Temporal Structure of the Muon Disk at Large Distances from Core of EAS with $E_0 > 6{\cdot}10^{16}$ eV

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Abstract

Preliminary investigation results of the temporal structure at the big muon detector of the Yakutsk EAS array for the primary energy $E_0 \geq 6{\cdot}10^{16}$ eV at distances of 100-1500 m from a shower core are presented. The big muon detector of 184 m^2 area with the registration threshold $E_\mu \approx 0.5{\cdot}\sec\theta$ GeV began to operate since November 1995. Experimental data are compared with calculations according to the QGS model. At $E_0 > 10^{18}$ eV the tendency to the decrease of the muon disk thickness is observed.

1. Introduction:

Since 1974 muons with threshold energy $E_\mu \approx 1.0{\cdot}\sec\theta$ GeV are continuously investigated at the Yakutsk array. A large amount of experimental data has been accumulated over this period of time, making it possible to investigate in detail the lateral distribution function (LDF) of muons in extensive air showers (EAS) with primary energy $E_0 \approx 10^{17} - 3{\cdot}10^{19}$ eV and zenith angles $\theta \leq 60^o$ over a wide range of distances R from the EAS core. Glushkov et al. (1995) showed that a form of the LDF for $E_0 \geq (3\text{-}5){\cdot}10^{18}$ eV differs from that at lower energies. Specifically, it becomes much steeper at distances $R > 400$ m.

To determine the reasons for such a difference in the LDF and to perform further investigations, a big muon detector (BMD) consisting of 92 scintillation counters of 2 m^2 area each arranged in six rows over an area of 26×12 m^2 (Afanasiev et al., 1997) was built at the Yakutsk array. The detector is located at 180 m from the center of the array. The ground screen gives a muon detection threshold of $0.5{\cdot}\sec\theta$ GeV. Each counter operates independently and is equipped with a individual amplitude-time channel for measuring the number of particles and the arrival time of the first particle with an accuracy of ~ 6 ns.

Here we report the preliminary analysis results of BMD data obtained by using 30 counters (Glushkov et al.,1998). Experimental results are compared with calculations by the QGS model (Kaidalov, Ter-Martirosyan & Shabelski, 1986) for the primary protons.

2. Investigated Characteristics:

Fig.1 presents one of delay distributions T for the muon arrival with $E_\mu \approx 0.5{\cdot}\sec\theta$ GeV relative to a flat front (a plane perpendicular to a shower core at the point where the core intersects the array plane) calculated by this model for EAS with $E_0 = 10^{18}$ eV and $\cos\theta \geq 0.9$ at the distance R = 630 m (curve 1). The muon density at this distance is $\rho_\mu(630) = 0.35$ m^{-2}. The distribution is of the average $\langle T \rangle = 156$ ns, the standard deviation $\sigma_T = 114.2$ ns.

In fact we measured experimentally not values T but the relative delays $t_i = T_i - T_1$, where T_1 is the arrival time of the fastest muon at any of n operated counters of BMD for each shower; T_i is the arrival time of the first muon on the i-th counter. The distribution of these delays is a form close to the exponential one:

$$P(t) \approx \exp(-t/\lambda) \qquad (1)$$

Characteristics of (1) are strongly dependent on the mean density $<\rho_\mu(R)>$ of registered muons, more precisely, on the number of muons m passed through a counter of the area S (in our case, S = 2 m^2), and the expected value is $<m> = <\rho_\mu(R)>\cdot S$ according to the Poisson law

$$P_m(<m>) = <m>^m / m! \cdot \exp(- <m>).$$

The curve 2 in Fig.1 is the distribution derived from the curve 1 by the Monte-Carlo method at $<m> = 0.7$ and $n = 2$. It has $<t> = 99$ ns and $\sigma_t = 115.8$ ns.

Below we will consider only average delays of $<t>$ derived from (1).

