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COSMIC RAYS IN THE PEV RANGE: RESULTS FROM KASCADE

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Abstract

KASCADE is determining flux spectra for different primary mass groups to disentangle the knee feature of the primary cosmic-ray energy spectrum. The energy spectra of the light element groups result in a knee-like bending and a steepening above the knee. The topology of the individual knee positions show a dependency on the primary particle. To quantify this dependence the KASCADE array is now extended by a factor of 10 in area. The major goal of the new KASCADE-Grande array is the observation of the 'iron-knee' in the cosmic-ray spectrum at around 100 PeV which is expected following from the KASCADE results presented below.

1 Introduction

The all-particle energy spectrum of cosmic rays shows a distinctive feature at few PeV, known as the *knee*, where the spectral index changes from -2.7 to approximately -3.1. At that energy direct measurements are presently not possible due to the low flux, but indirect measurements observing extensive air showers (EAS) are performed. 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.

Despite of 50 years of EAS measurements the origin of the kink is still not clear, as the disentanglement of the threefold problem of estimate of energy and mass plus the understanding of the air-shower development in the Earth's atmosphere remains an experimental challenge. To solve the puzzle the access is to reconstruct energy spectra of individual elements (or mass groups), accompanied by a careful investigation of the hadronic interaction mechanisms driving the air-shower development. For a detailed discussion of the subject see a recent review [1].

The KASCADE (KArlsruhe Shower Core and Array DEtector) experiment [2] approaches this goal by measuring as much as possible redundant information from each single air-shower event. The multi-detector system allows to measure the total electron and muon numbers ($E_\mu > 240\,\mathrm{MeV}$) of the shower separately using an array of 252 detector stations containing shielded and unshielded detectors at the same place in a grid of $200 \times 200\,\mathrm{m}^2$. The excellent time resolution of the detectors allows also decent investigations of the arrival directions of the showers in searching large scale anisotropies and, if exist, cosmic ray point sources. Additionally muon densities at three more different

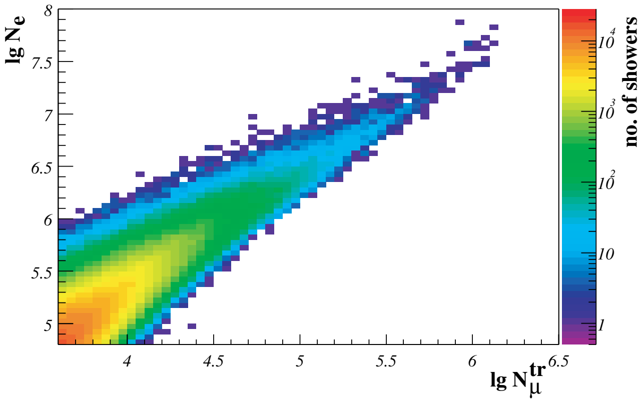

Figure 1: Two dimensional electron (N_e) vs. muon ($N_\mu^{\rm tr}$, i.e. number of muons in 40-200m core distance) number spectrum measured by the KASCADE array. Only showers with zenith angle <18° are included.

muon energy thresholds and the hadronic core of the shower by a 300 m^2 iron sampling calorimeter are measured. These redundant information is mainly used for tests and improvements on the hadronic interaction models unavoidably needed for the interpretation of air shower data.
In the following we present the results of KASCADE, in particular an unfolding of the measured two-dimensional electron vs. muon number spectrum into energy spectra of five primary mass groups. The results motivate the extension of KASCADE to measure higher primary energies, which will be realized by KASCADE-Grande.
Covering a wide energy range KASCADE-Grande is also the ideal test-ground for the development of new techniques of air-shower detection. With this view, recently an array of dipol-antennas for measuring the radio emission in the Atmosphere by high-energy cosmic rays were put into operation.

2 KASCADE results

2.1 Energy spectra of individual mass groups

The content of each cell of the two-dimensional spectrum of electron number vs. muon number (Fig. 1) is the sum of contributions from the 5 considered primary elements. Hence the inverse problem $g(y) = \int K(y,x)p(x)dx$ with $y = (N_e, N_\mu^{\rm tr})$ and $x = (E, A)$ has to be solved. This problem results in a system of coupled Fredholm integral equations of the form

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

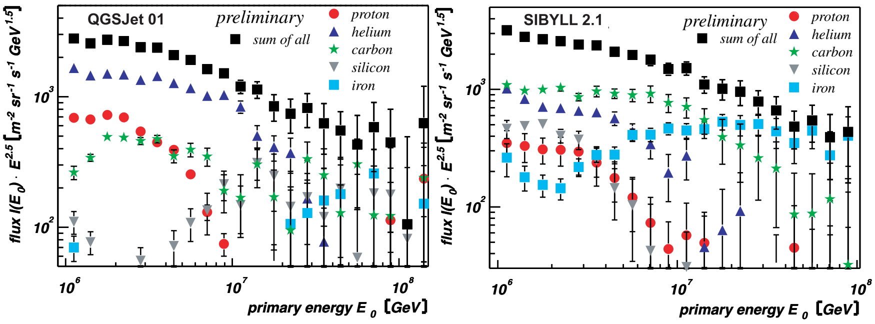

Figure 2: Result of the unfolding procedure. Left: based on QGSJet 01; right: based on SIBYLL 2.1.

