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Reconstruction of primary mass group energy spectra with KASCADE

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Abstract: The KASCADE-Grande experiment was designed for the measurement of extensive air showers induced by cosmic rays of the knee region, i.e. with energies between 0.5 PeV and 1 EeV. Main focus of the experiment is the precise determination of energy and composition of the primary cosmic rays, thus clarifying the nature of the knee. Data of the preceding KASCADE experiment have been used in a composition analysis[1], proposing the knee to be caused by a steepening in the light-element spectra. Furthermore, the analysis identified insufficiencies of the simulations and the interaction models used therein in describing the considered data. In the following, an update on the analysis will be presented.

Introduction

Even though the majority of recent air shower experiments aims at the highest energy (well above 10^{19} eV), the much lower PeV-range is still of considerably interest. Here, at an energy of approx. 4 PeV, a sudden steepening of the energy spectrum occurs, which is refered to as the so-called *knee* of cosmic rays. Hypotheses for its origin range from astrophysical scenarios, like changing acceleration mechanisms or escape from the Galaxy, to particle physics models. For restricting or even rejecting different models, detailed knowledge about the energy dependent chemical composition of cosmic rays is necessary.

At present, measurements in the knee region are only possible by the detection of extensive air showers (EAS) induced by primary cosmic-ray particles. While gaining statistical significance by this approach, any reconstructed properties of the primary particles have to rely on simulations and the description of high energy hadronic interactions used therein. By nature, these interaction models have to be phenomenological and differ in their predictions. In this sense any thorough analysis of EAS data offers the opportunity of testing and improving high energy interaction models.

The KASCADE experiment[2], precursor and now part of the KASCADE-Grande experiment[3], aims at these questions. By analyzing the KASCADE key observables (electron and muon shower size) a strong dependence of the result for the elemental abundances on the used interaction model was demonstrated[1]. In addition, an insufficient description of the data by the considered simulations could be revealed.

In the following, an update on this composition analysis is given with special emphasis on the influence of the low energy interaction model. Furthermore, the analysis was repeated for data of different zenith angle intervals, thus testing for consistency of the procedure. A brief discussion of the properties of simulations using the new EPOS[4] model finally concludes this article.

Outline of the analysis

Starting point for the analysis is the number of measured EAS depending on electron number $\lg N_e$ and muon number $\lg N_\mu^{tr}$ (muons with core distances between 40 m and 200 m), the so-called two-dimensional shower size spectrum. For showers inside the KASCADE array and with inclination less than 18° this spectrum is also shown in Fig. 3. The content N_j of each histogram cell j is

$$N_j = C \sum_{A=1}^{N_A} \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A \, d\lg E. \qquad (1)$$

C is a normalizing constant (time, aperture). The sum is carried out over all primary particle types of mass A. The functions $p_A = p_A(\lg N_{e,j}, \lg N_{\mu,j}^{tr} | \lg E)$ give the probability for an EAS of primary energy E and mass A to be measured and reconstructed with shower sizes $N_{e,j}$ and $N_{\mu,j}^{tr}$. The probabilities p_A include shower fluctuations, efficiencies, and reconstruction systematics and resolution. For reasons of clarity integration over solid angle and cell area is omitted in Eqn. 1, but taken into account.

With this notation the two-dimensional size spectrum is interpreted as a set of coupled integral equations. This set can be solved for the primary energy spectra $\frac{dJ_A}{d\lg E}$ by the application of unfolding algorithms. In the analysis the particles H, He, C, Si, and Fe were chosen as representatives for five mass groups of primary cosmic ray particles. The corresponding probabilities p_A were determined by Monte Carlo simulations using COSRIKA[5] and a GEANT[6] based simulation of the experiment. Details of the procedure can be found in Ref.[1].

