Letter of Intent: Search for sub-millicharged particles at J-PARC

Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], David Stuart[2], Chris Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], and Martin Gastal[6]

[1]*Korea University, Seoul, Korea*
[2]*University of California, Santa Barbara, California, USA*
[3]*The Ohio State University, Columbus, Ohio, USA*
[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

Abstract

We propose a new experiment sensitive to the detection of millicharged particles produced at the 30 GeV proton fixed-target collisions at J-PARC. The potential site for the experiment is B2 of the Neutrino Monitor building, 280 m away from the target. With $N_{POT} = 10^{22}$, the experiment can provide sensitivity to particles with electric charge $3 \times 10^{-4}\, e$ for mass less than 0.2 GeV/c^2 and $2 \times 10^{-3}\, e$ for mass less than 1.6 GeV/c^2. This brings a substantial extension to the current constraints on the charge and the mass of such particles.

1 Motivation for the experiment

Electric charge quantization is a long-standing question in particle physics. While fractionally charged particles (millicharged particles hereafter) have typically been thought to preclude the possibility for Grand Unified Theories (GUTs), well-motivated dark-sector models have been proposed to predict the existence of millicharged particles while preserving the possibility for unification. Such models can contain a rich internal structure, providing candidate particles for dark matter. One well motivated mechanism that leads to millicharged particles is to introduce a new $U(1)$ in dark sector with a massless dark-photon (A') and a massive dark-fermion (χ) [1],

$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}\left(\slashed{\partial} + ie'\slashed{A}' + im_\chi\right)\chi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu} \tag{1}$$

where the last term shows that A' and B kinetically mix with the mixing parameter κ. After replacing $\slashed{A}'$ with $\slashed{A}' + \kappa B_\mu$, the coupling between the dark fermion and B becomes $\kappa e'$ ($\kappa e'\bar{\chi}\slashed{B}\chi$). The charge of χ varies by the size of mixing, so χ can be a millicharged particle. Hereafter, χ is used to denote millicharged particles.

A number of experiments have searched for millicharged particles, including in an electron fixed-target experiment [2], proton-proton colliders [3–5], and neutrino experiments [6]. A comprehensive review is in Reference [7]. In the parameter space of the charge (Q) and the mass (m_χ), the region of $m_\chi > 0.1$ GeV/c^2 and $Q < 10^{-2}e$ is largely unexplored.

Proton fixed-target experiments provide a solid testing ground for χs. The particle flux is much larger than the collider experiments and they can reach higher energy regime than electron fixed-target experiments. The sensitivity of such experiments to χs can reach beyond $Q_\chi \sim 10^{-3}e$ for a wide mass range from a few MeV/c^2 to a couple of GeV/c^2. We propose an experiment, SUBMET (SUB-Millicharge ExperimenT), which utilizes the 30 GeV J-PARC proton beam to search for χs in this unexplored region.
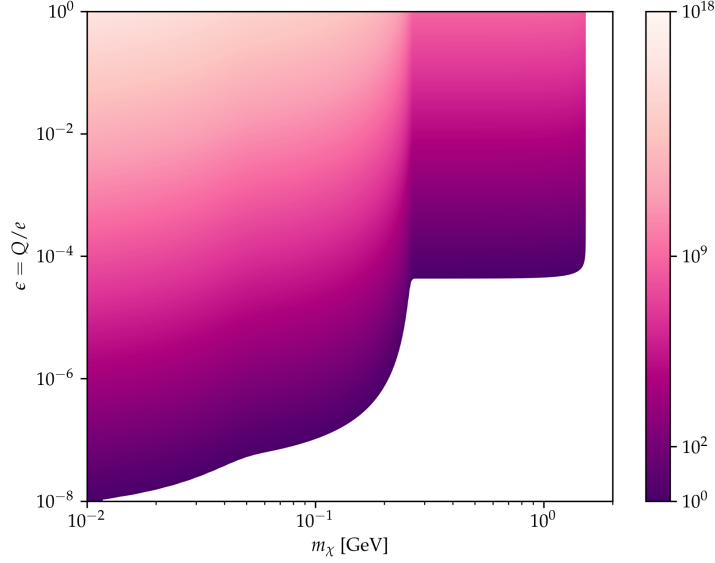
Figure 1: Expected number of χs that reach a 0.5 m^2 detector located at 280 m from the target. $N_{POT} = 10^{22}$ is assumed.

