Charged Lepton Flavor Violation Experiments

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The experimental status of charged lepton flavor violation searches is briefly reviewed, with particular emphasis on the three classical searches involving muon transitions: $\mu \rightarrow e\gamma$, $\mu \rightarrow e$ conversion and $\mu \rightarrow 3e$.

PRESENTED AT

2013 Flavor Physics and CP Violation (FPCP-2013),
Buzios, Rio de Janeiro, Brazil, May 19-24 2013
1 Introduction

Charged lepton flavor transitions are forbidden in the Standard Model because of the vanishing neutrino masses. The introduction of neutrino masses and mixing induces flavor transitions radiatively, but at a negligible level. In fact the expected branching ratio for $\mu \rightarrow e\gamma$ with the present knowledge on neutrino mixing parameters is $\approx 10^{-51}$. The observation of charged lepton flavor transitions would represent a clear signal of physics beyond the Standard Model, being virtually background free.

This situation is completely different from that in the quark sector where flavor transitions are already present through the Cabibbo-Kobayashi-Maskawa mixing matrix, and signals of new physics would appear as deviations from the predicted branching ratios, whose computation is not always free from theoretical difficulties.

In what follows I will review the current experimental status and near-future perspectives of the “classical” searches involving muon transitions, namely the $\mu \rightarrow e\gamma$ decay, the $\mu \rightarrow e$ conversion and the $\mu \rightarrow 3e$.

2 Charged Lepton Flavor Violation

Charged Lepton Flavor Violation (CLFV) is related to new couplings and can be described in the effective operator language by dimension-5 or dimension-6 operators

\[
\frac{1}{\Lambda} \bar{\ell}_i \sigma_{\mu\nu} \ell_j F^{\mu\nu} \quad \frac{1}{\Lambda^2} \bar{\ell}_i \gamma_{\mu} \ell_j \left( \bar{q}_k \gamma_{\mu} q_m + \bar{\ell}_k \gamma_{\mu} \ell_m \right)
\]

where $\Lambda$ is the effective scale, $\ell_i$ and $q_i$ are the leptons and quarks of different generations. The dimension-5 operator summarizes the couplings with the electro-magnetic field, and it is responsible of the $\mu \rightarrow e\gamma$ vertex present also in tree-level $\mu \rightarrow e$ and $\mu \rightarrow 3e$ transitions, while the dimension-6 operators enter in the four-fermion vertices responsible for the two latter processes, but gives no contribution to the $\mu \rightarrow e\gamma$ decay.

The same effective operators describe also flavor-diagonal transitions (such as the muon and electron anomalous magnetic moment) and lepton flavor violating decays of taus and flavored mesons.

It is in fact possible to correlate, in a model dependent way, many of these processes, making it extremely interesting the investigation of different decays (see, e.g., [1] and references therein). In Table 1 we show the main CLFV processes with their naive probability scaling, their present limits on the year of the last measurement.

The experimental effort can be divided in two categories: the “exotic searches”, that is processes that if seen could indicate the existence of physics beyond the SM, and are generally limited by the experiment side, and “beyond SM physics”, i.e. processes where new physics would appear as deviations from SM predictions, and
are generally theory-limited. In some cases such processes can be searched for by multi purpose experiments (as in the case of the B-factories) but sometimes dedicated experiments are mandatory, due to the extreme specialization of the detector and to the performance requirements.

3 The classical searches

In this paper I will concentrate on the three “classical” searches of CLFV decays involving muons, which fall in the category of dedicated experiments for exotic searches. They are $\mu \to e\gamma$, $\mu \to 3e$ and $\mu \to e$ conversion on nuclei. In Figure 1 we show the evolution of the limits set on these processes along the last 65 years, where we can see the three groups of experiments done with cosmic-ray muons (1940s) stopped pion beams (until mid-60s) and stopped muon beams (1970s onward). Each experiment proved to be an improvement over the previous one in either beam or detector technology.

3.1 Kinematic and backgrounds

The three processes involving muons share common characteristics, but each one shows a peculiarity that makes it impossible to have a common experiment to search for all three simultaneously.

