DeeMe — an experiment searching for μ-e conversion in nuclear field at sensitivity of 10^{-14} with pulsed proton beam from RCS

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Abstract. A new experiment searching for μ-e conversion in nuclear field by fully utilizing the high-power pulsed proton beam available at J-PARC Material Life Science Facility is described. A Monte Carlo simulation whose validity was confirmed by a test measurement indicates the muonic carbon atom formation rate in a muon target of J-PARC Material Life Science Facility being approximately 10^{10}/sec for 1 MW operation of a J-PARC RCS. With this high formation rate of the muonic atoms, it is possible to perform a competitive search for μ-e conversion in nuclear field. The sensitivity of the measurement is 1.5×10^{-14} for silicon nuclei after 2×10^7 sec of the physics run if a new large-acceptance beamline for 105-MeV/c electron is built in timely manner. The discovery potential of seeing the signal beyond the Standard Model is very high.

1. Introduction

Lepton flavor invariance, which has been a feature of the original Standard Model (SM) *a priori*, no longer holds since neutrino oscillations have been firmly established[1]. This fact generally implies the existence of lepton-flavor violation in charged sector (CLFV) due to the mixing of neutrino flavors in the intermediate state. However the strength of such a process is suppressed by a GIM-like mechanism to the level of 10^{-60}[2], far beyond the experimental accessibility. CLFV is practically still forbidden in the framework of neutrino-oscillation-extended SM. Therefore, the experimental observation of CLFV is an unquestionable proof of the existence of new physics beyond the SM.

There are numerous theoretical models describing the physics beyond the SM those give predictions for the branching ratios of CLFV processes[3, 4, 5]. One of such models, for example, is based on the combination of a supersymmetric model (SUSY) with a see-saw mechanism by right-handed heavy neutrino[6]. An interesting mass range of the right-handed heavy neutrino could be explored by CLFV experiments such as $\mu \to e\gamma$ and μ-e conversion in nuclear field. Therefore experimental studies of these processes will certainly help to understand the structure of neutrino sector. Another model based on SUSY Grand Unified Theory[7, 8] also gives predictions for the branching ratio of $\mu \to e\gamma$ and μ-e conversion in nuclear field. In this model, a relatively large top-quark mass results in rather larger radiative corrections to the slepton mass matrix, and the off-diagonal elements of the slepton mass matrix become sizable. As a result, smuon-selectron mixing in the intermediate state of the processes might induce CLFV, and calculations show the branching ratios being only a few orders of magnitude below the current experimental limits. There is also an example of theoretical calculations for the decay branching ratio of $\mu \to e\gamma$ shown as a function of the muon anomalous magnetic dipole moment [9]. A calculation with appropriate assumptions on SUSY parameters and GUT relations shows that the current obseravation of the muon $g-2$ would correspond to 10^{-11}–10^{-12} of $\mu \to e\gamma$ decay branching ratio.

It is naively concluded that, if the $\mu \to e\gamma$ process exists, the μ-e conversion in nuclear field should also exist at the branching ratio of about $\alpha\times$ Br($\mu \to e\gamma$) where α is the fine structure constant. This is because the photon exchange contributes to the μ-e conversion in nuclear field. The current observation of the muon g-2 strongly favors μ-e conversion above 10^{-14}. There are, of course, potential differences in the type of interactions mediating $\mu \to e\gamma$ and μ-e conversion in nuclear field: there is a possibility of other particle exchanges like Higgs bosons contributing to the μ-e conversion in nuclear field[10]. In this case, the branching ratio of the μ-e conversion in nuclear field will be larger than $\alpha\times$ Br($\mu \to e\gamma$). This means that performing searches for both processes (and others) is very important to maximize the discovery potential, and even after a discovery of CLFV in any processes, other studies will stay complementary and provide indispensable information to understand the details of CLFV process and physics source behind that.

A CLFV signal may be seen in near future by experiments which improve the current limits. It is conceivable that the CLFV signal lies waiting to be discovered right under the current limit. A new experiment searching for μ-e conversion in nuclear field at the 10^{-14} level would be a highly competitive addition to the field of particle physics.

