

Constraints on millicharged particles from nuclear γ -decays

Ting Gao^{1,*} and Maxim Pospelov^{1,2,†}

¹*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

²*William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*



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We consider nuclear gamma decays and γ -emitting reactions that can be an efficient source of hypothetical millicharged particles (χ). In particular, we revisit the production of millicharged particles in nuclear reactor environment, pointing out that γ cascades from ^{239}U is an overlooked yet a powerful source of $\chi\bar{\chi}$ pairs. This leads to an increased flux compared to previous studies. We then apply new estimates of the flux to derive novel limits on the value of millicharge, $\varepsilon = Q_\chi/e$, from the electron recoil searched for in a variety of experiments placed in proximity to the reactor cores. The derived limits on ε are the strongest in the interval of masses $\sim 0.7\text{--}2$ MeV. We also derive the millicharged particles flux from the Sun and point out potential sensitivity of the low-threshold dark matter search experiments.

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I. INTRODUCTION

While Standard Model (SM) of particles and fields has been extremely successful in describing observable world, it cannot be a “final theory.” Notable exceptions include neutrino physics (mixing and oscillations) as well as cold dark matter (DM) that must be associated with new degrees of freedom. Generalization of existing ideas about neutrino masses as well as particle dark matter leads to the notion of dark sectors (DS). DS constructions are not tied to any specific energy scale and can be indeed much lighter than the scale of weak interactions. Light DS, by necessity, would have to have states with rather small couplings to the SM states, and their search would typically require high-intensity experiments [1,2]. In light of this, all possible connections (or portals) between light DS and SM have been described, classified, and searched for in ever-increasing number of high-intensity experiments. One unique portal to DS is via the so-called millicharged particles (MCPs).

In this paper, we will revisit some aspects of searches for the MCP χ that we will assume to be a fermion state χ with an electric charge much smaller than the proton charge, $Q_\chi \equiv \varepsilon e \ll e$. We note that, while such construction may look totally artificial, there are theoretically natural ways of

ascribing the smallness of ε to a small amount of mixing between regular and “dark” photons [3]. There has been a steady interest in phenomenology of millicharged particles, not least because they are capable of inducing a variety of interesting phenomena. MCPs can bring change to the early Universe cosmology [4–6]; they can be produced and accelerated by supernova [7–9]; their population on Earth can be enhanced due to possibly small collision lengths within Earth’s material [10,11]. Several years ago, MCP dark matter was invoked as a possible explanation of the abnormal hydrogen spin temperature signal observed by the EDGES Collaboration [12] that consists in stronger-than-expected 21 cm absorption feature at redshifts of $z \sim O(15\text{--}20)$. An explanation of such a phenomenon may reside in late recoupling of ordinary baryonic matter and dark matter and that can naturally occur if DM has a small millicharge [13–15]. These scenarios, in particular, prefer relatively light, sub-100-MeV MCP particles with $\varepsilon \sim O(10^{-5})$.

All existing MCP limits and proposals for future searches can be subdivided into two categories: those that exploit production and detection of MCPs and those that search/constrain DM-style MCP relics. Any signal in the first method would typically scale as the fourth power of $\sim \varepsilon$, while the second class of searches is $\sim \varepsilon^2$ but is more model dependent.¹ We will concentrate on the first method that involves the production and detection of the MCPs and limit our study to relatively light, sub-10-MeV particles. Specifically, the MCPs were searched for in the electron

*Contact author: gao00212@umn.edu

†Contact author: pospelov@umn.edu

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¹An interesting class of its own is the search of MCPs via missing energy/missing momentum, that also has ε^2 type of scaling [16].

beam dump experiments [17] that provide the most direct limits in the sub-100-MeV range. Similar style limits can be derived from the past proton beam dump/neutrino experiments [18] and new dedicated experiments placed along the line of sight of various particle beams [19–25]. Moreover, cosmic-ray-initiated production of MCPs can be used to derive equally stringent limits on ϵ [26–29].

If masses of DS particles are light, below 10 MeV, one must anticipate that the strongest direct constraints may come from the particle physics experiments in direct proximity of nuclear reactors. This is because commercial nuclear reactors can be viewed as very powerful beam dump experiments, where nuclear fission generates copious amounts of $\bar{\nu}, \gamma, n$ radiation with $O(\text{MeV})$ energy spectra. Recent years have seen the proliferation of low-threshold detectors installed in $O(30 \text{ m})$ distance from cores of nuclear reactors with the main goal of detecting coherent neutrino-nucleus recoil. Low threshold achieved in these experiments also helps to set stringent constraints on MCPs, as a typical cross section for detection scales inversely proportionally with the kinetic energy of the outgoing electron, E_{recoil}^{-1} . Several collaborations have placed limits on MCPs using such devices [30,31]. Previous searches of the neutrino magnetic moments as well as actual measurements of the $\bar{\nu}e$ scattering can also be used to be recast as limits on the MCPs. The intense photon flux in nuclear reactors also provides an efficient environment to probe other DS particles, such as axionlike particles, as has been done in Refs. [32–34].

Several experimental studies [30,31] have recognized the potential of nuclear reactors and the enormous photon flux that they generate as an important source of MCPs. They derived stringent limits on such particles already. Our present study is motivated by the observation that existing treatments for MCPs [30,31] seem to have rather limited reach in terms of m_χ stemming from the fact that only $e + \gamma \rightarrow e + \bar{\chi} + \chi$ reactions are included as the source of MCPs. Yet it is clear that *any* nuclear process resulting in emission of a gamma quantum of energy ω can in principle emit a charged pair [35]. We adopt this production mechanism for nuclear reactors, following recent treatment of pair emission in Ref. [36]. We find that the stringent limits can be extended to higher masses.

While nuclear reactors provide the largest fluxes of MCPs for the closely located detectors, we note that there is also an ambient flux of MCP created by natural radioactivity (mostly caused by the radioactive isotopes of K, U, and Th). While fluxes of MCP created this way are going to be much lower than those in proximity of reactor cores, the detection methods that can be employed could involve neutrino detectors, and large self-shielding dark matter detectors (such as those based on xenon dual-TPC technology). These are large deep-underground detectors operating in a maximally background-free environment, capable of achieving much lower counting rates than

detectors placed in reactors' proximity. Similarly, the MCPs can be created as a byproduct of nuclear reactions in the Sun. Here, however, the value of ϵ must be much smaller to avoid the slowdown and thermalization of MCPs by the solar matter.

Along with the new estimates of fluxes from MCPs, we also calculate the production of massive dark photons. If the mass is above $2m_e$, the dark photons are unstable against the decays to e^+e^- . If kinematically allowed, they can be produced in nuclear reactors and possibly detected by, for example, experiments studying neutrino-electron scattering.

The rest of our paper is organized as follows. Section II of this work describes the production of MCPs accompanying nuclear decays. Section III treats different experiments and derives corresponding limits on $m_\chi - \epsilon$ plane. Section IV estimates the fluxes and detection rates of MCPs from natural radioactivity and solar production. Section V addresses limits on massive dark photons. We reach our conclusions in Sec. VI.

II. PAIR PRODUCTION FROM NUCLEAR DEEXCITATION

Any process that results in the emission of an on-shell γ of frequency ω may also produce a pair of MCP particles with $2m_\chi < \omega$. For nuclear-initiated emission, the recoil is negligible, and therefore the entire energy of a photon can go into the MCP pair, so that the kinematic limit for m_χ is close to $\omega/2$. For photons emitted from the electron lines, in contrast, the kinematic limit is lower due to the electron recoil. In previous analyses [30,31], the main source of the MCP was assumed to originate from $e + \gamma \rightarrow e + \chi + \bar{\chi}$ reaction. This results in a sharp drop of the χ flux for $m_\chi > 0.5 \text{ MeV}$. We note, however, that the spectrum of photons emitted in nuclear fission is extended into a several MeV range, and therefore higher m_χ than those considered in Refs. [30,31] can be emitted. The photons can be emitted in the deexcitations of the fission products and in the process of the subsequent capture of free neutrons. As $\sim 60\%$ of the neutrons produced in fission undergo mostly (n, γ) reactions on protons or on heavier elements, there is a plenty of MCP sources that should be added to the production mechanisms discussed in Refs. [30,31].

In this section, we calculate the rate of $\chi\bar{\chi}$ pair production from neutron capture in the core region of the nuclear reactor. Each fission in the reactor releases an average of 200 MeV energy [37] and 2.5 neutrons [38], which corresponds to the neutron yield per second as

$$N_n(\text{s}^{-1}) = 7.8 \times 10^{19} \times \text{Power}(\text{GW}). \quad (1)$$

Following their emission, neutrons undergo relatively rapid thermalization before either contributing to the next fission cycle or being captured by ^{238}U , by protons in

natural-water reactors, or by other elements. A large fraction of the neutron capture events leads to the emission of γ rays, and, in the presence of millicharged particles, off-shell γ^* which decays into a MCP pair. Following the procedure in Ref. [36], we first calculate the cross section ratio between these two processes,

$$r := \frac{\sigma(n + N \rightarrow N' + \chi + \bar{\chi})}{\sigma(n + N \rightarrow N' + \gamma)}, \quad (2)$$

and then use the well-studied γ -ray emission branching ratios to calculate the MCP pair production. The key assumption here is that the nuclear matrix elements for photon emission do not change in a significant way when the photon is taken off shell. This is ultimately related to the small size of atomic nuclei compared to wavelengths of emitted photons and MCPs.

