SECONDARY AND PRIMARY ANTIPROTON SPECTRA AND SOLAR MODULATION

T.K. GAISSER
Bartol Research Institute, University of Delaware
Newark, DE 19716, USA
E-mail: gaisser@bartol.udel.edu

ABSTRACT

Solar modulation affects the antiproton spectrum differently from that of protons. Modulation effects are especially important at low energy where a component of primary antiprotons from WIMP annihilation or from evaporation of primordial black holes might be expected to appear. Here I give a brief overview of recent calculations of the spectrum of secondary antiprotons in interstellar space and comment on its two aspects, (1) as a background for a primary component and (2) as a probe of solar modulation.

1. Introduction

Primary cosmic ray protons and nuclei occasionally interact with gas as they wander through the interstellar medium (ISM). The most distinctive feature of the gamma-ray sky is the diffuse radiation from the disk of the galaxy produced in these interactions, as mapped most recently by the EGRET detector on the Compton Gamma-Ray Observatory[1)]. Studies of the intensity and distribution of this radiation are the basis for comprehensive models of cosmic-ray propagation[2)]. Secondary antiprotons are those produced in the same processes in the ISM. New data from recent balloon flights[3,4,5,6)] and data anticipated from longer exposures in space[7,8)] motivate a renewed investigation of this component of the cosmic radiation.

Production of antiprotons is intrinsically a high energy process because of the threshold $\sqrt{s} > 4\,M_{proton}$. This has two consequences. First, only the high energy ($E \gtrsim 10$ GeV) part of the primary spectrum plays a role. For such high energies the effect of solar modulation is small, so there is essentially no ambiguity in demodulating the observed primary spectrum to obtain the parent spectrum in interstellar space. Second, the production spectrum of antiprotons has a distinctive kinematic peak around 2 GeV of kinetic energy. Even after the production spectrum is smeared out during propagation, the equilibrium interstellar spectrum of antiprotons remains considerably harder than that of protons. A consequence is that for $E \lesssim 1$ GeV the amplitude of modulation of the antiproton spectrum through eleven-year solar cycle is not as great as for protons[9)]. Assuming that a component of primary antiprotons would have a steep spectrum, Mitsui *et al.*[10)] suggested that its greater degree of modulation could be used as a signature to distinguish it from the background of secondary antiprotons produced in the ISM. It turns out that several effects conspire to obscure this effect.

2. Secondary interstellar spectrum

The production spectrum of secondary antiprotons is a convolution of the primary spectrum of nucleons in interstellar space with the gas density. For antiprotons with energies in the GeV range and below, the most important part of the primary spectrum is in the range from 10 to 100 GeV[11)]. This region is now particularly well-studied by a series of balloon-borne spectrometer measurements–for the most part the same experiments designed for the antiproton measurements[12,3,4,5,13)]. The spectrum is now considerably lower than the original spectrum[14)] used in many previous calculations. The specific form of the interstellar spectrum we[15)] use is described by Gaisser et al.[16)].

To obtain the equilibrium interstellar spectrum from the production spectrum, it is necessary to use a model of cosmic-ray propagation in the galaxy. For calculation of the spectrum of secondary antiprotons, where the source is spread over the gaseous disk, it is possible to use a standard "leaky box" model with parameters tuned[17)] to reproduce the ratio of secondary (Li, Be, B) to primary (C, O) nuclei. It is important to account for inelastic, non-annihilation interactions of antiprotons in the ISM[18,19)] because this process softens the spectrum by shifting some particles out of the peak region of the production spectrum to lower energy. Second order Fermi acceleration during propagation ("reacceleration") has a similar effect of softening the spectrum[20)]. In our calculation[15,16)] we include the first process but not the second.

The equilibrium interstellar antiproton spectrum that we find[15,16)] (shown as the heavy solid line) is compared with several other calculations in Fig. 1. The spectrum shown by the dashed line is below the others at low energy because inelastic, non-annihilation interactions of antiprotons are neglected in that calculation[11)]. In the energy region above 5 GeV our result falls below the band (pair of thin lines) of Simon, Molnar & Roesler[21)], possibly as a result of the new interstellar spectrum that we use. Most remarkably, our result agrees well with the much more elaborate calculation of Bergström, Edsjö & Ullio[22)] (dotted line), which is based on a solution of the coupled equations for cosmic-ray propagation in a realistic model of the interstellar medium and the galactic halo. This agreement is perhaps not as surprising as it might first appear because it is expected that an equivalent leaky box model can be found for a disk-like distribution of sources embedded in a larger galactic halo[23)]. The more exact propagation model is needed by Bergström et al. because they are also calculating the intensity of primary antiprotons from WIMP annihilation. In that case, the source distribution is related to the distribution of dark matter in the halo, which is concentrated in the galactic center and is therefore distinct from a distribution of sources in the disk.

