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Spectra of Abundant Nuclei in Sources, According to the ATIC Experiment

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Abstract—One of the most important results from the ATIC experiment is its collection of the energy spectra of abundant cosmic-ray nuclei: protons, He, C, O, Ne, Mg, Si, and Fe, measured in terms of energy per particle in the energy range of 50 GeV to tens of TeV. Starting with the spectra measured in the ATIC experiment, abundant nuclei spectra in sources are calculated using a number of propagation models. The results from comparing the spectra in sources of different nuclei are shown to depend only weakly on the propagation model. The spectrum of helium in sources is found to be harder than that of protons; this result is of high statistical significance and is virtually model-independent. From helium up to iron nuclei, the steepness of the spectra in sources is seen to grow notably as the charge of nuclei rises.

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INTRODUCTION

The ATIC (Advanced Thin Ionization Calorimeter) balloon spectrometer was designed to measure the energy spectra of primary cosmic-ray nuclei ranging from protons to iron, with elemental charge resolution in the energy range of ~50 GeV to 100 TeV per particle [1]. It was shown that the spectrometer is 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 spectra of electrons were measured by ATIC-2; and ATIC-4 measured only the electron spectrum, due to malfunctioning of the trigger. This work is based on the results from the ATIC-2 flight.

The ATIC spectrometer contains a fully active BGO calorimeter, a carbon target with scintillator hodoscopes, and a silicon matrix; in this experiment, the matrix was used as a primary particle charge detector for the first time. The design of the instrument and the calibration procedures were described in detail in [3–5].

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 [6]) in terms of energy per particle. The total kinetic energy per particle is the most natural unit for expressing the energy measured by the spectrometer, and the results from the ATIC measurements were given in this way in [6]. 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. Converting from observed energy per particle spectra to the 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 spectra according to source rigidity, however, the inverse problem of particle propagation 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.

SOLVING THE INVERSE PROBLEM OF PROPAGATION IN THE LEAKY BOX APPROXIMATION

It is generally quite difficult to solve the inverse problem for the diffusion transport equation. However, the homogenous solution [7] known as the leaky-box approximation [8] works well for the most abundant cosmic-ray nuclei. It was shown in [9] that numerical solutions to the diffusion equation for fluxes of abundant nuclei using the GALPROP system can be approximated very accurately (in terms of percent) for a number of assumptions about the character of diffusion using leaky-box models; i.e., the exact solution to the diffusion equation yields essentially the same results as a properly constructed leaky-box model. In the leaky-box model, a solution to the inverse problem of propagation is obtained rather simply. The diffusion of cosmic rays in the Galaxy is described in this model by a single parameter: the

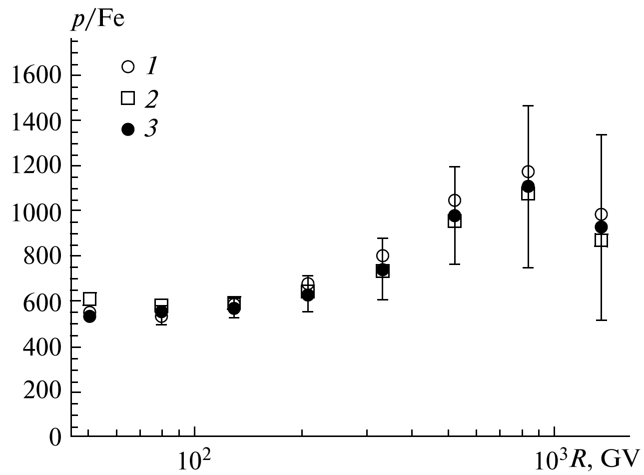

Fig. 1. Ratio of source spectra of protons and iron, obtained using different models of propagation: (*1*) plain GALPROP, (*2*) GALPROP reacceleration, (*3*) GALPROP damping. Statistical errors are specified only for the GALPROP damping points; for the other models, the errors are virtually the same.

