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Astrophysical implications of cosmic-ray antiprotons

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The production and propagation of secondary cosmic-ray antiprotons is discussed. The flux expected on the basis of the usual picture of cosmic-ray propagation, including an energy-dependent confinement time, is calculated. It is also pointed out that kinematical features of the expected secondary-antiproton spectrum provide a possible way to discriminate between secondary antiprotons and a hypothetical primary $\bar{p}$ component in the cosmic radiation.

I. INTRODUCTION

Data on $\bar{p}$ production in pp collisions at proton energies up to 1500 GeV have been used recently[1] to estimate the $\bar{p}$ flux produced by interstellar pp collisions. The use of new data from the CERN Intersecting Storage Rings (ISR) on $\bar{p}$ production[2] at very high energy enables one to remove, to a large extent, the uncertainty in the expected flux of secondary cosmic antiprotons due to lack of knowledge of the $\bar{p}$ production cross section that was present in earlier calculations.[3-5] To obtain an upper limit on the flux of secondary antiprotons it was assumed in I that the primary cosmic rays traverse 5 g/cm^2 of hydrogen independently of energy. An observation of significantly more antiprotons would then suggest the direct acceleration of antiprotons, presumably in antimatter sources. Furthermore, the secondary-antiproton spectrum has a characteristic shape with a low-energy cutoff—below about 2 GeV of kinetic energy—due to the kinematic properties of $\bar{p}$ production. A component of *primary* antiprotons in the cosmic radiation would very likely have a spectral shape similar to that of the primary protons. Therefore, a measurement of the antiproton energy spectrum offers an independent way to discriminate between primary and secondary antiprotons in the cosmic rays. We will return to this point at the conclusion.

The weight of general astrophysical evidence, summarized by Steigman,[6] suggests, however, that only secondary $\bar{p}$ will be seen in the cosmic-ray flux. The purpose of this paper is to examine the production and propagation of the secondary antiprotons to see to what extent the predicted flux depends on the crude astrophysical assumptions made in the course of the calculations. We are motivated by the expectation that the difficulty of observing a low secondary-$\bar{p}$ flux will soon be overcome.[7]

II. SECONDARY-$\bar{p}$ FLUX

For the present we will presume that cosmic-ray protons are accelerated to their final energies and leave the source in such a way that the amount of matter they pass through during the acceleration phase and immediately thereafter is negligible when compared with a few grams per square centimeter. Then the bulk of material encountered by a cosmic-ray particle is that through which it passes in the several million years during which it is confined to the galactic disk. In this case the average rate of antiproton production, per cubic centimeter of interstellar space, is

$$S_{\bar{p}}(\bar{E}) = 2N_{\rm H}\int_{\bar{E}}^{\infty}\frac{d\sigma_{\bar{p}}}{d\bar{E}}(\bar{E},E)\frac{dN_0}{dE}dE\ . \tag{1}$$

dN_0/dE is the observed differential flux of cosmic-ray protons and $N_{\rm H}$ is the average density of interstellar hydrogen.

Now the equation of continuity for antiprotons is

$$\frac{dn_{\bar{p}}(E)}{dt} = S_{\bar{p}}(E) - \frac{n_{\bar{p}}(E)}{\tau_A(E)} - \frac{n_{\bar{p}}(E)}{\tau_p(E)}\ , \tag{2}$$

where τ_A is the average time for an antiproton to annihilate during its propagation through the interstellar medium and τ_p is the galactic confinement time of protons. We have approximated the diffusion of cosmic rays and the appropriate boundary conditions by the last term on the right-hand side, and Eq. (2) ignores energy-loss mechanisms, which, for nucleons with $E \gtrsim 1$ GeV, are negligible. In the steady state

$$n_{\bar{p}}(E) = S_{\bar{p}}(E)\tau_{\bar{p}}(E)\,, \tag{3}$$

where

$$\tau_{\bar{p}}(E) = [\tau_A^{-1}(E) + \tau_p^{-1}(E)]^{-1}\ . \tag{4}$$

Since the matter traversed by a particle of velocity $V(E)$ in a time $\tau(E)$ is

$$\langle y_{\bar{p}}(E)\rangle = N_{\mathrm{H}} m_p V \tau_{\bar{p}} \ ,$$

we obtain for the equilibrium differential flux of antiprotons

$$\frac{dN_{\bar{p}}(\bar{E})}{d\bar{E}} = \frac{2\langle y_{\bar{p}}(\bar{E})\rangle}{m_p}\int_{\bar{E}}^{\infty}\frac{d\sigma_{\bar{p}}}{d\bar{E}}(\bar{E},E)\frac{dN_0}{dE}\,dE, \qquad (5)$$

where

$$\langle y_{\bar{p}}(E)\rangle = [\langle y_p(E)\rangle^{-1} + \langle y_A(E)\rangle^{-1}]^{-1}\ . \qquad (6)$$

