THE COSMIC RAY EXPERIMENT KASCADE-GRANDE

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The cosmic ray experiment KASCADE, set up in Forschungszentrum Karlsruhe, Germany as a multi-detector installation, studying the electromagnetic, the muonic and the hadronic extended air showers (EAS) component for each observed shower event, has explored the primary energy spectrum and the mass composition of cosmic rays in the energy range of the so called „knee" (around 3 PeV). The multi-dimensional analyses reveal a distinct knee (change of the spectral index of a power-law description) in the energy spectra of the light primary cosmic rays and the dominance of heavy particles with increasing energy. This result provides some important implications, discriminating various conjectures and astrophysical models of the origin of the knee. The KASCADE-Grande experiment is an upgrade of the KASCADE experiment extending the detection area by a factor of 10. It is motivated by studies of a higher primary energy range, looking for the knee-like features of the heavy components, which are expected to appear in the range of 100 PeV. The lecture describes details of motivation, of the experimental lay-out and of first studies with KASCADE-Grande.

1. Introduction

The energy spectrum of cosmic rays comprise more than 12 orders of magnitude, up to 10^{20} eV, following overall power laws, decreasing first $\propto E^{-2.7}$, with a distinct

change of the spectral index around 10^{15} eV, called ***„knee“*** and a further change, called ***„ankle“*** at ultrahigh energies [1], see figure 1.
At energies higher than 10^{14} eV, the observation of Extensive Air Showers, EAS, produced in the interaction of cosmic rays particle with atmosphere nuclei, can be done only by indirect observation with large surface experiments. From the lateral and longitudinal development of the particles cascades the energy and the mass of the primary particle can be inferred. The main EAS components are muons, hadrons and e^+, e^-, γ, usually observed by large arrays like KASCADE [2,3], recently upgraded to KASCADE Grande [4,5].
The analysis of EAS observables to deduce properties of primary particle relies on comparison with Monte Carlo (MC) simulations of the shower development, performed with the CORSIKA program [6], including the detector response. Using multivariate parameter distributions and advanced statistical methods, like Bayesian decision method [7] or neural network approaches [8], it is possible to infer the energy spectrum and mass composition of cosmic rays.

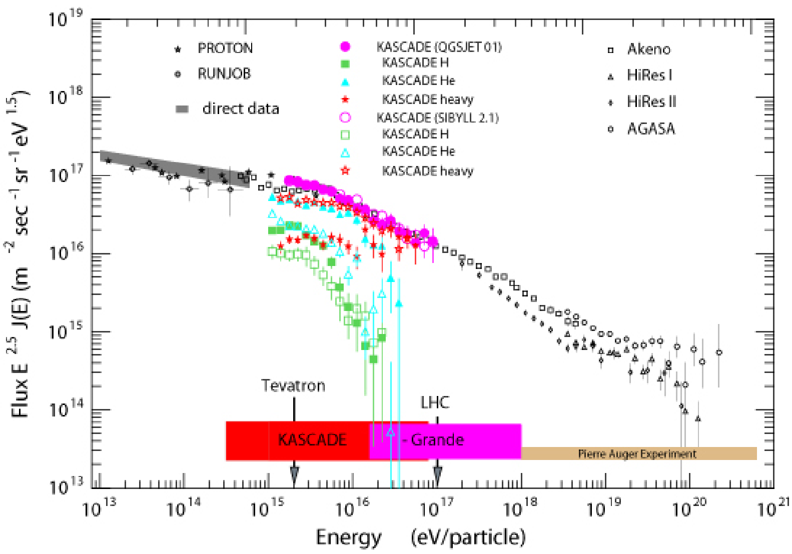

Figure 1. Primary cosmic ray flux covered by KASCADE and KASCADE Grande indicating the knee of the light component and the expectation for the heavy on (from [9])

