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Antiprotons from spallation of cosmic rays on interstellar matter

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Abstract. Cosmic ray antiprotons provide an important probe for the study of the galactic Dark Matter, as they could be produced by neutralino annihilations, primordial black holes evaporations or other exotic sources. On the other hand, antiprotons are anyway produced by standard nuclear reactions of cosmic ray nuclei on interstellar matter (*spallations*), that are known to occur in the Galaxy. This process is responsible for a background flux that must be carefully determined to estimate the detectability of an hypothetical exotic signal.

In this paper we provide the first evaluation of the interstellar cosmic antiproton flux that is fully consistent with cosmic ray nuclei in the framework of a two-zone diffusion model. We also study and conservatively quantify all possible sources of uncertainty that may affect that antiproton flux. In particular, the primary cosmic rays (H and He) are by now so well measured that the corresponding error is removed. Uncertainties related to propagation are shown to range between 10% and 25%, depending on which part of the spectrum is considered.

1 Introduction

In this paper, we focus on the secondary antiproton flux, due to standard spallation reactions occuring in the galactic disk. We will consider it as "background" flux, having in mind the possibility of using it to determine whether one of primary components (such as from supersymmetric relic particles or evaporating primordial black holes) could be seen against it or not.

We use the results of our systematic analysis of nuclei in Maurin et al. (2001) (referred hereafter as Paper I; see also R. Taillet et al. 2001) to ascertain the theoretical uncertainties on the interstellar secondary antiproton energy spectrum due to propagation in the Galaxy. We emphasize that results from a systematic nuclei cosmic ray analysis are for the first time used to consistently derive an antiproton secondary flux in the framework of diffusion models.

As an important consequence we could study and quantify most of the uncertainties: in the propagation, in the nuclear physics and in the primary cosmic ray. We feel that our results will be valuable not only for speculations on primary contributions to that flux but also for the experimental groups which are going to perform very accurate antiproton measurements in the near future. The present work is based on the much more complete analysis in Donato et al. (2001) (Paper II hereafter), to which we refer for all details and references.

2 Antiproton production

The secondary antiprotons are yielded by the spallation of cosmic ray nuclei over the interstellar medium. The most abundant species in cosmic rays are protons and helium.

Recent measurements made by the balloon–borne spectrometer BESS (Sanuki et al. 2000) and by the AMS detector during the space shuttle flight (Alcaraz et al. 2000a, 2000b, 2000c) dramatically reduced the uncertainties both on proton and helium spectra. We fitted the high energy (T $>$ 20 GeV/n) part of these measured spectra with the power law $\Phi(\mathrm{T}) = \mathrm{N}\,(\mathrm{T}/\mathrm{GeV/n})^{-\gamma}$, where T is the kinetic energy per nucleon in units of GeV/n. The fit on each of the two set of data is very similar to the one on the combined data.

For proton, the best fit corresponds to $N = 13249\,\mathrm{m}^{-2}\mathrm{s}^{-1}$ sr^{-1} $(\mathrm{GeV/n})^{-1}$ and $\gamma = 2.72$, while for helium $N = 721$ $\mathrm{m}^{-2}\mathrm{s}^{-1}\ \mathrm{sr}^{-1}(\mathrm{GeV/n})^{-1}$ and $\gamma = 2.74$. The 1–σ deviation from the best fit spectrum does not exceed 1% for both species. Consequently, the corresponding uncertainty on the antiproton spectrum is smaller than the ones discussed in the next sections, and it will be neglected in the rest of this paper. The situation has significantly improved since Bottino et al. (1998), where an error of ± 25% was quoted.

Whereas p–p interactions are clearly the dominant process for secondary antiproton production in the Galaxy, p–nucleus and nucleus–nucleus collisions should also be taken into ac-

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count. They not only enhance the antiproton flux as a whole but can change its low energy tail, mostly for kinematical reasons.

So we calculated the total antiproton yield considering p–p, p–He, He–p and He–He interactions. Unfortunately, very few experimental data are available on antiproton production cross-sections in nuclear collisions. A model-based evaluation is therefore necessary.

