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Composition and energy spectra of elemental groups around the knee: Results from KASCADE

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A composition analysis of KASCADE air shower data is performed by means of unfolding the two-dimensional electron-muon number spectrum in energy spectra of 5 elemental groups. The results of the analysis are based on a vast number of Monte Carlo simulations with the two different high-energy hadronic interaction models QGSJet and SIBYLL. For both models the light elemental groups show a distinctive knee feature, causing the knee in the all particle spectrum at around 4 PeV, whereas heavy primaries do not. The relative abundancies of the elemental groups show a large model dependence. Moreover, the description of the data by the simulations shows to be imperfect and sensitive to the characteristics of the interaction model used.

1. Introduction

The origin of the knee in the cosmic ray energy spectrum (a steepening of the spectrum at $\approx$4 PeV) is still not convincingly explained. To discriminate between different proposals for its origin it is necessary to obtain information about the energy spectra of individual elements or at least elemental groups of primary cosmic rays.

The KASCADE experiment [1], especially designed for air shower measurements in the knee region, aims at this question. A major component is the field array whose main reconstructed observables are the electron number N_e and the truncated muon number N_μ^{tr} which are used in this analysis. The latter one is the number of muons with distances to the shower core between 40 m and 200 m. Information about the reconstruction and the measurement procedures are given in Ref. [1]. The accessible energy range covers the knee, the effective measurement time added up to 900 days.

The presented analysis makes use of unfolding algorithms, which are applied to the measured two-dimensional frequency spectrum of $\lg N_e$ and $\lg N_\mu^{tr}$. Since such an analysis depends crucially on air shower simulations, the analysis is performed twice using different hadronic interaction models for their generation. This approach also gives a lower limit of the uncertainties due to the modelling of the hadronic interactions.

2. Outline of the analysis

Starting point of the analysis is the correlated frequency distribution of $\lg N_e$ and $\lg N_\mu^{tr}$ displayed in Fig. 1 (left panel). The lower boundaries in $\lg N_e$ and $\lg N_\mu^{tr}$ were chosen in a way to minimize influences from efficiencies. Considered zenith angles range from $0°$ to $18°$. The content N_j of each cell can be written as

$$N_j = C \sum_{A=1}^{N_A} \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A(\lg N_{e,j}, \lg N_{\mu,j}^{tr} | \lg E)\, d\lg E. \qquad (1)$$

C is a normalizing constant (time, aperture), the sum is carried out over all primary types with mass A, and p_A describes the probability for an EAS with primary energy $\lg E$ to be measured and reconstructed with shower sizes $\lg N_e$ and $\lg N_\mu^{tr}$. This probability consists of the shower fluctuations s_A, efficiencies ϵ_A, and reconstruction properties r_A. For sake of simplicity the integration over cell area and solid angle is omitted in Eqn. 1 but of course accounted for in the analysis. The data histogram of Fig. 1 (left) is therefore interpreted as a system of coupled integral equations. For the analysis the primary particles H, He, C, Si, and Fe were chosen as representatives for five mass groups. The probability distributions s_A, ϵ_A, and r_A were determined by Monte Carlo simulations using CORSIKA[2] 6.018 with the low energy interaction model GHEISHA[3] (corrected version of 2002) and the two high energy interaction models QGSJet[4] (2001 version) and SIBYLL[5] (version 2.1). In order to solve the equation system unfolding methods were applied. Three different algorithms were used to cross-check systematic uncertainties. Details of the analysis and the used unfolding methods can be found in Ref. [6].

3. Results and conclusions

In the upper part of Fig. 2 the results for the spectra of light elements (left) and heavy elements (right) of the QGSJet based analysis are shown, in the lower part the corresponding spectra using SIBYLL simulations. The resulting all particle spectra for both cases are shown in the right panel of Fig. 1. The shaded bands in the figures represent an estimate of the methodical uncertainties.

