Bayesian Analysis of the Hardening in AMS-02 Nuclei Spectra

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Abstract

Based on the precise nuclei data released by AMS-02, we study the spectra hardening of both the primary (proton, helium, carbon, oxygen, and the primary component of nitrogen) and the secondary (anti-proton, lithium, beryllium, boron, and the secondary component of nitrogen) cosmic-ray (CR) nuclei. With the diffusion-reacceleration model, we consider two schemes to reproduce the hardening in the spectra: (i) a high-rigidity break in primary source injection; and (ii) a high-rigidity break in diffusion coefficient. The global fitting results show that both schemes could reproduce the spectra hardening in the current status. More precise multi-TV data (especially the data of secondary CR species) is needed if one wants to distinguish these two schemes. In our global fitting, each of the nuclei species is allocated an independent solar-modulation potential and a rescale factor (which accounts for the isotopic abundance for primary nuclei species and uncertainties of production cross section or inhomogeneity of CR sources and propagation for secondary nuclei species). The fitting values of these two parameter classes show us some hints on some new directions in CR physics. All the fitted rescale factors of primary nuclei species have values that are systematically smaller than 1.0, while that of secondary nuclei species are systematically larger than 1.0. Moreover, both the resale factor and solar-modulation potential of beryllium have values that are obviously different from other species. This might indicate that beryllium has the specificity not only on its propagation in the heliosphere, but also on its production cross section. All these new results should be seriously studied in the future.

Key words: acceleration of particles – cosmic rays

1. Introduction

Understanding the spectral features in cosmic rays (CRs) is of fundamental importance for understanding their origin and propagation. Great progress in CR spectrum measurement has been made in recent years with a new generation of space-borne and ground-based experiments in operation. The fine structure of spectral hardening for primary nuclei at ∼300 GV was observed by ATIC-2 (Panov et al. 2006), CREAM (Ahn et al. 2010), PAMELA (Adriani et al. 2011), and AMS-02 (Aguilar et al. 2015a, 2015b).

Recently, AMS-02 has released the energy spectra of He, C, and O (Aguilar et al. 2017), which confirmed the spectral hardening of CR primary nuclei. Moreover, the subsequently released energy spectra of Li, Be, and B (Aguilar et al. 2018b) show that the secondary nuclei spectra harden even more than that of the primary ones at a few hundred GV. After that, the released nitrogen spectrum (Aguilar et al. 2018a; which is made up of both primary and secondary components) shows that the spectral index rapidly hardens at high rigidities and becomes identical to the spectral indices of primary He, C, and O CRs above ∼700 GV. Because the secondary CR particles are produced in collisions of primary CR particles with interstellar medium (ISM), combining these data together would provide us an excellent opportunity to study the hardening of the CR nuclei spectra quantitatively.

Some previous works have proposed different solutions to this problem: (i) adding a new break in the high-energy region (∼300 GV) to the injection spectra (see, e.g., Korsmeier & Cuoco 2016; Boschini et al. 2017; Niu et al. 2018, 2019; Zhu et al. 2018); (ii) adding a new high-rigidity break to the diffusion coefficient (see, e.g., Génolini et al. 2017); (iii) inhomogeneous diffusion (see, e.g., Blasi et al. 2012; Tomassetti 2012, 2015a, 2015b; Feng et al. 2016; Guo & Yuan 2018); and (iv) the superposition of local and distant sources (see, e.g., Vladimir et al. 2012; Bernard et al. 2013; Thoudam & Hörandel 2013; Kachelrieß et al. 2015; Tomassetti & Donato 2015; Kawanaka & Yanagita 2018).

In this work, we perform a global fitting on these primary and secondary nuclei spectra from AMS-02. Two schemes are considered: (i) the hardening of the observed spectra comes from the sources (the breaks are already present in the spectra after the CR particles accelerated at the sources)—a new high-rigidity break is added in the primary source injections (Scheme I); and (ii) the hardening of the observed spectra comes from the propagation—a new high-rigidity break is added in the diffusion coefficient (Scheme II). We hope that the precise spectra data from AMS-02 would give us a clear result, at least a tendency.

The paper is organized as follows. We first list the setups in Section 2. The fitting results are given in Section 3. Then we give a test of the best-fit results in Section 4 and present some discussions and conclusions in Section 5.

2. Setups

In this section, we list some of the most important setups in this work, more detailed similar configurations could be found in Niu & Li (2018), and some important differences are listed and discussed in Section 2.3.

2.1. Model

As the setup in our previous work (Niu & Li 2018; Niu et al. 2018), we use independent primary source spectra settings for
proton and other nuclei species because of the significant difference observed in the slopes of proton and other nuclei species when $Z > 1$ (Aguilar et al. 2015a, 2015b, 2017). Moreover, in our calculation, a cylindrically symmetric geometry is assumed to describe the CR propagation in the galaxy, with a fixed maximum radius $r = 20$ kpc.

2.1.1. Propagation Model

We consider the diffusion-reacceleration (DR) model in the global fitting, which is widely used and consistent with the AMS-02 nuclei data (see, e.g., Yuan et al. 2017, 2018; Niu & Li 2018). $v_A$ is used to characterize the reacceleration, and $\zeta_b$ represents the half-height of the propagation region in the galaxy for the cylindrical coordinate system. In the whole propagation region, a uniform diffusion coefficient is used that depends on CR particles’ rigidity.

In Scheme I, the diffusion coefficient is parameterized as

$$D_{\alpha\alpha}(R) = D_0 \beta \left( \frac{R}{R_0} \right)^6,$$

where $\beta$ is the velocity of the particle in units of light speed $c$, $R_0$ is the reference rigidity (4 GV), and $R = pc/Ze$ is the rigidity.

For Scheme II, the diffusion coefficient is parameterized as

$$D_{\alpha\alpha}(R) = D_0 \cdot \beta \left( \frac{R_{br}}{R_0} \right) \times \begin{cases} \left( \frac{R}{R_{br}} \right)^{\delta_1} & R \leq R_{br} \\ \left( \frac{R}{R_{br}} \right)^{\delta_2} & R > R_{br} \end{cases}$$

where $R_{br}$ is the high-rigidity break, $\delta_1$ and $\delta_2$ are the diffusion slopes below and above the break.

