ENERGY SPECTRA AND CHEMICAL COMPOSITION OF COSMIC RAYS IN THE PEV REGION

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Recent results from the KASCADE experiment on measurements of cosmic rays in the energy range of the knee are presented. Emphasis is placed on energy spectra of individual mass groups as obtained from sophisticated unfolding procedures applied to the reconstructed electron and truncated muon numbers of EAS. The data clearly show a knee in the energy spectra of the light primaries (p, He, C) and an increasing dominance of heavy ones ($A > 20$) toward higher energies. This basic result is robust against uncertainties of the applied interaction models QGSJET and SIBYLL. Slight differences observed between experimental data and EAS simulations provide important clues for improvements of the interaction models. Astrophysical implications for discriminating models of maximum acceleration energy vs galactic diffusion/drift models of the knee will be discussed. To improve the reconstruction quality and statistics around 10^{17} eV, KASCADE has recently been extended by a factor 10 in area. The status and expected performance of the new experiment KASCADE-Grande is discussed.

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1. Introduction

A puzzling and most prominent feature of the cosmic ray (CR) spectrum is the so-called knee, where the spectral index of the all-particle power-law spectrum changes from approximately -2.7 to -3.1. Several models have been proposed in order to explain this feature shown in Fig. 1, but none of them has managed to become broadly accepted. Some of the models focus on a possible change in the acceleration mechanism at the knee [1,2,3], e.g. due to the limiting energy defined by the size and magnetic field strength of the acceleration region ($E_{\max} \lesssim Z \times (B \times L)$). Other models discuss an increased leakage of CRs from the Galaxy due to a change in the confinement efficiency by galactic magnetic fields [4,5] (see also Fig. 1). Again, this results in a rigidity scaling of the knee according to the maximum confinement energy. Finally, a third group of models attributes the effect of the knee to CR interactions at their sources, during their propagation in the Galaxy, or in the upper atmosphere. Such scenarios include nuclear photodisintegration processes by UV-photons at the sources [6], interactions of CRs in dense fields of massive relic neutrinos [7], production of gravitons in high-energy pp collisions [8], etc. A recent review about this topic can be found in Refs. [9,10].

To distinguish between these models and allowing to answer the long pressing question about the origin cosmic rays and about the knee in their spectrum, high quality and high statistics cosmic ray data are required over an energy interval ranging from at least 0.5 to 500 PeV. Due to the low flux involved, only extensive air shower (EAS) experiments are able to provide such data. In such experiments, primary CRs are only indirectly observed via their secondaries generated in the atmosphere. The most important experimental observables at ground are then the

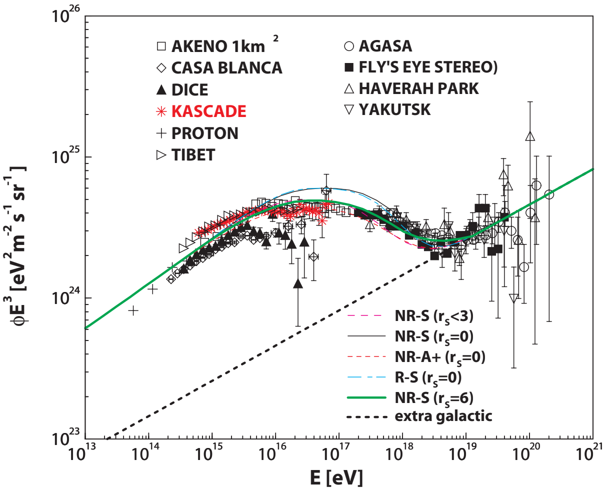

Figure 1. Compilation of the all-particle cosmic ray spectrum superimposed with results from a diffusion/drift scenario for different galactic models (Adapted from Ref. [11]).

electromagnetic (electrons plus photons), muonic, and hadronic components. In addition or alternatively, some experiments also detect photons originating from Cherenkov and fluorescence radiation of charged particles in the atmosphere. For a brief review about EAS observables and their experimental techniques the reader is referred to Refs. [12,13,10].

