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Current status and new perspectives on cosmic ray deuterons

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Deuterons are the most abundant secondary cosmic ray species in the Galaxy, but their study has been severely limited due to experimental challenges. In an era with new experiments and high-precision measurements in cosmic rays, having a low-uncertainty deuteron flux in a wide energy range becomes possible. The deuteron-over-helium ratio ($d/^4$He) is important to understand the propagation of cosmic rays in the Galaxy and in the heliosphere, complementing observations with heavier nuclei like the boron-to-carbon ratio. In this work, the most up-to-date results of the deuteron flux and the $d/^4$He ratio at the top of the atmosphere have been obtained using GALPROP [1] and a 3D solar modulation model. It was found that the simulation describes the deuteron flux and $d/^4$He data below 1 GeV/n within the uncertainties of the model. However, the model underestimates the best-published measurements available at high energy. This discrepancy suggests different effective diffusions have to be considered between secondary light species like deuterons and heavier nuclei. Either this is a consequence of a break in the universality of propagation between light and heavier nuclei or a lack of precision measurements, it is something AMS-02 [2] will help to resolve in the near future.

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1. Introduction

Hydrogen (H) and helium (He) isotopes are the most abundant species in cosmic ray (CR) nuclei. Protons (p) represent nearly 90% of these charged particles, and it is estimated that CR deuterons (d), the only other stable H isotope, are approximately 2%-3% of the proton abundance [3, 4]. Since CR deuterons are known to be destroyed in the nuclear processes that occur during stellar formation, they are not expected to be accelerated in supernova remnants like primary CRs such as protons, helium–4 (^{4}He), carbon (C), and oxygen (O) do. Instead, they are predicted to originate from fragmentation interactions between ^{4}He, carbon (C), oxygen (O), and other heavier nuclei with the interstellar medium (ISM), i.e., they are considered secondary CRs [5].

Secondary CRs such as d, helium–3 (^{3}He), lithium (Li), beryllium (Be), boron (B), etc., are probes to characterize the propagation process of CRs in the Galaxy. Secondary-to-primary CRs ratios are directly related to the amount of material traversed by CRs. This quantity is known as grammage (X), and is usually reported to have a value of around 10 $\mathrm{g\,cm^{-2}}$ for particles with an energy of about 10 GeV per nucleon [6, 7]. This value is typically obtained from the more abundant boron-to-carbon ratio (B/C) measurements, given the experimental advantage of separating both elements by measuring the charge rather than separating H or He isotopes by their masses. The measured B/C ratios demonstrate the diffusive motion of CRs in the Galaxy, and are a key component in constraining the diffusion parameters. In the standard propagation scenario all CR species are driven by the same diffusion parameters obtained with the B/C ratio, however, the lack of information about other secondary-to-primary ratios, especially lighter nuclei like d/^{4}He and ^{3}He/^{4}He, has not allowed rigorous testing of this “universality in propagation" postulate.

In this context, precision measurements of d/^{4}He or d/He in the region above 1 GeV, where solar effects are less critical, will help the cosmic ray community to probe the universality of cosmic ray propagation through the Galaxy and clarify if there is any difference in the transportation process between light and heavy CR nuclei.

2. Deuteron formation in Cosmic Rays

As mentioned before, CR deuterons are produced mainly by the fragmentation of primary ^{4}He and secondary ^{3}He interacting with the ISM. An additional contribution of around 20% comes from the fragmentation of heavier nuclei like C, N, and O [8]. Since the ISM is mostly composed of H ($\sim$ 90%) with a small contribution of He ($\sim$ 10%), the releveant reactions in this CR analysis are ^{4}He+p(He), ^{3}He+p(He), and CNO+p(He). After a fragmentation interaction, the produced deuterons carry most of the projectile's energy, showing a peaked Gaussian distribution around it. Thus, as an acceptable approximation, the final deuteron kinetic energy per nucleon is considered to be similar in magnitude to the incoming He kinetic energy per nucleon [8, 9]. Consequently, deuterons produced by fragmentation are dominant in the GeV region. Another important deuteron production process is the fusion of two protons through the reaction $p + p \rightarrow d + \pi^+$ [8, 10]. Although the pp fusion reaction cross section is smaller than the one from He fragmentation, the proton flux is ten times more abundant than the He flux, making this contribution a large component of the final deuteron spectrum. Deuterons generated in the pp fusion reaction contribute to the region below 1 GeV, especially in the region between 80 and 250 MeV/n [10].

