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Fragmentation cross-sections and model uncertainties in Cosmic Ray propagation physics

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Abundances and energy spectra of cosmic ray nuclei are being measured with high accuracy by the AMS experiment. These observations can provide tight constraints to the propagation models of galactic cosmic rays. In the view of the release of these data, I present an evaluation of the model uncertainties associated to the cross-sections for secondary production of Li-Be-B nuclei in cosmic rays. I discuss the role of cross section uncertainties in the calculation of the boron-to-carbon and beryllium-to-boron ratios, as well as their impact in the determination of the cosmic-ray transport parameters.

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1. Introduction

The determination of the Cosmic Ray (CR) transport parameters is a central question to astrophysics. Models of CR propagation accounts for particle diffusion off magnetic turbulence and interactions with the interstellar medium (ISM). *Primary* CRs such as C-N-O nuclei are those accelerated in supernova remnants. *Secondary* nuclei are created by collisions (or decays) of primary CRs off the ISM gas. *Secondary-to-primary* ratios of stable nuclei, and notably the B/C ratio, are used to determine the diffusion coefficient, D, and the half-size propagation region, L [1, 2]. The diffusion coefficient is usually expressed as $D \propto D_0 R^{\delta}$. The B/C ratio is sensitive to δ and to the D_0/L ratio. The degeneracy between D_0 and L can be resolved using the data on *unstable-to-stable* isotopic ratios, *e.g.*, the ^{10}Be/^{9}Be ratio. The *decaying-to-decayed* elemental ratio Be/B at $\sim$1–10 GeV can also be used in place of the isotopic ratio ^{10}Be/^{9}Be [3]. Thus, the data combination B/C + Be/B may allow to extract the basic information on the CR transport. An application on this study is the search of dark matter annihilation signals, for which resolving the L/D_0 degeneracy is of great importance. The spectra of B and Be nuclei are now being precisely measured by the Alpha Magnetic Spectrometer (AMS) on the *International Space Station* (ISS). Recent results on CR protons [4] and preliminary light nuclei data at GeV – TeV energies [5] have been recently presented. With the AMS standards of precision, it is timely to review the major uncertainties of the model predictions. In particular, the parameters extraction relies on the secondary production calculations for Be and B nuclei, which depend on several cross-section (XS) estimates. Our understanding of the fragmentation XS's relies on the available nuclear data. Thus, the accuracy of the inferred transport parameters is directly linked to the quality of the fragmentation XS measurements. In this paper, I estimate the impact of the nuclear uncertainties in the CR parameter extraction within the precision that we expect from AMS. In particular, my study is focused on simulated data on the ratios B/C and Be/B, and their connection with the D_0/L degeneracy. For this purpose, a survey of the literature was done in order to collect several Be and B production XS's from B-C-N-O collisions off hydrogen. These data are used to constrain the XS formulae in order to obtain an estimate of their uncertainties. The resulting XS uncertainties are then converted into model uncertainties of the predicted ratios, and eventually into the uncertainties on the relevant parameters that can be inferred by AMS.

2. Cosmic-Ray Transport and Interactions in the Galaxy

In this work I employ the *diffusive-reacceleration* model implemented under the numerical code GALPROP, which solves the CR propagation equation for a given set of input parameters [1]. The transport equation for a CR species j is expressed as:

$$\partial_t \psi_j = q_j + \vec{\nabla} \cdot \left[D \vec{\nabla} \psi_j \right] - \psi_j \Gamma_j + \partial_p \left[p^2 D_{pp} \partial_p p^{-2} - \dot{p}_j \right] \psi_j \tag{2.1}$$

where $\psi_j = \frac{dN_j}{dV dp}$ is the particle density per unit of momentum p. The CR acceleration in primary sources is described as $q_j^{\rm pri} \propto R^{-\nu}$, while the secondary production term is $q_j^{\rm sec} = \sum_k \psi_k \Gamma_{k \to j}$, for fragmentation/decay of k-type nuclei into j-type nuclei. The secondary production rate is:

$$\Gamma_{k \to j} = \beta_k c \sum_i n_i \sigma^i_{k \to j}(E) dE \,, \tag{2.2}$$

