Search for Lepton Flavour Violation, muon decay experiments

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Abstract

Search for Lepton Flavour Violation (LFV) has a long history since the discovery of the muon. Since then plenty of experimental efforts have been made and recently it has become a very excited field which is motivated by the discovery of the atmospheric neutrino oscillation, that is, a LFV phenomena in the neutral lepton sector. In this talk experiments searching for LFV processes using muon beams are introduced.

1. Introduction

1.1. Supersymmetric Grand Unified Theory

LFV processes are specially sensitive to the supersymmetric(SUSY) extension of the standard model, in particular supersymmetric grand unified theories (SUSY-GUT). In SUSY-GUT, finite slepton mixing appears through radiative corrections in the renormalization group evolution from the GUT scale to the weak energy scale, even if the slepton mass matrix is assumed to be diagonal at the Plank scale[1]. Recently, it was pointed out that the slepton mixing thus generated can be very large owing to the heavy top-quark mass[2], thereby enhancing $\mu \to e\gamma$ decay and μ-e conversion through loop diagrams. For example the predicted branching ratio of $\mu \to e\gamma$ in SUSY SU(5) models ranges from 10^{-15} to 10^{-13} for the smuon mass of 100 to 300 GeV. The SO(10) SUSY-GUT model predict an even larger value of 10^{-13} to 10^{-11}.

1.2. Connection with the Neutrino Oscillations

There have been growing evidences for the solar neutrino deficit [3, 4], which is most likely to be explained by the neutrino oscillation. Super Kamiokande has finally discovered the atmospheric neutrino oscillation[5], thereby making a breakthrough in the particle physics. The neutrino oscillation implies both non-zero neutrino masses and LFV. In SUSY models, these neutrino mixing is expected to enhance the rate of LFV processes such as $\mu \rightarrow e\gamma$ decay and μ-e conversion [6].

2. Previous Experiments

In this section, two experiments which have placed the best limits on $\mu^+ \rightarrow e^+\gamma$ and μ-e conversion processes are presented.

2.1. MEGA at LAMPF

The MEGA experiment used muons provided by a surface muon beam at the stopped muon channel at the Los Alamos Meson Physics Facility (LAMPF) for $\mu^+ \rightarrow e^+\gamma$ decay search. Muons were provided with a rate of 2.5×10^8/sec in a pulsed mode with a duty factor of 6%. 1.2×10^{14} muons were stopped on the target located at the center of a superconducting solenoidal magnet. Momentum of positrons from stopped muons were measured by a set of high-rate cylindrical multiwire-proportional chambers (MWPC) around the target. Photons were detected by one of three cylindrical pair spectrometers each of which consists of Pb conversion foils, a scintillation barrel and MWPC. The data for this experiment had been taken in three years, 1993-95. The full data set is based on 1.2×10^{14} muon stops collected over 8×10^6 sec live time. Since there was no excess in the positron and photon energy spectra, they could set the limit on Br($\mu^+ \rightarrow e^+\gamma$) of 1.2×10^{-11} with 90% confidence level[7].

2.2. SINDRUM II at PSI

SINDRUM II is searching for coherent μ-e conversion in muonic atoms at Paul Scherrer Institut (PSI) using Ti, Pb, and Au targets. The SINDRUM II spectrometer consists of a set of concentric cylindrical detectors. Muons entering the setup axially are stopped on the target at the center of the spectrometer after traversing a moderator and a plastic beam counter. The target consists of continuously arranged rectangular foils surrounded by drift chambers, scintillator hodoscopes, and Cerenkov hodoscopes. In 1992 they took data during the period of 10 days with an average beam rate of 10^7 muons/sec, corresponding to 2.1×10^{12} muon stops in a lead target. In 1989 and 1993 data taking was performed by stopping muons on a titanium target, amounting to 5×10^{12} and 3×10^{13} stops respectively. Since no evidence for μ-e conversion was found in any channel after event selections, upper limits of 4.6×10^{11}[8] for lead and 6.1×10^{13} for titanium[9] have been placed with 90% confidence level. SINDRUM II took data using a Ti target also in 1999 and the analysis is in progress.

3. Future Experiments

Two new experiments are now in preparation at Brookhaven National Laboratory (BNL) and PSI using intense muon beams.

