RECENT RESULTS FROM THE KASCADE AIR SHOWER EXPERIMENT

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High–energy cosmic rays are investigated by the air shower experiment KASCADE measuring the electromagnetic, muonic, and hadronic shower components simultaneously. The experiment allows an evaluation of high-energy hadronic interaction models by investigation of several hadronic observables. At present, QGSJET is the best model coupled with the air shower simulation program CORSIKA. The mass composition of primary cosmic rays is derived using different parametric and non–parametric methods. All analyses result in an increasing mean logarithmic mass above the *knee*. The primary cosmic ray energy spectrum is obtained consistently by several methods using the three shower components and a knee around 3 to 5 PeV is found in the all–particle spectrum.

1 Introduction

The Earth's atmosphere is permanently bombarded by highly relativistic ionized particles, first discovered and named "cosmic rays" by V. Hess in 1912. Present day experiments show the cosmic–ray energy spectrum extending up to more than 10^{20} eV. It follows a power law $dN/dE \propto E^{-\gamma}$ over many decades in energy. The only prominent feature is the *knee* in the spectrum around 4 PeV where the spectrum steepens from $\gamma \approx 2.7$ to $\gamma \approx 3.1$. The origin of cosmic rays is still under debate. Strong, relativistic shock fronts expanding from supernova explosions are favoured by popular models for the acceleration of the cosmic ray particles. Such models explain the particle acceleration up to energies of about $Z \cdot 10^{15}$ eV, with the nuclear charge Z of the particle. This coincidences with the mentioned steepening of the spectrum and the origin of the knee is related to the upper limit of acceleration in several models.

Since the charged particles are deflected in interstellar magnetic fields, the only hint for their sources are their energy spectrum and the mass composition, or more preferable, the energy spectrum for individual species of particles. Cosmic rays at energies below 1 PeV can be directly

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observed by balloon borne instruments in the upper atmosphere or in outer space. At higher energies, the steep falling flux spectrum requires large detection areas or long observation periods, only possible in ground–based installations. These detector systems measure the secondary particles produced by cosmic rays in the atmosphere.

2 The KASCADE Experiment

To investigate the cosmic rays from several 10^{13} eV up to 10^{17} eV the air shower experiment KASCADE ("Karlsruhe Shower Core and Array DEtector") [7,8] has been build on site of the Forschungszentrum Karlsruhe in Germany. The experiment measures the electromagnetic, muonic, and hadronic EAS components simultaneously and consists out of three major parts, a scintillator array, an underground muon tracking detector, and a central detector.

The 200×200 m^2 scintillator array is formed by 252 detector stations housing liquid scintillation counters to measure the electromagnetic component, and under an absorber of 10 cm lead and 4 cm iron, plastic scintillators to register muons with an energy threshold of 230 MeV. The position of the shower core, the angle of incidence as well as the number of electrons and muons is provided by this detectors.

Three layers of 144 m^2 streamer tubes in an underground tunnel shielded by 1 m of concrete and soil, corresponding to an energy threshold of 800 MeV, form the muon tracking detector. The production height of muons is obtained from this system by triangulation methods.

Main part of the central detector system is a 320 m^2 hadron calorimeter formed by 4000 t iron, lead, and concrete absorber material, interspaced with nine layers of liquid ionization chambers [4]. The calorimeter measures the point and angle of incidence as well as the energy of individual hadrons. A layer of plastic scintillators below the third absorber layer — with an energy threshold for muons of 470 MeV — serves as a fast trigger. Below the calorimeter, two layers of multi–wire proportional chambers and one layer of limited–streamer tubes are detecting muons with a threshold of 2.4 GeV.

3 Test of Hadronic Interaction Models

The astrophysical analysis of EAS is usually performed by comparing the result of measured data with EAS simulations. In the simulations the development of an air shower is calculated. All secondary particles, reaching ground level, are treated in a GEANT–based detector simulation, calculating the energy deposit and arrival time in each detector element. Physical observables are reconstructed from the detector signals for both, simulated and measured data, using the same algorithms. Comparing these quantities, the mass and energy of the primary particle are deduced.

Weakest element in the simulation chain is the model used to describe the high–energy hadronic interactions, since the model has to extrapolate into kinematical and energy regions not covered by present–day collider experiments. The Karlsruhe EAS simulation program CORSIKA [5] provides several high–energy hadronic interaction models — HDPM, DPMJET, NEXUS, QGSJET, SIBYLL, VENUS — based on different phenomenological descriptions. One objective of the KASCADE experiment is to evaluate these models and to provide criteria for their improvement.

