Muons with threshold 1 GeV in extensive air showers with energy greater than 5 EeV

S P Knurenko and I S Petrov
Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin ave., 677980, Yakutsk, Russia
E-mail: igor.petrov@ikfia.ysn.ru

Abstract. The paper presents an analysis of the characteristics of muons with a threshold greater than 1 GeV in showers with energies greater than 5 EeV and zenith angles less than 60 degrees. The analysis is based on the registration data of extensive air showers of the Yakutsk array. Estimation of muons at different distances from the shower core, fraction of
\[
\frac{\rho_{\mu}}{\rho_{\mu+e}} \quad \text{at a distance of 600 m are obtained. Calculations of the fraction of muons}
\]
are performed using the QGSJetII-04 hadronic interaction model for different primary nuclei, and compared with the data. Mass composition of primary particles is estimated by muon component. Several showers were found in the sample, with a low content of muons which possibly is produced by ultrahigh energy gamma rays.

1. Introduction
Cosmic rays in EAS experiments have been measured up to $10^{20}$ eV, but their sources are still unknown, the acceleration mechanisms and mass composition are not precise, and some features of the spectrum are not fully understood [1–5]. Large arrays such as TA [6] and Auger [7] EAS use optical methods that are highly dependent on atmospheric conditions, methods for processing the experimental data, hadronic interaction models etc. Therefore, in order to verify those data it is necessary to use a different method and a different component of the air shower to estimate mass composition, for instance muons.

The muon component is sensitive to mass composition of cosmic rays [8], as shown by calculations using the QGSJetII-04 [9] model for hadronic interactions for the primary proton and iron nucleus. And this component can be used to estimate mass composition over a wide range of energies. Muon measurements doesn’t depend on weather condition, times of day unlike optical measurements.

For this work, the data of the Yakutsk array for 1995-2015 were used. The data consists of EAS with energies greater than 5 EeV with muon measurements. The Yakutsk array measures the Cherenkov, charged, radio, and muon components of the EAS. It has an area of 8 km², which allows it to effectively measure showers in the range of $10^{15}$-10$^{20}$ eV [10].

2. Muon registration and results
At the Yakutsk experiment, muons with a threshold $\varepsilon_{\text{thr.}} \geq 1$ GeV are measured by 6 underground detectors of average size: 3 detectors of 16 m² — two of which are at a distance of 500 m and one at a distance of 300 m; 3 detectors of 20 m² — two of which are located at...
a distance of 800 m and one at a distance of 500 m. One large detector — 190 m$^2$, which is located at a distance of 150 m. Three muon telescopes with an area of 2 m$^2$ each, at a distance of 200, 300 and 500 m [11,12].

![Figure 1. Layout of observation stations at the Yakutsk EAS installation. Double dots show stations on the setup, each station has two scintillation detectors, triple dots show stations with Cherenkov detectors, rectangles show muon detectors.](image)

To select showers for analysis, the following criteria were applied: the distance from the shower axis to the center of the setup had to be within 1200 m from the center of the setup and measurements of muons in the distance range 400-800 m, the accuracy of measuring the characteristics of the shower was within 5-10 $\%$, $E_0 \geq 5$ EeV and zenith angles $\theta \leq 60 ^\circ$. Such criteria made it possible to determine with a good accuracy the flux density of muon component $\rho_\mu$ and the flux density of charged component $\rho_{\mu+}\epsilon$ at a distance of 600 m from the shower axis. The distance of 600 m from the axis was chosen due to the fact that fluctuations of charged particles and muons are small at this distance [13, 14]. Total of 802 showers were selected for the final sample.

![Figure 2. Dependence of the zenith angle on the fraction of muons.](image)

![Figure 3. Dependence of the shower energy on the muon flux density.](image)

Figure 2 shows the statistics of the showers as a function of the fraction of muons on the zenith angle and figure 3 shows the statistics of the showers as a function of energy on the muon flux density.

