FIRST RESULTS FROM
THE KASCADE AIR-SHOWER EXPERIMENT

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A new extensive air shower (EAS) experiment has been installed at the laboratory site of the Forschungszentrum Karlsruhe. The major goal of the experiment is to determine the chemical composition in the energy range around and above the knee of the primary cosmic ray spectrum. An important advantage of the installation is the capability to simultaneously measure the electromagnetic, muonic and hadronic components of EAS event-by-event, thereby reducing systematic uncertainties to a large extent. Data taking with a large part of the experiment has started at the end of 1995 with further installations continuing during 1996. First preliminary results are presented.

1 INTRODUCTION

Despite the fact that ultra-high energy cosmic rays (UHE-CR) are known for decades, their sources and the acceleration mechanism are still under debate. Mainly for reasons of the required power the dominant acceleration sites are generally believed to be supernova remnants in the Sedov phase. Naturally, this leads to a power law spectrum as is observed experimentally. Detailed examination suggests that this process is limited to \(E/Z \lesssim 10^{15}\) eV. Curiously, the CR spectrum steepens at approx. \(5 \times 10^{15}\) eV, indicating that the ‘knee’ may be related to the upper limit of acceleration. A change in the CR propagation with decreasing galactic

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containment has also been considered. A key observable for understanding the origin of the knee and distinguishing the SN acceleration model from other proposed mechanisms, is given by the mass composition of CR particles and by possible variations across the knee. Unfortunately, beyond the knee little is known about the CR’s other than their energy spectrum. Direct measurements using detector systems on satellites, spacecraft or high altitude balloons cannot provide the required data with sufficient statistics because of limited detector area and exposure time. Experiments at ground level do not suffer from these problems since they can cover large areas, measure for extended time periods, and also take advantage of the magnifying effect of the atmosphere. The latter is because sufficiently high energy CR particles initiate extensive air showers which spread out over large areas at observation level. 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 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, etc. The basic concept of the KASCADE experiment is to measure a large number of these parameters for each individual event in order to determine both the energy and mass of the primary particles.

2 LAYOUT AND STATUS 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 a large area muon tracking. Its schematic layout is shown in Fig. 1.

Scintillation detectors for the measurement of electrons and photons, and of muons outside the core region of extensive air showers are housed in 252 detector stations on a rectangular
grid of 13 m spacing forming a detector array of 200 × 200 m². Each station contains 2 or 4 scintillation detectors for the electron/photon component with a total area of (1.6 m²) 3.2 m². Energy deposits equivalent to 2000 m.i.p. can be detected with a threshold of 0.25 m.i.p. The 3.2 m² muon detector of a station is located below a shield of 20 X₀ thickness. It consists of 4 pieces of plastic scintillator, 90 × 90 × 3 cm³ each, read out by green wavelength shifter bars on all edges with a total of 4 phototubes. The supply and electronic readout of the detectors in the stations is organized in 16 clusters of 16 stations each (see Fig. 1). These clusters act as small independent air shower arrays.

The main part of the central detector system (Fig. 2) is the finely segmented hadron calorimeter. It consists of a 20 × 16 m² iron stack arranged into 9 horizontal slabs with a total absorber thickness corresponding to more than 11 nuclear interaction lengths. A total of 10,000 ionization chambers filled with the room temperature liquid tetramethyilsilane (TMS) is used for the measurement of energy in the gaps. The chambers are made of 50 × 50 × 1 cm³ stainless steel boxes and are read out by 4 independent central electrodes of 25 × 25 cm² size. Thus, the readout of the calorimeter amounts to 40,000 electronic channels spread out over 2,500 m². The fine segmentation allows for a separation of hadrons with distances as low as 50 cm. The detectors have a dynamic range of 10⁴ limited only by the amplifier chain and its performance ensures a very stable operation over many years. The top layer of ionization chambers is shielded against the electromagnetic component of EAS by 12 cm of iron and additional 5 cm of lead. 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. A prototype of the calorimeter has shown stable operation for about 3 years and has provided interesting results. In the third gap from the top of the iron stack (shielded by ∼ 30X₀) 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 hadrons. 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 50 m long and 5.5 m wide tunnel has been added to the experiment. In this tunnel 600 m² of limited-streamer tubes will be used in three layers for tracking of muons under a shielding of 18 X₀, corresponding to an energy threshold of 0.8 GeV. The tracking accuracy will be around 0.5°. The detector will have an effective area of about 150 m² 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. Shower simulations with the CORSIKA code show, that this observable provides another piece of information about the mass of the primary particle.

Data taking has started in late 1995 with large parts of the experiment in stand-alone mode. Correlated data are being collected since April 1996 with 100 m² area of the calorimeter operational at the beginning. By now the read-out area has been doubled. The remaining part of the calorimeter and the muon tunnel are expected to start operation in 1997. At present, trigger thresholds of the array, trigger plane, and top-cluster are adjusted to limit the total trigger rate to ∼ 1 Hz. In the near future this number will be increased to approx. 10 Hz thereby lowering the effective energy threshold to ∼ 10¹³ eV for specific events.

3 PRELIMINARY RESULTS

Owing to the ongoing installation and calibration work during normal working hours and data taking during nights and over weekends only, analysis is still in a preliminary stage and only a small fraction of the data available could be analyzed. Typically, about half a million of showers
Figure 3: Example of an EAS as observed by the electron/gamma detectors of the array. In the two parts, each column represents the energy deposit and the arrival time of the shower front, respectively. Reconstructed shower parameters are listed.

per week are collected during this mode of operation.

