

Exotic Dark Matter Search with the CDEX-10 Experiment at China's Jinping Underground Laboratory

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A search for exotic dark matter (DM) in the sub-GeV mass range has been conducted using 205 kg day data taken from a p -type point contact germanium detector of the CDEX-10 experiment at China's Jinping underground laboratory. New low-mass dark matter searching channels, neutral current fermionic DM absorption ($\chi + A \rightarrow \nu + A$) and DM-nucleus $3 \rightarrow 2$ scattering ($\chi + \chi + A \rightarrow \phi + A$), have been analyzed with an energy threshold of 160 eVee. No significant signal was found; thus new limits on the DM-nucleon interaction cross section are set for both models at the sub-GeV DM mass region. A cross section limit for the fermionic DM absorption is set to be 2.5×10^{-46} cm² (90% C.L.) at DM mass of 10 MeV/ c^2 . For the DM-nucleus $3 \rightarrow 2$ scattering scenario, limits are extended to DM mass of 5 and 14 MeV/ c^2 for the massless dark photon and bound DM final state, respectively.

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Introduction.—Various evidence from cosmological and astronomical observations strongly supports the existence of dark matter (DM) in our Universe [1]. The weakly

interacting massive particle (WIMP) DM candidate has been searched for several decades [2–4], and the limit on the WIMP-nucleus cross section has been pushed near the neutrino floor for DM masses around the GeV scale in direct detection experiments [5–12].

The null results in the WIMP search have motivated building of alternative dark matter models [13–15]. Recently, two sub-GeV light DM interaction scenarios, the neutral current (NC) fermionic DM absorption and

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DM-nucleus $3 \rightarrow 2$ scattering, have been proposed and searched for experimentally [16–21].

The fermionic DM (χ) may convert to a neutrino (ν) upon interaction with a target (A) via a neutral current absorption process ($\chi + A \rightarrow \nu + A$) [16,17]. The absorption generates a monoenergetic signal with an energy proportional to the DM mass in direct detection experiments. Experiments with a low energy threshold, low background, and good energy resolution can provide strong constraints on the interaction cross section. In direct detection experiments, only two searches have been performed to date. The most stringent limit at 15–125 MeV/ c^2 DM mass range is given by the PandaX-4T experiment and the lowest limit on the cross section of 1.7×10^{-50} cm 2 (90% C.L.) is placed at DM mass of 35 MeV/ c^2 [18]. The MAJORANA DEMONSTRATOR set limits on the fermionic DM absorption cross section at the DM mass of 25–190 MeV/ c^2 via the high purity germanium detector technology [19].

In recent Letter, another direct detection channel for sub-GeV DM via a DM-nucleus $3 \rightarrow 2$ scattering process ($\chi + \chi + A \rightarrow \phi + A$) is proposed [21]. Two DM candidates (χ) may combine into a DM composite state or dark radiation (ϕ) upon the interaction with a target (A). Similar to the fermionic DM absorption, a monoenergetic signal is generated in the three-body scattering, and the energy passed to the nucleon is related to the mass of the initial and final states of DM. The MAJORANA DEMONSTRATOR performed searches for DM-nucleus $3 \rightarrow 2$ scattering signals with 52.6 kg yr exposure data and an analysis threshold of 1 keVee [19].

In this Letter, we report the search results of the neutral current fermionic DM absorption and DM-nucleus $3 \rightarrow 2$ scattering using 205 kg day exposure data from the CDEX-10 experiment with an analysis threshold of 160 eVee.

CDEX-10 experiment.—The CDEX-10 experiment operates a 10-kg p -type point contact germanium (PPCGe) detector array to search for light DM in the China Jinping Underground Laboratory (CJPL) [11,22]. The detector array consists of three triple-element PPCGe detector strings, C10-A, B, C, respectively. The detector array surrounded by a 20-cm high-purity oxygen-free copper shielding is directly immersed in a liquid nitrogen cryostat for cooling. The liquid nitrogen cryostat and data acquisition systems are placed inside a polyethylene room at CJPL-I [23]. The detailed configuration of the experimental setup can be found in Refs. [11,23].

