The KASCADE Experiment: Status and Physics Overview

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Abstract
The new extensive air shower (EAS) experiment KASCADE has started data taking at the laboratory site of the Forschungszentrum Karlsruhe. The major goal is to determine the flux spectrum and the chemical composition of primary cosmic ray particles in the energy range around and above the knee ($10^{14} \leq E_{\rm prim} \leq 10^{17}$ eV). An important advantage of the new multi-detector installation is the capability to simultaneously measure the electromagnetic, muonic, and hadronic component of EAS event-by-event. This provides the means to address many different questions related to EAS and high-energy interactions and to reduce systematic uncertainties to a large extend. We shall present the status of the experiment, discuss the stability and reconstruction accuracies, and give a brief overview of the first results.

Introduction
Ultra-high energy cosmic rays (UHE-CR) are known for decades and have been studied in many experiments. However, their sources and acceleration mechanisms are still under debate. One of the major puzzles is the origin of the 'knee' in the CR spectrum at $E \approx 5 \times 10^{15}$ eV. It may be linked to the limiting acceleration power at the sources (presumably supernovae remnants) or to the limiting bending power in the galaxy. A key observable for understanding the origin of the knee and distinguishing the various proposed interpretations is given by the mass composition of CR particles and by possible variations across the knee. Unfortunately, beyond the knee very little is known about the CR's other than their energy spectrum. Very large experimental collection powers are required to compensate for the low particle fluxes, such as can be achieved only in ground based EAS arrays. Sampling detector systems with typical coverages of less than one percent can be used for registration of such showers. However, this indirect method of detection bears a number of serious difficulties in the interpretation of the data and requires detailed modeling of the shower development and detector responses. It is well

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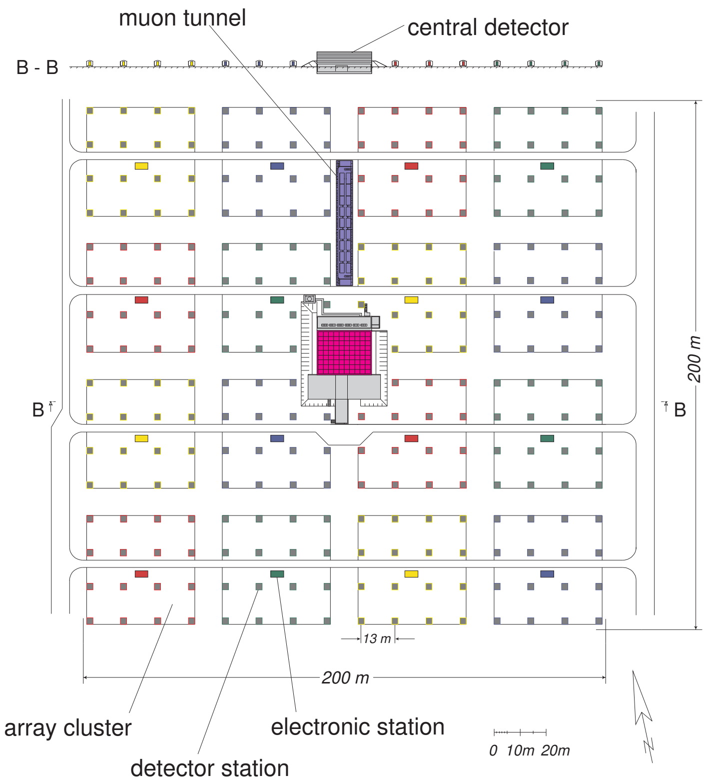

Figure 1: Schematic layout of the KASCADE experiment.

known, that a number of characteristics of EAS depends on the energy per nucleon of the primary nucleus, notably the ratio of electron to muon numbers, the energy of the hadrons in the shower, the shapes of the lateral distributions of the various components of the shower, the arrival times of particles, etc. The basic concept of the KASCADE experiment [1] is to measure a large number of these parameters in each individual event in order to determine both the energy and mass of the primary particles.

