Positron line radiation as a signature of particle dark matter in the halo

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We suggest a new signature for particle dark-matter annihilation in the halo: high-energy, positron line radiation. Because the cosmic-ray positron spectrum falls rapidly with energy and the contribution of conventional sources is only expected to be about 5% of the cosmic-ray electron flux, monoenergetic e^+'s from halo annihilations can be a significant and distinctive signal for very massive dark-matter particles (masses greater than about 30 GeV). If the e^+e^- annihilation channel has an appreciable branch—a few percent or more—the e^+ signal could be observable in a future detector, such as have been proposed for ASTROMAG. A significant e^+e^- branching ratio can occur for neutralinos or Dirac neutrinos. In spite of the fact that a heavy Dirac neutrino is no longer an attractive dark-matter candidate and the fact that the e^+e^- branching ratios expected for the currently popular models of the neutralino are very small, the positron signature is so distinctive that we believe it is worthy of note: If seen, it is a "smoking gun" for particle dark matter in the halo. We also note that the positron signature will be of general importance for any future particle dark-matter candidate whose annihilation into e^+e^- is not suppressed.

I. INTRODUCTION

Most of the matter in the Universe is dark,[1] and if $\Omega_{\rm tot} \gtrsim 0.15$, then dark matter must be nonbaryonic, as primordial nucleosynthesis constrains Ω_B to be less than 0.15.[2] There are strong theoretical arguments (e.g., inflation, structure formation, and the temporal Copernican principle) favoring $\Omega_{\rm tot}=1$, in which case nonbaryonic matter must account for 90% or more of the material in the Universe. These are numerous, well-motivated relic-particle candidates for the dark matter,[1] among them, the neutralino, the axion, a light-neutrino species, or a heavy-neutrino species. The nature of the ubiquitous dark matter is certainly one of the most important questions facing both particle physics and cosmology.

The intriguing hypothesis that relic weakly interacting massive particles (WIMP's) comprise the dark matter is being tested by a number of different and complementary experimental approaches.[3] There are accelerator searches for supersymmetric partners to the known particles, ν mass and oscillation experiments, double-beta decay turned-WIMP-ionization detectors, and other direct searches for the relic particles themselves (axions, magnetic monopoles, particle cold dark matter). In addition, there are efforts to search for high-energy neutrinos produced by the annihilation of WIMP's that accumulate in the Sun and Earth[4] and for various annihilation products of WIMP's that reside and annihilate in the halo, including $\bar{p}$'s,[5] γ's,[6] γ-ray lines,[7] and e^+'s.[8]

In this paper we will discuss high-energy ($\gtrsim 30$ GeV), positron line radiation as a possible signal for dark-matter annihilation in the halo.[9] Because the cosmic-ray positron spectrum falls so rapidly with energy above about 10 GeV (roughly as $E^{-3.3}$, see below; for comparison, the γ-ray spectrum falls only as $E^{-2.4}$, or so) and because the contribution of conventional sources is expected to be only about 5% of the cosmic-ray electron flux, this is a particularly interesting and potentially promising signature for high-mass WIMP's. While there are many uncertainties underlying both the astrophysics and the particle physics associated with the problem, the signature is so distinctive that we believe that it is worthy of note and promising enough to pursue. Moreover, it could be seen with future detectors proposed for the ASTROMAG facility.[10] We should emphasize that because of all the inherent uncertainties the positron signature is unlikely to be of any use in constraining the parameter space of a particle dark-matter candidate; rather, it is a distinctive signature that has a small, but finite, chance to be the means by which particle dark matter in the halo is discovered.

II. POSITRONS FROM HALO WIMP ANNIHILATIONS

Cold thermal particle relics are particle species that were once in thermal equilibrium and arise as relics because their annihilations "froze out" when the temperature of the Universe was about $\frac{1}{20}$ of their mass.[11] For such relics their abundance today is related to their annihilation cross section by

$$\Omega h^2 \simeq 10^{-37}\ {\rm cm}^2/\langle \sigma|\beta|\rangle_{\rm ann}\ ,$$

where Ω is the fraction of critical density contributed by relic WIMP's, the present Hubble parameter is $H_0 = 100h$ km s^{-1} Mpc^{-1}, and $\langle \sigma|\beta| \rangle_{\text{ann}}$ is the thermally averaged annihilation cross section times relative velocity over c (relative velocity $v = \beta c$) evaluated at the freeze-out temperature $T_F \sim m/20$. As is now well appreciated, the present abundance of a cold thermal relic is inversely proportional to its annihilation cross section. For an annihilation cross section of order 10^{-37}–10^{-36} cm^2, cold thermal relics provide closure density.

