

First Search for Light Fermionic Dark Matter Absorption on Electrons Using Germanium Detector in CDEX-10 Experiment

J. X. Liu,¹ L. T. Yang,^{1,*} Q. Yue,^{1,†} K. J. Kang,¹ Y. J. Li,¹ H. P. An,^{1,2} Greeshma C.,^{3,‡} J. P. Chang,⁴ Y. H. Chen,⁵ J. P. Cheng,^{1,6} W. H. Dai,¹ Z. Deng,¹ C. H. Fang,⁷ X. P. Geng,¹ H. Gong,¹ Q. J. Guo,⁸ T. Guo,¹ X. Y. Guo,⁵ L. He,⁴ J. R. He,⁵ J. W. Hu,¹ H. X. Huang,⁹ T. C. Huang,¹⁰ L. Jiang,¹ S. Karmakar,^{3,‡} H. B. Li,^{3,‡} H. Y. Li,⁷ J. M. Li,¹ J. Li,¹ M. C. Li,⁵ Q. Y. Li,⁷ R. M. J. Li,⁷ X. Q. Li,¹¹ Y. L. Li,¹ Y. F. Liang,¹ B. Liao,⁶ F. K. Lin,^{3,‡} S. T. Lin,⁷ S. K. Liu,⁷ Y. D. Liu,⁶ Y. Liu,⁷ Y. Y. Liu,⁶ H. Ma,¹ Y. C. Mao,⁸ Q. Y. Nie,¹ H. Pan,⁴ N. C. Qi,⁵ J. Ren,⁹ X. C. Ruan,⁹ M. B. Shen,⁵ M. K. Singh,^{3,12,‡} T. X. Sun,⁶ W. L. Sun,⁵ C. J. Tang,⁷ Y. Tian,¹ G. F. Wang,⁶ J. Z. Wang,¹ L. Wang,¹³ Q. Wang,^{1,2} Y. F. Wang,¹ Y. X. Wang,⁸ H. T. Wong,^{3,‡} Y. C. Wu,¹ H. Y. Xing,⁷ K. Z. Xiong,⁵ R. Xu,¹ Y. Xu,¹¹ T. Xue,¹ Y. L. Yan,⁷ N. Yi,¹ C. X. Yu,¹¹ H. J. Yu,⁴ M. Zeng,¹ Z. Zeng,¹ B. T. Zhang,¹ F. S. Zhang,⁶ L. Zhang,⁷ P. Zhang,⁵ Z. H. Zhang,¹ Z. Y. Zhang,¹ J. Z. Zhao,¹ K. K. Zhao,⁷ M. G. Zhao,¹¹ J. F. Zhou,⁵ Z. Y. Zhou,⁹ and J. J. Zhu⁷

(CDEX Collaboration)

¹Key Laboratory of Particle and Radiation Imaging (Ministry of Education) and Department of Engineering Physics, Tsinghua University, Beijing 100084

²Department of Physics, Tsinghua University, Beijing 100084

³Institute of Physics, Academia Sinica, Taipei 11529

⁴NUCTECH Company, Beijing 100084

⁵YaLong River Hydropower Development Company, Chengdu 610051

⁶College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875

⁷College of Physics, Sichuan University, Chengdu 610065

⁸School of Physics, Peking University, Beijing 100871

⁹Department of Nuclear Physics, China Institute of Atomic Energy, Beijing 102413

¹⁰Sino-French Institute of Nuclear and Technology, Sun Yat-sen University, Zhuhai 519082

¹¹School of Physics, Nankai University, Tianjin 300071

¹²Department of Physics, Banaras Hindu University, Varanasi 221005

¹³Department of Physics, Beijing Normal University, Beijing 100875

(Dated: April 16, 2024)

We present the first results of the search for sub-MeV fermionic dark matter absorbed by electron targets of Germanium using the 205.4 kg-day data collected by the CDEX-10 experiment, with the analysis threshold of 160 eVee. No significant dark matter (DM) signals over the background are observed. Results are presented as limits on the cross section of DM-electron interaction. We present new constraints of cross section in the DM range of 0.1–10 keV/c² for vector and axial-vector interaction. The upper limit on the cross section is set to be 5.5×10^{-46} cm² for vector interaction, and 1.8×10^{-46} cm² for axial-vector interaction at DM mass of 5 keV/c².

