Indications for a High-Rigidity Break in the Cosmic-Ray Diffusion Coefficient

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Using cosmic-ray boron to carbon ratio (B/C) data recently released by the AMS-02 experiment, we find indications (*decisive evidence*, in Bayesian terms) in favor of a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He). The result is robust with respect to currently estimated uncertainties in the cross sections, and in the presence of a small component of primary boron, expected because of spallation at the acceleration site. Reduced errors at high energy as well as further cosmic ray nuclei data (as absolute spectra of C, N, O, Li, Be) may definitively confirm this scenario.

Introduction.—The multiple deflections of cosmic rays (CRs) on magnetic irregularities cause their propagation to be a diffusive process. This increases their residence time in the Galaxy, and so their interaction probability with the interstellar medium (ISM). Their collision products include species which are otherwise rare or absent in the ISM, such as *"fragile"* elements like Li-Be-B or antiparticles, like antiprotons ($\bar{p}$). These so-called secondary species (SS) have long been used to set constraints on propagation parameters in the generalized diffusion-loss equations linking the CR injection to the observable fluxes at Earth [1]. Once tuned to measurements, these models define the framework within which other astroparticle physics investigations are performed, like indirect searches for dark matter via their charged (anti)particle annihilation (or decay) byproducts.

The last decade has witnessed a major improvement in the precision and dynamical range of direct CR measurements, culminating with the AMS-02 experiment on board the ISS. Traditional theoretical models are under strain, when challenged to match the precision of recent observations. On the one hand, the experimental error bars have shrunk to such a level that the stochastic nature of the sources provides an irreducible limitation to theoretical predictive power (see Ref. [2] for a recent study in that sense). On the other hand, the observations have revealed subtle features demanding an explanation, such as the broken power-law spectra in p [3] and He fluxes [4], and

also probably present in heavier nuclei, confirming earlier indications by PAMELA [5] and CREAM [6]. Theoretical studies should thus aim at reducing (or at least assessing) uncertainties, while enlarging the range of phenomena to explain, i.e., should do "more and better." For instance, a number of explanations have been put forward for the broken power laws. As reviewed in Ref. [7] (see also [8]), the most promising tool to distinguish between different classes of models resides in the study of SS, or alternatively of the ratio of a SS, like B, to a (mostly) primary one, like C. If breaks are already present in the spectra accelerated at the sources, such a ratio should appear featureless, since the daughter nucleus "inherits" its parent features. If these features are due to propagation (as suggested by the similar rigidity at which it is seen in different species) the effect should be twice as pronounced in SS, thus emerging in a secondary over primary ratio, provided that a sufficiently high-precision measurement extending up to high rigidities is available. The ratio of B/C fluxes recently released by AMS-02 [9] up to ~2 TV provides such an opportunity. Note that nontrivial features in B/C may be also due to the so-called *distributed* reacceleration (DR) process (see Ref. [10] for an early proposal). Although DR may have interesting implications for fine details of CR spectra [11–13], the idea to use it to explain p and He breaks [14] is not viable due to qualitative and quantitative problems, as pointed out, e.g., in Refs. [13,15].

Furthermore, its impact on secondary fluxes seems to be negligible compared to spallation processes at source (see, e.g., Ref. [16]) which are discussed in the following. Yet, it has been recently argued in Ref. [13] that even if prominent DR is present, SS spectra still show the need for an extra break, likely induced by diffusion. For these reasons, we exclude DR from the class of models tested hereafter.

In this study, we investigate several hypotheses with the USINE code, in the limit of a 1D diffusion model [17]. This geometry is sufficient to capture the physics encoded in the B/C ratio; the simplicity of the model is an asset to test the diffusion coefficient break and the robustness of our conclusions. We follow a strategy which is complementary to recent trends: we restrict the theoretical framework to a sufficiently simple scenario with few fit parameters, and compare different hypotheses without introducing additional ones. For this purpose, we make use of break parameters determined by the p and He analysis from AMS-02, thus performing a test "*a priori*".

