Proceedings of ICRC 2001: 137 © Copernicus Gesellschaft 2001

ICRC 2001

A measurement of the primary cosmic–ray energy spectrum using the hadronic air shower component

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Abstract. The *knee* in the cosmic–ray energy spectrum is investigated by measurements of the hadronic shower size spectra with the KASCADE hadron calorimeter. Two observables are used to characterize the shower size, the number of hadrons and the hadronic energy sum. Five energy thresholds for the reconstructed hadrons are introduced, in order to check for systematic effects in the procedures applied. A *knee* in the hadronic shower component is confirmed at energies corresponding to 2 PeV (7 PeV), if a pure proton (iron) composition is assumed.

1 Introduction

The all–particle cosmic–ray energy spectrum can be well described by a power law $dN/dE \propto E^{\gamma}$ in the energy range from 10 GeV up to 10 EeV. The most prominent structure is a change of the spectral index from $\gamma_1 \approx -2.7$ to $\gamma_2 \approx -3.1$ around energies of 3 PeV.

The *knee* has been discovered in the electromagnetic component about 40 years ago (Kulikov et al. 58). Meanwhile many experiments using different techniques have seen the *knee* in the all–particle spectrum, for a recent compilation see for example (Hörandel 01). The origin of the change in spectral slope is still under discussion. Explanation attempts include particle physics reasons, like new high–energy interactions in the atmosphere, or astrophysical reasons, like a rigidity dependent escape probability from the galaxis, as predicted by some cosmic–ray propagation models, resulting in a changing cosmic–ray composition around the *knee*.

To clarify the situation the experiment KASCADE (Klages et al. 97) measures the electromagnetic, muonic, and hadronic shower components simultaneously. The data allow to check the high–energy interaction models which are necessary for their astrophysical interpretation (Antoni et al. 99) (Milke et al. 01) and, therefore, cover the possible particle physics reasons for the *knee*. KASCADE measures a *knee* around 3 to 5 PeV simultaneously in all three shower components (Glasstetter et al. 98) (Glasstetter et al. 99).

Two observables have been used to investigate the hadronic component: the number of hadrons as well as their energy sum. From the shower size spectra a primary energy spectrum with a *knee* around 5 PeV has been derived (Hörandel et al. 99). In this article we report on progress of the analysis of the hadronic component.

2 Experimental set up

To investigate the cosmic rays from several 10^{13} eV up to 10^{17} eV the air shower experiment KASCADE ("KArlsruhe Shower Core and Array DEtector") has been built on site of the Forschungszentrum Karlsruhe in southern Germany, (110 m a.s.l.). The experiment consists of three major parts, a scintillator array, an underground muon tracking detector, and a central detector.

The 200×200 m^2 scintillator array is formed by 252 detector stations housing liquid scintillation counters to measure the electromagnetic component and, under an absorber of 10 cm lead and 4 cm iron, plastic scintillators to register muons with an energy threshold of 230 MeV. The position of the shower core, the angle of incidence as well as the number of electrons and muons is obtained from these detectors.

Three layers of 144 m^2 streamer tubes in an underground tunnel shielded by 1 m of concrete and soil, corresponding to an energy threshold of 800 MeV, form the muon tracking

