Primary Mass Composition at Energies 10^{17}-10^{18} eV according to the EAS MSU Array Data.

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***Abstract*. Experimental data on electron and muon component obtained with EAS MSU array are analyzed for investigation of mass composition of primary cosmic rays at the energies 10^{17}–10^{18} eV. EAS MSU array had 4 muon detectors with total area of 80 m^2. The threshold muon energy was 10 GeV. Muon lateral distribution functions were obtained for shower with particle number up to 4×10^8 and the dependence of the mean muon density at a fixed shower core distance on particle number was derived. Comparison of the experimental dependence with that simulated for different primary nuclei in the framework of the QGSJET model shows that for energy beyond the knee the abundance of heavy nuclei increases with shower size for sizes $\leq 10^7$ but above this value the abundance of light nuclei starts to grow. The mean value $\overline{\ln A}$ decreases from 3.2 to 1.7. This conclution has been confirmed by the new analysis of the EAS MSU experimental data on EAS radio emission. Using the simulatied correlation between the EAS radio emission lateral distribution form at the core distances 150–200 m and the shower maximum depth the mean experimental shower maximum depth was estimated as (657 ± 12) g/cm^2 ($\overline{\ln A} = 2.0 \pm 0.4$) for the primary energy 4×10^{17} eV.**

***Keywords*: Cosmic rays, extensive air showers, primary mass composition**

I. Introduction

Investigation of the mass composition of the primary cosmic rays at energies from 10^{15} to 10^{17} eV has been performed at the EAS MSU array over many years [1],[2]. It was shown that at energies above 3×10^{15} eV (the knee energy) the abundance of light nuclei decreases while the abundance of heavy nuclei starts to increase. This behavior is in agreement with the idea that energy $E_{cr}(Z)$ at which the knee is observed for nucleus with charge Z is proportional to Z. Such dependence follows, for example, from the shock acceleration in SN remnants and is compatible with the diffusion model of the knee also. At 10^{17} eV the knee should take place even for Fe-nuclei. However the experimental energy spectrum of all particles has the same index as for lower energies. It indicates that at energies near and above 10^{17} eV the flux of the primary cosmic rays is enriched with particles that are different from traditional Galactic cosmic rays accelerated by shocks.

II. Mass composition at energies above 10^{17} eV according to the muon component of EAS

It is a matter of common knowledge that the muon number in EAS with fixed size is sensitive to the mass number of a primary particle. For correct investigation of the mass composition at energies above the knee it is necessary to have experimental data for a wide primary energy interval because $E_{cr}(Z)$ of various nuclei differ very strongly (26 times for protons and Fe-nuclei). The EAS MSU array just gives a possibility to investigate EAS muons in a wide energy interval from 10^{15} to 10^{18} eV.

The primary mass composition according to the EAS MSU array data was considered in our previous publications [1], [2], [3]. Here we present the results based on the investigation of the muon component for higher primary energies up to 10^{18} eV. Using the data of four muon detectors (threshold energy 10 GeV and the total area 80 m^2) which were employed at the EAS MSU array muon lateral distribution functions (LDFs) were reconstructed in showers with numbers of particles N_e up to 4×10^8. It was obtained that the experimental muon LDFs are described good enough by the empirical formulae: $\rho_\mu \sim r^{-n} \exp(-r/R_0)$, where $R_0 = 80$ m, and n is changed from 0.5 at $N_e \sim 10^6$ to 0.75 at $N_e = 4 \times 10^8$.

These data were used for the determination of the dependence between muon density ρ_μ at 50 m from the shower axis and number of particles N_e. The choice of 50 m was conditioned by the fact that at this distance the muon density is determined with a good statistical accuracy for all ranges of N_e (from 10^5 to 4×10^8) registered by the EAS MSU array.

Fig **??** shows the $\rho_\mu(N_e)$-dependence which is approximated by relation: $\rho_\mu \sim N_e^\alpha$ where $\alpha = 0.77 \pm 0.02$ for $N_e < 4 \times 10^7$ and $\alpha = 0.64 \pm 0.05$ for $N_e > 4 \times 10^7$.

Two curves are presented also on the Fig 1–$\rho_\mu(N_e)$-dependences for pure protons (low curve) and for pure Fe-nuclei (upper curve). These simulated dependences were obtained in the framework of the QGSJET model [4]. It is clear from the plot that the experimental points at the beginning show an enhancement of heavy nuclei

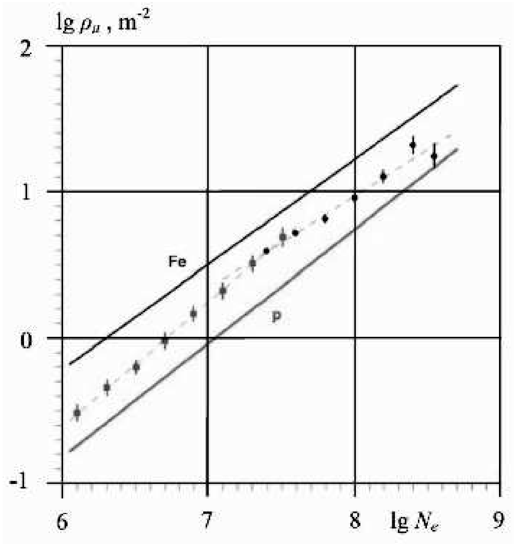

Fig. 1: $\rho_\mu(N_e)$–dependence, points–EAS MSU array experiment, lines–QGSJET simulation for primary protons and Fe-nuclei.

