

Search for Reactor-Produced Millicharged Particles with Skipper-CCDs at the CONNIE and Atucha-II Experiments

Alexis A. Aguilar-Arevalo,¹ Juan Carlos D'Olivo,¹ Youssef Sarkis,¹ Nicolas Avalos,² Xavier Bertou,² Pablo Bellino,³ Carla Bonifazi,^{4,5} Ana Botti,⁶ Gustavo Cancelo,⁶ Juan Estrada,⁶ Richard Ford,⁶ Kevin Kuk,⁶ Andrew Lathrop,⁶ Javier Tiffenberg,⁶ Mariano Cababié,^{7,8} Brenda A. Cervantes-Vergara,^{1,6} Claudio Chavez,^{6,9,10} Fernando Chierchie,⁹ David Delgado,¹¹ Eliana Depaoli,^{3,12} João dos Anjos,¹³ Herman P. Lima, Jr.,¹³ Guillermo Fernandez Moroni,^{6,9,14} Aldo R. Fernandes Neto,¹⁵ Ben Kilminster,¹⁶ Patrick Lemos,⁵ Katherine Maslova,⁵ Irina Nasteva,⁵ Ana Carolina Oliveira,⁵ Pedro Ventura,⁵ Martin Makler,^{4,13} Agustina Magnoni,^{17,18} Franciole Marinho,¹⁹ Jorge Molina,¹⁰ Diego Stalder,¹⁰ Santiago Perez,^{20,21,*} Dario Rodrigues^{10,21,†} Laura Paulucci,²² Ivan Sidelnik,²³ and Miguel Sofo Haro²⁴

(CONNIE and Atucha-II Collaborations)

¹*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Circuito Exterior s/n, C.U., CDMX, Mexico*

²*Centro Atómico Bariloche and Instituto Balseiro, Comisión Nacional de Energía Atómica (CNEA), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Universidad Nacional de Cuyo (UNCUYO), Av Bustillo 9500, San Carlos de Bariloche, Argentina*

³*Comisión Nacional de Energía Atómica, Centro Atómico Constituyentes*

⁴*International Center for Advanced Studies & Instituto de Ciencias Físicas, ECyT-UNSAM and CONICET, 25 de Mayo y Francia, Buenos Aires, Argentina*

⁵*Instituto de Física, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 149, Cidade Universitária, Rio de Janeiro, RJ, Brazil*

⁶*Fermi National Accelerator Laboratory, Batavia, IL, USA*

⁷*Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, 1050 Wien, Austria*

⁸*Atominstitut, Technische Universität Wien, 1020 Wien, Austria*

⁹*Instituto de Inv. en Ing. Eléctrica “Alfredo Desages” (IIIE), Dpto. de Ing. Eléctrica y de Computadoras, CONICET and Universidad Nacional del Sur (UNS), 800 San Andrés Street, Bahía Blanca, Argentina*

¹⁰*Facultad de Ingeniería, Universidad Nacional de Asunción, Campus de la UNA, San Lorenzo, Paraguay*

¹¹*Central Nuclear ATUCHA I-II, Nucleoeléctrica Argentina Sociedad Anónima, Buenos Aires, Argentina*

¹²*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Buenos Aires, Argentina*

¹³*Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud, 150, Urca, Rio de Janeiro, RJ, Brazil*

¹⁴*Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL, 60637, USA*

¹⁵*Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Campus Angra dos Reis, Rua do Areal, 522, Pq Mambucaba, Angra dos Reis, RJ, Brazil*

¹⁶*Physik Institut, Universität Zürich, Winterthurerstrasse 190, Zurich, Switzerland*

¹⁷*Departamento de Física, FCEN, Universidad de Buenos Aires, Buenos Aires, Argentina*

¹⁸*Laboratorio de Óptica Cuántica, DEILAP, UNIDEF (CITEDEF-CONICET), Buenos Aires, Argentina*

¹⁹*Departamento de Física, Instituto Tecnológico de Aeronáutica, DCTA, 12228-900, São José dos Campos, São Paulo, Brazil*

²⁰*Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, Buenos Aires, Argentina*

²¹*CONICET - Universidad de Buenos Aires, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina*

²²*Universidade Federal do ABC, Avenida dos Estados 5001, Santo André, SP, Brazil*

²³*Departamento de Física de Neutrones, Centro Atómico Bariloche, (CNEA, CONICET), Bariloche, Argentina*

²⁴*Universidad Nacional de Córdoba, CONICET (IFEG) and CNEA (RA0), Córdoba, Argentina*



(Received 10 June 2024; revised 5 November 2024; accepted 24 January 2025; published 19 February 2025)

Millicharged particles, proposed by various extensions of the standard model, can be created in pairs by high-energy photons within nuclear reactors and can interact electromagnetically with electrons in matter. Recently, the existence of a plasmon peak in the interaction cross section with silicon in the eV range was highlighted as a promising approach to enhance low-energy sensitivities. The CONNIE and Atucha-II

*Contact author: santiep.137@gmail.com

†Contact author: rodriguesfm@df.uba.ar

reactor neutrino experiments utilize Skipper-CCD sensors, which enable the detection of interactions in the eV range. We present world-leading limits on the charge of millicharged particles within a mass range spanning 6 orders of magnitude, derived through a comprehensive analysis and the combination of data from both experiments.