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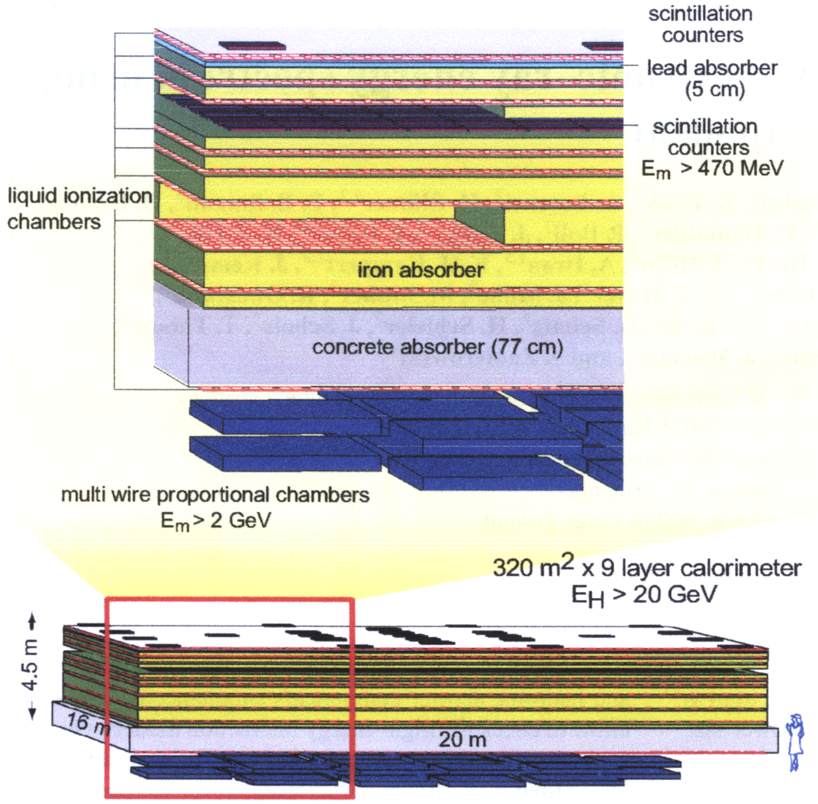

Fig. 1. Schematic view of the KASCADE central detector, detailed view (top) and total view (bottom). Main component is an iron sampling calorimeter equipped with nine layers of liquid ionization chambers and one layer of scintillation counters for triggering.

detector.

Main part of the central detector system is a 320 m^2 hadron calorimeter, sketched in Figure 1, formed by 4000 t iron, lead, and concrete absorber material, with a thickness of 11 hadronic interaction lengths. The absorber is interspaced by nine layers of ionization chambers filled with the liquids TMS or TMP (Engler et al. 99). In total 11 000 ionization chambers are installed, each containing four independent channels with a size of 25×25 cm^2. The fine segmentation of the read–out allows to reconstruct individual hadrons even in the core of air showers, measuring their point and angle of incidence as well as their energy. A layer of plastic scintillators below the third absorber layer — with an energy threshold for muons of 470 MeV — serves as a fast trigger. Below the calorimeter, two layers of multi–wire proportional chambers and one layer of limited–streamer tubes are detecting muons with a threshold of 2 GeV.

3 Simulations

EAS simulations were performed using the program CORSIKA (Heck et al. 98) version 5.644 with the hadronic interaction model QGSJET version from 1997 (Kalmykov et al. 97). Primary protons, helium, carbon, magnesium and iron nuclei have been chosen for the calculations as representatives for the most abundant mass groups, and a spectral index of $\gamma = -2.0$ is used. Using weights for each event, an appropriate energy spectrum is obtained for the investigations — see below. In the energy range from 10^{14} to 10^{17} eV about 130 000 showers with a zenith angle distribution from $0°$ to $42°$ have been simulated for each element. The shower cores are distributed uniformly within an area extending the calorimeter boundaries by 2 m. The detector response is obtained by using a detector simulation program based on the GEANT code.

4 Event selection and observables

For the analysis, events with zenith angle $\Theta \leq 30°$ and a shower core inside the calorimeter have been selected. From the reconstructed hadrons in the calorimeter the number of hadrons above an energy threshold of 50, 100, 200, 500 GeV, and 1 TeV, is calculated. Since the calorimeter measures the energy of individual hadrons, the sum of the hadron energies above threshold may serve as quantity for the hadronic shower size as well. Application of different thresholds and observables for the hadronic shower size allows to study systematic effects in the reconstruction.

