Improvement of Primary Mass Resolution Using the Simultaneous Registration of EAS Cherenkov Light, Muons and Electrons

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***Abstract*. The deployment of Tunka-133 EAS Cherenkov light array with 1 km^2 effective area will be completed this autumn. The installation of scintillation counters at the same array can provide EAS muon and electron numbers measurement. Simultaneous measurements of EAS energy, depth of maximum, muon and electron numbers can provide better resolution of primary mass in multi-parameter distribution. This is essential for the detailed study of the possible transition from galactic to extragalactic cosmic rays at energies 10^{17} – 10^{18} eV. Our preliminary simulation has shown that a network of about 20 muon detectors each of 10 m^2 area and distance between detectors (~150 m) provides good enough muon number measurement ($\delta N_\mu/N_\mu \leq$ 10%).**

***Keywords*: EAS Cherenkov light and muons, cosmic rays, mass composition.**

I. Introduction

The energy range 10^{17}–10^{18} eV is of particular interest because in this energy range the transition from galactic to extragalactic cosmic rays is expected [1]. According to the theoretic predictions confirmed by the data of some experiments ([2],[8]) the partial knee in the energy spectrum of Fe-nuclei has to occur close to the energy 10^{17} eV. Nevertheless the index of the all particles spectrum does not change in the whole region of 10^{16}–10^{18} eV. The most natural explanation of this fact one can search in the existence of the progressively enhanced contribution of extragalactic cosmic rays. The further investigation is needed to establish this point of view ultimately and such investigation is one of the main aims of the EAS Cherenkov light array Tunka-133 with geometric area of 1 km^2 [3], [4].

The Tunka-133 array has been detecting Cherenkov light from EAS during the last two years and it has to be completted (133 Cherenkov detectors) by the autumn 2009. For the next step of the array upgrading it is planned to deploy a dense enough network of the muon and electron scintillation detectors with a characteristic distance between the detectors of about 150 m, providing the measurement of a total number of muons with the relative error less than 10% for the energy more than 10^{17} eV. The simultaneous measurement of muon number N$_\mu$, reconstructed from Cherenkov light array data primary energy and the depth of EAS maximum X_{max} could provide more precise mass composition estimation in the energy range 10^{17}–10^{18} eV. The scintillation detectors array can be cross-calibrated by the data of Cherenkov light array and then can acquire the data independently during the time when Cherenkov light array is unable to operate (day time, moon or cloudy nights).

The idea of simultaneous measurements of several EAS components (muon, electron and Cherenkov) was considered many years ago in [5], but was not realized experimentally at that time. The suggested copmlex array on the basis of Tunka-133 will provide the first possibity to apply this idea at the sufficienty powerfull EAS Cherenkov light array.

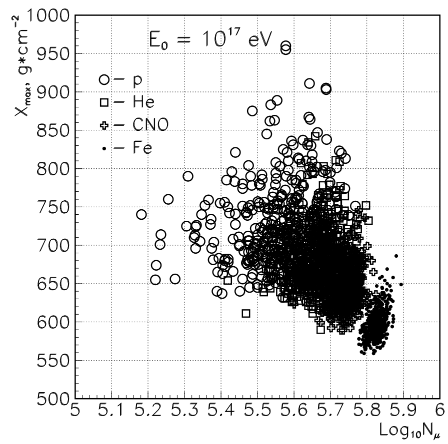
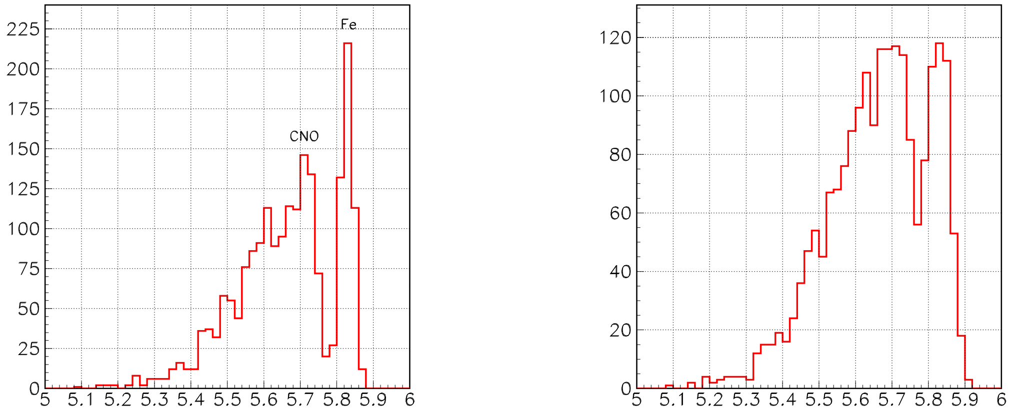


