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POSITRON LINE RADIATION FROM HALO WIMP ANNIHILATIONS AS A DARK MATTER SIGNATURE

Michael S. Turner

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Batavia, IL 60510-0500

and

Departments of Physics and Astronomy and Astrophysics
Enrico Fermi Institute
The University of Chicago
Chicago, IL 60637-1433

Frank Wilczek

Institute for Advanced Study
School of Natural Sciences
Princeton, NJ 08540

Abstract. We suggest a new signature for dark matter annihilation in the halo: high energy positron line radiation. Because the cosmic ray positron spectrum falls rapidly with energy, e^+'s from halo WIMP annihilations can be a significant, clean signal for very massive WIMP's ($\gtrsim$ 30 GeV). In the case that the e^+e^- annihilation channel has an appreciable branch, the e^+ signal should be above background in a future detector, such as have been proposed for *ASTROMAG*, and of potential importance as a dark matter signature. A significant e^+e^- branching ratio can occur for neutralinos or Dirac neutrinos. High-energy, continuum positron radiation may also be an important signature for massive neutralino annihilations, especially near or above the threshold of the W^+W^- and Z^0Z^0 annihilation channels.

Most of the matter in the Universe is dark,[1] and if $\Omega \gtrsim 0.15$, that dark matter must be non-baryonic, 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 $\Omega = 1$, in which case non-baryonic matter must account for 90% or more of the material in the Universe. There 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 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 experiments (which double as WIMP ionization detectors), and direct searches for the relic particles themselves (axions, magnetic monopoles, particle cold dark matter). In addition, there are efforts to search for the annihilation products of massive relics (weakly-interacting, massive particles, or WIMP's) that accumulate in the sun and earth[4] (high energy $\nu\bar{\nu}$'s) and for the annihilation products of WIMP's which reside in the halo[5] ($\bar{p}$'s, γ's, and e^+'s, including γ-line radiation[6]). In this paper we will discuss high energy ($\gtrsim$ 30 GeV) positron line radiation, and to a lesser extent high-energy continuum positron radiation.[5] Because the cosmic ray positron spectrum falls so rapidly with energy above $\sim$ 10 GeV (roughly as $E^{-3.3}$, see below; for comparison, the γ-ray spectrum falls only as $E^{-2.4}$, or so), 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, especially a positron line, appears promising enough to pursue, as it could be seen with future detectors proposed for the *ASTROMAG* facility.[7]

Cold, thermal particle relics are particle species that were once in thermal equilibrium and whose relic abundance arises because their annihilations froze out when the temperature of the Universe was $\sim 1/20$ of their mass.[8] For such relics their abundance today is related to their annihilation cross section by

$$\Omega \simeq 10^{-36}\,\mathrm{cm}^2/ < \sigma|v| >_{\mathrm{ANN}}$$

where $< \sigma|v| >_{\mathrm{ANN}}$ is the thermally-averaged annihilation cross section (evaluated at $T \sim m/20$). As is now well-appreciated, the present abundance of such a relic is inversely proportional to the annihilation cross section. For a value of order $10^{-36}\,\mathrm{cm}^2$, the relic particles 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 our galaxy has a roughly constant value, about $0.3\,\mathrm{GeV\,cm^{-3}}$, from the center of the galaxy out to about 10 kpc ($\sim$ the core radius of the halo), and well beyond this decreases as the radial distance squared.[9] The halo material inferred in spiral galaxies from flat rotation curves, in some cases measured out to 3 times the distance where the light has has all but disappeared, contributes at least $\Omega_{\mathrm{HALO}} \simeq 0.03$.[1] Since there is no convincing evidence for a rotation curve which turns over, the total mass contained in spiral galaxy halos has yet to be determined, and could be as great as $\Omega_{\mathrm{HALO}} = 1$. We will assume for now that the local WIMP density is that of the halo, so that the local number density of WIMP's is

