PROCEEDINGS OF SCIENCE

Study of Cosmic-Ray Light Nuclei Transport with GALPROP

N. Picot-Clémente[*]
Institute for Physical Science and Technology, University of Maryland, College Park MD 20742, USA
E-mail: `picot@umd.edu`

Eun-Suk Seo
Institute for Physical Science and Technology, University of Maryland, College Park MD 20742, USA
E-mail: `seo@umd.edu`

Andrew Strong
Max-Planck-Institut fuer extraterrestrische Physik, München, Germany
E-mail: `aws.mpe.mpg.de`

Yuxi Lu
Institute for Physical Science and Technology, University of Maryland, College Park MD 20742, USA
E-mail: `lyx12311@umd.edu`

The isotopes ^{2}H and ^{3}He in the cosmic radiation are mainly secondary products from interactions of primary cosmic rays in the interstellar medium. Secondary-to-primary ratios give important information on processes that occurred during the propagation of cosmic rays, independent of the unknown source spectrum. Boron-to-Carbon ratio data have been primarily used to study cosmic-ray transport. As statistics have increased and mass resolution have improved, recent measurements on cosmic-ray hydrogen and helium isotopes provide another probe for their propagation in the Galaxy. In this paper, we use the GALPROP program for calculating the propagation of relativistic charged particles. The standard GALPROP software had to be modified to be suitable for hydrogen and helium isotopes in the energy region 0.2 to 1.5 GeV/n. The proton fusion process for production of ^{2}H had to be implemented, and production cross sections for light isotopes had to be updated at these energies. We will present the modifications made on GALPROP for its application to proton and helium isotopes.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

---

[*] Speaker.

1. Introduction

In recent years, measurements of Galactic cosmic-ray nuclei fluxes have become more precise with experiments such as PAMELA [1, 2], BESS-Polar [3, 4] and AMS-02 [5]. Analytical or semi-analytical models [6, 7, 8] for cosmic-ray propagation or also simplistic models based on the Leaky Box approximation [9, 10], are reaching their limits in accurately reproducing observations. More realistic models, such as GALPROP [11, 12] or DRAGON [13], need to be used to further study and understand the history of cosmic-ray propagation in the Galaxy. GALPROP[1] is aimed to better reproduce observations of Galactic cosmic-ray charged particles and their diffuse emission during propagation, by incorporating as many processes and astrophysical data as possible such as nuclear reactions, diffusive reacceleration, synchrotron emission, gaz distribution, radiation field distributions, etc...

The GALPROP software calculates fluxes for many cosmic-ray nuclei, antiprotons, electrons, positrons or gamma rays. Although the program is already very complete and contains many physical processes and cross sections, some may be missing, incomplete, or obsolete for specific species. The study of hydrogen and helium isotopes has been shown to be as constraining on propagation models and parameters as the widely used Boron-to-Carbon ratio [14]. Cosmic-ray ^{2}H and ^{3}He are mostly secondary particles mainly produced after interactions of ^{1}H through fusion interaction (for ^{2}H) and ^{4}He through fragmentation (for ^{2}H and ^{3}He) in the interstellar medium. Heavier nuclei also contribute to a lesser extent. In GALPROP, the proton fusion reaction producing ^{2}H particles was not implemented, and some production cross sections for hydrogen and helium isotopes from fragmentation of heavier nuclei were approximate or missing.

In Section § 2 we recall the essentials of GALPROP. The implementation of the proton fusion reaction will be then detailed in Section § 3, and Section § 4 will describe the modifications performed on production cross sections for cosmic-ray hydrogen and helium isotopes. The results obtained before and after modifications will also be shown.

2. The GALPROP Software

GALPROP is a program mainly written in C++, with some routines in FORTRAN 77. The algorithm consists in solving the general transport equation for all cosmic-ray species using a Crank-Nicholson implicit second-order scheme. Nucleon injection spectra are modelled as power laws in momentum $dq(p)/dp \propto p^{-\gamma}$ in GALPROP. They can be artificially broken into two power laws to better reproduce observations. The spatial diffusion coefficient is defined as $D_{xx} = \beta D0_{xx}(\rho/\rho_0)^{\delta}$, where β is the velocity divided by the speed of light, ρ is the magnetic rigidity, δ is equal to $1/3$ for a Kolmogorov spectrum of interstellar turbulence or $1/2$ for a Kraichnan cascade, or can be set arbitrarily. D_{xx} may be also broken into two power laws with parameter δ_1 below the rigidity break ρ_0 and δ_2 above.

