PROCEEDINGS OF SCIENCE

Search for sub-millicharged particles at J-PARC

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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 of 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. A number of experiments have searched for millicharged particles (χs), but in the parameter space of the charge (Q) and mass (m_χ), the region of $m_\chi > 0.1$ GeV/c^2 and $Q < 10^{-3}e$ is largely unexplored. SUB-Millicharge ExperimenT (SUBMET) has been proposed to search for sub-millicharged particles using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs, and is proposed to be installed 280 m from the target. The main background is expected to be a random coincidence between the two layers due to dark counts in PMTs, which can be reduced significantly using the timing of the proton beam. With $N_{\mathrm{POT}} = 5 \times 10^{21}$, the experiment provides sensitivity to χs with the charge down to $7 \times 10^{-5}e$ in $m_\chi < 0.2$ GeV/c^2 and $10^{-3}e$ in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by the previous experiments.

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1. Motivation

The quantization of electric charge is a long-standing unresolved question in elementary particle physics. Well-motivated dark sector models have been proposed to predict the existence of millicharged particles. Such models may contain rich internal structures, which means they are candidates for dark matter. Thus, the existence of partially charged particles could be a stepping stone beyond the standard model.

One of the simplest extensions from the standard model is an introduction of an additional $U(1)$ gauge to the dark sector. If we assume that there is a new $U(1)$ gauge boson (hereafter dark photon A'), and the dark photon and the Standard Model photon B kinematically mix, dark fermion (ψ) can interact with B [1, 2].

The charge of the dark fermion is proportional to the size of the mixing, and this makes the dark fermion carry a fractional electric charge. In fact, our experiment is sensitive to any fractionally charged particles, not limited to this model.

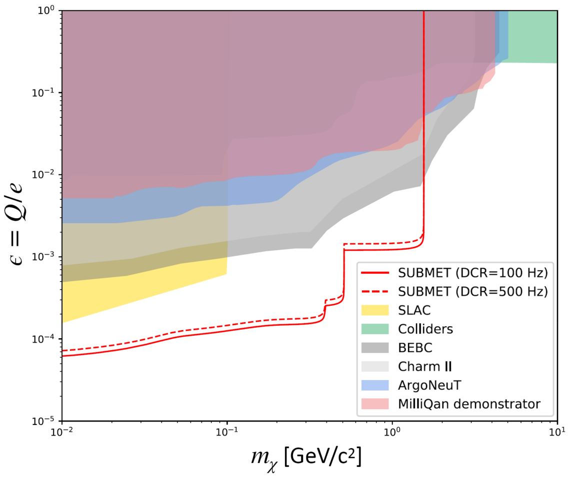


Figure 1: The constraints from previous experiments are shown as shaded areas.

There have been experiments searching for millicharged particles such as electron-fixed target experiments, proton-proton colliders, proton-fixed target experiments, and neutrino experiments. A comprehensive review is in Ref. [3]. Figure 1 shows the region in charge-mass parameter space excluded by the existing experiments. As shown in Figure 1, the region of $m > 0.1$ GeV$/c^2$ and $Q < 10^{-3}e$ of charge (Q) and mass (m_χ), respectively, is still largely not probed at present. In Figure 1, **SUB-Millicharge ExperimenT (SUBMET)** is the name of our new proposal. We aim to explore the unexplored region which is indicated by the red curves.

2. Site and Detector Concept

The experimental site is illustrated in Figure 2. Refer to Ref. [4] for details about the site and χs generation. If χs are produced, they will penetrate the space between the target and the detector without a significant energy loss because of their feeble interaction with matter. Therefore, they

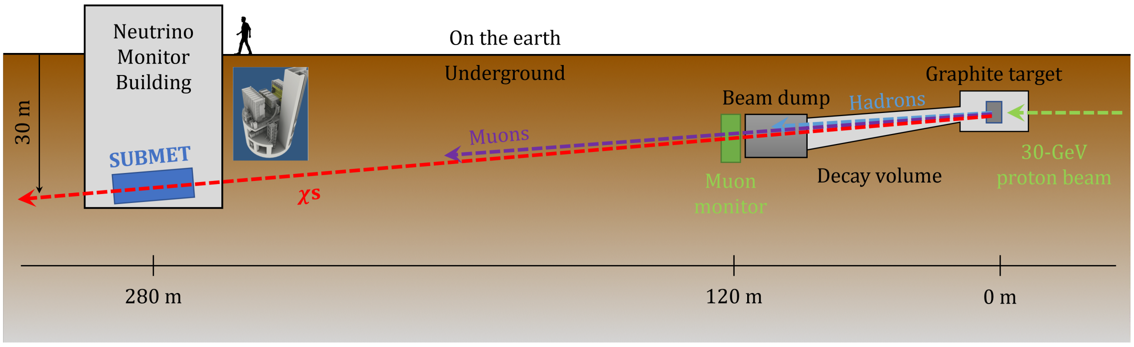


Figure 2: Illustration of the experimental site. χs are produced near the target and reach SUBMET after penetrating the beam dump, the muon monitor, and the sand.

can be detected at the Neutrino Monitor (NM) building if a detector sensitive to identifying such particles is installed.

