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Upturn in the Heavy Nuclei to Iron Ratio in the ATIC Experiment above 100 GeV/Nucleon

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Abstract—It is argued that the upturn observed in heavy nuclei to iron ratios as measured in the ATIC experiment can be understood within a model of a closed galaxy with embedded local regions containing sources of cosmic rays. This model predicts a universal upturn near energies of 200–300 GeV/nucleon in the spectra of abundant primary nuclei. It also predicts the source spectral index to lie near 2.5.

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INTRODUCTION

It is commonly believed that the relation between secondary cosmic ray flows and flows of corresponding parent primary nuclei must be a decreasing energy function as a result of the energy-related decline in the diffusive time of escaping from the galaxy. This belief was confirmed for energy values of several tens of gigaelectronvolts in the HEAO-3-C2 [1], HEAO-3-C3, and other experiments [2–4]. Meanwhile, an unexpected upturn in the indicated ratios in the region of 100–600 GeV/nucleon was revealed during the HEAO-3-C3 experiment [2–4]. The observed increase was thought to be related to systematic errors [2–4]. Such unexpected variation in the dependence on energy was established for the Ti/Fe ratio in the ATIC-2 experiment [5] near energies of 70–80 GeV/nucleon, but the statistical data on energies of over 100 GeV are rather poor, and the effect was recognized as statistically insignificant [5]. Even though the HEAO-3-C3 and ATIC-2 results were not taken very seriously, they did force us to examine the data on heavy nuclei in the ATIC-2 experiment more thoroughly.

THE ATIC-2 EXPERIMENT

ATIC (the Advanced Thin Ionization Calorimeter) is a balloon spectrometer for measuring the energy spectra of primary cosmic ray nuclei from protons to iron [6]. The ATIC spectrometer consists of a fully active BGO calorimeter, a carbonic target with integrated scintillation hodoscopes, and a silicon matrix used as the main detector of primary particle charges. The heavy nuclei to iron ratio was studied in the ATIC-2 experiment in [7]. The charge resolution in a group of heavy nuclei was insufficient to separate adjacent nuclei in the ATIC-2 experiment, and therefore the relation between heavy nuclei with $Z = 16–24$ and iron flow was constructed [7]. It should be noted that the considered group of heavy nuclei includes both secondary nuclei and a number of primary nuclei. Figure 1 demonstrates the heavy nuclei to iron ratio obtained in the course of our investigation.

SIMPLE LEAKY BOX MODEL

To describe particle transport, let us start with the simple leaky box model. Let N_1, N_2, ..., N_k be types of secondary nuclei produced upon iron fragmentation. The relation between the total flow of secondary

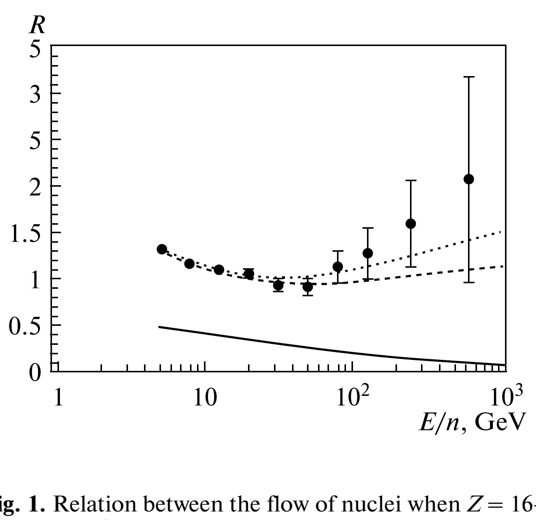

Fig. 1. Relation between the flow of nuclei when $Z = 16–24$ and iron flow. The ATIC experiment is indicated by the points; the leaky box model, by the solid line; the leaky box model + the contribution from primary nuclei, by the dashed line; and the model of a closed galaxy with super bubbles, by the dotted line.

nuclei $I_{\Sigma S} = \sum_{i=1}^{k} I_{N_i}$ and iron flow can then be written in the form

$$\frac{I_{\Sigma S}}{I_{\rm Fe}} = \sum_{i=1}^{k} \frac{\kappa N_i {\rm Fe}}{\kappa_{esc}^{N_i}(\varepsilon) + \kappa_{N_i}}, \qquad (1)$$