where n_i is the number densities of the ISM nuclei, $n_{\rm H} \cong 0.9\,{\rm cm}^{-3}$ and $n_{\rm He} \cong 0.1\,{\rm cm}^{-3}$, and $\sigma^i_{k\to j}$ is the j-th nucleus production XS at energy E from k-nuclei destruction off the i-th target. The term Γ_j is the destruction rate for a cross section $\sigma^{\rm tot}_j$ or particle decay with lifetime τ_j. The diffusion coefficient D is taken as $D(R) = \beta D_0 \left(R/R_0\right)^{\delta}$, where D_0 gives its normalization at $R = R_0 \equiv 4\,{\rm GV}$, and δ gives its rigidity dependence. The reacceleration is described as diffusion process acting in momentum space. The momentum diffusion coefficient is $D_{pp} \propto p^2 v_A^2/D$, where v_A is the Alfvén speed of magnetic plasma waves in the ISM. The term $\dot{p}_j = dp_j/dt$ is the momentum loss rate for Coulomb and ionization losses. The steady-state equation $\partial \psi_j/\partial t = 0$ is solved into a cylindrical halo of half-thickness L with the zero-flux condition at the boundaries. The local interstellar spectrum for each species as function of kinetic energy per nucleon is given by $\Phi^{\rm IS}_j(E) = \frac{cA}{4\pi}\psi_j(r_\odot, p)$. To describe the solar modulation effect, I will adopt the so-called *force-field approximation* [6]. After propagation, the primary primary nuclei spectra are of the type $\mathscr{P} \propto (L/K_0)E^{-\nu-\delta}$ *i.e.*, degenerated between source and transport parameters. The use of the B/C ratio allows to determine the parameter δ.The remaining D_0–L degeneracy can be lifted using unstable isotopes such as ^{10}Be (lifetime $\tau \approx 1.5\,{\rm Myr}$), because its mean propagation length is $\lambda_u = \sqrt{D\gamma\tau} \ll L$ below a few GeV/nucleon. In principle also data on the ratio Be/B can be used, because it maximizes the effect of the of radioactive decay $^{10}{\rm Be}\to{}^{10}{\rm B}+{\rm e}^- + \bar{\nu}_e$. The B/C and Be/B ratios are currently being measured by AMS.

3. Fragmentation Cross Sections and Uncertainty Estimates

Several fragmentation XS's are needed to compute the secondary production rate, because Be or B nuclei are produced by several *projectile→fragment* combinations (P→F). Popular algorithms are YIELDX [20] or WNEW [21, 22, 23], that provide energy-dependent XS's off hydrogen target for several P→F reactions. Under GALPROP, the production XS's come from the `CEM2k` and `LAQGSM` codes, normalized to the data [24, 25, 26, 27]. The XS's for isotopically separated fragment/target have been measured by several experiments, though the data are available in only narrow energy ranges. Figure 1 shows the data for Be and B isotopes from fragmentation of C-N-O nuclei off hydrogen at 30 MeV/n – 10 GeV/n. Beryllium is also produced via *tertiary* reactions, such as B→Be, that are considered in this study. Spallation of heavier nuclei such as Ne-Mg-Si or Fe gives a minor contribution and it is not considered here. Many reactions have an energy dependence at $E \lesssim 0.5\,{\rm GeV/n}$ which is often ignored in CR propagation, but may be important in the context of reacceleration models (considered here) At energy above than a few GeV/nucleon, all the XS's are nearly constant in energy. The data in Fig. 1 are compared with the XS formulae from WNEW, YIELDX, and GALPROP. Despite large discrepancies among the various formulae, the GALPROP XS's describe well the data. In order to determine the XS uncertainties using the data, I have performed a *re-normalization* of the GALPROP parameterizations $\sigma_{\rm G}(E)$ to the data. For each P→F channel, the XS has been re-fit as $\sigma_{\rm H}(E) = a\sigma_{\rm G}(bE)$, where the parameters a and b represent the normalization and the energy scale. Some of the re-evaluated XS's are shown as solid lines in Fig. 1. The shaded bands are the estimated uncertainties. These re-fitted XS's are often close to their original values, though the Be production under GALPROP is found to be over-estimated by a few percent. A Be overproduction was also reported in [30], and it was ascribed to the production XS's. To account for a 10% fraction of interstellar helium, it was applied

