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ELECTRON AND MUON SIZE SPECTRA OF EAS BELOW AND ABOVE THE "KNEE"

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ABSTRACT

The origin of the *knee* in the cosmic ray size spectrum is a longstanding unresolved problem. In view of this we have studied the electron and muon size spectra of extensive air showers above $\log N_e = 4.5$. Spectral indices for electrons and muons below and above the knee are determined for narrow zenith angle bins.

INTRODUCTION

The extensive air shower (EAS) experiment KASCADE (Klages et al., 1997) is located at the site of the *Research Center Karlsruhe* (Germany) at a height of 110m above sea level. Its main scientific aim is to investigate the primary cosmic ray composition and energy spectrum from 10^{14}eV to 10^{17}eV, in the so-called *knee*-region, where the slope of the power law spectrum is changing. For this purpose, KASCADE consists of several independent detector systems to measure the different particles and aspects of an EAS. This is necessary because of the large fluctuations in the shower parameters at fixed primary energy and the unknown type of the primary particle (besides effects of detector sampling and reconstruction accuracy).

The main observables reflecting the energy and nature of the primary particle are the number of electrons N_e, and muons N_μ, at the observation level. Sufficiently far beyond the shower maximum (which is valid for KASCADE) the average logarithmic particle numbers scale to first order approximation only linearly with the logarithm of the primary energy and with the atmospheric depth (which corresponds to variable zenith angle θ at fixed observation level):

$$\log N_i = \alpha_i \log E - \frac{\beta_i}{\cos\theta} + \delta_i \quad \text{with } i = e, \mu \tag{1}$$

Actually, α increases slightly with depth and β decreases with primary energy because energetic showers develop deeper in the atmosphere and therefore are dying out more slowly. Monte Carlo simulations with CORSIKA (Capdevielle et al., 1992) show that α_e increases from light to heavy primaries whereas α_μ decreases (i.e. $\theta = 22°$: $\alpha_e \approx 1.27 \to 1.32$ and $\alpha_\mu \approx 0.96 \to 0.92$). Both parameters may vary also with different hadronic interaction models. Using Eq. 1, the relation between the differential energy and size spectra can be written with the integral flux j as:

$$\frac{\mathrm{d}j}{\mathrm{d}E} E = \frac{\mathrm{d}j}{\mathrm{d}N_i} N_i \alpha_i \tag{2}$$

With $dj/dN_i \propto N_i^{\gamma_i}$ and the spectral index γ of the primary differential energy spectrum, one obtains from the above two equations for the index of the differential size spectra

$$\gamma_i = \frac{\gamma + 1}{\alpha_i} - 1 \quad \text{with } i = e, \mu \tag{3}$$

It follows that the electron size spectrum must be flatter and the muon size spectrum slightly steeper than the primary energy spectrum. α_i is simply the ratio of the integral indices.

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RECONSTRUCTION AND DATA SELECTION

For the detection of the electron and muon component of an EAS the KASCADE experiment uses a $200 \times 200\text{m}^2$ scintillator array of 252 single detector stations containing about 500m^2 of electron detectors and 620m^2 of muon detectors under 20 r.l. shielding (for details see Klages et al., 1997). These detectors measure the energy deposit of the mostly minimal ionizing particles in an air shower. The conversion to particle numbers is done with so-called lateral energy correction functions which additionally take into account the energy loss by accompanying particles like gammas and hadrons, the relativistic rise in ionisation losses and the electromagnetic punch-through in the muon detectors as function of the core distance (Weber et al., 1997).

The corrected lateral distribution of charged particles is fitted to a *NKG*-function (r_m=79m, Greisen et al., 1959) to obtain the shower core position and a first approximation for the number of charged particles N_c. The muon densities are described with a *Greisen* function $\rho_\mu(r) \sim r^{-S}(1 + r/320\text{m})^{2.5}$ with slope parameter S=f(θ, N_c) taken from simulations. In a second step the fitted muon densities are subtracted from the charged particle densities and then the electron number N_e is fitted together with the age parameter of the electron lateral distribution. The direction of the air shower is determined by a cone fit to the arrival times of the electrons.

