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Recent Results of KASCADE
Phenomenology of Extensive Air Showers

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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 in the energy region around the "knee" of the primary spectrum. Its main aim is to determine energy spectrum and composition of hadrons in primary cosmic rays. This is attempted by registring a large number of observables for each EAS including measurements of electrons, muons and hadrons. This contribution gives a short description of the experiment and then presents some results on the lateral distributions of various particle types and on the spectrum of hadrons. The status of our analyses to determine mass composition is presented in an accompanying contribution by A. Haungs.

1. INTRODUCTION

The Karlsruhe extensive air shower (EAS) experiment KASCADE aims to investigate the composition of primary cosmic rays in the knee region of the energy spectrum. The experiment is a multi-detector system which registers simultaneously a large number of observables for each individual EAS. Particles of all three main shower components (electromagnetic, muonic and hadronic) are measured. The basic idea behind KASCADE is to use this multi-parameter feature to reduce, or hopefully avoid, the ambiguities of interpretation which are known to result from our incomplete knowledge of high energy strong interactions. Building of KASCADE started in 1990 and first measurements, with a yet incomplete detector system, started in 1996.

This contribution gives an up-date of the hardware of the experiment and discusses results concerning the measured properties of EAS. The analysis of the data to determine energy and mass of primary cosmic ray particles from EAS measurements rely heavily on the comparison with simulations. It is therefore essential to verify that EAS are phenomenologically well described by such calculations. This is the idea behind the discussions of this contribution. The present status of our attempts to determine energy spectrum and composition of primary cosmic rays are described in an accompanying paper presented by A. Haungs [1].

The experimental activities of the KASCADE

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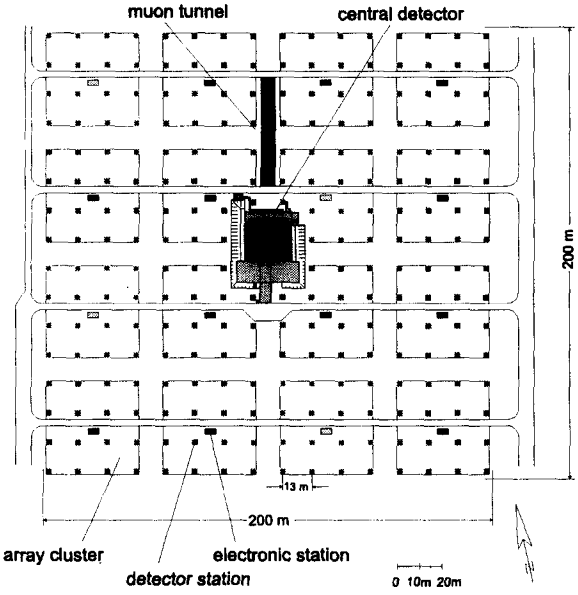

Figure 1. *Lay-out of the KASCADE experiment.*

collaboration are complemented by the development and continual improvement of the Monte Carlo code CORSIKA [2]. This program simulates the shower development for all particle components in three dimensions down to observation level. Several high-energy interaction models have been implemented to allow an estimate of systematic uncertainties resulting from different treatments of high energy interactions.

2. STATUS OF HARDWARE AND ANALYSIS

The KASCADE experiment has been described in detail previously [3] and the reader is referred to this reference for more details. A lay-out is shown in Fig.1. Its main parts are a detector array, a central detector and an underground tunnel. The latter part is a new addition to the experiment. It houses 600 m^2 of streamer tube detectors arranged as a three-layer tracking detector of 150 m^2 effective area. This part of the experiment allows to measure the direction of muons in EAS[4]. The muon tunnel became operational stepwise between fall 1999 and spring 2000. Therefore no data obtained with these detectors are included in the present paper.

A nontrivial problem of EAS experiments is the reconstruction of shower observables such as the number of electrons, muons etc. from the various detector outputs. The signals of the muon detectors in the array, e.g., will contain contributions from e.m. particles (owing to punchthrough) and vice versa (since muons pass through the e.m. detectors above). A discussion of this important question is beyond the scope of this contribution. Details can be found in [5–7]. The development of analysis procedures was based on CORSIKA and a complete Monte Carlo program to simulate the response of the various detector components to all kinds of shower particles.

