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Fine Structure in the Cosmic Ray Electron Spectrum Measured by the *ATIC-2* and *ATIC-4* Experiments[1]

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Abstract—A strong anomaly in form of a wide peak in the energy range 300–800 GeV was discovered in the first measurements of the electron spectrum in the energy range from 20 GeV to 3 TeV by the balloon-borne experiment *ATIC* [1]. The experimental data processing and analysis of the electron spectrum with different criteria for selection of electrons completely independent of the results reported in [1] is employed in the present paper. New independent analysis generally confirms the results of [1] but shows that the spectrum in the region of the anomaly is represented by a number of narrow peaks. Measured spectrum is compared to the spectrum of [1] and to the spectrum of the Fermi/LAT experiment.

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INTRODUCTION

The *ATIC* (Advanced Thin Ionization Calorimeter) balloon-borne spectrometer was designed to measure the energy spectra of nuclei from H to Fe with individual resolution of charges in primary cosmic rays. *ATIC* had three successful flights around the South Pole in 2000–2001 (*ATIC*-1), 2002–2003 (*ATIC*-2), and 2007–2008 (*ATIC*-4). *ATIC* -1 was a test flight and is not discussed in this paper. The *ATIC* spectrometer is comprised of a fully active bismuth germinate (*BGO*) calorimeter, a carbon target with embedded scintillator hodoscopes, and a silicon matrix that is used as a main charge detector. The calorimeter is comprised of eight layers of *BGO* crystals for *ATIC*-2 and ten layers for *ATIC*-4. The details of construction of the apparatus and the procedures of its calibration were described in [2–4]. It was shown that *ATIC* is capable to measure not only spectra of cosmic ray nuclear components, but also the spectrum of electrons plus positrons [5] (hereafter this spectrum will be referred to as the "electron spectrum" for brevity).

To separate the electrons from a much higher background of protons and other nuclei the differences in shower development in the apparatus for the electrons and for nuclei are used. This way measured spectrum of electrons in the *ATIC* spectrometer was published in [1]. The most notable reported detail of the electron spectrum was an "anomaly" in a form of a wide peak in the electron spectrum between energies of 300–800 GeV. In [1] a possible connection of this "*ATIC* anomaly" with nearby cosmic ray electron sources like pulsars and supernova remnants or with annihilation of dark matter particles with mass of 600–700 GeV had been already discussed. Such possibilities had provoked a very extensive discussion in the literature.

As far as the result obtained in [1] is considered to be a very important one it should be tested and confirmed in the *ATIC* experiment by other methods. The solution of just that problem is the main objective of this paper and is carried out by the Skobeltsyn Institute of Nuclear Physics group of the *ATIC* collaboration starting from the low-level procedures related to the apparatus calibration and up to the analysis of the final results completely independently on the previous work reported in [5, 1].

1. SELECTION OF ELECTRONS FROM INPUT PARTICLE FLUX

To distinguish the electrons from protons in the incident flux of cosmic ray particles some special electron filters are constructed that describe the shape of the shower in the apparatus in longitudinal and transverse directions in such way that these quantities took sharply different values for "typical" electrons and for "typical" protons. Unlike the papers [5, 1] where only

[1]The article was translated by the authors.

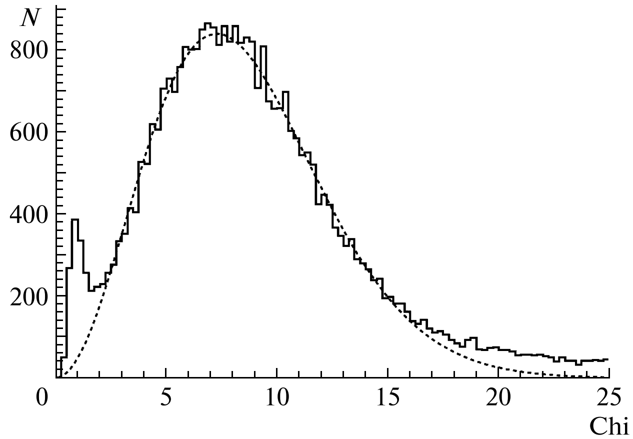

Fig. 1. The distribution of the filter Chi values for single-charge particles (*ATIC*-2, the energy deposit range 100–200 GeV). The narrow peak on the left side is related to electrons, the wide peak is related to protons. Dashed line shows the approximation of the proton distribution for substracting the proton background (see Section 3).