DOI: [10.1103/PhysRevLett.134.071801](https://doi.org/10.1103/PhysRevLett.134.071801)

Short baseline reactor antineutrino experiments arise as an opportunity to look for beyond the standard model (BSM) particles, such as QCD axions [1,2], and other dark matter candidates [3–5]. Among the extensions to the standard model, millicharged particles (mCP) have gained significant attention and are considered highly compelling BSM candidates [6–8]. The TEXONO collaboration employed a point-contact 500 g germanium detector with a low-energy threshold of 300 eV, positioned 28 m away from a 2.9 GW_{th} nuclear reactor, using 124.2/70.3 kg-days of reactor ON/OFF data, to set the most stringent direct laboratory exclusion limits below 1 MeV up to date [9].

Silicon detectors have pushed the energy thresholds to lower values, allowing for higher sensitivity in the dark matter low-mass range. CONNIE [10,11] was the first experiment to use silicon charge-coupled devices (CCD) at nuclear reactor to look for coherent elastic neutrino-nucleus scattering and impose competitive constraints on BSM physics [12]. Recently, CONNIE upgraded its detector by substituting the CCDs with a pair of Skipper-CCDs [13], increasing its sensitivity and low-energy reach [14]. At the same time, the Atucha-II experiment has deployed a Skipper-CCD sensor inside a nuclear power plant, situated just 12 m from the reactor core. The initial results demonstrate promising potential to explore both standard-model physics and exotic searches [15].

In a recent contribution, the SENSEI experiment has achieved the most stringent exclusion limit for mCPs in the 30 to 380 MeV mass range using Skipper-CCDs [16]. Based on this, additional promising scenarios for enhancing this search have been proposed using a kg-scale experiment with the same technology [17]. There is, however, a compelling reason to conduct such an experiment in the vicinity of a nuclear reactor, as its core represents the most potent source of gamma rays on Earth. Moreover, mCPs produced by Compton-like interactions from gamma rays enable the exploration of sub-MeV masses, making the reactor experiments the most competitive in this energy range.

Tracking mCPs passing through a stack of detectors has also been proposed as a highly sensitive strategy for observing these particles when produced in an accelerator [18]. However, this strategy is not competitive below 1 MeV, where the fraction of the elementary charge, ϵ , have already been excluded well beneath to 10^{-5} [9]. Observing tracks for even smaller values of ϵ would require extremely large stacked detectors.

In this Letter, we present world-leading direct laboratory exclusion limits for mCPs below 1 MeV, covering 6 orders of magnitude in mCP mass. This work also represents a collaborative effort between the CONNIE and Atucha-II experiments—the first to use Skipper-CCD technology for this type of search in reactor experiments—achieving combined results that enhance the robustness of the analysis and yield a stronger limit.

A possible channel for the generation of mCPs (χ_q) in the sub-GeV mass range is through a Compton-like process, in which a γ photon scatters off an electron in the material of the reactor core (Uranium), the photon could then kinetically mix with a dark photon [19,20]. As a result, a new dark fermion pair $\chi_q - \bar{\chi}_q$, coupled to the dark photon, can acquire a small electric charge $q = \epsilon e$ proportional to the kinetic mixing parameter. In the case of a pure mCP, the dark photon is massless and the resulting particles has an electromagnetic charge ϵ , which is a real number with $|\epsilon| < 1$ and e is the elementary charge.

Approximately half of the γ flux in the reactor core arises from highly excited fission fragments, with the remainder originating from radioactive de-excitation of the daughter nuclei, inelastic neutron scattering, and capture of neutrons by core materials. The γ -ray spectrum characteristic of neutron-induced fission of uranium, determined for an FRJ-1 (Merlin) research reactor core, can be parameterized by

$$\frac{dN_\gamma}{dE_\gamma} = K P \exp(-1.1E_\gamma), \quad (1)$$

which holds for photon energies E_γ above 0.2 MeV, where $K = 0.581 \times 10^{18} \text{ MeV}^{-1} \text{ s}^{-1}$, and P is the reactor thermal power in MW. This model has been applied by the TEXONO collaboration [9] and has also been employed in recent dark matter searches [2,9,21–23]. To the best of our knowledge, however, secondary γ rays were not taken into account in previous calculations although they are also able to produce mCPs. In this work, we calculate the limits in both scenarios, reflecting the contributions to mCP production of only primary γ rays, as well as including secondary γ rays from transport and energy loss in the nuclear core. The secondary contribution was estimated from a simulation using GEANT4 [24,25].

