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PROCEEDINGS
SUPPLEMENTS

The KASCADE Experiment

KASCADE Collaboration

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A new extensive air shower (EAS) experiment has been installed at the site of the Forschungszentrum Karlsruhe. The main aim of the KASCADE [1] project is the determination of the chemical composition in the energy range around the knee of the primary cosmic ray spectrum. The main advantage of the new installation is the simultaneous measurement of a large number of observables for each individual event. This is achieved by the combination of various advanced detection techniques for the electromagnetic, the muonic, and the hadronic component of the extensive air showers. Data taking with a large part of the experiment has started at the end of 1995. The estimated accuracy of air shower data is discussed for the various detector components of KASCADE and first preliminary results are presented.

1. INTRODUCTION

The chemical composition of ultrahigh energy cosmic ray particles is an important clue for the modelling and understanding of cosmic ray origin, acceleration and transport. Especially in the energy range around the knee, a distinct change of the spectral index in the primary spectrum at about 5×10^{15} eV, the determination of the relative abundances of light and heavy nuclei and the change of this ratio with energy is of prime interest. Direct measurements using detector systems on satellites, space craft or high altitude balloons are limited in detector area and in exposure time. Therefore, data above 10^{14} eV are sparse and lack statistical accuracy [2,12].

Experiments at ground level make use of the magnifying effect of the atmosphere. In the high energy interactions of the primary cosmic rays with atomic nuclei of the air molecules a large number of secondary particles are produced which in turn can produce new generations of particles etc.. The resulting extensive air showers spread out over large areas. A sampling detector system with a typical coverage of less than one percent

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can be used for the effective registration of these showers. However, this indirect method of detection of the primary cosmic rays bears a number of serious difficulties in the interpretation of the data.

First of all the development of the extensive air showers depends strongly on the detailed properties of high energy interactions. In the interaction models [3] used for shower simulations these details must be extrapolated from the state of our experimental knowledge from accelerator data - in rapidity to extreme forward angles not yet covered in collider experiments and in energy by up to several orders of magnitude. The total thickness of the atmosphere corresponds to more than 10 hadronic interaction lengths, depending on the zenith angle. Therefore, the experimental information obtained at ground level is only indirectly connected to the properties of the primary particles. In addition, the low air density at the top of the atmosphere contributes to the intrinsic fluctuations in air showers. The height of the first interaction is an important parameter for shower development because the branching between decay and interaction of the secondary hadrons depends both on particle energy and target density. It fluctuates considerably, especially for light primaries like protons and this gives rise to large fluctuations of the shower properties at ground level.

A common feature of the detector systems is the limited sampling, which is restricted to far below 1% in most experiments, due to financial limitations.

The basic idea of the KASCADE experiment is to measure a large number of observables of each individual event with good accuracy and a very high sampling of more than 1% for the electromagnetic and about 2% for the muon component of the EAS together with a precise calorimetric measurement of the hadrons in the shower cores using an iron - TMS calorimeter. A group of scintillation detectors on top of the calorimeter enables the identification of small central showers with a threshold of around 10^{13} eV. These low energy events can be used to test the predictions of the simulations and to compare the experimental results with data from direct measurements e.g. from balloon borne experiments. A determination of the flux spectrum of single hadrons in the energy range up to more than 10 TeV will also be possible. Multiwire proportional counters (MWPCs) below the calorimeter allow the study of muon lateral distributions in shower cores. Flash ADCs in the detector array and a segmented layer of scintillation detectors in the central detector system will enable the measurement of arrival time distributions for electrons, muons and hadrons. Shielded muon tracking detectors will be used to study longitudinal shower development.

2. EXPERIMENT

KASCADE (Karlsruhe Shower Core and Array Detector) is located on the site of the Forschungszentrum Karlsruhe, Germany, at 8° E, 49° N, 110 m above sea level. The experiment consists of several, nearly independent parts. Its schematic layout is shown in fig. 1 with the three main components: detector array, central detector system, and muon tunnel.

