

Neutrino magnetic dipole portal with low energy neutrino nucleus scattering data

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We scrutinize neutrino magnetic dipole portals of sterile neutrinos in the mass range of 0.1–50 MeV through the nuclear and electron recoils at neutrino scattering experiments. For the e -flavor dipole portal, we show that Dresden-II can provide leading constraints for $m_N \lesssim 0.5$ MeV, setting aside unresolved theoretical uncertainties. For the μ -flavor case, we employ a two-dimensional fitting method which could utilize the timing structure measurement of the full dataset collected by the CsI[Na] scintillation detector. With such, we demonstrate that the COHERENT experiment can probe a wide unique parameter region for m_N in the range of 10–40 MeV. Exclusion regions for τ -flavor dipole portal based on latest measurements of the solar neutrino from dark matter direct detection experiments are also presented.

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I. INTRODUCTION

Observations of nonzero neutrino mass point to physics beyond the Standard Model, which generically extends the neutrino sector with new singlet fermionic states. These new states, dubbed as sterile neutrinos, can couple to the Standard Model (SM) sector via its mixing with active neutrinos at the renormalizable level (see, e.g., the review in [1]). Sterile neutrinos can also couple to the SM sector via the neutrino dipole portal (NDP) described by the following dimension-five operator [2,3]

$$\mathcal{L}_{\text{NDP}} \supset \frac{d_\alpha}{2} (\bar{N} \sigma_{\mu\nu} \nu^\alpha F^{\mu\nu}) + \text{H.c.} \quad (1)$$

where ν^α is the active neutrino of flavor α , N is the sterile neutrino, and d_α is the neutrino transitional magnetic moment. Without specifying the flavor, we will denote d_α as d . In the last few years, significant attention has been paid to search for N via this dipole portal. In the high sterile neutrino mass m_N regime, the Large Electron-Positron Collider and LHC can probe the magnetic moment at

the level of $d \sim 1/(10^3 \text{ GeV})$ [4]. In the sub-GeV mass region, sterile neutrinos produced from supernova explosion can escape and carry away energies. The energy loss requirements can exclude the band $1/(10^7 \text{ GeV}) \gtrsim d \gtrsim 1/(10^{11} \text{ GeV})$ [4]. Below this cooling band, looking for decay products of sterile neutrino originated from supernova explosion at neutrino detectors [5,6] and γ -ray telescopes [5] can probe even smaller values of d .

To probe the parameter regions above the cooling band, high intensity beam dump and neutrino experiments are the main tools under consideration. There are searches via measuring neutrino scattering spectrum distortions at dark matter detectors [7,8], upscattering of solar and atmospheric neutrinos to N which decay at detectors [9,10], upscattering at forward LHC detectors [11], Borexino $e - \nu$ scattering [8,12], CHARM-II $e - \nu$ scattering [13,14], etc. With these efforts, parameter regions above the cooling band for $m_N \lesssim 10$ MeV can be comprehensively probed, while for larger m_N up to 50 MeV, existing studies can cover the parameter region to $d \gtrsim 1/(2 \times 10^6 \text{ GeV})$, leaving an unexplored regions for smaller d .

On the other hand, the vast number of neutrinos produced from reactors and spallation neutron source (SNS) are energetic enough to produce N with $m_N \gtrsim \text{MeV}$ via upscattering. Once this happens, this process will modify the neutrino scattering data from the SM predictions and can thus be probed at experiments. Given its more energetic spectrum, upscattering of neutrinos from SNS can produce sterile neutrinos as heavy as 50 MeV, which might cover the unexplored parameter regions mentioned above.

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Until recently, coherent elastic neutrino-nucleus scattering (CE ν NS) has been observed by the COHERENT Collaboration [15], and a suggestive evidence of this process has also been reported by the Dresden-II experiment [16] with reactor antineutrinos. Elastic neutrino-electron scattering (E ν ES), a concurrent process to CE ν NS, can contribute similarly to the scattering data and may not be separated from CE ν NS. These scattering data have been utilized to search for N via the dipole portal recently [17–19] based on the measured energy spectra.

