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Self-interacting dark matter without direct detection constraints

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ABSTRACT

We explore the self-interacting dark matter scenario in a simple dark sector model where the dark matter interacts through a dark photon. Splitting a Dirac fermion dark matter into two levels using a small Majorana mass can evade strong direct detection constraints on the kinetic mixing between the dark and normal photons, thus allowing the dark sector to be more visible at high intensity and/or high energy experiments. It is pointed out that such a mass splitting has a strong impact on the dark matter self-interaction strength. We derive the new parameter space of a pseudo-Dirac self-interacting dark matter. Interestingly, with increasing mass splitting, a weak scale dark matter mass window survives that could be probed by the LHC and future colliders.

1. Introduction

In spite of the well established evidence for its existence in the universe, the nature of dark matter remains elusive. At present, most of the survived hints for particular properties of dark matter seem to come from the cosmological and astrophysical side. In the case the dark matter or part of it has a particle physics origin, it would be of great importance to probe the theory behind in the laboratories, just like probing the other known particles.

In this paper, we focus on a very simple setup where the dark matter is a fermion charged under a dark $U(1)$ gauge symmetry and its interactions are mediated by a massive vector gauge boson (dark photon)—a massive dark QED model. Both the dark matter and the dark photon are singlets under the standard model gauge symmetries. The dark sector communicates with the standard model sector through the kinetic mixing term between the dark photon and the normal photon. Th model is very simple and allows one to do concrete calculations of many observable quantities about the dark matter. Over the recent years, it has been extensively studied in the literature for understanding various phenomena and experimental hints of dark matter, from the underground to the cosmos [1–5]. It also serves as an alternative to the supersymmetric WIMP paradigm and can accommodate much more freedom in the relative importance of direct and indirect detections [6]. More recently, it has been shown that the "long" range force nature due to a light dark photon exchange enables the dark matter to have large enough self-scattering cross section [7–12] to be a self-interacting dark matter (SIDM) candidate [13]. This allows it to provide an explanation to a few puzzles in the small scale structure formation such as the dwarf galaxy core/cusp and too-big-to-fail problems [14]. Moreover, the experimental impact of the photon–dark-photon kinetic mixing has received tremendous interests. Currently, an industry has formed utilizing the existing or building novel experiments to look for light and weakly-coupled new particles [15,16].

The goal of our work is the following. We will explore the possibility of having sizable dark matter self-interaction and at the same time having a sizable photon–dark-photon kinetic mixing so as to make the dark sector accessible to the laboratories. In other words, we want to ask the questions how visible a SIDM candidate can be, and if visible enough what are the leading experimental channels for probing it.

Before proceeding, we find a couple of clarifications of our motivation necessary. First, although SIDM is quite an attractive scenario offering special correlations between the dark matter and dark photon masses (especially when many other dark matter anomalies have faded away these days), there are still ongoing debates about to what extent the self-interaction is needed as the solution to the small-scale structure problems. See, *e.g.*, [17], which simply resorts to baryonic physics. The fate of SIDM will eventually be dictated by more precise observations and simulations of dwarf galaxy formation. In this work, we would like to keep an open mind and consider a very wide range of dark matter self-interaction cross sections, instead of just the most preferred value for SIDM. We expect our results to be more useful this way. Second, one might argue that the laboratory detection of SIDM is not guaranteed, because setting the photon–dark-photon kinetic mixing parameter to zero does not upset the SIDM picture which involves only the dark sector interactions. There is nothing wrong with this argument. However, if it were the case, the dark sector would be totally decoupled from the standard model sector, and

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the only hope to further explore the nature of dark matter would be through astrophysical observations (see, *e.g.*, [18]). This is not the direction we would like to go here.

For a pure-Dirac fermion dark matter, shortly after the parameter space of SIDM was obtained, it was pointed out that if the dark matter mass lies above a few GeV, direct detection experiments place by far the strongest upper bound on the kinetic mixing parameter [19,20], largely due to the small dark photon mass ($\lesssim$100 MeV) required by SIDM. For a (sub-)GeV scale SIDM, the direct detection limits are weaker and the low-energy high-intensity searches for dark photon and/or dark matter become more important. In this region, it has been pointed out that with a sufficiently large dark gauge coupling, the *B*-factories play the leading role in probing the SIDM [21].

On the other hand, because the dark photon is already massive in the model, it is allowed to introduce a Majorana mass term to the dark matter. If the Majorana mass is much smaller than the Dirac mass, the dark matter becomes pseudo-Dirac, *i.e.*, the physical states are two Majorana particles with a small mass splitting of order the Majorana mass. Assuming dark matter particles are all in the lighter state, the scattering of dark matter on nucleus target via a dark photon exchange at tree level has to convert it to the heavier state. If this mass splitting is much larger than the typical incoming kinetic energy in the center-of-mass frame, the up-scattering process simply cannot happen and the strong direct detection constraints are evaded. At the same time, one has to worry what will happen to the SIDM in the presence of such a mass splitting. Naively, the dark matter self scattering with a tree-level dark photon exchange will also become up scattering from two lighter states to two heavier ones. If the kinetic energy is not large enough to compensate for the splitting, one may have to go to the next order and consider elastic scattering with two dark photon exchange (a box diagram, see below). If this were the case, the expected self-interaction cross section would be much smaller than that for a pure-Dirac dark matter.