Ionization and Coulomb interaction energy losses are included for nuclei. A 2D cylindrically symmetrical or a 3D option to resolve the propagation equation is available in GALPROP. The nuclear reaction network is computed using a cross section database that includes measurements

---

[1] http://galprop.stanford.edu/

and energy-dependent fitting functions. Every nuclei, starting from the heaviest (^{64}Ni) to the lightest (^{1}H), are computed by solving the propagation equation and resolving all secondary source functions. More detailed information can be found in [15].

The missing proton fusion interaction was implemented in the latest GALPROP version r2754[2]. This version was used to modify fragmentation cross sections for the light-quartet isotopes, which will be made publicly available in the future. See A. W. Strong [16] at this conference which describes latest GALPROP enhancement, including the implementation of the proton fusion reaction in GALPROP.

3. The Proton Fusion Reaction

Cosmic-ray deuterium particles are mainly produced by fusion of primary protons and fragmentation of helium nuclei in the interstellar medium. Although the fusion reaction cross section $p + p \rightarrow d + \pi^{+}$ is small compared to helium fragmentation p-He^{4}, it can contribute equally at a given energy to the production of deuterium due to the large abundance of protons in the cosmic rays. The production cross section as a function of proton kinetic energy for the proton fusion reaction is shown in Figure 1. Cross section data were compiled by [17] and digitized from [14]. The distribution peaks around 600 MeV, reaching ~ 3 mb, and rapidly decreases both at lower and higher energies.

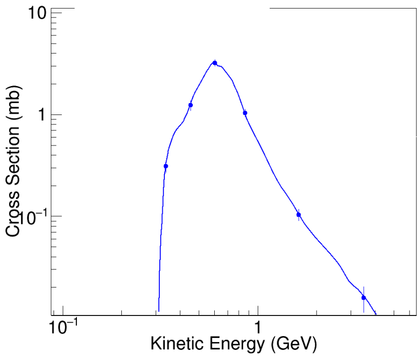

Figure 1: Cross section Vs. proton kinetic energy of the fusion reaction $p + p \rightarrow d + \pi^{+}$. Data points were compiled by [17], and the curve was digitized from [14].

The implementation of deuterium production through proton fusion is based on calculations from [18]. GALPROP works in momentum, so the differential cross section in deuterium kinetic energy was modified to differential cross section in momentum $d\sigma/dP$ with:

$$\frac{d\sigma}{dP} = \sigma_{tot} \times \beta_3 \frac{0.22 + \cos^2(\theta_3')}{2B(E_1) \times (0.22 + 1/3)}, \tag{3.1}$$

where σ_{tot} is the total production cross section at a given proton kinetic energy, taken from Figure 1. β_3 is the relative speed of deuterium, θ_3' is defined as $E_3 = A(E_1) + B(E_1)\cos(\theta_3')$ with E_3 the deuterium kinetic energy, and A, B functions of the incident proton kinetic energy E_1. Hence, at a

---

[2] The latest version of GALPROP is available at https://sourceforge.net/projects/galprop/

given proton kinetic energy, the upper and lower limits for the energy of deuterium are driven by $\cos(\theta'_3) = \pm 1$. As a result, with a maximum production cross section of ~ 600 MeV, the reaction $p + p \rightarrow d + \pi^+$ should mainly produce deuterium with energies between ~ 80 MeV/n and ~ 250 MeV/n [18].