Antiproton production *via* the proton–proton interaction was parameterized according to Tan and Ng (1982, 1983). The Monte Carlo program DTUNUC[1] version 2.3 was used to evaluate the cross-sections for p–He, He–p and He-He antiproton production reactions. The resulting cross-sections have been compared with experimental data on proton–nucleus collisions. In most cases, measurements and DTUNUC simulations are compatible within uncertainties. The discrepancies are, anyway, taken into account further in this work as uncertainties on the computed cross-sections.

Once they have been created, antiprotons may annihilate on interstellar protons. This process dominates at low energy, and its cross-section has been taken from Tan and Ng (1983). Also, antiprotons may survive inelastic scatterings where the target proton is excited to a resonance: these so–called tertiary antiprotons do not annihilate but lose a significant amount of their kinetic energy. This mechanism does not actually create new antiprotons. It merely redistributes them towards lower energies and tends therefore to flatten their spectrum. Notice that the secondary antiproton spectrum that results from the interaction of cosmic ray protons impinging on interstellar helium is already fairly flat below a few GeV. Since it contributes a large fraction to the final result, the effect under scrutiny here may not be as large as previously thought (Bergström et al., 1999).

For a complete discussion on the above–discussed interactions and on the treatment of the tertiary component, we refer to Paper II.

3 Propagation in a diffusion model

Propagation of cosmic rays can be studied within different theoretical frameworks, the most popular being the so-called Leaky Box model and the diffusion model. There is a mathematical equivalence of these two approaches, which is valid only under special circumstances. Our preference for the diffusion model has several justifications. First, it is a more physical approach, in the sense that cosmic rays are believed to diffuse in the galactic disk and halo, which is in disagreement with the spatial homogeneity assumed in the Leaky Box. Moreover, the parameters entering the diffusion models are related to measurable physical quantities (at least in principle), like the galactic magnetic field, so that their value could be cross-checked with independent measurements. Finally, the diffusion approach is mandatory if one wants to take primary sources into account.

The geometry of the problem used here is a classical cylindrical box whose radial extension is $R = 20$ kpc, with a disk of thickness $2h = 200$ pc and a halo of half–height L lying in the interval [1-20] kpc. Sources and interactions with matter are confined to the thin disk and diffusion which occurs throughout disc and halo with the same strength is independent of space coordinates. The Solar System is located in the galactic disc ($z = 0$) and at a centrogalactic distance $R_\odot = 8$ kpc.

Our model takes into account the minimal known physical processes thought to be present during the propagation. Firstly, the diffusion coefficient $K(E) = K_0\,\beta \times \mathcal{R}^\delta$, where the normalisation K_0 is expressed in kpc^2 Myr^{-1} and δ is the spectral index ($\mathcal{R} = p/Z$ stands for the particle rigidity). Along with the spatial diffusion, one has the associated diffusion in energy space represented by a reacceleration term $K_{EE}(E) = \frac{2}{9}{V_a}^2\frac{E^2\beta^4}{K(E)}$. Here K_{EE} stands for the energy diffusion coefficient and V_a is the alfvénic speed of scatterers responsible of the energetic diffusion. A constant convective wind directed outward in the z direction may be present. This term is represented by the velocity V_c. Last, we have to include effects of energy losses. Formulæ for the latter are those used for nuclei with the appropriated charge for an antiproton (see Paper I).

We emphasize that this model is exactly the one that has been used for the propagation of charged nuclei (Paper I) where it has been described in details. The model has thus five free parameters: K_0, δ, V_c, V_a, and L.

Here we employ all the configurations giving a good χ^2 (less than 40 for 26 data points and 5 parameters) in the B/C analysis of Paper I (see this paper for an extensive description of the nuclei analysis). We insist on the fact that none of this parameter is further modified or adjusted, they are not free parameters.

To compare our results to experimental data, solar modulation must be taken into account. We chose to use the so-called force-field approximation. In all the subsequent results, the top–of–atmosphere antiproton flux has been obtained from the interstellar one with a modulation parameter of $\phi = 500$ MV ($\Phi \equiv Z/A \times \phi = 250$ MV), adapted for a period of minimal solar activity. This choice is motivated by the comparison to BESS data taken during the last solar minimum.

