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Mass Composition of Cosmic Rays in the Energy Region 10^{16} - 10^{18} eV by data the Small Cherenkov Array at Yakutsk. Comparison with other Arrays

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In the paper are present the new results for the mass composition of cosmic rays, obtained of the energy region 10^{16} - 10^{18} eV. The data were obtained at Small Cherenkov array over a 20 year period of continuous observation. Our experimental data are indicate at changed in the mass composition in the energy range 10^{16} - 10^{18} eV and it's confirmed by independent results obtained by other EAS arrays.

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1. Introduction

In this review, we used the work of Yakutsk group in which were introduced estimation of the mass composition of cosmic rays at ultrahigh energies [1 - 5]. In these studies were analyzed the characteristics of longitudinal and lateral development of EAS, reconstructed according to observations at the Yakutsk array. This primarily refers to measurements of Cherenkov light of EAS and muons with a threshold energy $\geq$ 1 GeV. These components, in accordance with, the calculations were considered the most sensitive characteristics of the shower to the atomic weight of the primary particle. The results were obtained using different models of hadron interactions [6 - 8]. One can assume that all presented results on the mass composition are rather indicative, because its are not direct measurements of the mass composition and depend on many factors. However, it is necessary to make the estimation of CR mass composition in the region of ultra-high energies and compare these results with direct measurements, so called "normal" composition, which obtained at high energies from satellite and balloon measurements. This leads to a refinement of our knowledge of the nature of cosmic radiation and a better understanding of the physics of EAS development in the field of the highest energies.

2. Mathematical methods of analysis and results

2.1 The method of joint analysis of the average characteristics of the longitudinal development of EAS and their fluctuations: X_{max}, $\sigma(X_{max})$,dE/dX_{max}

In paper [11] was suggested that composition of primary particles consist of a mixture of protons and iron nuclei. The analysis also used the superposition hypothesis, it was assumed that the collapse of the primary nucleus did not occur on the top of the atmosphere, but at a depth corresponding to a run for the collision of nuclei in the air. Therefore, the average depth of the shower maximum for this superposition is modified by the value of the path is lower than X_{max} calculated from the diffusion equations of nuclear cascade process. In the method were used the hydrodynamic model with $n_{ch} \sim E^{1/3}$ [6]. Let the distribution of the maximum depth of showers from primary nuclei has an exponential form with the first moment equal to their run for the nuclear interaction. Then, the average depth of the shower maximum for the sum of two exponential functions will be equal.

$$\bar{X}_{max} = \eta \cdot X_p + (1-\eta) \cdot X_{Fe} \tag{2.1}$$

Where η - the fraction of protons in the primary cosmic radiation, X_p and X_{Fe} - the depth of maximum development of the primary proton and iron nuclei by the chosen model of the EAS. For the dispersion we have X_{max} expression

$$D(X_{max}) = \beta\{\eta \cdot \lambda_p^2 + \eta(1-\eta) \cdot (X_p - X_{Fe})^2 + (1-\eta) \cdot \lambda_{Fe}^2\} \tag{2.2}$$

Here λ_p and λ_{Fe} respectively the path for the nuclear interaction of the proton and iron nuclei. β multiplier takes into account the increase of the dispersion X_{max} due to fluctuations of the inelasticity coefficient and is taken to be $(1 - 1 \langle k \rangle)^{-1}$, where $\langle k \rangle$ - the mean value of the inelasticity coefficient of the leading particle. If we assume that the ratio $\lambda_{Fe}(E) / \lambda_p(E)$ is constant and known, then equations (2.1) and (2.2) in the framework of a two-component composition can determine the

proportion of protons in the primary radiation and the cross section of the proton - nucleus of an atom from the experimental values X_{max} and $D(X_{max})$. Technically, the above simplification can be extended to multi-component composition of the primary particles, but the accuracy of formulas of the type (2.1) and (2.2) for X_{max} and $D(X_{max})$ will be slightly worse. We also found an indication of a gradual increase of the protons percentage in the region of energy $3 \cdot 10^{17}$ - $3 \cdot 10^{18}$ eV.