Data measured from October 1996 to March 2001 are used for the analysis. About $4.5 \cdot 10^5$ events out of about $2 \cdot 10^8$ events recorded by KASCADE hit the central calorimeter and survive all cuts required in this analysis.

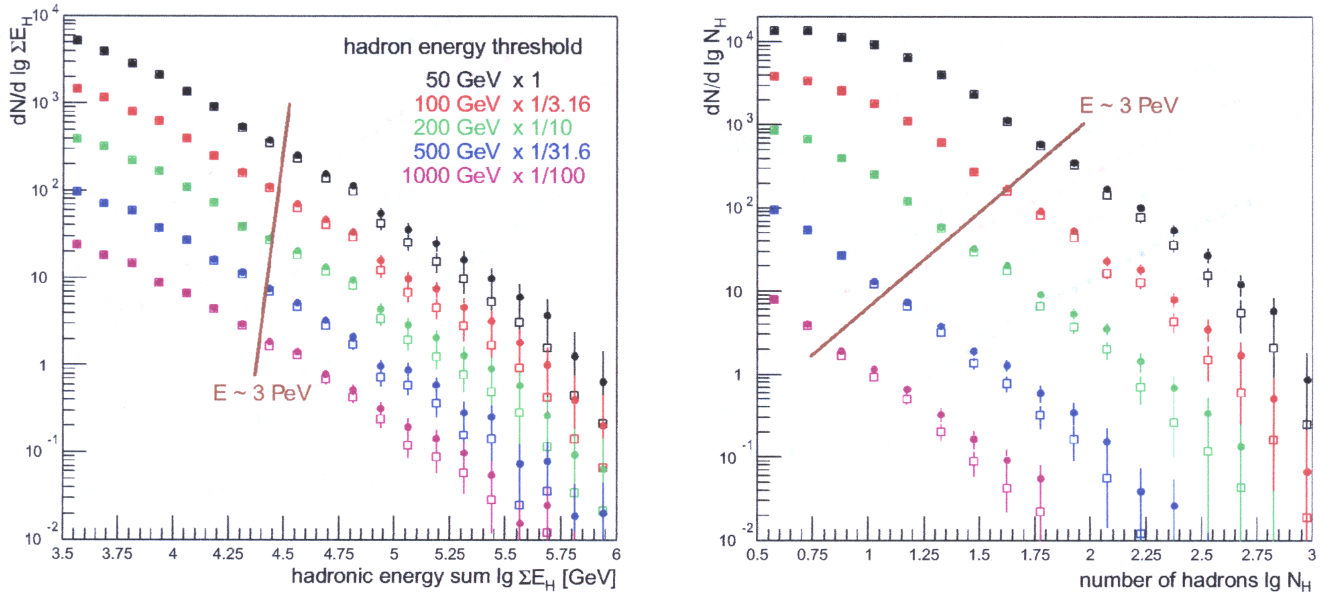

Fig. 2. Simulated hadronic shower size spectra for primary protons, using the hadronic energy sum (left) and the number of reconstructed hadrons (right) for several energy thresholds. A spectrum with $\gamma = -2.7$ is assumed for the filled symbols, a *knee* at 3 PeV with a change to $\gamma = -3.1$ is assumed for the open symbols. The spectra are multiplied by the specified factors to reduce overlapping data points.

5 Results from simulations

A major question of cosmic–ray physics in the *knee* region is the origin of its structure. In a first step we examine the question how a *knee* in the primary spectrum would influence the hadronic shower size spectra measured near sea level. Simulated differential shower size spectra for primary protons are shown in Figure 2 for energy thresholds of the reconstructed hadrons of 50, 100, 200, 500 GeV, and 1 TeV. Both observables, hadronic energy sum and number of hadrons, are presented. Two shapes for the primary spectrum are assumed in the simulations: A power law with an index of $\gamma = -2.7$ and two power laws with $\gamma_1 = -2.7$, $\gamma_2 = -3.1$, intersecting at an energy $E_k = 3$ PeV.

