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Energy dependence of direct detection cross section for asymmetric mirror dark matter

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In a recent paper, four of the present authors proposed a class of dark matter models where generalized parity symmetry leads to equality of dark matter abundance with baryon asymmetry of the Universe and predicts dark matter mass to be around 5 GeV. In this paper, we explore how this model can be tested in direct search experiments. In particular, we point out that if the dark matter happens to be the mirror neutron, the direct detection cross section has the unique feature that it increases at low recoil energy unlike the case of conventional weakly interacting massive particles. It is also interesting to note that the predicted spin-dependent scattering could make significant contribution to the total direct detection rate, especially for light nucleus. With this scenario, one could explain recent DAMA and CoGeNT results.

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I. INTRODUCTION

It is now widely accepted that almost a quarter of the mass-energy in the Universe is dark matter and one of the major challenges of particle physics and cosmology is to discover the nature of the dark matter. Since the standard model of particle physics does not contain any stable particle that can play the role of dark matter, this provides evidence for physics beyond standard model (BSM) and many BSM scenarios have been proposed that include stable or very long-lived weakly interacting massive particles (WIMPs) which can play this role [1]. Dark matter being pervasive in our galaxy with an energy density of $\rho_{\rm DM} \simeq 0.3\ \mathrm{GeV/cm^3}$, it could be observable by detection of nuclear recoils produced when it scatters off nuclei in a very low-background detector [2,3]. The recoil energy distribution which is in the keV range could provide clues to the nature of the WIMP.

Among the direct detection experiments, e.g., CDMS [4] and XENON10 [5], have not found any signal from WIMPs and set the most stringent constraints on the WIMP-nucleon elastic scattering cross section. On the other hand, DAMA collaboration has reported an annual modulation signal in the scintillation light from their DAMA/NaI and DAMA/LIBRA experiments, which is interpreted as evidence of dark matter [6,7]. The CDMS II collaboration has observed two possible dark matter signal events for an expected background of 0.8 ± 0.2 events [8]. More recently the CoGeNT collaboration has published their results from the ultra low noise germanium detector with a very low-energy threshold of 0.4 keVee in the Sudan Underground Laboratory [9]. Although the observed excess is consistent with an exponential background, it also could be explained by a WIMP in the mass range $5 \sim 10$ GeV, with a rather large WIMP-necleon spin-independent (SI) elastic scattering cross section $\sim 10^{-40}\ \mathrm{cm}^2$ [10,11].

It is well known that the null experiments have already ruled out the case of canonical WIMP masses ~ 100 GeV to be capable of producing the DAMA results. Yet for a low mass ($\mathcal{O}(10)$ GeV) WIMP, the compatibility is possible.

The light dark matter fits of DAMA and CoGeNT motivate many light dark matter (DM) models; among them, a class of very attractive ones are the asymmetric dark matter (ADM) models. The ADM models are different from the usual WIMP models in that whereas the latter have a relic thermal abundance determined by the thermal 'freeze-out', ADM abundance is related to the baryon asymmetry in the universe [12–26].

Recently, we proposed an ADM model [26] in which the standard model is accompanied by a dark standard (or mirror) model which is a complete duplication of the matter and forces in the visible standard model (SM). A mirror symmetry guarantees that prior to symmetry breaking there are no free coupling parameters in the dark sector. This is therefore distinct from models where an arbitrary dark sector is appended to the standard model. Symmetry breaking is assumed to be different in the mirror sector compared to the familiar SM sector so that the model is consistent with cosmology.

There are several ways that the two sectors are connected: the first, of course, is via gravity as every matter would couple to gravity. To understand small neutrino masses in our sector, we invoke the seesaw mechanism and add three right-handed neutrinos. A novel aspect of our model [26] is that instead of adding right-handed (RH) neutrinos separately to two sectors, we add a common set of three RH neutrinos that provides a second link between the two sectors [27]. Finally, we add a kinetic mixing between the $U(1)$ bosons of the two sectors. Other details of the model are reviewed in Sec. III.

The right-handed neutrinos not only help in understanding of the small neutrino masses by a variation of the usual seesaw mechanism [28], they also play a crucial role in our understanding of dark matter abundance: in the early universe, the RH neutrinos decay out of equilibrium and generate equal leptonic asymmetry in both sectors. These asymmetries are then transferred into baryonic and mirror-baryonic asymmetries through the sphaleron processes in both sectors. Thus, the full weak $SU(2)_L$ group in both sectors are essential to our scenario. The lightest mirror baryon is considered as the dark matter particle. Thus baryogenesis via leptogenesis explains both the origin of matter as well as dark matter, making their number densities equal to each other due to mirror symmetry. This allows us to predict the dark matter mass to be $m_N\Omega_{\rm DM}/\Omega_B \sim 5$ GeV. The $U(1) - U'(1)$ kinetic mixing along with a massive mirror photon helps us to maintain consistency of the model with big bang nucleosynthesis (with a mirror photon mass in the 10–100 MeV range). The mirror photon, therefore, provides a portal linking the two sectors and makes the direct detection of the dark matter possible. Furthermore, the dark matter in our model has self interaction and as pointed out in [26], the self interaction cross-section is safely below the bullet cluster constraint.

