Constraining Dark Matter Models with a Light Mediator from PandaX-II Experiment

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We search for nuclear recoil signals of dark matter models with a light mediator in PandaX-II, a direct detection experiment in China Jinping underground Laboratory. Using data collected in 2016 and 2017 runs, corresponding to a total exposure of 54 ton day, we set upper limits on the zero-momentum dark matter-nucleon cross section. These limits have a strong dependence on the mediator mass when it is comparable to or below the typical momentum transfer. We apply our results to constrain self-interacting dark matter models with a light mediator mixing with standard model particles, and set strong limits on the model parameter space for the dark matter mass ranging from 5 GeV to 10 TeV.

The existence of dark matter (DM) is supported by a wide range of observations in astronomy and cosmology, but its particle nature remains elusive. Leading candidates such as weakly interacting massive particles (WIMPs) [1] that could explain the observed cosmological DM abundance, have been actively searched for in indirect and direct detection experiments, as well as at the Large Hadron Collider. The direct WIMP searches often assume a point-like contact interaction between the DM candidate and the nucleus, since the momentum transfer in nuclear recoils is much smaller than the weak-scale mediator mass. However, this assumption breaks down if the DM-nucleus interaction is mediated by a force carrier that has a mass comparable to or lighter than the momentum transfer [2,7].

Dark matter models with a light mediator are well-motivated. For example, in many hidden-sector DM models [8–12], DM particles annihilate to the light mediator to achieve the observed abundance. It can induce an attractive potential between two DM particles and boost the annihilation cross section [13,14]. Furthermore, it has been shown the self-interacting DM (SIDM) model with a light mediator can explain observed stellar kinematics from dwarf galaxies to galaxy clusters [15,16], a challenge for the prevailing cold DM model (see, e.g., [17]). If it couples to the standard model (SM) particles, the DM signal event in direct detection can be enhanced towards low recoil energies, a smoking-gun signature of SIDM [18–20]. In recent years, there has been great progress in the search for the light force mediator at the high-luminosity facilities (see, e.g., [21] for a review).

In this Letter, we report upper limits on the DM-nucleon scattering cross section induced by a light mediator and then interpret them to constrain SIDM models proposed in [1]. Our analysis is based on the data from the PandaX-II experiment, which is the phase-II experiment in the PandaX project that consists of a series of xenon-based rare-event detection experiments, located at China Jinping underground Laboratory (CJPL). The central apparatus of PandaX-II is a dual-phase xenon time projection chamber (TPC). The active volume con-
contains 580 kg liquid xenon. Particle interacting with xenon results in prompt scintillation photons (S1 signal) in liquid xenon as well as delayed electroluminescence photons (S2 signal) in gaseous xenon. Both signals are detected in one event by two arrays of photomultiplier tubes (PMTs), located in the top and bottom of the TPC. More detailed descriptions of the PandaX-II experiment can be found in Ref. [22].

We first consider a general case, where DM interacts with the nucleon through a vector or scalar force mediator, \( \phi \), and further assume \( \phi \) has equal effective couplings to the proton and neutron as in the standard WIMP model. The general form of the DM-nucleus elastic scattering cross section can be parametrized as [23]

\[
\sigma(q^2)_{\chi N} = \sigma|_{q^2=0} A^2 \left( \frac{\mu}{\mu_p} \right)^2 \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} F^2(q^2),
\]

where \( \sigma|_{q^2=0} \) is the DM-nucleon cross section in the limit of zero momentum transfer (\( q^2 = 0 \)), \( A \) the mass number of the nucleus, \( \mu, \mu_p \) the DM-nucleus (nucleon) reduced mass, \( m_\phi \) the mediator mass, and \( F(q^2) \) the nuclear form factor. We see that \( \sigma_{\chi N} \) is momentum-dependent and it approaches the standard WIMP case when \( m_\phi \gg q \).

The differential recoil rate (in unit of counts per day per kg per keV) is [24]

\[
\frac{dR}{dE} = \frac{\sigma(q^2)_{\chi N} \rho}{2m_\chi \mu^2} \int_{v \geq v_{\text{min}}} d^3 v v f(v, t) \]

where \( \rho \) is the local DM density which we set to be 0.3 GeV/cm\(^3\), \( m_\chi \) is the DM particle mass, \( f(v, t) \) is the time-dependent DM velocity distribution relative to the detector, and \( v_{\text{min}} \) is the minimum DM velocity that results in a recoil energy \( E \).