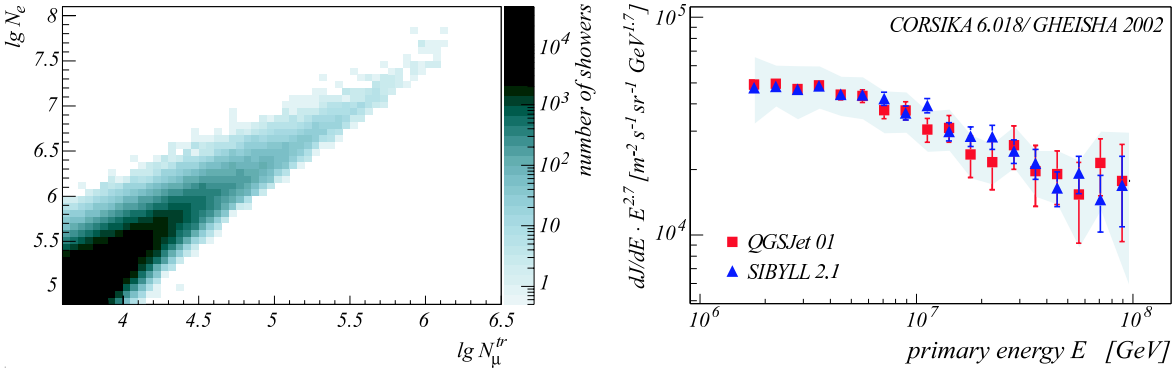

Figure 1. Left: Two-dimensional shower size spectrum as measured by KASCADE. The range in $\lg N_e$ and $\lg N_\mu^{tr}$ is chosen to avoid influences of inefficiencies. Right: Result for the all particle energy spectrum using QGSJet01 and SIBYLL 2.1 simulations. The shaded band represents the estimated systematic uncertainties for the QGSJet solution, being of the same order as for the SIBYLL solution.

The all particle energy spectrum shows a knee at ≈4 PeV for both results and inside the statistical uncertainties the results coincide. The decrease of light elements across the knee, i.e. the occurence of knee-like features in the light element spectra is also revealed independent of the used simulation code. In contrast the spectra of Si and Fe differ significantly and look quite unexpected. This can be understood by judging the ability of the simulations to describe the data. Fig. 3 (upper row) shows the distribution of residuals of a χ^2-comparison between data and forward folded (according to Eqn. 1) solutions. For both interaction models the overall value of χ^2 p.d.f. is about 2.4 and strong systematic effects are found in the distribution of the residuals. These systematics reflect properties of the used interaction models and are not caused by improper understanding of reconstruction or detector simulation.

To demonstrate the kind of these deviations a comparison between the measured and the $\lg N_e$-distribution resulting from forward folding for two fixed $\lg N_\mu^{tr}$ bins are displayed in the lower row of Fig. 3. It turns out that both interaction models fail to reproduce the overall correlation between $\lg N_e$ and $\lg N_\mu^{tr}$ as observed in the data. In the case of QGSJet simulations the predictions are incompatible with the data in the low energy regime (simulations look too heavy), for SIBYLL incompatibility occurs at higher energies (simulations look too light). Summarizing the results of this analysis the knee in the all particle spectrum is due to kinks in the light element spectra resulting in a heavier composition above the knee. A more specific statement seems inappropriate since neither QGSJet nor SIBYLL describe the measured data consistently over the whole measurement range. The analysis is ongoing, using the new version of QGSJet and other high and also low energy interaction models, e.g. replacing GHEISHA by FLUKA [7] in the simulations.