Introduction.— Various astronomical and cosmological observations support the existence of dark matter (DM), which accounts for approximately 26.8% of the universe [1]. As the most popular candidates for DM, weakly interacting massive particles (WIMPs) have been searched by a lot of direct detection experiments, such as XENON [2], LUX-ZEPLIN [3], PandaX [4], DarkSide [5], SuperCDMS [6], and CDEX [7–15]. These direct detection experiments have set stringent limits on the cross section of DM interaction with Standard Model (SM) particles within the DM mass range of GeV/c² to TeV/c² via DM–nucleus scattering (χ -N). Meanwhile, the cross section of sub-GeV DM interaction with SM particles is less constrained. Recently, physics channels, such as the Migdal effect of χ -N [15–18], fermionic DM absorbed by nuclear targets ($\chi + A \rightarrow \nu + A$), DM–nucleus 3 → 2 scattering ($\chi + \chi + A \rightarrow \phi + A$) [19–25], and DM–electron scattering (χ -e) [26–34], have been explored to search for DM in the MeV/c² mass scale ($m_\chi \sim \mathcal{O}(\text{MeV}/c^2)$).

However, if we want to explore lighter (sub-MeV) DM, particularly DM of few keV/c² in a direct detection experiment with a typical $\mathcal{O}(1)$ keV experimental threshold, considering the aforementioned physics scenarios, the energy deposited by DM in the detector will decrease to below the threshold. There are two strategies to probe lighter DM: (1) increasing the energy deposition from DM in targets and (2) using lower experimental threshold detectors. To increase the energy deposited by DM in targets, DM particles with higher kinetic energy boosted by interaction with SM particles; for example, DM boosted by cosmic rays have been searched [35–42]. On the other hand, considering a new DM interaction paradigm, where the energy transfer from DM particle to SM particle is not dominated by kinetic energy but by rest energy $E = mc^2$, the energy deposit by sub-MeV DM can also overcome the experimental threshold. This is the main motivation to study DM absorption for bosonic DM [43–52] (e.g. dark photon and axion-like

particle [51]), and fermionic DM [19, 20, 53]. Recently, a new type of interaction where fermionic DM is absorbed by electron target ($\chi + e^- \rightarrow \nu + e^-$) has been proposed and searched [53–55]. When fermionic DM is absorbed by electron, the electron obtains a kinetic recoil through the mass of χ . As mentioned above, the lower experimental threshold detectors, the lighter DM can be probed. In CDEX-10 experiment, a threshold of 160 eVee is achieved.

The CDEX-10 experiment is the second phase of the CDEX experiment operated in the China Jinping Underground Laboratory(CJPL) with a 2400 m rock overburden [12, 13, 56]. CDEX-10 has three detector arrays named C10A(B, C). Each detector array comprises three p-type point contact germanium (PPCGe) detectors: Ge1, Ge2, and Ge3. The detectors are shielded with 20 cm high-purity oxygen-free copper and immersed in a liquid nitrogen cryostat. Details of the experimental setup can be found in Refs. [12, 13]. One of the detectors, C10B-Ge1, achieved the lowest analysis threshold (160 eVee, “eVee”represents the electron equivalent energy derived from energy calibration), with an exposure of 205.4 kg·day [57]. The data processing procedure includes data quality check, physics event selection, energy calibration, and bulk or surface event discrimination [13, 58]. The 0.16–2.16 keV spectrum after all event selections and efficiency corrections is used in this analysis. In this letter, we report the search results of keV/c^2 scale DM absorbed by electron using 205.4 kg·day exposure data from the CDEX-10 experiment with an energy threshold of 160 eVee.

Expected signal.— Fermionic DM is absorbed by the electron target via the following process:

$$\chi + e^- \rightarrow \nu + e^-, \quad (1)$$

where a DM particle χ is absorbed by an electron and a neutrino is emitted [53, 54].

In this analysis, for effective interaction, the vector type and axial-vector type operators are considered and can be written as follows [54]:

$$\begin{aligned} \mathcal{O}_{e\mu\chi}^V &= \frac{1}{\Lambda^2} (\bar{e}\gamma_\mu e)(\bar{\nu}_L \gamma^\mu \chi_L), \\ \mathcal{O}_{e\mu\chi}^A &= \frac{1}{\Lambda^2} (\bar{e}\gamma_\mu \gamma_5 e)(\bar{\nu}_L \gamma^\mu \chi_L), \end{aligned} \quad (2)$$

where the DM is treated as a Dirac particle, and the SM left-handed neutrino is considered. $1/\Lambda^2$ is the Wilson coefficient, with a dimension of [mass] $^{-2}$.