A particular primary energy corresponds to different shower sizes for different energy thresholds. This is indicated by the lines in the figure, the same primary energy corresponds to smaller shower sizes with raising hadron thresholds. For the hadronic energy sum, 3 PeV correspond to about $\lg(\sum E_H/\text{GeV}) \approx 4.45$ for primary protons, almost independent of the energy threshold, only a small dependence is visible. For the number of hadrons the dependence is rather strong, the assumed *knee* position corresponds to $\lg N_H \approx 1.85$ for $E_H > 50$ GeV changing to $\lg N_H \approx 0.80$ for $E_H > 1$ TeV.

For both observables, the hypothetical *knee* in the primary spectrum clearly appears in the shower size spectra for all thresholds. The resulting spectra agree well with each other for shower sizes smaller than the assumed *knee* position and start to exhibit deviations at larger shower sizes. The shower sizes corresponding to the assumed *knee* position are indicated by the lines.

6 Results from measurements

Measured shower size spectra are plotted in Figure 3, again for several thresholds for the reconstructed hadrons.

The hadronic energy sum spectra are fitted using an ansatz of two power laws:

$$\frac{dN}{d\lg\sum E_H} = \begin{cases} C\cdot(\lg\sum E_H)^{-\beta_1} & ; \quad \lg\sum E_H/\text{GeV} \le \\ C\cdot(\lg\sum E_H)^{-\beta_2} & ; \quad \lg\sum E_H/\text{GeV} > \end{cases}$$

with two spectral indices β_1 and β_2, a *knee* position ξ, and an overall normalization C as free parameters.

The fits for the 5 thresholds have been repeated using different bin widths for the spectra and different limits for the fits. The results for the *knee* positions and spectral indices are

$E_H >$	β_1	ξ	β_2
50 GeV	1.63 ± 0.03	4.40 ± 0.03	1.72 ± 0.03
100 GeV	1.63 ± 0.04	4.40 ± 0.03	1.71 ± 0.02
200 GeV	1.60 ± 0.03	4.39 ± 0.03	1.72 ± 0.02
500 GeV	1.58 ± 0.02	4.39 ± 0.03	1.73 ± 0.02
1 TeV	1.59 ± 0.05	4.34 ± 0.03	1.72 ± 0.02 .

The *knee* positions are indicated in Figure 3 as yellow squares. A trend to smaller values for increasing thresholds, as predicted by the simulations, is observed in the measurements as well. These *knee* positions correspond to primary