4 Results and discussion

We have calculated the secondary top–of–atmosphere antiproton spectrum obtained with the procedure described above. A particular set of diffusion parameters giving a good fit to the B/C data has been chosen: $K_0/L = 0.0345$ kpc^2 Myr^{-1}, $L = 9.5$ kpc, $V_c = 10.5$ km/s and $V_a = 85.1$ km/s. This set gives the best χ^2 for δ fixed to 0.6 and the resulting antiproton spectrum will be used as a reference in the results presented below.

Fig. 1 displays this computed antiproton flux along with experimental data collected by the BESS spectrometer during

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[1] http://sroesler.home.cern.ch/sroesler/

two flights in a period of minimal solar activity, as a function of the kinetic energy. Circles correspond to the combined 1995 and 1997 data (Orito et al. 2000) and squares to the 1998 ones (Maeno et al. 2000). The dotted lines represent the contribution to the total flux coming from the various nuclear reactions: from top to bottom are represented the contribution of p–p, p–He, He–p and He–He. subsequent figures.

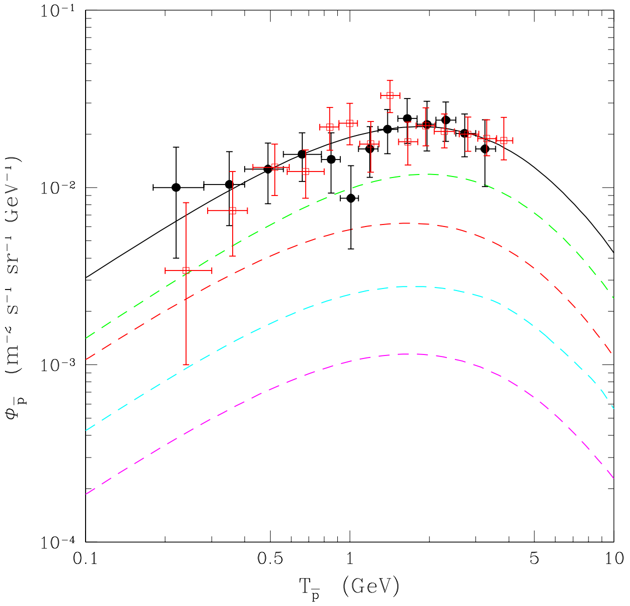

Fig. 1. Solid line shows the total secondary antiproton spectrum for the reference set of diffusion parameters (see text for details). Dashed lines are the contributions to this total flux from various nuclear reactions (from top to bottom: p–p, p–He, He–p and He–He). Data points are taken from BESS 95+97 (filled circles) and from BESS 98 (empty squares).

First of all, we notice that the calculated spectrum agrees very well with the BESS data points. This strong result gives confidence in our consistent treatment of nuclei and antiproton propagation. Second, even if the main production channel is the spallation of cosmic ray protons over interstellar hydrogen, we see that the contribution of protons over helium is very important, particularly at low energies (where a hypothetical primary signature would be expected). It emphasizes the necessity of having a good parameterization of the p–He reaction.

Since the propagation parameters are not perfectly known, some uncertainty must affect the antiproton spectrum. To estimate it, we calculated the antiproton spectra corresponding to all the combinations of the free parameters (δ, K_0, L, V_c and V_a) giving a good fit to B/C. The result is presented in Fig. 2.

The two curves represent the minimal and the maximal flux obtained with this set of parameters. The resulting scatter depends on the energy. More precisely, it is 9% from 100 MeV to 1 GeV, reaches a maximum of 24% at 10 GeV and decreases to 10% at 100 GeV. This gives our estimate of the uncertainties related to diffusion. They may be considered as quite conservative, as the range of allowed parameters could probably be further reduced by a thorough analysis of radioactive nuclei (Donato et al, in preparation) and also by new measurements of stable species.

