ON THE COSMIC RAY ENERGY SPECTRUM "KNEES" – PHENOMENOLOGICAL APPROACH

Yuri V. Stenkin (INR RAS)

The cosmic ray spectrum



Up to 1949 EAS was considered as a pure e-m cascade in atmosphere. Then George Zatsepin showed that this simplification was not true and EAS is a hadronic cascade while e-m component is produced by π^0 decays. This results in that the two components are in equilibrium and all EAS features are defined by the hadronic component being a "skeleton" of the shower. (G.T. Zatsepin, DAN SSSR, 67, 993 (1949)).

The latter means one needs to study hadronic component first of all.

But up to date people use e-m theory of cascade development (NKG function, ages, etc.) and measure mostly electronic component, sometimes muonic and very rarely hadronic one.

Up to date nobody put lower limit to primary energy when the EAS method starts working properly.

Experimental data compilation



arXiv:1803.01288v1 [astro-ph.HE] 4 Mar 2018

P, He by Tibet hybrid Experiment (Phys. Lett. B, 632, 58 (2006))



1) Our results shows that the main component responsible for the knee structure of the all particle spectrum is heavier than helium nuclei.

The knee for light components @ 200-300 TeV?

KASCADE conclusion: the knee is caused by proton flux decrease above 3 PeV !



FIG. 3. H&He spectrum by the hybrid experiment with ARGO-YBJ and the imaging Cherenkov telescope. A clear knee structure is observed. The dashed line represents the fit to the data. The singleindex spectrum below 700 TeV and its extrapolation up to 3160 TeV (solid line) has been used as an *a priori* assumption. The H&Hespectra by CREAM⁵, ARGO-YBJ¹³ and the hybrid experiment¹⁵ below the knee, the spectra by Tibet AS γ^7 and KASCADE⁸ above the knee are shown for comparison. The shaded areas represent the systematic uncertainty.

arXiv:1502.03164v1 [astro-ph.HE] 11 Feb 2015

It would be very strange to believe in existence of 3 "knees" between 0.3 and 5 PeV.

More probably to suppose an existence of a methodical knee depending on the array altitude and on the data processing.

Phenomenological approach can solve this problem.

Phenomenological approach

(proposed in: Yu. Stenkin. Mod. Phys. Lett. A, **18**, 1225 (2003)

<u>The idea is:</u>

1. Primary spectrum follows pure power law: $F \sim E^{-\gamma}$. 2. The «knee» visible in the EAS e-m component ($\sim N_e^{-\gamma/\alpha}$) is caused by a <u>break of equilibrium</u> between the main hadronic and secondary e-m components at a point where the number of cascading hadrons becomes close to 1 and then to 0, resulting in a break of α in a function $N_e(E_0) \sim E_0^{\alpha}$. 3. There are no knees in other EAS components (h, μ). To check this we proposed the PRISMA project to measure hadronic component

$$I \sim E^{-\gamma}$$

$$N_{x} \sim E^{\alpha}$$

$$I \sim N_{x}^{-\beta}$$

$$\beta = \gamma/\alpha$$

$$\beta_{e} = \gamma/\alpha_{e} = 1.7/1.1 \approx 1.5$$

$$\beta_{h} = \gamma/\alpha_{h} = 1.7/0.9 \approx 1.9$$

$$\mu = \alpha_{h} \approx 0.9$$

$$\mu = \alpha_{h} \approx 0.9$$

The array of 64 en-detectors (4 clusters) under construction in conjunction with LHAASO project cluster

PRISMA-LHAASO

Future plan: 400 en-detectors (25 clusters)







WASDHA2018, Moscow

How correct reconstruction must be done:



 $N_e \neq E_0^{\ \alpha}$ because $\alpha \neq \text{const}$

Therefore, the knee is produced by change of α not γ

Such plot should be calculated for each experiment with the highest accuracy

Yu. V. Stenkin. WASDHA2018, Moscow





Simulations for the future PRISMA-LHAASO-64 experiment (CORSIKA+GEANT)

4300 m a.s.l.

<u>Tibet-AS fit from:</u> ArXiv: 0803.1005v1[astro-ph] 6Mar 2008

ARGO-YBJ calculations



Mass independent Energy reconstruction



M-C at 4300 m a.s.l. Ne8 \rightarrow number of particles inside the ring of 8 m



Simulation for PRISMA-64: EAS size spectrum for $\gamma=2.7$



Therefore, by measuring neutrons we can reject hadronless (coreless) EAS

Simulation for PRISMA-64: EAS size spectrum for $\gamma=2.7$ at E<1 PeV and $\gamma=3.1$ at E>1 PeV



Therefore, the most informative region in Ne is Ne>6.5: In case of knee the slope above Ne>6.5 could give the answer while below Ne=6.5 not!

Experimental data compilation



arXiv:1803.01288v1 [astro-ph.HE] 4 Mar 2018

KASCADE

No knee in hadrons!

simulations



CASCADE data on hadron number spectrum, agree well with spectrum without knee! Maybe this is a reason for absence of journal papers?

J. Horandel, et al. A measurement of the primary cosmic–ray energy spectrum using the hadronic air shower component. ICRC2001, ID 137.

Result of PRISMA-YBJ from Nn measurement



Result of PRISMA-YBJ from Nn measurement



Altitude knee dependence (shown in Pune ICRC, 2005)

So, the "knee" was observed at fixed Ne and NOT at fixed E₀ as expected in astrophysical model





Yu. V. Stenkin. WASDHA2018, Moscow

Conclusion

- On my opinion so-called "knees" in EAS size spectra are the features of EAS phenomenology – its specific behavior at some threshold energy depending on altitude of observation producing a systematic "knee" (at fixed Ne).
- Conventional EAS method gives correct result only above Ne ~ 10⁶.
- Only above this size an equilibrium between EAS components is reached and EAS method works properly.
- There are two ways to solve this problem:
- recording of hadronic component over full EAS area and using it as energy estimator (the easiest way),
- > or make very careful simulations and take into account that recalculation from Ne to E_0 gives non power law function.

