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Study of neutron bursts with Baksan Array

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Abstract. An experiment has been performed using Baksan Carpet-2 Air Shower Array to study so called *neutron bursts* in Extensive Air Showers. Some evidences for existence of such events with very high neutron multiplicity in a Neutron Monitor (NM) triggered by EAS array were published last years. We also confirm the existence of such events and give a natural explanation for them, lying mostly in a field of well-known nuclear physics.

1 Introduction

The phenomenon of *neutron bursts* observed in last years (Aushev et al., 1997; Antonova et al., 1999; Stenkin et al., 1999; Stenkin et al., 2001) is very interesting and promising instrument in EAS study. In this paper we present results of an experiment being carried out at Baksan neutron monitor 6NM64 running as a part of Carpet-2 array. The results have confirmed again the conclusion made in (Stenkin et al., 1999; Stenkin et al., 2001) concerning the origin of delayed by milliseconds pulses both in inner boron proportional counters and in outer plastic scintillators. Usage of scintillators for neutron detection has experimentally shown the saturation of boron counters and it has allowed us to measure the real thermal neutron flux both inside and outside the NM.

2 Experiment

The Baksan experimental set-up (Fig.1) differs from that in Mexico City (Stenkin et al., 1999; Stenkin et al., 2001) mainly by the absence of an air gap, so the scintillators (6 x $1\ m^2$) were put only above the 6NM64 monitor. An advantage of this experiment is a possibility to modify the set-up during the experiment 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 special detectors play a crucial role in the experiment: they are rather fast (~ 200 ns), have no recovery time and are insensitive to charged particles

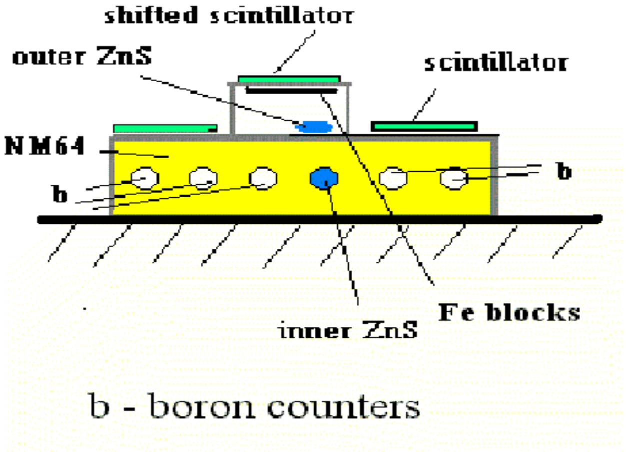

Fig. 1. Experimental set-up.

Correspondence to: Yu.V.Stenkin (stenkin@sci.lebedev.ru) and to gammas. The data are accumulated for each detector using shift register with a full scale of 10 ms with a step of 50 μs. The main trigger for data recording was a burst of > 20 pulses in 6 boron counters or in other words, > 20 neutrons detected by 6NM64 during a time window 10 ms. The trigger rate is ~0.5 min^{-1}. In addition, Carpet-2 array triggers mark the events. Each event is marked by the absolute time with 1 ms accuracy. Due to this, the events from all Carpet-2 detectors (NM, 175-m^2 Muon detector and 200-m^2 Carpet) can be identified.

3 Data analysis

The data were accumulated during 2 Runs of ~3 months duration each: 1) NaI crystal detector instead of one boron counter (fourth) inside the NM and one plastic scintillator detector shifted by 1m apart the NM and 2) ZnS detector instead of a boron counter; the same detector on the NM surface just above the first one and one plastic scintillator shifted 60 cm in height with addition of iron blocks for increasing of thermal neutron absorption (for Fe σ_{abs}=2.6 b). The latter configuration is shown in Fig. 1. Note that NaI is an effective detector for thermal neutrons due to rather high cross section for radiation absorption in iodine (~7 b). As we shall see below, the efficiency of 8-cm crystal is very close to that for ZnS detector. The latter is shaped as a lucit cylinder covered with a thin (hundreds of microns) compound of Zn + boron oxide enriched with B^{10}. This makes it insensitive to charged particles while for thermal neutron it is semitransparent. The efficiency for thermal neutron detection given by producer is 40%.

