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What is known about the Proton Spectrum in the Energy Range 1÷40 TeV?

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The results of 14 direct and 2 indirect measurements of the proton spectrum index β_p in the energy range (1÷40) TeV have been collected and compared (results published over the 1969 - 2004). Analysis revealed that only in 3 papers β_p was found to be less than 3.0, furthermore, two of the experiments were performed by identical instruments with a tendency to methodically decrease the measured β_p value. The value of β_p averaged over all the 16 experiments was found to be $< \beta_p > = 3.1 \pm 0.05$.

The issue of identity or qualitative difference between the spectra of protons and $Z \geq 2$ nuclei in the (1÷10) TeV energy range remains unresolved for more than 35 years. Confirmation that these spectra are in fact different would lead to significant changes in the theory of GCR origin. Therefore, we decided to put together all available information on the proton spectrum spectral index β_p, published before 2005 and compile it into a certain 'reference-book'.

For the energy range $E \leq 1$ TeV we give Table 1. The data in it are taken from the USSR State Standard [1], i.e. they are the result of averaging over a large number of experiments and do not need any additional comments regarding the methodology used. All the other results discussed in this paper correspond to the energy range $E > 1$ TeV.

Table 1. Energy spectra [1]

Protons

Energy, MeV	$4\cdot10^{4}$	$1\cdot10^{5}$	$4\cdot10^{5}$	$1\cdot10^{6}$
J_p, $m^{-2} s^{-1} sr^{-1}$ MeV^{-1}	$5.6\cdot10^{-4}$	$4.9\cdot10^{-5}$	$1.2\cdot10^{-6}$	$1.0\cdot10^{-7}$
$< \beta_p > = 2.68 \pm 0.02$ [1]				

Helium

Energy, MeV/nucleon	$1\cdot10^{4}$	$2\cdot10^{4}$	$1\cdot10^{5}$	$2\cdot10^{5}$
J_{He}, $m^{-2} s^{-1} sr^{-1}$ (MeV/nucleon)$^{-1}$	$1.0\cdot10^{-3}$	$1.7\cdot10^{-4}$	$2.5\cdot10^{-6}$	$3.8\cdot10^{-7}$
$< J_p/J_\alpha > = 2.2 \pm 0.2$ [1]; $< J_p/J_\alpha > = 2.15 \pm 0.06$ [2]				

1. Direct measurements of the proton spectrum in the energy range of $E > 1$ TeV

The main techniques for direct measurements of the proton spectrum are the ionization calorimeter method [3-8], X-ray emulsion chamber method [9-11], and the method of measuring the global all-particle flux. Table 2 shows the β_p values and comments concerning the type of technique, reference and energy E_{min}, starting from which the spectrum was measured.

In [3] the proton spectrum measurement actually starts at $E \approx 0.03$ TeV and in the whole range of measured energies it can be approximated by the function:

$$J_p(\geq E) = 3 \cdot (100/E)^{1,62}\left[1 + (E/a)^2\right]^{-\Delta\beta/2} \mathrm{m}^{-2} s^{-1} sr^{-1} \qquad (1)$$

Table 2.

Technique and reference	$E_{\min}$, TeV	β_p
SEZ-14 [3,4]	1÷2	3.1 ÷ 3.3
«Sokol», [6]	4	3.11 ± 0.15
«Sokol», [7]	5	2.85 ± 0.14[*)]
XEC, MSU [11]	10	3.14 ± 0.08
XEC, JACEE [9]	6	2.80 ± 0.04
XEC, RUNJOB [10]	6	2.80
XEC, JACEE [9]	≥ 20	3.05 ± 0.19
XEC, MSU [11]	≥ 20	3.17 ± 0.19

[*)] Paper [8] discusses the errors, committed in [7]. If these errors are eliminated $\beta_p = 3.02$

Experimental data do not contradict a = (1÷2) TeV and $\Delta\beta/2$ = (0.25 ÷ 0.3). In Table 2 as $E_{\min}$ we give the value of 'a', which determines β_p in the energy range $E > 1$ TeV.