One of the C10 detectors, C10-B1, achieved the lowest analysis threshold (160 eVee) during its data taking from February 2017 to August 2018 [11,24]. The dead layer thickness of C10-B1 is evaluated to be (0.88 ± 0.12) mm [11,12]. The dead layer results in a fiducial mass of 939 g and, accordingly, an exposure of 205 kg day.

The data processing procedures, including energy calibration, pedestal cut, physics event selection, and bulk or surface event discrimination, were discussed in our previous

works [11,25]. The dead time of the data acquisition system was measured to be 5.7% by random trigger signals. Efficiencies of event trigger and event selection were derived from a ^{137}Cs source following the method described in our previous works [11,12]. The analysis threshold is selected to be 160 eVee, corresponding to a combined efficiency of $(5.7 \pm 1.48)\%$. The 0.16–4 keVee spectrum after all event selections and efficiency correction is used for DM analysis.

Data analysis.—A minimum χ^2 method, similar to our previous WIMP analysis [11,24,26], is used to search for the fermionic DM absorption and DM-nucleus $3 \rightarrow 2$ scattering. The χ^2 is constructed as

$$\chi^2 = \sum_i \frac{[n_i - S_i(m_\chi, \sigma_\chi) - B_i]^2}{\sigma_{\text{stat},i}^2 + \sigma_{\text{syst},i}^2}, \quad (1)$$

where n_i is the measured event rate in the i th energy bin, and $\sigma_{\text{stat},i}$ and $\sigma_{\text{syst},i}$ are the statistical and systematic uncertainty, respectively. The systematic uncertainty includes uncertainties in exposure, event select efficiency, and bulk or surface event discrimination [11]. $S_i(m_\chi, \sigma_\chi)$ is the expected DM event rate in the i th energy bin at DM mass m_χ and DM-nucleus interaction cross section σ_χ . B_i is the background event rate in the i th energy bin.

The background event rate (B , in counts per keVee per kg per day) of the C10-B1 detector consists of a flat continuum (p_0) plus L -shell and M -shell x-ray peaks from ^{68}Ge ($E_L = 1.298$ keV, $E_M = 0.16$ keV), ^{68}Ga ($E_L = 1.194$ keV, $E_M = 0.14$ keV), ^{65}Zn ($E_L = 1.096$ keV), ^{55}Fe ($E_L = 0.764$ keV), ^{54}Mn ($E_L = 0.695$ keV), and ^{49}V ($E_L = 0.564$ keV):

$$B = p_0 + \sum_L I_L \cdot \frac{1}{\sqrt{2\pi}\sigma_L} \exp\left(-\frac{(E - E_L)^2}{2\sigma_L^2}\right) + \sum_M I_M \cdot \frac{1}{\sqrt{2\pi}\sigma_M} \exp\left(-\frac{(E - E_M)^2}{2\sigma_M^2}\right), \quad (2)$$

where E_L and E_M are the energies of the L -shell and M -shell x rays, and I_L and I_M are the corresponding peak intensities. σ_L and σ_M are the energy resolutions at the peak energy. As shown in Fig. 1, the K -shell x-ray peaks in the 4–12 keVee spectrum are measured to constrain the intensities of the L - or M -shell peaks with known K/L and K/M ratios [11,27]. The energy resolution function $\sigma(E) = a + \sqrt{b \cdot E}$ [28] is fitted by resolutions of K -shell x-ray peaks ($a = 35.5$ eV, $b = 2.8$ eV). Energy resolutions of L - or M -shell x-ray peaks are constrained to the $\pm 3\sigma$ uncertainty region of the energy resolution function.

