

Comparison of Proton and Helium Spectra in the $10^2, 10^5$ GV Rigidity Range

N.L.Grigorov and E.D.Tolstaya

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

Abstract

It is shown, that data of X-ray emulsion chambers (XEC) in the range of 20÷100 TeV/nucleon give the index of proton spectrum $b_p = -3.07 \pm 0.14$. At the same time the spectral index of nuclei in the whole range of rigidities $10^2 \div 10^5$ GV is equal to $b_{He} = 2.64 \pm 0.7$. In other words, the ratio H / He decreases with increasing E . The reasons are discussed why this tendency is veiled in XEC measurements in the range of energies $E < 20$ TeV/nucleon.

1 Introduction:

In the rapporteur talk at the 23-rd ICRC in 1993 Swordy with certain caution mentioned that the H / He ratio decreases with increasing E in the TeV region, which may indicate a sharp steepening of the proton spectrum. If this were to be confirmed, stated the rapporteur, this would be an important discovery in cosmic ray physics (Swordy 1993).

This comment for the first time drew attention to the importance of clarifying the situation with the proton spectrum, and the possibility that it may be qualitatively different from the spectrum of helium and, apparently, of other nuclei.

Experimental data on the proton spectrum, which were available to the rapporteur in 1993, in the range of TeV energies were (and still remain), rather controversial. In the range of higher energies, a certain tendency of the spectrum steepening could be noticed also, but the statistical errors of the measurements were so large, that this tendency could not be confidently confirmed.

In 1997 at the 25th ICRC the JACEE collaboration reported their new data on the spectra of protons and helium (Cherry 1997). These new data with doubled statistics in comparison to the previous ones do not clarify the situation in the TeV region ($\sim 1 \div 20$ TeV), though significantly clarify the situation in the region of higher energies.

Therefore, we thought it expedient to consider the energy dependence of the H / He ratio in the high energy range, where, the answer is, strangely enough, quite unambiguous, and then to try to understand why, in the range of smaller energies, the ratio H / He loses its unambiguity.

2 The range of energies $E \geq 20$ TeV/nucleon:

Careful consideration of the proton spectrum in the new JACEE data (Cherry 1997) shows, that in the range of energies $E \geq 30$ TeV/nucleon they are in good agreement with the data of 1993, which yielded the spectrum index value $b_p > 3$, but with a large error. Therefore, we decided to derive the value of b_p from the new data in the range of energies $E > 30$ TeV/nucleon. In order to do this, from the figure (Cherry 1997), we defined the energy E_i and the corresponding intensities J_p and errors $s(J_p)$. These data are given in Table 1.

Table 1.

E, TeV	$J_p E^{2.5} \cdot 10^{-3} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1.5}$	N_p	$J_p \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1.5}$
7.9	2.08 ± 0.14	208	$\left. \begin{array}{l} (9.09 \pm 0.79) \cdot 10^{-9} \\ (1.24 \pm 0.17) \cdot 10^{-9} \\ (8.24 \pm 0.17) \cdot 10^{-11} \\ (1.4 \pm 0.5) \cdot 10^{-11} \end{array} \right\} b_p = -3.05 \pm 0.19$
14.3	$1.36 \pm (\leq 0.10)$	≥ 176	
30.7	1.50 ± 0.13	133	
58.8	1.04 ± 0.14	55	
134	0.54 ± 0.14	15	
286	0.63 ± 0.22	7	

Here N_p is the number of protons, which was used to derive the intensity J_p . The value N_p was derived from the error $s(J) = J_p / \sqrt{N_p}$ (assuming, that the errors in (Cherry 1997) are statistical). The fourth column is intensity $J_p(E)$. The spectrum index in the energy interval $E \geq 30$ TeV, derived by the least-square method, gives the value -3.05 ± 0.19 .

