Origin of the hardening in AMS-02 nuclei spectra at a few hundred GV

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ABSTRACT

Many experiments have confirmed the spectral hardening in a few hundred GV of cosmic ray (CR) nuclei spectra, and 3 different origins have been proposed: the primary source injection, the propagation, and the superposition of different kinds of sources. In this work, the break power law has been employed to fit each of the AMS-02 nuclei spectra. The fitting results show complicated relationships between different nuclei species, which could not be reproduced naturally by the primary source injection and propagation scenarios. However, with a natural and simple assumption, the superposition of different kinds of sources could explain the fitting results successfully. CR nuclei spectra from one single experiment in future will provide us the opportunity to do cross checks and reveal the properties of the different kinds of sources.

Keywords: cosmic rays — acceleration of particles

1. INTRODUCTION

Cosmic-ray (CR) physics has entered a precision-driven era. More and more fine structures have been confirmed by a new generation of space-borne and ground-based experiments in recent years. For CR nuclei spectra, the most obvious fine structure is the spectral hardening at \( \sim 300 \) GV, which was observed by ATIC-2 (Panov et al. 2006), CREAM (Ahn et al. 2010), and PAMELA (Adriani et al. 2011).

The space station experiment Alpha Magnetic Spectrometer (AMS-02), which was launched in May 2011, improve the measurement precision of the CR fluxes by an order of the systematics (Aguilar et al. 2013). Up to now, AMS-02 has released the spectra of different nuclei species, including the primary CR species: proton (Aguilar et al. 2015), helium (He), carbon (C), oxygen (O) (Aguilar et al. 2017), neon (Ne), magnesium (Mg), and silicon (Si) (Aguilar et al. 2020); the secondary CR species: lithium (Li), beryllium (Be), and boron (B) (Aguilar et al. 2018a); the hybrid CR species: nitrogen (N) (Aguilar et al. 2018b). All these CR nuclei species show spectral hardening in the region of 100 \( - 1000 \) GV, which confirms the previous observational results.

Moreover, it shows that the secondary nuclei spectra harden even more than that of the primary ones at a few hundred GV, and the spectral index of N spectrum rapidly hardens at high rigidities and becomes identical to the spectral indices of primary He, C, and O CRs.

This spectral hardening phenomenon has been studied by many previous works. Generally speaking, the spectral hardening could come from: (i) the primary source injection (see, e.g., Korsmeier & Cuoco (2016); Boschini et al. (2017); Niu & Li (2018); Niu et al. (2019); Zhu et al. (2018); Niu et al. (2019)); (ii) the propagation (see, e.g., Génolini et al. (2017); Niu et al. (2019); Blasi et al. (2012); Tomassetti (2012, 2015a,b); Feng et al. (2016); Guo & Yuan (2018)); (iii) the superposition of different kinds of sources, such as different population of sources or of local and distant sources (see, e.g., Vladimirov et al. (2012); Bernard et al. (2013); Thoudam & Hörandel (2013); Tomassetti & Donato (2015); Kachelrieß et al. (2015); Kawanaka & Yanagita (2018); Yang & Aharonian (2019); Yue et al. (2019); Yuan et al. (2020)). Based on the galactic CR diffusion model, all these scenarios could provide good fits to specific data sets. No scenario has stood out yet.

In order to avoid the artificial effects from propagation models, date sets selection, and the systematics between different CR experiments’ data, it is helpful to analyze all the AMS-02 nuclei spectrum directly via a uniform method. The model independent results would give us
clearer hints to the propagation models and then the origin of the spectral hardening.

In the following, we first analyze the spectra in Section 2; discussions are shown in Section 3; conclusion and outlook are represented in Section 4.

2. ANALYSIS ON THE SPECTRA

Because we focus on the spectral hardening in a few hundred GV, the data points whose rigidity less than 45 GV are not used in this work, which are also affected by solar modulation and cannot be fitted by a simple break power law. When the rigidity is greater than 45 GV (up to a few thousand GV), all the nuclei spectra can be well fitted by a break power law or smooth break power law (Aguilar et al. 2015; Aguilar et al. 2017; Aguilar et al. 2020; Aguilar et al. 2018a,b). Considering the date precision of the AMS-02 data, it is unnecessary to employ a smooth factor to describe the spectra index transformation.

