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Secluded WIMPs, dark QED with massive photons, and the galactic center gamma-ray excess

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ABSTRACT

We discuss a particular secluded WIMP dark matter model consisting of neutral fermions as the dark matter candidate and a Proca-Wentzel (PW) field as a mediator. In the model that we consider here, dark matter WIMPs interact with standard model (SM) particles only through the PW field of ~MeV–multi-GeV mass particles. The interactions occur *via* a $U(1)'$ mediator, V'_μ, which couples to the SM by kinetic mixing with $U(1)$ hypercharge bosons, B'_μ. One important difference between our model and other such models in the literature is the absence of an extra singlet scalar, so that the parameter with dimension of mass M_V^2 is not related to a spontaneous symmetry breaking. This QED based model is also renormalizable. The mass scale of the mediator and the absence of the singlet scalar can lead to interesting astrophysical signatures. The dominant annihilation channels are different from those usually considered in previous work. We show that the GeV-energy γ-ray excess in the galactic center region, as derived from *Fermi*-LAT Gamma-ray Space Telescope data, can be attributed to such secluded dark matter WIMPs, given parameters of the model that are consistent with both the cosmological dark matter density and the upper limits on WIMP spin-independent elastic scattering. Secluded WIMP models are also consistent with suggested upper limits on a DM contribution to the cosmic-ray antiproton flux.

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1. Introduction

The clear astronomical [1] and cosmological evidences for large amounts of dark matter (DM) in the universe [2] have led to the construction of various theoretical models that go beyond the standard model (SM) weak-scale theories and which attempt to account for the DM abundance in the universe [3]. The observational evidence for DM has motivated various experimental searches to find dark matter [4].

Data from colliders are used to search for evidence of dark matter particles. Experiments with detectors like DAMA, CoGeNT, CDMS, XENON and LUX are used to search for evidence of the recoil energy of nuclei that would be produced by scattering with dark matter particles [5,6]. High-energy colliders like LHC (Large Hadron Collider), have obtained significant upper limits on the annihilation of WIMPs to quarks [7]. They also offer very interesting possibilities to investigate interactions involving DM mediators.

Space-borne detectors have been used to search for evidence of the products of dark matter annihilation, particularly γ-rays and cosmic-ray positrons. These searches have conservatively produced constraints on dark matter annihilation, both from cosmic γ-ray studies [8] and cosmic-ray positron studies [9]. However, analyses of the *Fermi*-LAT data have indicated the existence of an “excess” flux of γ-rays above that expected from cosmic rays interacting with interstellar gas. This flux appears to be extended around the region of the galactic center. It appears to peak in the 2–3 GeV energy range. This excess has been interpreted to be a possible indication of the annihilation of weakly interacting dark matter (WIMP) particles having a mass in the 20–45 GeV range, annihilating primarily into quarks or, less likely, in the 7–12 GeV mass range annihilating primarily into charged τ leptons [10,11]. Models involving other annihilation channels have also been considered [12]. We note, however, the determination of various possible components of γ-ray emission from the galactic center is complicated and the γ-ray data are not precise enough to point to a unique origin. Other possible interpretations of this excess that include other contributions to the γ-ray flux in the region of the galactic center have been suggested [13].

Neutralino supersymmetric WIMPs, *viz.*, the lightest supersymmetric dark matter particles, have been a popular choice to be the DM WIMPs because they are stable and neutral and their cross section naturally leads to the correct cosmological DM density. However, as of now, the LHC has not found any evidence for such particles. Therefore, other candidate WIMP models have been explored and should be further explored.

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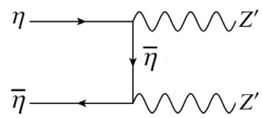

Fig. 1. Feynman diagram for $\eta + \overline{\eta} \to Z' + Z'$.

In this work we consider a model of WIMP dark matter in which the dark sector is just quantum electrodynamics (QED) extended with a new massive photon field, usually dubbed a Proca-Wentzel (PW) field. It is well known that this is a renormalizable theory because it couples to a conserved vector current. Hence, the dark sector is made up of Dirac fermions, η, that only interact *via* a PW field, here denoted by V'_μ, that serves to mediate between DM fermions and standard model particles.

Diagonalization of the kinetic terms in the Lagrangian give both the standard Z boson and an extra neutral gauge boson that we denote as Z'. We will show that this DM model can produce the observed cosmological DM abundance and that its annihilation into standard model (SM) particles can also lead to astronomically observable fluxes of γ-rays in the galactic center and in dwarf galaxies.

In our model secluded DM interactions occur only through Z' mediators which subsequently decay to SM particles. Thus, they have a very small elastic scattering cross section with nuclei. This distinguishes such secluded WIMP models from other WIMP models. The decay of Z''s into quark-antiquark channels produces pions, among which are π^0's that decay to produce γ-rays. The π^0-decay γ-ray spectrum has a characteristic peak at $m_\pi/2$ [14] and is bounded by the rest-mass of the WIMP, m_η (*e.g.*, [15]). The Z' decay, particularly into charged leptons and light quarks, also yields γ-rays through internal bremsstrahlung. In this process, a γ-ray spectrum is produced that peaks near m_η [16]. Electrons resulting from this process can produce γ-rays *via* Compton scattering in the interstellar medium.

Other Z' models have recently been discussed in the context of astrophysical γ-ray production (see, *e.g.*, Ref. [17]). However, our model, in which the Z' is the mediator of the DM interactions through the annihilation channel $\eta + \overline{\eta} \to Z' + Z'$, as shown in Fig. 1, and with $m_{Z'} \ll m_\eta$, was not considered in Ref. [17]. (See also the discussion in Section 4).

