LEPTON FLAVOR VIOLATION IN RARE MUON DECAYS: AN EXPERIMENTAL REVIEW

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Lepton Flavor Violation in muon decays is gaining more and more interest as a sensitive probe for Supersymmetry. The current status of the experimental search for lepton flavor violation in rare muon decays is reviewed, with emphasis laid on $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^+$ decays and $\mu^- \to e^-$ scattering. Future perspectives are examined, as well as the impact of an increased muon source intensity on the experimental sensitivity to the above LFV channels.

1 Theoretical motivation

In the Standard Model (SM), Lepton Flavour is conserved as long as neutrino fields are massless. Extensions of the SM to include massive Dirac neutrinos, so as to explain neutrino oscillations, give rise to Lepton Flavour Violation (LFV from now on). The resulting branching ratios depend on neutrino masses involved, but they are so tiny ($10^{-45} \div 10^{-55}$) to be ever observed.

On the other hand, LFV is predicted at much higher rates by a wide class of Grand-Unified, Supersymmetric theories (often referred to as Gravitation-mediated SUSY), as a result of a finite mixing in the slepton sector. For instance, $\mu^+ \to e^+\gamma$ decay should occur, apart from accidental cancellations, with a branching ratio (BR) above 10^{-14}, as shown in Fig. 1[a]. LFV processes are therefore not contaminated by the background of any simple extension of the Standard Model and constitute unambiguous signals of new physics beyond the Standard Model.

[a] Even larger rates are predicted by theories based on symmetry groups other than SU(5); in SO(10), for instance, BR($\mu^+ \to e^+\gamma$) is enhanced by two orders of magnitude about, induced by loop diagrams whose amplitude is proportional to the τ mass.

LFV mainly arises through radiative corrections due the heavy top quark mass[1] and these predictions depend both on the symmetry group and on the parameters of the theory. Even within a selected model the expected BRs span more than 3 orders of magnitude depending on the model parameters. Generally, in SUSY-GUT the relative amplitudes of the three processes are more stable and the branching ratios of muon decays, such as $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^-e^+$ and $\mu^- \to e^-$ conversion in nuclei, are expected to be

$$\frac{B(\mu^+ \to e^+e^-e^+)}{B(\mu^+ \to e^+\gamma)} \approx 10^{-2}$$
$$\frac{B(\mu^- \to e^-)}{B(\mu^+ \to e^+\gamma)} \approx 10^{-2} \qquad (1)$$

for $\mu^- \to e^-$ conversion on high Z targets.

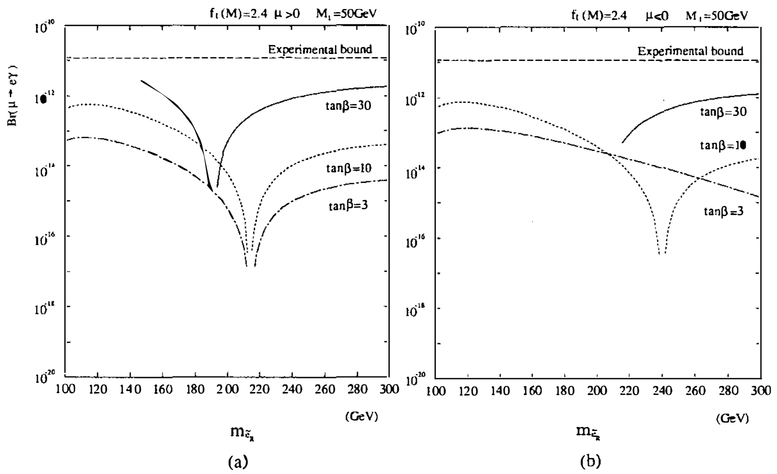

Figure 1: Predictions for BR($\mu^+ \to e^+\gamma$) in the minimal SU(5) SUSY model. Also shown is the current experimental limit set by the MEGA experiment. Values of $\tan\beta < 3$ were excluded at 95% C.L. by recent analyses of LEP data.