Unfortunately, progress on interpreting EAS data has been rather slow mostly because of two reasons: Firstly, the EAS development is driven by the poorly known high-energy hadronic interactions and their particle production in the very forward kinematical region and, secondly, due to the stochastic nature of particle interactions, most importantly the height of the very first interaction in the atmosphere, EAS are subject to large fluctuations in particle numbers at ground. To make things even more complicated, the amount of fluctuations depends, amongst others, sensitively on the primary CR energy and mass [12]. Here, it is very important to realize that EAS fluctuations are not to be mistaken as random Gaussian errors associated with the statistics in the number of particles observed at ground. The latter one can be improved by the sampling area of an EAS experiment, while the former one is intrinsic to the EAS itself, carrying - for a sample of events - important information about the nature of the primary particle. Clearly, both kinds of fluctuations have to be accounted for in the data analysis of the steeply falling energy spectrum in order to not misinterpret the observations.

2. Results from the KASCADE Experiment

KASCADE (Karlsruhe Shower Core and Array Detector) is a sophisticated EAS experiment for detailed investigations of primary CRs in the energy range of the knee. For reconstructing the CR energy and mass and for investigating high-energy hadronic interactions, KASCADE follows the concept of a multi-detector set-up providing as much complementary information as possible as well as redundancy for consistency tests. Most relevant for the results presented in this paper is a scintillator array comprising 252 detector stations of electron and muon counters arranged on a grid of 200×200 m^2. In total, it provides about 500 m^2 of e/γ- and 620 m^2 of μ-detector coverage. The detection thresholds for vertical incidence are $E_e > 5$ MeV and $E_\mu > 230$ MeV. More details about the e/γ- and μ-detectors, as well as about all the other detector components can be found in Ref. [14].

The traditional and perhaps most sensitive technique to infer the CR composition from EAS data is based on measurements of the electron (N_e) and muon numbers (N_μ) at ground. It is well known [12] that for given energy, primary Fe-nuclei result in more muons and fewer electrons at ground as compared to proton primaries. Specifically, in the energy range and at the atmospheric depth of KASCADE, a Fe-primary yields about 30 % more muons and almost a factor of two fewer electrons as compared to a proton primary. The basic quantitative procedure of KASCADE for obtaining the energy and mass of the cosmic rays is a technique of unfolding the two-dimensional electron-vs-muon number spectrum of Fig. 2 into the

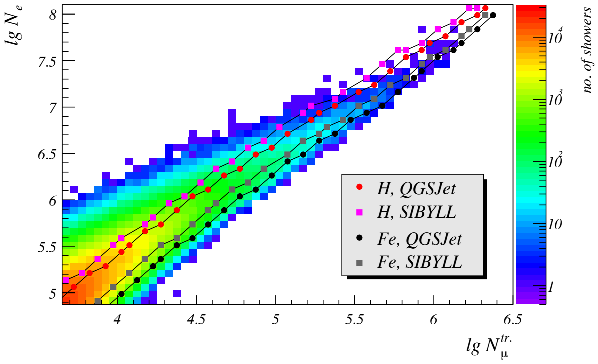

Figure 2. Two dimensional electron (N_e) and muon ($N_\mu^{\rm tr}$) number spectrum measured by the KASCADE array. Lines display the most probable values for proton and iron simulations employing two different hadronic interaction models [15].

