

Proposal for a dedicated search for millicharged and fractionally charged particles at LANL

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In this paper, we propose an experiment, LANSCE-mQ, aiming to detect fractionally charged and millicharged particles (mCPs) using an 800 MeV proton beam fixed target at the Los Alamos Neutron Science Center (LANSCE) facility at Los Alamos National Laboratory. This search can shed new light on numerous fundamental questions, including charge quantization, the predictions of string theories and grand unification theories, the gauge symmetry of the Standard Model, dark sector models, and the tests of cosmic reheating. We propose to install two-layer scintillation detectors made of plastic (such as EJ-200) or CeBr₃ to search for mCPs. Dedicated GEANT4 detector simulations and *in situ* measurements have been conducted to obtain a preliminary determination of the background rate. The dominant backgrounds are beam-induced neutrons and coincident dark current signals from the photomultiplier tubes, while beam-induced high-energy photons (γ 's) and cosmic muons are subdominant. We determined that LANSCE-mQ, the dedicated mCP experiment, has the leading mCP sensitivity for mass between ~ 1 and 300 MeV.

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I. INTRODUCTION

The study of fractionally charged and millicharged particles (mCPs), which carry rational or irrational electric charges, is a strong test of fundamental theories and can help answer the deepest questions in particle physics. First, it is one of the most powerful tests of the theories proposed to explain empirical charge quantization [1,2], including the grand unification theories [3]. Fractionally charged particles are also one of the most distinctive low-energy signatures of string theory [4]. Recently, the search for mCPs has also been considered as a way to determine the gauge theory of the Standard Model (SM) of particle physics [5–7] and as a way to test reheating scenarios in early-Universe cosmology [8]. mCPs can also naturally arise from the kinetic mixing between our SM photon and a beyond the Standard Model (BSM) massless U(1) gauge field [9], which serves as viable dark matter candidates and

can help explain the recently observed cosmic microwave background absorption spectrum (see, e.g., Ref. [10]).

mCPs have become an important benchmark model for accelerator experiments [11]. One can directly search for them at LHC (see fractionally charged particle searches at CMS [12]) and CEPC [13]. Scintillator-based mCP detectors have been developed for deployment at SLAC [14], the LHC (as milliQan [15–17] and FORMOSA [18]), Fermilab [19], and J-PARC [20]. Neutrino experiments such as DUNE, MiniBooNE, and SBND [21,22] (as well as ArgoNeuT [22,23], FLArE [24], and SENSEI [25]) also present opportunities to search for mCPs. Other accelerator probes and detector technologies like those of NA64 [26], LDMX [27,28], SENSEI [25], OSCURA [29], and SHiP [21] can similarly further the current mCP explorations. In addition to the accelerator searches, there are numerous studies of millicharged particles produced in the atmosphere and subsequently detected in large observatories [30–32], as well as millicharge dark matter searches in astrophysical and cosmological observations [33–39] and with direct-detection experiments [40–43,43–49].

In this paper, we propose an experiment, LANSCE-mQ, aiming to detect the mCPs using an 800 MeV proton beam fixed target at the Lujan Center at the Los Alamos Neutron Science Center (LANSCE) [50]. Leveraging existing

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facilities as well as ever-maturing detector technologies, LANSCE-mQ can provide one of the strongest searches for low-mass mCPs, shedding new light on fundamental theories, reheating cosmology, and dark sector models.

II. MILLICHARGED PARTICLES

Here, we discuss models of mCP, χ , which is assumed to be a fermion throughout this paper. Scalar mCPs would yield similar results in accelerator studies.

A. Pure mCP

The so-called “pure” mCP, as discussed in [8], can originate from string theory [4,51] (predicting fractionally charged particles) or from BSM theories that predict violation of charge quantization. For the “pure” mCP, a dark photon is not needed, and the Lagrangian of the mCP is

$$\mathcal{L} \supset i\bar{\chi}(\not{\partial} - ig'\epsilon_\chi \not{B} + m_\chi)\chi - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}. \quad (1)$$

Here, B is the SM hypercharge $U(1)_Y$ gauge boson, $g' = e/\cos\theta_w$ is the gauge coupling of $U(1)_Y$, and e is the electron electric charge. $B = \cos\theta_w A - \sin\theta_w Z$ after the electroweak symmetry breaking. χ is coupled to both the SM photon A and the Z boson accordingly and becomes a particle with an effective small electric charge Q_χ , and $\epsilon_\chi \equiv Q_\chi/e$.

B. Effective dark photon mCP

mCPs can also be generated effectively through a massless dark photon theory. The theory includes an additional dark gauge symmetry $U(1)_d$ with the gauge field, dark photon A' , coupled to a new particle χ with a coupling g_d , and we define $\alpha_d \equiv g_d^2/4\pi$.

One then introduces a kinetic mixing between A' and SM hypercharge $U(1)_Y$ gauge field B [9,52] that can originate from integrating out heavy fermions charged under both $U(1)_Y$ and $U(1)_d$. We have

$$\mathcal{L} \supset i\bar{\chi}(\not{\partial} - ig_d A' + m_\chi)\chi - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{\epsilon}{2\cos\theta_w}B_{\mu\nu}A'^{\mu\nu}. \quad (2)$$

$B_{\mu\nu}$ is the usual field strength of $U(1)_Y$, and ϵ is the kinetic mixing between $U(1)_Y$ and $U(1)_d$, with $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$. When A' is massless, one can choose a basis diagonalizing the kinetic terms [assuming $\epsilon \ll 1$ and up to $O(\epsilon^2)$] under the field redefinition $A' \rightarrow A' + \frac{\epsilon}{\cos\theta_w}B$. The Lagrangian becomes

$$\mathcal{L} \supset g'\epsilon_\chi \bar{\chi}\gamma^\mu \chi B_\mu, \quad \text{where} \quad \epsilon_\chi = \frac{\epsilon g_d}{e}, \quad (3)$$

and again $g' = e/\cos\theta_w$.