It has been pointed out that an additional contribution to LFV is associated with neutrino oscillations via the see-saw mechanism induced by heavy right-handed Majorana neutrinos, which is invoked to explain the extremely small neutrino masses[2]. A possible contribution to the slepton mixing between $\tilde{\mu}$ and $\tilde{e}$ comes from V_{21}, the neutrino mixing matrix element to account for solar neutrino deficit[3]. With this mixing parameter confined to the MSW large mixing angle (LMA) solution and right-handed neutrino mass scale above 10^{12} GeV, the BR for $\mu^+ \to e^+\gamma$ is predicted to be larger than 10^{-13}.

In conclusion, LFV in the charged sector, including $\tau \to \mu\gamma$, as well as new measurements of $g_\mu - 2$ and μ-EDM, have solid theoretical motivations. Moreover, the predicted BRs are not far from present experimental upper limits.

It should be emphasized that experimental searches in all channels should be pursued. The comparison of different channels provides, even in the presence of a single positive results, a powerful tool to discriminate among the various grand unification models.

2 Why to use muons?

Muon beams provide the most powerfool tool to search for LFV. High beam intensity is mandatory to search for rare events. In fact, fully polarized muons are copiously produced at meson factories from decays of pions obtained by hitting a target by low momentum protons ($E_p < 1\text{GeV}$). Available beams, like those at PSI, TRIUMF and RAL, can reach an average intensity of the order of $10^7 \div 10^8 \mu/\text{s}$.

Future projects in LFV search plan to improve their sensitivity by using even more intense muon beams. One possibility is to use muon storage rings, which are currently being considered as options for future machines hosted in international laboratories. The primary aim of these machines is the study of neutrino properties, but they are also an ideal place to study muon properties, since they could provide muon fluxes larger than current beams by 4 order of magnitude and with a large choice of momentum. Apart from rare decays, other searches could be operated, like the determination of the muon anomalous magnetic moment and the electric dipole moment, which may provide hints for new physics beyond the Standard Model. A more complete review of future muon beams and their use in searches for new physics can be found in [4].

3 History of LFV muon decays

Searches for LFV processes have a long history reaching back 1947, when a first attempt was operated by Pontecorvo[5] without a muon beam available yet[b].

During the last 25 years, the experimental sensitivity was raised by two order of magnitudes per decade, as shown in Fig.2. These searches were sometimes limited by the detector itself, but often by the muon beam intensity. In this paper we discuss the possible benefits that the experimental searches could obtain from muon beams with intensities improved by 2 or 3 orders of magnitude with respect to those currently available.

4 The $\mu^+ \to e^+e^-e^+$ process

4.1 Event signature and background

This channel differs from Michel decay as the final state consists of charged particles. The event selection relies on kinematical criteria: the three final particles are required to have the muon invariant mass, null total momentum (muons decay at rest in the lab frame), a common vertex and the same emission time. The detetion concept is therefore based on a tracking system sensitive to the whole momentum spectrum of the decay products, which extends down to low energy.

This signature can be mimicked by the internal conversion of radiative muon decays, $\mu^+ \to e^+e^-e^+\overline{\nu}_\mu\nu_e$, which is the source of the so-called "correlated" background, or by the accidental coincidence of a Michel positron with a e^+e^- pair originated by the Bhabha scattering of another Michel positron, which is often referred to as "uncorrelated" background. It is worth noting that the correlated background is linear with the muon stop rate in the target, while the uncorrelated one depends quadratically.

[b] Even if the limit obtained ($BR < 10\%$) is too loose if compared with more recent searches, it used to be low enough to safely exclude $\mu^+ \to e^+\gamma$ as the dominant branch in muon decay. Just one year after, Steinberger[6] measured the continuous electron spectrum, which lead to formulate the hypothesis of two neutrinos in the final state.

