Ankle-like Feature in the Energy Spectrum of Light Elements of Cosmic Rays
Observed with KASCADE-Grande


(KASCADE-Grande Collaboration)

1 Institut für Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
2 Universidad Michoacana, Instituto de Física y Matemáticas, Morelia, Mexico
3 Dipartimento di Fisica, Università degli Studi di Torino, Italy
4 Institut für Experimentelle Kernphysik, KIT - Karlsruher Institut für Technologie, Germany
5 National Institute of Physics and Nuclear Engineering, Bucharest, Romania
6 Osservatorio Astrofisico di Torino, INAF Torino, Italy
7 Universidade São Paulo, Instituto de Física de São Carlos, Brasil
8 Fachbereich Physik, Universität Wuppertal, Germany
9 Department of Physics, Siegen University, Germany
10 Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
11 National Centre for Nuclear Research, Department of Cosmic Ray Physics, Lodz, Poland
12 Department of Physics, University of Bucharest, Bucharest, Romania

(Dated: April 29, 2013)

Recent results of the KASCADE-Grande experiment provided evidence for a mild knee-like structure in the all-particle spectrum of cosmic rays at $E = 10^{16.92\pm0.04}$ eV, which was found to be due to a steepening in the flux of heavy primary particles. The spectrum of the combined components of light and intermediate masses was found to be compatible with a single power law in the energy range from $10^{16.3}$ eV to $10^{18}$ eV. In this paper, we present an update of this analysis by using data with increased statistics, originating both from a larger data set including more recent measurements and by using a larger fiducial area. In addition, optimized selection criteria for enhancing light primaries are applied. We find a spectral feature for light elements, namely a hardening at $E = 10^{17.08\pm0.08}$ eV with a change of the power law index from $-3.25\pm0.05$ to $-2.79\pm0.08$.

PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd

Keywords: ultra-high energy cosmic rays, KASCADE-Grande, air-showers

High energy cosmic rays exhibit a power law like energy spectrum with some features, which have been subject to investigations for many years. For energies above $10^{14}$ eV the flux gets too low to be measured directly, therefore one has to extract information about the primary particles from extensive air showers (EAS), for example, by measuring the secondary particles with ground-based detector arrays. The most prominent features are the steepening (knee) of the spectrum at about $4 \times 10^{15}$ eV and its recovery to a harder slope (ankle) at about $4 \times 10^{18}$ eV. The knee is due to a decrease in the flux of light primaries, as shown by the KASCADE experiment \cite{1,2} and others, e.g. the EAS-TOP installation \cite{3,4}. In case of a rigidity dependent steepening in the spectra of the different primaries, the knee in the spectrum of the heavy component should appear at an energy of around $10^{17}$ eV \cite{3,4}. According to results from the KASCADE-Grande experiment \cite{1,2} a knee-like feature in the spectrum of heavy particles is visible at $E = 10^{16.92\pm0.04}$ eV, as recently published \cite{3}. It was shown that indeed the bending in the all-particle spectrum at $E = 10^{16.92\pm0.04}$ eV is caused by a decrease in the flux of the heavy component. The combined spectrum of light and intermediate primaries, however, was therein found to be compatible with a single power law.

It is generally argued (see e.g. \cite{3,11}) that the transition from galactic to extragalactic origin of cosmic rays is expected in the energy range from $10^{17}$ eV to $10^{19}$ eV \cite{11}. In these models one should expect a hardening of the proton or, more generally, light primaries component of the cosmic ray spectrum to take place below or around $10^{18}$ eV - due to the onset of the extragalactic contribu-
tion dominated by light primaries. The present study aims to search for experimental evidence for such a spec-
tral feature. We use the same reconstruction and analysis
procedures as described in [8], but with increased statis-
tics and optimized selection criteria for enhancing light
primaries.

The number of charged particles, \( N_{\text{ch}} \), and the num-
ber of muons, \( N_{\mu} \), are the observables used in this anal-
ysis. Both values are defined as total numbers of parti-
cles reaching the observation level, where a lateral dis-
tribution function is fitted to the measured densities at
the detector stations and integrated. The layout of the
KASCADE-Grande experiment is shown in Fig. 1, where
the Grande array records the number of charged parti-
cles exceeding an energy of 3 MeV by means of 37 scin-
tillation detector stations, distributed over an area of
700 × 700 m². The total number of muons is determined
by the measurements of shielded scintillation detectors
at the KASCADE array, where the threshold energy for
vertically incident muons is 230 MeV. A detailed descrip-
tion of the event reconstruction is given in [7].