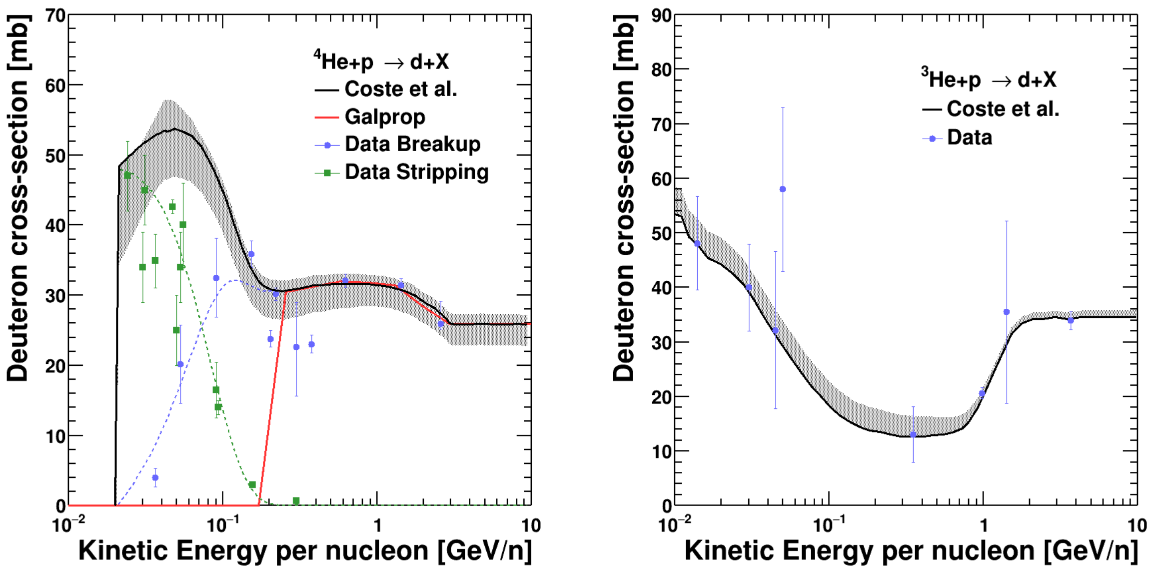

Figure 1: Deuteron production cross sections: From ^{4}He fragmentation (left plot) and from ^{3}He fragmentation (right plot). Parametrizations from Coste *et al.* and GALPROP are compared to measurements (squares and circles) [10–17]. More details are in the text.

Measurements of the reactions mentioned above are essential to model deuteron production cross sections at different energies and, therefore, to predict the deuteron flux correctly. An updated summary of these measurements from accelerator experiments as of 2008 is presented in Coste *et al.* [8] (see Appendix B in [8]) and revised in this paper (see Fig. 1). In the work by Coste *et al.*, an improved parametrization of the cross sections based on the works by Cucinotta *et al.* [9] and Meyer [10] is shown. This parametrization is the result of two contributions: a pickup process dominating below 0.1 GeV/n, where the incident proton tears a neutron or proton off the He nuclei, and a break-up process ruling above 0.1 GeV/n, where the energy is enough to dissociate the incoming He in nucleons that can form new light nuclei by coalescence. In Fig. 1, the data samples [10–17] and parametrizations used by Coste *et al.* are presented for ^{4}He+p and ^{3}He+p fragmentation reactions as a function of kinetic energy per nucleon. In the case of the ^{4}He+p reaction (Fig. 1 left panel), the parametrization for pickup and break-up contributions are shown as green and blue dashed lines respectively. Likewise, green squares and blue circles data points represent measurements for these two processes accordingly. The sum of these two contributions results in the total production cross section shown as a solid black line. For the ^{3}He+p reaction (Fig. 1 right panel), only the total deuteron production cross section is shown along with available measurements.