2. The KASCADE Experiment

2.1. Results of KASCADE data analysis

The KASCADE experiment, located in FZK, Germany (8^0E, 49^0N and 110 m a.s.l.) is the main part of KASCADE-Grande, being able to measure all three main components of EAS for primary energies 10^{14}-10^{16} eV, (figure 2).
It consists of an array of 200 · 200 m^2 with 252 scintillation detectors, (with detection threshold for electrons E_e> 5 MeV and for muons, E_μ> 230 MeV), a central detector, 320 m^2, (formed by a hadronic calorimeter using liquid ionization chambers, a trigger plan of scintillation counters in the third layer and at bottom, 2 layers of position sensitive, MWPC and Limited Streamer Tubes, LST, for muon tracking at E_μ> 2.4 GeV) and a muon tracking detector MTD, (in a 44 · 54 · 2.4 m^3 tunnel, using limited streamer tubes MWPC, E_μ> 0.8GeV).
For an approximate energy identification, the KASCADE experiment uses the truncated muon number, $\mathbf{N_\mu^{tr}}$, the muon intensity integrated between 40 m and 200 m from the shower axis, as simulations studies have shown a nearly independence of this estimator on the primary mass.

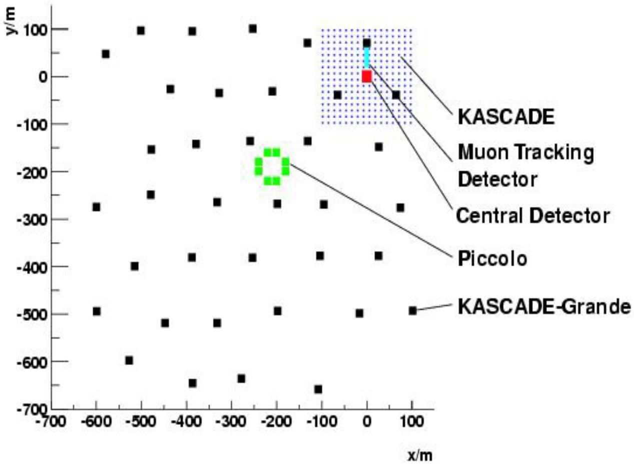

Figure 2. Schematic layout of KASCADE-Grande experiment (from [9])

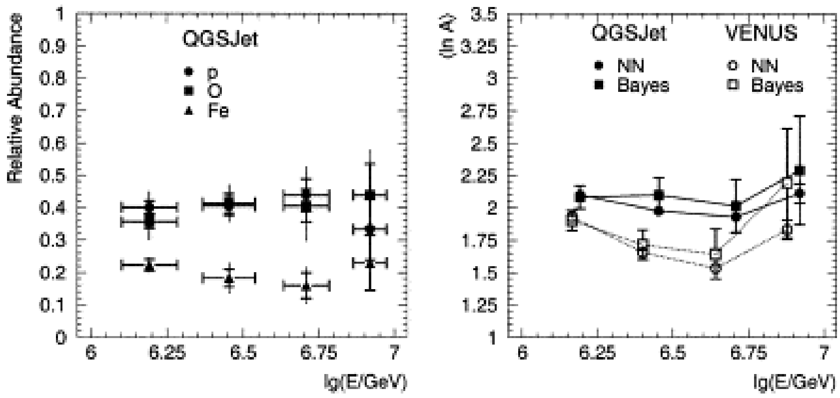

Figure 3. The relative abundances of the classes H, O and Fe vs. log N_μ^{tr}, reconstructed on the basis of two hadronic interaction models and using the EAS observables N_e and N_μ^{tr}. The right graph shows the corresponding mean logarithmic mass < lnA> vs. N_μ^{tr}, (from [8]). Statistical (thick) and methodical (thin lines) uncertainties are indicated as error bars.

The most powerful quantity measured by KASCADE informing about the primary mass is the correlation between the electron size and the muon component.
The non-parametric statistical methods can be used to explore the significance of the observed features for a discrimination of different EAS primaries, by applying Bayesian decision rules [7] or neural networks [8], (figure 3).
The data indicate a mixed composition [8] which becomes heavier above the knee.

2.2. Main conclusions from KASCADE data

Using CORSIKA code for different hadronic interaction models, studies of some hadronic observables indicate that the QGSJET seems to be more adequate [1].
Different procedures of analysis lead to the interesting result that *the knee* is a change of the spectral index in the all-particle spectrum due to the light component. A change towards a heavier composition above the knee is expected in acceleration models, where the knee is supposed to be rigidity dependent. A verification of this model would be the observation of the knee in the heavy component in a primary energy region around $E_0 = 10^{17}$ eV.

The question where is the knee of the iron component [9,10], determined the extension of KASCADE to KASCADE-Grande.

