GALACTIC COSMIC RAY ANTIPROTONS AND SUPERSYMMETRY

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ABSTRACT

We consider the physics of the annihilation of photinos ($\tilde{\gamma}$) as a function of mass in detail, in order to obtain the energy spectra of the cosmic-ray $\bar{p}$'s produced under the assumption that $\tilde{\gamma}$'s make up the missing mass in the galactic halo. We then compare the modulated spectrum at 1 a.u. with the cosmic-ray $\bar{p}$ data. A very intriguing fit is obtained to all of the present $\bar{p}$ up to 13.4 GeV data for $m_{\tilde{\gamma}} \sim 15$ GeV. We predict a cutoff in the $\bar{p}$ spectrum at $E = m_{\tilde{\gamma}}$ above which only a small flux from secondary production should remain.

1. Introduction. It has recently been suggested (1) that annihilation from a dark matter halo made up of 3 GeV $\tilde{\gamma}$'s may account for the suprisingly large low-energy $\bar{p}$ flux reported in Ref. 2. Other interesting possibilities exist for producing such fluxes which are also of potential cosmological and astrophysical importance (e.g. Ref. 3 and OG 6.1-8). The photino hypothesis also affords a test for whether we live in a universe where supersymmetry (boson-fermion symmetry) is relevant. Indeed, measurements of cosmic-ray $\bar{p}$'s from $\tilde{\gamma}$ annihilation can enable the cosmic-ray physicist to determine the mass of the $\tilde{\gamma}$. This, however, requires a calculation of the energy spectrum of cosmic-ray $\bar{p}$'s produced in $\tilde{\gamma}$ annihilation and $\bar{p}$'s and modulation of this spectrum in order to directly compare with observed fluxes. We present here the results of such a calculation.

2. Photino (and Higgsino) Physics. Supersymmetry is a relatively new principle in particle physics which has been invoked to account for the "smallness" of the W-boson mass (compared with the grand unification scale) and possibly to incorporate gravity into a unified field theory. According to this principle, each ordinary boson and fermion has a supersymmetric partner and the lightest supersymmetric particle (LSP) should be stable. A prime candidate for the LSP is the $\tilde{\gamma}$ (or, more generally, a possible mass state admixture of the $\tilde{\gamma}$ (having gauge interactions) and neutral higgsino (having Yukawa interactions)). If such a stable particle is made in the early big-bang, it becomes a candidate for the dark matter in the universe (along with other possibilities such as massive neutrinos, axions, black holes, etc.). The mass density of such particles in the universe scales inversely with the annihilation cross section times velocity $\langle\sigma v\rangle$. A value near the critical density can be obtained by choosing a reasonable value for the prime unknown parameter involved in the calculation (4,5), viz., the mass of the scalar fermion which mediates the annihilation, $m_{\tilde{f}}$. For two particular values for the $\tilde{\gamma}$ mass, $m_{\tilde{\gamma}} = 3$ GeV, chosen in Ref. 1, and

$m_{\tilde{\gamma}}$ = 20 GeV, we obtain the following formulas for the mass density of photinos as a fraction of the closure density:

$$\Omega_{\tilde{\gamma}} \simeq \binom{1.0}{0.4} h^{-2} (m_{\tilde{f}}/50 \text{ GeV})^4 \quad \begin{array}{l} , m_{\tilde{\gamma}} = 3 \text{ GeV} \\ , m_{\tilde{\gamma}} = 20 \text{ GeV} \end{array} \qquad (1)$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}. In both cases, the mass of the scalar fermion $\tilde{f}$ required to obtain $\Omega_{\tilde{\gamma}}$ = 1 is ~50 GeV, a value which may find some support in interpretations of the monojet events observed at the CERN $p\bar{p}$ collider (6). Photinos of mass much above 20 GeV will not give cosmologically significant mass densities.

