Prospects for CLFV experiments

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Abstract. Understanding lepton-flavor violation in the charged lepton sector (Charged Lepton-Flavor Violation, CLFV) is a complementary approach to neutrino physics experiments in order to understand elementary particle behavior at high energy scale above TeV. A number of experiments are recently being conducted based on this perspective. They are expected to explore the physics beyond the Standard Model in a cooperative way with future neutrino experiments.

1. Introduction

As has been suggested by many theoretical models and proved by leading experiments, studying known particles with a great precision has a potential not only to test the Standard Model (SM) but also to find a clue to new physics beyond it. Neutrino experiments have actually played this role and will certainly keep their importance in future. Muon is also expected to take lead in this field thanks to its fruitful characteristics. The muon is in most cases produced as a decay product of a pion and decays to an electron and two neutrinos to conserve the lepton flavor. We can relatively easily produce muons in an accelerator and study precisely its properties by measuring the electron.

Neutrino oscillation, Lepton-Flavor Violation (LFV) in the neutral lepton sector, is now an established phenomenon by many experiments around the world; understanding details of the oscillation parameters is currently the most important subject as discussed in this workshop. In parallel to this, it is also important to understand the origin of neutrino mass, which is proved to be non-zero by finding oscillation of neutrinos between different flavors. One of the possibilities to explain the neutrino masses is the see-saw mechanism [1,2], in which the smallness of neutrino masses is naturally explained by large Majorana masses of their chiral partners (right-handed neutrinos). If these heavy neutrinos exist, they can contribute to enhance processes violating the lepton flavor in the charged lepton sector (Charged Lepton-Flavor Violation, CLFV) [2-4]. Because any kind of CLFV is strictly forbidden in the SM or extremely small even if we take into account the neutrino oscillation, observation of any CLFV processes would be a clear evidence of new physics, while improvements on existing limits would stringently constrain many of the new physics models beyond the SM.

2. Recent result from $\mu\rightarrow e\gamma$ search at PSI (MEG)

The MEG experiment at Paul Scherrer Institute is a precursor in CLFV search using muons. The experiment searches for the lepton-flavor-violating decay $\mu\rightarrow e\gamma$ which is forbidden within the SM of elementary particles. The experiment aims at exploring the decay mode with the world best sensitivity using the high intensity DC muon beam ($3\times10^7$ positive muons per second) provided at PSI, and innovative detector system composed of a positron spectrometer and a photon detector in search of back-to-back, monoenergetic, time coincident photons and positrons.
Recently the MEG experiment updated the result by combining data samples taken in 2009 and 2010. The statistics corresponds to $1.8 \times 10^{14}$ $\mu^+ \rightarrow e^+ \gamma$ decays. A likelihood analysis method was adopted with a blind procedure on examining the data. The probability density functions (PDFs) needed for the likelihood analysis were constructed using the real event data outside of the blind region. Details of detector performance and data analysis were presented in a separated presentation in this workshop [5]. They successfully obtained a 90% C.L. upper limit of $2.4 \times 10^{-12}$ on the branching ratio of the $\mu^+ \rightarrow e^+ \gamma$ decay [6]. This gives the most stringent limit on the existence of this decay mode as present.

The result described above is not limited by the background yet, but by data statistics; they plan to increase statistics by continuing data acquisition in 2011 and 2012. Detector upgrade plan is also considered to further improve the sensitivity of the experiment.

3. Future experiments

There are a couple of experiments planned in the world with better sensitivities than the MEG experiment. The current best limit on the $\mu$-$e$ conversion is set to be $7 \times 10^{-13}$ by the SINDRUM II experiment [7]. Two major experiments are in the planning phase to improve the physics sensitivity by more than an order of magnitude compared to the MEG experiment. They use the $\mu$-$e$ conversion process for this purpose. One is the Mu2e experiment at FNAL in the U.S. and the other is the COMET experiment at J-PARC in Japan. Both experiments set their goal of the branching ratio sensitivity at $10^{-16}$, starting physics data acquisition around 2018.

3.1. $\mu$-$e$ conversion search experiments

An advantage of the $\mu$-$e$ conversion search experiment over the $\mu \rightarrow e\gamma$ search comes from the fact that the pulsed muon beam with high intensity can be used in the $\mu$-$e$ conversion search. This is simply because the $\mu$-$e$ conversion signal is characterized by only one energetic electron emerging from muonic atoms. The energy of the signal electron will be as large as the muon mass with a reduction corresponding to the binding energy of a muon in a muonic atom. This is 105 MeV for the case of aluminum used as a muon stopping target material. A possible background to the signal would come from decay-in-orbit electrons, which can extend to the signal region although its spectrum rapidly decreases in proportion to $E^{-5}$; the background can be suppressed sufficiently below the sensitivity with reasonable electron spectrometer resolution. Thus there is a lot of room for improvement in the physics sensitivity for CLFV in the $\mu$-$e$ conversion search. It should be also pointed out that the $\mu$-$e$ conversion can be induced not only by photon exchange but also by other particle exchanges. In the former case the $\mu$-$e$ conversion will generally have a branching ratio smaller by a factor of $\alpha$ compared to the branching ratio of the $\mu \rightarrow e\gamma$ decay, while in the latter case the $\mu$-$e$ conversion can be enhanced by an exchange of other particles than a photon. This means that measuring the $\mu$-$e$ conversion branching ratio with a similar sensitivity to that for the $\mu \rightarrow e\gamma$ decay is quite important to understand the physics behind them.

