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Energy spectra of nuclei from protons to iron in sources, according to the ATIC experiment

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One of the main results of the ATIC experiment is a collection of energy spectra of abundant cosmic ray nuclei – protons, He, C, O, Ne, Mg, Si, Fe measured in terms of energy per particle in the energy range from 50 GeV to tenths of TeV. In this report the ATIC energy spectra of abundant nuclei are back propagated to the spectra in sources in terms of magnetic rigidity using a number of GALPROP-based models of cosmic rays propagation. It is shown that the results of comparison of the slopes of the spectra are relatively weakly model-dependent within a set of studied models. It is shown that the helium spectrum in sources is flatter than the proton spectrum with high statistical significance. A regular growth of steepness of the spectra is found for a charge range from helium to iron, and this conclusion is also statistical significant. The results are discussed and compared with data of other modern experiments

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1. Introduction

The ATIC (Advanced Thin Ionization Calorimeter) balloon spectrometer was designed to measure the energy spectra of primary cosmic ray nuclei from protons to iron with elemental charge resolution in the energy range of $\sim$50 GeV to 100 TeV per particle [1]. It was shown that the spectrometer is also capable of measuring the total spectrum of cosmic ray electrons and positrons [2]. ATIC had three successful flights around the South Pole: in 2000–2001 (ATIC-1), in 2002–2003 (ATIC-2), and in 2007–2008 (ATIC-4). ATIC-1 was a test flight; nuclear spectra from protons to iron and the spectum of electrons were measured in ATIC-2 flight; and only the electron spectrum was measured in ATIC-4, due to malfunctioning of the pretrigger system. Present work is based on the results from the ATIC-2 flight.

The ATIC spectrometer consists of a fully active BGO calorimeter, a carbon target with embedded scintillator hodoscopes, and a matrix of silicon detectors. The silicon matrix was used as a primary particle charge detector. The design of the instrument and the calibration procedures were described in detail in [1, 3, 4].

The data obtained by the ATIC spectrometer includes high precision energy spectra of the most abundant cosmic ray nuclei (protons, He, C, O, Ne, Mg, Si, and Fe) [5]) in terms of energy per particle. The total kinetic energy per particle was the most natural quantity for expressing the energy measured by the calorimetric spectrometer, and the results from the ATIC measurements were given in this way in [5]. From the viewpoint of the physics of the propagation and acceleration of cosmic rays, however, it is more important to know the magnetic rigidity spectra of cosmic rays, and it is information on the rigidity spectra *in sources* that is most important in studying mechanisms of acceleration of cosmic rays. Converting from observed energy per particle spectra to the observed rigidity spectra using the ATIC data poses no difficulties, since the charge of each particle is measured along with its energy. In order to obtain the source spectra in terms of magnetic rigidity, however, the inverse problem of propagation of particles must be solved using one model of propagation or another. In this work, the inverse problem is solved using several simple models of propagation, and the resulting source spectra of abundant nuclei are discussed.

2. Solving the inverse propagation problem in the leaky box approximation

We restrict ourselves in this paper by a number of propagation models which consider the interstellar medium to be homogeneous within the magnetic galactic halo. Some more complicated models which consider the interstellar medium to be essentially inhomogeneous also are studied elsewhere (see, for example the model of closed galaxy with super bubbles embedded [6, 7]). But at the present time the basis of such models looks insufficiently firm. For example, the model of Local Bubble within closed galaxy [7] explains the upturn in the ratio of fluxes of nuclei of Z=16-24 to iron near the energy 50 GeV/n, but the same model is in contradiction with the latest data on B/C [8] showing no such upturn. Therefore we will consider only the simplest case of homogeneous interstellar medium.

It is generally quite difficult to solve the inverse problem for the diffusion transport equation. However, the homogenous model [9] known also as the leaky box approximation [10] works well for the most abundant cosmic ray nuclei. For a number of different assumptions about the character

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of diffusion it was shown in [11] that numerical solutions of the diffusion equation for fluxes of abundant nuclei using the GALPROP system can be approximated with a percentage accuracy using leaky box models; i.e., the exact solution of the diffusion equation yields essentially the same results as a properly constructed leaky box model. In the leaky box model, a solution of the inverse problem of propagation may be obtained very simply.

