Remarks on astrophysical origin of the knee in cosmic ray spectrum

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All astrophysical explanations of the knee in cosmic ray spectrum accept the hypothesis of its existence a priori without any doubt. But, there exist experimental evidences against this hypothesis. Experimental data on the knee in various secondary cosmic ray components obtained by KASCADE array as well as by many other arrays reveal the existence of the knee ($\Delta \gamma \approx 0.4 \div 0.5$) in electromagnetic component (e and $\gamma$ including Cherenkov light) and the absence of it or a very small knee ($\Delta \gamma \approx 0.1 \div 0.2$) in muonic and hadronic components. But, one could expect the inverse relationship in case of the astrophysical knee origin. A brief review of experimental data concerning this problem is given.

1. Introduction

The astrophysical origin of the so-called "knee" in primary cosmic ray spectrum in PeV region is very popular and is widely exploited in practice for a long time of about 50 years. This hypothesis seems to have begun a new life in the recent years after discovering some new Supernova remnants. But, experimental data accumulated up to now in cosmic ray physics seed some doubt on the "knee" existence. One could argue that there exists no theory able to explain pure power law spectrum in a very wide range from $10^{10}$ to $10^{20}$ eV. But, such a theory does exist [1]. It was published many years ago and proposed a universal mechanism of cosmic ray acceleration in the cosmic plasma pinches. This theory can explain not only power law spectrum but even the value of its power law index $\gamma$. This mechanism can generate cosmic rays up to the highest energy with the integral exponent $\gamma = \sqrt{3} \approx 1.73$. Another outgoing feature of this mechanism is as follows: the index does not depend on a particle mass or charge. It is really a universal value.

2. Brief review of the experimental data

Let us look at the problem from the experimental point of view [2]. Direct measurements do not show any significant change in the spectrum slope up to energy 1 PeV. The "knee" in the size spectrum is only seen in secondary cosmic ray components measured by Extensive Air Shower (EAS). If primary spectrum index is $\gamma$ and a secondary x-component depends on primary energy $E_0$ as $N_x(E_0) \sim E_0^{\alpha_x}$ then the EAS-size distribution on $N_x$ is $P(N_x) \sim N_x^{-\beta}$, where $\beta = \gamma/\alpha$. If the "knee" in primary spectrum does exist (let it be $\Delta \gamma = 0.5$) one can predict with rather high accuracy a relationship between the "knees" in all detectable secondary components: electromagnetic, muonic and hadronic. Index $\alpha$ commonly used for electrons is equal to $\alpha_e = 1.15 - 1.25$ (so $\Delta \beta_e = \Delta \gamma/\alpha_e \approx 0.42$) and that for muons and hadrons is equal to $\alpha_{\mu,h} = 0.8 - 0.95$.

Therefore, the visible "knee" ($\Delta \beta_{\mu,h} \approx 0.5/0.87 \approx 0.57$) in muonic and hadronic components is expected to be bigger than in electrons (in EAS size spectrum) and even bigger than in primary spectrum, because $\alpha_{\mu,h} < 1$ while $\alpha_e > 1$. It is a very strict limitation because $\alpha_{\mu,h}$ and $\alpha_e$ were measured in many experiments and were calculated by many authors using different Monte-Carlo programs. In this paper I would like to emphasize that experimental data on a visible "knee" in different secondary components contradict this limitation. In other words, the values of the "knee" in primary cosmic ray spec-
Table 1
Measurements, predictions or expectations for the knee value

