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Energy spectrum and elemental composition of cosmic rays in the PeV region

Recent results and future prospects of the KASCADE experiment

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Abstract. KASCADE (KArlsruhe Shower Core and Array DEtector) is determining flux spectra for different primary mass groups to disentangle the knee feature of the primary cosmic-ray energy spectrum. The energy spectra of the light element groups result in a knee-like bending and a steepening above the knee. The topology of the individual knee positions suggests a rigidity dependence. To proof the rigidity dependence the KASCADE array is now extended by a factor 10 in area. The major goal of KASCADE-Grande is the observation of the 'iron-knee' in the cosmic-ray spectrum at around 100 PeV which is expected following the KASCADE observations.

PACS. 98.70.Sa Cosmic rays

1 Introduction

The all-particle energy spectrum of cosmic rays shows a distinctive feature at few PeV, known as the *knee*, where the spectral index changes from -2.7 to approximately -3.1. At that energy direct measurements are presently not possible due to the low flux, but indirect measurements via the observation of extensive air showers (EAS) are performed. Astrophysical scenarios like change of the acceleration mechanisms at the cosmic ray sources (supernova remnants, pulsars, etc.) or effects of the transport mechanisms inside the Galaxy (diffusion with escape probabilities) are conceivable for the origin of the knee as well as particle physics reasons like a new kind of hadronic interaction inside the atmosphere or during the transport through the interstellar medium. Whereas the astrophysical scenarios require a charge (rigidity) dependence of the kink position for the various primary cosmic ray particles, the particle physics scenarios let expect a mass dependence. Despite 48 years of EAS measurements the origin of the kink is still not clear, as the disentanglement of the threefold problem of estimate of energy and mass plus the understanding of the air-shower development in the Earth's atmosphere remains an experimental challenge. To solve the puzzle the access is to reconstruct energy spectra for individual elements (or mass groups), with an accompanying careful investigation of the hadronic interaction mechanisms during the air-shower development. As more general introduction to the subject see a recent review [1].

The KASCADE experiment [2] aims to follow this concept by measuring as much as possible redundant information from each single air-shower event. The multidetector system allows to measure the total electron and muon

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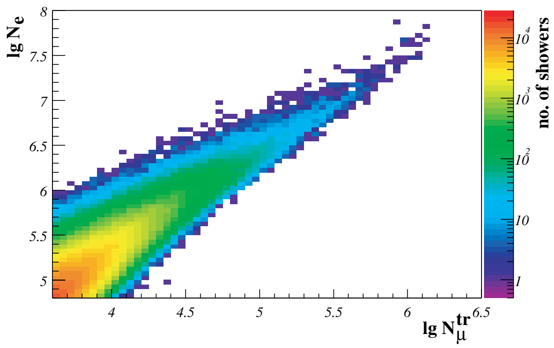

Fig. 1. Two dimensional electron (N_e) and muon ($N_\mu^{\rm tr}$) number spectrum measured by the KASCADE array. Only showers with a reconstructed zenith angle < 18° are included

numbers ($E_\mu > 240\,\mathrm{MeV}$) of the shower separately using an array of 252 detector stations in a grid of $200 \times 200\,\mathrm{m}$. Additionally muon densities at further three muon energy thresholds and the hadronic core of the shower by a $300\,\mathrm{m}^2$ iron sampling calorimeter are measured. In the following we present the method and results of a procedure unfolding the two-dimensional electron-muon number spectrum (Fig. 1) into the energy spectra of five primary mass groups. It will be shown that the results motivate the extension of KASCADE to measure higher primary energies, which will be realized by KASCADE-Grande.