The results of 1st experimental Run is shown in Fig. 2. This figure shows pulse time distributions in NaI detector and in a neighboring boron counter for two neutron multiplicity ranges: M_n <40 and M_n >200, where M_n is total number of neutrons recorded by all boron counters. In both cases, the data for NaI were multiplied by a factor of 18 to superpose them with that for boron proportional counter. In this figure as well as in others below, EAS trigger position is located in 10th bin just to see the prehistory.

The graphs demonstrate a saturation of boron counter at high multiplicity events without any doubt. Another interesting thing here is an excess of NaI counts in the first two bins at low multiplicity and absence of the excess at high multiplicity. An explanation is following: NaI is sensitive to gammas produced by fast neutrons through inelastic scattering and detect them in the beginning of thermalization process (τ=13.5 μs in polyethylene); trigger position (EAS start) is known only with 50 μs accuracy (it is not synchronized with bin position), so the excess can be both in a bin containihg trigger or in the next one; discriminator dead time is equal to 5 μs so it can not resolve several pulses during first several μs. This is why counts can not exceed 1 in the first bin. At higher multiplicity, we have just reached this level.

Fig. 3 shows neutron integral multiplicity spectra multiplied by M^3 for 5 boron counters and that measured by NaI. Taking into account difference in recording efficiency and in the size (factor 18 as in Fig. 2) one can recalculate the last spectrum and predict what a boron counter would measure without saturation. One can see that in such a case a power spectrum with index equal to 3 should be extended up to M≈1000. How this steep spectrum is connected with hadron energy spectrum? Further investigations would explain this.

Comparison of data obtained in both runs for NaI and ZnS detector is shown in Fig. 4 along with boron counter data. It is seen that the data for NaI and ZnS detectors almost coincide. Statistically significant excess exists only in the first two bins but it can be easily explained by the effect mentioned above: NaI is sensitive to gammas from fast neutron inelastic scattering while ZnS detector is not. Note that data for these detectors are not normalized. Nevertheless, their data coincide. This means these detectors have equal detection efficiency 40% because the

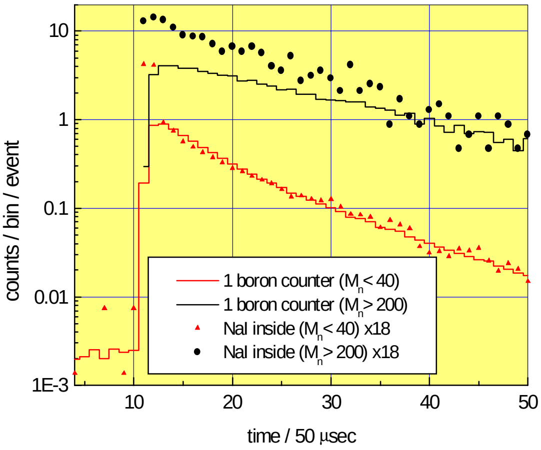

Fig. 2. Delayed pulse time distributions for various total neutron multiplicity M_n as measured by NaI detector and by a boron counter.

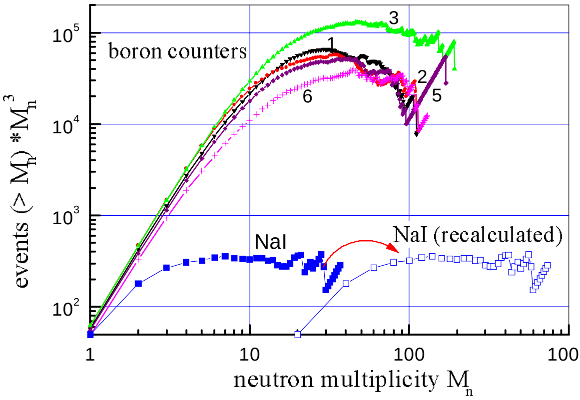

Fig. 3. Neutron integral multiplicity spectra for various neutron detectors.

ZnS detector has known efficiency 40%. In contrary, the data of boron counter were normalized by a factor of 18. Thus, its efficiency is estimated to be 15%, very close to that one could expect.