The outline of the paper is as follows: in Section 2 we present the model. In Section 3 we classify massive photon models. In Section 4 we discuss the differences between our model and previously explored WIMP DM models. In Section 5 we give the specific details of our model. In Section 6 we calculate the relic density of our Dirac fermion DM candidate. In Section 7 we discuss the astrophysical production of γ-rays from annihilation of our secluded WIMPs as a possible explanation of the so-called γ-ray excess from the galactic center and potential γ-ray signals from the Milky Way satellite dwarf galaxies. In Section 8 we summarize our results and conclusions. In Appendix we give the full couplings for the interactions described by the model.

2. The basic model

The possible existence of an extra $U(1)'$ symmetry of nature beyond the SM has been considered for a long time. The addition of this new symmetry factor to the electroweak $SU(2) \otimes U(1)$ of the SM occurs *via* the so-called kinetic mixing portal, by mixing with the hypercharge gauge boson B^μ. A real massive vector field coupled to a fermionic vector current is a well behaved theory. The mass term breaks what would-be a gauge symmetry (which is valid in the kinetic term). However, this only implies the constraint $\partial_\mu V'^\mu = 0$. For earlier references see [18].

The dark matter fermion WIMPs of the model, η, interact only with the PW field that is the connection between DM and ordinary matter, designated by V'_μ. The PW field mixes through the kinetic term with the $U(1)_Y$ vector field of the SM, at this stage designated by B'_μ. DM interactions occur only through Z' mediators which subsequently decay to SM particles. As such, secluded DM WIMPs have a very small elastic scattering cross section with nuclei. This distinguishes secluded WIMP models from other WIMP models, thus allowing for a potential experimental test.

After the diagonalization of the mixing in the kinetic terms,

$$V'_\mu = (1/\sqrt{1-g_{VB}^2})V_\mu, \quad (1)$$

where V_μ is a linear combination of Z and the extra neutral gauge boson Z'. Cosmological DM abundance constraints on the DM annihilation cross section will then require a small mixing angle between V and Z' so that $V \simeq Z'$ [19]. Depending on the mass of Z', interesting signatures for these types of mediators could come from the Drell-Yan channel $pp \to Z' \to l\bar{l}$ and from non-conventional decays of SM Higgs boson such as $h \to ZZ'$, potentially observable with the Large Hadron Collider (LHC). In this work we consider a scenario where the Z' is light, such that $M_{Z'} \ll m_\eta$. The scalar sector is the same as that of the SM, viz., a doublet with $Y = +1$.

Empirical bounds on Z' couplings exist for these kinds of models. Such bounds depend on the mass scale of Z'. High energy colliders are sensitive to $M_{Z'} \gtrsim 10$ GeV and the constraints for lighter Z''s are given mainly by precision QED observables, B meson decay and some fixed target experiments [21]. Besides these constraints, there is also a constraint on the lifetime of a Z'. Its lifetime should be less than one second in order to guarantee that the Z' decays before the onset of big-bang nucleosynthesis [22]. As a consequence, the secluded DM fermion will annihilate preferably into a Z' pair [19].

The full Lagrangian of the model is given by

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Dark} + \mathcal{L}_{Dark+int}, \quad (2)$$

where $\mathcal{L}_{SM}$ is the SM Lagrangian, and $\mathcal{L}_{Dark}$ is the dark Lagrangian given by

$$\mathcal{L}_{Dark} = \overline{\eta}(i\partial_\mu\gamma^\mu\eta - m_\eta)\eta. \quad (3)$$

The mixing between dark and SM matter, occurs through the third term in Eq. (2), which is

$$\begin{aligned}\mathcal{L}'_{Dark+int} &= g_\eta\overline{\eta}\gamma^\mu\eta V'_\mu + \frac{1}{2}M_V^2 V'_\mu V'^\mu \\ &\quad -\frac{1}{4}V'_{\mu\nu}V'^{\mu\nu} + \frac{g_{VB}}{2}V'_{\mu\nu}B'^{\mu\nu} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu},\end{aligned} \quad (4)$$

where $X_{\mu\nu} = \partial_\mu\nu + \partial_\nu X_\mu$, with $X_\mu = V'_\mu, B'_\mu$, and B'_μ is the abelian gauge boson of the $U(1)_Y$ factor in the SM Lagrangian. In Eqs. (3) and (4), the masses m_η, M_V and the couplings g_{VB} and g_η are free parameters. The mixing in the kinetic term in Eq. (4) can be diagonalized by a $GL(2,R)$ transformation [23]

$$\begin{pmatrix} V \\ B \end{pmatrix} = \begin{pmatrix} \sqrt{1-g_{VB}^2} & 0 \\ -g_{VB} & 1 \end{pmatrix}\begin{pmatrix} V' \\ B' \end{pmatrix} \quad (5)$$

Using (5) in (4) we obtain

$$\begin{aligned}\mathcal{L}'_{Dark+int} &= \frac{g_\eta}{\sqrt{1-g_{VB}^2}}\overline{\eta}\gamma^\mu\eta V_\mu + \frac{M_V^2}{2(1-g_{VB}^2)}V_\mu V^\mu \\ &\quad -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}.\end{aligned} \quad (6)$$

After symmetry breaking we get the mass matrix in the (B^μ, $W^{3\mu}$ and V^μ) basis

$$M^2 = \frac{g^2 v_h^2}{4c_W^2}U^\dagger\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -\xi s_W \\ 0 & -\xi s_W & \xi^2 s_W^2 + 4r \end{pmatrix}U, \quad (7)$$

where s_W is the usual weak mixing angle, $\xi = g_{VB}/\sqrt{1-g_{VB}^2}$, $r = M_V^2/M_Z^2$, and where the matrix U is given by

$$U = \begin{pmatrix} c_W & s_W & 0 \\ -s_W & c_W & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (8)$$