First Measurement of the Knee in the Hadronic Component of EAS

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Abstract

The number of hadrons and their energy sum in extensive air showers has been measured using the KASCADE hadron calorimeter. Shower size spectra of the hadronic component have been derived using both observables. The spectra can be described by a power law and exhibit a change in the spectral index at energies around 5 PeV. The primary cosmic–ray flux spectrum is derived from the measurements in the energy range from 0.2 PeV up to 50 PeV.

1 Proem:

The cosmic–ray primary–flux spectrum for all particles is well described by a power law in a large energy interval ranging from 10 GeV up to 100 EeV. The only fine structure between 10 GeV and 10 EeV is a break in the exponent at energies of about 3 to 5 PeV. This phenomenon is commonly called the "knee" where the all–particle differential energy spectrum changes from $E^{-2.7}$ before the knee to $E^{-3.1}$ beyond it.

The origin of this break is not yet clear in spite of being known for 40 years by now. Explanations of the knee usually assume astrophysical reasons, but it could be caused by new physics in the high–energy particle interaction as well, since the available interaction models are not able to predict the measurements in all observables satisfactorily (Hörandel et al. 1999a).

Direct observations at the top of the atmosphere run out of statistics well below the knee due to limited size of the instruments and short exposure times. The knee has been observed by ground–based extensive air shower experiments mainly in the electromagnetic size spectrum. Observations in the muonic size and by Čerenkov light are scare. To solve the problem of the origin of the knee, it is useful to measure the shower size spectra of all shower components. The KASCADE experiment (Klages et al. 1997) determines the shower size spectra of the electromagnetic, muonic and hadronic component. Using its large hadron calorimeter the number of hadrons and their energy sum in extensive air showers has been measured and size spectra of the hadronic component are derived as presented in the following.

2 Experimental Set up:

The fine segmented hadron calorimeter allows to measure individual hadrons in the core of an EAS. The 16×20 m^2 calorimeter is of the sampling type, the energy being absorbed in an iron stack and sampled in

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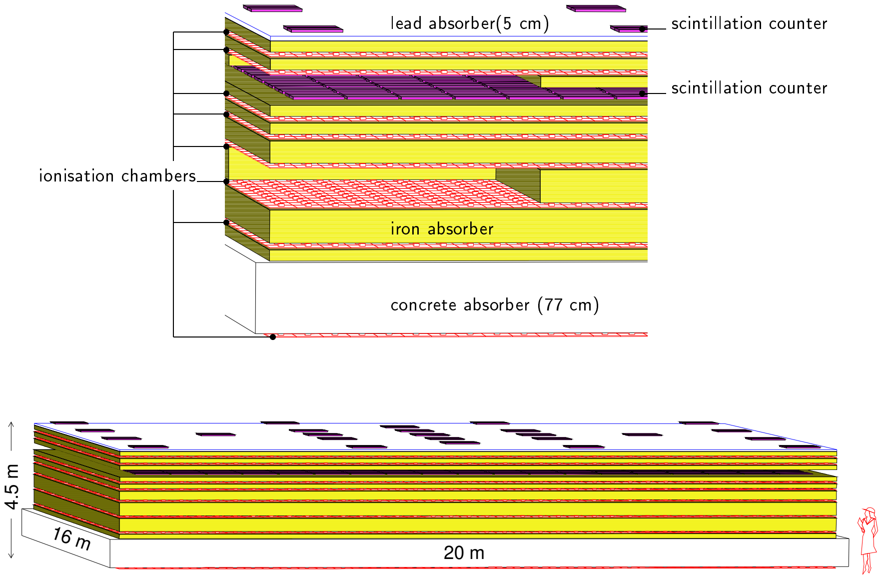

Figure 1: Sketch of the KASCADE hadron calorimeter. Detailed view (top) and total view (bottom).

eight layers by 10 000 ionization chambers (Engler et al. 1998). As sketched in Figure 1, the iron slabs are $12-36$ cm thick, becoming thicker in deeper parts of the calorimeter. The energy resolution varies slowly from $\sigma/E = 20\%$ at 100 GeV to 10% at 10 TeV. The concrete ceiling of the detector building is the last part of the absorber and the ionization chamber below acts as tail catcher. In total, the calorimeter thickness corresponds to 11 interaction lengths λ_I for vertical hadrons. On top, a 5 cm lead layer filters off the electromagnetic component to a sufficient low level.

A ionization chamber contains four independent electronic channels with a dimension of 25×25 cm^2 each and is filled with the room temperature liquids tetramethylsilane or tetramethylpentane. Liquid ionization chambers exhibit a linear signal behaviour with a very large dynamic range. The latter is limited only by the electronics to about 5×10^4. The chambers are able to prove a signal of one traversing minimum ionizing particle up to an energy deposition of 10 GeV per channel without saturation. The latter corresponds to more than 10^4 passing muons. This ensures the energy of vertical incident individual hadrons to be measured linearly up to 25 TeV. The containment losses at this energy are about 2%. The energy calibration is performed by means of through–going muons, taking their energy deposition as standard. Due to the fine lateral segmentation, the minimal distance to separate two equal–energy hadrons with 50% probability amounts to 40 cm. The reconstruction efficiency for hadrons increases with energy from 70% at 50 GeV to almost 100% at 100 GeV.