Fig. 5. shows the data of outer ZnS detector (multiplied by a factor of 8) in comparison with that of 1 m^2 plastic scintillator. Making once again simple calculations one can obtain thermal neutron recording efficiency for our 5 cm plastic scintillator as ε_{plas}= 2%. As it was mentioned in (Stenkin et al., 1999; Stenkin et al., 2001), these detectors having 4 MeV threshold can produce measurable pulses through (n,γ) reactions in surrounding matter. The best candidate for such a reaction target is detector housing made from 0.5 mm iron. The probability for thermal neutrons to be captured by 0.5 mm Fe (λ_{Fe}= 45.4 mm) is equal to 1- exp(-0.5/45.4) =1.1% and 2.2% in 2 iron box walls. This figure is very close to what we have measured.

Another interesting result is shown in Fig. 6 where one can see the effect of shifting in height of one plastic scintillator detector with simultaneous addition of iron blocks. Subtraction procedure has been applied here: data without shift (1^{st} Run) were subtracted from the data of 2^{nd} Run for 2 ranges of neutron multiplicity.

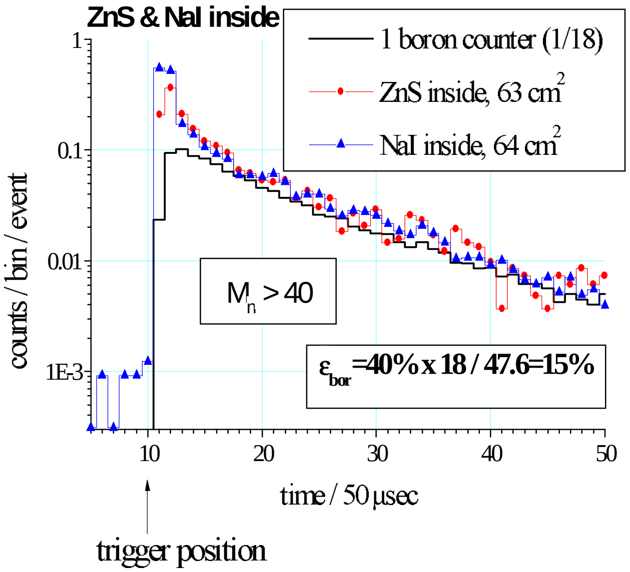

Fig. 4. Comparison of data obtained with different detectors inside the NM.

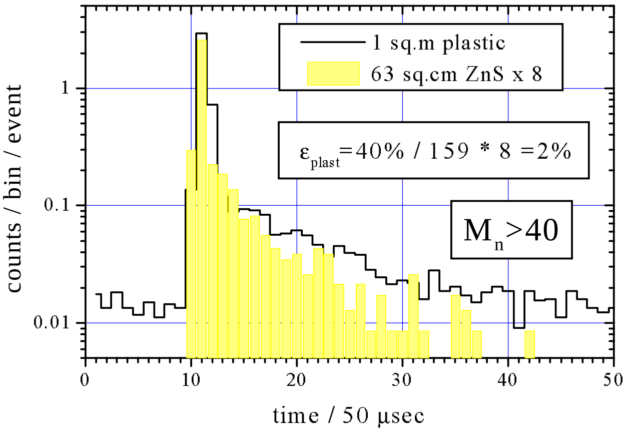

Fig. 5. Outside ZnS data in comparison with that for plastic scintillator detector.

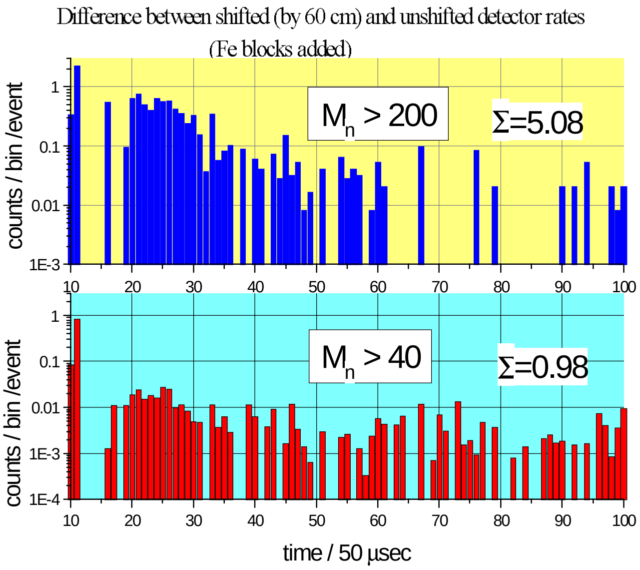

Fig. 6. Effect of a detector shifting and addition of Fe blocks.