Consequently, the following formula is used to describe each of the AMS-02 nuclei spectra (including the primary CR species: proton, He, C, O, Ne, Mg, and Si; the secondary CR species: Li, Be, and B; the hybrid CR species: N) when the rigidity is greater than 45 GV:

\[
F_i(R) = N^i \times \begin{cases} 
\left( \frac{R}{R_{br}^i} \right)^{\nu_1} & R \leq R_{br}^i \\
\left( \frac{R}{R_{br}^i} \right)^{\nu_2} & R > R_{br}^i 
\end{cases},
\]

where \( F \) is the flux of CR, \( N \) is the normalization constant, and \( \nu_1 \) and \( \nu_2 \) are the spectral indexes less and greater than the break rigidity \( R_{br} \), and \( i \) denotes the species of nuclei.

The Markov Chain Monte Carlo (MCMC) algorithm is employed to determine the posterior probability distribution of the spectral parameters belonging to different CR nuclei species. The best-fit values and the allowed intervals from 5th percentile to 95th percentile of the parameters \( \nu_1, \nu_2, R_{br}, \) and \( \Delta \nu \equiv \nu_2 - \nu_1 \) are listed in Table 1, together with the reduced \( \chi^2 \) of each fitting. The best-fit results and the corresponding residuals of the primary, the secondary, and the hybrid CR species are given in Figure 1, 2, and 3 of the Appendix, respectively.

Generally speaking, the \( \chi^2 \)'s of primary CR species are smaller than the other 2 types of species, which are caused by the dispersion of the data points (especially high rigidity region) in the latter cases.

3. DISCUSSIONS

In order to get a clear representation of the fitting results, we use boxplot to show all the distributions of \( \nu_1, \nu_2, R_{br} \) and \( \Delta \nu \) in Figure 1.

In the subfigure (a) of Figure 1, it is obvious that the values of \( \nu_1 \) can be divided into 3 groups, which correspond to the primary, the secondary, and the hybrid CR species. As the transition between the primary and the secondary CR species, it is reasonable that the hybrid species (N) have a value of \( \nu_1 \) between the other 2 species. Moreover, the proton have a distinct value of \( \nu_1 \) compared with other CR primary species. What’s more interesting, \( \nu_1 \) of O and Si (especially O) are larger than that of others. Based on the above principle of classification, O and Si CR spectra should have the least secondary components, while all the other primary nuclei species (especially the proton) should have a considerable secondary components which could influence the spectral index obviously in this rigidity region. This explanation contradicts with the common CR models which produce a few percent or even fewer secondary components in primary CR spectra, and they cannot have enough secondary components to change the spectral index seriously. Another explanation to the different \( \nu_1 \) values of primary CR species is the different primary source injections for them. In such case, it might straightforward ascribe the specific \( \nu_1 \) of proton to its charge-to-mass ratio, but it is difficult to find a universal mechanism to explain the different \( \nu_1 \) values for other primary species.

In the subfigure (b) of Figure 1, the uncertainties of \( \nu_2 \) are larger than that of \( \nu_1 \) because of the fewer data points with larger uncertainties in high rigidity region in the AMS-02 CR spectra. The clear 3 groups in subfigure (a) are replaced by complicated relationships. Different from the relationships of \( \nu_1 \) for primary species, the \( \nu_2 \) of Ne, Mg, and Si have even larger uncertainties and cover a large interval from that of the primary species (proton, He, C, and O) to the secondary species (Li, Be,

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1 We also test the smooth break power law to fit the data, and it gives similar fitting results with slightly larger uncertainties on the parameters.

2 The python module emcee (Foreman-Mackey et al. 2013) is employed to perform the MCMC sampling. Some such examples can be referred to Niu & Li (2018); Niu et al. (2018, 2019) and references therein.

3 The information of the parameter \( N \) is not listed in the table, which is not important in the subsequent analysis. The information of \( \Delta \nu \equiv \nu_2 - \nu_1 \) is derived from that of \( \nu_1 \) and \( \nu_2 \).