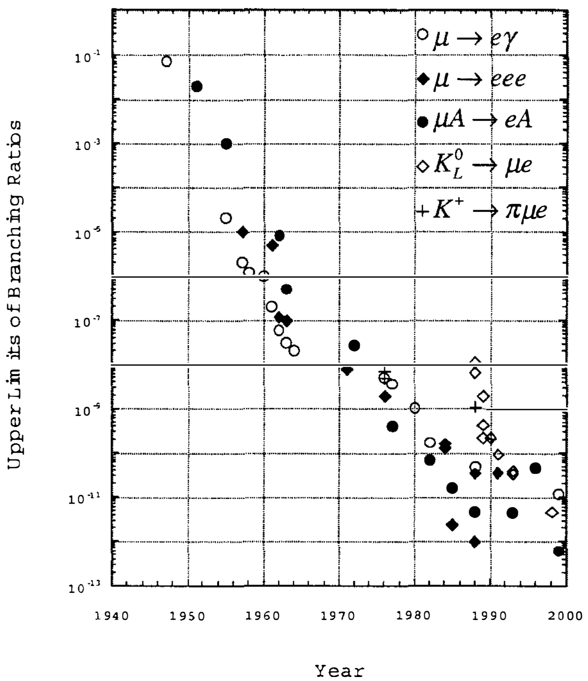

Figure 2: Historical progress in LFV searches involving muons and kaons since 1947.

4.2 The latest result

The present experimental limit on the $\mu^+ \to e^+e^-e^+$ decay branching ratio [7] is $B < 1 \times 10^{-12}$ at 90% C.L., obtained by the SINDRUM experiment[8] in 1988. No other experimental searches for $\mu^+ \to e^+e^-e^+$ have been proposed later on, so the SINDRUM experiment has to be taken as a reference.

The SINDRUM detector used to be a solenoidal spectrometer equipped with MWPCs concentric with the beam axis. Three dimensional hit positions used to be determined by means of cathode strips oriented at $\pm 45°$ relative to the sense wires. The angular acceptance used to be 24% of 4π with a momentum resolution $\sim$ 10%. A continuous muon beam with 25 MeV/c momentum used to be stopped on a low mass target,2.4g, with a surface density of 11 mg/cm^2, at a rate of 6 $\times$ 10^6 μ^+/s. Table 1 lists the SINDRUM detector parameters.

The data sample collected by SINDRUM is background free in the sense that the background equivalent branching ratio was $B_{unc} \sim 10^{-13}$ for a beam intensity of 0.6 $\times$ 10^7 μ^+/s.

A future new proposal should aim at a single–event sensitivity of the order of 10^{-16} and therefore it would require a beam of $10^{10}\mu^+$/s. At this stop rate the backgrounds would raise up to $B_{cor} \sim 10^{-10}$ and $B_{unc} \sim 10^{-7}$ respectively for the correlated and uncorrelated components. The quadratic dependence of the uncorrelated background on the muon stop rate would require, even in the optimistic assumption, substantial detector improvements. To reach the stated sensitivity a background suppression by ≈ 9 orders of magnitude has to be obtained, which is

Table 1: Summary of the SINDRUM detector performances relevant for the $\mu^+ \to e^+e^-e^+$ decay search.

Parameter	SINDRUM
stop rate	0.6×10^7 μ^+/s
muon momentum	25 MeV/c
magnetic field	0.33 T
ang. acceptance	24%
momentum resolution	10%FWHM
vertex resolution	≈ 2 mm^2
timing resolution	≈ 1 ns
target length	220 mm
target surface density	11 mg/cm^2

very unlikely to be achieved, even with improved our-days experimental techniques.

5 The $\mu^+ \to e^+\gamma$ process

5.1 Signal and background

The signature for these events is based on the simple kinematics of a two-body decay. In this case it requires the coincidence of monochromatic photon and positron, with $E_e = E_\gamma = 52.8$MeV, emitted back-to-back in the lab frame where the muon is stopped before decaying. Hence the optimization of the detector resolutions requires different sub-detectors for the photon and the positron, resulting in a more elaborated layout with respect to the $\mu^+ \to e^+e^-e^+$ case.