Following the aftermath of electroweak symmetry breaking, $B = \cos\theta_w A - \sin\theta_w Z$, χ becomes an mCP with an effective fraction of electric charge $\epsilon_\chi \equiv Q_\chi/e$.

III. THE LANSCE FACILITY AND LANSCE-MQ DETECTOR

The LANSCE facility [50] uses a 1 MW linear proton accelerator that produces an 800 MeV proton beam. At a rate of 120 pulses/s, 800 MeV proton beam pulses are delivered to different neutron spallation targets. Each pulse is a 625 μ s long macropulse separated by 8.3 ms. A macropulse contains micropulses with a 5 ns gap between them. Twenty macropulses per second are directed toward the Lujan Neutron Scattering Center, where they impinge on a Lujan tungsten spallation target. A beam current monitor (BCM) detects these pulses. The BCM provides a copy of transistor-transistor logic for all flight paths in the Lujan Center. Using BCM, we can measure each pulse's width, height, and total charge individually.

The 800 MeV proton beam is directed toward the Lujan target after passing through the proton storage ring (PSR). The beam from the PSR is high intensity and has a triangular pulse shape with approximately 290 ns at the base. The Lujan target receives 20 pulses every second, each containing 3.1×10^{13} protons and spaced 50 ms apart. The Lujan target generates a significant amount of neutral pions, which have a very short lifespan of 8.5×10^{-8} ns and decay while in flight, rather than being halted by nuclear interactions. The total number of pions N_{π^0} is directly correlated to the quantity of protons on the target (POT), at the Lujan target, $N_{\pi^0} = 0.115 \times \text{POT}$ [53]. While the distribution of pions is mostly isotropic, there is a slight increase in the forward direction. A neutral pion can have a three-body decay into a photon and two mCPs ($\pi^0 \rightarrow \gamma\chi\bar{\chi}$), where the mCPs are from a virtual photon. In our analysis, we also take into account η meson and the three-body decays that produce the mCPs.

The LANSCE-mQ operation does not require a specific flight path and will not disrupt any ongoing nuclear physics and material science programs at Lujan Center. Two locations are considered for the LANSCE-mQ detector: a distance from the Lujan target of around 6 m (ER1) and 35 m (ER2). Both the signal flux and neutron background at ER1 are increased by around an order of magnitude compared to ER2. Therefore, the ER1 location is only viable if neutrons can be efficiently shielded (as discussed in Sec. V B). Given the uncertainties in achieving this shielding, which will be studied with further beam tests, the ER2 location provides a robust minimal sensitivity that can be expected to be achieved, while the ER1 location represents the optimal sensitivity that can be achieved. For both locations, we consider the detector operational for 3 yr (accumulating 5.9×10^{22} POT).

The Lujan target operates at a beam current of $100 \mu\text{A}$, corresponding to a proton delivery rate of 6.42×10^{14} protons/s on target. With an annual beam time of six months, this results in a yearly total of approximately 9.8×10^{21} POT. Over a 3 yr period—equivalent to 18 months of beam operation—the cumulative exposure reaches 2.95×10^{22} POT. For a 6 yr duration, the total POT increases to 5.96×10^{22} .

A. Detector design

The base design of the LANSCE-mQ detector is two layers of 100 plastic scintillator bars that each measure $50 \times 50 \times 1500$ mm. Each of these bars will be optically coupled to a high-gain photomultiplier tube (PMT). Segmentation of the volume is beneficial in reducing background interference caused by the PMT dark currents and cosmic muons, as well as utilizing the directionality of incident mCPs to suppress nonpointing particles further. A diagram of the detector is shown in Fig. 1, and the considered locations are shown in Fig. 2.

Alternative high light-yield scintillator materials would allow a smaller detector that reduces the dominant neutron background rate while maintaining high signal efficiency. Ideally, this would comprise a fast scintillator for efficient rejection of uncorrelated backgrounds. One such promising alternative to plastic scintillator is CeBr_3 . This new material has 6 times higher light yield and is 5 times as dense as the plastic scintillator, leading to a factor of 30 times higher total photon production. It also has a fast scintillation time constant of 20 ns and low intrinsic radioactivity [54]. Currently, CeBr_3 crystals can be produced with lengths of up to ~ 200 mm. However, the cost may be prohibitive, so we consider CeBr_3 volumes of 50 mm in length. This shorter 50 mm detector has the same charge sensitivity as the equivalent 1.5 m of plastic scintillator. We can use these shorter detectors to construct a full detector with CeBr_3 .

As shown in the simulation section below, the dramatically reduced volume and lower neutron scattering cross

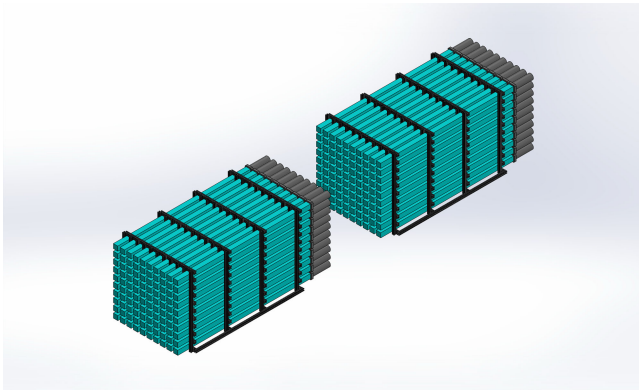


FIG. 1. Diagram of the detector showing the scintillator bars in blue and PMTs in gray. The bars are held together by a support structure shown in black.

