The GCR All-Particle Spectrum in the 0.1-100 TeV Energy Range

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Abstract

The results of direct measurements of the all particle spectra by five different instruments on satellites and balloons are considered. It is shown, that is the representatio as the flux multiplied by energy to the power of 2.6 the all-particle spectrum shows a 'step'. The parameters of this 'step' and its origin are analyzed.

Historically it has so happened that the all-particle spectrum obtained as the sum individual components, the energy range $1 < E < (5-10)$ TeV in the proton spectrum is not covered by direct measurements. Usually this energy interval in the all-particle spectrum is filled via interpolation, which is bases on the assumption that the proton spectrum is similar to the spectrum of nuclei. This spectrum is usually considered to be the all-particle GCR spectrum $I_o(E)$ [1]. Direct information on the all-particle spectrum in the energy range from 1 to 10 TeV can be obtained using direct measurements of the of the all-particle spectrum by electronic instruments. For the first time such information was obtained in 1972 as a result of the all-particle spectrum measurements by the SEZ-14 instrument on the 'Proton1,2,3' satellites and the SEZ-15 instrument on the 'Proton-4' satellite [2,3]. These measurements revealed an anomaly in the all-particle spectrum in the 1-10 TeV energy range. In 1997 the spectrum was measured again by the TIC instrument [4]. The TIC instrument measured the energy release of all-particles arriving from arbitrary directions. As it was shown by the authors in [4,5] the energy release spectrum revealed the same anomaly in the all-particle spectrum, previously observed in the measurements made on 'Proton' satellites [2]. The results of the measurements made by the TIC, SEZ-14 and SEZ-15 are shown in Fig.1. The solid line in Fig.1 shows the function $\Phi(E)$, which gives a good approximation of the experimental all-particle spectrum at a =0.4 TeV.

$$\Phi(E) = E^{2.6} I_o(E) = \frac{0.11}{[1+(E/a)^3]^{0.2}}\{1 + 0.37\frac{(E/a)^3}{1+(E/a)^3}\} + 0.130 m^{-2}s^{-1}sr^{-1}TeV^{1.6} \quad (1)$$

It can be seen from Fig.1 that the anomaly in the all-particle spectrum shows a

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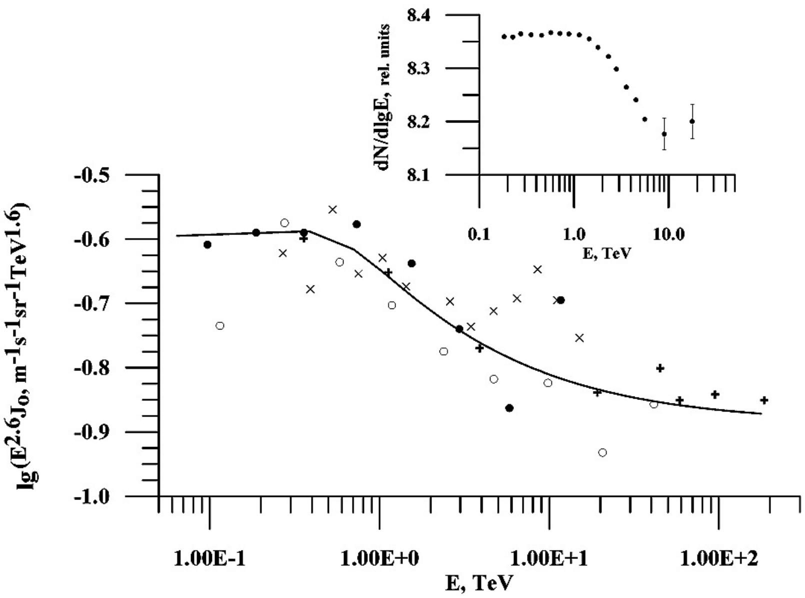

Fig. 1. The depenence of $E^{2.6}I_o$ on E measured by different instruments: $\bullet$ - SEZ-14 [3];+ - SEZ-15 [3]; $\circ$ - TIC [5]; $\times$ - BFB-S (this paper). The upper right panel shows data of ATIC [8], the vertical axis is in arbitrary units, and the horizontal axis shows the energy release in the calorimeter.

'step' if we express it in terms of $E^{\beta}I_o(E)$. Figure 1 shows, that the anomaly in the all particle spectrum is revealed independently of the thickness of the ionization calorimeter (IC) used in the instrument (in TIC it was about $1\lambda_p$ in SEZ-14 about $1.7\lambda_p$ in SEZ-15 about $3\lambda_p$). Therefore, we decided to look for a similar anomaly in the all-particle spectrum, measured by the BFB-S instrument [6], in which the IC had the average thickness of $0.7\lambda_p$. The BFB-S instrument was installed on the 'Intercosmos-6' satellite. The obtained spectrum in the course of the experiment was of no particular interest and was not published. Here we are interested in the existence (or absence) of an irregularity in a narrow interval of the spectrum. Therefore, we recalculated the energy release in the all-particle spectrum measured by the BFB-S instrument $I_0(E)$ and plotted the value $E^{\beta}I_o(E)$ in Fig.1 (skew crosses). It can be seen, that the spectrum measured by the BFB-S instrument also shows an irregularity in the form of a 'step' in the all-particle spectrum in the same energy range as the other instruments. The smaller size of the 'step' is a natural consequence of the small thickness of the IC.