Considering the standard halo model, the DM velocity follows the Maxwell–Boltzmann distribution with a cutoff at the Galactic escape velocity $v_{\chi max} \sim 544 \text{ km/s}$, indicating that the DM is nonrelativistic. In the DM absorption process, the entire DM mass is released as energy of the final-state particles. The kinetic energy of DM $T_\chi \approx \frac{1}{2}m_\chi v_\chi^2$ can be neglected, $T_\chi/m_\chi \sim \mathcal{O}(10^{-6})$ [54].

The law of energy conservation gives

$$m_\chi + E_B^{nl} = q + E_R, \quad (3)$$

where m_χ is the mass of DM χ , E_B^{nl} ($E_B^{nl} < 0$) is the binding energy of the electron in the initial state (n, l) shell, q is the neutrino energy, and E_R is the electron recoil energy in final state.

The total detectable energy E_{det} can be expressed as follows:

$$E_{det} = E_R + |E_B^{nl}|, \quad (4)$$

where E_R is the electron recoil energy and $|E_B^{nl}|$ is the deexcitation energy. The deexcitation process contains characteristic x-rays and Auger electrons, with a total energy of $|E_B^{nl}|$.

Following the procedures in Refs. [53, 54], the expected differential event rate of the detectable energy can be expressed as follows:

$$\frac{dR}{dE_{det}} = N_T \frac{\rho_\chi}{m_\chi} \sum_{n,l} \frac{|\mathcal{M}(q)|^2}{64\pi m_\chi m_e^2} \frac{q}{E_{det} - |E_B^{nl}|} |f_{ion}^{nl}(k', q)|^2, \quad (5)$$

where N_T is the number of Ge atoms, ρ_χ is the local DM density taken as $0.3 \text{ GeV}/c^2/\text{cm}^3$ [59, 60], m_e is the electron mass, and $|f_{ion}^{nl}(k', q)|^2$ is the ionization form factor for an atomic orbit (n, l) [53, 61], which is calculated by modifying the public code **DarkART** [61, 62]. $k' = \sqrt{2m_e \cdot (E_{det} - |E_B^{nl}|)}$ is the final momentum of the outgoing electron, and $|\mathcal{M}(q)|^2$ is the scattering matrix element, which can be expressed as follows:

$$|\mathcal{M}^{V,A}(q)|^2 = (4, 12) \times \frac{4\pi m_e^2 q}{m_\chi} (\sigma_e v_\chi), \quad (6)$$

for $\mathcal{O}_{e\mu\chi}^V$ and $\mathcal{O}_{e\mu\chi}^A$, respectively [54]. σ_e is the total scattering cross section between the DM and free electron. For the tiny mass DM ($m_\chi \ll m_e$), σ_e can be expressed as follows:

$$\sigma_e = \frac{m_\chi^2}{4\pi\Lambda^4 v_\chi}, \quad (7)$$

Considering Ge, the expected energy spectra of fermionic DM absorbed by the electron target via a vector interaction are shown in Fig. 1, with $m_\chi = 2 \text{ keV}/c^2$ and $\sigma_e v_\chi = 10^{-45} \text{ cm}^2$.

Notably, the electronic band structures of Ge crystal are not considered in this study. Ge atoms are treated as isolated atoms. Only the contribution from core electrons, i.e., K , L , and M shells ($n = 1, 2, 3$), are considered. Because the electronic band structures near the band gap (N shell, $n = 4$, valence and conduction electronic states as stated in Ref. [63]) in Ge crystal are non-negligible and do not fit the assumption of isolated atoms.

