IL NUOVO CIMENTO Vol. 24 C, N. 4-5 Luglio-Ottobre 2001

Cosmic ray physics around the knee with the KASCADE experiment(*)

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(ricevuto il 14 Settembre 2000; approvato il 12 Febbraio 2001)

(*) Paper presented at the Chacaltaya Meeting on Cosmic Ray Physics, La Paz, Bolivia, July 23-27, 2000.
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Summary. — KASCADE (KArlsruhe Shower Core and Array DEtector) is a multi-detector setup to observe the electromagnetic, muonic and hadronic air shower components simultaneously for the primary energy region around the knee. The large body of observables per single shower allows to follow the main aims of the experiment in analyses on an event-by-event basis, mainly: 1) slopes and structures of the primary energy spectrum; 2) the energy dependence of the chemical composition of the primaries; 3) tests of the air shower simulation tools underlying the analyses, in particular of the Monte Carlo generators based on different high-energy interaction models; 4) examinations of the air shower development in the atmosphere. Examples and results of different analysis methods are presented for the different subjects.

PACS 96.40.De – Composition, energy spectra, and interactions.
PACS 96.40.Pq – Extensive air showers.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The word “knee” is used as paraphrase for a steepening of the all-particle cosmic ray energy spectrum in the PeV region. In spite of many confirmations by different experiments since the first detection of the “knee” 1959 [1], the origin of the steepening is still an enigma. Theoretical approaches of the knee vary from the idea of a change of the source of cosmic rays and other astrophysical reasons like effects of the transport mechanisms up to explanations by a changing of the hadronic interaction features of the primary in the atmosphere. To solve the problem of the physical origin of the knee, a precise knowledge of the chemical composition and a detailed investigation of the primary energy spectrum is necessary. But the low flux of these ultra high energy cosmic rays allows only indirect measurements via extensive air showers created in the atmosphere. Fluctuations in the shower development hinders detailed spectroscopic measurements of the primary particles. Therefore simulations of the development of EAS in the atmosphere and moreover of the high-energy nucleus-nucleus interactions play an important role for the reconstruction of the nature of the primaries.

KASCADE [2] is an experiment especially dedicated to the measurement of extensive air showers around the knee. From beginning the philosophy of the experiment was to build a modern multidetector setup to measure the different air shower components simultaneously, and in addition to promote the development of the tools for the reconstruction of primary energy and mass of the cosmic rays. CORSIKA [3] is a Monte Carlo program for the detailed three-dimensional simulation of the air shower development in the atmosphere. The hadronic interactions are optional described by different reaction models. KASCADE measures the electromagnetic, the muonic (for different threshold energies) and the hadronic component of air showers simultaneously and reconstructs a large set of observables for each single event. This allows to follow the reconstruction of the primary mass and energy of the infalling cosmic nuclei on an event-by-event basis using sophisticated multivariate analyses methods. By comparing different methods and variable sets of observables systematics can be decreased, moreover, the shower devel-