4 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 dataset, the box shows the quartiles, and the whiskers extend to show the rest of the distribution which are edged by the 5th percentile and the 95th percentile.
Table 1. The fitting results of the spectral parameters for the different nuclei species. Best-fit values and allowed 5th to 95th percentile intervals (in the square brackets) are listed for each of the parameters.

| Species | $\nu_1$ | $\nu_2$ | $R_{br}$ (GV) | $\Delta\nu$ | $\chi^2$/d.o.f |
|---------|---------|---------|---------------|------------|----------------|
| proton  | -2.815 [-2.823, -2.806] | -2.71 [-2.76, -2.62] | 379 [300, 544] | 0.10 [0.06,0.19] | 1.21/27 = 0.045 |
| Helium  | -2.725 [-2.733, -2.715] | -2.62 [-2.65, -2.56] | 331 [281, 448] | 0.10 [0.07,0.16] | 2.65/28 = 0.095 |
| Carbon  | -2.74 [-2.76, -2.72] | -2.64 [-2.68, -2.59] | 202 [148, 299] | 0.10 [0.05,0.15] | 5.26/28 = 0.188 |
| Oxygen  | -2.696 [-2.712, -2.680] | -2.49 [-2.63, -2.27] | 664 [488, 964] | 0.21 [0.07,0.43] | 1.91/28 = 0.068 |
| Neon    | -2.74 [-2.76, -2.72] | -2.33 [-2.61, -1.98] | 670 [405, 995] | 0.41 [0.13,0.76] | 6.01/27 = 0.222 |
| Magnesium | -2.74 [-2.76, -2.72] | -2.61 [-2.79, -2.31] | 410 [287, 978] | 0.13 [-0.06,0.42] | 4.68/27 = 0.173 |
| Silicon | -2.71 [-2.73, -2.69] | -2.79 [-3.24, -2.51] | 922 [491, 988] | -0.08 [-0.53,0.21] | 7.21/27 = 0.267 |
| Lithium | -3.18 [-3.20, -3.10] | -2.98 [-3.01, -2.72] | 123 [112, 351] | 0.20 [0.14,0.41] | 22.51/27 = 0.834 |
| Beryllium | -3.13 [-3.16, -3.08] | -2.95 [-3.06, -2.77] | 199 [173, 438] | 0.17 [0.04,0.34] | 18.29/27 = 0.677 |
| Boron   | -3.10 [-3.13, -3.07] | -2.84 [-2.96, -2.66] | 275 [194, 422] | 0.26 [0.14,0.44] | 11.42/27 = 0.430 |
| Nitrogen | -2.93 [-2.95, -2.87] | -2.66 [-2.70, -2.34] | 208 [188, 454] | 0.27 [0.21,0.56] | 11.06/27 = 0.406 |

Figure 1. Boxplots for $\nu_1$, $\nu_2$, $R_{br}$, and $\nu_2 - \nu_1$. The band inside the box shows the median value of the dataset, the box shows the quartiles, and the whiskers extend to show the rest of the distribution which are edged by the 5th percentile and the 95th percentile.
and B). The $\nu_2$ of N is somewhat consistent with that the primary component dominates the N spectra in high rigidity region.

In the subfigure (c) of Figure 1, it is shown that the values of $R_{br}$ could be divided into 2 groups: proton, He, C, Li, Be, B, and N in one group; O, Ne, Mg, and Si in another group. As the daughter species of C, N$^5$, O, Ne, Mg, and Si, the secondary species (Li, Be, and B) have similar $R_{br}$ values with C and N, but show systematically different $R_{br}$ intervals with O, Ne, Mg, and Si. For the primary CR species, it is interesting that the $R_{br}$ values of proton, He, C, and N are different from that of O, Ne, Mg, and Si.

In the subfigure (d) of Figure 1, the values of $\Delta\nu$ inherit large uncertainties from $\nu_2$, especially for N, O, Ne, Mg, and Si. If we do not consider these species, it shows that the $\Delta\nu$ values of primary species (proton, He, and C) are systematically smaller than that of the secondary species (Li, Be, and B), which is the reason why AMS-02 spectra data favor a break in diffusion coefficient index rather than a break in the primary source injection (see, e.g., Génolini et al. (2017); Niu & Xue (2020)). Same as the case of $\nu_2$, the $\Delta\nu$ values of Ne, Mg, and Si have even larger uncertainties and covers a large interval from that of the primary species (proton, He, C, and O) to the secondary species (Li, Be, and B). Additionally, the $\Delta\nu$ of Si even has a negative best-fit value.

