Direct detection prospects of dark vectors with xenon-based dark matter experiments

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Dark matter experiments primarily search for the scattering of WIMPs on target nuclei of well shielded underground detectors. The results from liquid scintillator experiments furthermore provide precise probes of very light and very weakly coupled particles that may be absorbed by electrons. In these proceedings we summarize previously obtained constraints on long-lived dark matter vector particles V (dark photons) in the $0.01 - 100$ keV mass range. In addition, we provide a first projected sensitivity reach for the upcoming XENON1T dark matter search to detect dark photons.

arXiv:1510.04530v2 [hep-ph] 16 Oct 2015

1. Introduction

The particle nature of Dark Matter (DM) is poorly understood and the range of theoretical possibilities remains wide open. There are high expectations that new physics exists at or near the electroweak scale, for which a weakly interacting massive particle (WIMP) becomes a viable DM option. Models of this type typically predict a significant scattering rate for WIMPs in the galactic halo on nuclei, when up to 100 keV of WIMP kinetic energy can be transferred to atoms. Such direct detection searches present a rapidly growing field and particularly significant gains in sensitivity are to be expected with upcoming ton-scale experiments [1, 2].

However, WIMPs are not the only possibility. Dark matter could be in form of super-weakly interacting particles with masses well below the electroweak scale. A prominent example of this type is the QCD axion. Another example is that of a massive vector particle that kinetically mixes with the Standard Model (SM) hypercharge field strength, often referred to as "dark photon". Such forms of DM are harder to detect directly, as the couplings to the SM are usually smaller than those of WIMPs by many orders of magnitude.

The phenomenology of keV-mass vector particles was first considered in [5, 6], where in [5] the sensitivity of liquid xenon experiments to keV-mass vector particles with couplings of $O(10^{-10})$ and below was pointed out. Recently, this has been explored in greater detail in [7, 8] and here we summarize the findings of [8] which derive the leading limits to date on dark photon dark matter in the mass window of 10 eV to several hundreds of keV. In addition, we also provide a first sensitivity projection for the future XENON1T experiment.

2. Dark photon dark matter

A technically natural extension of the SM is a new Abelian $U(1)'$ massive vector field that is coupled to SM hypercharge $U(1)$ through kinetic mixing [3, 4]. For phenomena with involved energies well below the electroweak scale, the mixing with the photon is the most important,

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{em}^\mu A_\mu. \tag{2.1}$$

The effective parameter κ controls the coupling between the dark photon (V) and photon (A) with respective field strengths $V_{\mu\nu}$ and $F_{\mu\nu}$; J_{em}^μ is the electromagnetic current and m_V is the dark photon mass. In the following, m_V is assumed to added by hand (Stückelberg mass), rather than being induced via a Higgs mechanism. The search for dark photons has become a significant effort, and it defines one of the prime targets of intensity frontier experiments, see, *e.g.*, [9] and references therein.

The cosmological abundance of V with $m_V < 2m_e$ receives various contributions in the early Universe, such as production through scattering or annihilation, $\gamma e^\pm \to Ve^\pm$ and $e^+e^- \to V\gamma$. If dark photons are to be dark matter, it turns out that the thermal production is not sufficient to generate the correct relic abundance in the mass window of interest. However, dark photon dark matter remains possible when the relic density receives contributions from inflationary perturbations. Even in absence of any initial misalignment, the gravitational production of V can account

for the observed dark matter density in longitudinal modes [10],

$$\Omega_V \sim 0.3 \sqrt{\frac{m_V}{1\,\text{keV}}} \left(\frac{H_{\text{inf}}}{10^{12}\,\text{GeV}} \right). \tag{2.2}$$

For keV vector particles, the relic density requirement then points to an inflationary Hubble scale, H_{inf}, in the $10^{12}\,\text{GeV}$ ballpark. In the following we assume that dark matter is made from dark photons and the galactic distribution is smooth and neglect any effects from substructure.

3. Absorption in liquid xenon experiments

Galactic dark photon dark matter can induce ionization of xenon atoms in the encounter with the detector when their mass exceeds the binding energy of electrons of the outermost atomic shell, $m_V \simeq E_V \gtrsim 12\,\text{eV}$,

$$\text{Xe I} + V \to \text{Xe II} + e^-. \tag{3.1}$$

It is of course possible that multiple electrons are produced in the absorption. The electron multiplicity is of great importance when seeking the discrimination of a potential dark photon signal from other electromagnetic backgrounds. For the purpose of setting conservative constraints, however, we are allowed to neglect such complications [12, 8] but note the improvement potential for future studies.