Methodology.—Within a very large class of models, CR fluxes observed at Earth in the high-rigidity regime (tens of GV to hundreds of TV) are expected to depend mainly on the source term and the diffusion properties. Moving toward lower energies, additional effects enter, such as convective winds, reacceleration, solar modulation, and energy losses. Given our primary goal to isolate features in the (effective homogeneous and isotropic) diffusion coefficient $K = K(R)$, we focus in the following on the rigidity range above $\mathcal{O}(10)$ GV and keep as primary fit parameters its normalization K_0 and power-law index δ. We also fix the diffusive halo height L to 10 kpc, since it is a parameter largely degenerate with K_0. We emphasize that our goal here is not to find "the best fit" parameters for the description of the data over the whole energy range, but identify and use the key physical variables on which the high-rigidity data depend. In this context, we test for two models, with the same number of free parameters. The conventional diffusion model

$$K(R) = K_0 \beta (R/\mathrm{GV})^\delta \tag{1}$$

vs

$$K(R) = K_0 \beta \frac{(R/\mathrm{GV})^\delta}{\{1 + (R/R_b)^{\Delta\delta/s}\}^s}, \tag{2}$$

where s, $\Delta\delta$, and R_b are, respectively, the smoothing, the magnitude, and the characteristic rigidity of the break. These parameters are not extra parameters adjusted to the B/C data, but result from a fit on the breaks in the AMS-02 p and He spectra. In practice, we treat the break parameters as *nuisance parameters*, whose best fit values and errors are extracted from p and He. To do such an analysis correctly, it is necessary to take into account degeneracies between the parameters. This could be done thanks to their covariance matrix, which is unfortunately not provided

by the AMS-02 Collaboration. Hence, we perform a new *simultaneous* fit to the p and He data, taking into account statistical and systematic uncertainties as described in Ref. [18]. Our results ($R_b = 312^{+31}_{-26}$ GV, $\Delta\delta = 0.14 \pm 0.03$, $s = 0.040 \pm 0.015$) are consistent with both sets of values found by AMS-02, and we checked that adopting the best fit values found in their publication would not affect our conclusions. Note that the hypothesis Eq. (2) means attributing the breaks in p and He to diffusion. There are several proposals in the literature to produce such a behavior with microphysical mechanisms (e.g., Ref. [19]) or more complicated geometries and functional forms for $K(R)$ [20]. The role played by the velocity parameter V_a (as implemented in USINE [21]) and the convective speed V_c lessens as the rigidity increases. For instance, the data prove to be insensitive to the convective velocity V_c as the fit yields a result consistent with zero when limited to higher and higher R. However, because of parameter degeneracies, we treat V_a and V_c as nuisance parameters whose variation range (from 0 to 10 km/s) is estimated via a preliminary fit over the full B/C data. We treat the solar modulation in the force field approximation, setting the Fisk potential to 0.730 GV, the average value over AMS-02 data taking period [22]—as retrieved from the online tool CRDB [23]. We work in a 1D approximation since, apart from a renormalization in the effective value of the diffusion parameters (and particularly K_0), moving to a 2D geometry leads to similar fitting performances [21,24]. We checked that assuming a different low-R dependence of the diffusion coefficient ($K \propto \beta^0$ instead of β^1 as discussed in Ref. [25]) does not affect the statistical significance of the results obtained below. Needless to say, the best-fit values of the propagation parameters such as δ *depend* on the theory framework (and the range of R) one is fitting to Ref. [25], and we warn the readers that a comparison of the parameters obtained in our setup with similar parameters obtained in parametrically extended global fits to all data would be misleading, just like an extrapolation of our model to very low R, where it is expected *a priori* to fail.

