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What spectrum should the galactic cosmic ray acceleration theory explain?

N. Grigorov and E. Tolstaya

Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119899, Moscow, Russia

Abstract . The all-particle spectra measured by three different instruments: 'Proton-1,2,3,', 'Proton-4', and TIC are discussed. It is shown that all three experiments reveal a 'knee' in the all particle spectrum at ~ 1 TeV. Analysis of all these experimental data proves, that in the energy range E > 1 TeV the all particle spectrum is the sum of two power law spectra: one with spectral index β=2.6 and the other one with β≈3.1

1 Introduction

In his rapporteur talk at the 24th ICRC in 1995 T.Shibata presented the all-particle spectrum in the energy range from 0.1 TeV to 10^5 TeV (Shibata, 1997).

The presented spectrum was obtained by the author by summarizing the spectra of individual components and adding the EAS spectrum. Since the spectra of most nuclei are measured upto energies of 10-20 TeV/particle, they had to be extrapolated to the range of higher energies. We will not comment on the proton spectrum in the energy range above 1 TeV used by the author. Therefore, without discussing the details of the initial data, which defined the spectrum in (Shibata, 1995), we will mention its main features:

a) In a wide range of energies from 0.1 TeV to ~10^3 TeV the value $E^{2.67} I(E) = const$. I.e. in the above stated range of energies the spectrum is purely power-law with spectral index $\beta \cong 2.67$.

b) In the energy range (3÷5) 10^{15} eV there is a well-known bend, associated with a sharp change in thespectral index (by ~0.5).

In his rapporteur talk at the 25th ICRC (in 1997) A. Watson practically repeated the spectrum shown by the previous rapporteur without any comments (Watson, 1997) whereas, at the 26th ICRC S.Yoshida (the rapporteur on Cosmic Ray Measurements above 1 TeV) gave a clear definition of the all particle spectrum. We will cite two of his statements : …'The cosmic ray energy spectrum is well represented by a power law form with three bends. The first knee appears around 3x10^{15} eV…'; …' it has now been well established, that all compositions (underlined by us) including the heavy component constitute spectra of power law form without bending at least below 10 TeV. No evidence of steepening has emerged….'(Yoshida, 1999).

Hence, there is a stable opinion, that the form of the spectrum upto the knee is well established and is not subject to further experimental research, but rather to theoretical consideration.

2 Analysis of the experimental data

However, the features of the GCR spectrum, described in (Yoshida, 1999) are in sharp contradiction with direct measurements of the all-particle spectrum in the energy range 0.1-10^3 TeV. There are direct measurements of the all-particle spectrum in a wide range of energies, made by three different instruments: "Proton -1,2,3"(Grigorov, 1995), "Proton-4" (Grigorov, 1995) and TIC (Adams et al., 1997). The energy intervals for these measurements overlap each other and fully cover the above stated interval from 0.1 to 10^3 TeV. The results of these measurements are shown in Fig.1. in linear scale for $E^{2.62} I_0(E)$ values versus E. Curve 1 in the same figure shows the all-particle spectrum according to (Shibata, 1995).

Fig.1. clearly demonstrates the qualitative difference of the directly measured all-particle spectrum $I_0(E)$ and the all-particle spectrum which is a sum of all the components (according to (Shibata, 1995) which we will denote $I_0^*(E)$.

We will note the main features of the experimentally measured all-particle spectrum:

Correspondence to: E.Tolstaya (katya@srdlan.npi.msu.su)

a) In the energy range $E < 1$ TeV the value $E^{2.62} I_0$=0.256±0.003 m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$ and is practically constant in the 0.1-1 TeV energy range;

b) In the energy range 4÷10^3 TeV the value of $E^{2.62} I_0$=0.149±0.003 m^{-2}s^{-}1sr-^{1}TeV $^{1.62}$, i.e. is constant in this energy range, giving evidence that the spectrum index is also constant;

c) In the energy range 1-4 TeV the value of $E^{2.62} I_0$ is $\sim E^{-0.2}$, i.e. quickly falls off with increasing E, this causes a 'step' in the all-particle spectrum , which inevitably leads to a 'knee' at about 1 TeV.

