Analysis of the mass composition of high-energy cosmic ray

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Abstract. This paper analyses mass composition of high-energy cosmic ray, comparing simulation and experimental results. Using the nuclear interaction models QGSJET-II and Sibyll, we simulate EAS initiated by the primary nuclei representing all mass groups (p, He, O, Si, Fe). EAS is simulated for several energy levels between $1 \times 10^{18}$ and $5 \times 10^{19}$ eV. For each generated simulation data, we compute X-max distributions, mean X-max and RMS and compare these values with the experimental data from the Auger Experiment. The results show that for the 2-sigma confidence level, mass composition including nuclei from the CNO group and heavier can be fitted for Sibyll model only. For any combination of 3 and 4 primary particles, no model fits the experimental data at the 1-sigma confidence level. For the p + Fe bi-particle composition, or other combination of two particles, also no model fitting the experimental data can be found for the analysed energy interval.

1. Introduction
Experiments analysing extensive air showers (EAS) register, among others, depth Xmax in the Earth's atmosphere, where the shower has a maximum number of particles. From the simulation-based distribution of Xmax, it is possible to compute the average and standard deviation ($<\text{Xmax}>$ and RMS).

The analysis of paper [1] presented experimental values $<\text{Xmax}>$ and RMS, as found in the Auger experiment. Additionally, the paper gives the corresponding values for primary particles p and Fe, obtained from EAS simulations, as well as the possibility of changing the energy mass composition for primary particles $E_o$ around $1 \times 10^{19}$ eV.

The objective of this paper is to establish whether it is possible to choose such a mass composition, which would describe experimental results without the necessity of changing the model of nuclear interactions.

2. Simulation assumptions
This paper conducts the calculations simulating EAS for models QGSJet2 and Sibyll. We use CORSIKA v.6.98 [2]. Particles initiating showers were selected atom nuclei from the particular mass groups, i.e. p, He, O, Si and Fe. Simulations were conducted for set energy levels of $E_o$: $1 \times 10^{18}$, $5 \times 10^{18}$, $1 \times 10^{19}$, $2 \times 10^{19}$ and $5 \times 10^{19}$ eV. For each energy level $E_o$ and each primary particle, minimum 200 showers have been simulated.

Using the results, Xmax distributions have been made and estimators $<\text{Xmax}>$ and RMS have been calculated for these distributions. The results for both models, QGSJet2 and Sibyll, are presented in Figures 1 - 4. Data from the Auger experiment are also indicated in the figures.
3. Analysis of calculation results

The calculations are conducted for each of selected energies $E_o$ for all combinations of 2, 3 and 4 primary particles. We estimate the percentage of nuclei in each mass composition, which sum to 100%. For each combination of particles, we estimate $<X_{\text{max}}>\text{ and RMS for mixed distribution and compare it with the experimental results. The correspondence to experimental results is checked according to the following formula (1):}

$$|\langle X_{\text{max}}\rangle_{\text{exp}} - \langle X_{\text{max}}\rangle_{\text{calc}}| < \varepsilon$$

where $\varepsilon$ is the confidence band of width 1-sigma, 2-sigma i 3-sigma of experimental data (RMS values).

3.1. Bi-particle mass composition

For each analysed combination of 2 primary particles, their percentage is estimated so that the value of $<X_{\text{max}}>\text{ for complete Xmax distributions of these particles equals the experimental value. For this, formula (2) was used.}

$$\langle X_{\text{max}} \rangle = (1 - \alpha) \langle X_{\text{max}} \rangle_p + \alpha \langle X_{\text{max}} \rangle_{\text{Fe}}$$

$$\sigma^2 = (1 - \alpha) \sigma_p^2 + \alpha \sigma_{\text{Fe}}^2 + (1 - \alpha) \langle X_{\text{max}} \rangle_p - \langle X_{\text{max}} \rangle_{\text{Fe}}^2$$

Figures 1 - 4. $<X_{\text{max}}>$ and RMS values for experiment and simulation, for both models, QGSJet-II (upper raw) and Sibyll (bottom raw). The Auger experiment data are presented in the figures as red dots.
Further, RMS is estimated for the calculated mass composition, according to formula (3). The results show that none of the bi-particle combinations matches the data from the Auger experiment.

