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On the cosmic ray energy spectrum "knees"

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Abstract. Primary cosmic ray energy spectrum around and above 1 PeV is of great interest due to its non-power law behavior found many years ago using the indirect EAS (Extensive Air Shower) method. The method is based on secondary particles measuring on Earth's surface under a thick atmosphere. Traditionally people use detectors sensitive to ionization produced mostly by electromagnetic component and so called "knee" was found for EAS size spectrum many years ago. Later it was assigned to a steepening of cosmic ray spectrum at 3-5 PeV. Recently some new "knees" were claimed by high altitude experiments, for primary protons and helium: at ~200-300 TeV (Tibet ASγ) and at ~700 TeV (ARGO-YBJ) thus widening the "knee" region from ~0.2 to 5 PeV and demonstrating disagreement with the existing experimental data. The natural explanation of such a strange spectrum behavior can be found in the phenomenological approach to the knee problem.

Introduction

Up to 1949 Extensive Air Shower (EAS) was considered as a pure electro-magnetic (e-m) cascade in atmosphere. Then George Zatsepin [1,2] had shown that this simplification was not true and EAS is a hadronic cascade, while e-m component is produced by π^0 and K^0 decays. This results in the two components are in equilibrium and all EAS features are defined mostly by the hadronic component being a "skeleton" of the shower. The latter means one needs to study hadronic component first of all. But, due to absence of a cheap, large and fast enough hadron detector, up to date people measure mostly e-m component, sometimes muonic one and very rarely hadronic one. Up to date people use e-m theory of cascade development (NKG - function, ages, N_e, etc.) and use N_e (number of electrons) as energy estimator when recovering primary particle energy. Up to date nobody put lower limit to primary energy when the EAS method does work properly. Probably this is a reason for appearance of 3 various "knees" for light primaries: at ~200 TeV (Tibet ASγ), at ~700 TeV (ARGO-YBJ) and at 3-5 PeV (KASCADE and many others) last years. Are all of them real (astrophysical) or "artificial" (systematic)?

Phenomenological approach to the "knee" problem proposed in 2003 [3,4] allowed us to look to the problem from another side and could explain many "puzzles" observed during decades in cosmic ray physics, including the "multiple knee" problem.

1. Phenomenology of EAS

Experimental data accumulated over a long period of ~ 70 years of EAS observations have a lot of contradictions and non-statistical dispersion. Situation in cosmic ray physics is now similar to that 70 years ago, lead Zatsepin to his discovery. By introducing hadronic component to EAS, he had explained such discrepancies as: wide particle lateral distribution, slow attenuation in atmosphere, very large fluctuations, etc. Hadronic cascade in air forms a "hadronic skeleton" defining all EAS properties, while e-m component is secondary one, being in equilibrium with cascading high energy hadrons through decays of neutral pions and kaons.

This idea was later confirmed in many experiments and nobody could doubt in its correctness. But, the problem is that not Zatsepin nor anybody else up to date put a lower energy limit to the EAS' method usage. PeV energy region is very high for e-m cascade where particle's critical energy is low (~80 MeV in air) while number of particles is very high. In hadronic cascade mean particle energy is much higher while number of cascading hadrons (N_{ch}) is low. One should keep in mind that pion production threshold put a limit to ability of hadrons to be involved in the cascading process and this results in significant reduction of the cascading hadrons N_{ch} in comparison with the total hadron number. This is a discrete value and cannot be less than 1. If the last cascading hadron lost its energy and stopped or decayed or captured by a nucleus than N_{ch}=0 and the cascade becomes hadronless or *coreless* [3] and equilibrium between EAS components becomes broken [4] (actually it is broken when N_{ch}<10). Properties of such showers differ significantly from that of normal EAS. When looking to old experimental data or making EAS simulations one could see that this crucial point in EAS development (N_{ch}=0) corresponds to $N_e \approx 10^6$ and primary energy $E_{0t}\approx$100 TeV/nucleon (defined by the Earth's atmosphere thickness). Below this energy shower is coreless one, looking as very old electromagnetic shower with muons addition, it has shorter attenuation length, wider particle lateral distribution (not following NKG-function), etc. and cannot be processed as normal shower. Its age parameter is equal to ~2 resulting in poor core location and thus erroneous Ne estimation. The EAS method does not work properly in this region. Therefore, this energy (depending on altitude of observation) put a lower energy limit to EAS method usage. Processing of recorded showers altogether, one can obtain erroneous primary spectrum below the above-mentioned threshold E_{0t} being equal to $E_0\approx$5 PeV for primary iron.