After a multipole expansion of the nuclear matrix element, the differential ratios for electric dipole (E1) and magnetic dipole (M1) transitions are given as

$$\frac{dr_{\mathcal{E}(B)}}{dE_\chi dE_{N'}} = \frac{M}{8\pi^2\omega} \mathcal{R}_{\mathcal{E}(B)}, \quad (3)$$

$$\mathcal{R}_{\mathcal{E}} = \frac{4\pi\alpha\epsilon^2}{\omega^2} \frac{1}{k^4} \left[(E_\chi + E_{\bar{\chi}})^2 (4m_\chi^2 + 2k^2) - 4k^2 E_\chi E_{\bar{\chi}} + k^4 \right], \quad (4)$$

$$\mathcal{R}_B = \frac{4\pi\alpha\epsilon^2}{\omega^2} \frac{1}{k^4} \left\{ 4m_\chi^2 [(E_\chi + E_{\bar{\chi}})^2 - k^2] - k^4 + 2k^2 (E_\chi^2 + E_{\bar{\chi}}^2) \right\}, \quad (5)$$

where M is the mass of the excited state formed by neutron capture, $\omega = M - M_{N'}$ is the available energy, $k = p_1 + p_2$ is the total momentum of the millicharged particle pair, and $\mathcal{R}_{\mathcal{E}(B)}$ is the ratio between the angular-averaged pair production and photon emission amplitudes for E1(M1) transition. We assume recoil-less processes, i.e., taking the leading-order expansion in $1/M$ in the above and in the following discussion. The kinematical limits of $E_{N'}$ are determined by having χ and $\bar{\chi}$ moving either parallel or antiparallel to each other. After integrating over $dE_{N'}$, we get the differential ratios as functions of E_χ , which is convenient for the discussion of detection rates,

$$\frac{dr_{\mathcal{E}}}{dE_\chi} = \frac{\alpha\epsilon^2}{2\pi\omega^3} \left[2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}| + \frac{2m_\chi^2\omega^2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|}{(E_\chi E_{\bar{\chi}} + m_\chi^2 + |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|)(E_\chi E_{\bar{\chi}} + m_\chi^2 - |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|)} + (E_\chi^2 + E_{\bar{\chi}}^2) \ln \frac{E_\chi E_{\bar{\chi}} + m_\chi^2 + |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|}{E_\chi E_{\bar{\chi}} + m_\chi^2 - |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|} \right], \quad (6)$$

$$\frac{dr_B}{dE_\chi} = \frac{\alpha\epsilon^2}{2\pi\omega^3} \left[-2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}| + \frac{2m_\chi^2\omega^2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|}{(E_\chi E_{\bar{\chi}} + m_\chi^2 + |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|)(E_\chi E_{\bar{\chi}} + m_\chi^2 - |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|)} + (E_\chi^2 + E_{\bar{\chi}}^2 - 2m_\chi^2) \ln \frac{E_\chi E_{\bar{\chi}} + m_\chi^2 + |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|}{E_\chi E_{\bar{\chi}} + m_\chi^2 - |\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|} \right], \quad (7)$$

where

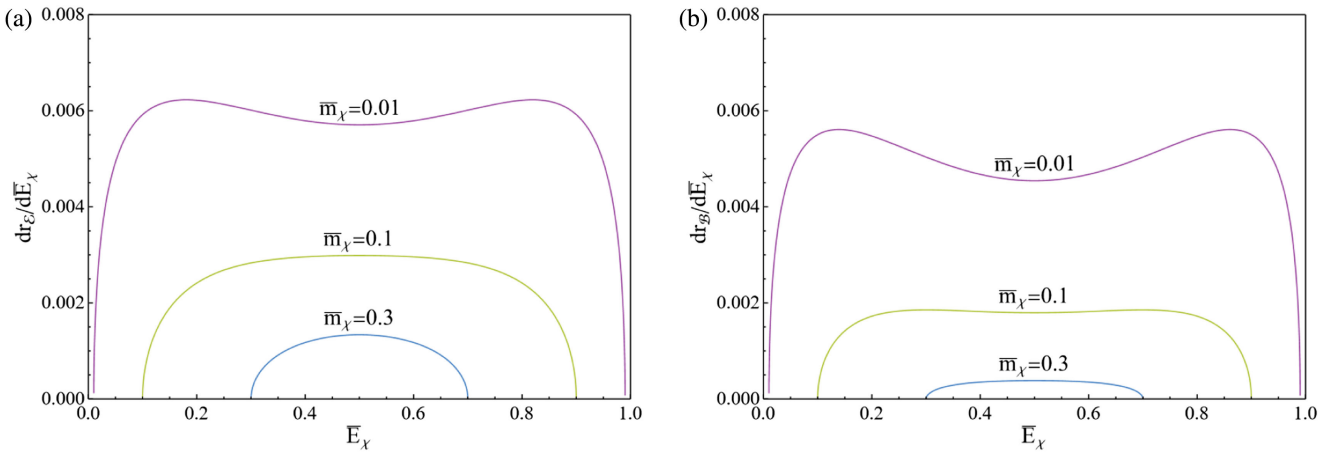


FIG. 1. Differential ratios for E1 Fig. 1(a) and M1 Fig. 1(b) transitions with $\epsilon = 1$ for different values of m_χ/ω . Quantities with a bar on top are normalized by ω for universality: $\bar{m}_\chi = m_\chi/\omega$, $\bar{E}_\chi = E_\chi/\omega$. Notice that when $m_\chi \ll \omega/2$, the E1 and M1 yields of MCP are similar, while for heavier MCP (relative to $\omega/2$), the M1 yields are more suppressed, as expected.

$$E_{\bar{\chi}} = \omega - E_{\chi}, \quad |\mathbf{p}_{\chi}| = \sqrt{E_{\chi}^2 - m_{\chi}^2},$$

$$|\mathbf{p}_{\bar{\chi}}| = \sqrt{(\omega - E_{\chi})^2 - m_{\chi}^2}. \quad (8)$$

These results are plotted in Fig. 1.

The type of neutron capture interactions along with their yield per fission are listed in Ref. [38],² and the emission lines resulting from neutron capture are documented in the evaluated nuclear structure data file database [39]. The two most important reactions we consider is $p(n, \gamma)^2\text{H}$ and $^{238}\text{U}(n, \gamma)^{239}\text{U}$. With the goal of producing $\sim\text{MeV}$ MCP pairs, we include the 3.297 and 4.060 MeV E1 transitions from the decay of the ^{239}U state at the threshold of $^{238}\text{U} + n$ and the 2.223 MeV M1 transition from ^2H . The number of γ emission events per second for each emission line is given as

$$N_{\gamma}^{(N, \omega)} = N_n \times \frac{Y_n^{(N)}}{\sum Y_n} \times \frac{I_{\gamma}^{(N, \omega)}}{100}, \quad (9)$$

where $Y_n^{(N)}$ is the neutron capture yield on isotope N per fission and $I_{\gamma}^{(N, \omega)}$ is the number of γ with energy ω emitted per 100 neutron captures on the isotope N .

The differential flux of millicharged particles is then found by

$$\frac{d\phi_{\chi}}{dE_{\chi}} = \frac{2}{4\pi D^2} \sum_{N, \omega} \frac{dr_{\mathcal{E}(\mathcal{B})}}{dE_{\chi}} N_{\gamma}^{(N, \omega)}, \quad (10)$$

where the factor of 2 comes from counting both χ and $\bar{\chi}$, and D is the distance from the reactor core to the detector. The summation runs over the aforementioned transitions, and for both transitions of ^{239}U , we use $r_{\mathcal{E}}$, while for the ^2H transition, we take $r_{\mathcal{B}}$.

III. MILLICHARGED PARTICLE DETECTION VIA ATOMIC IONIZATION

The MCPs entering the detector can interact electromagnetically with the detection material. If the energy exchange is comparable to the binding energy of atoms, an electron could be released from the atom, producing a detectable signal. The use of this atomic ionization process in millicharged particle searches as well as methods to calculate the cross section are discussed in Refs. [30, 31, 40]. In the asymptotic regime, when the binding energy and the momentum of the initial electron can be neglected, the cross section for a MCP to transfer at least an energy of T_0 to the electron is given by the free electron approximation (FEA), $\sigma(T > T_0) \simeq \epsilon^2 \times 2.6 \times 10^{-25} \text{ cm}^2 \times (\text{MeV}/T_0)$ [18].

²Although the study [38] simulates the neutron capture yields Y_n in specific environment of the reactor used by the TEXONO Collaboration, we consider it to be a plausible estimate of a generic Y_n for any natural water reactor.

