Cosmic Ray Energy Spectrum around the Knee by Muon Density Measurements at KASCADE

A. Haungs[1]*, T. Antoni[1], W.D. Apel[1], A.F. Badea[2], K. Bekk[1], K. Bernlöhr[1], E. Bollmann[1], H. Bozdog[2], I.M. Brancus[2], A. Chilingarian[3], K. Daumiller[4], P. Doll[1], J. Engler[1], F. Feßler[1], H.J. Gils[1], R. Glasstetter[4], R. Haeusler[1], W. Hafemann[1], D. Heck[1], J.R. Hörandel[4] †, T. Holst[1], K.-H. Kampert[1,4], H. Keim[1], J. Kempa[5], H.O. Klages[1], J. Knapp[4‡], K.U. Köhler[1], H.J. Mathes[1], H.J. Mayer[1], J. Milke[1], D. Mühlenberg[1], J. Oehlschläger[1], M. Petcu[2], H. Rebel[1], M. Risse[1], M. Roth[1], G. Schatz[1], F.K. Schmidt[4], T. Thouw[1], H. Ulrich[1], A. Vardanyan[3], B. Vulpescu[2], J.H. Weber[4], J. Wentz[1], T. Wibig[5], T. Wiegert[1], D. Wochele[1], J. Wochele[1], J. Zabierowski[6], S. Zagromski[1],

[1]*Forschungszentrum Karlsruhe, Institut für Kernphysik, D-76021 Karlsruhe, Germany*
[2]*National Institute of Physics and Nuclear Engineering, RO-7690 Bucharest, Romania*
[3]*Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia*
[4] *Institut für Experimentelle Kernphysik, University of Karlsruhe, D-76021 Karlsruhe, Germany*
[5]*Department of Experimental Physics, University of Lodz, PL-90950 Lodz, Poland*§
[6] *Soltan Institute for Nuclear Studies, PL-90950 Lodz, Poland*§

Abstract

A system of large-area position sensitive multiwire proportional chambers (MWPC), installed below the hadron calorimeter of the KASCADE (KArlsruhe Shower Core and Array DEtector) central detector is able to measure the muon density spectra at fixed distances from the core of EAS in the knee region. Comparisons of these muon density spectra with Monte Carlo simulations for different primaries and various high-energy interaction models lead to an estimation of the slopes before and after the knee and its position. In contrast to many other knee determinations this method does not invoke the integration of sampled lateral particle distributions, and the muon density spectrum is a directly measurable observable with reduced systematic uncertainties.

1 Introduction:

Since forty years a conspicuous change of the spectral index from ca. -2.7 to -3.1 of the power law description of the primary cosmic ray spectrum around 3 PeV is known. In spite of a lot of experimental efforts, there remain many open questions, in particular about the detailed position and the shape of the knee region, about the variation of the primary mass composition, in addition to the question of the astrophysical origin of the observed features at all. There is a number of theoretical conjectures about the mass composition, predicting a variation from dominantly light nuclei to a composition of heavier nuclei.

Local muon density spectra at fixed distances from the shower axis have been measured and display conspicuous kinks at certain values of the local muon density. The analysis of this observation by use of extensive Monte Carlo EAS simulation calculations relates the observed kinks to the knee of the primary cosmic ray energy spectrum and implies new a methodical approach of EAS investigations.

2 Apparatus:

KASCADE is a multidetector setup (Klages et al. 1997) built in Karlsruhe, Germany for measurements of EAS especially in the primary energy range of the knee region. The KASCADE detector array has an area of $200 \times 200\,\mathrm{m}^2$ and 252 detector stations (positioned on rectangular grids with 13 m spacing) consisting of liquid scintillators for measuring the electromagnetic and of plastic scintillators for measuring the muonic component

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[*] corresponding author; e-mail: haungs@ik3.fzk.de

[†] present address: University of Chicago, Enrico Fermi Inst., IL 60637; [‡] now at: University of Leeds, Leeds LS2 9JT, U.K.