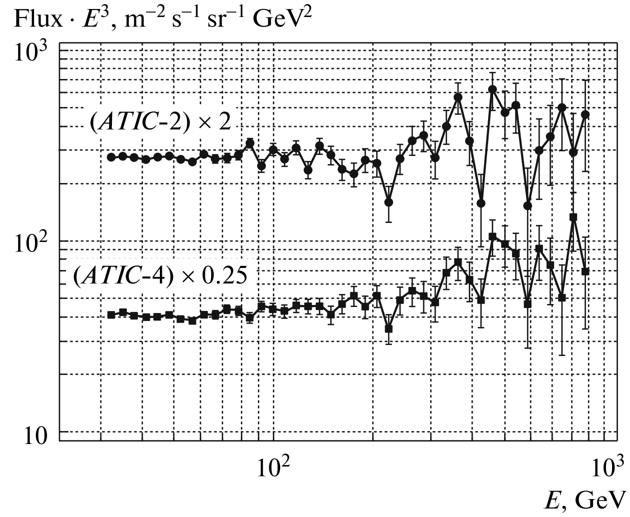

Fig. 2. The spectrum of electrons at the top of the apparatus without the subtraction of proton background and without an atmospheric correction as measured in the *ATIC*-2 and *ATIC*-4 experiments.

one filter was used, we constructed five different filters to provide the cross-check of the results and an evaluation of the methodological reliability. Different sets of basic parameters for the description of the shower shape and different mathematic ideas are used in the different filters. The following results refer to only one filter, called Chi, but are confirmed by other filters as well. The basic parameter for the construction of Chi are relative energy deposits in the layers of the calorimeter $C_l = E_l/E$ (l is the number of the layer) and root mean square widths of the shower in the layers R_l. The value of the filter Chi is given by the formula $\mathrm{Chi} = \sqrt{[\sum_{l=0}^{3}((R_l - \bar{R}_l)/\sigma_l^R)^2 + \sum_{l=4}^{7}((F_l - \bar{F}_l)/\sigma_l^F)^2]/8}$, where $F_l = R_l\sqrt{C_l}$, and the mean values and dispersions of the quantities R_l and F_l are calculated for the incident electrons by simulation of the showers in the *ATIC* apparatus with the *FLUKA* code [6]. The distribution of Chi-values for the single-charge particles after preliminary selection of events on energy deposits in the layers of the calorimeter is shown in Fig. 1.

2. FINE STRUCTURE IN THE ELECTRON SPECTRUM

The calorimeter of the *ATIC* spectrometer is practically thick for electrons (18 radiation lengths for *ATIC*-2 and 22 radiation lengths for *ATIC*-4), therefore the incident energy of an electron can be easily determined by the total energy deposit in the calorimeter. The test measurements on the electron beam at *CERN* [7] and the simulations have confirmed that the *ATIC* spectrometer has very high energy resolution for electrons. The resolution is slow-varying function of energy and in the terms of half the line width at half maximum is less than 3% at energies 200–600 GeV. High resolution enables us to investigate the electron spectrum for the presence of a structure on the scale of 0.1–0.2 decade in energy. It is essential that to detect such a structure there is no need to investigate the "absolute" electron spectrum obtained after the subtraction of the proton background (see Fig. 1) and the correction for electron scattering in the residual atmosphere. Neither the background nor the scattering of electrons in the atmosphere can lead to a short-period structure in the electron spectrum (it has been shown by the simulations explicitly).

The spectra of electrons as measured in the *ATIC*-2 and *ATIC*-4 experiments without the atmospheric correction and without the subtraction of the proton background are shown in Fig. 2 in the energy range 30–900 GeV with the step of 0.035 decades in energy. It is easy to see a structure in the energy range 200–600 GeV, which is well reproduced in the both experiments *ATIC*-2 and *ATIC*-4.

Below 200 GeV no repeatable structure is seen, and above 600 GeV it is difficult to draw definite conclusions due to the lack of statistics. The statistical significance of the observed fine structure is determined by two different factors: firstly, by the statistical significance of the correlation (similarity) of structures of the spectra measured separately in *ATIC*-2 and *ATIC*-4; secondly, by the statistical significance of the presence of non-random structure with the usual χ^2-criterion for the total spectrum *ATIC*-2 plus *ATIC*-4. It is found that the statistical significance for the correlation is $(99.69^{+0.10}_{-0.07})\%$, and according to χ^2 criterion is $(99.68^{+0.07}_{-0.05})\%$. High statistical significance practically eliminates random nature of the observed fine structure.

Several tests were also performed to exclude possible methodological causes of the observed structure. The statistics of the proton background in the range of the filter values free of the electron signal were investigated: no signs of the structure were found. The different electron filters were studied—all the filters produced very similar structure. The spectra for different solid angles and different time periods of the experiments were compared. The fine structure was reproduced in all the cases. Thus, no evidence that the observed fine structure could be caused by some methodological effects was found.

