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On the scent of the *knee* — air shower measurements with KASCADE

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Detailed investigations of extensive air showers have been performed with the data measured by the KASCADE experiment. The results allow to evaluate hadronic interaction models, used in simulations to interpret air shower data. The all-particle spectrum of cosmic rays and their mass composition, as well as individual spectra for groups of elements have been reconstructed. The results suggest, the *knee* in the all-particle cosmic-ray energy spectrum is caused by a rigidity-dependent cut-off of individual element groups.

1. INTRODUCTION

The earth's atmosphere is continuously 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. The flux spectrum follows a power law $dN/dE \propto E^{-\gamma}$ over many decades in energy. The most prominent feature is the *knee* in the spectrum around 3 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 ionized 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 upper limit coincides for primary protons 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 the interstellar magnetic fields, the only hint of their sources are their energy spectrum and the mass composition, or more preferable, the energy spectra of individual elements. Cosmic rays at energies below 1 PeV have been directly observed by balloon-borne instruments at the top of the atmosphere or in outer space. At higher energies, the steep falling flux spectrum requires large detection areas or long observation periods, presently only possible in ground-based installations. These detector systems measure the secondary particles produced by cosmic rays in the

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atmosphere, the extensive air showers (EAS).

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") [1] has been built on-site at the Forschungszentrum Karlsruhe in Germany. The experiment detects the three main components of EAS 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 [2] with several muon detection systems [3]. In addition, high energetic muons are measured by an underground muon tracking detector [4].

2. INVESTIGATION OF HADRONIC INTERACTIONS

In order to obtain the mass and energy of the shower-inducing particle, measured EAS observables are compared with predictions of simulations. These simulations describe the development of an EAS in the atmosphere and, thereafter, the signal response for all individual particles hitting the detectors. A critical part 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. Below 80 GeV the codes GHEISHA and URQMD are available. One objective of the KASCADE experiment is to evaluate these models and to provide criteria for their improvement.

The hadron calorimeter is a valuable detector for testing the interaction models. The structure of the hadronic component is examined in energy and spatial coordinates. 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 an EAS, the maximum hadron energy, and the spatial distribution of the hadrons. All observables are investigated as functions of the number of electrons and muons as well as of the hadronic energy sum.

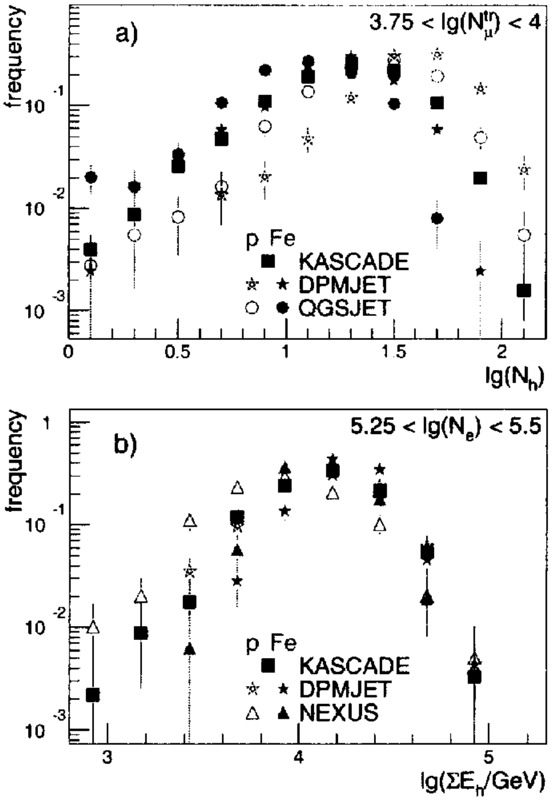

Figure 1. Frequency distribution for a) the number of reconstructed hadrons and b) their energy sum in EAS for two shower size intervals [6].

An example of such investigations is given in figure 1. Shown are frequency distributions for the number of reconstructed hadrons above 50 GeV and the hadronic energy sum for two shower size intervals for EAS with shower core inside the calorimeter. KASCADE findings are compared with predictions of the models QGSJET, DPMJET, and NEXUS for two extreme mass scenarios, the primaries being only protons or iron nuclei [6]. Combining all observables, it turned out that the model QGSJET delivers the most reliable description [6,7]. This model is used for the analyses described in the following sections.