A widely used means of GCR study is measuring the energy, deposited by the cosmic particle in a sufficiently thick layer of material (more than ~ (10 ÷ 15) cascade lengths). In the absence of specific restrictions for the deposited energy, the energy-deposit spectrum can be considered as identical to the energy spectrum of GCR $J_{a\ell\ell}(E)$. Since the all-particle flux is the sum of the proton flux and the flux of nuclei with $Z \geq 2$, we can write:

$$J_{a\ell\ell}(E) = J_p(E) + J_{Z\ge2}(E) = J_p^o(E_o/E)^{\beta_p} + J_{Z\ge2}^o(E_o/E)^{\beta_z}\,. \tag{2}$$

Within one order of magnitude the sum of two power-law spectra $AE^{-\gamma_1} + BE^{-\gamma_2}$ can be approximated by another power-law function $CE^{-\gamma}$ with good accuracy, where $C = A + B$, $\gamma = (A\gamma_1 + \gamma_2 B)/(A + B)$. In our case $J_{a\ell\ell}(E) = J_p^o E^{-\beta_p} + J_{Z\ge2}^o E^{-\beta_z} = CE^{-\beta_{a\ell\ell}}$, where

$$\beta_{a\ell\ell} = (\beta_p J_p^o + \beta_Z J_Z^o)/(J_p^o + J_Z^o)\,. \tag{3}$$

After simple transformations we obtain:

$$\beta_p = \beta_Z + \frac{J_p^o + J_Z^o}{J_p^o}(\beta_{a\ell\ell} - \beta_Z). \tag{4}$$

Since $\beta_Z \approx 2.6 \div 2.65$, β_p in a broad range of energies E (several orders of magnitude) is an unambiguous function of $\beta_{a\ell\ell}$. Up to $E \sim 1$ ТэВ $\beta_{a\ell\ell} \approx 2.6 \div 2.65$, therefore respectively $\beta_p = \beta_Z$.

Direct measurements of the all-particle spectrum by different types of instruments show, that starting from E = (1÷2) TeV, $\beta_{a\ell\ell}$ increases. The $\beta_{a\ell\ell}$ values for the energy range E > (1÷2) TeV, taken from [12], are shown in Table 3. For each instrument we show the mean thickness ℓ of the energy detector

Table 3.

Instrument	$\beta_{a\ell\ell}$	β_p	
and ℓ (in cascade lengths)	at E > (1÷2) TeV	for $\beta_Z = 2.6$	for $\beta_Z = 2.65$
SEZ-14, $\ell = 17$	3.0	3.48	3.42
SEZ-15, $\ell = 37$	2.94	3.34	3.28
TIC, $\ell = 9$	2.80	2.80	2.98
BFB-S, $\ell = 12$	2.78	2.99	2.94
ATIC, $\ell = 22$	2.87	3.19	3.13

(in cascade lengths). The values of β_p were obtained from expression (4). It can be seen from the Table 3 that the different experiments give β_p values, which are very close. The mean β_p obtained using all the measurements weakly depend on the β_Z value.

The $J_p = J_{a\ell\ell} - J_{Z\geq 2}$ technique appears to be methodically the most reliable, since the only actual measurement in this case is the energy deposited by the particle, and the measurements are the same for all the particles, independent of their nature.

There is also another technique for measuring the proton spectrum, which is practically direct. This technique involves measurement of the $J_p(E)/J_{He}(E)$ ratio under the same measuring conditions by the same instrument

We will write the following expressions for protons and helium: $J_p(>E) = J_p^o E^{-(\beta_p-1)}F(E), \quad J_{He}(>E) = J_{He}^o E^{-(\beta_\alpha-1)}$, where $F(E)$ is defined by expression (1). Hence, $\frac{J_p}{J_{He}} = \frac{J_p^o}{J_{He}^o} E^{(\beta_\alpha-\beta_p)}F(E)$. At $E \leq 1$ TeV $F(E) = 1$, we obtain: $\beta_P = \beta_{He}$ and $J_p^o / J_{He}^o = 2.2$ (see Table 1). Therefore, at $E \leq 1$ TeV $J_p / J_{He} = 2.2$.