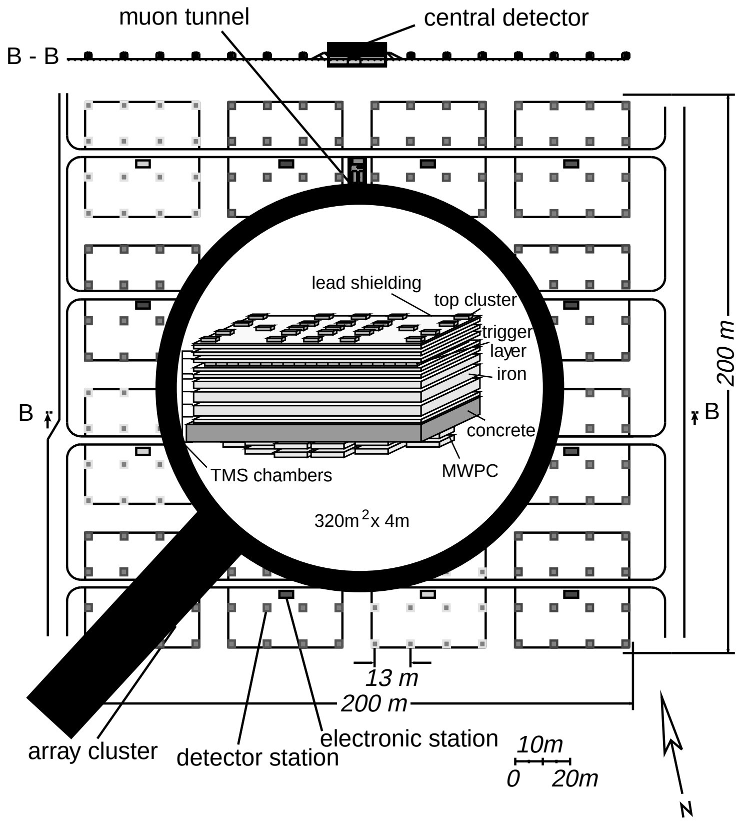

Fig. 1. – Schematic view of the KASCADE experiment. In the center of the 252 detector stations of the array there is the KASCADE central detector. The muon tracking detector (150 m^2 of streamer tubes in the muon tunnel) is in full operation since summer 2000.

opment can be examined and the hadronic interaction models underlying the different analyses of energy and composition can be tested.

2. – KASCADE

The KASCADE (KArlsruhe Shower Core and Array DEtector) array consists of 252 detector stations in a $200 \times 200\,\mathrm{m}^2$ rectangular grid comprising unshielded liquid scintillation detectors (e/γ-detectors) and below 10 cm lead and 4 cm steel plastic scintillators as muon-detectors (fig. 1). The total sensitive areas are 490 m^2 for the e/γ- and 622 m^2 for the muon-detectors. In the center of the array a hadron calorimeter ($16 \times 20\,\mathrm{m}^2$) is built up, consisting of more than 40000 liquid ionization chambers in 8 layers. In between the calorimeter a trigger layer consisting of 456 scintillation detectors of 0.456 m^2 each, enables to measure energy deposit and arrival times of muons with $E_\mu > 490\,\mathrm{MeV}$. Below the calorimeter a setup of position-sensitive multiwire proportional chambers in two layers measures EAS muons with $E_\mu > 2.4\,\mathrm{GeV}$. Various methods and results of the analysis of KASCADE data are described in detail in the proceedings of the last ICRC conference in Salt Lake City, Utah [4] or in ref. [5], where the KASCADE contributions

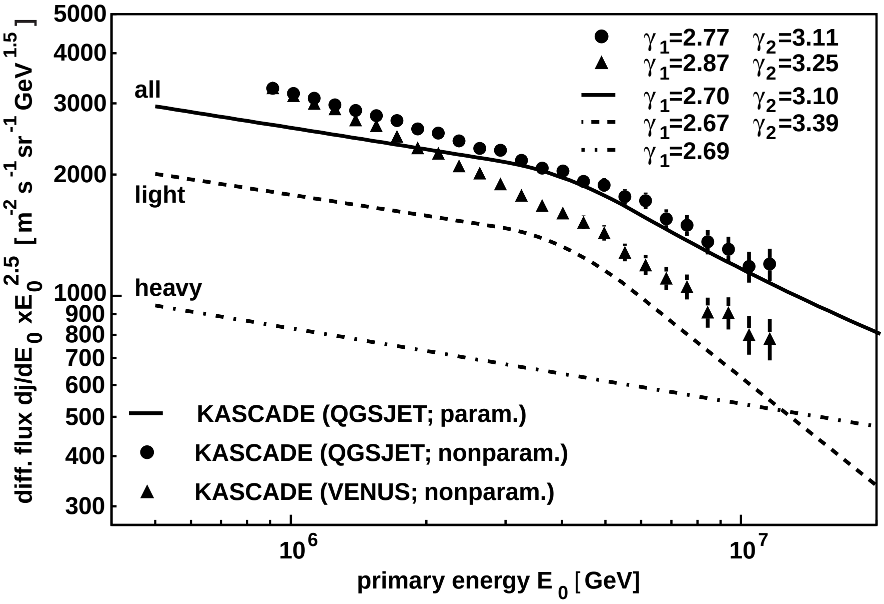

Fig. 2. – The primary cosmic ray energy spectrum from KASCADE reconstructed by two different methods.

are sampled. In the following overview only examples for different topics will be touched.

Main observables of KASCADE per single shower are the so-called shower sizes, *i.e.* total numbers of electrons N_e and number of muons in the range of the core distance $40 - 200\,\mathrm{m}$ N_μ^{tr}, local muon densities measured for the different thresholds, and number and energy sum of reconstructed hadrons at the central detector. As a phenomenological result of KASCADE it should be remarked that the frequency spectra of all these observables, *i.e.* for the different particle components, show a clear kink at same integral event rates. This is a strong hint for an astrophysical source of the knee phenomenon based on pure experimental data, since same intensity of the flux corresponds to equal primary energy.