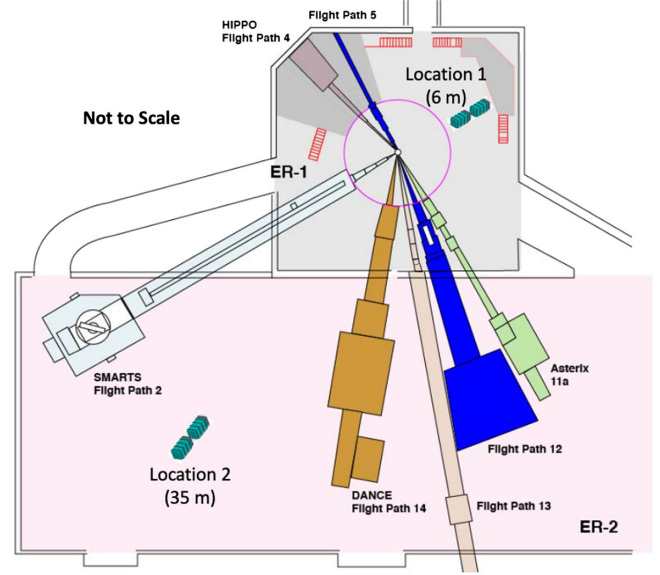


FIG. 2. An illustration plot of the possible locations of the detector in ER1 and ER2 of the Lujan Center at LANSCE, Los Alamos National Laboratory, from the bird's-eye view. The plot is not to scale.

section of CeBr_3 allows for a significant reduction in neutron backgrounds, the primary background source at the proposed location. In addition, the small volume of CeBr_3 allows for the design of a much thicker neutron shield. These combined effects result in neutron backgrounds being made subdominant compared to dark rate backgrounds for CeBr_3 detectors.

IV. MCP PRODUCTION AND SIGNAL

The main contribution to mCP production at Lujan Center is the decay of neutral mesons, $\pi^0, \eta \rightarrow \gamma\chi\bar{\chi}$. The total number of mCPs is given by

$$N_\chi \simeq 2N_m \epsilon_\chi^2 \alpha_{\text{EM}} \text{Br}(\mathbf{m} \rightarrow \gamma\gamma) I^{(3)} \left(\frac{m_\chi^2}{m_m^2} \right). \quad (4)$$

Here, N_m is the number of meson $\mathbf{m}$ and $I^{(3)}$ is a phase space integral [19]. The meson productions per POT at Lujan Center were previously discussed in [53,55,56]. Proton bremsstrahlung production [31,57] of mCPs is subdominant for the beam energy at Lujan Center.

The potential installation sites at Lujan Center are in close proximity to the target but oriented perpendicular to the beam direction. To account for this, we introduce geometrical acceptance A_{geo} defined as a fraction of mCPs produced that reach the detector. We assume a similar momentum distribution with the charged pions for π^0 and η [55] and generate mesons with the Burman-Smith distribution [58]. While the Burman-Smith distribution is currently the available model, further study with dedicated efforts may improve the prediction of the meson spectrum.

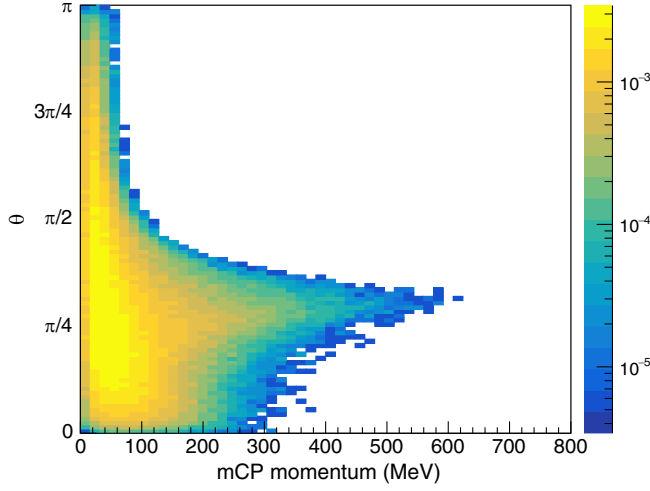


FIG. 3. Polar angle θ and momentum distribution of mCPs with $m_\chi = 10$ MeV produced by π^0 decay.

This exceeds the scope of this proposal and is left for future study. The decay $\mathbf{m} \rightarrow \gamma\chi\bar{\chi}$ is then simulated according to

$$\frac{d\text{Br}(\mathbf{m} \rightarrow \gamma\chi\bar{\chi})}{dsd\cos\theta} = \frac{\varepsilon_\chi^2 \alpha_{\text{EM}}}{4\pi s} \left(1 - \frac{s}{m_\mathbf{m}^2}\right)^3 \left(1 - \frac{4m_\chi^2}{s}\right)^{\frac{1}{2}} \times \left[2 - \left(1 - \frac{4m_\chi^2}{s}\right)\sin^2\theta\right] \text{Br}(\mathbf{m} \rightarrow \gamma\gamma), \quad (5)$$

where $s = (p_\chi + p_{\bar{\chi}})^2$ is the invariant mass of the off-shell photon V^* and θ is the polar angle of χ momentum measured in the rest frame of V^* with its z axis aligned to the boost direction of V^* [59]. Going into the laboratory frame, we obtain the angular distribution of mCPs. Figure 3 illustrates the angular distribution of mCP with mass of 10 MeV produced by π^0 decay. The A_{geo} is estimated for a range of mCP mass m_χ and the detector located at various distances from the target, whose cross-sectional area is $50 \text{ mm} \times 50 \text{ mm} \times 100 \text{ bars} = 0.25 \text{ m}^2$. We find a probability of $\mathcal{O}(10^{-4})$ for mCPs to reach the detector at ER1 and $\mathcal{O}(10^{-5})$ at ER2.