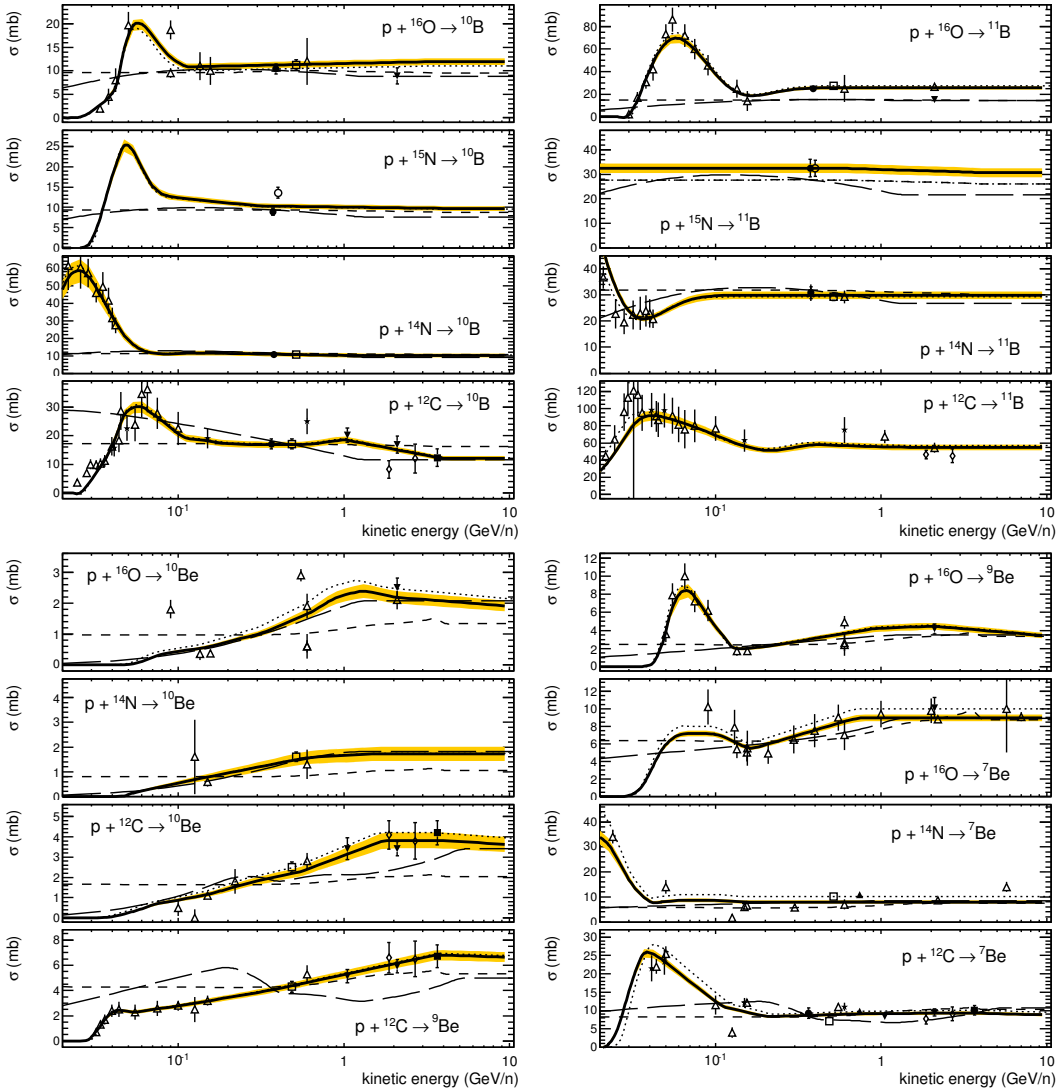

Figure 1: Fragmentation XS's for ^{10}B, ^{11}B, ^{7}Be, ^{9}Be, and ^{10}Be production from C-N-O collisions off hydrogen. The data are from [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. The lines are from the WNEW (short-dashed), YIELDX (long-dashed), GALPROP (dotted), and the re-normalized XS's of this work (thick solid lines) with their uncertainty band.

the rescaling factor $F_{\alpha/p}$ from [31], and the He-target XS's are assumed to have the same relative uncertainties of the H-target XS's. For the total destruction I have employed the formula of [32]. These reactions are known with better precision and their uncertainty has a negligible impact on the Be-B propagation.