The differential production cross section for mCP through the mentioned channel can be estimated by adapting the lepton-pair production process [9]. To do

this, the $\chi_q - \bar{\chi}_q$ production vertex is parameterized by ε and the lepton mass is replaced by the proposed mCP mass, m_{χ_q} ,

$$\frac{d\sigma}{dE_{\chi_q}}(\gamma e \rightarrow \chi_q \bar{\chi}_q e) = \frac{4}{3} \frac{\varepsilon^2 \alpha^3}{m_e^2 E_\gamma^3} [(3(E_{\chi_q}^2 + E_{\bar{\chi}_q}^2) + 2E_{\chi_q} E_{\bar{\chi}_q}) \log \times \left(\frac{2E_{\chi_q} E_{\bar{\chi}_q}}{E_\gamma m_{\chi_q}} \right)], \quad (2)$$

where m_e is the mass of the electron, α is the fine structure constant, and $E_{\bar{\chi}_q} = E_\gamma - E_{\chi_q}$.

The total differential flux of mCP is calculated by taking the convolution of the reactor γ -ray spectrum and the differential production cross- as in Eq. (3). The integral is normalized by the total interaction cross section, σ_{tot} . Following the same argument as in Refs. [9,26], restricting the integral between 1 and 5 MeV, σ_{tot} can be approximated by the Compton cross section, since this mechanism dominates over other interaction processes. The flux then becomes

$$\frac{d\phi_{\chi_q}}{dE_{\chi_q}} = \frac{2}{4\pi D^2} \int \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{dE_{\chi_q}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma, \quad (3)$$

where D is the distance between the detector and the center of the reactor core, and there is a factor of 2 from the fact that mCPs are produced in pairs.

Millicharged particles can be described as charged particles traveling with a velocity $\beta = (p/E_{\chi_q})$, and are expected to interact electromagnetically, leading to the production of ionization wherein free charge carriers are released for energy depositions above the band gap of silicon. A first description of this phenomenon can be found in Ref. [27]. This description is semiclassical in the sense that the particle is considered to be relativistic with a p_μ and a classical source of electromagnetic fields. The effective cross section for the interaction is then given by

$$\frac{d\sigma}{d\omega} = \frac{8\alpha\varepsilon^2}{N_e\beta^2} \int_0^\infty dk \left\{ \frac{1}{k} \text{Im} \left(-\frac{1}{\varepsilon(\omega, k)} \right) + k \left(\beta^2 - \frac{\omega^2}{k^2} \right) \text{Im} \left(\frac{1}{-k^2 + \varepsilon(\omega, k)\omega^2} \right) \right\}, \quad (4)$$

where information regarding the interaction between virtual photons emitted by the mCP and the material is encoded in the complex dielectric function $\varepsilon(\omega, k) = \varepsilon_1(\omega, k) + i\varepsilon_2(\omega, k)$, N_e is the electron number density of the material, and k is the momentum transfer to the material.

The Photo Absorption Ionization (PAI) model (also known as Fermi virtual photon or Weizsacker-Williams approximation) has been used to describe the energy loss per unit length for standard model particles, but it has also been employed in mCP searches by scaling the coupling