2. Experimental Apparatus

The main idea of the experiment described here is to utilize the muonic atom that formed in the production target itself, and use the ordinary secondary beamline to extract electrons coming from $\mu^- + \mathrm{A(N,Z)} \to e^- + \mathrm{A(N,Z)}$ reactions in the production target. The experimental apparatus is divided into the following components.

Production Target A part of low-energy pions produced by the primary proton beam will decay in flight to muon only within a few centimeters after the production. Some of those muons from the pions decay-in-flight will stop in the production target itself. The muonic atom yield in the production target will be 10^{10}/sec for 1-MW operation of the J-PARC Rapid-Cycle-Synchrotron booster (RCS). The material of the production target will be either carbon or silicon carbide.

Secondary Beamline An ordinary secondary beamline will be used for extracting 105-MeV/c electrons from the target. There are huge amount of low-energy Michel electrons and positrons from $\mu^\pm$ decay in the target, but most of them are blocked by the secondary beamline. In order to increase the statistical significance, the beamline should transport the 105-MeV/c electrons with large transport efficiency.

Kicker System There will be a huge number of electrons promptly produced by the primary proton hitting the production target. One of such production process would be $p + N \to \pi^0 N'$, $\pi^0 \to \gamma\gamma$ and $\gamma \to e^+e^-$ in material, for example. The rate of such prompt electrons is estimated to be 10^7 per proton pulse. If these electrons hit the detector, it will be blinded for while and will miss the chance to detect the delayed signal electrons. The kicker system is used to reduce the rate of the prompt electrons by factor 10^3–10^4.

Detector The detector system should measure the electron momentum with 0.5% (rms) of resolution in order to distinguish the signal from the decay-in-orbit backgrounds. It also has to withstand the prompt electrons up to 10^4 per pulse. Since the size of electron beam is about 200×200 mm, the instantaneous rate of the prompt electrons is about 0.25 MHz per mm^2. It is very high but still within the reach of the existing technology of the gas wire chamber.

The apparatus will be installed in the muon experimental area in the Material LIfe Science Facility (MLF) of J-PARC.

2.1. Production Target

When a high intensity proton beam from the MLF hits a production target, a great number of pions are copiously produced. The energy distribution of these pions shows a very diverse spectrum ranging from very low energy to high energy, and the production yield of low energy pions is quite large. Some of those low energy pions stop in the production target itself and decay to muons by $\pi^+ \rightarrow \mu^+\nu_\mu$ decays. Since the energy of those decay-at-rest muons is only 4 MeV and the range is not longer than 0.1 g/mm^2, most of those muons do not emerge out of the production target. However, muons from the pions stopped in the very thin surface layer of the production target can emerge out of the target. This is the mechanism of how "surface muons" are produced. Since the yield of low energy pions is very large, the yield of surface muons is also large. For example, the typical yield is about 4×10^8/sec at the PSI μE4 beamline (135 msr, $\Delta p/p = 9.5\%$)[11].

In contrast to the "surface μ^+", it is well known that the "surface μ^-" does not exist because the parent particle π^- is promptly absorbed by the target nucleus after it stops. However, low energy pions can still decay in flight and produce low energy μ^-s. These muons are called "cloud μ^-", and some fraction of the low energy cloud μ^- can stop in the production target. Then, those μ^- will form muonic atoms in the production target.

In order to estimate the production yield of the muonic carbon atom from the mechanism described above, a Monte Carlo calculation by using Geant4 was performed. The hadron code used in the calculation is QGSP_BERT_HP. Then, the lower energy ($<$ 200 MeV/c) pion production rate from the calculation is compared with the HARP measurement[12]. The Geant4 calculation is fairly consistent with the HARP measurement.