In this work, we investigate the direct detection of the dark baryons that arise in the class of asymmetric mirror models proposed in [26]. We write down the general operators for neutral dark baryon interaction with the visible sector through a light massive mirror photon portal. We find that the interactions are energy/momentum dependent and the differential cross section has nonuniform angular distribution. These new features are absent in the conventional WIMP case for both spin-independent (SI) and spin-dependent (SD) interactions. This provides a way to distinguish between this type of DM from many familiar DM candidates. We also consider the scenarios when the charged dark baryon p' or Δ' is the dark matter, in which case there is no such momentum dependence.

The paper is organized as follows: in Sec. II, we give a general operator analysis of dark matter and nuclear interaction that applies to the asymmetric dark matter and similar models. In Sec. III, we discuss the implications of the general operator analysis and the energy dependent direct detection cross section that results for this general case. In Sec. IV, we present our conclusions.

II. DIRECT DETECTION: OPERATOR ANALYSIS AND CROSS SECTIONS

Dark matter direct detection experiments measure the recoil energy deposited when a WIMP collides with a nucleus in the detector. For a WIMP of mass m_χ scattering with a nucleus of mass m_A, the recoil energy E_r is given by $E_r = \mu^2 v^2/m_A(1-\cos\theta)$, where $\mu = m_\chi m_A/(m_\chi + m_A)$ is the reduced mass and θ is the scattering angle in the center of mass frame.

The differential detection rate can be written as

$$\frac{dR}{dE_r} = N_T\frac{\rho_0}{m_\chi}\int_{v_{\rm min}}^{v_{\rm max}}\frac{d\sigma}{dE_r}vf(v, v_e)d^3\mathbf{v}, \qquad (1)$$

where $\rho \approx 0.3$ GeV cm^{-3} is the local DM density in the solar system, $f(v, v_e)$ is the distribution of DM velocity, and v is the velocity with respect to the Earth, N_T is the number of scattering nucleus per unit detector mass. For elastic scattering with given recoil energy E_r, the limits of the above integral are given by $v_{\rm min} = \sqrt{m_A E_r/(2\mu^2)}$ and $v_{\rm max} \approx 650$ km/s, the escape velocity from our galaxy.

The differential cross section induced by DM-nucleus scattering is given by the spin-independent and spin-dependent contributions, which are conventionally written as

$$\frac{d\sigma}{dE_r} = \frac{m_A}{2\mu^2 v^2}[\sigma^0_{\rm SI}F^2(|\mathbf{q}|) + \sigma^0_{\rm SD}S(|\mathbf{q}|)/S(0)], \qquad (2)$$

where $\sigma^0_{\rm SI,SD}$ are the integrated SI and SD DM-nucleus cross sections. $F(|\mathbf{q}|)$ is the SI form factor and takes the common Helm form factor [29]

$$F^2(|\mathbf{q}|) = \left[\frac{3j_1(|\mathbf{q}|R_1)}{|\mathbf{q}|R_1}\right]^2\exp(-(|\mathbf{q}|s)^2), \qquad (3)$$

where j_1 is the first spherical Bessel function, $|\mathbf{q}| = \sqrt{2m_A E_r}$, $R_1 = (R^2 - 5s^2)^{1/2}$, $R = 1.2\ {\rm fm}A^{1/3}$ and $s \approx 1$ fm. The SD form factor $S(|\mathbf{q}|)$ is specific to the target nucleus.

The velocity distribution of DM in the galactic halo is often assumed to be given by a standard Maxwellian distribution

$$f(\mathbf{u}) = f(\mathbf{v} + \mathbf{v}_e) = \frac{1}{(\pi v_0^2)^{3/2}}e^{-\mathbf{u}^2/v_0^2}, \qquad (4)$$

where $v_0 \sim 270$ km/sec, $\mathbf{v}$ is the velocity of DM with respect to the detector and $\mathbf{v}_e$ is the Earth's speed velocity relative to the halo and it is time dependent: $v_e = v_\odot + 14.4\cos[2\pi(t-t_0)/T]$ km/sec with $t_0 = 152$ days and $T = 1$ year. Because of the rotation of the Earth around the Sun, the direct detection signal for DM has a well-known annual modulation effect

$$S(E, t) = S_0(E) + A(E)\cos\left[\frac{2\pi(t-t_0)}{T}\right]. \qquad (5)$$

It is worth pointing out in regard to Eq. (2) that in the discussions so far, the differential cross section is assumed to be momentum independent except for the nuclear structure form factor with low momentum transfer. In other words, the dark matter-nucleon interactions are assumed to be such that they do not generate momentum dependence in the differential cross section. However, in general there can be interactions which can lead to $\mathbf{q}$-dependence and if the dependence comes with a large coefficient, it could be detected in laboratory searches. Examples of DM particles which could lead to such situations are millicharged particles or DM particle interacting with dipole moment. In the model recently proposed by us in [26], the mirror neutron is considered as the dark matter candidate. It interacts through a light mirror photon portal. We will show that the cross sections in this case are $\mathbf{q}$-dependent and large enough for direct detection. For other examples of dark matter models with momentum dependent scattering cross section, see Refs. [30–35].

A. General operators analysis

In this section, we give a general operator analysis of dark matter-nuclear interaction where there is a kinetic mixing $\frac{\varepsilon_\gamma}{2}F^{\mu\nu}F'_{\mu\nu}$ between the mirror sector gauge field and the visible sector, and the hidden $U(1)'$ is broken so that the mirror photon has a mass in the range 10–100 MeV. The light mirror photon becomes the portal linking the dark matter and SM particles.