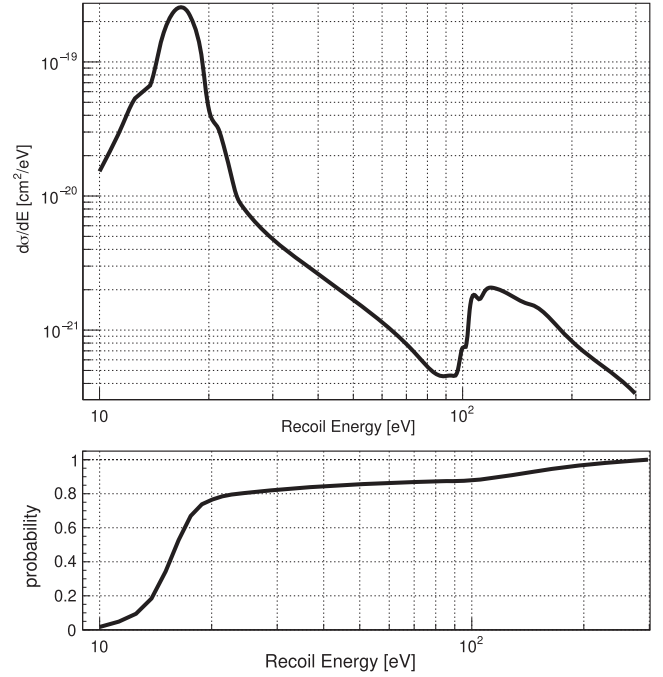


FIG. 1. (Top) Differential interaction cross section in silicon for mCP with mass $m_{\chi_q} = 1$ eV and charge fraction $\varepsilon = 10^{-6}$, and (bottom) cumulative probability of interaction normalized to the energy interval under consideration.

with the electron charge to the mCP charge [28,29]. A full derivation of the modeling of the cross section can be found in Ref. [30], as well as a discussion on the physical meaning of each term. This differential cross section can be expressed as

$$\begin{aligned} \frac{d\sigma}{dE} = & \frac{\alpha}{\beta^2 \pi} \frac{\sigma_\gamma(E)}{EZ} \ln[(1 - \beta^2 \varepsilon_1)^2 + \beta^4 \varepsilon_2^2]^{-1/2} \\ & + \frac{\alpha}{\beta^2 \pi N_e \hbar c} \left(\beta^2 - \frac{\varepsilon_1}{|\varepsilon|^2} \right) \Theta + \frac{\alpha}{\beta^2 \pi} \frac{\sigma_\gamma(E)}{EZ} \ln \left(\frac{2mc^2 \beta^2}{E} \right) \\ & + \frac{\alpha}{\beta^2 \pi E^2} \int_0^E \frac{\sigma_\gamma(E')}{Z} dE', \end{aligned} \quad (5)$$

where σ_γ is the photoabsorption cross section and $\tan \Theta = \varepsilon_2 \beta^2 / (1 - \beta^2 \varepsilon_1)$.

Figure 1 illustrates the energy dependence of the interaction cross section for an mCP with 1 eV mass and $\varepsilon = 10^{-6}$. The sizable enhancement observed in the low-energy region comes from the interaction of the particles with bulk plasmons. The tabulated complex index of refraction and photoabsorption data is not valid for energy deposits below ~ 50 eV as there is a crucial difference between optical absorption and the scattering of relativistic particles. Photons are always transversely polarized, whereas a charged particle can also interact with the material via longitudinal Coulomb modes which dominate the response function in this regime. Optical absorption

data have then been identified as a poor proxy for a relativistic scattering of charged particles at low energies.

To precisely calculate the interaction cross section for mCPs near the plasmon peak, in Ref. [31] the electron loss function $\text{Im}[-1/\epsilon(\omega, k)]$ is calculated for different models of the dielectric function in the DARKELF package [32], producing reliable results when compared to electron energy loss spectroscopy data when $\beta \geq 0.01$.

Thus, we turn to the DARKELF (GPAW) model to calculate the expected rate of mCPs below 50 eV as the PAI model underestimates the cross section near the plasmon peak, while GPAW provides a more accurate description, as stated in Ref. [31]. This integration constitutes the main contribution to systematic uncertainty (see Supplemental Material [33] for details).

The differential rate of events due to χ_q interactions can then be calculated by integrating the flux obtained in Eq. (3) convolved with the interaction cross section,

$$\frac{dR}{dE} = \rho \int_{E_{\min}}^{E_{\max}} \frac{d\phi_{\chi_q}}{dE_{\chi_q}} \frac{d\sigma}{dE} dE_{\chi_q}, \quad (6)$$

where ρ is the atomic number density and $(E_{\min}, E_{\max})$ are the values of the mCP energy.

Fully depleted high-resistivity silicon CCDs are being used in various experiments dedicated to dark matter [34] and low-energy neutrino detection, which require low thresholds and excellent background control. Skipper-CCDs [13] are the new generation of this imaging technology, achieving single-electron sensitivity by using the nondestructive readout of the charge packets held in each pixel [18,35–37]. This capability allows for an excellent signal-to-noise ratio with detection thresholds as low as 15 eV in above-ground experiments [38]. Both the CONNIE and Atucha-II experiments employ Skipper-CCD sensors of 675 μm thickness and 15 μm pixel size, designed by LBNL Microsystems Laboratory and manufactured by Teledyne-DALSA. They are read out using a low-threshold acquisition controller board [39].