2.1.2. Primary Sources

The primary source injection spectra of all kinds of nuclei are assumed to be a broken power law form. In Scheme I, it is represented as:

$$q_i = N_i \times \begin{cases} \left( \frac{R}{R_{A1}} \right)^{-\nu_{A1}} & R \leq R_{A1} \\ \left( \frac{R}{R_{A1}} \right)^{-\nu_{A2}} & R_{A1} < R \leq R_{A2} \\ \left( \frac{R}{R_{A2}} \right)^{-\nu_{A2}} \left( \frac{R_{A2}}{R_{A1}} \right)^{-\nu_{A3}} & R > R_{A2} \end{cases}$$

where $i$ denotes the species of nuclei, $N_i$ is the normalization constant proportional to the relative abundance of the corresponding nuclei, and $\nu_A = \nu_{A1}(\nu_{A2}, \nu_{A3})$ for the nucleus rigidity $R$ in the region divided by 2 breaks at the reference rigidity $R_{A1}$ and $R_{A2}$. In this work, we use an independent proton injection spectrum, and the corresponding parameters are $R_{p1}, R_{p2}, \nu_{p1}, \nu_{p2}, \nu_{p3}$. All the $Z > 1$ nuclei are assumed to have the same value of injection parameters.

For Scheme II, we have

$$q_i = N_i \times \begin{cases} \left( \frac{R}{R_A} \right)^{-\nu_{A1}} & R \leq R_A \\ \left( \frac{R}{R_A} \right)^{-\nu_{A2}} & R > R_A \end{cases}$$

which are described by one break at the rigidity $R_A$ and two slopes below ($\nu_{A1}$ or $\nu_{p1}$) and above ($\nu_{A2}$ or $\nu_{p2}$).

2.1.3. Solar Modulation

We adopt the force-field approximation (Gleeson & Axford 1968) to describe the effects of solar modulation in the solar system, which contains only one parameter: the so-called solar-modulation potential $\phi$. Considering the charge- and suspected nuclei species dependence of the solar modulation that is represented in the previous fitting (Niu & Li 2018), we adopt $\phi_p, \phi_{He}, \phi_{C}, \phi_{O}, \phi_{Be}, \phi_{N}, \phi_{Li}, \phi_{B}$ to modulate the proton, He, C, O, Li, Be, and B nuclei data, respectively. This would give us the limitation of force-field approximation as a simple and effective theory to describe the solar modulation on local interstellar spectra (LIS). Moreover, it would show us the differences of the propagation between different nuclei species in the heliosphere.

2.1.4. Numerical Tools

The public code GALPROP v56 (Strong & Moskalenko 1998, 2001; Moskalenko et al. 2002, 2003; Puskin et al. 2006) is used to solve the diffusion equation numerically. In GALPROP, the primary source (injection) isotopic abundances are determined by fitting to the data from $ACE$ at $\sim 200$ MeV/nucleon assuming a propagation model (Wiedenbeck et al. 2001, 2008). This configuration appears to have some discrepancies when fit to some new data covering high-energy regions (Johannesson et al. 2016). As a result, we use factors $c_{He}^{p}, c_{C}^{p},$ and $c_{O}^{p}$ to rescale the helium-4 (with a default abundance of $7.199 \times 10^4$), carbon-12 (with a default abundance of $2.819 \times 10^6$), and oxygen-16 (with a default abundance of $3.822 \times 10^5$) abundances. At the same time, $c_{p}^{c}, c_{Li}^{c}, c_{Be}^{c},$ and $c_{He}^{c}$ are employed to rescale the secondary CR nuclei species ($p$, Li, Be, and B). On the one hand, these values could partially account for the production cross section uncertainties of these species (like that for $p$ in Niu & Li 2018). On the other hand, these values could also partially account for the local inhomogeneity of the CR sources and propagation. Here, we expect that a constant factor is a simple assumption, which would help us to get a better fitting result.

2.1.5. ISM Density and Distribution

The ISM density and distribution is important in production of secondary CR species and energy losses. In GALPROP v56, it consists of two different ISM components (hydrogen and helium). The ratio of the number density between helium and hydrogen is set to 0.11, and helium is assumed to be distributed like hydrogen.

\[ \text{http://galprop.stanford.edu} \]

\[ ^5\text{In GALPROP, the abundance of proton is fixed to } 10^6. \text{ All the other primary nuclei abundances are set to be a value that is relative to the proton abundance.} \]
For hydrogen, it contains three different gas components with distinctly different distributions. The H2 gas number density\(^7\) is defined in the form of Tables 3 and 4 in Bronfman et al. (1988), which is parameterized as \(N_{H_2}/c_{CO} = 10^{20} \times 10^{a+bR} \text{ cm}^{-2}/(\text{K km s}^{-1})\), where \(R\) is the distance to the galactic center, \(c_{CO}\) is the CO volume emissivity, \(a = -0.4\), and \(b = 0.066\). The H1 gas number density in the Galactic plane is defined by a table in Gordon & Burton (1976), which is renormalized to agree with the total integral perpendicular to the plane by Dickey & Lockman (1990).

The \(z\)-dependence is calculated by the approximation from Dickey & Lockman (1990) for \(R < 8\) kpc, by the approximation from Cox et al. (1986) for \(R > 10\) kpc, and interpolated in between them. The ionized component H II (atom cm\(^{-3}\)) is calculated using a cylindrically symmetrical model (Cordes et al. 1991), and more details can be found in Moskalenko et al. (2002).

The relevant parameters and their values in the GALDEF file are listed as follows:\(^8\):

1. \(\text{He/H ratio} = 0.11\).
2. \(n_{X_{CO}} = 10\).
3. \(n_{HI\_model} = 2\).
4. \(n_{H2\_model} = 2\).
5. \(n_{HII\_model} = 1\).

