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Lepton flavour violation in charged leptons

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Summary. — This paper shows the present status of lepton flavour violation experiments involving charged leptons (muons and taus).

PACS `12.60.-i` – Models beyond the standard model.
PACS `13.35.-r` – Decay of leptons.

1. – Introduction: Why search for the lepton flavor violation?

In the Standard Model of electroweak and strong interactions (SM), presently the most successful theory in explaining and predicting the elementary particle phenomenology, lepton flavor symmetry is preserved [1]. Nevertheless neutrino oscillations are now estabilished facts and neutrino masses are not vanishing: the Lepton Flavour Violation (LFV) in the neutral sector is an experimental reality. Introducing neutrino masses and mixing in the SM, the LFV in the charged sector is predicted but with negligible probability (Branching Ratios (BRs) $\approx 10^{-50}$). However, several new physics models (especially Supersymmetric and Grand Unified Theories, SUSY-GUT) predict relatively large BRs for LFV processes: measurable flavour violation processes in charged leptons would be a strong indication of new physics beyond the SM [2]. Many experiments are underway or in preparation which would test the theoretical predictions with unprecedented levels of sensitivity.

2. – The muonic channels

Muons are sensitive probes to search flavour violation for three imporatant resons: it is possible to obtain intense muon beam ($\approx 10^8 \frac{\mu}{s}$), they have a long lifetime ($2.2\,\mu$s), the final states are simple and clearly measurable. We will discuss the three most common channels to search for LFV: muon decay into an electron plus a gamma, muon decay in three electrons and muon-to-electron conversion. Table I shows the current limits and relative ratios between the three decays.

Table I. – *LFV muon decays: current limit and ratio.*

Muon decay	Current limit	Ratio (BR/BR($\mu e\gamma$))
$\mu \to e + \gamma$	BR $< 1.2 \times 10^{-11}$ [3]	1
$\mu \to 3e$	BR $< 10^{-12}$ [4]	$\approx$ 200–300
$\mu \to e$	BR $< 7 \times 10^{-13}$ [5]	$\approx$ 100

2·1. $\mu \to e + \gamma$ *decay.* – The signature of the decay is very simple: one electron and one gamma emitted simultaneously in back-to-back directions, both with kinetic energy equal to half of the muon mass (52.83 MeV). Two types of backgrounds could mime the process: the physical or correlated background from the radiative muon decay (RMD) ($\mu \to e\nu\overline{\nu}\gamma$) and the accidental background, the coincidence between an electron from an SM muon decay and a γ from another source (RMD, e$^+$-e$^-$ annihilation in flight, γ from electron bremsstrahlung, etc.). Due to the fact that BR(RMD) is proportional to the muon stopping rate R_μ and the accindetal BR to R_μ^2 (both particles come from beam), the last one is dominant. Then a continuous muon beam is preferred and high-resolution detectors are mandatory. The MEG experiment uses a $3 \times 10^7\, \mu^+$/s beam produced at the PSI (Paul Scherrer Institute) where there is the most powerful continuous hadronic machine in the world. The beam is stopped in a thin (205 μm) polyethylene target. The positron momentum is measured by a magnetic spectrometer made by an inhomegenous super-conductive magnet (COBRA) and a system of sixteen drift chambers; the positron time is measured by a double array system of plastic scintillator bars and fybers. Energy, time and direction of γ are measured by an innovative liquid-xenon calorimeter [6]. The data are analyzed with a combination of blind and likelihood analysis. A first result was pubblished using the 2008 data collection: BR($\mu \to e + \gamma$) $< 2.8 \times 10^{-11}$ at 90% of Confidence Level (CL) [7]. A preliminary result using 2009 data collection was shown: BR($\mu \to e + \gamma$) $< 1.5 \times 10^{-11}$ at 90% CL [8].

2·2. $\mu \to 3e$. – The signature of the $\mu \to 3e$ decay at rest is composed by three charged particles orgininating from a common vertex, with a total momentum equal to 0 and invariant mass equal to muon mass. The dominant background comes from accidendal coincidence between positron from usual muon decay and an e$^+$-e$^-$ pair from γ conversion or Bhabha scattering of another positron from SM muon decay. While the absence of neutral particles should give no need of the electromagnetic calorimeter, intense muon beams are expected to result in very high rate in the tracking system causing dead time, trigger and pattern recognition problems. At the moment there are no experiments dedicated to this channel.