energy spectrum of five primary mass groups [15]. The problem can be considered a system of coupled Fredholm integral equations of the form

$$\frac{dJ}{d\lg N_e \;\; d\lg N_\mu^{\rm tr}} = \sum_A \int\limits_{-\infty}^{+\infty} \frac{d\,J_A}{d\lg E} \cdot p_A(\lg N_e\,,\,\lg N_\mu^{\rm tr}\;\mid\,\lg E)\cdot d\lg E \qquad (1)$$

where the probability p_A

$p_A(\lg N_e, \lg N_\mu^{\rm tr} \mid \lg E) = \int\limits_{-\infty}^{+\infty} k_A(\lg N_e^t, \lg N_\mu^{\rm tr,t}) d\lg N_e^t \; d\lg N_\mu^{\rm tr,t}$

is another integral equation with the kernel function $k_A = r_A \cdot \epsilon_A \cdot s_A$ factorizing into three parts. Here, r_A describes the shower fluctuations, i.e. the 2-dim distribution of electron and muon number for fixed primary energy and mass, ϵ_A describes the trigger efficiency of the experiment, and s_A describes the reconstruction probabilities, i.e. the distribution of N_e and $N_\mu^{\rm tr}$ that is reconstructed for given true numbers N_e^t, $N_\mu^{\rm tr,t}$ of electrons and muons. The probabilities p_A are obtained by parameterizations of EAS Monte Carlo simulations for fixed energies using a moderate thinning procedure as well as smaller samples of fully simulated showers for the input of the detector simulations.

The procedure is tested by using random initial spectra generated by Monte Carlo simulations. It has been shown [15] that knee positions and slopes of the initial spectra are well reproduced and that the discrimination between the five primary mass groups is sufficient. For scrutinizing the unfolding procedure, different mathematical ways of unfolding (Gold-algorithm, Bayes analyses, principle of maximum entropy, etc.) have been compared and the results are consistent [15]. The application of the unfolding procedure to the data is performed on basis of two different hadronic interaction models (QGSJET [16] and SIBYLL [17]) as option embedded in CORSIKA [18] for the reconstruction of the kernel functions [15,19].

The result of the unfolding is presented in Fig. 3 for each of the interaction mod-

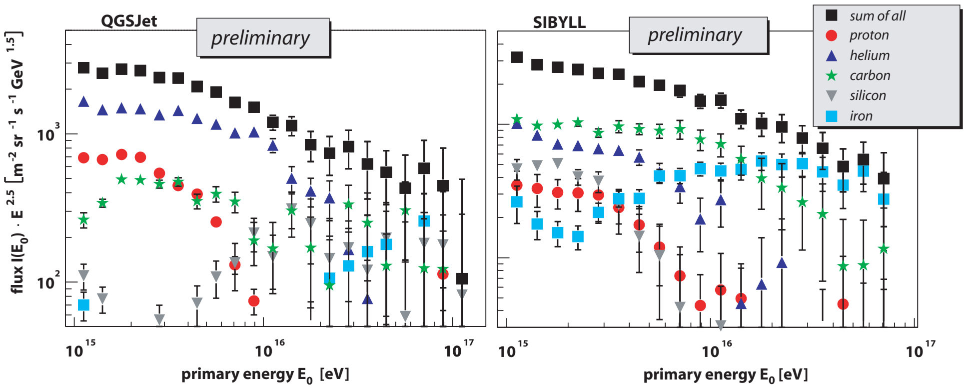

Figure 3. Results of the unfolding procedure using QGSJET (left) and SIBYLL (right) as hadronic interaction model [15].

els. Clearly, there are common features but also differences in the energy distributions obtained with the two interaction models. The all-particle spectra coincide very nicely and in both cases the knee is caused by the decreasing flux of the light primaries, corroborating results of an independent analysis of Ref. [20]. Tests using different data sets, different unfolding methods, etc. show the same behaviour [19]. As the most striking difference, SIBYLL suggests a more prominent contribution of heavy primaries at high energies. This difference results from the different N_e-$N_\mu^{\rm tr}$ correlation seen in Fig. 2, i.e. SIBYLL predicts higher electron and lower muon numbers for given primaries as compared to QGSJET. In order to judge which of the two models provides a better representation of the data, the respective forward folded two-dimensional N_e vs $N_\mu^{\rm tr}$ distributions can be compared to the actual input data of Fig. 2. Such an analysis demonstrates that SIBYLL encounters problems in describing the high-N_e - low-$N_\mu^{\rm tr}$ tail of the experimental data at 10 PeV and above[15]. If not being prepared to accept a significant contribution of very heavy primaries ($A > 60$) in case of SIBYLL simulations, the results point to a muon deficit (a/o electron abundance) in this model. Definitely, this problem needs further attention and is very important also for composition studies at higher energies [21].

