Upturn in the ratios of nuclei of Z=16-24 to iron as observed in the ATIC experiment above 50 GeV/n

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Abstract: The ratios of heavy nuclei from sulfur (Z=16) to chromium (Z=24) fluxes to the flux of iron nuclei were measured recently in the ATIC-2 experiment [1]. These ratios are the decreasing functions of energy from 5 GeV/n to approximately 50 GeV/n as expected. However, an unexpected sharp upturn in the ratios is observed at energies ~ 50 GeV/n. In this paper, we revise the data and show that the statistical confidence of the observed upturn in ATIC data is 99.7%. A possible cause of the upturn is discussed and it is demonstrated that it can be explained within a model of 'closed galaxy with an embedded Local Bubble'. It is shown that a universal upturn at energies 200-300 GeV/n in the spectra of abundant even primary nuclei observed previously in the ATIC, CREAM and PAMELA experiments is also predicted by this model.

Keywords: secondary nuclei, primary nuclei, iron, ratio, escape length, statistical significance, super-bubbles

1 Introduction

It is generally accepted that the ratio of fluxes of secondary cosmic ray nuclei to the fluxes of corresponding parent primary nuclei is a decreasing function of energy. It is a very general consequence of the galaxy diffusion escape length decrease with higher energies. This expectation was confirmed very well for the energies up to several tens of GeV in HEAO-3-C2 [2], HEAO-3-C3 [3], CRN [4] and some other experiments. However, an unexpected upturn was observed in the Ti/Fe ratio data in ATIC-2 experiment [5] near the energy of 50–70 GeV/n in spite of the fact that titanium is mainly secondary nucleus produced by iron spallation. The statistics above 100 GeV/n was low in [5] and this upturn was not recognized as a real phenomenon. Later, in a new ATIC's paper [1] this upturn was confirmed with a higher statistics for the ratio of spectrum (in terms of the energy per nucleon) for charges $H^- = (16 \leq Z \leq 24)$ (see Fig. 1) to the spectrum of iron. As the fraction of secondary nuclei in the charge region H^- is expected to be high, some decreasing function for the H^-/Fe ratio should be observed, but the data are in a sharp contradiction with these expectations (see Fig. 2). It was argued in [1] that the observed upturn could not be due to a systematic error, but a statistical significance of the phenomenon was not addressed in there. In this paper we evaluate the statistical significance of the phenomenon and discuss a possiblle explanation.

2 The statistical significance of the upturn

As can be seen in Fig. 2 an upturn occures at energy ≈ 50 GeV/n. We will test the hypothesis that five last points in Fig. 2, starting with 50 GeV/n, represent an increasing function of energy. Such a hypothesis means exactly that there is an upturn in the graph in upward direction with a positive derivative.

A simple idea as to fit a straight line to the last five points in Fig. 2 and to investigate the sign of its slope proves to be misleading. The problem lies in the statistical properties of data points. Each point in the graph is obtained as a ratio of the two Poisson's random integer numbers. The denominator may take a zero value with a finite

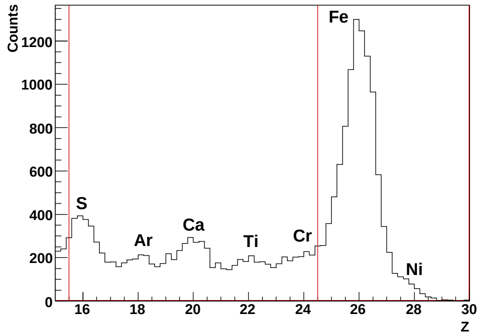

Figure 1: A fragment of charge spectrum as measured by ATIC spectrometer for $E > 60$ GeV per particle. The charge region between two vertical red solid lines corresponds to H^- region (see the text).

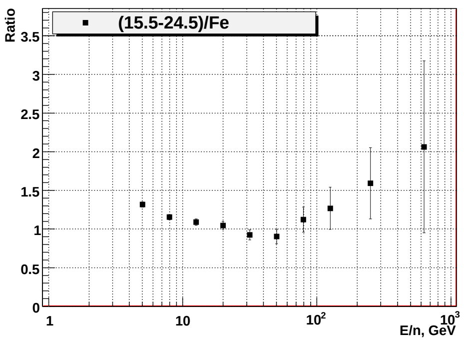

Figure 2: Ratio of heavy nuclei spectrum to iron, H^-/Fe, measured in ATIC experiment [1].

