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Dissecting the knee — Air shower measurements with KASCADE

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Recent results of the KASCADE air shower experiment are presented, in order to shed some light on the astrophysics of cosmic rays in the region of the knee in the energy spectrum. The results include investigations of high-energy interactions in the atmosphere, the analysis of the arrival directions of cosmic rays, the determination of the mean logarithmic mass, and the unfolding of energy spectra for elemental groups.

1. INTRODUCTION

The origin of high-energy cosmic rays is among the most interesting questions in astrophysics. The origin of a structure in the all-particle energy spectrum around 4 PeV, the so-called knee, is generally believed to be a corner stone in the understanding of the astrophysics of high-energy cosmic rays. The knee is proposed to be caused by the maximum energy reached in cosmic-ray accelerators or due to leakage of particles from the Galaxy. Hence, an understanding of the origin of the knee reveals hints on the acceleration, and propagation of cosmic rays. Experimental access to the understanding of the sources, acceleration, and propagation mechanisms is provided by detailed investigation of the arrival directions, energy spectra, and mass composition of the ultrarelativistic particles.

While at energies below 1 PeV cosmic rays can be measured directly at the top of the atmosphere, the strongly decreasing flux as function of energy requires large acceptances and exposure times for higher energies. Presently they can be realized in ground-based facilities only. There, the secondary products, generated by interactions of high-energy cosmic-ray particles in the atmosphere, the extensive air showers, are registered. It turns out that a correct description of the high-energy interactions in the atmosphere is crucial for a precise astrophysical interpretation of air shower measurements.

To investigate cosmic rays from several 10^{13} eV up to beyond 10^{17} eV, the air shower experiment KASCADE ("Karlsruhe Shower Core and Array DEtector") [1] has operated since 1996. The experiment detects the three main components of air showers simultaneously. A 200×200 m^2 scintillator array measures the electromagnetic and muonic components. The 320 m^2 central detector system combines a large hadron calorimeter with several muon detection systems. In addition, high-energy muons are measured by a 128 m^2 underground muon-tracking detector.

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2. HIGH-ENERGY INTERACTIONS IN THE ATMOSPHERE

A correct understanding of high-energy interactions in the atmosphere is indispensable for a good astrophysical interpretation of air shower data. The electromagnetic part of the showers is well understood and described by QED. For the air shower development, the understanding of multi-particle production in hadronic interactions with a small momentum transfer is essential. Due to the energy dependence of the coupling constant α_s and the resulting large values for soft interactions, the latter cannot be calculated within QCD using perturbation theory. Instead, phenomenological approaches have been introduced in different models.

For the numerical simulation of the development of air-showers, the program CORSIKA [2] is widely used. It offers the possibility of using different models to describe low- and high-energy hadronic interactions. A principal objective of the KASCADE experiment is to investigate the air shower development in detail and test the validity of the models included in simulation codes, such as CORSIKA, using as much information as possible from the simultaneous measurement of the electromagnetic, muonic and hadronic components.

With these investigations, several problems in existing codes could be pointed out and some interaction models (or particular versions of them) could be shown to be incompatible with the measured data [3–6]. As an example of present activities, Fig. 1 shows the hadronic energy sum as function of the number of electrons. Presented are measured values compared to predictions of three different interaction models for showers induced by primary protons or iron nuclei. For a presentation of the data as function of the number of electrons, one expects an enrichment of light primaries within the particular intervals, hence, the data should approach the values for the proton component. One recognizes that the data are compatible with the predictions of QGSJET and SIBYLL, while on the other hand NEXUS 2 predicts less hadronic energy in most of the electron number range. From such distributions, one

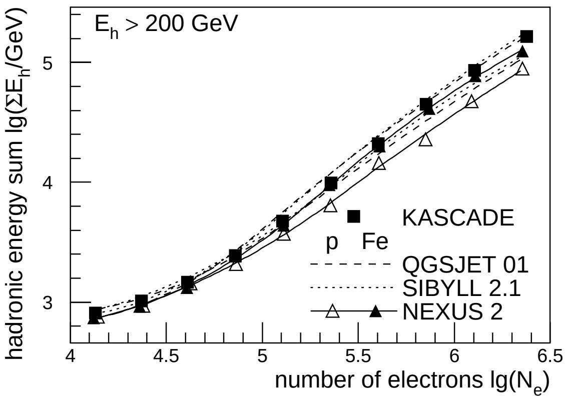

Figure 1. Hadronic energy sum versus number of electrons.

can conclude that the present version of NEXUS is not compatible with the data. More detailed investigations of the models QGSJET 01 and SIBYLL 2.1 are presently in progress.

3. ARRIVAL DIRECTIONS

The investigation of the arrival directions of cosmic rays improves the understanding of the propagation of the particles through the galaxy and their sources. Model calculations of the diffusion process in the galactic magnetic field indicate that there could be an anisotropy on a scale of 10^{-4} to 10^{-2} depending on particle rigidity, as well as strength and structure of the galactic magnetic field [7]. Diffusion models relate a rigidity-dependent leakage of particles from the galaxy to the steepening (or knee) in the all-particle energy spectrum around 4 PeV. Thus, anisotropy measurements can provide substantial information on the origin of the knee.

In KASCADE investigations [8,9] attention has been drawn to a search for point sources and large-scale anisotropy. Of special interest is the search for potential gamma-ray-induced showers. Since photons are not deflected in the galactic magnetic field, they are suitable for a direct search for the sources of high-energy particles. Experimentally such an investigation is realized by the selection of muon-poor showers.

