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Neutron bursts in EAS: New physics or nuclear physics?

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Abstract. An analysis has been done of events with very high multiplicity of neutrons (neutron bursts) observed in two experiments with neutron monitor triggered by EAS: at Mexico City and at Baksan. The explanation of the phenomenon of delayed by milliseconds pulses can be found in neutron physics, while the origin of EAS with abnormally high multiplicity of neutrons is still a question. Monte Carlo simulations of slow neutron flux using known cross sections and real geometry of the experiments show rather good agreement with observed data.

1 Introduction

In the last years, there appeared evidences (Aushev et al., 1997; Antonova et al., 1999; Stenkin et al., 1999; Stenkin et al., 2001a; Stenkin et al., 2001b) for the existence of abnormal high multiplicity events in a neutron monitor (NM), which we called as *neutron bursts*. Main features of the observed effect are following: i) delayed by milliseconds pulses with very high multiplicity both in NM and in the outer detectors can accompany EAS; ii) rate of such events is $\lesssim$ 1 day^{-1}; iii) multiplicity of delayed pulses in such events is ~2÷3 time higher in the bottom outer scintillator detectors than in top detectors; iv) pulse time distributions in outer detectors have maxima if there exists an air gap between them and ground.

As we claimed in (Stenkin et al., 1999; Stenkin et al., 2001a), peculiar time distributions in outer counters can be satisfactory explained by the existence of thermal neutron flux associated with EAS. Time distributions for the inner boron proportional counters are distorted by poor time resolution (long recovery time) of gas counter for burst of pulses and should not be trusted. Here we present detailed analysis of the phenomenon and the results of Monte Carlo simulations for both experiments.

2 Experiments

First, we would like to remind the experimental details. With the aim to detect *neutron bursts* we performed an experiment (Stenkin et al., 1999; Stenkin et al., 2001) using the Mexico City neutron monitor 6NM64 and associated muon telescope, consisting of 8 plastic scintillator counters of 100x100x5 cm^3 each, located just above and just below the NM (see Fig.1a). The signals from upper 4 counters were added and designated detector “s”, likewise the 4 lower counters constituted detector “i”. In addition, a NaI scintillator (∅10cm x 10cm) detector was used as a detector for gammas detection and for triggering. These 3 signals and a signal from one of the neutron monitor standard boron counter (BP 28) were put to 4 channels of a digital oscilloscope TDS420A. 1m air gap existing between the NM body and ground was used as a place for additional detector (NaI) and for additional paraffin layer.

The Baksan experimental set-up (Fig.1b) differs from that in Mexico City mainly by the absence of an air gap, so the scintillators (6 x 1 m^2) were put only above the 6NM64 monitor. But, we were able to modify the set-up during the experiment (Stenkin et al., 2001b) as this NM is working now only for this experiment. Instead of fourth boron counter we used special detectors for neutron detection: first NaI (∅8cm x 8cm) and then ZnS +B^{10} (∅6.3cm x 10cm) detector (SDK-01). The same detector was also put on the top of NM. These additional detectors as well as shift in height of one plastic scintillator detector permits us

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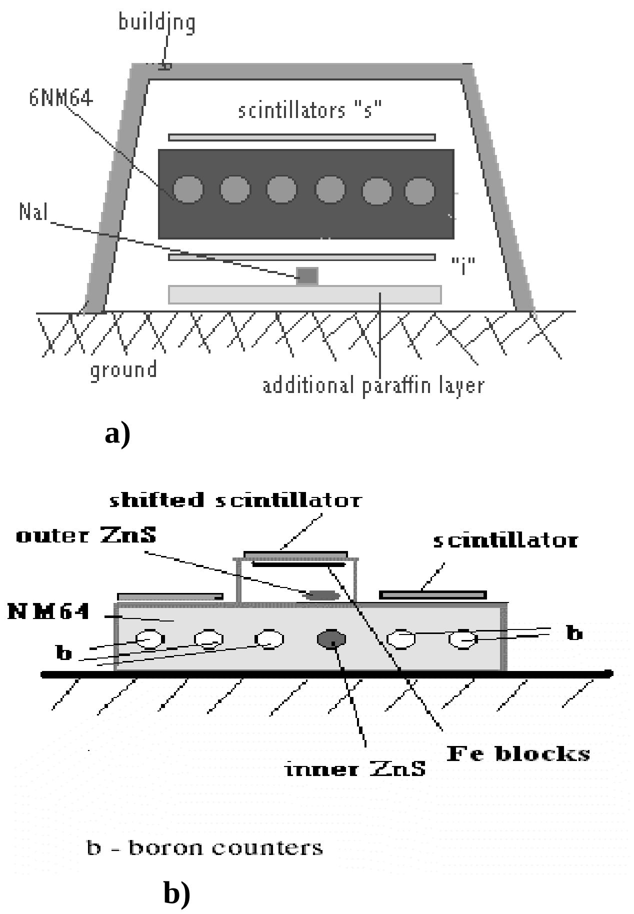