Similarly to $\mu^+ \to e^+e^-e^+$ case, this signature is affected by two types of background: a correlated background, associated with radiative muon decays ($\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$), and the uncorrelated background, due to the accidental pile-up of a positron (with an energy close to the end-point of Michel spectrum) and a high energy photon (which might originate either from radiative muon decay or from positron annihilation-in-flight). Again, the rate of uncorrelated background depends quadratically on the muon decay rate, so it becomes dominant at increasing beam intensity. It also depends on detector performances according to the following formula:

$$B_{unc} \propto R_\mu^2 \cdot \Delta E_e \cdot \Delta t_{e\gamma} \cdot (\Delta E_\gamma)^2 \cdot (\Delta\theta_{e\gamma})^2 \qquad (2)$$

So an increased muon stop rate, which is envisaged to improve the statistics, must be accompanied by improvements in detection techniques (in particular for what concerns the photon) so as to keep the background at an acceptable rate.

5.2 The present: the MEG experiment

The present experimental limit on the $\mu^+ \to e^+\gamma$ decay branching ratio[9] is $B < 1.2 \times 10^{-11}$ at 90% C.L., obtained by the MEGA experiment in 1998.

The MEG collaboration is presently building a new detector to search for $\mu^+ \to e^+\gamma$ decay with a sensitivity of $\sim 5 \times 10^{-14}$. The experiment is planned to start in 2006, and it is expected to be completed in 2008, before the start-up of LHC experiments. The experiment[10] will be operated at the Paul Scherrer Institut (PSI) laboratory, Switzerland, using the πe5 beam line, the most intense continuous muon beam available so far.

A schematic view of the MEG detector layout is shown in fig. 3. The positive muon beam is brought to stop in a thin target after passing a stage in which most of the contaminating positrons are eliminated. Depending on the resolution achieved with the final detector, the

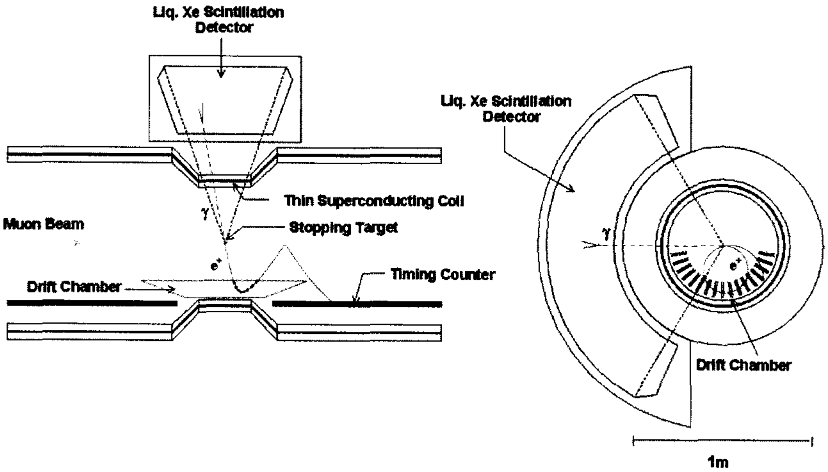

Figure 3: A schematic view of the MEG detector layout along a longitudinal section and a transverse one.

beam intensity will be tuned in order to optimize the signal/background ratio. The beam line could deliver a muon flux up to $2 \times 10^8 \mu^+/s$ on $\sim$ 0.5cm radius spot.

The momentum and the direction of the e^+ and the decay vertex are measured by a magnetic spectrometer, composed of a quasi-solenoidal magnetic field and a set of ultra-thin drift chambers. The field has an axial gradient in order to sweep low longitudinal momentum e^+s out of the tracking volume, so as to reduce the chamber occupancy. The gradient is shaped so that monochromatic e^+s from the target follow trajectories with constant projected bending radius, independent of the emission angle over a wide angular range. Both features greatly reduce the accidental pile-up of Michel e^+, decrease the pattern recognition problems and enhance the system efficiency. Simulation shows the expected FWHM resolution ranges between 0.7 and 0.9% for the positron momentum and from 9 to 12 mrad for the angle. An array of plastic scintillators is placed on each side of the spectrometer to measure the e^+ emission time with a FWHM resolutions of 0.1ns.