However, the HARP cross section data do not completely cover whole the kinematics region, and the QGSP_BERT_HP model is just a model with some uncertainty in its precision at the low energy region. Therefore, we performed a test experiment to measure the muonic atom formation rate in the Muon Target at MLF Muon Science Facility MUSE[1]. Figure 1 shows a typical time spectrum of delayed electrons with the beamline momentum setting being 40 MeV/c at D-line of MUSE[14]. The shape of time spectrum was fit to $Ae^{-\frac{t}{\tau}}$, by using MINUIT, and the result is $\tau = 2.094 \pm 0.005$ μs. According to the Geant4 Monte Carlo study, this time spectrum should composed of two components: exponential decay with $\tau_1 = 2.0$ μs and $\tau_2 = 2.2$ μs. The former comes from the decay of μ^- in a carbon atom. The latter comes from μ^+ decay in the carbon target followed by the Bhabha scattering off the electrons in material. Since the yield of μ^+ decay is more than 500 times larger than μ^-, the effect of the Bhabha scattered e^- is not negligible. The percentage of the Bhabha scattered e^- in the spectrum is estimated to be 20% by Geant4 Monte Carlo. If the statistics of the plot was much more, then these two components could be separated. Nonetheless, the observed time spectrum is fairly consistent with the μ^- life time in carbon. The rate of the muonic carbon atom formation obtained from this result with the correction of D-line transmission acceptance is 0.7×10^9/sec for 120 kW operation of MLF at the time of measurement. By scaling up with the primary beam power, it corresponds to 6×10^9/sec for 1 MW operation of RCS, and it is consistent with the estimation by the Geant4 within 20–30%.

The current production target will be replaced with rotating-disk one in a few years in order to overcome the radiation damage problem. If the size of the rotating-disk target is optimized for

[1] A similar measurement was also performed at TRIUMF in 2008[13]

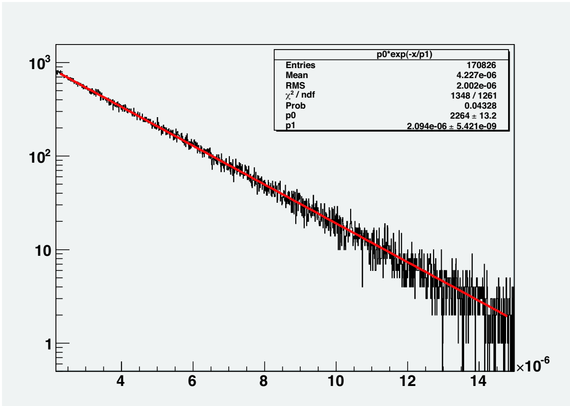

Figure 1. Typical time spectrum of delayed-timing charged particles observed at the exit of D-line. The origin of horizontal axis is a time of the 1st proton pulse. In order to protect the counter from the prompt burst, signal at around the proton pulses are masked.

this experiment, the yield of the muonic carbon formation rate will become almost 15×10^{10}/sec for 1 MW operation of RCS.

2.2. Secondary Beamline

The μ^--e^- electrons produced in the muon production target will be extracted by a secondary beamline. The secondary beamline should have the following functions:

(i) Capability of extracting high momentum 105-MeV/c electrons,

(ii) Large solid angle to increase the physics sensitivity,

(iii) Suppression to low-energy DIO electrons,

(iv) Modest (not so small) momentum bite to monitor high-momentum background electrons and

(v) Pulse kicker system to suppress the prompt burst.

The model of the beam line is the existing beam line at MLF Muon Facility, D-line. It can be operated up to 120 MeV/c, which satisfies the 1st requirement above. Three dipole magnets almost completely eliminate low momentum particles passing through the beam line, and the momentum bite is wide enough so that the signal electrons and high-momentum background electrons can be monitored simultaneously. A pulse kicker system is already installed for μSR application, and it can be used for this experiment. However, the geometrical acceptance is only 10 msr for widely distributed electron source.[2] Therefore, the physics sensitivity is limited due to the smallness of the acceptance of D-line.