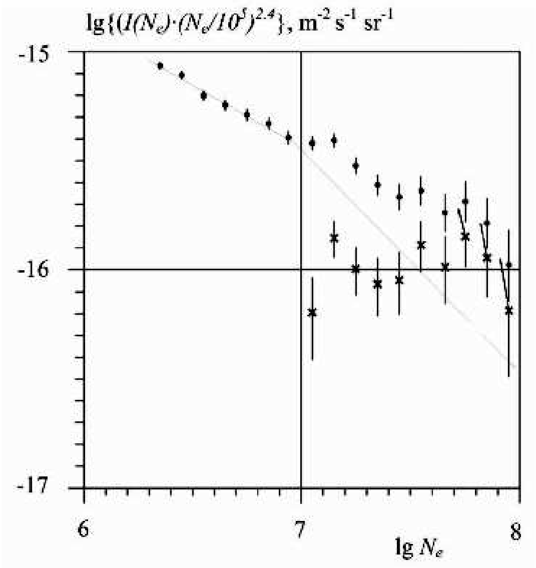

Fig. 2: Experimental particle number spectrum -• ,line–simulated spectrum, crosses–additional component of EAS spectrum.

abundance in primary cosmic rays up to $N_e \sim 4 \times 10^7$ and then the index of $\rho_\mu(N_e)$-dependence is changed and the experimental points come nearer to the proton curve. It indicates that primary composition is enriched with light nuclei.

III. Additional component at energies above 10^{17} eV

Previously it was shown [2] that the all particle energy spectrum constructed from the partial spectra changing their indexes from 2.7 to 3.7 at $E_{cr}(Z)$= $Z \cdot 3 \times 10^{15}$eV provided the best fit of the experimental electron and muon number spectra obtained with the EAS MSU array. However the primary mass composition which fits best all primary spectra at energies below 10^{17} eV does not describe the spectrum at energies corresponding to $N_e > 10^7$ (see Fig 2). Fig 2 shows that at $N_e > 10^7$ the predicted intensity is essentially less than experimental one. So for the description of the experimental spectra it is necessary to assume that at energies greater than 10^{17} eV there exists an additional cosmic ray component which is not significant at lower energies. The existence of this component and its nature has been discussed already earlier (see for instance [5]).

The experimental EAS MSU array particle number spectrum for $10^7 < N_e < 10^8$ can be approximated by the formulae: $I(N_e) = (0.50 + 0.20 - 0.14) \cdot 10^{-16} \cdot N_e^{-2.36\pm0.08}\ m^{-2} \cdot s^{-1} \cdot sr^{-1}$

Thus we can see that the spectrum index in this region is approximately the same one as in the region before the knee at 3×10^5.

From the experimental data and the extrapolation of the simulated spectrum to the region of $N_e > 10^7$ it is possible to derive the number of showers generated by the additional component. If we suppose that the additional component consists from protons only and using the QGSJET model [4] the energy spectrum of the additional component can be described by the formulae: $I(N_e) = (1.45 + 0.58 - 0.41) \cdot E_0^{-2.55\pm0.09}\ m^{-2} \cdot s^{-1} \cdot sr^{-1}$.

The presence of the additional component influences the value of $\overline{\ln A}$, used for the quantitative description of the mass composition. Our analysis shows that $\overline{\ln A}$=3.2 at $N_e \approx 10^7$, about 2.3 at $N_e \simeq 3 \times 10^7$ and decreases to 1.7 at $N_e \sim 10^8$. These values are in a good agreement with the conclusions derived from the $\rho_\mu(N_e)$ dependence.

IV. Mass composition according to the EAS radio-emission

A new analysis of the EAS radio-emission data obtained at the EAS MSU array has been carried out [6]. The analysis has been performed in the framework of the QGSJET model [4]. It was obtained that the experimental lateral distribution function of the EAS radio-emission at the core distances 150–200 m correlates with the depth of a shower maximum. The mean depth of the shower maximum for primary particles with energy $\sim 4 \times 10^{17}$eV is estimated as (657 ± 12) g/sm^2.

This depth corresponds to the value $\overline{\ln A} = 2.0 \pm 0.4$ that agrees with the results presented above.

V. Conclusion

Fig 3 presents the value $\overline{\ln A}$ obtained by the various EAS arrays. All experimental data shows an enrichment of the primary cosmic ray flux by heavy nuclei at energies above the knee and then at energies above 10^{17} eV the flux becomes enriched with more light nuclei. Thus the results presented confirm the existence of the

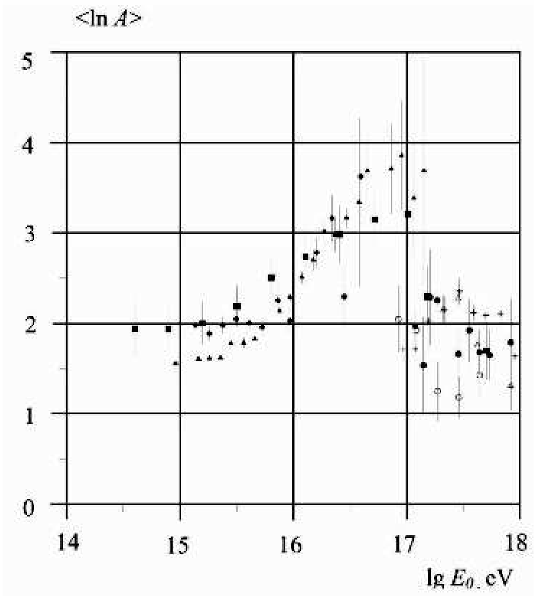

Fig. 3: Dependence $\overline{\ln A}(E_0)$ according to the various experimental data: full squares -EAS MSU, full rhombs -Tunka [7], full triangles -KASKADE [8], open circles-Blanka [9], full circles-Jakutsk [10], open triangles - Havera Park [11], crosses -Fly's Eye [12]

additional component of the primary cosmic ray flux consisting most probably of light nuclei.

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