The interaction of nucleons with the mirror photon can then be written as

$$\mathcal{L} = \varepsilon_\gamma e \bar{p}\gamma^\mu p A'_\mu + \varepsilon_\gamma \frac{\mu_N}{2}\bar{N}\sigma^{\mu\nu}NF'_{\mu\nu}, \tag{6}$$

where $N = p$, n stands for proton and neutron, respectively, and μ_N is the anomalous magnetic dipole of the nucleons.

Consider a particle from the mirror sector as the dark matter candidate, and it carries vanishing mirror electric charge. Therefore, it interacts with the mirror photon through its anomalous magnetic dipole moment or other higher dimensional operators. In analogy to the effective field theories of nucleons in QCD, we write down all possible operators up to dimension six.

$$\begin{aligned}\mathcal{L}' = {}& c_1\frac{e}{2m_\chi}\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu} + c_2\frac{e}{2m_\chi^2}\bar{\chi}\gamma^\mu\chi\partial^\nu F'_{\mu\nu} \\ & + c_3\frac{e}{m_\chi^2}\bar{\chi}\gamma^\mu\partial^\nu\chi F'_{\mu\nu} + \text{H.c.},\end{aligned} \tag{7}$$

where $\mu_\chi = c_1 e/m_\chi$ is defined as the anomalous mirror magnetic dipole moment of the mirror neutron. It is easy to check that other operators such as $(e/m_\chi^2)\varepsilon^{\mu\nu\rho\sigma}\times \bar{\chi}\gamma_\mu\gamma_5\partial_\nu\chi F'_{\rho\sigma}$ can be decomposed into linear combinations of the above three.

The matrix element of the low-energy scattering between the nucleon and dark matter can be obtained by integrating out the mirror photon.

$$\begin{aligned}\mathcal{M}_{\text{eff}} = {}& \varepsilon_\gamma\frac{c_1}{m_\chi}\frac{e^2}{m_{\gamma'}^2}(\bar{p}\gamma^\mu p)q^\nu(\bar{\chi}\sigma_{\mu\nu}\chi) \\ & + i\varepsilon_\gamma\frac{c_1\mu_N}{m_\chi}\frac{e}{m_{\gamma'}^2}(\bar{N}\sigma^{\mu\nu}N)q_\mu q^\alpha(\bar{\chi}\sigma_{\alpha\nu}\chi) \\ & + i\varepsilon_\gamma\frac{c_2}{2m_\chi^2}\frac{e^2}{m_{\gamma'}^2}(\bar{p}\gamma^\mu p)q^2(\bar{\chi}\gamma_\mu\chi) \\ & + i\varepsilon_\gamma\frac{c_3}{m_\chi^2}\frac{e^2}{m_{\gamma'}^2}(\bar{p}\gamma^\mu p)q^\nu[\bar{\chi}(\gamma_\mu P_\nu - \gamma_\nu P_\mu)\chi],\end{aligned} \tag{8}$$

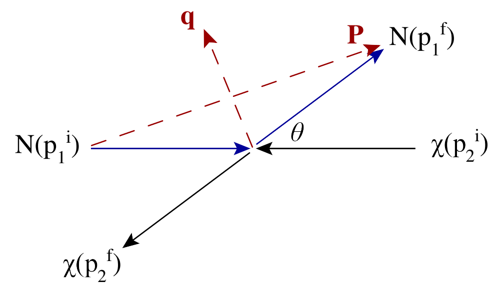

FIG. 1 (color online). The kinematics of scattering: $|\mathbf{q}|^2 = 2\mu^2 v^2(1-\cos\theta)$, $|\mathbf{P}|^2 = 2\mu^2 v^2(1+\cos\theta)$ and $\mathbf{q}\cdot\mathbf{P} = 0$ in the CM frame.

where q is the momentum transfer and P is the sum of momenta of the initial and final nucleons. The kinematics of scattering is shown in Fig. 1. In the center of mass (CM) frame, one has $P^0 \sim 2\mu$, $q^0 \sim \mathcal{O}(\mu v^2)$, the three-momenta P^i, $q^i \sim \mu v$ satisfying $\mathbf{q}\cdot\mathbf{P} = 0$, μ is the reduced mass and v is the velocity of the incoming dark matter particle in the laboratory frame. Based on the power counting, we perform a nonrelativistic reduction of the above operators.[1] The nonrelativistic reduction of the scattering amplitude yields

$$\begin{aligned}\mathcal{M}_{\text{nr}} = {}& \varepsilon_\gamma\frac{(c_1+c_2)e^2}{2m_\chi^2 m_{\gamma'}^2}|\mathbf{q}|^2(p_h^\dagger p_h)(\chi_h^\dagger\chi_h) + \varepsilon_\gamma\frac{c_1 e^2}{2\mu m_\chi m_{\gamma'}^2} \\ & \times(\mathbf{q}\times\mathbf{P})^i(p_h^\dagger p_h)(\chi_h^\dagger\sigma^i\chi_h) + \varepsilon_\gamma\frac{(\frac{e}{2m_p}+\mu_p)c_1 e}{m_\chi m_{\gamma'}^2} \\ & \times(|\mathbf{q}|^2\delta_{ij} - q^i q^j)(p_h^\dagger\sigma^i p_h)(\chi^\dagger\sigma^j\chi_h) \\ & + \varepsilon_\gamma\frac{\mu_n c_1 e}{m_\chi m_{\gamma'}^2}(|\mathbf{q}|^2\delta_{ij} - q^i q^j)(n_h^\dagger\sigma^i n_h)(\chi^\dagger\sigma^j\chi_h).\end{aligned} \tag{9}$$

where $p_h(n_h)$, χ_h are the nonrelativistic two-component nucleon and dark matter fields, respectively.