The Coherent Neutrino-Nucleus Interaction Experiment (CONNIE) [10–12,14] is operating in a ground-level laboratory outside the dome of the 3.95 GW_{th} Angra 2 nuclear reactor near Rio de Janeiro, Brazil, at a distance of about 30 m from the core. The experiment has been taking data with two Skipper-CCDs of 0.247 g mass each since July 2021, totaling an exposure of 18.4 g-days. The sensors achieved an ultralow readout noise of 0.15e[−] by sampling 400 times each pixel charge, allowing to measure for the first time the energy spectrum near a reactor down to a threshold of 15 eV and obtaining a background rate in reactor-OFF data of around 4 kg^{−1} d^{−1} kgV^{−1} [14].

The Atucha-II nuclear power plant is a 2.175 GW_{th} pressurized heavy water reactor that utilizes natural UO₂ as fuel, located in Buenos Aires province, Argentina. Since December 2021, a Skipper-CCD with 2.2 g mass is taking

TABLE I. Experimental observables of each experiment.

Observable	CONNIE	Atucha-II
Reactor ON exposure [g-day]	14.9	59.4
Reactor OFF exposure [g-day]	3.5	22.6
Energy bin [eV]	15–215	40–240
Reactor ON counts	6	168
Reactor OFF counts	2	71
90% C.L. upper limit on events	6.2	30.9

data inside the containment sphere, 12 m away from the nuclear core. The sensor is operated with a readout noise of 0.17e[−], achieved by averaging 300 samples of the charge in each pixel, and a background rate in reactor-OFF data of around 30 kg^{−1} d^{−1} kgV^{−1}. The dataset used in this Letter corresponds to 82 g-days of unpublished data from the 2023 run.

In the interaction cross section from Fig. 1, the plasmon peak located between 10 and 25 eV is easily identified as the most convenient region to look for mCPs. Above 25 eV, the cross section decreases significantly until reaching 100 eV. At this point, the energy released in the detector is sufficient to ionize the silicon *p* shell, increasing in 6 the number of electrons acting as targets. Based on this and before unblinding the data, a 200 eV energy interval starting at the lowest energy possible in each experiment was established (see Table I). It is noteworthy that the CONNIE threshold of 15 eV enables the inclusion of most of the plasmon peak while extending the interval above 240 eV for Atucha II would result in a loss of sensitivity due to the decrease in the cross section against a constant background rate.

Table I summarizes the results obtained from each experimental run. Upper limits at 90% CL on the numbers of events were computed using the frequentist approach, as outlined in Ref. [40]. Efficiency corrections were implemented by convolving the expected theoretical event count with the efficiency curves from Refs. [14,15].

Figure 2 depicts the independent exclusion limits attained by each experiment. The results show an improvement by the CONNIE and Atucha-II experiments for two cases: primary plus secondary (solid lines), or only primary γ -ray production (dashed lines). Moreover, a combined analysis of the outcomes from both experiments is performed following Ref. [40], yielding a further improvement on the individual results (see Supplemental Material [33] for details). The upper limit was derived based on the attenuation of mCPs in the material between the reactor and the detector, accounting for Bremsstrahlung and ionization stopping power, as outlined in Ref. [41]. The total combined error obtained through Monte Carlo propagation was 9.5%. A detailed description of each source and its contribution can also be found in Supplemental Material [33].

The mCP search is particularly challenging because the number of observed events scales with ϵ^4 . A factor ϵ^2