2. Monte-Carlo simulations

EAS method of primary cosmic ray study is an indirect method when primary particle energy E_0 and mass A cannot be measured directly and are recovered through the experiment simulation. It is easy to show that if we have a pure power law primary spectrum $I(E_0) \sim E_0^{-\gamma}$ and a secondary component N_x also following power law dependence on E_0:

$$N_x(E_0) \sim E_0^{\alpha} \qquad (1)$$

then distribution on this component also follows power law function looking as:

$$F(N_x) \sim N_x^{-\gamma/\alpha} \qquad (2)$$

The latter means both parameters γ and α can be responsible for the above distribution behavior. α – parameter can be obtained only through calculations and therefore it depends on EAS phenomenology, on interaction models used in calculations, on Monte-Carlo statistics and on the used fitting functions, etc. Sure, the calculations should be done with the highest possible accuracy because otherwise any change of measured spectrum slope can be assigned to primary spectrum. We have made such simulations, using CORSIKA (v. 7560, QGSJET+FLUKA) and GEANT4.10, for the future PRISMA-LHAASO experiment being now under construction in China [5] at 4400 m a. s. l. Results on correlation between E_0 and N_e is shown in figure 1 for primary gamma, proton, nitrogen and iron, pure power law spectrum with γ=2.7 and PRISMA-LHAASO-64 configuration (8x8=64 en-detectors with 5 m spacing). Only EAS' producing at least 6-fold coincidences of detector hits with energy deposit above 3 m.i.p. in each, were selected for analysis. Looking to the pictures one can see that such a "comma-like" distribution cannot be fitted by a straight line below $Log(N_e) < 6\div6.5$ or $E_0 < 1$ PeV, especially for light primaries. Widely used simplefigure 4 scatter plot is not able to show such "comma". Such a behaviour is explained by a transition stage from coreless to normal showers, incorrect axis location and thus erroneous calculation of Ne in this region. Only above this EAS size, cascading hadrons reach observation level, the equilibrium between EAS components is achieved, hadronic axis is formed and EAS method begins working properly. Pure power law fit for heavy mass composition published by the Tibet ASγ experiment [6] is also shown along with our best power law fits for each primary. Rather good agreement with our iron curve is established in absolute values but not in the slope.