2 Production of millicharged particles at J-PARC

We consider χs with charge Q produced from π^0, η and J/ψ neutral meson decays. The Υ production is irrelevant because the center-of-mass energy $\sqrt{s}$ is 7.5 GeV for the collisions between the 30 GeV proton beam and the fixed target. The lighter mesons ($\mathfrak{m} = \pi^0, \eta$) decay through photons ($\pi^0, \eta \to \gamma\chi\bar{\chi}$), while J/ψ mostly decay to χs directly ($J/\psi \to \chi\bar{\chi}$). In both cases, m_χ up to $m_\mathfrak{m}/2$ is kinematically allowed. The number of produced χs N_χ can be calculated by the equation in [8],

$$N_\chi \propto c_\mathfrak{m} \epsilon^2 N_{POT} \times f\left(\frac{m_\chi^2}{m_\mathfrak{m}^2}\right) \tag{2}$$

where $c_\mathfrak{m}$ is the number of mesons produced per proton-on-target (POT), N_{POT} is the total number of POT, $\epsilon = Q/e$, and f is a phase space related integral that goes to 0 as m_χ approaches $m_\mathfrak{m}/2$. Figure 1 shows the expected number of χs that reach the detector with face area of 0.5 m^2, located 280 m from the target. Assuming $N_{POT} = 10^{22}$ that corresponds to running the

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experiment for ~ 3 years, the expected number of χs is in the order of 10^{16} at $\epsilon = 1$ and it is in the order of 10^9 at $\epsilon = 10^{-4}$.

3   Site and detector concept

In J-PARC, a 30 GeV proton beam is incident on a graphite target to produce hadrons that subsequently decay to a muon and muon neutrino in the decay volume. The remaining hadrons are then dumped in the beam dump facility. Since they are MIPs, muons penetrate the beam dump and are identified by the muon monitor located behind the beam dump facility. The on-axis near detector (INGRID) is inside the Neutrino Monitor (NM) building located at 280 m from the target. The space between the muon monitor and INGRID is filled with rock.
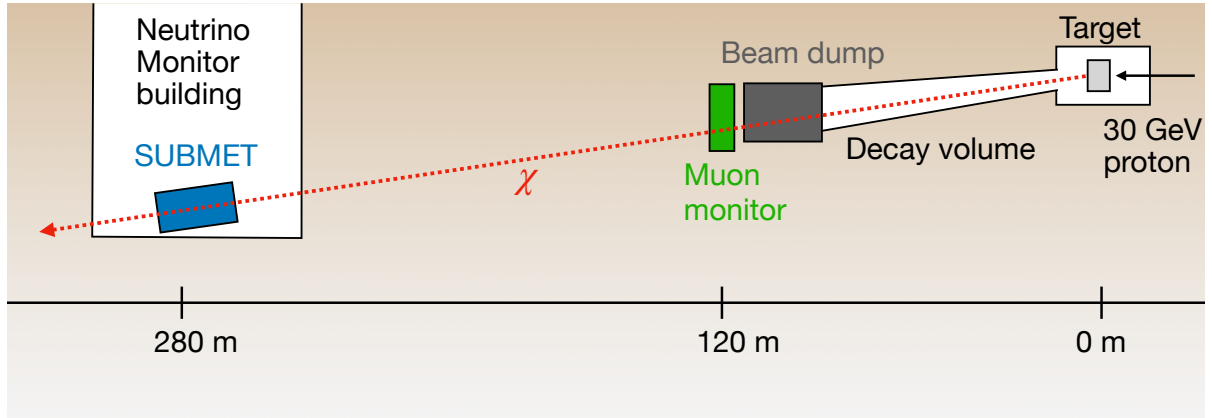

Figure 2: Illustration of the experimental site. χs are produced near the target and reach SUBMET after penetrating the beam dump, the muon monitor and the rock.

If χs are produced, because of their low interaction probability, they will penetrate the beam dump facility, the muon monitor, and the rock without a significant energy loss. Therefore, they can be detected at the NM building if a detector sensitive to identifying such particles is installed. We consider the area behind the V-INGRID on B2 (~ 30 m underground) as a potential detector site. The distance from the axis of the neutrino beam is ~ 5 m. As described below, the signal acceptance is only slightly smaller than the on-axis location.