A first step to increase statistics is to define a larger
fiducial area than that used in the first analysis [6] (see
Fig. 1). Since the probability to misreconstruct the num-
ber of muons increases with larger distances to the KAS-
CADE detectors and for lower energies, events with core
positions farther away from the KASCADE array are
omitted resulting in the selected fiducial area. By in-
creasing the fiducial area by 28%, we also shift the en-
ergy threshold to higher energies. This is no problem for
the present analysis, because we are mainly interested
in the development of the spectrum of light elements at
energies well above threshold. After including additional
87 complete days of data taking, the total increase in sta-
isistics is about 36% above energy of full efficiency.

An adequate combination of \( N_{\text{ch}} \) and \( N_{\mu} \) is used to es-
timate the primary energy. To classify the events into
primary mass groups, we use the ratio of \( N_{\text{ch}} \) to \( N_{\mu} \)
in terms of the parameter \( k \) (Eq. (1)). As a function of
\( \log_{10} N_{\text{ch}} \), \( k \) is centered around 0 for protons and it in-
creases with the mass of the primary particle to become
1 for iron. In the same way, the reconstructed energy for
a given \( \log_{10} N_{\text{ch}} \) increases with \( k \) from the proton energy
towards the energy for iron primaries. The \( k \) parameter is
then used in the energy-calibration-function (Eq. (3), see also reference [12]).

\[
\begin{align*}
  k &= \frac{\log_{10}(N_{\text{ch}}/N_{\mu}) - \log_{10}(N_{\text{ch}}/N_{\mu})_{\text{H}}}{\log_{10}(N_{\text{ch}}/N_{\mu})_{\text{Fe}} - \log_{10}(N_{\text{ch}}/N_{\mu})_{\text{H}}} \tag{1} \\
  \log_{10}(N_{\text{ch}}/N_{\mu})_{\text{H}} &= c_{\text{H,Fe}} \cdot \log_{10}(N_{\text{ch}}) + d_{\text{H,Fe}}, \tag{2} \\
  \log_{10}(E/\text{GeV}) &= (a_{\text{H}} + (a_{\text{Fe}} - a_{\text{H}}) \cdot k) \cdot \log_{10}(N_{\text{ch}}) + b_{\text{H}} + (b_{\text{Fe}} - b_{\text{H}}) \cdot k \tag{3}
\end{align*}
\]

\( a_{\text{H,Fe}}, b_{\text{H,Fe}}, c_{\text{H,Fe}} \) and \( d_{\text{H,Fe}} \) are obtained by fitting linear functions to the mean \( \log_{10} E_{\text{true}} \) (coefficients \( a \) and \( b \)) and to the mean \( \log_{10}(N_{\text{ch}}/N_{\mu}) \) (coefficients \( c \) and \( d \)) of simulated events as a function of the logarithm of their reconstructed number of charged particles. This has been done separately for 5 zenith angle intervals of equal exposure with the upper limits 16°, 24°, 29.9°, 35.1° and 40°, to take the shower attenuation into ac-
count. The parameters are slightly different from those used in [6], because they are determined using the larger fiducial area and taking into account the higher energy threshold. For the simulations of the air showers, the CORSIKA code [13] was used employing the QGSJET-II-2 high energy hadronic interaction model [14]. Fluka (version 2002.4) [15] was used for interactions at low en-
ergies. The systematic/statistical uncertainties in deter-
mining the all-particle spectrum as well as the energy res-
olution of the present analysis are shown in Table 1.

**TABLE I.** Energy resolution and systematic and statistical uncertainties for the all-particle spectrum are given for three
different energies. A more detailed discussion of the un-
certainties can be found in reference [12].

<table>
<thead>
<tr>
<th>Energy resolution (eV)</th>
<th>Syst. uncertainty</th>
<th>Statistical error</th>
<th>Energy resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{16.6} ) eV</td>
<td>11.6%</td>
<td>0.5%</td>
<td>22.1%</td>
</tr>
<tr>
<td>( 10^{17.0} ) eV</td>
<td>11.1%</td>
<td>1.2%</td>
<td>20.5%</td>
</tr>
<tr>
<td>( 10^{17.8} ) eV</td>
<td>24.4%</td>
<td>12.0%</td>
<td>16.1%</td>
</tr>
</tbody>
</table>
In the following, $k$ is used to separate the all-particle energy spectrum into two mass groups: the heavy (electron-poor) and the light (electron-rich) component. This is done by fitting a separation line to the simulated mean $k$-values over the reconstructed energy and comparing the calculated $k$-value of each event with the value given by the separation line. The distributions of $k$ for 5 different masses are shown in Fig. 2. Shower-to-shower fluctuations are larger for lighter primaries.