There is every reason to believe that cold particle dark matter will find its way into the halos of spiral galaxies, including our own, when they form. It is believed that the halo density in the solar neighborhood is about 0.3 GeV cm^{-3}; further, it is often *assumed* that from the center of the galaxy out to about 10 kpc (the core radius of the halo) the halo density is approximately constant. Well beyond 10 kpc from the galactic center the halo density decreases as the distance from the galactic center squared (for further discussion of the Galaxy and its halo, see Ref. 12 and below). The halo material inferred in spiral galaxies from flat rotation curves, in some cases measured out to three times the distance where the light has all but disappeared, contributes at least $\Omega_{\text{halo}} \simeq 0.03$.[1] Since there is no convincing evidence for a rotation curve that turns over, the total mass contained in spiral galaxy halos has yet to be determined and could be as great as $\Omega_{\text{halo}} = 1$. We will assume for now that $\Omega \simeq 1$ and that the local WIMP density is equal to the halo density. In this case $\langle \sigma|\beta| \rangle_{\text{ann}} \sim 10^{-37}$–$10^{-36}$ cm^2 and the local number density of WIMP's is

$$n \simeq 10^{-2} m_{30}^{-1} \text{ cm}^{-3} ,$$

where $m_{30} = m/30$ GeV. Later we will consider the possibility that $\Omega < 1$ and the possibility that WIMP's only contribute a fraction of the halo density.

High-energy positrons created by WIMP annihilations will accumulate in the halo for a time of order 10^7 yr, the estimated containment time for cosmic-ray electrons and positrons in the galaxy, before they diffuse out of the galaxy. (We are quick to remind the reader that the confinement time is easily uncertain by an order of magnitude and could very well be energy dependent.[13]) In addition, as they propagate they slowly lose energy, the dominant losses at the energies of interest being synchrotron radiation and inverse Compton scattering off the 2.75-K background radiation and the background of integrated light from the stars in our Galaxy. The effect of energy loss will be discussed below. To be sure there are uncertainties in the estimate of the containment time; but we can be confident that it is greater than the light travel time across the halo (only about 3×10^4 yr), and so the flux of positrons builds up over a containment time. Thus the integrated line flux is given by

$$\mathcal{F}_+ = \frac{n^2 \langle \sigma|v| \rangle_{\text{ann}}}{4\pi} (c\tau) B , \tag{1}$$

where τ is the containment time for positrons in the halo and B is the branching ratio to the e^+e^- annihilation channel. For the moment we will not differentiate between the annihilation cross section relevant for freeze-out in the early Universe and that relevant for halo annihilations, other than to include the branching ratio factor B; we will return to this point later.

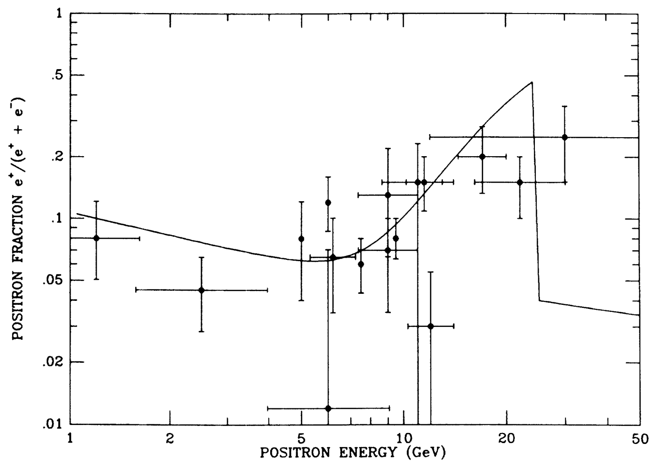

FIG. 1. The predicted positron fraction, $e^+/(e^+ + e^-)$, and the existing experimental data (from Ref. 14). In calculating the predicted positron fraction we have taken $m = 25$ GeV, $r = 1$, and *increased* the flux estimate over the fiducial value by a factor of 20 in order to make the comparison to the existing data intriguing. In addition, we have assumed a contribution to the positron fraction from conventional sources of the form, $e^+/(e^+e^-) = 0.02 + 0.10(E/\text{GeV})^{-0.5}$, which is consistent with the models discussed in Ref. 15.

