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Results and perspectives of cosmic ray mass composition studies with EAS arrays in the Tunka Valley

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Abstract. The study of the cosmic ray mass composition in the energy range $10^{16} - 10^{18}$ eV is one of the main aims of Tunka-133. This EAS Cherenkov array started data acquisition in the Tunka Valley (50 km from Lake Baikal) in autumn 2009. Tunka-133 provides a measurement of the EAS maximum depth (X_{max}) with an accuracy of about 30 g/cm^2 . Further mass composition analyses at the highest energies ($10^{17} - 10^{18}$ eV) will be based on the comparison of primary energy measured by the radio method and the densities of charged particles measured by shielded and unshielded detectors. The high duty cycle of the common operation of the new scintillation array (Tunka-Grande) and the radio extension of the experiment (Tunka-REX) will provide a high statistics of events.

1. Introduction

The study of energy spectrum and mass composition of primary cosmic ray particles in the energy range of $10^{15} - 10^{18}$ eV is of crucial importance for the understanding of the origin of cosmic rays and their propagation in the Galaxy [1, 2]. The change from light to heavier composition with growing energy marks the energy limit of cosmic ray acceleration in galactic sources (like Supernova Remnants, SNR) and of the galactic containment. This effect was confirmed by various experiments (e.g. [3, 4]) and by detailed theoretical calculations [5, 6]. An opposite change from heavy to light composition at higher energy would show the transition from



galactic to extragalactic sources. Experimental evidence of such an behavior of the composition was reported in [7].

To get more statistics at the the highest energies the new scintillation array Tunka-Grande is constructed, where "Grande" means that the scintillation counters used for the new array construction are coming from former KASCADE-Grande experiment. The main physics goal of the new array is to study the primary cosmic ray energy spectrum and mass composition in the energy range of $10^{17} - 10^{18}$ eV, filling the gap in coverage between small and giant EAS arrays.

2. Brief overview of experiments in the Tunka Valley

There are four different arrays in the Tunka Valley collecting experimental data now or ready to start operation at the end of 2015. The first of them is Tunka-133. It consists of 175 wide angle atmospheric Cherenkov light detectors [8]. Each detector contains a single PMT of 20 cm diameter. The detectors are grouped into 25 clusters with 7 detectors in each cluster. 19 clusters provide the data acquisition in the circle of 450 m radius, 6 other clusters are situated at the radius about 1 km around the center and help in data acquisition and processing of events with higher energy threshold in the circle of 800 m radius.

The second Cerenkov light array is TAIGA-HiSCORE [9]. This array is under construction and it consists of 28 optical stations in the version of 2015. Each station has much lower threshold than the optical detector of Tunka-133, because it contains 4 PMTs supplied with the Winston cone light collectors. The total effective area is 16 times larger the Tunka-133 detector. Moreover the time resolution of HiSCORE station is two times less than for the Tunka-133 detector. All the stations are tilted to the South for 25° to increase the time of observation of Crab Nebulae.

The third array is Tunka-REX [10], recording radio emission from EAS. The array consists of 44 radio antennas connected to the Tunka-133 and Tunka-Grande data acquisition systems.

The 4-th array is the new scintillation array Tunka-Grande. Scintillation counters with area of 0.64 m^2 from former KASCADE-Grande array are used for arrangement of the new array stations. Each station contains 12 counters on the ground surface for registration of charged particles and 8 counters in the underground chamber for registration of muons with 0.5 GeV threshold. The array is planned to start operation at the end of 2015.

