Physics Letters B 673 (2009) 152–155

Contents lists available at ScienceDirect

Physics Letters B

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Dark matter: The leptonic connection

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ARTICLE INFO

Article history:
Received 19 January 2009
Received in revised form 30 January 2009
Accepted 3 February 2009
Available online 12 February 2009
Editor: M. Cvetič

ABSTRACT

Recent observations of high-energy positrons and electrons by the PAMELA and ATIC experiments may be an indication of the annihilation of dark matter into leptons and not quarks. This leptonic connection was foreseen already some years ago in two different models of radiative neutrino mass. We discuss here the generic interactions $(\nu\eta^0 - l\eta^+)\chi$ and $l^c\zeta^-\chi^c$ which allow this to happen, where χ and/or χ^c are fermionic dark-matter candidates. We point out in particular the importance of $\chi\chi \to l^+l^-\gamma$ to both positron and gamma-ray signals within this framework.

1. Introduction

Dark matter (DM) is widely recognized as a necessary component of the Universe, but its nature remains unknown. A possible hint to solving this mystery is the recent observation of high-energy positrons and electrons by the PAMELA [1,2] and ATIC [3] experiments without any accompanying evidence of antiprotons. Consider the interactions

$$f(\nu\eta^0 - l\eta^+)\chi + f' l^c \zeta^- \chi^c + \text{h.c.} \tag{1}$$

in addition to those of the standard model (SM) of quarks and leptons, where the new scalars η^0, η^+, ζ^-, and the new fermions χ, χ^c are odd under an exactly conserved Z_2 symmetry, while all SM particles are even. Assume also the conservation of lepton number L so that χ (or η) has $L = -1$, and χ^c (or ζ) has $L = 1$. To accommodate nonzero neutrino masses, the usual seesaw mechanism may be invoked with the term $(\nu\phi^0 - l\phi^+)N^c$, where $\Phi = (\phi^+, \phi^0)$ is the SM Higgs doublet and N^c is a neutral singlet fermion with $L = -1$, both of which are even under Z_2. A large Majorana mass for N^c will then break L to $(-)^L$ and allow ν to acquire a naturally small Majorana mass, as is well known. Similarly, a Majorana mass for χ may also break L to $(-)^L$, in which case the quartic scalar term $(\lambda_5/2)(\Phi^\dagger\eta)^2 + \text{h.c.}$ is allowed and a neutrino mass is generated in one-loop order [4]. If N^c is absent, m_ν will be generated solely by particles which are odd under Z_2, as proposed already three years ago [5], and may be called *scotogenic*, i.e. caused by darkness. As for the f' interaction of Eq. (1), it was used in a three-loop model of neutrino mass [6] and in two models of leptogenesis [7,8].

Whereas the interactions of Eq. (1) are motivated by neutrino mass and leptogenesis, we adopt the viewpoint in this Letter that the couplings f and f', as well as the masses of the new particles, are unconstrained parameters, to be explored for their DM properties. For definiteness, we will study the case where $f' = 0$ and χ is Majorana or Dirac. Our results are easily adaptable to the case where $f = 0$ and χ^c is Majorana or Dirac, and to the case where both f and f' are nonzero, with χ and χ^c forming a Dirac fermion.

2. Elaboration

The f interaction of Eq. (1) has been studied before. The case of $L = -1$ for (η^+, η^0) and $L = 0$ for χ is the leptonic Higgs model [9]. There L is broken explicitly by the soft term $\Phi^\dagger\eta$, so that a small $\langle\eta^0\rangle$ is obtained which allows ν to pair up with χ $(= N^c)$ to acquire a Dirac mass. Together with the allowed Majorana mass for χ, a seesaw mass for ν is obtained. The case of $L = 0$ for (η^+, η^0) and $L = -1$ for χ where both are odd under an exactly conserved Z_2 is the prototype model of scotogenic neutrino mass [5]. In this case, the quartic scalar term $(\lambda_5/2)(\Phi^\dagger\eta)^2 + \text{h.c.}$ is allowed, which splits η^0 into two particles, $\text{Re}(\eta^0)$ and $\text{Im}(\eta^0)$, with different masses [10]. This allows the lighter of the two to be considered as dark matter [5,11–13]. The collider signature of this scenario has also been discussed [14], as well as its cosmological implications [15].