3. The KASCADE Grande experiment

3.1. Description of KASCADE-Grande array

KASCADE Grande covers a large area of detection 0.5 km^2, (figure 2), being possible to measure EAS produced by primaries cosmic rays with energies 10^{14}eV-10^{18}eV. It consists of three arrays: KASCADE (previously described), Grande and Piccolo [5,6].
Grande is formed by 37 stations at a distance about 130 m on an area of 0.5 km^2. Each of 10 m^2 station is split into 16 individual scintillators, $80 \cdot 80$ cm^2 area, 4 cm thick. Each scintillator is viewed by photo-multipliers for timing and particle measurements, with a dynamic range of 0.3 to 750/10 m^{-2} mips.
Piccolo consists of an array of 8 huts (10 m^2 each), with 12 scintillator plates each. The aim of Piccolo is to provide an external trigger to KASCADE and Grande for coincidence events, allowing the recording of data from all detectors of KASCADE-Grande. A trigger condition of 1 Hz will provide an efficiency $\varepsilon > 0.6$ at 10^{16} eV.
The basic observables obtained from both KASCADE and the new detectors from KASCADE-Grande are the following: the shower core position, the angle-of-incidence, the total number of charged particles, given from Grande array data, the muon density, ρ_μ, the reconstruction of the total muon number, provided by KASCADE muon detectors, the lateral electron density profile from the extended electromagnetic array and the total electron number (by subtracting the muon number from the charged particle number), the reconstructed production heights, h_μ, from the tracking modules,

3.2. Results of KASCADE-Grande data

Figure 4 (left) shows for a single shower, the lateral distribution of electrons and muons measured by KASCADE and the charge particle densities measured by Grande station [9]. The good agreement between the two sets of data indicates the capability of KASCADE Grande experiment and the high quality of the data.
For simulated H and Fe showers at 10^{17}eV primary energy and 22^0 zenith angle, the reconstruction accuracy of the shower core position and direction is in the order of 4 m (13 m) and 0.18^0 (0.32^0) with 68% (95%) confidence level. For both primaries, the statistical uncertainty of the shower is around 15%.

The critical point of KASCADE-Grande reconstruction is the estimation of the muon number due to the limited range of KASCADE muon detectors. The systematic uncertainty of the muon number depends on the radial range of the data measured by the KASCADE array and the chosen lateral distribution.

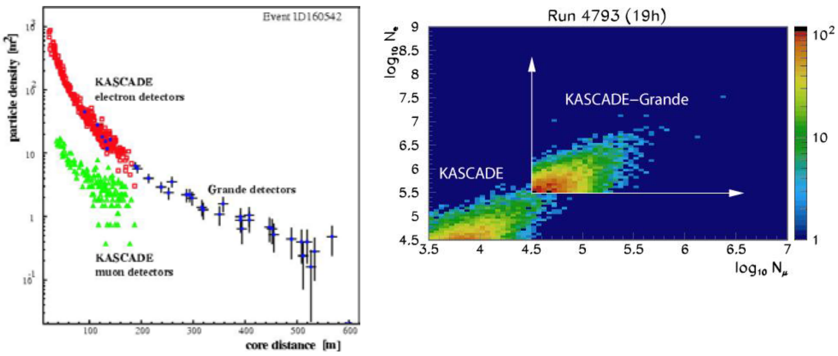

Figure 4. Left: Particle densities in the different detectors of KASCADE Grande measured for a single event (from [9]); Right: The comparison between KASCADE and KASCADE-Grande data for a combined test-run (from [9])

Figure 4 (right) compares the correlation of the electron and muon distributions for KASCADE and KASCADE-Grande in a 1-day test-run [9]. Due to the larger area of KASCADE-Grande, about 10 times larger than KASCADE array, the numbers of showers increases significantly at primary energies approximately 10 times higher.