Any mCPs entering the detector will pass through n layers, producing photons that can be detected in each layer by PMTs. The probability of observing a coincidence signal of n layers follows the Poisson distribution P ,

$$P = (1 - \exp[-\varepsilon_\chi^2 N_{\text{PE}}])^n. \quad (6)$$

ε_χ is the fractional charge of the mCP and N_{PE} is the number of photoelectrons for $\varepsilon_\chi = 1$. The N_{PE} is proportional to the number of photons generated in a scintillator reaching the photocathode of a PMT, the quantum efficiency of the PMT, and the mean energy loss of a charged particle in a scintillator bar [60]. The factor ε_χ^2 has been

introduced since the energy deposition of a charged particle within the scintillator is proportional to Q^2 . We consider $n = 2$ as our nominal design.

To estimate signal efficiency, a GEANT4 [61] simulation of a minimum ionizing muon passing through a $5 \times 5 \times 150 \text{ cm}^3$ m scintillator bar has been made. To properly measure the detected N_{PE} , the simulation was configured using the simulation spectra and material properties of a Eljen-200 scintillator wrapped in 97% reflective white Tyvek paper and coupled to a Hamamatsu R7725 PMT. The 46 mm PMT photocathode was explicitly modeled and used as the sensitive region for the photodetector. A small air gap was modeled between the Tyvek wrapping and the scintillator, and the wrapping reflectivity and PMT quantum efficiency were tuned to reflect bench measurements of a Cd-109 radioactive source exposed to a wrapped scintillator bar and PMT. The simulation found that, for a minimum ionizing particle of charge $Q = 1$, we detect $N_{\text{PE}} = 2.5 \times 10^5$. This is used to estimate the expected total number of signal events s ,

$$s = PA_{\text{geo}}N_\chi. \quad (7)$$

V. BACKGROUND DETERMINATION

In this section, we discuss the simulations, measurements, and shielding of the background. The dominant physical background sources are neutrons from the beam, along with beam-induced and ambient photons. The beam can irradiate materials in the proposed detector locations that can generate ambient neutron and γ backgrounds. Borated polyethylene and water are effective in reducing neutron backgrounds, and lead shielding is effective in reducing γ backgrounds. A mix of shielding materials can, therefore, be used to reduce these beam-induced backgrounds.

A. Simulations

Given the significant neutron flux at the proposed detector location, understanding backgrounds arising from soft neutron scatters in scintillator is critical to detector design and sensitivity estimates. A GEANT4 simulation was used to model the impacts of these soft neutron scatters in a 1500 mm plastic scintillator bar and in a 50 mm CeBr_3 detector, each with a $50 \times 50 \text{ mm}^2$ cross section. A geometry with a neutron shield consisting of 300 mm of 5% borated polyethylene and 50 mm of lead was studied in addition to an unshielded geometry. The poly is used to attenuate incoming neutrons, while the lead is used to shield γ 's generated during neutron interactions in the poly. The incident neutron energy distribution was generated using a simulation in MCNP, as in Fig. 4.

Figure 5 illustrates the probability across a range of input neutron energies for two coincident neutrons to deposit the

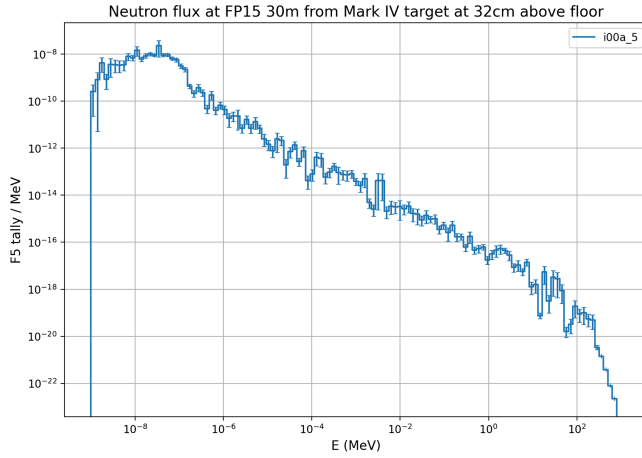


FIG. 4. Background neutron energy spectrum generated by the Monte Carlo N-Particle (MCNP) code. Neutron backgrounds are composed of thermal neutrons that are approximately uniform in time and high-energy neutrons, which are more likely to be coincident with the beam.

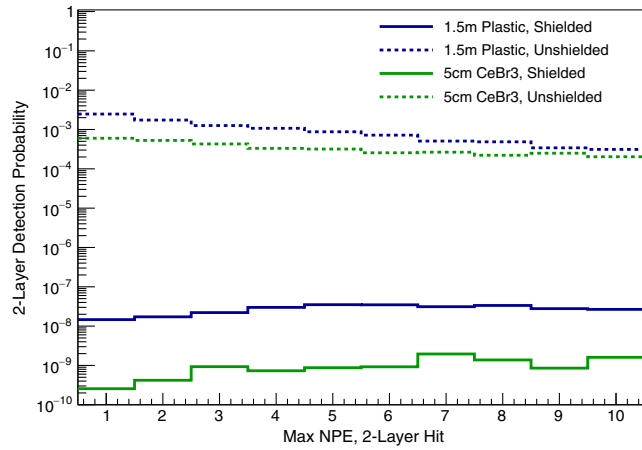


FIG. 5. Plastic scintillator with and without shielding. Shielding is composed of 300 mm of 5% borated polyethylene and 50 mm of lead. Detection probabilities are given assuming two independent neutrons are coincident on each detector layer at the same time, with the value on the x axis given as the maximum detected N_{PE} between each layer. The total effect of the shielding results in a reduction of background coincidence of 10^5 for low N_{PE} events. Further reductions in background are expected when considering timing inefficiencies.

specified number of photoelectrons in a shielded and unshielded detector. Signal-like energy deposits are in the 1–3 photoelectron range. The total effect of the shield results in a factor 10^5 – 10^6 reduction in coincident neutron background events. As lower-energy neutrons are out of time with the beam, another significant background reduction is expected from timing inefficiencies. As detailed in Sec. VB, this total background rejection factor of 10^6 is sufficient to reduce neutron background activity to the frequency of other background sources.