Note the accumulation effect enhances the positron flux by a factor of order $\tau/3 \times 10^4$ yr over the flux of positrons that would propagate directly to us (in the absence of a galactic magnetic field). (Since γ rays are not contained within the galaxy, there is no similar enhancement for γ rays produced by WIMP annihilations.) For further discussion, it is convenient to reexpress the expected positron-line flux relative to some canonical parameters, as

$$\mathcal{F}_+ = 3 \times 10^{-7} \frac{\langle \sigma|\beta| \rangle_{-36} \tau_7 B_{-1}}{m_{30}^2} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} , \tag{2}$$

where $\tau_7 = \tau/10^7$ yr, $B_{-1} = B/10^{-1}$, and $\langle \sigma|\beta| \rangle_{\text{ann}} = \langle \sigma|\beta| \rangle_{-36} \times 10^{-36}$ cm^2.

The cosmic-ray positron flux has been measured up to energies of almost 30 GeV. For energies from 1 to 10 GeV the positron flux is about 5% to 10% that of the electron flux; for energies from 10 to 30 GeV the positron fraction seems to increase monotonically to about 25% (see Fig. 1).[14] (While we do not consider ourselves qualified to discuss the reliability of the data, we note that the sizes of the error flags provide the reader with some idea of the uncertainties associated with these observations.) The cosmic-ray electron flux itself has been measured up to energies of about 2 TeV. For energies greater than about 10 GeV the differential electron flux is given (to within a factor of 2) by[14]

$$d\mathcal{F}_-/dE_- \simeq 0.07(E_-/\mathrm{GeV})^{-3.3}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1} . \quad (3)$$

If as a crude baseline (see below) we take the expected positron flux to be about 5% of the electron flux, this then implies an extrapolated differential positron flux of

$$d\mathcal{F}_+/dE_+ \simeq 4\times10^{-8}(E_+/30\ \mathrm{GeV})^{-3.3}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1} . \quad (4)$$

While there is a paucity of γ-ray data above energies of a few GeV, for comparison, the extrapolated, diffuse γ-ray flux is roughly $10^{-9}(E_\gamma/30\ \mathrm{GeV})^{-2.4}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1}$.

The conventional explanation for origin of the positron flux is that it results from interaction primary cosmic rays (protons and ^{4}He nuclei) with nuclei in the interstellar medium (ISM). Such interactions produce K mesons, π mesons, and μ mesons, whose subsequent decays produce positrons.[15] The theoretical expectation, which to be sure depends upon a purely theoretical model for e^+ production and propagation, is an e^+/e^- flux ratio of about 10% at energies form 0.3 to 1 GeV, decreasing above energies of a few GeV to a value of 3–5 % (see Fig. 1).[15] In light of the ideas discussed here, it is interesting to note that the measured e^+/e^- flux ratio seems to rise from about the expected value of 10% at an energy of 1 GeV to about 25% at the highest energies measured, a value that is about five times that predicted from conventional sources (see Fig. 1). (Lest we be guilty of overinterpreting the data or inciting the reader to overinterpret the data, we again remind the reader of the uncertainties associated with both the data and the theoretical expectations for the positron flux from conventional sources.)

Since the extrapolated positron flux falls as $E^{-3.3}$ while the predicted flux from WIMP annihilations falls only as m^{-2}, the prospects for its detection become better with increasing energy (assuming for the moment that the accumulation time τ is energy independent). The positron line from WIMP annihilations is expected to be very narrow, $\Delta E_+ \sim mv \sim 0.03 m_{30}$ GeV. However, because of the energy resolution of proposed detectors (a few percent[10]) and line broadening due to energy loss (see below), we have expressed the extrapolated differential positron flux per GeV. For the canonical values used as normalizations above, the positron line radiation from WIMP annihilations starts to dominate the positron flux expected from conventional sources at an energy of about 20 GeV. Now let us turn to the astrophysical considerations in some detail.

