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Is the primary energy spectrum around the "knee" a statistical game?(*)

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Summary. — The present state of research of the shape of the energy spectrum of primary cosmic ray nuclei and the chemical composition in the region of the so-called, "knee", and beyond is highly unsatisfactory. We are not very successful when using extensive air showers. In the present paper an attempt is made to explain what is the cause of such a situation. The experimental results as to which there is no doubt that they were wrongly interpreted, will be indicated.

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1. – Introduction

The experimental situation in the region up to the bending and above the "knee" changes very slowly through the years. The new experimental results of RUNJOB [1] explain the situation up to the energy of several times 10^{14} eV per nucleus. On the basis of these experimental data it can be observed that there is a good agreement between the intensities of the nuclei at the top of the atmosphere, measured directly in different experiments (JACEE, SOKOL). The slopes of the spectra, for the description of which the power of $E^{-\gamma}$ was assumed, are different for various groups of nuclei: $\gamma_{\mathrm{H}} = \gamma_{\mathrm{He}} = 2.8$, $\gamma_{\mathrm{CNO}} = 2.65$, $\gamma_{\mathrm{Fe}} = 2.55$, $\gamma_{\mathrm{all}} = 2.6$–$2.7$. It was confirmed by the new RUNJOB data that in case of heavy nuclei (CNO, Fe) the spectra are flatter than for the primary light nuclei (H, He). At present, the data concerning helium is more coherent than it was in the earlier experiments. Additionally, the received values of $\langle \ln A \rangle$ indicate at the same time that the primary light nuclei dominate; however, they are encumbered with a large error and this makes it difficult to extrapolate them up to higher energies. The given interval

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of γ values for all the nuclei corresponds well to the results of the KASCADE [2], where the value $\gamma = 2.7$ is given with great accuracy (± 0.05) in the region up to the "knee" in the all nuclei primary spectrum. The KASCADE collaboration has also proved that neither the total number of charged particles N_{ch} nor the total number of electrons N_{e} are appropriate parameters when the values of energies E_{p} are estimated for the primary nuclei, initiating showers. According to the data of this collaboration, at the evaluation of primary energies the values of the ratio of logarithms of the measured number of muons in the showers N_{μ}^{tr} to the number of electrons N_{e} should be used.

The new results of CASA-MIA [3] lead to a similar conclusion. In this experiment a parameter $\log(N_{\mathrm{e}}+\xi N_{\mu})$ is used for evaluation of the primary energy. A new method of estimating primary energy is essentially different from the methods used so far, *i.e.* AKENO, TIBET. The value of the total number of muons in showers is of great importance as that is the component of the fluctuations which are considerably narrower than fluctuations of the number of electrons. In spite of the marked progress, made by the use of uncorrelated components (see below) for the estimation of primary energies, there are still many problems requiring explanation.

2. – Correlation of different components in the showers

It is generally believed by the Extensive Air Shower physics researches that measurement of a greater number of shower components improves the quality of the obtained estimations of energy spectrum and primary mass composition of cosmic radiation. From the logical point of view such a standpoint seems to be correct, although a theory of information recommends some caution in the uncritical adoption of such an approach.

In the KASCADE experiment a group of several thousand of the "so-called" central showers [4] has been investigated. They are the showers the axes of which were localized in the middle part of the calorimeter. Localization of such showers is about two times better than those localized inside the arrays. Additionally, full information about the cores of such showers, fractal structures in the images of those cores can be available. It is important that the detectors around the calorimeter should be placed symmetrically that provides the best evaluation of such parameters as the shapes of lateral distributions and total numbers of registered particles.

Fractal structures of high energy muons were used for the separation of proton-like and iron-like showers from the group of total showers. Then the integral spectra of such showers, divided into groups of all proton-like and iron-like showers, were obtained; the following parameters were used to construct such spectra: the total number of electrons N_{e}, the total number of hadrons N_{h}, the number of measured muons N_{μ}^{tr} as well as the energies of hadrons with the highest energy in these showers $E_{\mathrm{h\,max}}$. The results obtained by us are [4] presented in fig. 1.

At least two conclusions can be drawn when comparing the spectra shown in the figures and the figures themselves:

a) if, for the analysis of the data, the parameters N_{e} or N_{h} are chosen, then the received results are very similar, which means that the spectrum of all showers is dominated by protons and is flatter (see fig. 1a and c);

b) the second couple of parameters, N_{μ}^{th} and $E_{\mathrm{h\,max}}$ of hadrons, give results considerably different form the former; namely, the spectra are steeper, approximately parallel to each other in particular groups (fig. 1b and d).

