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How accurate are our models of production and propagation of secondary cosmic-ray antiprotons?

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Cosmic-ray antinuclei are particular informative probes of high-energy processes in the Galaxy and can hint at exotic sources of energetic particles, such as dark-matter annihilation. Antinuclei are expected to be produced at a low level in conventional reactions, and their flux can even be dominated by exotic contributions. However, the interpretation of cosmic antinuclei measurements requires a good understanding of all processes involved in their creation and propagation and a realistic estimate of the involved modeling uncertainties to distinguish potential exotic contributions from ordinary production. In this contribution, we review the current understanding of the production and propagation of charged cosmic-ray antinuclei in the Galaxy and the modeling of their fluxes, with a special focus on cosmic-ray antiprotons. In particular, we quantify systematic deviations of the modeled flux that arise from inaccuracies of the numerical solution of the propagation equation, different models of propagation processes, and different models of the antiproton-production cross-section.

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1. Introduction

Antiprotons and antinuclei are particularly suitable for probing cosmic-ray origin and propagation models. Since no primary sources of such particles are expected in our Galaxy, they are believed to be solely produced by cosmic-ray collisions with interstellar material. The flux of ordinary cosmic rays, the distribution and abundance of interstellar matter, and their production cross-section determine their flux. An overabundance of antinuclei hints at exotic sources of antimatter or a systematic misunderstanding of cosmic-ray production and propagation processes in the Galaxy.
To predict the flux of antinuclei or antiprotons near Earth, one needs to model the distribution of ordinary cosmic rays in the Galaxy, their interactions with the interstellar material, and the propagation of the produced antinuclei through the Galaxy and the heliosphere to our cosmic-ray detectors. This modeling requires a self-consistent propagation scheme that can reproduce the flux of ordinary cosmic-ray nuclei and a production model of antinuclei that follow measurements from accelerator-based experiments.
In this contribution, we discuss the models of propagation and production of antiprotons—the lightest antinucleus—and try to quantify current systematic differences between different available models commonly used to interpret available cosmic-ray antiproton measurements.

2. Cosmic-Ray Propagation in the Galaxy and the Heliosphere

A diffusion equation describes the distribution of the Galaxy's primary and secondary cosmic rays. Its solution provides the energy-dependent cosmic-ray particle density of a specific particle species at a given location and time. A current state-of-the-art diffusion equation for cosmic-ray propagation in the Galaxy that includes the spatial distribution of particle sources, effects induced by a potential galactic wind, momentum gains and losses by interactions of the cosmic rays with the interstellar medium, and particle losses due to spallation reactions and radioactive decays are described in Strong et al. [1].
In order to compare the modeled cosmic-ray fluxes at the solar system's position in the Galaxy with cosmic-ray measurements, the additional time-dependent shielding effect of solar modulation has to be considered[1] [2].
The force-field approximation is a commonly used effective model to describe the effect of solar modulation [3]. However, it becomes inaccurate with decreasing energy of the cosmic rays, and deviations between the model and experimental data are found up to several GV [4]. Effects that stem from the detailed structure of the heliosphere—like charge-sign-dependent particle drifts—are not included in the model, leading to further inaccuracies.
More accurate models are often based on solving the heliospheric diffusion equation numerically. One of the most commonly used numerical models is the HELMOD model [5].
The selection of the solar-modulation model for a cosmic-ray study strongly influences the resulting local interstellar particle spectra (LIS) of the study in cases where galactic propagation parameters are constrained by a fit of the modeled fluxes to measurements inside the heliosphere.

