On the angular distribution of extensive air showers

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Angular distributions of extensive air showers with different number of charged particles in the range $2.5 \times 10^5 - 4 \times 10^7$ are derived using the experimental data obtained with the EAS MSU array. Possible approximations of the obtained distributions with different empiric functions available in literature, are analysed. It is shown that the exponential function provides the best approximation of the angular distributions in the sense of the $\chi^2$ criterion.

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Introduction

The angular distribution of extensive air showers (EAS) reflects the process of development and the following absorption of an air shower as it traverses the atmosphere of the Earth. This is the reason why an interest to the subject does not decrease in spite of the long-time study.

The first results on the altitude development of EAS and their angular distribution were obtained in the middle of the twentieth century, see, e.g., a review by Greisen [1]. The results related to air showers detected at a fixed density of the particle flux. The results of the experiments for the lower third of the atmosphere witnessed about an exponential absorption of showers with altitude. As a rule, the distribution of the zenith angle obtained from data on the altitude development was approximated as $\sim \cos^n \theta$ with $n \approx 8.3$ for the sea level.

This result was confirmed more than once in numerous works in which individual EAS characteristics, including those performed with the KASCADE experiment, which was begun in 1996 especially for investigating the problem of the knee in the primary cosmic ray energy spectrum at $3 \times 10^{15}$ eV [2]. However, it was claimed recently basing on the results obtained with the Tien Shan experiment (atmosphere depth 690 g cm$^{-2}$) that there is a considerable excess of air showers with $\cos \theta$ being equal to 0.6–0.7 for EAS with the size above $10^7$ particles [3, 4]. The result was interpreted by the authors as an indication of the increasing role of the so called “long-flying component” in the longitudinal development of an EAS [4]. Due to this, it is appropriate to discuss the problem of the altitude development of EAS and their angular distribution once again.

1 Experimental Data

In our paper, we present results of an analysis of angular distributions of air showers in sufficiently narrow intervals in accordance with the number of charged particles $N_e$ in a wide range of $N_e$ from $2.5 \times 10^5$ up to $4 \times 10^7$. Experimental data obtained with the EAS MSU array from 1984 to 1990 were used for the analysis. A detailed description of the array can be found in [5]. The array covered an area of $\sim 0.5$ km$^2$ and included 77 detectors of density of the flux of charged particles. The values of $N_e$ were determined with the help of an empiric function of lateral distribution that provided the best fit for the experimental data [6].
Arrival directions of EAS, defined by the zenith and azimuthal angles $\theta$, $\phi$ respectively were determined using a system of fast scintillation counters via measuring relative time delays of triggering of these counters, located at different places of the observation plane. Thirty-six counters with 5-cm thick scintillators having an area of 0.5 m$^2$ each were used for the measurements. Eight counters were located at the central unit of the array, six were placed at the distance of about 60 m from it. Other 22 counters were placed uniformly over the area covered by the array.

An arrival direction of each EAS was determined in two steps. The method of least squares with a flat air shower front assumed was used as the first approximation. The method of maximum likelihood was employed next. The method took into consideration experimental data on the distribution of particles over the depth of a shower disc and the curvature of a shower front obtained with the EAS MSU array [7].

Accuracy in determination of the zenith angle was of the order of 3$^\circ$ for the majority of EAS, improving for greater values of $\theta$ and decreasing for nearly-vertical air showers. Methodical errors increased the values of the zenith angles due to relatively lesser delays of triggering of counters located closer to the shower axis because of higher flux density of the incident particles and their narrower temporal distribution.

### 2 Main Results

All showers registered with the probability greater than 0.95 were selected for the analysis of angular distributions. The effective region for selecting the registered EAS was determined taking into account fluctuations in air shower development. It was determined by the triggering system of EAS, the value of $N_e$, and the parameter of the function of the lateral distribution of charged particles in each shower. Air showers with $\theta > 45^\circ$ were excluded from consideration. These EAS formed approximately 1% of the whole data set. Air showers with $\theta < 6^\circ$ were also excluded from the analysis because of the greatest errors in determination of their zenith angles. Radii of regions of effective registration, intervals of $N_e$ that include the knee in the size spectrum of EAS at $N_e \approx 4 \times 10^5$, and the number of air showers in each of the intervals are presented in the Table.

**Table.** Intervals of $N_e$, radii of regions of effective registration, the number of air showers in each interval, values of $P(\chi^2)$, and values of the absorption path $\lambda$ of EAS.

| $\Delta \lg N_e$ | 5.4–5.6 | 5.6–5.8 | 5.8–6.0 | 6.0–6.2 | 6.2–6.6 | 6.6–7.0 | 7.0–7.6 |
|-----------------|---------|---------|---------|---------|---------|---------|---------|
| $R_{\text{eff}}$, m | 20 | 30 | 40 | 50 | 59 | 85 | 158 |
| Number of EAS | 12923 | 13699 | 10608 | 7302 | 5720 | 1925 | 1338 |
| $P(\chi^2)$, % | 7 | 60 | 6 | 42 | 54 | 64 | 80 |
| $\lambda$, g cm$^{-2}$ | 120 | 115 | 112 | 110 | 115 | 120 | 116 |

Angular distributions for the listed intervals of $N_e$ were obtained by splitting the data for the zenith angle into 3$^\circ$-wide intervals. Figure 1 demonstrates angular distributions of air showers for three intervals of $N_e$.