### 2.2. Data Sets and Parameters

In this work, the proton flux (from AMS-02 and CREAM Ahn et al. 2010; Aguilar et al. 2015a), helium flux (from AMS-02 and CREAM Ahn et al. 2010; Aguilar et al. 2017), carbon flux (from AMS-02 Aguilar et al. 2017), oxygen flux (from AMS-02 Aguilar et al. 2017), anti-proton flux (from AMS-02 Aguilar et al. 2016), lithium flux (from AMS-02 Aguilar et al. 2018b), beryllium flux (from AMS-02 Aguilar et al. 2018b), and boron flux (from AMS-02 Aguilar et al. 2018b) are added in the global fitting data set. The CREAM data is used as the supplement of the AMS-02 data because it is more compatible with the AMS-02 data when \(R \gtrsim 1\) TV. The errors used in our global fitting are the quadratic sum of statistical and systematic errors.

Altogether, the data set in our global fitting is

\[
D = \{D_{p_{AMS-02}}, D_{He_{AMS-02}}, D_{C_{AMS-02}}, D_{O_{AMS-02}}, D_{Li_{AMS-02}}, D_{Be_{AMS-02}}, D_B_{AMS-02}, D_B^{CREAM}, D_{He}^{CREAM}\}.
\]

The parameter sets for Scheme I is

\[
\theta_1 = \{D_0, \delta, \zeta, \nu_{he}, \nu_{li}, \nu_{be}, \nu_{o}\}.
\]

\[
R_{p1}, R_{p2}, R_{p3}, R_{a1}, R_{a2}, R_{a3}, N_{p}, \phi_{he}, \phi_{li}, \phi_{be}, \phi_{o}, \phi_{p1}, \phi_{p2}, \phi_{p3}, N_{p1}, N_{p2}, N_{p3}, \phi_{p1}, \phi_{p2}, \phi_{p3}\}
\]

for Scheme II is

\[
\theta_2 = \{D_0, \delta, \zeta, \nu_{he}, \nu_{li}, \nu_{be}, \nu_{o}\}.
\]

\[
R_{p1}, R_{p2}, R_{p3}, R_{a1}, R_{a2}, R_{a3}, N_{p}, \phi_{he}, \phi_{li}, \phi_{be}, \phi_{o}, \phi_{p1}, \phi_{p2}, \phi_{p3}\}
\]

These parameters can be separated into four classes: the propagation parameters, the primary source injection parameters, the normalization parameters,\(^9\) and the solar-modulation potentials. Their priors are chosen to be uniform distributions with the prior intervals given in Tables 2 and 3.

### 2.3. Comparing with Previous Work

Compared with our previous work (Niu & Li 2018), we list some of the most important updates as follows:

(i) Because we have proved that the DR model is good enough to reproduce current AMS-02 nuclei spectra (proton, helium, B/C, and \(p/p\)), we use it as the unique propagation model in this work, and do not consider other models.

\[\text{Notes.}\]

\(^7\) Here, the H2 gas is traced by the distribution of CO.

\(^8\) Please note that all these keys and values correspond to GALPROP v56.

\(^9\) This class includes the normalization parameters of proton (\(N_p\)) and the \(c_{SS}\) (which are called rescale factors hereinafter).
Figure 1. Global fitting results and the corresponding residuals to the primary nuclei flux (proton flux, helium flux, carbon flux, and oxygen flux) for two schemes. The $2\sigma$ (deep red) and $3\sigma$ (light red) bounds are also shown in the figures. The relevant $\chi^2$ of each nuclei species is given in the subfigures as well.
Figure 2. Global fitting results and the corresponding residuals to the secondary nuclei flux (anti-proton flux, lithium flux, beryllium flux, and boron flux) for two schemes. The 2σ (deep red) and 3σ (light red) bounds are also shown in the figures. The relevant χ² of each nuclei species is given in the subfigures as well.
Table 2

Constraints on the Parameters in Set \( \theta_1 \)

| ID | Prior Range | Best-fit Value | Posterior Mean and Standard Deviation | Posterior 95% Range |
|----|-------------|----------------|---------------------------------------|---------------------|
| \( D_0 (10^{28} \text{ cm}^{-2} \text{s}^{-1}) \) | [1, 30] | 18.36 | 17.69 ± 1.96 | [14.58, 20.97] |
| \( \beta \) | [0.1, 1.0] | 0.284 | 0.284 ± 0.005 | [0.277, 0.293] |
| \( z_0 \) (kpc) | [0.5, 30.0] | 11.30 | 10.32 ± 1.43 | [7.85, 12.31] |
| \( v_0 \) (km s\(^{-1}\)) | [0, 80] | 56.89 | 57.74 ± 2.76 | [53.39, 62.31] |
| \( R_{p1} \) (GV) | [1, 30] | 24.61 | 24.13 ± 1.38 | [21.48, 26.28] |
| \( R_{p2} \) (GV) | [60, 1000] | 528.31 | 673.70 ± 125.00 | [484.97, 893.13] |
| \( \nu_{i1} \) | [1.0, 4.0] | 2.177 | 2.172 ± 0.015 | [2.145, 2.196] |
| \( \nu_{i2} \) | [1.0, 4.0] | 2.474 | 2.474 ± 0.007 | [2.463, 2.485] |
| \( \nu_{i3} \) | [1.0, 4.0] | 2.367 | 2.352 ± 0.015 | [2.326, 2.375] |
| \( R_{i1} \) (GV) | [1, 30] | 22.23 | 21.47 ± 1.06 | [19.91, 23.43] |
| \( R_{i2} \) (GV) | [60, 1000] | 540.03 | 504.07 ± 68.20 | [400.28, 622.79] |
| \( \nu_{i1} \) | [1.0, 4.0] | 2.096 | 2.082 ± 0.015 | [2.056, 2.107] |
| \( \nu_{i2} \) | [1.0, 4.0] | 2.411 | 2.409 ± 0.006 | [2.401, 2.420] |
| \( \nu_{i3} \) | [1.0, 4.0] | 2.252 | 2.259 ± 0.015 | [2.233, 2.283] |
| \( N_B \) | [1, 8] | 4.45 | 4.45 ± 0.02 | [4.42, 4.48] |
| \( \phi_{B} \) (GV) | [0.1, 5.0] | 0.643 | 0.645 ± 0.004 | [0.638, 0.652] |
| \( \phi_{B} \) (GV) | [0.1, 5.0] | 0.551 | 0.553 ± 0.005 | [0.545, 0.561] |
| \( \phi_{B} \) (GV) | [0.1, 5.0] | 0.504 | 0.504 ± 0.008 | [0.492, 0.518] |
| \( \phi_{B} \) (GV) | [0.1, 5.0] | 1.72 | 1.74 ± 0.10 | [1.58, 1.91] |
| \( \phi_{Li} \) (GV) | [0.1, 5.0] | 1.43 | 1.44 ± 0.07 | [1.31, 1.57] |
| \( \phi_{Li} \) (GV) | [0.1, 5.0] | 1.70 | 1.72 ± 0.09 | [1.57, 1.87] |
| \( \phi_{Li} \) (GV) | [0.1, 5.0] | 1.10 | 1.11 ± 0.05 | [1.03, 1.19] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.70 | 0.70 ± 0.02 | [0.66, 0.74] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.61 | 0.60 ± 0.02 | [0.56, 0.64] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.72 | 0.71 ± 0.02 | [0.67, 0.75] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.74 | 0.72 ± 0.03 | [0.68, 0.76] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.008 | 0.02 ± 0.02 | [0.001, 0.054] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.65 | 0.62 ± 0.04 | [0.56, 0.69] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.27 | 0.27 ± 0.04 | [0.20, 0.33] |
| \( \phi_{B} \) (GV) | [0, 1.5] | 0.63 | 0.62 ± 0.04 | [0.56, 0.69] |

