

Air Shower Measurements in the Primary Energy Range from PeV to EeV

Andreas Haungs

*Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany

E-mail: haungs@ik.fzk.de

Abstract. Recent results of advanced experiments with sophisticated measurements of cosmic rays in the energy range of the so called knee at a few PeV indicate a distinct knee in the energy spectra of light primary cosmic rays and an increasing dominance of heavy ones towards higher energies. This leads to the expectation of knee-like features of the heavy primaries at around 100 PeV. To investigate in detail this energy region several new experiments are or will be devised.

1. Introduction

In the primary energy range of PeV to EeV direct measurements of cosmic rays are presently hardly possible due to the low flux, but indirect measurements observing extensive air showers (EAS) are performed. The all-particle energy spectrum in this range shows one distinctive discontinuity at few PeV, known as the knee, where the spectral index of a power-law dependence changes from -2.7 to approximately -3.1 . In addition, at a few hundred PeV, there are weak experimental hints for a further, much less pronounced, change of the the power law index, assigned as so called second knee (see Fig. 1).

Astrophysical scenarios like the change of the acceleration mechanisms at the cosmic ray sources (supernova remnants, pulsars, etc.) or effects of the transport mechanisms inside the Galaxy (diffusion with escape probabilities) are conceivable for the origin of the knee as well as particle physics reasons like a new kind of hadronic interaction inside the atmosphere or during the transport through the interstellar medium. The highest energies above the so called ankle at a few EeV are believed to be exclusively of extragalactic origin. Thus, in the experimentally scarcely explored region between the first (proton) knee and the ankle there are two more peculiarities of the cosmic ray spectrum expected: (i) A knee of the heavy component which is either expected (depending on the model) at the position of the first knee scaled with Z (the charge) or alternatively with A (the mass) of iron. (ii) A transition region from galactic to extragalactic origin of cosmic rays, where there is no theoretical reason for a smooth crossover in slope and flux. Dependent on the considered astrophysical model the second knee is allocated to case (i) or (ii), respectively.

It is obvious that only detailed measurements over the whole energy range from 10^{14} eV to 10^{18} eV and the reconstruction of individual primary energy spectra for the different incoming particle types can validate or disprove some of these models.

Despite EAS measurements with various different experimental setups in the last decades this demand could never accomplished, mainly due to the weak mass resolution of the measured shower observables [1].