The $\mu \to e\gamma$ decay is a two body decay where the daughter particles are monoenergetic (52.8 MeV) and emitted simultaneously back-to-back in the muon rest frame. It is natural therefore to stop the muons in a thin target and for this reason a beam of positive muons is necessary, since negative muons would undergo nuclear capture before decaying. Two background processes can mimic a signal event: a muon radiative decay $\mu^+ \to e^+\nu\bar{\nu}\gamma$ in which the two neutrino carry little energy and both positron and photon are close to their kinematic edge, and an accidental coincidence between a positron from a normal muon decay (“Michel positron”) and a high energy photon coming from a radiative decay, bremsstrahlung or positron annihilation in flight. It is

| Process           | Relative probability | Present Limit   | Experiment     | Year  |
|-------------------|----------------------|-----------------|----------------|-------|
| $\mu \to e\gamma$ | $1$                  | $5.7 \times 10^{-13}$ | MEG            | 2012  |
| $\mu^{-}\text{Ti} \to e^-\text{Ti}$ | $Z\alpha/\pi$ | $4.3 \times 10^{-12}$ | SINDRUM II     | 2006  |
| $\mu^{-}\text{Au} \to e^-\text{Au}$ | $Z\alpha/\pi$ | $7 \times 10^{-13}$ | SINDRUM II     | 2006  |
| $\mu \to eee$    | $\alpha/\pi$        | $4.3 \times 10^{-12}$ | SINDRUM II     | 1988  |
| $\tau \to \mu\gamma$ | $(m_\tau/m_\mu)^{2/4}$ | $3.3 \times 10^{-8}$ | B-factories    | 2011  |
| $\tau \to e\gamma$ | $(m_\tau/m_\mu)^{2/4}$ | $4.5 \times 10^{-8}$ | B-factories    | 2011  |

Table 1: Relative sensitivities and experimental limits of the main CLFV processes.
possible to show [3] that for competitive resolutions the dominant background is the accidental one. For this reason a continuous muon beam is preferred, since the probability of random coincidences from daughter particles coming from different muons is minimized.

In the $\mu N \rightarrow eN$ transition monoenergetic electrons are emitted against the spectator nucleus, with an energy equal to the muon rest mass minus the muon binding energy. A single particle is present in the final state and the main background events come from muon decay in orbit (DIO) or from interactions of particles present in the primary muon beam. A beam of negative muons is needed to have the formation of muonic atoms, and in order to suppress the dominant beam-related background a pulsed beam is preferred. Monoenergetic electrons are searched for in the time interval between two pulses, when particles from the primary beam must be kept at a minimum. A figure of merit in this kind of experiments is therefore the relative number of particles in the primary beam between two pulses, called the extinction factor.

In the $\mu \rightarrow 3e$ decay the three positrons, emitted simultaneously, share the muon rest energy, and are emitted on a plane with the further constraint of zero total momentum. In analogy with the $\mu \rightarrow e\gamma$ process the background from radiative decays is less important than the accidental coincidence of three particles from different muons, therefore a continuous positive muon beam is the preferred experimental solution.
4 The MEG experiment

The MEG experiment at PSI [4] aims at searching for the $\mu^+ \rightarrow e^+\gamma$ decay with a sensitivity of a few $\times 10^{-13}$. A beam of $3 \times 10^7 \mu^+/\text{sec}$ is stopped on a thin polyethylene target at the center of a superconducting magnet. The momentum and time of flight of positrons is measured by a set of drift chambers followed by a set of plastic scintillation counters, while energy, conversion point and interaction time of $\gamma-$rays is measured by a single volume liquid xenon detector, whose scintillation light is read by 846 UV-sensitive photo-multiplier tubes. An important feature of the MEG detector is its abundance of continuous and redundant calibration and monitoring which allow, for instance, a knowledge of the absolute energy scale of the photon detector with a systematics below 0.2%.