Several comments are in order.

- The higher dimensional operators in Eq. (7) are parity even, which differ from those considered in [34]. We write down the operators up to dimension six in the mirror sector. The dimension six operator [c_2 term in Eq. (7)] is relevant for the completeness of studying the momentum-dependent direct detection, since it

[1] We choose the following representation

$$\gamma^0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \qquad \gamma^i = \begin{bmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{bmatrix},$$

$$N(p) = \sqrt{\frac{p^0 + m_N}{2p^0}}\begin{bmatrix} N_h \\ \frac{\mathbf{p}\cdot\boldsymbol{\sigma}}{p^0+m_N}N_h \end{bmatrix}$$

where σ^i is the Pauli matrix and N_h is the nonrelativistic two-component nucleon field. The dark matter has a similar form, with the nonrelativistic field denoted as χ_h.

contributes in the same order as the magnetic dipole, as shown in Eq. (9).

- It is interesting to note that each term in the amplitude $\mathcal{M}_{\rm nr}$ is $\mathbf{q}$-dependent, and proportional to (suppressed by) the momentum power $|\mathbf{q}|^2$ or $(\mathbf{q}\times\mathbf{P})\cdot\boldsymbol{\sigma}$. The dark matter nucleon scattering happens at higher partial waves ($\ell > 0$) instead of s-wave. This is due to the fact that the dark matter is electrically neutral. Thus, the leading order interaction includes those between the proton electric charge and the dark matter magnetic dipole or two dipoles. In the denominator, we also have a small mass scale $m_{\gamma'}^2 \approx (10\text{–}100\ \mathrm{MeV})^2$, which will compensate for the suppression in the numerator.
- The nucleon part of each term has the form of either $p_h^\dagger p_h$ or $N_h^\dagger \sigma^i N_h$, corresponding to spin-independent and spin-dependent cross sections, respectively. No new form factor is needed for calculating the nuclear-level cross sections.
- The c_3 term does not contribute to the amplitude. The reason is that after nonrelativistic reduction, the corresponding operator results in either $\mathbf{q}\cdot\mathbf{P}$ or $\mathbf{q}\times\mathbf{q}$ and both vanish.

For the scenario when the mirror charged baryon is chosen as the DM candidate, as we will show in Sec. III B, an additional term $c_0 e\bar{\chi}\gamma^\mu\chi A'_\mu$ will be added into Eq. (7). Therefore, in the nonrelativistic limit the operator $\bar{\chi}\chi\bar{p}p$ with zeroth power of $|\mathbf{q}^2|$ will dominate the interaction and it is the conventional SI type interaction.

B. General q-dependent cross sections

The SI differential cross section induced by dark matter nucleon effective interactions is

$$\frac{d\sigma_{\rm SI}}{dE_r} = \varepsilon_\gamma^2 \frac{Z^2 e^4 m_A \mu^2 v^2}{2\pi m_\chi^2 m_{\gamma'}^4}\left[(c_1+c_2)^2\frac{\mu^2}{m_\chi^2}(1-\cos\theta)^2 + c_1^2\sin^2\theta\right]F^2(|\mathbf{q}|), \tag{10}$$

where θ is related to $|\mathbf{q}|^2$ and v via $|\mathbf{q}|^2 = 2\mu^2 v^2(1-\cos\theta)$.

The SD part of differential cross sections is

$$\frac{d\sigma_{\rm SD}}{dE_r} = \frac{m_A|\mathbf{q}|^4}{3\pi v^2 m_{\gamma'}^4}[a_0^2 S_{00}(0) + a_0 a_1 S_{01}(0) + a_1^2 S_{11}(0)] \times \frac{J_A+1}{J_A}\frac{S(|\mathbf{q}|)}{S(0)}. \tag{11}$$

For the SD form factor, we will choose that given in [36],

$$\frac{S(|\mathbf{q}|)}{S(0)} = \exp(-|\mathbf{q}|^2 R_A^2/4), \tag{12}$$

where $R_A = 1.7A^{1/3} - 0.28 - 0.78(A^{1/3} - 3.8 + \sqrt{(A^{1/3}-3.8)^2 + 0.2})$ fm, and $S_{00}(0) = (S_p^A + S_n^A)^2$, $S_{11}(0) = (S_p^A - S_n^A)^2$ and $S_{01}(0) = 2(S_p^A + S_n^A)(S_p^A - S_n^A)$, where $S_N^A \approx 0.5$ ($N = p, n$) or 0 for a nucleus containing odd or even number of nucleons N. The isoscalar and isovector part coefficients are $a_0 = \xi_p + \xi_n$ and $a_1 = \xi_p - \xi_n$, where ξ_N are defined here as

$$\xi_p = \varepsilon_\gamma\left(\frac{e}{2m_p} + \mu_p\right)\mu_\chi, \qquad \xi_n = \varepsilon_\gamma \mu_n \mu_\chi, \tag{13}$$

with $\mu_\chi \equiv c_1 e/m_\chi$. When $\mu_\chi \neq 0$, there are always both SI and SD contributions.

