Detecting Dipolar Dark Matter in Beam Dump Experiments

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Abstract

We study interaction of low mass dark matter within beam dump experiments. In particular we study the dipolar dark matter model which assumes that the dark matter couples to Standard Model particles via its electric or magnetic dipole moment. We analyse the constraints on this model in the context of a particular beam dump experiment E613 conducted in the Fermilab. We find that dark matter mass in the range of \( 1 - 10 \) GeV with a magnetic dipole moment between \((0.33 - 1.5) \times 10^{-7} \mu_B\) and a electric dipole moment between \((0.5 - 3) \times 10^{-17}\) e-cm. We compare the bounds from other experimental data, such as helioseismological data and direct detection experiments.
I. INTRODUCTION

Evidence from galactic rotation curves as well as bullet cluster collisions have strongly suggested the existence of dark matter (DM). However, the nature of DM is unknown. In theory there exist many candidates for DM, the most popular of them being the case of weakly interacting massive particle (WIMP). The WIMP scenario is realized in many models, with neutralino in supersymmetric theories being the most well studied of them. However, there also exists the possibility of DM interacting electromagnetically with Standard Model (SM) particles\[1–10\]. We refer to this model of DM interactions as dipolar DM model.

The dipolar DM model assumes that dark matter couples to photons through loops to give rise to electric and magnetic dipole moments. Here we study the case in which DM particles are Dirac fermions. The effective Lagrangian for such a DM particle interacting with an electromagnetic field ($F_{\mu\nu}$) through its electric dipole moment ($D$) and magnetic dipole moment ($\mu$) is

$$L_{ddm} = -\frac{i}{2} \bar{\chi} \sigma_{\mu\nu} (\mu + \gamma^5 D) F^{\mu\nu} \tag{1}$$

Here we consider this particular scenario in the context of DM detection in so-called beam dump experiments also known as fixed target experiments. Complimenting the searches from direct and indirect detection experiments, beam dump experiments feature a high energy beam incident on a fixed target. The DM particles produced from this collision are then detected in a suitable detector. In this work we particularly focus on the E613 experiment at Fermilab in which a 400 GeV proton beam is incident on a tungsten target with the resultant DM produced from the annihilation of beam proton and target proton being detected in a lead detector after passing through iron shielding. The advantage over direct detection in such experiments is that of higher luminosity. But the reach of such experiments and in particular of E613 is restricted to low mass DM due to the kinematics of fixed target experiments. Future experiments like the new fixed target facility proposed at the CERN SPS called SHiP (Search for Hidden Particles) \[11\] can explore this possibility. The possibility of DM detection at beam dump experiments has been studied in the case of light mediators in the dark sector mediating DM interactions with SM particles \[12, 13\] and also in the case of $Z'$ as the mediating particle \[14\]. More recently a similar model with dark vector boson was studied in the context of E613 \[15\]. We follow the approach in \[15\] and study the constraints on the dipolar DM model from E613.

The paper is organized as follows: In section 2 we describe the method for calculating the production cross section of dipolar DM when the 400 GeV proton beam strikes the tungsten target. In section 3 we describe the deep inelastic scattering that takes place between the DM and the lead target nuclei. In section 4 we give the results from analysing the dipolar DM in the case of E613 and compare constraints from other experiments. Finally we conclude in section 5.

II. DIPOLAR DM PRODUCTION IN E613

Here we follow the procedure outlined in \[15\]. In a beam dump experiment like E613, DM particles are produced through t-channel annihilation process from constituent quarks of protons in the beam and the target nucleus. In case of the E613 we have a 400 GeV proton beam striking a tungsten target. The DM particles are produced from the process,
$pp \rightarrow \bar{\chi}\chi + X$. The cross section for this hard process is calculated by incorporating the Lagrangian in eq. (1) into MADGRAPH 5 [18] using FEYNRULES [19]. The number of $\chi$’s produced is then given by

$$\frac{dN}{dE d\theta} = n_t N_{beam} L_t \frac{d\sigma(pp \rightarrow \bar{\chi}\chi)}{dE d\theta}$$  \hspace{1cm} (2)$$

where $n_t$ is the number density of nucleons inside the tungsten target, $N_{beam}$ is the number of protons in the beam that are incident on the tungsten target and $L_t$ is the length of the tungsten target. The geometry of the E613 detector is such that only those DM particles are accepted for which the scattering angle $\theta < 0.0134$ [15]. This is a conservative limit on the scattering angle compared to the detector acceptance in the original experiment where $\theta < 0.037$. Thus we integrate eq. (2) for $0 < \theta < 0.0134$ to obtain DM distribution $dN/dE$.