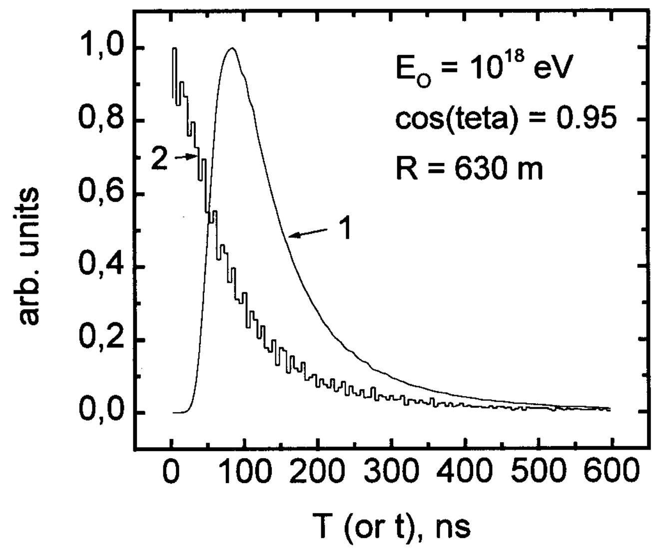

Figure 1: Distribution of arrival delays of muons with $E_\mu \approx 0.5\cdot\sec\theta$ GeV at a distance from the core R = 630 m ($\rho_\mu(630) = 0.35$ m^{-2}) in EAS with $E_0 = 10^{18}$ eV and $\cos\theta = 0.95$ according to the QGS model for primary protons: 1 - relative to a flat front, 2 - relative to the first muon in each of 5000 showers under the operation of 2 counters of 2 m^2 each ($<m> = 0.7$)

3. Comparison of Experimetal Results and Calculations:

Fig.2 presents the dependence of $<t>$ for the showers with $10^{17} \le E_0 \le 10^{18}$ eV and $\cos\theta \ge 0.95$ at the distances R = 100 - 1500 m. The solid circles are BMD measurements, the curve is the calculation by the QGS model at $<m> = 0.9$.

All measured delay distributions are of the form (1). Parameters λ coinside with $<t>$ at $<m> = 1$ within experimental errors. On this bases it is not difficult to find the relation for the estimation of T_η - a time necessary for the registration of part η of all muons:

$$T_\eta \approx - <t> \ln(1- \eta). \qquad (2)$$

From (2) it follows that the effective thickness of muon disk (95% of all particles) in EAS with $E_0 \le 10^{18}$ eV at $R \le 1000$ m is no more than 400 ns.

Fig.3 demonstrates $<t>$ versus $\sec\theta$ for EAS with $E_0 = 10^{17} - 10^{18}$ eV ($<E_0> \approx 3\cdot10^{17}$ eV) at R = 630 м, and - Fig.4 shows a change of $<t>$ versus E_0 at the same distance in the showers with $\cos\theta \ge 0.8$. All experimental values $<t>$ were obtained in selecting the events with the number of registered muons ≤ 1.5. This corre-

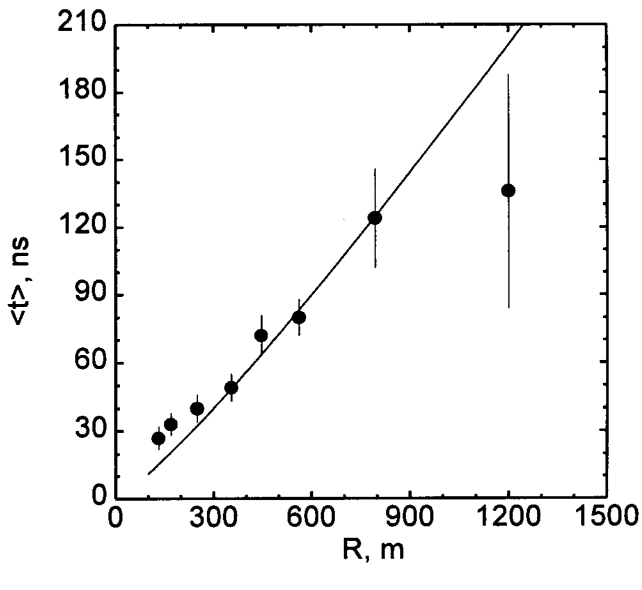

Figure 2: $<t>$ vs R in EAS with $<E_0> \approx 3\cdot10^{17}$ and $\cos\theta \ge 0.9$: ● – experiment; a line is the QGS model for primary protons ($<m> = 0.9$)

sponds to a sampling with <m> ≈ 0.9. In this case in each selected shower on the average <n> ≈ 2.2 counters were operated.