2 Unfolding procedure

The content of each cell in Fig. 1 is the sum of contributions from the 5 considered primary elements. Hence the inverse problem

$g(y) = \int K(y,x)p(x)dx$

with $y = (N_e, N_\mu^{\rm tr})$ and $x = (E, A)$ has to be solved. This problem results in a system of coupled Fredholm integral equations of the form

$$\frac{dJ}{d\ \lg N_e d\ \lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{d\,J_A}{d\ \lg E} \cdot p_A(\lg N_e\ ,\ \lg N_\mu^{tr}\ \mid\ \lg E) \cdot d\ \lg E$$

where the probability p_A

$$p_A(\lg N_e, \lg N_\mu^{tr}\ \mid\ \lg E) = \int_{-\infty}^{+\infty} k_A(\lg N_e^t, \lg N_\mu^t) d\ \lg N_e^t\ d\ \lg N_\mu^t$$

is a further integral with the kernel function

$k_A = r_A \cdot \epsilon_A \cdot s_A$

factorized into three parts. The qunatity r_A describes the shower fluctuations, i.e. which distribution of electron and muon number is given for a primary energy and mass. The quantity ϵ_A describes the trigger efficiency of the experiment, and s_A describes the reconstruction probabilities, i.e. which distribution of N_e and $N_\mu^{\rm tr}$ are reconstructed for given true numbers of electrons and muons. The probabilities p_A are obtained by parameterizations of Monte Carlo simulations for fixed energies using a moderate thinning procedure as well as fully simulated showers for the input of the detector simulations.

The procedure is tested by using random initial spectra generated by Monte Carlo simulations. It could be shown that knee positions and slopes of the initial spectra could be reproduced and that the discrimination between the five primary mass groups is sufficient. For proofing the unfolding procedure, different mathematical ways of unfolding (Gold-algorithm, Bayes analyses, etc.) have been compared and the results are consistent [3].

The application of the unfolding procedure to the data is performed on basis of two different hadronic interaction models (QGSJet [4] and SIBYLL [5]) as option embedded in CORSIKA [6] for the reconstruction of the kernel functions [7].

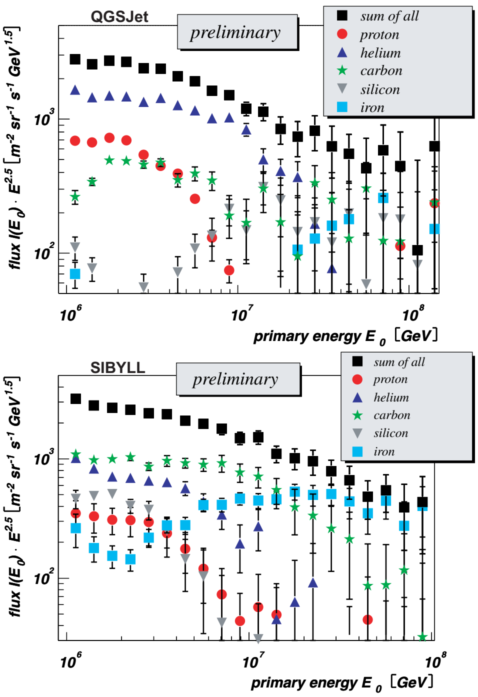

Fig. 2. Result of the unfolding procedure. *Upper part*: based on QGSJet, *lower part* for SIBYLL

3 Results

After applying the above described procedures to the experimental data the energy spectra are obtained as displayed in Fig. 2. Knee like features are clearly visible in the all particle spectrum as well as in the spectra of primary proton and helium. This demonstrates that the elemental composition of cosmic rays is dominated by light components below the knee and dominant by a heavy component above the knee feature. Thus the knee is caused by a decrease of the flux of the light primary particles. This corroborates results of the analyses of muon density measurements at KASCADE [8], which were performed independently of the present reconstructions.

But in addition the present results suggest a rigidity dependence of the knee feature. Compared to the kink in the proton spectrum the helium kink seems to be shifted by a factor of two, implying a charge dependence, and not by a factor of four what a mass dependence would require.