2·3. $\mu \to e$ *conversion.* – The $\mu \to e$ conversion is a coherent flovour change in a nuclear field of a negative muon captured by the matter. The final state is a single electron only. The experiments that studies this decay uses a pulsed negative muon beam (produced by proton collisions on a fixed target) stopped in the thin target where muons are captured. The signature is a monochromatic electron with energy $E_e = m_\mu - E_B - E_R$, E_B and E_R being the muon atom binding energy and the nucleus recoil energy, respectively. These two energies are related to the nucleus of the stopping material: for example, E_e is $\approx$ 105 MeV for Al and 104.3 MeV for Ti. The main backgrounds come from a muon decay in orbit (MDIO) and from a radiative pion capture ($\pi^- A \to \gamma X$, RPC), not limited by accidental background. To reduce MDIO low momentum muon

Table II. – *Comparison between Mu2E and COMET.*

	Mu2E	COMET
Proton beam	8 GeV, 1.69 μs between bunches, Extinction factor $\approx 10^{-9}$	8 GeV, 1.18–1.76 μs between bunches, Extinction factor $\approx 10^{-9}$
Muon transport	Shape S solenoid	U-shape solenoid
Detector	Intensity variable solenoide, Tracker and electromagnetic calorimeter, DAQ $\approx$ 500 kHz	Intensity variable solenoide, Tracker and electromagnetic calorimeter, DAQ $\approx$ 1 kHz
Single event Sensitivity	2.5×10^{-17}, Upper limit 6×10^{-17} 90% CL	2.6×10^{-17}, Upper limit 6×10^{-17} at 90% CL

beams are used; to reduce RPC collimators and appropriate transport system are used to reach a high beam purity (very low π contamination). Moreover, since the lifetime of muonic atoms is some hundreds of ns, one can use a pulsed beam with very short buckets ($\approx$ 100 ns), leave pions decay and search for $\mu \rightarrow e$ conversion in a delayed time window. This requires, however, that the fraction of protons arriving on the pion production target between two separate bunches is as small as possible ($\approx 10^9$): this factor is called extinction factor and is an important parameter to determine the final sensitivity of the experiment. Two projects of $\mu \rightarrow e$ conversion experiments are present: Mu2E at Fermilab [9] and COMET at J-PARC [10]. Mu2E will produce negative muon beam from decay of pions produced by a 8 GeV proton beam, with 100 ns bunches. Muons will be transported using a curved solenoid to reject antiprotons and other positive and neutral particles. Selected negative muons will be stopped in thin Al foils and the momentum of electrons from muon decay or capture will be measured by using a high-resolution spectrometer (900 keV FWHM at 105 MeV/c) and by an electromagnetic calorimeter. There will be a magnetic field configuration that allows the selection of high energy electrons and the recovering of backward going electrons. About 10^{18} stopped muos and 40 signal events are expected in two years of data taking (assuming $\mathrm{BR}(\mu \rightarrow e) = 10^{15}$ and extinction factor $\approx 10^9$). The estimated background is less than 0.5 event, the analysis is almost background free. In case of no signal observation, the expected limit is $\mathrm{BR} < 6 \times 10^{-17}$. COMET is conceptually similar to Mu2E (the main differences are reported in table II).

3. – The tauonic channels

The large τ mass (≈ 1.78 GeV, $\approx 18\,\mathrm{m}_\mu$) implies many LFV channels and, in many SUSY-GUT schemes, BRs enhanced by a factor $(\frac{m_\tau}{m_\mu})^\alpha$, $\alpha \geq 3$ with respect to muonic LFV decays (*i.e.* $\frac{\tau \rightarrow \mu+\gamma}{\mu \rightarrow e+\gamma} \approx 10^{(3-5)}$) [11, 12]. As consequence, a sensitivity of the order of $\approx 10^{-9}$ is necessary to be competitive with dedicated muon LFV decay experiment. However, the short τ lifetime (2.9×10^{-13} s) makes it impossible to produce τ beam and so large samples could be obtained only using accelarators that operate in a favorable energy range. At the moment the high production rates came from BaBar and Belle experiments ($\approx 10^8$ particles/year). The most studied LFV decays are: $\tau \rightarrow l + \gamma$ ($l = e, \mu$), $\tau \rightarrow 3l$ and $\tau \rightarrow l + h$ (hadronic). Table III shows the current limits.

