KASCADE-Grande measurements of energy spectra for elemental groups of cosmic rays

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Abstract: The KASCADE-Grande experiment, located at KIT-Karlsruhe, Germany, consists of a large scintillator array for measurements of charged particles, $N_{\mu}$, and of a array of shielded scintillation counters used for muon counting, $N_E$. KASCADE-Grande is optimized for cosmic ray measurements in the primary energy range $10^{16}$ eV to $10^{18}$ eV, thereby enabling the verification of a possible second knee expected at approximately $10^{17}$ eV. Exploring the composition in this energy range is of fundamental importance for understanding the transition from galactic to extragalactic cosmic rays. Following earlier studies of elemental spectra reconstructed in the first knee energy range from KASCADE data, we shall now extend these measurements to beyond $10^{17}$ eV. By analyzing the two-dimensional shower size spectrum $N_D$ vs. $N_E$, we reconstruct the energy spectra of different mass groups by means of unfolding methods. The procedure and its results, which yield a strong indication for a kink in the iron spectrum at around 80 PeV, will be presented.

Keywords: Cosmic ray, energy spectrum, composition, knee, iron knee, KASCADE-Grande

1 Introduction

The spectrum of cosmic rays follows a power law over many orders of magnitude in energy, overall appearing rather featureless. However, there are a few structures observable. In 1958 Kulikov and Kristiansen [1] discovered a distinct steepening in the spectrum at around $10^{15}$ eV. Three years later Peters [2] concluded that the position of this kink, also called the cosmic ray “knee”, will depend on the atomic number of the cosmic ray particles if their acceleration is correlated to magnetic fields. Round about half a century later, the KASCADE experiment [3] clarified that this change in spectral index is caused by a decrease of the so far dominating light1 component of cosmic rays [4]. This result was achieved by means of an unfolding analysis disentangling the manifold convoluted energy spectra of five mass groups from the measured two-dimensional shower size distribution of electrons and muons at observation level. Based on the high energy interaction model QGSJET 01 [5] it was shown, that the kink in the all-

1. The description “light” refers to the atomic mass of the cosmic ray particles, which are primarily nuclei.
KASCADE-G RANDE MEASUREMENTS OF ENERGY SPECTRA


proximately 1 318 (Fe) nuclei, from (H), helium (He), carbon (C), silicon (Si) and iron of five2 cosmic ray mass groups, represented by hydro-

The analysis’ objective is to compute the energy spectra of five2 cosmic ray mass groups, represented by hydro-

The convolution of the sought-after differential fluxes \(dJ_n/\text{d} \log E\) of the primary cosmic ray nuclei \(n\) into the measured number of showers \(N_i\) contributing to the cell \(i\) of shower size plane, and thus to the content of this specific

charged particle and muon number bin \((\log(N_{ch}), \log(N_{\mu}))\)

\begin{equation}
N_i = \sum_{n=1}^{N_n} \int \int \int \frac{dJ_n}{\text{d} \log E} p_n \text{d} \log E \cos \theta \text{d}A \text{d}\Omega \text{d}t,
\end{equation}

with

\begin{equation}
p_n = p_n \left((\log(N_{ch}), \log(N_{\mu})) \mid \log E\right).
\end{equation}

One has to sum over all \(N_n\) elements contributing to the all-particle cosmic ray spectrum, in this analysis the five representative primaries. \(T_m\) is the measurement time, \(\Omega_{\text{tot}}\) the total solid angle accessible for the experiment and used for the analysis, and \(A_f\) the chosen fiducial area. The term \(p_n\) represents the conditional probability to reconstruct a certain combination of charged particle and muon number, respectively to get an entry in the cell \((\log(N_{ch}), \log(N_{\mu}))\), if the air shower inducing particle was of the type \(n\) and had an energy of \(E\). More precisely, \(p_n\) itself is a convolution combining the intrinsic shower fluctuations occurring whilst the air shower development, the detection and reconstruction efficiency as well as the properties of the observables’ reconstruction process. The cosine term in \(\cos \theta \text{d}A\) accomplishes the transformation from the horizontal surface element to the effective detection area.

Equation (1) can mathematically be understood as a system of coupled integral equations referred to as Fredholm integral equation of first kind. There are various methods to solve such an integral equation, albeit a resolvability often doesn’t per se imply uniqueness. In some preliminary tests it was found, that the unfolding algorithm of Gold [8] yields appropriate and robust solutions. It is an iterative procedure and de facto related to a minimization of a chi-square function. For countercheck purposes all results are validated by means of two additional algorithms, an also iterative method applying Bayes’ theorem [9] performing very stable, too, and an regularized unfolding based on a combination of the least-squares method with the principle of reduced cross-entropy [10], that yields slightly poorer results. All these solution strategies have in common that the response’s function \(p_n\) of Eq.(1) has to be known a priori. It is parametrized based on Monte Carlo simulations. The air shower development is simulated by means of CORSIKA [11] 6.307 based on the interaction models QGSJET-II-02 [12] and FLUKA 2002.4 [13]. The experiment’s response is simulated using CRES5 1.16/07, which bases on GEANT 3.21 [14] detector description and simulation tool.

2. Due to effects of limited resolution not any number of mass groups can be treated.

3. Most of the cuts, e.g. the chosen zenith angle range, are also applied to the simulated air showers.

4. Also named kernel or transfer function; and more precisely it is rather a matrix than a simple function.


Vol. 1, 228
3 Error analysis

The determination of the elemental energy spectra will be subjected to influences of different error sources. They can roughly be classified in two categories: uncertainties induced, or at least appearing whilst the deconvolution process and those embedded in the computed response function caused by the limited Monte Carlo statistics.