Using FLUKA instead of GHEISHA

In Ref.[1], the probabilities p_A were determined using the high energy interaction models QGSJet[7] (2001 version) and SIBYLL[8] 2.1 in the simulations. In both cases low energy interactions ($<$ 80 GeV) were modeled with the GHEISHA[9] code. For the present analysis, GHEISHA was replaced by the FLUKA[10] package, and only the QGSJet 01 model was used. Differences between these simulations are rather small, with nearly energy and primary independent differences of $\Delta \lg N_e \approx 0.015$ and $\Delta \lg N_\mu^{tr} \approx 0.02$ (more electrons and less muons with FLUKA).

Because of these small differences of the simulation predictions, it is not surprising, that the results of the complete unfolding analysis differ for the FLUKA case only little from those of the GHEISHA case. As an example, the results for the energy spectra of H, He, and C obtained with GHEISHA and FLUKA are compared with each other in Fig. 1. The differences between the two solution sets are small, especially in comparison with methodical uncertainties (shaded bands in the figure). In case of the heavy elements (Si, Fe) the influence is somewhat larger, but still of same or smaller order than methodical uncertainties. To summarize, the overall picture of the solution seems to be affected insignificantly by using FLUKA instead of GHEISHA.

Analysing data of different zenith angle ranges

In the presented analysis only EAS with zenith angles smaller than 18° were considered so far. Apart from increasing statistics, the analysis of more inclined shower data could serve as a consistency

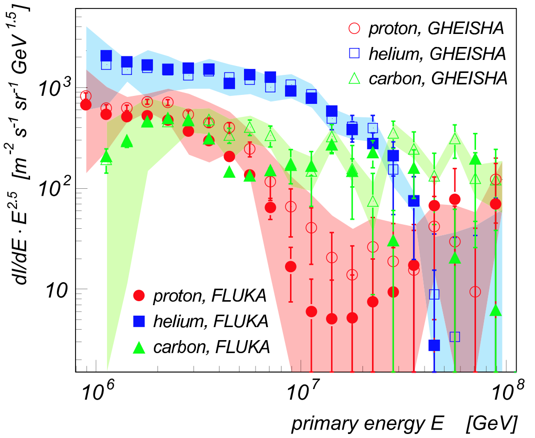

Figure 1: Results for the energy spectra of H, He, and C using QGSJet/FLUKA and QGSJet/GHEISHA based simulations. Shaded bands correspond to estimates of methodical uncertainties for the QGSJet/GHEISHA spectra.

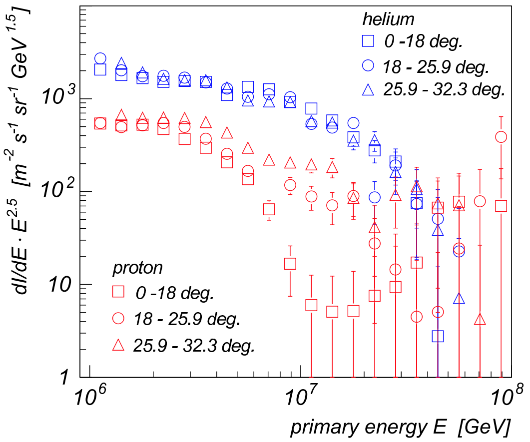

Figure 2: Energy spectra of H and He based on the analysis of EAS data originating from different zenith angle intervals. For reasons of clarity estimates of methodical uncertainties are omitted.

check. Since the data could not be described satisfactorily by the simulations (see Ref.[1]), identical results compared to the vertical data set cannot be expected. Nevertheless, strong and large differences between the solution sets would indicate a severe problem in either the simulation code or the applied analysis technique. For this kind of cross-check the QGSJet/FLUKA analysis was repeated for two more data sets of EAS with higher inclination. In the first one considered zenith angles range from 18° to 25.9°, in the second from 25.9° to 32.3°.

The results for the all-particle spectrum coincide very well inside their statistical uncertainties, only for the underlying mass group spectra small differences can be detected. For lack of space, only the results for H and He are discussed in the following. The spectra for Helium derived from the three data sets coincide inside their statistical uncertainties, as can be seen in Fig. 2. In the same figure, obvious systematic differences can be observed for the proton spectra at energies above the proton knee. Here, the change of index decreases with increasing zenith angle, i.e. gets less pronounced.