3.2. 3- and 4-particle mass compositions
For each of the compositions, percentages of nuclei between 0% and 100% are ascribed so that the sum is 100%. For each case we calculate \( \langle X_{\text{max}} \rangle \) and RMS of the distribution, which is composed of the partial distributions in the assumed proportions, according to the formulas (4) and (5).

\[
\langle X_{\text{max}} \rangle = \sum_A \alpha_A \langle X_{\text{max}} \rangle_A 
\]

\[
\sigma^2 = \sum_A \left( \alpha_A \sigma_A^2 + \alpha_A \left( X_{\text{max}}_A - \langle X_{\text{max}} \rangle_A \right)^2 \right) 
\]

### Table 1. Results of comparison simulation and experimental data for the 2-sigma confidence level.
The empty box means that the model matches the data, the cross means that the model does not match the data.

| Eo(eV) | pHeN | pHeO | pHeSi | pHeFe | pNO | pNSi | pNeFe | pOSi | pOFe | HeNO | HeNSi | HeOFe | HeOFe | HeSiFe | NOSi | NOSi | NOFe | NOSi |
|-------|------|------|-------|-------|------|------|-------|------|------|------|-------|-------|-------|-------|------|------|------|------|
| QGSJet II | 1·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 1·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 2·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Sibyll | 1·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 1·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 2·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

### Table 2. Results of comparison simulation and experimental data for the 2-sigma confidence level. The empty box means that the model matches the data, the cross means that the model does not match the data.

| Eo(eV) | pHeNO | pHeNSi | pHeNeFe | pHeOFe | pHeSiFe | pNOsi | pNOFe | pNSiFe | pOFe | HeNOsi | HeNSiFe | HeOFe | HeOFe | HeSiFe | NOSi | NOSi | NOFe | NOSi |
|-------|-------|--------|--------|--------|--------|-------|-------|--------|------|--------|--------|-------|-------|-------|------|------|------|------|
| QGSJet II | 1·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 1·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 2·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Sibyll | 1·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{18} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 1·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 2·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| 5·10^{19} | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
The obtained values are compared with the experimental data. For 1-sigma confidence level, none of the particle combinations for both models describes the data of Auger experiment. For the 2-sigma confidence level, model QGSJet2 does not overlap with the experimental data for any of the energies (tables 1 and 2). Model Sibyll allows to describe experimental data with the distribution of nuclei from light and middle groups. For example, the following nuclei combinations match the experimental data for 2-sigma confidence band: p+He+N, He+N+Si, He+N+Fe, p+He+N+Si or He+N+Si+Fe. Looking at the results across energy levels, the most difficult is the $E_o = 2 \cdot 10^{19}$ eV, for which the correspondence with the experimental data is very difficult to establish for narrow confidence intervals.

4. Conclusions

This paper analyses mass composition of high-energy cosmic ray, comparing simulation and experimental results. Mass compositions for primary energies $E_o$ from the interval $1 \cdot 10^{18} – 5 \cdot 10^{19}$ eV were composed from the following particles: p, He, O, Si and Fe, for QGSJet II and Sibyll interaction models. For the combinations of two particles, none of them describes the data from the Auger experiment. Mass compositions of 3 and 4 particles are acceptable only for the model Sibyll for the confidence level of 2 standard deviations for the corresponding values of $<X_{\text{max}}>$ and RMS. Model QGSJet2 does not match the experiment data for any of the energies and for the confidence level of 2-sigma. For the confidence level of 3-sigma (RMS $\approx 15$) most of the 3- and 4-particle combinations match the experimental data for both models.

References
[1] Abraham J at al (Pierre Auger Collaboration) 2010 Phys. Rev. Lett. 104 091101
[2] D. Heck et al 1998 Preprint FZKA 6019