The DM-nucleus interaction cross section is probed by minimizing the χ^2 value at a certain DM mass, and the upper limit at the 90% C.L. (confidence level) is computed using the Feldman-Cousins method [29]. The nuclear recoil quenching factor of Ge calculated by the TRIM software package [11,30–32] with a 10% systematic error is adopted in this analysis like our previous works [26,28].

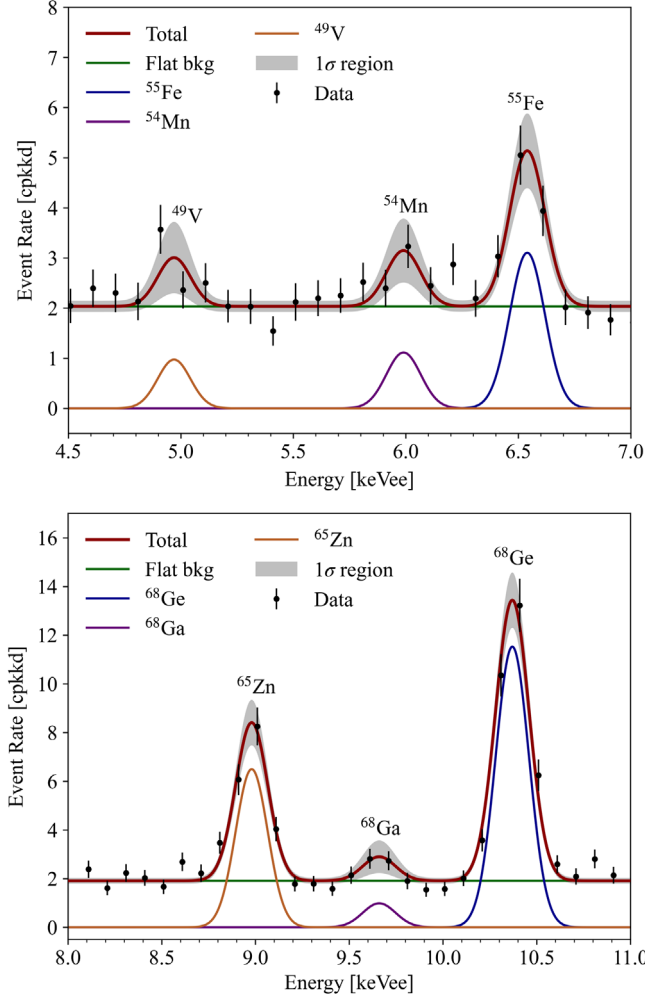


FIG. 1. Spectra fit for the intensities of the six K -shell x-ray peaks; the 1σ uncertainty band derived from the fit uncertainty is labeled in gray. The intensity of L - or M -shell x-ray peak is constrained by the K -shell x-ray peak with the known K/L and K/M ratio [11,27]. cpk/kd denotes count per keVee per kg per day, and bkg denotes background.

Fermionic DM absorption.—As proposed in Refs. [16,17], the fermionic DM may interact with Ge via a neutral current absorption, $\chi + \text{Ge} \rightarrow \nu + \text{Ge}$, modeled as a Yukawa-like interaction with a bosonic mediator. Considering a nonrelativistic fermionic DM, its mass dominates its energy and results in a momentum transfer $q \simeq m_\chi$ and nuclear recoil energy $E_R \simeq m_\chi^2/2M$, where M is the mass of the target. The differential event rate (dR_{NC}/dE_R) and total event rate (R_{NC}) of the neutral current absorption signal can be expressed as [17]

$$\frac{dR_{\text{NC}}}{dE_R} = \frac{\rho_\chi}{m_\chi} \cdot \sigma_{\text{NC}} \frac{1}{M_T} \sum_j N_j M_j A_j^2 F_j^2(m_\chi) \frac{\sqrt{2E_R M_j}}{2p_\nu m_\chi^2} \times \left\langle \frac{1}{v_\chi} \right\rangle_{v_\chi > v_{\min}}, \quad (3)$$