Positron-energy losses and line broadening. Because of synchrontron and inverse Compton energy losses the WIMP-produced positron line (which is of negligible intrinsic width) will be broadened. The energy loss of a cosmic ray e^+ (or e^-) is given by[16]

$$-\frac{dE}{dt} = \frac{4}{3}\frac{E^2}{m_e^2}\sigma_T(\rho_\gamma+\rho_{\mathrm{mag}}) , \quad (5)$$

where $\sigma_T = 0.665\times10^{-24}$ cm^2 is the Thomson cross section, $\rho_\gamma \simeq \pi^2T^4/15 = 0.27$ eV cm^{-3} is the energy density in the 2.75-K background (we neglect the subdominant and position-dependent starlight contribution), $\rho_{\mathrm{mag}} = B^2/8\pi \simeq 0.22$ eV cm$^{-3}B_3^2$ ($B = 3B_3\times10^{-6}$ G), and we have taken the rms average of the sine of the angle between the magnetic field and $e^\pm$ momentum to be $\sqrt{2/3}$. The first term accounts for energy loss due to inverse Compton scattering and the second energy loss due to synchrontron radiation. Equation (5) can be written in a more suggestive form:

$$-\frac{dE}{dt} = \frac{E^2}{\tau_{\Delta E}(E_0)E_0} , \quad (6a)$$

$$\tau_{\Delta E}(E_0) = \frac{1.2\ \mathrm{Gyr}}{(E_0/\mathrm{GeV})(1+0.81B_3^2)} . \quad (6b)$$

The quantity $\tau_{\Delta E}(E_0)$ corresponds to the energy-loss time scale for an e^+ or e^- of energy E_0: $\tau_{\Delta E}(E_0) = -E_0/(dE/dt)$. The strength of the galactic magnetic field is about 3×10^{-6} G; however, our halo population of WIMP-produced positrons may be exposed to a smaller (or larger) rms field strength. Moreover, little information exists about the magnetic field of the galaxy outside the disk.[17] Noting these uncertainties we will adopt $B_3 = 1$. [In Eqs. (5) and (6) only B and B_3 are used to denote the magnetic field strength of the galaxy and not the branching ratio to the $e^\pm$ annihilation channel.]

We will use the following very simple, spatially homogeneous model to estimate the broadening effect of energy loss on the positron line: a δ-function source of positrons at energy m and strength $a = n^2\langle\sigma|v|\rangle_{\mathrm{ann}}\, B/4\pi$; a diffusion time $\tau \simeq 10^7$ yr, and energy loss given by $-dE/dt = E^2/\tau_{\Delta E}(m)m$. Implicit in this model is the assumption that WIMP-produced positrons are not accelerated by any processes in the ISM, and thus can only lose energy. For this simple model the partial-differential equation governing the differential energy flux $\mathcal{F}_+(E,t)$ is[16]

$$\frac{\partial}{\partial t}\frac{d\mathcal{F}_+}{dE} = a\delta(m) - \frac{1}{\tau}\frac{d\mathcal{F}_+}{dE} + \frac{\partial}{\partial E}\left[\frac{E^2}{m\tau_{\Delta E}(m)}\frac{d\mathcal{F}_+}{dE}\right] . \quad (7)$$

It is simple to find the following analytical solution for the steady-state flux:

$$\frac{d\mathcal{F}_+}{dE} = \frac{n^2\langle\sigma|v|\rangle_{\mathrm{ann}}(c\tau)B}{4\pi}\frac{mr}{E^2}\exp[r(1-m/E)] , \quad (8a)$$

$$r = \frac{\tau_{\Delta E}(m)}{\tau} \simeq \frac{3}{m_{30}\tau_7} , \quad (8b)$$

valid for $E \le m$. For energies $E > m$, the flux of course vanishes. Note that the first term in the expression for the predicted flux is just the previous expression for the integrated line flux, cf. Eq. (1), and that the shape of the line is controlled by the ratio ($\equiv r$) of the energy loss time to containment time. The predicted differential flux rises up to an energy m, and then sharply drops to zero; the width of the broadened line is $\Delta E_+/m \sim r^{-1}$. That is, a larger ratio of energy-loss time to containment time results in a sharper positron line.

While energy losses do significantly broaden the positron line, the sharp dropoff expected for energies $E \geq m$ is a very distinctive signature. Moreover, the predicted e^+/e^- flux ratio

$$\frac{d\mathcal{F}_+/dE}{d\mathcal{F}_-/dE} \simeq 3.5\% m_{30}^{-2} \langle \sigma |v| \rangle_{-36} \times B_{-1}(E/30 \text{ GeV})^{1.3} \exp[r(1-m/E)] ,$$

has an even sharper shape. The predicted e^+/e^- ratio is shown in Fig. 1 for a "provocative" set of parameters.

