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Search for fine structure of the knee in EAS size spectra

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Abstract. 28 size spectra of extensive air showers in the knee region from 7 different experiment are analysed consistently. They are fitted by adjusting either 4 or 5 parameters: knee position, power law exponents above and below the knee region, overall intensity and, in addition, a parameter describing the smoothness of the bend. The residuals are then normalized to the same knee position and averaged. When 5 parameters are employed no systematic deviation from a simple smooth knee is apparent at the 1 % level up to about a factor of 4 above the knee. At larger shower sizes a moderately significant deviation can be seen whose shape and position are compatible with a second knee caused by iron group nuclei.

1 Introduction

The existence of the 'knee' in the spectra of extensive air showers (EASs) has been known by now for more than 40 years (Kulikov and Khristiansen 1959). First seen in the number of electrons (the shower 'size') observed near sea level it was later also observed in the muon number (Stamenov et al 1972, Glasstetter et al. 1999), hadron properties (Yoshii 1972, Hörandel et al. 1999) and muon densities (Haungs et al. 1999). In fact it seems to show up in all shower observables if investigated in sufficient detail. Nevertheless its origin is still obscure. Of the explanations proposed two seem to have found more general acceptance.

The first of these relates the knee to the influence of interstellar magnetic fields during propagation of the cosmic ray particles in or leakage from the Galaxy or in the course of acceleration for which magnetic fields probably play a major role. Since the radius of curvature of an extremely relativistic particle in a magnetic field is proportionate to its energy E and inversely proportionate to its nuclear charge Z one would expect the knee then to show up at different energies for different nuclear species among the primary particles. In fact one would expect the energy spectra of each element to show a knee at an energy displaced by a factor of Z with respect to that of protons. This was probably first realized by Peters (1961) who discussed the implications on various shower observables in great detail.

The second proposal, less popular than the first one though recently reasserted by Nikolsky and Romachin (2000), attributes the origin of the knee to the properties of high energy interactions in the atmosphere. A change of the spectrum of observables on ground level might of course occur if strong interaction changes by some kind of threshold phenomenon. The knee energy is estimated to be near a few PeV which is approximately a factor of 2 above the highest centre of mass energy available in the laboratory today. Therefore such an effect cannot at present be excluded. Since an EAS induced by a nucleus of mass number A and energy E may, to a reasonable first approximation, be considered as a superposition of A showers induced by nucleons of energy E/A (superposition principle) one would expect, under this assumption, a similar shift of the knee position as described above but by a factor of A instead of Z. Again a more complex structure of the knee would appear natural.

It should be mentioned that the KASCADE collaboration has recently presented evidence that the knee is to be attributed to light nuclei and that the spectrum of heavier nuclei does not exhibit a change of slope in the vicinity of the 'main' knee. This claim is based on a comparison of electron and muon numbers of EASs with Monte Carlo simulations (Kampert et al. 1999) but also on a phenomenological classification of EASs by their electron to muon ratios (Haungs et al. 1999, Antoni et al. 2001)

Erlykin and Wolfendale have recently, in a series of papers (Erlykin and Wolfendale 1997a to 2000b), claimed observational evidence for a more complicated structure of the knee region. This structure which according to the authors does not show up clearly in single measurements but becomes vis-

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ible when averaging several ones, is attributed to the influence of a recent nearby supernova. It is probably not unfair to say that not many have been convinced by the empirical evidence claimed by the authors. But the underlying idea appears very intriguing and reasonable. The solar system has, during the 4.5 billion years of its existence, probably been passed by several if not many shock fronts from supernovae exploding in its vicinity. One of these clearly must be the most recent one and it appears well conceivable that the cosmic ray spectrum which we observe today is influenced by this individual event (and hence not typical for the whole Galaxy). The possibility of a single source having a large impact on the energy and mass distributions of cosmic rays at the earth was already realized by Peters (1961).

For all these reasons it appears interesting to study the shape of the knee region in more detail and to look as to whether it can be really described by a simple bend between two power laws or whether any of the effects mentioned above can be identified. Except for the work by Erlykin and Wolfendale the author is not aware of any other attempt in this direction. A definite negative result would clearly present difficulties for the usual models of the origin of the knee whose existence, on the other hand, is beyond any doubt.

In this paper I attempt to compare 28 different measured spectra of the electron number N in the knee region. (I drop the usual subscript e because there can be no confusion in this paper.) The data originate from 7 experiments and cover a range of atmospheric depths between 730 and 1250 $[g/cm^2]$. The electron number (or shower 'size') is probably the shower observable for which the largest amount of measurements exist. The basic procedure adopted is the following: Each spectrum is first fitted separately by an adequate function adjusting either 4 or 5 parameters. In a next step the residual spectra are shifted to the same knee position and averaged. It may be expected that this averaging reduces not only the statistical fluctuations of the measurements but also (at least part of) the systematic ones and hence should make any deviations from the pre-chosen fit function more conspicuous.

