Hybrid origins of the cosmic-ray nuclei spectral hardening at a few hundred GV

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2021.10.27 **@TeVPA 2021**

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Related Ariticles

- Jia-Shu Niu; “**Origin of hardening in spectra of cosmic ray nuclei at a few hundred GeV using AMS-02 data** ,”arXiv:2009.00884.
- Jia-Shu Niu; “**Hybrid origins of the cosmic-ray nuclei spectral hardening at a few hundred GV**,”arXiv:2107.12289.

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Motivation

Proton spectrum from different experiments

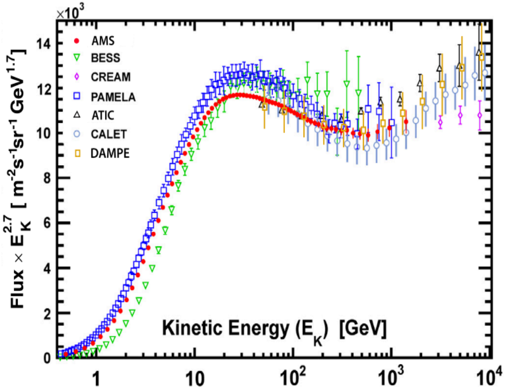

Fig. 59. Latest AMS proton flux multiplied by $E_K^{2.7}$ together with other recent measurements.

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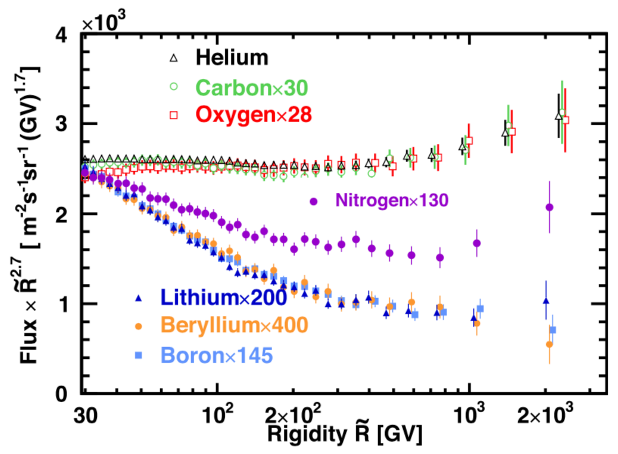
Spectra of primary, secondary, and hybrid species (AMS-02, $>$ 30 GV)



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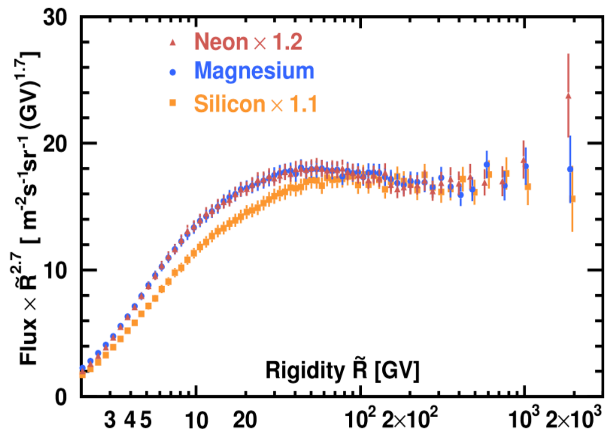
Newly released spectra of primary species



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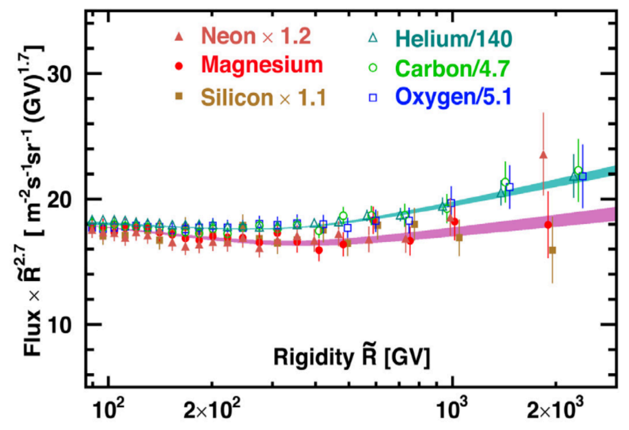
Spectra of different primary sepcies



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Info about the hardening/breaks @100-1000 GV

The main features of the AMS-02 nuclei spectra:

- the hardening is universally existing in the nuclei spectra (primary, secondary, and hybrid species);
- the hardening is different from different primary species (proton/He, C, O/Ne, Mg, Si)
- the hardening is also seems different from the primary, secondary, and hybrid species

We need quantitative results.

