Galactic Antiprotons from Photinos

F. W. Stecker
NASA Goddard Space Flight Center, Greenbelt, Maryland 20771

and

S. Rudaz and T. F. Walsh
School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455
(Received 13 June 1985)

Stable photinos, the photino being the supersymmetry partner of the photon, can explain both the "missing mass" in galactic halos and the cosmic-ray antiproton spectrum up to the highest energies observed so far. This requires a photino mass around 15 GeV; significantly higher masses are cosmologically disfavored. As a consequence, the observed cosmic-ray antiproton-to-proton ratio is predicted to decrease abruptly just above the measured energy range, at $E = m_\chi$. If observed, this striking effect would strongly support the hypothesis that photinos make up the missing matter in our galaxy and also lead to a measurement of the photino mass from cosmic-ray data.

PACS numbers: 98.60.Ce, 14.80.Pb, 98.60.Ln

If broken supersymmetry is realized in nature, its most striking consequence is the existence of as yet unobserved supersymmetry partners to the known fundamental particles. In the presence of an appropriate symmetry distinguishing these superpartners from ordinary particles, the lightest superpartner must be stable. This lightest stable new particle is most probably the supersymmetric partner of the photon, the photino, with spin $\frac{1}{2}$. We denote it by χ. (The lightest superpartner could, in fact, have an admixture of the fermion superpartners of the Higgs scalars in addition.) Any evidence for the existence of these particles would be of the greatest importance. It is well known that such stable photinos would be produced in the big bang and could account for the nonluminous matter which makes up most of the mass of galaxies. Annihilation of light photinos of mass 3 GeV in the halo of our own galaxy could plausibly account for the observed low-energy antiproton flux observed in cosmic-ray experiments.[1,2] However, there is no clear observational signature which could confirm such light photinos as the source of the observed low-energy antiprotons. Moreover, the data exhibit an unexpectedly large antiproton flux at all energies measured so far.[3,4] We will show here that the hypothesis that photinos make up a nonluminous mass component of our galaxy compatible with that in other nearby galaxies can, in fact, account for the entire observed antiproton spectrum. This requires a photino mass around 15 GeV. Moreover, this hypothesis leads to the prediction that at energies just above those measured so far, the ratio of antiprotons to protons should show a steep drop. This is due to the kinematic bound on the antiproton energy for slow galactic photinos. Above this cutoff energy, antiprotons will be found at only a small flux due to production by cosmic rays on gas, if one accepts the current view, as we will do in this paper.[5] The presence of this steep drop would confirm the presence of massive neutral particles annihilating in our galaxy and would allow a measurement of their mass. Identifying these particles as photinos requires that the superpartners of the fundamental quarks and leptons not be significantly heavier than about 30 or 35 GeV, so that they should be observable in accelerator experiments.[6]

For photinos of mass 3 GeV and for a Hubble constant 50 km/s·Mpc (which we will use in the following), production in the big bang leads to a present density which can be expressed as a fraction of the closure density, $\Omega_\chi \cong 1$. (This estimate assumes a common mass $m_{\rm sp} = 50$ GeV for the scalar superpartners of the known left- and right-handed fermions.) For large photino masses, the same considerations lead to a rough estimate[7]

$$\Omega_\chi \approx 0.05[(20\ \text{GeV})/m_\chi]^2[m_{\rm sp}/(50\ \text{GeV})]^4. \quad (1)$$

Theoretical uncertainties in (1) arise from several sources. Reheating of the photon gas is affected by the relation of the photino freezeout temperature to the hadronic phase-transition temperature. The weak cross section is uncertain because we do not know the masses of the superpartners of quarks compared to the masses of the superpartners of leptons, or of the superpartners of left-handed fermions compared to the masses of the superpartners of right-handed fermions. A conservative estimate is that the right-hand side of (1) could be uncertain by a factor of 2 to 4 in either direction; we can easily make it a factor of 4 in a direction convenient to us.

