Energy Spectrum and Mass Composition around the Knee by EAS Measurements‡

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Abstract. Primary cosmic ray particles above energies of about 100 TeV are investigated by large-area ground based detector installations, observing various components of the development of extensive air-showers (EAS). By such an indirect access to the primary cosmic ray spectrum a steepening of the power-law falls off at around 3-5 PeV, known as the knee has been identified. Different experimental techniques are used to deduce mass- and energy-sensitive observables of EAS experiments. The experiments involve measurements of secondary particle distributions at various observation levels and of muons deep underground as well as of observables reconstructed by measuring the air Cherenkov light emitted with the shower development in the atmosphere. Recently methods for analysing multidimensional distributions get favoured since they are able to take into account the correlations between different observables and the influence of large intrinsic fluctuations of the air-shower development. Additionally the use of a larger set of observables provides the possibility to test simultaneously the consistency of the Monte-Carlo models underlying the reconstruction procedures. By many experiments the existence of the knee in the primary energy spectrum is confirmed and a tendency of an increasing mean mass above the knee energy is indicated. Recent results show that the knee originates from a decrease of the flux of light primary particles, whereas heavy cosmic ray particles seem to miss a kink in the energy range of 1 and 10 PeV.

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1. Introduction

The knee of the primary cosmic ray (CR) energy spectrum has been discovered by Khrustiansen and Kulikov [1] in the year 1958. In their first conclusion the discoverers claimed that the kink in the spectrum is a consequence of the superposition of cosmic rays of galactic and supergalactic origin. Two years later B. Peters pointed out with a theoretical argumentation that the position of the knee should get shifted in proportion to the charge of the primaries if magnetic fields would be responsible for the acceleration of the CR [2]. For the following 40 years a lot of experiments [3] confirmed the kink in the energy spectrum (i.e. the change of the power-law index), displayed by various observables mapping the primary spectrum. Also astrophysical models

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accounting for such a kink got more detailed. Nevertheless the key questions of the origin of the knee are still not convincingly solved. The ideas vary from astrophysical reasons like rigidity cut-off at the acceleration, rigidity dependent escape from our galaxy, or the single-source model predicting a dominance of the flux at the knee by particles coming from a nearby supernova to a scenario adopting a new channel of the primaries interaction producing new unobserved particles carrying away some energy. Many of these ideas and conjectures predict a detailed shape of the primary cosmic ray spectrum around the knee with specific variations of the elemental composition. Thus the experimental access to attack the basic questions are detailed and accurate measurements of the energy spectra of the various cosmic ray primaries, which imply also a determination of the energy variation of the CR mass composition.

It should be emphasised that all measurements around the knee are only of indirect character, i.e. the observation of primary CR is based on the interpretation and reconstruction of extensive air-showers (EAS). These techniques require a good knowledge of the shower development in the atmosphere and of the interaction mechanisms of high-energy particles with air-molecules. Extensive Monte Carlo simulation procedures are used for these purposes. For the high-energy hadronic interactions more or less bold extrapolations from lower energies, formulated as theoretical models and parameterizations, are at disposal. For the knee-energies accelerator data are not yet available (though the Tevatron collider is now close to the knee-energies) neither for relevant target-projectile combinations nor for the kinematic region of extreme forward interactions. This situation leads to an uncertainty of unknown order, in some sense only to be estimated by using same reconstruction procedures based on the different hadronic interaction models. Though in the last years the improved understanding of the high-energy hadronic interaction has reduced larger disagreements in predictions of air-shower observables, it remains unclear if there are common systematic uncertainties in the interaction models by unknown features and interaction paths, not yet considered. Hence results of air-shower experiments around the knee region may be considered in three categories:

i) Information on the primary energy spectrum and chemical composition in absolute scale.

ii) Phenomenological information with a minimised influence of the Monte Carlo simulations, but with general results for the understanding of the origin of the knee.

iii) Proofs and tests of Monte Carlo models by using redundant information of the experimental investigations.

