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Towards the Energy Spectrum and Composition of Primary Cosmic Rays in the Knee Region: Methods and Results at KASCADE

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KASCADE (KArlsruhe Shower Core and Array DEtector) is a multi-detector setup to observe the electromagnetic, muonic and hadronic air shower components simultaneously at primary energies in the region of the "knee". A large number of observables per single shower are registered. The main aims of the experiment are the determination of the primary energy spectrum around the "knee" and the energy variation of the chemical composition. The measurements reveal an increasing mean mass of the primary cosmic rays above the observed kink, and a sharper knee for the light primary component than for the all-particle spectrum, and the absence of a knee for the heavy component between 1 and 10 PeV.

1. INTRODUCTION

In the 40 years since the first observation of a kink in the size spectrum of extensive air showers (EAS) between 1 and 10 PeV primary energy [1], in a lot of experiments the so-called "knee" has been confirmed. The proof of the kink was mainly shown in EAS observables like the shower size, i.e. the total number of particles of the EAS. But to clarify its origin, a precise knowledge about the energy variation of the mass composition and the shape of the primary energy spectrum is required. The Karlsruhe air shower experiment KASCADE [2] aims to investigate the knee region of the charged cosmic rays by precise measurements together with sophisticated methods of data analyses. An energy and mass estimation of the primaries are aspired on an event-by-event basis. KASCADE is a multi-detector setup for measuring simultaneously a large number of observables in the different EAS particle (electromagnetic, muonic and hadronic) components (see also the contribution of G. Schatz to these proceedings [3]). This feature of KASCADE enables to perform a multivariate analysis of the registered EAS on an event-by-event basis to account for the stochastic process of the EAS development. In parallel the KASCADE collaboration tries to improve the tools for the Monte Carlo simulations of the relevant physics. The program code CORSIKA [4] allows the detailed three dimensional simulation of the shower development of all particle components down to observation level,

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and has implemented several high-energy interaction models to facilitate comparisons [5].

2. ENERGY AND MASS ESTIMATION

The KASCADE array consists of 252 detector stations in a $200 \times 200\,\mathrm{m}^2$ rectangular grid containing unshielded liquid scintillation detectors (e/γ-detectors) and below 10 cm lead and 4 cm steel plastic scintillators as muon-detectors. In the center of the array a hadron calorimeter ($16 \times 20\,\mathrm{m}^2$) is built up, consisting of more than 40,000 liquid ionisation chambers in 8 layers. Below the calorimeter a setup of position sensitive multiwire proportional chambers in two layers measures EAS muons with an energy larger than 2.4 GeV, used for the estimation of a local muon density $\rho_\mu^\star(R_{core})$ for each single event.
In general, for each single shower a large number of observables are reconstructed with small uncertainties. For example, the errors are 10-20% for the shower sizes, i.e. total numbers of electrons N_e and the number of muons in the range of the core distance $40 - 200\,\mathrm{m}$ N_μ^{tr}, both reconstructed from the array data. The array data are also used for determining core position and shower direction. Especially for central showers additional EAS parameters can be reconstructed from data of the Central Detector. Examples of such observables are the number of reconstructed hadrons in the calorimeter ($E_h^{\mathrm{thres}} = 50GeV$), their energy sum, the energy of the most energetic hadron ("leading particle" in the EAS), the number of muons in the shower center $N_\mu^\star$, or parameters deduced by a fractal analysis of the hit pattern of muons and secondaries produced in the calorimeter by high-energy hadrons. The latter ones are sensitive to the structure of the shower core which is mass sensitive due to different shower developments of light and heavy primaries in the atmosphere.
The principle way for the estimation of energy and mass composition of the cosmic rays is based on the comparison of the measurements with the output of Monte Carlo simulations. At KASCADE these comparisons are followed in a non parametric way on an event-by-event basis as well as by parametrisations of the measured and simulated distributions.