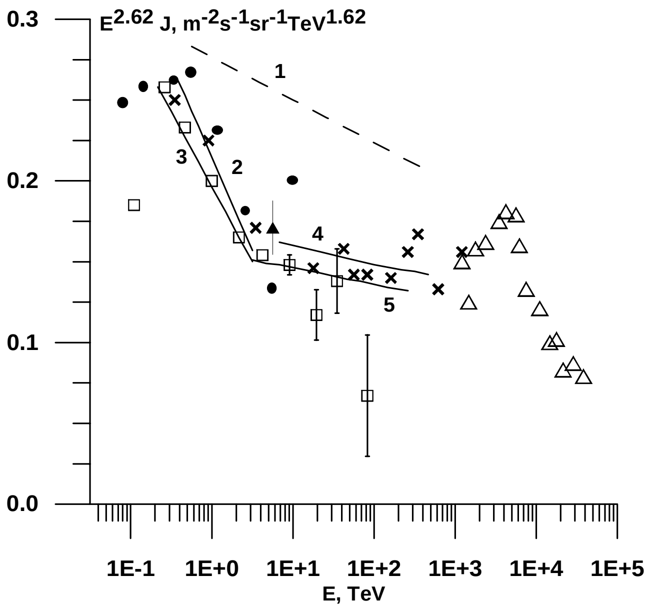

Fig.1. The all particle spectrum: • - the data of 'Proton-1,2,3' (Grigorov, 1995); x - 'Proton-4' data (Grigorov, 1995); - TIC data (Adams et al., 1997); Δ - AKENO data;
▲- 'Sokol' data (Grigorov, 1990). Curves 2 and 4 are the least square approximation for the data in (Grigorov, 1995);
curves 3 and 5 are the same for the data in (Adams et al., 1997).
Curve 1 is the spectrum according to (Shibata, 1995).

Thus, the main difference between the two spectra is that the $I_0^*(E) = \sum_{z=1}^{z=26} J_z$ spectrum in the energy range 0.1-10^3 TeV is purely power-law, is described by a constant spectral index and has one knee at (3-5)10^{15} eV, whereas the experimentally measured spectrum $I_0(E)$ has <u>two</u> 'knees' : at $E \sim 1$ TeV and $E =$ (3-5)10^{15} eV.

The discrepancies between the experimentally measured all-particle spectrum ($I_0(E)$) and the summarized spectrum of all components $I_0(E)$ pose two issues for discussion :

1) Which spectrum should the GCR acceleration and propagation theory explain?

2) What the reason for $I_0 \neq I_0^*$, since these values should be equal according to the definition of the 'all-particle spectrum'?

The answer to the first question will, obviously, be given when equality $I_0 = I_0^*$ will be achieved experimentally in the whole range of energies from 0.1 TeV to ~10^3 TeV. But this will only happen in the future. As for the second issue certain comments can be made now.

First of all we will mention several significant facts.

1. For the energy range 0.1-1 TeV, where all the components have been numerously measured and are well-known, from the data, published in (Shibata, 1995) it can be obtained, that $E^{2.62} I_0^*$=0.250 m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$ I.e. is practically equal to the value measured directly on the 'Proton-1,2,3' satellites which is $E^{2.62} I_0$=0.256 m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$. In other words $I_0 = I_0^*$. Simultaneously, this equality provides evidence, that the instruments on the 'Proton-1,2,3' satellites measured the all-particle flux $I_0(E)$ correctly.

2. At $E > 1$ TeV the value of $E^{2.62} I_0^*$, according to (Shibata, 1995) is the sum of the flux of nuclei with $Z \geq 2$, for which $E^{2.62} I_{Z\geq2}$=0.134 m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$ and the proton flux with $E^{2.62} I_p$=0.116 m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$. Here $E^{2.62} I_p / E^{2.62} I_0^*$=0.46.

Due to the similarity of the spectrum of nuclei with $Z > 2$ and the spectrum of helium nuclei, which has the spectrum index β_{He}=2.64±0.07 in the energy range between 0.2-300 TeV (Grigorov et al., 1999) it can be expected, that the value $E^{2.62} I_{Z\geq2}$=0.134 m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$ will remain constant.

It should be noted, that $E^{2.62} I_{Z\geq2}$=0.134 m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$ does not significantly differ from $E^{2.62} I_0$ in the energy range $E > 10$ TeV , indicating that the all-particle flux contains mostly nuclei and the proton contribution is small. (This was noted by the authors in (Zatsepin, 1994)).