$\langle y_p(E)\rangle$ is the mean matter traversed by cosmic-ray protons and $\langle y_A(E)\rangle$ is the mean path for $\bar{p}p$ annihilation. $\langle y_p(E)\rangle$ is generally thought to be of the order of 3 to 6 g/cm^2 when E is of the order of a few GeV; by contrast $\langle y_A(E)\rangle$ in the same energy range is found, from accelerator data,[8] to be 30 to 50 g/cm^2 so that annihilation reduces the $\bar{p}$ flux by 10 or 15 percent at several GeV of kinetic energy. At very low energies (a few hundred MeV) the reduction can be as large as a factor of two; for the present this is of only academic interest. In Fig. 1 we have plotted the interstellar antiproton flux on the assumption that $\langle y_{\bar{p}}(\bar{E})\rangle = 5$ g/cm^2 over the entire energy range. The flux to be expected on the basis of some other form for $\langle y_{\bar{p}}(\bar{E})\rangle$ is easily found using Fig. 1 and Eq. (5). Note that in this most straightforward picture of cosmic-ray acceleration and propagation, the secondary-$\bar{p}$ spectrum depends on the amount of material traversed by cosmic rays at the $\bar{p}$ energy rather than at the primary-proton energy. Clearly Eq. (5) is unchanged if the cosmic rays are confined to an extended halo rather than to the disk of of the galaxy.

We also estimated the effect of solar modulation on the $\bar{p}$ differential flux in Fig. 1. The modulation estimate was calculated on the basis of the force-field solution of the modulation equation.[9]

The basic structure of the $\bar{p}$ production curve arises from combined effects of the steeply falling primary-proton spectrum and the kinematics of $\bar{p}$ production. In particular, the high threshold for antiproton production ($E_{\text{total}}^{\text{threshold}} = 7m_p$) is associated with a minimum $\bar{p}$ lab total energy

$$(E_{\bar{p}})_{\min} \cong m_p\left(1 + \frac{m_p}{E - 6m_p}\right)\ , \qquad (7)$$

where E is the incident proton total lab energy, and the approximation becomes exact at threshold and as $E \to \infty$. Thus antiprotons with kinetic energy less than 940 MeV must come from incident protons above threshold, so that the low-energy $\bar{p}$ spectrum decreases with decreasing $E_{\bar{p}}$ because of the steeply falling primary spectrum. The dynamics of $\bar{p}$ production in pp collisions, which strongly favors antiprotons produced near rest in the center of mass,[10] also contributes strongly

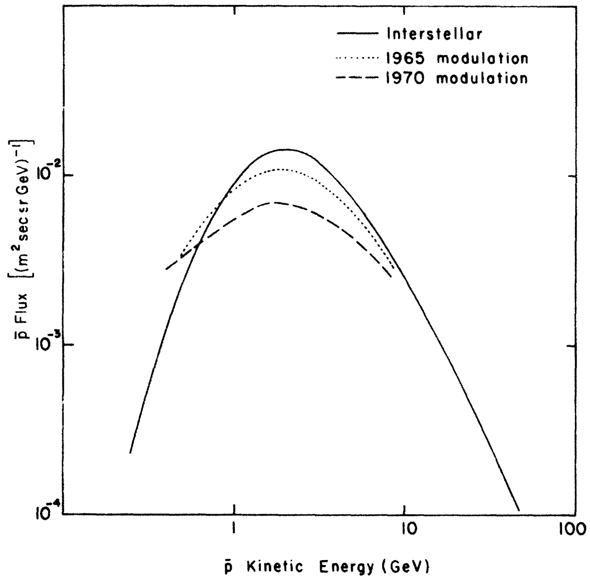

FIG. 1. Equilibrium differential $\bar{p}$ flux expected to be produced by the observed primary-proton spectrum if cosmic rays traverse an average of 5 g/cm^2 of matter during their confinement to the galaxy.

to this low-energy cutoff. Kinematics for $\bar{p}$ production is modified, when one of the colliding nucleons is bound in a nucleus (~20% of all interactions), due to Fermi motion of the nucleons. This has a negligible effect on the secondary-antiproton spectrum; in particular, the spreading of the low-energy cutoff from this source is unimportant since the characteristic nuclear thermal energy is ~100 MeV as compared to $\gtrsim 1$ GeV for the half width of the low-energy side of the secondary-antiproton spectrum. Therefore, we have not included this small effect in the calculation.