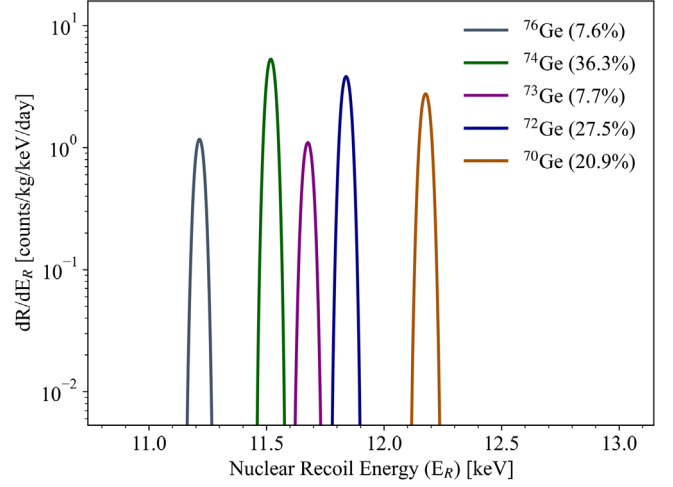


FIG. 2. Nuclear recoil energy spectra of the fermionic DM absorption signals for Ge target, with a DM mass $m_\chi = 40 \text{ MeV}/c^2$ and the DM-nucleon cross section $\sigma_{\text{NC}} = 10^{-45} \text{ cm}^2$ for all Ge isotopes.

$$R_{\text{NC}} = \frac{\rho_\chi}{m_\chi} \cdot \sigma_{\text{NC}} \cdot \frac{1}{M_T} \sum_j N_j M_j A_j^2 F_j^2(m_\chi), \quad (4)$$

where σ_{NC} is the DM-nucleon interaction cross section, m_χ is the DM mass. The local DM density ρ_χ is set to $0.3 \text{ GeV}/\text{cm}^3$ as recommended in Ref. [33]. $M_T = \sum_j N_j M_j$ is the total target mass with N_j and M_j corresponding to the number and mass of isotope j , respectively. $F_j(m_\chi)$ is the normalized Helm form factor for isotope j evaluated at momentum transfer $q = m_\chi$ [34]. $p_\nu = \sqrt{q(2m_\chi - q - 2E_R)}$ denotes the momentum of the outgoing neutrino. v_{\min} is the minimum DM velocity at a given recoil energy E_R [17].

As shown in Eq. (3), the DM signal rate is contributed by all Ge isotopes, and their abundance in the natural Ge are adopted for the C10-B1 detector: ^{76}Ge (7.6%), ^{74}Ge (36.3%), ^{73}Ge (7.7%), ^{72}Ge (27.5%), and ^{70}Ge (20.9%). Contributions from different Ge isotopes in the nuclear recoil energy spectrum are shown in Fig. 2. Converting the nuclear recoil energy in Eq. (3) into visible energy and folding the energy resolution of the detector, the expected spectra of the fermionic DM absorption signals are derived for several m_χ and a certain σ_{NC} , as shown in Fig. 3.

We scan the DM mass in the range of $10\text{--}45 \text{ MeV}/c^2$ (corresponding to $0.16\text{--}4 \text{ keVee}$ in the measured energy spectrum), and no significant signal is observed. The best-fit spectrum for $m_\chi \sim 40 \text{ MeV}/c^2$ and the corresponding best-fit DM peak signature at 3 keVee are displayed in Fig. 4. Upper limits of the DM-nucleon cross section superimposed with previous results from direct detection experiments [18,19] and Z_0 monojet searches at the LHC [35] are illustrated in Fig. 5. Note that we take a local DM