3. LATERAL DISTRIBUTIONS OF ELECTRONS AND MUONS

In a study completed recently the average lateral distibution functions (LDFs) of electrons, muons and hadrons were investigated [8]. The somewhat unexpected result was that, within the radial range of KASCADE, all LDFs are best described by the usual NKG function albeit sometimes with other than the usual parameters. Measured electron densities were averaged for showers within a certain bin of total electron number N_e. Fig.2 shows the results. The fits have been restricted to densities below $200\,\mathrm{m}^{-2}$ to avoid saturation. As can be seen NKG functions fit the LDFs very well. For these fits the age parameter was kept fixed at s=1.65 and the Molière radius (which we therefore prefer to call r_e) was allowed to vary. The optimum values of r_e then are in the range of 20 to 30 m, i.e. much smaller than the usual Molière radius of c. 80 m. When other age values are preselected the optimum value of r_e changes revealing the well-known strong nonlinear correlation between s and r_e. The fact that a good fit can be obtained with a fixed age implies a simple radial scaling of LDFs within the range of radii and sizes considered in this paper. The characteristic radius r_e increases with zenith distance in proportion to its secant and decreases with N_e, not unexpectedly. KASCADE measures muons at three different thresholds: 230 MeV (array), 490 MeV (trigger

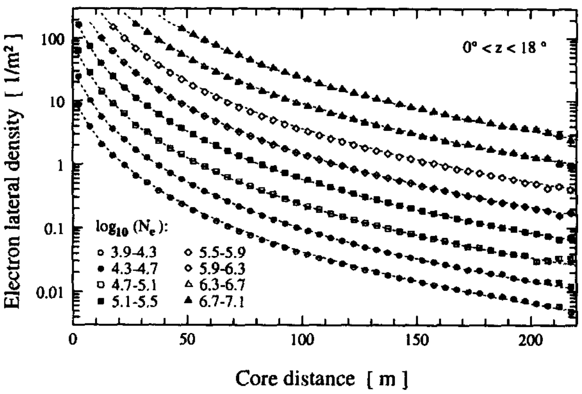

Figure 2. *Observed LDFs for electrons above 5 MeV and their NKG fits (from ref. [8]).*

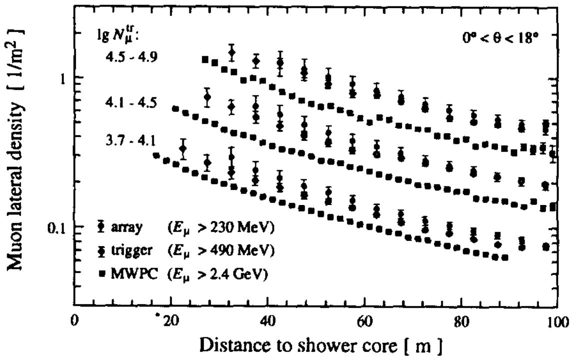

Figure 3. *Measured muon LDFs for three different energy thresholds (from ref. [8]).*

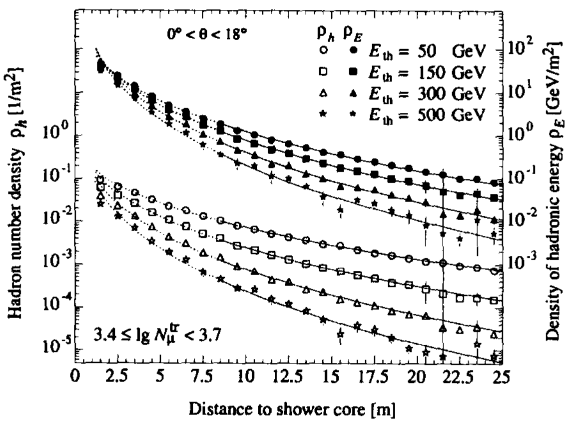

Figure 4. *Measured hadron LDFs for different energy thresholds (from ref. [8]).*