MEG has been taking data since 2009 and the analysis of 2009–2011 data yields an upper limit on the branching ratio $\Gamma(\mu \rightarrow e\gamma)/\Gamma(\mu \rightarrow e\nu\bar{\nu}) < 5.7 \times 10^{-13}$ at 90% confidence level [5]. This represents a factor of 5 improvement on the analysis of 2009–2010 data alone, due not only to the doubled statistics, but also to some hardware modifications (a new laser tracker for drift chamber alignment, a new BGO calibration detector) and analysis improvements (better $\gamma-$ray pile-up unfolding on the photon side, and software noise reduction and revised track fitter for the positron side).

The analysis of the 2012 data sample is in progress and further statistics is being accumulated in 2013, when the experiment is expected to shut down due to the saturation of its sensitivity. In the meanwhile the MEG collaboration has presented a proposal for an upgraded experiment [6] which aims at a sensitivity enhancement of one order of magnitude compared to the final MEG result. The key features of the MEG upgrade are to increase the rate capability of all detectors (up to $7 \times 10^7 \mu^+/\text{sec}$) while improving the energy, angular and timing resolutions, for both the positron and photon arms of the detector. This is especially valid on the positron side, where a new low-mass, single volume, high granularity tracker is under development. A new highly segmented, fast timing counter array will replace the old system, to sustain the increased event rate.

The photon-arm will also be improved by increasing the granularity of the liquid xenon detector at the incident face, by replacing the current photomultiplier tubes (PMTs) with a larger number of smaller photosensors and optimizing the photosensor layout also on the lateral faces. Finally, a new DAQ scheme involving the implementation of a new combined readout board capable of integrating the various functions of digitization, trigger capability and splitter functionality into one condensed unit, will be necessary to cope with the increased rate and number of channels.

The upgraded detector is expected to be built in the years 2013-2015 and first engineering runs are planned at the end of 2015. A sensitivity of $5 \times 10^{-14}$ on the $\mu \rightarrow e\gamma$ branching ratio is expected after data taking in the years 2016-2018.
Figure 2: A schematic representation of the MEG upgrade. An increased muon beam (1) impinges on a thinner target (2). The new tracker (3) will provide more points and the coupling (4) with the timing counter will be improved (5). The liquid xenon detector will be modified to provide more acceptance (6) and finer granularity (7).

schematic representation of the present and upgraded MEG detectors is shown in Figure 2.

5 Mu3e at PSI

A proposal to search for the $\mu \rightarrow 3e$ decay was recently submitted at the PSI scientific committee [7]. A low energy muon beam is stopped on a double cone target. Positron trajectories are measured by a low material tracker made of ultra-thin silicon detectors based on high-voltage monolithic active pixel sensors (HV-MAPS). A set of scintillating fibers and scintillating tiles will give a precise determination of the electrons and positrons time of flight. Since all charged particles have very low momentum (from 15 to 50 MeV/c) the dominant effect that deteriorates the momentum resolution is multiple scattering. Minimizing the amount of material along the electrons/positrons trajectories is mandatory, but a careful design of the tracking system (see Figure 3) allows for partial cancelation of multiple scattering effects at first order for most of the reconstructed trajectories.

The experimental quest is divided in phases: in phase IA only minimum detector
configuration for early commissioning, by means of a central silicon tracker only is envisaged. This will be supplemented in phase IB by scintillating recurl stations made of scintillating tiles and a fiber tracker. Adding the recurl stations will significantly enhance the momentum resolution and thus improve the suppression of background. The insertion of the fibre tracker and the tile detector stations gives a much better time resolution in comparison to the silicon pixel only. The high time resolution will allow running at the highest possible rate at the $\pi E5$ muon beam line at PSI of $\approx 10^8 \mu^+/\sec$. The sensitivity reach in this phase of the experiment of $O(10^{-15})$ will be limited by the available muon decay rate.

Figure 3: A schematic of the complete Mu3e detector. Phase IA will have only the central barrel, while the second and third pairs of stations will be added in phase IB and II respectively.