| $\Delta \beta_e$ | $\Delta \beta_\mu$ | $\Delta \beta_h$ | $\Delta \gamma$ | Reference |
|------------------|-------------------|-----------------|---------------|-----------|
| 0.42             | 0.57              | 0.57            | $\equiv 0.5$  | (in a case of knee) |
| $\approx 0.47$ (Č) | -                 | -               | -             | TUNKA\textsuperscript{10} |
| 0.57 (e); 0.52 (Č) | -                 | -               | 0.5 ± 0.6     | HEGRA\textsuperscript{12} |
| $\approx 0.40$   | $\approx 0.2$ for all | -               | 0.2 ± 0.02 for all | KASCADE\textsuperscript{3} |
| $-$              | $-$               | 0.11 ± 0.02 for $\Sigma E_h$ | - | KASCADE\textsuperscript{4} |
| $-$              | -                 | 0.2 ± 0.1 for $N_h$ | - | KASCADE\textsuperscript{4} |
| 0.35 ± 0.1 (vertical) | 0                 | -               | 0.40 ± 0.12   | AKENO\textsuperscript{5} |
| 0.42 ± 0.03      | -                 | -               | $\approx 0.4 \div 0.5$ | MSU EAS\textsuperscript{6} |
| $\sim 0$         | $\sim 0$         | -               | -             | MSU EAS\textsuperscript{7} |
| 0.43 ± 0.09      | 0.4 ± 0.1         | -               | 0.4 ± 0.1     | EAS-TOP\textsuperscript{8} |
| $-$              | $\approx 0$      | -               | -             | GAMMA\textsuperscript{13} |
| $-$              | $\sim 0$         | -               | 0             | underground $\mu$\textsuperscript{9} |
| $-$              | $\sim 0$         | -               | -             | DELPHI\textsuperscript{14} |
| $-$              | $\sim 0$         | -               | -             | ALEPH\textsuperscript{15} |
| $\approx 0.5$    | $\sim 0$         | $\sim 0$        | 0             | prediction\textsuperscript{2} |

trum reconstructed from different secondary components are not equal and contradict each other as is seen in Table 1. In all experiments shown above $\Delta \beta_e > \Delta \beta_\mu \approx \Delta \beta_h$. The most detailed and careful measurements in the knee region have been performed by KASCADE experiment specially designed to solve this problem. The "knees" claimed by the authors in muonic and hadronic components are much less than expected ones (even equal to 0 for 'e-poor' EAS's) and are very smooth and thus could be regarded from my point of view as a smooth change of the power index in a very wide range due to methodical or other reasons to be discussed below. Therefore, their values could be regarded as the upper limits for the "knee". If so, the KASCADE data are consistent with the "zero knee" hypothesis made on the basis of all available data analysis\textsuperscript{3} of the deep underground muon experiments (Baksan, Frejus, NUSEX, MACRO, SOUDAN2). In fact, only 2 experimental groups have confirmed the existence of the knee in the EAS muonic component comparable with that for the electron component: MSU EAS and EAS-TOP. But their data need special comments. MSU EAS muon data obtained with muon detectors do not reveal a knee. What is usually shown by the authors is a muon number spectrum recalculated from the electron number spectrum. Therefore, it must have the knee close to that in EAS size spectrum. As for EAS-TOP data, their muon number spectra shown in\textsuperscript{8} (and in other publications as well) could be successfully fitted by a pure power law by taking into account statistical errors and the points spread. Moreover, the results of these two experiments contradict each other because EAS-TOP claimed the knee in muonic component ($E_\mu > 1$ GeV) at $N_\mu = 10^{4.9}$ while MSU EAS group ($E_\mu > 10$ GeV) do not see any knee above $N_\mu = 10^{4}$ (the difference in muon threshold energy gives a factor of 5-6 while the difference in figures is higher and the difference in altitude of $\sim 200g/cm^2$ is negligible for muons). The result of AKENO combined in\textsuperscript{5} with SUGAR data\textsuperscript{16} gave a rather strict limitation for muon size spectrum as follows: "...there is no change of slope in muon size spectrum between $10^5$ and $10^9$ ". Another strict limitation starting from a very low muon
size has been given by GAMMA data \[13\] for muons with energy above 5 GeV: "The spectrum above \(N_\mu > 7000\) is well described by the power law dependence \(F(> N_\mu) \sim N_\mu^{-2.18}\)."