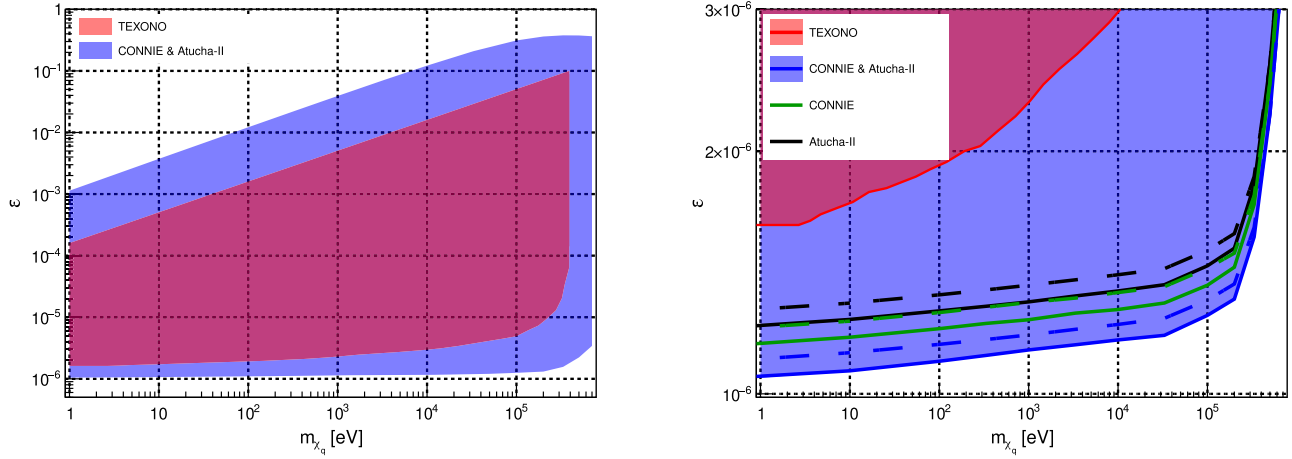


FIG. 2. Exclusion limits at 90% CL as a function of the mCP mass and charge fraction for the CONNIE (green), Atucha-II (black), and their combination (blue). The TEXONO exclusion limit [9] is also included for comparison (red). Left: Upper limits are derived from the attenuation of mCPs as they travel from the reactor to the detector according to Ref. [41]. Right: Solid lines represent results considering mCP production from both primary and secondary γ rays, while dashed lines account for only primary γ rays.

originates from the mCP production within the reactor core (Eq. (3)), while another factor ϵ^2 results from the probability of interaction (Eq. (4)). Therefore, achieving a 2.5-fold improvement in the limit around 100 keV (see Fig. 2) is equivalent to a 40-fold increase in experimental exposure. Such an enhancement is impractical with previous strategies, given that the best results to date was achieved with a half-kilogram detector and exposure times of hundreds of days [9]. On the other hand, mCP flux scales linearly with the thermal power of the reactor but inversely with the square of the distance. Achieving such an increase in flux would require reducing the distance by a factor of 6, which is unfeasible in most reactor experimental scenarios.

The capability of observing interactions at the eV scale allows CONNIE to take advantage of the plasmon resonance [42]. This collective mode of electronic excitation in semiconductor materials significantly enhances the detection sensitivity for sub-MeV relativistic particles. Accessing recoil energies in the eV range results in a flatter cross-section dependence on mCP mass, compared to the TEXONO experiment, which operated above 300 eV, showing a logarithmic dependence on the inverse of the mCP mass through the equivalent photon approximation cross section [9]. The Atucha-II experiment possesses a 3 times higher mCP flux and a 4 times higher reactor ON exposure compared to the CONNIE experiment. This is compensated by the fact that the CONNIE's energy interval accounts for a 4.5 times larger probability of mCP interaction (see Fig. 1) than Atucha's energy interval, as well as a background rate 6 times lower. Consequently, both experiments feature a similar signal-to-square-root-of-background ratio, which explains the closeness of the achieved exclusion limits.

We have demonstrated an alternative approach to improving limits using Skipper-CCD technology, which

combines a 1.1 eV silicon band gap with subelectron readout noise. This enables experiments with sensitivity at the eV scale to exploit the significant enhancement in the cross section. We present for the first time a combined analysis of the collaborative effort between the two experiments, resulting in a very robust limit that strongly mitigates systematic errors eventually introduced by any of them. The combined result extends the experimental exclusion limits further towards 700 keV in mCP mass, as well as down toward $\epsilon \sim 1 \times 10^{-6}$ for the lowest mCP masses of 1 eV, thus becoming the best direct laboratory constraint on mCP coupling. Furthermore, both experiments are currently conducting this search with only around 1 g of sensor, and have plans for substantial increases in sensor mass [14,15]. The scaling of mass to reach the kilogram range has already been developed [17,18], and the potential physics impact of such an experiment has also been evaluated [43,44].

Acknowledgments—CONNIE thanks the Silicon Detector Facility staff at the Fermi National Accelerator Laboratory for hosting the assembly and test of the detector components used in the CONNIE experiment. The CCD development was partly supported by the Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We are grateful to Eletrobras Eletronuclear, and especially to G. Coelho, I. Soares, I. Ottoni and L. Werneck, for access to the Angra 2 reactor site, infrastructure and the support of their personnel. We express gratitude to R. Shellard (in memoriam) for supporting the experiment. We thank M. Giovani for the IT support and M. Martínez Montero for the technical assistance. We acknowledge the support from the Brazilian Ministry for Science, Technology, and Innovation and the funding agencies FAPERJ, CNPq and

FINEP; Argentina's CONICET and AGENCIA I + D + i; (Grant No. PICT-2019-2019-04173; No. PICT-2021-GRF-TII-00458; No. PICT-2021-GRF-TI-00816) and the LAA-HECAP Network. We acknowledge the support from Mexico's CONAHCYT (grant No. CF-2023-I-1169) and DGAPA-UNAM (PAPIIT Grant No. IN104723). This work made use of the CHE cluster, managed and funded by COSMO/CBPF/MCTI, with financial support from FINEP and FAPERJ, and operating at the Javier Magnin Computing Center/CBPF. Atucha-II thanks the NA-SA team in Argentina for all the support during the deployment and operation of the Skipper-CCD system at Atucha-II. This work was supported by Fermilab under DOE Contract No. DE-AC02-07CH11359. We thank Eneas Kapou from NA-SA for assisting in data transportation outside the plant. We thank Eduardo Arostegui and Nicolas Lazzaretti for their continuous help and assistance to this project.