Fig. 1: X_{max} vs. N$_\mu$. 500 events for proton, He, N and Fe EAS. E$_0$ = 10^{17} eV, vertical direction.

II. Simulation

Cherenkov light measurements provides the primary particle energy and the depth of EAS maximum X_{max}. The analysis of the last value distribution provides the possibility of mean mass composition estimation [8]. To make such estimations more reliable, one should continue the search of possibility of resolving of mass groups or even the possibility to resolve at least one of nuclei groups (i.e. Fe-nuclei group).

To study what additional information can be obtained by the measurement of EAS muon component simulation for the different primaries has been made. We used the AIRES code [6] with QGSJET-II hadronic



[A] [B]

Fig. 2: Distribution of $lg(N_\mu)_{cor}$ (see eq. 4). $E_0 = 10^{17}$ eV.
A. No exeperimetal errors. B. $\delta N_\mu/N_\mu = 5\%$, $\delta X_{max} = 20 g \cdot cm^{-2}$

interaction model for simulations. The simulation was provided for four primary nucleus types (proton, helium, nitrogen and iron), 3 values of a primary energy (10^{17} eV, $3{\cdot}10^{17}$ eV and $5{\cdot}10^{17}$ eV) and 3 zenith angles ($\theta = 0°, 30° and 45°$). The muon energy threshold was 1 GeV.

Figure 1 presents the 2-dimensional plot of X_{max} vs. the logarithm of muon number lgN_μ for energy 10^{17} eV and vertical arrival direction of the EAS. Comparison of simulations for heavy nuclei (Fe and N) of different energies and different zenith angles has shown that every simulated plot can be transformed to the plot with fixed primary energy and vertical arrival direction by the following transforming equations:

$$N_\mu(E_0) = N_\mu(E_1) \cdot (\frac{E_1}{E_0})^{-0.8} \quad (1)$$

$$N_\mu(\theta = 0°) = N_\mu(cos\theta) {\cdot} exp(\frac{X_0 \cdot (1/cos\theta - 1)}{1300}) \quad (2)$$

where $X_0 = 945\ g/cm^{-2}$ - the depth of atmosphere at the Tunka-133 site.

$$X_{max}(E_0) = X_{max}(E_1)(1 - 65 \cdot lg(E_1/E_0)) \quad (3)$$

So we analyze only plot presented in fig.1 (10^{17} eV, $\theta = 0°$). It is well seen that the fluctuations both in the maximum depth and in the number of muons are much smaller for the Fe-nuclei and mass resolution from the point of view of muon number is better than from the poit of view of X_{max}. Even better mass resolution can be obtained for the combined value of lgN_μ, corrected with the X_{max}:

$$lg(N_\mu)_{cor} = lg(N_\mu) - \frac{X_{max} - 600}{1500} \quad (4)$$

The histogram of this value is presented in fig. 2A. The Fe-nuclei peak is well separated from the other nuclei histogram.

Of course, real apparatus errors will distort this ideal picture. Figure 2B presents the simulation with taking into account the expected relative errors in determination of muon number of 5% and the error in X_{max} measurement δX_{max} = 20 $g \cdot cm^{-2}$. The Fe-nuclei peak is still visible for the measurement with such an accuracy. When the realative error of N_μ determination becomes more than 10%, one gets the smooth histogram without the separation of Fe-nuclei peak.

