Structure of scintillation detector response at Yakutsk array in showers with energy above 10 EeV

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Abstract. **During the period from 2006 to 2009 more than 30 extensive air showers with energy above 10 EeV were registered at Yakutsk EAS. We present results obtained with differential scintillation detectors with different threshold energies. Time structure of a shower front was analyzed, thin structure of the signal from detector was revealed and magnitudes of signals from ground and underground detectors were compared.**

Keywords: **extensive air showers, time-related measurements, particle interaction**

I. INTRODUCTION

For many years at the Yakutsk EAS array studies of the pulse shape from Cherenkov and scintillation detectors have been performed [1], [2]. Initial measurements of the pulse shape from 2-m^2 scintillation detector at the Yakutsk array have been performed in 1975, continued in 1988-1990 and renewed in 2005. Lately, a special designed setup has been used for this purpose, which consists of scintillation and Cherenkov detectors and quick-response electronics. All this allowed reconstruction of time-related characteristics of forward and back fronts and curvature and thickness of shower disk with a good precision. Measurements have shown that time-base of the signal in scintillation detector can be used in quantitative analysis of EAS data, including cosmic ray mass composition data.

There are two stations measuring pulse shape at Yakutsk array separated by 500 m from each other. Each station has several scintillation detectors, differing by time resolution (fast and slow) and by energy threshold (2 and 10.5 MeV). Events are selected by scintillation and Cherenkov "masters".

II. EQUIPMENT USED FOR REGISTERING THE PULSE SHAPE FROM CHARGED PARTICLES

For measurements at the Yakutsk EAS array scintillation detectors of different areas and thickness were used. Two detectors were 2 m^2 and were separated by 51 m from each other, the rest six were 1, 0.25, 0.10 and 0.02 m^2 correspondingly and were placed in apexes of a tetragon with sides 7 and 4.5 m. One of the detectors ($s = 0.10$ m^2) had a lead ceiling (thickness 10 cm), similar detector had no top and was covered with thin black paper. These detectors were appointed for studying the influence of the cover material on detector response and the ratio between muons with $E_{thr.} \geq 0.3$ GeV and
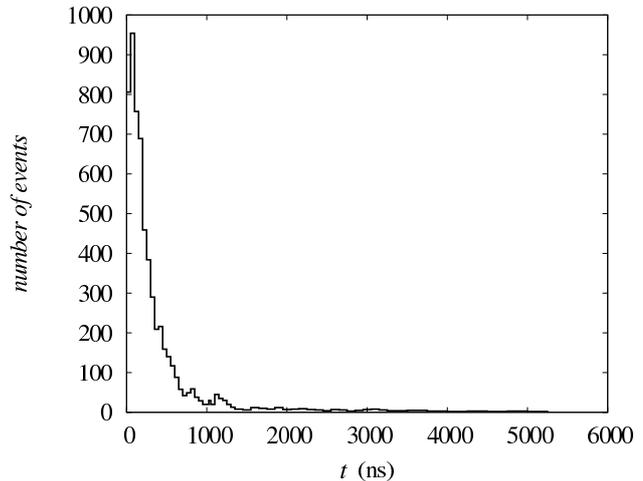

Fig. 1. Delayed pulses distribution (relative to the "fastest" particle) over delay time t. Considered core distances in the range of $80 - 1500$ m

electrons in a shower. Scintillation detector with area of 1 m^2 was 1 cm thick and effectively registered particles with $E_{thr.} \geq 2$ MeV. For studying the spati-temporal characteristics of Cherenkov radiation a camera obscura was used [3].