The proton spectrum, in the range of energies $E \geq 20$ TeV, measured by the MSU group by XEC is published in (Zatsepin 1994) in the form of a table. From this table we used the range $E \geq 18$ TeV and defined the spectral index by the least-square method. Its value was -3.17 ± 0.19 .

As it can be seen, using XEC, both groups JACEE and MSU report the same spectrum, within the statistical error bars, with spectral indices -3.05 ± 0.19 and -3.17 ± 0.19 in the energy range $E \geq 20$ TeV.

In order to minimise the error these spectra can be added (due to their similarity). When adding we defined the mean-averaged value of energy $E \geq 20$ TeV and the mean-weighted intensity values. The resulting spectrum in the energy range $E \geq 20$ TeV has the spectral index $\langle b_p \rangle = -3.07 \pm 0.14$. It is shown in Fig.1. (curve 1).

We used a similar approach to obtain the mean-weighted spectrum of He. The initial data we used were those presented in the rapporteur talk of Swordy (Swordy 1993). We also added the latest JACEE data (Cherry 1997). The points close in E were combined with account for their 'weights'. The final result is shown in Fig.1. (curve 4). the spectral index for He $\langle b_{He} \rangle = -2.64 \pm 0.07$. Curves 2 and 3 in Fig.1. show the well-known spectra of protons in the range of rigidities 100 ± 1000 GeV for the two values $b_p = -2.6$ and -2.7

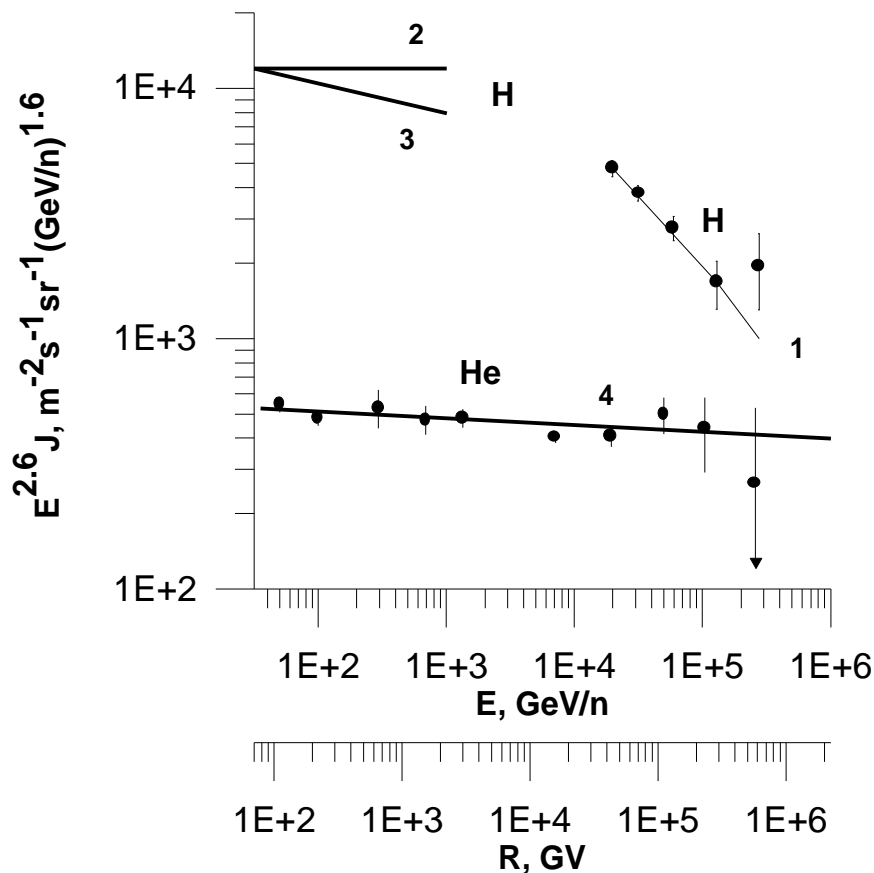


Fig.1. The spectra of protons : 1- the mean-weighted sum of JACEE and MSU spectra; 2 and 3 – the spectra of protons $b_p = -2.6$ and -2.7 , respectively; 4- the spectrum of He.