where the probability p_A

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

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

The procedure is tested by using random initial spectra generated by Monte Carlo simulations. It shows that knee positions and slopes of the initial spectra can be reproduced and that the discrimination between the five primary mass groups is sufficient. For proofing the unfolding procedure, different mathematical ways of unfolding (Gold-algorithm, Bayes analyses, etc.) have been compared and the results are consistent [3].

The application of the unfolding procedure to the data is performed on basis of two different hadronic interaction models (QGSJet 01 [4], SIBYLL 2.1 [5]) as options embedded in CORSIKA [6] for the reconstruction of the kernel functions [7].

By applying the above described procedures to the experimental data energy spectra are obtained as displayed in Fig. 2. Knee like features are clearly visible in the all particle spectrum as well as in the spectra of primary proton and helium. This demonstrates that the elemental composition of cosmic rays is dominated by light components below the knee and dominated by a heavy component above the knee feature. Thus the knee feature originates from a decreasing flux of the light primary particles. This observation corroborates results of the analysis of muon density measurements at KASCADE [8], which are performed independently of the unfolding procedure.

2.2 Inaccuracy of hadronic interaction models

Comparing the unfolding results based on the two different hadronic interaction models, the model dependence when interprating the data is obvious. The first interaction of the primary particle in the atmosphere is inaccessible for the present man made accelerator experiments in both, in the energy and in the kinematic region of the extreme forward direction. Hence modeling these interactions underlies assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by the discrepancies of the results presented here. Hints for the inadequate description of the hadronic interactions at the atmosphere are also given by additional KASCADE data analyses taking the advantage of the multi-detector information, i.e. investigations of the hadron component in air-showers with the KASCADE hadron calorimeter [9] and comparing muon densities for different muon energy thresholds [10]. These investigations show that none of the present hadronic interaction models are able to describe all the KASCADE data consistently (on a level of a few percent). Recently some efforts are made to sample the information from accelerator experiments and cosmic ray investigations [11, 12] to improve the hadronic interaction models.

2.3 Search for anisotropies and point sources

Investigation of anisotropies in the arrival directions of the cosmic rays give additional information on the cosmic ray origin and of their propagation. Depending on the model of the origin of the knee one expects large-scale anisotropies on a scale of 10^{-4} to 10^{-2} in the energy region of the knee and depending on the assumed structure of the galactic magnetic field. For example in Fig. 3 (left panel) the predictions from calculations of Candia et al. [13] are compared with the limits of anisotropy given by KASCADE results [14]. The KASCADE limits were obtained by investigations of the Rayleigh amplitudes and phases of the first harmonics. Taking into account possible nearby sources of galactic cosmic rays like the Vela Supernova remnant [15] the limits of KASCADE already exclude certain model predictions. But for a complete picture the investigations have to be performed with air shower samples of the different mass groups which need a higher statistics in measurements.
Interest for looking to point sources in the KASCADE data sample is given by the possibility of unknown near-by sources, where the deflection of the charged cosmic rays would be small or by sources emitting neutral particles like high-energy gammas or neutrons. Due to their small decay length the latter ones are

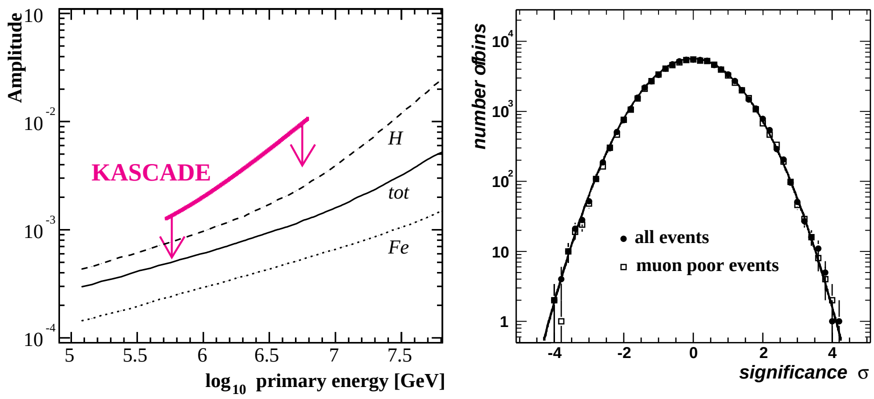

Figure 3: Left: Rayleigh amplitude of the harmonic analyses of the KASCADE data [14] (limit on a 95% confidence level). Right: Significance distributions for searching point sources on the sky map seen by the KASCADE experiment [16].

of interest for near-by sources only. Fig. 3 (right panel) shows the distribution of significances for a deviation of the flux from the expected background for all bins of the visible sky of KASCADE. Shown are the distributions for the full sample of air showers as well as for a sample of "muon-poor" showers which is a sample with an enhanced number of candidates of γ-ray induced events. No significant excess was found in both samples [16].

