event factors, $n(\Delta t)$ is differential probability to get interval Δt duration (μs) in the array data of multiplicity given M . At the same time, the distribution in Figure 3a and 3b are good approximated by simple exponential dependences:

$$n_b(\Delta t) = n_3 \cdot \exp(-\Delta t / \tau_3) \quad (6)$$

$$n_t(\Delta t) = n_4 \cdot \exp(-\Delta t / \tau_4) \quad (7)$$

where $n_b(\Delta t)$ is differential probability to get interval duration Δt (μs) in the array data only among body phases of events given M , $n_t(\Delta t)$ is differential probability to get interval duration Δt (μs) in the array data only among tail phases of events given M . As we can see, a single Poisson process with the corresponding characteristic time is in each phase only. Thus the presence of phases, which was previously carried out from time profiles (see Figure 2b), is confirmed more reliable and on independent way. Phase presence points that the differences are fundamental and based on two different processes. Similar DTIDs were obtained for different $M > 20$, the results were the same.

Another study was carried out to determine the nature of the phases in multiplicity. For this purpose a certain condition was specified (it was the condition "the interval number K in the events of given M is not less than $T \mu\text{s}$ "). Then the average time profile of multiplicities selected under this condition was found. On Figure 2a two profiles are shown. T was set $100 \mu\text{s}$. Dark yellow line shows the profile under the condition on the interval K in the tail phase, red one is the profile under the condition on the body phase. We can see a different manifestation of its properties in different phases. The condition on the tail phase keeps only duration changing of the interval K (it is reasonable, since only events M with the interval of number K at $> T \mu\text{s}$ was selected). The condition on the body phase affects not only by the interval of number K , but also to the neighboring. We called this effect "coherence" in multiplicity. Intervals (or pulses) in the body phase are

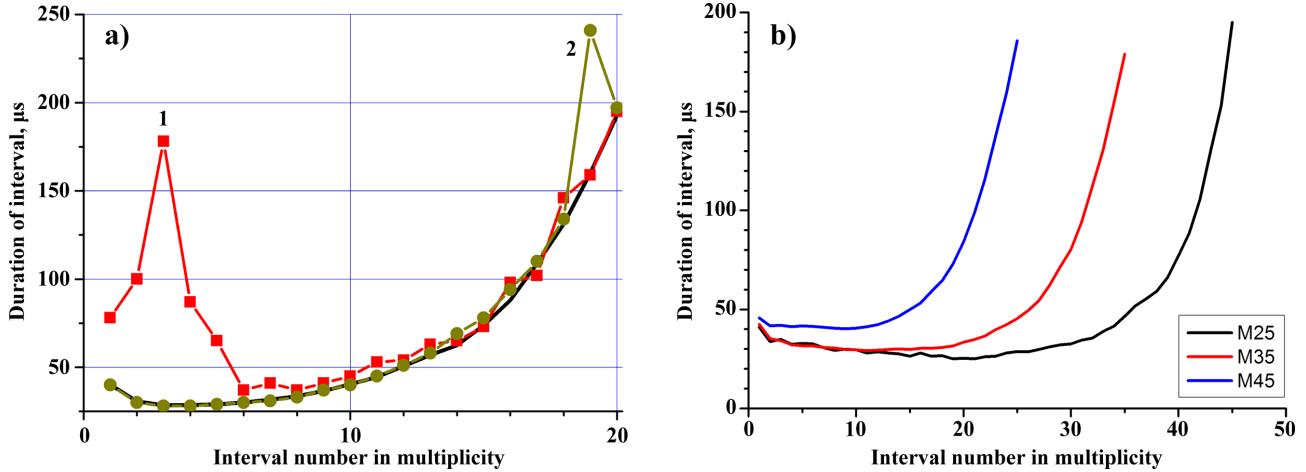


Figure 2: a) Result of multiplicity testing to coherence. Red line is the profiles under condition on body phase. Dark yellow line is profiles under condition on tail phase. Black is the profile without condition. There where used multiplicity $M = 20$ data array. b) Average time profiles of multiplicity different M .

