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Abstract:
The proton spectra, measured by the ATIC instrument in a broad energy range and reported by the Maryland University (MU) and Moscow State University (MSU) teams, are discussed.

It is shown, that the MSU spectrum is in good agreement with the proton spectrum having a ‘knee’ at energies of ~2 TeV and the spectrum, measured on the ‘Proton’ satellite. The MU spectrum differs from the MSU spectrum and does not have a ‘knee’. The possible reasons of such discrepancies between the MU and MSU spectra are discussed.

It is shown that the possible reason for such discrepancies can be the backscattered particles arriving in the charge detector from the calorimeter. If the backscatter is taken into account the MSU and MU results can be brought to quantitative agreement.

Н.Л.Григоров, Е.Д.Толстая

ОБОБЩЕННАЯ КАРТИНА ВЛИЯНИЯ ОБРАТНОГО ТОКА НА ИЗМЕРЯЕМЫЙ СПЕКТР И АНАЛИЗ ДАННЫХ ПРИБОРА ATIC НА ЕЕ ОСНОВЕ

Аннотация:
Рассмотрены протонные спектры, измеренные в широком интервале энергий прибором ATIC и опубликованные группами Мерилендского университета (MU) и Московского университета (MSU).

Показано, что спектр MSU хорошо согласуется с протонным спектром с «коленом» при энергии ~2 ТэВ и со спектром, измеренным на ИСЗ «Протон». Спектр MU отличается от спектра MSU и «колена» не обнаруживает. Анализируются возможные причины различия спектров MU и MSU.

Показано, что возможной причиной различия спектров может быть обратный ток частиц из калориметра в детекторы заряда. При учете влияния обратного тока результаты MSU и MU можно количественно согласовать.

Introduction

It has been more than 30 years since the SEZ-14 instrument installed on the 'Proton' satellite discovered a bend in the proton spectrum: up to $E \leq 1$ TeV the power index of the integral spectrum is ~1.6, whereas in the energy range $E > 1$ TeV it is equal to 2.1-2.2 [1]. Since then there have been many papers, reporting on the proton spectrum measured in the energy range above 5 TeV [2,3,4,5,6], several direct measurements of the all-particle cosmic ray spectrum [7,8], and also a number of indirect experiments, permitting to estimate the power index of the proton spectrum in the TeV energy region. All this scope of very different papers gives the same value of the spectral index β of the proton spectrum in the TeV energy range equal to 3.0 [9].

Nevertheless, the issue of the 'knee' in the proton spectrum at energies of several TeV is still the subject of discussion. This is quite understandable, since the acknowledgement of this fact would mean that the proton spectrum qualitatively differs from the spectra of all other nuclear components. Undoubtedly, acceptance of this fact would require serious corrections of the currently existing concept of cosmic ray origin.

A weakness of the existing experiments is that they concern individual narrow ranges of the proton spectrum: some before the 'knee', others beyond it. In order to solve this problem measurements made by a single instrument in a broad energy range, covering the region before and after the possible 'knee' were needed. It was expected that the ATIC instrument [10] would be capable of making such measurements. Therefore, the first publications of the results of ATIC [11,12,13] naturally attracted great attention of all those interested in the proton spectrum issue.

Unfortunately, these publications do not give an unambiguous answer to the most important question: is there a 'knee' in the proton spectrum in the energy range of several TeV? Furthermore, the proton spectrum, published by the Maryland University (MU) team does not agree with the spectrum published by the Moscow State University (MSU) team.

It was our goal to reveal the reason of such discrepancies, and, if possible, to reach conformity of these results using the information contained in [12] and [13].

1. Short list of physical results, obtained by the ATIC instrument

In [12] and [13] the results are presented in graphical form as $E^{2.75}I(E)$ (in the MU paper) and $R^{2.75}I(R)$ (in the MSU paper). We have digitized all the points of the figures, transformed rigidity R into energy E, and plotted both the proton spectra in one figure (Fig.1). Here the $E^{2.75}I(E)$ values are plotted in linear scale, permitting to reveal small discrepancies in the spectra. In the lower part of Fig.1 we show the spectra of He obtained by both groups in the energy range up to 1000 GeV/n.

The following facts can be derived from Fig.1:

The He spectra published by both teams are practically identical, the mean values of $E^{2.75}I$ are equal to 695±19 $m^{-2} s^{-1} sr^{-1}(GeV/n)^{1.75}$ and 707±11 $m^{-2} s^{-1} sr^{-1}(GeV/n)^{1.75}$ for the MU and MSU teams respectively. This result permits to conclude that both teams process the initial experimental data identically.

There is no such agreement between the proton spectra published by the two teams. It can be seen from Fig.1 that the intensity in the MU spectrum is larger than in the MSU spectrum. Also, this discrepancy increases monotonously with increasing energy.

In order to transform this 'visual' characteristic into a quantitative one, we averaged the $E^{2.75}I$ values of each spectrum over the same energy intervals. These averaged values are shown in Table 1: the first row is the averaging energy interval, the second one the averaged $E^{2.75}I$ value of the MU spectra, the third - the same values for the MSU spectrum and the fourth – the difference between these averaged values divided by $<E^{2.75}I>$ for the MU spectrum (in percent).

Table 1.

The averaging energy interval	$<E^{2.75}I>\cdot 10^{-4}$ MU	$<E^{2.75}I>\cdot 10^{-4}$ MSU	Difference in % divided by MU values
0.2<E<1 TeV	1.433±0.008	1.338±0.005	7.0±0.7%
1<E<3 TeV	1.590±0.045	1.350±0.042	15.0±3.8%
6<E<14 TeV	1.510±0.100	1.090±0.110	28.0±10%

We tried to find out the reason of monotonous divergence of both spectra. This is even more important since the MSU spectrum gives indications of steepening after E~2 TeV, whereas the MU spectrum does not show such a steepening. In order to do this we determined the number of particles N_i contained in each energy interval.

