Elemental Composition of Cosmic Rays above the Knee from X_{max} measurements of the Tunka Array

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Abstract: We present the technique of cosmic rays mass composition study above the knee applied to the shower maximum distributions measured with the Tunka EAS Cherenkov array. The experimental data of three winter seasons of operation have been used in the analysis. The results are based on the large number of Monte Carlo simulations with the recent hadronic interaction model QGSJETII-04 for 4 nuclei groups: H, He, CNO, Fe. The elemental group spectra and mean logarithmic mass are discussed.

Keywords: Tunka, cosmic rays, elemental composition, depth of shower maximum, QGSJETII-04

1 Introduction

The Tunka EAS Cherenkov array has been operating since 2009 in Siberia. It provides detailed study of the primary cosmic ray energy spectrum and mass composition in the PeV energy range [1].

The array consists of 133 wide-angle Cherenkov light detectors grouped into 19 clusters with 7 detectors in each one with nearly 1 km^2 geometric area, and 42 detectors in 6 additional external clusters at 1 km from the center of the array.

The study of the primary mass composition in the 10^{15} – 10^{18} eV energy range is critically important to understanding of acceleration and propagation of cosmic rays in the Galaxy. An increasing dominance of heavy nuclei above the "knee" up to 10^{17} eV [2, 3] indicates the energy limit of cosmic ray acceleration in galactic sources (SNRs). Above 10^{17} eV the composition becomes lighter again [6] and this may hint at a transition to extragalactic origin. Both changes are expected in the energy range of interest in the present investigation.

While the cosmic-ray composition and energy spectrum are well known from direct balloon and satellite observations up to energies of about 100 TeV, no general agreement has been reached at higher energies. Due to the low flux of CR above 1 PeV, only large ground-based arrays observing the extensive air showers induced by cosmic rays in the atmosphere can provide experimental data. However, the sensitivity of EAS observables, mainly the depth of shower maximum X_{max} and the ratio of electrons to muons at ground level N_e/N_μ, to the mass of the primary CR is weak. The analyses are rendered even more difficult due to theoretical uncertainties concerning the high energy interactions in the atmosphere.

Whereas fluorescence detectors provide reliable measurements of X_{max} above 10^{17} eV, only the Cherenkov technique is sensitive to shower maximum below this energy. Registration of Cherenkov light using the atmosphere of the Earth as a huge calorimeter has a much better energy resolution (15%) than EAS arrays detecting only charged particles. Cherenkov light from air-shower mainly describes the well-defined development of the electromagnetic cascade in atmosphere. It gives unique possibilities for composition exploration independent of the chosen hadronic interaction model.

We present the technique of elemental composition analysis for 4 nuclei group (H, He, CNO, Fe) applied to Tunka X_{max} data from three winter seasons (2009-12). The statistics were taken during 980 hrs of 165 clean moonless nights. In the present analysis only data from the inner part of Tunka array are used.

2 X_{max} reconstruction

Recording the Cherenkov pulse waveform for each detector allows to use two methods of X_{max} reconstruction based on tail steepness b_a of the Amplitude-Distance Function (ADF) and on pulse width τ_{400} of the Width-Distance Function (WDF) which has a higher energy threshold. Both parameters are associated with the thickness of the atmosphere between detector and shower maximum, valid for any primary nucleus, energy and zenith angle of the shower, and interaction model [4].

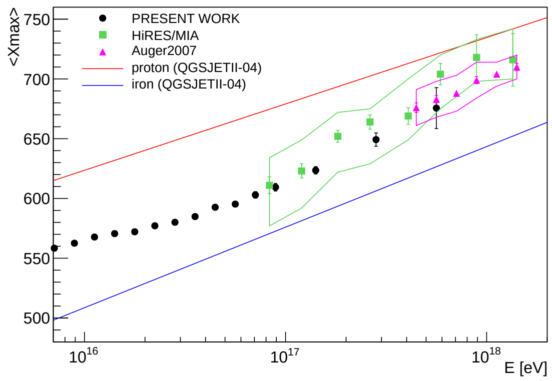

Fig. 1: $< X_{max} >$ as function of energy in comparison with fluorescence experiments. Errors bars and bands represent statistical and systematic uncertainties.

To avoid possible differences of parametrization in simulation and experiment, the so-called, "phenomenological approach" is being used where parameters are derived from experimental zenith angle dependence of b_a and τ_{400} for a fixed energy bin. The average X_{max} was calibrated to a value of $< X_{max} >$=580 g/cm^2 for an energy of 3×10^{16} eV [4]. It gives an acceptable agreement of $< X_{max} >$ behavior with fluorescence experiments HiRES/MIA [5] and Auger [6] in energy range $10^{17} - 10^{18}$ eV (Fig. 1).

