Evaluation of the gamma-quanta fraction in the primary cosmic ray flux with energy about $10^{17}$eV according to the EAS MSU array data

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Abstract. Using the data of the EAS MSU array and model calculations we have performed the search of events with abnormally small fraction of muons with energy above 10 GeV in showers with particle numbers greater than $2 \cdot 10^7$ and with zenith angles less than 30 degrees. The aim of the work – to estimate a fraction of muon-poor showers in which the underground muon detector registered no muons. These events may be identified as showers generated by primary gamma-quanta of ultrahigh energies. With good statistical accuracy we have confirmed our earlier conclusion that the content of gamma-quanta in the primary cosmic ray flux may be as much as 2 % at energies about $10^{17}$ eV.

1. Introduction

Investigation of the mass composition of ultrahigh energy primary cosmic rays (PCR) is one of the actual problems of cosmic ray physics as these experimental data are very important for creation of the adequate theory of cosmic ray generation in sources and their subsequent propagation from sources to the Earth. Because of the low intensity of ultrahigh energy cosmic rays the direct measurements are not possible, therefore the only method of their registration is the extensive air shower (EAS) employment.

Naturally, at considering of the PCR mass composition there is a question whether particles of other nature exist among usual nuclear cosmic rays, in particular, we mean gamma-quanta of ultrahigh energies. This question was studied still in the sixties of the last century (see, for example, [1]), however the final quantitative answer still has not been received.

One of the approaches to the solution of this problem is the investigation of the EAS muon component, as the share of muons in EAS generated by gamma-quanta is tens times lower than in showers from particles of the nuclear nature. Therefore the search of events with an abnormally small fraction of muons is an adequate tool for the evaluation of gamma-quanta content in primary cosmic rays.

In the present work the portion of muons in EAS with number of particles above $2 \cdot 10^7$ and with zenith angles below than 30 degrees registered at the EAS array of Moscow State University [2] from 1982 to 1990 is discussed.
2. EAS MSU array
The EAS MSU array had the total area of 0.5 km² and consisted of 70 scintillator detectors for the particle density registration and 30 detectors for measurement of the arrival time of particles. The latter group was used for the estimation of EAS zenith and azimuthal angles. Besides the surface detectors for the electron-photon component measurements the array had 4 underground detectors located on the depth of 40 m of water equivalent. These detectors registered muons with energy above 10 GeV. The detector of the area of 36.4 m² was placed in the center of the array and consisted of 1104 Geiger-Muller counters, other three detectors of 18.2 m² area were located at distances 150 – 300 m from the array center. During 1982 – 1990 a substantial statistics of EAS in the primary energy range of $10^{15} – 10^{18}$ eV containing the data on both of electron-photon and of muon components was obtained.

The results of the analysis of the array data obtained earlier were presented in many publications. However the big statistical material continues to be processed and now allows to get new scientific results.

3. Evaluation of the gamma-quanta fraction according to the EAS MSU array data.
Existence of the muon detectors of rather big area (80 m²) allows to estimate a probable fraction of gamma-quanta in a flux of primary cosmic rays at energy above $2 \cdot 10^{17}$ eV. This method is based on the fact that in showers with $N_e \geq 10^7$ the absence of muons with energy more than 10 GeV in the underground detector of the area of some tens square meters is improbable if the EAS axis is within a circle of radius of ~200 m from the muon detector and shower is created by a proton or heavier nucleus. At the same time such events are quite compatible to a hypothesis that they are results of the development of a shower generated by a primary gamma-quantum as in this case the density of muons essentially decreases in comparison with usual nuclear showers.

![Figure 1. Radial distribution of the experimental muon-poor showers](image1)

![Figure 2. Relative contribution of various primary energies to the total number of EAS with $N_e \geq 2 \cdot 10^7$. $E_0$ – the energy of particle that gives the average $N_e = 2 \cdot 10^7$. Points – fluctuations are accounted for, solid line- without fluctuations](image2)
The full statistics of events with energy above $10^{17}$ eV registered by EAS MSU array includes 1679 showers and the total number of zeroes in the muon detector is equal 48.

Figure 1 shows distribution of events with the zero indication of the detector depending on its distance from the EAS axis. It is quite natural that the greatest number of zero events is observed at large distances from the EAS axis. However there are some events near the axis. It is very difficult to explain such events by usual fluctuations in shower development. In the analysis of the muon-poor events it is necessary to take into account that the true number of the zero events is more than the experimentally observed one because of the existence of the background which is not connected with the EAS registration. The probability of absence of random functioning of the detector is equal 0.52.

4. Modeling of the artificial showers.

To evaluate the fraction of the muon-poor showers generated by primary gamma-quanta, experimental results were compared to the theoretical calculations of the muon-poor shower fraction by the Monte-Carlo method with use of the AIPES program for the proton primary composition. The assumption of the purely proton composition gives the maximum probability of the random events with the zero number of muons in the muon detector, as in showers from heavier nuclei the muon number is more than in proton showers.