The hardening/breaks can be quantitatively described by the

position of the breaks & spectral index differences

of different species.

Direct fitting to the AMS-02 CR nuclei spectra above 45 GV

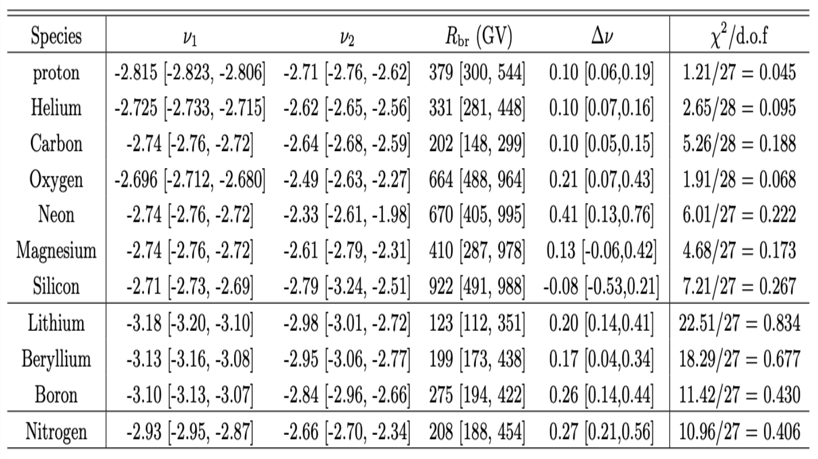
Setups

- AMS-02 nuclei spectra (proton, He, C, O, Ne, Mg, Si, Li, Be, B, N), ≥ 45 GV.
- For different nuclei species:

$$F^{\mathrm{i}}(R) = N^{\mathrm{i}} \times \begin{cases} \left(\dfrac{R}{R_{\mathrm{br}}^{\mathrm{i}}}\right)^{\nu_1^{\mathrm{i}}} & R \leq R_{\mathrm{br}}^{\mathrm{i}} \\ \left(\dfrac{R}{R_{\mathrm{br}}^{\mathrm{i}}}\right)^{\nu_2^{\mathrm{i}}} & R > R_{\mathrm{br}}^{\mathrm{i}} \end{cases} \tag{1}$$

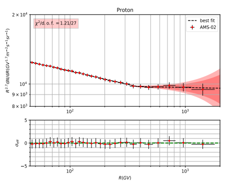
- MCMC.

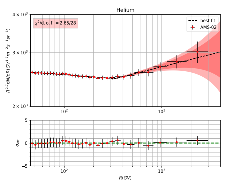
Fitting Results

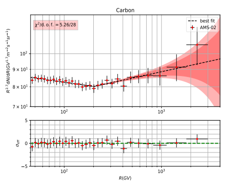


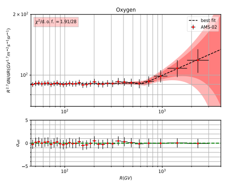
Species	ν_1	ν_2	$R_{\rm br}$ (GV)	$\Delta\nu$	χ^2/d.o.f
proton	-2.815 [-2.823, -2.806]	-2.71 [-2.76, -2.62]	379 [300, 544]	0.10 [0.06,0.19]	1.21/27 = 0.045
Helium	-2.725 [-2.733, -2.715]	-2.62 [-2.65, -2.56]	331 [281, 448]	0.10 [0.07,0.16]	2.65/28 = 0.095
Carbon	-2.74 [-2.76, -2.72]	-2.64 [-2.68, -2.59]	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]	10.96/27 = 0.406