Compared to a plastic scintillator, a CeBr_3 detector has significantly reduced acceptance to neutron backgrounds. The significant decrease in material along with a reduction in neutron scattering cross section for cerium and bromine compared to hydrogen results in this effect [62]. The relative incidence of signal-like soft neutron scatters behaves similar to plastic, but with an overall decrease in rate of approximately 10^2 for the shielded configuration.

B. *In situ* measurements

In situ measurements have been performed at the potential detector site at both ER1 and ER2 to estimate the background rate and determine the optimal shielding configurations. A custom readout system cascading four input channels of a domino ring sampler-4 chip [63] to obtain a $5 \mu\text{s}$ acquisition window was used for data acquisition. As mentioned in Sec. III, the LANSCE facility provides the T0 signal for each micro pulse impact on the target by which the readout system was triggered. We used EJ-200 plastic scintillators measuring $50 \times 50 \times 800$ mm, coupled with Hamamatsu R7725 PMTs (hereafter referred to as modules) operating at 1300 V.

1. Coincidence rate

Two bare modules placed in a row were used to estimate the coincidence event rate by detecting subsequent single photoelectronlike (SPE-like) pulses from both modules with 20 ns time window. We selected SPE-like pulses that occur within a 200 ns window after the beam trigger for both modules to avoid major neutron flux [53]. The estimated number of coincidence events per 1000 bunch collisions is 7.7 ± 0.2 at ER1 and 1.2 ± 0.1 at ER2. Considering the 20 Hz bunch repetition rate of the proton beam at LANSCE, these rates imply that, over three years of beam-on time, an unshielded neutron background rate is of order 10^8 at ER1 (10^7 at ER2), compared to an expected dark count rate of order 10^2 . We assume that the two layers are spatially separated and have uncorrelated neutron events for simplicity. Using the neutron shielding efficiency measured in Fig. 5, we estimate that a 300 mm neutron shield would mitigate the neutron background in both sites to a level comparable to the dark-current-induced background. If further neutron shielding is necessary, additional shielding material can be added to increase neutron background rejection.

C. Dark current

Another background source is the random coincidence signal event due to the dark current of PMTs. The random coincidence rate R of n layers is given by $v_b^n \tau^{n-1}$, where v_b is the dark count rate, and τ is the coincidence time window. Since the total number of random coincidence signals is proportional to the data taking time, the beam timing information can be incorporated to significantly reduce

the dark current backgrounds. For the proton beam with 280 ns bunch width, we set the data acquisition window as 200 ns after the beam trigger signal to capture most of the mCP events. This leads to an overall dark rate background of around 400, assuming a typical dark count rate of ~ 500 Hz [18,64] for a R7725 PMT [65] over three years of operation. One can cool the PMT to further reduce this background.

D. Cosmic background

Given the very short trigger live time, the cosmic-ray-induced background is subdominant, as discussed in detail in the SUBMET experiment with a similar environment [66]. For the proposed 10×10 detector with two layers, nearby cosmic muon flux has a rate of approximately 1 kHz. Rarely, these muons generate γ 's from secondary electromagnetic showers that deposit energy in the detector. According to estimates made for the SUBMET detector, a similar two-layer mCP detector, these cosmic backgrounds are expected to be subdominant [20]. Added shielding designed to reduce beam-induced photon and neutron backgrounds offers additional protection against cosmic showers. These backgrounds will be measured during beam-off periods to ensure the contributions are small.

E. Summary of background reduction strategy

To significantly reduce the beam-related backgrounds, we require at least 300 mm shielding with polyethylene and/or water, combined with the incorporation of the precise arrival time of mCPs and neutrons, and elaborated pulse finding with characterization of neutron signals and after pulses.

In addition, the compact size of a CeBr_3 scintillation detector, with significantly reduced neutron interaction length and cross section, would result in reduced neutron backgrounds and allow larger space for shielding materials in comparison to plastic scintillators.

VI. SENSITIVITY PROJECTIONS

In Fig. 7, we show the 95% confidence level (CL) exclusion limit of the LANSCE-mQ detector with nominal setup over six years of operation at ER1 and ER2. The breakdown of mCPs produced and reaching the detector placed at ER1 by the production channels is shown in Fig. 6.

Considering the background sources discussed in the previous section, we expect to use sufficient shielding (around 300 mm of borated polyethylene or water) to reduce the rate of neutron backgrounds to be the same order as dark-current-induced backgrounds. In this plot, we assume a typical dark count rate of ~ 200 Hz [18,64] for a R7725 PMT, resulting in dark-current-induced coincidence events over three years of live time of 150. We then assume twice the number of neutron backgrounds and 50 events

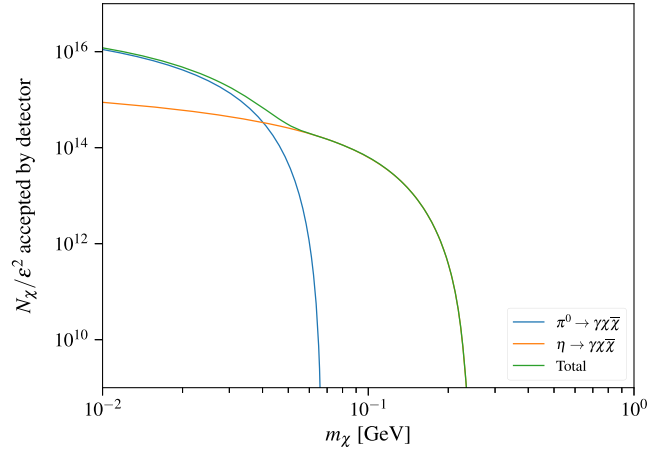


FIG. 6. Breakdown of mCPs reaching the detector placed at ER1, by the production channels.