Fig.1. Schematic view of Mexico City (a) and Baksan (b) experimental set-up.

to confirm our previous conclusions about the peculiar delayed pulses distributions in gas proportional counters and its explanation by poor time resolution of such a counter. Usage of scintillator detectors for neutron detection has showed this experimentally (Stenkin et al., 2001b) without any doubt and also, it helped us to measure thermal neutron fluxes inside and outside the NM.

3 Experimental results

In our previous papers (Stenkin et al., 1999; Stenkin et al., 2001a) we presented and explained the "strange" time distributions of delayed pulses in the NM boron counters by a methodical reason and in outer scintillator counters by the flux of thermal neutrons associated with EAS. We have proved there that very high multiplicity neutron events do exist in NM. These events occur with a rate of less or ~1 day^{-1}. As we mentioned in (Stenkin et al., 1999; Stenkin et al., 2001a), neutrons produced in lead producer can escape the NM in the first moments while their energy is high enough and cross section is low. To check this we plotted the beginnings of pulse time distributions with a step of 1 µs in both plastic scintillator layers covering the NM (Mexican experiment) in Fig. 2. This part of time distributions can be fitted by 2 exponential decay curve as follows:

$$F(t)=0.001+0.389\exp(-(t-127)/1.07\mu s)+0.178\exp(-(t-127)/3.41\mu s)$$

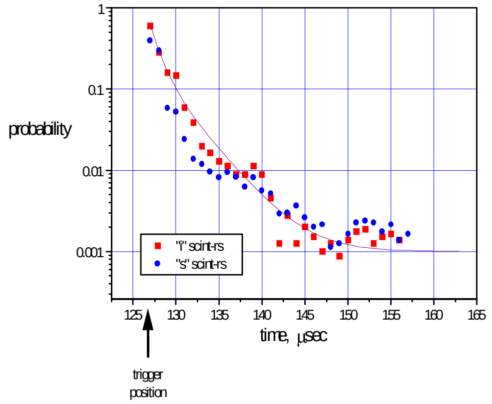

Fig.2. Beginning of pulse time distributions in scintillators

As one can see we do record fast neutrons (or γ-quanta associated with them during inelastic scattering) in the first several microseconds. Therefore, we can use the number of such pulses integrated over first 10 µsec (**m**) as a measure of total number of fast (evaporation) neutrons produced in the NM producer. This is better than the number of neutrons recorded by boron counters because the latter is saturated in high-energy events. In this way we plotted scatter graph in Fig. 3 where correlation between this number in both scintillators "i" and "s" and total number of pulses integrated over 2.5 msec (**M_i+M_s**) is shown. In other words, this plot shows the correlation between the number of fast evaporation neutrons produced in the lead producer and the total number of thermal neutrons detected by scintillators. As one can see, some events (bursts) lie absolutely out of the main trend: they have normal number of fast neutrons and abnormally high number of thermal neutrons. The explanation of such a behavior can be found if one supposes that the great bulk of slow neutrons come from outer source in these events. As we supposed in (Stenkin et al., 1999; Stenkin et al., 2001a), this source is the EAS core. From (Stenkin et al., 2001b) we know that the efficiency to detect thermal neutrons by our plastic scintillator detector with 0.5 mm iron housing is as low as ~2%. Thus, in the biggest event (in Fig.3) there was a burst of 130/0.02=6500 neutrons passed through an area of 8 m^2 around the NM and the mean thermal neutron flux during the burst was as high as ~80 n/cm^2/sec. Note that the NM polyethylene outer shield is not transparent for thermal neutrons. This results in different fluxes and its different behavior inside and outside the NM. From (Stenkin et al., 2001b) we can estimate the NM inner thermal neutron flux during the biggest Baksan burst as measured by ZnS detector (55 pulses): ~ 2200 n/cm^2/sec; corresponding outer flux (>713 pulses on 6 m^2) was measured to be > 600 $n/cm^2/sec$ above the NM. The inner flux during the burst lasting for some milliseconds can be compared for example with that one could observe from 2 curies of Ra-γ-Be source in graphite column just near the source.