The falloff of the secondary-$\bar{p}$ spectrum above maximum reflects the primary spectrum in the usual way, and its spectral index slowly approaches that of the primary spectrum if the $\bar{p}$ production spectrum eventually reaches a Feynman scaling limit in the forward fragmentation region. As shown in I, saturation of the limit is, however, very slow, and the question of whether an asymptotic Feynman scaling limit exists is of negligible practical relevance for calculating secondary antiprotons below about 10 GeV.

The astrophysical information in the equilibrium antiproton spectrum, Eq. (5), is contained in the mean path length and in the assumptions about when the primary-proton flux encounters the major part of the material through which it passes. Equation (5) results from the assumptions made above it. Suppose, alternatively, that most of the matter, through which the protons pass, is encountered in the immediate surroundings of the cosmic-ray sources but after acceleration. In this case the appropriate primary-proton spectrum to use when calculating the $\bar{p}$ production rate is the spectrum at the source rather than the equilibrium interstellar proton spectrum. Proceeding from Eq. (2) (for protons) we find the relativistic proton source spectrum to be given by

$$S_p(E) = \frac{1}{c\tau_p(E)} \frac{dN_0}{dE}, \qquad (8)$$

normalized to the volume of the cosmic-ray confinement region. It is easy to see now that the equilibrium antiproton flux is approximately

$$\frac{dN_{\bar{p}}(\bar{E})}{d\bar{E}} \cong \frac{2\langle y\rangle}{m_p} \tau_{\bar{p}}(\bar{E}) \int_{\bar{E}}^{\infty} \frac{d\sigma_{\bar{p}}(\bar{E},E)}{d\bar{E}} \frac{1}{\tau_p(E)} \frac{dN_0}{dE} dE. \qquad (9)$$

In Eq. (9) $\langle y\rangle$ is the thickness of the shell of matter surrounding the cosmic-ray source. Note that if the galactic confinement time of the cosmic rays is independent of energy over the range relevant for antiproton production—roughly 1 to 100 GeV—then Eq. (9) reduces to Eq. (5). Very likely $\tau(E)$ is almost constant over that energy range. However, it has been suggested[11] that τ might fall by as much as a factor of 2 over the range from 1 to 100 GeV. Then, it is easy to see that the antiproton flux produced by passage through circumsource material would be about twice the flux produced by passage through matter in the interstellar medium.

Altogether, comparing Eqs. (5) and (9), or considering some combination of those two extreme cases, we can draw the following conclusion about the secondary-antiproton flux in the galactic cosmic rays. Assuming that the primary cosmic-ray protons are accelerated to their final energies and leave the source before they encounter the major part of the material through which they pass, then the secondary-antiproton spectrum will be given closely by Eq. (5) or Eq. (9), in which the matter traversed by the energetic particles is a parameter. Consequently, a large departure from this predicted $\bar{p}$ would point to cosmic-ray processes which are exotic within the framework of our present picture of cosmic-ray propagation.

If cosmic rays pass through a substantial amount of matter during the process of acceleration (clearly any material passed through before acceleration above the $\bar{p}$ threshold contributes nothing to the secondary-$\bar{p}$ flux), then the secondary-$\bar{p}$ flux produced by the evolving primary-proton spectrum will differ from what we have calculated here. (It should be remembered that, in this case, the $\bar{p}$ will necessarily undergo further acceleration after production.) Alternatively, if the primary cosmic rays are confined to the source region for a time which depends strongly on energy and if they pass through a significant (on the scale of a few grams per square centimeter) amount of matter there, then the equilibrium secondary-$\bar{p}$ spectrum will be different from Eqs. (5) and (9) by an obvious generalization. For the present, in the absence of positive experimental data, there is no point in pursuing these ideas quantitatively, as the results are highly model-dependent. We refer the reader to a paper by Wayland and Bowen[4] for an example. (But note that their results are suspect to the extent that they depend on extrapolation beyond 30 GeV of their formula for the $\bar{p}$ production rate.)

There are indeed indications that the simplest picture of cosmic-ray production and propagation may have to be augmented.[11] In this connection secondary antiprotons offer a unique supplement to the development of our ideas since, in the highly probable absence of a primary component,[6] the source abundance is necessarily zero. We should also like to mention here that a secondary-$\bar{p}$ flux provides a useful tool with which to study adiabatic deceleration of cosmic rays in the solar wind. The advantage of using $\bar{p}$ for such a study is that the rapid decrease in its spectrum at low energies will allow the low-energy tail of the adiabatic deceleration curves[9] to be more easily discerned.