3.1 Uncertainties whilst the deconvolution

Firstly, the used data set is only a small sample based on a limited exposure, and hence suffering from statistical uncertainties. They are propagated through the unfolding algorithm and affect the quality of the solution. Furthermore, the used deconvolution method itself can introduce a systematic bias. The influences of both sources can be evaluated by means of a frequentist approach. Assuming appropriate spectral indices some trial elemental energy spectra are specified based on which a test data sample can be generated using Eq.(1). Subsequently, these data samples are unfolded. Since the true solution is a priori known, the deconvolution result can be compared to it to reveal statistical fluctuations induced by the limited measurement time and a possible systematic bias induced by the unfolding method.

3.2 Influences of limited Monte Carlo statistics

The amount of simulated air showers is strongly limited by reason of computing time. Due to the limited Monte Carlo statistics, the computation of the response function, i.e. the parametrization of the intrinsically shower fluctuations as well as of the detector properties, will only be possible under certain uncertainties resulting in a systematic error of the finally unfolded solution. In Fig. 2 exemplarily the simulated charged particle number distribution in case of hydrogen induced air showers with primary energy of $2 \times 10^{15}$ eV is shown. A scattering around the used parametrization (“normal”) can be observed. This statistical uncertainty will be treated conservatively: Considering the computed fit parameters and their errors some new sets of parameters are calculated by means of a random generator. Based on each set, new response functions can be computed and used to unfold the data. Comparing the results reveals the caused systematic uncertainty in the solution. The distributions’ tails have to be inspected in more detail. Because of the very low statistics, the tails can vary within a certain range without worsen the fit result. In particular the right tail describing the fluctuations in direction to higher energies can have an important impact on the unfolded solution due to the steeply falling flux of cosmic rays. The systematic influence of the tails will conservatively be estimated by computing two additional response functions assuming in contrast to the standard case, in agreement with the statistical uncertainties, either a very fast decreasing or an elongated tail (cf. Fig. 2). Using both for a deconvolution and comparing the results yields the maximal systematic error range caused by the uncertainty in the tails description.

4 Results and conclusion

In Fig. 3 left panel the unfolded differential energy spectra of hydrogen and iron as well as the sum of the three single spectra of helium, carbon, and silicon are shown, representing respectively the fluxes of the light, heavy, and intermediate mass groups of cosmic rays. In addition, all five unfolded spectra are summed up to the all-particle flux, which is compatible to the results of other experiments (right panel) and agrees very well with the KASCADE-Grande all-particle spectrum published in [15]. The shaded band indicates the methodical uncertainties while the error bars represent the statistical error originating from the limited measurement time. With increasing energy the heavy component gets the dominant contributor to the cosmic ray composition. This agrees with the results of KASCADE [4] where a reduction of the light component beyond the first knee was found.

Both in the all-particle and the iron spectrum there is by eye a slight bending discernible at around $10^{17}$ eV. However, the change in the all-particle spectrum reveals not to be significant. In this context, one should keep in mind that this spectrum is the sum of all five elemental spectra unfolded separately, and by this is affected by their uncertainties. For the determination of the all-particle spectrum with KASCADE-Grande, there are more precise methods available, e.g. that one introduced in [15] stating a high significance for a change in the spectral index of the all-

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6. Spectral indices close to those estimated by KASCADE are used in order to have realistic ones. However, some unlikely spectra are tested, too.

7. The intermediate component was combined because of the poorer results suffering from low statistics and making the plot confusing without giving further insights.
D. FUHRMANN et al. KASCADE-G RANDE MEASUREMENTS OF ENERGY SPECTRA

Figure 3: Depicted are the unfolded energy spectra for H and Fe, a combined spectrum for He, C and Si, as well as the all-particle spectrum (left panel). The all-particle spectrum conforms well to those of other experiments (right panel).

In order to judge the possible structures in the unfolded iron spectrum, it was fitted preliminarily by a single power law. However, the resulting chi-square probability for such a featureless single power law was below 1% ($\chi^2/ndf = 18.9/7$). In Fig. 4, the residual flux between the iron spectrum shown in Fig. 3, left panel, and such a spectrum that was derived by a single power law fit is depicted in order to emphasize the deviations between the single power law and the unfolded spectrum. Additionally, the iron spectrum is now fitted by a double power law:

$$\frac{dJ(E)}{d\log E} = p_0 \times E^{p_2} \times \left(1 + \left(\frac{E}{E_{knee}}\right)^{p_1/p_4}\right)^{p_3-p_2/p_4}, \quad (2)$$

where $p_1 = \log(E_{\text{knee}}/\text{GeV}) = 7.9 \pm 0.1$ corresponds to the knee position, while $p_2 = -2.62 \pm 0.02$ and $p_3 = -3.7 \pm 0.4$ are the spectral indices below and above the knee. The sharpness of the knee structure is encoded in $p_4 = 7.0$ and was fixed without worsening the fit's quality, while $p_0$ is a free normalization parameter. This fit describes the spectrum significantly better (chi-square probability at around 30% with $\chi^2/ndf = 6.2/5$), giving strong indications for a kink in the iron flux at around 80 PeV.

Comparing the position of this potential iron knee to that for hydrogen (at around 2 PeV to 4 PeV) gives indications for a scaling of the knee positions with the charge of the nuclei rather than with their atomic mass number. This would encourage the cosmic ray acceleration models based on magnetic fields.

To summarize, there is a strong indication for a kink in the iron-like spectrum at around 80 PeV as well as for a dependence of the cosmic ray acceleration process on the charge of the nuclei, both on the premise that especially the used model QGSJET-II-02 describes the physics of hadronic interactions at these energies with a high level of reliability.

References


8. And assuming that the mass groups represented by H and Fe actually consist only, or at least primarily, of that two primaries.