The Proton Spectrum in the 0.1-100 TeV Energy Range Obtained From Direct Measurements of the All-Particle Spectrum

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Abstract

The proton spectrum was obtained as the difference between the all-particle flux and the flux of all nuclei with $Z \geq 2$ The obtained spectrum has a 'knee' at the energy of about 1 TeV. The spectral index $\beta_p = 2.6 - 2.7$ in the energy range $E < 1$ TeV and $\beta_p = 3.0 - 3.1$ in the energy range $E \geq 1$ TeV.

The proton spectrum $I_p(E)$ can be obtained from the obvious equality $I_o(E) = I_p(E) + I_z(E)$, where I_o is the all-particle spectrum, and I_z - is the spectrum of all nuclei with $Z \geq 2$. Multiplying all the terms of this equality by $E^{2.6}$ and inter-substituting I_o and I_p, we obtain:

$$E^{2.6} I_p = E^{2.6} I_o - E^{2.6} I_z \tag{1}$$

In a broad range of energies $E^{2.6} I_z = const = \Phi_z$, therefore, expression (1) can be rewritten as $E^{2.6} I_p = E^{2.6} I_o - \Phi_z$. In the energy range $E < 1$ TeV $E^{2.6} I_o = const = 0.248 \pm 0.005 m^{-2} s^{-1} sr^{-1} TeV^{1.6}$ [1] and $\Phi_z = 0.138 \pm 0.005 m^{-2} s^{-1} sr^{-1} TeV^{1.6}$, hence, $E^{2.6} I_p = const = 0.11 \pm 0.009 m^{-2} s^{-1} sr^{-1} TeV^{1.6}$. Thus, $\beta_p = 2.6$.

In the energy range $E > 1$ TeV the all-particle spectrum index $\beta = 2.88 \pm 0.04$, therefore, β_p should be greater than 2.6. The value of β_p at $E > 1 TeV$ can be obtained from the all-particle spectrum characteristics, if we rewrite the proton spectrum in a somewhat simplified form: as $I_p(E) \sim E^{-2.6}$ at $E \leq E_c$ and as $I_p \sim E^{-\beta_p}$ at $E > E_c$. For such a proton spectrum the all-particle spectrum will have the following form: $E^{2.6} I_o(E) = B E^{-(\beta_p - 2.6)} + \Phi_z$. At $E = E_c$ we have $E^{2.6} I_o = \Phi_1$ and $B = (\Phi_1 - \Phi_z) E_c^{(\beta_p - 2.6)}$. Therefore, $E^{2.6} I_o(E) = (\Phi_1 - \Phi_z)(E/E_c)^{-(\beta_p - 2.6)} + \Phi_z$. The sum of two power-law functions $BE^{-\gamma_1} + CE^{-\gamma_2}$ can be substituted with good accuracy by one power-law function $DE^{-\gamma}$, where $\gamma = \frac{B}{C+B}\gamma_1 + \frac{C}{C+B}\gamma_2$ [2]. In our case $\gamma_1 = \beta_p - 2.6$ and $B = \frac{\Phi_1 - \Phi_z}{\Phi_1}$,$\gamma_2 = 0$ and $C = \Phi_z/\Phi_1$. Therefore, the power index of the sum of the spectra will be equal to $\frac{\Phi_1 - \Phi_z}{\Phi_1}(\beta_p - 2.6)$. In the $E > E_c$ energy range the spectral index of the all particle

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Table 1.

Author and technique	E_{min}, TeV	Spectral index	N_o
Ya.Kawamura, et al. XEC, [3]	5	$\beta_p - 1 = 1.82 \pm 0.13$	90*
N.Grigorov, calorimeter, [4]	4	$\beta_p - 1 = 2.11 \pm 0.15$	90
I.Ivanenko et al., calorimeter, [5]	5	$\beta_p = 2.85 \pm 0.14$	160*
V.Zatsepin, et al. XEC, [6]	10	$\beta_p = 3.14 \pm 0.08$	602
JACEE collaboration, XEC,[7]	6	$\beta_p = 2.80 \pm 0.04^{\times}$	656

$^{\times}$ Comment: The error of 0.04 given in the JACEE paper, has no physical sense, since it is smaller than the statistical error equal to 0.07.

spectrum is equal to β. Therefore, $E^{2.6}I_o(E)$ is a power-law function with the index of $\beta - 2,6$. Therefore, $\frac{\Phi_1 - \Phi_z}{\Phi_1}(\beta_p - 2.6) = (\beta - 2.6)$. If we use the mean values from Table 2 [1]($\Phi_1 = 0.249 \pm 0.007$) and Table 1 [1] $(\beta - 2.6) = 0.24 \pm 0.035$ and $\Phi_z = 0.138 \pm 0.005$, we obtain $\beta_p - 2.6 = (0.24 \pm 0.035) \times (2.26 \pm 0.18) = 0.54 \pm 0.09$ and $\beta_p = 3.14 \pm 0.09$ in the energy range $E > 1$ TeV.