III. UNCERTAINTIES AND BACKGROUND

There are several uncertainties implicit in the calculation of the secondary-$\bar{p}$ flux which, together, we estimate to total about 60%. Uncertainties in the $\bar{p}$ production data and the necessarily large interpolation between the lower-energy data[12] and the ISR data[2] contribute about a 30% uncertainty in the secondary-$\bar{p}$ flux.[10] An estimated ±0.1 uncertainty in the primary-proton spectral index and a 10% error in the normalization of the primary-proton flux[13] together lead to a further ~30% uncertainty in the computed $\bar{p}$ flux.

In a balloon experiment a layer y_{air} (in g/cm^2) thick of overlying atmosphere will produce a background of

$$\frac{dN_{\bar{p}}^{(\text{air})}}{dE} = \frac{y_{\text{air}}}{15 m_p} \int_E^{\infty} \frac{d\sigma_{\bar{p}}^{(\text{air})}(E,E')}{dE} \frac{dN_0}{dE'} dE' \qquad (10)$$

antiprotons per GeV of total energy. [There is no factor of two in Eq. (3) because $\bar{n}$ produced in air will not decay to $\bar{p}$ above the detector.] Since the yield of $\bar{p}$ on light nuclei is about the same as the yield on protons,[14] the flux of $\bar{p}$ produced by the overlying atmosphere can be obtained by multiplying the $\langle y\rangle = 5$ g/cm^2 curve of Fig. 1 by $\frac{1}{2}(\frac{1}{5}y_{\text{air}}) \times (\lambda_{p-\text{H}}/\lambda_{p-\text{air}})$, where $\lambda_{p-\text{H}}$ and $\lambda_{p-\text{air}}$ are respectively the proton interaction length in hydrogen and in air. (Modulation of the primary-proton flux is unimportant here because of the high threshold for $\bar{p}$ production.) For ~20 GeV protons[15] $\lambda_{p-H}/\lambda_{p-air} \sim 0.65$, so that for $y_{air} = 4$ g/cm^2 the multiplying factor (relative to 5 g/cm^2 of hydrogen) is 0.26. Equivalently, 4 g/cm^2 of overlying atmosphere has the same effect as ~1.3 g/cm^2 of interstellar hydrogen in producing antiprotons. Because of the ~60% uncertainty involved in relating an observed $\bar{p}$ flux to the thickness of matter that produced it, the flux of secondary interstellar protons will be lost in the background of $\bar{p}$'s produced in the overlying atmosphere if the effective amount of interstellar hydrogen is less than 1 g/cm^2. Such a limitation would obviously be removed in a satellite experiment. We also note that this background problem, characteristic of a balloon experiment, is less severe for primary antiprotons because of the probable difference in shape between low-energy secondary- and primary-$\bar{p}$ spectra. In making this estimate of the atmospheric contribution to the observed $\bar{p}$ flux we have neglected the effect of the geomagnetic field on the propagation of primary protons with energies above the threshold for $\bar{p}$ production.

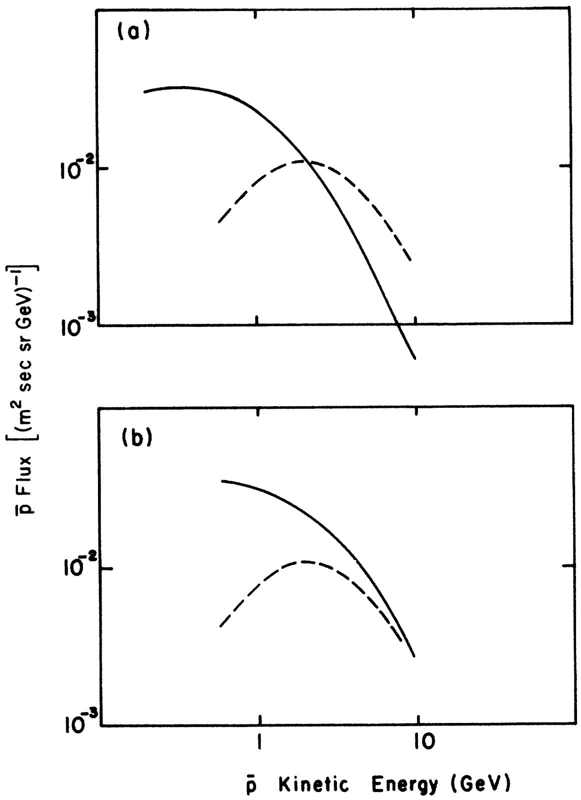

FIG 2. (a) Expected secondary-$\bar{p}$ flux (dashed line) compared with a hypothetical primary-$\bar{p}$ flux having the same spectrum as primary proton normalized to equal intensity near the maximum in the secondary spectrum. (b) Secondary-$\bar{p}$ flux alone (dashed line) compared with the sum of secondary flux and the hypothetical primary-$\bar{p}$ flux. The differential fluxes are modulated according to 1965 solar-wind conditions.