For the range of m_{χ} and E_{χ} of our interest, the Photo Absorption Ionization model (PAI) is more realistic as it accounts for the asymptotically FEA behavior when the energy transfer is significantly larger than the electron binding energy, as well as for the deviation from FEA when these two energy scales become close. Thus, we adopt PAI model where the differential cross section per atom is given by

$$\frac{d\sigma}{dT} = \frac{\epsilon^2 \alpha \sigma_{\gamma}(T)}{\beta^2 \pi T} \ln[(1 - \beta^2 \epsilon_1)^2 + \beta^4 \epsilon_2^2]^{-1/2}$$

$$+ \frac{Z \epsilon^2 \alpha}{\beta^2 \pi N_e} \left(\beta^2 - \frac{\epsilon_1}{|\epsilon|^2} \right) \Theta + \frac{\epsilon^2 \alpha \sigma_{\gamma}(T)}{\beta^2 \pi T} \ln \left(\frac{2m_e \beta^2}{T} \right)$$

$$+ \frac{\epsilon^2 \alpha}{\beta^2 \pi T^2} \int_0^T \sigma_{\gamma}(T') dT'. \quad (11)$$

In these expressions, T is the energy transfer, σ_{γ} is the photoabsorption cross section, β is the speed of χ , ϵ_1 and ϵ_2 are the real and imaginary parts of the dielectric constant (not to be confused with the value of the millicharge, ϵ), N_e is the electron number density, and $\Theta = \arg(1 - \epsilon_1 \beta^2 + i \epsilon_2 \beta^2)$. Details of the model can be found in Ref. [41]. A comparison between the PAI model and other models is shown in Fig. 2.

The differential count rate is then determined by the MCP flux and the atomic ionization cross section,

$$\frac{dR}{dT} = \rho_A \int_{E_{\chi, \min}}^{E_{\chi, \max}} \frac{d\sigma}{dT} \frac{d\phi_{\chi}}{dE_{\chi}} dE_{\chi}, \quad (12)$$

where ρ_A is the number of atoms per unit mass. To set the constraint on the millicharge, we compare the differential count rate in this work with the experiment and analysis performed by the TEXONO Collaboration [30], which utilizes a point-contact Germanium detector with an energy threshold of 300 eV and a mass of 500 g located at 28 m away from a 2.9 GW thermal power nuclear reactor. The limiting value for ϵ is determined when the counting rate (12) is matched to the experimental rate in Ref. [30]. An example of this type of comparison is shown in Fig. 3(a). Note that the millicharge is proportional to the fourth root of the count rate; therefore, a small uncertainty in the comparison will only lead to a tiny change in the constraint. The constraint we get and comparison with other work at the relevant mass range are shown in Fig. 3(b). We observe that the inclusion of nuclear transition enhances the sensitivity to ϵ , and indeed in the range of 0.7–2 MeV produces the strongest constraint to date.

We discuss in passing a number of other near-reactor experiments with different thresholds and counting rates. The CONNIE and Atucha-II experiments [31] utilize Skipper-CCDs, allowing the detection of particles interacting with bulk plasmons at the eV energy scale. For MCP pair production from photons scattering with electrons,

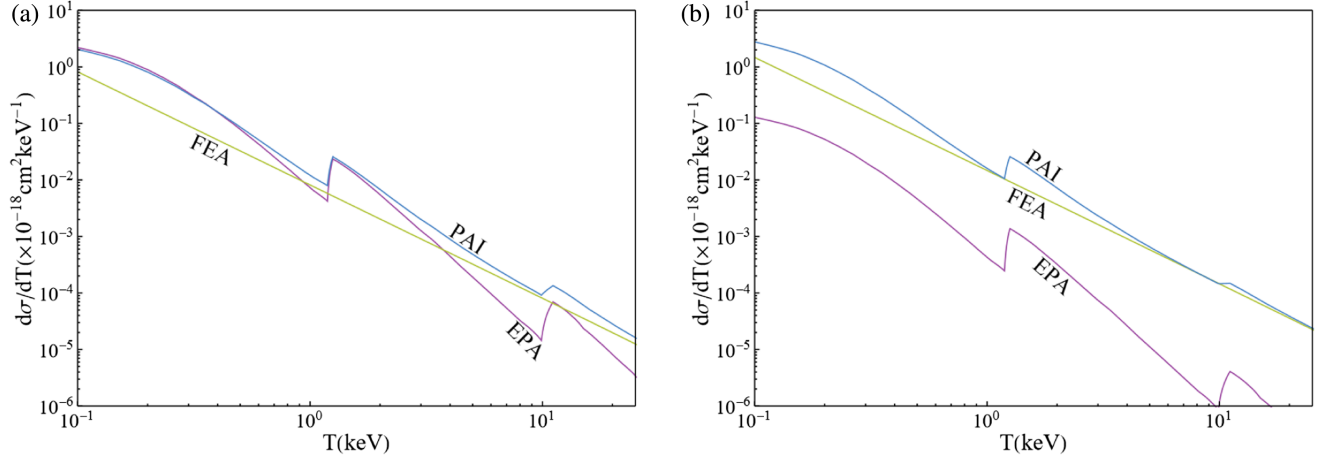


FIG. 2. Atomic ionization differential cross sections for germanium crystal under PAI, FEA, and equivalent photon approximation (EPA) for $m_\chi = 1$ keV, $E_\chi = 1$ MeV Fig. 2(a) and $m_\chi = 1$ MeV, $E_\chi = 1.5$ MeV Fig. 2(b). The photoabsorption cross section is obtained from Ref. [42]. When the millicharged particle is ultrarelativistic, PAI agrees with the maximum between FEA and EPA as expected, when E_χ and m_χ are relatively close; EPA ceases to be a good approximation; and PAI continues to capture the enhancement at low energy transfer and the free electron behavior at high energy transfer.

their result shows a better sensitivity compared with TEXONO. On the other hand, for the pair production from nuclear deexcitation, our calculation shows TEXONO has a slightly better sensitivity, but the details depend on a precise knowledge of the interaction cross section at low energy transfer. The MUNU experiment [43] tracks electron recoils above 0.7 MeV with a differential counting rate of $\sim 10^{-1}$ MeV $^{-1}$ kg $^{-1}$ day $^{-1}$ from the hypothetical neutrino magnetic moment, which could as well be from MCPs. Our estimate shows the sensitivity to ϵ^4 from the MUNU experiment on millicharged particles is a factor of a

few hundred weaker than the TEXONO experiment, mostly because of $1/T$ scaling of the cross section. The TEXONO $\bar{\nu}_e$ -electron scattering experiment [44] could also in principle receive signals from MCPs, although at a threshold of $T > 3$ MeV both the allowed MCP mass range and the available phase space become limited. Finally, this year, the CONUS+ experiment has achieved very low counting rates and very low thresholds, finally detecting the neutrino-nucleus coherent scattering for reactor neutrinos [45]. These results could potentially be also recast as constraints on MCPs.

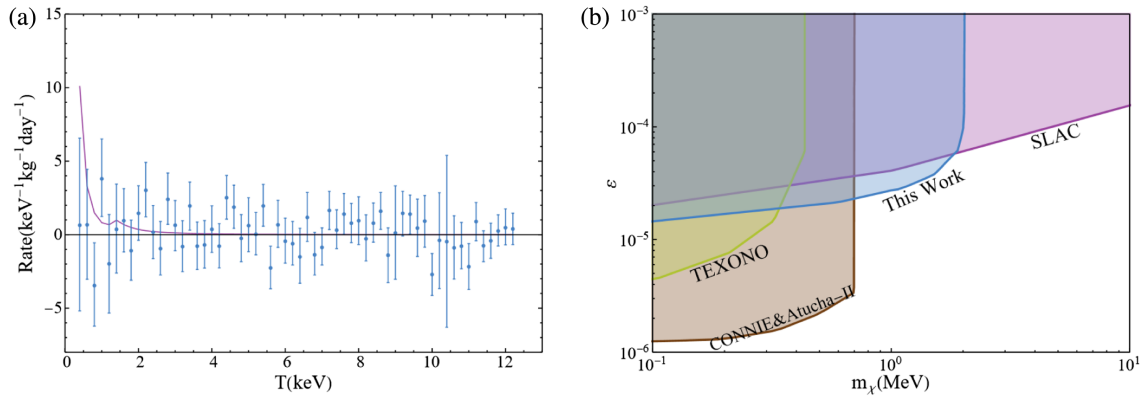


FIG. 3. (a) An example of the comparison between the analysis from TEXONO (blue dots) and this work (purple line) with $m_\chi = 1$ MeV, $\epsilon = 2.7 \times 10^{-5}$. The constraint on the millicharge is obtained by requiring that the differential counting rate does not exceed the 2σ region of the TEXONO analysis. Near $T = 1.4$ keV, the energy transfer becomes enough to ionize electrons in the L shell of Ge (as documented in Ref. [42]) and thus produces a small peak in the rate. (b) The constraint we get on MCPs based on comparing the MCP flux generated by nuclear deexcitation process with the TEXONO analysis [30], in comparison to the constraints from TEXONO [30], CONNIE and Atucha-II [31], and SLAC [17]. Our result, based on theoretical reevaluation of the MCP flux in conjunction with past experimental searches, provides the strongest constraint in the mass range 0.7–2 MeV.