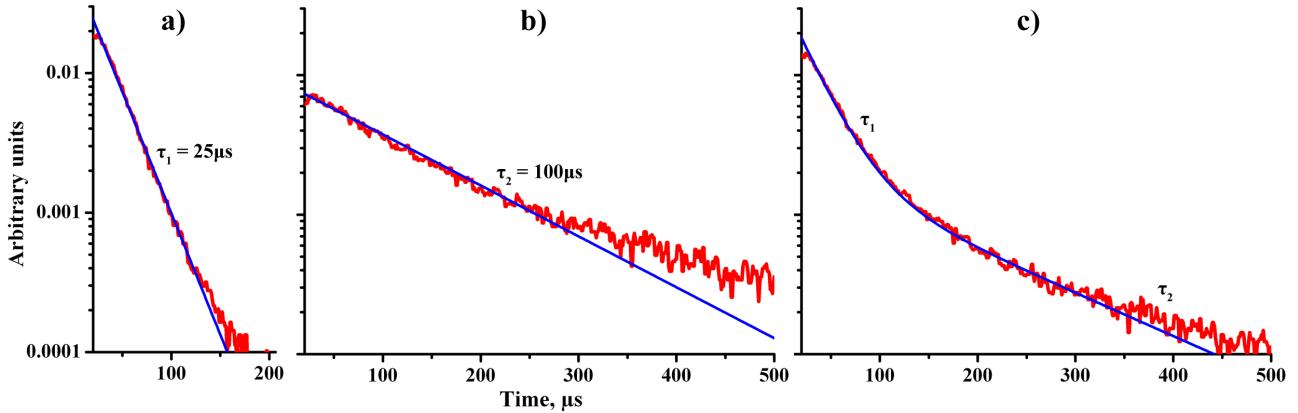


Figure 3: Differential time interval distribution of multiplicity given $M = 35$. a) Distribution is calculated using intervals of body phases of all $M = 35$; b) Distribution is calculated using intervals of tail phases; c) Distribution is based on the full array of events $M = 35$ without separation. Red is experimental, blue is fitting function (6), (7) and (5) correspondently to a), b), c).

coherence. Condition imposing on one of them leads to a change in the neighboring ones.

The following explanation for these features is offered. It was shown [3], that multiplicity $M > 10$ can't be formed by a single energetic particle. At the same time, there are a multiplicity $M \approx 100$ and over is observed on NM. To explain such high values of M a concept of local atmospheric hadron showers (LAHS) was offered. These showers are produced by primary cosmic rays with energies below the threshold of extensive air shower (EAS) [1], however, sufficient to produce in the atmosphere over NM a number of energy neutrons. Despite both neutron absorption by the detector tubes or leaving them out from NM, new energetic neutrons of LAHS restore losing. They create in HM new "fast" and "evaporation" neutrons. As a result, the density of neutrons in NM is about constant during LAHS action and the average interval between the neutron detection (amplifier pulses) is a constant too. Setting our condition means that LAHSs were separated only, which have a time gap more than T within. During this gap NM is losing neutrons, i.e. intervals around number K is increasing. It turns as it is shown on profile 1 in Figure 2a. The tail phase is relaxation.

It is coming after the LASH action. The neutron density decreases due to absorption in the detector or leaving them out from NM. The intervals between the registrations are growing monotonically. All neutrons in the relaxation phase are completely independent of each other, and their energy is not sufficient to produce new neutrons in NM. Therefore, setting our condition doesn't affect on neighboring intervals.

4 Conclusions

By high precision measuring of time interval distribution three distinct particle populations, corresponding to three different processes in NM were found. They are registration of single neutrons falling in NM, neutrons produced by lead nucleus destruction by energetic cosmic ray particle and "evaporated" neutrons. The characteristic times of these processes has been found. Differential time intervals distribution, which was calculated using the array of the multiplicity events given M , shows the presence of two populations of particles in the events of multiplicity ($M > 10$). Moreover, these populations exist separately in multiplicity

event, when one is finished, another is coming. Each population corresponds to the different phase of multiplicity. Characteristic times of the phase are carried out. All results of multiplicity studying, taken into account totally, prove the fact: a multiplicity ($M > 10$) can be only produced by local atmospheric hadronic shower.

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