In this work, with the full dataset collected at the CsI[Na] detector from the COHERENT experiment [20,21] at hand, we will employ a two-dimensional fitting method to utilize the precise timing structure measurements in the probe of sterile neutrinos. As we will demonstrate, the timing structure is particularly powerful in the case of flavor-specific neutrino dipole portals d_α in which N couples only to active neutrinos of flavor α . This method can potentially enhance such searches and be applied to other new physics searches in general. We will also consider the latest measurements of solar neutrino fluxes by PandaX-4T and Xenon1T experiments and present their potentials in the probe of N via the dipole portal of the τ flavor.

II. CE ν NS AND E ν ES IN THE STANDARD MODEL

The differential cross section of the CE ν NS process between neutrino with energy E_ν and a nucleus in the SM can be written as [22–26]

$$\frac{d\sigma_{\text{SM}}^{\nu-N}}{dT_n}(E_\nu, T_n) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) (Q_V^{\text{SM}})^2, \quad (2)$$

where T_n is the kinetic energy of nuclear recoil, M is the nucleus mass, and G_F is the Fermi constant. The cross section of CE ν NS benefits from the coherent effect and is enhanced based on the square of the weak charge of the nucleus Q_V^{SM} , which can be written as

$$Q_V^{\text{SM}} = g_V^p Z F_Z(|\vec{q}|^2) + g_V^n N_n F_N(|\vec{q}|^2) \quad (3)$$

for a nucleus with Z protons and N_n neutrons at the given the momentum transfer $\vec{q}$. The vector neutrino-proton coupling g_V^p and the vector neutrino-neutron coupling g_V^n are given by

$$\begin{aligned} g_V^p(\nu_e) &= 0.0401, & g_V^p(\nu_\mu) &= 0.0318, \\ g_V^p(\nu_\tau) &= 0.0275, & g_V^n &= -0.5094, \end{aligned} \quad (4)$$

employing the radiative corrections in the $\overline{\text{MS}}$ scheme [27]. $F_{Z,N}(|\vec{q}|^2)$ are the form factors of nucleon distributions in the nucleus, and we will employ the Helm parametrization [28]. Note that the cross section for CE ν NS in the SM is universal for neutrinos of different flavors and the

minimum neutrino energy to produce a recoil kinetic energy T_n is $E_{\min} = \sqrt{MT_n/2}$ in the region $T_n \ll M$.

The differential cross section of the E ν ES process between a neutrino and the electrons with mass m_e in the target can be written as [25]

$$\begin{aligned} \frac{d\sigma_{\text{SM}}^{\nu-e}}{dT_e}(E, T_e) &= Z_{\text{eff}}^A(T_e) \frac{G_F^2 m_e}{2\pi} \left[(g_V^{\nu_l} - g_A^{\nu_l})^2 \left(1 - \frac{T_e}{E}\right)^2 \right. \\ &\quad \left. + (g_V^{\nu_l} + g_A^{\nu_l})^2 - ((g_V^{\nu_l})^2 - (g_A^{\nu_l})^2) \frac{m_e T_e}{E^2} \right], \end{aligned} \quad (5)$$

where T_e is the kinetic energy of electron recoil. The cross section is not universal for the electron neutrino and the neutrinos of the other two flavors since an electron neutrino can uniquely scatter with an electron through charged current process. This difference is represented with the flavor-dependent neutrino-electron couplings

$$\begin{aligned} g_V^{\nu_e} &= 2\sin^2\theta_W + 1/2, & g_A^{\nu_e} &= 1/2, \\ g_V^{\nu_{\mu,\tau}} &= 2\sin^2\theta_W - 1/2, & g_A^{\nu_{\mu,\tau}} &= -1/2. \end{aligned} \quad (6)$$

For antineutrinos, the vector couplings are given by $\bar{g}_V^{\nu_l} = g_V^{\nu_l}$ while the axial couplings satisfy the relation $\bar{g}_A^{\nu_l} = -g_A^{\nu_l}$. As the cross section is derived based on the free electron approximation hypothesis, where the electrons are considered to be free and rest in the materials [29–32], the effective electron charge term $Z_{\text{eff}}^A(T_e)$ is employed to quantify the number of electrons that can be ionized with the deposited recoil kinetic energy T_e [33–35].

