The KASCADE Air Shower Experiment: Composition Analyses and Energy Spectrum

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Abstract

Since its start-up early 1996 KASCADE has collected more than 200 Mio. events with an energy threshold of approx. 10^{14} eV. A unique feature of KASCADE is the simultaneous measurement of electrons, muons, and hadrons at high quality. 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_{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. at an energy not accessible to direct measurements. Measuring the chemical composition as function of primary energy across the knee, again, would provide the key to an understanding of this remarkable phenomenon.

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).

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The goal of the KASCADE experiment (Doll et al., 1990) 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 and 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., *HE 2.5.28* and refs. therein) and were compared to measured data (Hörandel et al., *HE 1.3.01*). 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 (Klages et al., 1997). At present, trigger 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 Fig. 1. 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.

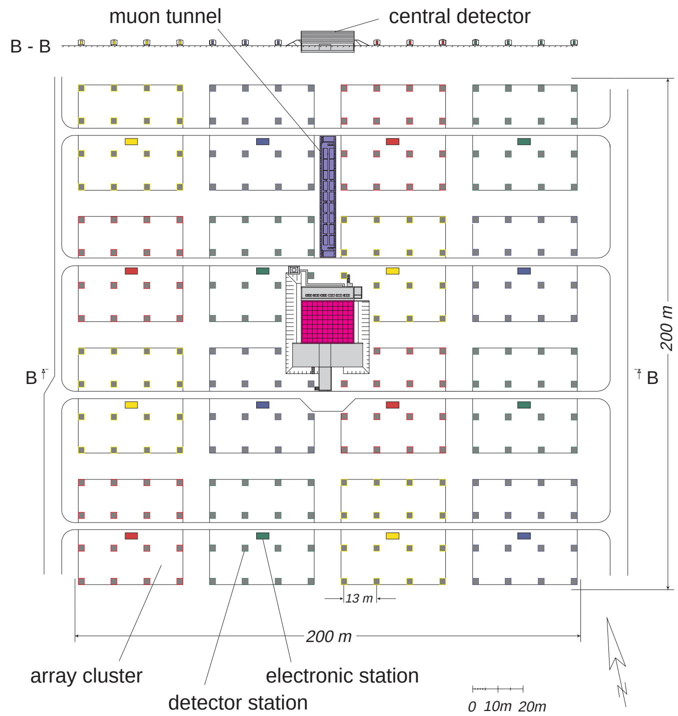

Figure 1: Schematic layout of the KASCADE experiment.

The central detector 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., *HE 1.3.02*). 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 Composition Analyses

An important prerequisite in any study of the chemical composition is the availability of reliable hadronic interaction models. Usually, such models are tuned to describe data measured in the central rapidity region at high-energy particle accelerators. Their application to EAS simulations at the knee requires extrapolations to the very forward region which has not been measured in sufficient detail. 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. In KASCADE, such data have successfully been used for detailed comparisons. The QGSJET model was found to provide the best overall description of the experimental data in the energy range up to the knee, similarly to the results by Erlykin and Wolfendale (1998). However, at energies of 10 PeV, also QGSJET fails to describe the hadron data, i.e. 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 are raised. A comment to such approaches seems appropriate: Already at energies below 10 PeV QGSJET (and other models) require an iron dominated flux to be conform to high-energy hadron data. This should not be considered evidence that the model predictions are still reliable but only, there is no obvious reason to reject the model. Consequently, the chemical composition extracted from hadronic data, thus will tend to be rather heavy. In fact, this is observed by KASCADE as well as in Chacaltaya data (Fig. 2). Following general practice, we plot the mean logarithmic mass $\langle \ln A \rangle$ as a function of primary energy, bearing in mind its ambiguity for different elemental compositions. The grey band at energies up to $3 \cdot 10^{14}$ eV indicates the uncertainty of direct measurements. The composition indicated by the hadron data (Engler et al., *HE 2.2.44*) follows the general trend of increasing masses and reaches $\langle \ln A \rangle \simeq 3$ at energies of 10 PeV.