![FIG. 2. (color online). The mean values of $k$ over the reconstructed energy are shown for events simulated with QGSJet-II-2, and with zenith angles between $0^\circ$ to $24^\circ$, and five different primaries. The distributions of $k$ over $E$ are similar in adjacent zenith angle intervals. By combining two angular bins, we increase simulation statistics. The increase of systematic uncertainties is taken into account. For comparison, the measured data (empty squares) is also shown (shifted from the bin center to the right for better visibility of the error bars). The error bars represent the RMS for the measured data and the error of the mean for the simulated data. The dotted line was used in [8] to separate the events into a light and a heavy component. For an enhanced light selection on cosmic rays, the continuous line is taken for the separation, where the dashed lines depict the uncertainty of the separation, taking into account also the reconstruction uncertainty of $k$.](image1)

The dotted line was used in [8] to separate the events into a light and a heavy component. For comparison, the measured data (empty squares) is also shown (shifted from the bin center to the right for better visibility of the error bars). The error bars represent the RMS for the measured data and the error of the mean for the simulated data. The dotted line was used in [8] to separate the events into a light and a heavy component. For an enhanced light selection on cosmic rays, the continuous line is taken for the separation, where the dashed lines depict the uncertainty of the separation, taking into account also the reconstruction uncertainty of $k$.

![FIG. 3. (color online). Shown are simulated and reconstructed all-particle energy spectra using QGSJet-II and EPOS-1.99 as hadronic interaction models, where for EPOS a smaller number of events are available. For the simulations, a composition of five elements (H, He, CNO, Si, and Fe) equally abundant has been used. The combined proton and helium component for QGSJet-II and the pure hydrogen component for EPOS are also displayed. In addition, reconstructed spectra for the light component (separation between He and CNO) are shown, where in both cases the QGSJet based reconstruction and selection criteria are applied. In case of QGSJet-II the light component is reproduced, whereas for EPOS simulations the reconstructed light component shows an agreement with the initial pure proton spectrum.](image2)
resulting in a larger $k$-value. Especially helium events migrate (by calibrating with QGSJet-II) to the heavy mass group. This effect might be slightly compensated by the higher reconstructed energy of the events [8]. Using an EPOS calibration, the measured showers appear to originate from lighter primaries and of lower energy compared to the QGSJet-II calibration. Figure 3 also demonstrates that the selection of events according to the $k$-parameter does not induce any artificial structures in the spectra of light primaries. If the data are well described by QGSJet-II, then the spectrum of light primaries with the separation between He and CNO should consist mainly of protons and helium, maybe with some additional, less abundant elements between helium and carbon. This can be seen in Fig. 3 where the combined simulated proton and helium component for QGSJet-II is in good agreement with the reconstructed spectrum of light elements, which has been obtained by applying the QGSJet-II based reconstruction and selection criteria to the data simulated using QGSJet-II. Assuming that the data simulated with EPOS are closer to real data, then the measured spectrum of light particles is an almost pure proton spectrum. The simulated proton spectrum for EPOS is similar to the reconstructed spectrum of light primaries, which has been derived from EPOS generated events using again the QGSJet-II based reconstruction and selection criteria. According to QGSJet-II, the spectrum of heavy elements for the same separation would contain carbon and primaries heavier than that. For EPOS it should also contain most of the helium component.

In Fig. 4 the results of the present analysis are shown. To cross-check the results from [8], the all-particle spectrum and the spectrum of light primaries for the former used area and data are compared with the ones obtained with higher statistics from the present studies. Both all-particle spectra and spectra of light elements based on the separation between CNO and Si are in good agreement. The spectra of light and heavy particles with the separation between He and CNO are obtained using the separation-line shown in Fig. 2. The spectrum of the heavy component, which now contains also the medium mass component, exhibits a change of index at $E = 10^{16.88 \pm 0.03}$ eV and it therefore agrees inside the corresponding uncertainty with the previous result [8] at $E_{\text{knee}} = 10^{16.92 \pm 0.04}$ eV. The hardening or ankle-like feature visible in the enriched spectrum of light primaries is more prominent compared to the one that includes the CNO component. Although statistics gets quite low for the spectrum of light elements with the separation on He (obtained by a fit to the mean $k$-values for He in Fig. 2), it is obvious that it cannot be described by a single power law only. Formula (4) [19] is used for fitting the spectra of the light and heavy components:

$$\frac{dI}{dE}(E) = I_0 \cdot E^{\gamma_1} \cdot \left[1 + \left(\frac{E}{E_b}\right)^{\epsilon}\right]^{-(\gamma_1 - \gamma_2)/\epsilon},$$

$I_0$: normalization factor,
$\gamma_1/2$: index before/after the bending,
$E_b$: energy of the break position,
$\epsilon$: smoothness of the break.