2˙1. *Primary energy spectrum.* – The shower sizes N_e and N_μ^{tr} are used as input parameters for a neural network analyses to reconstruct the primary energy on an event-by-event basis. The necessary *a priori* information in form of probability density distributions are won by detailed Monte Carlo simulations in large statistics. The resulting energy spectrum depends on the high-energy interaction model underlying the analyses (fig. 2). But the spectrum shows a clear kink at ≈ 6 PeV and power law dependences below and above the knee.

Parametric approaches for the analyses of the KASCADE data lead to the results also shown in fig. 2: A simultaneous fit to the N_e and N_μ^{tr} size spectra is performed for the reconstruction of the primary energy spectrum. The kernel function of this fit contains the size-energy correlations for two primary masses (proton and iron) obtained by Monte Carlo simulations. This approach leads to the all-particle energy spectrum as a superposition of the spectra of light and heavy particles. For the light particle spectra a steep kink is revealed, whereas for the heavy particle component a knee is missing

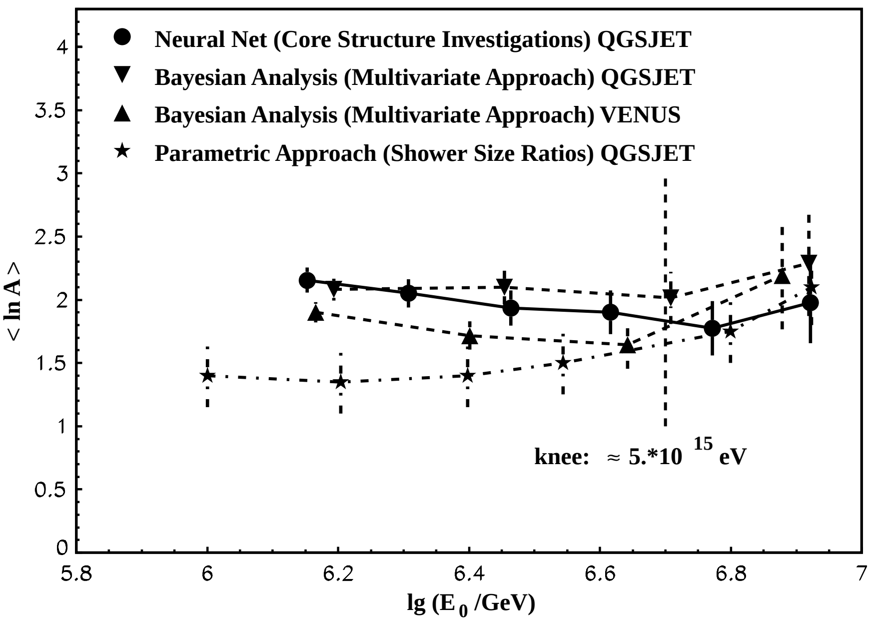

Fig. 3. – The chemical composition estimated with the KASCADE data, using different methods and different sets of observables from different particle components.

between 1 and 10 PeV, thus leading to an increase of the average mass above the knee.

2˙2. *Chemical composition.* – Besides the use of global parameters like the shower sizes, sets of different parameters (describing different shower particle components) are used for neural network and Bayesian decision analyses for showers with their axes within the central detector area. Examples of such observables are the number of reconstructed hadrons in the calorimeter ($E_\mathrm{h} > 100\,\mathrm{GeV}$), their reconstructed energy sum, the energy of the most energetic hadron ("leading particle" in the EAS), number of muons in the shower center ($E_\mu > 2\,\mathrm{GeV}$), or parameters obtained by a fractal analysis of the hit pattern of muons and secondaries produced in the passive calorimeter material. The latter ones are sensitive to the structure of the shower core which is mass sensitive due to different shower developments of light and heavy particles in the atmosphere. In fig. 3 results of a Bayesian analysis and of a separate neural net analysis are shown. Monte Carlo statistics limit the number of parameters, which can be used for one multivariate analysis. Therefore a set of approaches using different observables are averaged in case of the actual result of the Bayesian analysis. The resulting classifications are corrected with misclassification matrices leading to relative abundances. Afterwards the results are converted in distributions of the mean logarithmic mass.

