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Muon Storage Ring PRISM-FFAG to Improve a Sensitivity of μ-e Conversion Experiment Below 10^{-17}

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In experiments to search for the coherent neutrino-less conversion of a muon into an electron in the field of a nucleus, the characteristic of a muon beam can limit the achievable sensitivity. Two main limiting factors of the sensitivity, a backgrounds level and an energy resolution of the conversion electrons, are discussed for the MECO-type experiments. The PRISM/PRIME experiment is a solution to improve the sensitivity below 10^{-18} using a muon storage ring, which is called PRISM-FFAG. Its R&D status is also described briefly.

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1. Introduction

Searches for charged lepton flavor violating processes have attracted much attention recently due to their high potential to discover and elucidate new physics beyond the Standard Model [1]. Experiments to search for the coherent neutrino-less conversion of a muon into an electron in the field of a nucleus, in particular, are most attractive from the point of view of their extendability to achieve a higher sensitivity using an intense muon beam. In a material, a stopped negative muon forms a muonic atom. After the muon cascades down to the $1s$ state of the muonic atom, it is captured by a nucleus or decays in an orbit ($\mu^- \rightarrow e^-\nu_\mu\overline{\nu}_e$) in the Standard Model. The physics beyond the Standard Model, however, can excite another process of neutrino-less muon capture, $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$, which is called $\mu^-{-}e^-$ conversion in a muonic atom. This process violates the conservation of the lepton flavor numbers, L_e and L_μ, by one unit, but conserves the total lepton number, L. The electron emitted by the $\mu^-{-}e^-$ conversion in a muonic atom has mono-energetic energy of $E_{\mu e} = m_\mu - B_\mu - E^0_{rec} \approx m_\mu - B_\mu$, where m_μ is the muon mass, and B_μ and E^0_{rec} are the binding energy of the $1s$ muonic atom and the nuclear-recoil energy respectively. B_μ is different for various nuclei. For example, $E_{\mu e}$ = 104.97 MeV for aluminum. Therefore, the event signature of the $\mu^-{-}e^-$ conversion is very simple: a single electron emitted from the conversion with the energy of $E_{\mu e}$. Background sources of the $\mu^-{-}e^-$ conversion experiment can be classified under three categories: (i) *intrinsic physics backgrounds* (muon decay in orbit of a muonic atom and radiative muon capture on a nucleus), (ii) *beam-related prompt backgrounds* (radiative pion capture on a nucleus, scattering of electrons in a beam, pion decay in flight, muon decay in flight, and antiproton interaction), and (iii) *non-beam-related backgrounds* (cosmic-rays). These backgrounds must be suppressed as strongly as possible to improve the sensitivity. The backgrounds (i) are unavoidable, because they are intrinsic to muons stopped in the material. End points of energy spectrums of the electrons from these sources can come close to the signal region of $\mu^-{-}e^-$ conversion. Therefore, in order to eliminate these backgrounds, a precise energy measurement is necessary. The backgrounds (ii) must be reduced in a variety of ways including not only timing and kinematical cuts but also improvements of beam quality.

At present, there are two proposals of the $\mu^-{-}e^-$ conversion experiment at the sensitivity of 10^{-16}: COMET at J-PARC [2] and Mu2E at FNAL [3]. Design of these experiments is based on MECO experiment [4]. They will be referred as "MECO-type Experiments". The COMET experiment has its upgrade plan to improve the sensitivity to 10^{-18}, PRISM/PRIME. In this paper, limiting factors for their achievable sensitivity and the necessity of PRISM-FFAG including its R&D status are discussed.

2. MECO-type Experiments

Figure 1 shows a schematic drawing of the COMET experiment, which consists a production target, stopping target, and trackers and calorimeter in a solenoid channel. The MECO-type experiments use the pulsed muon beam with a pulse separation on the order of the muon lifetime in the stopping target ($\sim$1 μs separation for the aluminum target) in order to reduce the prompt backgrounds, as illustrated in Fig.3. The signal of $\mu^-{-}e^-$ conversion is detected in a timing window, which starts at about 700 ns after the primary proton pulse hits the production target. No proton

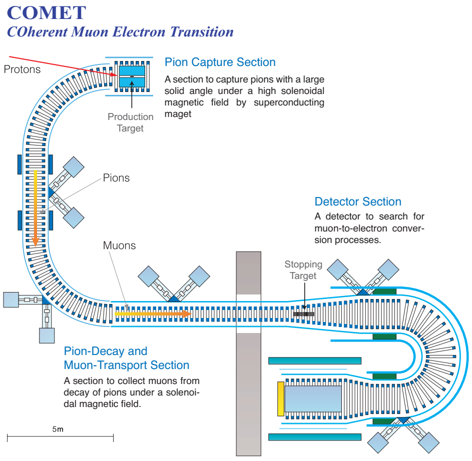

Figure 1: Schematic layout of the muon beamline and detector for COMET experiment with the sensitivity of BR$\sim 10^{-16}$.