As shown in Fig. 5 a change of the spectral index from $\gamma_1 = -3.25 \pm 0.05$ to $\gamma_2 = -2.79 \pm 0.08$ at an energy of $10^{17.08 \pm 0.08}$ eV is observed for the light component. The dashed lines mark the systematic error band for the separation between He and CNO obtained by using the selection shown in Fig. 3. The measured number of events
above the bending is \( N_{\text{meas}} = 595 \). Without the bending we would expect \( N_{\text{exp}} = 467 \) events above this ankle-like feature. The Poisson probability to measure at least \( 286 \) \( N_{\text{meas}} \) events above the bending, if \( N_{\text{exp}} \) events are expected, is \( P(N \geq N_{\text{meas}}) = \sum_{k=N_{\text{meas}}}^{\infty} \frac{N_{\text{exp}}^k e^{-N_{\text{exp}}}}{k!} \approx 7.23 \times 10^{-69} \). This corresponds to a significance of 5.8 \( \sigma \) that in this energy range the spectrum of light primaries cannot be described by a single power law. If we shift the separation criteria in order to obtain an even purer proton sample (sep. on He, fig. 4) the slope difference cannot be described by a single power law. If we shift the separation criteria in order to obtain an even purer proton sample (sep. on He, fig. 4) the slope difference even increases (\( \gamma_1 = -3.32 \pm 0.03 \) to \( \gamma_2 = -2.59 \pm 0.28 \) at an energy of \( 10^{17.16 \pm 0.19} \) eV).

So far, possible uncertainties due to the underlying hadronic interaction model have not been taken into account. But, as discussed in [20], applying different methods in energy calibration does not result in different conclusions on changes of the spectral slopes. Spectral slopes do not significantly change, when corrections for the bin-to-bin fluctuations (i.e. by unfolding methods correcting the reconstruction uncertainties) are applied [16]. Therefore, it is not expected that such a correction would result in a spectrum of light primaries compatible with a single power law.

One important observation is that the knee in the heavy component occurs at a lower energy compared to the bending in the spectrum of light primaries. This is still the case, if the break positions are shifted by their uncertainties. Therefore, the steepening of the heavy spectrum and the recovery of the light component is not due to a bias in the reconstruction or separation procedures. In addition, such a bias should result in a bending in the spectrum of light elements at a lower energy compared to the spectrum of heavy particles: a bias in the separation would be visible in the spectrum of light particles first, because its flux is much smaller. A bias in the reconstruction, where the calculated \( k \)-value is too low, would result in a recreation of heavy particles as light particles with a lower energy. It is worth to point out that the slope of the heavy mass spectrum above the knee-like feature is very similar to the slope of the light mass spectrum before the ankle-like feature. This could be a hint to a similar source population, as described e.g. in [21]. Correspondingly, the slope index of \( \gamma_2 = -2.7 \) might be an indication of an injection spectrum of a new (extragalactic) source population of high energy cosmic rays [21].

In summary, after redefining what is considered as a electron-poor/electron-rich event and increasing the statistics, a significant hardening, i.e. an ankle-like feature in the cosmic ray spectrum of light primaries, is observed at \( E = 10^{17.08 \pm 0.08} \) eV. The slope index of the underlying power law changes at this energy from \( -3.25 \pm 0.05 \) to \( -2.79 \pm 0.08 \), which might be an indication that the transition from galactic to extragalactic origin of cosmic rays starts already in this energy range.

ACKNOWLEDGMENTS

The authors would like to thank the members of the engineering and technical staff of the KASCADE-Grande collaboration, who contributes to the success of the experiment. The KASCADE-Grande experiment was supported by the BMBF of Germany, the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education, and the Romanian Authority for Scientific Research UEFISCDI (PNII-IDEI grants 271/2011 and 17/2011). J.C.A.V acknowledges the partial support of CONACyT and the DAAD-Proalnex program (2009-2012). The present study is supported by the 'Helmholtz Alliance for Astroparticle Physics - HAP' funded by the Initiative and Networking Fund of the Helmholtz Association, Germany.

---