An absolute value of the power law index \((\beta_\mu)\) has to be discussed separately. As it was demonstrated in \[17\] the indices of primary spectrum derived from measurements by different experimental groups are in disagreement. In our approach \(\gamma = \text{const}\) and everything is explained by the index \(\alpha\) behaviour, which is not constant in different experiments. This can be explained at least for the measurements of primary spectrum through the muonic component. As it has been shown \[18\] muon number spectrum is connected with the primary cosmic ray spectrum and follows power law if primary spectrum does so. In case of an infinite area detector, the simplest one corresponding to the total number of muons in EAS when \(\alpha_\mu \approx 0.7 \pm 0.8\) (let it be equal to 0.7 for estimations), the index of muon number distribution in asymptotics should be equal to \(\beta_\mu = \gamma/\alpha_\mu \approx 1.7/0.7 \approx 2.4\). Low multiplicities \((m < 5)\) are produced by low energy primaries and can be described by Poissonian or binomial distributions characteristic for the discrete values. Such a spectrum was observed in many underground experiments (see for example \[9\]) using large area detectors for recording of muons with a high energy threshold without any EAS trigger (case (a)). A similar result is expected for small underground detectors but only the ratio of single muon flux \((m=1)\) to that for muons in groups \((m > 1)\) is expected to be much higher. Another interesting feature of such experiments (without EAS core location) is the so-called core attraction effect \[20\]: the higher multiplicity in the detector is - the sharper recorded EAS core lateral distribution centered in the detector is. This effect results in a measurement of not the total number of muons integrated over all distances up to infinity but of only the central muon density having a pole in the axis where the exponent is equal to \(\alpha_\mu \approx 1\). Therefore, the measured muon number spectrum at very high multiplicity (where the pole does exist) should be flatter \[21\] having the index \(\beta_\mu = \gamma/\alpha_\mu \approx 1.7/1.0 = 1.7\). The latter could probably explain the problem with the highest multiplicity events observed in the CERN detectors ALEPH and DELPHI. In real underground experiments due to different experimental and trigger conditions and due to different statistics, the measured integral index should lie between these two extreme values \((\beta \approx 2.4 \div 1.7)\).

The opposite case (b) occurs when the muon detector is working under the EAS array trigger. If the data are corrected for the trigger bias then the EAS muon size spectrum will follow the power law with \(\beta \approx 2.4\). If no corrections are applied then the measured muon multiplicity spectrum is very flat at low multiplicity \((\beta \approx 0.7)\) \[18,19,20\] according to the Poissonian distribution with the high mathematical expectation \((m_0 > 1)\) which depends on the EAS size threshold and on the muon detector total area. Only at a high enough number of muons, the spectrum becomes as steep as in case (a). This effect could imitate the expected knee in primary spectrum. If muon density is measured at fixed core distances (as in KASCADE and many other EAS experiments) then the core attraction effect does not work and no flattening occurs at high multiplicity in such experiments. Here could be probably found the difference in experimental data at the highest muon density measurements between EAS arrays and underground detectors.

Unfortunately there exist very few data on the hadronic EAS size spectrum measurements free of trigger conditions bias. I found only one experiment \[11\] providing such data.

We can conclude that none of the experiments has shown undoubtedly the knee existence in muonic or hadronic component in the needed place and of the needed size as could be expected in case of real knee existence in primary spectrum.

3. Summary

Summarizing the experimental data shown above we can conclude that the question "Does the knee exist or not?" is still open. Therefore, the main efforts should be directed now not to explanations of the "knee" but to the question...
above. Only when this question is answered positively an astrophysical explanation of the "knee" existence in primary cosmic ray spectrum will be needed. Up to date I incline to a negative answer to this question, because only in this case we could understand the experimental data. In the frame of the approach proposed in [2] there exists a natural explanation of the visible "disagreement" of the experimental data shown in Table 1: the "knee" does not exist in primary cosmic ray spectrum and should be observed only in electromagnetic component due to non-power law behaviour of the $N_e(E_0)$ in a region of $\sim 100$ TeV/nucleon when hadron core reaches the sea level and coreless EAS's become coreful or normal ones. Muons and hadrons are almost insensitive to this critical point of the EAS development and follow a power law much better.

Looking at Table 1 we can conclude that the measured data are more consistent with the prediction [2] shown in the last line than with the expectations made above under a supposition of the "knee" existence (first line). And finally: if the answer is negative then we probably have a natural universal theory of cosmic ray acceleration [1]. To confirm or to reject this theory we have to measure the spectrum index $\gamma$ with high accuracy and answer the question: "Does it equal to $\sqrt{3}$ or not?"

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