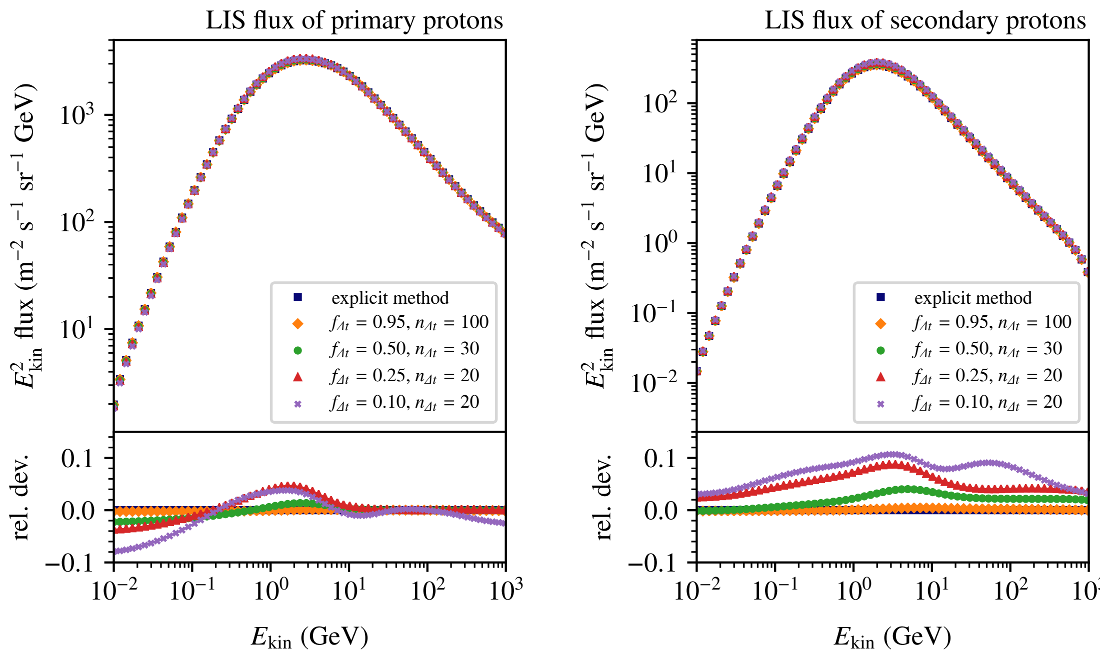
[1]Except for measurements from the Voyager probes, the only cosmic-ray measurements outside of the heliosphere.

3. Recent Studies of Cosmic-Ray Propagation with GALPROP

The cosmic-ray production and propagation processes in the Galaxy are assumed to happen continuously for much longer than the typical confinement time of cosmic rays. Therefore, the cosmic-ray density is expected to have reached a steady-state distribution within the galactic volume [6]. The task of the propagation models is to solve the diffusion equation and obtain the steady-state solution at the solar system's position.
The most common frameworks to numerically evolve the particle distributions in the diffusion equation are the DRAGON-II [7, 8] and the GALPROP [9] codes. Based on them, various studies have been published that constrain propagation parameters and injection spectra by fitting the modeled particle fluxes at Earth to cosmic-ray measurements. These studies often used different combinations of experimental data to fit to, distinct parameterizations of the involved propagation processes, and different settings for the numerical scheme to solve the diffusion equation. The effect of the latter on the obtained results in GALPROP has not yet been studied in detail. Therefore, we investigate the influence of the numerical settings on the accuracy of the obtained modeled cosmic-ray fluxes in the following.

3.1 Numerical Accuracy of the Studies

For this study, we use version 56 of GALPROP, which can be downloaded from `https://galprop.stanford.edu/`. GALPROP employs a finite-difference method with discrete timesteps to evolve the momentum-dependent particle density in the Galaxy until a steady-state distribution is reached [6]. The spatial and momentum dimensions are also discretized to apply the finite-difference method for spatial and momentum derivatives. From the discretization, one obtains a multidimensional grid where the particle density has to be evaluated on each grid point per timestep, Δt. To get an accurate approximation of the time derivative by the finite difference, Δt must be smaller than the smallest timescale of the processes included in the diffusion equation [6].
For charged cosmic rays, the processes with the smallest timescales are energy losses by ionization or radiative emission, which have timescales of approximately 10^3 to 10^4 years for nuclei. On the contrary, the time required to reach the steady-state solution depends on the processes with the largest timescale. For nuclei, these are the diffusive motion through the Galaxy and the secondary production, which have timescales on the order of 10^7 years. Thus, one needs to evolve the particle-density distribution on each grid point for at least a few-billion years in steps of a few-thousand years, which requires many iterations. Nevertheless, this approach is most accurate in approximating the diffusion equation's steady-state solution. In GALPROP, this method is implemented as the so-called explicit method. However, this method is impractical for cosmic-ray propagation studies as it is computationally expensive and cannot be sped up by larger timesteps to not become unstable as the timesteps exceed the shortest timescale of the propagation processes [6].
To speed up the evolution to the steady-state solution, most studies employing GALPROP use the implemented accelerated Crank-Nicolson method [10]. In this method, the timesteps are successively decreased during the evolution to sequentially include the effects of shorter timescale processes acceleratedly. The hyperparameters of this method are the time-



(a) Primary protons. **(b)** Secondary protons.