While all e^+ are confined inside the magnet, the γ-rays penetrate through the thin superconducting coil of the spectrometer ($\simeq$ 80% transmission probability) and are detected by a liquid Xenon scintillation calorimeter. It consists of a single volume of liquid Xenon viewed from all sides by about 800 photomultipliers (PMT). All the kinematical variables of the impinging photons can be reconstructed from the PMT signals only. Tests on a large scale prototype, as well as a full simulation, show that one can expect FWHM resolutions of 4% for the energy, 10.5 mm for the position of the γ interaction point and 0.1 ns for the timing measurements for 52.8MeVγ-rays. The expected detector performances are summarized in Table 2. The expected

Table 2: Expected MEG detector performances. Detector resolutions are quoted as FWHM.

Stop rate	$0.3 \cdot 10^8 \mu^+/s$
muon momentum	28MeV/c
ang. acceptance	9%
e^+ momentum resolution	0.8%
γ energy resolution	4%
e^+–γ alignment	19 mrad
timing resolution	0.15 ns

correlated background can be evaluated by numerical integration over the selection region, chosen at 1.4 FWHM for each selection variable. This background is expected to contribute with $\approx 3.1 \times 10^{-15}$ events per muon decay, with the resolution values shown in Table 2. With the same selection applied, the uncorrelated background is expected to be $B_{unc} \approx 3 \times 10^{-14}$ events per muon decay, for a muon stop rate $R_\mu = 0.3 \times 10^8$ μ^+/s. As in the case of $\mu^+ \to e^+e^-e^+$, rejection of uncorrelated background represent the bottleneck for this search.

6 The $\mu^- \to e^-$ conversion process

6.1 Signal and background

When μ^- are brought at rest in matter, muonic atoms in the ground state are quickly formed. These atoms unndergo either muon decay in orbit (MDIO) $\mu^-(A,Z) \to e^+\nu_\mu\overline{\nu}_e(A,Z)$ or nuclear muon capture (MC) $\mu^-(A,Z) \to \nu_\mu(A,Z-1)$. The amplitude of the latter decay mode increases with the atomic number, thus reducing the muonic atom lifetime to less than 100 ns for atoms heavier than Lead.

However, if Lepton Flavour is violated at some extent, the exotic process of neutrinoless muon capture (which we will refer to as muon conversion and indicate $\mu^- \to e^-$) might occur in the nuclear field with a branching ratio depending, within 1 order of magnitude, on the atomic number Z. This coherent conversion, occurring when the recoiling nucleus remains in the ground state, is expected to be enhanced and the emitted electrons have the MDIO-decay end–point energy. The signature is a single monochromatic electron emerging from the target with an energy of $E_e = m_\mu - B_\mu$, where m_μ is the muon mass and B_μ is the binding energy of the muonic atom. Since the latter is different for various nuclei, the signal energy changes (for instance, it is $E_e = 104.3$MeV for Titanium and $E_e = 94.9$MeV for Lead).

With only one detectable particle in the final state, this process is not affected by uncorrelated background, which is instead the main source of background in the previous two LFV processes. Electrons in the signal energy window may originate from MDIO or from radiative muon capture (RMC, $\mu^-N \to \nu_\mu\gamma$ N*), often called muon-decay related background. The radiative pion capture (RPC, $\pi^-N \to \nu_\mu\gamma$ X) and the beam contamination by electrons are examples of beam-related background. The first background class can be reduced mainly by improving the detector resolution, while the second one might be suppressed by improving the beam purity.

As this physical background increases only linearly with the muon stopping rate, $\mu^- \to e^-$ conversion provides the most promising tool for future LFV searches.

6.2 Present status and future perspectives

The current limits on $\mu^- \to e^-$ conversion on different materials were obtained by the SINDRUM-II experiment operated in different configurations: $B(\mu^- \to e^-\text{onTi}) < 1.7 \times 10^{-12}$ at 90% C.L. [11] $B(\mu^- \to e^-\text{onAu}) < 3 \times 10^{-13}$ at 90% C.L. [12]. The electron momentum spectra, measured by the SINDRUM-II detector during the $\mu^- \to e^-$ conversion search on Gold, is shown in fig. 4 for three different beam configurations.