(Above we have assumed that the confinement time τ is energy independent; it is possible, perhaps even likely, that the diffusion time τ is energy dependent, say $\tau(E)=\tau(m)m/E$. In this case one obtains a qualitatively similar solution: $d\mathcal{F}_+/dE = \{n^2\langle\sigma|v|\rangle_{\text{ann}}[c\tau(m)B]/4\pi\}(r/m)(E/m)^{r-2}$, where $r=\tau_{\Delta E}(m)/\tau(m)$.)

Cosmic-ray confinement. In estimating the expected signal we have made the very simple assumption that all, and only, those positrons produced within the volume where the cosmic-ray $e^{\pm}$'s are confined contribute to the positron signal. This is clearly a gross simplification. For example, it could be imagined that only some fraction of the positrons produced become confined, as those near the surface of the confinement region can diffuse out more easily; in this case our estimate must be decreased. Less likely is the possibility that annihilations throughout the halo, even in regions outside the confinement volume, make their way into the smaller confinement volume, in which case our estimates should be increased. Since the cosmic rays are magnetically confined and little is known about the magnetic field outside the galactic disk the uncertainties are great.

Along the same lines there is the confinement time τ. While it is estimated to be of the order of 10^7 yr the uncertainties here too are substantial, likely an order of magnitude.[13] Moreover, τ could be energy dependent. Both the strength and shape of the line depend upon τ.

The galactic halo. Consider the halo density (for detailed discussion of the halo of our galaxy, see Ref. 12). The flat rotation curves of spiral galaxies (including our own) strongly indicate the presence of a dark halo whose density decreases as r^{-2} at large distances from the center of the galaxy (spherical symmetry has been assumed, for which there is little direct evidence). (Of course at very large distances ρ_{halo} must deviate from r^{-2}, otherwise the halo mass would diverge.) Close in to the center of a spiral galaxy the orbital velocities of stars are supported by the gravitational force of the luminous matter. For our own Galaxy it is estimated that the dark halo matter interior to the position of the solar system ($R \simeq 8-10$ kpc) supports about $\frac{1}{2}$ of our orbital velocity.[12] At most, the halo matter can support the entire orbital velocity. This fact constrains the total halo mass interior to our position: $M(R)=4\pi\int_0^R \rho_{\text{halo}} r^2 dr$.

The halo density is often assumed to have the form

$$\rho_{\text{halo}}(r)=\rho_{\text{local}}(R^2+a^2)/(r^2+a^2) ,$$

where a is the core radius and ρ_{local} is the local value of the halo density. For such a model the mass interior

$$M(R)=\frac{4\pi}{3}\rho_{\text{local}}R^3 f(a/R) ,$$

where the function $f \rightarrow 1$ as $a/R \rightarrow \infty$ and $f \rightarrow 3$ as $a/R \rightarrow 0$. The best estimates of ρ_{local} are about 0.5×10^{-24} g cm$^{-3} \simeq 0.3$ GeV cm^{-3}, with an estimated uncertainty of about a factor of 2. The core radius is estimated to be comparable to R (see Ref. 12).

In computing the annihilation rate we have implicitly taken $\rho_{\text{halo}}=mn$ to be constant within the region where the positrons are produced. With such an assumption the predicted line strength depends upon n^2 which could vary by about a factor of 4 either way. However, depending upon how ρ_{halo} varies for small r, there could be a significant additional enhancement. Although $M(R)$, the quantity directly constrained by our orbital velocity, is relatively insensitive to a/R, the integrated-annihilation rate (interior to our position)

$$\Gamma(R) \propto 4\pi\int_0^R \rho_{\text{halo}}^2 r^2 dr = \frac{4\pi\rho_{\text{local}}^2 R^3}{3}\left[1.5(1+a^2/R^2)^2 \times \left[\frac{R}{a}\arctan\frac{R}{a} - \frac{1}{1+a^2/R^2}\right]\right] ,$$

is not because it depends upon ρ_{halo}^2. For example, if we hold $M(R)$ fixed for different assumed values of a/R by changing ρ_{local}, $\Gamma(R)$ can vary by a large factor. For $a/R \ll 1$, $\Gamma(R)$ is enhanced over its value for $a/R \rightarrow \infty$ (i.e., constant n) by a factor of $\pi R/12a$. Thus, if $a/R \ll 1$, as could occur if there is a galactic-bulge population of WIMP's,[18] our estimates for the positron flux would have to be revised upward by a significant factor.