The other ingredient upon which the results depend is the source spectrum. Boron is often considered as fully secondary, mostly produced by spallation of O and C. Fortunately, there is virtually no dependence of the B/C ratio upon the spectral shape of the primary C and O spectra [24,26], at least as long as they are similar, which seems to be confirmed anyway from preliminary AMS-02 data. For definiteness, we fixed the injection power-law index to 2.1, but the specific choice is not essential. Hence, the main uncertain inputs determining the B source term, and thus the transport parameters, are the spallation cross sections [24,25]. We compare our results for two choices, the GALPROP (GAL) data set [27] and Webber 2003 (W03) one [28]. Since both cross-section formulations assume a constant extrapolation above some energy, this comparison

might not capture the whole uncertainty, in particular on the *shape* of the B/C in the energy range of interest. To assess its importance, we also test a different extrapolation, assuming a very mild growth of all cross sections with $\ln^2 E$, E being the energy per nucleon. This is certainly the reasonable leading growth behavior for the total and inelastic nucleon-nucleon cross section [29], and leads to a corresponding growth in nucleus-nucleus collisions, as expected based on Glauber models and experimentally checked in proton-air cross-section measurements in extensive air-shower detectors, see, e.g., Ref. [30]. Lacking a more certain alternative, we further assume that the branching ratio into B is E independent. In practice we adopt for C, O, and B cross sections, the same rise in E as σ_{pp} (see, e.g, Ref. [31]), starting at the energy at which the total pp cross section starts growing (zero derivative), i.e., around 100 GeV/nuc (Lab frame). Continuity with the low-energy cross section is imposed. The resulting behaviour resembles—at least at visual inspection—the trends reported in the recent Monte Carlo study [32].

Finally, the hypothesis that all B is secondary implicitly assumes that the acceleration time at the source is small if compared to diffusion time $t_K \propto K^{-1}$. For a time scale t_A of a source capable of accelerating particles to $E \gtrsim$ TeV/nuc, one expects a primary to secondary fraction of B proportional to t_A/t_K. For a gas density value typical of the ISM $n \sim 1$ cm^{-3}, a C nucleus interacts producing a B daughter with a probability of the order of $r\sigma nct_A \sim 0.6\%$ for a cross section $\sigma \simeq 60$ mb, where $r = 4$ accounts for the standard strong shock compression factor and an active lifetime of 3×10^4 yr is assumed. This is of the order of the age of the oldest supernova remnants detected in TeV γ rays—hence capable of accelerating charged parent CRs to higher energy—such as the one in the W51 complex [33]. Accounting for the contribution to B by other nuclei, a benchmark value for primary B at the level of 1% of C is reasonable and consistent with past publications, see, e.g., Eq. (10) in Ref. [34].

It would also be important to account for correlations between different energy bins, usually captured by the correlation matrix. Lacking this information, we focus on two extreme cases: (i) completely correlated systematics; (ii) completely uncorrelated systematics. As this study is insensitive to global normalization factor **s**, a good approximation for the former case is to use the statistical errors only (σ_{stat}). For the latter case, the total uncertainty for each data point is defined as the quadratic sum of statistical and systematic uncertainties (σ_{tot}). Note that a toy-correlation matrix can be constructed based on the detailed systematic errors in Ref. [9] and a model of the energy correlations for each of these systematics. We checked that our qualitative results do not change using this toy model, although they indicate the quantitative importance of the covariance matrix, whose publication by AMS-02 could prove very useful.

Results.—Since we focus on high R, we fit the B/C data above R_{min}, and gauge how the fit changes with a break in the diffusion coefficient, calculating the $\Delta\chi^2$ between the best-fit obtained using Eqs. (2) and (1). To check that the exact choice of R_{min} is not crucial, we perform a scan on R_{min}. The $\Delta\chi^2$ vs R_{min} are plotted in Fig. 1, for the Webber (solid lines) and GALPROP (dashed lines) cross-section formulations. In all cases, the fit improves when the break is introduced. As expected, a larger $\Delta\chi^2$ is found when σ_{stat}'s only are considered, although the nominal quality of the fit (in a frequentist approach) degrades. Within cross-section errors, $\Delta\chi^2$ is approximately constant up to $R_{min} = 20$ GV, and decreases above. This confirms that any choice 2 GV $\lesssim R_{min} \lesssim 20$ GV would lead to similar results of our test, while cutting at too high rigidities would hamper its statistical power since the baseline in R becomes too short to highlight significant changes in the effective δ. Hypothesis tests are better performed by computing the *Bayesian evidence* κ of the two models [35–37]. In our case