3. Experimental results

The Cherenkov light array Tunka-133 operates in clear moonless nights every year since October till the beginning of April. During other seasons nights are too short and weather conditions are mostly unsatisfactory. The data taking by the Tunka-133 array continued during 5 winter seasons 2009-2010, 2010-2011, 2011-2012, 2012-2013 and 2013-2014. Here we present the data of 5 seasons. The total time of data acquisition is 1540 hrs. The mean trigger rate was about 2 Hz. The number of recorded events is about 10^7 . Such an amount of recorded data provided the possibility of calibration of the apparatus using the data themselves. The procedure of data processing and EAS parameters reconstruction are described in [8]. The main results are published in [11]. To analyze the mass composition we use the method of EAS maximum depth X_{max} reconstruction from the measured steepness of amplitude-distance function (ADF) described in [8]. Events for this analysis are selected in a circle of radius 450 m. To get a uniform estimation for ADF steepness over a wide range of energies, we remove from the analysis detectors at distances larger than 250 m from the core during the last step of parameters reconstruction. The experimental dependence of mean $\langle X_{max} \rangle$ vs. primary energy E_0 in the energy range of $10^{16} - 10^{18}$ eV is presented in Fig. 1. The experimental points are compared with the points of HiRes-MIA experiment [12] and fluorescent light detectors of Pierre Auger Observatory (PAO) [13]. In 2015 the PAO authors expanded the energy range of measurements with the results of HEAT fluorescent detectors and reanalyzed the results of the main detectors claiming the shift of their points to about 20 g/cm^2 deeper into the atmosphere [14]. One can see an agreement

of Cerenkov light Tunka experiment results with previous fluorescent light observations. But we have no enough statistics to discuss the discrepancy with the current PAO results.

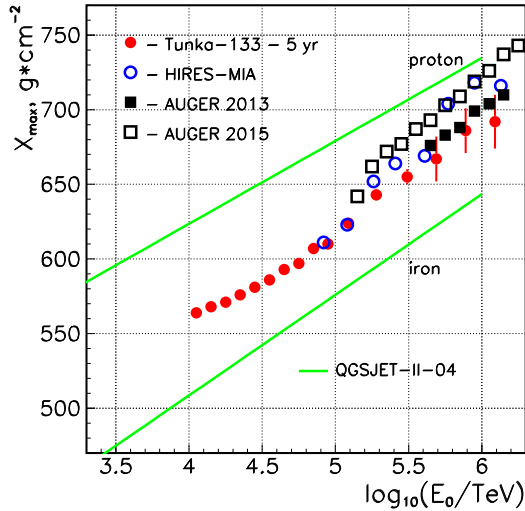


Figure 1. Mean experimental depth of EAS maximum vs. the primary energy. Other experiments – HiRes-MIA [12], AUGER 2013 [13], AUGER 2015 [14].

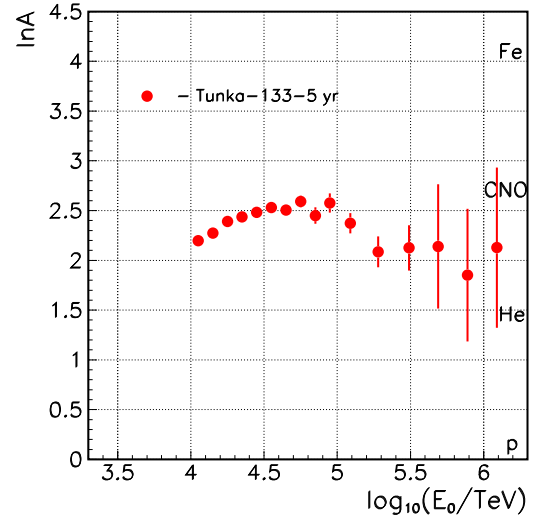


Figure 2. Mean experimental logarithmic mass vs. the primary energy.

The experimental results are compared with the theoretical curves simulated with the QGSJET-II-04 model for primary protons and iron nuclei. The mean values of $\langle X_{max} \rangle$ can be recalculated to the mean values of $\langle \ln A \rangle$ by a simple method of interpolation. The result of such an approach are shown in Fig. 2. Primary mass composition becomes heavier in the energy range $10^{16} - 3 \cdot 10^{16}$ eV and lighter again in the range $10^{17} - 10^{18}$ eV.