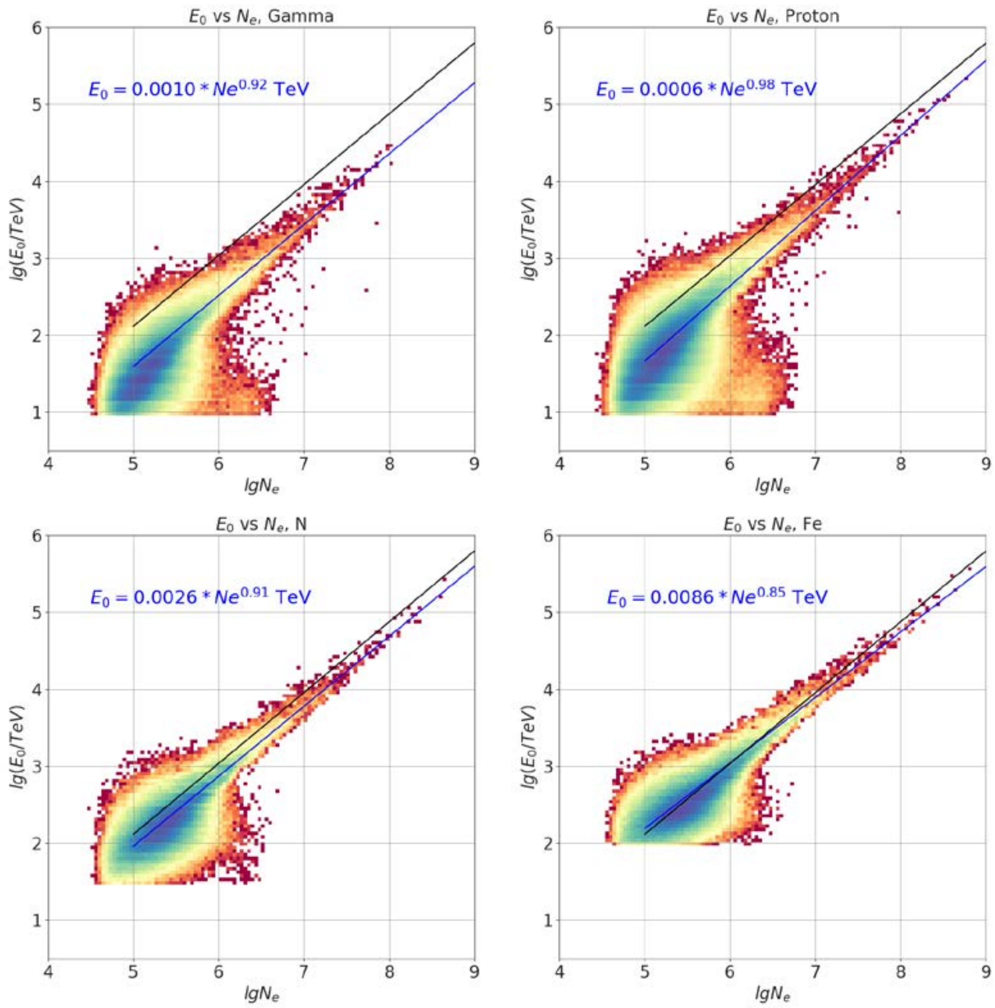

Figure 1. Correlation 3-dimension scatter plots between N_e and E_0 for different primaries: γ, p, N, Fe. Strait upper lines show best fit used by Tibet ASγ collaboration for the same altitude and our best linear fit in log-log scale (lower lines).

Nevertheless, the primary energy spectrum can be recovered using nonlinear fit as it is shown in figure 2, where results of simulation of PRISMA-LHAASO-64 is plotted using averaged points with errors. One can see here that power law fit similar to equation (2) cannot fit the data shown in both panels. It is interesting that $N_e(E_0)$ dependence slope changes just at the point where ARGO-YBJ experiment [7] claimed existence of a "knee" at ~700 TeV. Referring to equation 2 one could note that parameter α is highly likely responsible for the observed "knee", not primary index γ. We have to note that the fitting curve for $E_0(N_e)$ function used for primary energy recovering, depends on A (the higher the A, the higher nonlinearity) and some suppositions on c. r. mass composition should be done *a priori*, making this method of primary energy estimation (through N_e) depending on the suppositions. The latter can cause additional systematic errors, while the main systematic error appears if one uses pure power law fit for N_e to E_0 recalculation thus assigning the "knee" in measured parameter N_e to primary energy spectrum. On our opinion it would be better to use another energy estimator: N_h or N_n if the detector array can measure hadrons or neutrons as our PRISMA-LHAASO experiment will do. In this case measured spectrum on N_n starts from the point when hadrons reach observational level and all coreless (hadronless) showers are automatically skipped and dependence on EAS size in neutrons follows power law [8].