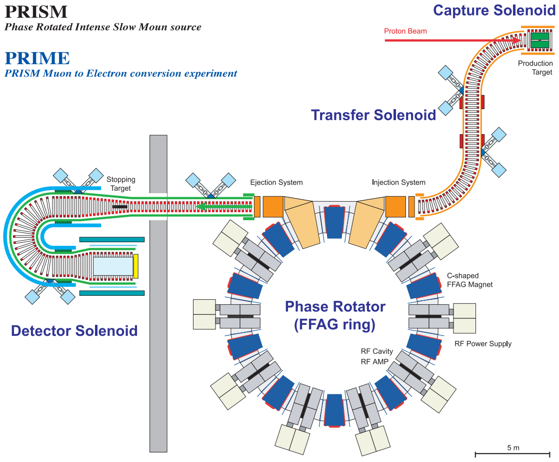

Figure 2: Schematic layout of the muon beamline, storage ring, and detector for PRISM/PRIME experiment. Its target sensitivity is BR$\sim 10^{-18}$.

between the pulses reduces the prompt backgrounds to a negligible level. The only remaining backgrounds are the prompt background events produced by off-timing protons coming between main pulses. A ratio of the number of protons in the pulse $N_{\rm in}$ and that of off the pulse $N_{\rm off}$ is defined as the beam extinction level $R_{\rm extinction} = N_{\rm off}/N_{\rm in}$. A low beam extinction level is dispensable for the MECO-type experiments, since rates of most of the prompt backgrounds are proportional to the beam extinction level. A number of backgrounds from the radiative pion capture $N_{\rm RPC}$, for example, can be estimated by the following equation:

$$N_{\rm RPC} = N_p \cdot R_{\rm extinction} \cdot R_{\pi/p} \cdot P_{\pi-{\rm survive}} \cdot P_{\pi-{\rm stop}} \cdot P_{\rm RPC} \cdot P_\gamma \cdot R_{\rm acceptance}, \qquad (2.1)$$

where N_p is a number of protons, $R_{\rm extinction}$ is the beam extinction level, $R_{\pi/p}$ is a number of pions transport through the curved muon beam line per one proton hitting the production target, $P_{\rm RPC}$ is a probability of a gamma emission from a pion capture, $P_{\pi-{\rm survive}}$ is a survival probability in the decay solenoid that follows the curved muon beam line until the stopping target, $P_{\pi-{\rm stop}}$ is a stopping efficiency of pions in the stopping target, P_γ is a probability of photon conversion in an aluminum target with a conversion electron in a signal region from 104.0 MeV to 105.2 MeV, and $R_{\rm acceptance}$ is an signal acceptance without a timing-window factor. For the COMET to achieve the sensitivity of 10^{-16} with $N_{\rm RPC}$ = 0.1, the beam extinction level of 10^{-9} is required. A further sensitivity with sufficient background levels is impossible, unless at least one of the factor in Eq. 2.1 is improved.

The energy resolution of the conversion electrons is another limiting factor of the sensitivity. It is very important to distinguish the signal electrons from the background electrons coming from the muon decay in orbit of a muonic atom (DIO), because the energy spectrum of the electrons from DIO is approximately promotional to $(E_0 - E_e)^5$ near the endpoint, where E_0 and E_e are the energy of $\mu^- - e^-$ conversion electrons and that of DIO electrons respectively. The required resolution is 350 keV in σ for the sensitivity of 10^{-16}. Although the transfer solenoid before the stopping target is designed to select charge and momentum of particles in the beam, the muon beam in the MECO-type experiments has wide momentum spread. In order to stop the muons effectively, therefore, the

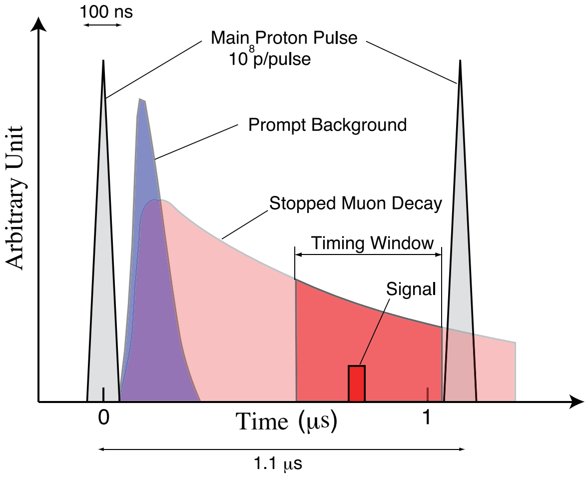

Figure 3: Timing structure of the proton beams and the signal/background electrons for the MECO-type experiments.

stopping target must be massive. The energy resolution of COMET would be σ = 350 keV, which is mainly dominated by effect of energy loss of outgoing electrons in the stopping target. A thiner stopping target is necessary to improve the sensitivity.