The model used in GALPROP version 56 for deuteron production cross section in ^{4}He+p interactions can be seen in the left panel of Fig. 1 (solid red line). GALPROP's parameterization of the cross section is based only on the most recent data by [11] for energies above 0.2 GeV/n. Furthermore, GALPROP does not include a deuteron production cross section from the ^{3}He+p reaction. Therefore, the first goal of this work was to implement updated parametrizations of the

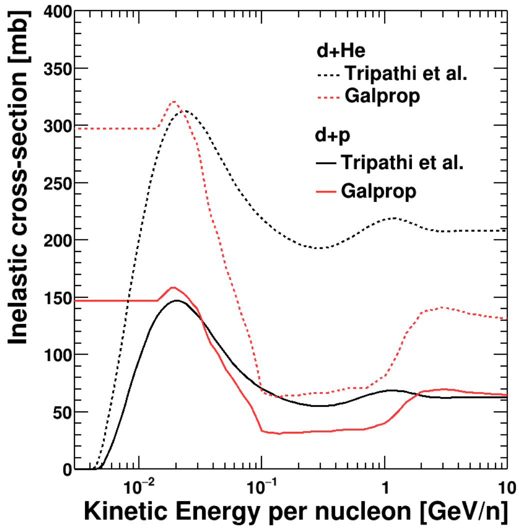

Figure 2: Deuteron total inelastic cross sections: The parameterization by Tripathi *et al.* [19], used in this work, is compared to the parameterization generally used with `GALPROP` [20], for d+H and d+He interactions.

deuteron production cross sections developed by Coste *et al.* in `GALPROP` (a similar study was made by [18]). An essential component in calculating the deuteron production in CRs is the uncertainty related to the production cross section. This uncertainty can be seen in Fig. 1 as a gray band in both reactions, and it was estimated based on residuals between parametrization and available data, weighted by the errors reported and considering an approximated systematic error of 5% for the most accurate dataset [11].

After production, deuterons undergo a series of inelastic interactions with the ISM, reducing the number that arrives at Earth. Total inelastic cross sections of light nuclei with H and He targets are described by Tripathi *et al.* [19] using a parametric model from the MeV to GeV energy range. Differences between the model considered in `GALPROP` and Tripathi's prediction for d+He and d+p interactions are shown in Fig 2. The reason for these differences is that `GALPROP` uses a general parameterization for p+A reactions by Barashenkov and Polanski [20], while Tripathi's parameterization is specific for light-nuclei interactions. Hence, in this work, Tripathi's parametrization was implemented in `GALPROP` for a better description of the deuteron total inelastic cross sections.

3. Results for Cosmic Ray Deuterons

After introducing the updated deuteron production cross sections described in Sec. 2 into the `GALPROP` propagation model, the LIS deuteron flux was calculated following the propagation parameters found in Boschini *et al.* [21] (see solid black line in Fig. 3 (a)). The modulated deuteron spectrum averaged over a period of one year was obtained for three different periods of time, using a full three-dimensional propagation model for describing CR modulation throughout the heliosphere [22]. The three modulated spectra are representative of different periods of solar activity: 2007 (dotted red line), which was a period in between a maximum and a minimum of solar activity, 2009 (continuous red line), which was the minimum of the solar cycle 23, and 2014 (dashed red line), which corresponds to the period of the maximum of solar cycle 24. [23].