4 Calculations

To explain the observed time distributions a Monte Carlo simulation of the experiments has been done taking into account real NM geometry and known cross sections for thermal neutrons. The main aim of this work is explanation of time distributions of delayed pulses in the outer scintillator detectors, because those for boron counters are affected by poor time resolution of proportional counters in high multiplicity events and so does not correspond to real pulse time distributions. Full simulation of all processes in NM is very complicated.

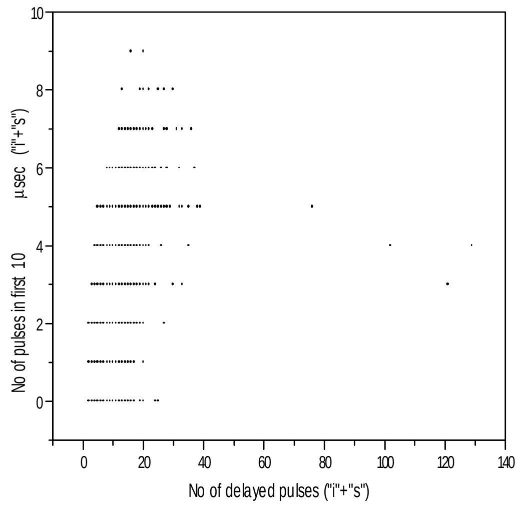

Fig. 3. Correlation between fast and slow neutrons recorded by scintillators.

Nevertheless, the problem can be easily simplified if one begins the calculation just at the moment when the thermalization process is over. We assumed that during this process, while absorption cross sections are low (due to 1/v law), fast neutrons spread widely around the monitor and accumulate in condensed matter in according with its scattering cross section. This simplification is correct for our purpose, as we are interesting only for long delayed pulses in a msec range. In such assumptions, we can use only thermal neutron cross sections (tabulated in handbooks), isotropic angular distribution in elastic scattering and simple velocity distribution. The only problem here is unknown chemical composition of real construction materials (concrete etc.) and ground. There are no problems with NM materials: lead, paraffin, air, iron and boron counters content. Instead of real ground and concrete we used SiO_2 as the main component of any ground. Note that small additions of Mg or/and Al (or many other elements) oxides do not affect significantly on the neutron time distributions we are interesting for.

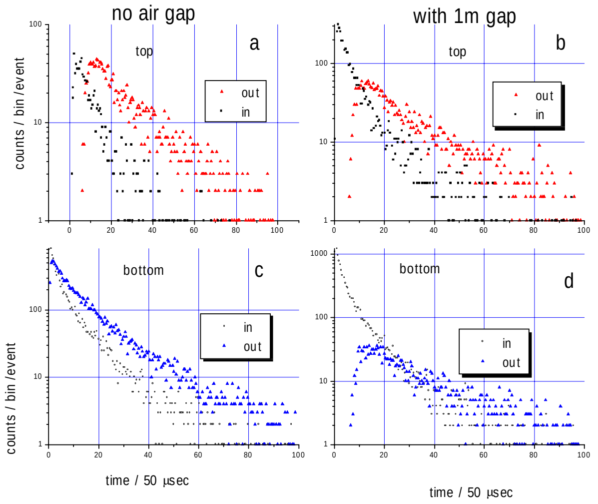

Fig. 4. Results of M-C simulations.

- **a-** top scintillators without air gap;
- **b-** top scintillators with air gap;
- **c-** bottom detectors without air gap;
- **d-** bottom detectors with air gap

The great bulk of usual elements have small neutron absorption cross-section. The exclusions are B, Li, Cd, Cl, Fe, Cu, I, etc, but usually they are rare additions. Presence of ground water can change the neutron lifetime in it. It can also affect on the thermalization process. As we estimated in (Stenkin et al., 1999; Stenkin et al., 2001a), thermalization in dry "standard ground" should be of about 400 μsec. In a presence of water, this time will be less. In this calculation, we did not add water to ground. Concrete building with the corresponding air gaps was taken into account. We made simulations for two cases: with and without 1m air gap between ground and NM. In both cases, we also used 20-cm concrete ceiling at 1 m above the top scintillators. Results for outer scintillator detectors are shown if Fig.4. Points marked as "in" and "out" correspond to thermal neutrons emitted by inner materials of NM64 or by surrounding materials (ground and construction concrete). As one can see, neutrons emitted by NM64 have steeper time distributions than that emitted by ground. This can be easily explained by the difference in neutron lifetime for absorption in these materials. The influence of air gap is clearly seen. The latter should be taken into account in comparison of different experiments.