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

where $m_{30} = m/30\,\mathrm{GeV}$. Later we will consider 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 yrs, the estimated containment time for cosmic ray $e^{\pm}$'s in the galaxy, before they diffuse out of the galaxy.[10] In addition, as they propagate they slowly lose energy, the dominant losses at the energies of interest being synchrontron radiation and inverse Compton scattering off the 2.75 K background radiation and background starlight. The effect of energy loss will be discussed below. While there are uncertainties in the estimate of the containment time, it is certain to be greater than the light travel time across the halo (only $\sim$ 30,000 yrs). Thus the flux of positrons builds up over a containment time, and the integrated line flux is given by

$$\mathcal{F}_{+} = \frac{n^2 < \sigma|v| >_{\mathrm{ANN}}}{4\pi}(c\tau)(f^2 g)BR \tag{1}$$

Here τ is the containment time for positrons in the halo, f is the ratio of the actual WIMP mass density to the fiducial value of the halo density we have assumed ($0.3\,\mathrm{GeV\,cm^{-3}}$), BR is the branching ratio to the e^+e^- annihilation channel, and g is a geometrical factor which we will discuss shortly. [Note the accumulation effect enhances the positron flux by a factor of order $\tau/30{,}000$ yrs; there is no similar enhancement for γ rays produced by WIMP annihilations.] For further discussion, it is convenient to re-express the expected positron line flux relative to some canonical parameters, as follows:

$$\mathcal{F}_{+} = 3 \times 10^{-7} \frac{< \sigma|v| >_{-36}\, \tau_7 BR_{-1}}{m_{30}^2}(f^2 g)\mathrm{cm^{-2}\,sr^{-1}\,s^{-1}} \tag{2}$$

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where $\tau_7 = \tau/10^7\text{yrs}$, $BR_{-1} = BR/10^{-1}$, and $< \sigma|v| >_{\rm ANN} = 3 < \sigma|v| >_{-36} \times 10^{-26}\,{\rm cm^3\,s^{-1}}$ (in cgs units).

The cosmic ray positron flux has been measured up to energies of almost 30 GeV. For energies of order 1-10 GeV the positron flux is $\sim 10\%$ that of the electron flux; for energies of 10-30 GeV the fraction rises monotonically to $\sim 25\%$.[11] 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[11]

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

If as a crude estimate and guide we take the positron flux to be about 5% of the electron flux, this then implies an *extrapolated* differential positron flux of

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

[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 $10^{-9}(E_\gamma/30\,{\rm GeV})^{-2.4}\,{\rm cm^{-2}sr^{-1}s^{-1}GeV^{-1}}$.]

The conventional explanation for origin of the positron flux is that it results from interaction of primary cosmic rays (p's and ^{4}He nuclei) with nuclei in the ISM producing K-mesons, π-mesons, and μ-mesons whose decays produce positrons.[12] 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 $\sim 10\%$ at energies of 0.3-1 GeV, decreasing above energies of a few GeV to a value of 3-5%.[11] In light of the ideas discussed here, it is interesting to note that the measured e^+/e^- flux ratio actually rises from the expected value of $\sim 10\%$ at an energy of 1 GeV to $\sim 25\%$ at the highest energies measured, a value that is ~ 5 times that predicted from conventional sources (see Fig. 1).

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 (few %)[7] 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 extrapolated positron flux at an energy of ~ 20 GeV. Now let us discuss the astrophysical parameters τ, g, and f in more detail.

Due to 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[13]

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

where $\sigma_T = 0.665 \times 10^{-24}\,{\rm cm}^2$ is the Thomson cross section, $\rho_\gamma \simeq \pi^2 T^4/15 = 0.27\,{\rm eV\,cm}^{-3}$ is the energy density in the 2.75 K background (we neglect the subdominant and position dependent starlight contribution), $\rho_{\rm mag} = B^2/8\pi \simeq 0.22\,{\rm eV\,cm}^{-3} B_3^2$ ($B = 3B_3 \times 10^{-6}$ 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 to synchrontron radiation. Eqn. (5) can be written in a more suggestive form,

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

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

Here $\tau_{\Delta E}(E_0)$ corresponds to the energy loss timescale for an $e^\pm$ of energy E_0, $\tau_{\Delta E}(E_0) = -E_0/(dE/dt)$. The field strength of the galactic magnetic field is $\sim 3 \times 10^{-6}$ G; moreover, our halo population of WIMP-produced positrons may be exposed to a smaller *rms* field strength (however, little information exists about the magnetic field of the galaxy outside the disk).[14] Noting these uncertainties we will adopt $B_3 = 1$.