### III. DEEP INELASTIC SCATTERING OF DIPOLAR DM

Following [15] we place an energy cut of 20 GeV as the minimum energy required to register an event in the detector. Now in order to find the number of events we need to find scattering cross section of the DM produced in the experiment with the detector nuclei, having energy $E_\chi$ where $E_\chi > 20$ GeV. Since these DM particles are produced in a collision with CM energy of 400 GeV, their scattering off the lead nuclei in the detector is deeply inelastic. The energetic DM particle therefore undergoes a deep inelastic scattering with the lead nucleus inside the detector via photon exchange. The DM couples to the photon through its electric/magnetic dipole moment. The initial DM momentum before scattering being $k$ while that after scattering being $k'$ the momentum transfer carried by the photon is $q = k - k'$. Now using the formalism of deep inelastic scattering of leptons we define the Bjorken scaling variable $x = \frac{Q^2}{2m_N \nu}$, with $Q^2 = -q^2$ and $\nu$ being the energy of the photon in the rest frame of the nucleus. With this the differential scattering cross section in terms of leptonic matrix element $L^{\mu\nu}$ and hadronic matrix element $W^{\mu\nu}$ is given by

$$\frac{d\sigma}{d\nu dQ^2} = \frac{e^2 g_{dipole}^2}{16\pi m_N (E_\chi^2 - m_\chi^2)} \frac{L^{\mu\nu} W^{\mu\nu}}{Q^4}$$  \hspace{1cm} (3)$$

where $g_{dipole} = \mu$, with $\mu$ being the magnetic dipole moment of DM and for DM interacting via the electric dipole moment, $g_{dipole} = D$.

Now the leptonic current for the magnetic dipole moment interaction of DM corresponding to the Lagrangian in eq. (1) is

$$L^{\mu\nu} = Q^2 [4 k^{\mu} k^{\nu} - 2 (k^{\mu} q^{\nu} + q^{\mu} k^{\nu}) + q^{\mu} q^{\nu}] - 4m_\chi^2 (Q^2 g^{\mu\nu} + q^{\mu} q^{\nu})$$  \hspace{1cm} (4)$$

And similarly for the electric dipole moment interaction we have

$$L^{\mu\nu} = Q^2 [4 k^{\mu} k^{\nu} - 2 (k^{\mu} q^{\nu} + q^{\mu} k^{\nu}) + q^{\mu} q^{\nu}]$$  \hspace{1cm} (5)$$

The hadronic matrix element $W^{\mu\nu}$ can be written in terms of structure functions such that we separate out contributions from longitudinally polarized photons and transversely polarized photons as [15].
\[ W_{\mu\nu} = \left( -g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2} + 2xa_{\mu\nu} \right) F_T(x, Q^2) + a_{\mu\nu} F_L(x, Q^2) \]  
(6)

where

\[ a_{\mu\nu} = \frac{1}{p \cdot q + 2xm_\chi^2} \left( p_\mu - \frac{p \cdot q}{q^2} q_\mu \right) \left( p_\nu - \frac{p \cdot q}{q^2} q_\nu \right) \]  
(7)

At the lowest order in perturbation theory the structure function \( F_L = 0 \) while \( F_T = \frac{1}{2x} \sum_q xf(x, Q^2) \).

Contracting the leptonic and hadronic tensors in eqs. (4) and (6) we have for the magnetic dipole interaction

\[ d\sigma = \frac{e^2 \mu^2}{16\pi} \frac{d\nu dQ^2}{E^2 - m_\chi^2} \frac{\nu}{Q^4} \left[ \frac{Q^2 (2E - \nu)^2}{\nu^2 + Q^2} - Q^2 + 4m_\chi^2 \right] \sum_q x f_{q/A}(x, Q^2) \]  
(8)

Similarly for the electric dipole interaction we have

\[ d\sigma = \frac{e^2 D^2}{16\pi} \frac{d\nu dQ^2}{E^2 - m_\chi^2} \frac{\nu}{Q^4} \left[ \frac{Q^2 (2E - \nu)^2}{\nu^2 + Q^2} - Q^2 - 4m_\chi^2 \right] \sum_q x f_{q/A}(x, Q^2) \]  
(9)

For the nuclear parton distribution functions we use those provided by Hirai et al. [20]. The above expression when integrated over \( \nu \) and \( Q^2 \) gives the cross section for scattering of DM with nucleon inside the target. The limits of integration are as follows:

\[ E_{\text{cut}} < \nu < E - m_\chi \]  
(10)

\[ Q_1^2 < Q^2 < 4(k^2 - E\nu) - Q_1^2 \]  
(11)

where \( Q_1^2 = \frac{2m_\chi^2 \nu^2}{k^2 - E\nu \pm \sqrt{(k^2 - E\nu)^2 - m_\chi^2 \nu^2}} \) with \( k^2 = E^2 - m_\chi^2 \).