The concern to the latter aspect has been emphasised in last years by invoking the possibilities of multi-detector setups. The validity of the hadronic interaction models used as generators of Monte Carlo simulations has got an important subject in context of EAS analyses. Here a co-operation between present and future accelerator experiments and the cosmic ray investigations is aspired. Some recent initiatives have been started to establish such interrelated efforts, e.g. the NEEDS (Needs from Accelerator Experiments for the Understanding of High-Energy Extensive Air-Shower) workshop, held in Forschungszentrum Karlsruhe in April 2002, where physicists of both the high-energy accelerator and the cosmic ray communities commonly discussed about future possibilities of mutual assistance and exchange of relevant data.
2. The all-particle cosmic ray energy spectrum

The reconstruction of the all-particle energy spectrum from air-shower measurements was proceeded over many years with basically similar experimental devices and procedures: An array of detectors spread over an area of several thousands of square-meters measures particle and/or Cherenkov light densities. The lateral density distributions and integral quantities of them are analysed (adopting some experiences gained by Monte Carlo simulations) to infer the primary energy of the incident particles, either for single events or more often for the average of the measured distributions. These procedures require a-priori assumptions of the elemental composition, since the lateral distributions and total intensities differ for different primary masses of the shower inducing particle. The idea is to realise a calorimetric determination of the energy of shower cascades by the total Cherenkov light intensity produced in the atmosphere or by the total number of (charged) particles at a certain observation level. The determined quantities are assumed to be proportional to the primary energy.

Typical examples of such measurements are presented by the energy spectra obtained by the Akeno [16] and Tibet [17] detector arrays. Both experiments use a field of scintillation detectors to measure the charged particle component. Akeno converted the obtained size of the showers into the primary energy by help of EAS results measured at observation levels of high altitude (conversion in N_{\text{max}}^{\text{EAS}}) and a theoretically anticipated parameter for the dependence of the shower size maximum from the primary energy. Tibet uses Monte Carlo simulations for fitting the obtained size spectrum introducing the elemental composition as free parameters. The two energy spectra from the two different experiments (see Fig. 1) differ by the position and the

![Figure 1. Compilation of different experimental results on the cosmic ray all-particle energy spectrum around the knee. The effect of a 15% uncertainty in energy reconstruction is indicated. (Refs.: Akeno [16], Tibet [17], MSU [18], HEGRA [19], DICE [20], Casa-Mia [21], Blanca [22], Gamma [23], EAS-TOP [24], Yakutsk [25], Norikura [26], Tunka [27], KASCADE [28, 29, 30], compilation of direct data by Watson [31].)
sharpness of the knee: Akeno attained a much sharper knee at an energy position higher than the results of the Tibet experiment show. Such differences are subject of current discussions.

Fig. 1 compiles the energy spectra obtained by various different experiments. Most of them use for the reconstruction of the energy a single observable like the EAS size and convert the obtained size spectrum with help of Monte Carlo simulations. In contrast, the multi-detector setup of the KASCADE experiment e.g. enables to determine both the electron and muon sizes of each single EAS event. Various methods are applied to reconstruct the primary energy spectra in a consistent way using both informations simultaneously. In this manner the correlated uncertainty on energy and mass gets disentangled. A common fit to the electron and muon size spectra with the assumption of two primary mass group spectra following two power laws with a knee (8 free parameters: spectral indices below and above the knee, the knee position, and the normalization factors for the light and heavy spectra, respectively) leads to the energy spectra of the two components and the all-particle energy spectrum as sum \[29\]. The fit is based on a Fredholm integral with the detector response function as kernel. This response function is prepared by detailed Monte Carlo calculations including a full simulation of the detector properties. A step forward is the application of an unfolding procedure on the two size spectra \[30\] leading to the mass group spectra of four components. A further analysis using the two sizes per single event is based on neural net estimations of the primary energy \[28\]. The latter procedure is also sensitive to the influence of different hadronic interaction models as the net is trained by two different models.

Despite of considerable differences of the applied methods analysing the observables, different simulation procedures, and different observation levels the compiled experimental results agree in a remarkable way. Assuming an uncertainty of 15\% for the energy reconstruction (shown in Fig. 1 at \(3 \cdot 10^{15}\) eV) all the results appear to be concordant with each other. Only at the high-energy ends the spectra exhibit somehow larger differences, may be as consequence of saturation effects of the different detector devices in addition to missing statistical accuracy and also due to larger uncertainties of the models providing the reference patterns. This observation is remarkable, first of all as most of the experimental results have been published without quoting systematic uncertainties due to the reconstruction procedures or the model dependence. After compiling the data (14 spectra) the average values and their variances result in a slope below the knee to \(\gamma_1 = -(2.68 \pm 0.06)\) and above the knee to \(\gamma_2 = -(3.06 \pm 0.08)\) with the knee position at \(E_k = (3.2 \pm 1.2) \cdot 10^{15}\) eV, without taking into account the statistical accuracy of the different experiments or any further systematic uncertainty.