4. AMS Physics Potential and Impact of Nuclear Uncertainties

The anticipated AMS data for the ratios B/C and Be/B have been computed as in [8] using the input fluxes for $\Phi_{\rm Be}$, $\Phi_{\rm B}$, and $\Phi_{\rm C}$ generated with a *reference model*. In the reference model, the pri-

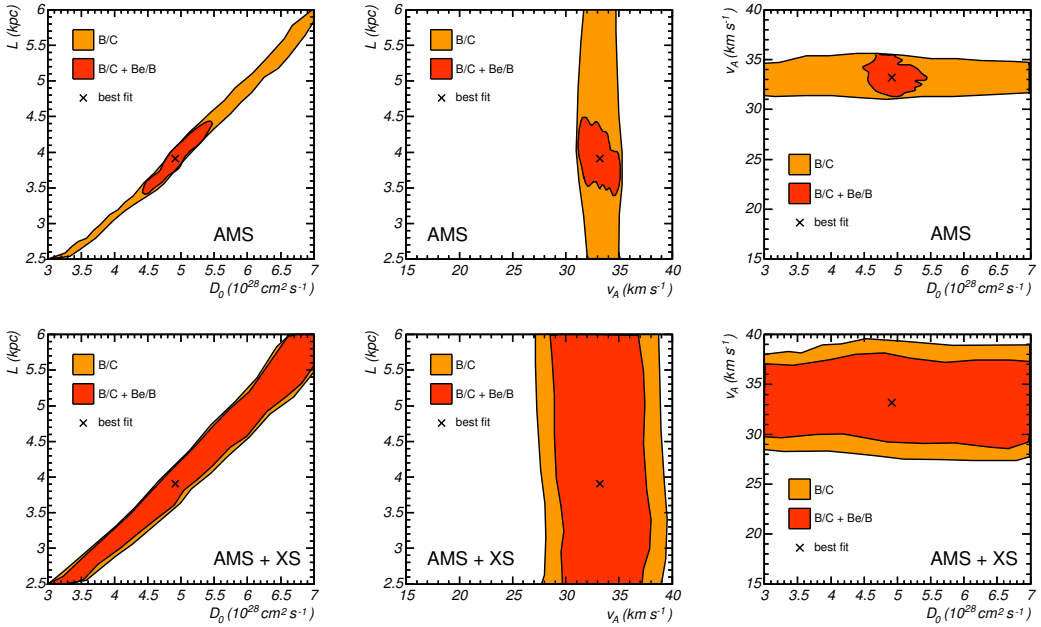

Figure 2: Top: estimation of the AMS capabilities in constraining the parameters D_0, L, and v_A with with the B/C and Be/B ratios. Bottom: same as above after accounting for *nuclear uncertainties* in the Be-B production rates.

mary CRs injection spectra are taken as power-law with index $\nu = 2.38$. The diffusion parameters are $D_0 = 5 \cdot 10^{28}\,\mathrm{cm^2\,s^{-1}}$, $\delta = 0.38$, and $v_A = 33\,\mathrm{km\,s^{-1}}$. The propagation region has half-height $L = 3.9\,\mathrm{kpc}$. The modulation parameter is taken as $\phi = 550\,\mathrm{MV}$. For the Be-B production I have used the XS's re-determined in this work, and their estimated uncertainties have been translated into uncertainties for the propagated fluxes and ratios. Typical uncertainties are $\sim 5\,\%$ for B production and $\sim$ 7-10% for Be production, with $\sim 10\%$ for ^{10}Be productions. The Be-B elements are being measured by AMS at energies from $\sim 0.5\,\mathrm{GeV}$ to $\sim 1\,\mathrm{TeV}$ per nucleon. In this work, I consider the B/C ratio between 2 and 200 GeV/n and the Be/B ratio between 1 and 100 GeV/n. In this energy range, the influence of solar modulation is below $\sim 1\,\%$. The expected AMS ability in constraining the model parameters is first estimated *without* accounting for the nuclear uncertainties. A grid scan is performed in the parameter space $D_0 \times L \times v_A$, running GALPROP 3,420 times, over a $19 \times 15 \times 12$ grid. Thus, the resulting spectra are tri-linearly interpolated to a finer parameter grid corresponding to 187,245 models. From the B/C ratio predicted by each model, $(\mathrm{B/C})_{\mathrm{mod}}$, the χ^2 is computed for the AMS mock data, $(\mathrm{B/C})_i$, that are generated with the *reference model*:

$$\chi^2_{\mathrm{B/C}} = \sum_{\mathrm{i}} \left[\frac{(\mathrm{B/C})_{\mathrm{mod}} - (\mathrm{B/C})_i}{\delta(\mathrm{B/C})_i} \right]^2 \tag{4.1}$$

