First Search Result for Neutral Current Fermionic Absorption Dark Matter from PandaX-4T 0.63 Tonne-Year Data

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Compared to the signature of dark matter elastic scattering off nuclei, absorption of fermionic dark matter by nuclei opens up a new searching channel for light dark matter with a characteristic mono-energetic signal. In this letter, we explore the 95.0-day data from PandaX-4T commissioning run and report the first dedicated searching results of the fermionic dark matter absorption signal through neutral current. No significant signal was found and the lowest limit on the dark matter-nucleon interaction cross section is set to be $1.7 \times 10^{-50} \text{ cm}^2$ (90\% C.L.) at a fermionic dark matter mass of 35 MeV/c$^2$.

Cosmological and astronomical observations strongly indicate the existence of dark matter (DM), but the nature of DM is still a mystery \[1\]. While searching for the popular weakly interacting massive particle (WIMP) is in full swing \[2,8\], other promising DM candidates have also been put forward and searched for experimentally, especially with mass below 1 GeV/c$^2$ \[9,11\]. However, due to the detection threshold in direct detection experiments, there are no stringent constraints on sub-GeV light DMs scattering with the Standard Model particles...
and the cross section can still be large. Recently, DM absorption scenarios have been proposed and studied, which can generate some novel inelastic signatures in direct detection experiments and enhance the sensitivity of light DM searches.

In this letter, we considered a fermionic DM absorption scenario through “neutral current” process, which can be generated by a ultra-violet (UV) complete model with an additional $U(1)'$ symmetry breaking. In this model, a lepton number charged DM $\chi$ mixes with approximately massless Dirac neutrino $\nu$ through a Yukawa interaction of a scalar field $\phi$, giving the $U(1)'$ invariant mass term:

$$\mathcal{L}_{\text{mass}} \supset m_\chi \chi \chi + (y\phi P_R \nu + \text{h.c.}).$$

The $\chi\nu$ mixing term naturally derives a completely massless state, which is identified as the SM neutrino, and a massive state with mass $\sqrt{m_\chi^2 + y^2 \langle \phi \rangle^2}$, after diagonalization. The right-handed component $\chi_R \equiv P_R \chi$ is mixed with the right-handed neutrino $\nu_R$ with a mixing angle $\theta_R$.

$$s_{\theta_R} = \frac{y \langle \phi \rangle}{\sqrt{y^2 \langle \phi \rangle^2 + m_\chi^2}}.$$ 

Through a heavy $Z'$ mediator coupled to quarks and $\chi$, the effective operator at the nucleon scale is

$$\mathcal{O}_{\text{NC}} = \frac{1}{\Lambda^2} (\bar{n} \gamma^\mu n + \bar{p} \gamma^\mu p) \tilde{\chi} \gamma_{\mu} P_R \nu + \text{h.c.},$$

where the energy scale cut-off $1/\Lambda^2 \equiv Q_\chi g_\chi^2 s_{\theta_R} c_{\theta_R}/m_{Z'}$, with $g_\chi$ denoting the $U(1)'$ gauge coupling and $m_{Z'}$ the mediator mass, $Q_\chi$ the charge of dark matter under the $U(1)'$, yielding the absorption process described above.

Similar to the WIMP spin-independent (SI) elastic scattering model, the absorption rate is coherently enhanced for heavier nuclei by a factor of $\sim A^2$, making xenon a preferable target. For a given DM mass, the nuclear recoil energy in xenon of the fermionic absorption process could be $\sim 10^6$ times larger than the SI elastic scattering, leading to a possibility of searching for MeV/c$^2$ scale DM with xenon-based experiments. The “neutral current” absorption of fermionic DM process involved in the xenon-based experiment is described as

$$\chi \rightarrow Xe^A \rightarrow \nu + Xe^A,$$ 

where $A = \{ 128 (1.9\%), 129 (26.4\%), 130 (4.1\%), 131 (21.2\%), 132 (26.9\%), 134 (10.4\%), 136 (8.9\%) \}$ denotes the mass numbers (abundances) of major abundant xenon isotopes, $\chi$ is the DM (anti-)particle, and $\nu$ (anti-$\nu$) is a Standard Model (SM) (anti-)neutrino. With the standard halo model (SHM) for the Earth nearby DM distribution, the differential event rate of the neutral current nuclear absorption signal as a function of recoil energy $E_R$ is given by (with $j$ denoting any specific isotope of xenon)

$$\frac{dR}{dE_R} = \frac{\rho_\chi \sigma_{\chi-N}^{\text{NC}}}{2\pi^3 M_T} \sum_j \frac{q_j}{p_{\nu,j}} N_j M_j A_j^2 F_j^2 \left( \frac{1}{v} \right)^{\nu v - v_{\text{min},j}},$$