If $\text{Re}(\eta^0)$ or $\text{Im}(\eta^0)$ is dark matter, then its annihilation to a pair of gauge bosons or the SM Higgs boson will result in both quarks and leptons. If χ or χ^c is dark matter, then only leptons are expected. If $f' = 0$, then χ may annihilate to neutrinos and charged

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0370-2693
doi:10.1016/j.physletb.2009.02.015

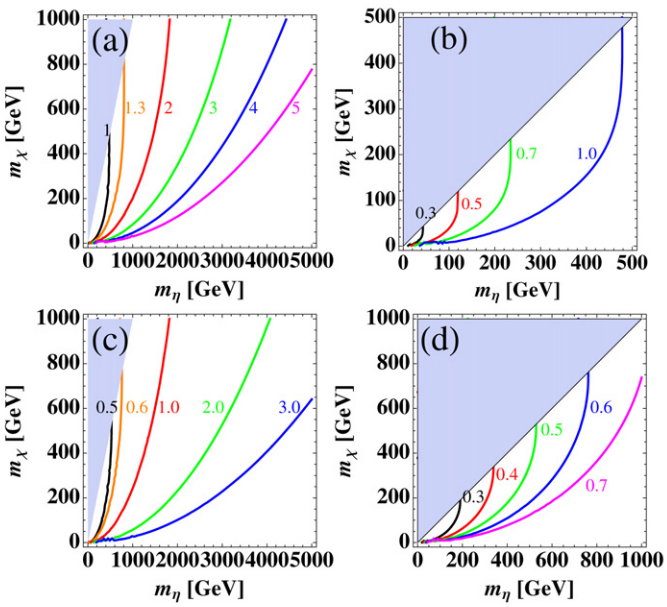

Fig. 1. Correlation between m_χ and m_η, giving rise to the correct amount of relic abundance for different Yukawa coupling strengths: (a) and (b) for Majorana χ, (c) and (d) for Dirac χ. The shadow region where $m_\chi > m_\eta$ is excluded.

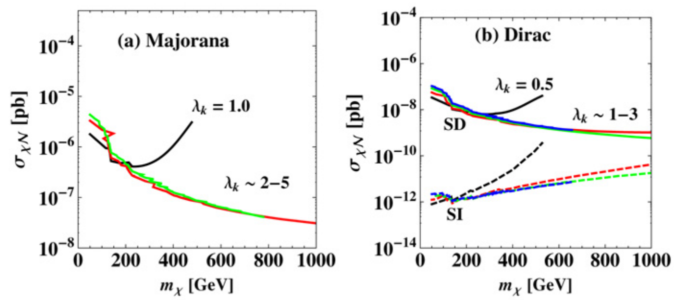

Fig. 2. Cross sections for the direct detection of χ: (a) Majorana case, SD only; (b) Dirac case, both SD and SI. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

leptons through the exchange of η^0 and η^+. If $f = 0$, then χ^c may annihilate only to charged leptons through the exchange of ζ^-. In these two cases, we can assume χ or χ^c to be either Majorana or Dirac. In the case $f \neq 0$ and $f' \neq 0$, the natural scenario is that χ and χ^c together form a Dirac fermion. To avoid flavor-changing leptonic interactions, such as $\mu \to e\gamma$, which is an intrinsic problem [16] in models of scotogenic neutrino mass if χ is considered as dark matter, we will assume for simplicity that χ couples only to e and ν_e.

3. Relic abundance

As mentioned earlier, we will consider for definiteness, only the f interaction of Eq. (1). However, we will make the important distinction between whether χ is Majorana or Dirac. The observed relic abundance of χ is determined by its thermally averaged annihilation cross section into charged leptons and neutrinos multiplied by its velocity at the time (or equivalently the temperature) of its decoupling from the SM particles in the early Universe. To this end, we use the well-known nonrelativistic approximation $\langle \sigma v \rangle = a + bv^2$. If χ is Majorana, we have

$$(\mathrm{A}) \quad a = 0, \qquad b = \frac{f^4 r^2 (1 - 2r + 2r^2)}{24\pi m_\chi^2}, \tag{2}$$

where we have assumed for simplicity equal masses for $\eta^\pm$ and η^0, with $r \equiv m_\chi^2/(m_\eta^2 + m_\chi^2)$. If χ is Dirac, we have

$$(\mathrm{B}) \quad a = \frac{f^4 r^2}{16\pi m_\chi^2}, \qquad b = \frac{f^4 r^2 (11 - 40r + 24r^2)}{384\pi m_\chi^2}. \tag{3}$$