The calorimeter of the KASCADE experiment is a valuable detector for testing these interaction models. The structure of the hadronic component is investigated in energy and coordinate space. Observables used include the number of hadrons as well as their energy sum, their lateral distribution and their energy spectrum, the energy of each individual hadron relative to the most energetic hadron in each shower, the maximum hadron energy, and the spatial distribution of the hadrons. All observables are investigated as functions of the number of electrons and muons

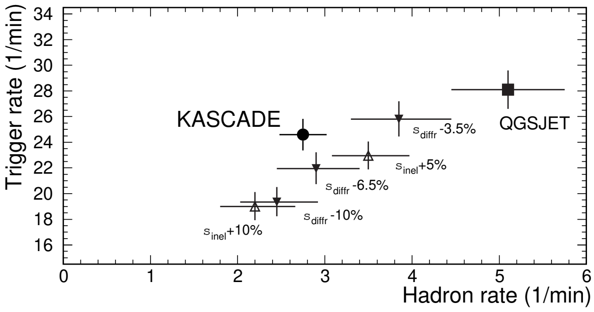

Figure 1: Trigger rate versus hadron rate. KASCADE measurements are compared to predictions of the model QGSJET with different modifications of the cross section.

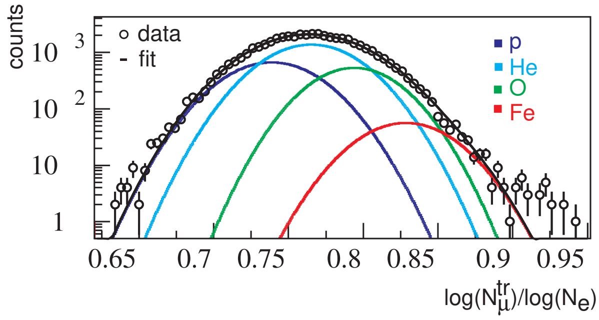

Figure 2: Measured ratio of $\log N_\mu / \log N_e$ fitted with model predictions for four groups of primary nuclei.

as well as of the hadronic energy sum. It turned out that the model QGSJET delivers the most reliable description. But even for this model deviations between predictions and measurements have been found at high energies [1]. This model is used for the analyses described in the following sections.

As an example, the sensitivity of the investigations is illustrated by comparing trigger and hadron rate in the central detector [2]. A trigger is generated by energy depositions in more than eight detectors in the layer of scintillation counters. The signals are mostly due to muons originating from showers of primaries in the TeV range. Figure 1 shows the trigger rate as function of the rate of reconstructed hadrons. One observes that the model overestimates the number of hadrons by a factor of two. It turns out, that the hadron rate is very sensitive to the inelastic and diffractive cross sections applied, as can be seen in the figure by the simulations with modified cross–sections. Starting with the values as implemented in the standard QGSJET, the inelastic cross section σ_{inel} has been increased by 5% and 10%, and the diffractive cross section σ_{diff} has been decreased by 3.5%, 6.5%, and 10% relative to σ_{inel}. The influence on the rates, especially the hadron rate is clearly visible. Both modifications reduce the observed rates. A closer inspection shows, that the fraction of diffractive processes in proton nucleus collisions has to be decreased by up to a factor of two.

4 The Mass Composition of Cosmic Rays

The ratio of the number of muons to the number of electrons is very sensitive to the primary mass composition. This ratio is shown in Figure 2 for a certain interval of the muonic shower size, corresponding to a primary energy of about 2 PeV. Model predictions for the major cosmic–ray nuclei protons, helium, oxygen, and iron are fitted to the measurements to obtain their relative abundances. Only the scale factors are fitted, while the positions of the individual distributions are fixed by the model predictions. The mean logarithmic mass is calculated from the relative abundances and shown as a function of energy in Figure 3, together with a non–parametric analysis. The latter uses a neural network dealing with the following observables: The number of electrons, the number of muons for several thresholds ($E_\mu > 230$ MeV, and $E_\mu > 2.4$ GeV), the number of hadrons, the hadronic energy sum, the maximum hadron energy as well as the spatial structure of high–energy muons ($E_\mu > 2.4$ GeV). In the analysis a probability to belong to a class of nuclei (for example protons, oxygen, or iron) and an energy is assigned to each event. Different combinations of observables have been used [3], indicating the same general behaviour of an increasing mean logarithmic mass with energy. The absolute value of $\langle \ln A \rangle$ depends on the observables employed, hadronic observables result in a slightly heavier mass than electromagnetic observables, which may be explained by inconsistencies within the hadronic interaction models.