At non-relativistic relative velocities the distinction between longitudinal and transverse modes disappears and that the polarization state of V is inconsequential. It also turns out that matter effects in liquid xenon are of little importance when considering the absorption (3.1); the vacuum mixing angle κ times the electric charge e controls the coupling to electrons and hence the rate of ionization. Restricting our attention to electric dipole (E1) transitions provides a reasonably good approximation to the absorption cross section [5],

$$\sigma_V(E_V = m_V)v_V \simeq \kappa^2 \sigma_\gamma(\omega = m_V)c, \tag{3.2}$$

where v_V is the velocity of the incoming DM particle, σ_γ is the ordinary photon ionization cross section, and ω is the photon energy. Improvements to the estimate (3.2) are possible through atomic theory calculations; for the case of axion-like DM, these have already been performed [11]. The expression (3.2) is nearly independent of the dark photon velocity, with the consequence that the possibly intricate DM velocity distribution is of almost no importance; this is in stark contrast to the case of elastic scattering of electroweak-mass dark matter on nuclei. In our numerical calculations, we employ the optical theorem which includes matter effects (for a derivation see the original works [12, 8].) The total absorption rate of non-relativistic dark photons with keV-masses in the lab-frame of the detector is then given by [12, 8],

$$\Gamma \simeq \kappa^2 \omega \times \text{Im}\, n_{\text{refr}}^2 = \kappa^2 \sigma_\gamma \times \left(\frac{N_{\text{at}}}{V} \right), \tag{3.3}$$

Here, n_{refr} is the (complex) refractive index of liquid xenon which we obtain from tabulated atomic scattering data [13]; N_{at} is the number of target nuclei in the fiducial detector volume V.

The ensuing limits using the results from the XENON10 and XENON100 experiments are shown in Fig. 1. The XENON10 limit is obtained from the number of detected electrons in a
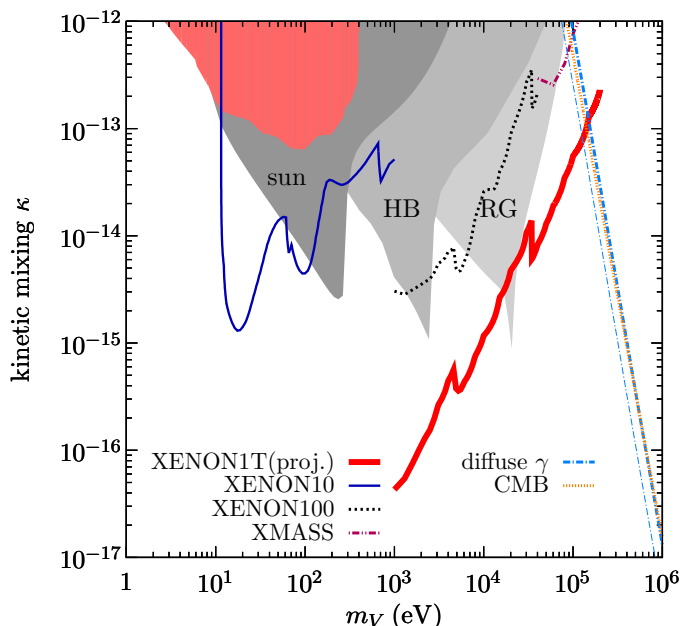
Figure 1: A summary of constraints on the dark photon kinetic mixing parameter κ as a function of vector mass m_V. The regions above the thin lines are excluded for dark photon dark matter. Shaded regions are astrophysical limits that are independent of the dark photon relic density; see [12, 8] for details. The thick red line is a projected sensitivity curve for the upcoming XENON1T experiment (see main text for details.)

relatively small data set with 15 kg-days exposure; similar ionization-only analyses were previously performed to constrain WIMP-electron scattering [14, 15]. The XENON100 limit is obtained from the scintillation signal S1 with an exposure of 224.6 live days and an active target mass of 34 kg liquid xenon [16]. Finally, the XMASS limit is taken from [17]. In addition to the direct laboratory limits, dark photon dark matter with $m_V \gtrsim 100$ keV is constrained by observations of the diffuse γ-ray flux from $V \to 3\gamma$ decays as well as by energy injection during recombination (CMB). All these limits, together with the astrophysical constraints that are independent of the dark photon relic density are described in detail in [8].

We expect that the sensitivity to the kinetic mixing below 1 keV will be further improved by the upcoming ionization-only analyses from XENON100. The XENON1T project, currently under final integration with ultra-low radioactive materials and self-shielding with volume fiducialization, is expected to reduce the electron recoil background by two orders of magnitude compared to that of XENON100. The electron recoil background of XENON1T in the one-ton fiducial volume is mostly from solar neutrinos, ^{85}Kr, ^{222}Rn and material radioactivities below 25 keV and from ^{136}Xe above 25 keV and up to 200 keV [18]. The background spectrum shape is almost flat and feature-less, in contrast to a energy peak at position m_V from dark photon absorption. Following the calculation for the XENON100 limit [8], we derive the projected sensitivity of XENON1T for a dark photon mass above 1 keV, shown in Fig. 1. The simulated background of the XENON1T detector used in the derivation is from Ref. [18], and the energy resolution is assumed to be the same as that in XENON100 as shown in Ref. [19]. In this analysis, we assume the detection efficiency to be 100% down to 1 keV. The sensitivity for dark photon masses below 1 keV depends on the

energy threshold of scintillation light and the rate of ionization-only events, which will be available once the experiment starts operating.

4. Conclusions

The model of light, kinetically mixed hidden vector particles with Stückelberg mass is particularly simple and owing to its UV-completeness, well-motivated. These proceedings summarize the results on dark photon dark matter that some of us have obtained in [8]. In addition, we provide an update that shows the potential sensitivity gain with ton-scale direct detection experiments focusing on the example of XENON1T. Making reasonable assumptions on the expected background rates, more than an order of magnitude improvement on the limit of the kinetic mixing parameter κ is possible, constraining electron-dark photon effective couplings that correspond to a dark fine-structure constant as small as $\alpha_{\text{dark}} = \kappa^2 \alpha \sim 10^{-35}$.

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