To be sensitive to charges below $10^{-3}e$, a thick sensitive volume is needed. It is advantageous to segment the large volume because it helps reduce 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 2 layers of stacked $50 \times 50 \times 1500$ mm^3 plastic scintillator bars. They are aligned

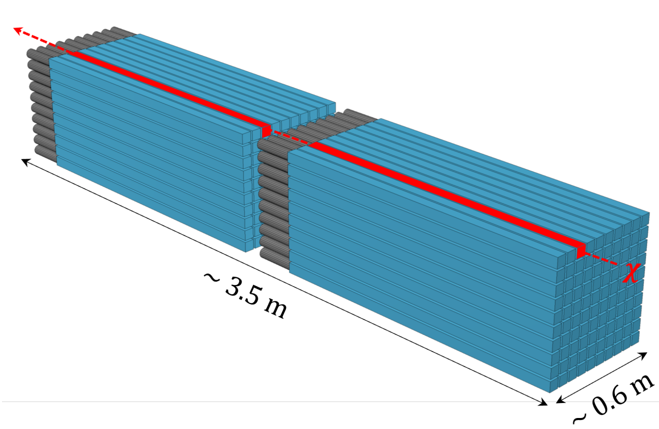


Figure 3: Demonstration of the SUBMET detector. A module is composed of a $50 \times 50 \times 1500$ mm^3 scintillator bar (blue) and a PMT (black). 10×10 modules are stacked together. Two layers of stacks are aligned such that a χ penetrates both layers in a narrow time window.

such that the produced χs pass through both layers in a narrow time window. In each layer there are 10×10 scintillator bars, so the area of the detector face is about 0.25 m^2.

3. Background Sources

χs that reach the detector will go through both layers within a ~ 10 ns time window producing a 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. First, there can be output PMT pulses even when no photons hit the PMT. These are called Dark Current Pulses and its rate is called Dark Count Rate (DCR). A random coincidence of such pulses in different layers can be identified as a millicharge signal. A typical size of the pulses is very small and this makes random coincidence the major background source in the $Q < 10^{-3}e$ regime. This random event can be suppressed by requiring coincidence in the two layers. Second, muons are produced from pion decays together with neutrinos. Requiring coincidence in two layers, the expected number of events from this background source becomes negligible. Third, cosmic muons that penetrate the cavern or the materials above the detector can produce a shower of particles that is large enough to hit both layers simultaneously. According to GEANT4 simulation, this contribution is $O(10^{-2})$ per year.

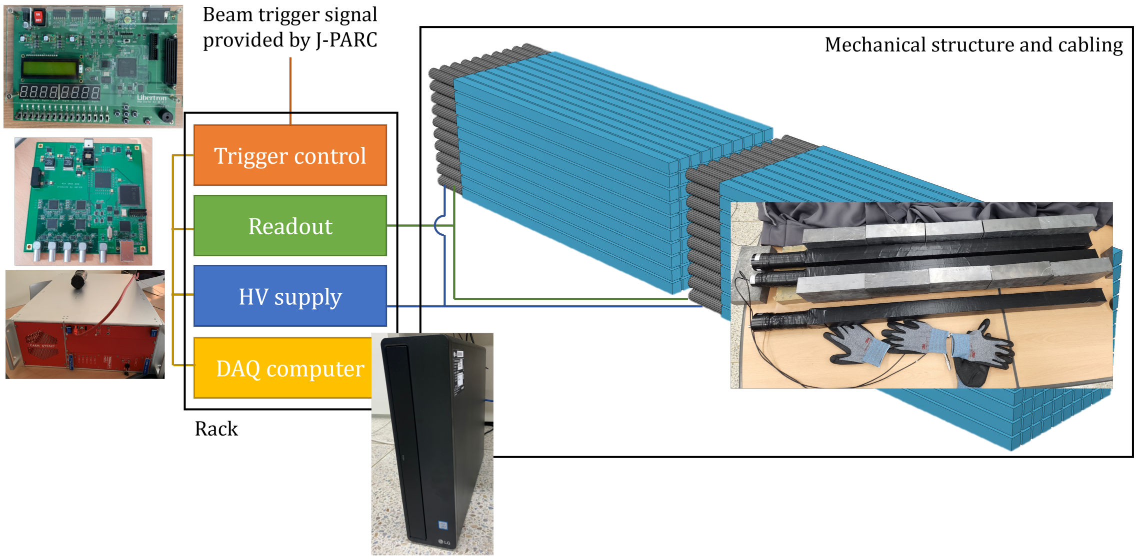


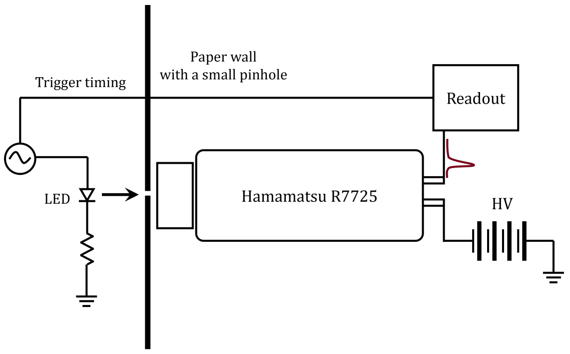
Figure 4: Picture of a prototype detector system.