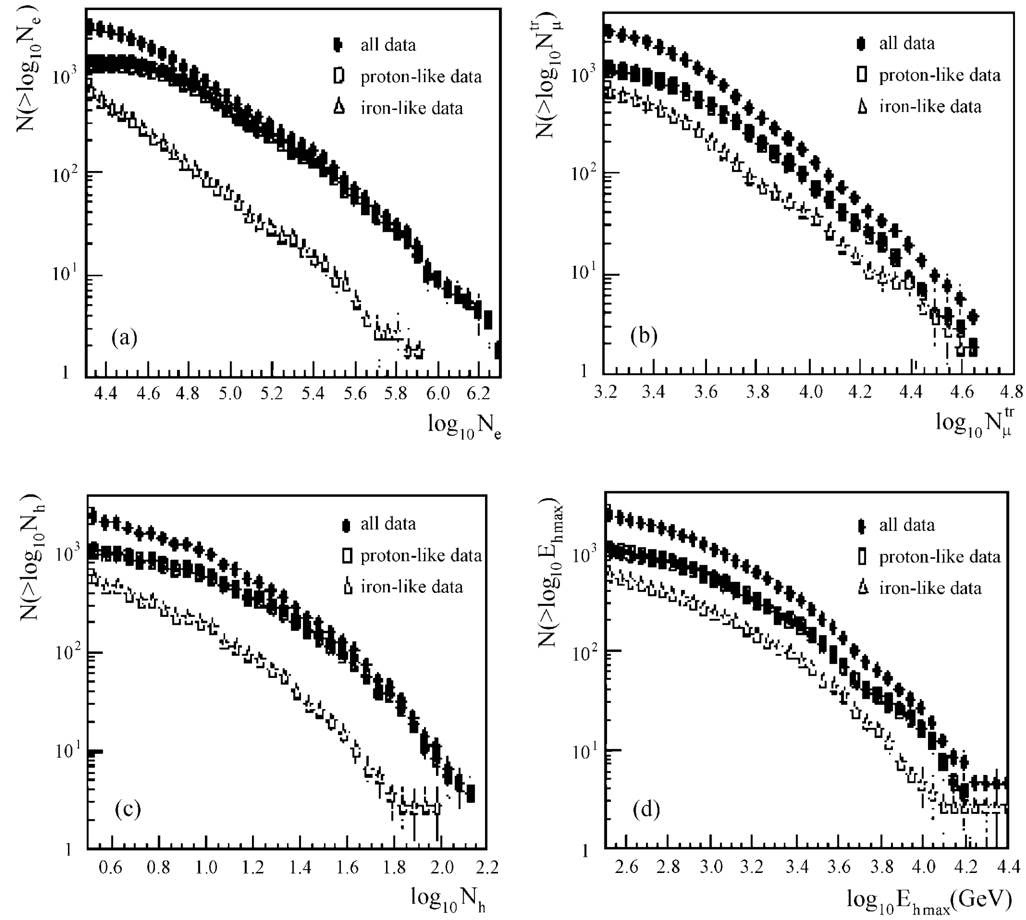

Fig. 1. – Integral spectra of different components for the “central” showers: the spectra of the total number of electrons N_{e} top left (a); total number of the measured muons N_{μ}^{tr} top right (b); hadrons N_{h} down left (c) and of hadrons with the highest energies E_{hmax} down right (d). Fractal analysis of the central part of individual showers made it possible to separate proton-like and iron-like showers out of the group of the total showers.

When reconstructing the energy spectrum of primary nuclei on the basis of N_{e} or N_{h} parameters as well as on N_{μ}^{th} and $E_{\mathrm{h\,max}}$ we can easily get results, which differ from each other. It concerns not only the shapes of these spectra but also the possible attempt of the evaluation of the chemical composition of the primary cosmic radiation. That is the reason why we refer to “the statistical game” in the title of the present paper. The following fact should be taken into considerations in pairs: When such results of two components are used in the analysis of the data, the attention should also be paid to the fact of whether those components are correlated or not. If they are, there is no use of applying them together.