3. The cosmic ray elemental composition

Whereas the energy reconstruction can be based on one single measurable quantity, the determination of the mass composition needs at least a second observable, which characterises in relation to the first the actual status of the EAS development which is specific for the mass of the primary. The first interaction of a cosmic nucleus of mass A with an air molecule determines the further development of the air shower, and the mechanisms of this interaction are responsible for the formation of mass sensitive observables at earth-bound experiments. With increasing mass of the target or projectile the cross sections of nucleus-nucleus interactions get larger. For example, the inelastic cross section \(\sigma_\text{inel}^{A\text{-Air}}\) of iron is at 1 PeV approximately 6 times larger
than for protons of equal energy. Hence an EAS starts earlier in average and develops faster in the atmosphere with increasing primary mass. In a first good approximation a primary nucleus of mass $A$ and energy $E_0$ can be regarded for the shower development as a swarm of $A$ independent nucleons generating $A$ superimposed independent proton showers of the energy $E_0/A$ (superposition principle). As a consequence showers induced by heavy primaries generate more secondary particles, each of smaller energy, and due to the faster attenuation of the electromagnetic component with a smaller number of electrons at the observation level (after the EAS maximum). Simultaneously the number of muons is larger. The muons interact weakly with the atmosphere, they are less absorbed and their decay time is long compared to pions, so that they add up throughout the shower development. The superposition model predicts for all additive observables power law dependences with the mass. Even if the principle is an approximation, this dependence is sufficiently valid (Fig. 2). From statistical reasons the fluctuations of the sum of $A$ independent showers should be smaller than of a shower generated by a single proton of higher energy (Fig. 2). The effect is smeared out by the limits of the superposition model in the interaction, but it remains efficient for mass separation in experiments. Further, surviving hadrons have less energy, and compared to the electron or muon number the total number of hadrons in EAS is small and they are concentrated around the shower axes. The faster development of showers induced by heavy primaries lead additionally to larger relative angles to the shower axes and flatter lateral distributions.

The atmospheric Cherenkov light, produced dominantly by relativistic electrons and positrons is directly sensitive to the height of the shower maximum, which is more distant from the observation level for heavier primaries (Figs. 2 and 3). Further mass
sensitive differences in the longitudinal shower development, but less pronounced and with difficulties to measure, are the relative arrival times of the secondary particles of the shower disc, in particular of the muons or of the Cherenkov light and the relative angles of incidence of EAS muons.

In addition to different observables considered in various experiments, also different reconstruction techniques are applied. One approach implies the comparison of the distributions of the mass sensitive observables with Monte Carlo predictions for different primary masses in bins of energy. Examples for that are the MSU [18] experiment (fluctuations of muon numbers), Blanca [22] (slope of the

**Figure 3.** Compilation of different experimental results on the estimation of the shower maximum by measuring the Cherenkov light. (Refs.: Yakutsk [25], Blanca [22], HEGRA [19], Tunka-25 [34], Spase [35], Cacti [36], Dice [37]).

**Figure 4.** Distributions of mass sensitive observables (left panel: slope of the lateral distribution of the atmospheric Cherenkov light as measured with Blanca [22] for the energy range of $10^{14.9} - 10^{15.3}$ eV, right panel: muon multiplicity distribution measured with MACRO [38] deep underground) compared with predictions of Monte Carlo simulations for an energy range just below the knee.
Figure 5. Energy dependence ($\propto N_{\text{tr}}^{\mu}$) of the mean logarithmic mass using different sets of observables (shower sizes $N_e$, $N_{\text{tr}}^{\mu}$ as well as hadronic and high-energy muon observables reconstructed at the central detector of KASCADE) in a multivariate approach. Systematic differences appear when the EAS electron size is included in the correlation or not (from [28]).

![Graph of energy dependence of mean logarithmic mass](image)

Figure 6. Compilation of different experimental results of the mean logarithmic mass around the knee. The lines are for guiding the eyes and connect the data points of the experiments (Chacaltaya [39], MSU [18], HEGRA-CRT [42], HEGRA [19], Casa-Mia [41], Blanca [22], Dice [20], KASCADE [30, 28, 40, 43]).