III. NEUTRINO DIPOLE PORTAL

Sterile neutrinos can be produced via the active neutrino upscattering through the neutrino magnetic dipole portal. The cross section of producing N of mass m_N via neutrino-nucleus scattering can be written as [7,8]

$$\begin{aligned} \frac{d\sigma_{\text{NDP}}^{\nu-N}}{dT_n} &= d^2 \alpha_{\text{EM}} Z^2 F_Z^2(|\vec{q}|^2) \left[-\frac{m_N^2}{2E_\nu M T_n} \left(1 - \frac{M - T_n}{2E_\nu}\right) \right. \\ &\quad \left. - \frac{m_N^4 (M - T_n)}{8E_\nu^2 M^2 T_n^2} + \frac{1}{T_n} - \frac{1}{E_\nu} \right], \end{aligned} \quad (7)$$

where α_{EM} is the fine structure constant. Contributions to Eq. (7) from nuclear magnetic moments, without the Z^2 enhancement, are subdominant and neglected [8]. The active neutrino masses are negligibly small comparing to m_N , E_ν , and T_n . As only protons contribute to this process, the enhancement factor only depends on Z .

The cross section of neutrino-electron scattering via the dipole portal can be written similarly as [8]

$$\frac{d\sigma_{\text{NDP}}^{\nu-e}}{dT_e} = d^2\alpha_{\text{EM}} \left[-\frac{m_N^2}{2E_\nu m_e T_e} \left(1 - \frac{m_e - T_e}{2E_\nu} \right) - \frac{m_N^4(m_e - T_e)}{8E_\nu^2 m_e^2 T_e^2} + \frac{1}{T_e} - \frac{1}{E_\nu} \right]. \quad (8)$$

Since the target electron is much lighter than the nucleus and the recoiled electron will take away a considerable amount of the deposited energy, the minimum neutrino energy to produce a massive sterile neutrino in the $\nu - e$ upscattering is larger than that in the $\nu - \mathcal{N}$ scattering case [36].

IV. EXPECTED EVENT SPECTRA

To probe flavor-specific magnetic dipole portal d_α for m_N in the range 0.1–50 MeV, we consider experiments with a large neutrino flux of flavor α . This is to consider experiments with neutrino sources from reactor, SNS, and the Sun for $\alpha = e$, $\alpha = \mu$, and $\alpha = \tau$, respectively.

For $\alpha = e$, we consider the measurements of the large $\bar{\nu}_e$ flux from the Dresden-II reactor based on the data collected by a 3 kg ultralow noise germanium detector in an exposure of 96.4 days [16]. The reactor $\bar{\nu}_e$ spectra are obtained from the weighted average of $\bar{\nu}_e$ fluxes from isotopes ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu . We will employ the $\bar{\nu}_e$ fluxes predicted from Ref. [37] to construct the expected $\bar{\nu}_e$ spectra above 2 MeV and for the low energy part we rely on the $\bar{\nu}_e$ fluxes predicted from Ref. [38]. In the CE ν NS process, part of the nuclear recoil energy T_n will be transformed into the electron-equivalent recoil energy T_e described as the quenching effect $T_e(T_n)$. The CE ν NS event number in each T_e bin can be calculated as

$$N_i^{\text{CE}\nu\text{NS}}(\mathcal{N}) = N_{Ge} dt \int_{T_e^i}^{T_e^{i+1}} dT_e \int_{T_n^{\text{min}}}^{T_n^{\text{max}}} dT_n R(T_e, T_e(T_n)) \times \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{dN_{\bar{\nu}_e}}{dE}(E) \frac{d\sigma^{\bar{\nu}_e-e}}{dT_n}(E, T_n), \quad (9)$$

where $\mathcal{N}$ denotes different germanium isotopes and $N_{Ge} = 2.43 \times 10^{25}$ is the number of germanium atoms in the detector. The energy resolution function $R(T_e, T_e(T_n))$ can be described as a truncated Gaussian [25], and later, in [26], an uncertainty on the normalization of the antineutrino flux was used, which we will adopt here. The total CE ν NS event number is integrating over contributions from different isotopes. The theoretical E ν ES event number in each T_e bin can be expressed in a similar way as