IV. MCPS FROM NATURALLY OCCURRING DECAYS AND REACTIONS

Away from the nuclear reactors, excited nuclei are naturally produced from the decay chain of natural radioisotopes. This will result in a geobackground of MCPs detectable by large deep-underground detectors including Borexino [46], XENON [47], LZ [48], and PANDAX [49]. Also, pp and carbon–nitrogen–oxygen (CNO) reaction chains in the Sun produce photons in the 0.5–7.5 MeV range, which should also contribute to the natural MCP abundance.

The main γ emission channels from natural terrestrial radioactivity with energy above 1 MeV include a number of emission lines in the deexcitation of ^{214}Po in the ^{238}U chain, ^{208}Pb in the ^{232}Th chain, and ^{40}K in the ^{40}K decay. Especially promising are the 2.615 MeV E3 emission line from the deexcitation of ^{208}Pb occurring at the highest energy and the 1.461 MeV E2 emission line in ^{40}K decay accompanied by the highest component of the geoneutrino flux [50].³

To estimate the MCP flux, we focus on the XENONnT experiment [47] and normalize the MCP flux on the geoneutrino flux from the same decay chain measured by the Borexino experiment [51] at the same site. Different from neutrinos which travel through the Earth almost freely, MCPs lose energy as they travel through the Earth as a result of the electromagnetic interaction with the surrounding material, based on the review in Ref. [52], the energy loss rate for typical values of $\beta\gamma$ under consideration for MCPs traveling through the Crust is estimated to be

$$\frac{dE}{dx} = -\frac{(0.003-0.03) \text{ MeV}}{100 \text{ km}} \left(\frac{\varepsilon}{10^{-5}}\right)^2; \quad (13)$$

therefore, for the values of ε of our interest, it is appropriate to focus on the MCPs produced from the Local Crust (LOC, within ~ 300 km from the detector, see Ref. [50] for details), where the energy loss of MCPs can be neglected. Based on the geoneutrino measurement available at Borexino, we focus specifically on the MCP pair production accompanying the 2.615 MeV emission line in the ^{232}Th chain. The geo-MCP flux is then determined by

$$\frac{d\phi_\chi}{dE_\chi} = \frac{2}{6} \frac{dr_{\text{E3}}}{dE_\chi} \phi_\nu(^{232}\text{Th}, \text{LOC}), \quad (14)$$

where the prefactor 2/6 comes from one ^{208}Pb deexcitation per six neutrino emission in the ^{232}Th chain and two MCPs per pair production; dr_{E3}/dE_χ is the ratio between MCP pair production events and γ emission events for E3 multipole transition, with the explicit form derived in the

Appendix. Finally, $\phi_\nu(^{232}\text{Th}, \text{LOC})$ denotes the neutrino flux from ^{232}Th decay in the Local Crust. Assuming that the $^{238}\text{U}/^{232}\text{Th}$ abundance ratio is independent of the material considered, $\phi_\nu(^{232}\text{Th}, \text{LOC})$ corresponds to approximately $\sim 10\%$ of the total geo-neutrino flux measured by the Borexino experiment.

Under the above assumption, the constraint we get is $\sim \varepsilon < 10^{-4}$ at $m_\chi \sim 1$ MeV; however, at this value of ε , the energy loss in the Local Crust becomes nonnegligible; therefore, we were not able to set a solid independent bound on ε based on the XENONnT experiment. We also considered the Borexino experiment which has a larger detector volume, but due to the higher detection threshold, the MCP slowdown is even more crucial, and the conclusion is similar.

It is well appreciated that the total solar neutrino flux dominates over geoneutrino $\bar{\nu}_e$ flux by ~ 4 orders of magnitude. Using well-understood properties of the solar energy generation cycles, we can easily calculate the MCP production rate. Of course, for the $O(10^{-5})$ values of the millicharge, the χ particles produced in the core of the Sun will be thermalized and trapped in the solar interior for considerable time. The main processes that will create χ 's are listed below:

$$e^+ + e^- \rightarrow \chi + \bar{\chi}; \quad m_\chi^{\text{max}} = 0.511 \text{ MeV}, \quad (15)$$

$$\text{D} + p \rightarrow {}^3\text{He} + \chi + \bar{\chi}; \quad 2m_\chi^{\text{max}} = 5.5 \text{ MeV}, \quad (16)$$

$${}^3\text{He} + {}^3\text{He} \rightarrow {}^6\text{Be} + \chi + \bar{\chi}; \quad 2m_\chi^{\text{max}} = 11.5 \text{ MeV}, \quad (17)$$

$${}^{12}\text{C} + p \rightarrow {}^{13}\text{N} + \chi + \bar{\chi}; \quad 2m_\chi^{\text{max}} = 1.9 \text{ MeV} \quad (18)$$

$${}^{13}\text{C} + p \rightarrow {}^{14}\text{N} + \chi + \bar{\chi}; \quad 2m_\chi^{\text{max}} = 7.5 \text{ MeV} \quad (19)$$

$${}^{14}\text{N} + p \rightarrow {}^{15}\text{O} + \chi + \bar{\chi}; \quad 2m_\chi^{\text{max}} = 7.3 \text{ MeV}. \quad (20)$$

In addition, there are processes with the deexcitations of ${}^7\text{Be}$ and ${}^7\text{Li}$ that create 0.43 and 0.48 MeV energy pairs. The corresponding photon-emitting cross sections for most of the listed reactions are relatively well known. Before evaluating the rate of MCP production, we would like to make several remarks:

- (i) One positron is emitted for each unit of pp cycle. e^+ annihilation is an important source of MCP, because in that case the probability of χ production scales as $O(\varepsilon^2)$, and not $O(\alpha\varepsilon^2)$.
- (ii) Process (17), ${}^3\text{He} + {}^3\text{He} \rightarrow {}^6\text{Be}$, is not very well known as the transition occurs due to E0 multipole and should be suppressed. This reaction is expected to be subdominant as the main ${}^3\text{He} + {}^3\text{He}$ fusion reaction occurs without photon emission.
- (iii) $\text{N}(p, \gamma)\text{O}$ reaction to the ground state of oxygen is suppressed ($\text{Br} \sim 6\%$) and can be neglected.

³More nuclear data resources can be found at website <http://www.lnhb.fr/home/nuclear-data/nuclear-data-table/>.

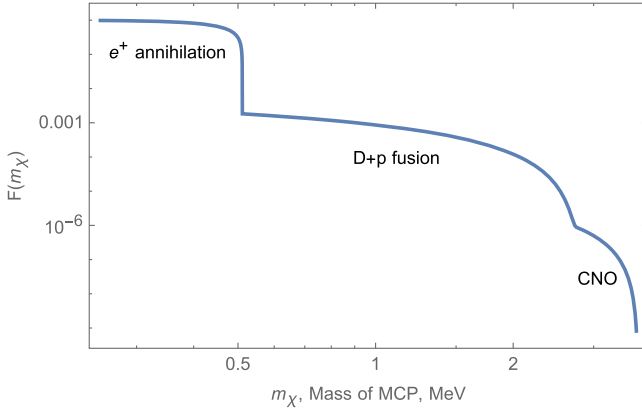


FIG. 4. Relative production of solar MCPs due to different reactions. For $m_\chi < m_e$, the flux is dominated by the positron annihilation.

Reaction (19), on the other hand, occurs mostly due to E1 transition to the ground state (see, e.g., Ref. [53] and TUNL Nuclear Data Project compilations⁴). Reaction (18) can be neglected on account of small Q value and the overall subdominance of the CNO chain.

- (iv) We shall assume that $D + p$ fusion reaction at solar energies is an equal mix of E1 and M1 transitions with more advanced treatment possible if needed [54]. This assumption is not crucial if $2m_\chi$ is away from 5.5 MeV threshold.
- (v) MCPs can also be emitted at order $O(\alpha^2 \varepsilon^2)$ from weak decays of, e.g., ^8B . These are even smaller contributions than the rest, and we neglect them.

In light of the above, we use reactions (15), (16), and (19) together with our results for the branching ratios into $\chi\bar{\chi}$ to calculate the overall production rate as function of m_χ . A convenient way of expressing the answer is

$$\frac{1}{4\pi(\text{A.U.})^2} \frac{dN_{\chi\bar{\chi}}}{dt} \simeq 12 \text{ cm}^{-2} \text{ s}^{-1} \times \left(\frac{\varepsilon}{10^{-5}} \right)^2 \times F(m_\chi), \quad (21)$$

where the function $F(m_\chi)$, plotted in Fig. 4, is dictated by the available phase space as well as the relative strength of pp and CNO chains. Notice that the probability to create a MCP pair from the positron annihilation is given by

$$\frac{\langle \sigma v \rangle_{e^+ e^- \rightarrow \chi\bar{\chi}}}{\langle \sigma v \rangle_{e^+ e^- \rightarrow \gamma\gamma}} = \varepsilon^2 \times \left(1 + \frac{r^2}{2} \right) \sqrt{1 - r^2}, \quad r = m_\chi / m_e. \quad (22)$$

In the limit of $m_\chi \ll m_e$, $F = 1$, and this probability is just ε^2 . Therefore, the total MCP flux is $2\varepsilon^2$ times the pp neutrino flux, which explains the prefactor in Eq. (21). The

discussion of production of other exotic particles in solar nuclear reactions can be found in recent work [55].