2.2 Method of comparing the asymmetry of distribution at different X_{max} at different fixed energies

This method does not depend from model of air shower development. Since the distribution of X_{max} at fixed energy is formed by nuclei of different masses, therefore, its shape will reflect their contribution to a statistical contribution of X_{max}, g / cm^2. This is understandable, since showers produced by particles of different masses have either rapid development, for example, the iron nucleus or slow development as it happens, if we consider the proton. In paper [2] the ideology of asymmetry of X_{max} distributions at different energies were used. Its essence is as follows. The value of the effective cross section for inelastic collisions of protons with air nuclei on the distribution of heights of the maxima of the EAS in the energy range of the primary particles 10^{17} - 10^{18} eV and 10^{18} - 10^{19} eV was studied. Right-hand side of such distributions is determined mainly by the effective cross section for inelastic collisions of protons with air nuclei. Height of the maximum development of the shower was determined by the spatial distribution of the Cherenkov light at the distance range of 100 - 600 m from the shower axis. Next, assuming that at high energies only protons are presented and rationing distribution at lower energies by the proton (deeper than 700 g / cm^2), simply by subtracting the estimated fraction of nuclei in the primary radiation with energy $\sim 10^{17}$ - 10^{18} eV. Thus the indication that in the energy range 10^{16} - 10^{19} eV observed systematic increase in the fraction of protons: $\sim 1.2 \cdot 10^{16}$ eV - (43$\pm$5), $\sim 9 \cdot 10^{16}$ eV - (50$\pm$6), $\sim 5 \cdot 10^{17}$ eV - (60$\pm$10)% and $\sim 5 \cdot 10^{18}$ eV - (90$\pm$10)% was obtained.

2.3 Distribution of X_{max} shape analysis jointly with calculated distribution using QGSJET model by maximum likelihood method.

In this method we used experimental data of X_{max} at energies 10^{15} - 10^{19} eV and simulated showers according to QGSJET 01 model [8]. Joint analysis of showers allowed to obtain quantitative estimates of the mass composition of primary CR, using the distribution of X_{max} at fixed energy [3]. To do this, we compared the experimental data and theoretical predictions of predictions according QGSJET for different primary nuclei with applied criterion χ^2. The value was determined by the equation χ^2.

$$\chi^2(X_m) = \sum_n (N_e(X_{max}) - N_T(X_{max}))^2 / N_T(X_{max}) \tag{2.3}$$

where N_e (X_{max}) - experimental number of showers in the range ΔX_{max}. N_T (X_{max}, A_i) - the same number of showers, calculated under the assumption that the mass number of the nucleus is equal to A_i, and P (A_i) - the probability that a storm of energy E_0, is formed by the primary particle A_i. Then

$$N_T(n) = \sum_{i=1}^{n} P(A_i) \cdot N_T(X_{max}, A_i) \tag{2.4}$$

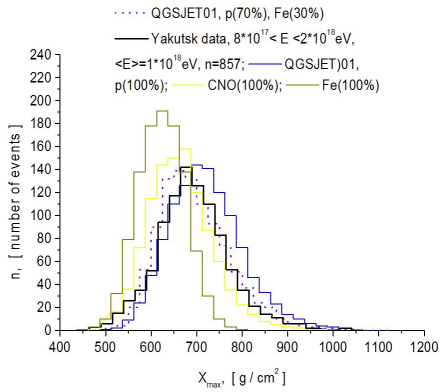

Figure 1: Distribution of Xmax at fixed energy. Point result - test provided p (70%) and Fe (30%)

Analysis of the shape of experimental and calculated distribution of X_{max} showed that at optimal value of χ^2 obtained result does not conflict with the following relationships for 5 nuclei components:

1). $\bar{E_0} = 5{\cdot}10^{17}$ eV - p : (39 $\pm$ 11) % , α: (31 $\pm$ 13) % , M : (18 $\pm$ 10) % , H : (7 $\pm$ 6) % , Fe : (5 $\pm$ 4) % ;

2). $\bar{E_0} = 1{\cdot}10^{18}$ eV - p : (41 $\pm$ 8) % , α : (32 $\pm$ 11) % , M : (16 $\pm$ 9) % , H : (6 $\pm$ 4) % , Fe : (5 $\pm$ 3) % ;

3). $\bar{E_0} = 5{\cdot}10^{18}$ eV - p : (60 $\pm$ 14) % , α : (21 $\pm$ 13) % , M : (10 $\pm$ 8) % , H : (5 $\pm$ 4) % , Fe : (3 $\pm$ 3) %.