Comparing the results based on the two different interaction models, the problem is obvious. The first interaction of the primary particle in the atmosphere at the

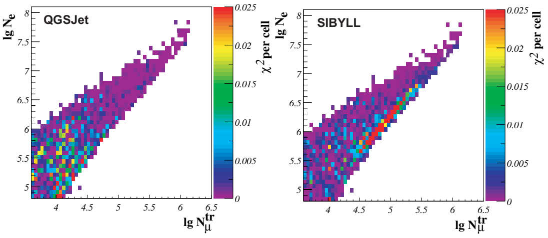

Fig. 3. χ^2-distribution for the comparison of data with simulations including the unfolding result

relevant energy region is inaccessible for the present man made accelerator experiments in both, in energy and in the kinematic region of the extreme forward direction. Hence modeling these interactions underlies assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by the discrepancies of the presented results on the basis of two different models. Figure 3 displays the χ^2-distribution after the unfolding for the two cases, pointing out that both models cannot describe the data. Hints for the unadequat description of the hadronic interactions at the atmosphere are also given by further KASCADE data analyses using the multidetector information: By Investigations of the hadron component in air-showers with the KASCADE hadron calorimeter [9] and by comparing muon densities for different muon energy thresholds [10]. Currently large efforts are made to sample the information from accelerator experiments and cosmic ray investigations [11] to improve the hadronic interaction models.

The uncertainties of the models influence mainly the relative abundancies of the various mass groups, but the basic results keep very stable if interaction models, unfolding methods or data samples are varied.

4 Future

For solving the puzzle of the origin of the knee further information is obviously required. For example, assuming a rigidity dependent knee position, for a discrimination between acceleration and transport mechanisms investigations of the anisotropy of the incoming primary particles could help. In Fig. 4 the results from a harmonic analysis of the arrival directions of the KASCADE showers are shown. The data set is divided in electron rich (dominantly induced by light particles) and electron-poor (dominantly induced by heavy particles) showers. The resulting Rayleigh amplitudes are within the level of sensitivity (90% confidence limit) of the data set well compatible with fluctuations from an isotropic arrival direction distribution [12].

A confirmation of the rigidity dependence would be the observation of an 'iron-knee' at around 100 PeV primary energy. For that the KASCADE experiment has been extended to KASCADE-Grande by an installation of additional 45 detector stations (37 as Grande array plus 8 as Piccolo trigger array) in a grid of 700 × 700 m^2 (Fig. 5). In the present configuration KASCADE-Grande consists of sensitive detectors of an area of 965 m^2 for the electron component, of 1070 m^2 for measuring muons at four different thresholds, and of 300 m^2 for hadron detection. Thus KASCADE-Grande displays the full capability of a multidetector experiment [13,14]. Data taking has started in July 2003.

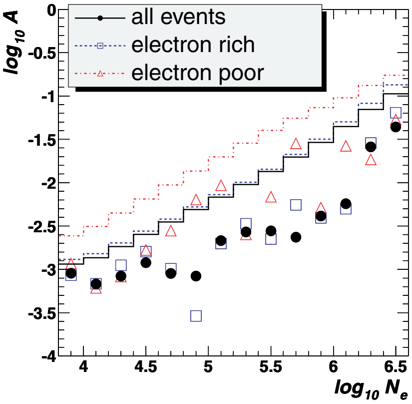

Fig. 4. Rayleigh amplitudes of the harmonic analyses of the KASCADE data. Lines show 90% sensitivity limit

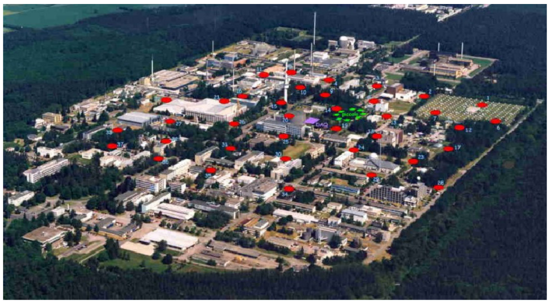

Fig. 5. Layout of the KASCADE-Grande experiment. At the *right part* of the photo the original KASCADE array is seen

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