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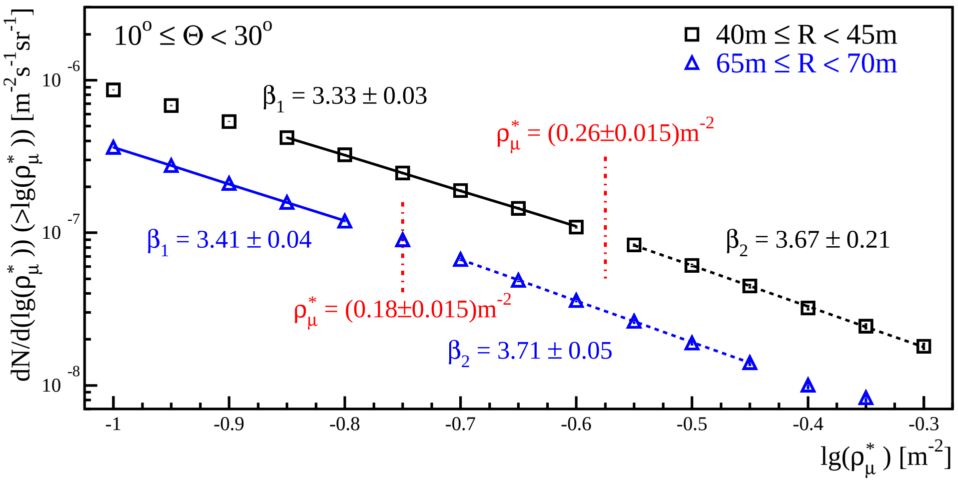

Figure 1: Integral muon density spectra measured by the MWPC for showers with two different core distances. The vertical lines assign the position of the knee in the muon density spectra. The β represent the indices of the fitted power law functions.

of EAS. This array provides the data necessary for the reconstruction of the basic EAS characteristics like the size N_e, muon size N_μ^{tr}, core location, and angle of incidence of each single air shower. The present measurements of the muon densities use a setup of 32 multiwire proportional chambers (MWPC) of the central detector. It consists of 16 stacks ($5\,\mathrm{m}^2$-$9\,\mathrm{m}^2$) of two chambers one upon another. Each chamber consists of three layers of crossed anode wires and cathode stripes. The crossing angle of the cathodes to the anode wires is $\pm 34^\circ$ at each of the three different size types of the chambers. The MWPC allows a accurate determination of the position and angle of single muons with a spatial resolution of around 1 cm. The total sensitive area of the MWPC setup is $2 \times 129\,\mathrm{m}^2$. The absorber of the calorimeter effects an energy threshold of 2 GeV for vertical muons. For each single shower the local muon density ρ_μ^* can be estimated with help of the number of reconstructed muons in the MWPC setup and its sensitive area as a function of the angle of incidence of the EAS (Haungs et al. 1999).

3 Muon Density Spectra:

The spectrum of ρ_μ^* of the EAS observed in a certain distance from the shower core and for a certain range of the angle of shower incidence is the quantity of the present investigation. Figure 1 display integral muon density spectra measured with the MWPC system ($E_\mu > 2\,\mathrm{GeV}$) for two particular core distances and for the zenith angle range $10^\circ \leq \Theta \leq 30^\circ$ measured in c. 5000 hours. The spectra follow a power law form $dN/d\rho_\mu^* \propto (\rho_\mu^*)^{-\beta}$. Both spectra show a kink, expressed by the change of the spectral index β. The spectral indices and the positions of the estimated knees are included in Figure 1. The quoted errors represent the statistical uncertainties. Due to the reduced efficiency of the trigger threshold for small sized showers the first data points of the spectrum of the smaller core distance have not been included in the fit procedure. With increasing distance from the shower core the position of the kink shifts to lower muon densities as a consequence of the lateral distributions of the EAS muons of decreasing muon densities with increasing R. This explains also the steeper slopes of the density spectra at larger R.

