Estimate of the Cosmic Ray Composition by a Pattern Analysis of the Core of PeV EAS

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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 observe the density distributions of the high energy muons and hadrons penetrating the calorimeter. By use of a classification in terms of multifractal moments, a mass sensitive parametrisation of the density distributions is given. In combination with additional measured parameters, i.e. number of reconstructed muons in the core and the shower size an artificial neural net analysis leads to an estimation of the relative abundances of the different primary components in cosmic rays in the energy region around the "knee".

1 Introduction:

The KASCADE (KArlsruhe Shower Core and Array DEtector) experiment (Klages et al. 1997) aims at the determination of the chemical composition of cosmic rays in the energy region around the so-called "knee" by extensive air shower (EAS) observations. The multi detector arrangement of KASCADE allows to measure simultaneously observables in all three charged particle components of the air shower and, especially for EAS with the core inside the $300\,\mathrm{m}^2$ central detector, a measurement of structures of the particle density distributions in the center by a pattern analysis with multifractal moments. With an eligible choose of a set of such observables an event by event classification of the EAS with respect to the primary mass can be performed. The resulting relative abundances of groups of equal primary masses and with the measured primary energy spectrum could help to discriminate between different theories of the source, acceleration and transport of the charged cosmic rays in the Galaxy.

2 Reconstruction of a Mass Parameter per single EAS:

2.1 The KASCADE Detector: The KASCADE detector array consists of a detector field having an area of $200 \times 200\,\mathrm{m}^2$ and 252 detector stations positioned on rectangular grids with 13 m spacing. Each station contains liquid scintillators in stainless steel containers of 100 cm diameter with a photomultiplier on the top for the electron-photon detection. The 12 clusters in the outer (inner) region of the field contain two of such electron-photon detectors, positioned in the diagonal of each station, while the stations of the inner four clusters contain four of such detectors. The outer 12 clusters are additionally equipped with muon detectors.

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These are four plastic scintillators ($90 \cdot 90 \cdot 3\,\text{cm}^3$ each) placed under absorber material of 10 cm lead and 4 cm iron. The array provides the general EAS trigger and the data necessary for the reconstruction of the basic EAS characteristics like electron and muon number, core location and angle of incidence.

Apart from an iron sampling calorimeter the KASCADE central detector consists of a setup of two layers multiwire proportional chambers (MWPC), installed in the basement of the central detector. Each muon chamber consists of three layers of crossed wires and stripes in a 16 mm thick argon-methane volume which allow a reconstruction of the crossing point of hit particles. The particles observed with the MWPCs are mainly muons with $E_\mu \geq 2\,\text{GeV}$, but also the "punch-through" of tails of hadron cascades in the shower core, penetrating the iron absorber (c.$1000\,\text{g/cm}^2$) above. Due to the good spatial resolution (c.8 mm) of the MWPCs and in total a sensitive area of 122 m^2 covering more than 60 percent of a central area with $R < 8$ 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).

2.2 Observables: For this analysis the relevant parameters reconstructed for each registered shower from the data of the field array are: the core location, the arrival direction of the shower, the shower size N_e (total number of electrons), and the so-called truncated muon number N_μ^{tr}. The latter is the content of muons with $E_\mu > 250\,\text{MeV}$ in the limited range of the lateral distribution in the distance of 40 m - 200 m from the shower center. 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 (Figure 1). 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 ($E_{\text{prim}} > 10^{15}$ eV) and central ($R_{\text{core}} < 5$ 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.

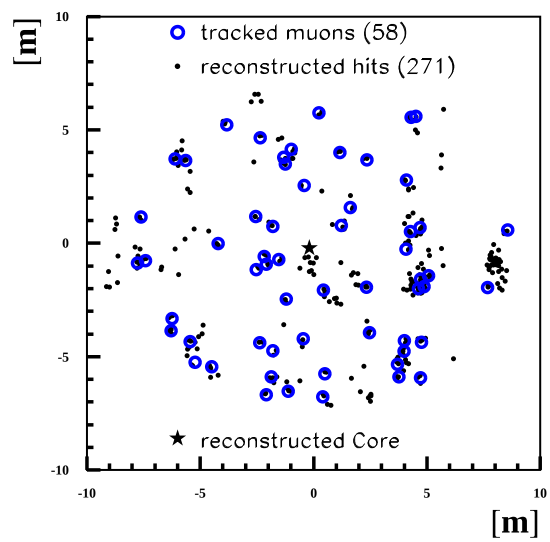

Figure 1: Example of a typical hit density distribution measured by the MWPC system. Additionally the positions of tracked muons are included.

