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How accurate are our models of production and propagation of secondary cosmic-ray antiprotons? (Preliminary version)

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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. These particles 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 the creation and propagation of the antiparticles 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 based on this, 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 for propagation processes, and different models of the antiproton-production cross section. Based on the systematic uncertainties found, we comment on the agreement between the modeled flux and the measurement.

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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 only produced by cosmic-ray collisions with interstellar material. Their abundance is determined by the flux of ordinary cosmic rays, the distribution and abundance of interstellar matter, and their production cross section. An overabundance of antinuclei hints at exotic sources of antimatter or a systematic misunderstanding of the processes of cosmic-ray production and propagation in the Galaxy.

To predict the flux of antinuclei or antiprotons at Earth, one needs to model the distribution of cosmic rays in the Galaxy, the interactions of them with the interstellar material, and the propagation of the antinuclei through the Galaxy and the heliosphere to our particle detectors. This requires a self-consistent propagation scheme that can reproduce the flux of other cosmic-ray particle species and a production model of antinuclei that follow measurements from accelerator-based experiments.

In this contribution, we discuss the propagation and production of antiprotons to model their cosmic flux and try to quantify current systematic differences between different available models that are commonly used to interpret the current cosmic-ray antiproton measurements.

1.1 Cosmic-Ray Propagation in the Galaxy

A diffusion equation can describe the distribution of primary and secondary cosmic rays in the Galaxy. Solving it obtains 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 is described in Strong et al. [1].

1.2 Solar Modulation

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 of the study in cases where galactic propagation

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

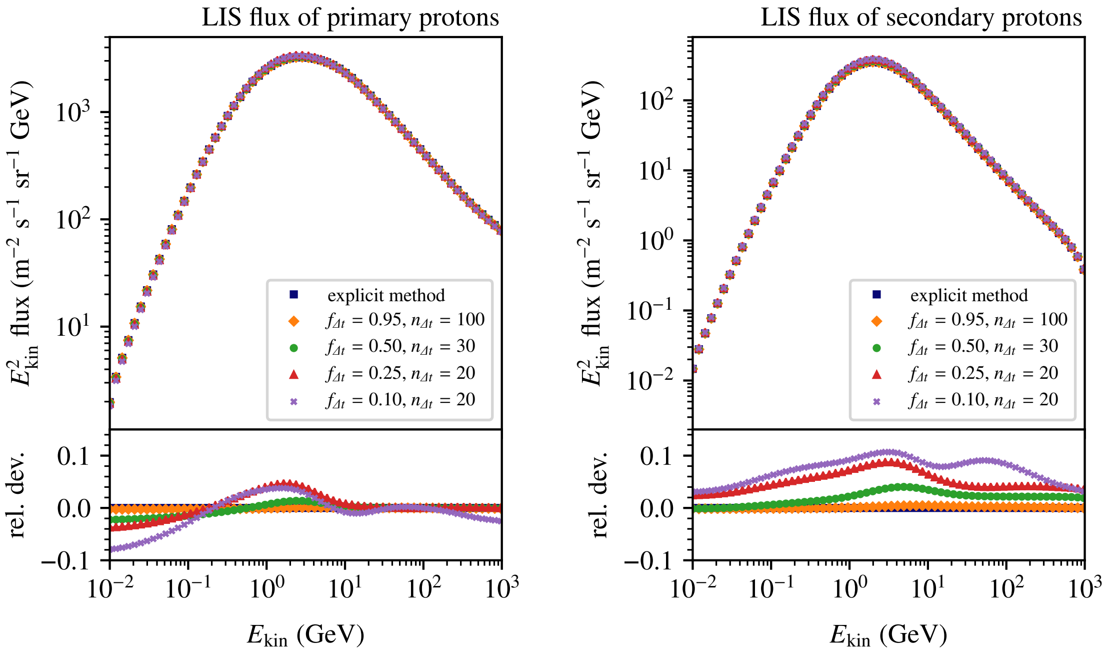
parameters are constrained by a fit of the modeled fluxes to measurements inside the heliosphere.

2. 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 position of the solar system.
The most common frameworks to numerically evolve the particle distributions in the diffusion equation are the DRAGON-II [7, 8] and the GALPROP [9] computer 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 has not yet been studied in detail. Therefore, we investigate the influence of the numerical settings in GALPROP on the accuracy of the obtained modeled cosmic-ray fluxes.

2.1 Numerical Accuracy of the Cosmic-Ray Studies

For the study, we use version 56 of the code, 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 the 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 this 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 using 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 if the steps are longer than the smallest timescales of the propagation processes [6].



(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.

To speed up the convergence to the steady-state solution, GALPROP uses the so-called accelerated Crank-Nicolson method. In this method, the timescale is successively decreased to sequentially include the effects of shorter timescale processes but in an accelerated manner with respect to the explicit method. The hyperparameters of this method are the time-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 $20 \leq n_{\Delta t} \leq 100$ [10]. 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 [10]. Especially for studies focusing on determining propagation parameters, these inaccuracies lead to systematic deviations of the obtained parameters from the accurate value.