In order to analyze these results and to relate the local muon densities to the energy and nature of the primaries detailed Monte Carlo calculations simulating the EAS development have been performed. Using the CORSIKA v 5.62 code (Heck et al. 1998) samples of proton and iron induced EAS of the energy range of $5 \cdot 10^{14}$ eV

	δ (QGSJet)		δ (VENUS)	
	proton	iron	proton	iron
40 m$\leq R \leq$ 45 m	0.718 ± 0.015	0.807 ± 0.009	0.776 ± 0.016	0.784 ± 0.010
65 m$\leq R \leq$ 70 m	0.727 ± 0.017	0.809 ± 0.012	0.811 ± 0.015	0.763 ± 0.012

Table 1: Exponents of the power law function $\rho_\mu^* \propto E^\delta$ for different core distances, primaries and high-energy interaction models.

	proton	iron
	QGSJet	
γ_1	2.71 $\pm 0.01_{stat} \pm 0.38_{sys}$	2.92 $\pm 0.01_{stat} \pm 0.27_{sys}$
γ_2	2.95 $\pm 0.04_{stat} \pm 0.46_{sys}$	3.18 $\pm 0.04_{stat} \pm 0.34_{sys}$
E_{knee}	(7.27 $\pm 0.43_{stat} \pm 2.33_{sys}$) $\cdot 10^{15}$ eV	(4.56 $\pm 0.10_{stat} \pm 1.10_{sys}$) $\cdot 10^{15}$ eV
	VENUS	
γ_1	2.88 $\pm 0.01_{stat} \pm 0.27_{sys}$	2.83 $\pm 0.01_{stat} \pm 0.25_{sys}$
γ_2	3.14 $\pm 0.04_{stat} \pm 0.35_{sys}$	3.08 $\pm 0.05_{stat} \pm 0.32_{sys}$
E_{knee}	(5.34 $\pm 0.24_{stat} \pm 1.36_{sys}$) $\cdot 10^{15}$ eV	(4.60 $\pm 0.21_{stat} \pm 0.99_{sys}$) $\cdot 10^{15}$ eV

Table 2: Spectral indices γ_i of the primary energy spectrum, obtained with different high-energy interaction models and primary particles by combining both core distance spectra. Additionally the estimated position of the knee is given. The main sources of the systematic errors are the evaluation of the position of the kink in the measured muon density spectra and the uncertainty of δ due to the multiple use of single showers in the detector simulation.

to $1 \cdot 10^{16}$ eV, distributed along a primary energy spectrum $\propto E^{-2.7}$ are generated with two different interaction models (QGSJet and VENUS). The detector efficiency has been included in the simulations, using each simulated EAS ten times in the considered ranges of the core distance. Figure 2 displays the relations between the average muon density ρ_μ^* and the primary energy, described by a power law $\rho_\mu^* \propto E^\delta$ as an example for one interaction model and one core distance. The values of all δ resulting from a fitting procedure are listed in Table 1. The quoted uncertainties are due to the limited statistics of the simulated showers. On basis of these results the position of the knee in the muon density spectra and the spectral indices β are related to the knee position and the index γ of the energy spectrum $dN/dE = dN/d\rho_\mu^* \cdot d\rho_\mu^*/dE$ leading to $\gamma = \delta \cdot (\beta - 1) + 1$. The results of this procedure are given in Table 2.

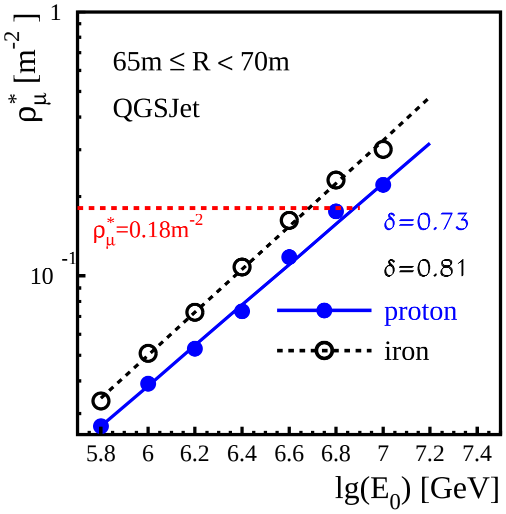

Figure 2: Example of the dependence of the local muon density on the primary energy for different primaries (CORSIKA simulations with full detector simulation included).