2.3 Simulations: For detailed studies first a set of EAS, simulated for the KASCADE observation level (110 m a.s.l.), has been prepared using the Monte Carlo air shower simulation program CORSIKA (Heck et al. 1998), which includes different packages of high-energy interaction models like VENUS and QGSJET. The simulation calculations cover the energy range of 10^{14} eV - 10^{16} eV for five different mass groups with isotropic incidence. Showers of different primary masses have different longitudinal developments in the atmosphere leading to different lateral distributions in the shower core (Figure 2). Detector effects and fluctuations smear out this signal, but still the different structure remains in the data of the MWPC system. The response of all KASCADE detector systems to the EAS components has been determined by simulations using the GEANT code. The output of the simulations is stored in the same way as the measured data, therefore measured and simulated data can be reconstructed with the same procedures.

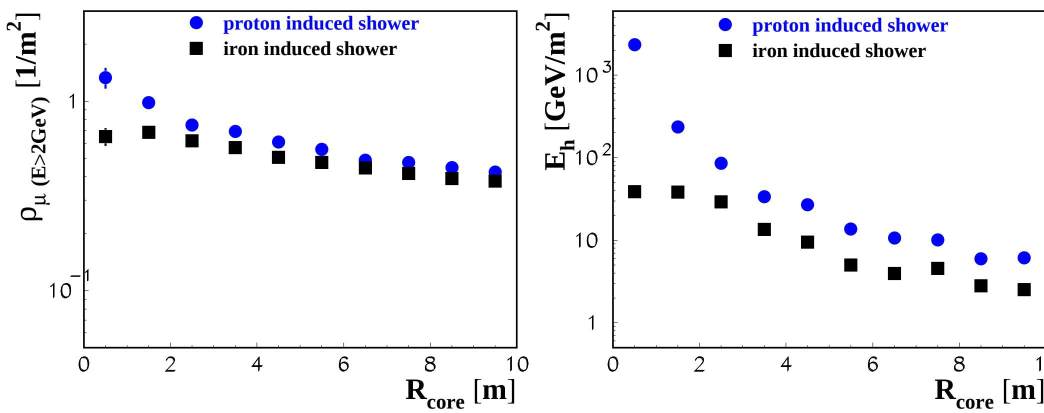

Figure 2: Average muon density and hadronic energy density of proton and iron induced showers in the inner region: CORSIKA (QGSJet) simulations taking into account the energy spectrum above 1 PeV with an isotropic shower incidence.

2.4 Classification: 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.

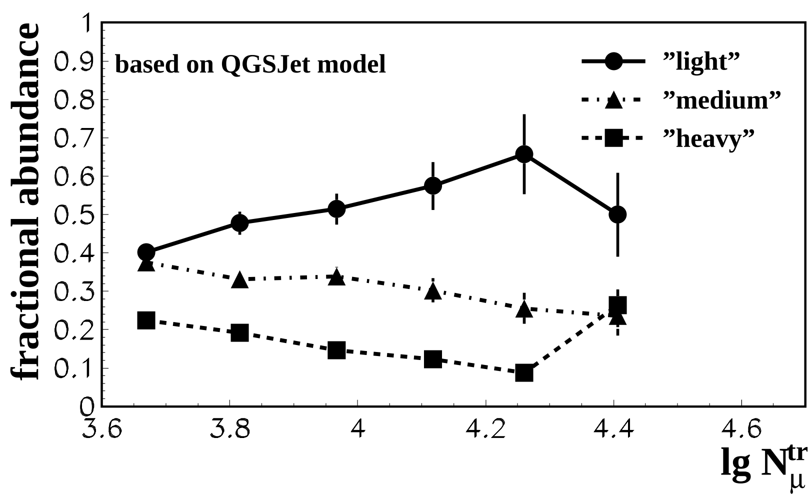

Figure 3: Relative abundances of different mass groups of primary cosmic rays in the energy region around the knee ($lgN_\mu^{tr} \approx 4.1$), analyzed on the basis of the interaction model QGSJet. The error bars contain the statistics of both, data and simulations.