2˙3. *Test of the hadronic interaction models.* – One test is the comparison of simulated integral muon trigger and hadron rates with the measurements. This test is sensitive to the energy spectrum of the hadrons which are produced in the forward direction at energies around 10 TeV, where the chemical composition is roughly known and included in the simulations presented in fig. 4. For higher primary energies the hadronic part of the interaction models are tested by comparisons of the mean of hadronic observables

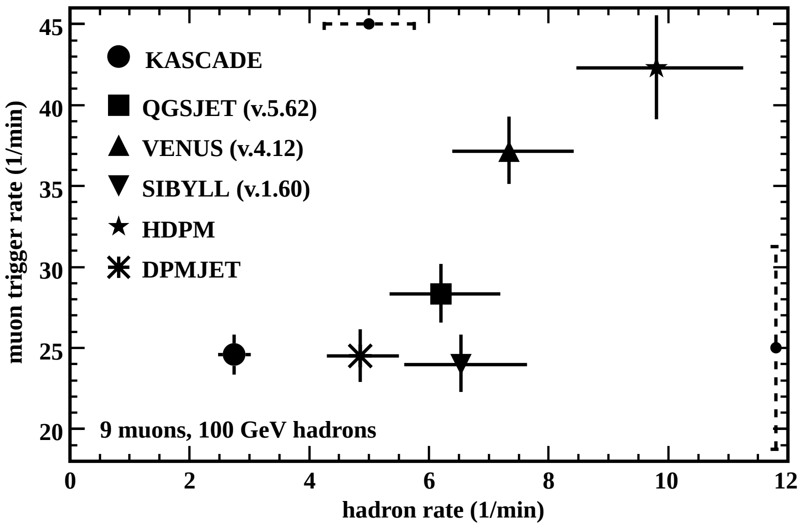

Fig. 4. – Comparison of simulated and measured integral muon trigger and hadron rates. Uncertainties of the chemical composition of the relevant energy range are indicated by dotted lines. References for the different models see at [3].

in ranges of shower sizes [6]. For both tests all of the high-energy interaction models predict a too large number of hadrons at sea-level compared with the measurements.

2˙4. *Examination of the shower development.* – The measurements of arrival times and angles-of-incidence of the muon component in air-showers provides a sensitivity to the longitudinal shower development. By analyzing the data of the trigger plane scintillators ($\sigma_t = 1.5\,\text{ns}$) the shower profiles (here the averaged thickness of the muon disc measured at each single shower *vs.* core distance) could be reconstructed [7]. A good agreement

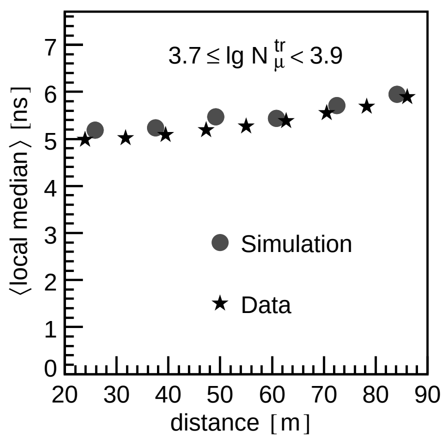

Fig. 5. – Comparison of the simulated and measured shower profile (thickness of the muon disc). For the given time resolution no variation by different primaries could be recognized.

between CORSIKA predictions and data could be found (fig. 5). Soon the production height of the muons will be reconstructed with help of the excellent angular resolution of the "muon tracking detector" (muon tunnel, see fig. 1).

3. – Discussion

The precise measurements of observables from different shower components and the sophisticated methods of analyzing the data reduce the systematics of the KASCADE results substantially. But still there are a large number of outstanding problems: None of the hadronic interaction models can describe all the observables in a consistent way to obtain a final result on chemical composition and energy spectrum. A tendency to heavier mean mass above the knee energy is given, but the relative abundances of the different primaries depend on the chosen observables and interaction models. In future increased attention will be given to the tests of the en-vogue models.

To extend the sensitive range of KASCADE, different upgrades are in work: For an improved study of the shower cores and of smaller showers the central detector will have an additional unshielded calorimeter layer on top and a layer of $300\,\mathrm{m}^2$ streamer tubes in the basement of the building. The extension to higher energies will be performed by the installation of $38 \cdot 10\,\mathrm{m}^2$ scintillation detectors around the KASCADE array. Also the development of CORSIKA in cooperation with the "model builders" will continue. For the tests of the hadronic interaction models an "extension of KASCADE" to an observation level on higher altitudes would be of large interest.

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