Figure 1: Obtained local interstellar flux of primary and secondary cosmic rays for an identical propagation scheme but different numerical settings. The relative deviations are calculated with respect to the obtained flux for the numerically accurate solution of the explicit method.

reduction factor, $f_{\Delta t}$, and the number of repetitions per timestep, $n_{\Delta t}$. Typical values used in studies of cosmic rays vary between $0.25 \leq f_{\Delta t} \leq 0.75$ and $20 \leq n_{\Delta t} \leq 100$ [11]. We tested different combinations of $f_{\Delta t}$ and $n_{\Delta t}$ and compared their predicted local interstellar proton flux with the result obtained by the accurate, explicit method. The results are shown in Figure 1, separately for the primary and secondary components of the proton flux. Especially for the secondary component, a too-coarse evolution leads to significant deviations from the numerically accurate solution.
Other hyperparameters of the numerical solver, like the spacing of the grid points in the spatial or momentum dimensions, can introduce similar inaccuracies. An extensive study of the accuracy of the obtained particle fluxes for different settings of hyperparameters can be found in [11]. Especially for studies focusing on determining propagation parameters, these inaccuracies lead to systematic deviations of the obtained parameters from the accurate value.

3.2 Differences in Propagation Models

Besides differences in the settings of the numerical solution, different studies employ different parameterizations for processes in the Galaxy. We compare the propagated antiproton flux obtained for two recent propagation models employing an identical antiproton production model to examine how the different propagation changes the modeled antiproton flux.

The most comprehensive studies using GALPROP and the new experimental data from AMS-02 and Voyager are from Boschini et al. [12–15] and Korsmeier et al. [16–18]. Both employed a similar model of galactic propagation but with some distinctions: While Boschini et al. used the HELMOD solar-modulation model [19], Korsmeier et al. applied the force-field method for solar modulation; Boschini et al. used a gradually increasing velocity of the galactic wind with distance from the galactic plane, while Korsmeier et al. used a constant velocity, which results in an unphysical divergence of the galactic-wind velocity at the galactic plane. The most distinct differences, however, are the differing parameterizations of the injection spectra of primary cosmic rays: While Boschini et al. used an individual injection spectrum for each cosmic-ray species—violating the assumption of a universal particle injection in supernova remnants, Korsmeier et al. used a single spectrum for all nuclei except for protons, as it is established by experimental data that the proton spectrum has a significantly different slope compared to helium [18]. However, Korsmeier et al. concluded in their study that to match the data of AMS-02 for different nuclei, a single, universal injection spectrum requires a nuclei-dependent diffusion coefficient [18]. Therefore, both studies point to an inaccuracy of the understanding of the involved physical processes, as both obtained results contradict the assumption of a universal cosmic-ray injection and propagation for different nuclei but solve the discrepancy differently. Since both studies agree well with the available experimental data inside the heliosphere, a data-driven judgment of which implementation of the propagation processes and injection spectra is more valid is not easily possible.

The difference of the predicted propagated local interstellar antiproton flux for both models with an identical production model—here exemplarily the model by Tan et al. [20]—is shown in Figure 2. The obtained difference in the antiproton flux stems solely from the difference in the projectile spectra, primarily protons and helium, and the propagation of the antiprotons of the two models. The antiproton yield for the propagation model from Korsmeier et al. [16, 17] is lower than the obtained antiproton flux from the model by Boschini et al. [21] at antiproton energies above approximately 1×10^2 GeV/n, which is found to stem from a lower proton and helium yield at large energies in the Galaxy compared to the model from Boschini et al. At lower energies, the yield obtained by the Korsmeier et al. model, however, exceeds the antiproton flux obtained by the Boschini et al. model by up to 50 %, which stems from a different propagation of the antiprotons in the Galaxy. The force-field model used in the study of Korsmeier et al. modulates the antiproton flux stronger than the HELMOD model used by Boschini et al..

The extracted difference of the obtained local interstellar antiproton flux for these two state-of-the-art propagation models estimates the current model uncertainties of propagation in the Galaxy on the flux of cosmic antiprotons. Above around 10 GeV, the model uncertainty is on the order of 25 %; below, even up to 50 %. The much larger deviation at low energy arises from the large uncertainty of the solar-modulation process. This large model uncertainty hinders a better constrain of the propagation processes in the Galaxy for low-energy particles. In order to reduce the model uncertainties in the region below several GeV, the effect of solar modulation has to be modeled as accurately as possible to resolve any ambiguities in the low-energy local interstellar cosmic-ray fluxes.

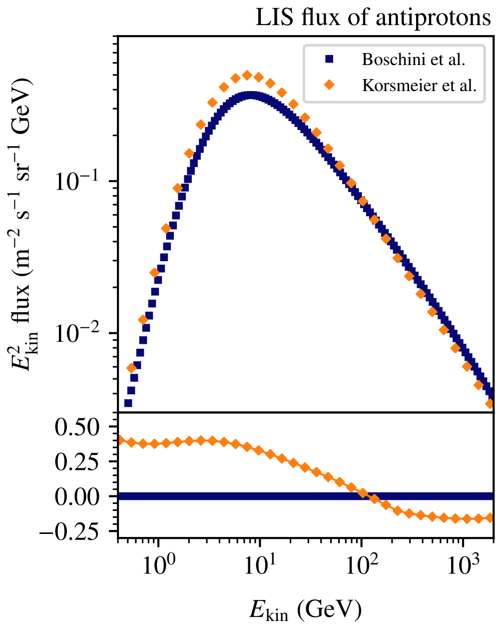


Figure 2: Comparison of the local interstellar antiproton flux obtained with the propagation model of Boschini et al. [21] and Korsmeier et al. [16, 17] for an identical antiproton-production model from Tan et al. [20].