A. Recording system and control

For pulse shape recording we used an industrial computer of increased reliability equipped with integrating board with 19 PCI slots. *La-n10-m8* boards with two fast 8-bit AD-converters with 100 MHz sampling rate and 2 Mb buffer store were plugged in these PCI slots. The computer is meant for 20 ADCs. Registration is controlled by external "masters". Masters generated by the main array when signals from three noncollinear scintillation detectors spaced by 500 m coincide (so-called *Trigger-500*). Masters are generated by the small Cherenkov array when signals from three integral Cherenkov detectors located in apexes of equilateral triangle with side 50, 100 and 250 m coincide. After registration program start, ADCs continuously convert signals from detectors outputs and repeatedly record them into the area of buffer memory called "pre-history". In the "pre-history" the latest data on digitization of valid signals are stored, period between neighbouring counts is 10 ns. After accepting the "master", signals of "master" coloring and data on the amplitude of calibration LED are recorded into the area of buffer memory called "history". Accepted frames of events are
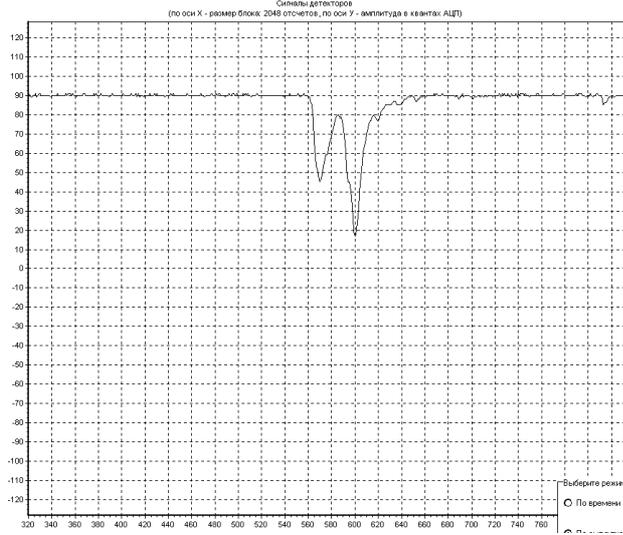
Fig. 2. An example of anomalous pulse shape. Channel number 16 (detector without ceiling). There are also double pulses in other detectors but with very small amplitude

Fig. 3. Pulse shape recorded at the core distance $R = 1298$ m. $E_0 = 1.7 \times 10^{19}$ eV, zenith and azimuth angles equal to $18°$ and $78°$ respectively

formed as a file record and added to the initial file, created automatically at the beginning of observation. Such a selection system allows pulse registration in showers with energies $10^{15} - 10^{19}$ eV.

III. REGISTRATION RESULTS

After ~ 18000 hours of array duty cycle $\sim 1.2 \times 10^5$ showers were registered with energy above 10^{15} eV. In every event arrival time of forward front of charged particles and Cherenkov light, build-up time and pulse half-width were measured and pulses from delayed particles were recorded on a time scale up to 15 mcs. Shower characteristics such as primary energy, zenith and azimuth angles, shower size (full number of charged particles, full number of muons with $E_{\text{thr.}} \geq 1$ GeV) and depth of maximum development were estimated with scintillation and Cherenkov detectors of the main array.

During the analysis several peculiarities were discovered in the shape of registered pulses as well as in their time distribution. This concerns both "young" (vertical) showers and "old" (inclined) showers. The former have half-width of the pulse $200 - 250$ ns, the latter — $150 - 180$ ns. There are showers with large amount of delayed particles and in some events the time scale notably extends up to 10 mcs.

As it follows from fig. 1, in most EAS events delayed particles are distributed over the interval $\Delta t = 40 - 2000$ mcs, which coincides with particles picking time of ADC at the Yakutsk array.