One iteration of the program produces deuterium from fragmentation only since cosmic rays are computed for particles from high to low atomic numbers. A second iteration is then needed to compute first primary, secondary protons, and then deuterium from fusion. Figure 2 presents the differential flux of deuterium as a function of its kinetic energy per nucleon after implementing the fusion process. To see the deuterium produced from proton fusion interaction only, we computed GALPROP by considering only the propagation of singly-charged particles, so that no deuterium is coming from fragmentation of higher atomic number particles. As test case, a proton injection spectrum with index γ of 0 was considered. The "Plain Diffusion" model from [19] was used here, with diffusion parameters $D0_{xx} = 2.2 \times 10^{28}$ cm^{2}s^{-1}, $\rho_0 = 3$ GV, $\delta_1 = 0$ and $\delta_2 = 0.6$. Figure 2 exhibits two peaks, one around 90 MeV/n and one around 210 MeV/n, which correspond to the minimum and maximum energies for deuterium produced by the fusion of incident protons with total energy of 600 MeV. Such feature hasn't yet been seen in observations, due to high measurement uncertainties on deuterium flux, but also because the peaks may be washed out by solar modulations and stochastic reaccelerations (not considered in the computation of GALPROP here).

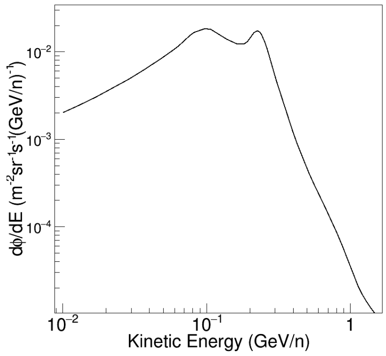

Figure 2: Differential flux of deuterium as a function of its kinetic energy per nucleon after implementating the proton fusion reaction $p + p \rightarrow d + \pi^+$ in GALPROP. The "Plain Diffusion" model from [19] was used with diffusion parameters $D0_{xx} = 2.2 \times 10^{28}$ cm^{2}s^{-1}, $\rho_0 = 3$ GV, $\delta_1 = 0$ and $\delta_2 = 0.6$. The proton spectrum was injected with index 0 as test case. Solar modulations are not considered here.

4. Light Isotope Production Cross-sections

In GALPROP, the reaction network uses ^{64}Ni as the heaviest nucleus to start. The code reads the cross section database and first computes all the resulting secondaries from this species. Then it proceeds to the atomic number $\mathrm{A}-1$ nucleus and continues until $A = 1$. Currently, the database consists of more than 2000 points collected from sources published since 1969, with some parametrizations from author's own fits, and some cross sections calculated from phenomenological approximations [20].

Cross sections for production of hydrogen and helium isotopes from fragmentation of heavier nuclei are mostly relying on few data points in the GALPROP database. Gaps are linearly interpolated between measurements, and extrapolations are performed above maximum energies available in the database. Below minimum energies, cross sections drop to zero. With measurements becoming more precise with time, cross sections that are currently used in GALPROP are being too approximate to reproduce data.