3. The least-square technique was used to find the dependence of $E^{2.62} I_0(E)$ on E for the measurements made by the 'Proton -1,2,3,4' instruments and TIC in two energy intervals: 1-4 TeV (curves 2 and 3 in Fig.1) and E >4 TeV (curves 4 and 5 in the same figure). (When calculating curve 5 the statistical significance of the

experimental points was taken into account *). The dependencies $E^{2.62}I_0$ (obtained using the least-square technique) for the measurements made by different instruments are practically identical. From these obtained dependencies it follows:

a) the magnitude of the 'step' in the value of $E^{2.62}I_0$ is equal to 0.42 of its value prior to the 'step' (is equal to the contribution of protons in the GCR flux);
b) both types of instruments ('Proton' and TIC) show the same difference in the spectral indices $\Delta\beta$ =0.177±0.017 for the 1-4 TeV and $E > 4$ TeV energy ranges.

From these facts it follows, that the 'knee' in the all-particle spectrum at $E \sim 1$ TeV is associated with a rapid decrease of the proton flux in the 1-4 TeV energy range. (Only one component - the protons - constitutes about 42% of the whole GCR flux).

The rapid fall off of protons, i.e. the bend in the proton spectrum at $E \sim 1$ TeV, leads to the appearance of a 'knee' in the all-particle spectrum and a 'step' in the value of $E^{2.62}I_0(E)$.

In the energy $E > 10$ TeV the protons constitute only a small fraction of the whole GCR flux and this flux contains mostly nuclei (with a small admixture of protons, which constitutes about 10-15% of the whole GCR flux).

The fact that $I_0^* \neq I_0$ in the $E > 10$ TeV energy range is due to the addition of an overestimated proton flux (which is apparently absent in the all-particle GCR flux) to a sufficiently correct flux of nuclei with $Z \geq 2$ in (Shibata, 1995).

In order to find out to what extent the all-particle spectrum is sensitive to the proton spectrum, we considered three proton spectra.

#1 The JACEE spectrum of 1997. (Cherry et al., 1997)
$I_p(E) = (0.111 \pm 0.009)E^{-2.8}$ m^{-2}s^{-1}sr^{-1}TeV^{-1};

#2 The MSU spectrum (Zatsepin et al., 1994).
$I_p(E) = 0.117E^{-2.62}(1+X^2)^{-0.25}(1+0.31X^2(1+X^2)^{-1})$ m^{-2}s^{-1}sr^{-1}TeV^{-1};at $X = E/3.75$;

#3 The spectrum, measured on "Proton-2,3" satellites (Grigorov, 1995). It can be described by the same dependence on E as spectrum #2, but $X = E/0.7$.

Then we determined the all-particle flux $I_0^* = I_p + I_{z\geq 2}$ and the value $E^{2.62}I_0^* = E^{2.62}I_p + E^{2.62}I_{z\geq 2} = E^{2.62}I_p + 0.134$ m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$ since $E^{2.62}I_{Z\geq 2} = const$ = =0.134 m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$).

* The TIC instrument measured the energy release of the particles, whereas the 'Proton' instruments measured the particle energy E. The comparison of these data are discussed in detail in the Appendix.

The results for all the three types of proton spectra are shown in Fig.2. by curve 1 (spectrum #1); curve 2 (spectrum #2), and curve 3 (spectrum #3).

The dashed curve 4 is the approximation of experimental data in Fig.1. and curve 5 is the spectrum from (Shibata, 1995).

