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Spectrum of the galactic secondary antiprotons considering tertiary and antineutron decay components

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The antiprotons fluxes estimated by considering the interactions of CR with interstellar matter are lower when compared with the results of the balloon experiments. The estimates in case of leaky box model can be improved by considering the tertiary component and the antineutron decay especially at energies below GeV. Utilizing the SHIELD code [1] for nuclear reactions, we calculated the contributions of these components and estimated the total flux of antiprotons of interstellar origin both during the maximum and minimum solar activity. The results provided better estimates at low energies in agreement with the calculations of Tan & Ng [2] who considered this tertiary component, and produce much satisfactory comparison with the observations. Also the inclusion of contribution of magnetosphere particles to these estimates will be of interest to better these estimates.

1. Introduction

The numerous modeling estimates of the galactic antiproton flux of secondary origin considered the interactions of Cosmic Rays (CR) with the interstellar matter and showed that the calculated flux is lower than that observed near the Earth at sub-GeV energies. However, before considering the existence of the exotic sources of primary antiprotons in our Galaxy such as WIMPS or the evaporation of primordial black holes, one needs to eliminate all possible uncertainties in the parameters of antiproton flux modeling. These include the incomplete knowledge of cross sections for antiproton production, annihilation and scattering, and the inadequacy in the formulation of models of antiproton propagation in the galaxy and heliosphere.

In the present work to compute the secondary interstellar antiproton flux we utilized the SHIELD code nuclear reactions [1]. The code produces energy and angular distributions of the reaction products through Monte Carlo simulation of the intranuclear cascade. The contribution of the tertiary component, i.e. flux produced in nuclear interaction of the secondary antiprotons with the interstellar matter and the antiproton from the antineutron decay are considered. The SHIELD code gives the tertiary component spectra significantly different from the calculations of Tan & Ng [2], and the antineutron or its decay antiproton production is greater than the secondary by about $\sim 55\%$. The crucial point of this work is how this difference influences the final secondary interstellar antiproton spectrum. Thus the study of the antiproton spectrum depends strongly on aspects like the origin and transports of cosmic rays related to the fundamental problems of cosmology.

2. Interstellar Antiproton Flux

The SHIELD code employed for the projectile and secondary particle have the following parameters: The kinetic energies of the projectiles (protons and antiprotons) are in the range of 0.01-10^6 MeV; for the target nuclei hydrogen, helium and oxygen were considered; the energy of secondary antiproton and antineutron spanned the range of 0.01 to 100 GeV. The antiproton angle distribution is essentially confined to $\sim 5^o$ around the incident proton velocity vector.

The interstellar antiproton production spectrum is a total yield of the antiprotons from all the reactions produced by CR protons and heavy nuclei in a unit volume (i.e. g/cm^2) of the interstellar matter. The production spectrum was obtained by the integration of the antiproton differential spectrum, with F_p the local interstellar CR proton spectrum deduced from BESS-TeV experiment [3], and the production rate Γ_{pA} for the interstellar elemental composition of H, He and O in proportions 1: 0.1:10^{-3} [4].

$$Q(E_{\bar{p}}) = 4\,\pi\,\xi \int \Gamma_{pA}(E_p)\,\frac{dN_{\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}})\,F_p(E_p)dE_p. \tag{1}$$

The coefficient ξ ($\sim$ 1.25) is the correction factor due to heavy nuclei and account for the antiproton contribution from the CR heavy nuclei. The production also includes antiprotons from the decay of antineutrons produced in the same reactions, and the tertiary component due to the secondary antiprotons interacting with interstellar matter. We utilized two types of the tertiary spectra: those derived from Tan & Ng [2] and from the SHIELD code. The SHIELD and Tan & Ng source functions of antiprotons practically coincide at energies greater than 5 GeV, but the SHIELD provides a source that is about twice intense in the range of energies from 100 MeV up to 5 GeV, and at lower energies <100 MeV is about an of order of magnitude lower the Tan & Ng estimates and the tertiary component can contribute more strongly to the interstellar antiproton flux. Thus one expects that such a difference in the tertiary spectrum could affect the source function and the resulting interstellar antiproton flux.

To calculate the flux of antiprotons $F_{\bar{p}}(E_{\bar{p}})$, the production or source function $Q_{\bar{p}}$ was employed in a simple leaky-box model to illustrate the influence of the spectral shape of the tertiary antiproton component and the antineutron decay on the resulting interstellar antiproton spectrum. The corresponding continuity equation for the interstellar antiproton flux is:

$$\frac{F_{\bar{p}}(E_{\bar{p}})}{\lambda_{esc}} + \frac{F_{\bar{p}}(E_{\bar{p}})}{\lambda_{inel}} + \frac{d}{dE_{\bar{p}}}\left(F_{\bar{p}}(E_{\bar{p}})\frac{dE_{\bar{p}}}{dx}(E_{\bar{p}})\right) = Q_2(E_{\bar{p}}) + Q_3(E_{\bar{p}}) + Q_{\bar{n}}(E_{\bar{p}}). \tag{2}$$

where λ_{esc} is the escape path length of antiprotons in the Galaxy, λ_{int} is the interaction length of antiprotons including annihilation, and dE/dx the ionization losses. The source functions are represented by Q_2 the secondary production, Q_3 the tertiary component, and $Q_{\bar{n}}$ from antineutron decay computed through Eq. 1.