- [1] 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).
- [2] 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.
- [3] Z. Atif *et al.* (RENO and NEOS Collaborations), Search for sterile neutrino oscillations using RENO and NEOS data, *Phys. Rev. D* **105**, L111101 (2022).
- [4] M. Andriamirado *et al.* (PROSPECT Collaboration), Limits on sub-GeV dark matter from the PROSPECT reactor antineutrino experiment, *Phys. Rev. D* **104**, 012009 (2021).
- [5] M. Andriamirado *et al.* (PROSPECT Collaborations), PROSPECT-II physics opportunities, *J. Phys. G* **49**, 070501 (2022).
- [6] M. I. Dobroliubov and A. Y. Ignatiev, Millicharged particles, *Phys. Rev. Lett.* **65**, 679 (1990).
- [7] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Millicharged particles in neutrino experiments, *Phys. Rev. Lett.* **122**, 071801 (2019).
- [8] C. A. Argüelles, K. J. Kelly, and V. M. Muñoz, Millicharged particles from the heavens: Single- and multiple-scattering signatures, *J. High Energy Phys.* **11** (2021) 099.
- [9] L. Singh *et al.* (TEXONO Collaborations), Constraints on millicharged particles with low threshold germanium detectors at Kuo-Sheng reactor neutrino laboratory, *Phys. Rev. D* **99**, 032009 (2019).
- [10] A. Aguilar-Arevalo *et al.* (CONNIE Collaborations), Exploring low-energy neutrino physics with the coherent neutrino nucleus interaction experiment, *Phys. Rev. D* **100**, 092005 (2019).
- [11] A. Aguilar-Arevalo *et al.* (CONNIE Collaborations), Search for coherent elastic neutrino-nucleus scattering at a nuclear reactor with CONNIE 2019 data, *J. High Energy Phys.* **05** (2022) 017.
- [12] A. Aguilar-Arevalo *et al.* (CONNIE Collaborations), Search for light mediators in the low-energy data of the CONNIE reactor neutrino experiment, *J. High Energy Phys.* **04** (2020) 054.
- [13] J. Tiffenberg, M. Sofo-Haro, A. Drlica-Wagner, R. Essig, Y. Guardincerri, S. Holland, T. Volansky, and T.-T. Yu (SENSEI Collaborations), Single-electron and single-photon sensitivity with a silicon Skipper-CCD, *Phys. Rev. Lett.* **119**, 131802 (2017).
- [14] A. A. Aguilar-Arevalo *et al.*, Searches for $\nu\bar{\nu}$ ns and physics beyond the standard model using Skipper-CCDs at connie, [arXiv:2403.15976](https://arxiv.org/abs/2403.15976).
- [15] E. Depaoli *et al.*, Deployment and performance of a low-energy-threshold Skipper-CCD inside a nuclear reactor, *J. High Energy Phys.* **10** (2024) 155.
- [16] L. Barak *et al.* (SENSEI Collaborations), Search by the SENSEI experiment for millicharged particles produced in the NuMI beam, *Phys. Rev. Lett.* **133**, 071801 (2024).
- [17] A. Aguilar-Arevalo *et al.* (Oscura Collaborations), The oscura experiment, [arXiv:2202.10518](https://arxiv.org/abs/2202.10518).
- [18] S. Perez *et al.* (Oscura Collaborations), Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab, *J. High Energy Phys.* **02** (2024) 072.
- [19] P. Adshead, P. Ralegankar, and J. Shelton, Dark radiation constraints on portal interactions with hidden sectors, *J. Cosmol. Astropart. Phys.* **09** (2022) 056.
- [20] W.-Z. Feng, Z.-H. Zhang, and K.-Y. Zhang, Sub-GeV millicharge dark matter from the $U(1)_X$ hidden sector, *J. Cosmol. Astropart. Phys.* **05** (2024) 112.
- [21] H. Park, Detecting dark photons with reactor neutrino experiments, *Phys. Rev. Lett.* **119**, 081801 (2017).
- [22] F. Arias-Aragón, V. Brdar, and J. Quevillon, New directions for axionlike particle searches combining nuclear reactors and haloscopes, *Phys. Rev. Lett.* **132**, 211802 (2024).
- [23] M. Smirnov, G. Yang, J. Liao, Z. Hu, and J. Ling, Light dark bosons in the JUNO-TAO neutrino detector, *Phys. Rev. D* **104**, 116024 (2021).
- [24] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [25] J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Dubois *et al.* (GEANT4 Collaboration), GEANT4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
- [26] S. N. Gninenko, N. V. Krasnikov, and A. Rubbia, New limit on millicharged particles from reactor neutrino experiments and the PVLAS anomaly, *Phys. Rev. D* **75**, 075014 (2007).
- [27] E. Fermi, The ionization loss of energy in gases and in condensed materials, *Phys. Rev.* **57**, 485 (1940).
- [28] I. Alkhatib *et al.* (SuperCDMS Collaborations), Constraints on lightly ionizing particles from CDMSlite, *Phys. Rev. Lett.* **127**, 081802 (2021).
- [29] K. Kamdin, *Search for Lightly Ionizing Particles in the LUX Detector and Research and Development For Future Liquid Xenon Time Projection Chambers* (University of California, Berkeley, 2018).
- [30] W. W. M. Allison and J. H. Cobb, Relativistic charged particle identification by energy loss, *Annu. Rev. Nucl. Part. Sci.* **30**, 253 (1980).