![Graph of compilation of experimental results](image)

Figure 3 compiles different results on the quantity $X_{\text{max}}$ of experiments sensitive to the Cherenkov light, Fig. [3], EAS-TOP/MACRO [38] (muon multiplicity measured deep underground, Fig. [4]), Chacaltaya [39] (hadron multiplicity measured in burst chambers), or the ratio of muon to electron size like used in KASCADE [40] or CASA-MIA [41]. Fig[3] compiles different results on the quantity $X_{\text{max}}$ of experiments sensitive to the Cherenkov light and points out how sensitive the measurements are to the uncertainties. Up to 40 g/cm$^2$ difference for different high-energy interaction models, and up to 60 g/cm$^2$ variance due to systematic experimental uncertainties in addition...
to the uncertainty for the energy estimation may explain the scatter of the data points in the figure so that actually no definite conclusion is possible on the mass composition on basis of this observable.

Uncertainties in the model calculations for \( X_{\text{max}} \) are naturally transmitted to expectations of particle distributions at observation level. Consequently results obtained by measuring charged particles also scatter enormously (Fig. 6). It was found by the KASCADE collaboration that results of the mean logarithmic mass depend strongly on the choice of observables \(^{28}\). KASCADE is able to register a large set of observables for EAS hitting the Central Detector of KASCADE. The same analyses method (neural net classification trained with always the same set of simulations) is applied to sets of different observables (Fig. 5). Most of the results indicate an increase of the mean logarithmic mass above the knee. The results point to an invalid balance of energy and particle numbers predicted by the interaction models. Averaged values of such a multivariate approach are displayed for two different interaction models underlying the neural net training among some other experimental results at Fig. 6.

4. Behaviour of single mass groups

A deeper insight in the structure of the knee is provided by the spectra of single mass groups. The KASCADE experiment e.g., measures with its multi-detector setup local muon density spectra for different muon energy thresholds for event samples of fixed core distances \(^{44}\). The event selection is performed with help of the scintillator array, whereas the muon densities are estimated independently by devices placed in the center of the array. Moreover, the possibility to reconstruct the electron to muon number in each station of the array allows to divide the total sample of EAS in an electron-rich and an electron-poor subsample. This selection is nearly independent of Monte-Carlo assumptions, as it is well known that showers induced by light primaries have a larger ratio than EAS induced by heavy primaries. The analysis results in the statement that the local muon density spectra (which reflect the primary energy spectra) show a knee in the total sample, a even more pronounced knee for the electron-rich (light primaries) sample, and no knee for the electron-poor (heavy primaries) sample (Fig. 7).

The accessible energy range for this analysis lies between 1 and 10 PeV. This result...
was found to be valid for many different core distances and for two muon energy

| Primary Energy (eV) | \(10^{10}\) | \(10^{15}\) | \(10^{16}\) | \(10^{17}\) |
|---------------------|----------|----------|----------|----------|
| \(1.5\) GeV \(^{-1}\) s \(^{-1}\) sr \(^{-2}\) m \(^{2}\) | \(E \times 10^{2}\) |

Figure 8. Energy spectra of four primary mass groups as obtained from an unfolding procedure applied to the KASCADE size spectra (from [47]). The error bars display only the statistical uncertainties.

thresholds and is a strong experimental hint for the origin of the knee from a decrease of the flux of light primary particles.

Combining surface measurements of the shower size with underground muon multiplicities by the EAS-TOP and MACRO experiments also a decrease of the contribution of light primaries to the flux above the knee is observed [38].

A more promising way towards a solution of the puzzle of the knee is a new approach worked out by the KASCADE collaboration: Large statistical accuracy and reliable estimates of the electron and muon size per single shower allow to apply unfolding methods to the two-dimensional size distribution obtaining the energy spectra of different mass groups. Mathematically the inverse problem is put:

\[ g(y) = \int R(y, x)p(x)d(x) \]  

with \(y = (N_e, N_{\mu}^I)\) and \(x = (E, A)\). The quantity \(R(y, x)\) is the response matrix which includes additionally to the mass sensitive shower sizes also the intrinsic shower fluctuations, which are mass dependent, too. The response function has to be deduced from Monte Carlo simulations. Different methods are applied to solve the problem: An iterative procedure using the Gold-algorithm based on a minimization of the \(\chi^2\)-function [44]. Alternatively an approach based on the Bayes-theorem is applied [46], where for each mass-energy-bin the probabilities have to be calculated how the \(N_e - N_{\mu}^I\)-bins will be populated. An iterative procedure tries subsequently to reproduce the given two-dimensional size-distribution of the data.