The calculations made taking into account actual conditions of the experiment and selection of data under their treatment, are shown in Figs.3, 4 by lines.

The experimental data in Figs.2-4 satisfy to the relation

$$\langle t\rangle = a_0 + a_1 \cdot \log(E_o/10^{18}) + a_2 \cdot (1 - \sec\theta) + a_3 \cdot \log(R/630), \quad (3)$$

where $a_0 = 95 \pm 2$ ns, $a_1 = 6 \pm 3$ ns, $a_2 = 110 \pm 4$ ns, $a_3 = 170 \pm 9$ ns. This expression is applied for showers with $E_o \approx 6 \cdot 10^{16}$ - 10^{18} eV and $\theta \leq 45^o$ at distances $R \approx 300$ - 1000 m.

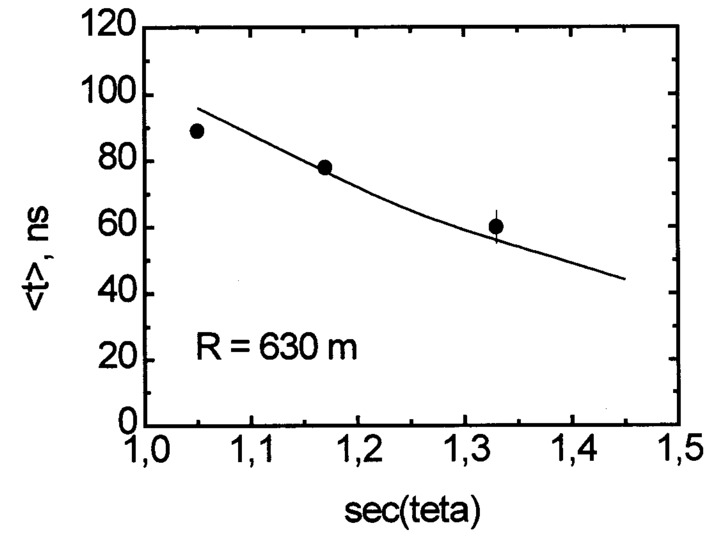

Figure 3: <t> vs secθ in EAS with $< E_o > \approx 3 \cdot 10^{17}$ at R = 630 m with the selection of counters by the number of registered muons ≤ 1.5 (<m> ≈ 0.9) for <n> = 2.2 operated in the individual shower of detectors; a line is the QGS model for primary protons

The data analysis shows that a growth of <t> with increase of E_o takes place with the velocity $\partial\langle t\rangle/\partial\log(E_o) \approx a_1$ for events of different θ and R (within indicated limits of changes of these parameters). It is caused by the shift of the shower development maximum depth X_m to the observation level (for Yakutsk $X = 1020 \cdot \sec\theta$), i.e. by the decrease of $X - X_m$ to the shower maximum.

From (3) we can estimate elongation rate: $ER = \partial X_m/\partial \log(E_o) \approx a_1 \cdot 1020/a_2 \approx 56 \pm 28$ g·cm^{-2}.

At $E_o > 10^{18}$ eV the showers are of another time structure of the muon disk. In Fig.4 it is seen that all measured values of <t> are less than those obtained by the QGS model and expected at the extrapolation of experimental data from $E_o < 10^{18}$ eV. From a physical point of view at first sight, it is difficult to understand.

