On The "Knee" In Primary Cosmic Ray Spectrum

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Abstract

An approach is proposed to solve the "knee" problem from the experimental point of view, whereas the primary spectrum would follow a pure power law.

1. The EAS technique: *pro et contra*

In 1958 there was published a paper[1] claiming the existence of the "knee" in primary cosmic ray spectrum and its possible explanation. Other experiments later confirmed the "knee" existence in various EAS components. Direct measurements of primary cosmic ray nuclei spectra at satellites[2] and balloons[3, 4] made up to energy ∼1 PeV do not confirm deviation from a pure power law at energies above 10 TeV. All the experimental data confirming the "knee" existence are originated from *indirect measurements* using the EAS technique. Some physicists tried to explain the visible knee by a dramatic change in parameters of particle interactions[5 − 7]. The details of current approach can found elsewhere[8].

An advantage of the EAS method is a possibility to work up to the highest energy. But, the indirect measurements have to be recalculated to primary spectrum. This is a complicated and model dependent problem. If the primary spectrum follows a power law function of a type: $I \sim E_0{}^{-\gamma}$ and a secondary component N_x also follows a power law: $N_x \sim E_0{}^{\alpha}$, then $I \sim N_x{}^{-\beta}$, where $\beta = \gamma/\alpha$. If a break in a power law of experimental data distribution exists , then a change in any of the two indices (γ or α) may be responsible for this.

Suppose the primary spectrum index γ changes at a point $E_0 = E_{knee}$ from γ to $\gamma + \Delta\gamma$. Then, one can expect a predictable break in the index β for each component: $\Delta\beta = \Delta\gamma/\alpha$. Typical values for α are the following: $\alpha_e \approx 1.1\text{-}1.25$ for electron component and $\alpha_h \approx 0.8$ - 0.9 for hadronic and muonic components. If $\Delta\gamma = 0.5$, then expected values are: $\Delta\beta_e \approx 0.44$ for electrons and $\Delta\beta_h \approx 0.6$ for hadrons and muons. But this contradicts observations[9 − 11] where the knee in muonic and in hadronic components is equal to only $\Delta\beta_h \approx 0.1\text{-}0.2$.

The problem of primary spectrum recovering from observable EAS parameters is additionally complicated due to uncertainties in primaries mass composition. But, there exists a clear experimental evidence[12] against a significant change in mass composition: position of EAS maximum in the atmosphere (x_{max}) can be described by a pure logarithmic law in a very wide primary energy (E_0) range from 10^{10} eV to 10^{20} eV. The latter can be drawn[12] as:

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$$x_{max}(E_0) = 70.149 log(E_0/1eV) - 555.5, \ [g/cm^2]. \tag{1}$$

2. Monte Carlo simulations and data analysis

The latest version of CORSIKA program[13] (v.6.012, standard HDPM model for high-energy hadrons) was used for calculations[8]. Simulations were performed for various primary nuclei. All-particle dependence $N_e(E_0)$ was obtained as a superposition of that for p, He, C and Fe primaries applying standard mass composition (label all-particle). As one can see from Fig.1, each distribution has a clear visible kink at energy ≈100 TeV/nucleon. We plot these distributions

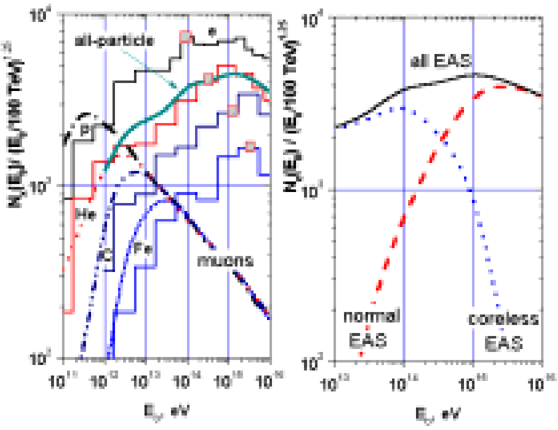

Fig. 1. Results of Monte Carlo simulations for 100 m a. s. l. altitude

Histograms – the electron number (inside R=300 m around axis) as a function of primary energy for various primaries;
— the same for all-particle standard mass composition;
- - - the same for muon number;
dashed squares indicate the start positions for *normal* EAS's;
right panel – all-particle composition EAS's and its *normal* and *coreless* branches.

divided by $(E_0/100TeV)^{1.25}$. The curve for all-particle distribution can be fitted in 3 energy ranges as follows:

$$N_e(E_0) \sim {E_0}^{1.5} \text{ at } E_0 < 0.1 \text{ PeV}; \ N_e(E_0) \sim {E_0}^{1.25} \text{ at } 2 \text{ PeV} > E_0 > 0.1 \text{ PeV}$$
$$\text{and } N_e(E_0) \sim {E_0}^{0.9} \text{ at } E_0 > 6 \text{ PeV}.$$

Therefore, for arrays with a low threshold there should be detected two "knees" in shower size distribution. The first "knee" at $E_0 \approx 0.1$ PeV is caused by proton originated showers and the second one (at $E_0 \approx 5.6$ PeV per nucleus) is caused by iron primaries. Applying obtained indices α_e to the relations derived above one can expect following values for β_e at a constant primary spectrum slope γ=1.8:

$$\beta_e = 1.8/1.25 = 1.44 \text{ at } E_0 < 2 \text{ PeV and } \beta_e = 1.8/0.9 = 2.0 \text{ at } E_0 > 6 \text{ PeV}.$$

These slopes are very close to those observed in experiments.