From the huge amount of data one can distinguish a small group of showers with clearly visible double-peaked shape (see fig. 2). Such a shape is traced at a single detector, as well as at two-three detectors. The delay time of the second group of particles lies within $60 - 350$ ns from the first one. The number of such events is all in all $\sim 1.5 - 2\%$ from the total
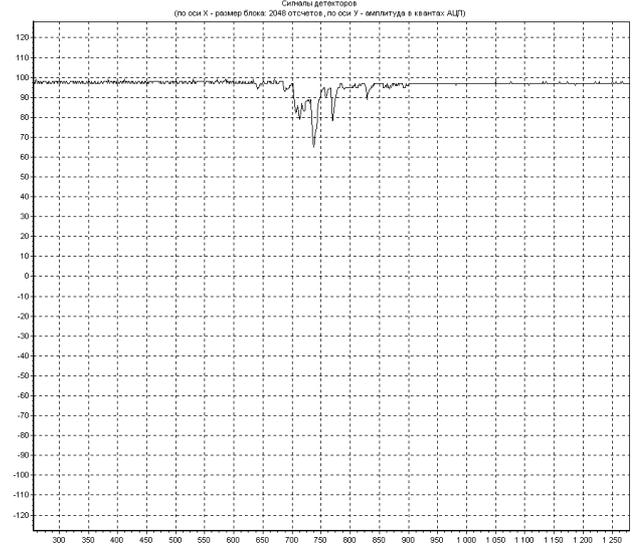
number of registered EAS events. From all the data listed above, it is possible to classify showers by their pulse shape. Electron-photon shower has larger pulse half-width and half-height compared to "muonic" one. Pulse structure consists of many saw-like peaks distributed in interval from 0 to 1000 ns starting with the first particle arrived at the detector (see fig. 3). Such pulses to a greater degree reflect string nature of shower particles generating including electron-photon component of the shower. Such a pulse shape usually is peculiar to vertical showers with low maximum in the atmosphere.

"Muonic" showers have round pulse peak and notably 30% lesser half-width compared to pulse from the electron-photon shower component (see fig. 4). Judging by the pulse such particles arrive compactly i.e. distributed in lesser time interval from 0 to 550 ns. Such a pulse shape can be observed in inclined showers and in showers with low maximum of development.

It has been assumed since the very beginning that both single detectors and their combinations are to be considered in the analysis. This is connected with the fact, that detectors have different relative apertures on core distances and different threshold for registering relativistic particles — 10, 5 and 2 MeV. Also, the relation of signals from two geometrically identical detectors, with and without additional shielding ($E_{\text{thr.}} \geq 0.3$ GeV for muons) was taken into account. Preliminary analysis of the experimental data has shown that scintillation detectors with different areas have different registering efficiency. In showers with $E_0 = 10^{17} - 10^{18}$ eV counters with $s = 0.1, 0.25$ m^2 effectively operate at core distance $R \leq 500$ m and counter with $s = 2$ m^2 does so at $R \leq 1500$ m. Thus, smaller counters can participate in the "trigger-500" generating and the larger ones — in the "trigger-1000" generating. It has been
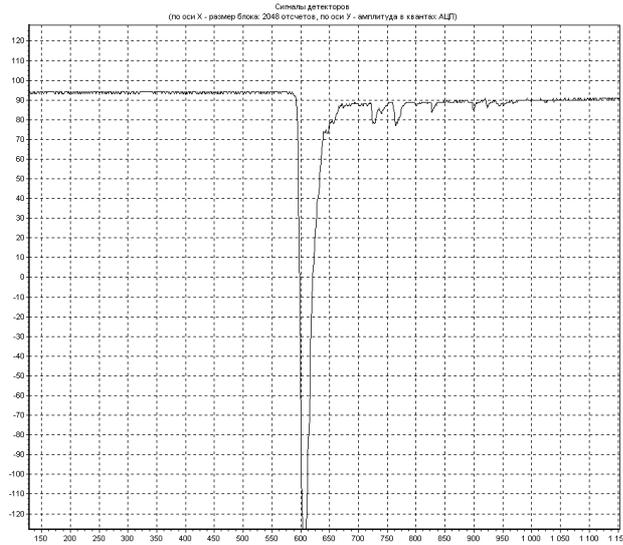
Fig. 4. Pulse shape recorded at the core distance $R = 1000$ m. $E_0 = 2.4 \times 10^{19}$ eV, zenith and azimuth angles equal to 56° and 200° respectively