In addition to the above limits one also has the upper limit \( x < 1 \) which translates to \( Q^2 < 2m_N\nu \). From the cross section so obtained we can now write the mean free path of the DM particle as

\[ \lambda = \frac{1}{\rho \sigma(\chi N \rightarrow \chi N)} \]  
(12)

where \( \rho \) is the number density of the nucleon inside the target material and \( \sigma \) is the scattering cross section of DM from a nucleon. The probability of a DM particle scattering inside the detector is then given by \( P = 1 - e^{-L/\lambda} \) and for a DM particle that behaves like a WIMP interacting through a weak dipole moment we can use the approximation \( P \sim L/\lambda \).

Finally the number of expected events in the detector is

\[ N_{\text{ev}} = \int dE \left[ P_{\text{Pb}}(1 - P_{\text{Fe}}) \right] \frac{dN}{dE} \]  
(13)

where \( P_{\text{Pb}} \) is the probability of DM scattering inside the lead detector and \( P_{\text{Fe}} \) is that inside the iron shielding.
FIG. 1: Left panel shows allowed parameter space (unshaded region) for electric dipole moment of DM in the $m_\chi - D$ plane while right panel shows allowed parameter space for magnetic dipole moment of DM in the $m_\chi - \mu$ plane.

IV. CONSTRAINTS ON DIPOLAR DM FROM BEAM DUMP (E613) AND OTHER EXPERIMENTS

From the number of events calculated using eq. (13), we constrain the magnetic and electric dipole moments of DM in the DM mass range of $1 - 10$ GeV. We use the interpretation in [21] also used in [15] of the experimental data in [16, 17]. We allow only those values of $m_\chi$ and $\mu, D$ for which the number of expected events is < 180. The results for electric and magnetic dipole interactions of DM are shown in Fig. 1. We have also added the bound from L3 experiment at LEP on the magnetic moment of DM [22]. The bounds on electric and magnetic dipole moments of DM from the analysis of L3 experiment are $< 1.8 \times 10^{-17}$ e-cm or equivalently $< 3.3 \times 10^{-8} \mu_B$. We see from the figure that for electric dipole interaction of DM the allowed DM mass ranges between $1 - 3$ GeV, however for the magnetic dipole case the DM mass lies between $1 - 8$ GeV. In addition to the bound from L3 collaboration at LEP, recently constraints from solar physics on dipolar DM and similar models have also been studied [23–25]. In [26] the bound on magnetic dipole moment of DM from helioseismological data is estimated to be $1.6 \times 10^{-17}$ e-cm, for DM mass $< 4.3$ GeV, which is quite similar to the bound from L3 collaboration. Also for momentum and/or velocity dependent scattering of DM studied in [23, 25] which is relevant for dipolar DM model since it also has momentum and velocity dependence, the most favorable DM mass is found to be $\sim 3$ GeV. Thus we see that the constraints from beam dump experiments are in broad agreement with those from solar physics. Also the most stringent bounds from direct detection currently come from LUX collaboration [27], however this bound is considerably weak for low mass DM particularly in the $1 - 10$ GeV range. As a result this bound is inconsequential for the results presented here.

V. CONCLUSIONS

We study the Dipolar DM model in the context of E613 beam dump experiment. We see that the constraint on electric and magnetic dipole interactions of DM from E613 experiment for light DM in the $1 - 10$ GeV mass range is quite stringent. It is restricted in that mass range
mainly by the bound on magnetic dipole moment from the L3 collaboration at \( < 1.8 \times 10^{-17} \) e·cm or \( 3.3 \times 10^{-8} \mu_B \). Bounds from solar physics data are also broadly compatible with this mass range and dipole moment. Thus the dipolar model of DM offers an alternative that is compatible with constraints from wide ranging experiments like beam dump or fixed target experiments as well as helioseismological data. In addition the low mass range of DM enables it to be compatible with the most stringent direct detection bounds from LUX\[27\].
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