In order to be sensitive to charges down to $10^{-3}e$, a thick sensitive volume is needed. It is
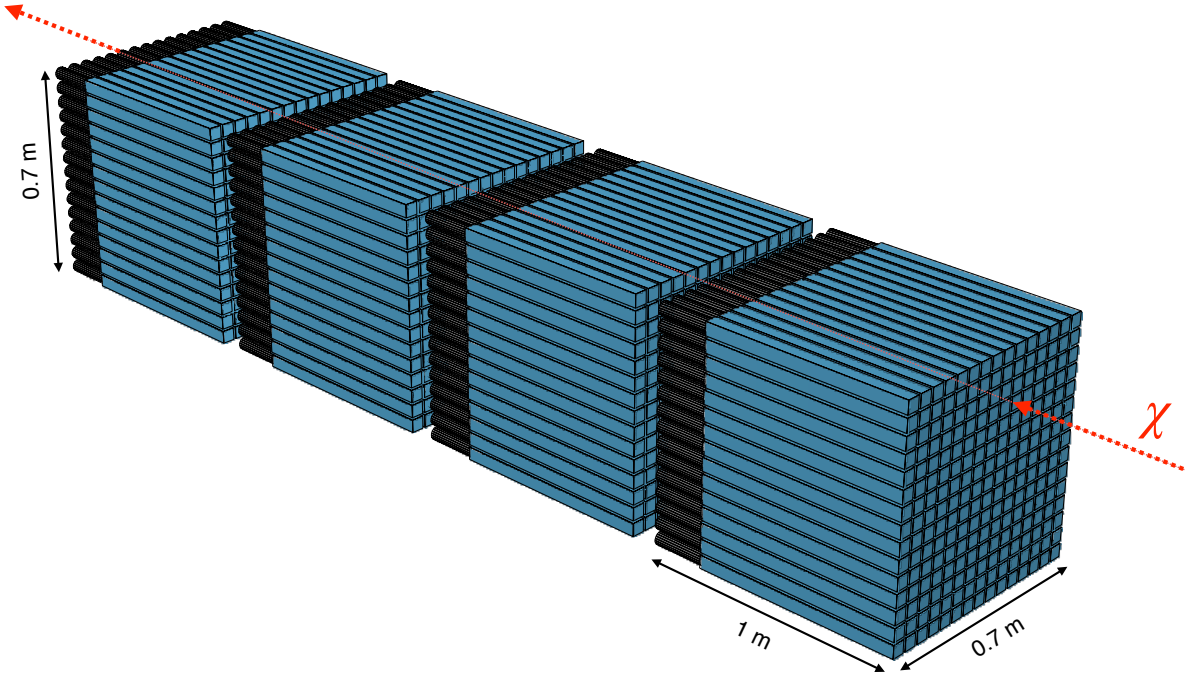
Figure 3: Demonstration of the SUBMET detector. There are four layers of scintillator bars (blue). At one end of each bar a PMT (black) is attached A χ will penetrate 4 layers in a narrow time window.

advantageous to segment the large volume because it reduces backgrounds due to dark currents and shower particles from cosmogenic muons to a negligible level. It also allows for utilizing the directionality of the incident χs to further suppress non-pointing particles. The detector, as shown in Figure 3, is composed of 4 layers of stacked $5 \times 5 \times 80$ cm^3 plastic scintillator bars. They are aligned such that the produced χs pass through all layers in a narrow time window. In each layer there are 14×14 scintillator bars, so the area of the detector face is about 0.5 m^2. A prototype of a detector with a similar design has been installed at the LHC, and shown robustness and sensitivity to χs [5].