Subcritical density of WIMP's. The total amount of halo material known with certainty to exist is small compared to closure density; a reasonable lower bound is probably $\Omega_{\text{halo}} \simeq 0.03$. That means that particle dark matter might contribute only 3% of closure density and yet still provide the observed halo material. If this were so the annihilation rate would be enhanced by a factor of about $\Omega^{-1} \sim 30$ (relative to previous considerations where $\Omega \simeq 1$ was assumed), while the halo density of particle dark matter would remain unaffected. The net effect would be an increase of about a factor of 30 in the predicted positron line flux.

If the particle dark matter contribution to the mass density of the Universe is even smaller than 0.03, then it is unlikely that WIMP's are the primary component of the halo. However, there is still every reason to believe that WIMP's would find their way into the halo (as they are dissipationless particles). We can use a simple argument based upon the equivalence principle to estimate their density in the halo. In astrophysical systems where gravity has played the dominant role, structures as large as or larger than galactic halos, the ratio of WIMP's to baryons should remain equal to its universal value: Ω/Ω_B. Taking Ω_B to be 0.03 (Ref. 2) and assuming that the halo density is dominated by that of baryons, we obtain the following simple estimate for the halo density of WIMP's; $n \simeq (\Omega/0.03)(\rho_{\rm halo}/m)$. Because of the two factors of $n \propto \Omega$ and the single factor of $\langle \sigma|\beta| \rangle_{\rm ann} \propto \Omega^{-1}$ in the formula for the positron line flux, cf. Eq. (1), the positron line flux should vary as Ω for $\Omega \lesssim 0.03$:

$$\mathcal{F}_+ \simeq 10^{-5} \frac{(\Omega/0.03)\tau_7 B_{-1}}{m_{30}^2} \ {\rm cm}^{-2}\,{\rm sr}^{-1}\,{\rm s}^{-1} \ .$$

To finish this discussion, we wish to remind the reader that relic WIMP's from the early Universe are interesting and important even if they do not contribute closure density or even the halo density. Recall that the fraction of critical density contributed by the microwave background is only about 10^{-4}.

Clearly there are substantial, irreducible astrophysical uncertainties in our expectations for the positron flux. It is possible that the flux is greatly enhanced relative to our estimates, perhaps by as much as a factor of 10^3. Because of the astrophysical as well as the particle-physics uncertainties the positron line is clearly not of much use in setting limits to the particle dark matter in the halo. Rather it is a potentially important signature for *detecting* dark matter. Viewed in this light we would argue that one should keep an optimistically open mind toward the uncertainties.

Relic-particle candidates. Up to this point we have not been explicit about the identity of the relic WIMP. We have done so in part because the $e^{\pm}$ annihilation channel is *a priori* generic, and unless suppressed one would expect a branching ratio B of order 10%. As we shall discuss below, for the most interesting candidate at present, the neutralino, the e^+e^- channel is unfortunately severely suppressed because of symmetry considerations.

First consider the Dirac neutrino. For a relic Dirac-neutrino species, $\Omega h^2 \simeq 3\ ({\rm GeV}/m)^2$, so that a 40-GeV Dirac-neutrino species only contributes about 0.1% or so of closure density.[19,20] (For the purposes of this simple example we will neglect the effect of the Z^0 pole on the annihilation cross section, which significantly decreases the relic abundance if the neutrino mass is very close to half that of the Z^0.) The branching ratio to the e^+e^- channel should be of order 3%. Using our previous formula for a species which contributes less than halo density we find that

$$\langle \sigma|v| \rangle_{-36} \simeq 10 m_{30}^{-2} \ , \qquad (9a)$$

$$\mathcal{F}_+ \simeq 3\times 10^{-6} \frac{\tau_7}{m_{30}^4} \ {\rm cm}^{-2}\,{\rm sr}^{-1}\,{\rm s}^{-1} \ . \qquad (9b)$$

Note that because of the dependence of the cross section on the mass, for Dirac neutrinos the flux *decreases* as m^{-4} (at least as long as $m \lesssim M_W$). Thus the positron line loses relative to the extrapolated positron spectrum as one goes to higher energies. Moreover, the results of the UCSB-Berkeley-LBL-germanium-double-beta-turned-WIMP-ionization detector exclude a Dirac neutrino in the mass range of 15–1500 GeV if it contributes the entirety of the halo density.[21] A Dirac neutrino of mass much greater than 3 GeV is likely to contribute only a small fraction of the halo density, in which case it is not clear that these results rule out a Dirac neutrino as a minor component of the halo.