Figure 4 shows as an example a shower as registered by the electron/gamma detectors of the array. In the upper part the deposited energies and in the lower part the corresponding arrival times of the same event are shown for each detector station. Parameters resulting from the analysis such as electron number $N_e$, core position, shower direction, and age are given in the figure. It is obvious from the distributions that these numbers can be determined to high accuracy. The lateral distribution of all charged particles in the shower is analyzed using a NKG function which fits the data nicely within the typical range of our measurement, say 10-200 m. The muon signals are analyzed in a similar way, however, due to electromagnetic punch through close to the shower core, this measurement is at present restricted to radii larger than 40 m. When we plot the event rate as a function of the reconstructed electron size of the showers in the zenith angle range $15^\circ$ to $25^\circ$ (see Fig. 4) we find a distinct change in the slope near $\log N_e = 5.5$. These data correspond to only one week of measurement. Both, the position of the break in the spectrum as well as the spectral indices below and above the knee are well in agreement with expectations from earlier experiments. Presently, these data are analyzed in much more detail to carefully correct for effects like trigger thresholds, array efficiency, trigger biases, etc. and to investigate their systematic uncertainties.

Simultaneous reconstruction of the electron- and muon size will enable us to determine
Figure 5: Pattern of signals for a shower core as seen in the 3rd layer of the calorimeter. Each box represents the signal of an individual ionization chamber, i.e. the total size of the figure corresponds to $10 \times 16 \text{ m}^2$. The energy of the shower corresponds to $3 \cdot 10^{15} \text{ eV}$.

Figure 6: Top:) Distribution of the total hadronic energy per EAS above the trigger threshold $10^{13} \text{ eV}$. The line shows a power-law fit with an index of $-2.62 \pm 0.09$. Bottom:) Observed experimental trigger- and hadron rate in comparison to expectations from different hadronic interaction models (see text for details).

their ratio event-by-event. This provides a parameter which has proven large sensitivity to the primary composition. Details of the electron and muon lateral distributions are also studied to get a better understanding of the basic properties of air showers. The influence of atmospheric parameters to the ground level observables of EAS has been calculated and the results will be checked in the ongoing analysis.

A unique feature of KASCADE is its large hadronic calorimeter. Measuring the properties of the shower core along with the information from the electron and muon detectors at larger distances will substantially improve the sensitivity to the chemical composition particularly at energies below the knee. Furthermore, the low trigger threshold of approx. $10^{13} \text{ eV}$ for proton induced showers provides a window of significant overlap with direct CR measurements where both the energy- and mass spectrum are known to a reasonable precision. The comparison of EAS and direct measurements will thus serve as a vital test of the hadronic interaction (and atmospheric shower propagation) models. Even in the energy range accessible to operating colliders, up to an equivalent laboratory energy of $1.6 \cdot 10^{15} \text{ eV}$, our knowledge of hadronic interactions is very limited because collider experiments do not cover the very forward fragmentation region. This region is most important to model the hadronic development of EAS and it can be studied by using the calorimeter data itself. Similarly, very energetic single hadrons not accompanied by an air shower can reach ground level after only very few hadronic interactions. Again, their rate as a function of energy is very sensitive to the average hadronic inelasticity and to the inelastic
cross section. Here, we report only on very first data on hadronic shower cores\textsuperscript{[10]}. Figure 6 shows as an example a two-dimensional pattern of energy deposition in the 3\textsuperscript{rd} layer of the calorimeter. This information is available for each of the 8 readout planes and is used to identify hadron tracks through the calorimeter. Simulations show that the tracking efficiency for $E_h \geq 100$ GeV is larger than 90\% for shower energies below $10^{15}$ eV\textsuperscript{[10]}. In the event shown, the total hadronic energy, as measured by the calorimeter, was 42 TeV and the energy of the primary particle, as reconstructed from the array data, was about $3 \times 10^{15}$ eV. The multiplicity of reconstructed hadrons in some events exceeds 100 and the total hadronic energy sum spectrum is plotted in Fig. 6 (top). The data are well described by a power-law with an index close to that of the primary spectrum. The lateral distribution of hadrons is found to flatten with increasing shower size. In order to quantitatively compare the observed experimental trigger and reconstructed hadron rates with model predictions, detailed simulations have been performed by using composition and energy distributions of primary CR’s as input. These simulated data were fed through the same chain of programs as used for real data and some of the results are shown in Fig. 6 (bottom). The still preliminary analysis indicates that even small variations of the inelastic cross section used in the model calculations lead to strong effects in the expected rates. Furthermore, none of the models seems to be able to reproduce both the trigger rate (multiplicity \geq 6 in the trigger layer) and the reconstructed hadron rate simultaneously. Although, more detailed studies are required to settle this problem, the data demonstrate the power to experimentally test hadronic interaction models in the very forward region.

4 CONCLUSIONS

The installation of the KASCADE experiment is nearing completion and data taking with a large part of the experiment has started. Preliminary data of the array and central detector look very promising. No reliable results of composition can be given at the time of writing this report. Mandatory for such an analysis is to prove that (i) the detector and reconstruction methods are understood in detail, and (ii) the hadronic interaction models and atmospheric shower simulations are well under control. An example of such kind of analysis has been discussed briefly. In parallel, multiparameter analyses are under development to infer the composition from the different components of the experiment.

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