$$N_i^{\text{E}\nu\text{ES}}(\mathcal{N}) = N_e dt \int_{T_e^i}^{T_e^{i+1}} dT_e \int_{T_e^{\text{min}}}^{T_e^{\text{max}}} dT_e' R(T_e, T_e') \times \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{dN_{\bar{\nu}_e}}{dE}(E) \frac{d\sigma^{\bar{\nu}_e-e}}{dT_e'}(E, T_e'), \quad (10)$$

where $N_e = ZN_{Ge}$ is the total electron number in the detector with $Z = 32$ being the germanium atomic number.

For neutrinos sources of flavor $\alpha = \mu$ produced from SNS, we consider the full dataset collected by the CsI[Na] detector¹ released by the COHERENT Collaboration [20,21]. The CsI data contain complete information on the energy and arrival time of the observed events. The neutrino fluxes from SNS include a monochromatic component of ν_μ flux from pion decay at rest $\pi^+ \rightarrow \mu^+ + \nu_\mu$, two components of $\bar{\nu}_\mu$ and ν_e that are produced in the subsequent muon decay $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$. The maximum energy of $\bar{\nu}_\mu$ and ν_e fluxes is about half of the muon mass $m_\mu/2 \simeq 52.8$ MeV. Since the ν_μ flux is from the pion decay, earlier than the production of $\bar{\nu}_\mu$ and ν_e fluxes from muon decay, its arrival is within about 1 μs after the beam-on trigger, while the arrival of the other two fluxes is delayed with a time interval of up to 10 μs . Therefore, the time information is crucial to distinguish signals induced by the ν_μ fluxes from those induced by other fluxes. As SNS also provides large neutrino flux of the e flavor, CaI data can be employed to probe d_e . The theoretical CE ν NS and E ν ES events can be calculated similar to that in Eqs. (9) and (10), respectively, but with the quenching factor and the detector geometry replaced accordingly.

For $\alpha = \tau$, we consider the solar ^8B neutrino flux that is produced from the fusion process inside the Sun and including neutrinos of all three flavors after oscillation. The total neutrino-nucleus scattering events $N_{\text{NDP}}^{\nu-\mathcal{N}}(\mathcal{N})$ for different isotopes $\mathcal{N}$ induced by sterile neutrino are

$$N_{\text{NDP}}^{\nu-\mathcal{N}}(\mathcal{N}) = \frac{\epsilon}{M} \int_{T_{\text{min}}}^{T_{\text{max}}} dT \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\nu \times \Phi^{\nu_\tau}(E_\nu) \eta(E_\nu) \frac{d\sigma_{\text{NDP}}^{\nu_\tau-\mathcal{N}}}{dT_n}, \quad (11)$$

where ϵ is the detector exposure, $M = 131.293$ g/mol is the isotope averaged mole mass of xenon, and $\Phi^{\nu_\tau}(E_\nu)$ is the ν_τ component in the ^8B neutrino flux. $\eta(E_\nu)$ is the energy-dependent detector efficiencies for PandaX-4T [40] and XENON1T [41], which is smaller than 1% when $T_n \lesssim \text{keV}$.

In Fig. 1, we present the expected event spectra of the CE ν NS process for the Dresden-II reactor antineutrino source with germanium detector, COHERENT experiment with CsI detector, and solar neutrino source with xenon detector, targeting d of specific flavor α from top to bottom. As we aim to illustrate the impact of d_α on the event spectra, we have set $\eta(E_\nu) = 1$, $T_e(T_n) = T_n$ and $R(T_e, T_e') = \delta(T_e - T_e')$ for simplicity. Spectra for the SM and for the case with light N ($m_N = 1$ MeV) considering

¹Given that a smaller number of events can be detected and the background is much larger [20,39], we have neglected the Ar dataset from COHERENT in our analysis.