Note. The prior interval, best-fit value, statistic mean, standard deviation and the allowed range at 95% CL are listed for parameters. With \( \chi^2/\text{d.o.f} = 383.45/521 \) for best-fit result.

* Post-propagated normalization flux of protons at 100 GeV in unit \( 10^{-2} \text{ m}^{-2} \text{s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1} \).

(ii) In previous work, the rigidity of the data we used in our global fitting: for the primary CR nuclei spectra (proton and helium), \( \lesssim 3 \text{ TV} \); for the ratio of secondary to primary nuclei species (B/C and p/p), \( \lesssim 1 \text{ TV} \). Although we got a trend in the results that shows the hardening in the spectra of the primary CR nuclei, there are not enough data points in high-energy regions to do a quantitatively study on the spectra hardening. In this work, based on the primary CR nuclei spectra reaching up to 200 TV and the secondary CR nuclei spectra reaching up to 3 TV with multiple species, it is possible to study the hardening in these spectra efficiently. With the new data set, we add a new high-rigidity break in diffusion coefficient and primary source injection to account for the hardening of the spectra.

(iii) In previous work, we have shown that it is difficult to describe the solar-modulation effects on different CR species by using a single solar-modulation potential. Consequently, we assign an independent solar-modulation potential to each of the CR species in this work.

(iv) Benefited from the data set we used in this work (spectra other than ratios), we employ an independent rescale factor to each of the CR species. This provides us an opportunity to study the abundances of the primary sources and inhomogeneity of CR sources and propagation or production cross section of secondary CR species.

(v) In this work, we use an updated version of GALPROP (v56), which have added some new features and updated some of the cross section data in it (see more details in Moskalenko et al. 2017).

(vi) In previous work, we focus on the comparison between different propagation models and the constraints on some special parameters (\( D_0 \) and \( z_0 \)) by different data sets. In this work, we focus on the origin of the hardening in the spectra based on one data set.

All the differences discussed above are summarized in Table 1.

3. Fitting Results

As in our previous works (Niu et al. 2018, 2019; Niu & Li 2018), we use the Markov Chain Monte Carlo (MCMC) algorithm to determine the posterior probability distribution of
the parameters in Schemes I and II. We take the samples of the parameters as their posterior probability distribution function (PDF) after the Markov Chains have reached their equilibrium states. The best-fit results and the corresponding residuals of the primary nuclei flux for two schemes are given in Figure 1, and the corresponding results of the secondary nuclei flux are shown in Figure 2.\textsuperscript{10}

The best-fit values, statistical mean values, standard deviations, and allowed intervals at 95% CL, for the parameters in $\theta_1$ and $\theta_2$ are shown in Tables 2 and 3, respectively. For best-fit results of the global fitting, we got $\chi^2$/d.o.f = 383.45/521 for Scheme I and $\chi^2$/d.o.f = 395.48/524 for Scheme II.

Generally speaking, the largest differences in the fitting results between Schemes I and II come from the fitting results of proton flux (which have a $\Delta \chi^2 = 2 \chi^2_{\text{proton}} - \chi^2_{\text{proton}} \approx 12.6$) and helium flux (which have a $\Delta \chi^2 = \chi^2_{\text{He}} - \chi^2_{\text{He}} \approx 9.4$). This might come from the fact that, in Scheme I, we use independent

\textsuperscript{10} Considering the correlations between different parameters, we could not get a reasonable reduced $\chi^2$ for each part of the data set independently. As a result, we present the $\chi^2$ for each part of the data set in Figures 1 and 2.

breaks and slopes to describe the hardening in proton and other nuclei species. Whereas in Scheme II, this lead to $\chi^2_{\text{proton}} < \chi^2_{\text{proton}}$. At the same time, because the slopes in He, C, and O spectra have almost the same value, it is natural that the $\delta_2$ would be mainly determined by these nuclei species in the global fitting, which leads to a result of $\chi^2_{\text{He}} > \chi^2_{\text{He}}$.

In other cases, there are no obvious differences between the results of the two schemes. Moreover, we can see that in Figure 2, the predicted tendency of the secondary nuclei spectra is different between the two schemes. Scheme I predicts a softer spectra when compared with our previous work ($\delta > 1$ TV) than Scheme II. This would be tested by high-rigidity ($>1$ TV) secondary nuclei data released in the future.