Similarly, the χ^2 is also computed for the Be/B ratio and for both ratios combined. In Fig. 2 (top panels) the one-sigma contour regions are shown as 2D projections of the parameter space using the χ^2 for the B/C ratio and for the B/C+Be/B combined ratios. The best-fit model is marked as "$\times$" on each plot. It always recovers the true reference model. The complementarity of the two ratios is apparent in resolving the L-D_0 degeneracy. While the B/C ratio constrains L and D_0

into a tight region of the (L, D_0) plane, only the combined B/C+Be/B ratios allow to determine their single values. On the other hand, Alfvén speed v_A can be determined by means of B/C data only. Using data below 2 GeV/nucleon one may expect even tighter constraints to these parameters. Nevertheless, the parameters are determined with accuracy $\delta D_0 \sim 0.5 \cdot 10^{28}\,\mathrm{cm^2 s^{-1}}$, $\delta L \sim 0.5\,\mathrm{kpc}$, and $\delta v_A \sim 2\,\mathrm{km/s}$. This *would* represent a great progress in CR propagation.

To study the impact of nuclear uncertainties, the procedure is now repeated after accounting for the estimated XS errors. In the χ^2 calculation of Eq 4.1, the AMS errors are now summed in quadrature to the nuclear uncertainties $\delta(\mathrm{B/C})_n$ and $\delta(\mathrm{Be/B})_n$. The results are shown in Fig. 2, bottom panel. The nuclear uncertainties have an appreciable impact on the constraints provided by the B/C ratio, and a dramatic impact in breaking the $D_0 - L$ degeneracy. In summary, this degeneracy remain unresolved when the nuclear uncertainties are taken into account. To lift the D_0/L degeneracy, the information to be extracted in the Be/B ratio contained in the $^{10}\mathrm{Be}\rightarrow{}^{10}\mathrm{B}$ decay, which produces only tiny variations in the Be/B ratio. This information is blurred by the large uncertainties on the ^{10}Be production as well as by the uncertainties on the more abundant ^{7,9}Be and ^{11}B components. Thus, a direct measurement of ^{10}Be at $\sim$ 1–10 GeV/n would probably bring tighter constraints. To test this idea, the procedure was repeated after accounting the sole uncertainties in the ^{10}Be production. In this case, the precision of the recontructed parameters is found to be $\delta D_0 \sim 1.5 \cdot 10^{28}\,\mathrm{cm^2 s^{-1}}$ and $\delta L \sim 1.5$ kpc, which still represents large uncertainties in comparisons to the AMS potential. However, given the unavoidable nuclear uncertainties of secondary production models, a direct measurement of ^{10}Be flux seems to bring much cleaner information than a precise Be/B measurement. Besides the impact of the XS uncertainties, it is also instructive to study the effect of systematic biases in single P$\rightarrow$F reactions. This study and other elaborations connected with this work will be presented in a forthcoming work [36]

5. Conclusions and Discussions

These estimates show a promising potential for the AMS experiment. AMS is able to pose tight constraints on the key transport parameters, thus we can expect a significant progress in CR propagation physics. Given its high level of precision the *nuclear uncertainties* implicit in the models are found to be a major limitation for the interpretation of the CR data. After accounting for these uncertainties, the D_0/L degeneracy remains poorly resolved and the Be/B ratio appears to bring little information for the parameter extraction. Isotopically resolved ^{10}Be/^{9}Be data would probably be preferable, though the ^{10}Be production rate is also affected by large uncertainties. On the other hand, precise Be/B data at $E \gtrsim 10$ GeV/nucleon may represent a powerful tool for testing the nuclear physics inputs of the propagation models, or to detect possible biases that may cause a parameter mis-determination. It worth stressing that this problem has a direct impact for the dark matter search [37]. In the AMS era, the uncertainties of nuclear data have become a major limiting factor for further progress in CR propagation. In this light, there is an urgent need for a dedicated experimental program of XS measurements and modeling.

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