The MECO project at BNL[13] has been proposed for a search of $\mu^- \to e^-$ conversion with a single event sensitivity of 2×10^{-17}. This would correspond to a 4-order of magnitude improvements of the SINDRUM-II result. The project requires a high intensity muon beam ($10^{11}\mu^-$/s), operated in pulsed mode. A curved superconducting solenoid is used to to select the muon momentum and to reduce the beam contamination. Muons are stopped in a series of thin targets and the e$^-$ momentum is measured with a resolution of 900 keV/c, dominated by the multiple scattering in the target. A schematic drawing of the MECO project is presented in fig. 5. The primary proton beam has to be operated in a pulsed mode with a challenging extinction factor of

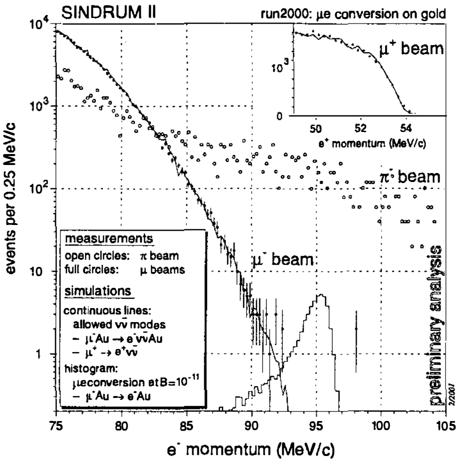

Figure 4: The electron momentum spectra measured with: μ^+ to measure the detector resolution, π^- to evaluate the RPC background and μ^- for the $\mu^- \to e^-$ search. Data were collected with different lifetimes. The expected momentum distribution for signal events is also shown.

10^9 between the beam off and the beam on periods. The $\mu^- \to e^-$ conversion can be searched for only during the beam off periods to ensure the adequate beam related background suppression. The MECO experiment is planned to start data taking in 2009.

Letters of intents for an even more ambitious project have been presented to the J-PARC scientific committee in Japan. The PRISM beam line[14] coupled to the PRIME[15] detector will aim to a sensitivity of 5×10^{-19} on the branching ratio.

PRISM is designed to deliver a high intensity muon beam of $10^{11} \div 10^{12} \mu^-/s$, with a narrow momentum spread of 2 %, a kinetic energy of ≈ 20 MeV and a negligible π^- contamination. The layout of the PRISM beam line is presented in fig. 6. The mentioned features are planned to be achieved by using a Fixed Field Alternating Gradient (FFAG) accelerator ring. The FFAG will operate a rotation of the muon energy-time phase space, thus reducing the momentum spread down to the quoted value. With such a performing beam, the PRIME muon target thickness could be reduced by a factor 10 with respect to MECO. The resulting electron multiple scattering in the target has been estimated to contribute to the momentum resolution only for ≈ 100 keV, thus helping in reducing the MDIO background.

The full PRISM beam line at J-PARC is not yet approved, but the PRISM FFAG has been funded by the Osaka University in 2003. The ring construction will last 5 years, and the technical issues related to the FFAG operation will be addressed.

7 Beams and conclusions

A concise summary of the beam requirements for the next generation of experiments aiming to high sensitivity searches for rare muon decays is presented in Table 3.

The main conclusion of this summary is that the physics potential of new high–intensity low-energy muon beams is very promising: muon physics may provide us crucial information concerning physics beyond the Standard Model.

In particular, rare processes violating muon number conservation, in many extensions of the Standard Model, may occur at rates close to the current experimental bounds. Furthermore