These results show that the kinematic peak in the production spectrum of an-

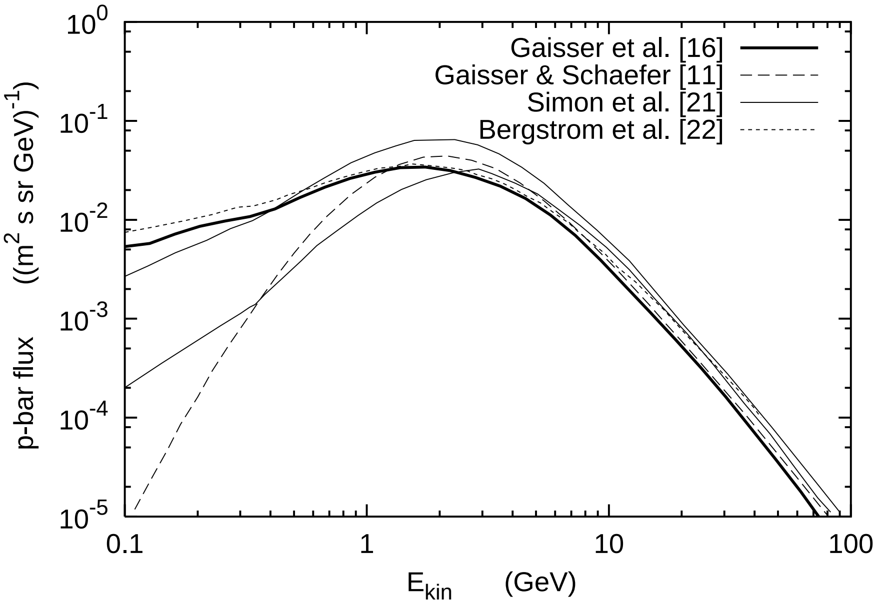

Fig. 1. Calculations of interstellar antiproton flux (see text).

tiprotons is to a large extent smeared by downscattering and that the interstellar antiproton spectrum is therefore relatively soft at low energy. This will make it more difficult to detect a component of primary antiprotons above the background of secondaries.

3. Solar modulation

Solar modulation is a consequence of the fact that galactic cosmic rays must diffuse into the inner heliosphere, going upstream into the expanding solar wind, as described, for example, by Longair[24)]. Low energy particles are excluded altogether and higher energy particles arrive at 1 AU typically having lost several hundred MeV (more or less depending on the degree of solar modulation).

3.1. Secondary vs. primary antiprotons

The main effect of modulation on the shape of the steep interstellar proton spectrum is to suppress strongly the sub-GeV part of the spectrum. Since the harder interstellar spectrum of secondary antiprotons has relatively few low energy particles, the shape of this spectrum is relatively more stable under modulation[9)]. This is because the number of high energy particles shifted down from higher energy during propagation into the inner heliosphere is more nearly comparable to the number of low energy particles excluded by the solar wind.

To the extent that a primary component of antiprotons has a steep spectrum, the degree of low energy modulation could be used as a signal of primary antiprotons. For example, a model of the galactic halo considered by Mitsui et al.[10] has neutralinos of mass 50 GeV annihilating to produce various particles including antiprotons. They find a factor of three variation of antiprotons with energies around 300 MeV between solar maximum and minimum as compared to a variation by only a factor of 1.2 for secondary antiprotons. More recent calculations[25,22] consider similar models. Bergström et al.[22] give the interstellar fluxes for a series of neutralino dark matter models. As an example, I have used the force field formulas[26] to modulate their model 4 (neutralino of mass $\approx$ 100 GeV) and compared it with the similarly modulated version of their interstellar secondary antiproton spectrum. At 300 MeV the solar max to solar min ratio of antiprotons from neutralino annihilation is 1.9, while the corresponding ratio of secondary antiprotons is 1.2.

Thus the difference in modulation of primary and secondary antiprotons is a subtle effect that would require both high statistics and good understanding of solar modulation to be useful as a discriminator.

3.2. Charge-sign-dependent modulation

Every 11-year cycle, the global solar magnetic field reverses sign during solar maximum. If there are drift effects in modulation as well as diffusion in the solar wind, then protons and antiprotons will be modulated differently at any given time, with antiprotons behaving like protons in the previous cycle. Using the detailed modulation theory of Burger & Hattingh[27], we have calculated this charge-sign-dependent modulation[15,28]. According to this model of modulation with drifts, we find that the $\bar{p}/p$ ratio should increase by about a factor of three when the solar magnetic field reverses sign, probably during the year 2000. This would be a striking difference and, if observed, would confirm an important aspect of solar modulation theory.

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