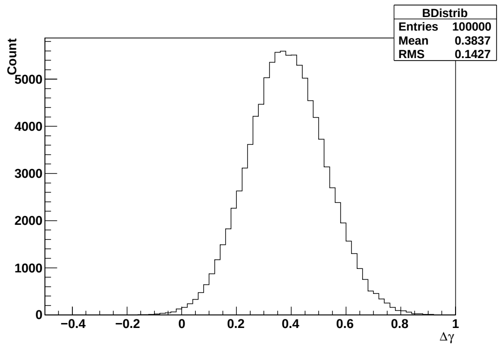

Figure 3: The probability distribution of $\Delta\gamma = \gamma_R - \gamma_L$, corresponding to Fig. 2.

and not really insignificant probability. In such a case the ratio has no meaning, and, therefore, the ratio of two Poisson's random numbers, strictly speaking, has no statistical distribution at all. Consequently, we should reformulate the problem in meaningful manner.

To do this, we shall consider separately the initial energy spectra that produce the ratio in Fig. 2 in the energy region corresponding the last five points. We approximate each initial differential spectrum by power-law functions like $AE^{-(\gamma+1)}$. Let the power index of the spectrum of the ratio numerator be γ_L (L means 'left', since the spectrum of nominator is related to the charges located in the left part in Fig. 1); and the index of the denominator spectrum be γ_R (R means 'right'). Then the condition $\gamma_R - \gamma_L > 0$ means exactly that the ratio of L to R spectra is an increasing function and this is a hypothesis that could be tested meaningfully.

We apply a maximum likelihood method for Poisson statistics in energy bins of a spectrum to obtain the spectral index. If a differential spectrum is $AE^{-(\gamma+1)}$, then for expected values S_i in the logarithmically-equidistant bins of the spectrum we have

$$S_i = BE_i^{-\gamma}, \tag{1}$$

where B is some constant. Taking S_i to be the mean values of Poisson random numbers, it is not difficult to obtain the likelihood function to fit B and γ from the equation (1):

$$F(B,\gamma) = \sum_i [BE_i^{-\gamma} - n_i \ln(BE_i^{-\gamma})], \tag{2}$$

where n_i is an experimental number of events in the energy bin with number i. Both parameters B and γ are included into function F in an essentially no-linear way and, therefore, we use standard general numerical methods for the minimization of likelihood function.

To estimate the statistical significance of the upturn we proceed in the following way. Each of the initial experimental spectra (L and R) is approximated by the power-law functions (1) using the likelihood method (2). The expectation values S_i are obtained for each energy bin of spectra L and R, and a sequence of pairs of L-like and R-like spectra is generated with Monte Carlo method . Each pair of spectra is processed with the same method as an experimental pair of spectra L and R, and the probability distribution for $\gamma_R - \gamma_L$ difference is build on. The distribution for 10^5 Monte Carlo simulations is shown in Fig. 3.

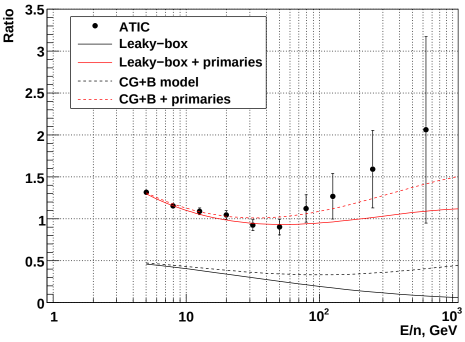

Figure 5: Ratio H^-/Fe measured by ATIC and a number of models (CG+B means Closed Galaxy with Bubbles, see the text).

The probability for the difference $\gamma_R - \gamma_L$ to be positive is exactly the statistical significance of the existence of the upturn in upward direction in H^-/Fe ratio, see Fig. 2, above 50 GeV/n. The probability value obtained with the distribution in Fig. 3 is 0.997 and this is high enough to consider the phenomenon seriously.