Where ε is particle energy per nucleon, $\kappa_{esc}^{N_i} = 1/\lambda_{esc}^{N_i}$ is the inverse diffusion escape length of the nucleus N_i with energy ε, $\kappa_{N_i} = 1/\lambda_{N_i}$ is the inverse length of fragmentation in the interstellar medium for nuclei N_i, and $\kappa_{N_i,{\rm Fe}} = 1/\lambda_{N_i,{\rm Fe}}$ is the inverse partial length of iron fragmentation in nucleus N_i. Length of escape λ_{esc} is regarded as a universal rigidity function for all nuclei, and the approximation from [1] is used: $\lambda_{esc} = 34.1R^{-0.6}$ g cm^{-2}. We used the λ_{N_i} values compiled by Ginzburg and Syrovatsky [8] and calculated partial lengths $\lambda_{N_i,{\rm Fe}}$ using the partial cross sections of fragmentation given in [9] suggesting that the interstellar medium consisted of 90% protons and 10% helium. The calculated relation between the secondary heavy nuclei in the group of Z = 16–24 and iron in the simple leaky box model (solid line) is shown in Fig. 1. This model predicts the lower ratios relative to the experimental ratios in the energy region of $\varepsilon <$ 40 GeV/nucleon. These could be due to the contribution from primary nuclei to the flow of heavy nuclei. Hence, the (Z = 16–24)/Fe ratio can be described by the total of secondary nuclei formed upon iron fragmentation, as was predicted by the leaky box model, and some contributions from primary nuclei. The spectra of the abundant primary C, O, Ne, Mg, and Si nuclei are very similar [7]. We may assume that the spectra of the heavier (but lighter than iron) primary nuclei have the same form, and the oxygen spectrum is therefore used as our form pattern. The ATIC experiment's fit, obtained using the relation of secondary spectra total in the leaky box model and some contribution from the primary spectra of the (Z = 16–24) group to the iron spectrum, is shown in Fig. 1 by the dashed line. This fit, while entirely suitable for $\varepsilon <$ 100 GeV/nucleon, does not describe the ratio upturn at $\varepsilon \gtrsim$ 100 GeV/nucleon.

MODEL OF A CLOSED GALAXY WITH LOCAL BUBBLES

The simple leaky box model with the addition of primary flows thus does not describe the experimental data at energies >100 GeV/nucleon. Some additional concepts are needed to understand the variations in the dependence of ratios on energy. One possibility is the closed galaxy model proposed in [10], where it was shown that such a model can yield the growth in the sub-Fe/Fe ratio. It should be noted that the closed galaxy model was used in [11] in discussing the anomalously high (Li + Be + B)/(C + N + O) value in the JACEE experimental data.

According to the closed galaxy model, the Galaxy has a number of compact regions, each of which contains sources of cosmic rays and is described by a simple leaky box model with respect to the diffusion escape of particles from this region. It is also suggested that all CR sources are concentrated in such local regions. It was originally proposed in [10] that the Galaxy's arms are such regions, and yet the super-bubbles produced by supernova explosions could also be local compact regions. The last suggestion appears logical, if supernovae explode mainly in stellar associations in which star formation is of recent origin, and where short-lived massive stars are formed. The exact nature of the local regions is not important for the model, but we will assume for the sake of clarity that these are super-bubbles and shall refer to this version as the closed galaxy with super-bubbles (CG + B) model. This model also assumes that the whole galaxy is closed with respect to diffusion escape. The Sun lies within the local bubble, and the aim of the model is to predict CR flows in this bubble. The flow of CRs in the bubble consists of two parts [10]: a local flow, which can be described using the simple leaky box model, and the global equilibrium galactic flow (referred to below as the bulk flow), which can be described by a model similar to the leaky box applied to the galaxy as a whole, but assuming that $\lambda_{esc}(\varepsilon) \simeq \infty$. This model also has one free parameter characterizing the ratio of the bulk flow to the total flow, which is not known a priori and must be determined to describe the experimental data.

