Tests of Interaction Models and Composition Measurements by KASCADE

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Abstract

Since its start-up early 1996 the KASCADE extensive air shower experiment has collected more than 200 Mio. events with an energy threshold of approx. 10^{14} eV at the site of Forschungszentrum Karlsruhe. A unique feature of KASCADE is the simultaneous measurement of electrons, muons, and hadrons. High energy hadrons and muons observed close to the shower core have been proven a sensitive tool to test hadronic interaction models, while electrons and muons and their respective shower sizes provide a direct link to the mass of the primary particle. Tracking of muons, furthermore, will allow to reconstruct their mean production height, thereby adding another important observable to the composition. The large body of data can consistently be described only, if an increasingly heavier composition is assumed above the knee. Quantitatively, subtle differences are identified between hadronic and electromagnetic measurements, with the former pointing to an overall heavier composition. The *knee* in the primary energy spectrum is observed at $E_{\rm k}$ = 4-5 PeV with a change of the spectral index from $\gamma \simeq 2.7$ to 3.1. We critically discuss the preliminary results and point out possible future improvements, particularly in the modeling of EAS.

1 Introduction

Detailed measurements of the primary cosmic ray (CR) energy spectrum and chemical composition can provide very powerful means of tracing both their origins and mechanisms of acceleration. Much progress has been made particularly in the energy range where direct measurements on high-flying balloons and satellites are possible (see e.g. Drury, Meyer, Ellison 1999). However, because of the rapidly falling energy spectrum, such measurements are restricted to energies $E \lesssim 5 \cdot 10^{14}$ eV. With only marginal overlap in primary energy, ground based extensive air shower (EAS) experiments take over and they presently allow measurements up to about 10^{20} eV. Ironically, a break in the primary energy spectrum, the so called "knee" is observed at $E \simeq 4 \cdot 10^{15}$ eV, i.e. close to the transition from direct to EAS experiments. Measuring the chemical composition as function of primary energy across the knee, again, would provide the key to an understanding of this remarkable phenomenon.

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It is hoped, that EAS experiments can provide such data. The measurements are relatively difficult and the interpretation of the ground level observations in terms of the characteristics of the primary flux requires the use of model calculations to simulate the propagation of the particles through the atmosphere. EAS simulations in turn depend on extrapolations applied to data of high-energy particle interactions studied at particle accelerators. Consequently, a wide spread of values about the primary composition have been reported, covering almost the entire range between a pure proton or pure iron distribution (see recent reviews by Watson 1997; Erlykin & Wolfendale 1998).

The goal of the KASCADE experiment (Doll et al., 1990; Klages et al., 1997) is to determine the primary CR spectrum and composition in the knee region by simultaneously measuring a large number of EAS observables on an event-by-event basis with high quality. This 'redundancy', as shall be demonstrated, uncovers systematic biases in the interpretation of the data, thereby enabling also tests of the high-energy hadronic interaction models plugged into EAS simulations. Related to this, various interaction models have been implemented into the CORSIKA simulation package (Heck et al., 1999) and were compared to measured data (Antoni et al., 1999; Risse et al., 1999). The most consistent results of the different observables are obtained using the VENUS and QGSJET model. The agreement on the primary energy spectrum is fairly satisfactory, however, reconstructions of the chemical composition still seem to require improved versions of hadronic interaction models. The available data already provide the means to contribute to the improvements of such models.