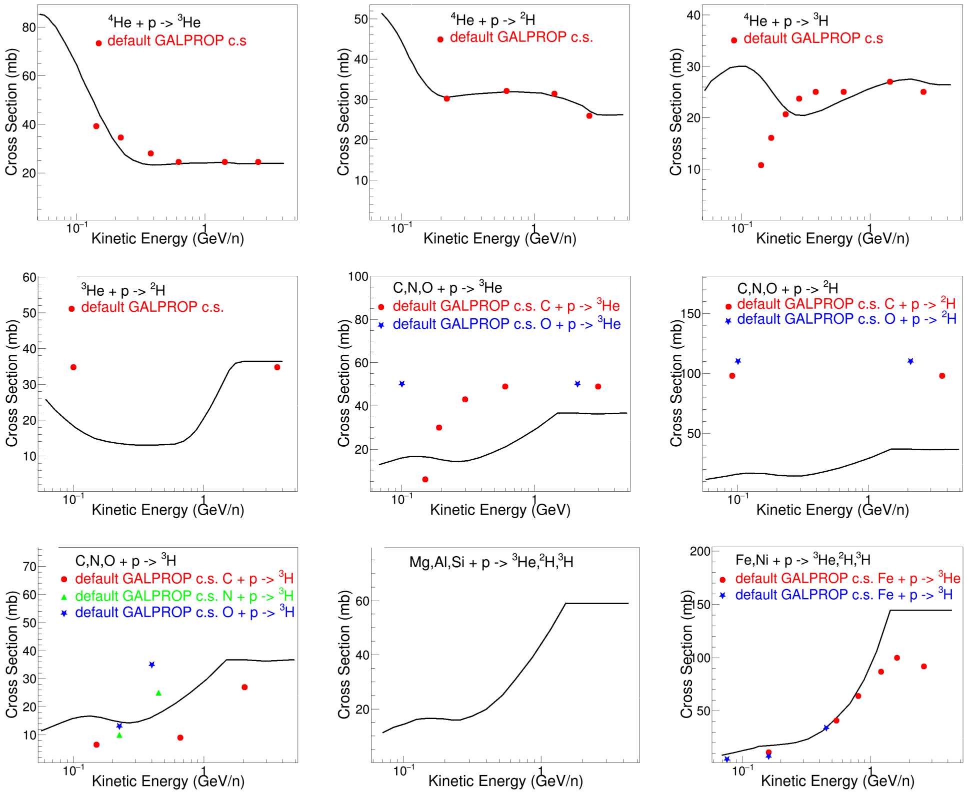

Figure 3: The new implemented parametrizations, digitized from [14] are shown with solid lines and are compared to previous cross section data used by GALPROP, represented with symbols.

In this work, we are using data from Coste et al. [14] who performed a thorough study on production cross sections for the quartet isotopes (^{1}H,^{2}H,^{3}He,^{4}He), using the most recent measurements and fitting them with updated formulae. We implemented into the GALPROP database new cross section parametrizations by replacing previous data and adding the missing one. Cosmic-ray fragmentations produce tritium ^{3}H, which are unstable particles decaying in ^{3}He with a short life time of 12.2 years in comparison to the time of propagation. New parameterizations for production cross sections of ^{3}H have then been implemented in the database. Cross sections for nuclei with similar atomic numbers (C,N,O), (Mg,Al,Si) and (Fe,Ni) have been incorporated with the same parametrizations. Figure 3 shows the new cross sections (solid lines), digitized from [14], compared to current GALPROP data (symbols). Fragmentation cross sections of ^{4}He are in good agreement down to ~0.2 GeV/n. Below this energy, new parameterizations are increasing whereas previous data are dropping down to zero. The cross section of ^{3}He fragmentation was constant in the range [0.1-3] GeV/n, while it is now energy-dependent, dropping by a factor of two below 1

GeV/n. Significant modifications of shape and absolute cross section values were also performed for (C,N,O) fragmentation reactions (e.g. up to an order of magnitude for $C,N,O+p\rightarrow^{2}H$), where only a few points were used in the GALPROP database. The reactions $[N+p\rightarrow^{3}He,^{2}H]$, $[Mg,Al,Si+p\rightarrow^{3}He,^{2}H,^{3}H]$, $[Fe+p\rightarrow^{2}H]$ and $[Ni+p\rightarrow^{3}He,^{2}H,^{3}H]$ were added, because not present in the GALPROP database.

Figure 4 presents the secondary-to-primary cosmic-ray ratios for hydrogen and helium isotopes estimated with GALPROP before and after modifications of light isotope production cross sections. ^{2}H/^{1}H is also shown with and without the proton fusion reaction using default GALPROP cross sections (c.f. Section 3). The "Plain Diffusion" model, with same injection and diffusion parameters than [19], was used to compute the program. Plots show that modifications of cross sections increase significantly the amount of deuterium produced below 200 MeV/n, by a factor of 2 around 100 MeV/n, and above 600 MeV/n by at most 25%. The amount of ^{3}He also increases significantly below 200 MeV/n by a factor of 4 around 100 MeV/n and decreases by at most 20% between 200 MeV/n and 1 GeV/n. Figure 4 shows that a good knowledge of production cross sections of hydrogen and helium isotopes is crucial to precisely calculate their fluxes and ratios. Most precise measurements are between 100 MeV/n and 1.5 GeV/n [2, 4], where changes performed to GALPROP cross sections have a significant impact[3]. In the future, possible development could involve using different cross section calculations, such as [21, 22].