2.1. The detector array

Scintillation detectors for the measurement of electrons and photons and of muons outside the core region of the extensive air showers are housed in 252 detector stations on a square grid with 13 m spacing forming a detector array of 200 × 200 m^2. A station (fig. 2) contains either two or four scintillation detectors for the electron/photon component (fig. 3) with an area of c. 0.8 m^2 each. About 38 l of custom made liquid scintillator in a circular stainless steel container of 100 cm diameter give a thickness of 48 mm. These detectors have been optimized for good resolution in energy and time (0.8 nsec) as well as for a very high dynamic range. Energy deposits equivalent to $2000\, m.i.p./m^2$ can be detected linearly with a threshold of 0.25 m.i.p. (3 MeV). In the outer 192 of the 252 detector stations two of these detectors are placed on an absorber plate of 10 cm of lead and 4 cm of iron which corresponds to more than 20 radiation lengths. Muons above 0.3 GeV will penetrate the absorber whereas the electromagnetic particles will be absorbed. Muon

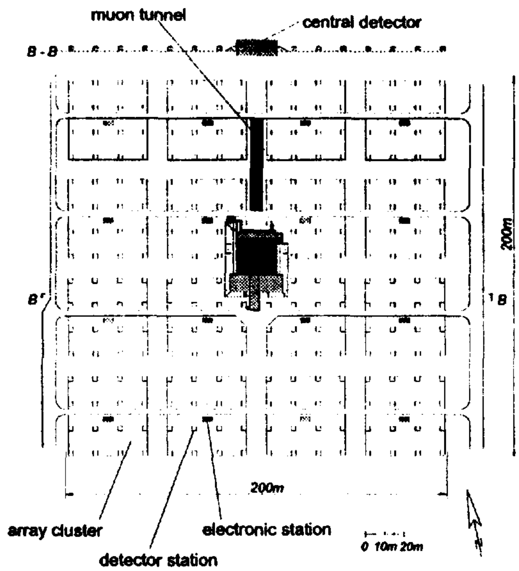

Figure 1. Schematic layout of KASCADE.

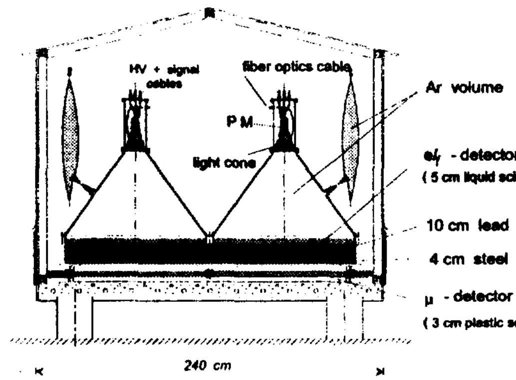

Figure 2. KASCADE array detector station.

detectors below consist of 4 sheets of plastic scintillator, $90 \times 90 \times 3$ cm^3 each, read out by green wavelength shifter bars on all edges with a total of 4 phototubes. 60 detector stations in the central part of the array each contain 4 scintillation counters for electrons and photons (total area 3.2 m^2) and no muon detectors.

The supply and the electronic readout of the detectors in the stations is organized in 16 clusters of 16 stations (15 stations in the inner 4 clusters of the experiment, cf. fig. 1). These clusters act as independent air shower arrays. The detector control and readout is performed using transputer based VME controllers as local intelligence. The fast transputer links are connected to a workstation host in the central data acquisition system. Trigger conditions [4] are cluster detector multiplicity **n** of 32 (**m** of 60 in the inner clusters) or a local high energy deposit in one station.

The most complete information will be obtained for showers whose cores hit the central detector. Hadrons and high energy electrons or gammas near the cores of such showers will not be stopped by the absorber plates in the detector stations of the array. Therefore no muon counters and absorber plates have been installed in the 60 stations of the 4 clusters near the central detector . The area of detection in the array is at present 500 m^2 for the electromagnetic and 620 m^2 for the muon component of the extensive air showers. The measurement of the energy deposit in the scintillators and of the arrival time of the first shower particle in a station will be supplemented by the installation of 64 flash ADC channels (250 Ms/s) for the determination of the time distributions of electrons and muons in the showers.