2 Experimental Status

Data taking in a correlated mode with most components in operation has been started in April 1996. At present, trigger

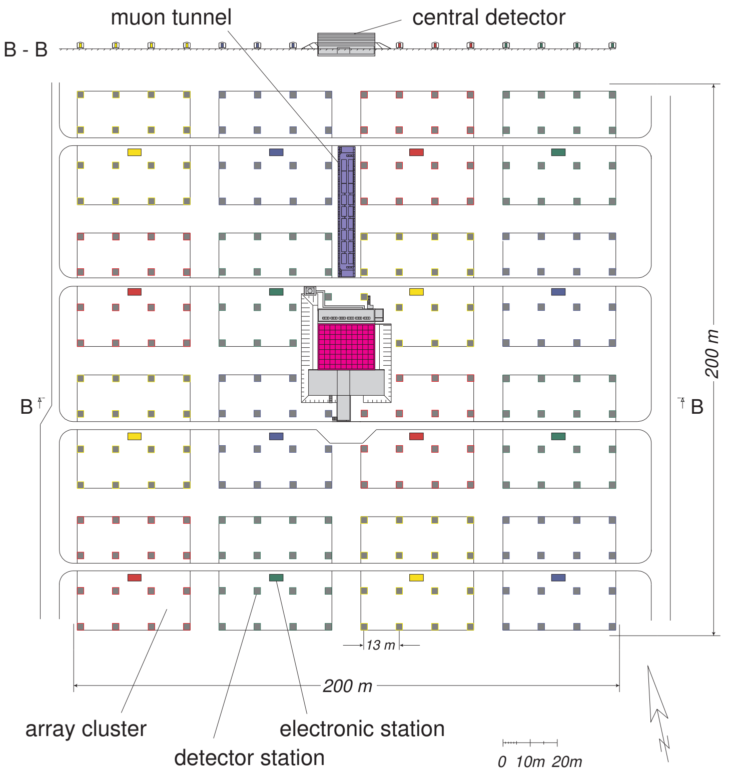

Figure 1: Schematic layout of the KASCADE experiment.

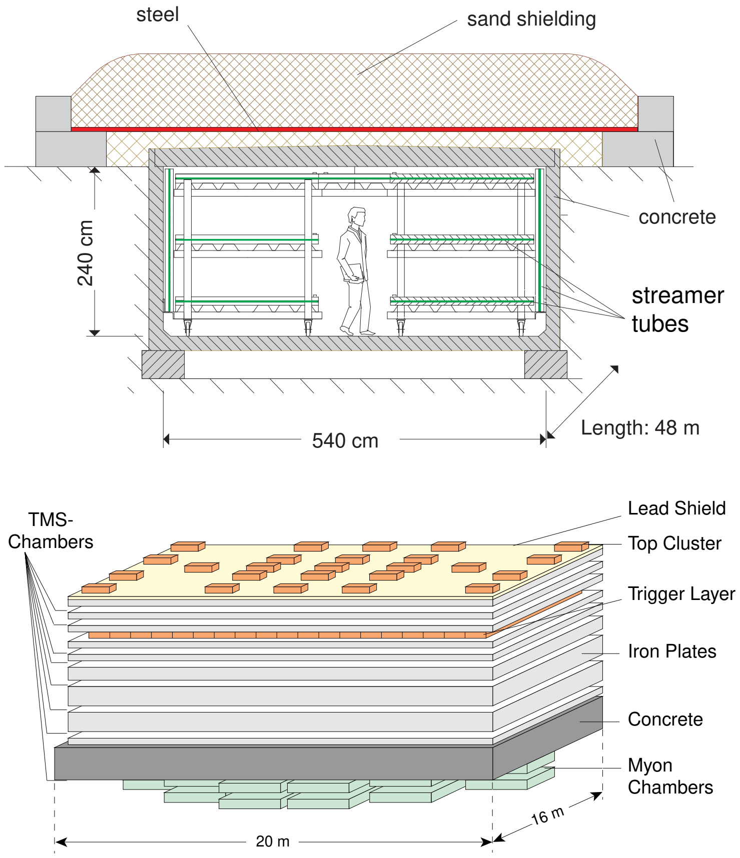

Figure 2: Enlarged view of the KASCADE muon tracking tunnel (top) and central detector (bottom).