Clearly a very low cosmic average Ω_χ would not be compatible with massive galactic halos made of photinos. We can estimate the fraction of closure density in nonluminous halo matter by exploiting the observational fact that galactic halos are at least ten times the mass of the visible matter, or $\Omega_{\rm halo} \approx 0.04$–$0.07$.[8] If galactic halos are due to photinos, then this is a lower bound on the cosmic average fraction of closure density in photinos. The reason is that energetics arguments as well as numerical simulations show that nondissipative material such as photinos cannot clump as efficiently as baryonic matter.[9] The clumping is at least partly due to energy dissipation in the baryonic matter (i.e., gas), and dissipation of kinetic energy in the photinos is due to gravitational coupling to the baryonic matter. This process is not fully efficient, so that the fraction of closure density in photinos needed to get the observed halos should satisfy $\Omega_\chi \gtrsim \Omega_{\rm halo}$. Taken at face value this limits m_χ to

$$m_\chi \leq (20\ \mathrm{GeV}) \left(\frac{0.05}{\Omega_{\rm halo}}\right)^{1/2} \left(\frac{m_{\rm sp}}{50\ \mathrm{GeV}}\right)^2. \tag{2}$$

Unfortunately, all astrophysical arguments of this sort have large uncertainties, as we have already emphasized. The right-hand side of (2) could easily be larger or smaller by a factor of order 2, and perhaps even more. Nevertheless, it is clear that the photino mass cannot be extremely large and still be responsible for galactic halos.

A uniform halo has a mass density on average of about 1 $\mathrm{GeV/cm^3}$ within 10 kpc of the galactic center.[1,8] A halo with an isothermal mass distribution would have a mean mass density at 10 kpc galactocentric distance of about 0.4 $\mathrm{GeV/cm^3}\cdot$ (We will use 1 $\mathrm{GeV/cm^3}$ in our numerical estimates.) Dividing this by the photino mass then gives the photino number density n_χ. The production rate of antiprotons produced by annihilation is then

$$Q(E_{\bar p}) = n_\chi^2 \langle \sigma\beta \rangle c F(E_{\bar p})\ \mathrm{cm^{-3}\,s^{-1}\,GeV^{-1}}, \tag{3}$$

where the production spectrum $F(E_{\bar p})$ is normalized to the number of antiprotons per annihilation. With our simplifying assumptions, the average total annihilation cross section is given by[7]

$$\langle \sigma\beta \rangle \cong [8\pi\alpha^2/m_{\rm sp}^4] \textstyle\sum_f q_f^4 \beta_f m_f^2, \tag{4}$$

where f denotes the fermions in the annihilation and β_f is the final-state velocity.

We require the branching ratio and antiproton spectrum in the decay $\chi\chi \to \tau\bar\tau + c\bar c + \ldots \to \bar p + \ldots$ as a function of the χ mass. There is no satisfactory theory for antiproton production in the final state. We know, however, that for m_χ only slightly greater than the quark mass, antiprotons will come principally from the decay of particles containing the heavy quark produced in $\chi\chi$ annihilation. When m_χ is much greater than the quark mass, production of generally low-momentum baryon-antibaryon pairs will dominate, and this production reaction does not depend at all on the type of quark created in $\chi\chi$ annihilation. The actual antiproton spectrum is thus an overlay of spectra due to two distinct physical processes: decay of heavy hadrons with a heavy quark in them, and the creation of pairs. Provided this latter process dominates, we can take data from any reaction with quark pair production and use it to approximate the antiproton branching ratio and spectrum of interest to us. The error in this approximation will be due to electron-positron annihilation and $\chi\chi$ annihilation having different fractions of quarks with $m_\chi/m_q \sim 1$ and $m_\chi/m_q \gg 1$ (we refer to these fractions as ϵ_h). The actual error made will be of order $\langle n(p)\rangle_h [\epsilon_h(\chi\chi) - \epsilon_h(e^+e^-)/\langle n(p)\rangle$. For a 20-GeV χ we estimate $< 10\%$ error in the antiproton fraction. Because antiprotons from heavy-quark decay will have slightly larger momentum than antiprotons from baryon-antibaryon pair creation, we expect this error to affect mainly the high-momentum tail of the spectrum. The high-energy tail of the spectrum will also be affected by the exact behavior near the kinematic limit, where there are no data. Compared to other uncertainties in our calculation, this is more than good enough for our purposes. Empirically, our approximation even appears good at low energy just above the c-quark threshold even though we do not need this for our considerations.