The observed systematic deviations of the solution sets to each other are small and can be understood by the increasing shower fluctuations with increasing zenith angle and shifted energy threshold due to the fixed data range in $\lg N_e$ and $\lg N_\mu^{tr}$. Therefore, no strong or unexplainable differences are found, which would hint to severe problems in the simulation or the analysis. Thus, conclusions[1] drawn from the analysis of nearly vertical showers are not affected.

New interaction model: EPOS

The most recent release of CORSIKA made the new EPOS[4] model available for the simulation of high energy hadronic interactions in EAS. Using the combination EPOS/FLUKA in CORSIKA a set of EAS similar to the ones used in the presented analyses was generated. Of special interest is the energy dependence of the shower fluctuations $s_A(\lg N_e, \lg N_\mu^{tr} | \lg E)$, describing the probability for an EAS of primary mass A and energy $\lg E$ to exhibit electron size $\lg N_e$ and muon size $\lg N_\mu^{tr}$ at observation level. Figure 3 compares the positions of the maxima of these distributions for proton and iron induced EAS using EPOS, QGSJet 01, and SIBYLL 2.1. For orientation, the two-dimensional electron and muon size spectrum is also shown.

It can be seen from the figure, that for each model the lines, which correspond to the most probable values of the shower sizes, belonging to different

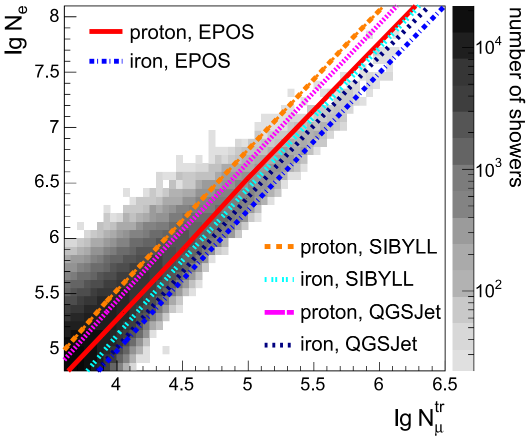

Figure 3: Predictions for the most probable values of proton and iron induced showers using QGSJet 01 and EPOS in the simulations. In addition the two-dimensional KASCADE shower size spectrum of $\lg N_e$ and $\lg N_\mu^{tr}$ is shown.

primary particle types are nearly parallel. Furthermore, the same holds for lines corresponding to QGSJet and SIBYLL simulations. A QGSJet line ”could be shifted” into a SIBYLL line. For EPOS simulations, this is no longer the case. The most-probable-lines exhibit a different slope as compared to QGSJet and SIBYLL. It is interesting to note, that the iron-lines of EPOS and QGSJet lie on each other at small shower sizes ($\approx$ 1 PeV). With increasing shower sizes, EPOS predictions for iron induced EAS resemble EAS induced by ultra-heavy primaries in the QGSJet framework.

A closer inspection reveals, that for high energies (around 10^{18} eV) the EPOS most-probable-line for proton induced EAS seems to cross the SIBYLL line for iron induced showers. This could alter any composition analysis at higher energies drastically.

Conclusions

In parallel to measurements and analyses with KASCADE-Grande[11], composition analyses with KASCADE data are ongoing. Besides the cross-check of the conducted composition analysis with data from different zenith angle intervals, the influence of the low interaction model (replacing GHEISHA by FLUKA) has been investigated.

It could been shown, that the influence of this replacement on the results of the analysis is small.

First simulations using the new hadronic interaction model EPOS have been carried out, indicating new and interesting properties of EAS predictions. Results of a complete unfolding analysis using EPOS will be published soon. Moreover, in the future this kind of analysis will give further information on the validity of hadronic interaction models and for their improvement.

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