A more promising and very well motivated cold particle relic is the neutralino.[22] For the simplest particle-physics models of the neutralino, the e^+e^- annihilation channel is severely suppressed, with a branching ratio of order 10^{-5}, or so, making it of interest only if the astrophysical parameters are very favorable. The reason for the suppression is easily understood as follows.[23] The neutralino is a self-conjugate (Majorana) fermion. In the s-wave annihilation channel the spatial part of the incoming-neutralino wave function must be symmetric; and so, to ensure that the overall wave function is antisymmetric, the spin part must be antisymmetric. Thus the incoming state has zero angular momentum. For most standard processes that contribute to neutralino annihilation chirality is conserved, so that massless fermions and antifermions in the final state come with opposite handedness. Therefore the angular momentum along the axis of the outgoing fermions is one, which precludes the s wave. Thus for massless outgoing fermions the s-wave amplitude is zero; for massive fermions it is proportional to m_f/m. p-wave annihilation is not so suppressed, but it is proportional to the relative velocity of the incoming neutralinos, squared. Generically then, the neutralino partial annihilation cross section to the fermion-antifermion channel is given by

$$\langle \sigma|\beta| \rangle_{\rm ann} \sim G_F^2 m^2 [(m_f/m)^2 + v^2] \ .$$

In the early Universe, when neutralinos decouple, $v^2 \simeq 6T/m \sim \frac{1}{3}$ is not so terribly small, and p-wave annihilation is not badly suppressed. Thus unfortunately, the cross section that determines the relic density is unsuppressed.[24] In the halo, where $v^2 \sim 10^{-5}$, p-wave annihilation is suppressed and neutralino annihilations proceed mainly through the heaviest fermion, usually the bottom quark. In this case the branching ratio relevant for our estimate for the positron line is order 10^{-5}.

There are, however, more complicated supersymmetric models where the right- and left-handed selectron masses are not equal. In these models, if there is mixing between the right- and left-handed selectrons, there is an additional contribution to neutralino annihilation into e^+e^- which is proportional to the mass splitting, but which should otherwise be unsuppressed.[25] In this case the e^+e^- branching ratio can be very substantial, making the positron line signature extremely interesting.

While we have focused on two specific examples of WIMP's for which the positron line radiation could possibly be interesting, we wish to emphasize the generality of this dark-matter signature. Aside from astrophysical uncertainties and the mass of the WIMP, our estimate only depends upon the e^+e^- branching ratio (and Ω in the case that Ω is not unity). Unless that branching ratio is suppressed for special reasons (as can be the case with the neutralino), one expects the branching ratio for a generic WIMP to be of order 10%, making the positron line signature of very general interest.

Continuum-positron radiation. Finally, we should comment on the continuum-positron radiation which arises from neutralino annihilations in general. Such radiation has been mentioned by other authors;[8] here we wish to emphasize its possible importance for heavier WIMP's, and especially the existence of additional annihilation channels which can be important for heavier neutralinos, namely the W^+W^- and Z^0Z^0 channels.[26] Continuum-positron radiation arises from the decays of the neutralino annihilation products. For orientation, consider first the usual channel $b\bar{b}$. The b and $\bar{b}$ decay to charmed quarks and a virtual W; the decay of the virtual W^+ produces a positron with a branching ratio of about 8%; the average energy of the positron is about $\frac{1}{4}$ the neutralino mass. (Of course, the virtual W can also produce τ's and μ's which ultimately produce positrons, albeit of degraded energy.) Secondary decays of the charmed quarks, and of their decay products, can produce additional positrons. The hardest positrons will be those produced in the initial b-quark decay, and as we argued above it is the most energetic positrons that are of the greatest interest.

When the neutralino mass exceeds half that of the W ($m_W \simeq 80$ GeV), a new channel for neutralino annihilation opens up: a real and virtual W. Further, when the neutralino mass exceeds that of the W, the channel to two real W's also opens up. These channels are not suppressed by any consideration of chirality. They can easily compete with or even dominate the annihilation into fermions, particularly if winos are lighter than sleptons and squarks. About 8% of the time the W decay will produce a positron and neutrino. Around threshold the W momentum is not very large so that the decay is like that of a W at rest, producing a positron which carries away of order 40 GeV. In addition, the positrons are produced in a two-, rather than three-, body decay. Thus the fraction of energy carried away by the positron should be larger than from b decay, and the spectrum should be sharper. (A similar discussion applies to the Z^0Z^0 channel, although the branching ratio to e^+e^- is only 3%.) Therefore, the positron signal from neutralino annihilations in the mass range near the W mass or above may too produce a sharp feature in the positron spectrum. Clearly, more quantitative work remains to be done.