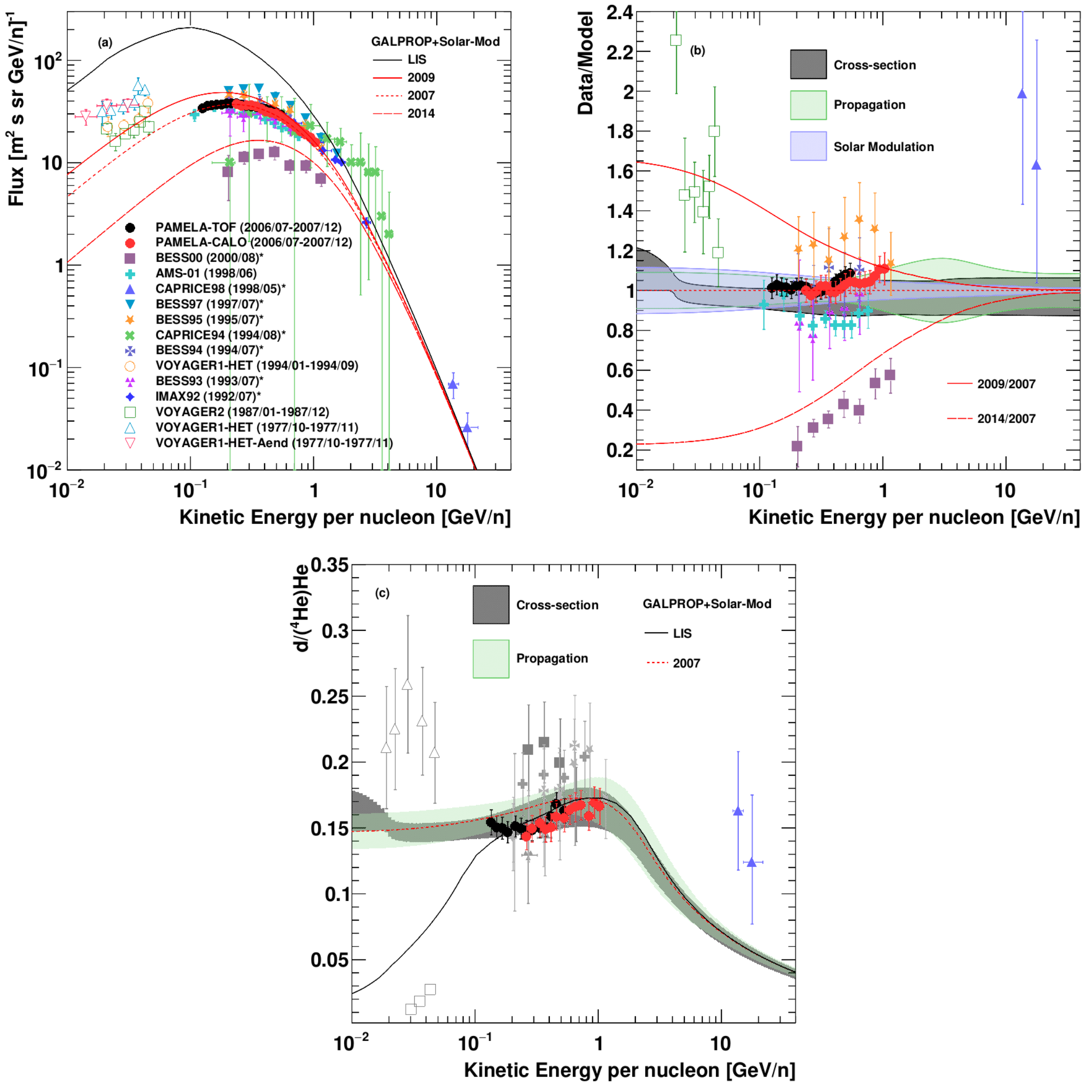

Figure 3: Deuteron results: Plot (a) shows the deuteron LIS obtained with GALPROP along with the deuteron spectra for three solar modulation periods obtained with the 3D numerical model corresponding to 2007, 2009, and 2014. Plot (b) shows the flux ratio between data and simulation for the 2007 solar period. Uncertainties derived from production cross section, propagation, and solar modulation are included. Plot (c) shows the deuteron over ^{4}He ratio simulation for the 2007 solar period compared to $d/^4$He and d/He(*) measurements.

The results from these simulations are compared to the available data as shown in Fig. 3 (a). In Fig. 3 (b), the data are compared to the model by calculating the ratio for every data sample to the predicted flux in 2007 (dashed red line). The model results in 2009 (solid red line) and 2014 (long dashed red line) were also divided by the flux from 2007. In this figure, shadow bands with different colors have been plotted to represent uncertainties from cross section (gray), propagation (green), and solar modulation (blue). The cross section uncertainty was derived from the study in Sec. 2, estimating the deviation between the best-fit model and accelerator data (see Fig. 1). This uncertainty was propagated to the flux calculation with GALPROP, obtaining a deviation of around 10% below the mean value of the parameterization for most of the energy range. In the low-energy region (<0.1 GeV/n) where the cross section is dominated by the stripping process the uncertainty increases in the flux as a consequence of the higher errors in accelerator measurements. The propagation uncertainty was obtained by varying the best-fit values of the propagation parameters between the minimum and maximum errors reported and calculating the deviation of the fluxes associated with those parameters. As observed in Fig. 3 (b), the propagation uncertainty is around 10% below 1 GeV/n, but increases to 20% around 3 GeV/n, and decreases to about 10% above 10 GeV/n. The bump at 3 GeV/n is mostly due to the variation of the normalization parameter in the spatial diffusion coefficient D_0 and the Alfvén velocity as part of the reacceleration process. The uncertainty associated with the solar modulation model was derived by calculating the deviation between the model and PAMELA measurements for He in similar periods. An approximate 10% difference is observed below 1 GeV/n, with a decreasing effect at higher energies, as expected.