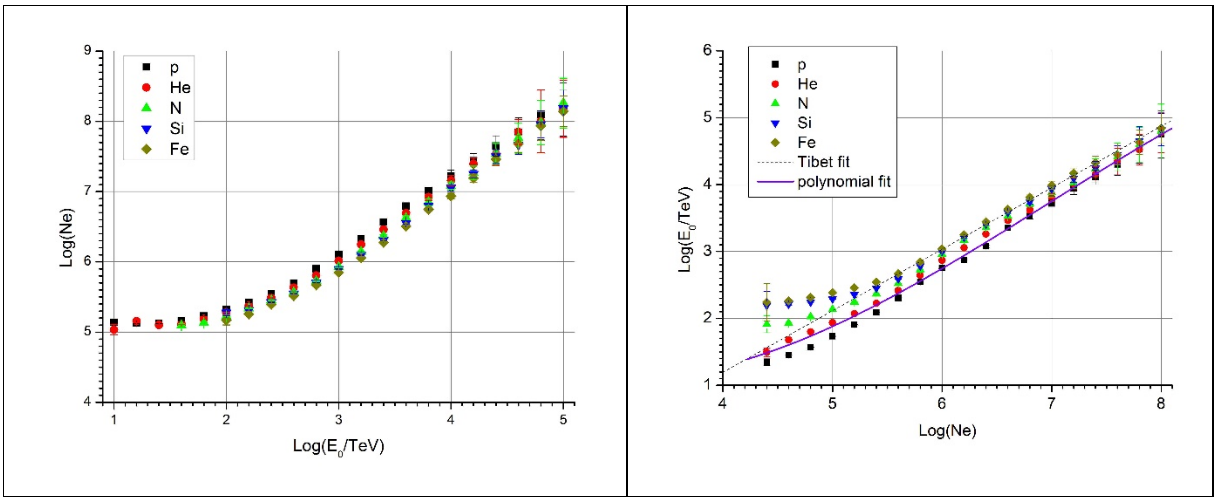

Figure 2. Averaged correlation plots between Ne and E_0 for different primaries: p, He, N, Si, Fe.
Left panel displays $N_e(E_0)$ dependence (for fixed E_0);
Right panel displays $E_0(N_e)$ dependence (for fixed Ne) where strait dashed line shows the fit used by Tibet ASγ collaboration while our best nonlinear fit for normal (light) composition is shown by a smooth curve.

Our simulations include the experimental conditions and all measurable parameters are written in the same format as experimental data and the same processing program is used both for experimental and simulated data. Results of such simulations for primary proton spectrum with the index equal to γ=2.7, is shown in figure 3.

3. Primary spectrum recovering

An interesting feature of the figure 3 is existence of a steep slope ≈1.95 below $\mathrm{Log}(N_e)<6.5$, while above this point the spectrum becomes flatter in accordance with the primary slope. The slope difference is close to 0.45 being in a good agreement with the experimental value. We have to emphasize that the result corresponds to pure power law primary spectrum! If one applies power law

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fit when recalculating from N_e to $E_{0,}$ then a “knee” will be “found” for pure power law primary spectrum. But, looking to figure 3