As can be seen (figure 2), the fraction of muons increases with the zenith angle, and the relative content of muons reaches almost 100% at 60 degrees, i.e. the shower consists almost entirely of the muon component. Red curve is approximation given by:

$$\lg A_{\theta=0^\circ} = \lg A_\theta - (1.98 \pm 0.45) \cdot \lg \sec \theta + (0.06 \pm 0.02) \lg \rho_{\mu+e},$$

(1)

Where $A = \rho_\mu/\rho_{\mu+e}$ — fraction of muons, $\theta$ — zenith angle.
The flux densities of the muon and charged components were determined from the lateral distribution function (LDF) (figure 4) [15].

\[ \rho_{\mu+e}(R) = \rho_{\mu+e} \cdot \frac{600}{r} \cdot \left( \frac{1 + \frac{600}{R_0}}{1 + \frac{r}{R_0}} \right)^{b_s - 1}, \]  

(2)

where \( R_0 \) is the Moliere radius in meters, \( b_s \) is the slope characteristic of the lateral development function of charged particles, which depends on the parameter \( \rho_{\mu+e} \) and the zenith angle \( \theta \), according to formula (3):

\[ b_s(\theta, \rho_{\mu+e}) = (1.38 \pm 0.06) + (2.16 \pm 0.17) \cdot \cos \theta + (0.15 \pm 0.03) \cdot \lg \rho_{\mu+e}(600), \]  

(3)

The LDF of the muon component is described by formula [15]:

\[ \rho_\mu(R) = \frac{N_\mu}{2\pi R_0^2} \cdot \frac{b - 2}{x} \cdot \frac{1}{(1 + x)(b - 1)}, \]  

(4)

where \( x = \frac{R}{R_0} \), \( N_\mu \) is the total number of muons, which is found by integrating the average LDF of muons, \( b \) and \( R_0 \) are parameters that are found from the experiment.

The classification parameters \( \rho_\mu \) and \( \rho_{\mu+e} \) were determined by formulas (2) and (4) for a distance of 600 m. The ratio of these values \( \rho_\mu/\rho_{\mu+e} \) for a fixed energy is the most sensitive characteristic to the mass composition of cosmic rays.

3. Distribution of muon fraction in showers with energy 5-50 EeV

To quantitatively estimate the atomic weight of a particle forming a shower, we used calculations using the QGSJETII-04 [9] model, which were compared with experimental data. The experimental data were compared with the calculations performed for the primary gamma quantum, proton, carbon nucleus and iron nucleus. The calculations took into account the response of underground and ground scintillation detectors to muons with a threshold \( \varepsilon_{\text{thr.}} \geq 1 \) GeV provided that more than one muon passes through the detectors. The calculations were normalized to the general statistics of the selected showers and reduced to the vertical \( (\theta = 0^\circ) \), so they could be directly compared with the experimental data.

Comparing the calculation results with the experimental data, it should be noted that the distribution for each particle is localized within certain boundaries and, when compared with the experiment, creates the effect of some similarity in the form of the shown distributions. For example, on the left side (figure 5), a group of showers with a low muon content in the interval...
(0-0.3) can be distinguished, a group of showers in the interval (0.4-1.3), a group in the interval (0.8-1.5) and the last group (1.1-1.8). Based on the calculations, it can be concluded that the first group of showers is formed by primary gamma quanta, the second — by a proton and helium nucleus, EAS events with a relatively low muon content, the third group — by CNO nuclei, and the last — by an iron nucleus. In percentage terms, the number of showers, presumably formed by protons and helium nuclei, is (40-50)%. Showers that can be formed by primary gamma quanta (1-2)%.

Figure 5. Calculations of the relative abundance of muons in extensive air showers performed using the QGSJETII-04 model for different primary nuclei (curves). Histogram — experimental data selected in the energy range 5-50 EeV and zenith angles $\theta \leq 60^\circ$.