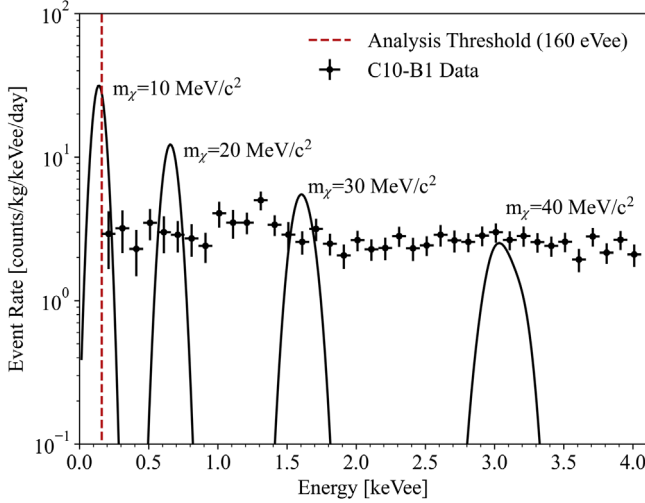


FIG. 3. Expected spectra of the fermionic DM absorption signals for $m_\chi = 10, 20, 30, 40$ MeV/ c^2 with a DM-nucleon cross section $\sigma_{\text{NC}} = 10^{-45}$ cm 2 . The C10-B1 spectrum is shown as the black crosses with a bin size of 100 eVee. The red dashed line represents the analysis threshold.

density (ρ_χ) of 0.3 GeV/cm 3 recommended in Ref. [33] other than 0.4 GeV/cm 3 used by the MAJORANA DEMONSTRATOR [19], resulting in more conservative constraints. The most stringent limit on the DM-nucleon cross section is $\sigma_{\text{NC}} < 2.4 \times 10^{-47}$ cm 2 at DM mass of 43.0 MeV/ c^2 in this Letter. The upper limit on the cross section is set to $\sigma_{\text{NC}} < 2.5 \times 10^{-46}$ cm 2 at 10 MeV/ c^2 DM mass.

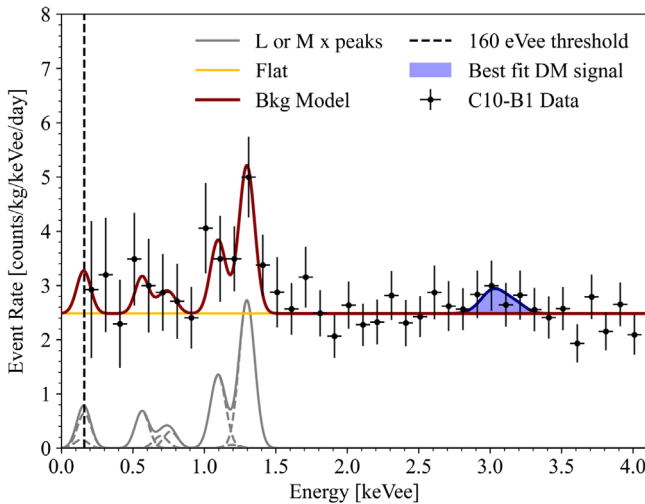


FIG. 4. An example of fermionic DM absorption analysis for $m_\chi = 40$ MeV/ c^2 with its corresponding best-fit peak signature at 3 keVee. The best-fit background model is shown in the red line, the gray lines represent the contributions from L -shell and M -shell x-ray peaks, and the flat background is depicted by the yellow line. The best-fit DM signal is labeled in blue.

DM-nucleus $3 \rightarrow 2$ scattering.—Recent Letter has proposed that the DM may interact with the nucleus via an inelastic $3 \rightarrow 2$ scattering process, $\chi + \chi + A \rightarrow \phi + A$, where the DM final state (ϕ) can be either a DM composite state or any dark radiation [21]. The signature of this process is similar to that of the fermionic DM absorption. Neglecting the initial kinetic energy of the DM particles, the monoenergetic nuclear recoil energy is

$$E_R \simeq \frac{(4 - \xi^2)m_\chi^2}{2(M + 2m_\chi)}, \quad (5)$$

where M is the mass of the nucleus, ξ is the mass ratio of the final and initial dark matter states ϕ and χ . The mass ratio ξ is model dependent. In this Letter, we considered two models: a massless DM final state (ϕ is a dark photon, $\xi = 0$) and a bound DM final state. For the bound DM final state, the mass ratio $\xi = 2(m_\chi + \epsilon)/m_\chi$, where the binding energy ϵ is decided by a new gauge coupling g_D : $\epsilon = -(g_D^4 \cdot m_\chi)/(64\pi^2)$ [36]. We set the gauge coupling $|g_D| = 3$ as in Ref. [21] and obtain a mass ratio $\xi = 1.87$ for the bound DM final state.