2.2. The central detector system

The main part of the central detector system (fig. 4) is a segmented hadron calorimeter. It consists of a 20×16 m^2 iron stack (4.000 tons) with 8 horizontal gaps.

10,000 ionization chambers filled with the room temperature liquid tetramethylsilane (TMS) are used for the measurement of hadronic energy in the gaps [5]. Each chamber has the size $50 \times 50 \times 1$ cm^3 and contains 4 electrodes of 25×25 cm^2. Thus the readout of the calorimeter amounts to 40,000 electronic channels. The fine segmentation enables the separation of hadrons with a distance as low as 50 cm. The amplifier chain has a dynamic range of 10^4 and its performance ensures a very stable operation. The thickness of the iron

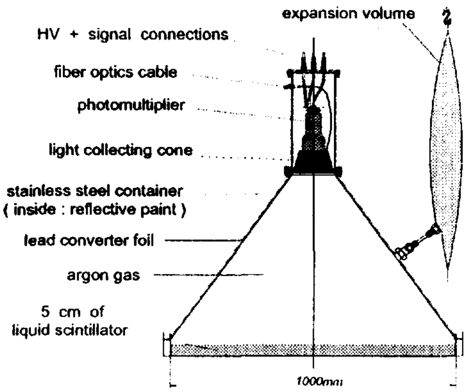

Figure 3. The liquid scintillation detectors for the electromagnetic shower component.

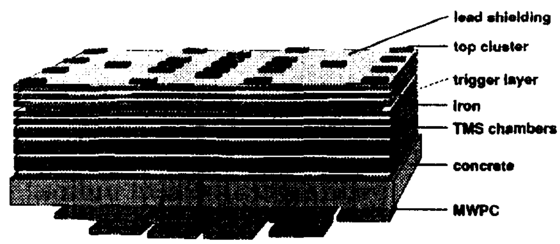

Figure 4. Schematic layout of the central detector system of KASCADE.

stack of about 1.7 m corresponds to more than ten nuclear interaction lengths. The top layer of ionization chambers is shielded against the electromagnetic component of the showers by 12 cm of iron and additional 5 cm of lead .

The calorimeter is able to measure the energy of vertical hadrons with about 10 % accuracy in the range from 100 GeV to more than 10 TeV. The angle of incidence can be reconstructed to 1.5°. The energy sum of the hadrons in the core of a 1 PeV shower can be determined to 8 %. Individual hadrons with energies down to 20 GeV are reconstructed. In this energy range 70 % of all hadrons are found. A prototype of the calorimeter has been operated very successfully for about 3 years and its results have been published [6].

A layer of 456 scintillation detectors is placed in the third gap from the top of the iron stack (shielded by about 30 r.l.). Each detector contains two modules of plastic scintillator read out by a green wavelength shifter bar and a single photomultiplier. The module area is 0.45 m^2, the time resolution 1.8 nsec. The scintillator layer is used for triggering the calorimeter readout in two different ways. A hadron trigger is accepted if the energy deposit is more than 300 MeV (50 m.i.p.) in one of the modules . By means of this trigger, also single hadrons can be detected. The second possibility is a muon multiplicity trigger when n of the 456 detector modules have been hit by a minimum ionizing particle.

The trigger layer acts, in addition, as a 220 m^2 compact hadron and muon detector with rather high segmentation and good time resolution. In large showers with cores far outside the central detector, it will make a sizable contribution to measuring the lateral and time distributions of the muons [7]. The threshold is 0.4 GeV and thus close to that of the muon detectors in the array.

Below the iron stack and the base of the calorimeter, two layers of multiwire proportional chambers (MWPCs, fig. 5) are used for the measurement of muon tracks with an accuracy of 1° and a muon threshold of 2 GeV. The MWPCs cover a total area of 122 m^2. The chamber readout can be triggered either from the trigger layer, from one of the array clusters or from the group of scintillation detectors on top of the central detector.