The comparison of both methods gives a reconstruction X_{max} resolution with ranging from 37 g/cm^2 at $10^{15.85}$ eV to 28 g/cm^2 at $10^{16.35}$ eV and above. This value is close to the width of natural shower fluctuations of iron induced showers in the atmosphere. This makes the steepness b_a and pulse width τ_{400} sensitive parameters for the chemical composition.

3 Monte Carlo simulations

For this analysis, partial X_{max} distributions were simulated using CORSIKA 7.35 (2013)[7] with an updated version of the high-energy interaction model QGSJETII-04/GHEISHA, based on recent LHC data at $\sqrt{s}$ =7 TeV[8]. Sets of simulated events were produced for 5 log-equidistant energies from $10^{15.5}$ to $10^{17.5}$ eV and for 4 different representative mass groups (proton, helium, nitrogen, iron) with 10000 vertical showers per energy and group using statistical thinning $\varepsilon = 10^{-4}$ with the weight $w = \varepsilon E(GeV)$. Thus, the total number of simulated showers is 200000.

Each partial distribution is fitted by a shifted Gamma distribution with following probability density function:

$$P_G(X_{max}) = \frac{(X_{max} - X_0)^{\gamma-1}}{\Gamma(\gamma)\beta^{\gamma}} exp\left(-\frac{X_{max} - X_0}{\beta}\right)$$

for $X_{max} \geq X_0; \gamma, \beta > 0$.

Mean and standard deviation:

$$< X_{max} >= \beta\gamma + X_0$$
$$RMS = \beta\sqrt{\gamma}$$

Statistical uncertainties of $< X_{max} >$ and RMS are less than 1 g/cm^2.

To recalculate distributions of nuclei for all energy intervals interpolations of Gamma distribution parameters

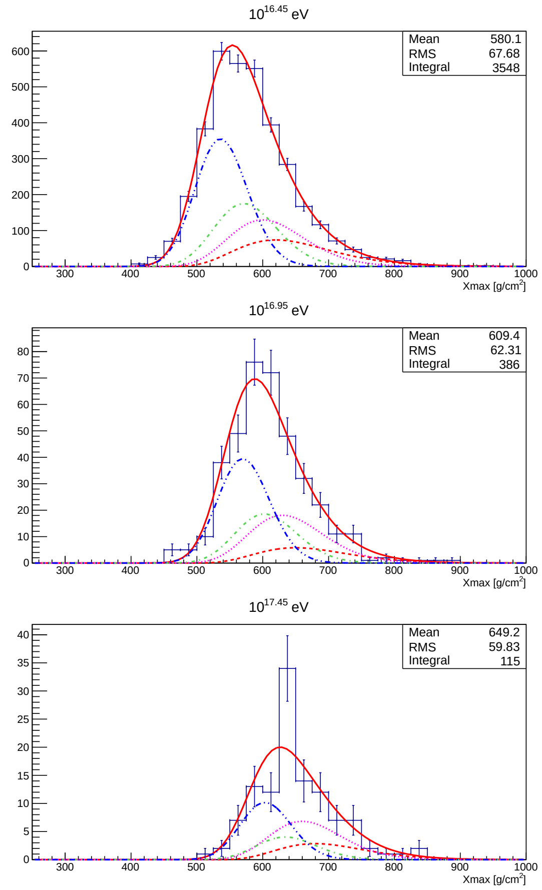

Fig. 2: Best fit (*solid*) for three different energy bins. The lines correspond to: proton (*dash*), helium (*dot-dot*), nitrogen (*dash-dot*) and iron (*dash-dot-dot*).

are used. For interpolation physically sensible parameters $< X_{max} >$, RMS and γ index were chosen. Their linear interpolations are:

$$< X_{max} >_H = 55.53 \log(E/PeV) + 568.02 [g/cm^2]$$
$$< X_{max} >_{He} = 58.45 \log(E/PeV) + 529.22 [g/cm^2]$$
$$< X_{max} >_N = 62.07 \log(E/PeV) + 487.96 [g/cm^2]$$
$$< X_{max} >_{Fe} = 67.40 \log(E/PeV) + 441.19 [g/cm^2]$$

$$RMS_H = -7.83 \log(E/PeV) + 84.73 [g/cm^2]$$
$$RMS_{He} = -3.54 \log(E/PeV) + 57.65 [g/cm^2]$$
$$RMS_N = -2.69 \log(E/PeV) + 42.90 [g/cm^2]$$
$$RMS_{Fe} = -1.31 \log(E/PeV) + 29.58 [g/cm^2]$$

$$\gamma_H = 4.27$$
$$\gamma_{He} = 7.52$$
$$\gamma_N = 12.36$$
$$\gamma_{Fe} = 16.73$$

Each gamma distribution is convolved with Gaussian with known X_{max} resolution and used for fitting.