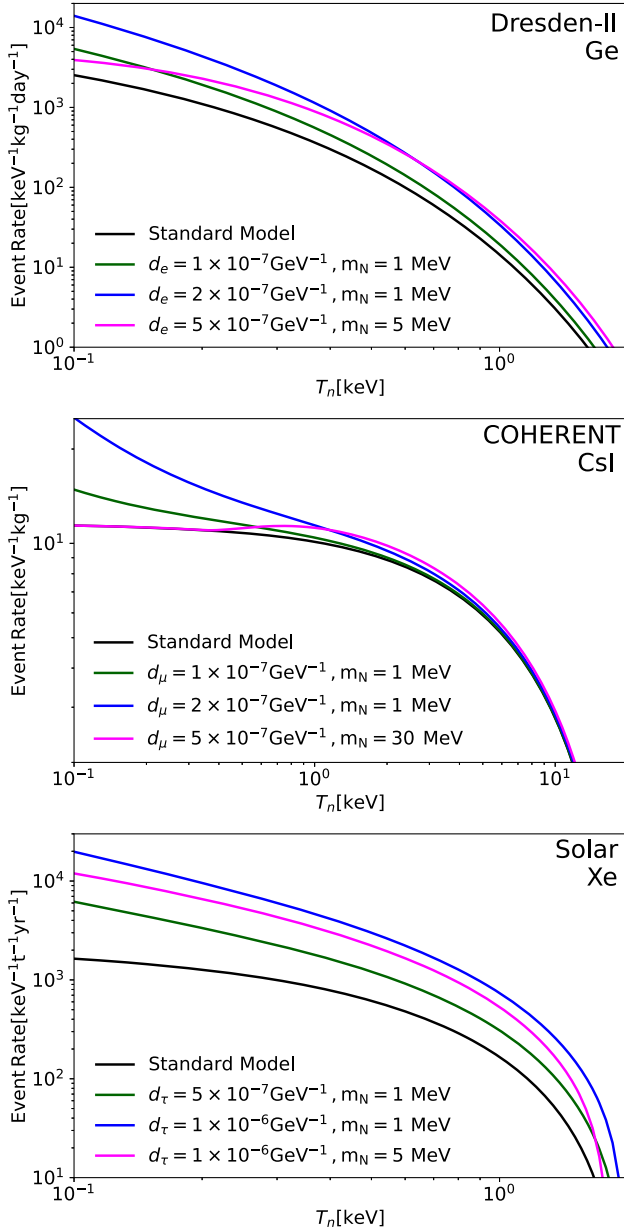


FIG. 1. Event rate of CE ν NS in germanium, CsI, and xenon detectors with the corresponding sources of Dresden-II reactor, COHERENT SNS, and solar neutrino, respectively, from top to bottom. The black lines show the event rate in the SM and the blue, green, and purple lines show the event rate in the presence of N for benchmarks of different m_N and d_α .

two different d_α values are shown. For these cases, the upscattering events are significantly increased at lower T_n , which will be the main contribution to the improvements on probing N . We also present the spectra for a heavier N with $m_N = 5$ MeV and a larger d_α (magenta line), where the event rate is suppressed as compared to the light N case (blue line), given that higher E_ν is required for the upscattering to happen in the heavy N case. Also, it should be noted that the spectra on the CsI detector, with SNS neutrinos of energy as high as 52.8 MeV, can expand to a