As shown in Fig. 1, there is a strong correlation between m_χ and m_η for a given f, in order that the correct amount of DM relic abundance [17] be produced. Smaller values of f are allowed if χ is Dirac (B) rather than Majorana (A) because of $a = 0$ in Eq. (2). It should also be mentioned that the coannihilation of χ and η can reduce f in both cases, if m_η is only slightly greater than m_χ [18]. Here we do not consider this scenario.

4. Direct detection

Even though χ couples only to leptons, it can interact with quarks through its one-loop effective coupling to the Z boson. It may thus be detectable in the next-generation direct-search experiments for dark matter using nuclear recoil. If χ is Majorana, its effective interaction with quarks is given by

$$\mathcal{L}_\mathrm{A} = \frac{\mathcal{G}}{m_Z^2} (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q), \tag{4}$$

where $\mathcal{G}$ is the loop-induced form factor. Fig. 2(a) shows the spin-dependent (SD) cross section (σ_SD) as a function of m_χ with $f = 1.0$ (black) and $f \sim 2$–5 (green, red), where m_η is determined by the relic abundance. It is clear that the SD cross section is well below the current experimental bounds, $\mathcal{O}(10^{-2})$ pb, owing to the loop suppression, but may be detectable in future experiments. If χ is Dirac, there exist both vector and axial-vector couplings, thus

$$\mathcal{L}_\mathrm{B} = \frac{\mathcal{G}'}{m_Z^2} (\bar{\chi}\gamma^\mu\chi)(\bar{q}\gamma_\mu q) + \frac{\mathcal{G}''}{m_Z^2} (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q). \tag{5}$$

This means that there is a spin-independent (SI) cross section which can be enhanced by coherent effects as well as a spin-dependent one. Fig. 2(b) shows both the SD (solid curves) and SI (dashed curves) cross sections. In this case, both may be outside the reach of experiments in the near future.

5. Observation of positrons

The measurement of secondary particles coming from the annihilation of dark matter in the halo of the galaxy provides a promising way of deciphering its nature. If positrons are produced and propagate through the galaxy, their spectrum is distorted as they pass through the turbulent galactic magnetic fields. This propagation can be described by a diffusion-energy-loss process [19]. The resulting flux seen at Earth is scaled by an overall normalization (boost) factor, due to the unknown level of clumping of dark matter at the positron source. Recently, two experimental collaborations, PAMELA and ATIC, have reported an excess of high-energy positrons and electrons. These confirm earlier results from HEAT and AMS-01, raising the exciting possibility that dark matter annihilates either directly, or indirectly to positrons, but not to antiprotons.

The PAMELA Collaboration observed an excess well above the expected background in the positron fraction at energies 10–100 GeV [1]. Many explanations have recently been proposed to account for this excess including SM extensions [20–35], decaying DM [36–38] and non-DM astrophysical sources [39,40]. Due to the abrupt rise in the positron fraction with increasing energy, the resulting positron spectrum injected into the halo is expected to be quite hard, indicating either direct annihilation to e^+e^-, or states such as μ and τ leptons which give off energetic secondary positrons. This has been quantified in recent studies [41–43]. To be consistent with PAMELA data, the DM masses favored are of the order a few hundred GeV, given a marginalization over all possible annihilation modes which result in positrons [42].

Recently, the ATIC [3] Collaboration also observes an excess of high-energy positrons and electrons. In addition, the data exhibit an excess in the $\Phi_{e^+} + \Phi_{e^-}$ spectrum in the range 300–800 GeV. This result at first sight seems to be at odds with the DM candidate favored by the PAMELA data. However, a combined fit shows that a 700–850 GeV DM candidate is consistent with both PAMELA and ATIC if only charged leptons are allowed.

