μe CONVERSION EXPERIMENTS: TESTING CHARGED LEPTON FLAVOR VIOLATION

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The recent evidence for neutrino mixing shows that lepton flavor is not a conserved quantity. Due to the smallness of the neutrino masses effective flavor changing neutral currents among charged leptons remain negligible in the Standard Model. Whereas $b \rightarrow s\gamma$ has a probability of $O(10^{-4})$ $\mu \rightarrow e\gamma$ is expected with a branching ratio around 10^{-50} . Observable rates would be an unambiguous signal for physics beyond the Standard Model and indeed, many extensions of the model are constrained best by the present experimental limits on charged lepton flavor violation. In this talk I will discuss experimental searches for charged lepton flavor violation with emphasis on μe conversion in muonic atoms.

1. Introduction

Figure 1. 2nd order weak contributions to $\mu \rightarrow e\gamma$ and $b \rightarrow s\gamma$.

ν -Oscillations directly lead to finite rates for rare muon decays (see Fig. 1). Such second-order charged weak interactions result, however, in negligible contributions to the branching ratios since they are strongly sup-

pressed dynamically:

$$B(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| V_{\mu i}^* V_{ei} \frac{m_{\nu i}^2}{M_W^2} \right|^2. \quad (1)$$

Note that the corresponding mechanism in the quark sector leads to $b \rightarrow s\gamma$ with a branching ratio of $O(10^{-4})$ due to the large top mass.

The observation of charged lepton number violation would thus be an unambiguous sign of new physics and indeed, a number of Standard Model extensions are probed sensitively^{1,2}.

2. Present constraints on charged lepton flavor violation

Table 1. Upper limits on branching ratios of particle decay modes that do not conserve lepton flavor.

Decay	Limit	[Ref] Exp./Lab.	Decay	Limit	[Ref] Exp./Lab.
$\mu^+ \rightarrow e^+ \gamma$	$1.2 \cdot 10^{-11}$	³ MEGA	$\tau \rightarrow 2\mu e$	$1.8 \cdot 10^{-6}$	¹⁴
$\mu^+ \rightarrow e^+ e^+ e^-$	$1.0 \cdot 10^{-12}$	⁴ SINDRUM	$\tau \rightarrow \mu 2e$	$1.5 \cdot 10^{-6}$	¹⁴
$\mu^+ e^- \leftrightarrow \mu^- e^+$	$8.3 \cdot 10^{-11}$	⁵ SINDRUM	$\tau \rightarrow 3e$	$2.9 \cdot 10^{-6}$	¹⁴
$\mu^- \text{Ti} \rightarrow e^- \text{Ti}$	$6.1 \cdot 10^{-13}$	⁶ SINDRUM	$K^+ \rightarrow \pi^+ \mu e$	$2.8 \cdot 10^{-11}$	¹⁵ BNL
$\mu^- \text{Ti} \rightarrow e^+ \text{Ca}^*$	$3.6 \cdot 10^{-11}$	⁷ SINDRUM	$K_L^0 \rightarrow \mu e$	$4.7 \cdot 10^{-12}$	¹⁶ BNL
$\mu^- \text{Pb} \rightarrow e^- \text{Pb}$	$4.6 \cdot 10^{-11}$	⁸ SINDRUM	$K_L^0 \rightarrow \pi^0 \mu e$	$4.4 \cdot 10^{-10}$	¹⁷ Fermi
$\mu^- \text{Au} \rightarrow e^- \text{Au}$	$1.9 \cdot 10^{-11}$	⁹ SINDRUM	$B^0 \rightarrow \mu e$	$1.2 \cdot 10^{-7}$	¹⁸ BaBar
$\tau \rightarrow e\gamma$	$2.7 \cdot 10^{-6}$	¹⁰ CLEO	$B^0 \rightarrow \tau e$	$5.3 \cdot 10^{-4}$	¹⁹ CLEO
$\tau \rightarrow \mu\gamma$	$1.1 \cdot 10^{-6}$	¹¹ CLEO	$B^0 \rightarrow \tau\mu$	$8.3 \cdot 10^{-4}$	¹⁹
	$1.0 \cdot 10^{-6}$	¹² Belle	$Z^0 \rightarrow e\mu$	$1.7 \cdot 10^{-6}$	²⁰ OPAL
	$2.0 \cdot 10^{-6}$	¹³ BaBar	$Z^0 \rightarrow e\tau$	$9.8 \cdot 10^{-6}$	²⁰
$\tau \rightarrow 3\mu$	$1.9 \cdot 10^{-6}$	¹⁴ CLEO	$Z^0 \rightarrow \mu\tau$	$1.2 \cdot 10^{-5}$	²⁰

Table 1 lists the present limits on processes forbidden by charged lepton flavor conservation. Best constraints come from the forbidden μ and K decays where dedicated experiments have been performed. One should keep in mind, however, that couplings to the third generation could be enhanced¹ in which case the τ limits start to become interesting as well.