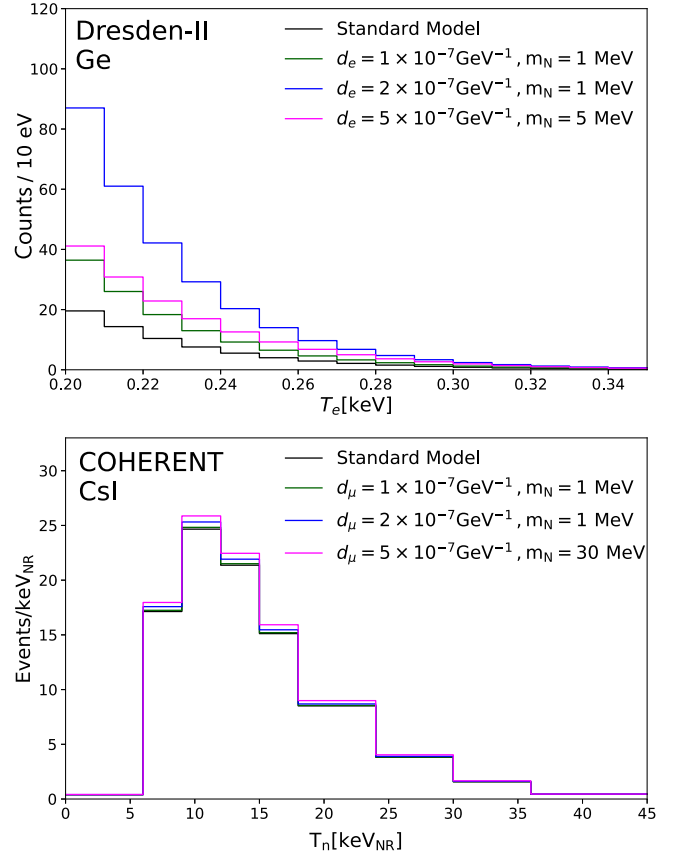


FIG. 2. Event rate of CE ν NS in germanium, CsI, and xenon detectors with the corresponding sources of the Dresden-II reactor and COHERENT SNS, respectively, from top to bottom. The color code is the same as that in Fig. 1.

higher T_n of around 10 keV. The reactor source and solar source exhibit similar shapes for the recoil energy spectra, while the reactor produces neutrino fluxes that are orders of magnitude larger.

With the realistic resolution function $R(T'_e, T_e(T_n))$, detector efficiencies $\eta(E_\nu)$, and quenching factors $T_e(T_n)$ included, we present the corresponding event rate of CE ν NS in germanium and CsI detectors in Fig. 2, which qualitatively preserves the behaviors aforementioned in Fig. 1. For the case of CsI detectors, we include all eight energy bins and the presence of a magnetic dipole portal significantly affects the event numbers in the first four energy bins.

V. CONSTRAINTS

In this section, we present the parameter regions that can be probed for d_α of each flavor. Considering Dresden-II, predictions of quenching effect from the Lindhard theory is in good agreement with the experimental data for T_e around the keV range [42,43]. However, recently, in [44], unexpected enhancements on quenching factor for T_e in the sub-keV region are observed [44], which is in great tension with the Lindhard theory. Therefore, we will consider two more

commonly used quenching models that are obtained from considering a photoneutron source (YBe) and iron-filtered monochromatic neutron beam (Fef) [44] at $k = 0.157$ [45]. For CsI data from COHERENT experiment, only the Fef quenching model is employed. In order to include the time information of the CsI data, we calculate the predicted event number $N_{ij}(\mathcal{N})$ at the energy bin i and time bin j from the neutrino flux with both energy and time dependence. We then employ the Poissonian least-squares function to analyze the data from Dresden-II and COHERENT following [26].

In Fig. 3, we present the 90% C.L. constraints on d_α as a function of m_N . Given that the neutrino energy for upscattering to N in the $\nu - \mathcal{N}$ process can be smaller than that in the $\nu - e$ process [36], signals from the $\text{CE}\nu\text{NS}$ process dominate the contribution to these constraints for $m_N \gtrsim \text{MeV}$, while at lower m_N , the contribution from $\text{E}\nu\text{ES}$ prevails. Constraints from other experiments are also shown for comparison, among which the constraints from SN1987A [3] consider flavor universal dipole portals. For the d_e case, the constraints are shown in the top plot of Fig. 3 using quenching models of Lindhard theory, YBe, and Fef separately. The YBe and Fef quenching models enhance the response of germanium detector in the sub-keV energy range and significantly improve the constraints on d_e . The dense reactor antineutrino flux provides stringent constraints at low mass range that exceed the existing limits obtained at Borexino and Super-K by searching for solar neutrino upscattering to N with subsequent decays (cyan dashed line) [10] and at TEXONO [46] by measuring neutrino-electron scattering. Constraints from COHERENT based on one-dimensional fit on the energy spectra (blue dashed) and two-dimensional fit including the timing information (blue solid) can be extended to $m_N \sim 50 \text{ MeV}$, with results from the two-dimensional fit as competitive as that from LSND [3] and atmospheric ν (Super-K) based on the nonobservation of atmospheric neutrino upscattering to N with subsequent decays (cyan shaded region) [10].