Layout of the Experiment

KASCADE (Karlsruhe Shower Core and Array Detector) is located on the laboratory site of the Forschungszentrum Karlsruhe, Germany (at 8° E, 49° N, 110 m a.s.l.). It consists of three major components; a scintillator array, a central detector system with a hadron calorimeter and muon detectors, and a large area muon tracking arm. Its schematic layout is depicted in Fig. 1. A fairly complete description of the individual components can be found in [1]. Here, only a brief summary of the aspects relevant to the different analyses presented at this conference is given.

The KASCADE-Array comprises 624 liquid scintillation counters (e/γ detectors) of 0.8 m^2 size each. They are housed in 252 detector stations arranged on a rectangular grid of 13 m spacing, thus forming an array of 200×200 m^2. Energy deposits with an equivalent of 0.25 – 2000 m.i.p. can be detected in each station. Furthermore, 192 muon detectors of 3.2 m^2 size (each of which is segmented into 4 pieces) are located below the e/γ detectors and are shielded by an Fe/Pb-absorber of 20 X_0 thickness. This imposes an effective energy threshold of $\sim$ 300 MeV to the muon detection in the array stations.

The main part of the central detector system (Fig. 2 bottom) is the finely segmented hadron

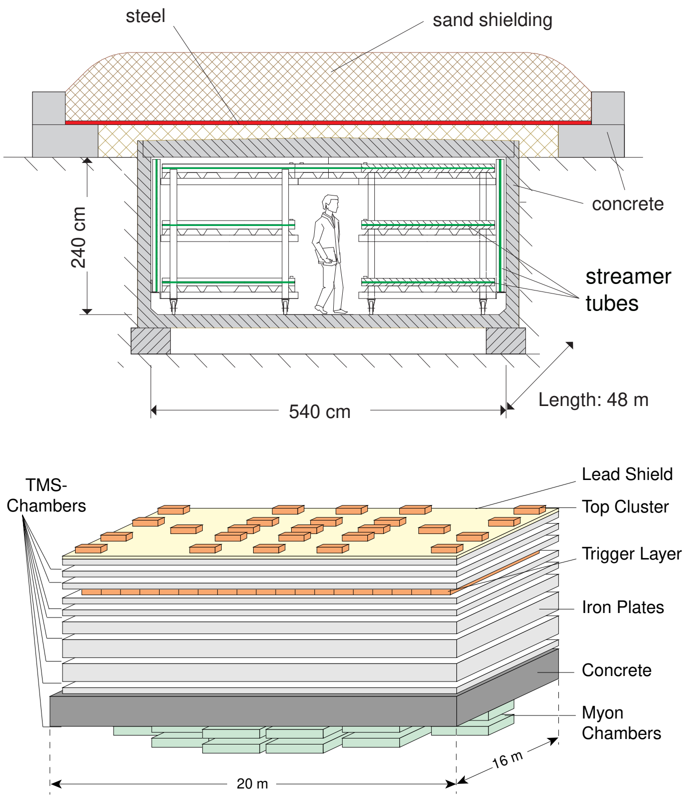

Figure 2: Schematic layout of the streamer tube tracking system (top) and of the central detector (bottom) of KASCADE.

calorimeter. It consists of a 9-fold longitudinally segmented iron stack of 20×16 m^2 size and is read out by 40,000 channels of warm liquid ionization chambers. Each cell covers an area of 25×25 cm^2 thus enabling to separate hadrons with distances as low as 50 cm [2]. The energy sum of the hadrons in the core of a 1 PeV shower can be determined with a resolution of 8 %. Individual hadrons with energies larger than 20 GeV are reconstructed.