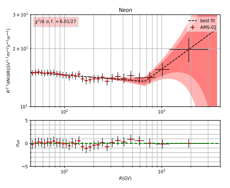
Fitting Results of the primary species

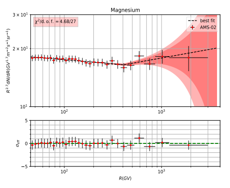


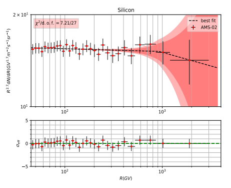




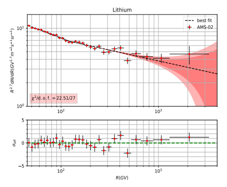


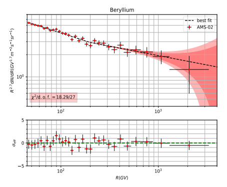


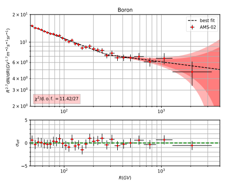


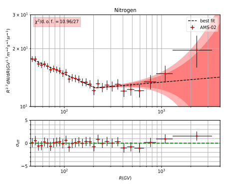


Fitting Results of the secondary and hybrid species

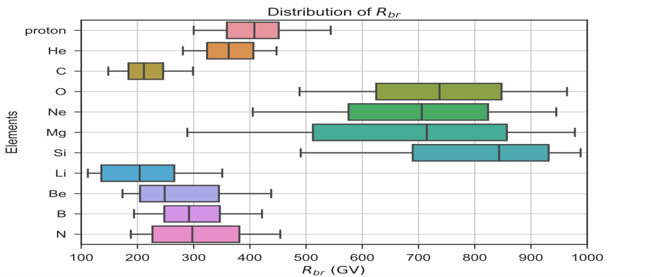


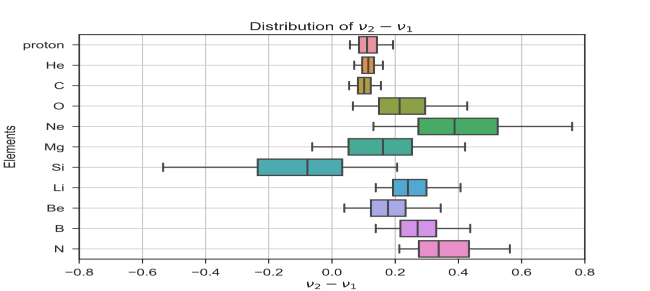






Distribution of R_{br} and $\nu_2 - \nu_1$





Quantitative results of the hardening/breaks @100-1000 GV

The fitting results show

different position of the breaks
& different spectral index differences

for different species.
The common origins of the hardening:

- the primary source acceleration (independent primary source injection for each of the primary species?);
- the propagation (independent breaks and relevant diffusion coefficient indexes?);
- the superposition of different kinds of sources (each kind of the sources could has a unique spectral index for all the primary source injection and has different element abundances of different kind of sources? seems natural).

Fitting to the AMS-02 nuclei spectra via a propagation model

Some contradictions

Some recent works (Genolini et al. PRL(2017), Niu & Xue JCAP(2020)) show that AMS-02 nuclei data favors the hardening coming from the propagation process rather than the CR source injection in a statistical meaning.

Is it necessary to employ a high-rigidity break in the diffusion coefficient?

In order to test this inference, we need

- a clean data set which includes all the relevant primary species (at least the dominating ones) and one daughter species without primary component (or has very small fraction of primary component) to check the propagation process itself;
- exclude all the irrelevant species;
- a proper handling of the solar modulation and a proper propagation model (diffusion-reacceleration);
- a configuration in which the data have the freedom to support or against the inference.

Setups (data set)

AMS-02 spectra of C, N, O, Ne, Mg, Si and B

Resons:

- including all the real parents species of B up to Si (because all the information of the breaks will inherit to the daughter species);
- excluding the spectra of proton and He (they are not the parents species);
- excluding the spectra of Li and Be (some recent works show that they might have extra primary components).

Could all these parents species (C, N, O, Ne, Mg, and Si) reproduce the breaks in their daughter species (B) ?

Setups (propagation model)

- A modified version of the diffusion-reacceleration scenario (Yuan SCPMA (2019); good performance in low-rigidity region);
-

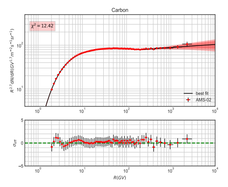
$$D_{xx}(R) = D_0 \cdot \beta^{\eta} \left(\frac{R_{\mathrm{br}}}{R_0}\right) \times \begin{cases} \left(\frac{R}{R_{\mathrm{br}}}\right)^{\delta_1} & R \leq \ R_{\mathrm{br}} \\ \left(\frac{R}{R_{\mathrm{br}}}\right)^{\delta_2} & R > \ R_{\mathrm{br}} \end{cases} ; \qquad (2)$$