The energy spectrum of the $\bar{p}$'s produced in $\tilde{\gamma}$ annihilations may be obtained from studies of quark-jet fragmentation in e^+e^- collider experiments. In these experiments, the fractional energy distribution functions obtained for the various secondary particles produced are observed to scale with energy (7). We may write

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = 2.89\,\beta\,\left(\frac{s}{\beta}\frac{d\sigma}{dx}\right) \qquad (2)$$

with the numerical factor in units of μb GeV^2. Here s is the square of the cms energy, β is the relative velocity and x is the energy of the $\bar{p}$ expressed as a fraction of the mass of the annihilating $\tilde{\gamma}$. From an analysis of the various experiments found in the literature, we find that the $\bar{p}$ distribution function can be represented as falling between upper and lower limits given by

$$\frac{s}{\beta}\left(\frac{d\sigma}{dx}\right) \simeq \left\{ \begin{array}{l} < 8.5 \exp(-11x) + 0.25 \exp(-2x) \\ > 7.7 \exp(-14.5x) + 0.17 \exp(-2.5x) \end{array} \right. \qquad (3)$$

The total annihilation cross section is given by (4)

$$\langle\sigma\beta\rangle \simeq \frac{8\pi\alpha^2}{m_{\tilde{f}}^4}\left[\Sigma_f\, q_f^2 \beta_f m_f^2\right] \qquad (4)$$

where the f's are the quarks and leptons (fermions) produced in the annihilation and $\beta_f = (1 - m_f^2/m_{\tilde{\gamma}}^2)^{1/2}$.

3. Fluxes from $\tilde{\gamma}$ Annihilation in the Galactic Halo. If we assume that the galactic halo mass is made up almost entirely of $\tilde{\gamma}$'s, from rotation curve determinations (see,e.g.(8)) we find that a uniform halo has a mass density on average of ~ 1 GeV/cm^3 within 10 kpc of the galactic center. A halo with an isothermal mass distribution would have a mean mass density at 10 kpc galactocentric distance of ~ 0.4 GeV/cm^3. Dividing by the photino mass $m_{\tilde{\gamma}}$ then gives the photino number density $n_{\tilde{\gamma}}$. The production rate of antiprotons produced by annihilation is

$$Q(E_{\bar{p}}) = n_{\tilde{\gamma}}^2 \sigma\beta c \zeta_{\bar{p}} f(E_{\tilde{\gamma}}) \quad cm^{-3}s^{-1}GeV^{-1}, \qquad (5)$$

where $\zeta_{\bar{p}}$ is the number of $\bar{p}$'s produced in the annihilation (determined by $m_{\tilde{\gamma}}$) and the spectral production function $f(E_{\tilde{\gamma}})$ is normalized so that its integral is unity. The diffusion coefficient for cosmic rays at 10 kpc (the solar galactocentric distance) in the energy range involved (rigidity P in GV) is (9)

$$D \simeq 10^{26} \beta \; P^{0.7} \; cm^2 s^{-1} \tag{6}$$

which implies that the relevant antiprotons diffuse ~ 100-200 pc in the mean lifetime $\tau \sim 5 \times 10^{14}$ s determined for the galactic disk in the solar neighborhood. The $\bar{p}$ flux in interstellar space is then

$$I_{\bar{p}} = Q\tau\beta c/4\pi = 1.2\times10^{24} Q \; cm^{-2}s^{-1}sr^{-1}GeV^{-1} \tag{7}$$