50 scintillation detectors of the same type as in the trigger layer form the top cluster above the calorimeter. This system can be used for the measurement of small central showers with sizes below the threshold of the detector array. It will also supply the information on charged particle densities in the area of the central detector where 4 stations of the array are missing.

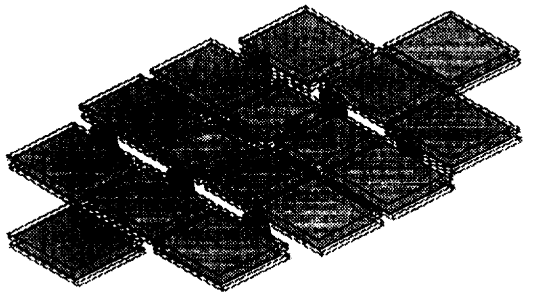

Figure 5. Two layers of MWPCs measure muon tracks in the basement of the central detector.

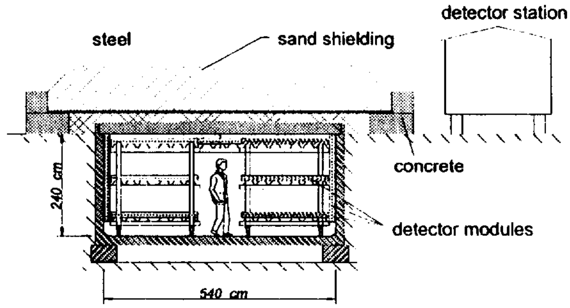

Figure 6. Cross section of the shielded tunnel for measuring muons with horizontal and vertical layers of streamer tubes.

2.3. The muon tunnel

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 m^2 of limited streamer tubes will be installed in three horizontal and two vertical layers for the tracking of muons under a 18 r.l. shielding of concrete, iron, and sand (fig. 6), corresponding to a threshold of 0.8 GeV. The tracking accuracy will be around 0.5°. The detector [8] will have an effective area of about 150 m^2 and will contribute to the determination of the size and lateral distribution of the muon component. It will, in addition, enable the approximate determination of the mean muon production height by triangulation. Shower simulations with the CORSIKA [9] code show that this observable is strongly dependent on the mass of the primary particle. Due to multiple scattering of the muons in the air and shielding above the detectors, about 50 muons have to be detected at a typical distance of 100 - 150 m from the shower core for a sufficiently precise determination of the mean angle of incidence. Therefore, this method is restricted to large showers corresponding to primary energies above 10^{16} eV.

2.4. Data handling and correlation

The 16 clusters of the array, the streamer tube muon detector and the four parts of the central detector system are (in principal) 21 independent experiments, which can be started, run, read out and stopped independently or in coincidence. To correlate the data from different parts of KASCADE common clock signals are used. They are derived from a GPS receiver and a rubidium high frequency generator. Synchronized pulse trails of 1 Hz and of 5 MHz are distributed with fiber optic cables to all parts of the KASCADE experiment. 5 MHz counters are used in every frontend electronics system. The contents of these counters are read and added to each detector count as time labels.

In case of a trigger the event data (including the time labels) are transferred from the local transputers to the central workstation host where they are checked for time labels identical or close to the trigger time. Eventbuilder software is used on the host to correlate the data before writing them to a mass storage device. A large number of other online tasks like detector control and calibration, track reconstruction etc. can also be performed on the transputer net. The event display is again handled on the central workstation.

2.5. Trigger sources - rates - thresholds

The different trigger sources in the KASCADE experiment can be used to study a broad variety of physics problems. The trigger layer of the central detector with a rate of about 0.5 sec^{-1} allows to study the flux and spectrum of unaccompanied high energy hadrons. Information from the top cluster and the array detectors is used to select clean single hadron events. Simulations show that these events allow to study the energy range of 1 TeV and higher for primary protons.

The top cluster multiplicity trigger (**n** of 50) is used to read out the whole experiment in the case of low energy central shower events. This enables the detailed and comprehensive study of all components of showers with energies typically down to 10^{13} eV. In this energy range the predictions from extensive air shower simulation codes like CORSIKA can be tested most effectively because strong interaction is well known. The numbers and distributions of muons and hadrons in the cores of these showers can be determined with good accuracy.