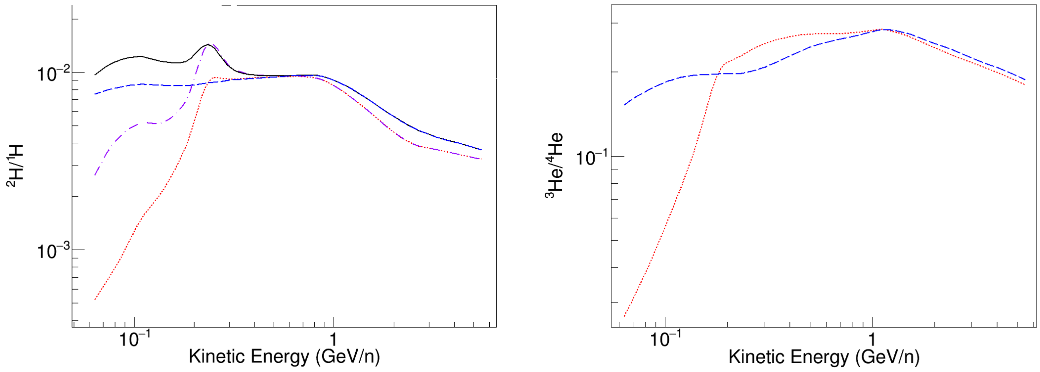

Figure 4: Secondary-to-primary ratios of ^{2}H/^{1}H (top) and ^{3}He/^{4}He (bottom). Our results obtained using Coste et al [14] cross sections are shown in blue dashed lines, and are compared to previous one using the default GALPROP cross section database, in red dotted lines. The ^{2}H/^{1}H plot is also showing calculations after implementing the proton fusion reaction in purple dashed dotted line, and the effect after adding both the fusion and new parametrizations in black solid line. GALPROP was computed with the "Plain Diffusion" model using parameters from [18], with diffusion $D0_{xx}=2.2\times10^{28}$ cm^{2}s^{-1}, $\rho_0=3$ GV, $\delta_1=0$ and $\delta_2=0.6$, and injection $\gamma_1=2.30$ below 40 GV and $\gamma_2=2.15$ above. Solar modulations are not considered here.

5. Conclusion

Although many processes and nuclear reactions are already available, some may be missing or

---

[3] We can notice that if stochastic reacceleration is considered in GALPROP, the flux would be even more strongly affected by the cross section modifications between 100 MeV/n and 1.5 GeV/n, from reacceleration of lower energy particles.

incomplete in the GALPROP program. This was the case for the hydrogen and helium isotopes for which the proton fusion reaction to produce ^{2}H was not implemented, and for which production cross sections from fragmentation were approximate or incomplete. This paper described the fusion process and its implementation in GALPROP, and presented the parametrizations from Coste et al. used as new fragmentation cross sections. The cross section of the fusion reaction $p+p \rightarrow d+\pi^+$ is sharply peaked around 600 MeV which results in producing a deuterium particle flux double-peaked at ~ 90 MeV/n and ~ 210 MeV/n. The new implemented parametrizations of hydrogen and helium isotope fragmentation cross sections significantly changed expected fluxes of ^{2}H and ^{3}He. Measurements of the light-quartet isotope have become more precise with experiments such as BESS, AMS-01 and more recently PAMELA. Upcoming results from BESS-Polar II and AMS-02 are expected to improve and extend previous measurements, and a good knowledge of production cross sections is now crucial to reproduce these data.

Acknowledgements

This work was supported by NASA grant NNX15AC16G and its predecessors.

References

[1] O. Adriani et al., *PAMELA Measurements of Cosmic-ray Proton and Helium Spectra*, Science 332, 69, 2011.

[2] O. Adriani et al., *Measurement of the Isotopic Composition of Hydrogen and Helium Nuclei in Cosmic Rays with the PAMELA Experiment*, Astrophys. J. 770, 2, 2013.