The diffusion of cosmic rays in the Galaxy is described in this model by a single parameter: the particle diffusion escape length from the Galaxy $\lambda_{esc}(R)$, measured in g/cm^2, which depends only on magnetic rigidity R of the particles. If abundant nuclei of a certain type are described by an effective source averaged over the Galaxy volume with rigidity spectrum $Q(R)$, their observed equilibrium spectrum takes the form

$$M(R) = \frac{1}{\rho v} \frac{1}{[1/\lambda_{esc}(R) + 1/\lambda_N]} Q(R), \tag{2.1}$$

where λ_N (g/cm^2) is the mean free path of a nucleus before nuclear interaction in the interstellar medium, v is the velocity of the particle. Equation (2.1) is a solution of the direct problem of cosmic ray propagation for the considered special case. The solution of the inverse problem of propagation (i.e., determining the source function from an observed particle spectrum) is obtained through trivial inversion of Eq. (2.1):

$$Q(R) = \rho v [1/\lambda_{esc}(R) + 1/\lambda_N] M(R). \tag{2.2}$$

There are many specific examples of selecting a particular expression for escape length $\lambda_{esc}(R)$ in the literature. Some of these are based on a direct approximation of experimental data, while others approximate different types of solutions of diffusion equations. In this work, we use the leaky box approximations for the three different numerical GALPROP solutions of the diffusion equation that were considered in [11]. These three models represent the currently existing range of uncertainty in understanding of the physics of cosmic ray propagation in the interstellar medium. Their respective diffusion escape lengths are [11]

$$\lambda_{esc}(R) = 19\beta^3 (R/3\,\mathrm{GV})^{-0.6},\ R > 3\,\mathrm{GV} \tag{2.3}$$
$$\lambda_{esc}(R) = 7.2\beta^3 (R/3\,\mathrm{GV})^{-0.34},\ R > 40\,\mathrm{GV} \tag{2.4}$$
$$\lambda_{esc}(R) = 13\beta^3 (R/3\,\mathrm{GV})^{-0.5},\ R > 10\,\mathrm{GV} \tag{2.5}$$

Formula (2.3) corresponds to the so called plain model, which is based on a direct approximation of the B/C ratio of the HEAO-3-C2 experiment [12]; formula (2.4) is based on a model of diffusion with reacceleration in a medium with Kolmogorov turbulence (referred to as the reacceleration model); and formula (2.5) corresponds to the model with nonlinear interaction between cosmic rays and the interstellar medium, which induces magnetic turbulence (known as the damping model). The details are described in [11]. It is seen that at high energies, functions (2.3)–(2.5) behave as power law functions of magnetic rigidity R, but the values of the exponent are different.

Using models (2.3)–(2.5) and Eq. (2.2), it is easy to obtain the corresponding versions of a source spectrum from the measured spectrum of a given nucleus. Due to the considerable difference between functions (2.3)–(2.5), the steepness of the reconstructed source spectrum will depend

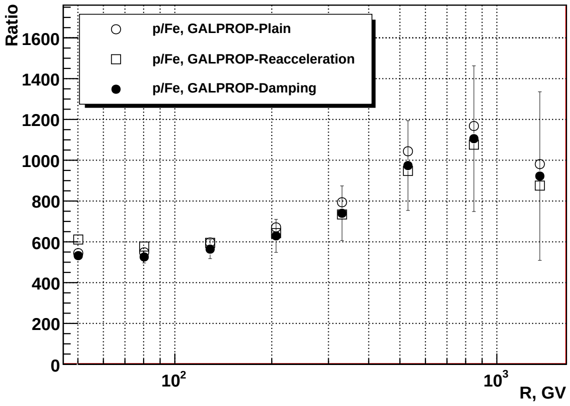

Figure 1: Ratio of source spectra of protons and iron, obtained using different models of propagation: GALPROP plain, GALPROP reacceleration, GALPROP damping (see the text for details). Statistical errors are specified only for the GALPROP damping model points; for the other models, the errors are virtually the same.

strongly on the model; i.e., considering the existing uncertainty in propagation models, the steepness of the spectrum can be reconstructed only with a high degree of uncertainty. However, as it will be seen below, the differences in the shape of the source spectra of different nuclei can be studied quite reasonably.

3. Differences between the forms of source spectra for different abundant nuclei

To compare the forms of the source spectra for different nuclei, one can use the ratios of the spectra: when the ratio is not constant, the shapes of the spectra are different. The ratios of spectra p/Fe for GALPROP models (2.3)-(2.5) are shown in Fig. 1. It is seen that the model dependence of the spectrum ratios is negligible, compared to the statistical errors. The greater the difference between the masses of the considered nuclei, the stronger is the model dependence, so the latter is most apparent for the p/Fe from all possible combinations in the list of abundant nuclei (p, C, O, Ne, Mg, Si, Fe). For all other ratios, the model dependence is weaker than for p/Fe (Fig. 1), and the ratios can be studied with virtually no model dependence. It is easily seen that the p/Fe ratio is not constant (the average spectrum for iron is steeper), but the χ^2 test shows that the difference actually is not statistically significant.