3 KASCADE-Grande

To solve the puzzle of the origin of the knee data extending to higher primary energy is obviously required. For example a confirmation of the dependence of the knee positions for the various elemental groups the experimental observation of an 'iron-knee', expected at around 100 PeV primary energy is required. For that purpose the KASCADE experiment has been enlarged by an installation of additional 45 detector stations (37 as Grande array plus 8 as Piccolo trigger array) in a grid of $700 \times 700\,\mathrm{m}^2$. In the present configuration KASCADE-Grande consists of sensitive detectors of an area of $965\,\mathrm{m}^2$ for the electron component, of $1070\,\mathrm{m}^2$ for measuring muons at four different energy thresholds, and of $300\,\mathrm{m}^2$ for hadron detection. Thus KASCADE-Grande displays the full capability of a multi-detector experiment [17] and continue to measure high-quality data as the original KASCADE experiment.

4 Radio measurements with LOPES

LOPES is a small array of radio antenna to operate in conjunction with KASCADE-Grande in order to calibrate the radio emission from cosmic ray air showers. At present, LOPES operates 10 dipole antennas in coincidence with KASCADE [18]. The antennas are positioned between the array detectors of KASCADE and data are collected when a special trigger for very high-energy events is received from the KASCADE array. The antennas are operated in the frequency range of 40-80 MHz. For several air-shower events a coincident and coherent signal has been found in the data of the radio antenna and a preliminary analysis has already been performed [19]. The main goal of further investigations is to calibrate the radio signal with help of the observables of the individual air-showers given by KASCADE-Grande.

5 Conclusions

Due to the uncertainties of the results described above, in particular arising from the inadequacy of the hadronic interaction models, still there are only weak constraints for astrophysical models to explain the knee in the primary cosmic ray energy spectrum. Hence most of the current models cannot be excluded by the present measurements. In future, by having the data of the KASCADE-Grande experiment and by improving the hadronic interaction models better constraints especially at higher primary energies are expected. Thus cosmic ray physics at energies around the knee remains a vital field of research with high scientific interest.

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References

[1] A.Haungs, H.Rebel, M.Roth, Rep.Prog.Phys.**66**,(2003),1145

[2] T.Antoni et al. KASCADE coll., Nucl. Instr. Meth. A **513** (2003) 429

[3] H.Ulrich et al., Nucl.Phys.B (Proc.Suppl.) **122**, (2003), 218

[4] N.N.Kalmykov, S.S.Ostapchenko, Yad.Fiz. **56**, (1993), 105

[5] R.Engel et al., 26^{th}ICRC(Salt Lake City) **1**, (1999), 415

[6] D.Heck et al., Rep.FZKA 6019, Forschungszentrum Karlsruhe (1998)

[7] M.Roth, H.Ulrich et al., 28^{th}ICRC(Tsukuba) **1**, (2003), 131

[8] T.Antoni et al.-KASCADE coll., Astrop.Phys. **16**, (2002), 373

[9] J.Milke et al., Nucl.Phys.B (Proc.Suppl.) **122**, (2003), 388

[10] A.Haungs et al., Nucl.Phys.B (Proc.Suppl.) **122**, (2003), 384

[11] R.Engel et al., Nucl.Phys.B (Proc.Suppl.) **122**, (2003), 437

[12] H.Rebel, Proc. of the 23^{rd} Int. Workshop on Nucl. Theory, Bulgarian Academy of Sciences, Rila Mountains, June (2004)

[13] J.Candia et al., J. Cosmol. Astropart. Phys. **5**, (2003), 3

[14] T.Antoni et al. - KASCADE coll., Astrophys. J. **604**, (2004), 687

[15] V.Ptuskin, Int.Symp.HE Gamma-Ray Astron. Heidelberg, July (2004)

[16] T.Antoni et al. - KASCADE coll., Astrophys. J. **608**, (2004), 865

[17] A.Haungs et al. - KASCADE-Grande coll., 28^{th}ICRC(Tsukuba) **2**, (2003), 985

[18] A.Horneffer et al., 28^{th} ICRC(Tsukuba) **2**, (2003), 969

[19] A.Horneffer et al., Proc. of SPIE conference, Glasgow (2004), in press.