III. CONCLUDING REMARKS

The identification of the composition of the ubiquitous dark matter in the Universe is a most important question facing both cosmology and particle physics. Quite correctly, a wide range of experimental approaches are being pursued. In this paper we have pointed out one more potential dark-matter signal: positron line radiation produced from WIMP annihilations within our own halo.[9] While the existence of a detectable signal is by no means assured and the inherent astrophysical, cosmological,[20] and particle-physics uncertainties are large, easily a factor of 10^3, the signature is so distinctive that it is very important to search for. While we would never argue that one could place limits on the properties of the halo material based upon the *absence* of positron line radiation, we would argue strongly that positron line radiation is a signature that could provide the first evidence for particle dark matter in the halo: If found it would be decisive evidence for particle dark matter of a definite mass. In this regard the positron line signature is similar to the γ-ray-line signature: Both are unlikely, although not impossible, to actually be of sufficient strength to be detected; however, if discovered, either would provide a very clean indication of particle dark matter in the halo. On the other hand, the flux of continuum annihilation products—γ rays, positrons, antiprotons, and neutrinos— can be more reliably predicted and thereby used to constrain the possibilities for particle dark matter in the halo. However, the continuum signature is not as distinctive, and it is difficult to imagine that continuum radiation could ever be used to argue convincingly for the discovery of particle dark matter in the halo.

In closing, positron line radiation provides a distinctive signature for dark matter in the halo. To be fair, the chances for actually detecting particle dark matter in the halo through this signal are slim. However, identifying the nature of the dark matter is a problem of such enormous importance that we would hope that the positron line signature provides additional motivation for future experiments that are designed to measure the high-energy electron and positron cosmic-ray spectra with good resolution.

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[9]D. Seckel called to our attention an unpublished manuscript by A. J. Tylka and D. Eichler which addresses the issue of the spectrum of cosmic-ray positrons expected from halo-photino annihilations. In this manuscript the authors also mention the possibility of positron line radiation from Dirac-neutrino annihilations in the halo. Since our manuscript was originally submitted for Tylka has submitted and published a paper on positron line radiation as a signature for dark-matter annihilation in the halo [A.J. Tylka, Phys. Rev. Lett. **63**, 840 (1989)].

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[17]We should note that based upon the measured electron and positron spectra Protheroe (Ref. 15) argues that the "ordinary" cosmic-ray $e^{\pm}$ population is exposed to an rms field strength of $\sim 6\times 10^{-6}$ G.

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[20]While it has long been appreciated that the relic abundance could easily be less than the canonical estimate, e.g., the relic abundance can be diluted by entropy production, it is usually assumed that the abundance cannot be enhanced. This point is addressed by M. Kamionkowski and M. S. Turner (unpublished), where they show that if the expansion rate of the Universe at early times is larger than the canonical value, the relic abundance of a species can be significantly enhanced. Several plausible possibilities for increasing the expansion rate of the Universe at very early times are discussed. The relevance for the present discussion is that for fixed Ω the annihilation rate *could* be significantly larger than in the canonical case, thereby enhancing our naive estimate for the positron line flux.

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[24]Because of the v^2-dependent terms in the annihilation cross section, the annihilation cross section in the early Universe around freeze-out (which determines the relic abundance and vice versa) and the annihilation cross section in the halo can be different. Were this not so, the branching ratio to $e^{\pm}$ would be $B \simeq v^2/(m_f/m)^2 \sim 3\times 10^{-4} m_{30}^2$ (taking $m_f = m_b$). Using the fact that $v^2 \sim \frac{1}{3}$ at freeze-out, it follows that $\langle \sigma|\beta| \rangle_{e^\pm} \sim v_{\rm halo}^2 \langle \sigma|\beta| \rangle_{\rm freeze\text{-}out}$. We have implicitly used this fact when we state that the canonical expectation for a neutralino is a branching ratio $B \sim 10^{-5}$.

[25]G. F. Giudice and K. Griest (private communication); Phys. Rev. D **40**, 2549 (1989).

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