The Ne, Mg, and Si spectra are not well statistically reliable in the ATIC data, so for further analysis it is convenient to combine the spectra of these nuclei with similar charge numbers into the summed rigidity spectrum Ne+Mg+Si with an effective charge number of $Z = 12$. Figure 2 shows the source spectra for protons, He, C, O, Ne+Mg+Si, and Fe obtained within the GALPROP reacceleration model. It can be seen that the spectra of protons and helium with high reliability are not described by a simple power law, and become flatter at high energies. For both protons and helium this phenomenon was confirmed by PAMELA experiment [13], for protons it was confirmed by AMS-02 [14]. The spectra of carbon and oxygen also become flatter at high energies. This phenomenon for the nuclei heavier than helium is confirmed by the data of the CREAM experiment [15]. This complicated behavior may be related to some no-linear phenomena during cosmic ray acceleration [16], heterogeneous structure of sources and nearby interstellar medium [17, 18], and quite naturally may be explained by mixing of no less than two sources with different spectra [19]. However the object of present paper is not to discuss the nature of complex behavior of the spectra,

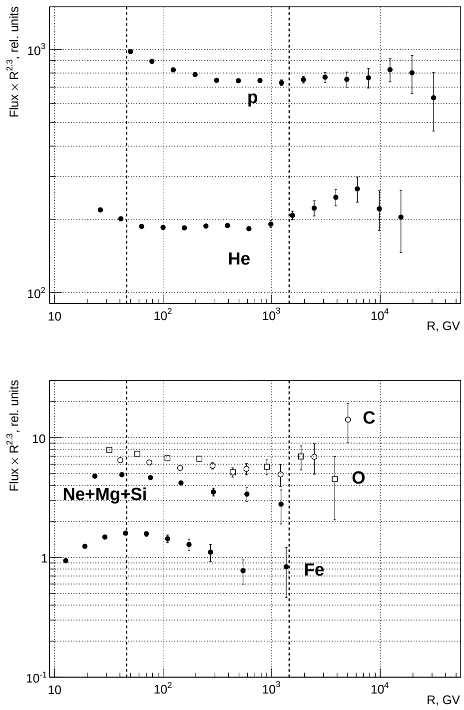

Figure 2: Source spectra of nuclei obtained for the GALPROP reacceleration model of propagation.

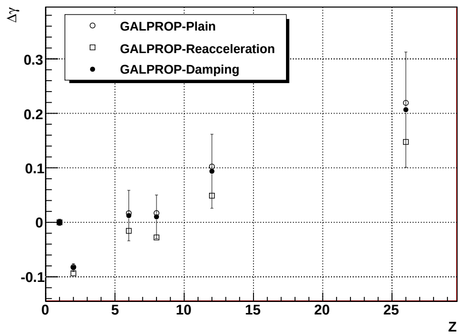

Figure 3: Differences between the source spectral indexes of abundant nuclei from the spectral index of protons. Statistical errors are specified only for the GALPROP damping model points; for other models, the errors are virtually the same.

but to compare the spectra of different nuclei in the source and answer the simple question: are the spectra in terms of magnetic rigidity in the source the same for different nuclei or not, and how much are the differences if the spectra are not the same.

There are total of six independent spectra, and $6(6-1)/2 = 15$ ratios can be constructed and viewed as model independent characteristics of cosmic ray sources. However, fifteen ratios are of little use as material for analysis, so in this work we used a simplified approach to consider important aspects of the behavior of the whole set of the spectra. We took the range of magnetic rigidity common to all of the obtained spectra (approximately from 50 to 1350 GV, indicated by the vertical dashed lines in Fig. 2) and found the average spectral index for each spectrum in this range, ignoring certain deviations from the pure power law behavior. Since the spectral indexes were highly model dependent, we were interested not in the spectral indexes themselves but in how they varied from one nucleus to another. Figure 3 shows the differences between the source spectral indexes of abundant nuclei from the spectral index of protons as a function of their nuclear charges. It is seen that while there is some model dependence in the final result, it is small in comparison to both the differences between the spectral indexes and the statistical errors.