4 Elemental Composition

The composition of CR is determined by the fit procedure of the EAS depth distributions as a superposition of weighted

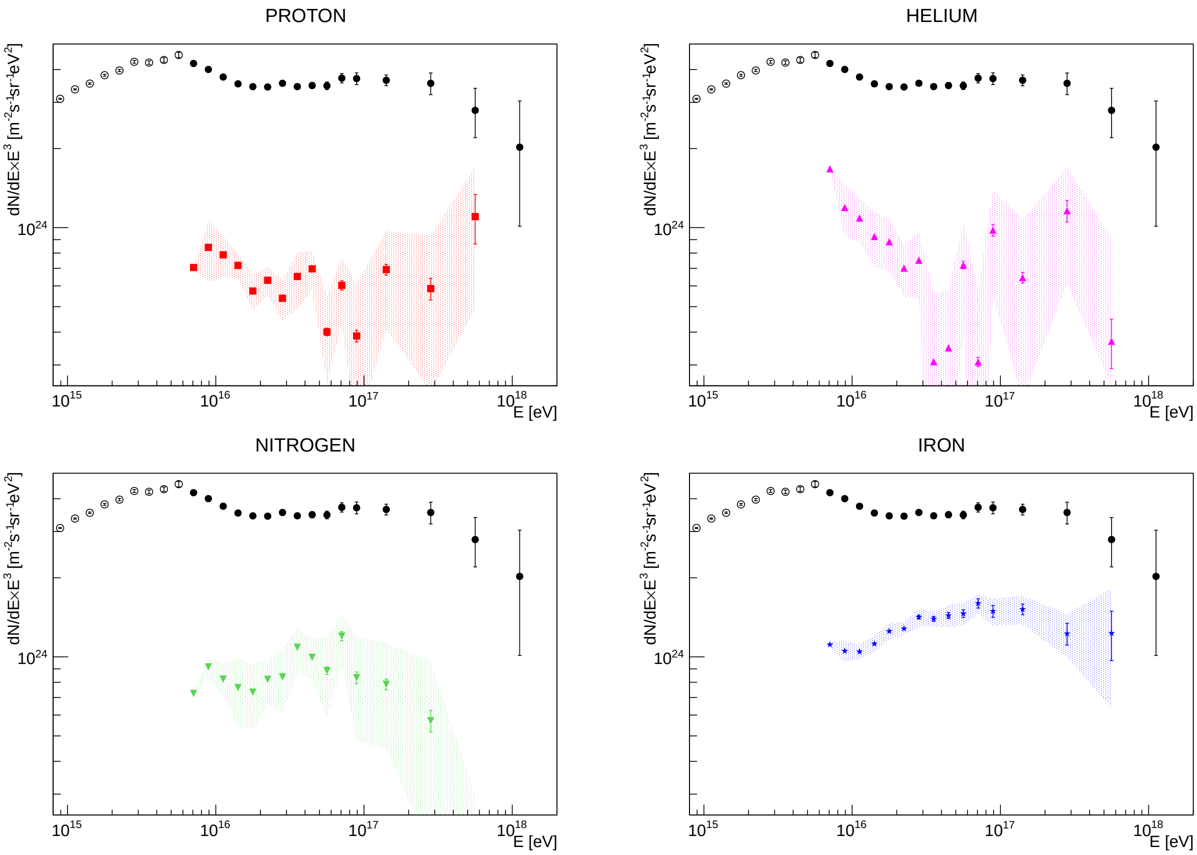

Fig. 3: Elemental spectra of H, He, N, Fe. The merged all-particle spectrum of Tunka-25(○) and Tunka-133(●). Errors bars and shaded bands represent statistical and systematic uncertainties.

elemental distributions in narrow logarithmic intervals of 0.1 of the reconstructed primary energy from 7×10^{15} to 10^{17} eV and in three merged intervals above 10^{17} eV. For analysis events were selected with core position inside the circle radius of 450 m and with a zenith angle cut of 45°. The total number of selected events is 99510 with 53399 ($> 10^{16}$ eV) and 617 ($> 10^{17}$ eV).

The weights of each group are found through log-likelihood minimization and can be used for recalculation of elemental spectra and mean natural logarithm of mass A.