length of particle diffusion escape 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

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

where λ_N (g cm^{-2}) is the mean free path of a nucleus before nuclear interaction in the interstellar medium. Equation (1) is a solution to the direct problem of cosmic ray propagation for the considered special case. The solution to the inverse problem of propagation (i.e., determining the source function from an observed particle spectrum) is obtained through trivial inversion of Eq. (1):

$$Q(R) = \rho v(1/\lambda_{esc}(R) + 1/\lambda_N)M(R). \quad (2)$$

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 straightforward approximation of experimental data, while others approximate different types of solutions to diffusion equations. In this work, we use the leaky-box approximations for the three different numerical GALPROP solutions to the diffusion equation that were considered in [9]. These three models represent the currently existing range of uncertainty in our understanding of the physics of cosmic-ray propagation in the interstellar medium. Their respective diffusion escape lengths are [9]

$$\lambda_{esc}(R) = 19\beta^3(R/3\text{ GV})^{-0.6}, \quad R > 3\text{ GV}, \quad (3)$$

$$\lambda_{esc}(R) = 7.2\beta^3(R/3\text{ GV})^{-0.34}, \quad R > 40\text{ GV}, \quad (4)$$

$$\lambda_{esc}(R) = 13\beta^3(R/3\text{ GV})^{-0.5}, \quad R > 10\text{ GV}. \quad (5)$$

Formula (3) corresponds to the so-called plain model, which is based on a straightforward approximation of the B/C ratios of the HEAO-3-C2 experiment [10]; formula (4) is based on a model of diffusion with reacceleration in a medium containing Kolmogorov turbulence (referred to as the reacceleration model); and formula (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 [9]. We see that at high energies, functions (3)–(5) behave as power law functions of magnetic rigidity R, but the values of the exponent are different. Using models (3)–(5) and Eq. (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 (3)–(5), the steepness of the reconstructed source spectrum will depend 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. As is shown below, however, the different forms of the source spectra from a variety of nuclei can be studied quite reasonably.

DIFFERENCES BETWEEN THE FORMS OF SOURCE SPECTRA FOR A VARIETY OF ABUNDANT NUCLEI

To compare the forms of the source spectra from a variety of abundant nuclei, we can use the ratios of the spectra: when the ratio is not constant, the shapes of the spectra are different. Spectrum ratios p/Fe for GALPROP models (3)–(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 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 is not statistically significant.

The Ne, Mg, and Si spectra are not statistically reliable in the ATIC data, so for further analysis it is

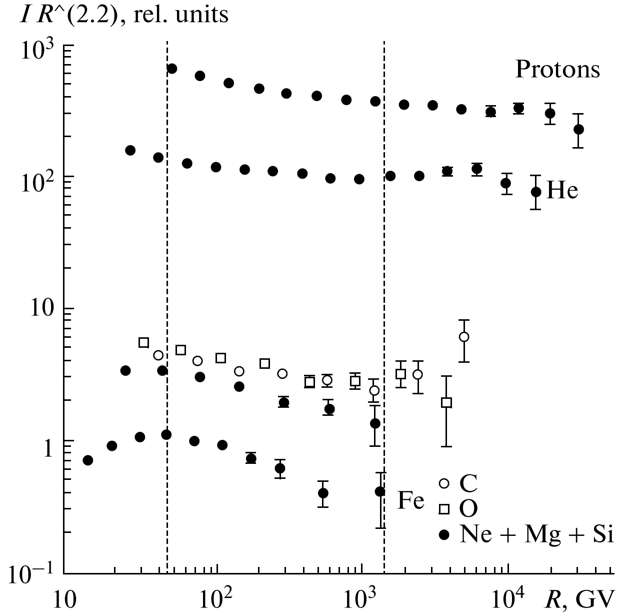

Fig. 2. Source spectra of nuclei obtained for the GALPROP reacceleration model of propagation.