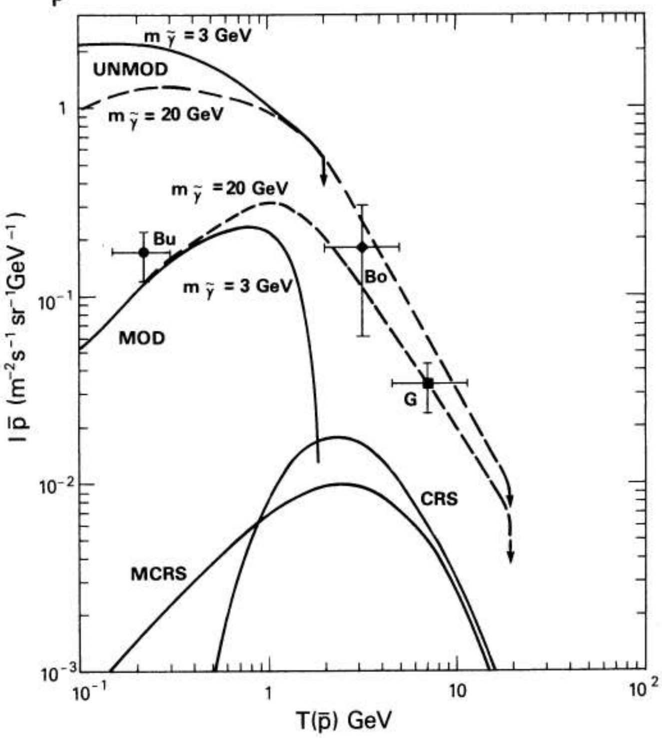

Fig. 1 Unmodulated and modulated spectra for 3 GeV and 20 GeV photino annihilation compared with data and cosmic-ray secondary production spectra (CRS) and modulated CRS (MCRS).

4. Solar modulation. The effect of solar modulation is most important in the low energy range of Ref.2. We have estimated the amount of proton modulation occurring during the relevant time period of the solar cycle, viz., June 1980, based on the Pioneer Helios-1 and ISEE-3 data (10). This yields expressions for the effective diffusion coefficient for modulation by the solar wind. The interstellar $\bar{p}$ spectrum may then be numerically modulated to compare with the observations (11).

5. Results. Fig. 1 shows the interstellar and modulated spectra obtained for 3 GeV and 20 GeV $\tilde{\gamma}$ masses, compared to the observations (2,12,13) and the standard secondary $\bar{p}$ calculations (14). The spectra are normalized to fall near the data points, however, such a fit is well within the uncertainty of the flux calculation. Both functions in eq. (3) yield similar results. Fig. 2 shows the $\bar{p}/p$ ratio as a function of energy for 3 GeV (A), 15 GeV (B) and 20 GeV (C) photino masses and the standard secondary production predictions (D). The data are from Refs. 2, 12, and 13.

There may be some evidence for a ~15 GeV photino mass cutoff in the highest data point. In any case, it is clear that (1) photino masses of this order yield an annihilation spectrum with a shape and possible flux that fits all of the present data on cosmic-ray $\bar{p}$'s, and 2) owing to the kinematic cutoff in the annihilation spectrum, future high energy observations (15,16) to look for a cutoff in the $\bar{p}$ spectrum can, in principle, determine both the existence of a galactic photino halo and the mass of the photino itself.

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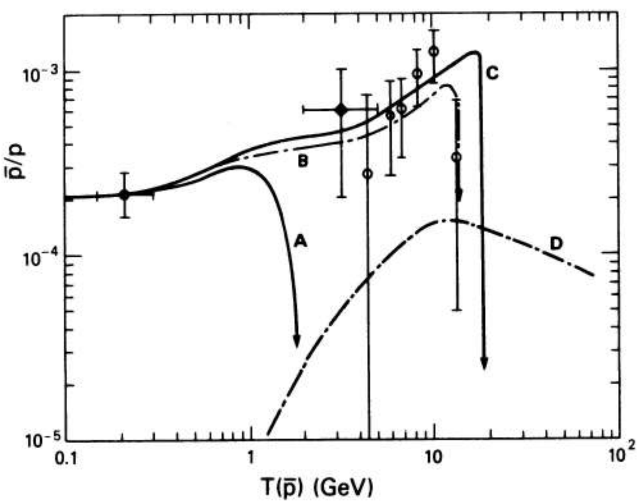

Fig. 2. $\bar{p}/p$ as a function of kinetic energy and data.

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