The conclusions presented in the paragraph are well confirmed by the the results obtained at Kiel [5] (fig. 2b) and ANI [8].

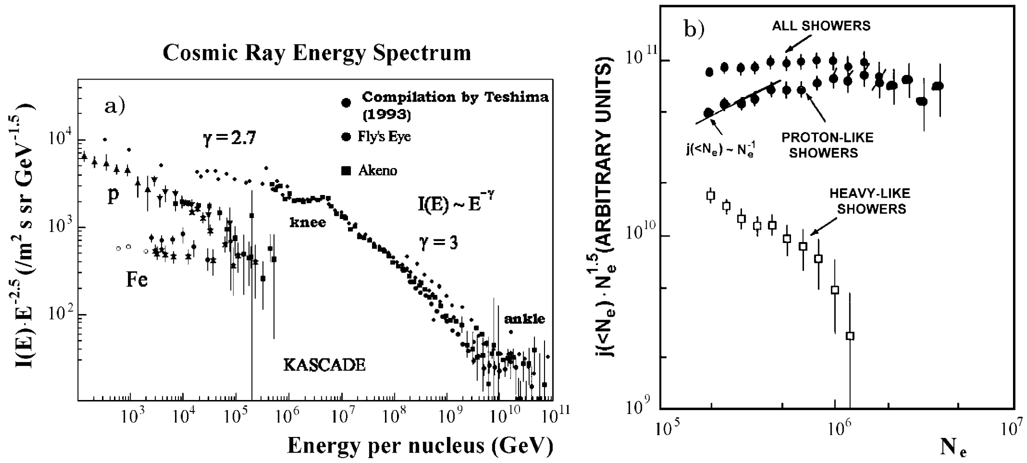

Fig. 2. – a) Compilation of the experimental data regarding the energy spectra of primary cosmic radiation (after [6]). A very flat part with $\gamma = 2.5$ is clearly visible in the region of the—so called—“knee” [7]. b) The integral spectra of the showers registered by the Kiel device [5].

3. – The shape of the spectrum and the chemical composition in the region of the “knee”

The shape of the spectrum at the “knee”, between 10^{14} eV and $4 \cdot 10^{15}$ eV, as received by the KASCADE collaboration [2] can be described by the power spectrum with the exponent 2.7 (fig. 3a). It is basically different from the spectrum obtained by AKENO [7], where the received exponent was $\gamma = 2.5$ (fig. 2a). In the light of what was said above, it is clear that these results were received in a sophisticated but false way, with the use of the total electron number N_e at the reconstruction of the primary spectrum. The value of

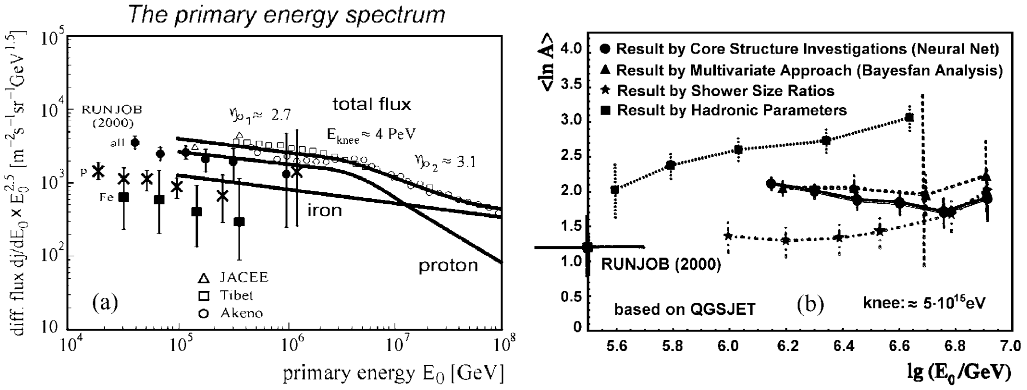

Fig. 3. – a) The comparison of the KASCADE results [2] with the new results of the RUNJOB(2000) [1]. It is clearly visible that there is a systematic shift of these two groups of data. b) Mean value $\langle \ln A \rangle$ of natural logarithm of the mass of primary cosmic radiation nuclei [2, 9] from the KASCADE experiment. The point for the highest energy from the RUNJOB(2000) [1] is also presented.