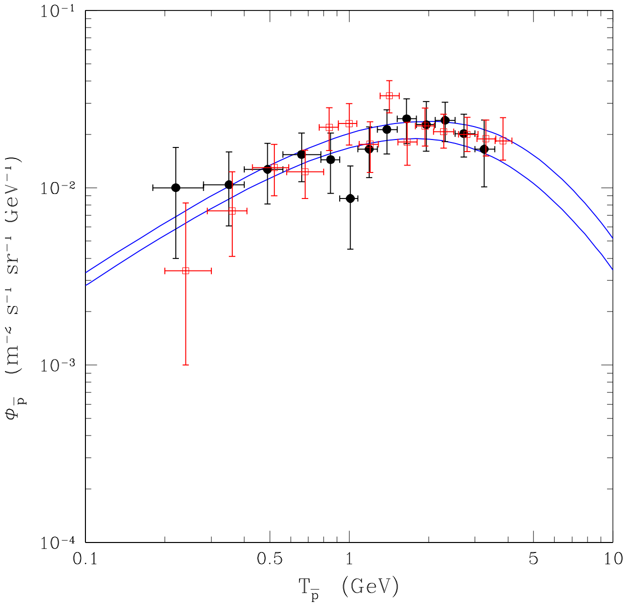

Fig. 2. Antiproton spectra generated with the whole region of parameter space consistent with B/C (Fig. 7 of Paper I). The resulting bounds give an estimation of the uncertainty due to the undeterminacy of the diffusion parameters (data are the same as in Fig. 1)

The uncertainties on the antiproton production cross-sections from p-He, He-p and He-He reactions have been evaluated using the most extensive set of experimental data available (see Paper II for details). All those measurements have been compared with DTUNUC results. As mentioned before, most of them are in excellent agreement with the simulation. The more important discrepancies were found for high-energy produced antiprotons in p-Be collisions and for low energy projectile proton in p-p collision. This latter point is not surprising as the physical input of DTUNUC can hardly be justified for a center of mass energy $\sqrt{s} < 10$ GeV. In both cases, experimental cross-sections were lower than the simulated ones. To account for such effects we parameterized *maxima* and *mimina* cross-sections as a correction to the computed ones, depending on the projectile and antiproton energies. The simplest, *i.e.* linear, energy variation was assumed and the slope was chosen to be very conservative with respect to experimental data. Finally, it has been checked that changes in the Monte Carlo results induced by small variations of the input physical parameters remain within the previously computed errors.

According to Tan and Ng (1982, 1983), the uncertainty in the parameterization of their p–p cross-section should not exceed 10%. In Fig. 3 we present our estimation of the uncertainties related to nuclear physics. The central curve is our reference presented above. The upper one is obtained with the set of maximal p–He, He–p, He–He cross-sections while increasing the p–p cross-section by 10%. Similarly, the lower curve is obtained with the minimal values for these cross-sections while decreasing the p–p cross-section by 10%. Indeed, such a variation for p–p has been included for the sake of completeness even if it modifies the antiproton spectrum only by a few percents. As a conclusion, the shift of the upper and the lower curve with respect to the central one is of the order of 22–25 % over the energy range 0.1–100 GeV.

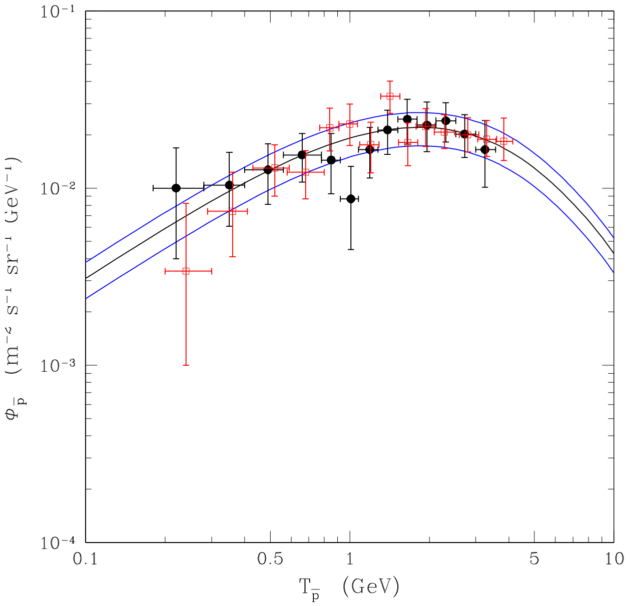

Fig. 3. The antiproton spectrum has been computed with extreme values of DTUNUC nuclear parameters. The central line is the reference curve showed in Fig. 1, while upper and lower curves correspond respectively to the maximum and minimum of the antiproton production rate. These two bounds give an estimation of the uncertainty due to the undeterminacy of the nuclear parameters (data are the same as in Fig. 1).