In the CG + B model, the bubbles' surfaces are the only source of CRs in the bulk flow. If we accept the usual assumption that the probability of a particle escaping a volume does not depend on the previously covered distance in the volume, we can obtain the equation for a modified bulk flow source,

$$Q_{\rm bulk}(\varepsilon) = \frac{\kappa_{esc}(\varepsilon)}{\kappa_{esc}(\varepsilon) + \kappa} Q(\varepsilon). \qquad (2)$$

where $Q(\varepsilon)$ is the spectrum of such nuclei in a source within the bubble, $\kappa_{esc}(\varepsilon)$ is inverse length to escape for these nucleus from the bubble, and κ is the inverse nuclear length for these nuclei. Using Eq. (2) and applying the normal leaky box formula to the bubble and Galaxy, we can obtain the ratio of the total flow of secondary nuclei N_i to the flow of iron in the CG + B model,

$$\frac{I_{N_i}(\varepsilon)}{I_{\rm Fe}(\varepsilon)} = \frac{\dfrac{\kappa_{N_i,{\rm Fe}}}{\kappa_{esc}^{N_i} + \kappa_{N_i}} + K\dfrac{\kappa_{N_i,{\rm Fe}}}{\kappa_{N_i}}\dfrac{\kappa_{esc}^{\rm Fe}(\varepsilon)}{\kappa_{\rm Fe}}}{1 + K\dfrac{\kappa_{esc}^{\rm Fe}(\varepsilon)}{\kappa_{\rm Fe}}}, \qquad (3)$$

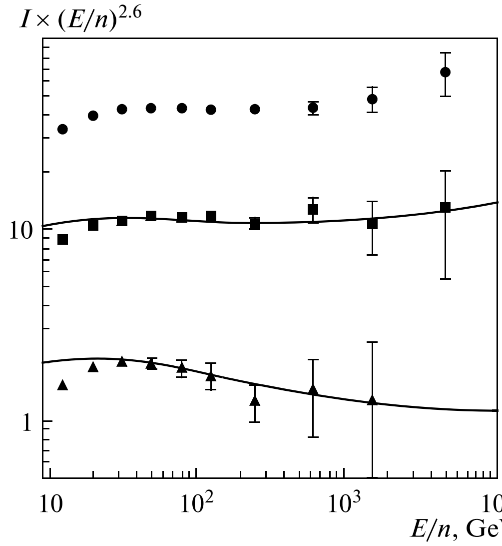

Fig. 2. Spectra of all nuclei with $Z \geq 3$ (points), oxygen (squares), and iron (triangles) measured in the ATIC experiment. The lines describe the oxygen spectra at $\alpha = 2.45$ and the iron spectra at $\alpha = 2.55$ in the model of a closed galaxy with super bubbles. Intensity I is measured in $m^{-2}\,s^{-1}\,sr^{-1}\,GeV^{-1}$.

where K describes the ratio of bulk flow to the total flow. Summation over i is needed for the flow of a group of nuclei in Eq. (3).

The CG + B model's predictions for a flow of secondary and primary nuclei in a group of $Z = 16–24$ with $K = 0.2$ are shown in Fig. 1 by the dotted line. The complicated model behavior with downturns and upturns in the ratio results from the competition between local and bulk flows. It is clear that a CG + B model that includes the contribution from primary flows can describe the experimental data in a relatively good approximation, but the ratio upturn in the experiment could be sharper than in the model.

Figure 2 presents the spectrum of all nuclei with $Z \geq 6$ measured in the ATIC experiment, which clearly indicates flattening at energies over ~200 GeV/nucleon. This spectrum is dominated by the contribution from primary abundant nuclei. The spectra of primary abundant nuclei can also be understood using the CG + B model. The ATIC oxygen and iron spectra described in [7] with the aid of the CG + B model are shown in Fig. 2. To fit the spectra, we had to accept the source spectrum index values of $\alpha = 2.45$ for oxygen and $\alpha = 2.55$ for iron. These are very soft spectra, and this could be a problem for the CG + B model. At the same time, the advantage of this model is its ability to predict the universal flattening of abundant nuclei spectra in a 200–300 GeV/nucleon region similar to the one discovered by ATIC [12] and confirmed by CREAM [13], without the hypothesis of an additional source of the soft CR spectrum.

One important result of the CG + B model needs to be recognized. The simple leaky box model estimates the diffusion coefficient at [14] $D(\varepsilon) \sim \rho c H^2/\lambda_{esc}(\varepsilon)$, where H is some characteristic size of the system. In terms of the ordinary leaky box model applied to the Galaxy, H denotes the half-width of the galactic halo (1–4 pc), while H is the half-size of the local bubble (~100 pc) in the context of the CG + B model [15, 16]. Since λ_{esc} is identical in both cases, the expected size of the bubble is much less than that of the halo, and ρ inside the bulb is assumed to be much lower than the average density in the Galaxy [15, 16], then CG + B model predicts diffusion coefficient to be much lower (by two–tree orders of magnitude and even lower) than the commonly accepted value.

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