Fitting fractions of the X_{max} distributions at ultra high energies

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Abstract. The mass composition of ultra high-energy cosmic ray (UHECRs) can be inferred from measurements of X_{max} distributions by fitting them with Monte Carlo (MC) predictions for different primary species of nuclei in each energy interval. On the basis of Monte Carlo (MC) simulations, we show that an appropriate approach is to fit the observed X_{max} distributions with all possible combinations of elements from a large set of primaries (in our case p, He, C, N, O, Ne, Si and Fe), and to find the "best combinations" of elements which best describe the observed X_{max} distributions. We apply this method to the X_{max} distributions recorded by the Pierre Auger (2014) and Telescope Array (TA) (2016) Observatories in the energy range lg E(eV) = [17.8 - 19.3] and lg E(eV) = [18.2 - 19.0], respectively, by employing MC predictions of the QGSJETII-04 hadronic interaction model. The results obtained from both data sets suggest that the mass composition of UHECRs is dominated by protons and He nuclei ($\gtrsim$ 70%) which present a modulation of their abundances as a function of primary energy, but keeping their sum roughly constant. We performed an indirect comparison between the two data sets measured by the two experiments and found a good degree of compatibility in some energy bins around and above the ankle (lg E(eV) $\sim$18.7), but worsening at lower energies. We consider that the current approach, completed with predictions of different hadronic interaction models, can be used in further studies on mass composition to obtain a more accurate image of the evolution of the individual fractions of nuclei as a function of energy on the basis of experimental X_{max} distributions.

1. Simulations

The MC templates were computed with CONEX v4r37 for each primary species (p, He, C, N, O, Ne, Si and Fe) in each energy intervals of 0.1 in lg(E/eV) between lg(E/eV) = [17.8 - 19.3] and lg(E/eV) = [18.2 – 19.0] for Auger and TA case, respectively. The true X_{max} values were modified in accord with the detector acceptance and resolution for the Auger case [1] and with the bias and resolutions computed in [2] for the case of TA. In the case of TA experiment, for the intermediate elements we used a polynomial interpolation.

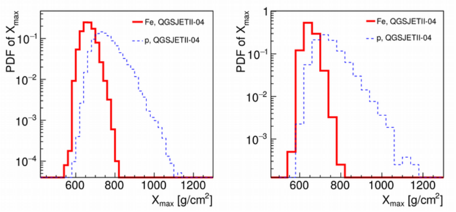

Fig. 1: PDFs of X_{max} for proton and iron induced showers in the energy range lg(E/eV) = [18.4 – 18.5] employing the QGSJETII-04 hadronic interaction model for Auger case (left) and TA case (right) .

In the fitting process we used the binned maximum-likelihood procedure, and the goodness-of-fit is characterized by the *p-value* parameter.

$$-\ln L = \sum_i y_i - n_i + n_i \ln(n_i/y_i) \qquad p\text{-}value = 1 - \Gamma\left(\frac{ndf}{2}, \frac{\chi^2}{2}\right)$$

n_i = data

y_i = MC prediction

We test the ability of the method which fits the observed X_{max} distributions with MC templates for four primary species (p, He, N/O and Fe) by using mock data sets of X_{max} distributions with random concentrations of 8 primary species. We found that in the case in which the prior abundance of Ne or Si is quite large (> 40%) the reconstructed fractions of the four MC templates are biased from their true fractions (see Fig. 2) and also the quality of the fit is affected (see Fig. 3).

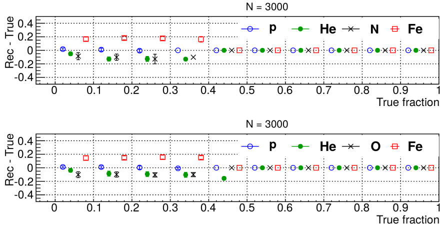

Fig. 2: The bias of the reconstructed fractions used in the fitting procedure as a function of their true prior fraction, when the concentration of Si is > 40% and the X_{max} distributions are fitted with (p, He, N, Fe) (up) and (p, He, O, Fe) (down), in the energy interval lg(E/eV) = [18.4 – 18.5]. The statistics in X_{max} distribution is N = 3000 events. The points corresponding to the true fraction interval [0.4 - 1] can be neglected.