At the end of each scintillator bar a photodetector is attached to convert the photons to an electronic signal. There are several options, but we consider Photomultipliers (PMTs), because of their large area coverage, low cost, and low dark current. Since the size of a bar is 5×5 cm^2, a fast commercial 50 mm diameter PMT is suitable. Including PMTs, the total volume of the detector is approximately $0.7 \times 0.7 \times 4$ m^3.
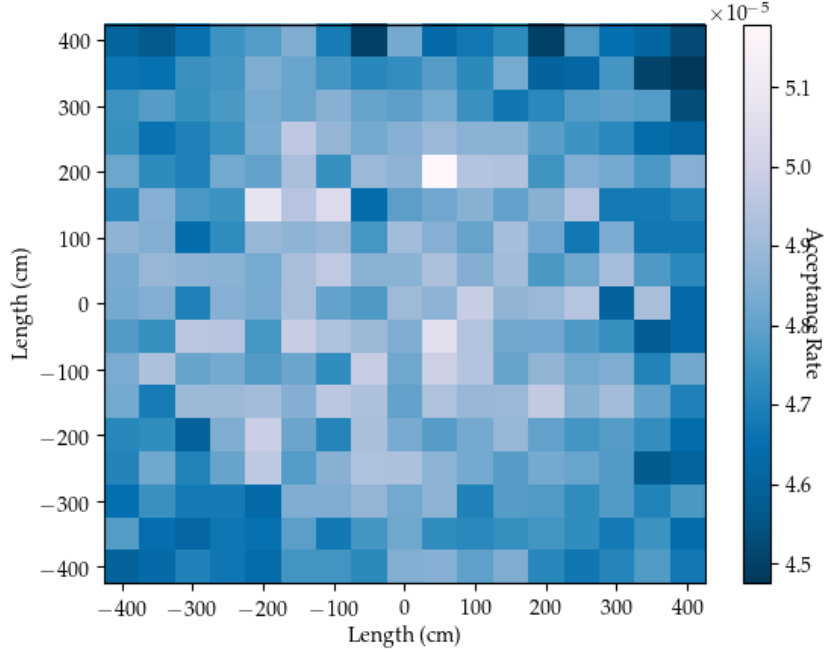
Figure 4: Signal acceptance rate for the detector area of 0.5 m^2 at 280 m from the target. One box corresponds to 0.5×0.5 m^2.

The signal acceptance rate, the fraction of χs that go into the detector area of 0.5 m^2 at 280 m from the target, is calculated. Since the photons are massless, the direction of the photons and that of χs should be aligned. Therefore, the direction of photons from π^0's is used as a proxy for the direction of χs. Figure 4 shows the acceptance rate in 8×8 m^2 plane where the axis of the neutrino beam is at the center. The acceptance rate does not depend on the location within this range strongly, *i.e.*, near the corners the rate is only $\sim 10\%$ lower than the central region because of the large distance from the target. This provides some flexibility in selecting the location of the detector.

The operation of SUBMET does not interfere with the operation of the neutrino program and dedicated beam time will not be required. The detector is located behind the V-INGRID detector, so we don't expect any interference with the measurements of the neutrino beam properties and the operation of the INGRID detector. The detector will be triggered by its own trigger system and the experiment will have an independent data stream. Therefore, the

operation of this new experiment does not have any conflict with the existing programs at J-PARC.

4   Background sources

The χs that reach the detector will go through all layers within a ~ 20 ns time window (coincidence signal). In this section, the background sources that can mimic this coincidence signal are discussed. They can be divided into three categories, random coincidence, beam-induced, and cosmic-induced backgrounds.

In PMTs, spurious current pulses can be produced by thermal electrons liberated from the photocathode. If the rate of such pulses (dark count rate, DCR) is high, the rate of random coincidence can be substantially large even if the time window for coincidence signal is 20 ns. The random coincidence rate can be calculated by $R = nN^n\tau^{n-1}$ where n is the number of layers, N is the DCR, and τ is the coincidence time window. Using a typical DCR of 1 kHz, $n = 4$, and $\tau = 20$ ns, the random coincidence rate is 2.5×10^{-4} per year. Since there can be $14 \times 14 = 196$ such coincidence signals, the total coincidence rate is 0.05 per year.