A phase II experiment is envisaged following the development of a new high intensity ($10^9 \mu^+/\sec$) beam line at PSI. The detector will be expanded with a second pair of recurl and tile station, which will allow the precise measurement of all particles crossing the inner silicon tracker. The expected sensitivity on the $\mu \rightarrow 3e$ branching ratio is expected to reach the $10^{-16}$ level in this phase with a time scale which is competitive with that of the MEG upgrade.

### 6 Muon to electron conversion experiments

Aluminum is the candidate target for the research of coherent muon conversion on nuclei. A single monoenergetic electron is present in the final state therefore the concept of accidental background is virtually absent in this case, and, unlike the $\mu \rightarrow e\gamma$ or $\mu \rightarrow 3e$ searches, there is no experimental wall at least until conversion rates of $O(10^{-18})$. It is anticipated that muon-to-electron conversion will provide the ultimate sensitivity to CLFV detection.

The background comes from radiative muon decay in orbit or radiative muon capture (background neutron and gamma rays will be produced), but mainly the beam related background (pion and electron contamination in the primary beam) will be particularly harmful. To set the detector in a high-purity environment an idea
of Dzhilkibaev and Lobashev [8] of using a curved transport solenoid to bring muons and electrons from the production target to the detector together with a pulsed beam with challenging extinction is being pursued.

There are presently two big projects under development: the Mu2e project at the Fermi National Accelerator Laboratory [9], and the COMET project at J-PARC [10]. The two experiments are quite similar in the outline (see Figure 4): a proton beam hits a target at the center of a solenoid, where pions and muons are produced. Negative muons are transported along a curved solenoid that acts as a very powerful momentum filter, therefore delivering a very clean low energy muon beam onto the aluminum capture target placed downstream, in turn placed in a strong magnetic field. Decay electrons are analyzed by a tracking device followed by a calorimetric/triggering station. In the COMET detector, after the capture target, another curved solenoid is placed in order to further decouple the electron spectrometer from the main beam transport line.

Both experiments are expected to reach a sensitivity of $3 \times 10^{-17}$ within 2020 and are heavily involved in detector development and extinction measurements.

COMET will follow a staged approach: COMET phase-I will be followed by COMET phase-II. For phase-I the first 90 degrees of the muon beamline will be built with a twofold purpose: to make a direct measurement of the proton beam extinction and other potential background sources for phase-II and to carry out a search for $\mu \rightarrow e$ conversion with a $3 \times 10^{-15}$ sensitivity. After these measurements, the muon transport will be extended up to 180 degrees for the COMET Phase-II, and a $\mu \rightarrow e$ conversion search with a sensitivity of $3 \times 10^{-17}$ will be carried on with an electron spectrometer and detectors.

In the meanwhile the DeeMe experiment at J-PARC [11] aims at making a $10^{-14}$ level measurement (a factor of 100 better than the present limit) before 2017 by simplifying the beamline-detector geometry, having the same target for muon production and capture. A rotating silicon carbide is the candidate target material and will be followed by an electron spectrometer made of multi-wire proportional chambers.

Figure 4: A schematic of the Mu2e detector.
7 Summary

The search for charged lepton flavor violation complements quark flavor physics measurements in search for new or unexpected phenomena. Transitions involving muons are the most sensitive ones due to the possibility of having very intense, low energy muon beams. The MEG experiment recently improved the limit on the $\mu \rightarrow e\gamma$ decay down to $5.7 \times 10^{-13}$ at 90% confidence level and it is presently finishing its data taking. An upgrade of the detector is in progress and will point to a ten times better sensitivity to be reached before 2018.

In parallel there are projects to search for the $\mu \rightarrow 3e$ decay in Europe, and to search for the $\mu \rightarrow e$ conversion both in the USA and in Japan that will complement our knowledge in this sector within the next few years.

ACKNOWLEDGEMENTS

I would like to thank the organizers of the FPCP2013 conference for their invitation. It was such a nice experience to visit Brasil and especially Buzios. Discussions with colleagues from the MEG collaboration are acknowledged.

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