The total event rate of the $3 \rightarrow 2$ scattering is similar in form to that of the fermionic DM absorption:

$$R_{3 \rightarrow 2} = \frac{\rho_\chi}{m_\chi} \cdot n_\chi \langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle \frac{1}{M_T} \sum_j N_j M_j A_j^2 F_j^2(q_{3 \rightarrow 2}), \quad (6)$$

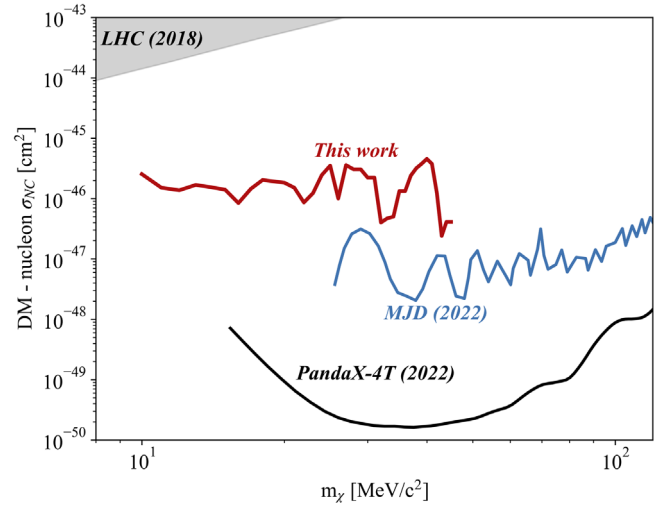


FIG. 5. Upper limit (90% C.L.) of the fermionic DM absorption cross section σ_{NC} . The gray shadow region represents the constraints from Z_0 monojet searches at the LHC (indirect detection). The result from this Letter is depicted in solid red, results from two other direct detection experiments, the MAJORANA DEMONSTRATOR [19] (MJD, blue line) and PandaX-4T [18] (black line), are superimposed. Constraint on σ_{NC} for DM mass of > 10 MeV/ c^2 is achieved in this Letter.

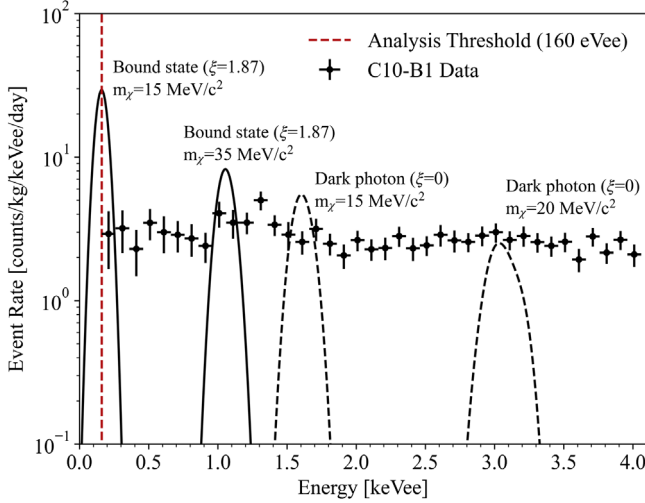


FIG. 6. Expected spectra of the DM-nucleus $3 \rightarrow 2$ scattering signals. Black dashed lines represent the spectra of the massless dark photon final state ($\xi = 0$), black solid lines denote a bound final state ($\xi = 1.87$). The DM-nucleus coupling $\langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle n_\chi$ is set to 10^{-45} cm^2 for both final states. The C10-B1 spectrum is shown as the black crosses with the red dashed line denoting the analysis threshold.