The μ -flavor neutrino flux from the SNS source in COHERENT is more intense than that of the e flavor, and thus the COHERENT CsI data can provide better constraints on d_μ . We first perform a one-dimensional fit, as adopted in previous literature [18,19], employing the full dataset released recently, which includes 3 times more statistics and an additional 2–3-fold reduction in systematic uncertainties. This full dataset leads to the constraints shown by the blue dashed line in the middle panel of Fig. 3, which represents an improvement of approximately a factor of 3 over those in [18,19]. Then, we adopt a two-dimensional analysis method that includes not only the energy information, but also the timing information. Contributions to upscattering induced by ν_μ fluxes can now be separated from that induced by $\bar{\nu}_\mu$ and $\bar{\nu}_e$ fluxes based on the arrival time. As a result, our limits for the COHERENT experiment can be further improved by

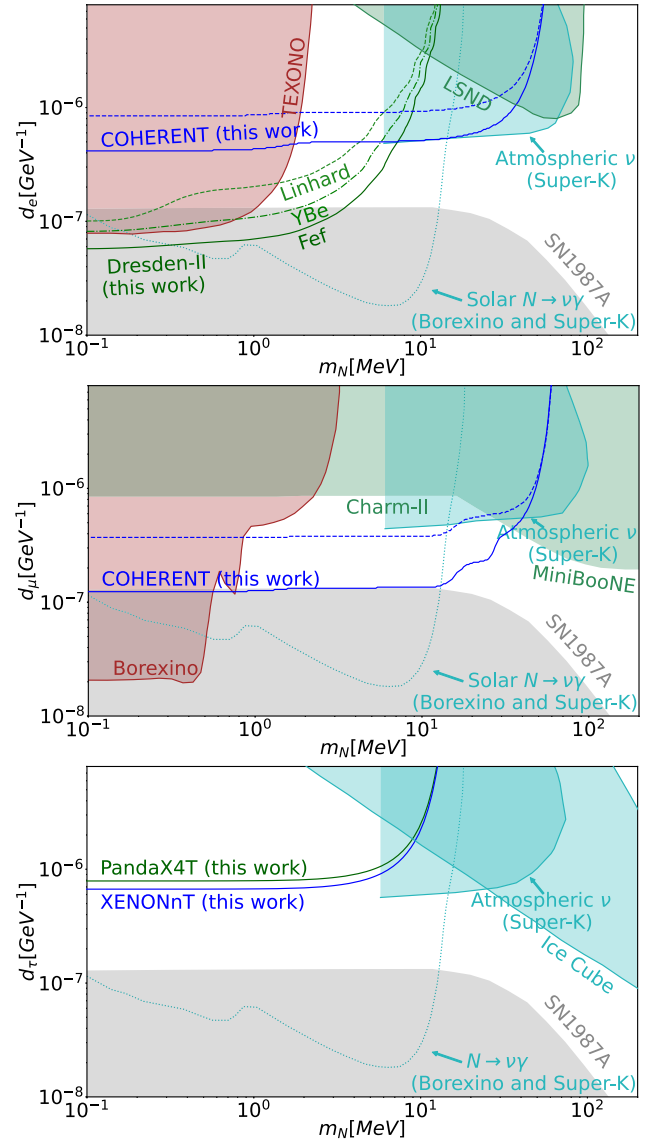


FIG. 3. Exclusion limits for sterile neutrino with magnetic dipole portal of specific flavor at 90% C.L. From top to bottom, results are shown for flavor e , μ , and τ , respectively. For the COHERENT analysis, the results including time information are shown in blue solid lines and the results without time information are presented in blue dashed lines. For the Dresden-II analysis, the results are shown using different quenching models. Constraints from other experiments are also presented, including SN1987A [3], TEXONO [46], LSND [3], atmospheric ν (Super-K) [10], which looks for atmospheric neutrino upscattering to N with subsequent decays, Borexino [8,47], Solar $N \rightarrow \nu\gamma$ (Borexino and Super-K) [9] for solar neutrino upscattering to N with subsequent decays, MiniBooNE [3,7,48], Charm-II [7,49], and IceCube [13] for comparison. Flavor-specific dipole portals are considered, except for the SN case where flavor universal couplings are used.