At the 26th ICRC a preliminary result of the all-particle spectrum measured by the ATIC instrument was published [7]. The energy deposit spectrum obtained in this experiment was subjected to accurate analysis in [8]. The results of this work are shown on the upper right panel of Fig.1.* It convincingly demon-

*The authors thank Yu.Stozhkov for permission to use the figure from [8] before official

Table 1.

Instrument	β_1	β_2	β_3	Reference
SEZ-14	2.59	3.00	-	[3]
SEZ-15*	-	2.94	2.63	[3]
TIC	-	2.80	2.65	[4,5]
BFB-S	2.59	2.78	2.66	this paper
ATIC	2.61	2.87	-	[8]
Published data	2.62	-	2.67	[3,1,9]
Mean value	2.60 ± 0.008	2.88 ± 0.04	2.65 ± 0.01	

* Comment: In some publications SEZ-15 is called IC-15

strates that the all-particle energy deposit spectrum in the ATIC instrument also demonstrates a 'step' similar to those recorded by the previous instruments. Hence, we have measurements of the spectrum by five different instruments: SEZ-14, SEZ-15, TIC, BFB-S and ATIC. All of them revealed the same type of anomaly in the spectrum - a 'step' with different values of the spectral index in different energy ranges: β_1 in the energy range before 1 TeV, β_2 in the 1-5 TeV energy range, β_3 in the $E \geq$10 TeV region, and the mean values of $E^{\beta} I_o(E)$ in the energy ranges $E <$1 TeV and $E \geq$5 TeV. These characteristics were determined for each experiment and brought together in Tables 1 and 2. The difference between the mean values of the spectral indices in different energy intervals is equal to: $< \beta_2 > - < \beta_1 >= 0.28 \pm 0.04$ and $< \beta_2 > - < \beta_3 >= 0.23 \pm 0.04$. These values permit to formulate the first characteristic of the anomaly in the all-particle spectrum: in the energy ranges $E < 1$ TeV and $E > 5$ TeV the spectral indices are practically identical and close to 2.6. In the energy range 1-5 TeV the spectral index is 0.2-0.25 larger than outside this region. If we represent the all-particle spectrum as the function $\Phi(E) = E^{\beta} I_o(E)$ at $\beta = 2.6$ then in the energy ranges, where $I_o(E)$ can be described by a power-law function with spectral index 2.6, the value of $\Phi(E)$ will be constant in the whole energy range. This means, that the all particle spectrum in the intervals $E < 1$ TeV and $E > 5$ TeV the values of Φ should have constant values Φ_1 and Φ_2, respectively. The values Φ_1 and Φ_2 obtained in each experiment are shown in Table 2. The second quantitative characteristic of the anomaly in the all-particle spectrum is the ratio of the 'step' height to the all-particle flux prior to the step, i.e. $(\Phi_1 - \Phi_2)/\Phi_1$. This value is close to the ratio of the flux of protons to the total flux of all GCR particles at equal energy per particle. Table 2 needs two comments. If we take the data, published in GOST (State Standard of Russia on Cosmic Rays) which correspond to the energy range $E < 1$ TeV, then the sum $\sum_{z=1}^{z=28} E^{2.6} I_z = 0.258 \pm 0.005 m^{-2} s^{-1} sr^{-1} TeV^{1.6}$,

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Table 2.

Instrument	$\Phi_1, m^{-2}s^{-1}sr^{-1}TeV^{1.6}$ $(E < 1TeV)$	$\Phi_2, m^{-2}s^{-1}sr^{-1}TeV^{1.6}$ $(E > 5TeV)$	$K = \Phi_1/\Phi_2$
SEZ-14	0.247 ± 0.009	-	1.66 ± 0.07
SEZ-15	-	0.149 ± 0.003	
TIC	0.240 ± 0.018	0.134 ± 0.008	1.79 ± 0.17
BFB-S	0.237 ± 0.012	0.198 ± 0.007	1.20 ± 0.07
ATIC [8]			1.49 ± 0.08
Published data	0.270 [1]	0.160 ± 0.007 [9]	1.69 ± 0.07
Mean value	0.249 ± 0.007	0.148 ± 0.008	1.66 ± 0.06

Note: The mean vales do not include the data of BFB-S. The errors of the mean values are mean-square deviations from the mean value. The first line in the $K = \Phi_1/\Phi_2$ row is obtained from the data of SEZ-14 and SEZ-15.

i.e is practically the same as that obtained from direct measurements of the spectrum by instruments, given in Table 2. The value $\sum_{z=1}^{z=28} E^{2.6} I_z = 0.258$ consists of a sum of two values: one corresponds to protons and is equal to $E^{2.6} I_p = 0.120 m^{-2}s^{-1}sr^{-1}TeV^{1.6}$, the other one corresponds to nuclei with $Z \geq 2$ and is equal to $E^{2.6} I_z = 0.138 \pm 0.005 m^{-2}s^{-1}sr^{-1}TeV^{1.6}$.

The second comment is the following. It is known, that for nuclei the value $E^{2.6} I_z = const$ in a broad range of energies. In the region $E < 1$ TeV $\sum_{z=2}^{z=28} E^{2.6} I_z = 0.138 \pm 0.005 m^{-2}s^{-1}sr^{-1}TeV^{1.6}$, and in the region $E > 5$ TeV for the **all-particle** spectrum I_o the value $E^{2.6} I_o = 0.148 \pm 0.008 m^{-2}s^{-1}sr^{-1}TeV^{1.6}$. Practical coincidence of these two values indicates, that in the region $E > 5$ TeV there are **very few** protons in the all-particle flux.

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