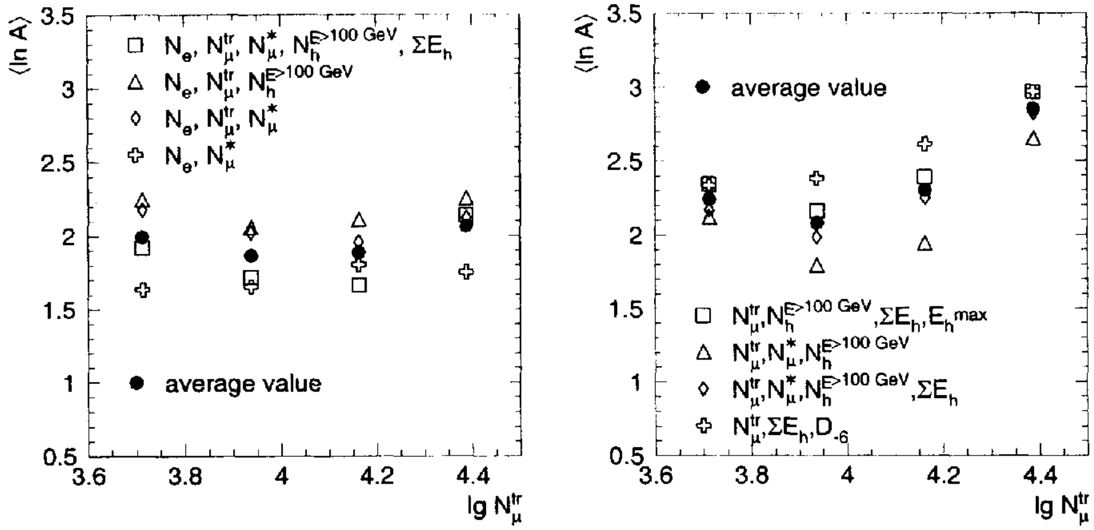

Figure 2. Mean logarithmic mass $\langle \ln A \rangle$ vs. muonic shower size N_μ^{tr} for different sets of observables [8].

3. ENERGY SPECTRA AND MASS COMPOSITION

Detailed investigations have been performed with the KASCADE data to study the influence of different observables and hadronic interaction models on the inferred cosmic–ray mass composition.

An example is shown in figure 2. In a Bayesian analysis [8], the mean logarithmic mass $\langle \ln A \rangle = \sum_i r_i A_i$, where r_i is the relative abundance of elements with mass A_i, is calculated for different combinations of observables. Several electromagnetic, muonic, and hadronic observables have been used, including number of electrons N_e and muons N_μ^{tr}, number of hadrons above 100 GeV N_h^{100}, their energy sum $\sum E_h$, the maximum energy of a hadron per shower E_h^{max}, the number of high energy muons ($E_\mu > 2$ GeV) N_μ^*, and their spatial distribution D_{-6}. The left graph summarizes results obtained including the electromagnetic shower size N_e, whereas the results in the right panel are obtained without N_e. The combinations including N_e lead to smaller $\langle \ln A \rangle$ values as compared to those without. The total spread between the results is $\Delta \langle \ln A \rangle \approx 0.8$. Similar systematic effects have been observed earlier for different hadronic observables [9]. These discrepancies are most probably caused by inconsistencies in the hadronic interaction models used to interpret the EAS data.

Several analysis methods have been carried out to obtain the cosmic–ray energy spectrum. The KASCADE data show a *knee* in the electromagnetic, muonic, and hadronic shower size spectra [10]. From the size spectra, the primary energy spectrum has been derived (see e.g. [11]), including the absolute flux spectrum obtained for the first time using hadronic observables [12].

A recent analysis [13] uses electromagnetic and muonic shower size spectra in three different zenith angle bins. With a four component assumption for the mass composition of primary cosmic rays (protons, helium, CNO-group, and iron group), an unfolding algorithm is applied, taking into account shower fluctuations and experimental effects. The hadronic interactions have been simulated using the model QGSJET above 80 GeV and the GHEISHA code below. Individual energy spectra for the four mass groups are obtained as shown in figure 3. Each spectrum shows a *knee*–like structure. The energy dependence of these cut–offs suggests a rigidity–dependent behaviour.