With this caveats kept in mind, the KASCADE data favor an astrophysical interpretation of the knee and are in agreement with a rigidity scaling of the knee position for different primaries. Similar results were very recently obtained from combined EAS-TOP / MACRO measurements [22], though for two mass groups only. Within the given error bars, the mean logarithmic masses of both experiments agree well with one another.

Discriminating models of maximum acceleration energy from galactic diffusion/drift models of the knee requires detailed inspection of the smoothness of the individual knee structures seen in the mass groups. Given the present uncertainties of the interaction models, such analyses may have to await better EAS simulations. Alternatively, studies of large scale anisotropies of CRs as a function of energy or

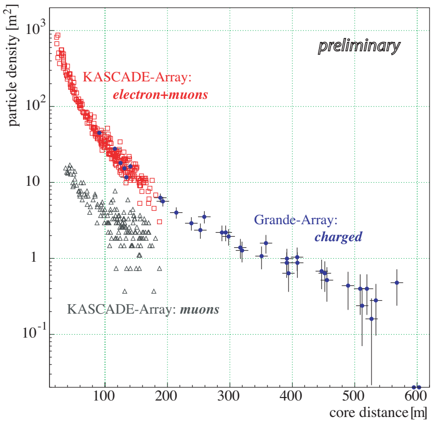

Figure 4. Particle densities observed with different detector components of KASCADE-Grande in a single EAS.

searches for point sources can be performed. Very recently, KASCADE has published results on this topic [23,24]. Inside the statistical limits no deviations from global anisotropy or signals from point sources were found.

3. Status of KASCADE-Grande

The upper energy range of KASCADE is - besides event statistics - mostly given by its sensitive area of 200×200 m^2 limiting the reconstruction quality of the highest energy events. To improve the situation for EAS beyond 10^{17} eV, KASCADE has recently been extended to KASCADE-Grande by an installation of additional 45 detector stations (37 as *Grande* array plus 8 as *Piccolo* trigger array) over an area of $700 \times 700\,\mathrm{m}^2$. In the present configuration KASCADE-Grande consists of $965\,\mathrm{m}^2$ of scintillator area for the electron component, of $1070\,\mathrm{m}^2$ for measuring muons at four different thresholds, and of $300\,\mathrm{m}^2$ for hadron detection. Thus, KASCADE-Grande displays the full capability of a multidetector experiment with much better muon sampling than any previous EAS experiment in this energy range [25]. Data taking has started in July 2003 and an example of lateral particle density distributions observed in a single EAS is shown in Fig. 4. The data quality and detector performance is evident. Not shown are muon densities measured additionaly with the KASCADE central detector and with the muon tracking detector. Sensitivity to the primary mass is again given by the electron-muon density measurements as well as by reconstructions of the muon production height by means of triangulation.

4. Summary and Outlook

KASCADE has provided a wealth of new high quality EAS data in the knee region giving important insight into the origin of the knee and of CRs in general. Conclusive evidence has been reached on the knee being caused by the light primaries mostly. Furthermore, the data are in agreement with a rigidity scaling of the knee position giving support to an astrophysical origin by either maximum acceleration or diffusion/drift models of propagation. More data and more observables are being analysed, particularly composition analyses employing reconstructions of the muon production height. Together with measurements of energetic hadrons in the central calorimeter, the unfolding technique of electron and muon numbers in EAS has become a powerful tool to reconstruct the properties of primary particles in EAS and to help improving high-energy hadronic interaction models.

KASCADE-Grande has just started data taking and will extend the measurements to 10^{18} eV, thereby allowing to verify the existence of the putative Iron knee marking the so-called second knee in the all-particle CR spectrum.

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