thresholds are adjusted to limit the total trigger rate to ~ 4 Hz, corresponding to an effective energy threshold in the array of $\sim 10^{14}$ eV for protons and $\sim 3 \cdot 10^{14}$ eV for iron. Most of the 200 Mio. raw data events have been processed with all detector calibrations and error checks. Parallel to data taking, installations still continue, most notably the streamer tube tracking detectors sketched as muon tunnel in Figs. 1 and 2. The installations will be finished in fall 1999 and preliminary data taken for a subsystem look very encouraging. The system will enlarge the area for muon measurements by 150 m^2 and will allow to reconstruct the mean muon production height on event-by-event basis for primary energies above the knee. This will add another important observable to determine the primary composition and to perform systematic studies relevant for tests of interaction models (*Transp. 41 & 42*).

The central detector (Fig. 2, bottom) is presently being upgraded by adding detectors at the very top and bottom. A top layer of TMP ionization chambers is added to improve the acceptance particularly for the electromagnetic component of low-energy air showers. This will improve the position reconstruction of the hadronic shower core and complement the muonic and hadronic measurements. Studying the balance of electromagnetic, muonic, and hadronic energy will put even stronger constraints on interaction models as is achieved presently (Risse et al., 1999). Muon measurements beneath the multi-wire proportional chambers are being improved by adding a plane of 300 m^2 streamer tubes with pad read-out. The pad-size of 8×16 cm^2 will enable muon density measurements in the center of shower cores without suffering from saturation effects. Again, such measurements are important for a reliable reconstruction of the CR composition.

3 EAS Event Classification

(Transparencies 9-14.) Using the KASCADE array, the number of electrons and muons can be reconstructed on a event-by-event basis. This is performed by integrating the measured radial profile of electron and muon densities observed in the individual detector stations. A fit to the lateral distribution functions yields, both, the shower core position and the total number of electrons and muons, respectively. In order to avoid too large systematic uncertainties, muon densities are integrated only in $40 \leq r \leq 200$ m, yielding the *truncated muon number*, N_μ^{tr}. Comparison to EAS simulations show, that N_μ^{tr} provides a very good estimate of the primary energy, which almost independent of its mass (Weber et al., 1997). Because of the steeper lateral density distribution of electrons, uncertainties caused by extrapolations to large distances from the shower core are small, so that electron numbers quoted refer to their total number.

Hadron tracks can be identified with good efficiency for energies above 50 GeV and for densities below 1.5 hadrons/m^2. Integration of their lateral distribution up to 24 m yields the hadron size, N_h. Relating electron or hadron shower sizes to the muon size, provides a direct link to the primary mass, as will be discussed in section 6.

4 Knee in the shower size distributions

(Transparencies 15-18.) Distributions of the shower size exhibit a distinct structure, attributed to the knee in the primary energy spectrum. In case of electrons and muons measured in the array, the variation of the knee can be studied also as a function of the atmospheric depth. The observed dependence agrees well with simulations. Also, the position of the knee in the electron size distribution agrees in an excellent way with the most recent EAS-TOP data (Navarra et al., 1999). Related studies of the atmoshperic attenuation lenghts are underway.

For the first time, a knee in the distribution of hadronic shower size and total hadronic energy is observed by KASCADE (Hörandel et al., 1999). The knee position and the spectral indices below and above the knee are in very good agreement to the results of the electron and muon size spectra. This observation is a clear indication that the knee is not produced in the atmosphere, e.g. by opening a new channel in hadronic interactions, but is an intrinsic poperty of the primary flux spectrum.