The mean logarithmic mass calculated from the individual energy spectra is shown in figure 4, in-

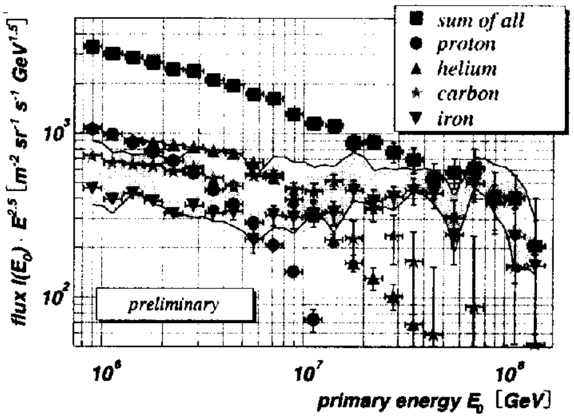

Figure 3. Cosmic ray energy spectrum for four groups of elements and the resulting all-particle spectrum [13].

dicating an increase of the average mass above the *knee*.

4. CONCLUSION

The EAS observables obtained by KASCADE are sensitive to hadronic interaction models used in simulations to interpret EAS data. At present, the combination CORSIKA/QGSJET best describes the measurements. The systematic dependence of the mean logarithmic mass on different observables and models has been investigated. The systematic error for the model QGSJET is in the order of $\Delta\langle\ln A\rangle \approx 0.8$. The reconstruction of individual energy spectra for groups of elements indicate a rigidity dependent cut–off, which explains the *knee* in the all particle cosmic–ray flux spectrum.

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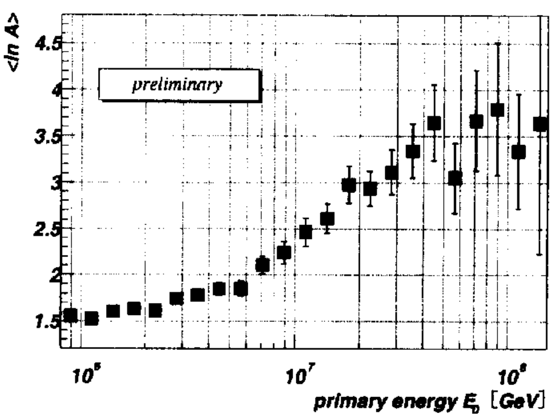

Figure 4. Mean logarithmic mass vs. energy calculated from individual spectra for four groups of elements as shown in figure 3 [13].

REFERENCES

1. H.-O. Klages et al., Nucl. Phys. B (Proc. Suppl.) 52B (1997) 92.
2. J. Engler et al., Nucl. Instr. and Meth. A 427 (1999) 528.
3. H. Bozdog et al., Nucl. Instr. and Meth. A 465 (2001) 455.
4. P. Doll. et al., Nucl. Instr. and Meth. A 367 (1995) 120.
5. D. Heck et al., Report FZKA 6019 (1998).
6. J. Milke et al., Proc. 27th Int. Cosmic Ray Conf., Hamburg 1 (2001) 241.
7. T. Antoni et al., J. Phys. G 25 (1999) 2161.
8. T. Antoni et al., Astropart. Phys. 16 (2002) 245.
9. J.R. Hörandel et al., Proc. 16th Europ. Cosmic Ray Symp., Alcala de Henares (1998) 581.
10. R. Glasstetter et al., Proc. 16th Europ. Cosmic Ray Symp., Alcala de Henares (1998) 563.
11. R. Glasstetter et al., Proc. 26th Int. Cosmic Ray Conf., Salt Lake City 1 (1999) 222.
12. J.R. Hörandel et al., Proc. 26th Int. Cosmic Ray Conf., Salt Lake City 1 (1999) 337.
13. H. Ulrich et al., Proc. 27th Int. Cosmic Ray Conf., Hamburg 1 (2001) 97.