The number of particles was determined differently in different energy regions. In the range of energies where the error bars of intensity are given, we assumed, that these errors are statistical. In this case the error in intensity I_i is determined only by the statistical error of the number of particles. I.e. $\sigma(I_i)/I_i = \sigma(N_i)/N_i = 1/\sqrt{N_i}$. Hence, $N_i = (I_i/\sigma(I_i))^2 = \delta_i^{-2}$, where $\delta_i = \sigma(I_i)/I_i$. The number of particles determined using this technique in the MU and MSU spectra is shown in Tables 2 and 3.

A different technique was used for those energy ranges ΔE_k where the intensity I_k was given without errors. Since $I_k = N_k/\Delta E_k \Gamma w T$, $N_k = I_k \cdot \Delta E_k \cdot \Gamma w \cdot T$. The widths of the ΔE_k intervals in the MU and MSU spectra are different. In the MU spectrum the interval between the points is 1/8 of an order of magnitude, whereas in the MSU spectrum it is 1/10 of an order of magnitude. This means that if the intensity value is given for the energy E_k, it was determined according to the number of particles N_k in an energy interval with the width of ΔE_k=0.335E_k and 0.259E_k in the MU and MSU spectra respectively. The value of Γw is the effective geometry factor, i.e. Γ multiplied by the coefficient w, which determines the probability of satisfying all the selection criteria. We determined the value of Γw for each intensity where the error was indicated. These values are also shown in Tables 2 and 3.

Table 2. The MU spectrum

E, GeV	δ_i	N_i	$I\cdot 10^7$ m^{-2} s^{-1}sr^{-1}GeV^{-1}	Γw, m^{2}sr
5620	0.095	111	7.28	0.085
7500	0.124	65	3.22	0.084
10000	0.146	47	2.08	0.071
13340	0.263	14	$5.18\cdot 10^{-1}$	0.063
17780	0.245	17	$3.94\cdot 10^{-1}$	0.076
23700	0.362	8	$1.39\cdot 10^{-1}$	0.076
31600	0.576	3	$4.32\cdot 10^{-2}$	0.069
42170	0.705	2	$2.17\cdot 10^{-2}$	0.068

Mean Γw=0.074±0.003

Table 3. The MSU spectrum

E, GeV	δ_i	N_i	$I \cdot 10^7$ m^{-2} s^{-1}sr^{-1}GeV^{-1}	Γw, m^{2}sr
2160	0.0585	292	86.4	0.061
2720	0.0733	186	45.1	0.059
3510	0.0706	200	26.3	0.084
4420	0.108	86	13.8	0.055
5480	0.156	41	5.61	0.051
6860	0.194	27	3.64	0.042
8600	0.234	18	1.57	0.052
11000	0.295	11	0.825	0.047
13700	0.425	6	0.36	0.047
17370	0.700	2	0.094	0.048

Mean Γw=0.055±0.004

These two tables show that the MU team uses an instrument with a wider angular aperture (Γw=0.074 m^2 sr) than the MSU team (Γw=0.055 m^2 sr). From table 2 it can be seen that the MU spectrum has 267±16 protons at energies exceeding ~5 TeV, whereas from Table 3 it can be seen that the MSU spectrum has only 105±10 such protons. If we take into account the discrepancy in the Γw factors used by both teams and bring the boundary energy to the same value E_{bnd}=4616 GeV, then, in the MSU spectrum we should expect 155±15 protons with $E > E_{bnd}$.

Hence, in the energy range $E \geq 5$ TeV for equal Γw values there turned out to be 70% more protons in the MU spectrum than in the MSU spectrum.

2. The nature of excess particles in the MU spectrum

In order to find out whether the discovered large discrepancy in the number of particles of the MU and MSU spectra in the energy range above ~ 5 TeV is an individual phenomenon adherent only to the range of large energies, where the errors of each individual point are already large, we extended the procedure for determining the number of particles in each energy interval applying it to the whole MSU and MU spectra. Here we used the second technique for determining the number of particles in each energy interval (described above). In order to apply this technique it is necessary to know Γw. We used the values obtained from Tables 2 and 3 for the corresponding spectra. Adding-up all the $N(E_k)$ for the given spectrum, we obtained the integral MU and MSU spectra, expressing the total number of particles with energy greater than given.

If we denote the obtained integral spectra $N_{MU}(>E)$ and $N_{MSU}(>E)$, then at equal energy E they should differ by a factor of at least 1.35 since for the MU spectrum Γw=0.074 m^{2}sr, whereas for the MSU spectrum Γw=0.055 m^{2}sr. Therefore, the difference in the number of particles, if it exists, we determined from the expression:

$$N_{exc}(>E) = N_{MU}(>E) - 1.35 N_{MSU}(>E) \qquad (1)$$

In table 4 we give the values of the numbers of particles from the obtained MU (second column) and MSU (third column) integral spectra at energies of 308, 615, 1544 and 3080 GeV. (These energies were chosen with fulfillment of two conditions. The first condition was that the threshold energies in both spectra should not differ significantly.

In this case bringing the number of particles to one common energy will require minimum corrections. The second condition: at neighboring energies the number of particles in the integral spectra should differ by not less than a factor of 3. Then they become quasi-independent.) In the fourth column of the table we give the number of excess particles obtained using expression (1).

Table 4.

E, GeV	$N_{MU}(>E)$	$N_{MSU}(>E)$	$N_{exc}(>E)$
308	29480	20320	2050±258
615	9250	6240	826±114
1544	1970	1190	364±64
3080	557	341	97±34

We plotted the integral spectrum of excess particles $N_{exc}(>E)$ (Fig.2) and became convinced that it has a power-law form $N_{exc}(>E) = 2100\left(\frac{E}{300}\right)^{\gamma}$. The power index, defined using the least-square technique equals to $\gamma = -1.17 \pm 0.1$.