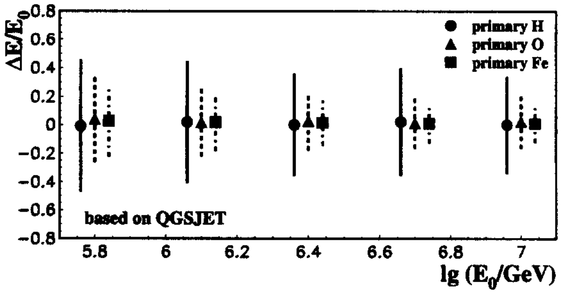

Figure 1. *Energy resolution for different primaries estimated by a neural net analysis.*

The estimate of the primary energy of each single shower is performed by a non-parametric multivariate analysis [6]. Fig.1 shows the energy resolution determined by a neural net analysis for different primaries in the relevant energy range. A large number of Monte Carlo simulations allows the well trained net to calculate the energy of each measured shower in a relatively mass independent way. As multivariate methods are based on a-priori knowledge gained by Monte Carlo simulations, the model dependence effects the largest systematical uncertainty (Fig.4). But it allows to compare different high-energy interaction models. The results of the analysis shown in Fig.4 are cross-checked by using various non-parametric techniques (Bayesian Classifier, Neural Network, k-Nearest-Neighbors), different samples of EAS (central showers with more different observables and showers with core inside the array with large statistics) and by using different sets of observables [7].
Similar multivariate analysis methods are applied for the estimation of the chemical composition of the primary cosmic rays around the knee. This is especially done for showers with their cores in the Central Detector where a larger number of observables are simultaneously available. As an example, the result of a neural net analysis using the shower size N_e, $N_\mu^\star$ and the fractal parameters as input is shown in Fig.2 [8]. The obtained classification of the EAS is corrected with a misclassification matrix (estimated including detailed de-

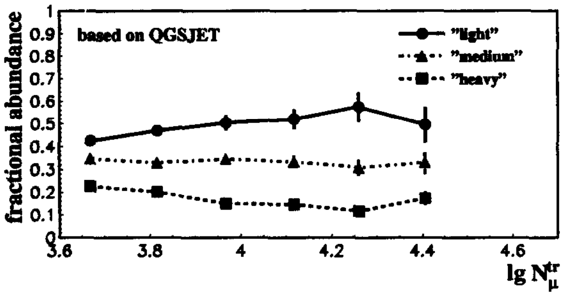

Figure 2. *Relative abundances of different mass groups obtained by a neural net analysis using N_e, $N_\mu^\star$ and fractal parameters as observables.*

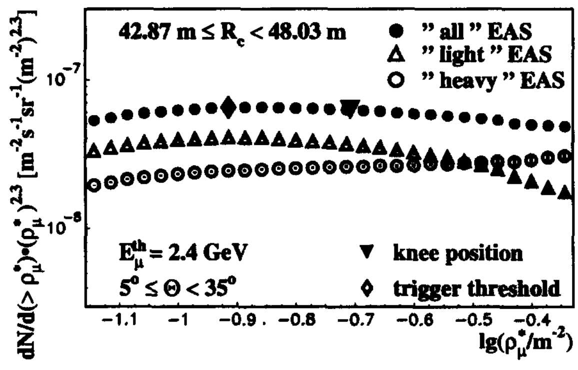

Figure 3. *Local muon density spectra for a certain core distance range. The division into light and heavy induced EAS are performed by analysing the shower size ratio of the EAS.*

tector simulations) leading to relative abundances (e.g. of three primary mass groups), from which the mean logarithmic mass is calculated (Fig.5). The number of primary mass groups considered is limited by the number of Monte Carlo events and by intrinsic fluctuations of the EAS development reducing the power of mass discrimination. In Fig. 5 results of Bayesian analyses are also shown [9]. The limited number of Monte Carlo simulations reduces not only the reasonable number of mass groups, but also the number of observables which can be used for one multivariate analysis. Hence a set of approaches using different observables are averaged in case of the actual result of the Bayesian analyses, but performed independently on basis of two models (QGSJET [10] and VENUS [11]).