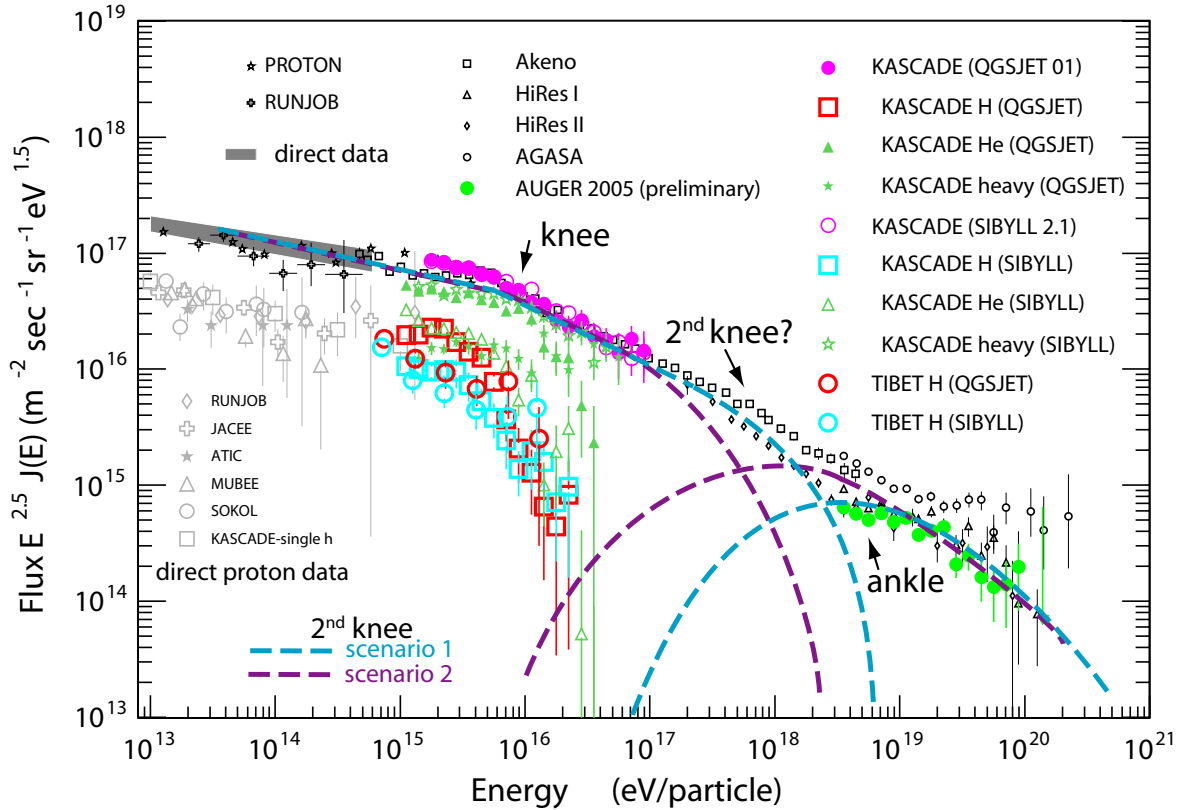


Figure 1. Primary cosmic ray flux. Results of some experiments for the all-particle spectrum as well as for spectra of individual mass groups, in particular for protons. Possible scenarios for the origin of a second knee are also shown (see text).

Recently, however, there are a few experiments which could reconstruct individual energy spectra for different mass groups in the knee region (KASCADE, Tibet- $AS\gamma$, EAS-TOP) by accurate hybrid air-shower measurements. And there are promising experiments in set-up or proposed (KASCADE-Grande, IceTop, Pierre-Auger-Observatory-, and Telescope Array - enhancements) which will provide a similar accuracy for measurements in the energy range from 50-1000 PeV.

2. The (first) knee

The most interesting results in analyzing EAS in the knee region are originating from the KASCADE experiment, where the data analyses aim to reconstruct the energy spectra of individual mass groups, taking into account not only different shower observables (muon and electron shower sizes), but also their correlations on an event-by-event basis. By applying unfolding procedures (based on Monte-Carlo simulations using different hadronic interaction models) to the experimental data individual energy spectra are obtained as displayed in Fig. 1. A knee like feature is clearly visible in the all particle spectrum, which is the sum of the unfolded single mass group spectra, as well as in the spectra of primary proton and helium. KASCADE claims that the elemental composition of cosmic rays is dominated by the light components below the knee and by a heavy component above the knee feature [2].

Data of the EAS-TOP air-shower experiment were also analyzed to obtain energy spectra of individual mass groups (of light, medium, and heavy primaries in case of correlating shower size with low energy muon densities [3], and of light and heavy in case of correlating shower

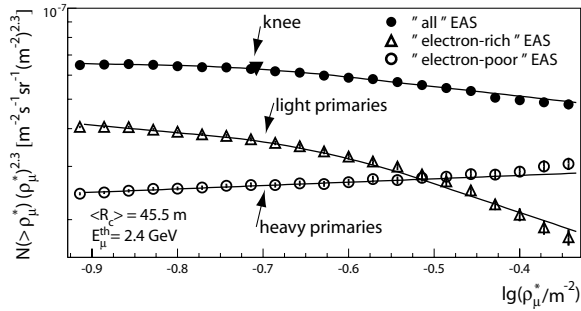


Figure 2. Muon density spectra for different samples of EAS as obtained by KASCADE measurements.

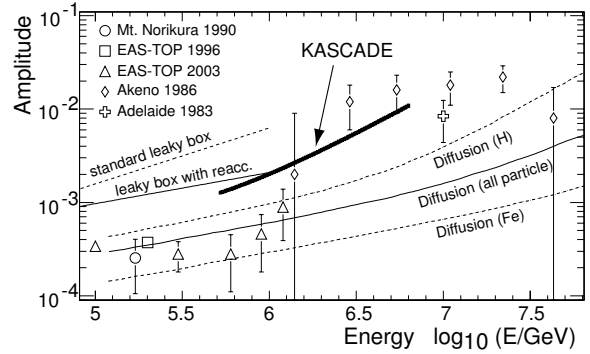


Figure 3. Rayleigh amplitude of the harmonic analyses of the KASCADE data (limit on a 95% confidence level).

size with high energy muons above 1 TeV measured by the MACRO detector [4]). The results confirm the more detailed investigations by KASCADE in the sense, that the knee is caused by the decreasing flux of the light component.

In contradiction to the results of KASCADE and EAS-TOP are the outcomes of the TIBET-AS γ group [5]. Whereas the all-particle spectrum is obtained by using air shower data alone which agree nicely with all other measurements, for getting individual mass spectra a different approach is chosen. From coincident measurements of the air shower array with high-energy particle families in emulsion chambers the spectra for primary protons and helium are extracted by using a neural net analysis. The small number of measured events (177 in 3 years), and the low detection efficiency, in particular for heavy elements, requires an efficiency correction of up to factor 100 (which estimate is also model dependent) to obtain the spectra as plotted in Fig. 1. Due to the fact that in the obtained proton spectrum no distinct structure appears to be visible, but the index of an assumed power law differs from results of direct measurements, the TIBET group claims that there must occur a proton knee at energies below 10^{15} eV. Hence the knee at a few PeV in the all-particle cosmic ray spectrum must be dominated by a heavy component.