The character of the dependence of the ratio of excess particles and the number of protons with the same energy draws attention. Since the power index of the integral proton spectrum is ~1.75, whereas the number of excess particles has the power index of 1.17, $N_{exc}(>E)/N_p(>E) \sim E^{-1.17}/E^{-1.75} \sim E^{0.58}$. In connection with this dependency we should recall, that the intensity of backscatter increases with increasing energy of the backscatter particles as $E^{0.5}$.

The integral number of particles in the MU spectrum can be described as: $N_{MU}(>E) = 30870\left(\frac{E}{300}\right)^{-1.75}$,

and the number of excess particles: $N_{exc}(>E) = 2100\left(\frac{E}{300}\right)^{-1.17}$. The above formulas permit to easily determine the number of particles of this or that nature in a given energy interval. Thus, in the energy interval 200÷1000 GeV the number of particles in the MU proton spectrum will be equal to 59007, and the number of excess particles – 2861, i.e. they constitute 4.8% of total number of particles. In the energy range 1000-3000 GeV there will be 3205 MU proton spectrum particles and 373 excess particles, i.e 11.6%. If we compare these numbers with the data of Table 1, it is easy to see that practically all the difference between MU and MSU proton spectra is due to excess particles whose intensity grows with increasing particle energy E in the same manner as the intensity of backscatter. Is this accidental?

3. Edge-effects in ATIC and their possible influence on the proton spectrum

We can point out two effects which should be present in instruments of the ATIC type. These are effects where the connection between the energy released in the detector, and the detector measuring the charge of the primary particle is established by means of re-tracing the primary particle trajectory.

Let us assume that the particle passes through the charge detector and the energy detector within the angular aperture of the instrument, i.e. that it satisfies all the requirements of particle selection and should be included in the recorded particle statistics. However, if the re-traced trajectory of the primary particle does not pass through the charge detector, then the particle will be excluded from the statistics.

Especially probable are the cases when a particle passes close to the edge of the charge detector. Part of the cases when a 'correct' particle is excluded from the statistics is determined by the mean-square error σ between the true and re-traced positions of the primary particle at the charge detector level. This fraction is defined according to the empirical formula [15]: $\frac{N(>R)}{N(<R)} = 0.46\frac{\sigma}{R}(1 + 0.87\frac{\sigma}{R} - 0.036(\frac{\sigma}{R})^2)$ (2)

This expression was obtained for a circular detector with radius R and is valid at $\sigma / R << 1$. It gives the ratio of the number of re-constructed trajectories with trajectory coordinates outside the circle to the number of trajectories inside the circle.

The described effect was experimentally observed in the 'Sokol' instrument in good agreement with expression (2). It leads to loss of particles.

There is another effect, which is a 'mirror' effect relatively to the first one. The particle actually passes outside the charge detector, but goes through the energy detector, i.e. outside the angular aperture of the instrument. (As a rule, close to the charge detector). The re-traced trajectory passes through the charge detector. If such an even is accompanied by the trigger, then it will be recorded, and the particle will we considered a 'correct' one.

If the first effect exists inevitably, since it is caused by 'correct' particles which satisfy all the necessary conditions for the trigger, the recording of the second effect significantly depends on the trigger: trajectories of 'incorrect' particles, re-traced to the charge detector, may not fulfill the conditions for trigger generating. Then such events will not be recorded. If the trigger operation includes the condition of a compulsory signal from the charge detector, and it records backscatter particles well, then the second effect can lead to recording of 'incorrect' particles with large efficiency. Such particles, which in reality arrive outside the angular aperture of the instrument, and, due to errors in the trajectory re-tracing are included in the statistics, we will call 'additional'.[*)]

All the cosmic ray particles participate in the production of 'additional' particles. Therefore, the contribution of such 'additional' particles will be approximately 2.5-3 times greater than the fraction of protons lost due to the first effect.

We will estimate the possible contribution of 'additional' particles in the ATIC instrument. If the charge detector (silicon matrix) was a circle with the same area of 10^4 cm^2, then its radius would be 56 cm. The mean error in the coordinates of a primary particle with energy ranging from 300 GeV to 3000 GeV is about (4.7+3.5)/2=4.1 cm. The error σ according to expression (2) is equal to $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$ =5.8 cm. Therefore, the fraction of lost protons equals to 5%. Since the contribution of 'additional' particles is larger than the fraction of lost ones by a factor of 2.5-3, it can be expected that they add up to 12-15% of the number of recorded protons. Will these 'additional' particles be recorded? The answer to this question to a large extent depends on the role of backscatter.

Comparison of the two figures shows that the role of backscatter in the ATIC instrument is much more significant than it is shown by the ATIC collaboration in the corresponding tables.

In [11] it is noted, that during the whole time of the flight (312 hours) the ATIC instrument recorded about $26{\cdot}10^6$ particles in the all-particle spectrum. It is not hard to find, using the all-particle spectrum presented in this paper, that events with energy release in the calorimeter exceeding 100 GeV comprise about 1.5% of all the events, i.e. their number was $3.9{\cdot}10^5$.

[*)] The term of 'additional' particles was first introduced by A.N. Charahtchyan in the beginning of the 50-ies, when he analyzed the process of recording cascade-generating particles by a telescope consisting of Geiger-counters with an absorber between them.

It should be especially stressed that the conditions for forming the trigger, besides the energy release exceeding a certain small threshold, simultaneously required the occurrence of pulses in the upper scintillators, located under the silicon matrix. Therefore, all the 390000 events with energy release of 100 GeV in the calorimeter were accompanied by a particle in the detector located near the charge detector.