5 Tests of Hadronic Interaction Models

(Transparencies 19-28.) Usually, high energy hadronic interaction models are tuned to describe experimental data measured in the central rapidity region at high-energy particle accelerators. Their application to EAS simulations at the knee then requires extrapolations to the very forward region which has not been measured in sufficient detail up to now. Consequently, large variations are observed in the predictions of various models with observable differences identified also in EAS parameters, most dominantly in hadronic observables of the shower core. Thus, using the large hadron calorimeter, hadronic cores of EAS can be studied with unprecedented quality and be compared to model predictions (Antoni et al., 1999). This is nicely illustrated by plotting the energy distribution of hadrons for given muon shower sizes (i.e. given primary energies) *(Transp. 25-27)*. Clearly, VENUS and QGSJET describe the data satisfactory if a composition between proton and Iron primaries is assumed. SIBYLL, however, fails unless a primary mass beyond that of Iron would assumed. Similar results have been obtained by Erlykin and Wolfendale (1998). It is hoped, that the new version of SIBYLL, discussed by Engel *et al.* on this workshop, will eliminate this problem.

While reasonable agreement is found at energies up to the knee region, problems are observed above 10 PeV also for QGSJET, because primary masses significantly heavier than Iron are required for consistency with the data. This is generally considered an 'unphysical' solution, and doubts about the reliability of the model in this energy domain have to be raised. The successor of QGSJET & VENUS, dubbed neXus (Werner et al., 1999), is expected to have overcome this deficiency.

6 Composition Analyses

(Transparencies 31-44.) An important prerequisite in any study of the chemical composition is the availability of reliable hadronic interaction models, such as have been verified in the previous section. In the present KASCADE data, composition analyses are mostly performed by relating the electron or hadron numbers to the muon size. However, a convincing argument can already be made based on the observed break in the electron and muon size spectrum (*Transp. 32 & 33*): Fitting both spectra *simultaneosly* is completely impossible when using a constant composition. Only an *increasingly* heavier composition above the knee can reproduce the steep electron spectrum in this energy range and at the same time be consistent with the muon spectrum (Glasstetter et al., 1999). This is mostly because of the smaller shower fluctuations in case of heavy primaries.

The composition infered from this analysis is in good agreement with the one based on the muon/electron ratios calculated event-by-event *(Transparencies 31-44.)*. Comparisons to simulations are remarkable, because they proof that no single mass component can describe the experimental data. Furthermore, protons are found to be the lightest and Iron the heaviest particles needed for a description of the data (Weber et al., 1999). Again, an increasingly heavier composition above the knee is required to describe the data. The sensitivity of this result to the interaction model is moderately weak, e.g. differences predicted by QGSJET and VENUS are within the error bars. However, as can be seen from *Transp. 44*, the overall composition appears to be significantly lighter than the one prefered by the hadronic observables. This seems to be a general trend, because Chacaltaya hadron data show a good agreement to those of KASCADE.

Finally, pattern analyses with high-energy muons and penetrating hadrons observed in the MWPC below the calorimeter have been presented by Haungs *et al.* on this workshop. Again, the composition becomes heavier above the knee, following closely the trends seen in hadronic observables.

7 Primary Energy Spectrum

(Transparencies 33, 35, 40.) Reconstructing the primary energy spectrum from EAS size distributions requires knowledge of the primary mass composition and of the relationship between shower size parameters and primary energy. Also, stochastic fluctuations in the shower development need to be corrected for. Results have been obtained using the information from electrons and muons, and of hadrons. To be consistent,

the energy spectrum extracted from the electron and muon size spectra is based on the composition extracted by these observables, while that of the hadrons, it is based on the composition prefered by the hadronic data. The agreement between different observables or interaction models is very good, as can be verified by Fig. 3. The result of the deconvolution into 'light' and 'heavy' based on the electron and muon size spectra is represented by the lines (dashed lines are extrapolations of the present data), while the hadronic data are given by the black squares. Interestingly, the knee seems to be caused by protons, i.e. by light primaries only. Within the fit range no indication of a knee is observed for the Iron (heavy) component. However, to be consistent with Akeno and other data also at energies above 10^{17} eV, a knee in the heavy component would be expected in that energy range, i.e. at the same rigidity as for protons. More data are still needed to verify this interesting observation. The position of the knee in the total flux spectrum is reconstructed at $E_{\rm k} \simeq$ 4-5 PeV and the indices are $\gamma_1 = (2.7 \pm 0.05)$ and $\gamma_2 = (3.1 \pm 0.07)$. The sharpness of the knee in the primary energy spectrum appears moderately mild. The average flux above the knee as deduced from hadrons, muons, and electrons, respectively, is $J(> 4.1\mathrm{PeV}) \simeq (11.3 \pm 1.0) \cdot 10^{-8}$ m^{-2} s sr^{-1}.