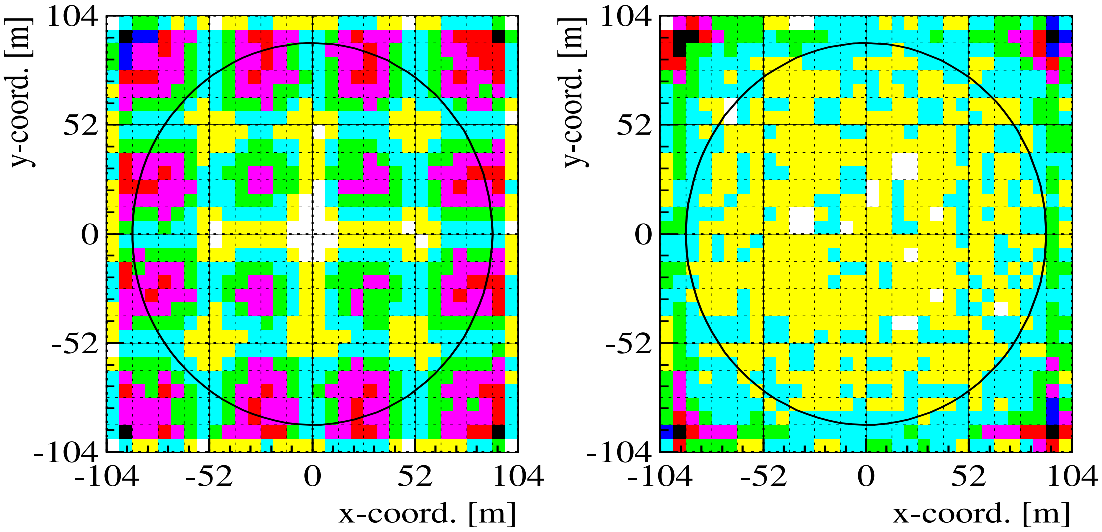

Fig. 1: Core position distributions for showers of all sizes (left) and $\log N_e > 4.5$ *(right).*

Figure 1 shows the distribution of reconstructed core positions inside the array with dark grey corresponding to a higher reconstructed shower density. Without a cut in shower size (left picture) the 4×4 cluster structure of the array is clearly visible, as each cluster works as an independent array with some multiplicity trigger condition which is harder to fulfill for small showers if they hit the border between the clusters. The center of the array, where four stations are missing due to the central calorimeter, also shows a smaller trigger efficiency.

For showers with more than 30000 electrons (right picture) the efficiency is almost independent from the core position and is larger than 95%. The enhancement at the edges of the array, particularly in the corners, is due to misinterpreted showers which are actually located outside the array. For this reason, showers with cores outside 91m from the center of the array are excluded from the following analyses. Furthermore, showers with very high (> 2.1) or low (< 0.2) age parameters are discarded because it can be shown from the number of hit stations that these actually are very small showers (<10000 electrons) which have been overestimated in size by the reconstruction.

THE SIZE SPECTRA

To study the zenith angle dependence, the size spectra are accumulated for different angular bins in such a way that the atmospheric thickness increases by a constant amount ($\approx 50\mathrm{g/cm}^2$). In that case a linear correlation between the fit parameters and the atmospheric depth can be expected (Eq. 1). The differential flux of air showers as function of their electron number is shown in Figure 2. The flux is multiplied by a factor $N_e^{2.5}$, emphasizing the change in slope between 10^5 and 10^6 electrons.