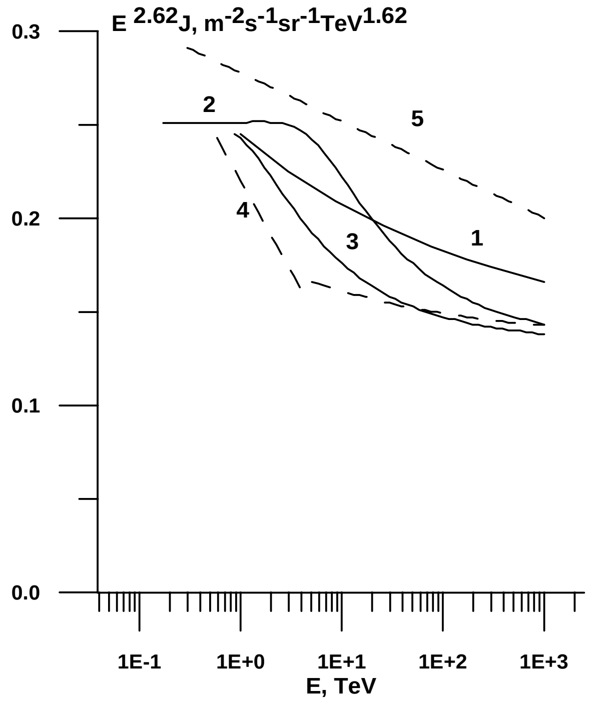

Fig.2. The all-particle spectrum as the sum of the spectra of all nuclei with $Z \geq 2$ and protons ; 1- protons , according to (Cherry et al., 1997); 2 - protons according to (Zatsepin et al., 1994); 3- protons according to (Grigorov, 1995); 4 -experimental data approximation (see Fig.1).; 5 - spectrum from (Shibata, 1995).

It can be seen from Fig.2., that the best agreement between the sum of the spectra of individual components $I_0^*(E)$ and the experimental all-particle spectrum $I_0(E)$ is reached for spectrum #3, i.e. the spectrum with the bend at $E \sim 1$ TeV. The other versions of the proton spectra lead to $I_0^* \neq I_0$.

Conclusions

The above consideration leads to one conclusion: the issue of the all-particle spectrum in the 0.1-10^3 TeV energy range cannot be considered resolved, and in order to do this new experimental data are needed.

Appendix

In (Adams et al., 1997) the integral energy release spectrum ε is presented in the form of $\varepsilon^{1.8}N(>\varepsilon)$ as a function of ε, where $N(>\varepsilon)$ is the number of events with energy release $\geq \varepsilon$. Apart from that the exposure factor ΓT =67.5 m^{2}sr hour is given. Taking from the figure the value of $\varepsilon^{1.8}N(>\varepsilon)$ and dividing it by $\varepsilon^{1.8}$ we can obtain the number of events $N(>\varepsilon)$. Dividing this value by the exposure factor $\Gamma \cdot T = 2.43\ 10^5$ m^{2}s sr, we obtain the integral energy release spectrum $J(>\varepsilon)$ m^{-2}s^{-1}sr^{-1}.

This we transform into the differential energy release spectrum $I_0(\varepsilon) = \frac{J(>\varepsilon_i) - J(>\varepsilon_{i+1})}{(\varepsilon_{i+1} - \varepsilon_i)}$ m^{-2}s^{-1}sr^{-1}TeV^{-1}.

The next step would be transition from the energy release ε to the particle energy E. For correct comparison of the TIC results with the results of the 'Protons', we made the transition from ε to E in the same way as we did it with the data of 'Protons', i.e. we assumed, that $E = k\varepsilon$. Hence, the next task was to determine k.

From Fig.1 we know, that in the energy range $E = k\varepsilon$ <1TeV the value $E^{2.62}I_0(E)$ =0.256 m^{-2}s^{-1}sr^{-1}TeV$^{1.62}$ and is constant in the whole 0.1-1 TeV interval.

Therefore, multiplying ε by k we transform the energy release spectrum into the energy spectrum of the particles $I_0(E)$, and multiplying it by $(k\varepsilon)^{2.62}$ we obtain $k^{1.62}\varepsilon^{2.62}I_0(\varepsilon) = E^{2.62}I_0(E) = 0.256$ m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$ if $k\varepsilon < 1$ TeV . We used this equality at the point $\varepsilon = 50.3$ GeV (the second point in the energy release spectrum, since the first point could be inaccurate due to the threshold effect). For this point we obtained $\varepsilon^{2.62}I_0(\varepsilon) = 0.0168$ m^{-2}s^{-1}sr^{-1}TeV $^{1.62}$. Therefore, $k^{1.62}$ 0.0168=0.256. Hence, $k = 5.4$.

Multiplying all the ε values by 5.4 we obtain the particle spectrum $I_0(E)$, and the values of $E^{2.62}I_0(E)$, which are denoted in Fig.2 by squares.

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