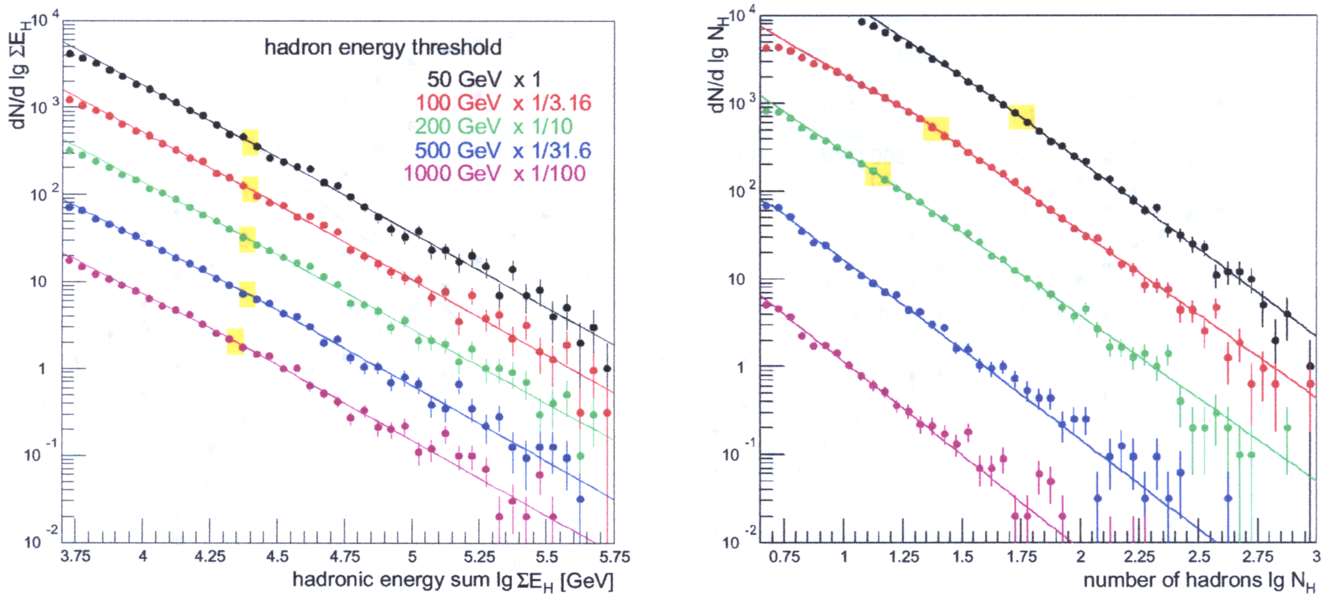

Fig. 3. Measured hadronic shower size spectra using the hadronic energy sum (left) and the number of reconstructed hadrons (right) for several energy thresholds. The spectra are multiplied by the specified factors to reduce overlapping data points.

energies of 2 PeV, if we assume as primary composition pure protons, and to about 7 PeV if we assume iron nuclei only. The slopes before and after the kink are almost independent of the threshold with an average spectral difference $\Delta\beta \approx 0.11 \pm 0.02$.

Fitting the N_H spectra is more critical, since the lever arm below the *knee* is very small for the higher energy thresholds, as can be inferred from Figure 2. Therefore, no *knee* positions are quoted for the two highest energy thresholds. Two power laws, as mentioned above for the energy sums, were fitted to the shower size spectra. The resulting *knee* positions are indicated in Figure 3 with yellow squares. The position of the kink is shifted towards lower hadron numbers with raising energy thresholds, as predicted by the simulations. The *knee* positions lg $N_H^{50} = 1.75 \pm 0.05$, lg $N_H^{100} = 1.35 \pm 0.05$, and lg $N_H^{200} = 1.15 \pm 0.05$ correspond to primary energies of 2 PeV for primary protons and about 7 PeV for iron nuclei. The spectral indices are approximately $\beta_1 \approx 1.80 \pm 0.05$ below and $\beta_2 \approx 2.0 \pm 0.1$ above the *knee*.

7 Conclusion

The fine segmented hadron calorimeter of the KASCADE experiment allows to study hadronic shower size spectra. Two observables, the number of hadrons and the hadronic energy sum, have been used for the investigations, applying five thresholds for the energy of the reconstructed hadrons.

Simulations show that a hypothetical *knee* in the primary cosmic–ray energy spectrum clearly appears in the hadronic shower size spectra.

The measurements consistently exhibit a *knee* at primary energies corresponding to 2 PeV for pure protons and to about 7 PeV, if we assume iron nuclei only. Earlier results (Hörandel et al. 99) could be confirmed.

The conversion of the shower size spectra for the five thresholds into primary energy spectra is in progress. From the two observables and five thresholds, ten energy spectra can be reconstructed, allowing for checks on systematic errors in the procedures applied.

Acknowledgements. The KASCADE experiment is supported by Forschungszentrum Karlsruhe and by collaborative WTZ projects in the frame of the scientific technical cooperation between Germany and Romania (RUM 97/014), Poland (POL 99/005) and Armenia (ARM 98/002). The Polish group (Soltan Institute and University of Lodz) acknowledges the support by the Polish State Committee for Scientific Research (grant No. 5 P03B 133 20).

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