Fig.1. gives a clear picture of the behaviour of H / He in the rigidity interval $\sim 10^2 \div 10^5$ GV. Up to energies of $\sim 10^{12}$ eV/nucl $H / He \cong \text{const}$. In the range of energies $E > 2 \cdot 10^{13}$ eV/nucl H / He decreases rapidly with increasing E . In the whole considered range of rigidities, the spectrum of He remains power-law with a constant power index. This leads us to the inevitable conclusion : in the range of energies $10^{12} \div 10^{13}$ eV the proton spectrum index b_p increases.

Naturally, the issue arises, why the change in H / He is practically unnoticeable, when we use experimental data obtained using XEC, corresponding to the $10^{12} \div 10^{13}$ eV energy range, whereas the change in H / He can be clearly seen in the range of higher energies, where the statistical accuracy of the measurements is significantly worse, than in the region below 20 TeV. Below we will try to consider this problem in more detail.

3 The range of energies $\sim 1, 20$ TeV:

In the energy range $\sim 6 \div 20$ TeV the predominant results are XEC measurements. Table 2 shows b_p reported by different authors, and the energy E_{\min} , starting from which the spectrum has been measured. (It should be mentioned, that the given value b_p actually describes the spectrum in a very narrow energy range from E_{\min} to $(3 \div 4) E_{\min}$).

Table 2.

Number	$ b_p $	E_{\min}	Reference
1	2.64 ± 0.06	~ 6 TeV	Asakimori et al 1993
2	2.80 ± 0.04	~ 6 TeV	Cherry et al 1997
3	3.14 ± 0.08	~ 10 TeV	Zatsepin et al 1994
4	2.85 ± 0.14	5 TeV	Ivanenko 1993

For the same interval of rigidities as in Fig.1. we can obtain $b_{He} = -2.7 \pm 0.08$. Therefore, the behaviour of H / He in this interval is fully defined by the value of b_p . However, it appears impossible to obtain any somewhat reliable value of value b_p from the data in Table 2.

Let us consider data #2. They are the most statistically reliable (656 recorded protons). We can derive the values of b_i in the adjacent intervals. They are shown in Fig.2. As it can be seen from the figure, in the first energy interval (9, 14 TeV) $b_1 = -3.17 \pm 0.11$, and in the next interval (14-30) TeV $b_2 = -2.37 \pm 0.15$ (the errors are statistical). I.e. $b_2 - b_1 = 0.80 \pm 0.19$. This discrepancy of $\sim 4\sigma$ cannot be explained by statistics. Therefore, it is due to methodical errors. Hence b_1 and b_2 cannot be averaged, and these data have to be eliminated from our consideration.

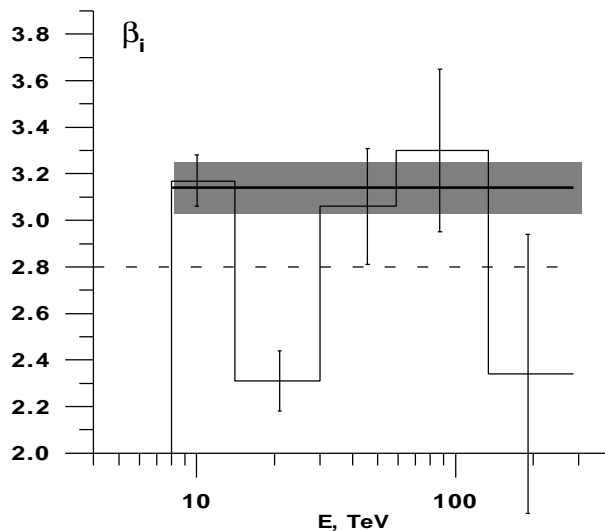


Fig.2. The values of spectral indices b_i in different energy intervals according to JACEE-97 data. The solid line is the mean-weighted over all b_i except b_2 (the second energy interval). The dashed region is the error corridor. The dashed line shows $b_p=2.80$.