From the integral proton spectrum the number of protons with E>300 GeV, recorded over the whole flight within the geometry factor 0.18 m^2sr amounted to 30000. Together with all the other particles this will add up to 90000 particles. Therefore, out of the 390000 particles in the all-particle spectrum about 300000 particles passed outside the angular aperture of the instrument, and were nevertheless accompanied by at least one particle, which started the trigger. This could only be a backscatter particle.

The maximum geometry factor of the calorimeter which is 1.4 m^2sr exceeds by a factor of ~8 the geometry factor of the instrument which is 0.18 m^2sr, and the count rate for particles with E>300 GeV, passing outside the instrument aperture (300000) exceeds by a factor of 3.3 their count rate within the aperture (90000). Therefore, the mean efficiency of recording 'additional' particles due to recording of backscatter is about 3.3/8=40% (in comparison to the recording efficiency for 'correct' particles).

Since all the 'additional' particles in the energy range of hundreds GeV can amount to 12-18% of the total number of protons, then, because of their 40% recording probability due backscatter they can contribute about 5-6% of excess particles. I.e. according to the order of magnitude (the numbers obtained above are only estimates) the 'additional' particle effect in ATIC can be responsible for the observed number of excess particles.

What charge value Z will be attributed to these particles?

Since they are recorded only due to the occurrence of a signal caused by backscatter particles in the charge detector, and in their pulse spectrum amplitudes of Z<1.5 are predominant (in charge units of the primary particles), the 'additional' particles will be attributed charge values of less than 1.5, i.e. they will be included in the proton statistics. (There will be few such 'additional' particles with charge values exceeding 1.5. Therefore, there will be no such particles in the helium statistics and the spectra of helium obtained by MU and MSU are in good agreement).

Thus:

1) we know why the MU and MSU proton spectra are different: due to the recording of 'additional' particles;
2) we know, how these excess ('additional') particles can be produced in the ATIC instrument;
3) we know that the recording of these 'additional' particles is associated with efficient recording of backscatter. Therefore, their contribution grows with energy in the same way as backscatter intensity;
4) we also know why 'additional' particles are included in the proton statistics but not in the helium one.

What remains is to understand, how the 'additional' particles effect the form of the proton spectrum and what spectrum the ATIC instrument measured in reality, and finally why is it the MU spectrum that contains excess particles. We will try to answer these questions in section 4.

4. What did the ATIC instrument measure?

At present the ATIC experiment is the only one, which measured the proton spectrum with one single instrument in the energy range 100-10000 GeV, i.e in the energy range where according to [1] there is a sharp change of the spectral index, a phenomenon which for over 30 years (!) has been neither confirmed nor ruled out.

Naturally, the measurements of ATIC should be first of all compared with the measurements described in [1]. In order to do this the results of both measurements should be recalculated to the same units

The results measured by SEZ-14 on the 'Proton' satellite were published as an integral spectrum, multiplied by $(E/100)^{1.62}$. Therefore, the integral spectrum of the number of particles in the MSU proton spectrum $N(>E)$ which we obtained earlier, was divided by ΓwT=6.16 10^4 m^2·s·sr, and thus we obtained the integral spectrum. Multiplying it by $(E/100)^{1.62}$, we plotted the obtained values in Fig.3 (points). We also plotted in the same figure the data, published in [1] (crosses).

From Fig.3 it can be clearly seen, that the crosses (SEZ-14) and points (ATIC) correspond to the same dependence: a flatter proton spectrum prior to the energy of ~1 TeV, and then in a narrow interval 1÷2 TeV the spectrum increases its spectral index by several tenths and in the energy range E>2 TeV becomes significantly steeper, i.e. demonstrates an obvious 'knee'. In order to give this visual pattern a quantitative description, we have found the function $\Phi(E)$, which gives a good approximation of the ATIC data.

The function $\Phi(E) = B(100/E)^{0.10}(1+(E/a)^2)^{-0.25}$ at B=2.36 and a=2300 GeV is represented by curve 1 in Fig.3. It can be seen, that in the energy range 300-8000 GeV the function Φ describes the experimental proton spectrum measured by ATIC and plotted as $(E/100)^{1.62} I(>E)$ $m^{-2}s^{-1}sr^{-1}$ with the accuracy of several percent. This means that the integral spectrum itself has the form $I(>E) = C \cdot E^{-1.72}/(1+(E/a)^2)^{0.25}$ $m^{-2}s^{-1}sr^{-1}$ at a=2300 GeV and C=6500. The same function $\Phi(E) = B(E/100)^{-0.1}(1+(E/a)^2)^{-0.25}$ at B=3 and a=2000 GeV (curve 2 in Fig.3.) is in good agreement with the experimental values of $(E/100)^{1.62} I_p(>E)$ measured in the experiment of the 'Proton' satellite.

Therefore, we can assert, that the MSU proton spectrum confirms the old proton spectrum obtained on the 'Proton' satellite and has a power-law form with a 'knee' at energies around 2 TeV.

These two spectra can be complemented by the proton spectrum derived from the MU spectrum. In order to do this we need to subtract from all the 'protons' $N_{MU}(>E) = 30870\left(\frac{E}{300}\right)^{-1.75}$ the number of 'additional' particles $N_{ad}(>E) = 2100\left(\frac{E}{300}\right)^{-1.17}$ and dividing the difference by ΓwT, we obtain integral proton spectrum $I_p(>E)_{MU}$. Multiplying it by $\left(\frac{E}{100}\right)^{1.62}$ we obtain after certain algebraic transformations $\left(\frac{E}{100}\right)^{1.62} I_p(>E)_{MU} = 2.2(1-0.067\left(\frac{E}{300}\right)^{0.58})$, $m^{-2}s^{-1}sr^{-1}$. This spectrum is plotted in Fig.3 (circles). It can be seen, that it practically coincides with the MSU proton spectrum.