Muons are produced from the pion decays in the decay volume together with neutrinos. The typical density of rock is 2.65 g/cm^3 and $dE/dx = 1.639$ MeV/cm^{2}g, so the energy loss of a MIP in > 100 m of rock is much larger than 30 GeV. Therefore, such beam-induced muons can't reach the detector. Although the muons from the pion decays can't reach the detector, neutrinos can and may interact with the scintillator material to produce small signals. The number of neutrino interaction events in INGRIND is $\sim 1.5 \times 10^8$ for $N_{POT} = 10^{22}$ [9]. Since a large fraction of INGRIND material is iron, we can use the rate of INGRIND as a upper bound for SUBMET. One layer of SUBMET is approximately 30 times smaller, so the rate is $\sim 5 \times 10^6$ for $N_{POT} = 10^{22}$ in one layer of SUBMET. Requiring coincidence in 4 layers, the expected number of this background is negligible. The interaction of the neutrinos and the material of the wall of the NM building in front of the detector can produce muons that go through the detector. These muons can be identified and rejected by installing a scintillator plate between the wall and the detector or by using the very large scintillation yield of a muon that can be separated

from millicharge signal.

Cosmic muons that penetrate the cavern or the materials above the detector can produce a shower of particles that is large enough to hit all layers simultaneously. In such events, the hits in multiple layers can be within the coincidence time window and will look like a signal event. The particles in the shower generate more photons than χs, so the signals from cosmic muon showers can be rejected by vetoing large pulses. As done to tag the muons produced in the wall of the NM building in front of the detector, scintillator plates can be installed covering the whole detector to tag any ordinary-charge particles incident from top and the sides of the detector. In addition, the cosmic shower penetrates the detector sideways, leaving hits in multiple bars in the same layer, while χs will cause a smaller number of hits. A cosmic shower overlapping with dark current can be another source of background. Since the rate of this background depends on the environment strongly, a precise measurement can be performed *in situ* only.

To estimate the sensitivity of the experiment, despite the additional layer in the design, we conservatively assume a similar background rate to a similar proposal at Fermilab (the FerMINI experiment [8]), leading to a total background over three years of running of 500 events.

5 Sensitivity

The probability of detecting a χ in a n-layer detector is given by Poisson distribution $P = (1 - e^{-N_{PE}})^n$ where N_{PE} is the number of photoelectrons. N_{PE} is proportional to the quantum efficiency (QE) of PMT, ϵ^2, and the number of photons that reach the end of the scintillator (N_γ). The ϵ^2 term comes from the fact that the energy loss of a charged particle in matter is proportional to ϵ^2. In order to get N_γ a GEANT4 [10] simulation is performed. Using a $5 \times 5 \times 80$ cm^3 Saint-Gobain BC-408 plastic scintillator with surface reflectivity of 98%, we get $N_\gamma = 6.3 \times 10^5$. Using $QE = 30\%$ and taking the area of the PMT into account, we get $N_{PE} = 1.3 \times 10^5 \epsilon^2$. We can now calculate the total number of signal events $s = N_\chi P$ measured by the detector. Figure 5 shows the number of detected signal events s in the plane of ϵ and m_χ.

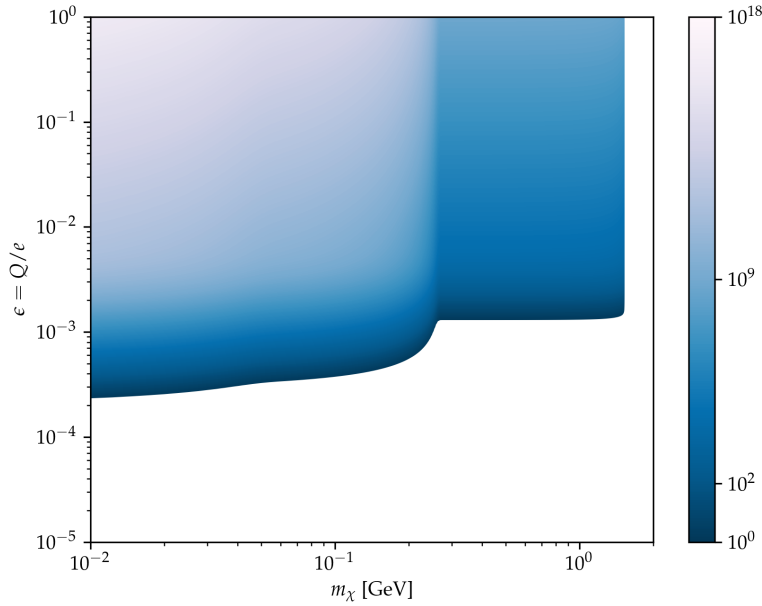For $b = 500$, s should be greater than $1.65\sigma_b = 1.65\sqrt{b} = 38$ to provide a 95% CL exclusion

Figure 5: Expected number of detected signal events s in $N_{POT} = 10^{22}$. There is a sharp drop in $\epsilon < 10^{-3}$.

limit. Figure 6 shows the 95% CL exclusion curve for $N_{POT} = 10^{22}$. SUBMET provides exclusion down to $\epsilon = 3 \times 10^{-4}$ in $m_\chi < 0.2$ GeV/c² and $\epsilon = 2 \times 10^{-3}$ in $m_\chi < 1.6$ GeV/c².