However, due to the fact that the fit function has a quite irregular behavior for minimization it is difficult to find a reliable minimum after a certain number of iterations. Procedure requests to specify initial values and the result of fitting depends on these values and statistical uncertainties of experimental distributions. As initial values, weights are ranged with step of 10%. Furthermore, to suppress influence of statistical fluctuations on the result each bin of the experimental distribution is varied according to Poisson law with a mean equal to the experimental value. Mean and standard deviation of found solutions are accepted as resultant composition and error of the method.

The best fit for three different energy bins are shown on Fig. 2.

5 Results and discussion

The results for the elemental spectra of proton, helium, nitrogen and iron of the X_{max} based analysis are shown on Fig. 3. Fig. 4 represents "light" (H+He) and "heavy" fraction

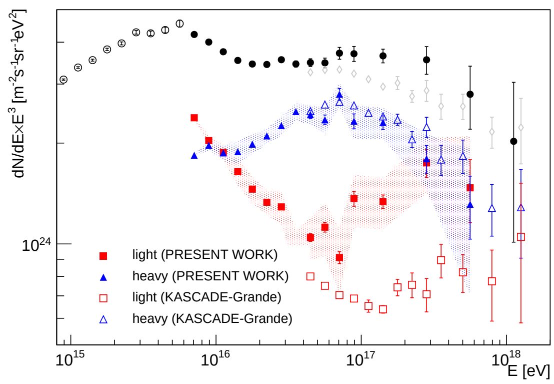

Fig. 4: Spectra of "light" and "heavy" fractions as compared with KASCADE-Grande.

(N+Fe) in comparison with recent results of KASCADE-Grande [3].

Features of the all-particle spectrum can be explained from the standpoint of the mass composition. Our investigations reveal that the complex "knee" at $3-6 \times 10^{15}$ eV in the all-particle spectrum is associated with a limit of acceleration of the proton and helium nuclei in the Galaxy. Moreover, from the energy 3×10^{16} eV and above a similar growth of the light component caused by the potential extra-galactic modulation can be seen [10]. The same "knee-like" structure in the spectrum of heavy component is obtained at

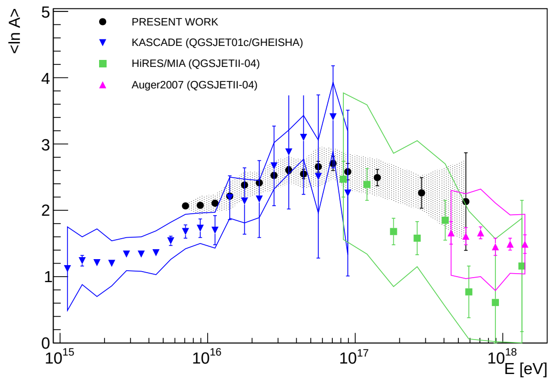

Fig. 5: $< \ln A >$ as function of energy. Errors bars and bands represent statistical and systematic uncertainties.

7×10^{16} eV. Both components have equivalent fractions at energies of 10^{16} and $3-5 \times 10^{17}$ eV.

This behavior implies an increase of the mean logarithmic of mass $< \ln A >$ as a function of energy (Fig. 5) up to 10^{17} eV from 2.0 to 2.7. Above 10^{17} eV the composition is becoming lighter down to 2.1 at an energy of 6×10^{17} eV. The obtained $< \ln A >$ has a quite smooth behavior and is consistent within experimental errors with KASCADE [2] and fluorescence experiments HiRES/MIA[5] and Auger[6]. In present study, the $< \ln A >$ of KASCADE are adopted from elemental spectra of an unfolding procedure for QGSJET01c/GHESHA hypothesis. In the case of fluorescence experiments, the simple interpolation of $< X_{max} >$ between proton and iron are used.

Moreover, the influence of high-energy interaction models on results inferring the mass composition has been considered. The choice of model affects mainly the absolute position and, to a lesser extent, the width of partial X_{max} distributions of nuclei. Thus, it was found for proton and iron the difference between QGSJETII-04 and QGSJET01c models for $< X_{max} >$ about 10 g/cm^2 and for RMS less than 1.5 g/cm^2. It gives a systematic shift $\Delta(< \ln A >) = 0.2-0.3$ toward to higher composition. This fact means that the partial X_{max} distribution has the universal shape, only depending on the primary energy and the type of nucleus.

6 Conclusions

In the present study, the new technique, applied to depth distributions data of Tunka EAS Cherenkov array, has been demonstrated for the analysis of the elemental composition of cosmic rays and can be used in future. The new data reexamination will provide a complete composition analysis in PeV range. Full detector simulation is still needed for improved X_{max} reconstruction and to include possible systematic effects.

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