6. Dark matter bremsstrahlung

The preference for DM annihilations to hard positrons suggests the scenario of Eq. (1). In this case, whether χ is Majorana or Dirac has a striking impact on the resulting positron spectrum. If it is Majorana, the annihilation cross section is helicity suppressed, leaving only the p-wave component in Eq. (2). However, the velocities at which dark matter annihilates today (as opposed to the early Universe) are so small, $v/c \approx 10^{-3}$, the p-wave term is even more negligible. Thus at tree level, annihilations to τ leptons are dominant because the s-wave terms are scaled by the mass-squares of fermions to which the DM pairs annihilate. However, the helicity suppression may still be severe enough that the bremsstrahlung process $\chi\chi \to e^+e^-\gamma$ can be much more important (see Fig. 3). This effect has been studied in the context of supersymmetry in the stau-coannihilation region for the PAMELA excess [44]. In the extreme nonrelativistic limit $v \to 0$, the cosmic positron spectrum is given by [44]

$$\frac{d\sigma}{dE_{e^+}}\bigg|_{v\to 0} = \frac{\alpha f^4}{256\pi^2 m_\chi^2}\frac{1}{(2x+\mu-1)^2} \times\bigg\{\big(4(1-x)^2-4x(1+\mu)+3(1+\mu)^2\big)\log\frac{1+\mu}{1+\mu-2x} -\big(4(1-x)^2-x(1+\mu)+3(1+\mu)^2\big)\frac{2x}{1+\mu}\bigg\}, \tag{6}$$

with $x \equiv E_{e^+}/m_\chi$ and $\mu = m_{\eta^\pm}/m_\chi$. The resulting positron spectrum can exhibit a sharp peak near the kinematic endpoint (red curves) in Fig. 4. Depending on the relative masses of χ and η, interference effects can distort the positron spectrum, yielding a secondary peak at lower energies.

The associated photon in this process may also be observable with the FERMI gamma-ray telescope [45]. With an upper energy range of ∼300 GeV, FERMI should be well positioned to catch a glimpse of the photon signal. The energy spectrum of the gamma-ray is given by

$$\frac{d\sigma}{dE_\gamma}\bigg|_{v\to 0} = \frac{\alpha f^4}{256\pi^2 m_\chi^2}\frac{y-1}{(1+\mu-y)^2} \times\bigg\{\frac{2(1+\mu)(1+\mu-2y)}{1+\mu-y}\log\frac{1+\mu-2y}{1+\mu} -\frac{4y[y^2+(1+\mu-y)^2]}{(1+\mu)(1+\mu-2y)}\bigg\}, \tag{7}$$

with $y \equiv E_\gamma/m_\chi$. The resulting gamma-ray spectrum from the bremsstrahlung photon (black curves) in the Majorana case peaks before the endpoint, then abruptly terminates. With increasing $m_{\eta^\pm}$ the peak positions are shifted to the low-energy regime, see the dashed curves, i.e. the positron and photon become softer.

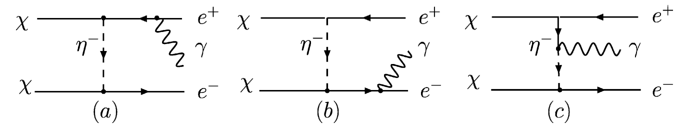

Fig. 3. Feynman diagrams of the bremstrahlung annihilation process.

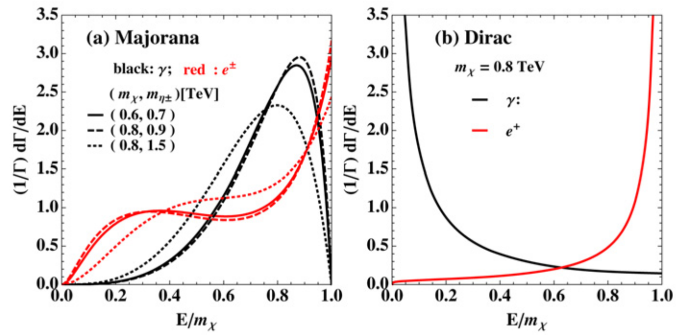

Fig. 4. Energy spectrum of the gamma-ray (black curve) and positron (red curve) in the limit of $v \to 0$ for $\chi\chi \to e^+e^-\gamma$ with various values of m_χ and m_η. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

