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Electron, muon and hadron size spectra of EAS in the "knee" region

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The shower size spectra of the electromagnetic, muonic and hadronic component of extensive air showers are measured simultaneously with the KASCADE detector. A knee is observed in all spectra corresponding to a primary energy about 4 PeV. The observation of a knee in the hadronic component is presented for the first time.

1. Introduction

The primary cosmic–ray energy spectrum exhibits a change in slope above 10^{15}eV, the so-called knee. The origin of the knee is still not clarified and remains an interesting question. In principle two reasons for the knee can be distinguished. Firstly, astrophysical reasons like the change of the cosmic–ray mass composition, or the transition from galactic to extragalactic sources. Secondly, particle physics reasons like changes in the hadronic interactions in the atmosphere. To settle this question, new observations using different techniques and all EAS components are desirable.

With the KASCADE experiment [1] three shower components are measured simultaneously. The experiment consists of 252 detector stations arranged in a 200×200 m^2 array. The liquid scintillation counters in the stations cover in total 490 m^2 to measure the electromagnetic component and, under an iron and lead shield with a thickness of 20 radiation lengths, 620 m^2 plastic scintillators to measure the muonic component. A 300 m^2 iron sampling calorimeter, equipped with eight layers of liquid ionisation chambers and a thickness of 12 hadronic interaction lengths serves to measure the hadronic component.

The following analysis is based on about $7 \cdot 10^7$ events, measured from October 1996 up to May 1998. Out of these events about $4 \cdot 10^6$ survived after various cuts in the shower reconstruction. In particular, showers with reconstructed core positions outside 91 m of the array center are excluded because of an appreciable amount of showers misinterpreted in that region. Due to the smaller area of the calorimeter the number of events for the hadron spectra is reduced to 28 000 events.

2. Electromagnetic and muon component

The measured energy deposits from the array scintillation counters are converted into particle numbers by taking into account the efficiency for high-energy gammas and hadrons for the electron detectors and electromagnetic punch-through for the muon detectors. To obtain the total electron number N_e, a NKG-function with a contribution resulting from the previously fitted muon densities is fitted to the distribution of charged particles. The fitted muon lateral distribution function is integrated in the range from 40 m to 200 m yielding to the *truncated muon number* $N_{\mu,tr}$. Simulations have shown that this parameter is less dependent on the primary particle type and systematic reconstruction errors than the total muon number.

In Figure 1 the differential flux of air showers as function of their electron (top) and truncated muon number (bottom) are plotted for five different angular bins. The bin widths correspond to a constant increase in atmospherical thickness of about 50 g/cm^2 between each. The flux is multiplied by a factor of $N_e^{2.5}$ and $N_{\mu,tr}^3$, respectively. The double-logarithmic spectra are well described by a combination of two straight lines connected by a parabola. As result of the fit the spectral in-

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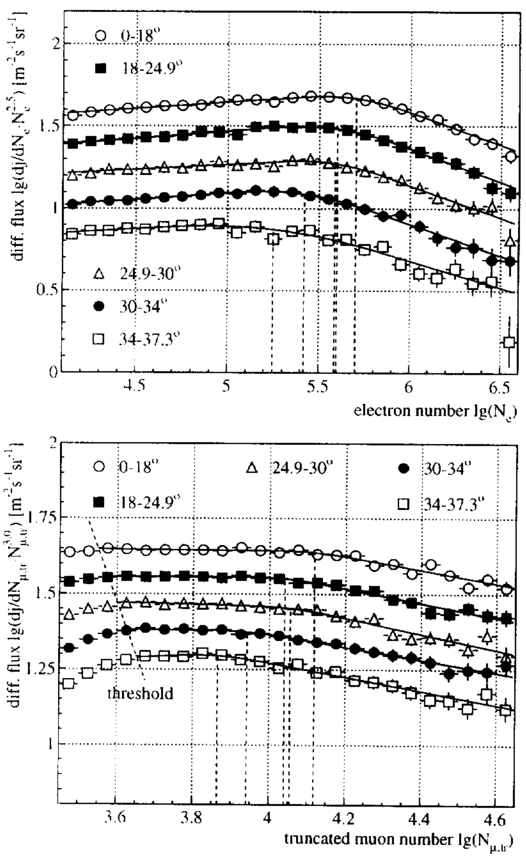

Figure 1. Electromagnetic (top) and muonic (bottom) shower size spectra for different zenith angle bins.

dices below and above the knee, the position and flux at the knee are obtained. The region where the parabola was fitted yields to a measure of the sharpness of the knee.

As can be seen in Figure 1 (top), the position of the knee is shifted with zenith angle from $\lg N_{e,knee}=5.7$ to 5.25 reflecting an attenuation of the electromagnetic component in the atmosphere of about $(43\pm6)\%$ per 100 g/cm^2 which is well in agreement with simulations. On the other hand, the spectral indices are rather independent from zenith angle and the weighted average values are determined to $\beta_{e,1} = -2.43\pm0.01_{stat}\pm0.1_{syst}$ below and $\beta_{e,2} = -2.88\pm0.02_{stat}\pm0.1_{syst}$ above the knee. The total width of the knee region is independent from the zenith angle and fitted to $\Delta \lg N_e = 0.66\pm0.18$.

As expected, the slopes in the $N_{\mu,tr}$ spectra (Figure 1, bottom) are steeper than in the N_e spectra because the number of muons increases less with primary energy ($\propto E_0^{0.95}$) than the number of electrons ($\propto E_0^{1.3}$). The indices below and above the knee are $\beta_{\mu,1} = -3.01\pm0.01_{stat}\pm0.1_{syst}$ and $\beta_{\mu,2} = -3.23\pm0.02_{stat}\pm0.1_{syst}$, respectively. There is no zenith angle dependence, either.