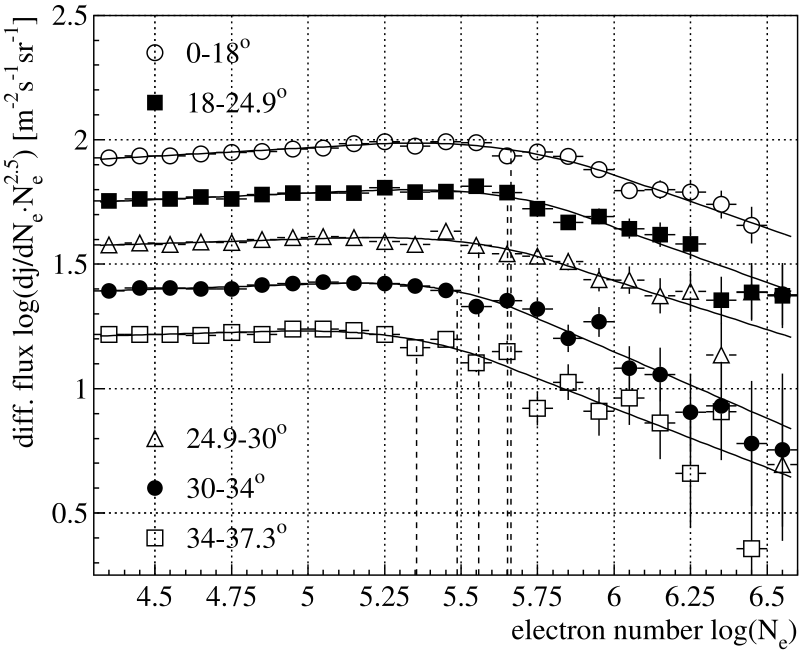

Fig. 2: Electron size spectra for various zenith angle bins.

Fit Method

For a quantitative description of their shape the flux spectra are fitted to a function which combines two straight lines connected by a cubic function in such a way that the first derivatives are identical. Free parameters of the fit are the slopes of the lines and the position and height of the knee. The knee is defined as the point where the slope of the cubic function takes the mean value of the slopes of the two lines. The range of the cubic function is defined before the fit.

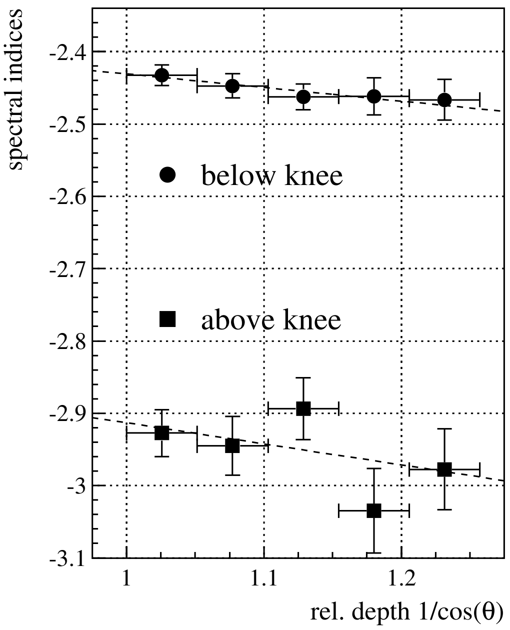

Fig. 3: Indices of the size spectra as function of rel. atmospheric depth.

Results

Figure 3 shows the spectral indices for the electron size spectra below and above the knee. The weighted average values are $\gamma_e = -2.45 \pm 0.01^{stat} \pm 0.05^{syst}$ below and $\gamma_e = -2.94 \pm 0.02^{stat} \pm 0.1^{syst}$ above the knee. The difference is rather large and with $\alpha_e = 1.17$, which is needed for a primary spectral index of $\gamma = -2.7$ below the knee, a very steep energy spectrum above the knee follows with an index $\gamma = -3.28$ or even steeper if primaries become heavier. Furthermore it seems that the spectra become steeper with increasing depth. This would imply a decreasing α_e in contradiction to simulations and requires further investigation.

The fitted position of the knee is plotted in Figure 4 as function of the relative depth of the atmosphere (see also dashed lines in Figure 2). As expected for a knee at a fixed primary energy the shower sizes become smaller with larger zenith angles, although the decrease is not as high as predicted by simulations of showers in that size region. From this Figure we derive $\beta_e = 1.4$. Depending on the type of the primary the corresponding primary energy region is estimated to be $3 - 6 \cdot 10^{15}$eV. Taking $E \approx 4.5 \cdot 10^{15}$eV and $\alpha_e \approx 1.16$, a differential flux at the knee of $\mathrm{d}j/\mathrm{d}E \times E^{2.5} \approx 3200\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{1.5}$ is calculated from Eq. 2 for the first angular bin ($0 - 18°$).