A search for point sources was performed for primary photon candidates, as well as for all (charged) particles. The search covers the whole

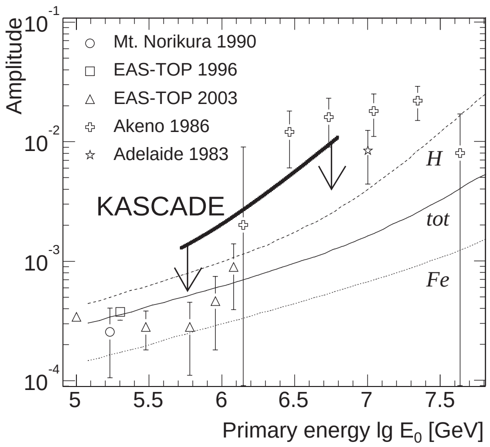

Figure 2. Rayleigh amplitudes A as function of primary energy. The KASCADE upper limit (bold line) is compared to results from the literature [10–13]. Model predictions [7] for the total anisotropy, as well as for the light and heavy component, are also shown (thin lines).

sky, visible by KASCADE (declination 15° to 80°). Special attention was drawn to the galactic plane and known gamma-ray sources in the TeV region. The search was complemented by an analysis of the most energetic showers registered and an investigation of the most photon-like primary particles. None of the searches reveals an indication for a significant excess of the flux. The distributions of the significance values over the whole sky follow the expectations for an isotropic cosmic-ray flux.

The results for the analysis of the large-scale anisotropy are illustrated in Fig.2. There, the Rayleigh amplitude is plotted versus the primary energy. The upper limit derived from the KASCADE data is compatible with other measurements from the literature and also with theoretical calculations [7] for different elemental groups.

4. ENERGY SPECTRA FOR ELEMENTAL GROUPS

The most direct experimental access to the astrophysics of cosmic rays is provided by measurements of their energy spectrum and mass composition. Investigations of the KASCADE experiment reveal that the knee in the all-particle spectrum is caused by a turn-off of the light component (protons and helium nuclei) [14]. This implies an increase of the mean logarithmic mass ($\langle \ln A \rangle$) as function of energy. While it is beyond doubt that the data reveal such an increase, the absolute values of $\langle \ln A \rangle$ depend on the observables investigated and on the interaction models used in the simulations to interpret the data [15–17]. The differences amount to about $\Delta \langle \ln A \rangle \approx 1$. This indicates that further and more detailed investigations of high-energy interactions in the atmosphere are necessary for an unambiguous astrophysical interpretation of the observed data.

Presently, the most promising approach is the unfolding of energy spectra for individual elemental groups from the data of the electromagnetic and muonic component [18–21]. Systematic studies are performed with different hadronic interaction models available in CORSIKA, for both low- and high-energy (> 80 GeV) interactions. Different unfolding methods are applied, in order to investigate the systematic effects introduced by the individual methods. The different methods result in similar flux values if the same code is used for the air shower simulation. But significant differences occur for different interaction models. This is illustrated in Fig. 3, where recent results of an analysis applying the Gold algorithm are depicted.

The figure also shows the flux of primary protons as obtained in an analysis of unaccompanied hadrons [22]. The flux is compatible with the proton flux as obtained from the unfolding procedure. For comparison, also the results of direct measurements at lower energies at the top of the atmosphere [23] are given in the figure.

The analyses indicate that, at present, the understanding of primary cosmic rays is limited by the insufficient knowledge of high-energy hadronic interactions in the atmosphere and not by too low statistics of the measurements or the systematic uncertainties introduced by different reconstruction methods.

5. CONCLUSION AND OUTLOOK

The present status of the KASCADE experiment to investigate high-energy cosmic rays in

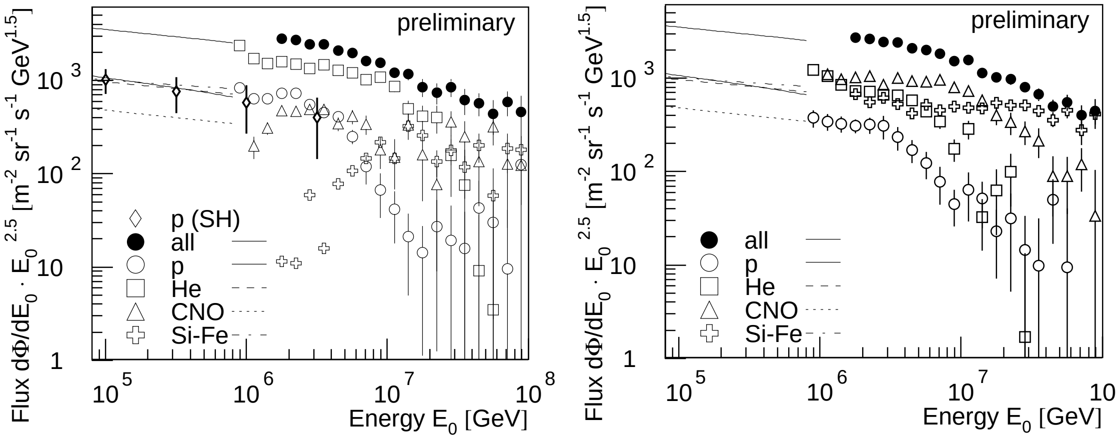

Figure 3. Energy spectra for groups of elements derived from the data using CORSIKA with the hadronic interaction models QGSJET (left) and SIBYLL (right). The lines indicate extrapolations of direct measurements [23].

the knee region has been discussed. Continuing efforts are taken in order to improve the understanding of high-energy interactions in the atmosphere. A search for point sources of charged particles as well as gamma rays did not reveal any significant excess. Upper limits for the large scale anisotropy have been derived. The observations reveal an increase of the mean logarithmic mass as function of energy in the knee region. Energy spectra for groups of elements have been derived. To extend the investigations to higher energies up to 5×10^{18} eV data taking with an enlarged array [24] was started in 2003.

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