We will use the following very simple, spatially-homogeneous model to estimate the broadening effect of energy loss on the positron line: a delta function source of positrons at energy m and strength $a = n^2 < \sigma|v| >_{\rm ANN} (gf^2)BR/4\pi$; a diffusion time $\tau \simeq 10^7$ yrs, and energy loss given by, $-dE/dt = E^2/\tau_{\Delta E}(m)m$. [Note we are assuming that WIMP-produced positrons are not accelerated by any processes in the ISM, and thus can only lose energy.] Based upon this simple model the partial differential equation governing the differential energy flux is[13]

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

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

$$\frac{d\mathcal{F}_+}{dE} = \frac{n^2 < \sigma|v| >_{\rm ANN} (gf^2)(c\tau)BR}{4\pi}\frac{mr}{E^2}\exp[r(1 - m/E)] \tag{8a}$$

$$r = \frac{\tau_{\Delta E}(m)}{\tau} \simeq \frac{3}{(m/30\,{\rm GeV})\tau_7} \tag{8b}$$

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., Eqn. (1), and that the shape of the line is controlled by the ratio r = energy loss time / containment time.[15] The predicted differential flux rises up to an energy m, and then sharply drops to zero; the width of the broadened line is, $\Delta E_+/m \sim r^{-1}$. While energy losses do significantly broaden the positron line, the expected sharp drop off for energies $E \geq m$ is a very distinctive signature. Moreover, the predicted e^+/e^- flux ratio,

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

has an even sharper shape (see Fig. 1).

Next, we mention a possible geometrical concentration effect. The population of WIMP-generated cosmic ray positrons is produced throughout the halo of the galaxy. In the usual models of cosmic ray propagation, cosmic rays are magnetically confined to some region in the galaxy of comparable size to that of the disk (or the disk plus bulge), and escape by diffusion, or other processes such as a galactic wind.[12] We note that the expected scale height of conventional cosmic rays, a few 100 pc, is very small compared to the scale of the halo, about 10 kpc.[12] If cosmic rays are most efficiently trapped within the disk (because of larger magnetic field strength and shorter diffusion lengths), then the density of halo WIMP annihilation produced positrons may be significantly higher in the disk. (This, of course, is where the detectors are). We have accounted for this possibility by the geometrical factor g; on naive geometrical grounds one might expect g to be of order the ratio of the volume of the halo to that of the disk, or about 30.

Finally, it is also possible that the local halo density is greater than the canonical value which we have chosen, perhaps by a factor of 2. On the other hand, if Ω_{WIMP} is less than about 0.03, it may be that WIMP's contribute only part of the halo density, the simplest expectation being a fraction of order $\Omega_{\text{WIMP}}/0.03$, implying that $f^2 \sim (\Omega^2_{\text{WIMP}}/10^{-3})$. Using the fact that $< \sigma|v| >_{-36} \simeq \Omega^{-1}_{\text{WIMP}}$, it follows that $f^2 < \sigma|v| >_{-36} \simeq 10^3 \Omega_{\text{WIMP}}$ for $\Omega_{\text{WIMP}} \lesssim 0.03$. We see that the maximum value of $f^2 < \sigma|v| >_{-36} \simeq 30$ obtains for $\Omega_{WIMP} \simeq \Omega_{HALO} \simeq 0.03$, where f could be order 1 and $< \sigma|v| >_{-36}$ order 30. Of course, for values of Ω_{WIMP} less than ~ 0.03, $f^2 < \sigma|v| >_{-36}$ decreases as Ω_{WIMP}. On an editorial note, 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^{-5}, and the microwave background radiation is certainly very interesting!

Clearly there are substantial, irreducible astrophysical uncertainties in our expectations for the positron flux. It seems fair to say, however, that values for $gf^2\tau_7$ as large as 10^3 are conceivable.