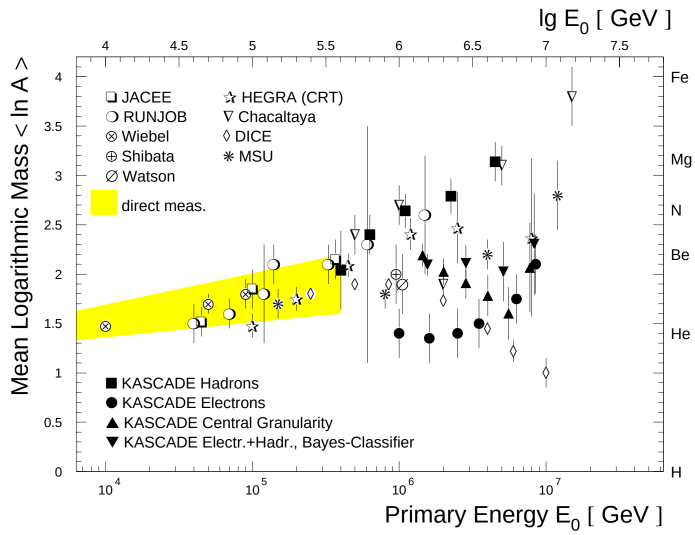

Figure 2: Compilation of preliminary KASCADE and other data on $\langle \ln A \rangle$ as a function of primary energy.

Another important approach of extracting the composition is given by the electron and muon sizes. Because of significantly smaller shower and experimental sampling fluctuations, their ratio can be calculated on an event-by-event basis, so that fluctuations caused by the height of first interaction in the atmosphere cancel out to some extend. 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., *HE 2.2.42*). Again, an increasingly heavier composition above the knee is required to describe the data. However, as can be seen from Fig. 2, the overall composition appears to be significantly lighter. 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. A related analysis has been presented by Glasstetter et al. (*HE 2.2.03*). Here, the composition is inferred from the absolute fluxes and spectral shapes of the muon and electron size distributions. The result is well in line with those discussed above. Finally, pattern analyses with high-energy muons and penetrating hadrons observed in the MWPC below the calorimeter (Haungs et al., *HE 2.2.39*) and multivariate approaches using several experimental observables (Roth et al., *HE 2.2.40*) have been performed. The results, also included in Fig. 2, are intermediate between those discussed above. For the latter one, this may be expected because of 'averaging' over several experimental observables.

4 Primary Energy Spectrum

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 presented at this conference

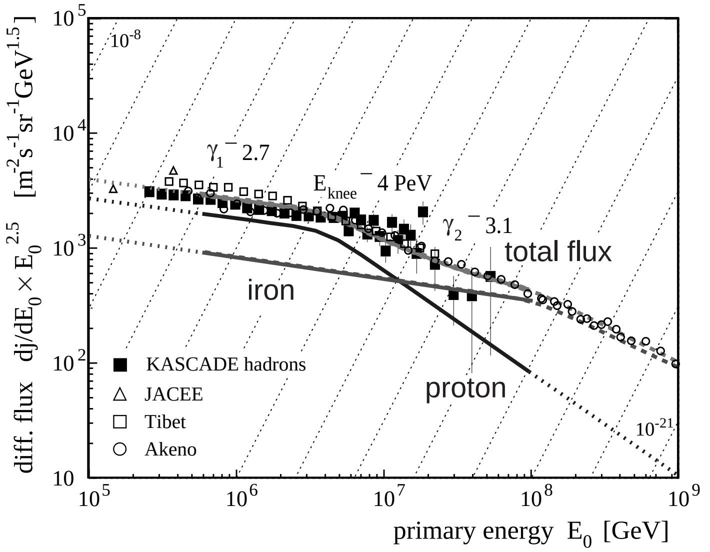

Figure 3: Primary CR energy spectrum from KASCADE and other experiments (see text for details).

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 preferred by the hadronic data (Hörandel et al., *HE 2.2.41*). The agreement between different observables or interaction models is very good, as can be seen from 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. 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 $E_{\mathrm{k}} \simeq$ 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 $J(> E_{\mathrm{k}}) \simeq (9.5 \pm 1.5) \cdot 10^{-8}$ m^{-2} s sr^{-1}.

5 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. 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. Such investigations are of very general interest for any EAS experiment and are pursued in close collaboration with the authors of the models. In parallel, the experimental techniques are getting more advanced, with new observables waiting to be included. We are confident, that this approach will lead to a more consistent interpretation of EAS parameters needed to solve the puzzles of the knee.

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