In order to reach the 10^{-14} of single event sensitivity (SES), it is critically important to increase the acceptance of beamline. Therefore, a new beamline using a High-Momentum Decay Muon port at MUSE (H-line) is under serious consideration. Figure 2 shows a conceptual optics design of the new beamline. The exepcted geometrical acceptance averaged over the widely distributed source image (H : 30 mm × V : 60 mm) is more than 110 msr, which is almost one order of magnitude larger than that of D-line.

It is note worth that the beamline is designed as a multi-purpose infrastructure. Not only μ-e conversion experiment, but also muon $g-2$ experiment and muonium hyper-fine-structure measurement can be performed with the same beamline. It is a cost effective way to make use of the beamline equipment. These experiments cannot run simultaneously and they have to time-share the beamline, but It will improve the efficiency of proton usage since one experiment can use it while the others are doing detector preparations.

[2] the acceptance is 30 msr if the source is point-like.

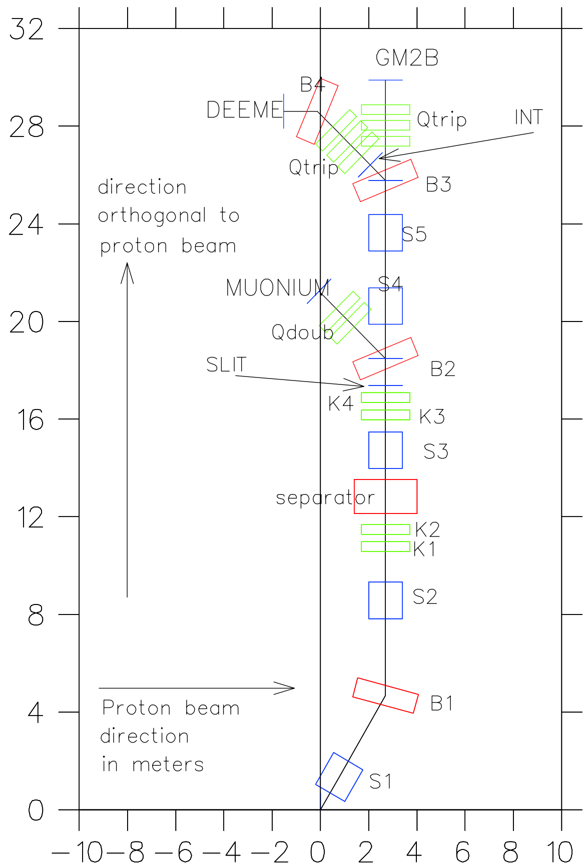

Figure 2. Layout of the new beamline for DeeMe (DEEME), surface muon (MUSR) and muon $g-2$ (GM2B) experiments. S1–5 are solenoids, B1–4 are dipole bends, K1–4 are kicker magnets, Qdoub and Qtrip are quadruple- doublet and triplet, respectively.

2.3. Kicker system

The time structure of the primary proton beam from RCS is pulsed. There are two bunches in one RCS cycle, and they are separated by 600 nsec, and extracted from the RCS at once by the fast extraction system. The repetition of the RCS extraction is 25Hz.

When the proton beam hits the production target, there is a large amount of electron production, where the electron presumably come from a conversion of γ from a π^0 decay. Since these electrons are promptly produced, they will merely fake the delayed signal electron unless the primary proton comes in delayed timing. On the other hand, when those electrons at the prompt timing hit a detector, the detector will be easily blinded for while and may not be able to detect the delayed electrons. In order to avoid it, the prompt particles should be suppressed by the secondary-beamline kicker system.

The kicker system consists of four kicker magnets. The location of the kicker magnets are labeled as K1–K4 in Fig. 2. Table 1 shows the parameter of the kicker system. The kicker is a transmission-line type, and a whole kicker magnet enclosed in a vacuum vessel. It consists of multiple ferrite segments, and copper conductors run through the ferrite cores to form a single turn coil. Ceramic capacitors are connected to the copper conductors in every gap between adjacent ferrite cores, and make the conductor as impedance-matched signal line. The cutoff frequency of the magnet is dominated by the inductance of single ferrite. A simulation shows that the fall time is less than 300 nsec.