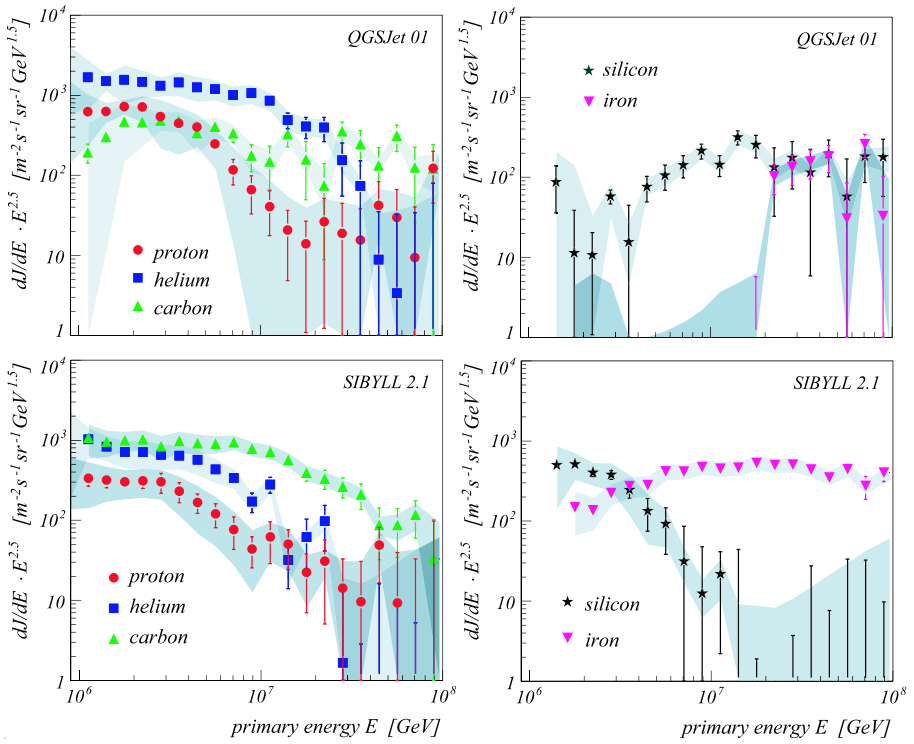

Figure 2. Results for the energy spectra, H, He, C in left column, Si and Fe in right column. Upper row: QGSJet01 hypothesis; lower row: SIBYLL 2.1 hypothesis. The shaded bands indicate methodical uncertainties.

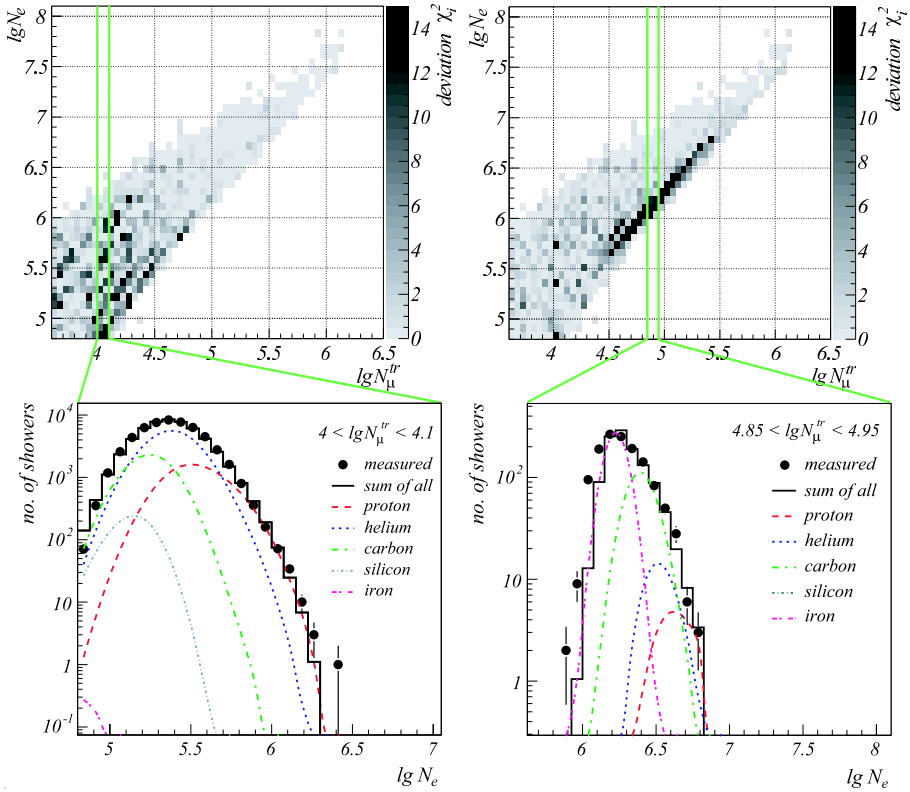

Figure 3. Upper part: Distribution of deviations between data and forward folded solution for QGSJet (left) and SIBYLL (right). Lower part: Example of insufficient description of measured data for fixed lg N_μ^{tr} bins; left panel for QGSJet, right panel for SIBYLL.

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