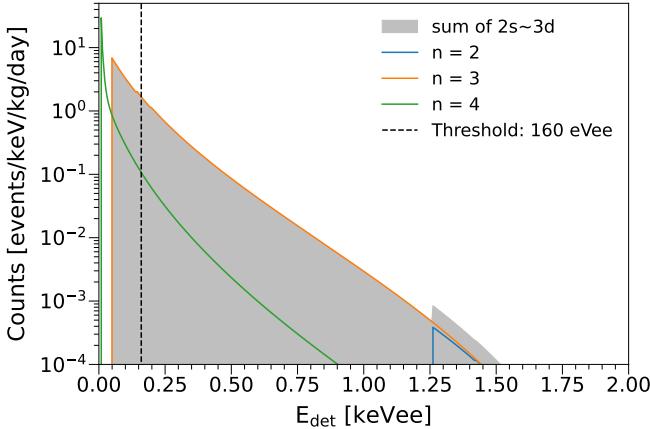


FIG. 1. Predicted visible energy spectra of the fermionic DM absorbed by electron targets of Ge for a vector-type operator for $m_\chi = 2 \text{ keV}/c^2$ and $\sigma_e v_\chi = 10^{-45} \text{ cm}^2$. Contributions by different shells of electrons are shown in different colors. The signals used in this analysis (summation from $1s$ to $3d$) are shown in gray shade. The Energy resolution is not considered in this figure.

TABLE I. Binding energies ($E_B^{n,l}$) of the electrons in Ge atom shells (n, l). (Data from [64])

n	$E_B^{n,l}$ [eV]		
	s	p	d
1	-1.1×10^4
2	-1.4×10^3	-1.3×10^3	...
3	-2.0×10^2	-1.4×10^2	-44
4	-15	-7.8	...

Treating Ge atoms as isolated atoms and only the contribution from core electrons (K , L , and M shells) are considered make our results conservative.

In Fig. 1, K -shell electrons cannot be ionized due to small m_χ . When $m_\chi > |E_B^{1,0}|$, contribution by K -shell electrons will be taken into account. The binding energies of electrons in different Ge atom shells are summarized in Table I. Figure 2 shows the spectra used in this analysis considering the detector energy resolution. The energy resolution of C10B-Ge1 is $\sigma(E) = 35.8 \times 10^{-3} + 16.6 \times 10^{-3}\sqrt{E}$ [42], where E and $\sigma(E)$ are in keV.

Data analysis.— Data used in this analysis are obtained from CDEX-10, specifically from the C10B-Ge1 detector between February 2017 and August 2018, with an exposure of 205.4 kg·day [57]. The sensitive mass of C10B-Ge1 is 939 g with a dead layer thickness of 0.88 ± 0.12 mm [11, 13]. After a series of data processing procedures, we derive the physics spectrum. The analysis threshold is set to be 160 eVee with a combined efficiency of 4.5%. In the interest energy range of 0.16–2.16 keVee, background events are composed of the radioactivity from cosmogenic isotopes inside the de-

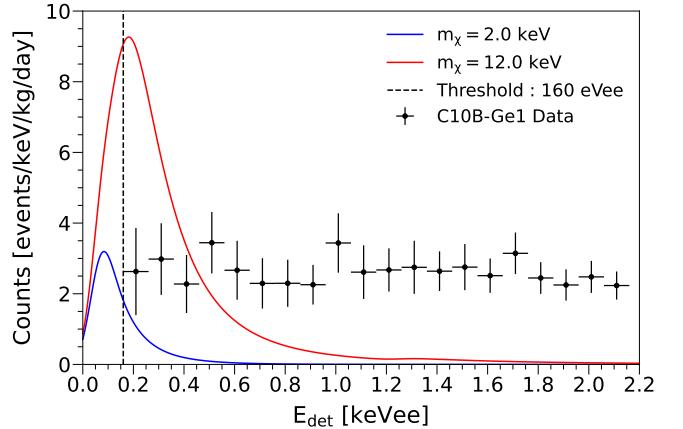


FIG. 2. Observable energy spectra of fermionic DM absorbed by electrons for DM mass of $2 \text{ keV}/c^2$ (blue) and $12 \text{ keV}/c^2$ (red) via a vector interaction with $\sigma_e v_\chi = 10^{-45} \text{ cm}^2$. The energy resolution is considered in this plot. Data from CDEX-10 with a 205.4 kg·day exposure are shown in black points with error bars; the bin width is 100 eVee.

tector and Compton scattering events from high-energy gamma rays. The radioactivity from cosmogenic isotopes are L - and M -shell x-ray peaks of cosmogenic isotopes, including ^{68}Ge , ^{68}Ga , ^{65}Zn , ^{55}Fe , ^{54}Mn , and ^{49}V . The K -shell peaks in 4–12 keVee spectrum are fitted to limit the intensity of their corresponding L - and M - shell peaks using the known K/L and K/M ratios. After fitting and subtracting L - and M -shell x-ray peaks, the residual spectrum used in this analysis is derived [12, 42, 57].