In the third gap from the top of the iron stack (shielded by $\sim 30X_0$) a layer of 456 scintillation detectors is placed to trigger the readout of the calorimeter and other components of the experiment and to measure the arrival times of muons. In addition, the trigger layer acts as a muon detector, allowing to determine the lateral- and time distributions of muons above a threshold of about 0.4 GeV. Underneath the calorimeter, two layers of multiwire proportional chambers (MWPCs) are used to measure muon tracks above an energy threshold of 2 GeV with an angular accuracy of about 1.0°.

North of the central detector a 48 m long and 5.4 m wide tunnel has been added to the experiment (Fig. 2 top). It will be equipped with limited-streamer tubes arranged in three layers and be used for tracking of muons under a shielding of 18 X_0, corresponding to an energy threshold of 0.8 GeV. The tracking accuracy will be around 0.5°. The detector [3] will add another 150 m^2 area for the determination of the size and lateral distribution of the muon component and will – for sufficiently large showers – enable approximate determination of the mean muon production height by means of triangulation. Installation is well in progress and data collection is expected to start end of 1998.

Experimental Status

Data taking in a correlated mode with most components in operation has been started in April 1996. At present, trigger thresholds are adjusted to limit the total trigger rate to ~ 4 Hz. This corresponds to an effective energy threshold in the array of $\sim 10^{14}$ eV for protons and $\sim 3 \cdot 10^{14}$ eV for iron. In total, more than 10^8 events have been collected and stored onto tape. Most of these raw data have been processed and all detector calibrations and error checks be performed. The results are stored as Data Summary Tapes (DST) for

further physics analysis.
The data acquisition system and all detectors are found to operate very reliable and stable. For example, the number of reconstructed hadrons per time interval above various energy thresholds and after correction for atmospheric pressure variations is found to be constant within a few percent over periods of a year.

Observables and First Analyses

A unique feature of KASCADE is the large hadron calorimeter. It allows to perform important tests of hadronic interaction models in an energy range not accessible to man made accelerators and provides valuable information about the chemical composition of CR particles. Tests of interaction models are being performed by investigating the transition curves of energetic single hadrons in the calorimeter, by measuring simultaneously the muonic and hadronic trigger rates, or by investigating hadronic EAS parameters. Particularly, the latter two tests demonstrate to be very sensitive to predictions of the different models. While VENUS [4] and particularly QGSJET [5] provide a rather good description of the experimental data, serious problems are identified for SIBYLL. A typical example is given in Fig. 3. Here, the energy fraction of hadrons is plotted relative to the most energetic hadron of the same event. Data and simulations [6] are restricted to the same (truncated) muon size as reconstructed from the array data. Experimental effects are taken into account by subjecting the simulations to a full detector Monte Carlo. The disagreement observed in SIBYLL can only partly be attributed to a deficit in the predicted muon numbers. Analyses of the chemical composition have therefore been based only on QGSJET and VENUS predictions.

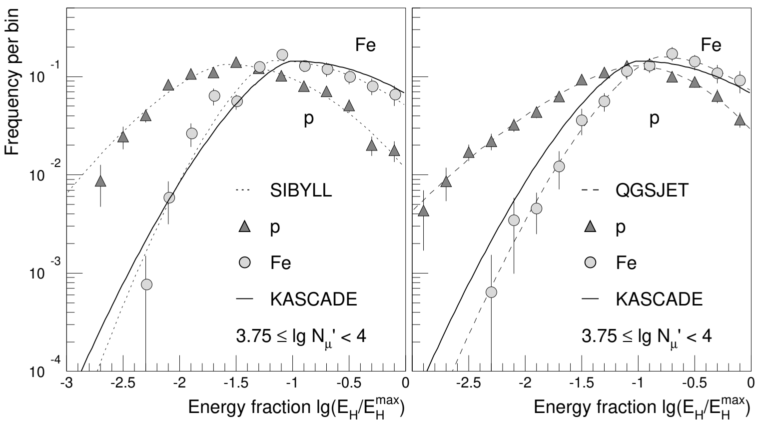

Figure 3: Energy fraction of hadrons ($E \geq 50$ GeV) relative to the most energetic hadron observed in the KASCADE calorimeter. The data (at $E_{\rm prim} \sim 2$ PeV) are compared to SIBYLL and QGSJET predictions assuming proton and iron primaries [7].