Hadrons play a crucial role in the EAS development. It has been understood by G.T.Zatsepin[14] in the beginning of systematic EAS study in the 40-s. Electromagnetic component plays a secondary role and is in equilibrium with the hadronic EAS content. The Earth's atmosphere is rather thick – more than 11 hadron interaction lengths at sea level. That is why at low primary energy, hadrons do not reach an observational level. Only muon and electron components can reach a detector level at low energy: muons due to its very high penetrating capability and electrons due its relatively high total amount. These EAS's can be called as *coreless showers*. As it is seen in Fig.1, a kink in $N_e(E_0)$ distribution coincides with an appearance of high energy hadrons in the EAS core. At sea level this energy is $\sim$ 0.1 Pev/nucleon. This results in a dramatic change in the EAS structure and development just above the detector. At energy higher than 5-6 PeV per nucleus all showers become *coreful*. These EAS's were selected by a condition that at least 2 hadrons reach the detector level inside a ring of 1 m around the axis. There is no doubt that the slope kink in the $N_e(E_0)$ distribution exists and it is caused by the change in EAS structure. The existence of *coreless* showers as well as the threshold ($N_e \sim 10^5$) for appearance of *coreful* EAS were established experimentally[15] many years ago. The dependence of the "knee" position on detector level is shown in Fig.2 for primary carbon (for example).

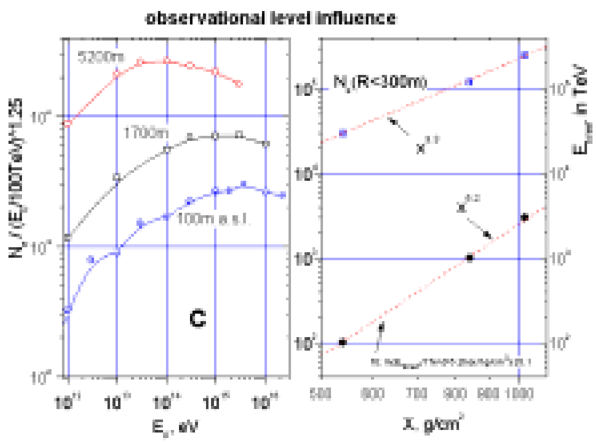

Fig. 2. Results of Monte Carlo simulations for primary carbon at various observational altitudes.

On the right panel: upper points correspond to N_e^{knee} and lower points to ${E_0}^{knee}$ dependence on the observational depth.

3. The longitudinal EAS development and primary spectrum

To explain slow attenuation of EAS, big fluctuations in its longitudinal development and an existence of a pole of particle density in its axis, one should suppose[16] that EAS development and all its components are in equilibrium with the number of high-energy hadrons in the core. The mean longitudinal development of the hadronic shower size after the maximum can be expressed[8] as:

$$N_e(x, E_0) \approx kN_h(E_0)exp(-(x - x_{max})/\Lambda_{att}), \tag{2}$$

where k= N_e/N_h =const. $N_h(E_0) \sim {E_0}^{\delta}$ is the number of hadrons in the core in the shower maximum, x_{max} is a depth of the shower maximum in the atmosphere (in g/cm^2) and Λ_{att} is the length of EAS attenuation (in g/cm^2). By combining eqs. (1) and (2) one obtains in a case of normal EAS an estimation of the slope:

$$\alpha_e = d(ln(N_e))/d(ln(E_0)) = \delta + 30.5/\Lambda_{att}. \tag{3}$$

Therefore, the slope depends on the EAS attenuation length. If δ=0.75 and measured[17] Λ_{att}=180 g/cm^2 then α_e=0.92. This value is very close to the CORSIKA result at energies above the "knee". As it was shown[8] the slope α_{e0} of the $N_{e0}(E_0)$ dependence in a case of *coreless* EAS is following:

$$\alpha_{e0} = d(ln(N_{e0}))/d(ln(E_0)) = \delta \times \Lambda_{att}/\Lambda_{em} + 30.5/\Lambda_{em} \quad (4)$$

Taking the same δ, Λ_{att} and Λ_{em}≈100 g/cm^2, one can obtain: α_{e0}≈1.6. This value is close to CORSIKA result below primary energy of 0.1 PeV/nucleon. The range between two "knees" is a transitional one with the mean slope equal to (1.6+0.9)/2=1.25. This coincides with CORSIKA result shown in fig.1.

The expected difference in the spectrum slope for normal and *coreless* EAS in a case of hadronic component is equal to zero. One can see this by substituting Λ_{att} instead of Λ_{em} in eq.(4). A similar situation exists in a case of muonic component. Calculations for Cherenkov light are in progress.

4. Summary

• The index of all-particle primary cosmic ray energy spectrum does not likely change significantly in a range of 0.1 – 10 PeV.
• The "knee" observed experimentally in secondary EAS components is caused by EAS structure change at energy $\sim 0.1 PeV/nucleon$. Below this energy, EAS's at sea level are mostly *coreless* while above this threshold EAS's are mostly *coreful*.
• Due to different primary masses the transition region lasts from ∼0.1 PeV/particle (proton "knee") up to ∼6 PeV/particle when iron primary exceeds the threshold (iron "knee").

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