It is natural to compare the experimental angular distributions of EAS with the exponential distribution expected a priori:

$$f(\theta) = A \exp \left[ -\frac{x_0}{\lambda} \left( \frac{1}{\cos \theta} - 1 \right) \right],$$ (1)
Figure 1: Angular distributions for $N_e = 5.4$–5.6, 6.0–6.2, 7.0–7.6 (from top to bottom). $N$ is the number of EAS in bins. The curves show the behaviour of distribution (1) for $\lambda = 110, 115, 120$ g cm$^{-2}$ ($\triangledown, \bigcirc, \triangle$ respectively) and $\cos^0 \theta$ (+).
as well as with its approximation given by \( \cos^n \theta \). In the above expression, \( A \) is a normalization factor, \( x_0 \) is the vertical atmosphere depth, \( \lambda \) is the absorption path of air shower. In both cases, an additional factor \( \cos \theta \), which takes into account the decrease of the effective area of the array with increasing angle of inclination of an air shower, was used. The value of the absorption path was found by minimizing \( \chi^2 \).

Results of the comparison of different distributions for the given intervals of \( N_e \) are also shown in Figure 1. It is clearly seen that agreement between the experimental distributions and their approximations is quite good, though for two of the intervals the probability \( P(\chi^2) \) is not high. Values of \( P(\chi^2) \) together with the values of the absorption path \( \lambda \) are given in the Table.

The optimal values of the absorption path \( \lambda \), which ensure a minimum to \( \chi^2 \), were found with an error \( \pm 0.5 \text{ g cm}^{-2} \). As it follows from the Table, the absorption path of the number of air showers remains almost constant in the considered range of \( N_e \) (the mean value \( \lambda \approx 115 \text{ g cm}^{-2} \) and the standard deviation \( \sigma \approx 4 \)). Small values of \( P(\chi^2) \) possibly relate to random fluctuations.

For the sake of comparison, calculated angular distributions in the usually accepted form \( \sim \cos^n \theta \), where \( n = x_0/\lambda \), are also shown in Figure 1. In our case, \( n = 9 \). As is clear from the figure, the agreement of this approximation with the experimental data is worse, especially for highly inclined air showers.

In the approximation that does not take into account fluctuations in the development of an air shower, the absorption path of an EAS relates to the absorption path \( \Lambda \) of the number of particles in an air shower as \( \Lambda = \kappa \lambda \), where \( \kappa \) is an exponent of the integral size spectrum [8]. For air showers with \( N_e \lesssim 10^6 \), \( \kappa \approx 1.5 \). For \( N_e \gtrsim 10^6 \), the value of \( \kappa \) grows approximately up to 2.0. Therefore, under the assumption that \( \lambda \) is almost constant in the considered range of EAS sizes, we come to the conclusion that the development of an air shower slows down for great values of \( N_e \) in spite of a change of the chemical composition of cosmic rays toward heavier nuclei.

### Conclusion

Results comparable with the presented above were obtained at the sea level with the KASCADE experiment during an investigation of EAS with the number of particles \( N_e \) in the range from \( 3 \times 10^4 \) to \( 3 \times 10^6 \), which includes the region of the knee in the size spectrum [2]. The absorption path of the number of particles \( \Lambda \) in an air shower was found by the method of constant intensity to be equal to \( 175 \text{ g cm}^{-2} \) before the knee and to grow up to \( 194 \text{ g cm}^{-2} \) above the knee. Assuming another location of the knee in the size spectrum, it was found in another work that also employed data from the KASCADE experiment that \( \Lambda = 222 \pm 28 \text{ g cm}^{-2} \) [9]. Close results were obtained in the EAS-TOP experiment (\( \Lambda = 219 \pm 3 \text{ g cm}^{-2} \) at depth \( 820 \text{ g cm}^{-2} \)) [10].

In conclusion, let us consider the results presented in [4]. The authors of that work reported an excess of EAS with zenith angles that correspond to atmosphere depth greater than \( 1100 \text{ g cm}^{-2} \) and have absorption path \( \lambda = 585 \pm 45 \text{ g cm}^{-2} \) instead of \( \lambda = 130 \pm 7 \text{ g cm}^{-2} \) observed for lesser angles. The EAS MSU and KASCADE experiments do not confirm this result.

Thus, the analysis performed and the comparison of its results with the results of the KASCADE experiment do not provide any ground for the conclusion about an increasing role of the long-flying component with the growth of the primary energy of cosmic rays.

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