3. PRISM-type Experiment

For the next generation experiments with a further sensitivity, not only higher muon beam intensity and improved detecters but also better beam quality to attain the sufficient backgrounds elimination is indispensable. Required characteristics of muon beams are (a) high muon intensity of more than 10^{11}-$10^{12}\mu$/sec, (b) pulsed beam with good extinction between pulses so as to reject the beam-related background sources, (c) narrow energy spread, which allows us the use of thinner stopping targets to improve the energy resolution, and (d) less beam contamination, which is also crucial to eliminate the background sources.

We proposed a new experiment PRIME to search for the $\mu^- - e^-$ conversion in muonic atoms with a new super muon source named PRISM, which combines the beam characteristics listed above. The beam characteristics of (b), (c) and (d) are realized using a muon storage ring named PRISM-FFAG as a phase rotator, as shown in Fig.2. In the ring, muons with higher energy are decelerated while muons with lower energy are accelerated by high field gradient RF systems. It corresponds 1/4-synchrotoron oscillation. The muon momentum spread of 68MeV/c ± 20% would be reduced to ± 2% in several turns in the ring. Moreover, pions can not live such a long time ($\sim$1.5μs) in the ring. Since the momentum and charge are selected in the FFAG ring, the extracted muon beam from the ring would have no contamination by other particles. Let's consider N_{RPC} again. In this case, $P_{\pi-\mathrm{survive}}$ in Eq.2.1 can be reduced to 1.8×10^{-27} due to a long flight length in the storage ring. N_{RPC} is, therefore, negligible small. Most of other backgrounds would be suppressed significantly like this. The energy resolution of σ=250 keV would be obtained, since a mono-energetic muon beam enables us to use thiner stopping targets. Thus a sensitivity of 10^{-18} would be achieved resolving two limiting factors that we have in the MECO-type experiments.

4. Development of PRISM-FFAG

An R&D program for the PRISM-FFAG was started in 2003 to construct a full scale PRISM-FFAG ring and demonstrate the phase rotation. There are two key components to be developed for the PRISM-FFAG: FFAG magnets with a large aperture to accept as many muons as possible and an RF system to produce a high gradient field, which is indispensable for rapid phase rotation (see Fig.5). These components were developed successfully. As the final step of the program, a ring has been constructed, as shown in Fig.4, to study the longitudinal phase rotation. The demonstration will be carried out using an FFAG ring consisting of six PRISM-FFAG magnets and one RF system in JPY 2008 [5].

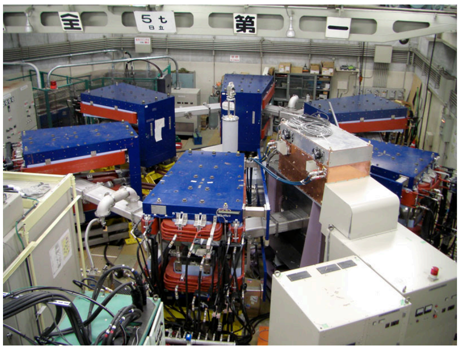

Figure 4: Six-sector FFAG ring at M-experimental hall of RCNP, Osaka University.

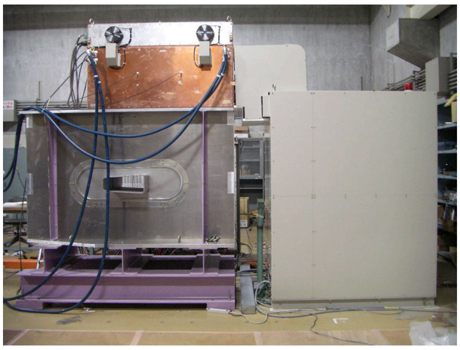

Figure 5: RF system of the ring showing which consists of an MA cavity, and an anode power supply.

5. Summary

The front-end of neutrino factories and/or a muon collider will provide an ultra intense muon beam. Using such muon beams the $\mu^- - e^-$ conversion searches should be carried out to reveal the nature of the new physics we will discover in the near future. The target sensitivity of such experiments will be below 10^{-18}. In order to achieve the high sensitivity, we should not persist the layout of the MECO-type experiments. The PRISM/PRISM experiment proposed one solution. We have still enough room and time to invent new ideas for future experiments.

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