Fig. 5. Delayed pulses distribution over the amplitude A. Histogram — the Yakutsk EAS array data. Curve – single muons (QGSjet [4]). (It should be noted, that there are showers, where response from a shielded detector with $E_{\text{thr.}} \geq 0.3$ GeV is bigger than that from an unshielded one)

noted, that pulse characteristics, build-up time of the forward front, half-width on the half-height and response strongly depend on the detector type (geometry, method of light gathering — direct or reflected) and on the type of voltage divider on PMT's dynodes. It was shown by comparing the responses from fundamentally different detectors with $s = 1$ m^2 and $s = 2$ m^2. Reaction of the scintillation counter with $s = 1$ m^2, gathering light with optical fiber mounted into the plastic scintillator and with fast PMT "FEU-115" is $200 - 300$ ns faster than that of the large scintillation counter with $s = 2$ m^2 and this fact makes it preferable for precise measurements of time-related characteristics of a shower. From the analysis of showers of different energies one may conclude, that the signal in showers with energy $\sim 10^{17}$ eV is represented by the single-peaked pulse, not unlike the pulse from inclined shower and this fact speaks well for faster development compared to showers with energy $\sim 10^{19}$ eV with maximum of development at the depth $750 - 850$ g/cm^2.

Analysis of the signal amplitude also has shown interesting results (see fig. 5). To begin with, in some cases the amplitude in shielded detectors is much higher, than in unshielded ones. Preliminary analysis of such showers ($E_0 \sim 10^{17} - 10^{18}$ eV, core distance $R \leq 200$ m) points to the presence of low-energy hadrons in a stream, which interact with shielding material and generate a micro-shower resulting in growth of the signal amplitude. Secondly, from the comparison of experimental amplitudes distribution with QGSjet simulation for single muons [4] it follows that in the range of $n \geq 5$ relativistic particles, there is an excess of registered particles over simulated, which also requires explanation. One of the versions — generating of Cherenkov radiation in glass of the PMT's photocathode, which we observed in special experiments with closed Cherenkov detectors at $R \leq 125$ m from the
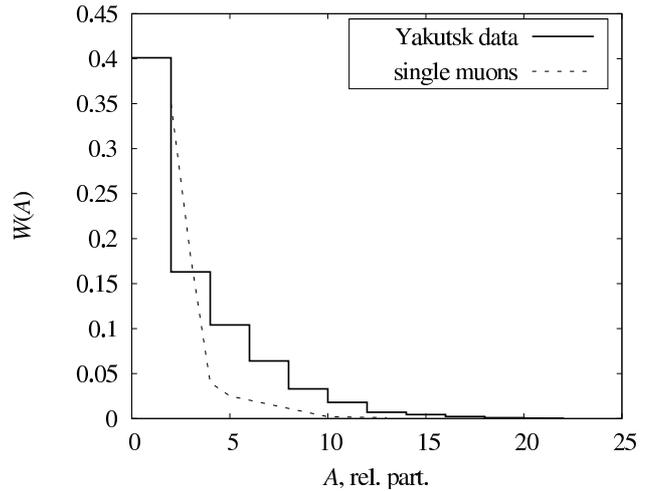
core in showers with energies $10^{17} - 10^{19}$ eV. It should be stressed out, that the portion of such events is rather small and makes about 3%.

A. Forward and rear EAS front. Thickness and curvature of the shower disk.

On fig. 6 time-related shower characteristics are shown, obtained in measurement of charged particles and Cherenkov photons arrival times at the array detectors. A wide distance range was covered, showers with energy above 10^{17} eV were selected. Measurements have shown, that up to distances ~ 300 m forward front is semi-flat and slightly exceeds the precision of zenith angle measurement at the Yakutsk array (100 ns). At $R \geq 300$ m from the core front delay increases significantly and at $1000 - 1500$ m amounts $400 - 800$ ns, requiring taking it into account in measurement of EAS arrival angles.