Parametric approaches for the analyses of the KASCADE data lead to the results also shown in Fig.4: A simultaneous fit to the N_e and N_μ^{tr} size spectra is performed for the reconstruction of the primary energy spectrum [12]. The kernel function of this fit contains the size-energy correlations for two primary masses (proton and iron) obtained by Monte Carlo simulations. This approach leads to the all-particle energy spectrum as a superposition of the spectra of light and heavy particles. For the light particle spectra a steep kink is revealed, whereas for the heavy particle component a knee is missing between 1 and 10 PeV, thus leading to an increase of the average mass above the knee. An analysis of the $lg(N_\mu^{tr})/lg(N_e)$ size-ratios of the same data sample results in the elemental composition also shown in Fig.5. The measured distribution of these ratios in a certain energy range is assumed to be a superposition of parametrised Gaussian distributions for different primary masses with mean values and widths expected from the simulations [13], leading to relative abundances of the primaries. The results show a tendency of an increasing mean mass above the knee energy in agreement with the results of the non-parametric methods. All these results are obtained by considering a certain range of zenith angles, only. Extensions of the analyses to different EAS angles of incidence are presently in work.

A further approach to the primary energy spectrum is the analyses of local muon densities. For a fixed core distance the local muon density (measured by the Central Detector) reflects the primary energy spectrum and the features of the knee region [14]. A classification of all events in light and heavy induced samples by the ratio of the muon to electron number (registered with the array detectors) allows to analyse the spectra for the different mass groups separately (Fig.3). The analyses results in a clear kink for the spectra of light particle induced showers, whereas the heavy particle induced EAS do not display a corresponding kink in the energy region of 1-10 PeV.

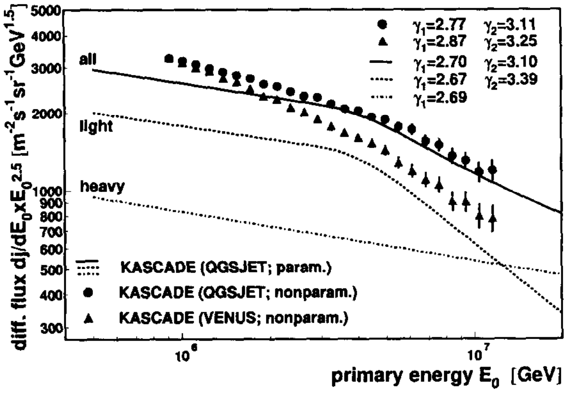

Figure 4. *The primary cosmic ray energy spectrum from KASCADE reconstructed by two different methods.*

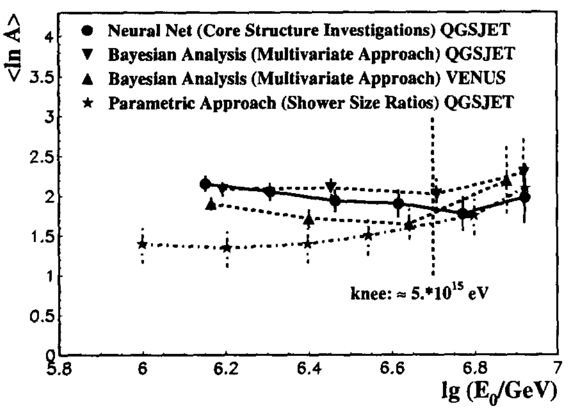

Figure 5. *The chemical composition estimated with the KASCADE data, using different methods and different sets of observables from different particle components.*

Conversion of the spectra to the primary energy spectrum is performed with help of Monte Carlo simulations (QGSJET), resulting in comparable slopes and knee positions as shown in Fig.4. An analogous analysis of densities of the hadronic component is presently in work.

3. CONCLUSIONS

The first results of KASCADE concerning the primary energy spectrum and mass composition between 1 and 10 PeV confirm the knee in the all-particle spectrum around $5\cdot10^{15}$ eV with a change of the power law index of $\Delta\gamma \approx 0.3 - 0.4$. When classifying the measured EAS in light and heavy induced showers, the kink is obviously more pronounced for the "light" spectrum, whereas a knee is missing in the spectrum of the heavy particle induced EAS. Consistent with that result, estimates of the elemental composition of the considered energy region show an increase of the heavy component above the knee.

But it should be mentioned, that the quantitative values of knee position, slopes of the spectrum, mean mass etc., depend on the high-energy interaction model underlying the interpretation and, in addition, on the observables used. This shows that our results are still subject to systematic uncertainties which require further investigations.

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