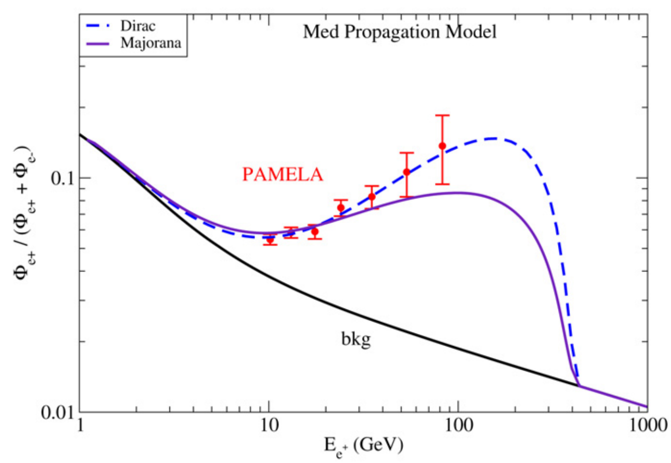

Fig. 5. Positron fraction in the leptonic dark matter scenario with $M_\chi = 450$ GeV and $m_\eta = 500$ GeV for χ Majorana and Dirac.

If χ is instead Dirac, the annihilation cross section is dominated by the s-wave component in Eq. (3). In this case, the DM pairs tend to annihilate to fermions more democratically. Further, since there is no suppression, the impact of the bremstrahlung process on the positron energy spectrum is negligible. Due to the strong suppression of the annihilation cross section to fermion pairs in the Majorana case, the boost factors required to give the same spectra seen by PAMELA are typically several orders of magnitude larger than in the Dirac case. On the other hand, the photon spectrum from bremstrahlung is much softer than in the Majorana case. Since the charged leptons in the final state are relativistic, the radiated photon predominately moves collinearly with the charged leptons, i.e. the "final state radiation" (FSR) regime. In this kinematic limit, the cross section factorizes into the short-distance part, $\sigma(\chi\chi^C \to \ell^+\ell^-)$, and a universal collinear factor:

$$\frac{d\sigma(\chi\chi^C \to \ell^+\ell^-\gamma)}{dy} \approx \sigma\big(\chi\chi^C \to \ell^+\ell^-\big) \times\frac{\alpha e^2}{\pi}\frac{1+(1-y)^2}{y}\log\frac{4m_\chi^2(1-y)}{m_\ell^2}. \tag{8}$$

The photon energy spectrum then peaks around zero.

We illustrate, in Fig. 5, the positron fraction as seen at Earth after propagation effects are included in the "Med" propagation scheme following Ref. [42]. Here, we take $M_\chi = 450$ GeV, $m_\eta = 500$ GeV and require the coupling f such that the relic density is saturated. In the Dirac case, the fit is quite good, with a boost factor of 91. However, in the Majorana case, the fit is marginal as the spectrum is suppressed at higher energies. Due to the helicity suppression, a huge boost factor of $\mathcal{O}(10^6)$ is also required to fit the data in this case. With enough precision, by comparing the correlated signals seen in high-energy positrons (PAMELA) and gamma-rays (FERMI), the specifics of dark matter and the associated exchanged particle in this scenario may be explored.

As this work is being completed, a similar paper [46] has appeared. However, our results do not agree in the case of Majorana dark matter. Specifically, it is claimed there that Majorana dark matter has a nonzero s-wave contribution in its annihilation.

7. Conclusion

The PAMELA and ATIC observations may be indicative of a leptonic connection in dark-matter interactions, as given by Eq. (1). If the neutral fermion χ is dark matter, then whether it is Majorana or Dirac will have very different predictions, especially in the dark-matter bremsstrahlung process of $\chi\chi \to e^+e^-\gamma$. As Fig. 5 shows, Dirac dark matter seems to be favored by current data.

Acknowledgements

Q.H.C. is supported in part by the Argonne National Laboratory and University of Chicago Joint Theory Institute (JTI) Grant 03921-07-137, and by the US Department of Energy under Grants No. DE-AC02-06CH11357 and No. DE-FG02-90ER40560. E.M. is supported in part by the US Department of Energy under Grant No. DE-FG03-94ER40837. G.S. is supported in part by the US Department of Energy under Grant No. DE-AC02-06CH11357.

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