In order to obtain a description of the proton spectrum in differential form, as it is presented in Fig.1, it is necessary to differentiate the integral spectrum $I_{MSU}(>E) = CE^{-1.72}[1+(E/a)^2]^{-0.25}$ and then to multiply it by $E^{2.75}$. As a result we obtain:

$$E^{2.75}\frac{dI(>E)}{dE} = 1.12\cdot 10^4 \cdot E^{0.03}\left[1+\frac{0.29\cdot(E/a)^2}{1+(E/a)^2}\right](1+(E/a)^2)^{-0.25}$$ $m^{-2}s^{-1}sr^{-1}$ $GeV^{1.72}$

This function for a=2300 GeV is shown in Fig.1 (curve 1). As it can be seen it is in good agreement with the MSU experimental data. In order to understand why there is a difference between the MU and MSU proton spectra we will have to make one (single!) assumption.

Earlier we revealed, that different values of Γw are used in the MU and MSU spectra, these values are 0.074 m^2sr and 0.055 m^2sr respectively. In [12] it was mentioned, that the MU team uses Γ=0.18 m^2sr and efficiency of proton registration 0.4, which brings to Γw=0.18·0.4=0.072 m^2sr.

In [13] there are no explanations concerning the used Γw value 0.055 m^2sr, we assume, that the MSU team uses a smaller geometry factor, i.e. selects those particles which are well off the edge of the silicon matrix. In this case the flux of particles in the MSU spectrum, in the first approximation is not distorted by 'additional' particles, and we will consider it correct. In this case the MU team should record the number of particles equal to:

$$N_{MU}(>E) = \frac{(\Gamma w)_{MU}}{(\Gamma w)_{MSU}} N_{MSU}(>E) + N_{exc}(>E)$$

The intensity measured by MU will be : $I_{MU} = \frac{dN_{MU}(>E)dE}{(\Gamma w)_{MU} \cdot T} = I_{MSU} + \frac{dN_{exc}/dE}{(\Gamma w)_{MU} \cdot T}$

$N_{exc}(>E) = 2100\left(\frac{E}{300}\right)^{-1.17}$, therefore $\frac{dN_{exc}(>E)/dE}{(\Gamma w)_{MU} \cdot T} = 23.5E^{-2.17}$

If we multiply $I_{MU}(E)$ by $E^{2.75}$, we obtain:

$$E^{2.75} I_{MU}(E) = E^{2.75} I_{MSU}(E) + 642\left(\frac{E}{300}\right)^{0.58} \text{ m}^{-2}\text{s}^{-1}\text{sr}^{-1} \text{ GeV}^{1.75} \qquad (3)$$

The value of $E^{2.75} I_{MU}(E)$ calculated according to expression (3) is shown in Fig 1 (curve 2). It can be seen that expression (3) is in complete agreement with the experimental data of the MU team.

Therefore, we can conclude, that if our assumption is correct, then there are no contradictions between the MSU and MU data: the MSU group should see a 'knee' in the proton spectrum at E ~2 TeV and it does see this 'knee' (if the spectrum is represented in integral form). The MU team could not see this 'knee' and did not discover it. Apparently, the main reason for the visible difference in the proton spectra measured by the ATIC instrument are 'additional' particles arriving outside the angular aperture of the instrument and recorded by the instrument due to backscatter.

A weakness of all the considerations described above is insufficient statistics of the initial data, i.e. the data in [12] and [13]. Therefore, in order to make the main conclusion drawn from the results of ATIC indisputable, it is necessary to mention one more result, which for some unclear reason, is constantly ignored by the authors of the ATIC experiment. We are speaking about the spectrum of energy release in the calorimeter of the instrument.

If the incident particles were of only one (any) type with a power-law distribution of energy, then the energy release spectrum would be a power-law spectrum of primary particles. If the incident particles are of different types, each type with a power-law spectrum, then the total energy release spectrum will be the sum of power-law spectra, i.e. will still be a power-law spectrum. If among these power-law components there is one with sufficient intensity and a 'knee' in the spectrum, then the total energy release spectrum will be the sum of two spectra: one purely power-law (from all the 'smooth' components) and a spectrum with a 'knee' introduced by the component having such a 'knee'. Therefore, the energy release spectrum inevitably records the presence of a component with a 'deformed' spectrum.

Since we have demonstrated, that the ATIC measurements clearly indicate the existence of a 'knee' in the proton spectrum, (and if all this is not a 'joke' of statistics) then a corresponding anomaly (change of the spectrum index) should be observed in the all-particle spectrum. This should be even more so, since the all-particle spectrum is recorded with statistics significantly exceeding that of the proton spectrum in the angular aperture of the instrument.

Therefore, Prof.Yu. Stozhkov undertook efforts to study the characteristics of the energy release spectrum in the ATIC instrument, which was published in [11]. Using a special code he digitalized the energy release spectrum which in [11] is given in graphical form. As a result he obtained the possibility to increase the energy intervals by a factor of almost 10, therefore, increasing the statistical accuracy of the relative particle intensity in the different energy intervals and presented the obtained result in the form of $E^{2.61}\frac{\Delta N}{\Delta E}$ [16]. This result is shown in Fig.4 *) As it can be seen, the all-particle spectrum, measured by the ATIC instrument unambiguously shows, that in the range of released energies of about 2 TeV the spectrum index falls sharply, i.e. the cosmic ray flux contains a component which quickly falls-off starting with energies of several TeV (a component with a 'knee' in the spectrum). The spectrum itself acquires the form of a 'step'. The size of the 'step' corresponds to the intensity of this component (about 40% of the total flux). Only the proton component has such intensity.

5. Specific features of backscatter and means of eliminating its influence on the measured spectrum

Consideration of the results obtained by the ATIC instrument showed that despite the measures undertaken to eliminate the backscatter (4400 autonomously operating silicon detectors with the area of only 3 cm^2 each) the measured proton spectrum (MU) turned out to be seriously affected by backscatter.