The main trigger source for the study of the primary spectrum and composition around the knee is a detector multiplicity (**n** of 32 ; **m** of 60) fulfilled in at least one cluster of the array. A typical trigger requirement used at present is **n** : 10 to 15, **m** : 20 to 30, corresponding to rates of 1 to 3 sec^{-1}. The resulting threshold of the measurements is a few times 10^{14} eV, depending on zenith angle and primary mass. The upper limit of the energy range of the KASCADE experiment is defined by the size of the array. We expect about one event/day at 10^{17} eV. Except for small showers the array trigger is usually accompanied by a muon multiplicity trigger from the trigger layer in the central detector.

The streamer tube muon detector in the tunnel will produce its own muon multiplicity trigger but the readout can be triggered also from the array clusters or the central detector system.

In the array, a local high energy deposit in one station can be used as a trigger condition also. This may be used to study very narrow events.

2.6. Experimental observables

The main strength of KASCADE lies in the large number of experimental quantities which can be measured simultaneously for each event. This enables multidimensional analyses for the determination of the basic properties of the event, the energy and the mass of the primary.

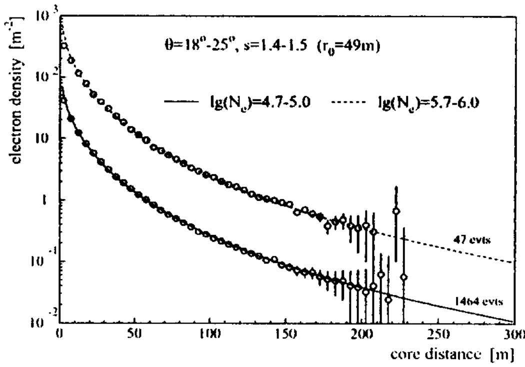

Figure 7. Average lateral distributions of the charged particles in samples of EAS with similar parameters are well described by NKG functions.

The most straightforward measurements are the determination of the **absolute time** of the event, of the **position of the shower core** and of the **zenith and azimuth angles**. The **electron size** of the shower and the lateral distribution of the electrons (the **shower age**) can be determined. The **density of muons** can be measured both in the shower core and in the outer parts of the array. In the shower cores, the **number and lateral distribution of hadrons** as well as the **hadron energy** are important quantities. **Arrival time distributions of hadrons, muons, and electrons** can be measured. In the shower cores the **pattern of the muon** hits can be studied. For higher energy events a determination of the muon **lateral distribution** parameter and of the **muon angle** relative to the shower axis will be possible. In the array the details of the distribution of electrons like (delayed) **subshowers**, asymmetric events, multiple cores or narrow events can be studied. The use of different muon detection techniques with thresholds from 0.3 to 2.0 GeV gives at least some information on the **muon energy** distribution in EAS.

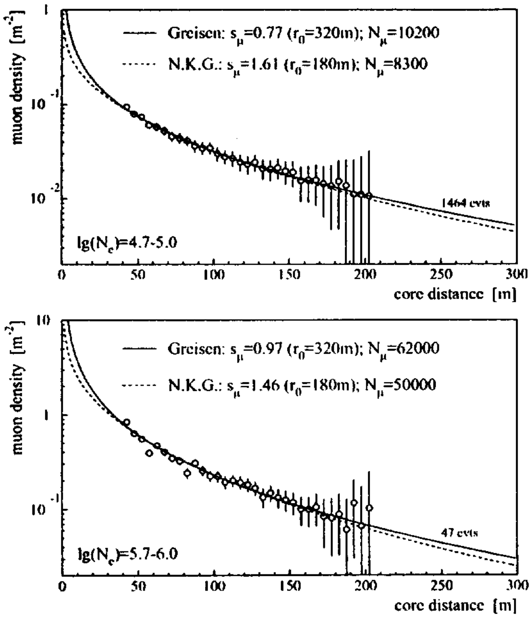

Figure 8. Lateral distributions of muons for the same showers as in fig 7. Integration outside the range of the data induces large uncertainties depending on the lateral function used.