3 The Chemical Composition:

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 hgas been calculated and the relative abundances of the three mass groups (light, medium and heavy) have been reconstructed for each N_μ^{tr}-range (Figure 3). Simulations have been shown, that primary Helium and Silicon nuclei in the present analysis are be representated by the light and heavy group, respectively. 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 (Figure 4). The fair independence of such a relation from the primary mass reduces the systematic error of such a simple transformation. Figure 5 shows the mean logarithmic mass of the primary cosmic rays versus the primary energy as a result of this analysis. For the "light" group an average A of 2.5 is assumed, for the "medium" group A=14 and for the "heavy" group A=42. A comparable analysis based on the VENUS interaction model show a variance in the final result of around 10%. By replacing the fractal parameters in the neural net by hadronic parameters like number of reconstructed hadrons above $100\,$GeV, and the sum of the reconstructed energy of this hadrons, a conspicuous increasing of the mean mass is resulting. This corroborates the suspicion of an insufficient description by the high-energy hadronic interaction models in the extreme forward direction (see Antoni et al. 1999). However in the analysis of all shower variables in all analyses the tendency to increasing heavy primaries after with a slightly decreasing just before the "knee" is seen.

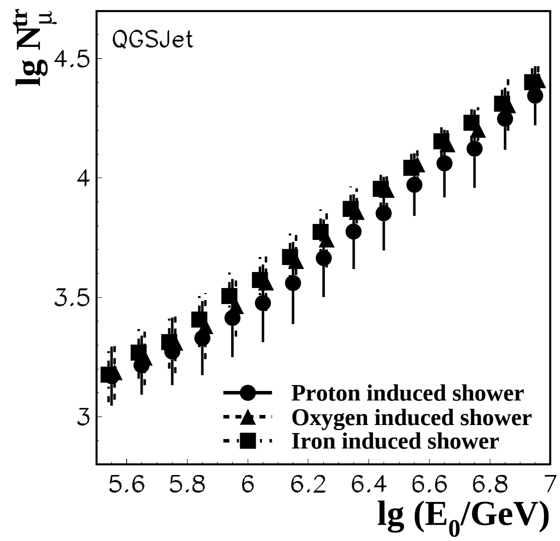

Figure 4: Dependence of the "energy estimator" N_{μ}^{tr} from the primary energy for different primary masses, based on the interaction model QGSJet including the detector simulation as well as all selection cuts. The error bars indicate the spread of N_{μ}^{tr} for each energy range.

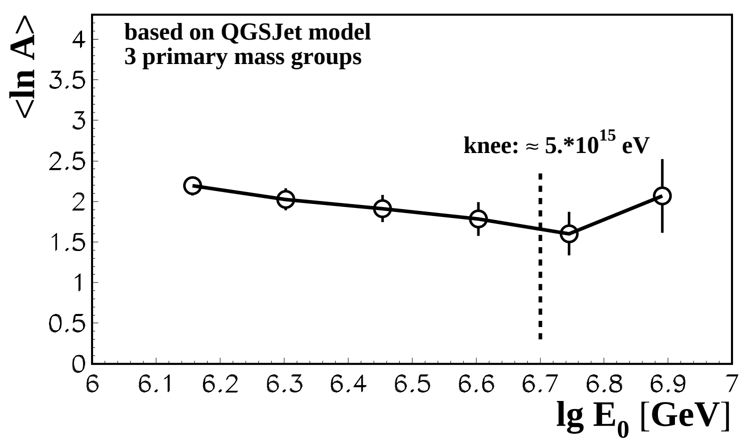

Figure 5: Mean of the logarithmic mass versus the primary energy. The position of the knee as estimated by the KASCADE experiment, is indicated.

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