This experience with most vividly raises the issue: are there techniques which radically protect spectrum measurements from the influence of backscatter? And if so, what are these techniques?

(We do not consider the time-of-flight technique which radically solves the problem, but to the same extent makes the instrument more complicated)

First of all we will note, that there are two types of backscatter influence on the spectrum.

In the first case the backscatter makes the measured spectrum steeper, that it is in reality. I.e. it increases the spectral index β of the power-law spectrum.

This type of influence is associated with simultaneous hitting of the charge detector by the primary particle and the backscatter particle. If the primary particle with charge value z_0 induces a signal with the amplitude of A_0 in the charge detector, and the backscatter particle induces a signal with the amplitude of A_{bsc} , then the measured charge will be equal to $z = \sqrt{A_0 + A_{bsc}} > \sqrt{A_0} = z_0$. If the measured charge value is greater than 1.5, then the proton will be identified as a heavier particle. Since the intensity of backscatter depends on the energy of the primary particle, then with increasing energy the probability of transferring of a proton to the group heavier particles also increases.

*) The authors thank Prof.Yu. Stozhkov for the possibility to use the spectrum obtained by him before its publication.

This mechanism of backscatter influence on the proton spectrum was understood a long time ago. One of the methods of eliminating this effect – is to decrease the charge detector size. This approach was used in the ATIC instrument by means of the silicon matrix.

The second type of backscatter influence on the proton spectrum is more complicated and characterized by decreasing the spectrum index β, therefore, making the spectrum more flat. In this second type of impact the backscatter is not the agent, directly influencing the spectrum (as in the first type of backscatter influence).

The second type of influence consists of two independent processes. One process is the production of 'additional' particles. Or, otherwise, the production of 'potential' particles. This process is based on the finite accuracy of the primary trajectory re-tracing. In this case, the primary particle misses the charge detector passing outside the aperture of the instrument and release the energy E in the energy detector. If the re-constructed trajectory lies inside the angular aperture of the instrument, a 'potential' particle appears.

Each recorded particle has two basic parameters : energy E and charge z. A 'potential' particle has only energy. In order to become a recorded particle it lacks charge. The charge value is created by the second process – the backscatter.

The primary particle in the energy detector creates a cascade of particles, which is the source of backscatter particles. Therefore, if simultaneously with the appearance of a 'potential' particle a backscatter particle enters the charge detector , then the instrument will record an event with E, z and trajectory direction within the angular aperture. This event will be attributed to a certain group of particles depending on the charge value z. Backscatter particles with greater probability create signals, close to $z=1$. Therefore, 'additional' particles will most often be attributed to the category of protons.

The number of particles N_z with charge z, which are recorded by the instrument in the energy range ΔE with account for 'additional' particles N_{ad} can be defined as:

$$N_z(E)\Delta E = I_Z^0(E)\Delta E \cdot \Gamma_{eff} T + K \cdot I_{CR}(E)\Delta E \cdot T \cdot P_{bsc}(E),$$

where $I_z^0(E)$ is the real intensity of particles in the z-group of the measured component, Γ_{eff} is the effective geometry factor of the instrument, which accounts for the recording probability, T is the recording time , K is the coefficient, accounting for the part of the geometry factor where 'additional' particles arrive, $I_{CR}(E)$ is the probability of the backscatter from a primary particle with energy E to create the required signal in the charge detector.

The intensity of measured particles can be obtained by dividing $N_z(E)$ by $\Gamma_{eff} T\Delta E$.

I.e. $I_z(E) = I_z^0(E) + I_{CR}(E)P_{bsc}(E) \cdot \dfrac{K}{\Gamma_{eff}}$.

In a certain range of energies the value of $P_{bsc}(E)$ is proportional to the intensity of backscatter current, i.e. $P_{bsc}(E) \sim E^{\alpha}$, where α=0.5-0.6. Keeping this in mind, and knowing that $I_{CR}(E) \sim E^{-\beta}$, finally we will obtain:

$$E^{\beta} I_z(E) = E^{\beta} I_z^0(E) + BE^{\alpha} \qquad (4)$$

In this equality the first term $E^{\beta} I_z^0(E)$ corresponds to the true primary spectrum. The second term is the contribution of 'additional' particles to the measured spectrum. We will discuss its influence on the spectrum using a concrete example of a proton spectrum with a 'knee'.

In this case the spectrum can be represented by the function :

$$E^{\beta} I_p(E) = C \cdot \Phi(E) = C\left\{ \frac{1}{\left[1+(E/a)^2\right]^{0.25}} \left[1 + 0.29 \frac{(E/a)^2}{1+(E/a)^2}\right] \right\}$$

The second term in expression (4) we will represent as $D(E/300)^{\alpha}$, where $D = B/C(300)^{\alpha}$.

In such a representation the measured proton spectrum will have the form:

$$E^{\beta} I_p(E) = C\left\{\Phi(E) + D(E/300)^{\alpha}\right\} \qquad (5)$$

We have calculated the expected spectrum at a =1500 GeV, α =0.58 and different values of the fraction of 'additional' particles at E =300 GeV D =0%; 2%; 4%; 6%. The results of these calculations are shown in Fig.5.

At D =0 we have the initial spectrum. In this spectrum the variation of the spectral index before and after the 'knee' $\Delta\beta$ =0.5. (Curve 1 in Fig.5.) At D =2% $\Delta\beta$ =0.3 (curve 2). At D =4% $\Delta\beta$ =0.18 (curve 3) and at D =6% the 'knee' disappears almost completely.

(Recalling that the MU spectrum at E =300 GeV has about 7% of ' additional' particles. Therefore, it is understandable , why their spectrum has no indication of a 'knee').

Fig.5. shows that even a very small fraction of recorded 'additional' particles radically changes the form of the proton spectrum, making it quite 'flat'.

A specific feature of 'additional' particles is generation of events with z =0. This happens due to the following reason.