where $\rho_\chi = 0.3 \text{ GeV}/\text{cm}^3$ is the local DM density, $\sigma_{\chi-N}^{\text{NC}} = m_\chi^2/(4\pi \Lambda^4)$ is the neutral current absorption cross section per nucleon, $q_j = \sqrt{2E_{R,j} M_j}$ is the momentum transfer to a target nucleus, $p_{\nu,j} = \sqrt{q_j(2m_\chi - q_j - 2E_{R,j})}$ denotes the momentum of the outgoing neutrino, $M_T = \sum_j N_j M_j$ is the total target mass with $N_j$ and $M_j$ corresponding to the number and mass of each isotope, respectively, $A_j$ is again the atomic mass number, $F_j \equiv F(q_j)$ is the normalized Helm nuclear form factor. The mass of the nonrelativistic incoming $\chi$ dominates the energy, so the momentum transfer $q_j \approx m_\chi$, giving a very sharp peak ($E_R \approx m_\chi^2/2M_j$) in the nuclear recoil energy spectrum, with contribution from different xenon isotopes ($j$) slightly offset, see Fig. 1.

![Figure 1](image1.png)

The PandaX-4T experiment, located in the B2 hall at China Jinping Underground Laboratory Phase-II (CJPL-II), is a multi-physics purposed xenon experiment aiming for exploring DM and neutrino physics. The PandaX-4T detector is a dual-phase xenon time projection chamber (TPC) well shielded by ultra-pure water, with a sensitive xenon target mass of 3.7 tonne. A total of 169 top and 199 bottom 3-inch photomultiplier tubes (PMTs) measure the primary prompt scintillation photons (S1) and the secondary delayed electroluminescence photons (S2) from ionized electrons. Another two rings of one-inch PMTs are installed outside of the TPC sensitive volume, serving as the veto PMTs for rejecting multi-scatter backgrounds. Unlike an
electronic recoil (ER) event, only partial of the recoil energy $E_R$ in a nuclear recoil (NR) event is converted into the scintillation photons and ionized electrons. The reconstructed electron-equivalent energy $E$ of a given event is

$$E = 13.7 \text{ eV} \times \left( \frac{S1}{PDE} + \frac{S2_b}{EE \times SEG_b} \right),$$

(6)

in which PDE, EEE, and SEG$_b$ are the photon detection efficiency for $S1$, single electron extraction efficiency and the single-electron gain using S2$_b$ (the S2 collected from the bottom PMT array), respectively, and the 13.7 eV is the work function in liquid xenon. The data used in this work consist of five sets during 95.0 calendar days of stable data taking, due to different hardware configurations. The parameters used for energy reconstruction in each set are summarized in Ref. [5].

At the end of PandaX-4T commissioning run, we inject $^{83m}$Kr source (41.5 keV$_{ee}$, electron equivalent energy) [31] into the detector in order to perform 3D uniformity correction for $S1$s and $S2$s. The energy resolution is $\sigma_E/E = 6.8 \pm 0.1\%$ at 41.5 keV$_{ee}$, in a good agreement with the value (7.0%) given by our ER signal response model, which will be discussed next (Fig. 2).

Determining the energy resolution in the region of interest (ROI) is essential for the mono-peaked characteristic of the fermionic absorption signal. For the low energy range, due to the lack of mono-energetic NR calibration source, we compare the distribution of $S1$ and $S2_b$ (S2 signal collected by the bottom PMT array) between simulation from our signal response model and the neutron calibration data in a narrow energy window (scanning from 1 to 16 keV$_{ee}$ electron recoil equivalent energy with a window size of 1 keV$_{ee}$). Fig. 3 shows such a comparison of NR events in two energy windows for illustration. A good agreement is observed, which indicates that the NR signal simulation from the tuned NEST v2.2.1-based signal response model is consistent with the data for energy within 16 keV$_{ee}$. The reconstructed energy resolution within ROI given by the simulation can be well depicted by

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E},$$

(7)

where $a = 0.498$ and $b = 0.324$ are fitting parameters. The energy resolution at 1 keV$_{ee}$ (16 keV$_{ee}$) is 0.59(0.13).

| Energy [keV$_{ee}$] | Normalized counts |
|--------------------|--------------------|
| 25 30 35 40 45 50 55 60 | 0.06 0.05 0.04 0.03 0.02 0.01 0.00 |

**FIG. 2.** Comparison between the $^{83m}$Kr internal conversion electrons ($\tau = 1.83$ h) energy spectrum and the simulation result for a 41.5 keV$_{ee}$ monoenergetic electronic recoil.

The signal response models in PandaX-4T are built based on the end-of-run low energy calibrations, including $^{220}$Rn, $^{241}$Am-Be neutrons and deuterium-deuteron (D-D) neutrons [5]. The response models follow the construction of the standard NEST v2.2.1 [32] [33]. Taking into account all possible detection effects, a simultaneous fit of ER and NR signal response models is performed, where the key parameters including the light yield, charge yield, and recombination parameters are determined [34]. The difference between the reconstructed electron-equivalent energy $E$ and the recoil energy $E_R$ for a NR event is modeled through the so-called Lindhard factor [35].