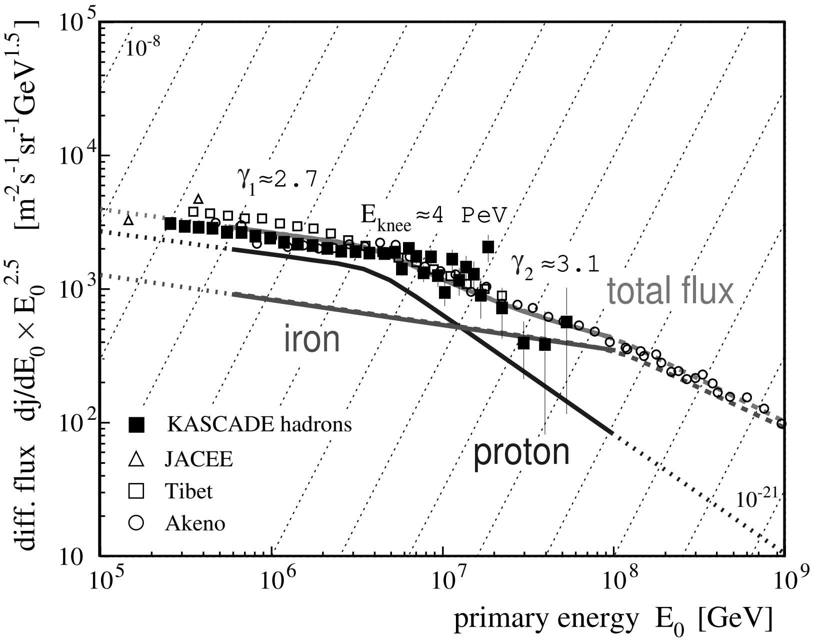

Figure 3: Primary CR energy spectrum from KASCADE and other experiments (see text for details).

8 Concluding Remarks

In summary, already after about 3 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 distributions, of the related primary energy spectrum, as well as preliminary estimates of the chemical composition of primary CRs. The 'redundancy' of the measurements turns out to be of vital importance in revealing systematic uncertainties. Reasonable agreement is found for the reconstructed primary energy spectrum, but firm conclusions about the mass composition - besides the overall trend of increasing masses above the knee - still have to await improved versions of interaction models and more detailed investigations of the experimental observables.

Sensitive parameters in the interaction models are inelastic cross-sections, as well as the 'inelasticity' of an interaction. Further improvements towards a more consistent description of EAS parameters are expected from more abundant electromagnetic processes and neutral particle production in the first (i.e. high-energy) interactions (Erlykin 1999). Such investigations are of very general interest for any EAS experiment and are pursued in close collaboration with the authors of the models. For example, the authors of VENUS and QGSJET have combined their models with many additional improvements (Werner et al., 1999). This new model neXus will be part of CORSIKA in the near future. In parallel, the experimental techniques are getting more advanced, with new observables waiting to be included. The identified cosmic-ray muon spectra measured in COSMO-LEP will be of vital importance for this purpose. We are confident, that such combined approaches of different experimental observables and improved theoretical backgrounds will lead to a more consistent interpretation of EAS parameters such as needed to solve the puzzles of the knee.

More details about the KASCADE experiment, status of data taking, and selected publications can be found at the www-page:
`http://ik1au1.fzk.de/KASCADE_home.html`

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