'Additional' particles acquire charge due to backscatter particles. The 'addition' process is characterized by the primary particle not passing through the charge detectors. The charge value z which is assigned to the primary particle in concordance with the pulse amplitude in the charge detector (which was caused to operate by a backscatter particle) in a primary particle search area of S cm^2 .

If we have a mean number of backscatter particles $< n_{bsc} >$ within the search area corresponding to a given energy of the primary particles, then with the probability of $P_0 = e^{-<n_{bsc}>}$ the number of backscatter particles will be equal to 0, i.e. this will be an event with Z =0. With the probability of $1 - P_0$ there will be 1 or more backscatter particles in the search area. In these cases in 80% the signal caused by backscatter particles will correspond to a particle with Z =1, i.e. these will be cases of proton imitations. Therefore, we can write, that for 'additional' events the number of events with Z =0 $N(Z=0)$ and the number of proton imitations N_{im} are connected according to the following relation: $N_{im} = 0.8(1-P_0)N(Z=0)/P_0$.

Events with Z =0 can occur in those cases when the re-traced trajectory deviates from the actual location of the primary particle by more than 3σ . In this case the primary particle does not pass through the search area, i.e. the situation is totally similar to the process of 'additional' particle recording. The difference between these two phenomena is only in the geometry of the location of the re-traced trajectories. For 'additional' particles the re-constructed trajectories with Z =0 are located on the periphery of the charge detectors. Whereas cases with Z =0 due to large errors in the coordinates of the re-traced trajectory can happen in any location of the charge detector.

Therefore, the existence of events with Z =0 if their number exceeds several tenths of a percent of the total number of recorded events N_0 , indicates the existence of proton imitations in the proton spectrum. A quantitative connection can be established between the number of zero events and the number of proton imitations, if we use two experimentally observed parameters: the fraction of zero events ν , relatively to the total number of recorded events with the same energy N_0 and the ratio of N_0 to the number of events with Z =1 $N(Z=1)$: $N_0 / N(Z=1) = \eta$. Then, $N(Z=0) = \nu N_0 = \nu\eta N(Z=1)$. The number of particles with Z =1 consists of real protons N_p and proton imitations N_{im} . Therefore, $N_{im} = 0.8\left(\frac{1-P_0}{P_0}\right)\nu\eta(N_p + N_{im})$. After simple transformations, we obtain:

$$N_{im} / N_p = \left[\frac{P_0}{0.8\nu\eta(1-P_0)} - 1\right]^{-1} \qquad (6)$$

In order to estimate the influence of zero events on the final result – the fraction of proton imitations, we will use some of the ATIC experiment data.

In zero events the backscatter is created by all cosmic rays, therefore, its intensity is equal to $5 \cdot 10^{-4}\sqrt{(E_d / 0.1)}$ particles cm^{-2} and the mean number backscatter particles in the search area S will be equal to $< n_{bsc} >= 5 \cdot 10^{-4} S\sqrt{(E_d / 0.1)}$. At high energies S =440 cm^2 and $< n_{bsc} >= 0.22\sqrt{(E_d / 0.1)}$. (E_d is the energy released in the calorimeter, in TeV).

The value of η lies within 3÷5. We will take η =4 and the fraction of zero events ν =0.05.

Using expression (6) we obtain, that at proton energies of 10 TeV N_{im} / N_p =0.9 , and at E =1 TeV N_{im} / N_p =0.09. This means, that in the measured proton spectrum at E =10 TeV ~50% of the particles are imitations which should be subtracted from the measured results. In other words, these imitations significantly decrease the power index of the proton spectrum in the Tev energy region.

Application of devices which equally well record particles entering the instrument and coming out of it as charge detectors, inevitably lead to the appearance of zero events. Even a small fraction of such events is a serious indication implying thorough study of their origin and account for possible distortions of the proton spectrum by backscatter.

It should be stressed, that the second type of backscatter influence on the recorded spectrum cannot be avoided due to small dimensions of the charge detector.

Therefore, protection from backscatter influence on the recorded spectrum should be sought not in the charge detector dimensions but in the essence itself of backscatter.

What is the difference between backscatter particles and primary particles? The main difference is the direction of their motion: primary particles always enter the instrument from surrounding space , whereas backscatter particles always exit the instrument into outer space.

Therefore, if the charge detectors record only those which enter the instrument, and do not record particles, exiting the instrument, then such charge detectors will ignore backscatter particles. In this way the influence of the first type will be eliminated (A_{bsc} =0) and 'potential' particles will not be able to turn into recorded ones. I.e. the backscatter influence of the second type will also be eliminated.

Hence, we arrive at the conclusion, that for radical protection from the first and second types of impact from backscatter in is necessary and sufficient to use charge detectors which are selective to the motion direction of the recorded particles.

One of the detectors of this type are cherenkov counters of directional operation. The experience of their implementation in the 'Sokol' instrument [3] showed, that they eliminate the first type of backscatter influence and decrease the probability of additional particle recording by a factor of ~50, practically bringing to zero the second type of backscatter influence.

Thus we can conclude, that choice of detector type is not diverse (scintillators, silicon detectors, diffuse cherenkov counters, gas-discharge instruments) but is non-alternatively dictated by the requirement of eliminating backscatter effect on the measured spectrum, i.e. inevitably leads to cherenkov counters of directional operation or instruments with similar features.

Ignoring of this fact leads to creation of instruments, sensitive to backscatter, i.e. hardly suitable for studying the form of the cosmic ray spectra.