3. Primary energy spectrum

To derive the primary energy spectrum from the shower size spectra it is necessary to know the mass composition as a function of shower size. In particular the electron size is highly dependent on the type of the primary particle. We reconstruct the primary energy E_0 under two extreme assumptions, namely, to have a pure proton or a pure iron composition. In Figure 2 the corresponding E_0 spectra are shown as obtained from the N_e and $N_{\mu,tr}$ spectra for the zenith angle bin from 18° to 25°. The simulations were performed with the CORSIKA air shower code using the QGSJET interaction model [2].

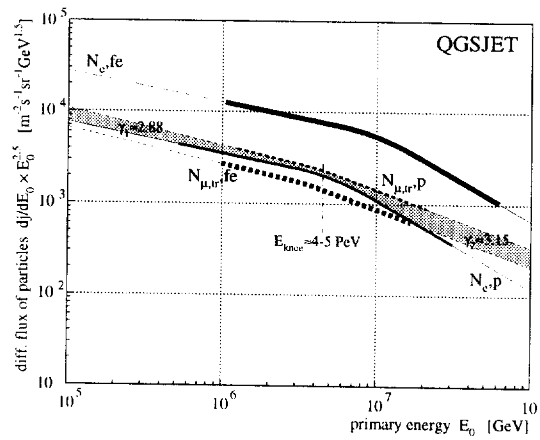

Figure 2. Primary energy spectra resulting from shower size spectra for pure compositions.

One notices that the differential fluxes resulting from the electron size spectra form a band limited by the two extreme primaries wherein any other composition has to lie (solid lines). The same holds for the spectra derived from the muons, however, the flux decreases if the composition changes from light to heavy (dashed lines).

With an assumed pure iron composition the flux differs by almost an order of magnitude between the muon and electron derived spectra in the low energy region. This is impossible within the systematic errors, therefore, a light composition is prefered. Also, the knee positions are inconsistent with the data if a heavy composition is assumed. However, above the knee the grey shaded consistency region allows the composition to become heavier.

The spectral indices and knee position for such a composition are given in the graph. The slopes are slightly larger than commonly assumed due to the fact that shower fluctuations and sampling statistics have not yet been taken into account.

4. Hadronic component

To determine the hadronic shower size spectrum the lateral distribution of hadrons with a 50 GeV threshold is measured. By integration of the lateral distribution up to 24 m one obtains the total number of hadrons [3]. The resulting hadronic shower size spectrum is plotted in Figure 3, the flux multiplied by $N_H^{2.5}$. The lines represent a fit of two power laws with a variable knee position. A knee can be observed at $\lg N_H = 1.89$ corresponding to a primary energy of about 3.5–7 PeV depending on the mass composition. The spectral indices are $\beta_1 = 2.81 \pm 0.03$ and $\beta_2 = 3.19 \pm 0.15$. To obtain the index of the primary spectrum the relation $\frac{dN}{dE_0} = \frac{dN}{dN_H}\frac{dN_H}{dE_0}$ has been used. From CORSIKA simulations we obtain $N_H \propto E_0^{0.98}$ nearly independent of the primary mass, and calculate the primary spectral indices to be $\gamma_1 = 2.77 \pm 0.03_{stat} \pm 0.14_{syst}$ below, and $\gamma_2 = 3.15 \pm 0.10_{stat} \pm 0.16_{syst}$ above the knee.

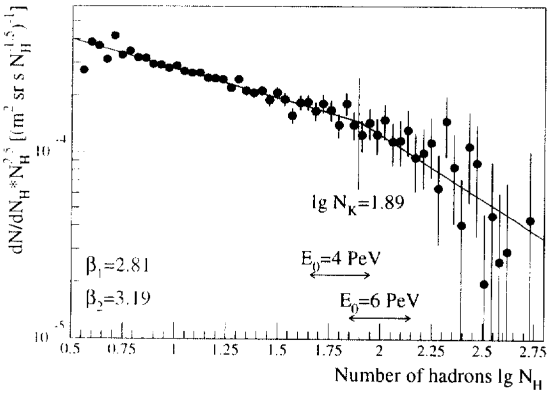

Figure 3. Hadronic shower size spectrum.

5. Summary

The knee positions and spectral indices measured by the three components are summarized in Figure 4. The horizontal lines in the top panel indicate the possible region for different mass compositions ranging from pure proton to pure iron. We observe a knee in all components investigated around 4–5 PeV. Within the plotted errors the spectral indices are nearly independent from the primary mass if pure compositions are assumed. The mean indices are 2.86 ± 0.04 below and 3.19 ± 0.04 above the knee.

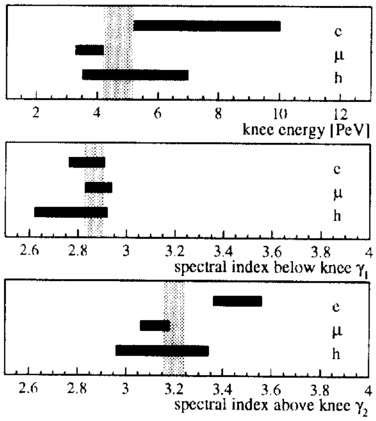

Figure 4. Knee position and spectral indices.

The large primary index derived from the electron component above the knee and the indices from the other components are consistent if an increasingly heavier composition above the knee is assumed and fluctuations are taken into account.

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