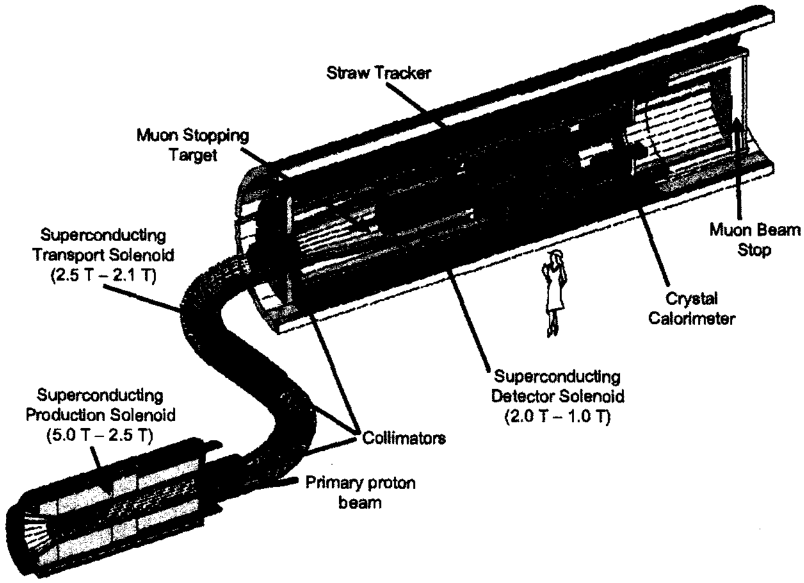

Figure 5: A schematic view of the MECO project.

Table 3: Beam requirement for the next generation of high-sensitivity searches for muon lepton number violating processes. N_μ is the time integrated number of stopped μ . In pulsed beams δT is the μ burst duration, while ΔT is the beam repetition period. I_{off}/I_{on} is the proton extinction factor between the measurement period ($\sim \Delta T/2$) and the μ burst.

Search	$\int I_\mu dt$	p_μ	$\Delta p_\mu/p_\mu$	BR	I_{off}/I_{on}	δT	ΔT
$\mu^+ \to e^+e^-e^+$	10^{17}	< 30	< 10	10^{-15}	n/a	n/a	n/a
$\mu^+ \to e^+\gamma$	10^{17}	< 30	< 10	10^{-15}	n/a	n/a	n/a
$\mu^- \to e^-$ pulsed	10^{21}	< 80	< 5	10^{-19}	10^{-10}	< 100ns	$> 1\mu$s
$\mu^- \to e^-$ DC	10^{20}	< 80	< 5	10^{-19}	n/a	n/a	n/a

these searches are free from any possible background induced by the Standard Model: any signal is an unambiguous evidence of new physics.

A future high–sensitivity $\mu^+ \to e^+e^-e^+$ search would be accidental background limited. A substantial detector improvement would be needed to exploit future high-intensity μ beams. No new experimental searches have been proposed so far.

A new $\mu^+ \to e^+\gamma$ search with a Single Event Sensitivity of $\sim 5 \times 10^{-14}$ have been approved and the MEG detector is currently under construction. The collaboration is planning to start the data collection in 2006. This experiment is making use of most intense μ-beam presently available. The main limitation to the sensitivity improvement comes from the background of uncorrelated events.

The $\mu^- \to e^-$ conversion in nuclei is not limited by the background of uncorrelated events. For this reason the search for this channel may benefit of high-intensity pulsed beams. The MECO collaboration is building a dedicated beam line and a detector at BNL to search for $\mu^- \to e^-$ conversion in nuclei with a sensitivity of $\sim 10^{-16}$. The key feature of this project is the pulsed μ beam with a large proton extinction factor between the pulses. A more ambitious project, named PRISM/PRIME, of even larger sensitivity, has been proposed at the J-PARC

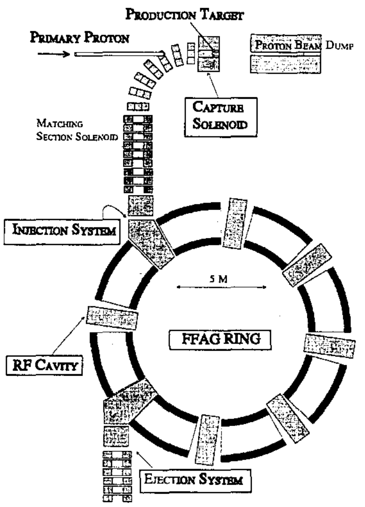

Figure 6: Layout of the PRISM muon source.

accelerator complex.

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