Therefore, the 'step' in the all-particle spectrum inevitably leads us to the conclusion that the proton spectrum has a 'knee' at energies close to 1 TeV. The shape of the proton spectrum may be obtained from the same expression (1), if we subtract from function $\Phi(E)$, describing the all-particle spectrum [1] the contribution of nuclei Φ_z. In this case the proton spectrum will have the form

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

It is important to stress, that the proton spectrum (2), which has a 'knee' at $E = a$ was obtained from the all-particle spectrum, i.e. from experiments in which the particle backscatter from the ionization calorimeter is of absolutely no concern.

Below we will consider the results of direct measurements of protons. Table 1 shows the values of the β_p indices obtained in different papers. The first column contains the author and measuring technique, the second column - the minimum energy of protons in the spectrum (in TeV), the third one - the value of β_p, given in the paper with its error and the fourth one - the number of protons N_o used to plot the spectrum. The N_o values were given in the paper and the N_o^* values were estimated by us according to the values of the statistical errors.

The mean value β_p from the five measurements given in table 1 is equal to $< \beta_p >= 2.94 \pm 0.07$. It is in good agreement with the value of $\beta_p = 3.14 \pm 0.09$ for the energy range of $1 - 5$ TeV (the region of the 'step' in the all-particle spectrum).

The XEC in [3,7] had targets. In such chambers, as it was noted in the paper of N.Konovalova [8] and in [9], the protons with energies close to the recording

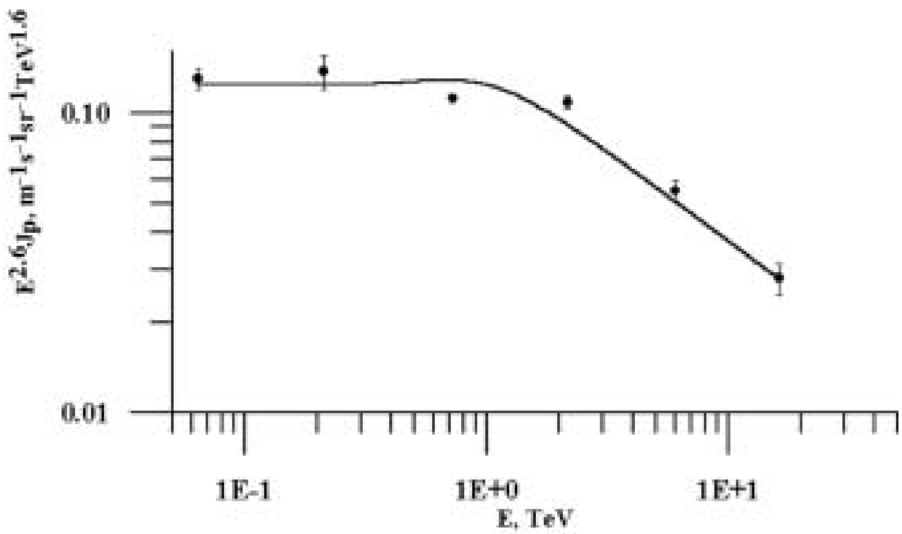

Fig. 1. The proton spectrum measured by the SEZ-14 instrument [2] . The curve is an approximation of the difference between the all-particle spectrum and the spectrum of nuclei with $z \geq 2$ (formula 2).

threshold , are measured with low efficiency, leading to a decrease of the value of β_p. Therefore, we determined β_p for energies $E \geq 20$ TeV, further away from the threshold energy in spectra [6] and [7]. It turned out, that in these spectra in the indicated energy range $\beta_p = 3.17 \pm 0.19$ and 3.05 ± 0.19. The mean value of β_p is equal to 3.11 ± 0.14 [10].

All the three values of β_p: 3.14; 2.94 and 3.11 within the error bars correspond to the same spectral index, which describes the proton spectrum in the energy range from ~ 1 TeV to $\sim 40 \div 50 TeV$. The mean-weighted value of β_p derived from these three values is equal to 3.02 ± 0.05.

There is only one experimentally obtained proton spectrum in the $\sim 0.1 - 10$ TeV energy range. It was obtained over 30 years ago on the 'Proton-2,3' satellites and is published in integral form in [11], and in differential form in [2]. We show it in Fig.1 (from [2]) together with the proton spectrum, obtained from the all-particle spectrum – equation (2) at $a = 0.8$ TeV. It can be seen from Fig.1 that the experimental spectrum of protons coincides with the spectrum, obtained from the all-particle spectrum, and the latter, as it was shown above, agrees with direct observations in the $\sim 5 - 40$ TeV energy range.

Hence, it can be asserted, that all direct measurements lead to the same conclusion: the proton spectrum has a 'kink' at energies close to 1 TeV. Before the 'kink' the spectral index $\beta_p = 2.6$ (maybe 2.7) and after the 'kink' it is about $0.5 - 0.6$ greater, i.e. 3.0-3.1.

To this conclusion it should be added, that all indirect measurements of secondary high-energy particles in the Earth's atmosphere (hadrons, muons, and γ-quants) lead to the conclusion, that in the TeV region $\beta_p \cong 3.0$ [2].

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