In electron-positron annihilation, it is an experimental fact that within statistical errors the spectra at all energies can be fitted by a single function of the form[10]

$$(4E_B^2/\beta_{\bar p})\, d\sigma/dx_E, \tag{5}$$

where $1 > x_E = E_{\bar p}/E_B > m_{\bar p}/E_B$, with E_B the beam energy; $\beta_{\bar p} = v_{\bar p}/c$. The energy dependence arises from the kinematic dependence on the lower bound of x_E. Our approximation, including direct $\bar p$ and also $\bar n$ decaying to $\bar p$, is to set $m_\chi F(E_{\bar p})$ equal to

$$\frac{1}{\sigma(\chi\chi)} \frac{d\sigma_{\bar p}(\chi\chi)}{dx_E} = 2\delta \frac{1}{\sigma(e^+e^-)} \frac{d\sigma_{\bar p}(e^+e^-)}{dx_E} = 2.89\beta_{\bar p}\delta \begin{pmatrix} 8.5e^{-11x_E} + 0.25e^{-2x_E} \\ 7.7e^{-14.5x_E} + 0.17e^{-2.5x_E} \end{pmatrix}, \tag{6}$$

where $x_E = E_p/m_\chi$ for $\chi\chi$ annihilation, $\delta \approx 0.5$ accounts for the difference in the amount of hadronic annihilation in $\chi\chi$ and e^+e^- and where we have put in numbers for the various quantities; the upper and lower expressions above bracket the experimental errors in the data. They are not intended as fits, but rather indicate the range to be expected from the electron-positron data (which has large errors). It turns out that errors in our approximation here are small enough so that we can simply use the upper expression in (6) for numerical purposes.

With the branching ratio and spectrum in hand we can calculate the flux. Antiprotons produced in the solar neighborhood wander away with a diffusion coefficient in the energy range of interest of[11]

$$D \cong 10^{26}\beta_{\bar{p}} P^{0.7} \text{ cm}^2 \text{ s}^{-1}, \tag{7}$$

which implies that the relevant antiprotons diffuse 100–200 pc in their mean lifetime in the galactic disk $\tau\beta_{\bar{p}} \cong 5\times10^{14}$ s; clearly, the relevant photino density in our calculation is that in the immediate solar neighborhood. The antiproton flux in interstellar space is then

$$I_{\bar{p}} = Q\tau\beta_{\bar{p}}c/4\pi = 1.2\times10^{24} Q \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \tag{8}$$

For photino masses above 10 GeV, our final expression for the antiproton flux becomes

$$I_{\bar{p}} = 4.6\left(\frac{15 \text{ GeV}}{m_\chi}\right)^3 \left(\frac{30 \text{ GeV}}{m_{\text{sp}}}\right)^4 \beta_{\bar{p}} \left[\exp\left(\frac{-11E_{\bar{p}}}{m_\chi}\right) + 0.03 \exp\left(\frac{-2E_{\bar{p}}}{m_\chi}\right)\right] \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}. \tag{9}$$

It is important to understand that we have not used extreme values of the parameters in obtaining the numerical coefficient in this equation. As an example, the nominal value of the antiproton diffusion time in Ref. 1 is much bigger than the one we used.

The observed antiproton flux is strongly affected by solar modulation at low energies, and we have to take this into account. The amount of proton modulation during the relevant time period of the solar cycle, viz., June 1980, has been estimated by use of Pioneer, Helios-1, and ISEE-3 data.[12] This yields expressions for the effective diffusion coefficient for modulation by the solar wind. The interstellar antiproton spectrum may then be numerically modulated to compare with observations.[13]

Figure 1 shows the normalized interstellar and modulated spectra obtained for 3- and 20-GeV photino masses, compared to observations and to the standard secondary antiproton calculations.[5] The 3-GeV curve used the appropriate numerical coefficient for that case, which differs from the coefficient in Eq. (9). We chose 20 GeV because it is a rough upper limit to the photino mass, as will soon become clear. Figure 2 shows the antiproton-proton ratio as a function of energy for (a) 3-, (b) 15-, and (c) 20-GeV photinos [(d) is MCRS as in Fig. 1.] The data are from Refs. 2–4.