With the help of the estimated shower sizes N_e and N_μ^{tr} (Glasstetter et al. 1999) by the KASCADE field detectors a global distinction between showers induced by light and heavy primaries is realized. The relevant parameter for the EAS separation is the muon number - electron number ratio $lg(N_\mu^{tr})/lg(N_e)$ with N_μ^{tr} and N_e corrected to the zenithal incidence with the measured attenu-

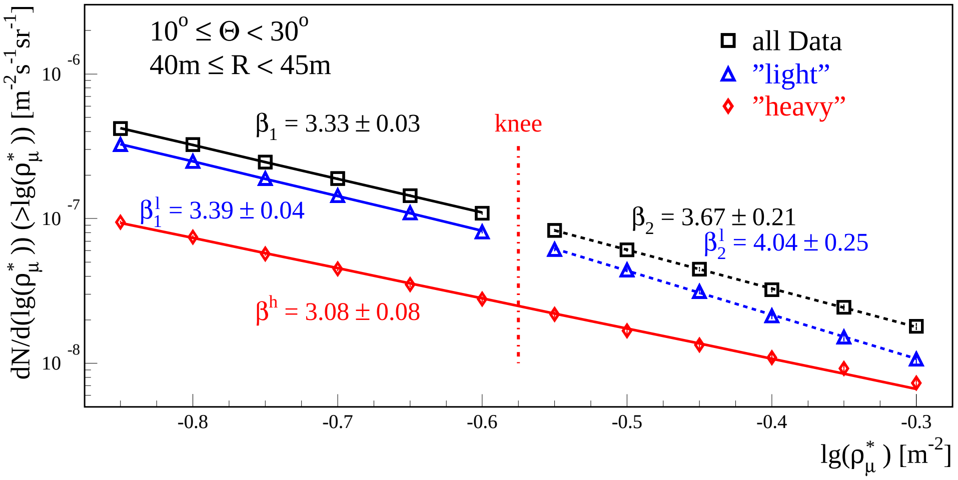

Figure 3: Integral muon density spectra measured by the MWPC for all showers for enhanced ”light” and for enhanced ”heavy” showers. The vertical line assigns the position of the knee in the muon density spectra estimated for ”all” EAS.

ation lengths λ_μ and λ_e by the KASCADE group. Figure 3 shows for one range of the shower core distance the obtained spectra for all, ”light” and ”heavy” induced EAS. The kink in the spectrum of the light induced showers is clearly rising. With the above described procedure, combining both ranges of core distance the indices of the primary energy spectrum for both samples are calculated using the interaction model QGSJet (VENUS). While the spectra of the light induced EAS with $\gamma_l^1 = 2.76(2.94)$ and $\gamma_l^2 = 3.20(3.42)$ show a clear knee, the spectra of the heavy induced EAS have a passing slope of $\gamma_h = 2.76(2.62)$ without any kink between 10^{15} eV and 10^{16} eV. The results has small statistical errors, and an estimated systematic error of ≈ 0.3 is mainly due to the limited statistic in the Monte Carlo simulations.

4 Concluding Remarks:

A result of considerable interest is the first observation of kinks in muon density spectra measured at fixed distances from the shower core. Adopting a particular mass composition and invoking Monte Carlo simulations (by CORSIKA), the kinks and slopes of the density spectra can be related to the knee position and spectral indices of the primary energy spectrum. The resulting indices for the all-particle energy spectrum are about -2.8 before and about -3.1 after the knee position of about $5 \cdot 10^{15}$ eV. Thus we may summarize that after the evidence for the existence of the knee discontinuity in the N_e spectrum by many experiments, lateron in the spectrum of the EAS muon content and recently in the hadron number by the KASCADE group (Hörandel et al. 1999), also the muon density is shown to reveal consistently the phenomenon. The present analysis give first hints that the knee appearance at ca. $5 \cdot 10^{15}$ eV is strongly dominated by the light component of the charged cosmic rays.

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