### 3.1. Propagation Parameters

The results of posterior probability distributions of the propagation parameters are shown in Figure 3 (Scheme I) and Figure 4 (Scheme II).

The most obvious differences between the fitting results of the parameters in this work and some previous works (see, e.g., Yuan et al. 2017; Niu & Li 2018) are the values of $D_0$, $\delta_1$, and $\nu_A$. Compared with our previous work (Niu & Li 2018),

### Table 3

| ID          | Prior Range | Best-fit Value | Posterior Mean and Standard Deviation | Posterior 95% Range |
|-------------|-------------|----------------|--------------------------------------|---------------------|
| $D_0$ (10$^{28}$ cm$^2$ s$^{-1}$) | [1, 30] | 18.27 | 17.98 ± 1.22 | [15.98, 19.94] |
| $R_0$ (GV) | [200, 800] | 541.73 | 559.80 ± 73.35 | [455.97, 693.90] |
| $\delta_1$ | [0.1, 1.0] | 0.275 | 0.278 ± 0.005 | [0.269, 0.287] |
| $\delta_2$ | [0.1, 1.0] | 0.139 | 0.148 ± 0.013 | [0.127, 0.170] |
| $\nu_0$ (km s$^{-1}$) | [0.5, 30.0] | 8.53 | 8.50 ± 0.05 | [8.42, 8.58] |
| $\nu_0$ (km s$^{-1}$) | [0, 80] | 65.66 | 65.04 ± 3.80 | [59.01, 71.27] |
| $R_0$ (GV) | [1, 30] | 27.88 | 26.56 ± 1.83 | [23.87, 29.38] |
| $\nu_1$ | [1.0, 4.0] | 2.203 | 2.191 ± 0.016 | [2.163, 2.217] |
| $\nu_2$ | [1.0, 4.0] | 2.494 | 2.487 ± 0.007 | [2.475, 2.498] |
| $R_0$ (GV) | [1, 30] | 20.71 | 20.84 ± 0.79 | [19.63, 22.20] |
| $\nu_1$ | [1.0, 4.0] | 2.073 | 2.066 ± 0.014 | [2.042, 2.087] |
| $\nu_2$ | [1.0, 4.0] | 2.407 | 2.406 ± 0.006 | [2.397, 2.416] |
| $N_0$ | [1, 8] | 4.49 | 4.47 ± 0.02 | [4.43, 4.51] |
| $e_{\text{He}}$ | [0.1, 5.0] | 0.644 | 0.646 ± 0.004 | [0.639, 0.653] |
| $e_{\text{C}}$ | [0.1, 5.0] | 0.551 | 0.552 ± 0.005 | [0.545, 0.560] |
| $e_{\text{O}}$ | [0.1, 5.0] | 0.497 | 0.500 ± 0.007 | [0.489, 0.512] |
| $e_{\text{He}}$ | [0.1, 5.0] | 1.89 | 1.89 ± 0.11 | [1.70, 2.07] |
| $e_{\text{C}}$ | [0.1, 5.0] | 1.53 | 1.52 ± 0.08 | [1.39, 1.65] |
| $e_{\text{O}}$ | [0.1, 5.0] | 1.80 | 1.79 ± 0.08 | [1.65, 1.92] |
| $e_{\text{He}}$ | [0.1, 5.0] | 1.18 | 1.17 ± 0.06 | [1.08, 1.26] |
| $\phi_0$ (GV) | [0, 1.5] | 0.73 | 0.72 ± 0.03 | [0.67, 0.76] |
| $\phi_{\text{He}}$ (GV) | [0, 1.5] | 0.57 | 0.56 ± 0.02 | [0.52, 0.60] |
| $\phi_{\text{C}}$ (GV) | [0, 1.5] | 0.69 | 0.67 ± 0.03 | [0.63, 0.72] |
| $\phi_{\text{O}}$ (GV) | [0, 1.5] | 0.71 | 0.70 ± 0.03 | [0.65, 0.74] |
| $\phi_{\text{He}}$ (GV) | [0, 1.5] | 0.002 | 0.01 ± 0.01 | [0.0006, 0.0352] |
| $\phi_{\text{C}}$ (GV) | [0, 1.5] | 0.56 | 0.55 ± 0.04 | [0.48, 0.61] |
| $\phi_{\text{O}}$ (GV) | [0, 1.5] | 0.18 | 0.17 ± 0.04 | [0.10, 0.24] |
| $\phi_{\text{He}}$ (GV) | [0, 1.5] | 0.56 | 0.56 ± 0.04 | [0.49, 0.62] |

Note. The prior interval, best-fit value, statistic mean, standard deviation, and allowed range at 95% CL are listed for parameters. With $\chi^2$/d.o.f = 395.48/524 for the best-fit result.

\textsuperscript{a} Post-propagated normalization flux of protons at 100 GeV in units $10^{-2}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$.
$D_0$, $z_h$, and $v_A$ have relatively larger values here (especially in Scheme I), while $\delta$ have a smaller value in this work. In view of the data sets and parameter configuration (the hardening of the spectra have been fully considered), the results in this work should have a higher level of confidence.

In Scheme I, the $\delta$ value obtained is obviously smaller than that in our previous work (in which $\delta \simeq 3.5$–3.7; Niu & Li 2018). This is because the added breaks in the primary source injection of proton ($\sim$480–890 GV) and other primary nuclei species ($\sim$400–620 GV) could take charge of the observed hardening in their observed spectra, rather than using only one break in the source injection and letting the only $\delta$ compromise the different slopes in high-energy regions in Niu & Li (2018).

In Scheme II, we got a high-rigidity break at $\sim$(450–700) GV in the diffusion coefficient, and a slope $\delta_2 \sim (0.13–0.17)$ above the break. Although the value of $\delta_1$ is not in the same posterior distribution region as that in Génolini et al. (2017; which gave $\delta_1 \sim 0.5$–0.7), we got a similar value of $\Delta \delta = \delta_1 - \delta_2 \sim 0.14$. Considering the simplifications which have been made in Génolini et al. (2017) when they do the calculations, we could conclude that we get a consistent result compared with their work.