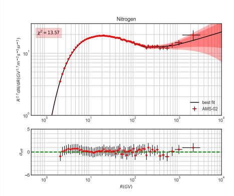
- For different nuclei species:

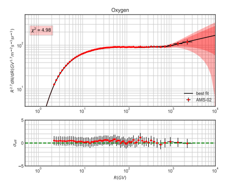
$$q_{\mathrm{i}} \propto N_i \times \begin{cases} \left(\frac{R}{R_1^{\mathrm{i}}}\right)^{-\nu_1^i} & R \leq R_1^i \\ \left(\frac{R}{R_1^{\mathrm{i}}}\right)^{-\nu_2^i} & R_1^i < R \leq R_2^i \\ \left(\frac{R}{R_2^{\mathrm{i}}}\right)^{-\nu_3^i} \left(\frac{R_2^{\mathrm{i}}}{R_1^{\mathrm{i}}}\right)^{-\nu_2^i} & R > R_2^i \end{cases} ; \qquad (3)$$

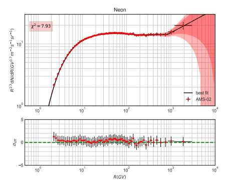
- Force-field approximation for solar modulation;
- galprop & MCMC.

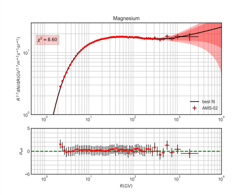
Fitting Results

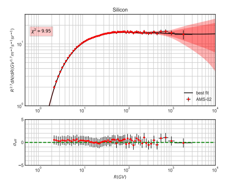


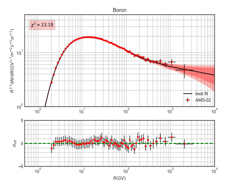




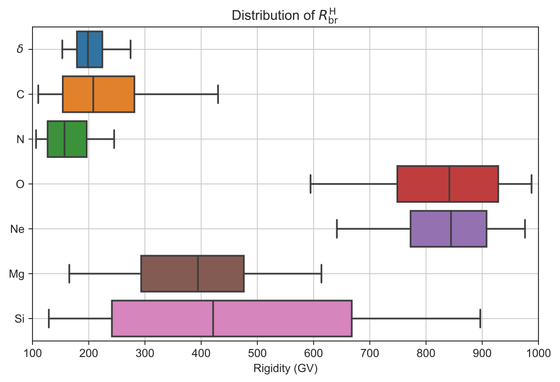








Distribution of $R_{\mathrm{br}}^{\mathrm{H}}$ [1]



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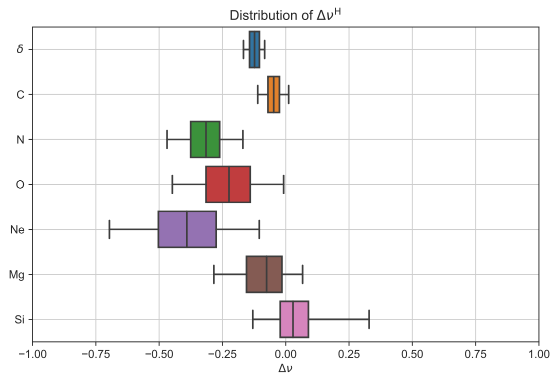
[1] $R_{\mathrm{br}}^{\mathrm{H}} \equiv R_2^i$ for C, N, O, Ne, Mg, and Si; $R_{\mathrm{br}}^{\mathrm{H}} \equiv R_{\mathrm{br}}$ for δ.

Distribution of $\Delta\nu^{\mathrm{H}}$ [2]



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[2] $\Delta\nu^{\mathrm{H}} \equiv \nu^i_3 - \nu^i_2$ for C, N, O, Ne, Mg, and Si; $\Delta\nu^{\mathrm{H}} \equiv \delta_2 - \delta_1$ for δ.

Summary

If we want to reproduce the spectral hardening in the CR nuclei species at a few hundred GV precisely, not only an extra break at about 200 GV in the diffusion coefficient is needed, but the extra independent high-rigidity breaks in the primary source injection for different CR species are also needed.

The former could come from the propagation process (such as the spatial-dependent propagation, see, e.g., Tomassetti ApJL(2012); Guo et al. ApJ(2016); Feng PRD(2016)), and the latter can be naturally explained by the superposition of different kinds of sources.
Consequently,

the CR nuclei spectral hardening @100-1000 GV has hybrid origins.

Thank you for your Attention!