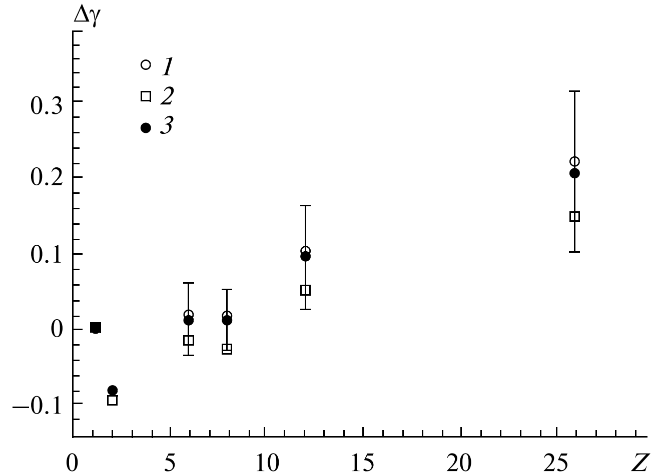

Fig. 3. Differences between the source spectral indices of abundant nuclei from the spectral index of protons. Statistical errors are specified only for the GALPROP damping points; for other models, the errors are virtually the same.

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 12. Figure 2 shows the source spectra for protons, He, C, O, Ne + Mg + Si, and Fe obtained within the GALPROP reacceleration model. 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 spectra. We took the range of magnetic rigidity common to all of the obtained spectra (approximately 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 indices were highly model-dependent, we were interested not in the spectral indices themselves but in how they varied for different nuclei. Figure 3 shows the differences between the source spectral indices of abundant nuclei from the spectral index of protons as a function of their nuclear charge numbers. It is seen that while there is some model dependence in the final result, it is negligible in comparison to both the differences between the spectral indices and the statistical errors.

Discussing the data in Fig. 3, it is worth mentioning that first the spectral index of protons differs from that of helium, and the difference is virtually model-independent and very statistically significant. Second, the steady rise in the spectrum steepness moving from helium to iron should be noted. This result is also statistically significant, 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 any statistical reliability.

CONCLUSIONS

The observed difference between the steepness of source spectra of different nuclei is evidence of different conditions during the acceleration of nuclei of different types. This could indicate either sources of different types or heterogeneity of the medium around a source (or both simultaneously). We intend to discuss these questions in subsequent works.

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REFERENCES

1. Guzik, T.G., Adams, J.H., Ahn, H.S., et al., *Adv. Space Res.*, 2004, vol. 33, p. 1763.
2. Chang, J., Adams, J.H., Ahn, H.S., et al., *Adv. Space Res.*, 2008, vol. 42, p. 431.
3. Guzik, T.G., Adams, J.H., Ahn, H.S., et al., *Adv. Space Res.*, 2004, vol. 33, p. 1763.
4. Zatsepin, V.I., Adams, J.H., Ahn, H.S., et al., *Nucl. Instrum. Methods Phys. Res., Sect. A*, 2004, vol. 524, p. 195.
5. Panov, A.D., Zatsepin, V.I., Sokolskaya, N.V., et al., *Prib. Tekh. Eksp.*, 2008, no. 4, p. 17.
6. Panov, A.D., Adams, J.H., Jr., Ahn, H.S., et al., *Bull. Russ. Acad. Sci. Phys.*, 2009, vol. 73, no. 5, p. 564.
7. Ginzburg, V.L. and Ptuskin, V.S., *Usp. Fiz. Nauk*, 1975, vol. 117, no. 4, p. 585.
8. Gaisser, T.K., *Cosmic Rays and Particle Physics*, New York: Cambridge Univ. Press, 1990.
9. Ptuskin, V., Strelnikova, O., and Sveshnikova, L., *Astropart. Phys.*, 2009, vol. 31, p. 284.
10. Engelmann, J.J., Ferrando, P., Soutoul, A., et al., *Astron. Astrophys.*, 1990, vol. 233, p. 96.

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