Moreover, is a high-rigidity break in diffusion coefficient needed in current AMS-02 nuclei data if we have already considered the high-rigidity break in primary source injection? Some conclusions are proposed in Yuan et al. (2018). It is $\delta$ value dependent. When $\delta \sim 0.3$, such a break is not needed; while $\delta \sim 0.5$–0.7, such a break is needed to reproduce current spectra data.

Another point that should be noted is that, in Scheme II, the uncertainty of $z_h$ could reach down to 0.05, which might be caused by the special configurations in this scheme (employing a break in diffusion coefficient to account for the hardening of all the primary and secondary spectra and not considering the differences between the spectra of proton and other species).

### 3.2. Primary Source Injection Parameters

The results of posterior probability distributions of the primary source injection parameters are presented in Figure 5 (Scheme I) and Figure 6 (Scheme II).

Same as our previous works (Niu & Li 2018; Niu et al. 2018), the rigidity breaks and slopes are obviously different between proton and other nuclei species in both schemes. Particularly, in Scheme I, the differences between the primary source injection high-rigidity slopes have values of $\nu_{p2} - \nu_{p3} \sim 0.1$ (for proton) and $\nu_{A2} - \nu_{A3} \sim 0.15$ (for other nuclei species). This indicates that if we want to ascribe the hardening of the spectra to the primary source injections, the
acceleration mechanisms in this energy region (500–800 GV) should be different between proton and other nuclei species.

In Scheme II, the hardening of the spectra is accounted by the break in diffusion coefficient, and the fitting results of the breaks and slopes in primary source injections are consistent with that in Scheme I. Consequently, these fitted values are reliable.

3.3. Normalization Parameters

The results of posterior probability distributions of the normalization parameters are given in Figure 7 (Scheme I) and Figure 8 (Scheme II).

In Tables 2 and 3, we find that the normalization parameters of the primary nuclei species have an uncertainty of <1%, and that of the secondary nuclei species ~5%. This shows us the necessity to employ them in the global fitting. Although their fitted values have slight differences between Schemes I and II, the relative relations can be kept in both of the two schemes.

Interestingly, the rescale factors of all the primary nuclei species are <1.0, and all that of the secondary species are >1.0. Here, $c_{p}^{\text{sec}}$ and $c_{\text{Be}}^{\text{sec}}$ should be given more attention because of the large deviations compared to other secondary species.

The value of $c_{p}^{\text{sec}}$ in this work (~1.7–1.9) is obviously different from that in previous works (~1.3–1.4), which could be partially explained by the usage of an independent $\phi_{p}$ to modulate the low-rigidity data (which contributes corrections on $c_{p}^{\text{sec}}$) in this work. At the same time, we should note that in Figures 9 and 10, the PDFs of $\phi_{p}$ reveal that even an independent solar-modulation potential $\phi_{p}$ (which is based on force-field approximation) could not handle the solar-modulation effects on $\bar{p}$, which have a negative charge. In this view, $c_{p}^{\text{sec}}$ could not be considered as a pure value to describe the uncertainty of $\bar{p}$ production cross section.

Besides $c_{p}^{\text{sec}}$, the following large deviation value is $c_{\text{Be}}^{\text{sec}}$. Not like $\bar{p}$, the solar modulation of Be could be well modeled in our fitting (see Figures 9 and 10). We cannot find any other reasons to interpret its specificity tentatively, and this needs more attention in future research.

3.4. Solar-modulation Potentials

The results of posterior solar-modulation potentials are shown in Figure 9 (Scheme I) and Figure 10 (Scheme II). For convenience, the boxplot of all the $\phi_{s}$ in Schemes I and II are shown in Figure 12.

What is interesting is that, all these $\phi_{s}$ have almost similar values (0.5–0.7 GV) except $\phi_{p}$ and $\phi_{\text{Be}}$. As we know, as an effective tool to handle solar modulation, force-field approximation is charge independent. The fitted values of $\phi_{p}$ clearly show that this approximation cannot deal with the solar-modulation effects on $\bar{p}$ at current data levels. Removing $\phi_{p}$ not to talk, it is strange that...
\[\phi_{Be}\] have a larger deviation compared with other \(\phi_j\)s. Considering the uncertainties and PDFs in Figures 9 and 10, the values of \(\phi_{Be}\) should be regarded seriously. The reasons and relevant physics behind \(\phi_{Be}\) should be studied in further research.

4. Nitrogen Spectrum As a Test

Nitrogen nuclei in CRs are thought to be produced both in astrophysical sources (mostly via the CNO cycle in stars...
Bethe 1939; Henry et al. 2000; Chiappini et al. 2003), and by the collisions of heavier nuclei with the ISM (Strong et al. 2007; Blasi 2013; Grenier et al. 2015). As a result, the nitrogen spectrum is expected to contain both primary and secondary components, which is the ideal data set to test not only the propagation model, but also the primary source injections.

Recently released nitrogen spectrum from AMS-02 (Aguilar et al. 2018a) with rigidity from 2.2 GV to 3.3 TV is used to do a test of the best-fit results in Section 3. In the test, based on the best-fit results of Schemes I and II in Section 3, the rescale parameters of the primary and secondary components of nitrogen nuclei ($c_{N}^{\text{pri}}$ and $c_{N}^{\text{sec}}$), and the solar-modulation potential $\phi_{N}$ are set to be free parameters to do a global fitting on the nitrogen spectrum.

As has been done in Section 3, MCMC algorithm is used to determine the best-fit results on the nitrogen spectrum (see in Figure 11) and the constraints on $c_{N}^{\text{pri}}$, $c_{N}^{\text{sec}}$, and $\phi_{N}$ (see in Tables 4 and 5) of the two schemes.

Considering the same degree of freedom in two schemes in the test, the results of the two schemes could be compared directly. As has been shown in Tables 4 and 5, both schemes give us a good best-fit result ($\chi^2_{1,N}/\text{d.o.f.} = 25.46/63$ and $\chi^2_{2,N}/\text{d.o.f.} = 23.22/63$), except the last three points with large uncertainties (see in Figure 11). Although $\chi^2_{2,N}$ is slightly smaller than $\chi^2_{1,N}$, it is not clear which scheme is better based on the current data set.