We find that $m_\chi = 20$ GeV requires $m_{\text{sp}} \approx 27$ GeV in (9) to get the low-energy spectrum normalization correct with the value of the coefficient quoted there. Even if we take into account generous uncertainties in (2) and (9), these are surely the largest and smallest values of m_χ and m_{sp} that we can tolerate. By contrast, a photino mass of about 15 GeV can account quite well for the antiproton-to-proton ratio without conflicting seriously with the soft bound (2). The low-energy normalization requires a superpartner mass of about 32 GeV and gives $\Omega_\chi \approx 0.015$. The smallest acceptable

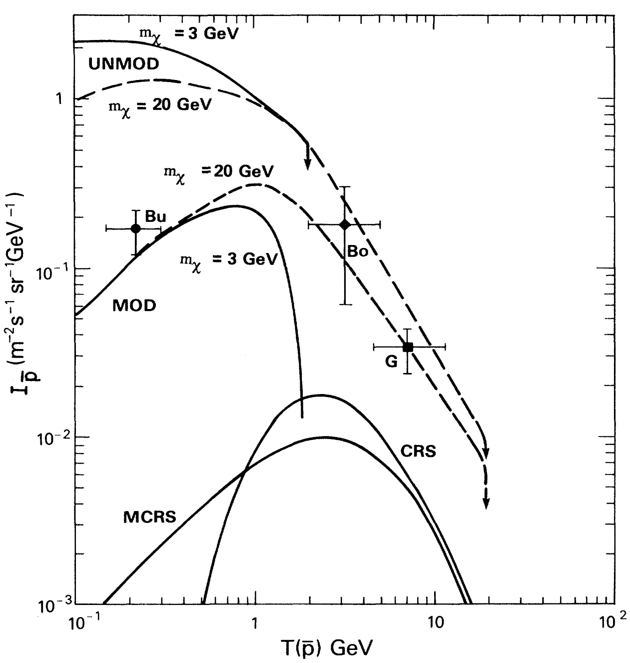

FIG. 1. Unmodulated and modulated spectra for 3- and 20-GeV-mass photino annihilation, compared to the data and to cosmic-ray secondary production (CRS) and modulated cosmic-ray-secondary production (MCRS).

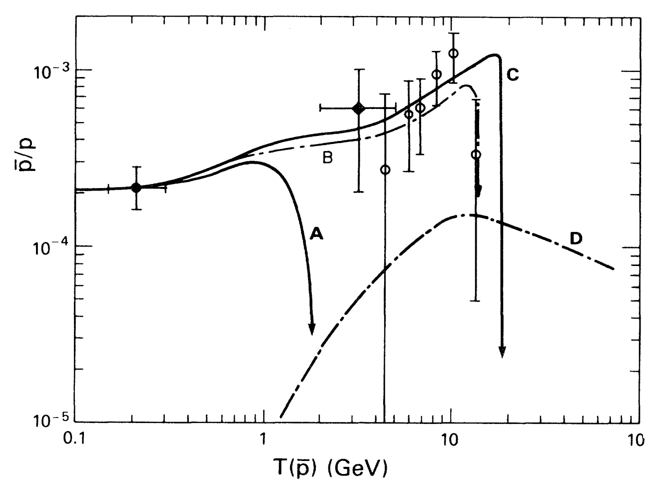

FIG. 2. Antiproton-proton ratio as a function of kinetic energy from photinos of mass (a) 3, (b) 15, and (c) 20 GeV. (d) is for cosmic-ray secondaries.

photino mass is about 12 GeV with a superpartner mass of about 35 GeV and $\Omega_X \approx 0.035$. With this value, the last datum point in Fig. 2 is above the cutoff in the decay spectrum; however, we can then get the overall normalization roughly correct and even approximately satisfy the bound (2) or reproduce (1) without having to invoke uncertainties. The ease with which we can avoid conflict with (1) or (2) may seem surprising, but in fact it is not surprising at all: Fixing the normalization of the spectrum in (9) at energies much below the photino mass and then using this to eliminate m_{sp} in Eq. (1) leads to the right-hand side of that equation having a dependence on the inverse fifth power of the photino mass. The actual dependence in practice is not this strong, but we see from this example why we need not worry excessively about Eq. (1).