$$2\log(\kappa) = \Delta\chi^2, \qquad (3)$$

since both models share the same parameters, and the ratio of the priors cancels in κ. In the conventional Jeffreys scale, a value of $2\log(\kappa) > 10$ is considered "decisive evidence" [35–37]. As shown below, in our analysis this criterion is always satisfied, for all assumptions tested (e.g., different choices for the spallation cross sections). Of course, one may worry that other physical effects could imitate the break in the diffusion coefficient. We test the robustness of our model against two of them: (a) we include a different, but physically motivated high-energy extrapolation of the cross sections; (b) by adding a reasonable amount of
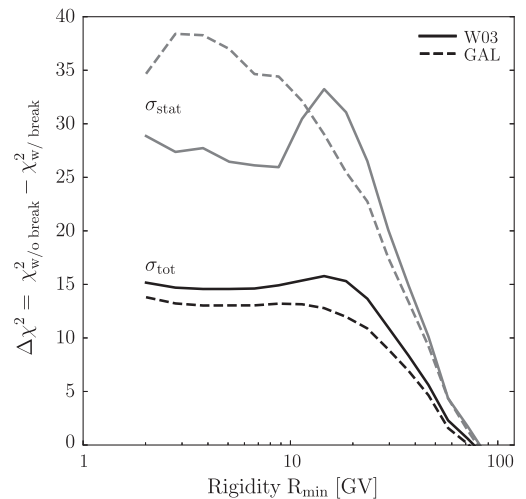

FIG. 1.   Evolution of $\Delta\chi^2$ (with and without the break) vs the minimal rigidity R_{min} above which the fit is performed. Several cases are reported, using the GALPROP (GAL) or Webber 2003 (W03) cross-section data sets, and considering either statistical (σ_{stat}) or total (σ_{tot}) uncertainties.

TABLE I.   Best fit values for K_0 (in units of 10^{-2} kpc^2 Myr^{-1}) and δ, using AMS-02 B/C data above $R_{min} = 15$ GV. The number of degrees of freedom is $46 - 2 = 44$. For each case described in the Letter, we compare the best χ^2 with and without the break. Two different spallation cross-section (Spal. XS) data sets are tested, i.e., GALPROP (GAL) and Webber (W03), as well as different choices for the data uncertainties. For guidance, typical best-fit errors in the σ_{stat} cases are of 1% on δ and 2% on K_0, whereas in the case of σ_{tot} they are of 2% and 6%, respectively.

Fit cases		Fiducial							Cross section enhanced							Primary boron $Q_B/Q_C = 1\%$						
Error	Spal. XS	Without break			With break				Without break			With break				Without break			With break			
σ_{stat}		K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$	K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$	K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$
	W03	2.7	0.67	197	2.7	0.68	164	**33**	2.7	0.67	190	2.7	0.68	160	**30**	2.8	0.69	155	2.8	0.69	131	**24**
	GAL	4.3	0.62	160	4.3	0.62	131	**29**	4.3	0.62	154	4.2	0.62	127	**27**	4.4	0.64	126	4.3	0.64	105	**21**
σ_{tot}	W03	4.5	0.58	84	4.3	0.59	68	**16**	4.4	0.58	80	4.3	0.59	65	**15**	4.4	0.60	69	4.2	0.61	57	**12**
	GAL	7.4	0.52	62	7.1	0.53	50	**12**	7.3	0.52	59	7.0	0.53	48	**11**	7.2	0.54	52	6.9	0.55	42	**10**