This analysis uses the same data sets as the recent WIMP search (unblind) in PandaX-II [22], consisting of 80 live day of exposure in 2016 and 77 live day of exposure in 2017, the largest published data set of its kind to date. We apply the same event selection criteria as in Ref. [22]. The range for S1 and S2 signals are between 3 photoelectron (PE) and 45 PE, and 4000 PE, respectively. The total data were divided into 18 sets to take into account variations of detector parameters and background rates. Background contributions have been estimated, and no excess of events in data was observed above the background. For a given DM model, the expected event distributions are modeled with the same procedure as in [22]. For each data set, we simulate the expected S1 and S2 signal distributions from the SIDM recoil-energy spectra using a tuned NEST simulation framework. Then, we apply the experimental efficiencies to make further corrections.

Figure 1 shows the simulated S1 distributions in PandaX-II for a 100 GeV DM particle with \( m_\phi = 10 \) MeV (red) and a WIMP with the same mass (blue). Both cases have the same integrated rate, but their spectra are very different, i.e., the S1 distribution of the light-mediated model is more peaked towards to small S1 than predicted in the WIMP model. We also plot PandaX-II detection efficiency as a function of S1 (magenta). It is nearly a constant over the range of 10–45 PE, but is reduced dramatically for S1 < 10 PE, where the event rate of the light-mediated model is maximized. Thus, we expect DM direct detection sensitivity becomes weak when the mediator mass is comparable or less than the typical momentum transfer in nuclear recoils, even though the DM mass is still at the weak scale.

The same statistical method as in Ref. [22] is used to derive upper limits on signal cross section. An unbinned likelihood function is constructed for these 18 data sets using the signal and background probability density functions in the S1-log10(S2/S1) plane, taking into account the normalization uncertainties for signal and background. For DM signal, we assign a conservative 20% uncertainty, estimated from different NEST simulations and uncertainties on the detector parameters. The standard profile likelihood ratio test statistic [25] is evaluated at grids of expected signal cross section (hypotheses) and compared to the test statistic distribution obtained from large number of toy Monte Carlo data produced and fitted using the same signal hypotheses.

Figure 2 shows the 90% confidence level (CL) upper
Our results improve significantly from previous ones. In what follows, we apply our results to constrain the SIDM models \(^4\) by explicitly calculating \(\sigma|q^2=0\). In these models, the force carrier mediating DM self-interactions has a mass \(\sim 1\) \(\text{MeV} - 1\) \(\text{GeV}\).

Following \(^4\), we assume DM is a Dirac fermion and it couples to a light mediator \(\phi\). If \(\phi\) is a vector (scalar) particle, it can couple to SM fermions through \(\gamma/Z\) (Higgs) mixing. The DM-nucleon cross section in the limit of \(q^2 = 0\) can be written as

\[
\sigma|q^2=0 = \frac{16\pi\alpha_SM\alpha_s\mu_\phi^2}{m_\phi^4} \left[ \epsilon_p Z + \epsilon_n (A - Z) \right]^2 / A, \tag{3}
\]

where \(\alpha_SM\) and \(\alpha_s\) are the fine structure constants in the visible and dark sectors, respectively, \(\epsilon_p,\epsilon_n\) are the effective proton or neutron couplings, and \(Z\) is the proton number of the nucleus. For photon kinetic mixing or Z mixing, \(\epsilon_{p,n}\) are given by

\[
\epsilon_p = \epsilon \gamma + \frac{\epsilon Z}{4s_W c_W} (1 - 4s_W^2), \quad \epsilon_n = -\frac{\epsilon Z}{4s_W c_W}, \tag{4}
\]

where \(s_W\) and \(c_W\) are the sine and cosine of the weak mixing angle, and \(\epsilon,\gamma, Z\) is the photon kinetic or Z mixing parameter. For Higgs mixing, they are

\[
\epsilon_{p,n} = \frac{m_{p,n} e_H}{e V} (1 - 7 f_{TG}^p)^/9, \tag{5}
\]

where \(e_H\) is the Higgs mixing parameter, \(e\) is the electron charge, \(V\) is the vacuum expectation value of the Higgs field, and \(f_{TG}^p\) is determined by the gluon hadronic matrix element, which we take \(f_{TG}^p = 0.943\) \(^2\).