A more detailed account of the present work is being published in Astroparticle Physics (Schatz 2001).

2 Data and analysis

Spectra from the following experiments have been analysed: AKENO (Nagano et al. 1984 and 1992, Nagano 2000), CASA (Glasmacher 1998), EAS-TOP (Aglietta et al. 1999), HEGRA (Heinzelmann 2000), KASCADE (Glasstetter 2000), MAKET-ANI (Chilingarian 2000) and MSU (Kalmykov 2000). The EAS-TOP experiment is the only one which has published the N spectra in numerical form[1]. The CASA data were read from fig. 6 of Glasmacher (1998) (which is equivalent to fig. 6 of Glasmacher et al. (1999)). Such a procedure is of course of limited accuracy and does not exhaust the statistical precision of the data (especially at low shower sizes). All other data sets were made available in numerical form by the authors. Five of the experiments registered events in different ranges of zenith distance which then of course correspond to different atmospheric depths. The total data set comprised 784 points which is to be compared with a total of 112 or 140 derived parameters for the four or five parameter fits, respectively.

The spectra were fitted independently by adjusting first 4 and then 5 parameters: knee position, power law exponents above and below the knee region, overall intensity and, in addition, a parameter describing the smoothness of the bend. For the five parameter fits the following mathematical expression was used:

$$I(N) = I_K \left(e^{\sigma^2\gamma_1^2/2}\, \Phi(u_1) \left(\frac{N_K}{N}\right)^{\gamma_1} + \; e^{\sigma^2\gamma_2^2/2}\, [1-\Phi(u_2)] \left(\frac{N_K}{N}\right)^{\gamma_2} \right)$$

$$u_i = \sigma\gamma_i - \frac{ln(N/N_K)}{\sigma} \quad (1)$$

Here $\Phi(u)$ is the error integral. This form is obtained when a spectrum with a sharp knee is folded with a log-normal distribution of standard deviation σ. It is straightforward to show that the expression approaches power laws at sufficient distances from the knee and tends to a spectrum with a sharp knee for $\sigma \to 0$. As far as the physical interpretation is concerned one should realize that σ incorporates instrumental effects as well as the effects of fluctuations of EAS development in the atmosphere.

After the fit, the differences between observed and fit values were calculated for each of the 28 spectra. These spectra of residuals were then shifted along the lgN axis to the same knee position. This amounts to choosing $lg(N/N_K)$ as the new independent variable where N_K is the knee position found for the respective spectrum. The scatter of the data points after these procedures is illustrated in fig. 1 which clearly exhibits the statistical nature of the residuals (and the increase of the errors with increasing N). No errors bars have been drawn because this would completely confuse the picture but most of them are compatible with 0.

As the next step, all data points within horizontal intervals of width 0.1 were averaged neglecting the horizontal uncertainties resulting from the errors of N_K. The latter were smaller than the chosen bin width for almost all spectra. The number of data points within a given interval was above 30 in the vicinity of the knee and dropped to near 1 at the extreme

[1] It should be mentioned that the scale factor quoted in the caption of the relevant table 1 of Aglietta et al. (1999) should read 10^{-7} instead of 10^{-8} (Navarra 2000).

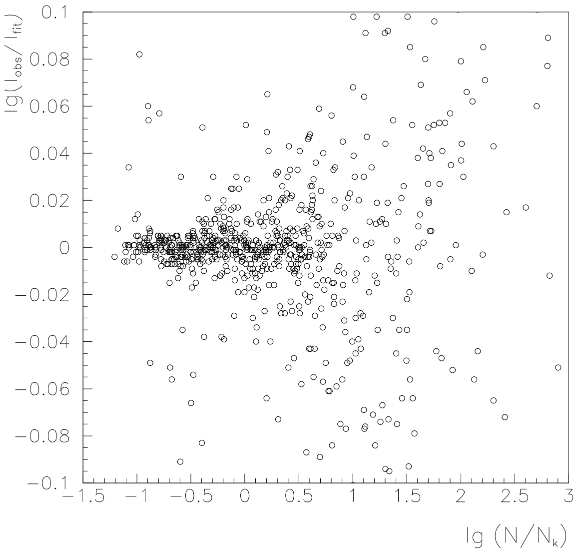

Fig. 1. Differences between observed and fit values of the differential flux normalized to the same knee position. The data are based on fits with four parameters. Each symbol represents one data point from one of the 28 spectra. No error bars have been drawn in order not to confuse the picture but most are compatible with 0.