Quantity (21) is not affected by the slowdown of milli-charged particles by the solar material and in the steady state regime will correspond to an outgoing flux at an astronomical unit away from the Sun. The average energy of particles arriving from the Sun is, however, a more difficult question. One expects that for $\varepsilon > 10^{-6}$ most of the MCPs will thermalize and leave the Sun with relatively small energies. In that case, their propagation near the Earth's surface may get affected by the magnetic fields. On the other hand, MCP particles with $\varepsilon < 10^{-7}$ are expected to exit the Sun without appreciable energy loss. They can be then very efficiently probed by the planned low electron recoil experiments such as Oscura [56]. We note that the recent results from the DAMIC-M experiment [57] have a potential sensitivity to $\varepsilon \sim 0.5 \times 10^{-6}$ via the flux of solar MCPs. However, more in-depth investigation of χ slowdown is needed to fully address this question. Our calculation of the overall flux (21) can be further augmented by the secondary Compton-like production of MCPs $e + \gamma \rightarrow e + \chi + \bar{\chi}$ from all photons produced in nuclear reactions.

V. DARK PHOTON FROM NUCLEAR DEEXCITATION

In addition to MCPs, the nuclear deexcitation could also produce massive dark photons A' which effectively interact with ordinary matter through the coupling $\kappa Q J^\mu A'_\mu$. Following the formalism in Ref. [36] and accounting for the dark photon mass, we obtain the ratio between dark photon and regular photon production rate for E1 and M1 transition as

$$r_\varepsilon^{(A')} = \kappa^2 \left(1 + \frac{1}{2} \frac{m_{A'}^2}{\omega^2} \right) \sqrt{1 - \frac{m_{A'}^2}{\omega^2}}, \quad (23)$$

$$r_B^{(A')} = \kappa^2 \left(1 - \frac{m_{A'}^2}{\omega^2} \right)^{\frac{3}{2}}. \quad (24)$$

The produced dark photons subsequently decay to an electron-positron pair, allowing the possibility for detection. The decay rate of dark photons is given by

$$\Gamma = \frac{\alpha \kappa^2 m_{A'}}{3} \left(1 + \frac{2m_e^2}{m_{A'}^2} \right) \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}}. \quad (25)$$

For a MeV scale dark photon with $\kappa \sim 10^{-7}$, the typical distance $L = \gamma\beta/\Gamma$ dark photons travel during their lifetime is a few kilometers, and at that distance, the geo-dark photons are unlikely to play any role. Therefore, we focus solely on detectors that are placed at a distance $D \ll L$ from the nuclear reactors. Since the loss of dark photons

⁴<https://nucldata.tunl.duke.edu/>.

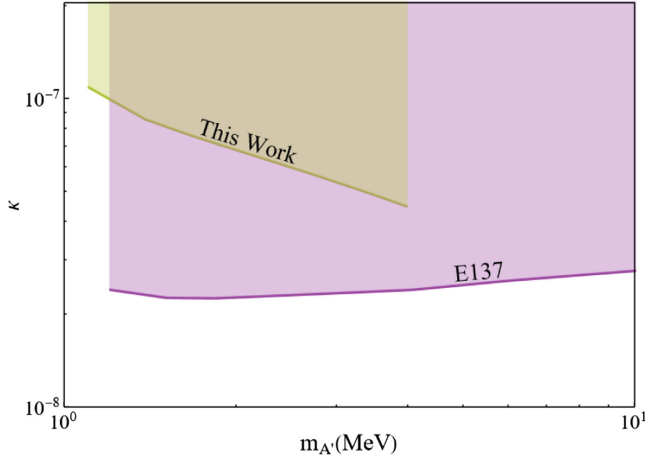


FIG. 5. Excluded region for dark photon from this work and the SLAC E137 experiment [59–61]. The entire plot region is also excluded by the constraint based on supernova [62].

from the source to the detector can be ignored, the dark photon decay event rate inside the detector is given by

$$R = \phi_{A'} V / L, \quad (26)$$

where $\phi_{A'} = N_{\gamma}^{(N,\omega)} r_{\mathcal{E}(B)}^{(A')} / (4\pi D^2)$ is the dark photon flux and V is the detector volume. Given the proportionality of the event rate to the detector volume, dark photons are ideally constrained by large size detectors near nuclear reactors. We considered the measurement by the TEXONO Collaboration with CsI(Tl) scintillating crystals [44], that measured $\bar{\nu}_e$ scattering on electrons. A dark photon decay inside the detector would be classified as a three-hit cosmic-ray unrelated event, and the counting rate that was observed for this class of events was at the level of $O(10^{-2} \text{ events/kg/day/MeV})$. Somewhat less competitive limits can be derived from Ref. [58], that searched for the appearance of e^+e^- pairs from a hypothetical massive neutrino decay. Among the emission lines under consideration, the 4.060 MeV emission line from $^{238}\text{U}(n, \gamma)^{239}\text{U}$ provides the strongest sensitivity. The constraint we get by repurposing results of Ref. [44], together with comparison with other constraints at the same mass range, is shown in Fig. 5. While our constraint does not exceed existing limits, the use of reactors as the source of dark photon provides an independent confirmation for the exclusion of dark photons at this mass and coupling range.

One can also set constraints on visibly decaying dark photons using large neutrino detectors deep underground. Specifically, KamLAND detector measured the solar ^8B neutrinos, achieving effectively ~ 5 MeV detection threshold [63]. A dark photon produced in nuclear reactors with $E_{A'} > 5$ MeV will appear in that sample and therefore can be constrained *if* energetic enough nuclear transitions can be found. The lines considered in this paper up to this point

are not suitable as they would be below the threshold. One candidate for more energetic transitions is the neutron capture on iron, $^{56}\text{Fe}(n, \gamma)^{57}\text{Fe}$, that does result in significant emission of 7.6 MeV gammas (corresponding to two fairly strong M1 transitions [64], discussed recently in connection with axion searches [65]). It is somewhat difficult to estimate exact fraction of neutrons captured on reactor walls without detailed simulations, and as a rough estimate, we adopt 1%. With these numbers in mind, and taking an average baseline of 180 km, and the total thermal power of all reactors to be ~ 100 GW, we can calculate the expected event rate from A' decay and compare it with recorded event rate in KamLAND in the electron energy bin 7.5–8 MeV. In this energy range, most of the observed signal is due to the solar neutrinos. For simplicity, we quote our result for a specific value of the dark photon mass of 2 MeV,

$$\left. \frac{dN_{A' \text{ decay}}/dt}{dN_{\text{observed}}/dt} \right|_{m_{A'}=2 \text{ MeV}} \sim 4 \times 10^{-4} \times \left(\frac{\kappa}{3 \times 10^{-8}} \right)^4. \quad (27)$$

Notice that the normalization of κ in this expression is chosen to coincide with the decay distance similar to KamLAND baseline, as larger κ would lead to a dominant fraction of A' decay before the detector. We conclude that the sensitivity of a “far detector” is less stringent than the results of the experiments near the reactor cores. It is possible that in the near future the JUNO experiment [66] could surpass KamLAND and set tighter bounds on visibly decaying A' .

We would also like to discuss a special case of $m_{A'} < 2m_e$. In this case, the visible decay mode is a loop-induced $A' \rightarrow 3\gamma$ [67,68], and it is very suppressed. The main mechanism for detecting A' is in fact a Compton-like scattering, $e + A' \rightarrow e + \gamma$. Using this process, Ref. [69] derived novel limits on dark photon in this mass range, obtaining $\kappa < 10^{-5}$. Would nuclear reactors be able to improve on this bound? The inverse Compton process will create $e\gamma$ in the final state, and it is not obvious what the limits are on this subcategory of events from the existing searches in detectors near the reactor cores. It will definitely have background from similar channels in ^{208}Tl decays. To avoid this complication, we use KamLAND signal again and estimate that

$$\left. \frac{dN_{e+A' \rightarrow e+\gamma}}{dN_{\text{observed}}/dt} \right|_{m_{A'} < 2m_e} \sim 0.1 \times \left(\frac{\kappa}{3 \times 10^{-5}} \right)^4. \quad (28)$$

As before, neutron capture on iron nuclei is used as a source of A' . We conclude that currently the reactors provide subdominant sensitivity to the LSND limits for dark photons below $2m_e$ mass. JUNO, however, would be able to improve this limit significantly, mostly due to a superb energy resolution and the possibility to look for sharp lines in the spectrum and from the ~ 3.5 times smaller baseline.

VI. CONCLUSIONS

Experiments at nuclear reactor experiments have been instrumental in determining the properties of neutrinos and constraining new physics such as axions and axionlike particles. Clearly, other MeV-scale particles from dark sectors can be constrained as well, with clear prospects of improving sensitivity to several classes of models (for an axionlike model, see, e.g., recent works [70,71], and for very light dark photons [72]). In this paper, we have revisited the constraints on millicharged particles imposed by detectors placed very near reactor cores. We have also calculated the production of MCPs from natural radioactivity and nuclear reactions powering the Sun. The main difference with the previous treatment is that we point out that every photon emission in nuclear γ decays can be accompanied by the $\chi\bar{\chi}$ production provided that $2m_\chi < \omega$. We have derived the corresponding energy spectrum of MCP particles, using previous simulations of the γ emission, mostly from (n, γ) reactions and decays of radioactive fission products. The calculated flux is typically much harder than the Compton-type production of MCP in the $e\gamma$ scattering. Consequently, higher m_χ masses can be probed, and we derive novel limits in the 0.7–2 MeV range, surpassing the sensitivity of the SLAC MCP search. These limits can be further improved, as the MCP scattering cross section scales inversely proportional to the electron recoil energy, and new low-threshold detectors will help to increase sensitivity.