In the energy range $E > 1$ ТэВ $J_p / J_{He} = 2.2F(E)$. For the integral proton spectrum $F(E) = \left[1 + (E/a)^2\right]^{-\Delta\beta/2}$. In Table 4 we show the experimental values of J_p / J_{He}, and also the same values calculated using the formula at $a = 1$, with good accuracy 5 TeV and two values of $\Delta\beta = 0.2$ and $\Delta\beta = 0.5$, corresponding to $\beta_p = 2.8$ и $\beta_p = 3.1$ in the energy range $E > 1$ TeV.

Table 4.

E, TeV	J_p / J_{He} (calculation)		J_p / J_{He}
	at $\beta_p = 2.8$	at $\beta_p = 3.1$	(experiment)
5	1.71	1.18	1.19 ± 0.26 [6]
10	1.50	0.85	0.78 ± 0.34 [6]
25	1.25	0.54	0.4 ± 0.2 [13]
10			1.2 ± 0.2 [9]

2. Indirect measurements

Some indirect measurements also give reliable results on the β_p value. In [14] it was shown, that

$$\beta_p - \beta_Z = (\beta_{SN} - \beta_{a\ell\ell})\left[1 + f(E,P)\right],$$

where β_{SN} and $\beta_{a\ell\ell}$ are the spectral indices of single and all hadrons, *P* is the depth of the atmosphere, at which the measurements are made. The data of [14] are shown in Table 5.

Table 5

P, g/cm^2	$\beta_{SN} - \beta_{a\ell\ell}$	$\beta_p - \beta_Z$	β_p at $\beta_Z = 2.6$
~ 650	0.42 ± 0.05	0.47 ± 0.06	3.07 ± 0.06
1000	0.61 ± 0.15	0.62 ± 0.14	3.22 ± 0.14

Conclusions

The Figures summarize the results of measurements shown in Tables (2 – 5). Fig. 1. shows the distribution of these results according to the β_p value. The line segment parallel to the 'X' axis corresponds

to the energy interval which contains ~ 90% of the experiment statistics. The solid lines correspond to direct measurements, the dashed lines correspond to results obtained from the all-particle spectrum, the dotted lines are indirect measurements. Fig.2. is a histogram of the same distribution. The mean β_p value for all the experiments is $< \beta_p > = 3.1 \pm 0.05$.

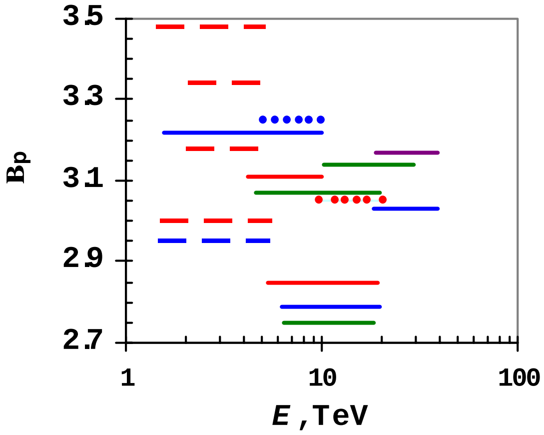

Figure 1.

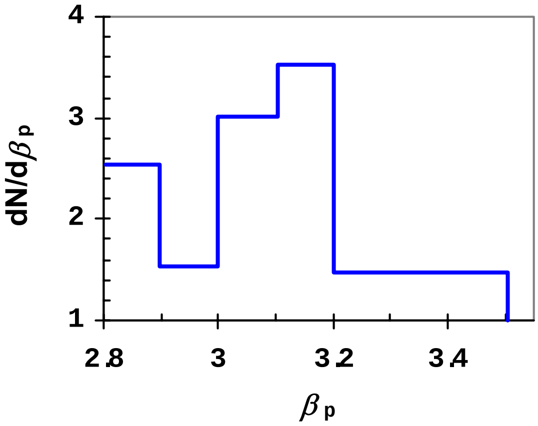

Figure 2.

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