TABLE I. – *a) Approximation of the spectrum of the total electron number* N_{e} *and the spectrum of the measured number of muons* N_{μ}^{tr} *in different intervals of these parameters. Proton showers. b) The slopes of differential spectra in various intervals of* N_{e} *and* N_{μ}^{tr}*. Iron showers.*

a)		b)	
$\log N_{\mathrm{e}}$	γ	$\log N_{\mathrm{e}}$	γ
4.0–4.7	1.98 ± 0.02	4.0–4.3	2.08 ± 0.05
4.7–5.2	2.39 ± 0.03	4.5–5.0	2.17 ± 0.01
5.2–5.9	2.73 ± 0.07	5.0–5.6	2.85 ± 0.05
$\log N_{\mu}^{\mathrm{tr}}$	γ	$\log N_{\mu}^{\mathrm{tr}}$	γ
2.8–3.5	2.77 ± 0.01	2.8–3.5	2.66 ± 0.01
3.5–4.0	3.03 ± 0.03	3.5–4.0	2.63 ± 0.08
		4.1–4.3	3.68 ± 0.11

$\gamma = 2.7$ is also in better agreement with the direct measurements of RUNJOB(2000) [1]. The chemical composition in the discussed region is still an open problem (fig. 3b). The results of RUNJOB(2000), although encumbered with a large error, seem to prefer a “light” composition. Various methods of data analysis in the KASCADE give a range of possible ways of behaviour of the chemical composition in the region up to and just above the bending in the primary spectrum.

4. – Which spectra are power spectra?

The spectra of different components of the shower as well as the energy spectra of particular groups of nuclei are usually described by a power function. To what extent is such a procedure justified? A series of two calculations were made with the use of the CORSIKA programm with the QGSJET model [10] for primary protons and for iron nuclei. The power spectrum assumed for primary protons was described with the exponent 2.7 up to the bending ($E_{\text{“knee”}} = 3 \cdot 10^{15}$ eV) and 3.1 above the bending. These spectra where checked again after Monte Carlo simulations were made. The N_{e} and N_{μ}^{tr} spectra were analyzed for the showers taken at random at the KASCADE level and then these spectra were approximated by a power function. The obtained results of such an approximation are presented in table Ia).

The results of similar calculations for the showers, which were initiated by primary iron nuclei ($\gamma_1 = 2.5$, $E_{\text{“knee”}} = 3 \cdot 10^{15}$ eV, $\gamma_2 = 3.1$) are presented in table Ib.

The results presented in the tables Ia and Ib show explicitly that it cannot be expected that from the power spectra of primary nuclei the spectra of the parameters N_{e} and N_{μ}^{tr}, such as measured in the showers, are derived from being described by a power function in the wide range of their values. The image received in the N_{e} spectra is similar to the discussed earlier results of the “central” showers in the KASCADE: at first the spectrum is flatter and then the slopes of the spectra slowly increase with N_{e}. For N_{μ}^{tr} the effect is different: there is no flattening caused by wide fluctuations, responsible for the shape of the N_{e} spectrum, although the slopes increase with the increase of N_{μ}^{tr}.

The results of the Kiel experiment (fig. 2b) for the integral spectra of the total electron number N_{e} seem to confirm the fact that this spectrum cannot be described with only one power function in the wide range on N_{e}. Similar results have been received lately in

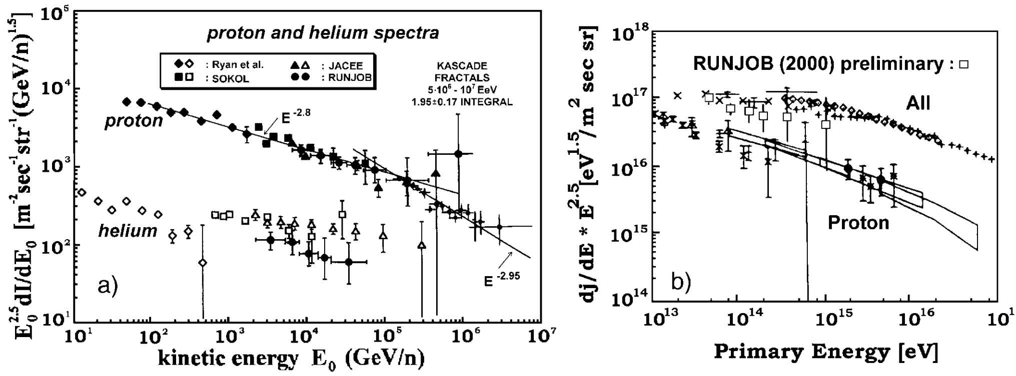

Fig. 4. – a) Differential primary spectra for hydrogen and helium nuclei [1] complemented with the Tibet [11] results as well as the KASCADE results [4] for the energy above 10^{14} eV. b) The energy spectra of all nuclei and also for primary protons (after [11]). For comparison there are also presented preliminary RUNJOB(2000) data [1] for all nuclei.