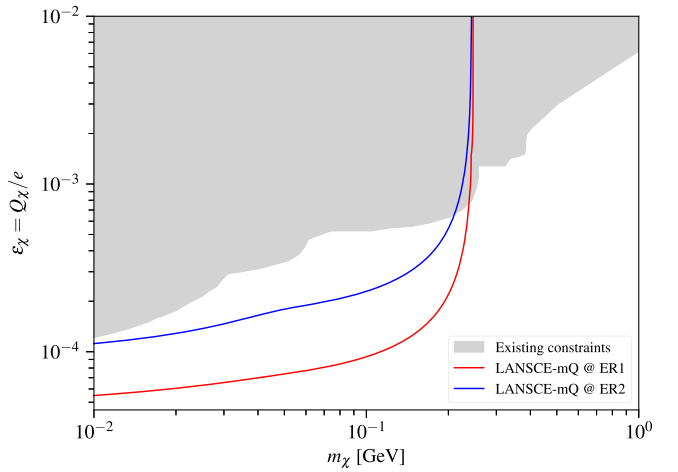


FIG. 7. The sensitivity projection of the 95% CL limit curves of the nominal design of LANSCE-mQ for six years of operation accumulating 5.9×10^{22} POT at ER1 (red curve) and ER2 (blue curve). Further details of the assumptions are described in Sec. VI.

from cosmic and environmental radiation sources to predict a total background over three years of operation to be 500 events. These numbers are determined based on our knowledge from dedicated simulation, *in situ* background measurements, and estimations of the shielding effects. Further *in situ* measurements can help determine the systematic errors for the full experiment. One interesting feature of the sensitivity projection is that the curve is smooth when the mCP becomes heavier and goes from pion-dominant production to η -dominant production, compared to other accelerator searches depending on meson productions. The reason for this is that η mesons produced by the 800 MeV beam are nearly at rest, leading to more isotropic mCP production when they decay. Given the unique Lujan beam and detector configuration in which the

detectors are located perpendicular to the beam direction, the isotropic production enhances the sensitivity compared to the pion production, resulting in a smooth transition.

VII. DISCUSSIONS

Now that we have established that LANSCE-mQ provides a leading search for sub-GeV mCPs, we discuss several related experiments and sites that can further the mCP searches with similar productions or search techniques. Most notably, at the CCM experiment [53], one experiences a similar level of mCP flux as discussed in this paper, and it has a larger detector volume. Although not a dedicated mCP search, one can study electron signatures from mCP scattering with this experiment.

The nominal design of LANSCE-mQ is two layers of plastic scintillator bars. To increase the signal efficiency, one can also require the scintillation in just one layer, but better shielding and background reduction may be needed for a single-layer design. In the case that backgrounds are larger than anticipated, the detector could also be expanded to consist of three layers.

Alternative sites for dedicated mCP searches: The studies in this paper motivate explorations of dedicated millicharged detectors at other neutron facilities, including n_TOF at CERN [67] and the future European Spallation Source [68]. Other promising sites for dedicated mCP searches include the “back room” behind the 10 m iron block of SpinQuest/DarkQuest at Fermilab, where LongQuest [57] was proposed. Millicharge searches at SHiP [21] with dedicated detectors can also provide excellent sensitivity for mCPs.

Furthermore, there are new opportunities and beam facilities based on the Fermilab booster replacement plan, which may provide the following capabilities [69]:

- (i) From the main injector, proton beam of 2.4 MW at 60–120 GeV energy to the LBNF beamline for the DUNE experiment;
- (ii) proton beam of 80 kW at around 8 GeV energy for the experiments, including short-baseline neutrino program and Mu2e experiments;
- (iii) 100 kW continuous wave (cw) at 800 MeV energy or higher for the next-generation Mu2e experiment.

The first two opportunities were considered for millicharge searches at similar energies and beam structures [21,22], but dedicated studies are necessary to determine the realistic sensitivity reaches. The 800 MeV option provides similar productions of mCPs, but given the cw mode, the longer trigger live time may lead to a larger dark current background.

Each of these alternative facilities offers distinct advantages and challenges. For example, n_TOF and ESS provide high neutron flux and well-characterized beams, which could enable high-statistics searches for neutral meson decays that produce mCPs. However, they would require new detector deployments and detailed background studies tailored to their beam characteristics. Similarly,

SpinQuest and DarkQuest offer heavy shielding and higher-energy proton beams that allow access to complementary mass and charge parameter space, but integrating a detector into these environments would demand careful synchronization with beam timing and shielding designs, which are not yet fully developed. SHiP represents a dedicated future long-lived particle platform, but it remains in its planning stages, with uncertainty in available infrastructure for mCP-specific instrumentation.

On the detector side, the nominal two-layer plastic scintillator design is motivated by its practicality, simplicity, and moderate cost, but we also considered various alternatives. CeBr₃ scintillators, for instance, provide significantly higher light yield and allow compact designs with enhanced shielding, but their cost and limited availability in large volumes constrain scalability. Overall, while these options are promising for future upgrades or alternative site deployments, we benchmark only the plastic scintillator baseline in this work for clarity and feasibility.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. Due to the nature of the data and in accordance with American Physical Society (APS) guidelines, the authors will provide access to the relevant datasets and simulation outputs used in this work upon request.