The first important observation in Fig. 3 (b) is the good agreement between the simulation result for 2007 (dashed red line) and PAMELA data. As can be seen, measurements are well within model uncertainties. The theoretical prediction for this period of medium solar activity is also close to AMS-01 [24], BESS93, and BESS94 [25], consistent with low-medium solar activity periods between solar cycles 22 and 23. The result for the 2014 period (long dashed red line) is close to BESS00 [26] data and is compatible with a high solar activity time in cycle 23. In the case of 2014 prediction, the overproduction by the model could be explained by a lower intensity in solar cycle 24 (2009) than in cycle 23 (2000). However, a dedicated analysis is outside the scope of this work. Additionally, the flux in 2009 (solid red line) corresponding to the solar minimum between cycles 23 and 24 is close to the BESS95 and BESS97 measurements taken during a solar minimum activity between cycles 22 and 23. This result in 2009 is also close to the data from VOYAGER 1 and 2 [27–29] taken during solar minimum in cycles 20, 21, and 22. It is essential to clarify that since solar cycles have different intensities, it is not expected that the simulation calculated in this work for cycle 24 entirely matches measurements taken in different solar cycles.

In Fig. 3 (c), the simulation result for deuterons over ^{4}He is presented in comparison to $d/^4$He and d/He measurements. As can be seen, the model describes PAMELA, BESS93, and BESS94 data within the model uncertainties (although it tends to overestimate PAMELA measurements). The result is also close to AMS-01 data and other BESS results that have uncertainties on the order of 20%. This result is remarkably satisfactory, considering none of the data shown in the plot were used to tune the model, and that the prediction is based entirely on B/C, p, and He flux data. At energies below 0.1 GeV/n, the model underpredicts VOYAGER 1 measurement by around 30%—as expected from what was observed in the deuteron flux. For the case of VOYAGER 2, measurements are closer to the LIS prediction, which is explained by an anomalously large ^{4}He measurement [29]. At higher energies, the result from this work is well below CAPRICE98 [30] measurements, for example, the difference between the lower error limit for the data point at 17.8 GeV/n and the model at that energy is around 30% (see Fig. 3 (c)), with an uncertainty in the model from cross section on the order of 6%. If the data point at 3 GeV/n in the left panel of Fig. 1 is not included due to its large error, the predicted value of the model for the $d/^4$He ratio could increase to about 10 to 15%, still below the lower limit measured by CAPRICE98. This could indicate a discrepancy in the diffusion model for light nuclei compared to B/C. However, given the magnitude of the uncertainties of these measurements (order of 30%-40%), it is difficult to reach a conclusion.

4. Conclusions

A state-of-the-art calculation of the deuteron flux and $d/^4$He was performed using GALPROP v56 as a propagation modeling tool, and considering a diffusion-reacceleration model with the Boschini *et al.* [21] parameters obtained by fitting AMS-02, HEAO-3-C2, VOYAGER 1, and ACE-CRIS data for nuclei from H to nickel and the B/C ratio. Deuteron and ^{3}He production cross sections were updated in GALPROP by using the latest parametrizations from accelerator experiments [8], and the related uncertainties were included in the calculations.

It was found that the simulation results describe the deuteron flux and $d/^4$He data below 1 GeV/n within the uncertainties of the model, and show consistency with ^{3}He/^{4}He ratio. However, the simulation underestimates the only measurements available at high energy by CAPRICE98 for $d/^4$He and ^{3}He/^{4}He ratios, characterized by their large uncertainties. If such a difference is corroborated by future high-precision measurements in CRs, and reduced uncertainties in the model, a general calibration of the propagation parameters using the B/C ratio would no longer be valid and could imply a break in the universality of cosmic ray propagation. Further studies and high-precision measurements of $d/^4$He for energies above 1 GeV/n are essential to arrive at a definite conclusion.

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