3 To the interpretation of the upturn in heavy to iron nuclei ratios: a simple leaky-box model

To describe the transport of particles in Galaxy it is suitable to start with a simple leaky-box approximation. Let $N_1, N_2, \ldots, N_k$ be the secondary nuclei produced by iron spallation. Then the ratio of a combined flux of the secondaries $I_{\Sigma S} = \sum_{i=1}^{k} I_{N_i}$ to the flux of iron nuclei can be written as

$$\frac{I_{\Sigma S}}{I_{\mathrm{Fe}}} = \sum_{i=1}^{k} \frac{\kappa_{N_i,\mathrm{Fe}}}{\kappa_{\mathrm{esc}}^{N_i}(\varepsilon) + \kappa_{N_i}}, \tag{3}$$

where ε is the energy of particle per nucleon, $\kappa_{\mathrm{esc}}^{N_i} = 1/\lambda_{\mathrm{esc}}^{N_i}$ is the inverse diffusion escape length for the leakage of nuclei N_i with energy ε from the galaxy, $\kappa_{N_i} = 1/\lambda_{N_i}$ is the inverse nuclear spallation path length in the inter-stellar medium for the nuclei N_i, $\kappa_{N_i,\mathrm{Fe}} = 1/\lambda_{N_i,\mathrm{Fe}}$ is the inverse partial spallation path-length of iron nucleus to produce a nucleus N_i. The escape length λ_{esc} is considered to be a universal function of rigidity for all nuclei and we choose an approximation from [2]: $\lambda_{\mathrm{esc}}(R) = 34.1R^{-0.6}\,\mathrm{g/cm^2}$. We use the values of λ_{N_i} as compiled in Ginzburg and Syrovatskii [6], and evaluate the partial path lengths $\lambda_{N_i,\mathrm{Fe}}$ with help of the partial spallation cross sections as given in [7], and under assumption of 90% protons and 10% helium in the interstellar medium.

The ratio H^-/Fe in the ATIC experiment together with a simple leaky-box model prediction (solid black lines) for the secondary fluxes calculated with formula (3) are shown in Fig. 5. The leaky-box model (3) accounts for only secondary nuclei in the region H^- and predicts lower ratio H^-/Fe for energies below 50 GeV/n than in the ATIC data. It is a sign of some contribution of primary fluxes to the group H^-. It is quite an expected result, since a prominent contribution of the primary fluxes to S, Ar, Ca is generally supposed. Obviously, a leaky-box model does not reproduce increasing ratios at energies above 50 GeV/n.

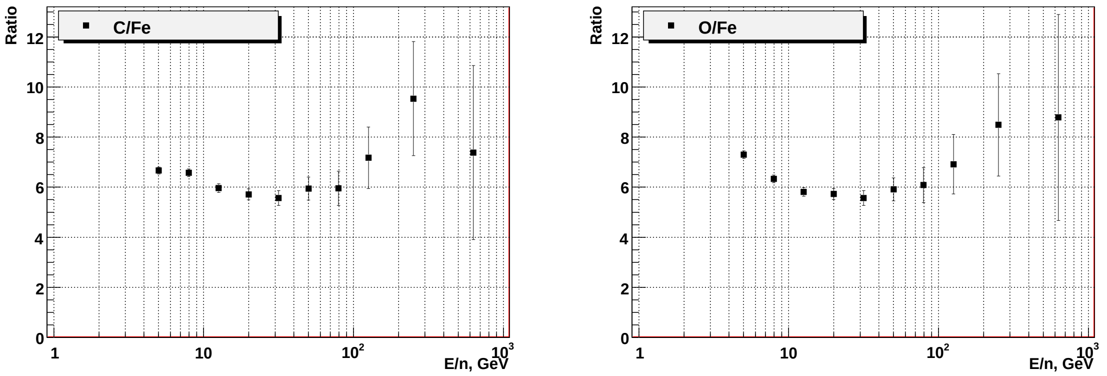

Figure 4: Ratio of carbon and oxygen fluxes to the flux of iron measured by the ATIC-2 experiment [1].

To improve a simple model (3) we should incorporate the primary component to the group H^-. The simplest way is to suppose that all primary nuclei obey the same power-law spectrum in the source. But that is an oversimplification. It was shown in [1] that the spectra of all abundant primary nuclei C, O, Ne, Mg, Si, being very similar to each other, show, however, a certain upturn in their ratio to the iron, similar to the upturn in H^-/Fe (but with a lower amplitude). The ratios of C/Fe and O/Fe fluxes are shown in Fig. 4. It means that the source spectrum of iron is not similar to the source spectra of other heavy abundant nuclei.