plane) and 2.4 GeV (multiwire counters; all values refer to vertical incidence). The fit ranges are 40 to 220 m, 20 to 100 m and $\leq$ 100 m, respectively. The lower limits are imposed in order to avoid excessive punchthrough by hadrons and e.m. particles. The upper limit is of course much lower than the diameter of the muon lateral distribution of an EAS. We therefore prefer to quote, as our experimental result, the number of muons in the radial range 40 to 200 m ('truncated muon number') rather than a total number because the latter would require extrapolation into a range not covered by our experiment. The observed LDFs are described well by NKG functions with fixed radial parameter r_μ=420 m and variable age parameter s. Alternative functions proposed by Greisen [9], Linsley [10] and Hillas et al. [11] did not yield better fits. Again a strong correlation between the optimum s and r_μ is observed when the latter is varied. It should be mentioned that the choice of r_μ does not effect the value of the truncated muon number but would result in very different values of the total muon number. Fig.3 shows some results of our measurements. The optimum age parameters decrease with increasing muon number and decreasing zenith distance reflecting steeper LDFs for larger and for vertical showers.

4. HADRONS: LATERAL DISTRIBUTIONS AND SPECTRA

In this section we only discuss hadrons in the cores of EAS. Spectra of single hadrons not associated with EASs have been studied previously [12]. It is worth mentioning, though, that data on single hadrons extend to above 50 TeV by now. Hadrons in EASs are the more concentrated in the shower core the higher their energy. Hence the LDFs depend strongly on energy threshold. This is borne out by the results shown in Fig.4. The lines represent NKG fits with a radius pa-

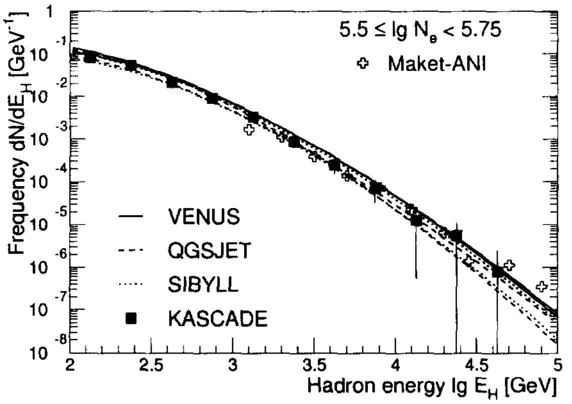

Figure 5. *Measured hadron spectrum in EAS with a limited range of shower sizes (from ref. [13]).*

rameter fixed at 10 m. In addition to the hadron densities the energy densities of hadrons are displayed. The fits describe the data well for radii above c. 2m. At smaller radii saturation effects may come into play especially for the number densities.

Energy spectra of hadrons in shower cores have been studied previously [13]. An example of a measured spectrum, corresponding to a primary energy of c. 6 PeV, is shown in Fig.5 together with data from the MAKET ANI experiment [14] and simulations with the CORSIKA program. Our main conclusion from more refined analyses is that the QGSJET model developed by the Moscow group [15] reproduces the experimental data satisfactorily at low energies (i.e. below approximately the "knee" energy). At higher energies all interaction models fail to describe the data in every respect. For more details we refer to the extensive publication [13].

5. CONCLUSIONS

The KASCADE experiment is in full operation by now and yields high quality data on electrons, muons and hadrons in EASs in a primary energy range from a few hundred TeV to c. 10 PeV. The lateral distributions of all particles can be well described by the NKG function. The derived parameters exhibit a number of expected features: steepening of lateral decline with increasing size (i.e. primary energy) and, for hadrons, with increasing particle energy, flattening with increasing zenith distance. Most observed features, though clearly not all, are well described by simulations with the CORSIKA program. We feel we have collected a high quality data base for approaching the really important problems: energy distribution and composition of primary cosmic rays in the region of the "knee" [1].

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