From Eqs. (10) and (11), one can see that the spectral distribution of the cross sections are quite different from the conventional SI and SD interactions, as shown in Fig. 2.

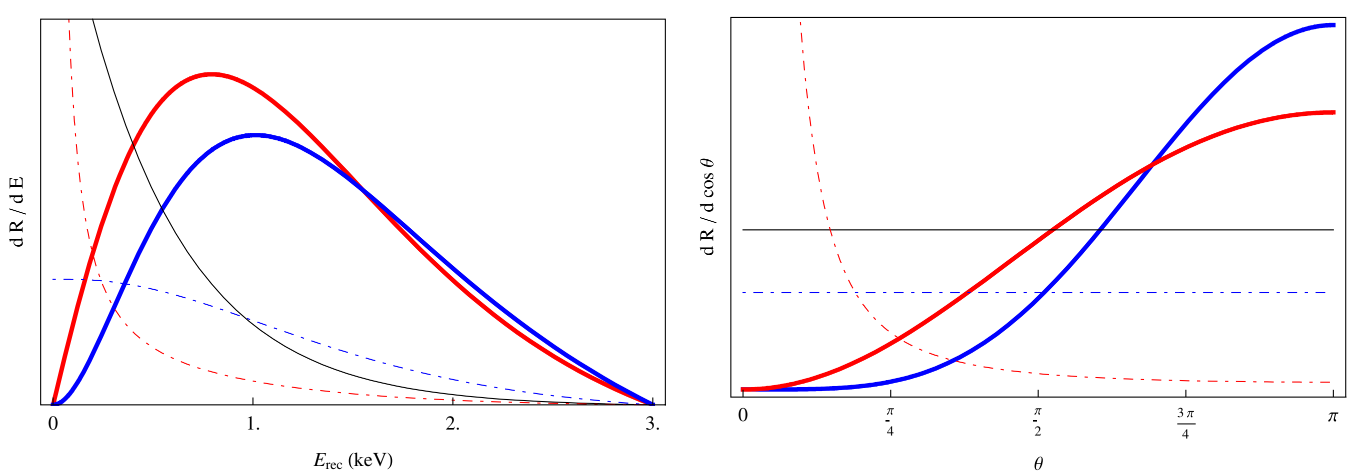

FIG. 2 (color online). These two graphs display the spectral and angular distribution of SI (thick solid lower line) and SD (thick solid upper line) differential cross sections. The dash-dotted upper line (SI) and dash-dotted lower line (SD) represent the special cases when $m_{\gamma'} = 0$, while the thin sold line stands for the conventional SI cross sections. We have chosen dark matter mass to be 5 GeV, $c_2 = 0$ and used an arbitrary scale in making the above plots.

We also plot the SI and SD differential cross sections as a function of the scattering angle θ in the CM frame. This is a distinct feature of the new type of interactions which could be tested in low threshold direction sensitive DM detectors [37].

Before closing this section, we comment that our formulas for the cross sections can be generalized to the case of a dark matter carrying magnetic dipole moment that couples directly to the normal photon in the visible sector as well [33] by simply replacing $\varepsilon_{\gamma'}^2/m_{\gamma'}^4$ with $1/|\mathbf{q}|^4$. In addition, we emphasize that the dimension six operators in Eq. (7) should also be taken into account for completeness.

III. DIRECT DETECTION IN AN ASYMMETRIC DM MODEL

We start this section with a few more details about the asymmetric DM model proposed in [26], in addition to those outlined in the introduction. The particle masses and symmetry breaking in the two sectors are generated via the usual Higgs mechanism. We introduce two Higgs doublets $H_{u,d}^{(\prime)}$ in both sectors obeying Z_2 symmetries so that the up-type fermions only couple to H_u or H_u'; whereas the down-type fermions to H_d or H_d'. This avoids the tree level flavor changing neutral currents. We add soft mirror symmetry breaking terms, which may arise from a mirror symmetric model at high scale via spontaneous symmetry breaking [38]. They allow us to have symmetry breaking patterns in the two sectors different while the interactions and associated coupling constants remain symmetric. This way, one can get the mirror Higgs doublet vacuum expectation values (VEVs) to be larger than those of the SM Higgs. We can also break mirror electric charge while keeping the familiar $U(1)_{\rm em}$ unbroken. In order to implement the inverse seesaw mechanism to give light neutrino masses, we add two $Y = 2$ triplet Higgs fields to both sectors [26] which acquire different vacuum expectation values. The asymmetric symmetry breaking pattern has several consequences:

- The dark sector particles are heavier than the SM particles. Taking the ratio $\tan\beta' \equiv v_u'/v_d' > \tan\beta \equiv v_u/v_d$ and proper parameters value,[2] one can have the mirror neutron as the lightest mirror baryon with mass $\sim$5 GeV, which then becomes the dark matter candidate.
- The mirror sector $U(1)_{\rm em}'$ breaking gives the mirror photon a mass and the kinetic mixing $(\varepsilon_\gamma/2)F^{\mu\nu}F_{\mu\nu}'$ between the two $U(1)$s allows the massive mirror photon to decay into the familiar electron-positron pair. The lifetime of the mirror photon is $\tau_{\gamma'} \approx (50\ {\rm MeV}/m_{\gamma'})(7\times 10^{-11}/\varepsilon_\gamma)^2$ sec. For $m_{\gamma'} = 50$ MeV, $\varepsilon_\gamma > 7\times 10^{-11}$ is needed to avoid the constraints from big bang nucleosynthesis (BBN). QED precision measurements provide constraints on the coupling ε_γ. The most stringent constraint comes from the measurement of the muon magnetic moment, which gives an upper bound $\varepsilon_\gamma^2 < 2\times 10^{-5}(m_{\gamma'}/100\ {\rm MeV})^2$ [39].
- The kinetic mixing between the familiar photon with the mirror photons allows dark matter to directly scatter against nuclei, making direct detection of asymmetric mirror dark matter possible.

[2] In particular, we take $m_u = 2.5$ MeV, $m_d = 5$ MeV, $m_s = 98$ MeV, $\Lambda_{\rm QCD} = 200$ MeV and $v_{\rm wk} = \sqrt{v_u^2 + v_d^2} = 246$ GeV. We also fix $\tan\beta = 50$ in the visible sector, which means $y_t \simeq y_b$. If the lightest mirror baryon mass is chosen to be 5 GeV, different values of $\tan\beta'$ determines $\Lambda_{\rm QCD}'$, $v_{\rm wk}'$ and the identity of DM, see Sec. III A

A. Mirror neutron as DM

As discussed in [26], the mirror neutron can be the lightest mirror baryon state and hence qualified to be the dark matter candidate, provided $\tan\beta'$ lies in the window $100 < \tan\beta' < 233$. Here we will choose $\tan\beta' = 150$ as an example and the mirror neutron mass to be $m_{n'} = 5$ GeV. Correspondingly, the next-to lightest mirror baryon, the mirror proton, has a mass $m_{p'} = 5.7$ GeV and mirror Δ-baryon $m_{\Delta'^-} = 5.8$ GeV, and $\Lambda_{\rm QCD}' = 1.1$ GeV, $v_{\rm wk}' = 210$ TeV.

At low energies, the mirror neutron dark matter interacts with the nucleons in the target via the kinetic mixing between the photon and the mirror photon (of the broken $U(1)_{\rm em}'$) characterized by the parameter ε_γ. The interaction takes the general form as we show in Sec. II A.

The mirror neutron is composed of three mirror quarks with masses higher than the intrinsic scale of mirror strong interaction. To calculate the direct detection rate, one must determine the Wilson coefficients c_1 and c_2 in Eq. (7). They are related to the electromagnetic form factors of the mirror neutron

$$\bar{\chi}(p')\left[F_1(q^2)\gamma^\mu + F_2(q^2)\frac{1}{2m_\chi}i\sigma^{\mu\nu}q_\nu\right]\chi(p)A_\mu'(q), \tag{14}$$

where the mirror electric charge is $F_1(0) = 0$ and

$$F_1'(0) = \frac{c_2}{2m_\chi^2}, \qquad F_2(0) = 2c_1. \tag{15}$$

Therefore the Wilson coefficients c_1 and c_2 are related to the physical quantities of the magnetic dipole moment and the generalized "charge radius" as defined in [40]

$$\mu_\chi = \frac{c_1 e}{m_\chi}, \qquad r_{E\chi}^2 = \frac{3(c_1 + c_2)}{m_\chi^2}. \tag{16}$$

Since the mirror nucleon is a composite particle, we estimate its anomalous magnetic dipole moment by using the naive quark model,

$$\mu_\chi \simeq -\frac{1}{3}\frac{Q_{u'}e}{2m_{u'}} + \frac{4}{3}\frac{Q_{d'}e}{2m_{d'}}, \tag{17}$$

and thereby fix c_1. However, due to the nonperturbative nature, the coefficient c_2 is not easily determined in the same picture. Therefore, in the following numerical discussions, we will take c_2 to be the same order as c_1 as a free parameter. In this case, we can rewrite Eq. (10) for SI interaction in terms of μ_χ

$$\frac{d\sigma_{\rm SI}}{dE_r} = \varepsilon_\gamma^2 \frac{Z^2 e^2 m_A \mu^2 v^2 \mu_\chi^2}{2\pi m_{\gamma'}^4} \times \left[\left(1+\frac{c_2}{c_1}\right)^2 \frac{\mu^2}{m_\chi^2}(1-\cos\theta)^2 + \sin^2\theta\right] F^2(|\mathbf{q}|). \tag{18}$$

1. CoGeNT

The CoGeNT experiment observed possible dark matter event counts between ionization energy 0.4–3.2 keVee [9]. While the excesses around 1–1.5 keVee are attributed to a background component describing the L-shell energy levels associated with electron capture in ^{68}Ge and ^{65}Zn, the first few bins below 1 keVee can be interpreted to arise out of dark matter scattering [35]. To fit the data, we take $m_{\gamma'} = 10$ MeV and $\varepsilon_\gamma^2 = 2\times 10^{-7}$. With a light dark matter mass of 5 GeV, the nuclear form factors are very close to 1 [41] and the upper bound on the recoil energy is only a few keV. The SI and SD contributions to the detection rates are displayed in the left graph in Fig. 3 for different values of c_2, the SI cross section is the dominant contribution. We also show the total rate spectral with different values of c_2 and a quenching factor $Q = 0.3$. As explained before, at very low energy, the event rate tends to vanish instead of increasing exponentially, due to the $\mathbf{q}$-dependent interactions. We find that when taking $c_2 \approx 3.5c_1$, one can fit the experimental data well.