Using the value of particle arrival delay at the detector $\langle \tau \rangle$, one can obtain curvature radius of the shower front. These times characterize areas of shower development in the atmosphere from which at a given core distance the main portion of particles arrives. Radius of curvature is determined by formula:

$$R_{\text{curv}} = \frac{R^2 - (c\tau)^2}{2c\tau},$$

where R — core distance, τ — particle delay, c — speed of light. For experimental data of the Yakutsk array at mean core distance 790 m and $\langle \tau \rangle = 248$ ns, $R_{\text{curv}} = 4180$ m. Along with the core distance the curvature radius increases, meaning that particles arrive from larger heights.

IV. CONCLUSION

Time-related measurements of the signal from scintillation detectors, extracting electron-photon and muon
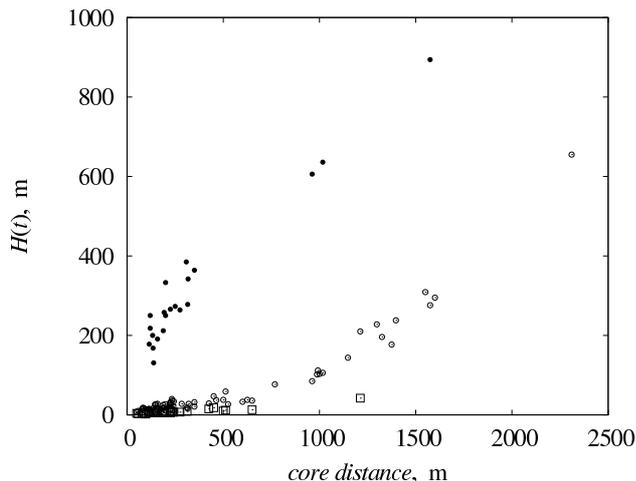
Fig. 6. Forward and back EAS fronts reconstructed by time delays measured in showers with energies above 10^{16} eV. Open circles — forward front (charged particles), filled circles — rear front. Squares — Cherenkov photons

components of a shower are important from different perspectives: a) to give an idea of shower development in the atmosphere, how do characteristics of a signal depend on kind of particle and what particles are we measuring essentially and finally, what exactly are we measuring with scintillator (thick and thin)? b) do pulse characteristics directly depend on atomic number of primary particle, initiated a shower? Our measurements for showers with ultra-high energies have shown:

1) pulse structure depends on parameter $\Delta X = X_0 \cdot \sec\theta - X_0$ (here $X_0 = 1020$ g/cm^2 for Yakutsk), i.e. on the amount of matter where the shower is developing;

2) slope of the lateral distribution function η (essentially the age) correlates with pulse shape;

3) pulse shape in vertical showers (these are showers with $E_0 \geq 10^{19}$ eV as a rule) reflects many-staged nature of nuclear interactions — multiple peaks in the pulse shape, where each peak represents a sub-cascade, i.e. generation of particles with greater portion of electron-photon component. In inclined showers particles arrive at observation level with compact group, most likely muons with a small fraction of electrons;

4) in time-base of several showers there are pulses of a small amplitude delayed by more than 2 mcs and which are well-detected with a thin scintillator (1 cm thick), proving that the energy of such particles is relatively small;

5) there are signals registered in shielded detectors ($E_{\text{thr.}} \geq 0.2$ GeV) with amplitude exceeding that from unshielded detectors ($E_{\text{thr.}} \geq 0.1$ GeV). The amount of such events is small and the nature of these signals is unclear. Increase of statistics and in-depth analysis of shower characteristics (e.g. portion of muons with different threshold energies, influence of gamma-photons on the pulse shape)

are required.

6) Difference in amplitudes of signals from shielded and unshielded detectors mentioned above speaks of additional source of particles arising in the shielding, since by-standing detectors of the same type don't show such signals. As a rule, it is an even number of particles (two, fore...), that can be associated with generation of pairs from bremsstrahlung of gamma-photon in the shielding material or forming of electron halo during significant ionization loss of muons in dense matter.

There is another opinion. In shower on mean core distances ($180 - 450$ m) there are particles capable for generation of small sub-cascades in the shielding material, for instance, hadrons of relatively small energy or other active particles.

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