III. Expected N_μ accuracy

For the first step towards the project of scintillation EAS array we have estimated an accuracy of EAS parameters reconstruction by using of 20 muon detectors with 10 m^2 area placed inside the Tunka-133 geometric area. The core position of a simulated shower is random inside the geometric area. The muon density at each detector was calculated by using the mean muon lateral distribution function:

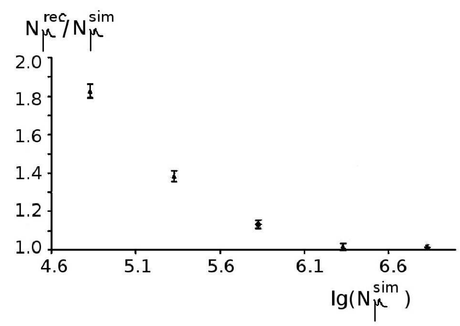
$$\rho_\mu(R) = C(\frac{R}{R_0})^{-0.75}(1 + R/R_0)^b \quad (5)$$

Where R_0 = 235 m, b = 2.5

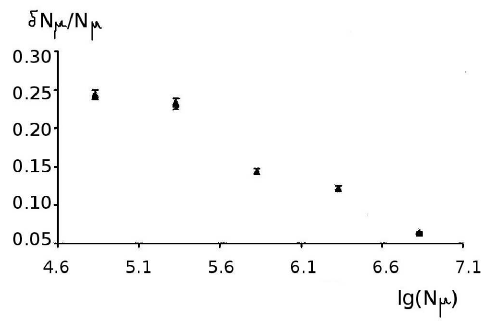
The number of muons at each detector simulated by the Poisson law with the mean value calculated with expresion (5). The simulated shower was reconstructed by minimization of χ^2 using expresion (5) as a fitting function. It was found that the core position accuracy is 10-15 m , depending on the core position inside the array. The result for the total muon number reconstruction is presented in fig 3. It is seen that the realtive error of the reconstructed N_μ becomes less than 10% for N_μ more than 10^6 and reaches 5% for $N_\mu > 5 \cdot 10^6$.

IV. Acquisition of muon detectors data

The new muon counters can be more or less easy inserted into the DAQ system of the Tunka-133 array. The complete Tunka-133 array consists of 133 optical



[A]



[B]

Fig. 3: Estimation of N_μ accuracy.
A. Ratio of reconstructed muon number N_μ^{rec} to the simulated one N_μ^{sim} vs. N_μ^{sim}.
B. Relative error of N_μ^{rec} vs. N_μ^{sim}.

detectors on the basis of PMT EMI 9350 (20 cm photocathode diameter). Detectors are grouped into 19 clusters with seven detectors in each one. Signals from PMTs are transmitted to the cluster electronics hut via the 100 m RG-58 coaxial cables. The cluster electronics [7] consists of a cluster controller, 4 blocks of four-channel FADCs, an adapter block connected with 7 detector controllers, and the separate temperature controller. All the electronic blocks (except the temperature controller) are implemented in VME standard. There are 3 vacant positions in the cluster crate which can be used for the additional detectors connection.

Each cluster electronics is connected to the DAQ center with a multi-wire cable consisting of four copper wires and four optical fibers. Two opical fibers are used for the data transmition and two fibers are free.

There are two possibilities of data acquisition from the muon counters. The first one is connection of the muon counters to the additional FADC boards inserted into existing cluster crate. The second possibility is connection of the muon counters to the additional electronics hut installed side by side with the existing cluster electronics hut. In such case the muon counters data will be transmitted to the DAQ center of Tunka-133 array via two free optical fibers of the existing cables. In both cases we don't need to expand the existing cable net of the array.

V. Conclusion

The results of our simulation shows that common operation of a net of muon counters together with the EAS Cherenkov light array Tunka-133 provides the better accuracy and reliability of cosmic rays mass composition study in the energy range 10^{17} – 10^{18} eV. The net of 20 muon detectors each of 10 m^2 area permits to measure the total muon number with relative error 10% for the energy $\sim 10^{17}$ eV and 5% for the energy more than $5{\cdot}10^{17}$. The infrastructure of Tunka-133 (the fiber-optical cables, cluster electronics crates and the data acquisition center) provides the possiblity to insert the muon counter into the DAQ system of the Tunka-133 array. The optimal number of muon counters, their locations and muon energy threshold demand an additional study.

VI. Acknowledgements

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