approximately a factor of 3 (blue solid line in the middle panel of Fig. 3). We also show constraints from experiments including MiniBooNE [3,7,48], Charm-II [7,49], solar neutrino $\text{E}\nu\text{ES}$ observation at Borexino [8,47], and the

atmospheric μ (Super-K) [10]. It should be noted that constraints on d_μ from COHERENT CsI data exclude a unique region in $10 \lesssim m_N \lesssim 40$ MeV and the monochromatic peak of ν_μ from the rest pion decay further lowers the border of exclusion region at $m_N \simeq 30$ MeV.

For $\alpha = \tau$, PandaX-4T and XENONnT recently reported the measured values of ^8B solar neutrino flux to be $8.4 \pm 3.1 \times 10^6$ [50] and $4.7_{-2.3}^{+3.6} \times 10^6 \text{ cm}^{-2} \text{ s}^{-2}$ [51], respectively. Since the ^8B neutrino flux from the B16 Standard Solar Model (SSM) [52] determination is $\Phi_{\text{SSM}}^{\nu_\tau} \simeq 5.16 \times 10^6 \text{ cm}^{-2} \text{ s}^{-2}$, the constraints can be expressed as

$$\frac{\langle N_{\text{SM}+\text{NDP}}^{\nu-\mathcal{N}}(\mathcal{N}) \rangle}{\langle N_{\text{SM}}^{\nu-\mathcal{N}}(\mathcal{N}) \rangle} \lesssim \frac{\Phi_{\text{max}}^{\nu_\tau}}{\Phi_{\text{SSM}}^{\nu_\tau}}, \quad (12)$$

with $\Phi_{\text{max}}^{\nu_\tau} = 11.5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-2}$ ($8.3 \times 10^6 \text{ cm}^{-2} \text{ s}^{-2}$) for PandaX-4T (XENONnT), which is taken to be the upper limit of the measured ^8B solar neutrino flux aforementioned, $\mathcal{N}$ denotes different xenon isotopes, and $\langle \cdot \rangle$ is the average event number over all isotopes based on the natural abundance of xenon. The subscript SM + NDP (SM) indicates event numbers predicted with (without) sterile neutrinos. The exclusion limits obtained are shown in the bottom plot of Fig. 3, which for XENONnT is a factor of 3 better than the previous limit in Ref. [8], as we use a significantly lower nuclear recoil energy threshold of 0.5 keV achieved in Refs. [40,41]. While being probed by Borexino, Super-K, and (or) Ice Cube as shown in Fig. 3, our results from XENONnT and PandaX-4T provide independent constraints for parameter regions with $m_N \lesssim 10$ MeV.

VI. CONCLUSIONS

We explore the potential of the collected CE ν NS and EL/ES data at the Dresden-II and COHERENT experiments in probing sterile neutrinos via the magnetic dipole portal. Given the large electron antineutrino flux from reactors, we find that the current Dresden-II data provide leading probes of the e -flavor dipole operator for $m_N \lesssim 0.5$ MeV in the case where the Fef quenching factor is used. Future research should try to reconcile predictions between various quenching models and also between predictions and data. With the large ν_μ flux from the spallation neutron source, we demonstrate that utilizing the timing information by employing a new two-dimensional fitting method, a wide unique parameter region can be probed for heavier m_N up to 40 MeV in the μ -flavor dipole operator case with the full dataset collected by the CsI[Na] detector from the COHERENT experiment. Such techniques with the timing information included can be further extended to searches of other flavor-dependent new physics. For the τ -flavor dipole portal, measurements of solar neutrino fluxes at PandaX-4T and XENONnT can provide independent probes for $m_N \lesssim 10$ MeV.

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