Note that vertical scale is logarithmic and so negative data are not shown. These plots also confirm undoubtedly that the plastic scintillator detectors record thermal neutrons. The delay appeared is very close to that one could expect for neutrons moving with thermal velocity 2.2 m / msec. The positive excess shown on the plots as Σ was also expected: this is effect of target mass increasing (Fe blocks) for n$\rightarrow\gamma\rightarrow$e conversion. For comparison we show the same data but for neighboring unshifted detector in Fig. 7. The difference is obvious.

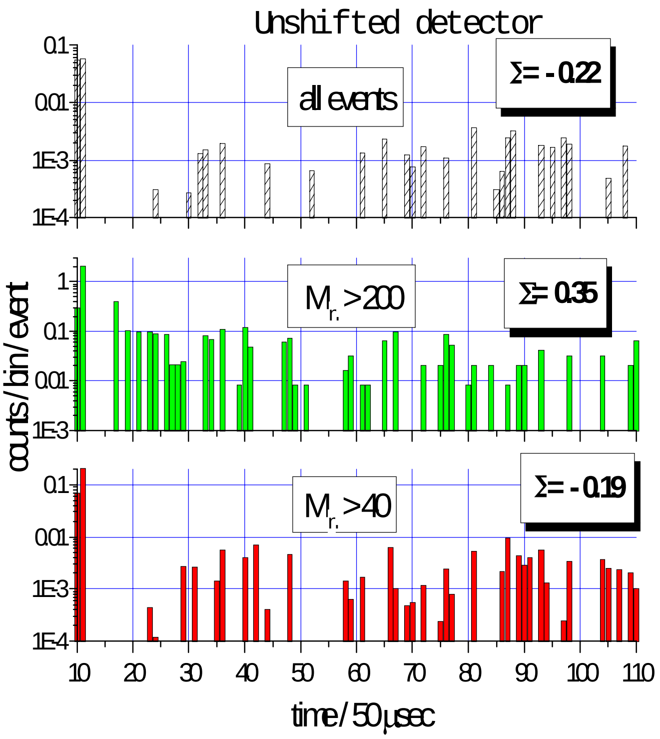

Fig. 7. Results of subtraction of different Runs data for unshifted detector.

The biggest event measured up to now counts >713 delayed pulses in 5 plastic scintillators and 55 neutrons recorded by inner ZnS detector. Taking into account the detection efficiencies given above one can recalculate these figures and obtain huge total number of neutrons in the burst: >35650 n's passed through outside scintillators and 55 / 0.4 x 18=2475 n's recorded only by one boron counter (equivalent) inside the NM64! Note this is only neutrons which could be captured by boron in an "ideal" boron counter. Taking into account that other counters usually detect at least the same amount of n's and ~95% of thermal n's are captured by hydrogen in NM moderator one could conclude that total number of neutrons thermalized inside the NM was as much as 2475 x 2 / 0.05 ≈ 10^5! Primary energy of this EAS estimated through electron component is ~ $2{\cdot}10^{15}$ eV and through muon component ~ 10^{16} eV.

4 Conclusion

The Baksan experiment has confirmed our previous conclusions about the peculiar delayed pulses distributions in gas proportional counter and its explanation by poor time resolution of such a counter. Usage of scintillator detectors for neutron detection showed this experimentally without any doubt. It also helped us to measure real thermal neutron fluxes inside and outside the NM during the bursts (Stenkin and Valdes-Galicia, 2001), to measure neutron detection efficiencies for boron proportional counters and for plastic scintillator detectors. We have measured neutron multiplicity spectrum in NM64 and have showed that if boron counter would be as fast as ZnS detector it could detect at least up to 1000 neutrons in one event and the multiplicity distribution should obey power low with integral index equal to -3.

- We confirm the existence of *neutron bursts* – events with very high neutron multiplicity;
- We have it proved experimentally that boron proportional gas counters are saturated during the bursts;
- We have it proved experimentally that delayed pulses in outer detectors are caused by thermal neutrons;
- We do not confirm the existence of delayed EAS component within time of several ms;
- New experiments and new calculations should be done to answer the question: Is it only fluctuations of the EAS hadron contents or we deal with abnormal EAS similar to Centauros?

Using Carpet-2 preliminary data we can say now that the burst events are very energetic (>10^{15} eV), EAS core in such events is located very close to the NM and the number of muons is also very high.

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