- [31] R. Essig, R. Plestid, and A. Singal, Collective excitations and low-energy ionization signatures of relativistic particles in silicon detectors, *Commun. Phys.* **7**, 416 (2024).
- [32] S. Knapen, J. Kozaczuk, and T. Lin, PYTHON package for dark matter scattering in dielectric targets, *Phys. Rev. D* **105**, 015014 (2022).
- [33] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.134.071801> for the statistical formalism applied for obtaining the limits.
- [34] A. Aguilar-Arevalo *et al.* (DAMIC Collaborations), Results on low-mass weakly interacting massive particles from a 11 kg-day target exposure of DAMIC at SNOLAB, *Phys. Rev. Lett.* **125**, 241803 (2020).
- [35] I. Arnquist *et al.*, First constraints from damic-m on sub-GeV dark-matter particles interacting with electrons, *Phys. Rev. Lett.* **130**, 171003 (2023).
- [36] A. Aguilar-Arevalo *et al.* (SENSEI, DAMIC-M, and DAMIC Collaborations), Confirmation of the spectral excess in DAMIC at SNOLAB with Skipper CCDs, *Phys. Rev. D* **109**, 062007 (2024).
- [37] P. Adari *et al.* (SENSEI Collaborations), SENSEI: First direct-detection results on sub-GeV dark matter from SENSEI at SNOLAB, *Phys. Rev. Lett.* **134**, 011804 (2025).
- [38] G. F. Moroni, F. Chierchie, J. Tiffenberg, A. Botti, M. Cababie, G. Cencelo, E. L. Depaoli, J. Estrada, S. E. Holland, D. Rodrigues, I. Sidelnik, M. S. Haro, L. Stefanazzi, and S. Uemura, Skipper charge-coupled device for low-energy-threshold particle experiments above ground, *Phys. Rev. Appl.* **17**, 044050 (2022).
- [39] G. I. Cencelo *et al.*, Low threshold acquisition controller for Skipper CCDs, *J. Astron. Telesc. Instrum. Syst.* **7**, 015001 (2021).
- [40] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011); **73**, 2501(E) (2013).
- [41] N. Arefyeva, S. Gninenko, D. Gorbunov, and D. Kirpichnikov, Passage of millicharged particles in the electron beam-dump: Refining constraints from slacmq and estimating sensitivity of NA64e, *Phys. Rev. D* **106**, 035029 (2022).
- [42] Z.-L. Liang, L. Su, L. Wu, and B. Zhu, Plasmon-enhanced direct detection of sub-MeV dark Matter, [arXiv:2401.11971](https://arxiv.org/abs/2401.11971).
- [43] G. Fernandez Moroni, P. Machado, I. Martinez-Soler, Y. Perez-Gonzalez, D. Rodrigues, and S. Rosauero-Alcaraz, The physics potential of a reactor neutrino experiment with Skipper CCDs: Measuring the weak mixing angle, *J. High Energy Phys.* **01** (2021) 186.
- [44] G. Fernandez-Moroni, R. Harnik, P. A. N. Machado, I. Martinez-Soler, Y. F. Perez-Gonzalez, D. Rodrigues, and S. Rosauero-Alcaraz, The physics potential of a reactor neutrino experiment with Skipper-CCDs: Searching for new physics with light mediators, *J. High Energy Phys.* **02** (2022) 127.