A layer of plastic scintillators on top of the lead absorber and a second one below the third iron layer act as trigger for the ionization chambers.

The electromagnetic and muonic components are measured by a 200×200 m^2 array of 252 detector stations. The stations consist of 3.1 m^2 liquid scintillation detectors to prove the electromagnetic component and below a lead and iron shield, corresponding to 20 radiation lengths, 3.2 m^2 plastic scintillator to measure muons with an energy threshold of 300 MeV. The scintillator array allows to determine the electromagnetic and muonic shower size with a resolution of about 10% for electrons and 30% for muons at PeV energies as well as the position of the shower core with an accuracy of about 2 m and the angle of incidence.

3 Measurements and simulations:

From October 1996 to August 1998 about 10^8 events were recorded. After all cuts 40 000 showers were left for the final analysis. The event selection and simulations used for the present analysis are described elsewhere in these proceedings (Hörandel 1999a). The total number of hadrons and the hadronic energy sum in each shower are obtained by integration of the lateral distribution and the lateral energy density up to a distance of 24 m from the shower axis.

4 The hadronic size spectrum:

The hadronic size spectrum is presented in Figure 2. The normalized flux is multiplied by $N_H^{2.5}$ in order to accentuate any possible structure. A kink is clearly visible around a hadron number of 65. The data can be described by a power law $dN/dN_H \propto N_H^{\beta}$ with $\beta_1 = -2.81 \pm 0.04$ below and $\beta_2 = -3.12 \pm 0.11$ above the knee. Following CORSIKA simulations the knee position corresponds to a range from 2 PeV up to 5 PeV for a pure proton or iron composition, respectively (Antoni et al. 1999). The abscissa in Figure 2 extends up to 500 registered hadrons. Accordingly, the caveat arises that the lower flux may be caused by saturation effects in the number of reconstructed hadrons. For this purpose, the hadronic size spectrum has been analysed by restricting the calorimeter acceptance to different surface areas. The acceptance has been reduced by up to a factor of 3. Hence, if the knee is brought about by a deficiency in hadron pattern reconstruction, this should have an even stronger influence in these examinations. The sizes have been chosen as a square of 10×10 m^2, and rectangles of 10×12 m^2 and 10×16 m^2. In all three cases the knee showed up near $N_H = 65$ and the kink in the slopes stayed within the errors at the same hadron number with an identical change of slope. In addition, the position of the knee and the spectral indices are stable with increasing statistics, since the first evidence of a knee in the hadronic component in 1997 (Hörandel 1998) the number of events has been increased from 14 000 to 40 000.

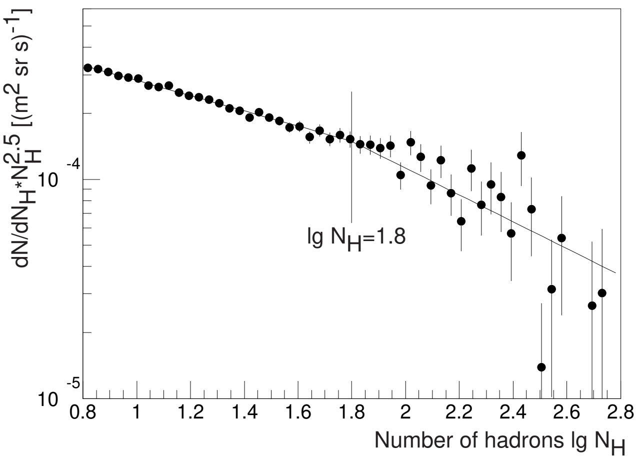

Figure 2: The hadronic shower size spectrum.

5 The hadronic energy spectrum:

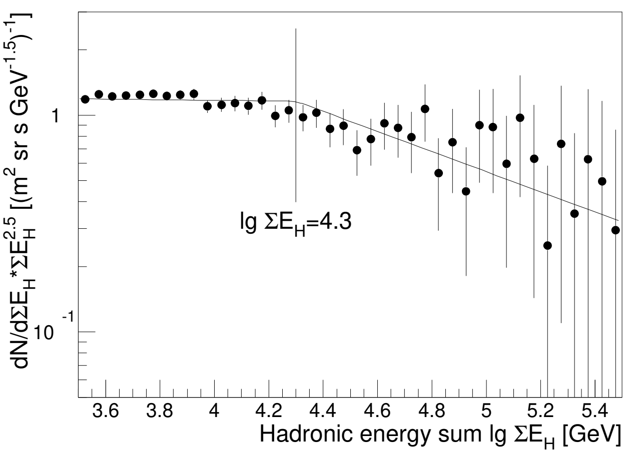

Figure 3: Frequency of showers detected versus total hadronic energy in the shower.