Data #4 $|b_p|=2.85\pm 0.14$. Due to a large statistical error they are uncertain, since with equal probability they give $|b_p|=2.71$ and $|b_p|=2.99$ i.e. $H/He=\text{const}$ and H/He - decreases with increasing E .

The remaining measurements are #1 and #3 with values of $|b_p|=2.64\pm 0.08$ and $|b_p|=3.14\pm 0.08$ the difference between these two values is 0.5 ± 0.1 is also not of statistical, but methodical nature. Therefore, these data also cannot be used to make reliable conclusions.

Hence, in spite of the availability of measurements in the range of energies up to ~ 20 TeV using XEC*, the index of the proton spectrum remains uncertain (For this reason we left the corresponding energy interval in Fig.1. open).

This interval can be filled by measurements, made by electronic instruments, as it is shown in Fig.3. taken from (Grigorov 1995).

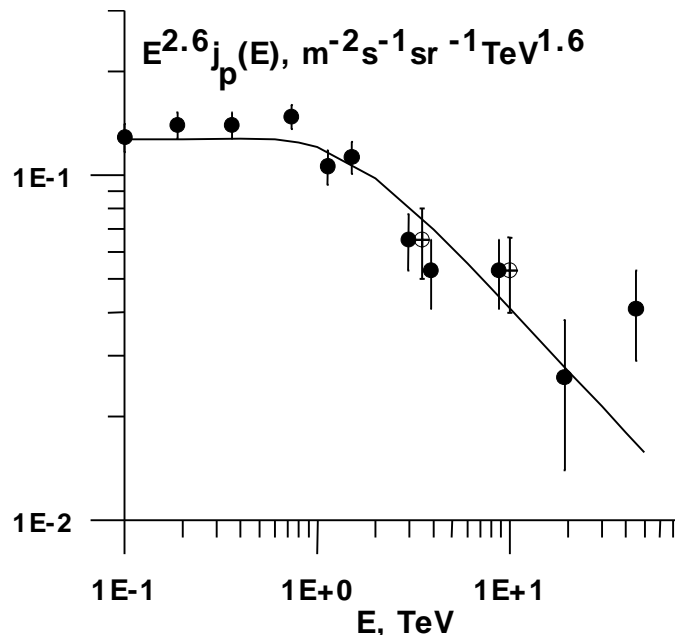


Fig.3. The spectrum of protons, measured by different electronic instruments. The figure is taken from (Grigorov, 1995); the same paper contains references on the initial data

These measurements as well as indirect evidence such as the ratio J_p / J_{He} at $E \sim 0.1$ TeV and $E \sim 20.0$ TeV indicate, that in the interval 1-20 TeV H/He decreases with increasing E .

Nevertheless, in order to regard this fact as a 'discovery', apparently, it is necessary to carry out a direct experiment, measuring H and He in a wide range of rigidities $10^2 < R < 10^5$ GV.

4 References:

- Swordy, S., Invited, Rapporteur & Highlight Papers, 23rd ICRC, 1993, 243.
 Cherry, M. et al., JACEE Collaboration Cosmic Ray Proton and Helium Spectra., Proceedings of the 25th ICRC, 1997, 4, OG 6.1.1.
 Zatsepin, V.I., Lazareva, T.V., Sazhina, G.P. et al. Energy spectra and composition of primary cosmic rays in the range of energies above 10 TeV/part, Yadernaya Phys., 1994, 57, 684-689.

* The most probable explanation is a methodical error in the energy range close to the beginning of measurements with XEC, due to the uncertainties introduced by the threshold effect, which depends on the XEC design and the exposure duration.