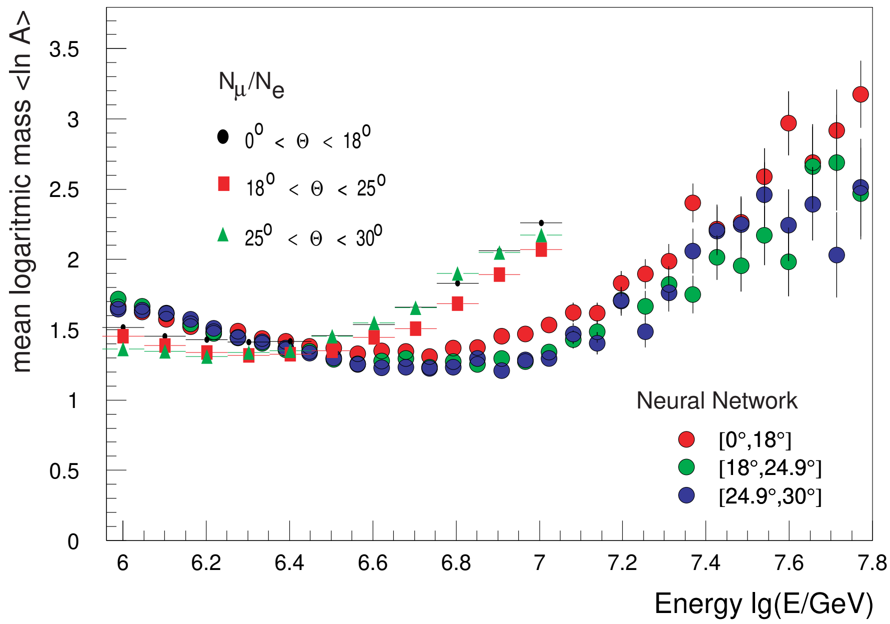

Figure 3: Mean logarithmic mass vs primary energy for two analysis methods and different zenith angle bins. A parametric method, using the N_μ/N_e–ratio, and a non–parametric neural network analysis.

The result of the neural network analysis, using N_e and N_μ from the scintillator array is shown in Figure 3 for different zenith angle bins.

Both methods shown in the figure, the parametric and the non–parametric analysis, yield the same general behaviour, the mean mass decreases slightly below the knee and increases beyond the knee at around 4 PeV. The two methods yield a slightly different absolute value of the mean logarithmic mass which may be caused by a different treatment of shower fluctuations in the analysis.

5 The Energy Spectrum of Cosmic Rays

Main objective of the KASCADE experiment is the determination of the all–particle energy spectrum as well as the energy spectra for individual mass groups. Several methods have been applied in the analyses.

The all–particle energy spectrum, obtained by the neural network analysis using N_e and N_μ as measured by the scintillator array, is shown in Figure 4 for different zenith angle bins. A good agreement of the flux spectra for the different angular bins can be inferred from the figure.

A parametric analysis deconvoluting the electromagnetic and muonic shower size spectra, measured with the scintillator array results in an all–particle energy spectrum as shown in Figure 4 in addition.

Another analysis uses the hadrons, reconstructed by the central calorimeter and the muons measured in the scintillator array [6]. The number of muons serves as an energy estimator. The mass composition is derived using several hadronic observables, like lateral distribution and energy spectrum. This mass composition allows to calculate the primary cosmic–ray energy spectrum from the hadronic shower size spectrum, the result is shown in Figure 4 as well.

The spectra derived from the electromagnetic and muonic shower components using two different methods agree well which each other. The spectrum obtained from the hadronic component yields smaller flux values below the knee, which may be caused by a different mass composition derived from hadronic observables.

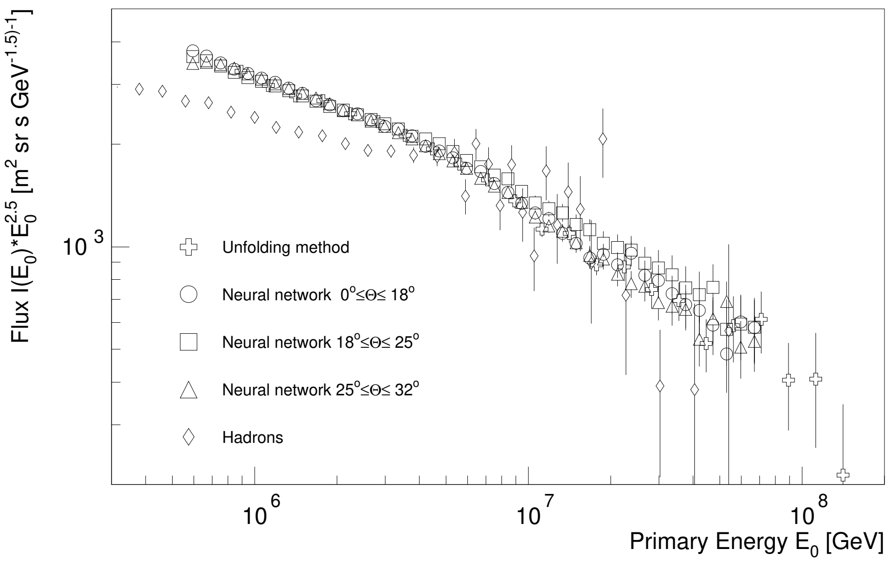

Figure 4: The all–particle cosmic ray energy spectrum obtained by several analyses using the electromagnetic, muonic, and hadronic shower components.

The KASCADE experiment is extended at the moment by adding a 825×750 m^2 scintillator array build with detectors from the EAS-TOP experiment. With this addition, the energy range can be extended up to almost 10^{18} eV. It is then possible to measure the heavy component up to at least $Z_{Fe} \cdot E^p_{knee}$ and to investigate the properties of the spectra of groups of cosmic ray species, especially to confirm a rigidity dependent knee for each mass group.

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