Usually the modeling of showers is carried out using the CORSIKA program, however in this work we preferred the AIPES program as it works much faster and the speed of the program is very important for providing a set of statistics sufficient for the interpretation of the experimental results. Preliminary estimates showed that for a set of the statistics comparable with experimental one (1679 events) taking into account fluctuations in EAS development and possibility of generation of showers with size $2 \cdot 10^7$ or higher by primary particles of small energies it is required to get more of simulated events. For calculations we used the version of the AIPES program (2.6.0) [3] with the QGSJET-01 model of hadron interactions [4]. Simulations were carried out for primary protons with energies in the range from $3 \cdot 10^{16}$ to $2 \cdot 10^{17}$ eV and in the range of zenith angles from 0 to 30 degrees. In total about 20000 showers were calculated. The integral index of primary energy spectrum was accepted as 2.0.

From the calculated set the showers with $N_e \geq 2 \cdot 10^7$ and $\Theta < 30^\circ$ have been selected. Figure 2 shows the probability of the required showers creation by protons of various energies.

The evaluation of the probability of the zero indication of the detector (m=0) in showers hitting a ring $\Delta R_k$ from the muon detector was made as follows.

Let $n_{tot}$ - the full number of selected showers. The muon density in a ring $\Delta R_k = R_{k+1} - R_k$ is defined by expression

$$\rho_k(\Delta R_k, i) = N_\mu(\Delta R_k, i) / (\pi (R_{k+1}^2 - R_k^2)),$$

where $N_\mu(\Delta R_k, i)$ - the number of muons in a ring, i - the number of a shower changing from 1 to $n_{tot}$.

Then the probability of the zero indication of the detector located in a ring $\Delta R_k$ is given by expression

$$P(m = 0, \Delta R_k) = 1 / n_{tot} \cdot \sum_{i=1}^{n_{m}} 0.52 \cdot \exp(-\sigma \cdot \cos \theta \cdot \rho_k(\Delta R_k, i)),$$

where $\sigma$ - the area of the muon detector of 36.4 m$^2$, $\cos \theta$ - the value of $\cos \theta$ for a given shower, 0.52 - the probability of absence of random functioning of the detector (see part 3).

The total probability of the event with $m = 0$ is equal

$$P_{tot}(m = 0) = \sum_{k=1}^{k_{max}} P(m = 0, \Delta R_k) \cdot P_k,$$

where $P_k = (R_{k+1}^2 - R_k^2) / R_{max}^2$ - the probability of the EAS axis hitting in an interval $\Delta R_k$ from the muon detector.
The calculated probability of the muon-poor events for various intervals $\Delta R$ from EAS axis and the number of the muon-poor events for the total number of experimentally registered events 1679 are given in the table.

| $\Delta R$, m | Experimental number of zeros | Simulated probability P(m=0, $\Delta R$) | Simulated number of zeros (QGSJET) | Simulated number of zeros (SYBILL) |
|---------------|-----------------------------|------------------------------------------|-----------------------------------|-----------------------------------|
| 60–90         | 3                           | $1.0 \cdot 10^{-7}$                     | 0                                 | 0                                 |
| 90–120        | 0                           | $4.3 \cdot 10^{-6}$                     | 0                                 | 0                                 |
| 120–150       | 2                           | $1.2 \cdot 10^{-4}$                     | 0.2                               | 0.5                               |
| 150–180       | 5                           | $4.5 \cdot 10^{-4}$                     | 0.8                               | 2                                 |
| 180–210       | 14                          | $1.8 \cdot 10^{-3}$                     | 3                                 | 5                                 |
| 210–240       | 24                          | $5.5 \cdot 10^{-3}$                     | 9                                 | 14                                |

The total probability of receiving of a muon-poor event for all distances from axis to 245 m is equal $7.8 \cdot 10^{-3}$ that corresponds to 13 muon-poor events. It should be noted that the greatest number of such events appears in two last rings (see Table) though the expected number of the muon-poor events arising from the natural fluctuations is in 3-4 times less than experimental one. Thus, comparing simulated and experimental data it is possible to define a fraction of gamma-quanta about 2 % in a flux of primary cosmic rays at energy about $10^{17}$ eV. So more detailed analysis of number of the muon-poor showers carried out in the present work confirms the earlier result of [5].

Naturally, a question arises whether our conclusion holds true if some model giving a smaller number of muons is used. According to our estimation the reduction of muon density by 30 % (that approximately corresponds to the transition from the QGSJET-01 to the SIBYLL model [6]) changes the result essentially only in the last interval. The contradiction is still retained, especially at radii less than 200 m.

5. Conclusion.
The detailed simulation in the wide range of primary energies and at various zenith angles of primary particles with good statistical accuracy confirmed the conclusion that about 2 % of gamma-quanta exist in the flux of primary cosmic rays with energy about $10^{17}$ eV.

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6. References
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