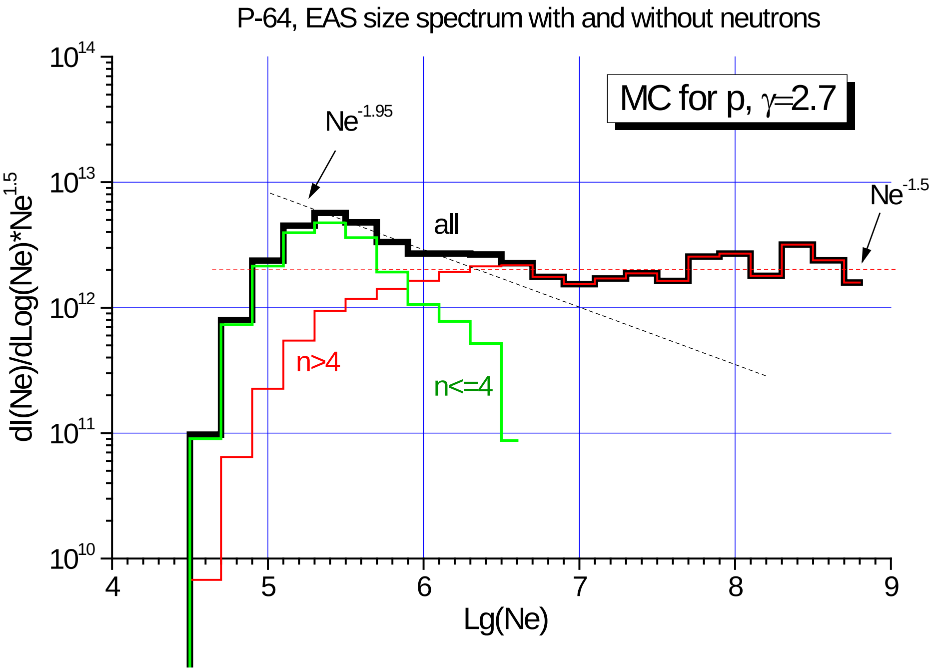

Figure 3. EAS size spectrum simulated for PRISMA-LHAASO-64.
Three groups of events are shown: with a number of recorded thermal neutrons n<=4 (neutronless), with n>4 (normal) and all events (thick histogram).

one can see that the steepening is caused by neutronless (coreless) showers marked as “n<=4” (note that neutron background included in the calculations is 1.3/event), while normal shower spectrum has no knee and goes asymptotically to the normal integral (or differential on a Log interval) slope ≈1.5. On the other hand, if one applies a polynomial fit when recalculating from N_e to $E_{0,}$ then no knee is obtained [8]. The same result was obtained for primary spectrum recovered from N_n size measurements [8] being in a good agreement with direct spectrum measurements below 1 PeV.

Another interesting feature of simulated spectra can be seen in figure 4 where the same proton spectrum is compared with the proton spectrum having a knee at 1 PeV ($\gamma1=2.7$, $\gamma2=3.1$). As it is seen, the spectra below $\text{Log}(N_e)\approx6.5$ are not sensitive to the “knee” in primary spectrum and only above this size a difference can be seen. Similar spectrum behaviour (ankle-like) between 10-100 PeV can be found in results of all experiments using EAS method (see data compilation plot in [9]), thus confirming our explanation of the “knee” origin. On our opinion, only the flat part of the “ankle” at 10-100 PeV corresponds to primary spectrum, while the steep left part does not. Note again that the spectrum index obtained in different experiments above the “knee” depends on the supposition they made concerning the cosmic ray mass composition and how carefully the simulations have been done.

Conclusion

- On our opinion so-called “knees” in EAS size spectra are the features of EAS phenomenology – its specific behavior below some energy depending on altitude of observation.

- EAS method gives correct result only above Log(Ne) > ~6.5 (or E_0>1-5 PeV depending on altitude).

Only above this EAS size threshold, an equilibrium between EAS components is reached and EAS method works properly.

- There are two ways to solve the problem:
- ➢ recording of hadronic component over full EAS area and using its number as an energy estimator;
- ➢ make very careful simulations using traditional EAS method and take into account that recalculation from N_e to E_0 gives non power law function depending on primary mass A, altitude, trigger conditions, etc.

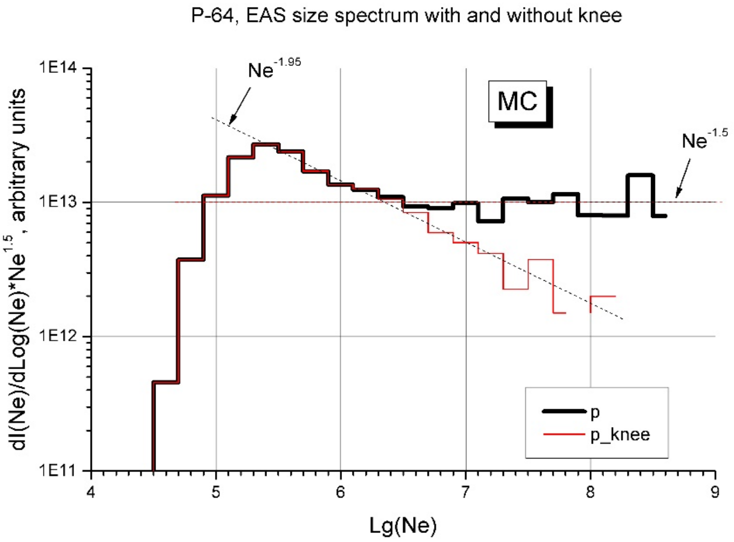

Figure 4. EAS size spectrum simulated for PRISMA-LHAASO-64 for primary proton spectrum with (thin line) and without a knee (thick line).

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