IV. PRIMARY-$\bar{p}$ FLUX

Arguments based on the symmetry of physics strongly suggest that *primary* antiprotons produced in antimatter sources will have a spectrum similar to the spectrum of primary protons. This argument, coupled with the strong kinematical features of the secondary-antiproton spectrum, provide a way to discriminate a small component of primary antiprotons in the cosmic rays. In Fig. 2(a) we have plotted the secondary-antiproton spectrum and compared it with a "primary antiproton" spectrum having the same shape as the primary-proton spectrum normalized to the secondary flux near maximum. Both spectra are modulated according to 1965 solar conditions. In Fig. 2(b) we compare the expected secondary flux alone with the sum of secondary-$\bar{p}$ flux and the hypothetical primary-$\bar{p}$ flux. A primary flux as low as 2×10^{-2} (m^2 sec sr GeV)$^{-1}$ at $\bar{p}$ kinetic energy of 1 GeV (corresponding to $\bar{p}/p \sim 2\times10^{-5}$) should be distinguishable from a background of secondaries by measurements made in the energy range 0.5 to 10 GeV. We emphasize, moreover, that observation of a cosmic $\bar{p}$ flux without the low-energy cutoff characteristic of secondary antiprotons would be a signal of a primary component of antiprotons in the cosmic rays.

On the other hand, it is interesting to speculate that a small extragalactic cosmic-ray $\bar{p}$ component may be partially excluded from the galaxy, or that the particles may have their energy changed to such a large extent, as they diffuse in through the galactic magnetic field, that they are difficult to distinguish from the secondary antiprotons. Whether a galactic modulation effect of this kind does, in fact, occur depends largely on the dynamical state of the interstellar medium and, in particular, on the details of the confinement of the galactic magnetic field and its appropriate boundary conditions. For example, in the case of a generally static galactic magnetic field, a steady isotropic distribution of intergalactic antiprotons would show itself with this same intensity everywhere throughout the presumably ergodic magnetic field of the galaxy, by virtue of Liouville's equation. However, Parker[16] has speculated that the state of the galactic magnetic field is dynamic rather than static and that the combined pressure of the magnetic field and galactic cosmic rays continuously inflates the magnetic field at the (loosely defined) boundary of the galaxy.

On this basis, the picture that one has is of a continually expanding halo of magnetic field surrounding the galaxy. Cosmic rays entering the galaxy from outside might then be partially excluded from the galaxy by these escaping magnetic fields and adiabatically decelerated by the expansion. Owing to our ignorance of the properties of such a dynamical halo, a quantitative discussion of galactic cosmic-ray modulation is beyond our present means. For now it will suffice to make a crude but plausible estimate of the energy loss suffered by a particle entering the galaxy against an expanding magnetic halo. Suppose the halo expands spherically. Then, in order of magnitude, the energy loss of a particle entering from outside is[17,18]

$$\frac{\Delta T}{T} \sim \frac{VR}{\kappa}, \tag{11}$$

where T is the particle's kinetic energy, V is the expansion velocity of the halo, R is the radius of the halo, and κ is the particle diffusion coefficient in the escaping magnetic fields. For this crude estimate we can set[16,19] $V \sim 10^7$ cm/sec and $R \sim 10^{22}$ cm. We see no way to make an independent estimate of κ in an expanding halo; for the purpose of this discussion we will assume that it is the same as the particle diffusion coefficient in the galactic disk. Cosmic rays escape the galaxy in a time of several million years, and to do so they must diffuse a distance of the order of 10^{21} cm to the "faces" of the galactic disk. Taken together, these numbers indicate that $\kappa \sim 10^{28}$ cm^2/sec. Then from Eq. (11) we have $\Delta T/T \sim 10$. Now Eq. (11) is only a crude measure of the energy loss and is only accurate when[18] $\Delta T/T \ll 1$; in addition the dynamical picture of the galactic halo which we have used as a point of departure in this discussion is by no means a unique one. However, we have illustrated the point that a dynamically expanding galactic halo could significantly modulate the intensity of a small extragalactic cosmic-ray $\bar{p}$ component and thus depress the flux observable at Earth. While this does not affect any of the positive statements we have made above, it illustrates the relatively greater difficulty of demonstrating that a primary-antiproton component does *not* exist.

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