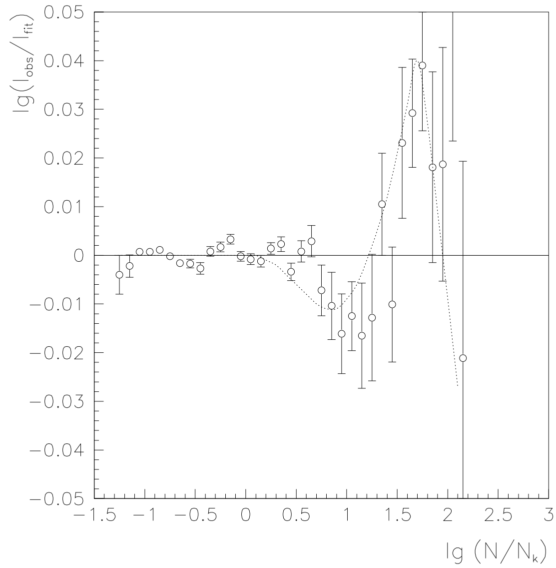

Fig. 2. Averaged differences between observed and fit values based on fits with 5 parameters. The dotted line is discussed in section 3.

ends of the total range because the N ranges of the various measurements did not coincide. It should be mentioned that most of the original data were also binned in intervals of 0.1 width so this choice was very natural. This averaging procedure actually amounts to taking the geometric means of I_{obs}/I_{fit} (with adequate weights). This eliminates all sensitivity to the absolute normalization of the data.

Fig 2 displays the result. The residuals are below 0.005 (which corresponds to a difference between fit and measurement of less than $\simeq 1\%$) for the whole lower part of the spectrum, up to $lg(N/N_K) \simeq 0.6$. The remaining deviations in the upper part amount to $\simeq$ 10% on the positive side and $\simeq$ 5% on the negative side. Their regular pattern with increasing size can hardly be called statistical in spite of the fact that only two of the last 15 data points differ from 0 by more than 2 standard deviations.

3 Discussion

The results displayed in fig. 2 show clearly that the lower part of the observed size spectrum is well described by two power laws and a simple smooth knee. I find it difficult to believe, on the other hand, that the discrepancy visible in the upper part of the size range is purely statistical, in spite of the large errors of the individual points. It is much more difficult to assess possible systematic errors. I will come back to the latter question later in this section and first turn to a possible explanation of the observed deviations assuming they are real.

The dotted line in fig. 2 was derived from a simple model: I have assumed that the size spectrum can be described by the sum of two functions of the type given in eq. (1) with different intensities, the same slopes and the two knees separated by $\Delta lgN_K = 1.7$. This model spectrum then has two free parameters to adjust, the ratio of intensities and the change of the power law exponents. For the latter $\Delta\gamma = 0.5$ was assumed. The parameters σ were chosen to reproduce the variance of the simulation results in tables 20 and 26 of Knapp et al. (1996) (for the QGS model) and were 0.44 for protons and 0.08 for iron. This choice neglects all instrumental effects on the size resolution and should therefore represent a lower limit. This calculated spectrum was then fitted by a single function of the same type with the knee at the same position as the lower of the other two. Intensity and slope below the knee were taken to be the same as those of the model spectrum, and the slope above the knee adjusted. The difference of the model and fit spectra are shown in fig. 2 as the dotted line. It should be emphasized that the widths of the knees were not varied but kept fixed at the values quoted above. The three new parameters (relative intensity, change of the exponent of the model function and slope above the knee of the fit function) were adjusted to some extent but no serious attempt was made to obtain a perfect fit. For this all elements expected to be present in primary cosmic rays should have to be taken into account. Also there is no compelling reason to believe that all partial spectra have the same exponents. This would then leave more parameters to adjust than data points in fig. 2. Although the dotted line does not reproduce the data perfectly the model gives a reasonable description in view of its crudeness. Hence the data can be said to be in agreement with a second component in the overall spectrum exhibiting a knee at higher shower size. It remains surprising, though, that the displacement is clearly in better agreement with a proportionality of the knee position to mass rather than to charge of the primary nuclei (if the second component is attributed to iron which appears to be the most reasonable).

I should like to add, though, that in my opinion systematic errors cannot be excluded as the origin of the observed finestructure. The number of experimental points averaged drops from 29 at $lgN = 0.6$ to 7 at 2.1. So the region where the deviation is observed covers the highest data points of several experiments and these might be under suspicion to suffer from saturation effects. Saturation will lead to an overestimate of the differential flux increasing towards the end of the range of measurement. Therefore it is, in my opinion, not possible to exclude at this moment systematic effects as a possible origin of the observed deviations without more detailed investigations. These require a better knowledge of experimental details and have to be performed for each experiment separately. This might be studied by comparing spectra taken by the same experiment in different bins of zenith distance. The measured size of a primary of given energy and mass decreases with increasing zenith angle. This results in a shift of the knee position to lower sizes with increasing zenith distance. This shift has been observed by many experiments and is also clearly visible in the data of the 5 experiments which have contributed more than one spectrum to this investigation. Hence vertical showers should saturate at lower values of $lg(N/N_K)$. If the same structure is observed at all zenith distances the influence of saturation can be ruled out. The range of shower sizes of such a study should of course extend up to at least two orders of magnitude above the 'main' knee. This implies a reduction of particle flux by about 4 orders of magnitude and hence requires very good statistics as well as detectors of a considerable dynamic range.

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