The χ^2 analysis [65] is applied in this work; the χ^2 function is defined as follows:

$$\chi^2(m_\chi, \sigma_e v_\chi) = \sum_{i=1}^N \frac{[n_i - S_i(m_\chi, \sigma_e v_\chi) - B]^2}{\sigma_{i,\text{stat}}^2 + \sigma_{i,\text{syst}}^2}, \quad (8)$$

where n_i is the experimental data in the i -th energy bin, S_i is DM signals in the i -th energy bin, B is the expected flat background contributed by the Compton scattering of high-energy γ rays. $\sigma_{i,\text{stat}}$ and $\sigma_{i,\text{syst}}$ are the statistical and systematic uncertainties in the i -th energy bin, respectively.

The DM signal is fitted using the minimum- χ^2 method [65] for a given DM mass m_χ . An example of best fit of $m_\chi = 12 \text{ keV}/c^2$ is illustrated in Fig. 3. Since no significant DM signals over the background are observed, an upper limit with 90% confidence level (C.L.) is derived using the Feldman–Cousins method [66]. Figure 4 (a) and (b) shows the exclusion results of vector and axial-vector operators, respectively. The upper limit on the cross section is set to be $5.5 \times 10^{-46} \text{ cm}^2$ for vector interaction, and $1.8 \times 10^{-46} \text{ cm}^2$ for axial-vector interaction at DM mass of $5 \text{ keV}/c^2$.

Since the observed value of DM relic density from the Planck Collaboration [67] avoided DM overproduction through the “freeze-in” mechanism [68], the DM decay

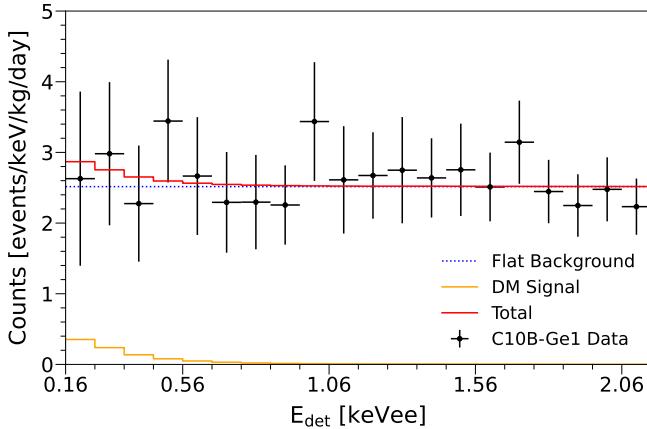


FIG. 3. The residual spectrum from CDEX-10 where the L - and M -shell x-ray contributions are subtracted (black point with error bar), together with the best-fit signal (orange histogram) for $m_\chi = 12 \text{ keV}/c^2$. The dotted blue histogram is the best fit for a flat background. The red histogram is the summation of the best fits of signal and flat background.

in invisible mode $\chi \rightarrow 3\nu$ would have injected more radiation into the early universe and hence will be limited by the Hubble constant and matter power spectrum [54]. The dominant visible mode of the DM decay for axial-vector operator $\chi \rightarrow \gamma\gamma\nu$ would contribute to X(gamma)-ray observations around the Earth, which will be limited by X(gamma)-ray fluxes from astrophysics observations [54]. For the vector operator, due to the gauge symmetry and quantum electrodynamics (QED) charge conjugation symmetry, $\chi \rightarrow \gamma\nu$ and $\chi \rightarrow \gamma\gamma\nu$ cannot arise. The dominant visible decay channel is $\chi \rightarrow \gamma\gamma\gamma\nu$, which is also limited by X(gamma)-ray fluxes from astrophysics observation. The constraints from $\chi \rightarrow 3\nu$ for both operators and $\chi \rightarrow \gamma\gamma\nu$ for the axial-vector operator are depicted in Fig. 4. The constraint from DM overproduction and $\chi \rightarrow \gamma\gamma\gamma\nu$ are not shown, which are outside the selected parameter space.