The interstellar antiproton fluxes resulting from Eq. 2 are shown in Fig.1 for Tan & Ng source and for SHIELD code. There is practically no remarkable difference between antiproton fluxes resulting from the two procedures excepting about 30% greater flux in the 100 - 500 MeV range in case of SHIELD and about 50% greater antiproton flux in case of Tan & Ng source at 10 MeV energy and these differences are of the same order as the experimental errors. Also for comparison the antiproton spectrum computed by Moskalenko (private communication 2004) with GALPROP computer code is shown in Fig. 1. In spite of the sophisticated calculations with propagation including diffusion of the galactic particles and the antiparticles and a different nuclear reaction model (DTUNUC, [4]) to produce secondary particles in the interstellar matter, the results in comparison with our estimates are essentially in satisfactory agreement, within a factor of two for the antiproton fluxes.

In Fig. 2, we present the computed interstellar antiproton fluxes together with the results of recent CR balloon experiments ([5] and references therein). The antiproton fluxes in the heliosphere for periods of minimum and maximum of solar activity were obtained from interstellar fluxes with the modulation coefficients derived from GALPROP code [6]. The computed interstellar antiproton flux modulated in the heliosphere in our modeling essentially agrees with the results of various BESS experiments conducted during near the minimum

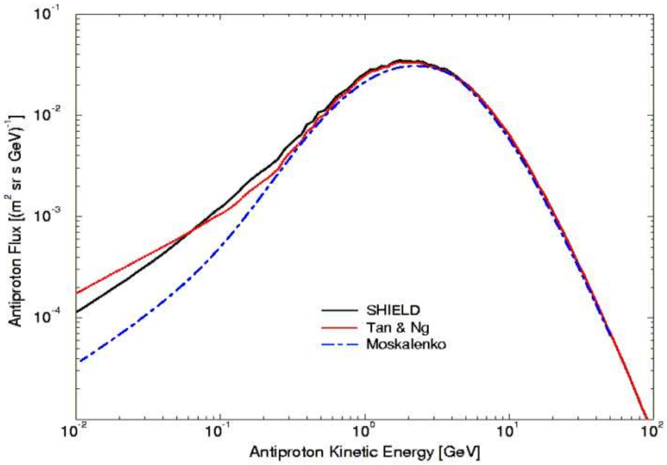

Figure 1. The computed interstellar antiproton spectra by leaky-box model with the SHIELD code compared with the Tang & Ng approach and the GALPROP code.

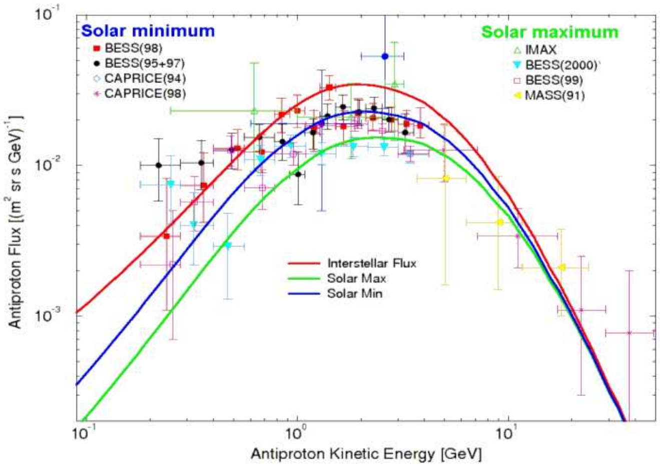

Figure 2. The comparison of the calculated and measured CR antiproton fluxes for the periods of solar activity. The interstellar flux is shown (red colour).

solar activity period of 1995 to 1998 and with BESS experiments in 1999 and 2000 at near the maximum solar activity, in the energy range from 0.2 to 20 GeV. Although in general the agreement is within the error limits, the measured antiproton flux is slightly more than the computed flux at energies < 0.4 GeV. Instead of considering new theoretical possibilities of antiparticle productions in exotic sources, more likely the measured flux has additional contribution of antiprotons from the magnetospheres secondaries which are about tens times greater at lower energies than the heliosphere antiproton flux [7].

In general, many particle populations exist in the magnetosphere domain as different particle species and with different energies. The radial diffusion permits regions of the magnetosphere to populate as an external source, or rearrange particles injected from an internal source. The antiproton source function Q inside the inner magnetosphere is calculated with SHIELD code from the secondary production of antiprotons in nuclear collisions of primary cosmic rays with the magnetosphere constituent [7]. The antiproton flux in particular, in the region of L=1.2 is of the same order of magnitude as antiprotons of interstellar origin and their diffusion towards polar regions can represent an additional source. This possibility may well explain the observed excess of antiprotons of sub-GeV in balloon experiments in near polar regions.

3. Conclusion

The secondary interstellar antiproton flux is calculated on the basis of nuclear reaction computer code SHIELD for the leaky-box propagation model and the tertiary antiproton from the approximations of Tan & Ng. In spite of differences in the tertiary antiproton spectral shape between the two modeling approaches, the flux estimates are not very different. The production of secondary antiprotons cannot alone explain the flux at energies of sub-GeV, and an additional source is necessary as well as experimental observations of the antiproton flux with more sensitivity in these regions.

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