If the existence of the fine structure in the electron spectrum is confirmed by independent experiments, then its most likely source will be nearby supernova remnants and/or pulsars, but not the annihilation or decay of the dark matter particles. A structure very similar to the observed one is predicted in [8], where it is especially emphasized that such a structure might be used as a signature to distinguish between the annihilation or decay of dark matter particles and the other sources of electrons, like the nearby pulsars. The dark matter can not be a source of the structure represented by several narrow peaks [8].

3. THE ELECTRON SPECTRUM AFTER PROTON BACKGROUND SUBTRACTION AND ATMOSPHERIC CORRECTION

The spectrum shown in Fig. 2 does not provide a basis for comparison with the results of other experiments, since it does not provide the correct absolute intensity of the electron flux. To obtain the correct absolute intensity of the spectrum the proton background should be subtracted and the spectrum should be corrected for the scattering of electrons in the residual atmosphere (and we neglect the background of secondary atmospheric electrons from the hadronic component of cosmic rays, since it is shown to be small [9]).

It is shown in our previous paper [10] that the procedure of subtraction of the proton background based on the simulations of proton cascades in the *ATIC* apparatus leads to an unstable result: the inevitable small errors in the simulations lead to large errors in the electron signal. In this paper we implemented a method independent of the simulations. The method is based on an approximation of the experimental plot of the proton distribution of Chi-values, which is clearly seen on the experimental curve (see Fig. 1), by means of simple functions; and on the interpolation of these functions to the coordinate origin through the area where the net proton background is not visible under the electron peak. The scale of possible systematic errors related to the background subtraction is evaluated by comparison of the results for different types of functions.

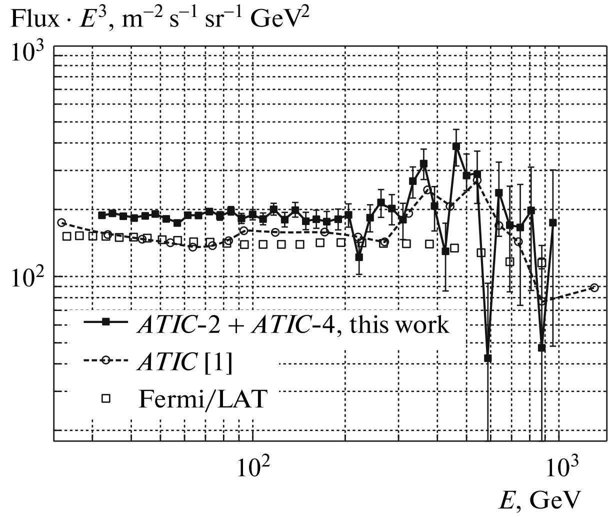

Fig. 3. *ATIC*-2 + *ATIC*-4 electron spectrum of this work after subtracting the proton background and after an atmospheric correction, *ATIC* spectrum of [1] and the results of Fermi/LAT experiment [11]. To simplify the picture, the experimental errors in the *ATIC* spectrum of [1] are not shown.

The atmospheric correction is calculated on the basis of simulations of the scattering of primary electrons in the atmosphere. As indicated in our paper [10], one does not need to correct the energy at the top of the *ATIC* apparatus to obtain the energy at the top of the atmosphere, since the scattering angles of the secondary gamma quanta are very small and the energy of an electron is recorded in the calorimeter together with the energies of almost all secondary gamma quanta which carry the energy lost by an electron. However, these gamma quanta may distort the shape of the cascade in the apparatus, which leads to some additional inefficiency of the electron filtration that was taken into account.

The absolute electron spectrum measured in the present paper along with the *ATIC* electron spectrum of [1] and the results of the space spectrometer Fermi/LAT [11] is shown in Fig. 3. An estimated corridor of possible systematic errors for the *ATIC* spectrum of the present work varies from $\left({}^{+15\%}_{-16\%}\right)$ at 40 GeV to $\left({}^{+57\%}_{-46\%}\right)$ at 700 GeV and is related mainly to the uncertainty in the detection efficiency at low energies, while at high energies it is related to errors in the subtraction of backgrounds. The systematic errors could not lead to an essential distortion in the shape of the spectrum. Our results confirm the existence of the "*ATIC* anomaly," but this anomaly is resolved into a fine structure. For the energies below 200 GeV our spectrum is identical in form to the spectrum of Fermi/LAT. The difference in the absolute fluxes does not exceed the systematic error of the experiments.

The question of the reality of the fine structure above 200 GeV requires further experimental study.

ACKNOWLEDGMENTS

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