2. DAMA

The DAMA collaboration has reported an annual modulation signal in the scintillation light [6,7]. The scattering of the light dark matter with the sodium nucleus yields 1–10 keVee ionization energy. Because of the relative small $Z = 11$ of the sodium, we find the SD cross section is numerically comparable to the SI counterpart, if $c_2 \simeq c_1$. This is because although the SI contribution is enhanced by a coherent factor Z^2, the SD amplitude merits a nonrelativistic factor $1/(m_\chi m_p)$ rather than $1/(2m_\chi^2)$ thus gaining an extra relative factor of more than $\sim 10^2$ in the cross section. The total detection rate is not very sensitive to the precise value of c_2, as long as c_1 and c_2 are of the same order. To study the annual modulation observed by DAMA, we take the parameter values as $m_{\gamma'} = 10$ MeV and $\varepsilon_\gamma^2 = 0.5\times 10^{-7}$ and choose a quenching factor $Q = 0.45$. The predicted annual modulation amplitude $A(E)$ is shown in Fig. 4.

Clearly, with our choice of parameters, simultaneous fits to both DAMA and CoGENT appears somewhat difficult. Note, however, that due to quantum corrections, the primordial mirror lepton asymmetry could easily be different from the lepton asymmetry in the visible sector. This could easily allow a dark matter mass higher than 5 GeV, which will improve the simultaneous fits. We feel that at this stage, it is premature to get into such detailed phenomenological study.

Second point, we wish to make concerns the recent paper by the Xenon100 collaboration [42], which seems to rule out the light dark matter region favored by CoGENT and DAMA. There appears to be some controversy [43] regarding the results and it is prudent to wait until the situation clears.

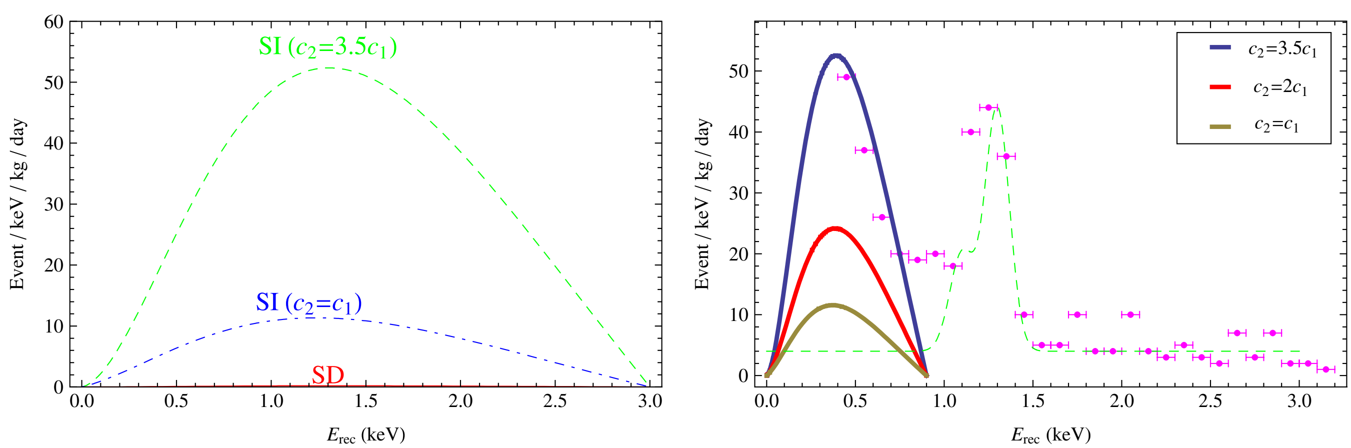

FIG. 3 (color online). The event rate spectral for ^{73}Ge target detector with 5 GeV mirror neutron as the DM. In the left graph, we show the SI and SD contributions separately. In the right panel, we show a fit for the CoGeNT data with different c_2 values. The dashed line represents the Gaussian peaks from the L-shell background component.