Much smaller effects of model dependencies are observed for the electron and muon sizes in the KASCADE array. For the first time, KASCADE allows to identify and analyze the properties of the knee and the spectral indices simultaneously in the electron, muon, and hadron size spectra. The individual shower sizes are obtained by fitting radial density distribution functions to the data (NKG-parameterizations for electrons and muons and an exponential function $\propto \exp\{-(r/r_0)^\kappa\}$ for hadrons) and integrating these functions in appropriate regions ($r \leq \infty$ for electrons, 40 m $\leq r \leq$ 200 m for muons, and $r \leq$ 24 m for hadrons). Because of the different effective energy thresholds for muon detection in the various detectors, muon size spectra can be extracted even for different energy thresholds. Within the uncertainties given by the poorly known chemical composition, a fairly good agreement among the observables is observed for the reconstructed primary energy

spectrum (**HE-7.4**). After correcting the distributions for effects of shower and sampling fluctuations, the position of the knee is found to be 4 ± 1 PeV and the indices below and above the knee are measured to be 2.75 ± 0.05 and 3.1 ± 0.08, respectively. The steep electron size spectrum observed above the knee, furthermore, can only be understood if an increasingly heavier composition above the knee is assumed. In an independent analysis, a knee has been identified also in the muon density spectrum, with the position and indices well in agreement with the observations from above (**HE-7.2**).
KASCADE offers several approaches to estimate the mass of the primary CR particle, either in an inclusive way or even event-by-event. The electron over muon ratio of EAS is considered the most sensitive parameter. Both numbers are reconstructed from the array data as described above. While the muon number has been proven to be an almost mass independent energy estimator, the electron number exhibits a strong dependence on the mass of the primary particle. The ratio of the numbers investigated as a function of the muon size thus provides a direct link to the primary mass as a function of energy. Such an analysis is presented in **HE-7.5** complemented by nonparametric methods in **HE-8.1** and **HE-8.2**. Furthermore, muons and hadrons measured in the shower core provide an independent approach to estimate the mass of the primary particles (**HE-8.3** and **HE-8.4**). The still preliminary but independent analyses all indicate an increasing mass above the knee. However, the rise is found to be more pronounced in measurements based on the hadrons than on the electrons/muons. Detailed investigations are being made in order to check, whether these discrepancies can be explained by deficiencies in the EAS simulations.
In summary, already after about 2 years of operation KASCADE has provided a variety of important results. These include stringent tests of hadronic interaction models and of EAS simulations, detailed investigations of the electron, muon, and hadron shower size spectra, as well as preliminary estimates of the chemical composition of primary CRs. The 'redundancy' of the measurements in KASCADE turns out to be of vital importance in revealing systematic uncertainties. All measurements of the chemical composition indicate an increasingly heavier mass above the knee, but definite conclusions require further tests (and improvements) of the interaction models. These are being pursued in close collaboration with the authors of the models.

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References
[1] H.O. Klages et al., KASCADE Coll. Nucl. Phys. B (Proc. Suppl.) 52B (1997) 92
[2] H.H. Mielke et al., Nucl. Instr. Meth. A360 (1995) 367
[3] P. Doll et al., Nucl. Instr. Meth. A367 (1995) 120
[4] K. Werner, Phys. Rep. 232 (1993) 87-299
[5] S. Ostapchenko et al., Nucl. Phys. (Proc. Suppl.) 52B (1997) 113
[6] D. Heck et al., FZKA 6019 Forschungszentrum Karlsruhe (1998)
[7] J. Hörandel, FZKA 6015 Forschungszentrum Karlsruhe (1998)