While nuclear reactors provide the largest fluxes of MCPs for the closely located detectors, we note that there is also an ambient flux of MCP created by natural radioactivity (mostly caused by the radioactive isotopes of K, U, and Th). While fluxes of MCP created this way are much lower than those in proximity of reactor cores, the detection methods that can be employed could involve neutrino detectors and large self-shielding dark matter detectors (such as those based on xenon dual-TPC technology). These are large deep-underground detectors operating in a maximally background-free environment, capable of achieving much lower counting rates than detectors placed in reactors' proximity. While a solid constraint on ϵ based on these detectors relies on a detailed knowledge of the composition of the Local Crust, our analysis shows that the constraints derived in this way are likely to fall within the ballpark of $\epsilon \sim 10^{-4}$.

Perhaps a more promising avenue for the future studies is the solar MCP flux. If m_χ is below the m_e , the MCPs will be very efficiently produced by the positron annihilation. For heavier MCPs, the reaction $D(p, \gamma)^3\text{He}$ will provide the dominant contribution up to $m_\chi \sim 2.5$ MeV. Future low recoil experiments will be sensitive to the flux even for a very small value of millicharge, $\epsilon < 10^{-6}$.

The improved energy reach achieved by considering the (n, γ) reactions also allows the on-shell production of dark

photons heavy enough to decay to e^+e^- pairs. We derived the rate for near-reactor detectors to detect such decay signals and converted the observed signal rate to the constraints on dark photon couplings in the 1.1–4 MeV range. While the constraints derived in this way do not supplant the existing limits, we note that this is the first dark photon constraint obtained from near-reactor experiments for the MeV range, and the limits can be further improved with a detailed analysis of the background and the use of larger volume detectors.

Before we close, we would like to point to several items of discussion:

- (i) We improved the reactor bounds on MCPs because (n, γ) reactions give access to higher frequencies and higher m_χ masses compared to bremsstrahlung pair production of $\chi\bar{\chi}$. It would be also important to investigate whether in the $m_\chi < m_e$ range the bounds could be improved even further. A considerable fraction of these hard γ 's would undergo an e^+e^- pair production on heavy nuclei such as uranium. Subsequent annihilation of e^+ with a branching to MCPs would produce χ 's with the $O(\epsilon^2)$ probability, which is much larger than $O(\alpha\epsilon^2)$ in case of the bremsstrahlung production. To be able to do this reanalysis, one would have to simulate the relative weight of the pair production and Compton degradation of hard γ or, in other words, determine the yield of e^+ . This will be best done by experimental collaborations themselves, accounting for photon conversions inside (possibly dominated by pair production) and outside (presumably dominated by Compton process) nuclear fuel rods.
- (ii) In light of the recent success in developing extremely low threshold DM detectors [57], one would need a better quality estimate of the solar MCP flux. More careful calculations will take into account the spatial distribution of $\chi\bar{\chi}$ pair production inside the solar core, and most importantly the subsequent slowdown, and, for large enough ϵ , eventual thermalization of these particles. Estimates show that $\epsilon \sim 10^{-6}$ appears to be a critical value of the millicharge, but a better calculation is feasible.
- (iii) The range of masses and couplings explored in this paper is relevant for the possible solutions of EDGES anomaly. One should not, however, lose sight of the fact that such light MCPs are troublesome from the point of the very early cosmology, as they would certainly modify the predictions of the big bang nucleosynthesis. "Fixing" deuterium and helium abundances will most likely require additional ingredients/actors from the DS at the time of big bang nucleosynthesis.
- (iv) While (n, γ) reactions explored in this paper are necessarily limited in their kinematic reach to $2m_\chi$ and/or $m_{A'}$ under 5 MeV, the question remains as to

how efficiently the process of direct nuclear fission, i.e., nuclear scission itself, may produce exotic particles. While it will be suppressed by some powers of v/c , where v is the velocity of separating fragments, the potential kinematic reach will be higher than for the (n, γ) sources, as up to 180 MeV is available per every single occurrence of fission.

- (v) It is worth noting that a deep-underground far detector can also be used for deriving constraints on visibly decaying A' . It remains to be seen if the ongoing JUNO program will improve on some of the discussed limits, once the solar ^8B neutrino signal (suitable for deriving such limits) is measured.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX: PAIR PRODUCTION FROM E2 AND E3 TRANSITIONS

In this Appendix, we derive the ratio between MCP pair production and γ emission rates in nuclear deexcitation for E2 and E3 transitions under the recoil-less approximation. Up to some normalization for the multipole moments, we expand the electric part of the nuclear transition current as

$$J_i = \omega Q_i^{(1)} + \omega Q_{ij}^{(2)} q^j + \omega Q_{ijk}^{(3)} q^j q^k, \quad (\text{A1})$$

$$J_0 = q_i J_i / \omega = Q_i^{(1)} q^i + Q_{ij}^{(2)} q^i q^j + Q_{ijk}^{(3)} q^i q^j q^k, \quad (\text{A2})$$

where $Q_i^{(1)}$, $Q_{ij}^{(2)}$, and $Q_{ijk}^{(3)}$ are the electric dipole, quadrupole, and octapole moments and $k = (\omega, \mathbf{q})$ is the photon's (or virtual photon's) 4-momentum. Evaluating the squared amplitude for pair production and γ emission involves products of the form $J_\mu J_\nu^*$, when averaged over all directions and spins, such products can only depend on the magnitude of the multipoles rather than their components; therefore, the products of the multipoles can be replaced by

$$Q^{(1)i} Q_j^{(1)*} \rightarrow \frac{1}{3} |Q^{(1)}|^2 \delta_{ij}, \quad (\text{A3})$$

$$Q^{(2)ij} Q_{kl}^{(2)*} \rightarrow \frac{1}{5} |Q^{(2)}|^2 \left(\delta_{(k}^{(i} \delta_{l)}^{j)} - \frac{1}{3} \delta^{(ij)} \delta_{(kl)} \right), \quad (\text{A4})$$

$$Q^{(3)ijk} Q_{lmn}^{(3)*} \rightarrow \frac{1}{7} |Q^{(3)}|^2 \left(\delta_{(l}^{(i} \delta_m^{j} \delta_n^{k)} - \frac{3}{5} \delta^{(ij} \delta_{(l}^{k)} \delta_{mn)} \right), \quad (\text{A5})$$

$$Q^{(m)i \dots j} Q_{k \dots l}^{(n)*} \rightarrow 0, \quad \text{for } m \neq n, \quad (\text{A6})$$

where the coefficients are determined by the requirement $Q^{(m)i \dots j} Q_{i \dots j}^{(m)*} = |Q^{(m)}|^2$ and the traceless condition of the multipole moments. These results then lead to

$$J_0 J_0^* \rightarrow \frac{1}{3} |Q^{(1)}|^2 q^2 + \frac{2}{15} |Q^{(2)}|^2 q^4 + \frac{2}{35} |Q^{(3)}|^2 q^6, \quad (\text{A7})$$

$$J_0 J_i^* \rightarrow \frac{1}{3} |Q^{(1)}|^2 \omega q_i + \frac{2}{15} |Q^{(2)}|^2 \omega q^2 q_i + \frac{2}{35} |Q^{(3)}|^2 \omega q^4 q_i, \quad (\text{A8})$$

$$J_i J_j^* \rightarrow \frac{1}{3} |Q^{(1)}|^2 \omega^2 \delta_{ij} + \frac{2}{15} |Q^{(2)}|^2 \omega^2 \left(\frac{3}{4} \delta_{ij} q^2 + \frac{1}{4} q_i q_j \right) + \frac{2}{35} |Q^{(3)}|^2 \omega^2 q^2 \left(\frac{2}{3} \delta_{ij} q^2 + \frac{1}{3} q_i q_j \right). \quad (\text{A9})$$

