Measurements of EAS Muons with $E_\mu > 2\,\text{GeV}$ at the KASCADE Experiment

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Abstract

The major goal of the KASCADE (KArlsruhe Shower Core and Array DEtector) experiment is to determine the flux spectrum and the chemical composition of primary cosmic rays around the so called "knee", i.e. in the energy range of the primaries of 10^{15} eV to 10^{16} eV. KASCADE is a multi-detector device to observe simultaneously the electromagnetic, muonic and hadronic component of the extended air shower (EAS), created by interactions of the primaries at the atmosphere. A system of large-area position-sensitive multiwire proportional chambers (MWPC) is able to measure the high-energy muon part ($E_\mu > 2\,GeV$) of the EAS. General properties of the measured muon density in EAS are discussed and different methods of the analysis of this parameter to evaluate primary mass composition and energy spectrum are presented.

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1 The muon chamber setup of KASCADE

(Transparencies nos.4-9) KASCADE is a multi-detector setup (Klages et al. 1997, Kampert 1999) set up in Karlsruhe, Germany (110 m a.s.l.) 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 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. N_μ^{tr} is the content of muons with $E_\mu > 250\,\mathrm{MeV}$ in the limited range of the lateral distribution in the distance of 40 m - 200 m from the shower center. 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 $2 \times 125\,\mathrm{m}^2$. 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).

2 Events with very large local muon density

(Transparencies nos.10-17) For a search of events with an unexpected large muon density, a sample of data measured in 300 hours are divided in two subsamples: events which have a successful reconstruction at the KASCADE array, i.e. normal "KASCADE-events"; and events which have reconstructed muons at the MWPC but no array information. While the first sample show a smooth distribution up to a density of $6\,\mathrm{m}^{-2}$ and are well confirmed by distributions obtained by EAS simulations with following detector simulations, at the second sample there are some events with even larger muon density. Looking to the raw data of such events, it could be clarified, that these events have large zenith angles and/or are huge showers ($E_0 > 5 \cdot 10^{16}\,\mathrm{eV}$) with its shower core outside of the KASCADE array (more than 100 m away from the MWPC setup).

3 Methods and Results for the Estimation of Chemical Composition and Energy Spectrum of the Cosmic Rays around the Knee.

3.1 Electron number - muon number correlation

(Transparencies nos.18-19) For the description of the measured mean muon lateral distribution for different ranges of the shower size N_e by a functional form the so-called Hillas function $\rho_\mu = C \cdot (R/r_0)^{-\beta} \cdot e^{(-R/r_0)}$ has been adopted ($r_0 = 100\,\mathrm{m}$ for $E_\mu > 2\,\mathrm{GeV}$). A powerful mass-sensitive EAS observable, measured in air shower investigations, is the correlation of the muon content N_μ with the shower size N_e (Blake and Nash 1998, Knapp 1997). In order to proceed in this way and to avoid questionable extrapolations of the form of the lateral muon distribution to large distances, the distributions are parameterized by the Hillas form and fitted to the data, are integrated in the range limited to $40 - 100\,\mathrm{m}$ from the shower center. For the data the exponent shows a significant change in the value from γ_1 to γ_2 at the N_e-value which is indicated as knee in the N_e spectrum observed by the KASCADE measurements (Klages et al. 1997).

3.2 Muon Density Fluctuations

(Transparencies nos.20-21) The EAS muon density and its fluctuations, locally measured at fixed distances from the shower center carry interesting information about the nature of the primary (Blake and Nash 1998). As already stressed, in an EAS sample classified along the shower size N_e the heavy primary induced EAS have systematically higher energies and consequently higher muon densities. Simultaneously in a sample of definite energy (approximately selected with a definite N_μ^{tr} value in case of the KASCADE detector) light-particle induced EAS are expected to show larger fluctuations of the shower observables. In order to work out these features for the density distributions of EAS muons, we analyze the local muon densities ρ_μ^*, measured for each single shower at a particular distance R from the shower core by use of the MWPC system of the KASCADE central detector. The measured EAS are selected for a zenith angle range of $15^\circ \leq \Theta \leq 20^\circ$ and core distance $30\,\mathrm{m} < R < 50\,\mathrm{m}$. This choice is a compromise between the Θ- and R- variation of the muon density and a sample size of statistical significance of the results (Köhler 1998, Haungs et al. 1999).
Since N_e is mass dependent in contrast to N_μ^{tr}, the showers of the sample with larger primary mass have a larger local muon density due to the larger primary energy at the same shower size. Consequently the broading of the distributions at showers classified to N_e result mainly from the mixture of different masses, and not from intrinsic shower fluctuations.
In order to clarify this point, the distributions are compared with predictions from

simulations. Shower samples grouped in N_μ^{tr} ($E_\mu > 250\,\mathrm{MeV}$), display negligible differences in the mean and in the width of the local muon density distribution ($E_\mu > 2\,\mathrm{GeV}$) between proton and iron induced showers at around 40 m core distance. In the highest energy range a slight distinction gets visible. For comparisons of Monte Carlo results and data with one-dimensional distributions a parametrisation of a Gauss-function of the natural logarithmic of the observables is often useful. The presented results show that the observed distributions do not follow a Gaussian distribution. When grouping the showers by N_e there appear differences in the mean and the width of the distributions between the simulated proton and iron induced showers. The general enhancement of light primary induced showers in samples of equal shower size obscures the effect. Nevertheless there appears slight shifts of the measured distributions in direction to the iron distribution with increasing shower sizes.