It is shown that not only the values of $\nu_1$, $\nu_2$ and $\Delta\nu$ are different for different primary CR species, but also the relationships of $\nu_1$ (low rigidity region) and $\nu_2$ (high rigidity region) between different primary species are obviously different (especially the CR spectra of Ne, Mg, and Si represent different properties compared with other primary species, which infers that they might come from different sources in different rigidity region).

Consequently, if the spectral hardening came from the primary sources injection or propagation, it is necessary to introduce independent primary source injection for each of the primary CR species first. For the propagation case, independent breaks and relevant diffusion coefficient indexes are also needed to reproduce the observed spectra precisely. However, except that of the proton who has a different charge-to-mass ratio, there is no clear physical motivations that other primary CR nuclei species should have different source injections, let alone the independent breaks and indexes in the diffusion coefficients for them.

In summary, the observed AMS-02 CR nuclei spectra show complicated relationships on the spectral indexes less and greater than the rigidity of the hardening (break) at a few hundred GV between the primary CR species, which disfavor that the spectral hardening comes from primary source injections or propagation if we adhere the principles of naturality and simplicity for our CR models.

Fortunately, the superposition of different kinds of sources could naturally reproduce all the spectral indexes ($\nu_1$ and $\nu_2$) and breaks ($R_{br}$) for different CR nuclei species with a simple and natural assumption that each kind of the sources has an unique spectral index for all the primary source injection and have different element abundances compared with the other kind. Considering the different kinds of potential CR sources (such as the different population of supernovae), the assumption represents the real astrophysical situations. In this scenario, the values of $\nu_1$ indicate that one kind of sources dominate in this rigidity region, and the values of $\nu_2$ and $R_{br}$ are the results of superposition of the other kind of sources with different spectral indexes and element abundances which have considerable flux in this rigidity region (see, e.g., Yue et al. (2019); Yuan et al. (2020)).

Because of the small number and large uncertainties of the data points greater than the break rigidity, the fitting values of $\nu_2$ and $R_{br}$ (which is closely related to the detailed properties of the second type of sources) have large uncertainties. However, the systematics between different experiments (mainly from the energy calibration process) prevent precise fittings on a data collection of them covering different rigidity regions. As a result, CR nuclei spectra from one single experiment are needed to do cross checks and reveal the properties of the different kinds of sources in future.

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Software: **emcee** (Foreman-Mackey et al. 2013)

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4. CONCLUSION AND OUTLOOK

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5 The break here is mainly determined by its primary component (Aguilar et al. 2018b).
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APPENDIX

Note that in the lower panel of subfigures in Figs. 1, 2, and 3, the $\sigma_{\text{eff}}$ is defined as

$$
\sigma_{\text{eff}} = \frac{f_{\text{obs}} - f_{\text{cal}}}{\sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}},
$$

where $f_{\text{obs}}$ and $f_{\text{cal}}$ are the points which come from the observation and model calculation; $\sigma_{\text{stat}}$ and $\sigma_{\text{sys}}$ are the statistical and systematic standard deviations of the observed points. This quantity could clearly show us the deviations between the best-fit result and observed values at each point based on its uncertainty.
Figure 1. Fitting results and corresponding residuals to the primary CR nuclei spectra (proton, He, C, O, Ne, Mg, and Si). The 2σ (deep red) and 3σ (light red) bounds are also shown in the subfigures. The relevant reduced $\chi^2$ of each spectrum is given in the subfigures as well.
Figure 2. Fitting results and corresponding residuals to the secondary CR nuclei spectra (Li, Be, and B). The $2\sigma$ (deep red) and $3\sigma$ (light red) bounds are also shown in the subfigures. The relevant reduced $\chi^2$ of each spectrum is given in the subfigures as well.

Figure 3. Fitting results and corresponding residuals to the hybrid CR nuclei spectra (N). The $2\sigma$ (deep red) and $3\sigma$ (light red) bounds are also shown in the subfigures. The relevant reduced $\chi^2$ of each spectrum is given in the subfigures as well.