For γ emission, the squared amplitude is given by

$$|\mathcal{M}_{(\gamma)}^2 = -g^{\mu\nu} J_\mu J_\nu^* \rightarrow \frac{2}{3} |Q^{(1)}|^2 q^2 + \frac{1}{5} |Q^{(2)}|^2 q^4 + \frac{8}{105} |Q^{(3)}|^2 q^6; \quad (\text{A10})$$

for pair production; the squared amplitude is given by

$$|\mathcal{M}|_{(\chi\bar{\chi})}^2 = T^{\mu\nu} J_\mu J_\nu^*, \quad T^{\mu\nu} = \frac{\varepsilon^2 e^2}{k^4} (-g^{\mu\nu} 2k^2 + 4p_\chi^\mu p_\chi^\nu + 4p_{\bar{\chi}}^\mu p_{\bar{\chi}}^\nu); \quad (\text{A11})$$

and after some algebra, we arrive at

$$|\mathcal{M}|_{(\chi\bar{\chi},\text{E1})}^2 = \frac{2e^2\varepsilon^2}{3k^4} |Q^{(1)}|^2 [k^4 + k^2(-4E_\chi E_{\bar{\chi}} + 2\omega^2) + 4m_\chi^2 \omega^2], \quad (\text{A12})$$

$$|\mathcal{M}|_{(\chi\bar{\chi},\text{E2})}^2 = \frac{e^2\varepsilon^2}{15k^4} |Q^{(2)}|^2 [-4k^6 + k^4(16E_\chi E_{\bar{\chi}} - 3\omega^2) + 6k^2\omega^2(-2E_\chi E_{\bar{\chi}} - 2m_\chi^2 + \omega^2) + 12m_\chi^2 \omega^4], \quad (\text{A13})$$

$$|\mathcal{M}|_{(\chi\bar{\chi},\text{E3})}^2 = \frac{4e^2\varepsilon^2}{105k^4} |Q^{(3)}|^2 [3k^8 - k^6(12E_\chi E_{\bar{\chi}} + \omega^2) + 2k^4\omega^2(10E_\chi E_{\bar{\chi}} + 4m_\chi^2 - 3\omega^2) + 4k^2\omega^4(-2E_\chi E_{\bar{\chi}} - 4m_\chi^2 + \omega^2) + 8m_\chi^2 \omega^6]. \quad (\text{A14})$$

To obtain the ratio of cross sections, we integrate over the phase space for each process. This gives the differential ratio in the form of Eq. (3). After changing variables using $k^2 = M^2 + M'^2 - 2ME_{N'}$, the problem reduces to calculating the elementary integral

$$I_n = \int_{k_{\min}^2}^{k_{\max}^2} k^{2n} dk^2, \quad (\text{A15})$$

the kinematical limits correspond to χ and $\bar{\chi}$ moving parallel or antiparallel to each other, with

$$k_{\min}^2 = 2E_\chi E_{\bar{\chi}} + 2m_\chi^2 - 2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|, \quad k_{\max}^2 = 2E_\chi E_{\bar{\chi}} + 2m_\chi^2 + 2|\mathbf{p}_\chi||\mathbf{p}_{\bar{\chi}}|. \quad (\text{A16})$$

Finally, in terms of I_n , the differential ratio is given by

$$\frac{dr_{\text{E1}}}{dE_\chi} = \frac{\alpha\varepsilon^2}{4\pi\omega^3} [I_0 + (-4E_\chi E_{\bar{\chi}} + 2\omega^2)I_{-1} + 4m_\chi^2 \omega^2 I_{-2}], \quad (\text{A17})$$

$$\frac{dr_{\text{E2}}}{dE_\chi} = \frac{\alpha\varepsilon^2}{12\pi\omega^5} [-4I_1 + (16E_\chi E_{\bar{\chi}} - 3\omega^2)I_0 + 6\omega^2(-2E_\chi E_{\bar{\chi}} - 2m_\chi^2 + \omega^2)I_{-1} + 12m_\chi^2 \omega^4 I_{-2}], \quad (\text{A18})$$

$$\frac{dr_{\text{E3}}}{dE_\chi} = \frac{\alpha\varepsilon^2}{8\pi\omega^7} [3I_2 - (12E_\chi E_{\bar{\chi}} + \omega^2)I_1 + 2\omega^2(10E_\chi E_{\bar{\chi}} + 4m_\chi^2 - 3\omega^2)I_0 + 4\omega^4(-2E_\chi E_{\bar{\chi}} - 4m_\chi^2 + \omega^2)I_{-1} + 8m_\chi^2 \omega^6 I_{-2}]. \quad (\text{A19})$$

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- [1] G. Lanfranchi, M. Pospelov, and P. Schuster, The search for feebly interacting particles, *Annu. Rev. Nucl. Part. Sci.* **71**, 279 (2021).
[2] J. Beacham *et al.*, Physics beyond colliders at CERN: Beyond the standard model working group report, *J. Phys. G* **47**, 010501 (2020).
[3] B. Holdom, Two U(1)'s and epsilon charge shifts, *Phys. Lett. B* **166**, 196 (1986).

- [4] S. Davidson, S. Hannestad, and G. Raffelt, Updated bounds on millicharged particles, *J. High Energy Phys.* **05** (2000) 003.
[5] H. Vogel and J. Redondo, Dark radiation constraints on minicharged particles in models with a hidden photon, *J. Cosmol. Astropart. Phys.* **02** (2014) 029.
[6] A. D. Dolgov, S. L. Dubovsky, G. I. Rubtsov, and I. I. Tkachev, Constraints on millicharged particles from Planck data, *Phys. Rev. D* **88**, 117701 (2013).

- [7] J. H. Chang, R. Essig, and S. D. McDermott, Supernova 1987A constraints on sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle, *J. High Energy Phys.* **09** (2018) 051.
- [8] D. Dunskey, L. J. Hall, and K. Harigaya, CHAMP cosmic rays, *J. Cosmol. Astropart. Phys.* **07** (2019) 015.
- [9] D. F. G. Fiorillo and E. Vitagliano, Self-interacting dark sectors in supernovae can behave as a relativistic fluid, *Phys. Rev. Lett.* **133**, 251004 (2024).
- [10] M. Pospelov and H. Ramani, Earth-bound millicharge relics, *Phys. Rev. D* **103**, 115031 (2021).
- [11] A. Berlin, H. Liu, M. Pospelov, and H. Ramani, Terrestrial density of strongly-coupled relics, *Phys. Rev. D* **109**, 075027 (2024).
- [12] J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen, and N. Mahesh, An absorption profile centred at 78 megahertz in the sky-averaged spectrum, *Nature (London)* **555**, 67 (2018).
- [13] R. Barkana, N. J. Outmezguine, D. Redigolo, and T. Volansky, Strong constraints on light dark matter interpretation of the EDGES signal, *Phys. Rev. D* **98**, 103005 (2018).
- [14] E. D. Kovetz, V. Poulin, V. Gluscevic, K. K. Boddy, R. Barkana, and M. Kamionkowski, Tighter limits on dark matter explanations of the anomalous EDGES 21 cm signal, *Phys. Rev. D* **98**, 103529 (2018).
- [15] H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Reviving millicharged dark matter for 21-cm cosmology, *Phys. Rev. D* **100**, 123011 (2019).
- [16] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, and N. Toro, Dark matter, millicharges, axion and scalar particles, gauge bosons, and other new physics with LDMX, *Phys. Rev. D* **99**, 075001 (2019).
- [17] A. A. Prinz *et al.*, Search for millicharged particles at SLAC, *Phys. Rev. Lett.* **81**, 1175 (1998).
- [18] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Millicharged particles in neutrino experiments, *Phys. Rev. Lett.* **122**, 071801 (2019).
- [19] K. J. Kelly and Y.-D. Tsai, Proton fixed-target scintillation experiment to search for millicharged dark matter, *Phys. Rev. D* **100**, 015043 (2019).
- [20] R. Harnik, Z. Liu, and O. Palamara, Millicharged particles in liquid argon neutrino experiments, *J. High Energy Phys.* **07** (2019) 170.
- [21] R. Acciarri *et al.* (ArgoNeuT Collaboration), Improved limits on millicharged particles using the ArgoNeuT experiment at Fermilab, *Phys. Rev. Lett.* **124**, 131801 (2020).
- [22] F. Kling, J.-L. Kuo, S. Trojanowski, and Y.-D. Tsai, FLArE up dark sectors with EM form factors at the LHC forward physics facility, *Nucl. Phys. B* **987**, 116103 (2023).
- [23] L. Barak *et al.* (SENSEI Collaboration), Search by the SENSEI experiment for millicharged particles produced in the NuMI beam, *Phys. Rev. Lett.* **133**, 071801 (2024).
- [24] Y.-D. Tsai, I. Hwang, R. Schmitz, M. Citron, K. Gunthoti, J. Steenis, H. Jeong, H. Moon, J. H. Yoo, and M. X. Liu, LANSCE-mQ: Dedicated search for milli/fractionally charged particles at LANL, [arXiv:2407.07142](https://arxiv.org/abs/2407.07142).
- [25] R. Essig, P. Li, Z. Liu, M. McDuffie, R. Plestid, and H. Xu, Probing millicharged particles at an electron beam dump with ultralow-threshold sensors, *J. High Energy Phys.* **04** (2025) 057.
- [26] R. Plestid, V. Takhistov, Y.-D. Tsai, T. Bringmann, A. Kusenko, and M. Pospelov, New constraints on millicharged particles from cosmic-ray production, *Phys. Rev. D* **102**, 115032 (2020).
- [27] R. Harnik, R. Plestid, M. Pospelov, and H. Ramani, Millicharged cosmic rays and low recoil detectors, *Phys. Rev. D* **103**, 075029 (2021).
- [28] M. Du, R. Fang, and Z. Liu, Millicharged particles from proton bremsstrahlung in the atmosphere, *J. High Energy Phys.* **08** (2024) 174.
- [29] H. Wu, E. Hardy, and N. Song, Searching for heavy millicharged particles from the atmosphere, *Phys. Rev. D* **110**, 115037 (2024).
- [30] L. Singh *et al.* (TEXONO Collaboration), Constraints on millicharged particles with low threshold germanium detectors at Kuo-Sheng reactor neutrino laboratory, *Phys. Rev. D* **99**, 032009 (2019).
- [31] A. A. Aguilar-Arevalo *et al.* (CONNIE, Atucha-II Collaboration), Search for reactor-produced millicharged particles with Skipper-CCDs at the CONNIE and Atucha-II experiments, [arXiv:2405.16316](https://arxiv.org/abs/2405.16316).
- [32] H. M. Chang *et al.* (TEXONO Collaboration), Search of axions at the Kuo-Sheng nuclear power station with a high-purity germanium detector, *Phys. Rev. D* **75**, 052004 (2007).
- [33] J. B. Dent, B. Dutta, D. Kim, S. Liao, R. Mahapatra, K. Sinha, and A. Thompson, New directions for axion searches via scattering at reactor neutrino experiments, *Phys. Rev. Lett.* **124**, 211804 (2020).
- [34] D. Aristizabal Sierra, V. De Romeri, L. J. Flores, and D. K. Papoulias, Axionlike particles searches in reactor experiments, *J. High Energy Phys.* **03** (2021) 294.
- [35] N. M. Kroll and W. Wada, Internal pair production associated with the emission of high-energy gamma rays, *Phys. Rev.* **98**, 1355 (1955).
- [36] C. Pitrou and M. Pospelov, QED corrections to big-bang nucleosynthesis reaction rates, *Phys. Rev. C* **102**, 015803 (2020).
- [37] P. Talou and R. Vogt, *Nuclear Fission: Theories, Experiments and Applications* (Springer Nature, Cham, Switzerland, 2023).
- [38] B. Xin *et al.* (TEXONO Collaboration), Production of electron neutrinos at nuclear power reactors and the prospects for neutrino physics, *Phys. Rev. D* **72**, 012006 (2005).
- [39] From ENSDF database as of December 14, 2024. Version available at <http://www.nndc.bnl.gov/ensarchivals/>.
- [40] J. Aalbers *et al.* (LZ Collaboration), First search for atmospheric millicharged particles with the LUX-ZEPLIN experiment, [arXiv:2412.04854](https://arxiv.org/abs/2412.04854).
- [41] W. W. M. Allison and J. H. Cobb, Relativistic charged particle identification by energy loss, *Annu. Rev. Nucl. Part. Sci.* **30**, 253 (1980).
- [42] B. L. Henke, E. M. Gullikson, and J. C. Davis, X-ray interactions: Photoabsorption, scattering, transmission, and reflection at $E = 50\text{--}30,000$ eV, $Z = 1\text{--}92$, *At. Data Nucl. Data Tables* **54**, 181 (1993).
- [43] Z. Daraktchieva *et al.* (MUNU Collaboration), Final results on the neutrino magnetic moment from the MUNU experiment, *Phys. Lett. B* **615**, 153 (2005).