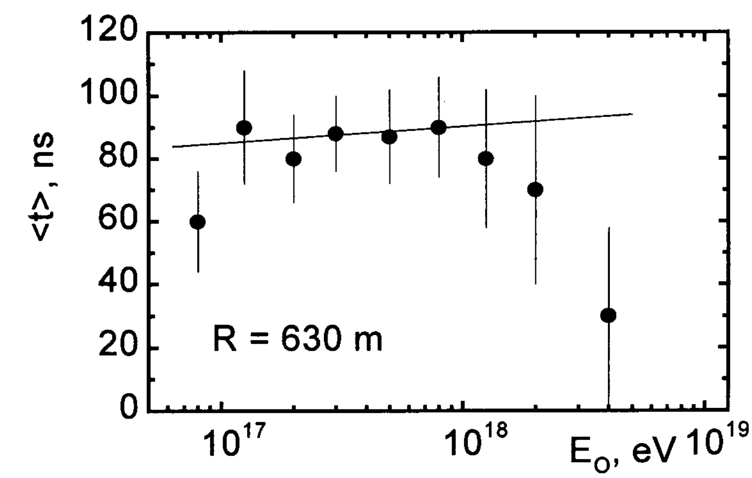

Figure 4: <t> vs E_o in EAS with <cosθ> = 0.9 at R = 630 m with the selection of counters by the number of registered muons ≤ 1.5 (<m> ≈ 0.9) for <n> = 2.2 operated in the individual shower of detectors; a line is the QGS model for primary protons

It is not connected with methodical reasons although there are a few measurements at present time. Here events of <m> ≈ 0.9 have also been selected. Deviations in these selections were $|\langle\cos\theta\rangle - 0.9| \leq 0.02$ by zenith angles and $|\langle\log R\rangle - \log(630)| \leq 0.2$ by distances. They were taken into account by means of reduction of obtained values <t> to the considered by us standard according to (3).

The calculations show (Fig.4) that at the fixed zenith angle the value <t> weakly depends on E_0, and therefore it is difficult to explain the observed tendency of the essential decrease of the muon disk thickness in the framework of a superposition model by the fast change of the primary particle composition even from protons to iron nuclei. On the assumption of the fast moving off of the shower maximum, i.e. the decrease of X_m, then the same rapid decrease of the total number of electrons in these showers is to be expected, but it is not observed (Glushkov, Pravdin & Sleptsov, 1997).

Note that many EAS parameters by Yakutsk array data have an anomaly at $E_0 > (2\text{-}5)\cdot10^{18}$ eV (Glushkov et al., 1995; Glushkov, Pravdin & Sleptsov, 1997; Glushkov et al., 1998). We consider that a reason of their appearance is common, but it is not caused by the methods of experiment at the Yakutsk array.

The analysis of the above data confirms the hypothesis of multiaxis EAS development suggested by us earlier (Glushkov et al., 1995). Its substance is that in the ultrahigh energy region some new processes of nuclear interactions take place. It may be suggested that they are of the threshold character in energy. The value of this threshold is $\sim (2\text{-}3)\cdot10^{18}$ eV. At higher energies in the first interaction act of cosmic rays the second exotic particles (one or several) are generated which divide all primary energy E_0 among themselves and define all future development of the shower, the cores of which are separated at sea level to 200-300 m. At the expense of that one of EAS cores is considerably nearer to the detector, it gives main contribution to its readings, the relative delays will be less (Fig.2).

4. Conclusion:

The preliminary analysis of BMD data showed that the measured time structure of the muon disk in EAS with $10^{17} \leq E_0 \leq 10^{18}$ eV and $\theta \leq 45°$ at distances from a core $R \leq 1000$ m was consistent with the calculated one according to the QGS model for the primary protons. At $E_0 > (1\text{-}2)\cdot10^{18}$ eV experimental data show that the muon disk thickness tends to be noticeably decreased. If this anomaly is verified with increasing statistics then the conception about the EAS development in the ultrahigh enegry region should be essentially changed. The effective thickness of the muon disk (95% of all particles) at $R \leq 1000$ m is $\leq$ 400 ns.

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References

Glushkov, A.V., Makarov, I.T., Nikiforova, E.S. et al. 1995, Astroparticle Physics 4, 1274
Afanasiev, B.N., Filippov, S.A., Glushkov, A.V. et al. 1997, Proc. 25th ICRC 7, 261
Glushkov, A.V., Kosarev, V.B., Makarov, I.T. et al. 1998, JETP LETTERS 67, N 6, 383
Kaidalov, A.V. Ter-Martirosyan, K.A. & Shabelski, Yu. M. 1986, Yad. Phiz. 43, 1282
Glushkov, A.V., Pravdin, M.I. & Sleptsov, I.Ye. 1997, Proc. 25th ICRC 6, 233