Discussing the data in Fig. 3, it is worth mentioning first, that the spectral index of protons differs from that of helium, and the difference is virtually model independent and has high statistical significance: $\Delta\gamma = 0.086 \pm 0.009(\mathrm{stat}) \pm 0.007(\mathrm{syst})$. Second, the steady rise in the spectrum steepness moving from helium to iron may be noted. This result is also statistically significant,

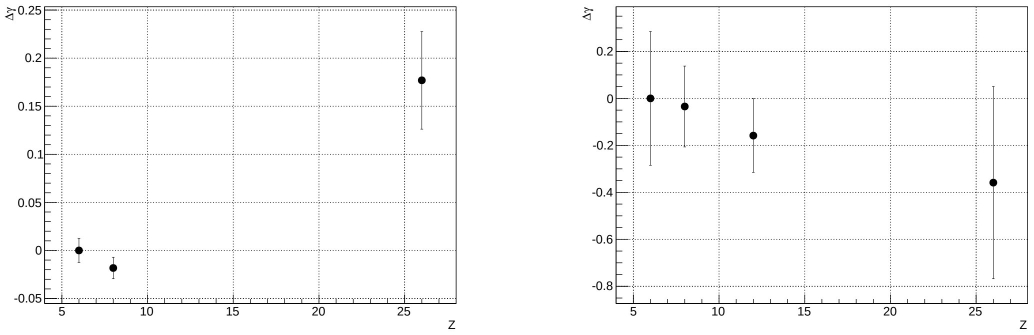

Figure 4: Differences between the source spectral indexes C, O, Fe obtained from the data of TRACER-LDB2 experiment [20] (left panel) and CREAM-II [15] (right panel). The point for Ne+Mg+Si is also shown for CREAM.

as the slope of this part of the curve in Fig. 3 is positive with statistical significance of 3.7σ to 4.8σ, depending on the model of propagation. It is not clear however, whether it makes physical sense to describe all nuclei from helium to iron using one curve, since the helium and heavy nuclei could originate from fundamentally different cosmic ray sources. It is therefore logical to consider nuclei heavier than helium separately. There is also a positive trend in the slopes of their curves, but it is maintained with a statistical significance of just 1.6σ to 2.0σ, depending on the model. We may therefore speak only of an indication of a trend in the latter case, and it is not observed with sufficient statistical reliability.

There are only a few experiments which can be compared with the results of the present paper. Differences between the source spectral indexes of oxygen, iron and carbon obtained from the data of TRACER-LDB2 experiment [20] and CREAM-II [15] are shown in Fig. 4. The reference point is the spectral index of carbon (separately for TRACER and for CREAM). To obtain these plots the original data of TRACER and CREAM for absolute energy spectra of C, O and Fe were processed by us with the same method as described above in the present paper. The reacceleration GALPROP model Eq. (2.4) was used to generate the plots in Fig. 4. It is seen that the TRACER's data show more steep spectrum for iron than for carbon and oxygen and this trend confirms the ATIC's data (Fig. 3). The result for TRACER is statistically significant: the difference of spectral indexes between C and Fe is 3.5σ. The TRACER-LDB1 data [21] show approximately the same result but with lower statistical significance. The CREAM data show no trends in spectral indexes but the statistical errors are large (about 0.4 for iron versus expected difference of spectral indexes of 0.2, as may be deduced from ATIC and TRACER data), therefore no conclusions may be drawn. We also should note that the results for TRACER and CREAM were obtained for magnetic rigidities less than 400 GV versus 1350 GV in ATIC. The absolute spectra are not quite power-law in all experiments, therefore the results of this comparison should be accepted accurately. The results are related to mean spectral indexes in power-law approximation only and the energy ranges are similar but not exactly the same for different experiments. Obviously, more exact experimental data are needed to draw final conclusions.

4. Summary

We would like to note that only rather restricted subset of possible propagation models (homogeneous galaxy halo) was investigated in this paper in respect of stability of the results of solution of back propagation problem. Our conclusion is that within this subset of models the results on ratios of source spectra of different nuclei are almost model-independent, but clearly other more complicated propagation models should be studied. We represented our results as differences of averaged source spectral indexes of different nuclei. This approximate method is adequate for rather low statistics and relatively narrow energy range for comparison of spectra of different nuclei, that were accessible for us. New experiments more precise are needed to obtain and study more detailed information. But we obtained clear indication that the acceleration conditions for different nuclei from protons to iron may be different and this indication is very important.

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