4. Experimental Evaluation of Accuracy of the EAS Main Parameters

The experimental evaluation of errors of reconstructed EAS parameters is interesting because of the complexity of the simulation of the all possible errors of measurements. The accuracy in determination of shower parameters can be estimated using the well known chessboard method [15]. To use this method the experimental array is divided into two independent subarrays of similar size and configuration. Then the EAS parameters are derived independently with each of the two subarrays. The accuracy of any parameter is given by the difference between the two reconstructed values divided by $\sqrt{2}$ because they represent two independent determinations of the same shower parameter. Applying this method to the Tunka-133 data we arranged the first subarray from odd detectors and the second one from even ones. The results are shown in figures 3 and 4.

The upper panel of Fig. 3 shows the errors of core position reconstruction. The error is less than 6 m for energy $E_0 \geq 10^{16}$ eV and less than 10 m for the large effective area ($R_{eff} \leq 800$ m) and $E_0 \geq 5 \cdot 10^{16}$ eV. The lower panel of Fig. 3 shows the energy relative errors. The error is less than 6% for energy $E_0 \geq 10^{16}$ eV and less than 8% for the large effective area ($R_{eff} \leq 800$ m) and $E_0 \geq 5 \cdot 10^{16}$ eV.

The Fig. 4 shows the errors in arrival direction and depth of maximum X_{max} obtained for the main effective area ($R_{eff} \leq 450$ m), used for analysis of mass composition. The error of

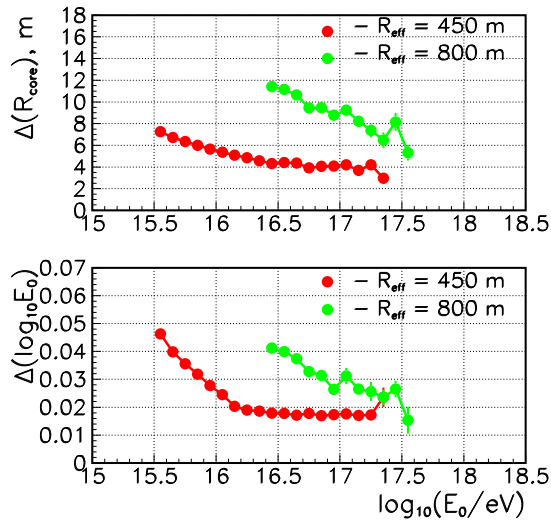


Figure 3. Upper panel – errors of core position reconstruction. Lower panel – relative errors of primary energy reconstruction.

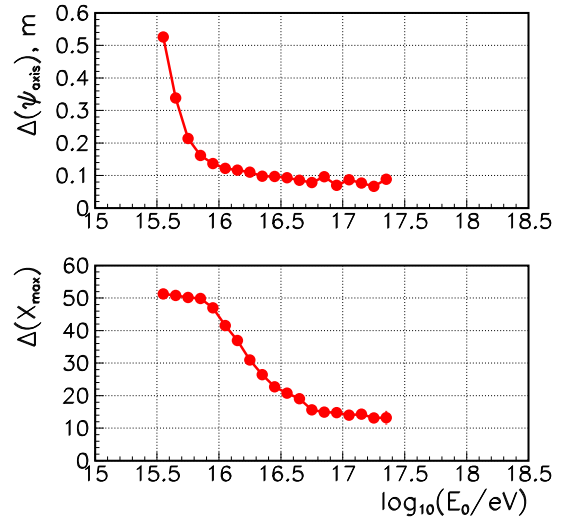


Figure 4. Upper panel – error of an arrival direction reconstruction. Lower panel – error of EAS maximum depth X_{max} reconstruction by the ADF steepness method.

arrival direction is smaller than 0.12° for energy $E_0 \geq 10^{16}$ eV. The error of X_{max} is smaller than $40 g/cm^2$ for energy $E_0 = 10^{16}$ eV decreasing as the energy increases, reaching $20 g/cm^2$ at $E_0 \geq 3 \cdot 10^{16}$ eV.