2.7. Event reconstruction

For the off-line analysis of the shower events the code KRETA is being developed. The analysis of the raw data from all parts of KASCADE proceeds in several steps (levels). In the first, fast level data calibration and correction procedures are performed. Muon and hadron tracks are identified and reconstructed. The core position and the shower direction are determined using fast algorithms like a neural network and a gradient method [10]. Electron and muon numbers are estimated using fast empirical approaches.

In the second level numerical fits are performed to the data, e.g. various analytic functions to the lateral distributions of electrons and muons, a cone fit to the shower front, etc.. In this step the main shower parameters, particle densities, distributions etc. are determined. The event reconstruction is then followed by a correlated multiparameter analysis of the measured observables. This part of the analysis procedure is still under development and will be improved further as our understanding of the details of extensive air shower events is growing.

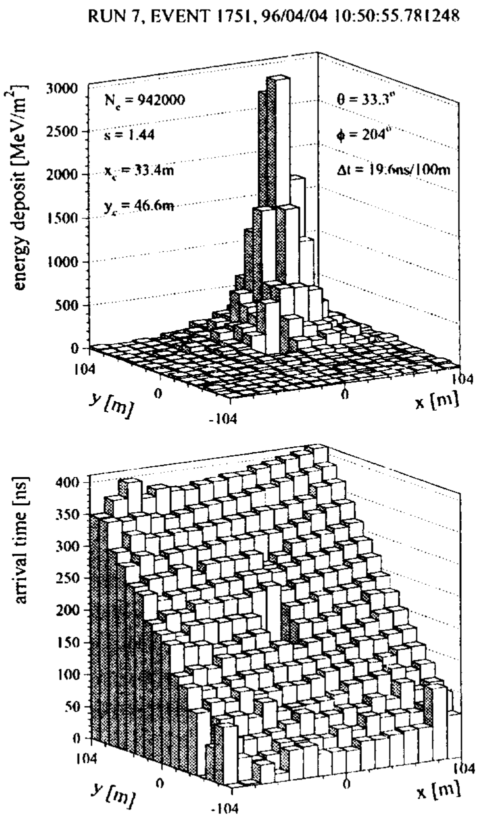

Figure 9. Example of an EAS as registered by the electron counters of the array. In the upper part, each column represents the energy deposit in one detector station. The lower part shows the arrival times of the shower front at the various detectors.

2.8. Reconstruction accuracy

To estimate the accuracy of the reconstructed shower parameters, some effort has been put into the understanding of the detector response to extensive air showers. The event simulation code CRES has been developed, based on the GEANT3 package. CRES accepts simulated air shower data from CORSIKA as input and delivers simulated detector signals. Due to the fast improvement of computing power in recent years detailed simulations of EAS for different primaries, zenith angles and primary energies and of the detailed response of the KASCADE experiment to these events could be performed with sufficient statistical accuracy. With these calculations it was possible to test and improve different reconstruction methods and to study the origin of systematic effects. It turned out that in general the reconstruction gets better for larger showers - relative fluctuations decrease with increasing energy.

The numbers quoted below are relative errors for showers with electron size greater than 10^5 which corresponds to a primary energy of about 10^{15} eV in our case. For these events the hadronic energy sum in the shower core is determined to a relative accuracy of 0.05, the number of hadrons to 0.08 and the muon number (above 2 GeV) in the core to 0.12 if the shower core falls inside the central detector. The shower disk is measured by the detector array with an error of 0.08 for the electron size, of 0.07 for the age parameter, and of 0.16 for the muon number. The core position is determined with an accuracy of about 2.5 m and the direction of the shower to better than 0.3^0.

3. FIRST MEASUREMENTS

Data taking with the detector array and a large part of the central detector system has started at the end of 1995. At present, the experiment is normally stopped during working hours for further installation, calibration, and tests whereas data taking is routinely performed at nights and over the weekends. Typically half a million of showers are registered per week in this mode of operation.