We emphasize yet again that there are numerous sources of uncertainty in a calculation of the antiproton spectrum, arising from particle physics as well as from astrophysics. It must be clear from this paper that we place more importance on the observational data than on a large number of theoretical input parameters which are ill known and hard to substantiate. For us, the central fact is that the dependence on m_X and m_{sp} is strong. Requiring that galactic halos be made of photinos and that the annihilation rate be large enough to account for the antiproton spectrum restricts these masses for plausible uncertainties in the quantities we use. We expect a photino mass around 15 GeV and definitely not larger than about 20 GeV. Thus we expect a sharp drop in the antiproton-to-proton ratio at energies just above those measured so far.[14] This is a prediction of the hypothesis that the galactic-halo mass is in photinos and that these photinos are responsible for the otherwise unexplained large antiproton flux at all energies. Observation of this expected steep decrease in the ratio would strongly support photinos as the "missing mass" in our galaxy, and allow a measurement of the photino mass and a crude estimate of the scalar fermion-superpartner mass. The somewhat extreme hypothesis that massive neutrals unrelated to supersymmetry are responsible for the cosmic-ray antiprotons can clearly be excluded only by observation of fermion superpartners in accelerator experiments. An explanation for the spectrum as being due to particles unrelated to supersymmetry should not be discarded out of hand, however. Much of our discussion depends only on the existence of stable particles annihilating by a weak interaction, with a nonnegligible branching ratio to quark-antiquark pairs. Here too, the mass of the annihilating particles cannot be very large if they are to provide the halo mass with an acceptable overall cosmological density. Thus we can expect to account for the spectrum in this case as well, and we also predict a cutoff in antiprotons at the mass of the particle as in the case of standard supersymmetry. If this cutoff is not observed, the present explanation of the entire antiproton spectrum can be discarded.

We thank John Perko for the numerical modulation of the antiproton flux and P. Freier, J. Ormes, and J. Waddington for conversations on cosmic rays. Two of us (F.W.S. and S.R.) thank A. Halprin and the Lewes Center for Physics for hospitality during the initial phase of the work. This work was supported in part by the U. S. Department of Energy under Grant No. DE-AC02-83ER-40105, by a University of Minnesota Graduate School grant, and by a Presidential Young Investigator Award to one of us (S.R.).

[1]J. Silk and M. Srednicki, Phys. Rev. Lett. **53**, 624 (1984).

[2]A. Buffington *et al.*, Astrophys. J. **248**, 1179 (1981).

[3]E. A. Bogomolov *et al.*, in *Proceedings of the Seventeenth International Cosmic Ray Conference, Paris, 1981* (Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France, 1981), Vol. 9, p. 146.

[4]R. L. Golden *et al.*, Astrophys. Lett. **24**, 75 (1984).

[5]R. Protheroe, Astrophys. J. **251**, 387 (1981).

[6]These results were reported at the Washington meeting of The American Physical Society, April 1985 [F. W. Stecker, S. Rudaz, and T. F. Walsh, Bull. Am. Phys. Soc. **30**, 764 (1985)].

[7]H. Goldberg, Phys. Rev. Lett. **50**, 1419 (1983); J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. Olive, and M. Srednicki, Nucl. Phys. **B238**, 453 (1984).

[8]A. Zee, Nucl. Phys. **B252**, 37 (1985); D. Schramm, Nucl. Phys. **B252**, 53 (1985).

[9]Ya. B. Zeldovich *et al.*, Yad. Fiz. **31**, 1286 (1980) [Sov. J. Nucl. Phys. **31**, 664 (1980)].

[10]R. Brandelik *et al.*, Phys. Lett. **94B**, 444 (1980); W. Bartel *et al.*, Phys. Lett. **104B**, 325 (1980); S. L. Wu, Phys. Rep. **107**, 59 (1984).

[11]J. Ormes *et al.*, in *Proceedings of the Eighteenth International Cosmic Ray Conference, Bangalore, India, 1983,* edited by N. Durgaprasad *et al.* (Tata Institute of Fundamental Research, Bombay, 1983), Vol. 2, p. 187.

[12]F. B. McDonald, private communication.

[13]J. Perko, Ph.D. Thesis, University of New Hampshire, 1984 (unpublished).

[14]Precise measurements of the high-energy antiproton flux can be made by use of an orbiting superconducting magnetic detector: F. W. Stecker and A. W. Wolfendale, Nature **309**, 37 (1984); J. Ormes, private communication.