where the $\langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle$ is the average three-body inelastic cross section with a DM initial velocity of v_χ . $n_\chi = \rho_\chi / m_\chi$ is the number density. The momentum transfer in the $3 \rightarrow 2$ scattering is $q_{3 \rightarrow 2} = \sqrt{4 - \xi^2} m_\chi$. In the calculation of DM expected spectra, the quenching factor and energy resolution are the same as in the fermionic DM absorption calculation. Figure 6 shows the expected spectra of the $3 \rightarrow 2$ scattering signals for the massless dark photon and bound DM final state. The shape of the expected spectra is also similar to that of the fermionic DM absorption.

We place limits on the $(m_\chi, \langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle n_\chi)$ parameter as suggested in Ref. [21] for the massless dark photon and the bound DM final state. The 90% upper limit for the coupling $\langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle n_\chi$ is shown in Fig. 7. Compared with the results from the MAJORANA DEMONSTRATOR [19], this Letter achieved a lower analysis threshold of 160 eVee and excluded new parameter space in lower DM mass regions.

Conclusion.—In this Letter, we report search results for the sub-GeV fermionic DM absorption and DM-nucleus $3 \rightarrow 2$ scattering using 205.4 kg day exposure data from the C10-B1 PPCGe detector in the CDEX-10 experiment. The expected DM signal is analyzed in the 160 eVee–4 keVee spectrum via a minimum χ^2 method. With an analysis threshold of 160 eVee, we set new experimental limits on the fermionic DM absorption cross section in 10–45 MeV/c^2 DM mass. For the DM-nucleus $3 \rightarrow 2$ scattering, we place the limit on lower DM mass of 5 MeV/c^2 for a massless dark photon DM final state, and 14 MeV/c^2 for the bound DM final state. Those limits

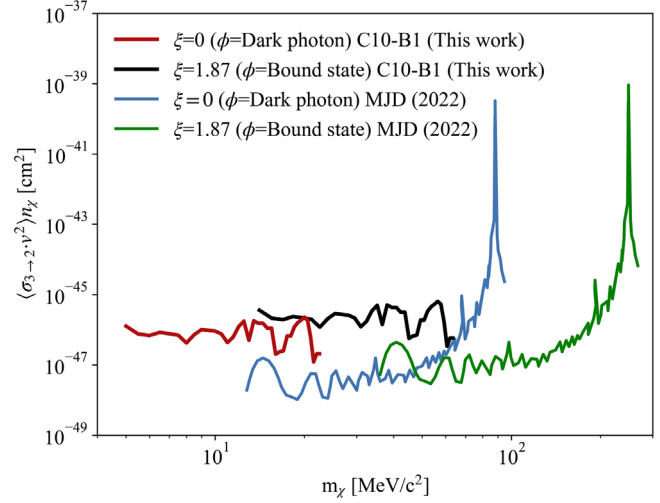


FIG. 7. Upper limit (90% C.L.) of the DM-nucleus $3 \rightarrow 2$ scattering coupling $\langle \sigma_{3 \rightarrow 2} \cdot v_\chi^2 \rangle n_\chi$. $\xi = 0$ is a massless dark photon final state, and $\xi = 1.87$ is a bound state. The results of this Letter (red and black lines) are compared with the results from the MAJORANA DEMONSTRATOR (MJD, blue and green lines). The MJD takes a local DM density (ρ_χ) of $0.4 \text{ GeV}/\text{cm}^3$ [19], while this Letter takes a ρ_χ of $0.3 \text{ GeV}/\text{cm}^3$ as recommended in Ref. [33]. This Letter places limits on a lower DM mass region for both massless and bound DM final states with a lower analysis threshold of 160 eVee.

achieve the lowest DM mass among the searches in direct detection experiments to date.

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