*3.3. **Event-by-event studies***

Based on the SHOWREC program [10] to reconstruct the charged particle component for KASCADE-Grande taking into account the response of the Grande detectors, extensive studies have been done to explore features for energy estimation and mass discrimination around 10^{17} eV [11]. A set of **H, C** and **Fe** induced EAS have been simulated with CORSIKA program for hadronic interaction QGSJET, (CORSIKA version 6.023), distributed randomly over an angle-incidence range 0^0 – 45^0, calculated with a spectral index of the power-law slope of –2.0 for 8 energy ranges from 10^{16} eV to 10^{18} eV. The reconstructed charged particle density in a range 500 m - 600 m from the EAS center, observed with KASCADE-Grande array was found sensitive to the energy of the primary particle with a relation nearly independent from the primary mass. The observables S^{500}/S^{600} and the charged particle number $N_{ch}^{400\text{-}600}$ can be used for energy estimation.

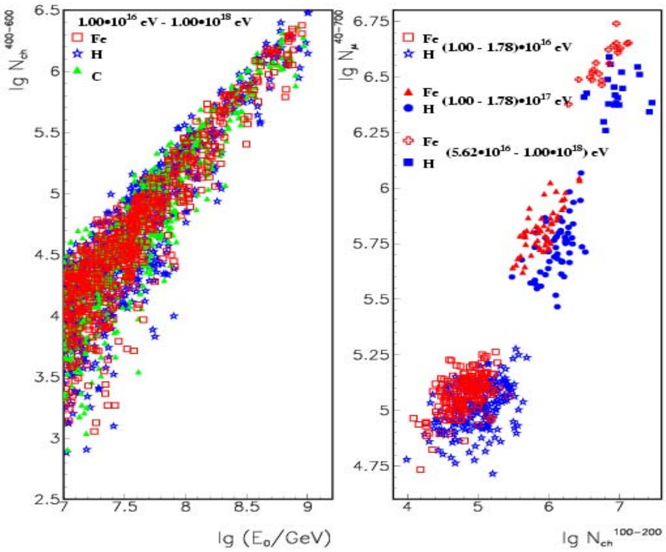

Figure 5 Left. The energy variation of the mean value of lg $N_{ch}^{400\text{-}600}$ corresponding to single events showers, the error bars represent the statistical errors (from [11]) ; Right. The $N_{\mu}^{40\text{-}700}$ - $N_{ch}^{100\text{-}200}$ correlation for selected energy ranges (from [11])

Figure 5 (left) displays the energy variation of lg $N_{ch}^{400\text{-}600}$ of 400 reconstructed showers in the energy range 10^{16}-10^{18} eV, the energy variation of the mean value indicates no variation between different primaries, but appreciable fluctuations.
While the lateral distribution of EAS particle in the radial range of 500 m – 600 m does practically not show significant differences for different primary masses at the same primary energy, the region 100 m - 200 m exhibits features for mass discrimination. S^{100}/S^{200} or the particle number $N_{ch}^{100\text{-}200}$ could play for KASCADE-

Grande a similar role as the electron size N_e in KASCADE experiment, which has to be correlated with an observable representing the muon component, a muon number $N_\mu^{40\text{-}700}$, integrated on the fit range 40-700 m.
Figure 5 (right) compares the relevant correlation for mass discrimination $N_\mu^{40\text{-}700}$ - $N_{ch}^{100\text{-}200}$ in selected energy ranges, indicating a better mass discrimination for higher primary energies.

4. Concluding Remarks

1. The extension of KASCADE to KASCADE-Grande experiment, accessing higher primary energies, is expected to prove the existence of the knee-like structure in the heavy component.
2. KASCADE-Grande experiment [4,5] keeps the multi-detector concept of KASCADE, but for a larger area of detection, being possible to test different interaction models for primary energies 10^{16}eV-10^{18}eV.
3. The first measurements of KASCADE-Grande, in comparisons with KASCADE [9], shows the capability of KASCADE Grande to perform unfolding procedure like in KASCADE and the high quality of the data.
4. Event-by-event studies give the charged density S^{500}/S^{600} and the charged particle number $N_{ch}^{400\text{-}600}$, with similar dependence for all primaries, indicating such observables as suitable for energy identification [11].
5. The correlations of the reconstructed particle density S^{100}/S^{200} or the particle number $N_{ch}^{100\text{-}200}$ with a muon number $N_\mu^{40\text{-}700}$, integrated on the fit range 40-700 m, presents features for mass discrimination, being analogous to $N_\mu^{tr} - N_e$ correlation used in KASCADE experiment [11].
6. KASCADE-Grande provides the environment detecting radio emission in extensive air showers, what is the aim of LOPES project [12].

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