Among the direct detection experiments, results from PandaX-4T using a liquid xenon time projection chamber [55] presents the most stringent constraints on the fermionic DM in the mass range of 35–55 (25–45) keV/c^2 for the vector (axial-vector) operator compared with constraints from x-ray satellites and large-scale observations. We place new constraints on the fermionic DM absorbed by electron targets for a lower DM mass below 10 keV/c^2 because of the low detector threshold of Ge semiconductor detectors used in CDEX experiment.

Summary.— In this letter, we report the constraints on $\sigma_e v_\chi$ for fermionic DM absorption by electron targets using data from the CDEX-10 experiment with an exposure of 205.4 kg-day. Comparing with $\chi + A \rightarrow \nu + A$, which is only sensitive to DM in the MeV/c^2 mass scale, $\chi + e^- \rightarrow \nu + e^-$ can explore lighter DM to as low as few keV/c^2 . The expected DM signals of the DM mass

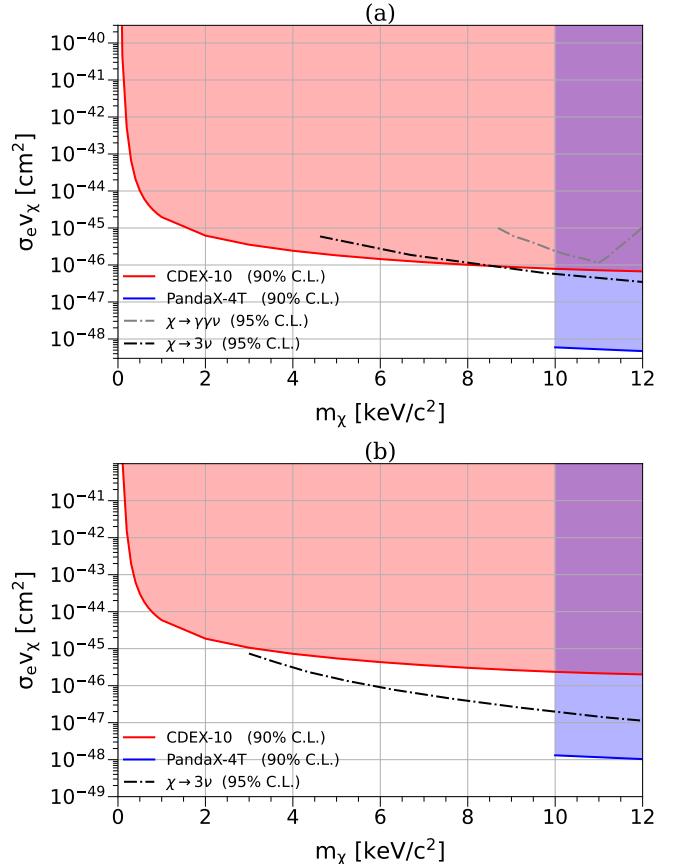


FIG. 4. The 90% confidence level (C.L.) exclusion limits on $\sigma_e v_\chi$ of the fermionic DM absorbed by electron target for the (a) axial-vector operator and (b) vector operator from CDEX-10 is shown in red. Results from PandaX-4T [55] (blue) are superimposed. The exclusion regions of direct detection experiments are shown with shade. Results of DM invisible decay($\chi \rightarrow 3\nu$) for both operators and DM visible decay($\chi \rightarrow \gamma\gamma\nu$) for the axial-vector operator are also shown (dashed dot line) [54, 67].

range of 0.1–10 keV/c^2 are analyzed together with the experiment spectrum from 160 eVee to 2.16 keVee using a χ^2 analysis method. With the analysis threshold of 160 eVee, we present new constraints on $\sigma_e v_\chi$ of the fermionic DM absorbed by electron targets in the DM range of 0.1–10 keV/c^2 for vector and axial-vector operators. Our limits reach the current lowest fermionic DM mass in direct detection experiments.

This work was supported by the National Key Research and Development Program of China (Grants No. 2023YFA1607100 and No. 2022YFA1605000) and the National Natural Science Foundation of China (Grants No. 12322511, No. 12175112, No. 12005111, and No. 11725522). We would like to thank CJPL and its staff for hosting and supporting the CDEX project. CJPL is jointly operated by Tsinghua University and Yalong River Hydropower Development Company.