The muon beam used for the $\mu$-$e$ conversion search is required to have a width between two consecutive pulses as large as the life of muons in muonic atom (0.88 $\mu$sec for aluminum). The width of the pulse itself is required to be small enough compared to this scale in order to reject prompt background. This prompt background is dominated by pions that can enter and flash the detector. The detector electronics will be switched off during this flash and invoked after a few hundred nsec to measure electrons from muonic atoms. As long as the $\mu$-$e$ conversion search experiment employs this scheme, another requirement on the beam structure must be met; leakage of protons from pulses to between pulses needs to be minimized. The degree is call “beam extinction”, which is defined as a ratio of the number of protons in between pulses to the number of protons in a pulse. In either of the Mu2e or COMET experiments, the extinction level needs to be suppressed well below $10^{-9}$ to $10^{-10}$.

The Mu2e experiment uses proton beam provided at the FNAL accelerator facility. The proton beam accelerated to 8GeV is sent to a storage ring to shape the beam pulse structure to satisfy the
requirement of the experiment. Then the beam is transferred to another ring before being extracted and transferred to the experiment. Figure 1 shows a set up of the Mu2e experiment. A pion production target is located in a solenoid magnet with gradient magnetic field to efficiently collect pions that decay to muons. These muons are transported through an S-shape curved solenoid; charge and momentum selections are performed during transportation by utilizing characteristics of beam optics in a curved solenoid. A muon stopping target composed of aluminum disks is located near the entrance of the spectrometer magnet. Muonic atoms are formed when muons are stopped in the target. Most of muons decay in the orbit or are captured by nucleus, emitting neutrinos in the final state to conserve the lepton flavor. However, if the $\mu$-e conversion occurs, an energetic electron of 105 MeV will be emitted from the muonic atom. The detector located inside the spectrometer magnet will measure the electron momentum and energy to identify the signal. Design of the experiment is in progress with intensive R&D work. The Mu2e plans to start physics data acquisition in 2018 by using proton beam of 20kW. Target sensitivity of the experiment is $6 \times 10^{-17}$ as 90% C.L. upper limit. Details of the experiment are presented in [8] in this workshop.

The COMET planned at J-PARC is a competing experiment to the Mu2e experiment. They also plan to achieve a sensitivity of $6 \times 10^{-17}$ as 90% C.L. upper limit. The COMET experiment uses proton beam of 8 GeV provided at J-PARC. The anticipated beam power is 50kW accelerated in the main ring of the J-PARC. The beam is extracted directly from the ring using the slow extraction technique and transported to the experiment. A pion production target is located in a solenoid magnet with gradient magnetic field. Pions decay to muons during transportation through a C-shape curved solenoid; and muons are finally stopped in a muon stopping target as shown in Figure 2. The C-shape curved solenoid has larger separation power of momentum than the S-shape curved solenoid, but compensating vertical magnetic field is required simultaneously because the center of the muon beam trajectory will drift upward or downward depending on the field direction. This makes the magnet design complicated although this can be realized by tiling the coil winding in the curved section by a proper angle. Another C-shape magnet is connected to the target solenoid to perform momentum selection of electrons emitted from the muon stopping target. A spectrometer magnet containing an electron tracker and calorimeter to identify the signal electron ends the magnet chain. The COMET experiment also plans to start physics data acquisition in 2018 after an engineering run in 2017.

Intensive R&D work is in progress also in the COMET experiment. Development of superconducting wire tolerable in high radiation environment is conducted in collaboration with a wire
manufacturer in Japan. Coil winding technique is also investigated by producing sample coils. These activities are summarized in presentations given in this workshop [10].

The COMET experiment successfully conducted the 1st beam extinction measurement using extracted bsm in 2010 and obtained a preliminary result of \((5.6\pm0.7) \times 10^{-7}\). In their careful analysis beam particle leakage corresponding to this extinction is attributed to pulse-forming inefficiency before acceleration and can be improved by modifying the injection scheme of protons from the booster ring to the main ring. A preliminary evaluation shows that improvement of \(10^{-6}\) will be achieved with this new injection scheme that will enable them to achieve the required extinction level. This has to be confirmed after the J-PARC operation is restarted in 2012. The status of the experiment was presented and summarized concisely in [11].

3.2. Other future CLFV experiments

There are more CLFV experiments using muons are planned. One of them is the DeeMe experiment at J-PARC. The experiment plans to use the pion production target also as a muon stopping target. They have actually found by measuring electron energy spectrum with delayed timing that huge amount of muonic atoms are certainly formed in the pion production target. An electron spectrometer with kicker magnets will be constructed to sweep prompt background efficiently. A single event sensitivity of \(2\times 10^{-14}\) is anticipated using a SiC target. Details of the experiment were presented in a separate presentation in this workshop [12].

Another effort in search of CLFV is being considered at PSI using a different decay mode of muons. The experiment intends to search for the decay \(\mu^+\rightarrow e^+e^+e^-\) using the surface muon beam provided at PSI. Detector concept using silicon trackers with a solenoid magnet is presented in this workshop [13] in order to improve the sensitivity on the branching ratio beyond the current best limit of \(1.0\times 10^{-12}\) obtained by the SINDRUM experiment [14].

4. Summary

Prospects of CLFV experiments are summarized in this article. The MEG experiment at PSI is leading in this field and expected to provide fruitful result soon. Detector upgrade plan is considered to further improve the physics sensitivity of the experiment. There are a number of activities trying to search for CLFV. These experiments plan to utilize high-intensity proton machines to go beyond the MEG sensitivity by using large amount of muon samples. They will certainly play a key role to understand the physics of neutrino oscillation from a different point of view.

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