4. DAQ System

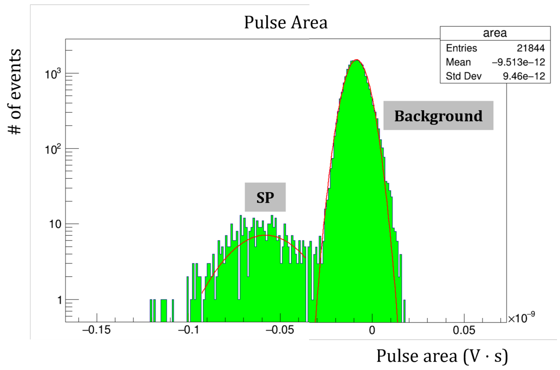
Figure 4 shows a diagram of the prototype system. It consists of a trigger controller, readout board, high voltage supply for the PMTs, and computer. We have built and tested prototypes for each part. The first picture in Figure 4 is an FPGA test board with trigger logic and the second one is a custom readout board. On the right, the picture shows test modules. From the study on the prototype, The design of the full system is nearing completion and will be manufactured soon.

5. Study with Prototype

The main question about the detector is whether it can detect a single photon signal with a high efficiency. The experimental setup to verify this is shown in Figure 5 (a). After putting the PMT in the dark box, a weak pulse from a function generator is sent to the light-emitting diode (LED) to generate several photons. A needle hole is drilled in the hardboard paper and placed between the



(a)



(b)

Figure 5: (a) A schematic diagram of the experimental setup for a single-photoelectric signal detection test. (b) SPE pulse area spectrum at HV = 1.2 kV. Red curves are the Gaussian fittings of each peak.

PMT and the LED to block most of the photons except a few of them. Figure 5 (b) shows the peaks due to SPEs and the pedestal, which can be clearly separated. The size of the pulse as well as the level of separation depends on the high voltage (HV). This is shown in Figure 6. The central value is the Gaussian mean and the error bars denote Gaussian sigma.

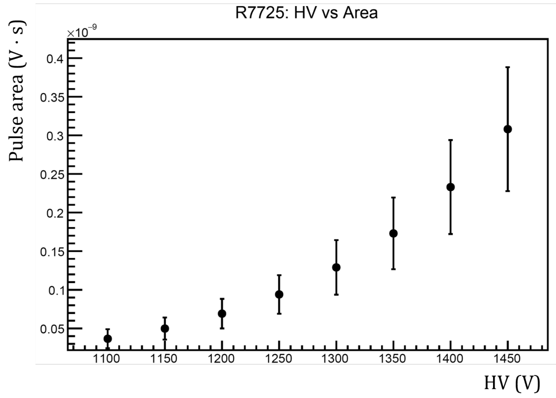


Figure 6: SPE pulse area vs HV supplied to the PMT

6. DCR Measurement

The DCR is expected to be the main background source for SUBMET because a random coincidence from such dark current pulses in different layers can be identified as a millicharge signal. The estimation of DCR and the coincidence rate becomes the study of background source and signal sensitivity. For this, we measured the DCR of sample PMTs (*Hamamatsu Photonics* R7725). Figure 7 shows the result of DCR measurement for several R7725 samples. Measured DCR values are in the range of typical value ∼ 500 Hz. Occasionally, significantly higher DCR was measured in some PMTs, irrespective of the model. (See “HA000” in Figure 7.) DCR of all PMTs for the detector will be inspected and high-DCR PMTs won’t be used for modules to prevent degradation of sensitivity to millichared particle detection.

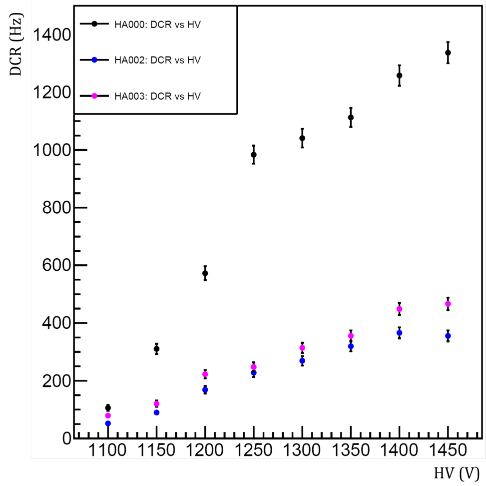


Figure 7: DCR vs HV. Blue and purple dots represent typical DCR values whereas black dots show abnormally high DCR.

7. Summary and Outlook

We propose a new experiment for millicharged particle search at J-PARC. In fact, the proposal had been submitted to J-PARC and stage-I has been given. We have already visited the J-PARC site in the spring of 2022 to understand the experimental environment. We aim to receive final approval in the upcoming winter. The prototype system is being tested and the full system design is being finalized. In September 2022, module assembly started and is expected to be completed by the end of 2022. If the final approval is obtained from the J-PARC, the manufactured modules will be shipped and installed at the site.

References

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