Results and status of the KASCADE experiment

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Abstract. The KASCADE experiment, nearly 10 years in operation, measures extensive air showers induced by cosmic rays in the knee region, i.e. with energies between 0.5 PeV and 100 PeV. The principal task of the experiment is the precise measurement of the energy and the chemical composition of primary cosmic rays in order to clarify the origin of the knee. Out of the KASCADE results a composition analysis is presented, showing the knee being caused by a steepening of the light element spectra. In addition, the limitations to these conclusions due to the dependence on the high energy hadronic interaction models used in the simulations are shown.

Keywords: cosmic rays, air showers, energy spectra, chemical composition
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INTRODUCTION

The origin of the so-called *knee* in the cosmic ray energy spectrum (a steepening of the spectrum around 4 PeV) is still not convincingly explained, even nearly 50 years after its discovery. To discriminate between different proposals for it's origin information about the energy spectra of individual elements or at least elemental groups of primary cosmic rays is needed.

Due to the low intensities cosmic rays in the knee region are measured by the detection of extensive air showers (EAS). When reconstructing the properties of primary cosmic ray particles out of air shower data one has to rely on the results of simulations and the description of high energy hadronic interaction used therein. Since the considered energy region is not accessible by accelerator experiments, the interaction models used are uncertain and different in their predictions. Therefore, the analysis of air shower data is also a test of the validity of high energy interaction models.

The especially designed KASCADE experiment [1] addresses these questions by measuring as many observables of individual EAS as possible. Besides a hadron calorimeter and different detector systems for tracking individual muons, a major component of the installation is the 208×208 m^2 field array consisting of scintillation detectors. It's main reconstructed observables are the electron number N_e and truncated muon number N_μ^{tr} (number of muons with core distances between 40 m and 200 m). The correlation between these quantities allows, in principle, the reconstruction of energy spectra for elemental groups, representing the chemical compostion of primary cosmic rays. The results of the analysis and their limitations are presented in the following.

ANALYSIS OF THE SHOWER-SIZE SPECTRUM

Starting point of the analysis is the frequency distribution of air showers with *shower sizes* $\lg N_e$ and $\lg N_\mu^{tr}$. This so-called two-dimensional shower size spectrum is 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 effective measurement time adds up to 900 days.

The content N_j of each histogram 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 describing the probability for an EAS with primary energy $\lg E$ and mass A to be measured and reconstructed with shower sizes $\lg N_e$ and $\lg N_\mu^{tr}$. The probablities p_A therefore include shower fluctuations, efficiencies, and reconstruction systematics and resolution. Integration over cell area and solid angle is omitted in Eqn. 1 but of course accounted for in the analysis.

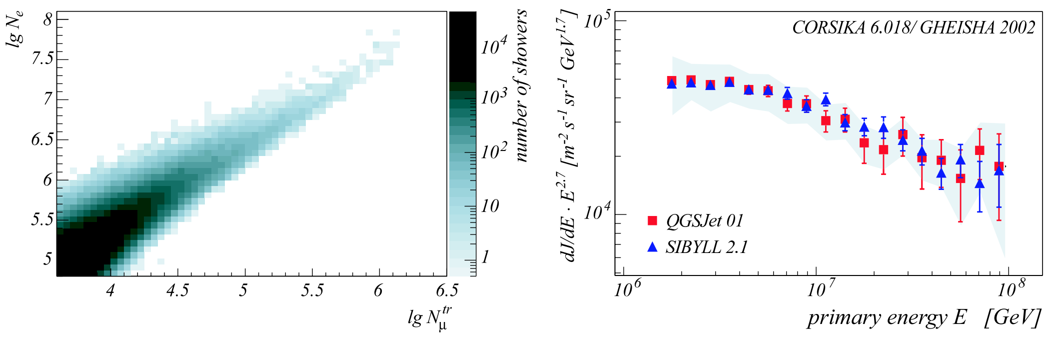

FIGURE 1. Left: Two-dimensional shower size spectrum as measured by KASCADE. Right: Result for the all particle energy spectrum using QGSJet 01 and SIBYLL 2.1 simulations. The shaded band represents the systematic uncertainties for the QGSJet solution.

With this notation the two-dimensional shower-size spectrum is regarded as a set of coupled integral equations. To solve this system for the elemental group energy spectra unfolding algorithms are applied. In the analysis the primary particles H, He, C, Si, and Fe were chosen as representatives for five elemental groups. The corresponding probability distributions p_A were determined by Monte Carlo simulations using CORSIKA [2] 6.018 with the low energy interaction model GHEISHA [3] and the high energy interaction models QGSJET [4] (2001 version) and SIBYLL [5] 2.1. Details of the analysis can be found in Ref. [6].

RESULTS

The results of the unfolding analysis are displayed in Fig. 1: in the upper part the spectra of light (left) and heavy (right) element groups using QGSJET simulations are shown, in the lower part the corresponding results of the SIBYLL based analysis. The results for the all particle spectrum are displayed in the right panel of Fig. 1.