Sensitivity of SUBMET is slightly worse than FerMINI because SUBMET uses 4 layers while FerMINI uses 3 layers. A 4-layer configuration is needed to reduce the random coincidence rate to a negligible level; as discussed in the previous section, random coincidence rate in SUBMET is 0.05 per year while it is 300 per year in FerMINI. In addition, dark current overlapping with a correlated shower, which may be the dominant background source, can be suppressed by an additional layer. If 3 layers are used for SUBMET, the exclusion limit is comparable with that of FerMINI (Table 1).

6   Alternative detector design

In this section, we discuss how sensitivity depends on the configuration of the detector. If further optimization of the detector is needed, we can use this quantitative study as a guidance.
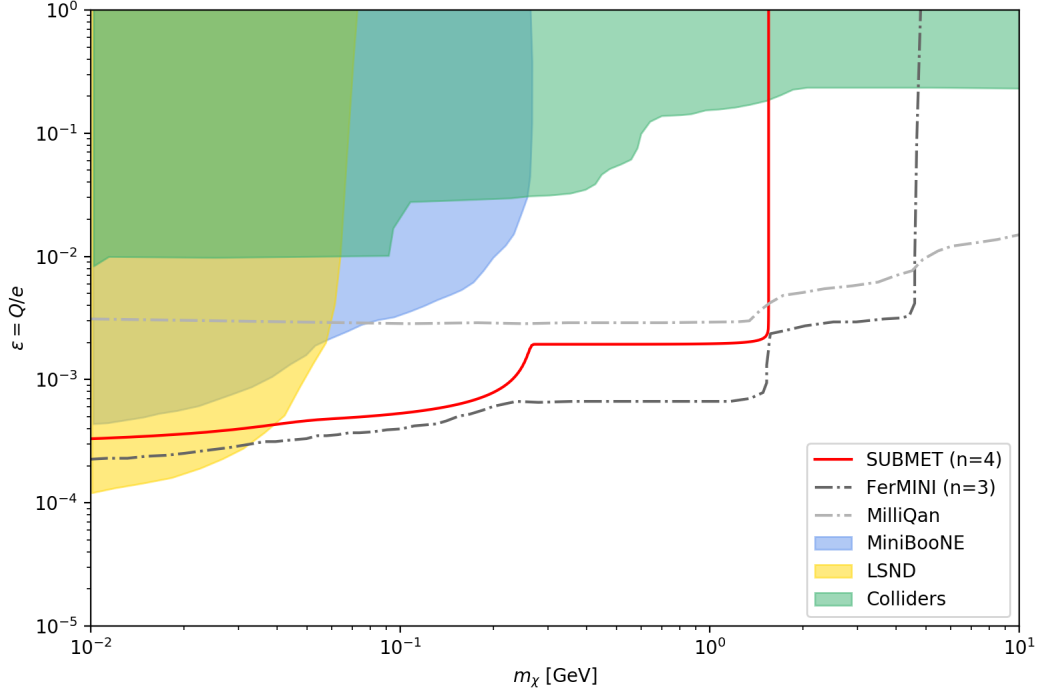
Figure 6: Exclusion at 95% CL for $N_{POT} = 10^{22}$. For comparison, the constraints from previous experiments are shown as shaded area and the expected sensitivity of the proposed experiments are drawn in gray dotted line. Note that FerMINI curve is from 3-layer detector design. If 3 layers are used for SUBMET, the limit curve moves down to the level consistent with FerMINI's (Table 1).