2.2 Differences of the Modeled Antiproton Flux from the Propagation Model

Besides the difference in the settings of the numerical solution, different studies employ different parameterizations for processes in the Galaxy. We compare the propagated antiproton flux of two recent propagation models with an identical antiproton production model to examine how these settings change 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. [11–14] and Korsmeier et al. [15–17]. Both employed a similar model of galactic propagation, with some distinctions: While Boschini et al. used the HELMOD solar-modulation model [18], 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 [17]. 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 [17]. 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 propagated local interstellar antiproton flux for both models with an identical production model—here exemplarily the model by Tan et al. [19]—is shown in Figure 2. The obtained difference in the antiproton flux stems solely from the difference in the projectile spectra, mostly protons and helium, and the propagation of the antiprotons of the two models. The antiproton yield for the propagation model from Korsmeier et al. [15, 16] is lower than the obtained antiproton flux from the model by Boschini et al. [15, 16] 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 used force-field model 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 can be used to roughly estimate the current model uncertainties of propagation in the Galaxy on the flux of cosmic antiprotons. Above around

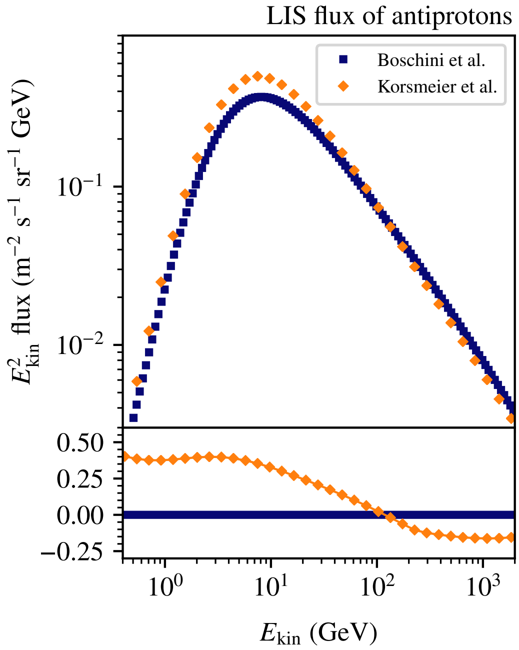


Figure 2: Comparison of the local interstellar antiproton flux obtained with the propagation model of Boschini et al. [20] and Korsmeier et al. [15, 16] for an identical antiproton-production model.

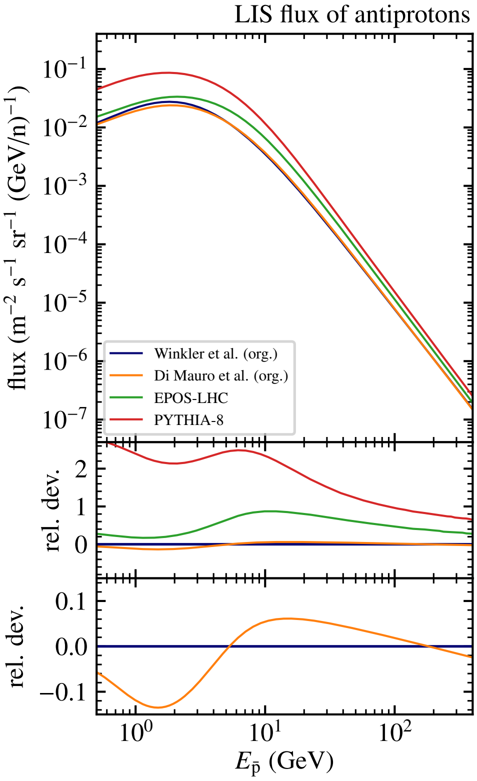


Figure 3: Comparison of the local interstellar antiproton flux obtained with different production models and the propagation model of Boschini et al. [20].

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 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 of a few GeV, the effect of solar modulation has to be modeled as precisely as possible to resolve any ambiguities.

3. Differences in Antiproton-Production Models

The second significant source of uncertainty of 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, considering 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. [21] and Di Mauro et al. [22].

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 [23] and EPOS [24], with several

different versions and tunes focusing on different use cases.
However, when comparing the empirical parameterizations and the event generators to a suite of experimental data on antiproton production, no model can be assumed to be accurate. A detailed study and comparison of the different models with various experimental data can be found in [10]. In general, the event generators deviate further from the experimental data than the parameterizations and often overestimate the production of antiprotons significantly. The parameterizations have a better agreement with experimental data as they are fitted to several datasets, but still not all available datasets can be simultaneously described. 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 production.
To qualitatively show the difference in cosmic-ray-antiproton production for the different models, Figure 3 shows the obtained LIS of antiprotons for an identical propagation model, namely from Boschini et al. [20], and different production models. The relative deviations between the models are compared arbitrarily to the model from Winkler et al. [21]. 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 an significant overproduction of antineutrons and the deviation of PYTHIA due to an overall overproduction of antiparticles.
Therefore, An accurate model consistent with all available experimental data on antiproton production has still to be developed.

4. Conclusion

We have investigated the accuracy of cosmic-ray propagation models based on GALPROP and production of antiprotons for the interpretation of the measured cosmic-ray antiproton flux. We found several model uncertainties that hinder a full exploitation of the currently available experimental data. Current propagation models have large uncertainties for low-energy particles due to the insufficient quantification of solar modulation and the limited experimental data on cosmic-ray fluxes above the energy range accessible by AMS-02 that act as projectiles to produce antiprotons. The insufficient knowledge of the antiproton-production cross section is another limiting factor. So far, no model of antiproton production accurately describes all available experimental data from accelerator-based experiments.
Concluding, both processes have model uncertainties for the prediction of the cosmic antiproton flux greater than 10 %, exceeding the current experimental uncertainties by far. An improvement of these models is therefore inevitable to fully interpret current cosmic-ray measurements of antiprotons.

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