The all particle spectrum, coinciding very well for the two interaction models, shows a knee at $\approx$ 4 PeV caused by occurence of knee-like features in the light element spectra. This is revealed independently from the used simulation code. In contrast the spectra of Si and Fe differ significantly and look unexpected. This behaviour can be understood by judging the ability of the simulations to describe the data. Fig. 3 shows the distribution of residuals of a χ^2-comparison between data and forward folded

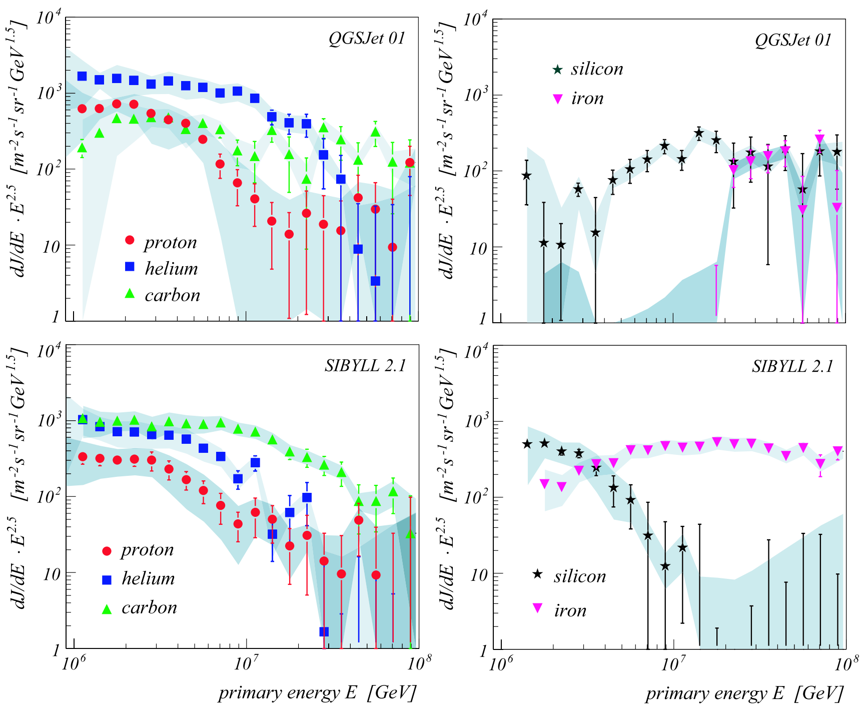

FIGURE 2. Results for the energy spectra. Left column: H, He, C; right column: Si, Fe. Results are based on QGSJet 01 (top) and SIBYLL 2.1 (bottom). Shaded bands indicate methodical uncertainties.

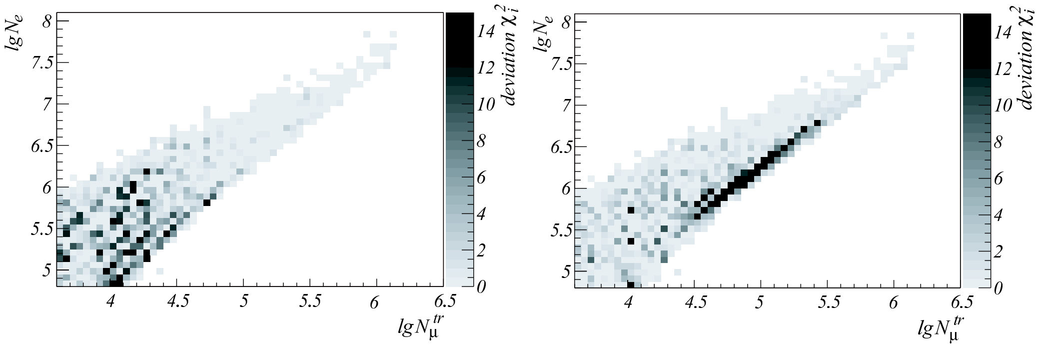

FIGURE 3. Deviations between data and forward folded solution for QGSJet (left) and SIBYLL (right).

(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 residuals. These systematics reflect properties of the used interaction models and are not caused by improper understanding of reconstruction or detector simulation.

ONGOING RESEARCH: KASCADE-GRANDE

Since the knee in the all-particle spectrum is caused by knee-like features in the light element spectra the question arises at which energy a steepening in the heavy element spectra takes place. For this reason the KASCADE experiment was upgraded by 37 additional detector stations supplied by the former EAS-Top experiment. Each of the stations consists of 10 m^2 plastic scintillator with a distance between two stations of 130 m on average. The whole installation – KASCADE-Grande [7] – covers an area of 0.5 km^2 allowing air shower measurements up to 10^{18} eV and therefore detailed investigation of a possible second knee around or above 10^{17} eV.

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