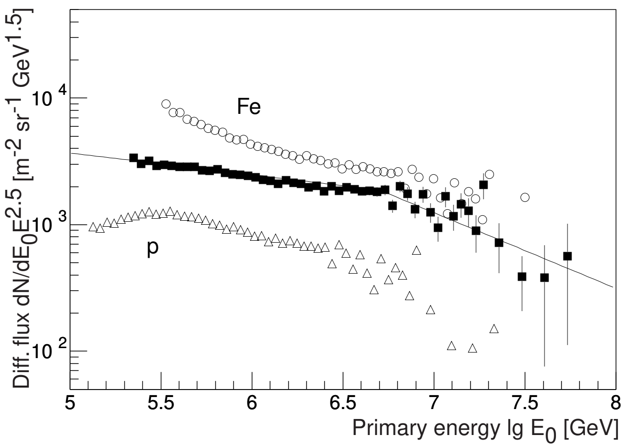

Figure 4: Differential all–particle flux versus primary energy as derived from the hadronic shower size spectrum.

Hitherto the knee has been observed in the spectra of particle numbers soley, apart perhaps from observations by means of Čerenkov light. The calorimeter allows in addition to the particle number, to measure the energy of the hadrons. Therefore, the knee can be investigated in the energy sum spectrum, too. The frequency of showers as function of their hadronic energy is presented in Figure 3. A kink in the spectrum at an energy sum of about 20 TeV is evident. Regarding the uncertainty in primary composition, the position of the knee corresponds to a primary energy of approximately 2 to 4 PeV. Once again a power law has been fitted to the data with spectral indices $\beta_1 = -2.5 \pm 0.1$ below and $\beta_2 = -2.9 \pm 0.2$ above the knee.

6 The primary energy spectrum:

When deriving the primary energy spectrum from the shower size spectrum, one encounters the uncertainty in primary composition. Since the currently available interaction models are not able to describe the measured observables in all respects, the mass composition depends on the observables used. Therefore, it is important to use for the calculation of the primary spectrum the mass composition as obtained from the observables used for the shower size spectrum, i.e. for the hadronic shower size spectrum a mass composition measured with the hadronic component has to be used. Almost all parameters which are sensitive to the primary's mass depend logarithmically on the mass number A (Hörandel 1998). The mean logarithmic mass as obtained from the hadronic component (Hörandel et al. 1999b) can be parametrised as a function of energy using a a straight line starting with $\langle \ln A \rangle = 1.5$ at 50 TeV increasing to $\langle \ln A \rangle = 3.3$ at 10 PeV.

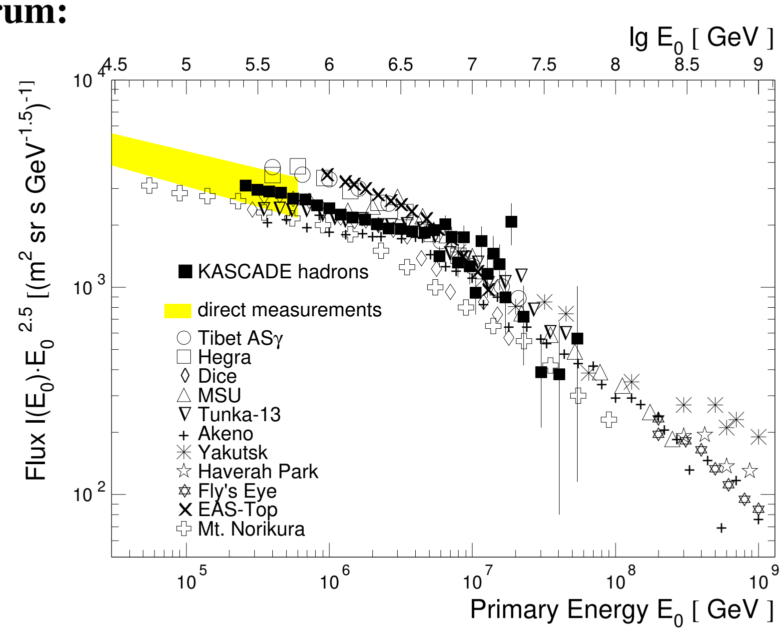

Figure 5: The all–particle primary energy spectrum as obtained from the hadronic component compared with world data. See (Antoni et al. 1999) for references.

The primary particle flux obtained by using the measured composition is plotted in Figure 4 together with results assuming a pure proton or pure iron composition. The straight lines represent fits of a power law to the data. A value of 5.0 ± 0.5 PeV is found for the knee position, and an energy scaled absolute flux of $1880/(\mathrm{m}^2 \text{ sr s GeV}^{-1.5})$. The slopes of the primary spectrum are $\gamma_1 = -2.66 \pm 0.12$ below the knee and $\gamma_1 = -3.03 \pm 0.16$ above. The primary spectrum as obtained from the hadronic component is in good agreement with other measurements as can be seen in Figure 5.

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