-
- * Corresponding author: yanglt@mail.tsinghua.edu.cn
 † Corresponding author: yueq@mail.tsinghua.edu.cn
 ‡ Participating as a member of TEXONO Collaboration
- [1] A. Cho, *Science* **339**, 1513 (2013).
 - [2] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **131**, 041003 (2023).
 - [3] J. Aalbers *et al.* (LUX-ZEPLIN Collaboration), *Phys. Rev. Lett.* **131**, 041002 (2023).
 - [4] S. Li *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **130**, 261001 (2023).
 - [5] P. Agnes *et al.* (DarkSide Collaboration), *Phys. Rev. Lett.* **121**, 081307 (2018).
 - [6] R. Agnese *et al.* (SuperCDMS Collaboration), *Phys. Rev. D* **97**, 022002 (2018).
 - [7] S. K. Liu *et al.* (CDEX Collaboration), *Phys. Rev. D* **90**, 032003 (2014).
 - [8] W. Zhao *et al.* (CDEX Collaboration), *Phys. Rev. D* **88**, 052004 (2013).
 - [9] Q. Yue *et al.* (CDEX Collaboration), *Phys. Rev. D* **90**, 091701 (2014).
 - [10] W. Zhao *et al.* (CDEX Collaboration), *Phys. Rev. D* **93**, 092003 (2016).
 - [11] L. T. Yang *et al.* (CDEX Collaboration), *Chin. Phys. C* **42**, 023002 (2018).
 - [12] H. Jiang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **120**, 241301 (2018).
 - [13] H. Jiang *et al.* (CDEX Collaboration), *Sci. China Phys. Mech. Astron.* **62**, 31012 (2019).
 - [14] L. T. Yang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **123**, 221301 (2019).
 - [15] Z. Z. Liu *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **123**, 161301 (2019).
 - [16] D. S. Akerib *et al.* (LUX Collaboration), *Phys. Rev. Lett.* **122**, 131301 (2019).
 - [17] Z. Z. Liu *et al.* (CDEX Collaboration), *Phys. Rev. D* **105**, 052005 (2022).
 - [18] G. Angloher *et al.* (CRESST Collaboration), *Eur. Phys. J. C* **77**, 637 (2017).
 - [19] J. A. Dror, G. Elor, and R. McGehee, *Phys. Rev. Lett.* **124**, 181301 (2020).
 - [20] J. A. Dror, G. Elor, and R. McGehee, *J. High Energy Phys.* **02**, 134 (2020).
 - [21] L. Gu *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **129**, 161803 (2022).
 - [22] I. J. Arnquist *et al.* (Majorana Collaboration), *Phys. Rev. Lett.* **132**, 041001 (2024).
 - [23] W. H. Dai *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **129**, 221802 (2022).
 - [24] W. Chao, M. Jin, and Y.-Q. Peng, *Phys. Rev. D* **107**, 093009 (2023).
 - [25] T. Li, J. Liao, and R.-J. Zhang, *J. High Energy Phys.* **05**, 071 (2022).
 - [26] A. Aguilar-Arevalo *et al.* (DAMIC Collaboration), *Phys. Rev. Lett.* **123**, 181802 (2019).
 - [27] P. Agnes *et al.* (DarkSide Collaboration), *Phys. Rev. Lett.* **121**, 111303 (2018).
 - [28] Q. Arnaud *et al.* (EDELWEISS Collaboration), *Phys. Rev. Lett.* **125**, 141301 (2020).
 - [29] C. Cheng *et al.* (PandaX-II Collaboration), *Phys. Rev. Lett.* **126**, 211803 (2021).
 - [30] L. Barak *et al.* (SENSEI Collaboration), *Phys. Rev. Lett.* **125**, 171802 (2020).
 - [31] D. W. Amaral *et al.*, *Phys. Rev. D* **102**, 091101 (2020).
 - [32] R. Essig, T. Volansky, and T.-T. Yu, *Phys. Rev. D* **96**, 043017 (2017).
 - [33] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **123**, 251801 (2019).