With the array of detector stations we are starting to study the shower rate as function of shower size, zenith angle, age, etc. to get information on the primary particle spectrum. For the same range of shower parameters the electron/muon ratio will be determined. This ratio is probably the parameter which is most sensitive to primary mass composition. Details of the electron and muon lateral distributions are studied to get a better understanding of the basic properties of air showers. The influence of atmospheric parameters on ground level observables of EAS has been calculated and the results will be checked.

From small subsets of the array data taken so far (typically from a few days of measurements) several observables have been reconstructed, mainly to perform consistency checks for the detector systems and the methods of data analysis. The reconstruction of zenith and azimuth angles e.g. was carried out using the array data and the MWPC muon data independently. The results are in good agreement. The zenith angle distribution of the reconstructed events peaks around 18°, a very small part of the rate comes from zenith angles greater than 40°.

The lateral distribution of all charged particles in the shower is analyzed using a NKG function with a fixed radius parameter of 49 m which fits the data (fig. 7) nicely in the typical radial range of our measurements, say 10 - 200 m. The measured muon lateral distributions in the range 40 - 200 m can be described equally well (fig. 8) by a Greisen (or modified NKG) function:

$\rho_\mu(r) = \frac{N_\mu}{r_0^2} C(s_\mu) (\frac{r}{r_0})^{-s_\mu} (1 + \frac{r}{r_0})^{-2.5}$

When the charged particle densities are corrected for the muon contribution, however, a NKG function does not seem to be optimum.

More detailed studies are necessary to find more suitable functions. Fig. 9 shows an example of a shower as registered by the array. In the upper part the amplitudes of the signals in the scintillation counters are displayed which detect the electromagnetic component. The lower part shows the arrival times of the particles at the various array stations. Parameters resulting from the analysis such as electron number N_e, core position, direction of incidence and shower age s are given in the upper part. It is obvious from the figure that shower size and direction of

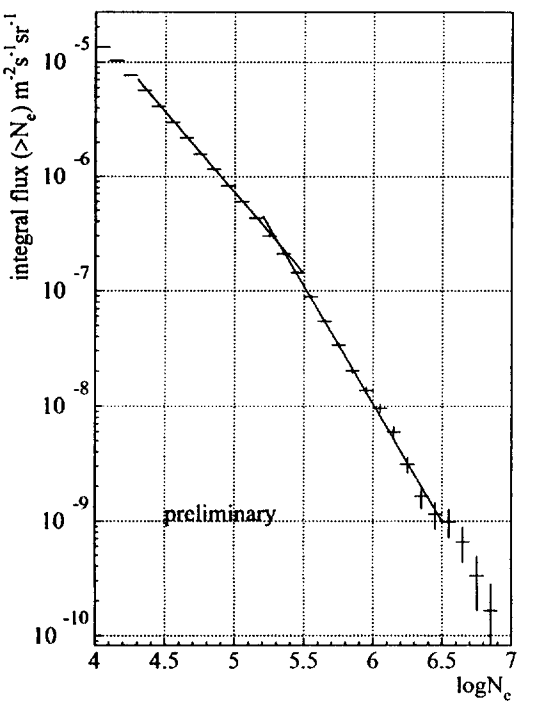

Figure 10. Event rate vs. reconstructed shower size for EAS in the zenith angle range 15° to 25° (one week of data).

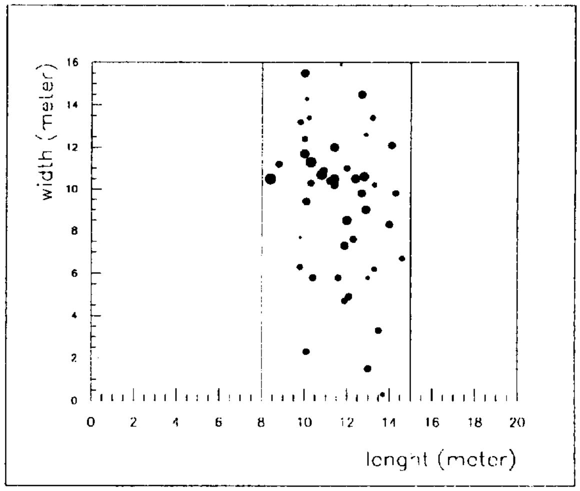

Figure 11. Pattern of signals for a shower core in the calorimeter. The size of the dots indicates the energy of identified hadrons. Their sum energy is c. 13 TeV. The vertical lines show the part of the plane with ionization chambers installed.

the showers can be determined to high accuracy.