3.1. MECO at BNL

MECO looks for the process of μ-e conversion using extremely pure, extremely intense beam of muons(10^{11}/sec) which will be realised by recent advantage in proton beam intensity available at BNL AGS. MECO plans to search for the process which violates lepton flavour at the level of 10^{-16}. Following three things are required to reach this goal: (1) create an intense muon beam, (2) filter the beam of all unwanted background generating particles, and (3) detect the final state electron with high precision. They plans to realise these things using three superconducting magnets, the production solenoid which corrects produced muons with large acceptance, the transporting solenoid which has an "S" curved shape to filter out unwanted and high energy particles from the muon beam, and the detector solenoid which is used to measure electron momentum with a straw and scintillating fiber tracking system to within a several hundred keV. The detector solenoid employs the adiabatically graded field shape, at the upstream end at 2 Tesla and reduced to 1 Tesla in the detector, thereby the detector acceptance is increased. The experiment plans to start data taking early in the next century.

3.2. $\mu \rightarrow e\gamma$ Search at PSI

This experiment is aiming to search for $\mu^+ \rightarrow e^+\gamma$ decays with a sensitivity down to 10^{-14}[10]. Muons for the experiment are provided by the surface muon beam at the ring cyclotron at PSI.

A schematic view of the setup is shown in Figure1.. Muons from the beam line will be stopped on the target located at the center of the superconducting magnet. Around the target, a tracking drift chamber and arrays of scintillator are installed inside the magnet and are used to measure the momentum and arrival time of positrons. Outside the magnet, a new type of a photon detector will be placed to measure the photon energy, arrival time, and interaction positions.

The experiment aims to improve the sensitivity by using (1) continuous beam to reduce accidental overlap of events even with high beam rate, (2) a Constant-Bending-Radius (COBRA) spectrometer to measure positron momentum, and (3) a liquid Xe scintillation detector for photon detection.

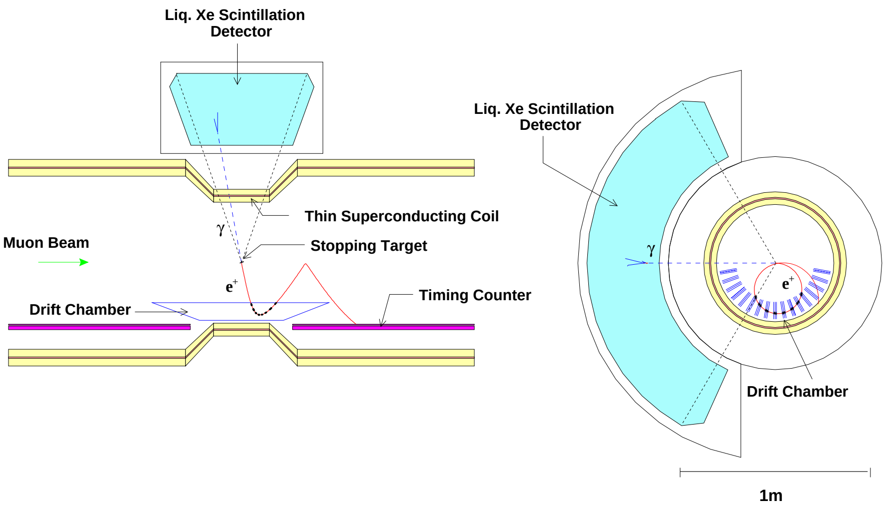

Fig. 1. Schematic view of the $\mu \rightarrow e\gamma$ detector

Muon beam utilizes surface muons produced at the production target on the primary proton beam line. The intensity of muons at the beam line reaches 10^9 muons/sec. According to the simulation, 10^8 muons/sec are expected to be delivered with a beam spot size of 5-mm on the stopping target.

The superconducting magnet shown in Figure 2. has a feature that magnetic field around the center is weaker than that of the outer sides with keeping the total magnetic flux. Therefore low momentum positrons from Michel decays of muons can be rapidly swept out as shown in Figure 2.(a), thus unwanted curling tracks of low momentum positrons do not remain in the effective area of the drift chambers. Besides thanks to its field shape, radii of charged tracks from the target have an unique value for given momentum independent of its emission angle, that is, it is possible to measure total momentum only by measuring the radius of the track as shown in Figure 2.(b).

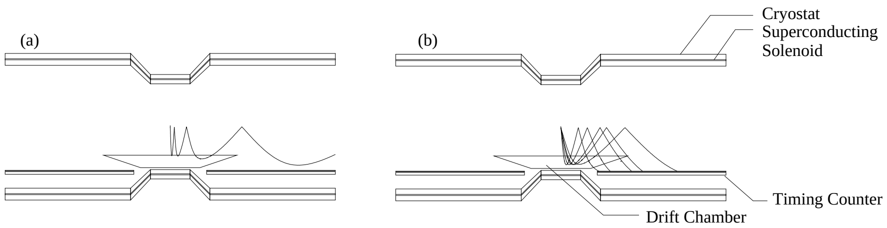

Fig. 2. COBRA spectrometer. (a) Low momentum particles are swept away rapidly. (b) Radii of charged tracks has an unique value independent of their emission angle.