5. Perspectives of mass composition analysis

To reach more reliable estimations of mass composition we plan to expand the energy range of the analysis. For low energy region the threshold will be reduced by using the data of the new Cerenkov light array TAIGA-HiSCORE [9]. The methods developed for Tunka-133 will be adjusted for the new data analysis.

In the energy range $10^{17} - 10^{18}$ eV we need more statistics than can be collected with Cherenkov array Tunka-133 that, operating only during clear moonless nights, has about a 5% duty cycle. More statistics can be collected with a scintillation detector array registering EAS charged particles operating (in principle) 100% of the total year time. Such an array Tunka-Grande briefly described above is ready for data acquisition now. The main parameter sensitive to the primary mass is a number of muons N_μ . To analyze the sensitivity of different EAS parameters to the primary mass a special simulation was made using AIRES code. Thousand events have been simulated for every type of nucleus (p, He, N, Si, Fe), every energy ($2 \cdot 10^{15}$, $5 \cdot 10^{15}$, 10^{16} , $2 \cdot 10^{16}$, $5 \cdot 10^{16}$, 10^{17} , $2 \cdot 10^{17}$, $5 \cdot 10^{17}$, 10^{18} eV) and zenith angles (0° , 30° and 45°). It was found that the best mass resolution can be reached with analysis of parameter $S = \log_{10} N_\mu - 0.2 \cdot \log_{10} N_e - 0.7 \cdot (\log_{10} E_0 - 17)$. The essential feature of this parameter is it's independence on the shower zenith angle. Figure 5 shows the distribution of simulated events for primary protons and iron nuclei by this parameter. These distributions are compared with the X_{max} distributions for the same events. One can see that S parameter provides much better mass resolution than X_{max} .

The only problem in this method usage is the necessity of the primary energy measurement. To solve this problem the data of the radio array Tunka-REX will be used. It was claimed by the authors that the accuracy of energy reconstruction by the radio data is about 15% for each

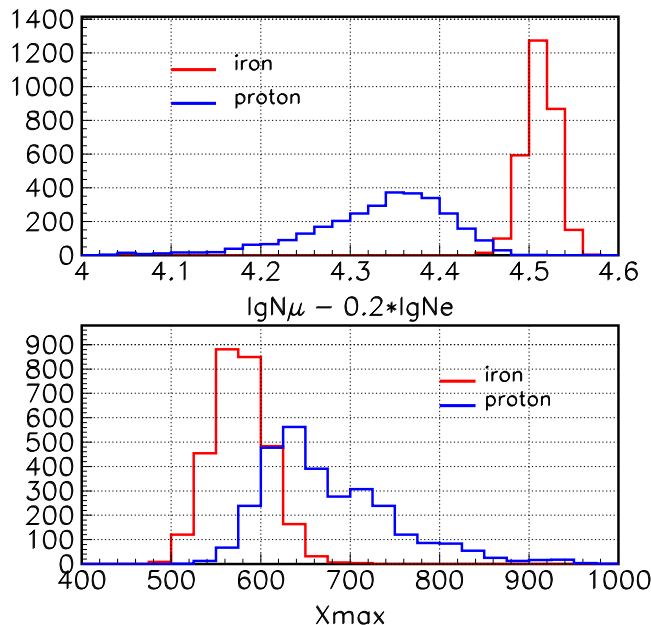


Figure 5. AIREES simulation with QGSJet-01 model for $E_0 = 10^{17}$ eV, zenith angles $\theta = 0^\circ$, 30° and 45° , primary protons and iron nuclei. Upper panel – event distribution by parameter:
 $S = \log_{10} N_\mu - 0.2 \cdot \log_{10} N_e - 0.7 \cdot (\log_{10} E_0 - 17)$. Lower panel – event distribution by parameter X_{max}

event [16].

Acknowledgments

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