Let us suppose that not only the abundant primary nuclei C, O, Ne, Mg, Si possess similar source spectra, but the same is valid for all primaries within the group H^-. Then one can fit the H^-/Fe ratio with the sum of the secondary fluxes given by leaky-box model (3) and a flux of primaries with the source spectrum of, for example, oxygen nuclei. The result is shown in Fig. 5 with the red solid line. There is a reasonable fit to the data at energies $\varepsilon < 50$ GeV/n, but there is no sufficient increase in the ratio at energies $\varepsilon \gtrsim 50$ GeV/n.

4 Model of closed galaxy with super-bubbles

Thus, a simple leaky-box model with an addition of primary fluxes does not reproduce the data. Some extra ideas are wanted to account for a sharp upturn of the H^-/Fe ratio. We consider below, as a possibility, a model of a 'closed galaxy' proposed in [8]. It is supposed in this model, that there are a number of compact regions in the galaxy that contain CR sources and can be described by a simple leaky-box model in relation to the diffusion leakage of particles from the region. Moreover, it is assumed that all the CR sources are concentrated in such local areas. In the original paper [8] it was proposed that these compact regions were the galaxy arms, but they can be as well super-bubbles produced by supernova explosions. The last opportunity looks reasonable if the supernovas explode preferably within star associations where a star formation process occurred shortly before and massive, short-living stars were created. The idea that super-bubbles can play an important role in forming the cosmic rays spectra was widely discussed (see [9, 10] and references herein). The exact nature of these local regions does not matter very much for our model, but for definiteness we will consider the super-bubbles and call the model a 'closed galaxy with bubbles' (CG+B). The second assumption of the model is that the entire galaxy is closed in relation to the diffusion leakage. And it is accepted that the Sun is located within one of the bubbles, a Local Bubble, and our purpose is to predict the CR fluxes within the Local Bubble.

A total CR flux in a bubble is, then, comprised of two parts [8]: 1) a local flux which can be described by the usual leaky-box model when applied to the bubble and 2) a global equilibrium galaxy flux (hereinafter we call it a 'bulk flux'), which can also be described by a model similar to the leaky-box model applied to the entire galaxy, but with an additional condition of $\lambda_{\rm esc}(\varepsilon) \simeq \infty$. The last condition means actually that the diffusion length is much longer than all nuclear spallation lengths under interest and for the considered energies. This condition, of course, can not be valid for all energies. There is one free parameter in our model that represents the fraction of the bulk flux in the total flux within a bubble, that is unknown apriory and is to be fitted to the data.

The only sources of CR for the bulk flux within a frameworks of CG+B model are the surfaces of the bubbles. With a standard assumption that the probability for a particle to leave a volume does not depend on the already travelled path within the volume one can obtain the equation for a modified bulk source:

$$Q_{\rm bulk}(\varepsilon) = \frac{\kappa_{\rm esc}(\varepsilon)}{\kappa_{\rm esc}(\varepsilon)+\kappa}\, Q(\varepsilon). \tag{4}$$

Here $Q(\varepsilon)$ is the spectrum of some nucleus in the source within a bubble, $\kappa_{\rm esc}(\varepsilon)$ is the inverse escape length for the nucleus from a bubble, and κ is the inverse nuclear interaction length for this nucleus. Using equation (4) and a standard formula of leaky-box approximation when applied to the bubble and to the galaxy, one can obtain the ratio of total flux of a secondary nuclei N_i to the flux of iron in CG+B model, as:

$$\frac{I_{N_i}(\varepsilon)}{I_{\rm Fe}(\varepsilon)} = \frac{\dfrac{\kappa_{N_i,{\rm Fe}}}{\kappa^{N_i}_{\rm esc}(\varepsilon)+\kappa_{N_i}} + K\,\dfrac{\kappa_{N_i,{\rm Fe}}}{\kappa_{N_i}}\;\dfrac{\kappa^{\rm Fe}_{\rm esc}(\varepsilon)}{\kappa_{\rm Fe}}}{1+K\,\dfrac{\kappa^{\rm Fe}_{\rm esc}(\varepsilon)}{\kappa_{\rm Fe}}}, \tag{5}$$

where K describes the contribution of the bulk flux to the total one. For the flux of some group of nuclei we shall do a summation over index i in equation (5).