 - [34] Z. Y. Zhang *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **129**, 221301 (2022).
 - [35] T. Bringmann and M. Pospelov, *Phys. Rev. Lett.* **122**, 171801 (2019).
 - [36] Z. H. Lei, J. Tang, and B. L. Zhang, *Chin. Phys. C* **46**, 085103 (2022).
 - [37] C. Xia, Y.-H. Xu, and Y.-F. Zhou, *Nucl. Phys. B* **969**, 115470 (2021).
 - [38] C. V. Cappiello and J. F. Beacom, *Phys. Rev. D* **100**, 103011 (2019).
 - [39] Y. Ema, F. Sala, and R. Sato, *Phys. Rev. Lett.* **122**, 181802 (2019).
 - [40] J. B. Dent, B. Dutta, J. L. Newstead, and I. M. Shoemaker, *Phys. Rev. D* **101**, 116007 (2020).
 - [41] X. Cui *et al.* (PandaX-II Collaboration), *Phys. Rev. Lett.* **128**, 171801 (2022).
 - [42] R. Xu *et al.* (CDEX Collaboration), *Phys. Rev. D* **106**, 052008 (2022).
 - [43] M. Pospelov, A. Ritz, and M. Voloshin, *Phys. Rev. D* **78**, 115012 (2008).
 - [44] H. An, M. Pospelov, J. Pradler, and A. Ritz, *Phys. Lett. B* **747**, 331 (2015).
 - [45] Y. Hochberg, T. Lin, and K. M. Zurek, *Phys. Rev. D* **94**, 015019 (2016).
 - [46] Y. Hochberg, T. Lin, and K. M. Zurek, *Phys. Rev. D* **95**, 023013 (2017).
 - [47] I. M. Bloch *et al.*, *J. High Energy Phys.* **06**, 087 (2017).
 - [48] D. Green and S. Rajendran, *J. High Energy Phys.* **10**, 013 (2017).
 - [49] A. Arvanitaki, S. Dimopoulos, and K. Van Tilburg, *Phys. Rev. X* **8**, 041001 (2018).
 - [50] B. von Krosigk *et al.*, *Phys. Rev. D* **104**, 063002 (2021).
 - [51] A. Mitridate, T. Trickle, Z. Zhang, and K. M. Zurek, *J. High Energy Phys.* **09**, 123 (2021).
 - [52] Y. Hochberg *et al.*, *Phys. Rev. Lett.* **128**, 191801 (2022).
 - [53] J. A. Dror, G. Elor, R. McGehee, and T.-T. Yu, *Phys. Rev. D* **103**, 035001 (2021).
 - [54] S.-F. Ge, X.-G. He, X.-D. Ma, and J. Sheng, *J. High Energy Phys.* **05**, 191 (2022).
 - [55] D. Zhang *et al.* (PandaX Collaboration), *Phys. Rev. Lett.* **129**, 161804 (2022).
 - [56] J. P. Cheng *et al.*, *Annu. Rev. Nucl. Part. Sci.* **67**, 231 (2017).
 - [57] Z. She *et al.* (CDEX Collaboration), *Phys. Rev. Lett.* **124**, 111301 (2020).
 - [58] L. T. Yang *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect A* **886**, 13 (2018).
 - [59] D. Baxter *et al.*, *Eur. Phys. J. C* **81**, 907 (2021).
 - [60] J.D. Lewin and P.F. Smith, *Astropart. Phys.* **6**, 87 (1996).
 - [61] R. Catena, T. Emken, N. A. Spaldin, and W. Tarantino, *Phys. Rev. Res.* **2**, 033195 (2020).
 - [62] T. Emken, “Dark Atomic Response Tabulator (DarkART)[Code, v0.1.0],” The code can be found under <https://github.com/temken/darkart>. (2021).
 - [63] S. M. Griffin, K. Inzani, T. Trickle, Z. Zhang, and K. M. Zurek, *Phys. Rev. D* **104**, 095015 (2021).
 - [64] C.F. Bunge, J.A. Barrientos, and A.V. Bunge, *At. Data*

- Nucl. Data Tables **53**, 113 (1993).
- [65] Q. Yue *et al.* (CDEX Collaboration), Phys. Rev. D **90**, 091701 (2014).
- [66] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873 (1998).
- [67] N. Aghanim *et al.* (Planck Collaboration), Astron. Astrophys. **641**, A6 (2020).
- [68] G. F. Abellán, R. Murgia, and V. Poulin, Phys. Rev. D **104**, 123533 (2021).