3.3 Core Structure Investigation

(Transparencies nos.22-25) The particles observed with the MWPCs are mainly muons with $E_\mu \geq 2\,\mathrm{GeV}$, but also the "punch-through" of tails of hadron cascades in the shower core, penetrating the iron absorber (c.1000 g/cm^2) above. Due to the good spatial resolution (c.8 mm) of the MWPCs and in total a sensitive area of 125 m^2 covering more than 60 percent of a central area with $R < 8\,\mathrm{m}$, the hit pattern in the shower core and, by tracking, the number of muons in the shower core can be measured accurately, enabling a reasonable analysis of signatures for the mass of the EAS primary (Haungs et al. 1996). The reconstruction of the data from the MWPC system provides the tracks of muons above a threshold of 2 GeV ($N_\mu^\star$) and a hit pattern: number and spatial distribution of muons and of produced secondaries. The analysis of this hit pattern in terms of multifractal moments leads to two generalized multifractal dimensions D_6 and D_{-6} (Haungs et al. 1996, Haungs et al. 1998), which characterizes the positions and sizes (number of secondaries in the MWPC) of the high-energy (punch-through) hadrons, the lateral distributions of muons and secondaries and the degree of fluctuations in the pattern, i.e. in the shower core. High-energy ($E_{\mathrm{prim}} > 10^{15}\,\mathrm{eV}$) and central ($R_{\mathrm{core}} < 5\,\mathrm{m}$ from the center of the MWPC system) showers are enriched by cuts of N_μ^{tr} and of the estimated core location; around 2500 measured showers are available for the analysis of the structure of the shower core. Using five experimentally determined mass sensitive observables for each shower (shower size N_e, number of tracked muons in the MWPC system $N_\mu^\star$, generalized multifractal dimensions D_6 and D_{-6}, and the zenith angle of the shower direction Θ) as input parameters, a simple artificial neural network is constructed. The net reduces the five parameters to one parameter, representing probability of the primary mass. The net is trained by simulated proton, oxygen and iron showers, which are generated on the basis of the QGSJet model, fulfilling the selection cuts and following a flattened power law spectrum and an isotropical distribution of the

arrival directions up to 40°. After the training independent samples of simulated and measured showers are classified according to this mass parameter. For exploring the variation of the mass composition, the mass parameter distributions have been specified by different ranges of the truncated muon number. Using the simulated distributions a misclassification matrix has been calculated and the relative abundances of the three mass groups (light, medium and heavy) have been reconstructed for each N_μ^{tr}-range. For transforming the variation from the muon number into the primary energy of the particles, the linear dependence of lgN_μ^{tr} from lgE_0 above the selection threshold of $lgN_\mu^{tr} > 3.5$ is adopted. The tendency to increasing heavy primaries after with a slightly decreasing just before the "knee" is seen in this analysis.

3.4 Muon Density Spectrum

(Transparencies nos.26-29) 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. The spectra, measured with the MWPC system ($E_\mu > 2\,\mathrm{GeV}$) for two particular core distances and for the zenith angle range $10° \leq \Theta \leq 30°$, 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. 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. 1999) samples of proton and iron induced EAS of the energy range of $5 \cdot 10^{14}\,\mathrm{eV}$ to $1 \cdot 10^{16}\,\mathrm{eV}$, 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. The relations between the average muon density ρ_μ^* and the primary energy are described by power laws $\rho_\mu^* \propto E^\delta$. 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 the transparency no.28.
With the help of the estimated shower sizes N_e and N_μ^{tr} (Kampert 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 attenuation lengths λ_μ and λ_e by the KASCADE group. 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 ion 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 ion induced EAS have a passing slope of $\gamma_h = 2.76(2.62)$ without any significant kink between 10^{15} eV and 10^{16} eV. The results have small statistical uncertainties, and the estimated systematic error of ≈ 0.3 is mainly due to the limited number of the Monte Carlo simulations.

4 Conclusions

(Transparency no.30) The described methods and results are published in more detail in two FZKA reports of the Forschungszentrum Karlsruhe (Haungs et al. 1998, Haungs et al. 1999), also available at http://www-ik3.fzk.de/KASCADE for a free download.

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