Thus, in the framework of the QGSJET 01 the indication was obtained: mass of the PCR in the transition from the energy (5 $\pm$ 30)$\cdot$ 10^{17} eV to the energy (3 $\pm$ 10)$\cdot 10^{18}$ eV changes. For $E_0 \cdot 3{\cdot}10^{18}$ eV primary cosmic radiation consists on $\sim$70% of protons and helium nuclei, the proportion of other nuclei does not exceed $\sim$30%.

2.4 Multicomponent analysis

In order to interpret experimental data of Yakutsk array we used CORSIKA code (v. 6.0. QGSJET model) to generate database of Xmax and $\rho_e(600)$. Simulation were done for five primaries (P, He, C, Si, Fe) and three energies 10^{17}, 10^{18}, 10^{19} eV. For each energy we simulated 100 showers in the standard atmosphere. In this paper, we used two-dimensional probability density F(X_{max}, ρ_e (600)), preliminary standardized experimental data of the entire array data (X_{max}, ρ_e (600)) for a given energy. At numerical implementation of this method instead of (X_{max}, ρ_e (600)) and used variables τ and ρ_e:

$$\tau = (X_{max}/\sigma_x) - < (X_{max}/\sigma_x) >) \tag{2.5}$$

$$\rho = (lg\rho(600)/\sigma_{lg}\rho) - < (lg\rho(600)/\sigma_{lg}\rho) >) \tag{2.6}$$

Where σ - standart deviation of the value.

Standardization performed on pooled data (X_{max}, ρ_e (600)) for all groups of nuclei and each energy 10^{17}, 10^{18}, 10^{19} eV. Distribution on X_{max} and ρ_e (600) separately and joint distributions for

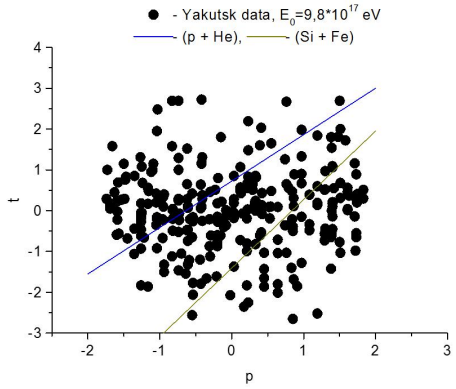

Figure 2: Standardized experimental data for X_{max} and ρ_e (600) at different energies. Line m1 - divides nuclei (P + He) and C, line m2 - divides C and (Si + Fe)

τ and ρ are described respectively by dimensional F (X_{max}) F (ρ(600)) and two-dimensional f(τ, ρ) logarithmically normal distribution. For each given energy and different types of primary nuclei, including for nuclei, combined in groups P + He, C, Si + Fe, were plotted probability distribution density f(τ, ρ). The intersection of f(τ, ρ) layers gives lines m1 and m2, which optimally separates nuclei into 3 groups: (P + He), C and (Si + Fe) respectively.

Fig. 2 shows the result of a multi-component analysis of the data binding (X_{max} ρ_e (600)) of Yakutsk array. A cloud of points in such a representation reflects standardized values, and lines represent areas that are directly associated with the mass number of the primary particle. In this case, the line m1 and lines m2 are optimally separates nuclei into groups (P + He), and C (Si + Fe).

Analysis has shown that the proportion of nuclei (p + He) increases from 50% to 53%, and the proportion of carbon nuclei from 23% to 31%. At the same time the proportion of nuclei of heavy chemical elements decreases from 27% to 16% while increasing energy from $2.4{\cdot}10^{17}$ to $4.8{\cdot}10^{18}$ eV.

2.5 Proportion of muons analysis method depending on the length of the track of the particles in the atmosphere

In paper [5] considered the dependence ρ_μ / ρ_s the length of the track of the particles after the maximum of EAS $\Delta\lambda = X_0 / \cos\theta$ - X_{max} where X_0 = 1020 g / cm^2 for Yakutsk. Here X_{max} determined from measurements of the Cherenkov light and ρ_μ and ρ_s by measuring a large EAS. Next, the experiment was compared with model calculations of QGSJETII 03 and EPOS. It is known that X_{max} of showers greatly differs depending on primary nucleus, therefore, this fact can be used to analyze the mass composition of cosmic rays, for example, by fixing the parameter $\Delta\lambda$ and analyzing fluctuations in the ratio of ρ_μ / ρ_s. This method is somewhat similar to the method of Christiansen, proposed in 1981 [9]. With sufficient precision of measurements of each parameter (better than 5%) in the distribution allocated single peaks from different nuclei.