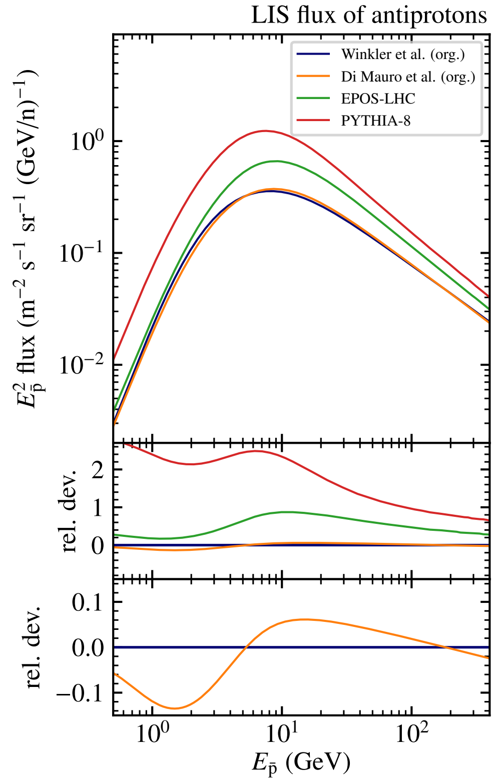


Figure 3: Comparison of the local interstellar antiproton flux obtained with different production models and the propagation model of Boschini et al. [21].

4. Differences in Antiproton-Production Models

The second significant source of uncertainty on the predicted antiproton flux in the Galaxy stems from uncertainties related to the production of antiprotons in cosmic-ray collisions with interstellar matter.

Different models have been developed that consider more and more recent experimental data. Two of the most recent models based on parameterizations of the antiproton-production cross-section are from Winkler et al. [22] and Di Mauro et al. [23].

A second family of particle-production models are multi-purpose event generators developed to model particle production in different collision systems for studies at accelerator-based collision experiments. Most commonly used are PYTHIA [24] and EPOS [25], with several versions and tunes focusing on different use cases.

However, when comparing the empirical parameterizations and the event generators to a suite of antiproton-production measurements from accelerator-based collision experiments, none of the tested models was found to be accurate. The detailed study and comparison of the different models with various experimental data can be found in [11]. In general, the event generators deviate further from the experimental data than the parameterizations and

often overestimate the production of antiprotons significantly. The parameterizations agree better with experimental data since they are fitted to several datasets. Nevertheless, they still cannot accurately describe all available data simultaneously. New parameterizations and more experimental data covering different regions of the phase space of the produced antiprotons and different collision energies are required to pin down the model uncertainties of the antiproton-production cross-section.
To qualitatively showcase the difference in the antiproton production of the tested models and the influence on the predicted cosmic-ray antiproton flux, Figure 3 shows the obtained local interstellar flux of antiprotons for the different production models and an identical propagation model, namely from Boschini et al. [21]. The relative deviations between the models are compared to the model from Winkler et al. [22]. As can be seen, the differences between the two parameterization-based models are on the order of 10 %, and the event generators deviate much further. The deviation of EPOS-LHC is mainly due to a significant overproduction of antineutrons, and the deviation of PYTHIA is due to an overall overproduction of antiparticles [11].

5. Conclusion

We investigated the numerical accuracy of cosmic-ray propagation models based on GALPROP and compared recent propagation studies. Additionally, we investigated the accordance of different antiproton-production models with experimental data from accelerator-based experiments. We compared the predicted local interstellar antiproton flux for different propagation and production models. We found that the predictions for the different propagation models differ by up to 50 %, mainly at low energies, due to differences in the modeling of the heliospheric transport. Differences stemming from the employed production model can be even larger. A comparison of the employed antiproton-production models with cross-section data from accelerator-based experiments showed that the tested models need to be revised.
The inaccuracies from the propagation and production model for antiprotons lead to a model uncertainty of the prediction of the cosmic-ray antiproton flux from secondary production. This uncertainty exceeds the current experimental uncertainty of the measurement by AMS-02 [26]. Therefore, improving the models of cosmic-ray propagation and antiproton production is inevitable to fully exploit the precision of the antiproton flux measurement.

Acknowledgments

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