Figure 6. Same as Figure 5, but for Scheme II.

11 The relative abundance of nitrogen-14 has a default value of $1.828 \times 10^{-7}$ in GALPROP.
The rescale factors of primary CR nitrogen nuclei ($c_{N}^{\text{pri}}$) in both schemes are compatible with the corresponding rescale factors of other primary CR species ($c_{\text{He}}^{\text{pri}}$, $c_{C}^{\text{pri}}$, and $c_{O}^{\text{pri}}$). On the other hand, the rescale factors of secondary CR nitrogen nuclei ($c_{N}^{\text{sec}}$) in both schemes are close to 1.0, which are similar to the values of $c_{B}^{\text{sec}}$ and are the most reasonable values in those $c_{j}^{\text{sec}}$s. The modulation potential of nitrogen ($\phi_{N}$) in both schemes are also compatible with other species.

Figure 7. Fitting 1D probability and 2D credible regions of posterior PDFs for the combinations of all normalization parameters from Scheme I. The regions enclosing $\sigma$, $2\sigma$, and $3\sigma$ CL are shown step by step in lighter gold. The red cross lines and marks in each plot indicate the best-fit value (largest likelihood).
5. Discussions and Conclusions

With the newly released data from AMS-02 (Aguilar et al. 2015a, 2015b, 2016, 2017, 2018a, 2018b), we studied the origin of the hardening in both the primary (proton, helium, carbon, oxygen, and primary components of nitrogen) and secondary (anti-proton, lithium, beryllium, boron, and secondary components of nitrogen) CR nuclei spectra based on two different schemes. Global fitting results have shown that, both of the schemes could have good fitting on current primary and...
secondary nuclei spectra from AMS-02, and could reproduce the hardening of the spectra obviously. Moreover, based on current AMS-02 nuclei data, we could not distinguish whether the hardening in these nuclei spectra comes from the sources or propagation. Note that in Figure 2, it is obvious that in Scheme II, the predicted spectra of the secondary nuclei are
harder than that in Scheme I when $R \gtrsim 1$ TV. This is because in Scheme II, the secondary CR nuclei spectra not only inherit the spectral hardening from primary CR nuclei spectra, but are also hardened by their own propagation processes. This is obviously different from the situation in Scheme I, the spectral hardening of secondary CR nuclei species is totally inherited from the primary source injections. As a result, more precise secondary nuclei data on high-energy/rigidity regions (>1 TV) is needed to distinguish these two schemes.

Figure 10. Same as Figure 9, but for Scheme II.
One such pioneering work can be found in Génolini et al. which mainly be generated by its negative charge. abundances as provided by which are iterated to achieve an agreement with the propagated fi abundance in GALPROP, the rescale factors of the primary nuclei species, which are systematically smaller than 1.0, could be interpreted as follows: (i) outer spaces have a higher proton abundance than the solar system; (ii) outer spaces have a lower abundances of other primary nuclei species (He, C, N, and O) than the solar system. All the element abundances we got in this work are listed in Table 6.

On the other hand, all the rescale factors of the secondary nuclei species are larger than 1.0, some of them can reach up to 1.7 ~ 1.8 (c\textsubscript{sec}\textsubscript{He} and c\textsubscript{sec}\textsubscript{Be}). When we employed these c\textsubscript{sec}s, we expected them to describe the production cross section uncertainties and local inhomogeneity of the CR sources and propagation. Considering the fitting results of these c\textsubscript{sec}s, it seems that the contribution from the production cross section is small. This is because (i) generally speaking, the production cross sections of these species are energy dependent. But in Figure 2, all the CR secondary spectra are well fitted. It is unnatural that all these species have an energy independent correction on their production cross sections. (ii) It is also unnatural that we underestimate all the production cross sections of these secondary species simultaneously. Consequently, the fitting results of the c\textsubscript{sec}s (which are systematically larger than 1.0) could be explained as follows: (i) The ISM density of the outer spaces is larger than that in the local environment. This could be regarded as evidence of the Local Bubble, which the solar system is located in and has a lower ISM density compared with its surroundings (Lallement et al. 2003). (ii) These secondary nuclei species can be produced in the CR sources before propagation, which provide an additional flux (see, e.g., Berezhko & Ksenofontov 2014; Mertsch & Sarkar 2014).

Taking off the systematic deviations, we could find that c\textsubscript{sec}\textsubscript{Be} and c\textsubscript{sec}\textsubscript{C} still have large deviations compared with other c\textsubscript{sec}s. This might be mainly ascribed to their production cross section uncertainties, which would lead to further studies on these cross sections on colliders and open a new door to study nuclear physics.\textsuperscript{16}

\textsuperscript{12} A box plot or boxplot is a method for graphically depicting groups of numerical data through their quartiles. In our configurations, the band inside the box shows the median value of the data set, the box shows the quartiles, and the whiskers extend to show the rest of the distribution which is edged by the 5th percentile and the 95th percentile.

\textsuperscript{13} Except for the situation for anti-proton flux, it comes from the charge-sign dependence of the solar modulation, which cannot be handled by force-field approximation.

\textsuperscript{14} Here we exclude another special species—anti-proton—whose particularity would mainly be generated by its negative charge.

\textsuperscript{15} Here, we remove the parameter N\textsubscript{f} and show the results of the c\textsubscript{s} (which are called rescale factors in this work).

\textsuperscript{16} One such pioneering work can be found in Génolini et al. (2018).

\textbf{Figure 11.} Global fitting results and the corresponding residuals to the nitrogen flux for two schemes. The 2\sigma (deep red) and 3\sigma (light red) bounds are also shown in the figures. The relevant $\chi^2$ of each nuclei species is given in the subfigures as well.

5.1. About $\phi_i$s

In our global fitting, each kind of the species has been employed an independent solar-modulation potential $\phi_i$ to account for the effects of solar modulation, which is based on the force-field approximation. As a widely used and effective treatment on solar modulation, such configuration could show us its limitations and the differences of the propagation between different species in the heliosphere.