The muon component

Figure 5 shows the spectra of the total muon numbers for the same angular bins as for the electrons. The flux is multiplied by a factor N_μ^3 because of the steeper slope of the muon spectra. The fits for the first two zenith angle bins are done from 10^4 to 10^5 muons. Below 10^4 muons the measured flux is affected by the trigger efficiency. This efficiency scales with electron number, therefore the threshold in muon number rises with the angle. Above 10^5 muons, corresponding to a primary energy of $\geq 10^{16}$eV, there is a bias probably coming from the reconstruction method which requires further detailed investigations.

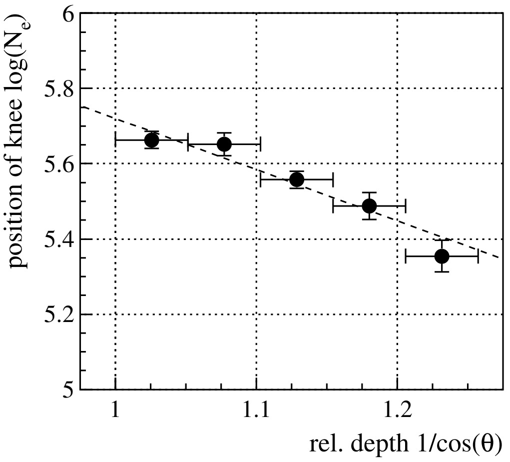

Fig. 4: Position of the knee in N_e vs. relative atmospheric depth.

The slope seems to be $\gamma_\mu \approx -3.0$ below and $\gamma_\mu \approx -3.4$ above the knee. This would imply an α_μ of 0.84 below and 0.88 above the knee to achieve the common indices of the primary energy spectrum of -2.7 and -3.1, respectively. Although the value of α_μ is lower than predicted by simulations, the increase in α_μ is inconsistent with some change in composition from light to heavy primaries if the used indices are correct.

The knee in the muon spectrum is in the region around $\log N_\mu = 4.6$. Together with the knee position in the electron spectrum $(0 - 25°)$ of $\log N_e = 5.65$ this is in good agreement with the average values for proton-induced showers of $4 \cdot 10^{15}$eV as simulated by CORSIKA (V4.6 with VENUS/GEISHA option). This does not necessarily imply a light composition at the knee as shower size spectra are proton dominated because of the steep decline of the primary flux and the higher energy of iron-induced showers with equivalent electron numbers.

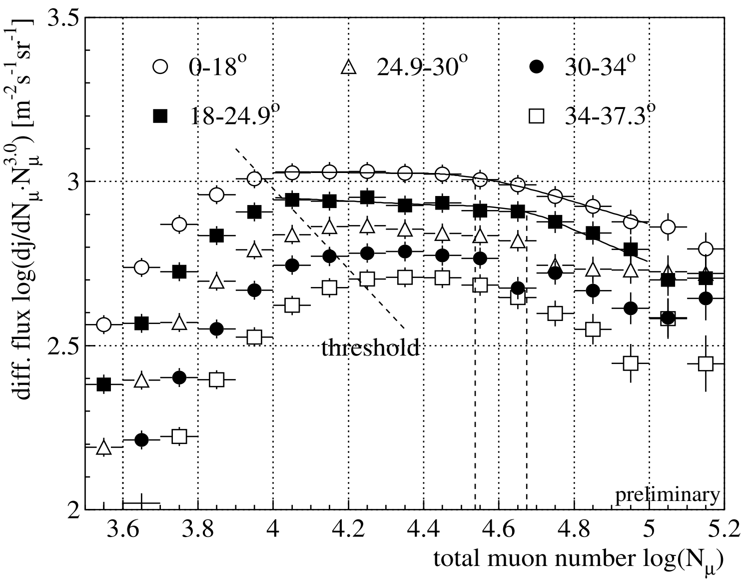

Fig. 5: Muon size spectra for various zenith angle bins.

OUTLOOK

To allow the use of less restrictive cuts especially on core position, detailed investigations concerning reconstruction efficiencies are in progress. Further studies are underway to determine whether the observed discrepancies are due to detector simulations or reconstruction methods or whether they indicate physical features of EAS. With improving statistics we expect to be able to determine two-dimensional intensity distributions, too.

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