Up to this point we have not been explicit about the identity of the relic WIMP. We have done so in part because the positron line signature is generic to any cold particle relic. Now we will consider some specific expamples; first, the Dirac neutrino. For a relic Dirac neutrino species, $\Omega \sim (3\,\mathrm{GeV}/m)^2$, so that a 10 GeV Dirac neutrino species only contributes about 1% of closure density.[16] In addition, 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

$$f^2 < \sigma|v| >_{-36} \simeq 10 m_{30}^{-2} \tag{9a}$$

$$\mathcal{F}_+ \simeq 2 \times 10^{-6} \frac{\tau_7}{m_{30}^4} \mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1} \tag{9b}$$

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. In addition, the results of the UCSB-Berkeley-LBL Germanium double beta decay experiment seem to exclude a Dirac neutrino in the mass range of 15-1500 GeV.[17] We use the phrase "seem to exclude," as the authors of this paper have assumed that the Dirac neutrinos contribute the full halo density, irrespective of their mass. Here we have taken the more realistic view that they contribute only a fraction of it; whether or not their results exclude this possibility is not clear.

A more promising and well-motivated cold particle relic is the neutralino.[18] 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 favorable. The reason for the suppression is easily understood as follows.[19] The neutralino is a self-conjugate (Majorana) fermion. In the s-wave annihilation channel the spatial part of the incoming neutralino wave function must symmetric; and so, to insure that the overall wavefunction 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 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

$$< \sigma|v| >_{\mathrm{ANN}} \sim G_F^2\, m^2 [(m_f/m)^2 + v^2]$$

Note that in the early Universe, when neutralinos decouple, $v^2 \simeq 6T/m \sim 1/3$ 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.[20] 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 [illegible]qual. In these models, if there is mixing between the right- and left-handed sel[illegible] there is an additional contribution to neutralino annihilation into e^+e^- which is proportional to the mass splitting, but which should otherwise be unsuppressed.[21] 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 our suggested dark matter signature. Aside from astrophysical uncertainties and the mass of the WIMP, our estimate only depends upon the e^+e^- branching ratio (and $\Omega_{\rm WIMP}$ in the case that $\Omega_{\rm WIMP}$ 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.

Finally, we should comment on the continuum positron radiation which arises from neutralino annihilations in general. Such radiation has been mentioned by other authors;[5] 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. 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 $\sim 8\%$; the average energy of the positron is $\sim 1/4$ 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 (~83 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 2 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 2, rather than 3, 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 $Z^0 Z^0$ 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 detectable positron signal.

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 *Letter* we have pointed out one more potential dark matter signal: positron line radiation produced from WIMP annihilations within our own halo. While the existence of a detectable signal is by no means assured, if found it would be decisive evidence for dark matter of a definite mass. This is an additional motivation for experiments to measure the high-energy electron and positron cosmic ray spectra, and to be sure that such experiments have adequate resolution.

Note Added: D. Seckel has called to our attention an unpublished manuscript by A.J. Tylka and D. Eichler[22] which discusses in detail the spectrum of cosmic ray positrons expected from halo photino annihilations, and also mentions the possibility of positron line radiation from Dirac neutrino annihilations in the halo.

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14. We should note that based upon the measured electron and positron spectra Protheroe[12] argues that the 'ordinary' cosmic ray $e^{\pm}$ population is exposed to an it rms field strength of $\sim 6 \times 10^{-6}$ G.

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15. If we consider the not unlikely possibility that the diffusion time τ is also energy dependent, say $\tau(E) = \tau(m)m/E$, one obtains a qualitatively similar solution: $d\mathcal{F}_+/dE = [n^2 < \sigma|v| >_{\rm ANN} (gf^2)(c\tau(m)BR)/4\pi](r/m)(E/m)^{r-2}$, where $r = \tau_{\Delta E}(m)/\tau(m)$.
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20. 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: $BR \simeq v^2/(m_f/m)^2 \sim 3 \times 10^{-4} m_{30}^2$ (taking $m_f = m_b$). We have implicitly taken this fact into account when we say that the canonical expectation for a neutralino is $BR \sim 10^{-5}$.
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Figure Captions

FIGURE 1—The predicted positron fraction, $e^+/(e^+ + e^-)$, and the existing experimental data (from Ref. 11). In calculating the predicted positron fraction we have taken $m = 25$ GeV, $r = 1$, and $gf^2 = 20$, values which 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, $e^+/(e^+ + e^-) = 0.02 + 0.10(E/\mathrm{GeV})^{-0.5}$, which is consistent with the models discussed in Ref. 12.