Besides these major sources of uncertainties, we have also investigated the influence of a possible error in the parameterization of the inelastic non–annihilating cross-section, which gives rise to the tertiary component. We modified it by 20%, which is thought to be very conservative. We found that the antiproton spectrum is modified by less than 1%. In the same line of thought, the effect of total inelastic plus non-annihilating reactions on interstellar He is found to be negligible.

There are few other sources of uncertainties. To begin with, as already discussed, primary cosmic ray fluxes (protons and helium) have been measured with unprecedented accuracy. For the first time, the induced uncertainties on the antiproton spectrum can be neglected.

Next, the only parameters which have not been varied in the previous discussion are those related to the description of the interstellar medium, *i.e.* the densities $n_{\rm H}$ and $n_{\rm He}$. In all the preceding analysis, these were fixed to $n_{\rm ISM} \equiv n_{\rm H} + n_{\rm He} = 1$ cm^{-3} and $f_{\rm He} \equiv n_{\rm He}/n_{\rm ISM} = 10\%$ (same as in Paper I). We have tested the sensitivity of our results to changes in both $n_{\rm ISM}$ and $f_{\rm He}$. For this purpose, we found the new values for the diffusion parameters (for $\delta = 0.6$) giving a good fit to B/C, and applied them to antiprotons. Varying $f_{\rm He}$ in the range $5\% < f_{\rm He} < 15\%$, the resulting flux is modified by less than 15% over the whole energy range. Notice that this range of $f_{\rm He}$ values can be considered as very conservative. A more realistic 10% error on $f_{\rm He}$ (i.e. $0.9\% < f_{\rm He} < 1.1\%$) would lead to a few % error on the antiproton spectrum. Alternatively, varying $n_{\rm ISM}$ from 0.8 to 1.2 cm^{-3}, the resulting flux is modified by less than 0.5% over the whole energy range. To sum up, the only contributing errors are from the helium fraction $f_{\rm He}$ through the dependence of antiproton production on corresponding cross-sections.

Finally, solar modulation induces some uncertainty. This problem is still debated, and a rigorous treatment of this effect is beyond the scope of this paper (see for example Bieber et al. 1999 for a recent analysis). However, in a "force-field" approximation, a general feature is that the steeper the spectrum, the greater the effect. Our antiproton spectra being rather flat, we do not expect them to be dramatically affected by a change in the modulation parameter. Anyway, this local effect is decorrelated from the propagation history. Solar modulation – which is the last energetic modification suffered by an incoming galactic cosmic ray – can thus be treated completely independently from the above analysis.

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References

Alcaraz, J. et al., Phys. Lett. B, 472, 215, 2000a;
——. Phys. Lett. B, 490, 27, 2000b;
——. Phys. Lett. B, 494, 193, 2000c.
Bergström, L., Edsjö, J., and Ullio, P., Astrophys. J., 526, 215, 1999.
Bieber, J.W. et al., Phys. Rev. Lett. 83, 674, 1999.
Bottino A., Donato, F., Fornengo, N., and Salati, P., Phys. Rev. D, 58, 123503, 1998.
Donato, F. et al., astro-ph/0103150, subm. to Astrophys. J.
Maeno T. et al., astro–ph/0010381.
Maurin, D., Donato, F., Taillet, R., and Salati, P., Astrophys. J., 2001, in press; astro-ph/0101231.
Orito S. et al., Phys. Rev. Lett., 84, 1078, 2000.
Sanuki T. et al., Astrophys. J., 545, 1135, 2000.
Taillet R., Maurin, D., Donato, F., and Salati, P., these Proceedings.
Tan, L.C.and Ng, L.K. Phys. Rev. D, 26, 1179, 1982;
——. J. Phys. G: Nucl. Phys, 9, 227, 1983.