Silicon Photomultipliers (SiPMs) can be considered instead of PMTs because of its excellent sensitivity to single photons and small size. A challenge is that they have a typical DCR of 5 MHz/cm² at room temperature, about three orders of magnitude larger than that of PMTs. This leads to a significantly larger random coincidence rate. Since the dark current is a thermal effect, it has a strong dependence on temperature. Typical reduction rate is a factor of ~ 2 per 10 °C. So, to suppress the DCR to the similar level of PMT's, the temperature should be lowered by an order of 100 °C. In the scenario where SiPMs are used, the size of scintillator bars is chosen to be 1×1 cm due to difficulty in covering the large area of the scintillator. In this case the light attenuation effect increases due to more reflections and the photon yields decreases by a factor of 2.

N_χ(relative)	N_{PE}(relative)	b	n	Exclusion limit on ϵ for $m_\chi = 10$ MeV/c^2
1	1	500	4	3.2×10^{-4}
10	1	500	4	2.6×10^{-4}
1	1	50000	4	4.1×10^{-4}
1	1	50	4	2.9×10^{-4}
1	2	500	4	2.5×10^{-4}
2	2	500	4	2.3×10^{-4}
1	1	500	3	1.9×10^{-4}

Table 1: Various detector configurations and their sensitivity. N_χ (relative) is the relative yields of signal events within the acceptance and N_{PE} (relative) the number of photon electrons relative to 1.3×10^5. b is the background yields and n is the number of layers.

Approximating $P \simeq N_{PE}$ to the first order for small ϵ, we arrive at the following relation

$$N_{\epsilon=1,\chi}\epsilon^2 (N_{\epsilon=1,PE}\epsilon^2)^n \geq 1.65\sqrt{b} \tag{3}$$

where the subscript $\epsilon = 1$ refers to the values at $\epsilon = 1$. Reordering in terms of ϵ, we recognize the exclusion limit at 95% CL is

$$\epsilon = \left(\frac{N_{PE}^n N_\chi}{1.65\sqrt{b}} \right)^{-\frac{1}{2n+2}}. \tag{4}$$

Not surprisingly, the ϵ-power term induces a sharp cutoff in signal at $\epsilon \sim O(10^{-4})$ as shown in Figure 5. This limits the sensitivity to the same regime regardless of the detector configuration.

Table 1 shows different detector configurations and the corresponding exclusion limit for $m_\chi = 10\,\text{MeV/c}^2$. The default configuration is in the first row, N_χ(relative)=1, N_{PE}(relative)=1, $b = 500$, and $n = 4$.

The improvements we can achieve by extending the duration of data collection or making the detector area larger (adding more bars to each layer) is highly negligible. Extending the duration or the detector area by a factor of 10 increases N_χ by the same amount. Making a conservative assumption that the background remains same, the sensitivity is only enhanced by 20% (2$^{\text{nd}}$ row in Table 1).

Impact of b is also small. If b is increased by a factor of 100, the limit increases by 25%

(3rd row in Table 1). If it is suppressed to a 1/10 level, the limit decreases by 20% (4th row in Table 1).

As the 5th and 6th rows in Table 1 show, the most effective component to increase the sensitivity is N_{PE}. Increasing N_{PE} by a factor of 2 improves the sensitivity limit by 25%. This can be achieved by using an inorganic crystal with large Z such as BGO or by making the scintillator bars longer. `GEANT4` simulation shows that a $5 \times 5 \times 20$ cm^3 BGO bar provides $N_\gamma = 1.2 \times 10^6$, about a factor of 2 larger than the $5 \times 5 \times 80$ cm^3 BC-408 scintillator. Further increasing the length of the bar to 40 cm, one can achieve $N_\gamma = 1.7 \times 10^6$.

7 Summary

We studied the feasibility of an experiment searching for millicharged particles using 30 GeV proton fixed-target collisions at J-PARC. With $N_{POT} = 10^{22}$, the experiment provides a sensitivity to χs with charge down to $\epsilon = 3 \times 10^{-4}$ in $m_\chi < 0.2$ GeV/c^2 and $\epsilon = 2 \times 10^{-3}$ in $m_\chi < 1.6$ GeV/c^2; this is the regime largely uncovered by the previous experiments. We also explored a few detector designs to achieve an optimal sensitivity to χs. There is a strong dependence on the photoelectron yields, but the sensitivity does not have a strong dependence on the detector configurations in the sub-millicharge regime.

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