2.4. Detector

Even if the beamline momentum is set at the 105 MeV/c, there will be many particles emerging out of the beam line with other momenta. Most of them are electrons coming from decay-

Table 1. Specification of the kicker magnet for the H-line.

Magnetic Field	> 385 Gauss
Gap	320 mm
Width	320 mm
Length	400 mm
Number of Kickers	4
Fall Time	< 300 ns
Repetition	25Hz

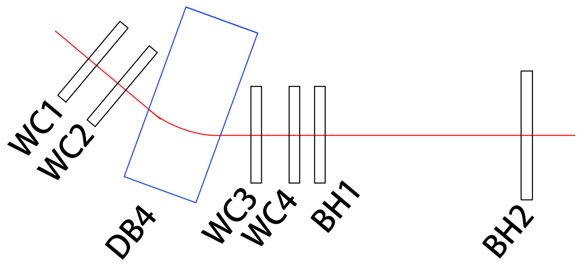

Figure 3. Schematic layout of the electron spectrometer.

in-orbit of muonic atoms (DIO). In order to reject those off-momentum electrons, an electron spectrometer should be installed at the downstream of beam line exit. The momentum resolution should be less than 0.5 MeV/c(rms) in order to separate the μ-e electrons from the DIO electrons. It should be noted that the electron spectrometer provides a measurement of the high momentum tail of DIO spectrum and the μ-e conversion signal simultaneously.

The detector has to be operational after prompt-burst of the beam. The expected rate of the prompt-burst is about 33k particles per proton bunch even after the suppression by the kicker system. A couple of the prompt-bursts separated by 600 ns will come in every 40 ms. The average rate is less than 2MHz, but the detector design needs some special cares since the beam is not DC beam and the instantaneous rate of the prompt-burst is very high.

The detector system proposed here is a simple magnetic spectrometer with a dipole magnet and several planner tracking chambers. A trigger hodoscope and a time-of-flight hodoscope are needed to define the timing and to reject muon backgrounds. Figure 3 shows a schematic layout of the spectrometer system.

3. Sensitivity

Single event sensitivity to μ-e conversion process is expressed by the following equation:

$$S = \frac{1}{N^{\mu}_{\rm obs}}, \tag{1}$$

where $N^{\mu}_{\rm obs}$ is a total number of muonic atoms observed. The $N^{\mu}_{\rm obs}$ can be expressed as:

$$N^{\mu}_{\rm obs} = R_{\pi^-} \times f_{\pi^- \to \mu^- {\rm stop}} \times f_{\rm C} \times f_{\rm MC} \times A_{\mu-e} \times T, \tag{2}$$

where $R_{\pi^-} \times f_{\pi^- \to \mu^- {\rm stop}}$ is a μ^- stopping rate per second, $f_{\rm C}$ is the atomic capture rate on the specific atomic species of interest constituting a compound, $f_{\rm MC}$ is a fraction of μ^- that goes to the muon nuclear capture process, $A_{\mu-e}$ is the total acceptance for μ-e electrons, and T is a time length of the measurement. The factor $f_{\rm C}$ was estimated by using the Fermi-Teller Z law[15], in which the atomic capture rate is claimed to be proportional to the nuclear charge of the atom. There are several reports indicating the deviation from the Fermi-Teller Z law, but the deviation is only a level of a few of 10% for light nuclei[16]. In this proposal, the Fermi-Teller Z law was simply used.

The factor $f_{\rm MC}$ is the fraction of the nuclear capture process. It increases as the atomic number increases since the overlap of the muon wave function with the nuclei increases as the Coulomb potential becomes deeper. There are both experimental and theoretical studies about $f_{\rm MC}$[17, 18].