We consider four cases. One is asymmetric SIDM with photon kinetic mixing. Asymmetric SIDM arises from the possibility that DM and anti-DM particles are not
equally populated in the early universe due to a primordial DM-number asymmetry [28, 29]. Other three are symmetric SIDM with photon kinetic mixing, Z mixing or Higgs mixing. For asymmetric SIDM, we set $\alpha_\chi$ to be 0.01, a choice motivated by the value of the electromagnetic fine structure constant in the SM [6]. For symmetric SIDM, the DM relic density is set by the annihilation process $\chi\bar{\chi} \rightarrow \phi\phi$, which sets $\alpha_\chi$ values as [3], $\alpha_\chi \approx 4 \times 10^{-5} \times (m_\chi/\text{GeV})$ for photon kinetic mixing or Z mixing, and $\alpha_\chi \approx 10^{-4} \times (m_\chi/\text{GeV})$ for Higgs mixing.

For each case, astrophysical observations set a preferred region in the $m_\phi$--$m_\chi$ plane, where the self-scattering cross section per mass in dwarf galaxies is $\sim 0.1$--$10 \text{ cm}^2/\text{g}$ [4, 6]. On the other hand, for a given DM mass, direct detection experiments put a constraint on the combination of the mixing parameter and the mediator mass. To present our limits in the $m_\phi$--$m_\chi$ plane, we will assume certain values of the mixing parameter. Note that Kaplinghat et al. [4] have reinterpreted an early XENON100 WIMP search result [30] to constrain the four cases, where a constant momentum transfer was assumed in calculating the total signal event. Furthermore, Del Nobile et al. [6] simulated full energy spectra and recasted results from early LUX [31] and SuperCDMS WIMP searches [52] to further constrain the asymmetric one. The present study uses the largest data set to date, and applies the complete analysis machinery in PandaX-II, including a thorough modeling the detector response to signal and background based on the calibration data.

Figure 3 shows the 90% CL lower limits on the
(m_\phi, m_\chi) parameter region for four SIDM models. Our limits (red) are reported at three \(\epsilon_\gamma\) values, \(10^{-8}, 10^{-9}\), and \(10^{-10}\). Previous limits from Del Nobile et al. \cite{2} by recasting a LUX result are included for comparison. The SuperCDMS limits are significantly weaker and not shown here. The shaded region is favored by observations in dwarf galaxies. Overall, a heavier DM particle requires a lighter mediator to enhance the self-scattering cross section, while keeping \(\sigma_\chi/m_\chi\) constant. If \(\epsilon_\gamma > 10^{-9}\), our results exclude all favored region with \(m_\chi > 7\) GeV. Even for \(\epsilon_\gamma = 10^{-10}\), we exclude a significant part of the favored region for DM masses ranging from 10 to 300 GeV. Previous limits are significantly weaker, in particular for a small mixing parameter.

The remaining panels in Figure 3 are for symmetric SIDM models, with photon kinetic mixing, Z mixing or Higgs mixing. Our limits are significantly stronger than the previous ones \cite{4}. The features in the shaded SIDM region are due to the quantum resonant effect of attractive DM self-interactions \cite{3}. For photon kinetic mixing \(\epsilon_\gamma > 10^{-9}\), our results exclude most of the favored region by observations in dwarf galaxies for \(m_\chi > 7\) GeV. Even for \(\epsilon_\gamma > 10^{-10}\), we exclude a large parameter space. Similarly, almost all favored heavy DM region is excluded for Z mixing and \(\epsilon_Z > 10^{-9}\). Our results are not yet sensitive to \(\epsilon_Z = 10^{-10}\), but for \(\epsilon_Z = 2 \times 10^{-10}\), we can exclude a large portion of the favored region. For Higgs mixing, almost all favored region shown is excluded if \(\epsilon_H > 10^{-6}\). We see that in most of the parameter region favored by the astrophysical observations, our results are sensitive to the mixing parameter as small as \(\sim 10^{-10}\) for photon kinetic or Z mixing, and \(10^{-7}\) for Higgs mixing. The latter is weaker due to the suppression factor of \(m_{p,n}/V\) in Eq. 5.

In conclusion, using a combined data corresponding to a total exposure of 54 ton day from the PandaX-II experiment, we have presented upper limits on the DM-nucleon scattering cross section with the mediator mass ranging from 1 MeV to 1 GeV. The mediator mass plays a critical role in setting the exclusion limits for these models and a full analysis of the scattering amplitude is required. We further interpreted them to constrain the parameter space in the context of the SIDM models with a light mediator mixing with SM particles, complementing constraints from astrophysical observations. These are the first kind of results reported by a direct detection experimental collaboration. With more data from PandaX, particularly the future multi-ton scale experiment at CJPL, we will continue to probe the DM interaction with a light mediator and the self-interacting nature of DM.

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