- [1] P. A. M. Dirac, Quantized singularities in the electromagnetic field, *Proc. R. Soc. A* **133**, 60 (1931).
- [2] J. S. Schwinger, Magnetic charge and quantum field theory, *Phys. Rev.* **144**, 1087 (1966).
- [3] J. C. Pati and A. Salam, Unified lepton-hadron symmetry and a gauge theory of the basic interactions, *Phys. Rev. D* **8**, 1240 (1973).
- [4] X.-G. Wen and E. Witten, Electric and magnetic charges in superstring models, *Nucl. Phys.* **B261**, 651 (1985).
- [5] R. Alonso, D. Dimakou, and M. West, Fractional-charge hadrons and leptons to tell the Standard Model group apart, *Phys. Lett. B* **863**, 139354 (2025).
- [6] H.-L. Li and L.-X. Xu, Understanding the SM gauge group from SMEFT, *J. High Energy Phys.* **07** (2024) 199.
- [7] S. Koren and A. Martin, Fractionally charged particles at the energy frontier: The SM gauge group and one-form global symmetry, *SciPost Phys.* **18**, 004 (2025).
- [8] X. Gan and Y.-D. Tsai, Cosmic millicharge background and reheating probes, *J. High Energy Phys.* **07** (2025) 094.
- [9] B. Holdom, Two $U(1)$'s and ϵ charge shifts, *Phys. Lett. B* **166B**, 196 (1986).
- [10] R. Barkana, N. J. Outmezguine, D. Redigolo, and T. Volansky, Signs of dark matter at 21-cm?, *Phys. Rev. D* **98**, 103005 (2018).
- [11] S. Davidson, S. Hannestad, and G. Raffelt, Updated bounds on millicharged particles, *J. High Energy Phys.* **05** (2000) 003.
- [12] A. Hayrapetyan *et al.* (CMS Collaboration), Search for fractionally charged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **134**, 131802 (2025).
- [13] Z. Liu, Y.-H. Xu, and Y. Zhang, Probing dark matter particles at CEPC, *J. High Energy Phys.* **06** (2019) 009.
- [14] A. A. Prinz *et al.*, Search for millicharged particles at SLAC, *Phys. Rev. Lett.* **81**, 1175 (1998).
- [15] A. Ball *et al.* (milliQan Collaboration), Sensitivity to millicharged particles in future proton-proton collisions at the LHC, *Phys. Rev. D* **104**, 032002 (2021).
- [16] A. Ball *et al.*, A letter of intent to install a milli-charged particle detector at LHC P5, [arXiv:1607.04669](https://arxiv.org/abs/1607.04669).
- [17] A. Ball *et al.*, Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **102**, 032002 (2020).
- [18] S. Foroughi-Abari, F. Kling, and Y.-D. Tsai, Looking forward to millicharged dark sectors at the LHC, *Phys. Rev. D* **104**, 035014 (2021).
- [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] J. H. Kim, I. S. Hwang, and J. H. Yoo, Search for sub-millicharged particles at J-PARC, *J. High Energy Phys.* **05** (2021) 031.
- [21] G. Magill, R. Plestid, M. Pospelov, and Y.-D. Tsai, Millicharged particles in neutrino experiments, *Phys. Rev. Lett.* **122**, 071801 (2019).
- [22] R. Harnik, Z. Liu, and O. Palamara, Millicharged particles in liquid argon neutrino experiments, *J. High Energy Phys.* **07** (2019) 170.
- [23] R. Acciarri *et al.* (ArgoNeuT Collaboration), Improved limits on millicharged particles using the ArgoNeuT experiment at Fermilab, *Phys. Rev. Lett.* **124**, 131801 (2020).
- [24] 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.* **B987**, 116103 (2023).
- [25] M. Crisler, R. Essig, J. Estrada, G. Fernandez, J. Tiffenberg, M. Sofo haro, T. Volansky, and T.-T. Yu (SENSEI Collaboration), SENSEI: First direct-detection constraints on sub-GeV dark matter from a surface run, *Phys. Rev. Lett.* **121**, 061803 (2018).
- [26] S. N. Gninenko, D. V. Kirpichnikov, and N. V. Krasnikov, Probing millicharged particles with NA64 experiment at CERN, *Phys. Rev. D* **100**, 035003 (2019).
- [27] 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).
- [28] T. Åkesson *et al.* (LDMX Collaboration), Light dark matter experiment (LDMX), [arXiv:1808.05219](https://arxiv.org/abs/1808.05219).
- [29] S. Perez *et al.* (Oscura Collaboration), Searching for millicharged particles with 1 kg of Skipper-CCDs using the NuMI beam at Fermilab, *J. High Energy Phys.* **02** (2024) 072.
- [30] 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).
- [31] M. Du, R. Fang, and Z. Liu, Millicharged particles from proton bremsstrahlung in the atmosphere, *J. High Energy Phys.* **08** (2024) 174.
- [32] H. Wu, E. Hardy, and N. Song, Searching for heavy millicharged particles from the atmosphere, *Phys. Rev. D* **110**, 115037 (2024).
- [33] H. Vogel and J. Redondo, Dark Radiation constraints on minicharged particles in models with a hidden photon, *J. Cosmol. Astropart. Phys.* **02** (2014) 029.
- [34] N. Vinyoles and H. Vogel, Minicharged particles from the Sun: A cutting-edge bound, *J. Cosmol. Astropart. Phys.* **03** (2016) 002.
- [35] 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.
- [36] H. Liu, N. J. Outmezguine, D. Redigolo, and T. Volansky, Reviving millicharged dark matter for 21-cm cosmology, *Phys. Rev. D* **100**, 123011 (2019).
- [37] J.-T. Li and T. Lin, Dynamics of millicharged dark matter in supernova remnants, *Phys. Rev. D* **101**, 103034 (2020).