Comparison of distribution of muon proportion with calculation results indicates to mixed composition at energies above 10^{18} eV. Large fluctuations do not allow allocating separate groups of nuclei with a good precision and evaluating percentage of each group. But, the use of "pure" response of muon detectors leads to conclusion that MC at energies 10^{18} - 10^{19} eV is light [10].

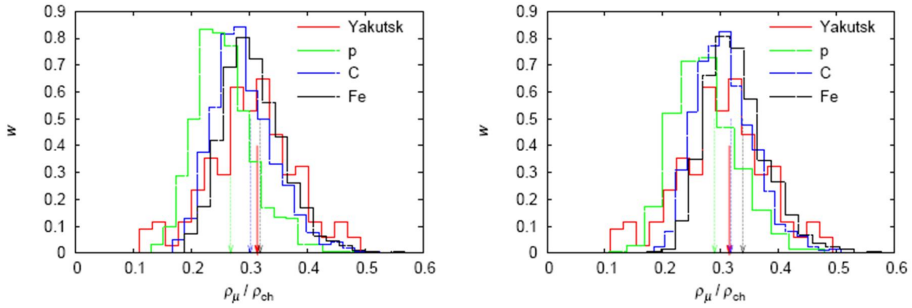

Figure 3: A distribution of the ρ_μ / ρ_s relation normalized to the track length 500 g / cm^2. On the left - according to models QGSJet II(FLUKA), on the right - according to EPOS(UrQMD)

2.6 Evaluation of the mass composition at average depth of maximum of EAS development. Interpolation method

In papers [11, 12], dependence of X_{max} from energy at range $\sim 10^{15}$ to $5 \cdot 10^{19}$ eV was considered. MC of PCR evaluated by this formula:

$$< lnA > \equiv \sum a_i \cdot lnA_i \tag{2.7}$$

Where a_i the relative proportion of nuclei with mass number A_i.

In each case experimental data compared with QGSJET 03 calculation made for proton and iron in the frame of superposition model:

$$< lnA > = ((P^{exp.} - P^p))/(P^{Fe} - P^p)) \cdot lnA_{Fe} \tag{2.8}$$

Where P_i - parameter, that characterize longitudinal development of air showers X_{max}.

In Fig. 4 shows dependence of X_{max} from energy (dots) derived from experiment and from simulation (lines) of this characteristics calculated by QGSJET 03 and SIBYLL model for proton and iron nuclei. Fig. 5 shows Yakutsk array results of MC PCR derived by method described above. Data obtained in the frame of QGSJETII 03 model and dual component MC (proton - iron). Value <ln(A)> in each case was determined by interpolation method.

Fig. 5 shows that nature of dependence of value <lnA> with increase of energy changes reaching maximum at energy range $(5 - 30) \cdot 10^{16}$ eV. This means, that MC of CR changes after first kink in the spectrum at $\sim 3 \cdot 10^{15}$ eV, reaching heavier particles $(3 - 30) \cdot 10^{16}$ eV and then, starting at energies $3 \cdot 10^{17}$ eV becomes much lighter.

3. Conclusion

a) For more than 40 years Yakutsk array continuously records air showers with ultrahigh energies. We obtain information about all main components of the shower: electrons, photons, hadrons and muons. All these data at different times were used to estimate the mass composition of cosmic rays involving different methods. This follows from the numerous publications in journals and proceedings of scientific conferences. According to the data shown in Figure 6 [13]. The mass composition is not uniform over a wide energy range, and has a peak at (0.8 - 2) 10^{17} eV

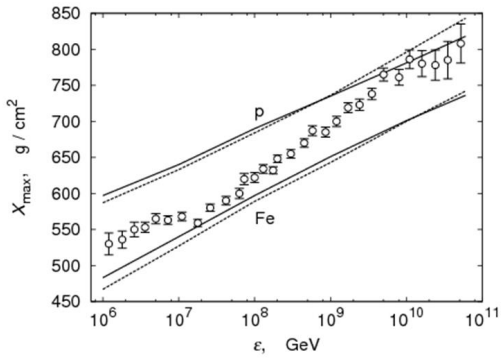

Figure 4: Dependence of X_{max} from energy. Lines are calculated values for proton and iron nuclei.