According to simulations more than half of the muons will hit ground level outside the array area. Hence the total muon number obtained by integrating the muon lateral distribution to infinity may be subject to considerable systematic errors depending on the choice of the lateral distribution function. This can be seen from the numbers quoted in fig. 8. We therefore tend to quote the number of muons within a specific radius interval as the primary result of our measurements.

When we plot (fig. 10) the event rate against the reconstructed electron size of the showers in the zenith angle range 15° to 25° we find a distinct change in slope near log N_e = 5.5. These data correspond to one week of measurement. To extract reliable spectral indices from this size spectrum and absolute flux values we still have to analyze very carefully threshold effects, array efficiency and systematic errors of the reconstruction.

Fig. 11 displays the hadrons in a shower core as measured by the calorimeter. Only 100 m^2 of the calorimeter were operational during this measurement. The size of the spots indicates the energy of individual hadrons on a logarithmic scale, the most energetic ones having 1.3 and 1.2 TeV. The total hadronic energy of the event displayed was around 13 TeV.

The first measurements with the central detector system include the determination of the flux spectrum and the zenith angle distributions of single cosmic hadrons in the energy range from 10 GeV to 10 TeV. In two weeks of data taking with about 1/3 of the calorimeter area the flux spectrum of single hadrons has been remeasured. The preliminary data are plotted in fig. 12. They are in good agreement with previous experiments especially with the results of the measurements performed with the prototype of the calorimeter

[6]. This demonstrates that the hadron reconstruction algorithm and energy assignment work correctly.

First measurements of the cores of EAS around $10^{15} eV$ in the trigger layer and the MWPCs demonstrate the possibility to infer information on the mass composition from a multifractal moment analysis of the hit patterns [11].

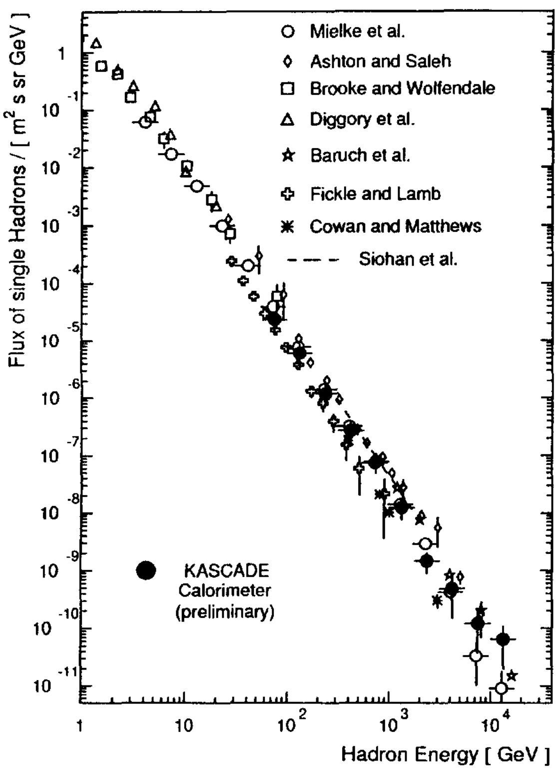

Figure 12. Preliminary data for the single hadron flux measured with the KASCADE calorimeter (two weeks of data) compared to previous measurements.

4. CONCLUSIONS

The installation of the KASCADE experiment is nearing completion. Data taking with a large part of the experiment, including 2/3 of the calorimeter area, has already started. The rest of the hadron calorimeter and the streamer tube muon detectors will be fully installed in 1997. Multiparameter analysis procedures are still under further development. Preliminary data look very promising.

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