Whereas the kernel function for the first approach is calculated by combining simulations of high statistical accuracy, using the thinning procedure and full simulations to describe all physical and experimental effects (fluctuations of shower size, efficiencies, reconstruction accuracies), the latter approach requires a larger statistical accuracy of full simulations, but does not require the inversion of the response matrix.

In a first step the unfolding method using the Gold-algorithm was applied to the one-dimensional spectra of the sizes, only. Preliminary results were reported by the KASCADE collaboration [30, 47] and confirm again (but still with large systematic uncertainties) that the knee is due to the spectrum of light primaries. As a new aspect the positions of the knee for the different mass groups suggest a rigidity dependent behaviour of the knee (Fig. 8). Though the absolute fluxes and slopes of the different
mass groups still have large uncertainties arising from the limited number of Monte Carlo simulations, from model uncertainties, and methodological reasons, the results indicate to the rigidity dependent knee position.

5. Conclusions and future

It remains still unclear if the present results are able to distinguish between different theoretical rigidity-dependent models for the origin of the knee. Fig. 9 shows results of the mean logarithmic mass deduced by 3 different methods applied for the KASCADE experiment using identical data samples and the same high-energy interaction model generating the reference patterns (QGSJET). Hence most sources of systematic uncertainties should be eliminated. Remaining differences in estimating mean mass and energy must be of methodical origin. It is evident that the resulting uncertainties are of the same order as the differences of the astrophysical models. The experimental results favour models predicting a lower mean logarithmic mass of the CR mass composition, and they have obvious difficulties to match e.g. the model of Erlykin and Wolfendale [6] where the knee display a composition dominated by oxygen nuclei, with a steeply falling proton component below the knee and leading to a large mean mass number. Models with a simple rigidity dependent knee and identical spectral indices before and after the knee (e.g. the Biermann-model [5]) tentatively better agree with the data. More definite conclusions, however, are presently hardly possible.

For a consolidation of the rigidity dependent knee position (i.e. ascribing the knee to an astrophysical origin and excluding features due to changements of the interaction scaling with the atomic mass) a kink for the heavy (iron) component at \( \approx 10^{17}\) eV should be observed. This is necessary in order to confirm the above stated results and to match the total energy spectrum at higher energies. A large number of the present
detector installations measure around the (proton) knee region or they are optimized for much higher energies around the Greisen-Zatsepin-Kuzmin cutoff (GZK). None of the modern multidetector experiments is optimised for the energy range of $10^{16}$ to $10^{18}$ eV. Only the Yakutsk array [25] which registers air-Cherenkov radiation from EAS covers the full energy range from knee region to GZK cutoff energies. The interest of newer EAS observation experiments (HESS, Argo, Milagro, e.g.) is directed to the detection of high-energy Gamma ray sources in the TeV region (in this way attacking also the origin of the charged primary cosmic rays - see G.Heinzelmann, these proceedings). These experiments measure as background charged cosmic rays up to the knee region. There are several ideas to use this background for physics relevant for the discussed subject, though corresponding activities are not well elaborated. Nevertheless the data can be used to improve the results and/or to test the interaction models at moderate energies.

In order to improve the present situation, the KASCADE experiment is being extended (KASCADE-Grande), covering an area of $600 \times 600$ m$^2$ by installing the former EAS-TOP detectors [24] at the site of the Forschungzentrum Karlsruhe. The extended detector installation will be able to measure the CR energy spectrum and mass composition up to $10^{18}$ eV in a total measuring time of 3-4 years. The data taking will start end of 2002. The KASCADE-Grande experiment will include the full information provided by the original KASCADE multi-detector setup for each measured single event. The multiparameter set-up will enable consistancy studies of the high-energy hadronic interaction models. This possibility is of great importance as a step towards the development and tests of the high-energy hadronic interaction models (see S. Ostapchenko, these proceedings) used for interpreting ultra-high energy cosmic ray observations.

The origin of the knee is still a puzzle. But a large progress is obvious thanks to larger statistical accuracy of multiparameter measurements combined with sophisticated analysis methods. The main uncertainty and hence pointing to the key to the solution is the missing knowledge of the detailed interaction mechanisms for the energy and kinematic ranges under consideration. Efforts in this direction are a common subject of particle and cosmic ray physicists [15]. Such efforts will become even more important with CR measurements at much higher energies, around the ankle of the CR spectrum and above with experiments like the Pierre-Auger-Project, HiRes, or EUSO (see H. Blümer, these proceedings).

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