In order to get a clear representation of the fitting results, we use a boxplot\textsuperscript{12} to show all the $\phi_i$ for Schemes I and II in Figure 12.

In most of the situations, it could give us an acceptable result. If we want to study the fine structures in low-energy regions of the spectra ($\leq$30 GV), we should consider more effects in solving the Parker transport equation, which contains diffusion, convection, particle drift, and energy loss (see, e.g., Boschini et al. 2018). On the other hand, the different fitted values of $\phi_i$ for different nuclei species indicate some of the species really experience different physical processes in the heliosphere. Especially for beryllium, it needs further research to reveal the physics behind the value of $\phi_{\text{Be}}$\textsuperscript{14}.

5.2. About the $c_i$s

Another interesting aspect comes from the fitting values of the rescale factors. For convenience, the boxplot of all the $c_i$s in Scheme I and II are shown in Figure 13.\textsuperscript{13} It is clear that, all the primary nuclei rescale factors have values (which represent their relative element abundances) of $\sim$(0.5–0.6). We know that in GALPROP, the primary source (injection) isotopic abundances are taken first as the solar system abundances, which are iterated to achieve an agreement with the propagated abundances as provided by ACE at $\sim$200 MeV/nucleon (Wiedenbeck et al. 2001, 2008) assuming a propagation model. As a result, it is natural that the abundance of the CR species in the solar system (relatively low-rigidity CR particles) is different from that in outer spaces (relatively high-rigidity CR particles). This provides us with an effective and independent way to study the isotopic abundance out of the solar system. Considering the definition of the relative abundance in GALPROP, the rescale factors of the primary nuclei species, which are systematically smaller than 1.0, could be interpreted as follows: (i) outer spaces have a higher proton abundance than the solar system; (ii) outer spaces have a lower abundances of other primary nuclei species (He, C, N, and O) than the solar system. All the element abundances we got in this work are listed in Table 6.

On the other hand, all the rescale factors of the secondary nuclei species are larger than 1.0, some of them can reach up to 1.7 ~ 1.8 (c\textsubscript{sec}\textsubscript{He} and c\textsubscript{sec}\textsubscript{Be}). When we employed these c\textsubscript{sec}s, we expected them to describe the production cross section uncertainties and local inhomogeneity of the CR sources and propagation. Considering the fitting results of these c\textsubscript{sec}s, it seems that the contribution from the production cross section is small. This is because (i) generally speaking, the production cross sections of these species are energy dependent. But in Figure 2, all the CR secondary spectra are well fitted. It is unnatural that all these species have an energy independent correction on their production cross sections. (ii) It is also unnatural that we underestimate all the production cross sections of these secondary species simultaneously. Consequently, the fitting results of the c\textsubscript{sec}s (which are systematically larger than 1.0) could be explained as follows: (i) The ISM density of the outer spaces is larger than that in the local environment. This could be regarded as evidence of the Local Bubble, which the solar system is located in and has a lower ISM density compared with its surroundings (Lallement et al. 2003). (ii) These secondary nuclei species can be produced in the CR sources before propagation, which provide an additional flux (see, e.g., Berezhko & Ksenofontov 2014; Mertsch & Sarkar 2014).

Taking off the systematic deviations, we could find that c\textsubscript{sec}\textsubscript{Be} and c\textsubscript{sec}\textsubscript{C} still have large deviations compared with other c\textsubscript{sec}s. This might be mainly ascribed to their production cross section uncertainties, which would lead to further studies on these cross sections on colliders and open a new door to study nuclear physics.\textsuperscript{16}
Table 4

The Constraints on the Parameters of $c_N^{p1}$, $c_N^{n1}$, and $\phi_N$ Based on the Best-fit Result of Scheme I in Section 3

| ID | Prior Range | Best-fit Value | Posterior Mean and Standard Deviation | Posterior 95% Range |
|----|-------------|----------------|---------------------------------------|---------------------|
| $c_N^{p1}$ | [0.1, 5.0] | 0.63 | 0.64 ± 0.08 | [0.56, 0.69] |
| $c_N^{n1}$ | [0.1, 5.0] | 1.06 | 1.06 ± 0.04 | [1.01, 1.12] |
| $\phi_N$(GV) | [0, 1.5] | 0.72 | 0.72 ± 0.02 | [0.70, 0.75] |

Note. The prior interval, best-fit value, statistic mean, standard deviation, and the allowed range at 95% CL are listed. With $\chi^2$/d.o.f = 25.46/63 for best-fit results.

Table 5

The Constraints on the Parameters of $c_N^{p1}$, $c_N^{n1}$, and $\phi_N$ Based on the Best-fit Result of Scheme II in Section 3

| ID | Prior Range | Best-fit Value | Posterior Mean and Standard Deviation | Posterior 95% Range |
|----|-------------|----------------|---------------------------------------|---------------------|
| $c_N^{p1}$ | [0.1, 5.0] | 0.63 | 0.05 ± 0.08 | [0.57, 0.69] |
| $c_N^{n1}$ | [0.1, 5.0] | 1.11 | 1.11 ± 0.04 | [1.06, 1.17] |
| $\phi_N$(GV) | [0, 1.5] | 0.67 | 0.68 ± 0.02 | [0.64, 0.70] |

Note. The prior interval, best-fit value, statistic mean, standard deviation, and the allowed range at 95% CL are listed. With $\chi^2$/d.o.f = 23.22/63 for the best-fit result.
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**Software:** GALPROP (v56; Strong & Moskalenko 1998, 2001; Moskalenko et al. 2002, 2003; Ptuskin et al. 2006), emcee (Foreman-Mackey et al. 2013), corner.py (Foreman-Mackey et al. 2016).

Note. Excluding the fitted values of $c_{p}^{\text{sec}}$ and $\phi_{p}$ for anti-proton’s negative charge, we find that the most special species is beryllium, not...
only its propagation in the heliosphere, but also its production cross section. This would be related to some interesting problems in stellar physics and cosmology on such special element, which needs further research based on more precise CR data.

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