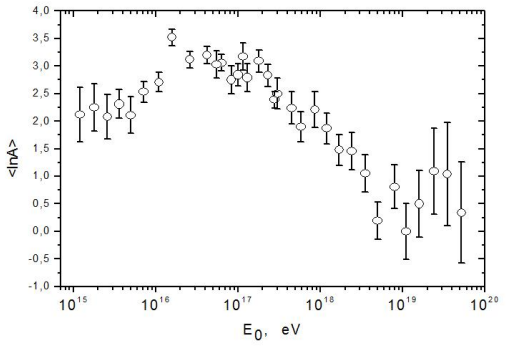

Figure 5: Mass composition of Cosmic rays highest energy are obtained at Yakutsk. Model QGSJETII-03

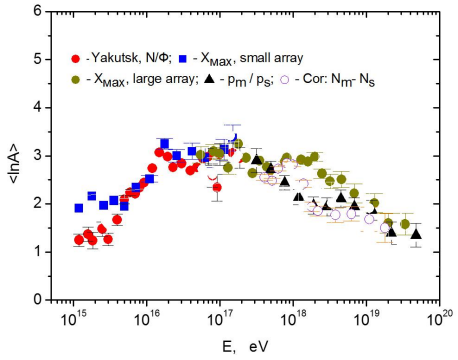

Figure 6: Estimation of MC CR with different method by use of different characteristics of air showers

Figure 7 shows the latest results on MC obtained using the interpolation method (see. Section 2.6) and the model QGSJET 04. Also the figure shows results obtained at compact and the large arrays. From Figure 7 it follows that MC is undergoing a change in the energy range (8 - 20) $\cdot 10^{16}$ eV and (8 - 20) $\cdot 10^{18}$eV. And most likely this is due to the nature of the formation of cosmic rays in the sources and their distribution in the galactic and intergalactic space.

b) At the Yakutsk we measured energy spectrum of CR (see. [14, 15]) and evaluated MC over a wide range in energy [16]. If we compare the energy scale with studied spectrum of CR and obtained results of cosmic rays of MC, than we observe matching of energy intervals, where the change in the shape of the spectrum and the change in the value of A = <lnA> are the same. Most likely, these two results are related and caused by the same astrophysical processes.

c) On the boundary of the transition from galactic to metagalactic cosmic rays. Recently developed nonlinear kinetic theory of CR acceleration in supernova remnants has allowed not only to achieve agreement in shape of CR spectrum up to energies $\sim 10^{17}$ with experimental data, but also to choose a class of SNR, which responsible for MC of particles similar to those observed in the satellite, balloon and ground experiments [11]. This is confirmed by the results of the calculation of work [16], which are shown in Figure 7 (lines). Figure 7 shows a comparison of MC obtained

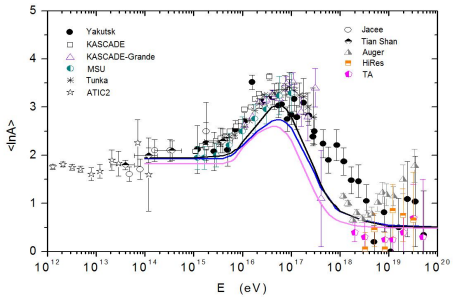

Figure 7: Mass composition of CRs from measurements of different EAS arrays. Lines show MC calculated from paper [16] in the case of near SNR

at different arrays, with MC generated in the sources, which are remnants of supernovas. There is not only a satisfactory agreement of experimental data with calculation in the energy range 10^{15} - 10^{19} eV, but also indicates that the sharp change in the MC at an energy $\sim 2 \cdot 10^{17}$ eV may be associated with the boundary of the transition from galactic CR to metagalactic CR. In this case mass composition of CRs at energies above $\sim 2 \cdot 10^{17}$ eV should be presented primarily by protons, which is consistent with mass composition obtained at the Yakutsk EAS.

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