Conclusions

1. Backscatter can decrease the spectral index of the proton spectrum. The ATIC instrument was found to be unprotected from such backscatter influence on the measured proton spectrum.
2. The form of the proton spectrum tuned out to be dependent on the conditions of particle selection with $Z = 1$.
3. Comparison of the MU and MSU spectra revealed the existence of excess particles (in the MU proton spectrum), which apparently are generated by backscatter particles.
4. After exclusion of excess particles from the MU spectrum it attains a 'bend' at the energy of $E \cong 2$ TeV.
5. In order to obtain an unambiguous answer to the question: 'What proton spectrum has the ATIC instrument measured?' additional information is need on the characteristics of particles with Z =1: on the distribution of these particles over the matrix area at different energies (in the TeV energy range); on the existence of 'zero' events (Z =0) and their number at different energies; on the energy release spectrum for all galactic cosmic ray particles.

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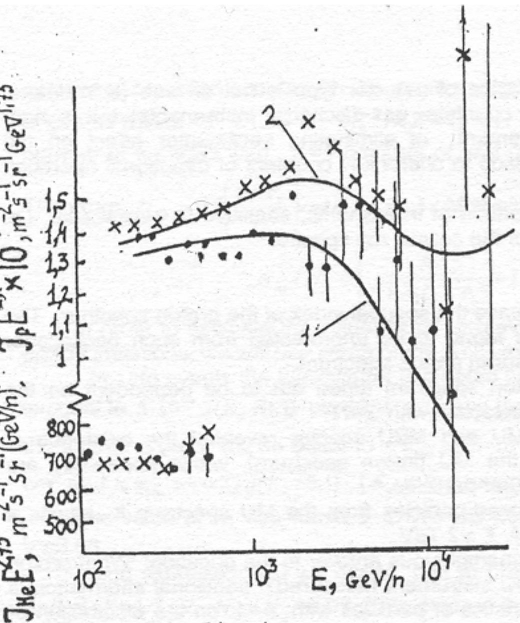

Fig. 1

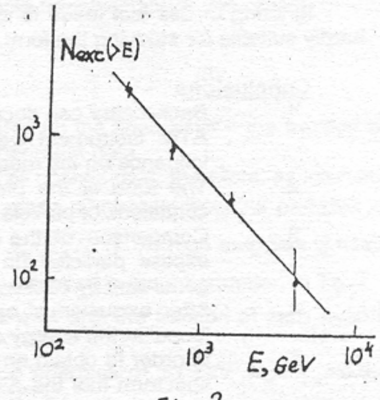

Fig. 2

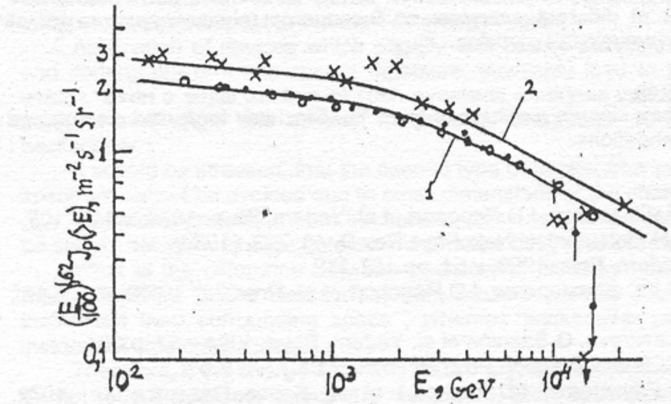

Fig. 3

Fig.1. Proton and helium spectra/ plotted in the same figure in linear scale on the vertical axis, x are the MU data, • are the MSU data. The helium spectra are in the lower left corner. The notions are the same. Curves 1 nad 2 are approximations of the proton spectra (see text).

Fig.2. The integral spectrum of excess particles, recorded ver the whole flight.

Fig.3. Integral proton spectra: • denote the MSU spectrum, o correspond to the MU spectrum, x – are the ‘Proton’ satellite data. Curves 1 and 2 are approximations of the spectra for different parameters (see text).

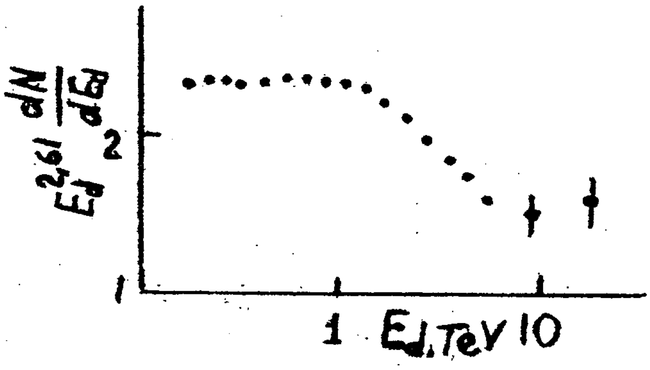

Fig.4.The energy release spectrum in the calorimeter of the ATIC instrument, published in [11] and processed in [16].

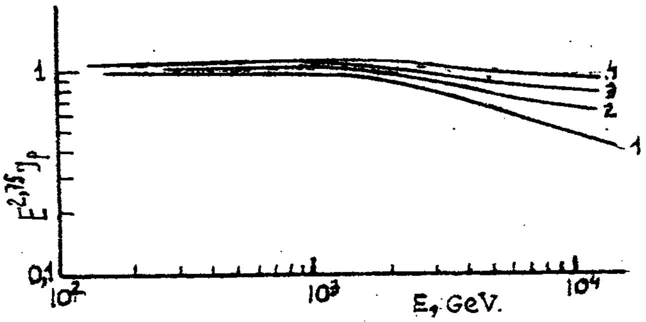

Fig.5. The dependence of the form of the spectrum with a 'knee' on the contribution of 'additional' particles. Curves 1,2,3,4 correspond to D=0, 2%, 4%, and 6%.

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ОБОБЩЕННАЯ КАРТИНА ВЛИЯНИЯ ОБРАТНОГО ТОКА НА ИЗМЕРЯЕМЫЙ СПЕКТР И АНАЛИЗ ДАННЫХ ПРИБОРА ATIC НА ЕЕ ОСНОВЕ

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