the ANI experiment [8]. So either the spectra of N_{e} and N_{μ}^{tr} are both of the power form while the primary spectra are not or the situation is quite opposite.

5. – The primary spectrum of light nuclei

The primary spectra of protons and alpha-particles, as measured by RUNJOB(2000) [1], are presented in fig. 4a and complemented with the results of Tibet AS γ [11] for the higher energies. The data were presented without any relative normalization. Preliminarily, they suggest that the slope of the primary proton spectrum changes from the value $\gamma = 2.8$ to the value $\gamma = 2.95$ at the energies above $E_0 \approx 2 \cdot 10^{14}$ eV. Some confirmation of the fact that the proton spectrum gets sharper above that energy $2 \cdot 10^{14}$ eV may be obtained from the results of fractal analysis of the central showers, which was made in the KASCADE [4]. If those results are confirmed by further measurements then they will become of great significance for the comprehension of the proton acceleration mechanism as well as heavier nuclei acceleration in cosmic radiation.

It is worth it to underline the fact that the results of the Tibet AS γ collaboration were obtained from the hybrid combination of the air shower results with the data received at the same time from the emulsion chambers. An emulsion calorimeter filled up with X-ray films was working in a typical regime: both the tracks with $E_{\mathrm{th}} > 4$ TeV and the families with $\Sigma E \geq 20$ TeV were analyzed. It is interesting to observe a comparison of the spectra received from the Tibet AS γ with the data from the RUNJOB(2000) (fig. 4b). The results for all the nuclei obtained from the RUNJOB(2000) are evidently lower than the results received from the extensive air showers (as was already mentioned earlier). The situation may suggest that the evaluation of primary nuclei energy, based upon extensive air shower measurements, is systematically overestimated in nearly all of the air shower experiments. The magnitude of such overestimation may be evaluated as being about 15%. Such a possibility has lately been discussed in the analysis of the DICE results in CASA-MIA [12].

If the results of the RUNJOB(2000) are confirmed, they will make it possible to explain why there is a huge dispersion between the extensive air shower data and the measurements made with the use of X-ray emulsion. It may happen that the latter measurements have presented for years the results, which are nearer to the reality than the extensive air shower measurements (fig. 4b).

6. – Conclusions

Even though, owing to the fact that there are great measurement errors at the direct measurements (RUNJOB, JACEE, SOKOL) of the primary energy spectrum, any final settlement still cannot be reached neither on the problem of the shape of the spectrum for different primary nuclei nor on the mass composition of primary cosmic radiation at the energies above 10^{14} eV, the comparison of these data with other experiments, *e.g.*, KASCADE, Tibet AS γ, AKENO made it possible to draw some new conclusions:

a) The slope of the all nuclei spectrum in the region up to the “knee” equals to $\gamma = 2.70 \pm 0.05$ (KASCADE). It is known that the result which has been for years given by the AKENO ($\gamma = 2.5$) is unreal. In the present paper the arguments which explain the cause of such a state have been set forth.

b) The value of $\gamma = 2.8$ (RUNJOB) for the slope of proton spectrum changes into $\gamma = 2.95$ at the energy $\sim 2 \cdot 10^{14}$ eV (Tibet AS γ).

c) Having analyzed the results, received in the KASCADE on the correlation between different components of the showers we have pointed to the necessity of non-correlated components being used at such an analysis and we have given a possible cause—a “statistical game” with these results.

d) We have also pointed to the correctness of the interpretation of the results which were received from the X-ray films.

In our opinion, it seems quite probable that the primary energies, which are evaluated in the extensive air shower measurements, are systematically overestimated by about 15%. The problem requires further investigation. We have also pointed to the fact that at the same time a power function cannot describe all of the spectra. If the primary spectra are represented by a power function, then the spectra measured deep in the atmosphere should not be expressed in a power form.

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