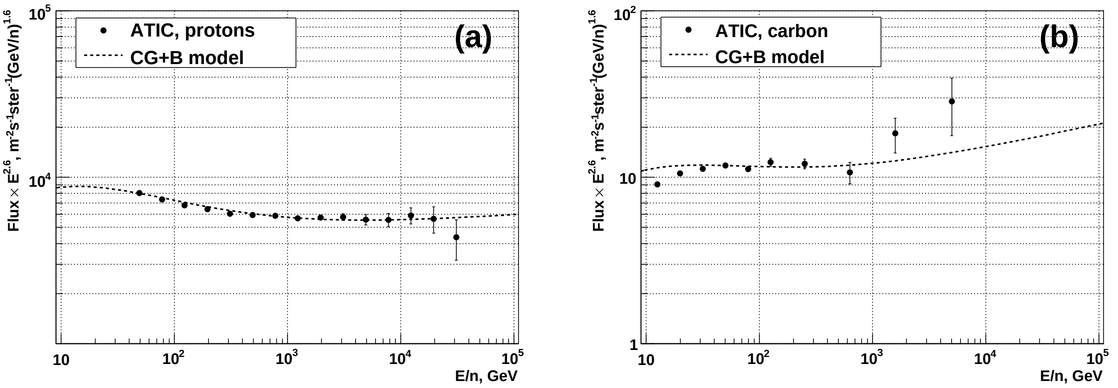

Figure 6: Fit of abundant nuclei spectra measured by ATIC-2 with the CG+B model: (a): protons, $\alpha_{\text{source}} = 2.55$; (b); carbon, $\alpha_{\text{source}} = 2.45$.

The predictions of CG+B model for the fluxes of secondaries in the group H^- with $K = 0.2$ are shown in Fig. 5 by dashed black line. The complicated behavior of the model with its decreasing and increasing regions of ratios is a result of competition between the local and bulk fluxes. The dashed red line shows the CG+B model prediction together with the contribution of primary fluxes, exactly in the same way as it was done for the simple leaky-box models (solid red line, Fig. 5). It is seen that CG+B model together with the contribution of primary fluxes agrees reasonably well with the data.

Interestingly, some other features of the primary abundant nuclei spectra can also be understood within CG+B model. The appropriate fits to the proton and carbon ATIC's spectra with the CG+B model are shown in Fig. 6(a) and Fig. 6(b), respectively; and we choose the source spectral indexes $\alpha(\text{protons}) = 2.55$ and $\alpha(\text{carbon}) = 2.45$ to fit the data. These are very soft primary spectra and it can mean a problem for the CG+B model. However, an advantage of the model is in the prediction of universal hardening of the spectra of abundant nuclei near 200–300 GeV/n similar to that discovered by ATIC [11] and confirmed by CREAM [12] and PAMELA [13], without a hypothesis of some additional special CR source with a soft spectrum.

There is one important physical consequence of the CG+B model. If one consider the leakage from the Local Bubble in the diffusion approximation, the diffusion coefficient can be estimated as [14, p. 124]: $D(\varepsilon) \sim \rho c H^2/\lambda_{\text{esc}}(\varepsilon)$, where H is some characteristic size of the system. In the case of leakage from the Galaxy, H means the half-width of the Galaxy halo $\sim$ 4 kpc, but in the context of CG+B model, H means the half-size of the Local Bubble ($\sim$ 100 pc [15, 16]). Since λ_{esc} (in g/cm^2) is the same in both cases, and the half-size of the Local bubble is much smaller than the half-width of the halo, and the gas density within the bubble is expected to be much less than the mean density in the Galaxy [15, 16], then, the CG+B model predicts the diffusion coefficient value much smaller ($\sim$3 orders of magnitude or even more) than normally accepted one. This estimate implies a free escape of particles from the border of the bubble, but this inference can be invalid. An alternative explanation of the confinement of cosmic rays in the Local Bubble is in the reflection of charged particles by the termination shock of the bubble [10]. This explanation looks preferable, since a predicted diffusion coefficient for a 'homogeneous diffusion' is unexpectedly low.

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