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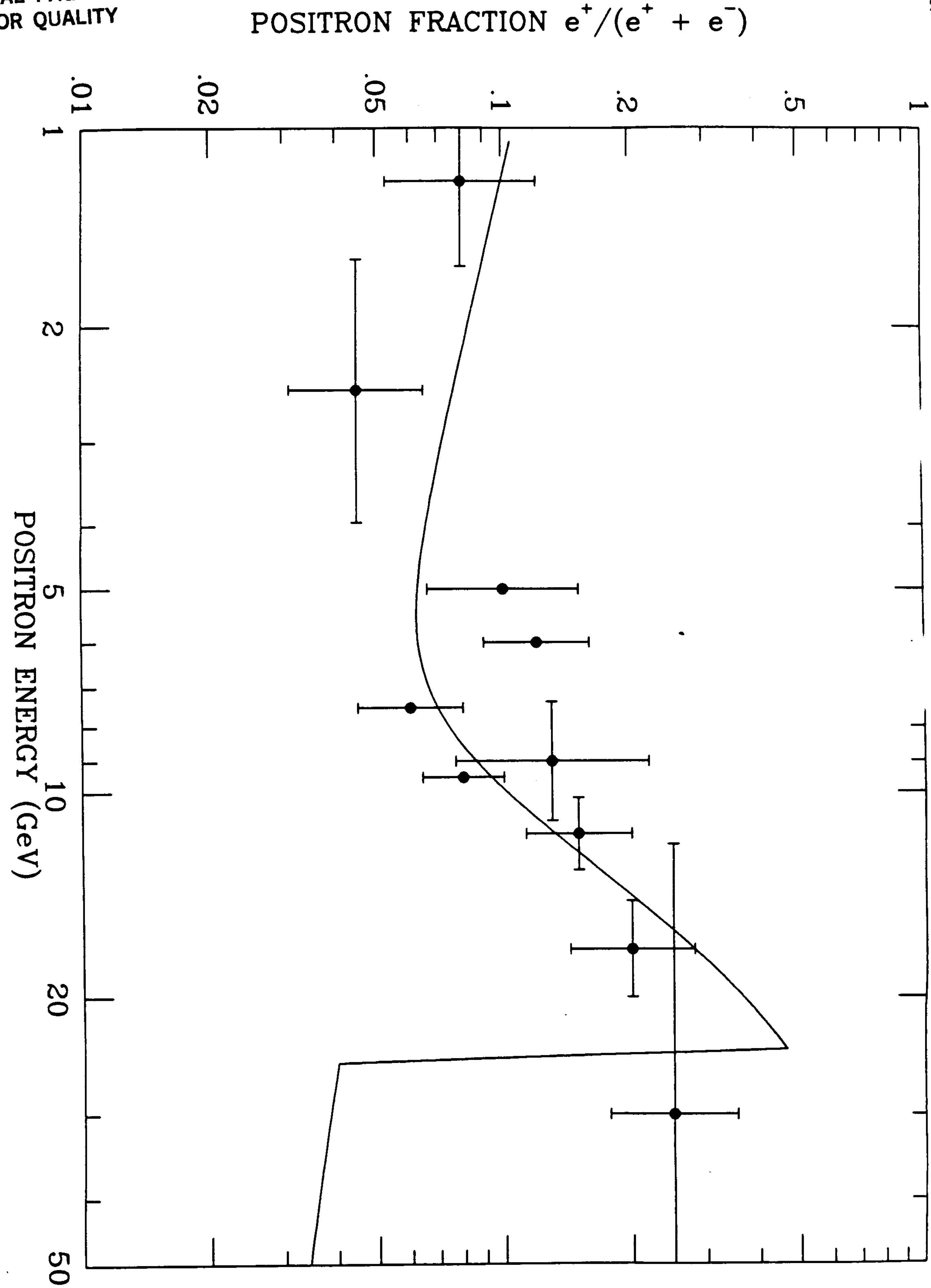

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