5 Discussion

Thus, the M-C simulations of the experiments (Stenkin et al., 1999; Stenkin et al., 2001a; Stenkin et al., 2001b) confirmed our supposition that the main effect of delayed pulses in outer scintillator detectors is produced by slow neutrons through (n,γ) reactions in surrounding materials close to the detectors. Neutrons captured by nuclei at distances bigger than ~ 1 radiation length can not produce pulses in the detectors due to gamma absorption. We should emphasise here that distance is in radiation lengths, thus in gas media (air) it can be as large as hundreds meters. This means that experiments can differ significantly due to differences in surrounding matter, construction details and materials. Nevertheless, the main features should be more or less the same. Any NM contains many hydrogenous materials accumulating neutrons during the burst. Thus, the NM itself is the first source of slow neutrons for outer detectors. Another source is surrounding materials such as ground, concrete etc., "filled" with neutrons after the EAS core passage. Lifetime of slow neutrons in these sources is different as one can see in Fig.4. This means that observed lifetime can lie between τ_1 ~600 μsec (NM lifetime) and τ_2 ~1 msec (SiO_2 lifetime) in accordance with contribution of one or another source. At low energy events, the first source prevails while at the highest observed multiplicities the second source should prevail. It is well known that due to trigger conditions the effective area for air shower detection increases if shower size increases. Effective area of EAS core also increases and significance of second source becomes more and more essential. This explains why in our experiments (Stenkin et al., 1999; Stenkin et al., 2001a; Stenkin et al., 2001b) τ in outer detectors slightly increases with rising of event multiplicity or EAS energy. This also explains why in high multiplicity events bottom detectors situated between ground and the NM record much more pulses: top detectors are shielded from ground by the NM itself and only walls, ceiling and the NM moderator are the sources of slow neutrons for them.

6 Conclusion

Our experiments (Stenkin et al., 1999; Stenkin et al., 2001a; Stenkin et al., 2001b) have confirmed the existence of *neutron bursts* i.e. events in the neutron monitor with very high multiplicity of recorded neutrons both in boron counter and in surrounding the monitor scintillator detectors. Our Monte Carlo simulations of the experiments confirm that the main effect of delayed pulses in outer detectors is produced by thermal neutron flux associated with EAS passage through the matter (we did not consider in this work induced radioactivity background which undoubtedly exists and produces a flat background increasing with shower size (Stenkin et al., 1999; Stenkin et al., 2001a). Albedo neutrons from ground and construction materials contribute to the observed effect through the (n,γ) reactions the more the higher is EAS energy. This results in:

1) delayed pulses time distributions in outer detectors are defined by that of thermal neutrons;
2) bottom scintillators unshielded from ground, record much more delayed pulses than top detectors do;
3) flattening of time distributions of delayed pulses in outer detectors at higher multiplicity of the event.

The latter is explained by increasing of a contribution of the outer sources of thermal neutrons associated with EAS core at higher EAS energies.

We can say nothing now about the origin of such bursts: is it simple fluctuations of EAS hadron content or we deal with abnormal EAS similar to Cenauro known from emulsion experiments? To understand the origin of such *neutron bursts* further calculations of EAS propagation in the atmosphere and its interaction with ground should be performed. New experiments in this field can also clarify some problems. Nevertheless, answering the question put in the title we can say: *all the observed phenomena can be satisfactory explained by known Nuclear Physics processes.* We can also add here that huge number of slow neutrons produced by EAS core does not contradict the power conservation law. Giant amount of neutrons is contained in surrounding matter and one needs only several MeV of energy to initiate nucleon disintegration and to release one or more neutrons. Thus, to produce 10^5 neutrons one needs energy $< 10^5 \cdot 10$ MeV= 10^{13} eV. This is less than 0.5% fraction of estimated energy for EAS produced up to date one of the biggest neutron burst, mentioned in (Stenkin et al., 2001b).

Moreover, in our opinion, this phenomenon can be successfully used in EAS technique to study neutron (hadron) component, to select γ-EAS in UHE γ-ray astronomy, to locate EAS core etc.

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