![Comparison between the $^{83m}$Kr internal conversion electrons (τ = 1.83 h) energy spectrum and the simulation result for a 41.5 keV$_{ee}$ monoenergetic electronic recoil.](image)

**FIG. 3.** Comparison between the simulated events and $^{241}$Am-Be + D-D calibration data, using 1.5-2.5 keV$_{ee}$ and 15.5-16.5 keV$_{ee}$ energy windows for illustration. Red line: simulated $S1$ or $S2_b$ distribution. Black dot: normalized $S1$ or $S2_b$ distribution of $^{241}$Am-Be and D-D calibration data.

The consistency of the NR simulation with the data is further validated through the D-D back-scatter energy peaks. Simulation events for the D-D calibrations are generated by the PandaX Monte Carlo package BambooMC [30] and processed with the signal response model. The reconstructed energy is compared with the
data. A Gaussian fit is performed on the right half part of the back-scatter peak, which is dominated by the detector resolution, see Fig. 4. The fitted width is consistent between the simulation and the data. The relative difference (~ 5%) is taken as a systematic uncertainty of the NR energy resolution.

The physical event selection criteria follows the WIMP search analysis [5], aiming to remove noise, surface backgrounds, accidentally paired events and events with low quality reconstructed waveform. In brief, our region of interest (ROI) is selected with $S_1$ from 2 to 135 PE, raw $S_2$ from 80 to 20,000 PE. The upper bound of this ROI corresponds to approximately 24 keV$_{ee}$. In total 1058 events are identified in the ROI from a 86.0 live-day exposure data in the PandaX-4T commissioning run, as shown in Fig. 5. The background compositions are summarized in Ref. [5], which include tritium, flat ER ($^{85}$Kr, Rn, material), surface, $^{127}$Xe, neutron, neutrino, accidental $S_1$-$S_2$ coincidence events. The 68% and 95% contours of the probability density function (PDF) for DM mass $m_\chi = 100$ MeV/c$^2$ are overlaid for illustration. The number of observed events within the 68% contour is 26, and the expected background contribution is estimated to be 21.0 $\pm$ 2.2. Neutral current absorption of fermionic DM signal is tested in the ROI, with a two-sided profile likelihood method [25]. The scanned DM mass parameter ranges from 15 to 125 MeV/c$^2$, the corresponding highest energy deposit peaks at 16 keV$_{ee}$. We construct a standard unbinned likelihood function $L_n$ as below

$$L_n = \text{Pois}(N_{\text{obs}}^n | N_{\text{fit}}^n) \times \prod_{i=1}^{N_{\text{obs}}} \frac{1}{N_{\text{fit}}^n} \left( N_{\text{fit}}^n P_s^n (S_1^i, S_2^i) \right) \left[ 1 + \sum_b N_{b}^n (1 + \delta_b) P_b^n (S_1^i, S_2^i) \right]. \quad (9)$$

For each data set $n$, $N_{\text{obs}}^n$ and $N_{\text{fit}}^n$ are the total observed and fitted numbers of detected physical events, respectively; $N_s^n$ and $N_b^n$ represent the amount of DM (signal) and background events; $P_s^n$ and $P_b^n$ denote their two-dimensional PDFs. The systematic uncertainties of signal ($\sigma_s$) and backgrounds ($\sigma_b$) are taken into account via Gaussian penalty function $G(\delta, \sigma)$ that constraints the nuisance parameters of signal response model and the normalization $\delta_b$ of each background composition.

There is no significant excess above 1$\sigma$ identified in the fit. The final 90% confidence level (C.L.) upper limit is shown in the top of Fig. 4. This limit curve is within the $\pm 1$σ sensitivity band, except for a slight downward fluctuation in the DM mass range $[40, 55]$ MeV/c$^2$, which is power-constrained to $-1$σ [39]. The strongest limit achieved is $1.7 \times 10^{-56}$ cm$^2$ at a fermionic DM mass of 35 MeV/c$^2$. Direct constraints of $Z'$ from collider experiment [20, 40] is marked as the grey shaded region in Fig. 4.

In the UV complete model with a mediator $Z'$, the DM $\chi$ can decay invisibly to neutrinos, $\chi \rightarrow \nu \nu$, which may yield some anomalous change in the equation of state of the Universe from the era of the Cosmic Mi-
A new model-independent exclusion limit is set on the sub-GeV DM-nucleon interactions, excluding the scattering cross section with nucleon as low as $1.7 \times 10^{-50}\text{ cm}^2$ for DM mass of 35 MeV/c$^2$. Together with cosmology indirect detection and collider search, this result provides strong constraints on the UV complete model with a $Z'$ mediator. Searching for light fermionic DM absorption interaction with electrons is also under study and will appear soon [44]. PandaX-4T continues taking more physics data and is expected to improve the sensitivity by another order of magnitude with a 6-tonne-year exposure.

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