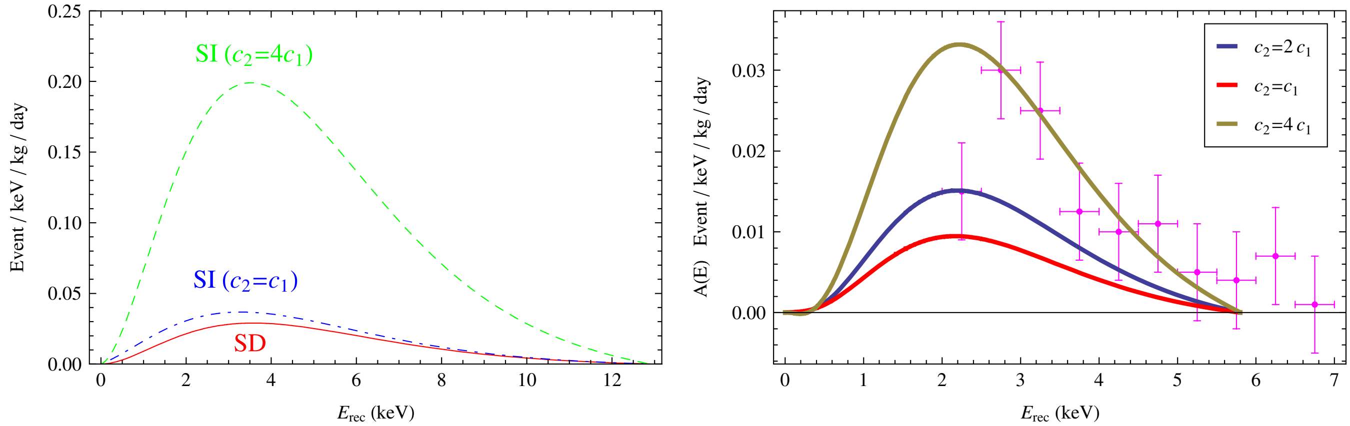

FIG. 4 (color online). The event rate spectral for DAMA and a fit for the annual modulation amplitude $A(E)$.

B. Mirror proton or Δ'-baryon as DM

For small $\tan\beta' < 100$, the mirror proton is lighter than the mirror neutron and will therefore be the dark matter. On the other hand, for very large $\tan\beta' > 233$, the mirror Δ'^{-}-baryon can be the dark matter candidate. In the quark model picture, the mirror neutron n' is composed of $(u'd'd')$, while the mirror Δ'^{-} is composed of $(d'd'd')$. In the large $\tan\beta$ regime, the $m_{d'} < m_{u'}$, so one might naively expect that $m_{\Delta'^-} < m_{n'}$. However, in the QCD where the current quark masses are negligible, there is a mass splitting between the neutron and Δ-baryons, which is about 300 MeV. This mass difference is understood to be due to the hyperfine interaction among the constituent quarks, which is proportional to the baryonic wave function at the origin,

$$m_\Delta - m_n \sim \frac{|\psi_B(0)|^2}{m_q^2} \approx \frac{\Lambda_{\rm QCD}^3}{m_q^2}, \tag{19}$$

where m_q is the constituent quark mass $\sim$300 MeV. For the mirror sector QCD, we can estimate by using a similar expression with the intrinsic scale and quark masses scaled,

$$\frac{m_{\Delta'^-} - m_{n'}}{m_\Delta - m_n} \approx \left(\frac{\Lambda'_{\rm QCD}}{\Lambda_{\rm QCD}}\right)^3 \left(\frac{m_q^2}{m_{u'}m_{d'}}\right), \tag{20}$$

where in contrast $m_{u'}$ and $m_{d'}$ are mirror quark current masses, since they are heavy in the mirror sector. The hyperfine interaction tends to compensate the mass difference due to $m_{u'} > m_{d'}$. Taking $\tan\beta' = 300$ and $m_{\Delta'^-} =$ 5 GeV as the DM, we get $m_{p'} = 9.6$ GeV, $m_{n'} =$ 6.2 GeV, $\Lambda'_{\rm QCD} = 1.2$ GeV and $v'_{\rm wk} = 365$ TeV.

The important point as far as direct detection is concerned is that both the mirror proton p' and the Δ'^{-}-baryon are charged under mirror electromagnetism and the interaction with detector nuclei is not suppressed by $\sim\mathbf{q}^2/m_N^2$. The Lagrangian for the interaction of dark matter with the mirror photon is given by

$$\mathcal{L}' = c_0 e\bar{\chi}\gamma^\mu\chi A'_\mu, \tag{21}$$

where $c_0 = \pm 1$ represents the mirror electric charge of dark matter.

This gives the conventional SI cross section with

$$\sigma_{\rm SI}^0 = \varepsilon_\gamma^2 \frac{Z^2 c_0^2 e^4 \mu^2}{\pi m_{\gamma'}^4}. \tag{22}$$

Taking a model-allowed value $\varepsilon_\gamma = 6 \times 10^{-8}(m_{\gamma'}/50\ {\rm MeV})^2$, one can obtain the cross section per nucleon $\sigma_{\chi N} \simeq \sigma_{\rm SI}^0 \mu_{\chi N}^2/(\mu_{\chi A}^2 A^2) \simeq 7 \times 10^{-41}\ {\rm cm}^2$, which is required to account for the events observed by the CoGeNT collaboration.

IV. SUMMARY

To summarize, we have presented a general operator analysis of an asymmetric dark matter interacting with nucleons via a mirror photon and applied it to an asymmetric mirror dark matter model suggested by four of us in a previous paper. We note that when the dark matter is neutral under dark electromagnetic forces (zero mirror electric charge), e.g., mirror neutron, it interacts with nucleons via the mirror magnetic dipole moment and electric charge radius. In this case, there is an energy dependence in the direct detection cross section as well as an angular dependence different from the usual massive symmetric WIMP case [e.g., supersymmetry (SUSY) case]. As the sensitivities of dark matter searches improve, one can use these results to pinpoint the detailed nature of dark matter interaction with matter.

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