As the main result of this work, our calculation reveals another key quantity, $\alpha_D^2 m_D$, where α_D is the dark fine-structure constant and m_D is the dark matter mass. Unlike the direct detection process, the dark matter particle could gain a potential energy as large as $\alpha_D^2 m_D$ during the low velocity ($v \ll \alpha_D$) self-scattering process. We find that if the available potential energy is large enough to compensate for the mass splitting, the up-scattering process becomes kinematically allowed within the potential well. In this case, the self-interaction cross section for a pseudo-Dirac fermion dark matter is not suppressed and remains comparable to the pure-Dirac fermion case. If we further increase the mass splitting beyond $\alpha_D^2 m_D$, the quantum mechanical effect stops being effective. As a result, the up-scattering is forbidden everywhere and the dark matter self-interaction potential becomes genuinely loop suppressed. To maintain as large self scattering cross section, one must resort to much smaller dark photon mass. Based on these observations, we derive the new parameter space for a pseudo-Dirac SIDM.

This paper is organized as follows. In Section 2 we introduce the massive dark QED model and discuss the role of adding a small Majorana mass to the dark matter in avoiding the strong direct detection constraints. In Sections 3–5, we describe our method of calculating the dark matter elastic self-scattering cross section at low velocities, taking into account of the non-perturbative effects. Our numerical results are presented in Section 6. We will conclude and outline several possible channels for probing the pseudo-Dirac SIDM in the future, in particular at high energy and intensity collider experiments.

We note that the dark matter self-interaction in the presence of mass splitting has been explored in [22], but their discussion focused on very small mass splitting less than ~10 keV. In that case the inelastic scattering of dark matter in direct detection is still kinematically allowed and the constraints on the kinetic mixing parameter remain very strong. The impact of the mass splitting Δm is less significant than what we shall show below.

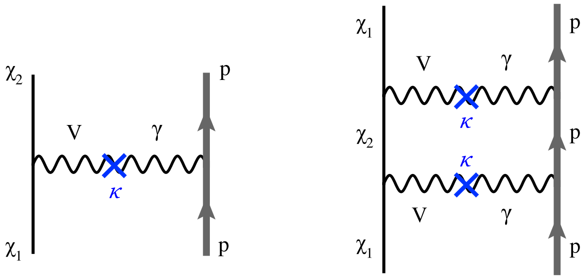

Fig. 1. Diagrams for dark matter direct detection. The loop diagram with crossed dark photon propagators is not shown.

2. Model

The Lagrangian for the massive dark QED model is

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar\chi i\gamma^\mu(\partial_\mu - i g_D V_\mu)\chi - m_D\bar\chi\chi - \frac{\Delta m}{4}\bar\chi^c\chi - \frac{\Delta m}{4}\bar\chi\chi^c - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu}\,, \qquad (1)$$

where in the limit $\Delta m = 0$ the Dirac fermion χ is the dark matter field, V_μ is the dark photon, g_D is the dark gauge coupling ($\alpha_D = g_D^2/(4\pi)$ will be the dark fine-structure constant) and κ is the kinetic mixing between the photon and the vector field V. The $U(1)$ kinetic mixing term can be removed at the price of redefining the photon field $A_\mu \to A_\mu + \kappa V_\mu$. This will result in an effective coupling between the dark photon and the usual electromagnetic current (made of standard model particles), $\kappa e J^\mu_{\rm em} V_\mu$.

Turning on the Majorana mass Δm will split χ into two Majorana fermion mass eigenstates,

$$\chi_1 = \frac{i}{\sqrt{2}}(\chi - \chi^c), \qquad \chi_2 = \frac{1}{\sqrt{2}}(\chi + \chi^c),$$
$$m_{1,2} = m_D \mp \frac{1}{2}\Delta m \qquad (2)$$

where χ^c is the charge-conjugation of χ field. Throughout the paper we assume that all the dark matter today are in the lighter state χ_1. We also assume that Δm is real and much smaller than the Dirac mass m_D. The dark gauge interaction vertex becomes off-diagonal with respect to χ_1 and χ_2

$$\mathcal{L}_{\rm int} = \frac{i}{2} g_D \bar\chi_2 \gamma^\mu \chi_1 V_\mu + {\rm h.c.} \qquad (3)$$

As a result, the tree level scattering of dark matter χ_1 on the proton target will convert it into the heavier state χ_2 (Fig. 1). Near the earth, the dark matter velocity distribution is peaked at $\sim 10^{-3}c$. Therefore, for most targets the typical kinetic energy in the dark matter-nucleus system is at most a few hundred keV. If the $\chi_1 - \chi_2$ mass difference Δm is greater than an MeV, the up-scattering process $\chi_1 p \to \chi_2 p$ is kinematically forbidden and the tree-level direct detection constraint is simply evaded. At next order, one could consider elastic scattering $\chi_1 p \to \chi_1 p$ happening at loop level with two dark photon exchange (see right plot of Fig. 1), but that will cost an additional power of $(\kappa\alpha\alpha_D)$ as well as the loop factor in the amplitude. Given the existing upper limit on κ (see Fig. 4 in Ref. [16]), such a contribution cannot lead to a competitive constraint.

Adding a Majorana dark matter mass will also generate a contribution to the dark photon mass at loop level, which is of order