The largest uncertainty of all the discussed investigations is due to differences in the hadronic interaction models underlying the analyses. Modeling the hadronic interactions needs assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by the discrepancies of the results presented here. These findings are confirmed by detailed investigations of further shower observables measured by KASCADE [6], in particular. These investigations of observable correlations have shown that none of the present hadronic interaction models is able to describe all the KASCADE data consistently (on a level of a few percent). It was also found that changing the hadronic interaction models do not change the form of the individual energy spectra, but the relative abundances, only. Nevertheless one should note that the uncertainties in the hadronic interaction model underlying the analyses prove to be the limit of the accuracy of the results.

Neglecting somehow the uncertainties by the interaction models, KASCADE used an additional independent and more direct approach to interpret the measurements (Fig. 2). By using three observables (one observable as energy identifier - the local muon density of high energy muons; and two observables as mass identifier - the ratio of electron to low energy muon number for dividing the whole EAS sample in a sample generated by light primaries and heavy primaries) KASCADE could impressively and in a nearly model independent way demonstrate that the knee is caused by the decreasing flux of light primaries [7].

In addition to the energy spectra of individual primaries, investigations of anisotropies in

the arrival directions of the cosmic rays can give additional information on the cosmic ray origin and of their propagation. Depending on the model of the origin of the knee and on the assumed structure of the galactic magnetic field one expects different amplitudes for the large-scale anisotropy in the energy range of the knee. The limits of large-scale anisotropy analyzing the KASCADE data [8] and other experiments are shown in Fig. 3. These limits already exclude particular model predictions.

In summary, despite the recent success of sophisticated experiments like KASCADE, EAS-TOP or TIBET there are still only weak constraints for distinguishing detailed astrophysical models explaining the knee in the primary cosmic ray energy spectrum. In particular, due to the weak mass resolution of the experiments, the question of mass or charge dependence of the knee positions for the different primaries still remains open.

3. The second knee

To distinguish between astrophysical models of the origin of the knee constraints can be given by clarifying the existence and source of the second knee, which is possible by determining the mass composition in the relevant energy range in detail. It is obvious that for the range between 50 and 1000 PeV sophisticated experiments are needed to measure the EAS with the same statistical and reconstruction accuracy as the experiments discussed in the previous section to distinguish between the two astrophysical scenarios shown in Figure 1. Presently, there are several efforts for that:

In 2003, the original KASCADE experiment was extended in area by a factor 10 to the new experiment KASCADE-Grande [9]. KASCADE-Grande allows now a full coverage of the energy range around the knee, including the possible second knee. KASCADE-Grande will be able to prove the existence of the knee corresponding to heavy elements.

At the south pole, the neutrino experiment IceCube has started its deployment. Parallel to this under-ice experiment an air shower array (IceTop) will be build on the surface. This setup will allow to measure in coincidence the charge particles of air-showers and high-energy muons above 500 GeV with high accuracy. Therefore it will be able to reconstruct energy spectrum and mass composition in the energy range of the second knee [10].

Finally, the Pierre-Auger-Observatory and Telescope-Array collaborations are discussing enhancements of their hybrid detection techniques to cover also lower energies.

4. Conclusions

From detailed EAS measurements at 1-10 PeV we do know that at a few times 10^{15} eV the knee is due to light elements, that the knee positions depend on the kind of the incoming particle, and that cosmic rays around the knee arrive our Earth isotropically. New experiments, measuring higher energies, will be able to prove, if existent, the knee corresponding to heavy elements, They will give by far more constraints to the various astrophysical models for explaining the origin and propagation of very high energy cosmic rays.

- [1] Haungs A, Rebel H, and Roth M 2003 *Rep. Prog. Phys.* **66** 1145
- [2] Antoni T et al. - KASCADE collaboration 2005 *Astrop. Phys.* **24** 1
- [3] Aglietta M et al. 2004 *Astrop. Phys.* **21** 583
- [4] Aglietta M et al. 2004 *Astrop. Phys.* **20** 641
- [5] Amenomori M et al. 2006 *Phys. Lett. B* **632** 58
- [6] Haungs A et al. - KASCADE collaboration 2005 *Nucl. Phys. B (Proc. Suppl.)* **151** 167
- [7] Antoni T et al. - KASCADE collaboration 2002 *Astrop. Phys.* **16** 373
- [8] Antoni T et al. - KASCADE collaboration 2004 *Astrophys. J.* **604** 687
- [9] Navarra G et al. - KASCADE-Grande collaboration 2004 *Nucl. Instr. Meth. A* **518** 207
- [10] Montaruli T for the IceCube collaboration 2006 *Proc. of VULCANO 2006* astro-ph/0608140