For photon detection a new detector is in preparation which uses liquid

Xe as a scintillation material because of its fast response, large light output yield, and high density. Scintillation light from liquid Xe is read out by photomultipliers (PMT) located inside the liquid in order not to loose light yield by installing any transmission window. The PMT has been newly developed so that it can be operated at 165K in liquid Xe. The active volume of the detector is viewed by PMTs from all sides. Total deposited energy and interaction position will be measured by the sum and spatial distribution of PMT outputs. Timing resolution of the detector is expected to be excellent because of fast rise time and large yield of scintillation light.

To study the detector response to real photons, a prototype has been constructed and tested with gamma-ray sources of 320 keV to 1835 keV. The active volume of the prototype is 2.34-liters which is viewed by 32 PMTs from all sides. Long term operation has been very successful and detector resolutions were evaluated for gamma-ray source energies. Figure 3. shows the results for energy and position resolutions. Extrapolating these curves to higher energy suggests that it is feasible to achieve energy and position resolutions of 0.7% and better than 2-mm at 52.8 MeV. As for the timing resolution, results obtained with the prototype shows that it is probable to achieve the resolution of better than 50 psec for 52.8 MeV photons.

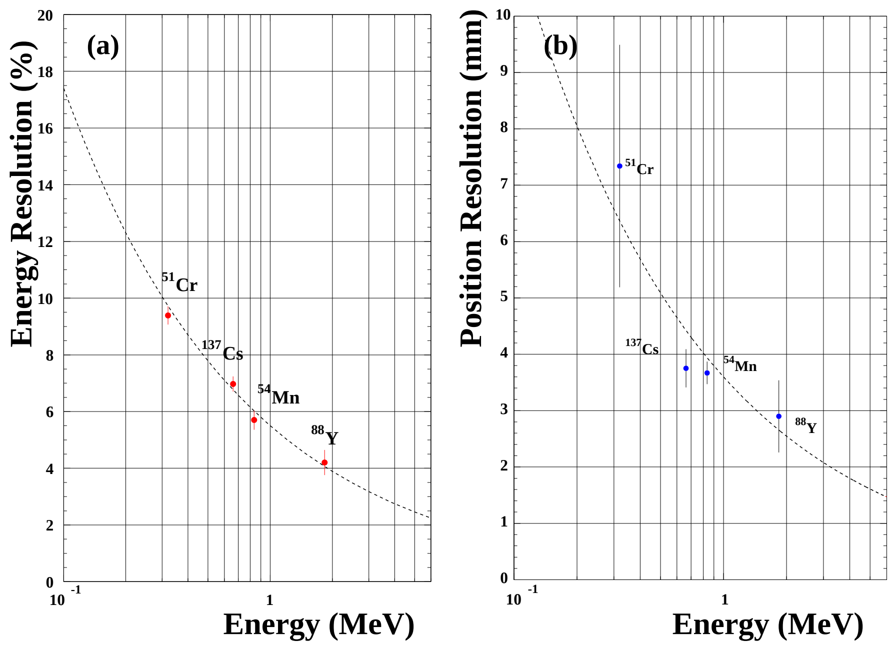

Fig. 3. Energy(a) and position(b) resolutions obtained with the prototype.

Expected sensitivity and background have been estimated with Monte Carlo simulation. Taking into account available muon intensity of 10^8/sec, running time of 2.2×10^7sec, acceptance of 9%, detection efficiencies of 95% for positrons and 70% for photons, and selection efficiency of 80%, the single event sensitivity is calculated as 0.94×10^{-14}. As for background, there are two major sources from radiative muon decay, $\mu^+ \to e^+\nu\overline{\nu}\gamma$, and accidental overlap of a high energy positron from the tail of Michel decays and a high energy photon from radiative muon decays or annihilation in flight of positrons. These rates are estimated to be reduced down to the 10^{-15} level, therefore the experiment is possible to keep the background free condition down to the 10^{-14} level. The experiment will start data taking in 2003 after further development of detectors.

4. Summary

There are strong physics motivations to search for LFV processes. Searches using muons is one of the most powerful tools to reveal the new physics beyond the standard model. Two new experiments are in preparation using intense muon beams at BNL and PSI. They are starting data acquisition early in the next century with improvement of their sensitivity by 2 orders over current world limits.

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