TABLE III. – *LFV tau decays: current limits.*

Tau decay	Current limit	Tau decay	Current limit
$\tau \to e + \gamma$	$\mathrm{BR} < 3.3 \times 10^{-8}$ [13]	$\tau \to \mu + \gamma$	$\mathrm{BR} < 4.4 \times 10^{-8}$ [13]
$\tau \to 3l$	$\mathrm{BR} < (1.5\text{–}2.7) \times 10^{-8}$ [14,15]	$\tau \to l + h$	$\mathrm{BR} < (3\text{–}20) \times 10^{-8}$ [14,15]

3˙1. $\tau \to l + \gamma$. – In Babar and Belle experiments, to search the decays, τ-pair events were selected by using the following criteria: identifying a standard τ decay ($\tau \to l\overline{\nu}\nu$, "tag side") and one single muon or electron plus at least one photon ("signal side"). Signal side events were studied in the $(\Delta E, M_{l\gamma})$-plane, $M_{l\gamma}$ being the reconstructed lepton-gamma invariant mass and ΔE the difference between $(E_{\mu(e)} + E_\gamma)_{CM} - \frac{E_{CM}}{2}$, being $E_{\mu(e)}$ the muon or electron energy and E_γ the gamma energy. Candidate events had $M_{l\gamma} \approx M_\tau$ and $\Delta E \approx 0$. The main background came from accidental coincidence between one γ from an initial (ISR) or final state decay and a lepton from the standard decay. It is important to note that ISR is an irreducible noise.

3˙2. $\tau \to 3l$. – This decay is more interesting since the final state with only charged particles allows higher-resolution mass measurements and no irreducibile noise. The analysis strategy was similar to the previous one with three charged tracks in the signal side and the invariant mass M_{3l} from each possible three leptons combination having the required sign of charge. Main background came from $q\overline{q}$ and Bhabha pairs. Upper limits for all the possible final states are reported in refs. [14] and [15].

3˙3. $\tau \to l + h$. – These decays can be divided in three different categories:

1) $\tau \to l + V$ with V vector meson (ϕ, ω),

2) $\tau \to l + h_0$ with h_0 pseudo-scalar mesons $(\pi^0, \eta, K_S^0, \ldots)$,

3) $\tau \to l + h_1, h_2$ with $h_{1,2}$ charged mesons $(\pi^\pm, K^\pm, \ldots)$.

Many of these channels are clean, without irreducible backgrounds. Both Babar and Belle showed results for these channels: summeries are reported in refs. [16, 17].

4. – A look at the future

4˙1. *Muonic channel*. – There are different perspectives for the different channels. About $\mu \to e + \gamma$ decay, the MEG experiment will take data at least until the end 2012 and with statistics and some detector improvements estimates to reach sensitivity around few times 10^{-13}. Future accelerators like NUFACT [18] or Project X [19] are expected to deliver high intense ($\approx 10^{15}$ p/s) proton beam and consequently high intense muon beams ($\approx 10^{14}\,\mu$/s). But as previously mentioned, sensitivities on $\mu \to e + \gamma$ and $\mu \to 3e$ are limited by accidental background that is proportional to R_μ^2. For this reason not considerable improvements are expected by increasing of beam intensity. The sensitivity could increase with detector improvements as high-resolution β spectrometers and finely segmented targets. We could do different considerations for $\mu \to e$ channel: it is not affected by accidental background and could have improved sensitivity using high-intensity machines. However, important studies and developments are necessary to solve or reduce problems related to high levels of radiation, large momentum spread, etc.

At the moment two experiments (Mu2E and COMET) are approved and will become operational in the coming years. In particular for COMET a second stage (PRISM) is expected: some modifications in experimental detectors and a coupling with a very intense muon beam will allow to reach sensitivity of the order of 10^{-18}.

4·2. *Tauonic channel.* – The SuperB [20] is a project of a very intense e^--e^+ machine with an expected luminosity of $L \approx 10^{36}\,\text{cm}^{-2}\,\text{s}^{-1}$ which would reach integrated luminosity about two orders of magnitude higher than Babar and Belle. The project was approved and construction will start in the coming years. It is important to note that the sensitivity scales as $\frac{1}{L}$ only for background-free experiment, otherwise scales only with $\sqrt{\frac{1}{L}}$. The channel $\tau \to l + \gamma$ has small but not negligible background; since no background events were observed by Babar and Bell, the channels $\tau \to 3l$ and $\tau \to l + h$ are more promising. Expected sensitivities at SuperB for tauonic channels are: $\text{BR}(\tau \to l+\gamma) < 2\times10^{-9}$, $\text{BR}(\tau \to 3l) < 2\times10^{-10}$ and $\text{BR}(\tau \to l+h) < (2-6)\times10^{-10}$.

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