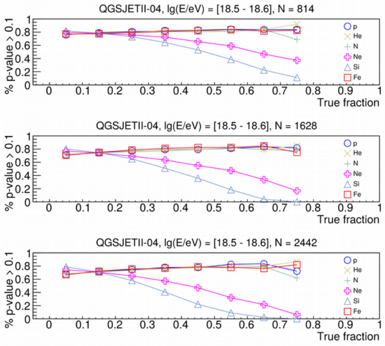

Fig. 3: Fraction of events with p-value > 0.1 as a function of prior abundances of each species corresponding to the energy interval lg(E/eV) = [18.5 – 18.6]. The fitting function includes only the four fixed elements (p, He, N and Fe). The statistics of X_{max} distributions is indicated on the top of the plots, corresponding to the Auger statistics $N = N_{Auger}$ *(up)*, $N = 2 \times N_{Auger}$ *(middle)* and $N = 3 \times N_{Auger}$ *(down)*.

2. Fitting Auger (2014) and TA (2016) X_{max} distributions

We fit the experimental X_{max} distributions with all possible combinations of elements from a larger set of primaries (p, He, C, N, O, Ne, Si and Fe) in each energy interval. We find the "best combination" of elements which best describe the observed distribution on the basis of the highest *p-value*.

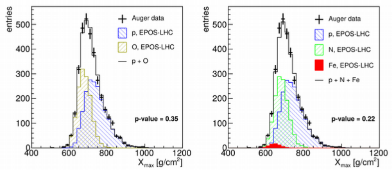

Fig. 4: X_{max} distribution recorded by Auger in the energy range lg(E/eV) = [17.9 – 18.0]. The reconstructed fractions using the "best combination" approach (*left*) and the method which uses the four elements (p. He, N and Fe) (*right*) [3].

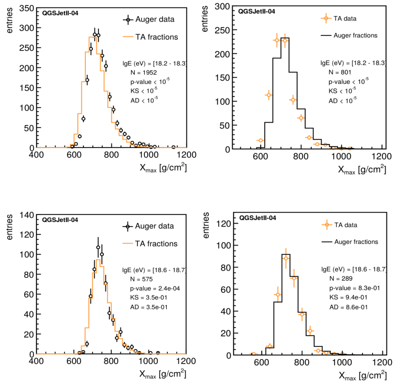

Fig. 6: Comparison between Auger data and PDFs of $X_{max}^{TA\to Auger}$ (*left*) and TA data vs. PDFs of $X_{max}^{Auger\to TA}$ (*right*) for the energy interval lg (E/eV) = [18.2 – 18.3] (*top*) and lg (E/eV) = [18.6 – 18.7] (*bottom*). The three parameters used to characterize the probability of compatibility are displayed on each plot.

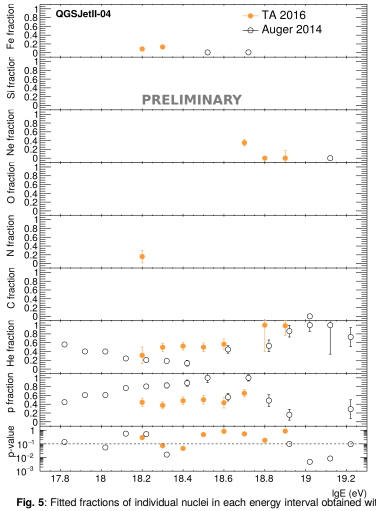

Fig. 5: Fitted fractions of individual nuclei in each energy interval obtained with the "best combination" approach predicted by QGSJETII-04 model.

Conclusions

Fitting the X_{max} distributions with the same four elements on the entire energy spectrum, the reconstructed fractions of the individual nuclei will be biased in some energy intervals as a consequence of not including into the fitting function of some intermediate elements which are in fact present.

An appropriate method is to fit the observed distributions with all possible combination of elements from a larger set of primaries, finding in this way the "best combination" of elements to describe the data.

Applying this method to Auger(2014) and TA (2016) we found that the mass composition is dominated by protons and He nuclei (>70 %) on the entire energy spectrum, using predictions of QGSJETII-04 model.

An indirect comparison between the two data sets show a good degree of compatibility in some high energy bins, but worsening at lower energies.

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