primary B, corresponding to 1% of the C source term. Again, note that we do not extend our theory space with extra parameters to be fitted. The best-fit values for each model are summarized in Table I for $R_{min} = 15$ GV. We have checked in each case the independence of the results from the exact choice of R_{min}. In all cases the fits with break are better, yielding a smaller χ^2. The inferred δ is only altered by ~ 0.01, well below the magnitude of the break. None of the potentially degenerate effects mentioned above significantly alters the $\Delta\chi^2$: the indication for the break remains "decisive" ($\Delta\chi^2 \geq 10$). Figure 2 displays the best fits reported in Table I, using GALPROP spallation cross sections and σ_{tot}. The residuals show the weight of the six high-energy data points lying between 300 GV and 800 GV, stressing the importance of reducing the error bars there to tighten the test.
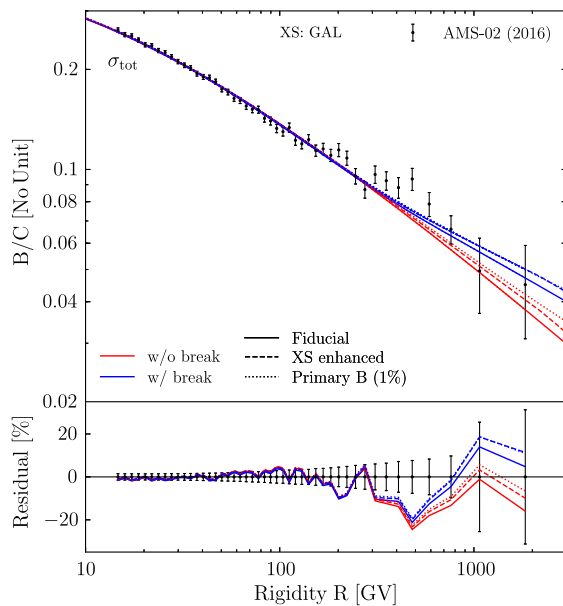

FIG. 2.   Best fits and residuals with (blue) and without (red) the break using GALPROP cross sections and σ_{tot}, for the different models considered in the text.

Discussion and conclusions.—By analyzing AMS-02 B/C data, we have found "decisive evidence" (in a Bayesian sense) in favor of a high-rigidity break in the cosmic-ray diffusion coefficient, matching the similar features found in p and He spectra. This suggests that the three observables (p, He, B/C) may find a *simultaneous* explanation for their spectral features in a model where the break is due to diffusion. We have conducted our study in a rather minimal theoretical setup, but we have tested the robustness of our conclusions with respect to effects such as the high-energy behavior of the cross sections or the presence of a reasonably small primary B component.

It is unclear at the moment if—in a frequentist approach—our results suggest that the underlying models are inadequate to describe the data. Overall, at least for GALPROP cross sections and for the analysis with σ_{tot}, our fits with the break are of acceptable quality. The fit quality assuming σ_{stat} is instead poor. Lacking AMS-02 information on the error correlations, we may speculate that the actual situation is in between. Even then, it might still be that the simple models considered here provide an acceptable description at high R: for instance, theoretical predictions are not error-free, but should be at the very least subject (via the primary C) to the kind of space-time source stochasticity effects first assessed in Ref. [2], comparable to AMS-02 statistical uncertainties.

None of the conventional parameters in more extended theoretical models (like V_c, V_a, etc.) appears degenerate with the kind of high-R feature discussed here. While their introduction is certainly important in attempts to explain the data over the whole range of R, it appears unlikely that those effects might significantly alter our conclusions, as confirmed by some preliminary tests. One may be tempted to achieve a better fit by extending the model space with "nonconventional" free parameters, such as leaving either the diffusion break parameters or the primary B fraction-free, as we have checked *a posteriori*. The consequences of a nominally better fit, however, are serious: allowing for a break significantly larger than the one found in p and He (or a primary B fraction as high as 4.5% of the C) would spoil the emerging global understanding of the broken power-law phenomenon. It may also raise additional

problems, such as a significant overshooting of high-energy antiproton data (see Supplemental Material [38] for an illustration of this tension, which includes Refs. [39–42]). We believe that a global understanding of the key features presented by CR data is preliminary to a detailed "element-by-element" modeling, if that is at all possible within current theoretical capabilities. In this spirit, a test of the ideas discussed here will probably benefit more from a first coherent understanding of an enlarged data set, including absolute flux measurements of primary species like C and O, "intermediate" ones like N, or secondary ones like Li, Be, B notably in the high-R regime, rather than of a complete description of the B/C down to very small rigidities. Needless to say, future results from AMS-02—including information on uncertainty correlations and/or high precision data covering even higher energies (e.g., CALET [43] on ISS, the DAMPE satellite [44], and ISS-CREAM [45] to be launched soon)—will be determinant.

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