[3] K. Abe et al., *Measurements of cosmic-ray proton and helium spectra from the BESS-Polar long-duration balloon flights over Antarctica*, astro-ph, arXiv:1506.01267.

[4] N. Picot-Clémente et al., *Measurements of Galactic Cosmic-Ray Hydrogen and Helium Isotopes with the BESS-Polar II Instrument*, Proc. 34rd Int. Cosmic Ray Conf., ID 1205, 2015.

[5] M. Aguilar et al., *Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 114 , 171103, 2015.

[6] F. Donato, D. Maurin, R. Taillet, *beta-radioactive cosmic rays in a diffusion model: Test for a local bubble?*, A&A 381, 539, 2002.

[7] D. Maurin, A. Putze, L. Derome, *Systematic uncertainties on the cosmic-ray transport parameters Is it possible to reconcile B/C data with $\delta = 1/3$ or $\delta = 1/2$?*, A&A 516, A67, 2010.

[8] A. Putze, L. Derome, D. Maurin, *A Markov Chain Monte Carlo technique to sample transport and source parameters of Galactic cosmic rays II. Results for the diffusion model combining B/C and radioactive nuclei*, A&A 516, A66, 2010.

[9] E. S. Seo and V. S. Ptuskin, *Stochastic Reacceleration of Cosmic Rays in the Interstellar Medium*, Astrophys. J. 431, 705, 1994.

[10] W. R. Webber, P. Ferrando, A. Lukasiak et al., *Studies of the low-energy galacticcosmicray composition near 28 AU at sunspot minimum - the primary-to-primary ratios*, Astrophys. J. 392, 91, 1992.

[11] A. W. Strong, I. V. Moskalenko, *Propagation of Cosmic-Ray Nucleons in the Galaxy*, Astrophys. J. 509, 212, 1998.

[12] I. V. Moskalenko, A. W. Strong, J. F. Ormes, M. S. Potgieter, *Secondary antiprotons and propagation of cosmic rays in the Galaxy and heliosphere*, Astrophys. J. 565, 280, 2002.

[13] C. Evoli, D. Gaggero, D. Grasso, L. Maccione, *Cosmic ray nuclei, antiprotons and gamma rays in the galaxy: a new diffusion model*, JCAP, 2000.

[14] B. Coste, L. Derome, D. Maurin and A. Putze, *Constraining Galactic cosmic-ray parameters with Z $\leq$ 2 nuclei*, A&A 539, A88, 2012.

[15] A. W. Strong, I. V. Moskalenko, T. A. Porter, G. Jóhannesson, E. Orlando, S. W. Digel, A. E. Vladimirov, *GALPROP Explanatory Supplement*, http://www.mpe.mpg.de/∼aws/galprop_explanatory_supplement.pdf.

[16] A. W. Strong, *Recent extensions to GALPROP*, Proc. 34rd Int. Cosmic Ray Conf., ID 548, 2015.

[17] W. O. Lock and D. F. Measday, *Intermediate Energy Nuclear Physics*, Ed. Methuen young books, 1970.

[18] J. P. Meyer, *Deuteron and He^3 Formation and Destruction in Proton Induced Spallation of Light Nuclei (Z$\leq$8)* A&A Supp 7, 417, 1972.

[19] V. S. Ptuskin, I. V. Moskalenko, F. C. Jones, A. W. Strong, V. N. Zirakashvili, *Dissipation of Magnetohydrodynamic Waves on Energetic Particles: Impact on Interstellar Turbulence and Cosmic Ray Transport* Astrophys. J. 642, 902, 2006.

[20] W. R. Webber, J. C. Kish, D. A. Schrier, *Formula for calculating partial cross sections for nuclear reactions of nuclei with E$\geq$200 MeV/nucleon in hydrogen targets*, Phys. Rev. C, 41, 566, 1990.

[21] C. D. Dermer, *Binary Collision Rates of Relativistic Thermal Plasma. II. Spectra*, Astrophys. J. 307, 47, 1986.

[22] R. J. Murphy, C. D. Dermer, R. Ramaty, *High-Energy Processes in Solar Flares*, Astrophys. J. Supp. 63, 721, 1987.