The $A_{\mu-e}$ can be further broken down to the following expression:

$$A_{\mu-e} \;=\; A_{\rm beamline} \times A_{\rm detector} \times A_{\rm tracking} \times A_{E_e\text{-cut}} \times A_{\text{time-window}}\,. \tag{3}$$

These factors were estimated by using the combination of Geant4 and G4Beamline simulation for D-line. Then the result of D-line was simply scaled by using the design parameter of H-line obtained by the optics calculation.

The $A_{\rm beamline}$ is a ratio between the electrons entering the detector and the electrons produced in the target. It includes all the effect from electron energy loss in the target, beamline acceptance, beamline momentum bite and so on. The $A_{\rm detector}$ is the ratio between the particle hit the final hodoscope and the one entering the detector.

The $A_{\rm tracking}$ and the $A_{E_e\text{-cut}}$ were estimated after performing the fourth-order Runge-Kutta track fitting. The $A_{\rm tracking}$ is mostly limited by the track quality cut, in which the track probability is required to be more than 5%. Those event rejected might be suffered from the large angle scattering by the chamber material. This effect might be treated in much better way by using double Gaussian approximation to the multiple-scattering angle distribution in the future, and the $A_{\rm tracking}$ could be higher than the current value. The momentum resolution of the track fitter itself becomes 0.36 MeV/c.

The $A_{E_e\text{-cut}}$ depends on the E_e cut threshold. The threshold was determined to suppress the DIO background lower than the SES level. It is about 102.5 MeV/c as will be described in the next section.

Table 2 summarizes the potential sensitivity for four different configurations. The best sensitivity will be obtained by using the H-line and a SiC target.

4. Backgrounds

There are two major sources of backgrounds: muon decay-in-orbit, and prompt backgrounds.

4.1. Muon Decay-in-Orbit Backgrounds

When a muonic atom is formed, the muon comes to its ground state very quickly. Then, it either be captured by a nucleus with emitting a neutrino (nuclear muon capture) or decays in orbit (DIO). These two processes are concurrently happening, and the total width of the muon reaction becomes wider than the width of the muon in free space. For instance, about 92% of muons decay in orbit for carbon. Their energy spectrum in the energy region lower than 52.5 MeV mostly resembles the Michel spectrum of ordinary muon decays, but a high energy tail exists due to nuclear recoils, and it extends up to the same energy as the μ-e conversion signal. Thus, the electrons from DIO become one of potential background sources.

The total energy spectra of DIO electrons were calculated by using the numerical values of the spectrum shapes compiled by Watanabe *et al.*[19] in the lower energy region in conjunction with the analytical equation near the endpoint of the spectrum[20]. Then, it was convoluted with the response function of the momentum measurement in order to evaluate the background contribution from DIO electrons. The response function is assumed to be a single Gaussian with $\delta p = 0.5$ MeV/c. The total amount of DIO is normalized to the nuclear capture process

Table 2. Breakdown of physics sensitivities.

	H-line SiC target	H-line C target	D-line SiC target	D-line C target
$R_{\mu^-\text{-stop}}$ (/s/MW)		15×10^9		10×10^9
Target Material	SiC	C	SiC	C
f_C	0.7	1.0	0.7	1.0
f_{MC}	0.66	0.08	0.66	0.08
$A_{\mu-e}$				
A_{beamline}	0.25%	0.25%	0.05%†	0.05%†
$A_{\text{detector}} \times A_{\text{tracking}}$	79%	79%	79%	78%
E_e cut threshold (MeV/c)	102.5	102.0	102.0	101.0
$A_{E_e \text{ cut}}$	52%	60%	60%	63%
$A_{\text{time-window}}$	0.49	0.75	0.49	0.75
T (s)		2×10^7		
SES	1.5×10^{-14}	5.7×10^{-14}	6.6×10^{-14}	3.2×10^{-13}
N_{DIO}	0.9×10^{-14}	5.5×10^{-14}	2.4×10^{-14}	2.7×10^{-13}

†: with a modification to improve the transmission efficiency.

since the μ-e conversion process is normalized to the nuclear capture process. The expected DIO backgrounds are shown in Table 2.