- [44] M. Deniz *et al.* (TEXONO Collaboration), Measurement of Nu(e)-bar -electron scattering cross-section with a CsI(Tl) scintillating crystal array at the Kuo-Sheng nuclear power reactor, *Phys. Rev. D* **81**, 072001 (2010).
- [45] N. Ackermann *et al.*, First observation of reactor antineutrinos by coherent scattering, [arXiv:2501.05206](#).
- [46] M. Agostini *et al.* (Borexino Collaboration), First simultaneous precision spectroscopy of pp , ${}^7\text{Be}$, and pep solar neutrinos with Borexino Phase-II, *Phys. Rev. D* **100**, 082004 (2019).
- [47] E. Aprile *et al.* (XENON Collaboration), Search for new physics in electronic recoil data from XENONnT, *Phys. Rev. Lett.* **129**, 161805 (2022).
- [48] J. Aalbers *et al.* (LZ Collaboration), Search for new physics in low-energy electron recoils from the first LZ exposure, *Phys. Rev. D* **108**, 072006 (2023).
- [49] X. Zeng *et al.* (PandaX Collaboration), Exploring new physics with PandaX-4T low energy electronic recoil data, *Phys. Rev. Lett.* **134**, 041001 (2025).
- [50] Y. Huang, V. Chubakov, F. Mantovani, R. L. Rudnick, and W. F. McDonough, A reference earth model for the heat-producing elements and associated geoneutrino flux, *Geochim. Geophys. Geosyst.* **14**, 2003 (2013).
- [51] M. Agostini *et al.* (Borexino Collaboration), Spectroscopy of geoneutrinos from 2056 days of Borexino data, *Phys. Rev. D* **92**, 031101 (2015).
- [52] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [53] F. Ajzenberg-Selove, Energy levels of light nuclei $A = 13$ –15, *Nucl. Phys. A* **523**, 1 (1991).
- [54] L. E. Marcucci, G. Mangano, A. Kievsky, and M. Viviani, Implication of the proton-deuteron radiative capture for big bang nucleosynthesis, *Phys. Rev. Lett.* **116**, 102501 (2016); *Phys. Rev. Lett.* **117**, 049901(E) (2016).
- [55] F. D'Eramo, G. Lucente, N. Nath, and S. Yun, Terrestrial detection of hidden vectors produced by solar nuclear reactions, *J. High Energy Phys.* **12** (2023) 091.
- [56] S. Perez *et al.* (Oscura Collaboration), Searching for milli-charged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab, *J. High Energy Phys.* **02** (2024) 072.
- [57] K. Aggarwal *et al.* (DAMIC-M Collaboration), Probing benchmark models of hidden-sector dark matter with DAMIC-M, [arXiv:2503.14617](#).
- [58] C. Hagner, M. Altmann, F. von Feilitzsch, L. Oberauer, Y. Declais, and E. Kajfasz, Experimental search for the neutrino decay $\nu_3 \rightarrow \nu_j + e^+ + e^-$ and limits on neutrino mixing, *Phys. Rev. D* **52**, 1343 (1995).
- [59] J. D. Bjorken, S. Ecklund, W. R. Nelson, A. Abashian, C. Church, B. Lu, L. W. Mo, T. A. Nunamaker, and P. Rassmann, Search for neutral metastable penetrating particles produced in the SLAC beam dump, *Phys. Rev. D* **38**, 3375 (1988).
- [60] S. Andreas, C. Niebuhr, and A. Ringwald, New limits on hidden photons from past electron beam dumps, *Phys. Rev. D* **86**, 095019 (2012).
- [61] L. Marsicano, M. Battaglieri, M. Bondi', C. D. R. Carvajal, A. Celentano, M. De Napoli, R. De Vita, E. Nardi, M. Raggi, and P. Valente, Dark photon production through positron annihilation in beam-dump experiments, *Phys. Rev. D* **98**, 015031 (2018).
- [62] J. H. Chang, R. Essig, and S. D. McDermott, Revisiting supernova 1987A constraints on dark photons, *J. High Energy Phys.* **01** (2017) 107.
- [63] S. Abe *et al.* (KamLAND Collaboration), Measurement of the ${}^8\text{B}$ solar neutrino flux with the KamLAND liquid scintillator detector, *Phys. Rev. C* **84**, 035804 (2011).
- [64] R. B. Firestone, T. Belgia, M. Krtićka, F. Bečvář, L. Szentmiklósi, and I. Tomandl, Thermal neutron capture cross section for ${}^{56}\text{Fe}(n, \gamma)$, *Phys. Rev. C* **95**, 014328 (2017).
- [65] L. Waites, A. Thompson, A. Bungau, J. M. Conrad, B. Dutta, W.-C. Huang, D. Kim, M. Shaevitz, and J. Spitz, Axionlike particle production at beam dump experiments with distinct nuclear excitation lines, *Phys. Rev. D* **107**, 095010 (2023).
- [66] F. An *et al.* (JUNO Collaboration), Neutrino physics with JUNO, *J. Phys. G* **43**, 030401 (2016).
- [67] M. Pospelov, A. Ritz, and M. B. Voloshin, Bosonic super-WIMPs as keV-scale dark matter, *Phys. Rev. D* **78**, 115012 (2008).
- [68] S. D. McDermott, H. H. Patel, and H. Ramani, Dark photon decay beyond the Euler-Heisenberg limit, *Phys. Rev. D* **97**, 073005 (2018).
- [69] M. Pospelov and Y.-D. Tsai, Light scalars and dark photons in Borexino and LSND experiments, *Phys. Lett. B* **785**, 288 (2018).
- [70] V. Brdar, B. Dutta, W. Jang, D. Kim, I. M. Shoemaker, Z. Tabrizi, A. Thompson, and J. Yu, Axionlike particles at future neutrino experiments: Closing the cosmological triangle, *Phys. Rev. Lett.* **126**, 201801 (2021).
- [71] B. J. Park *et al.* (NEON Collaboration), New constraints on axionlike particles with the NEON detector at a nuclear reactor, *Phys. Rev. Lett.* **134**, 201002 (2025).
- [72] M. Danilov, S. Demidov, and D. Gorbunov, Constraints on hidden photons produced in nuclear reactors, *Phys. Rev. Lett.* **122**, 041801 (2019).