The rest of the showers are formed by nuclei of heavier chemical elements: CNO nuclei and iron Fe nuclei. The result obtained cannot be considered final, since "smearing" of the histogram in figure 5 is due to the low statistics of showers, experimental errors in the measurement of muons, and the procedure for processing showers. To improve the quality of comparison, the measurement accuracy of muons and charged particles is required at the level of (3-5)% [9], which is still incomparable with the experimental accuracies, which are (5-15)% in the Yakutsk experiment.

4. Conclusion

In this work, we used the data of the Yakutsk array on the muon component obtained for 1995-2015. The development of the muon component is associated with the longitudinal development of EAS — the depth of the development maximum Xmax, which makes it possible to use the muon component for an independent assessment of the mass composition. For this, we used the $\rho_\mu/\rho_{\mu+e}$ parameter at a distance of 600 m, as the most sensitive parameter to the mass of the primary particle that formed the EAS. From measurements, the dependence of $\rho_\mu/\rho_{\mu+e}$ on the zenith angle and $\rho_\mu$ on the shower energy was established, which made it possible to bring all selected showers to the same conditions for the development of muons in the atmosphere. In turn, this made it possible to compare the experimental data with the calculations of the QGSJetII-04 hadron interaction model and to estimate the mass composition of cosmic rays.

Figure 5 shows the energy-normalized experimental distribution of the parameter $\rho_\mu/\rho_{\mu+e}$ as a function of the number of muons in the mean shower at a fixed energy. Calculations using the QGSJETII-04 model for different primary particles are also plotted there. As can be seen from the figure, the distribution has several maxima, and these maxima refer to particles with different atomic weights. A quantitative comparison of the experimental data with the calculations showed: a) in percentage terms, the group of showers with energies of 5-10 EeV, presumably formed by protons p and helium nuclei He, which is from 40 to 50 % of the total number of showers in the sample; b) (1-2) % of showers can be formed by primary $\gamma$ ray; c) the rest of the showers are formed by nuclei of heavier chemical elements, for example, CNO and iron nuclei Fe.
References

[1] Kampert K H and Unger M 2012 Astropart. Phys. 35 660–78
[2] Becker J 2008 Phys. Rep. 458 173
[3] Ahlers M, Anchordoqui L, Gonzalez-Garcia M, Halzen F and Sarkar S 2010 Astropart. Phys. 34 106
[4] Kotera K, Allard D and Olinto A 2010 J. Cosmol. Astropart. Phys. 10 013
[5] Gelmini G, Kalashov O and Semikoz D 2008 J. Theor. Phys. 106 1061
[6] Abbasi R, Abe M, Abu-Zayyad T, Allen M, Azuma R, Barcikowski E, Belz J, Bergman D, Blake S, Cady R et al. 2016 Astropart. Phys. 80 131–40
[7] Aab A, Abreu P, Aglietta M, Samarai I A, Albuquerque I, Allekotte I, Almela A, Castillo J A, Alvarez-Muñiz J, Anastasi G et al. 2017 J. Cosmol. Astropart. Phys. 04 038
[8] Atrashkevich A, Kalmykov N and Christiansen G 1981 JETP Lett. 33 236
[9] Ostapchenko S 2011 Phys. Rev. D 83 014018
[10] Knurenko S and Petrov I 2019 Adv. Space Res. 64 2570–7
[11] Artamonov V, Afanasyev B, Glushkov A et al. 1994 Bull. Russ. Acad. Sci.: Phys 58 98
[12] Ivanov A, Knurenko S, Pravdin M and Sleptsov I E 2010 MSU Bull. 65 292
[13] Ivanov A, Knurenko S and Sleptsov I 2007 J. Exp. Theor. Phys. 104 870–84
[14] Knurenko S, Ivanov A, Sleptsov I and Sabourova A 2006 JETP Lett. 83 473–7
[15] Glushkov A, Efimov N, Efremov N et al. 1983 Cosmic rays with energy greater than $10^{17}$eV 18th International Cosmic Ray Conference (Tata: Tata Institute of Fundamental Research) pp 3–18
[16] Glushkov A, Dyakonov M, Knurenko S et al. 1993 Bull. Russ. Acad. Sci.: Phys 57 91–3