4.2. Prompt Backgrounds

The other potential source of background is the prompt electrons coming from late-arriving protons. The total number of on-timing protons on the Muon Production Target for 1 MW operation of J-PARC RCS for 2×10^7 s of the running time is 4×10^{22}, and there should be about 2×10^{16} of prompt electrons produced. In order to suppress number of these events less than 1, the probability of the after protons in the detector time window should be 5×10^{-17} of the on-timing protons. Now, this requirement seems to be extremely high at the first sight, but it is not beyond-the-reach actually.

First of all, it is note worth that the proton beam in RCS will be fast-extracted at once by kicker magnet system. After extracting the beam from the RCS, the kicker magnets fall down very fast so that the residual protons, if there is any, would feel only 10% of the full excitation magnetic field. In addition, the acceptance of the extracted beamline from RCS has been designed so as to be located outside of the physical aperture of RCS: the ring collimator aperture is 324πmm·mrad, and the extraction aperture is outside of it with 9 mm of the safely margin[21]. The beam emittance will be 81πmm·mrad for the core[22]. Such design of RCS was originally motivated to reduce the beam loss during the extraction, but it is also beneficial to reduce the after protons. Even if there is beam halo in the RCS ring, any particles in the halo will hit the collimator before accidentally extracted from the RCS ring.

In addition, the momentum region from 105 MeV/c to 110 MeV/c, where neither signal nor DIO electrons but only prompt electrons may be observed if it exists, will be accepted by the beamline and transported to the spectrometer, and monitored simultaneously. Since the momentum spectrum of the prompt electrons is fairly flat from 100 MeV/c to 110 MeV/c, it is easy to extract the amount of the prompt background underneath the signal window.

The test measurement of the after proton is currently on-going in collaboration with accelerator scientists in RCS favorably. It is note worth that there are several ways to suppress the after protons if it exists. One is to scrape the halo of proton beam before the extraction by using bump magnets in RCS. The other is that the extra kicker could be placed between RCS and MLF to clean up the late-extracted particles. These kickers could be treated as spares to the main kicker system.

5. Cost and Schedule

The cost for building the detectors and the kickers are well within the framework of the Grant-in-Aid of Scientific Research of Japan. The beamline will cost more, but it is the multipurpose beamline. Other experiments can make use of the beamline.

Since the idea of the experiment is very simple, we are aiming to obtain physics result within 5 years.

6. Summary

A CLFV signal may be seen in near future by experiments which improve the current limits. It is conceivable that the CLFV signal lies waiting to be discovered right under the current limit.

A new experiment that we propose to search for the $\mu^- - e^-$ conversion in nuclear field at J-PARC MLF with a sensitivity of 10^{-14}, two orders of magnitude below current limits, would be a highly competitive addition to the field.

The experiment will be conducted by using the muon provided at MLF. Our intention is to realize the experiment in a timely manner by making a use of the MLF muon target system as a muon-stopping target to form muonic atoms, and the muon beam line with kicker to suppress the detector rate.

The muonic atom formation rate in the rotation muon target in MLF is as high as 10^{10}/sec/MW. If a large-acceptance high-momentum electron beamline is built in H-line, the single event sensitivity will be 1.5×10^{-14} for 2×10^7 sec of physics run. The proposed H-line is compatible with other muon experiments such as muon $g - 2$, muonium hyperfine structure measurement, muonium-antimuonium conversion, and so on.

The most serious source of backgrounds would be from the late-arriving protons from RCS. The amount of having such protons within the measurement time window has to be suppressed less than 10^{-17} of the number of main protons. Although it is very unlikely to having the late-arriving protons from RCS due to the extraction scheme of the RCS, dedicated studies would be very helpful. Since it will be simultaneously monitored in the main measurement, we can still go for the physics run without full understanding the yield of the after protons.

The cost that needed only for this experiment is within the framework of the Grant-in-Aid of Scientific Research of Japan. The construction of H-line is needed for the maximum sensitivity, but the beamline can be used for many other fundamental muon science programs.

7. Acknowledgement

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