- [38] R. Harnik, R. Plestid, M. Pospelov, and H. Ramani, Millicharged cosmic rays and low recoil detectors, *Phys. Rev. D* **103**, 075029 (2021).
- [39] D. F. G. Fiorillo and E. Vitagliano, Self-interacting dark sectors in supernovae are fluid, *Phys. Rev. Lett.* **133**, 251004 (2024).
- [40] M. Deniz *et al.* (TEXONO Collaboration), Measurement of $\text{Nu}(e)\text{-bar}$ -electron scattering cross-section with a CsI(Tl) scintillating crystal array at the Kuo-Sheng nuclear power reactor, *Phys. Rev. D* **81**, 072001 (2010).
- [41] S.-F. Ge and I. M. Shoemaker, Constraining photon portal dark matter with texono and coherent data, *J. High Energy Phys.* **11** (2018) 066.
- [42] 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).
- [43] S. Banik, Search for lightly ionizing particles in SuperCDMS and simulation of neutron backgrounds, Ph.D. thesis, Bhubaneswar, NISER, 2021.
- [44] J. Aalbers *et al.* (LZ Collaboration), First dark matter search results from the LUX-ZEPLIN (LZ) experiment, *Phys. Rev. Lett.* **131**, 041002 (2023).
- [45] M. F. Albakry *et al.* (SuperCDMS Collaboration), Investigating the sources of low-energy events in a SuperCDMS-HVeV detector, *Phys. Rev. D* **105**, 112006 (2022).
- [46] M. F. Albakry *et al.* (SuperCDMS Collaboration), Search for low-mass dark matter via bremsstrahlung radiation and the Migdal effect in SuperCDMS, *Phys. Rev. D* **107**, 112013 (2023).
- [47] 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).
- [48] K. K. Boddy, K. Freese, G. Montefalcone, and B. Shams Es Haghi, Minimal dark matter freeze-in with low reheating temperatures and implications for direct detection, *Phys. Rev. D* **111**, 063537 (2025).
- [49] A. A. Aguilar-Arevalo *et al.* (CONNIE and Atucha-II Collaborations), Search for reactor-produced millicharged particles with Skipper-CCDs at the CONNIE and Atucha-II experiments, *Phys. Rev. Lett.* **134**, 071801 (2025).
- [50] P. W. Lisowski and K. F. Schoenberg, The los alamos neutron science center, *Nucl. Instrum. Methods Phys. Res., Sect. A* **562**, 910 (2006).
- [51] G. Shiu, P. Soler, and F. Ye, Milli-charged dark matter in quantum gravity and string theory, *Phys. Rev. Lett.* **110**, 241304 (2013).
- [52] T. Gherghetta, J. Kersten, K. Olive, and M. Pospelov, Evaluating the price of tiny kinetic mixing, *Phys. Rev. D* **100**, 095001 (2019).
- [53] A. A. Aguilar-Arevalo *et al.* (CCM Collaboration), First dark matter search results from Coherent CAPTAIN-Mills, *Phys. Rev. D* **106**, 012001 (2022).
- [54] <https://www.berkeleyneutronics.com/cerium-bromide>.
- [55] P. deNiverville, Searching for light dark matter with proton-beam fixed target experiments, <https://indico.ibs.re.kr/event/47/contributions/2773/attachments/2517/2724/ProtonFixedTargets.pdf>.
- [56] P. deNiverville, C.-Y. Chen, M. Pospelov, and A. Ritz, Light dark matter in neutrino beams: Production modelling and scattering signatures at MiniBooNE, T2K and SHiP, *Phys. Rev. D* **95**, 035006 (2017).
- [57] Y.-D. Tsai, P. deNiverville, and M. X. Liu, Dark photon and muon $g - 2$ inspired inelastic dark matter models at the high-energy intensity frontier, *Phys. Rev. Lett.* **126**, 181801 (2021).
- [58] R. L. Burman and E. S. Smith, Parameterization of pion production and reaction cross sections at LAMPF energies, Technical Report No. LA-11502-MS, Los Alamos National Laboratory, 1989.
- [59] K. Jodkowski, F. Kling, L. Roszkowski, and S. Trojanowski, Extending the reach of FASER, MATHUSLA, and SHiP towards smaller lifetimes using secondary particle production, *Phys. Rev. D* **101**, 095020 (2020).
- [60] R. L. Workman *et al.* (Particle Data Group), Review of particle physics, *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
- [61] J. Allison *et al.*, Recent developments in Geant4, *Nucl. Instrum. Methods Phys. Res., Sect. A* **835**, 186 (2016).
- [62] Neutron News, Vol. 3, No. 3, 1992, pp. 29–37.
- [63] <https://www.psi.ch/en/drs>.
- [64] H. O. Meyer, Dark rate of a photomultiplier at cryogenic temperatures, [arXiv:0805.0771](https://arxiv.org/abs/0805.0771).
- [65] Hamamatsu Photonics K. K., Photomultiplier Tubes and Assemblies for Scintillation Counting and High Energy Physics, https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/High_energy_PMT_TPMZ0003E.pdf.
- [66] H. Jeong, Search for sub-millicharged particles at j-parc, in *31st International Symposium on Lepton Photon Interactions at High Energies*, Zenodo, [10.5281/zenodo.8347283](https://zenodo.org/record/105281) (2023).
- [67] C. Guerrero, A. Tsinganis, E. Berthoumieux, M. Barbagallo, F. Belloni, F. Gunsing, C. Weiß, E. Chiaveri *et al.*, Performance of the neutron time-of-flight facility n_tof at CERN, *Eur. Phys. J. A* **49**, 27 (2013).
- [68] H. Abele *et al.*, Particle physics at the european spallation source, *Phys. Rep.* **1023**, 1 (2023).
- [69] J. Arrington *et al.*, Physics opportunities for the Fermilab booster replacement, [arXiv:2203.03925](https://arxiv.org/abs/2203.03925).