3. μe conversion versus $\mu \rightarrow e\gamma$

Which limit from Table 1 gives the best constraint on charged lepton flavor violation not only depends on the experimental sensitivities but also on the

mechanism of the violation. In many scenarios, for example, the branching ratio for μe conversion is lower by a factor of $O(\alpha)$ compared to $\mu \rightarrow e\gamma$. In other cases, *i.e.* when the violations are mediated by leptoquarks²¹ or R-parity violating couplings to SUSY particles²², the situation is reversed.

In neutrino-less μe conversion leaving the nucleus in its ground state the nucleons act coherently, which boosts the conversion probability relative to the rate of nuclear muon capture which is the dominant competing process for medium and heavy nuclei. For the same reason transitions to the ground state are enhanced relative to other final states which are expected to occur with a probability below 10 % for all nuclear systems. Experiments have been performed on a variety of nuclei (see Table 1). Several authors have studied the nuclear physics aspects of the process, unfortunately with conflicting results^{24,25}.

From an experimental point of view coherent μe conversion has many nice features. Whereas the sensitivity to $\mu \rightarrow e\gamma$ is limited by the performance of large-solid-angle high-resolution photon detectors giving rise to background from accidental $e\gamma$ coincidences already at present beam intensities, μe conversion would fully benefit from future high-intensity muon beams.

4. Background sources in searches for μe conversion

The signature for μe conversion is a single mono-energetic electron with an energy (depending on the muon binding energy) around 100 MeV. There is a variety of processes that may result in the emission of electrons in the region of interest. Electrons resulting from μe conversion in muonic atoms are emitted at the kinematic endpoint of muon decay in orbit which constitutes the only intrinsic background. Since the decay rate drops steeply above $m_\mu c^2/2$ (see Fig.2 for muonic gold) the set-up may have a large geometrical acceptance and still the detectors can be protected against the vast majority of decay and capture events. The rate at the endpoint scales with the energy resolution to the 5th power and a resolution around 1% is sufficient to keep it below 10^{-16} .

Other potential background involves cosmic rays or beam contaminations. Radiative π^- capture followed by $\gamma \rightarrow e^+e^-$ produces electrons with energies around 100 MeV with a probability of $O(10^{-6}/\text{MeV})$. Such prompt beam related background can be suppressed by beam pulsing, a beam veto counter, or beam purity.

Figure 2. Electron spectrum for muon decay in orbit in the case of muonic gold obtained by scaling the lead spectrum from Ref.²⁶.

5. MECO

MECO²⁷, an approved BNL experiment, aims at a single-event sensitivity of 2×10^{-17} for conversion on aluminum (see Fig. 3). To achieve this large

Figure 3. MECO set-up. Pions are produced by 8 GeV/c protons on a W target situated in a graded solenoidal field. Negatively charged particles of <100 MeV/c are transported to the aluminum target by a curved solenoid. Electrons emitted from the experimental target are analysed in the detector solenoid with the help of a straw tracker.

gain in sensitivity a novel beam concept has been developed. Secondary beam particles from the interactions of $4 \times 10^{-13} \text{ s}^{-1}$ 8 GeV/c protons in a tungsten target are collected and transported to the experimental target by superconducting solenoids. The overall length of the solenoid system including the detection solenoid is 27 m. Both the production target and the

experimental target are situated in regions of diminishing field strength. As a result many particles originally moving backward are reflected resulting in increased solid angles. MECO uses beam pulsing to fight prompt beam induced background. After a bend solenoid particles get charge separated. With the help of a slit system halfway the s-shaped transport solenoid a wide momentum band of one charge polarity can be transmitted. During the 700 ns wide observation window starting ≈ 600 ns after a proton bunch the beam load has dropped by 2–3 orders of magnitude. Due to the 26 ns pion lifetime the π^- rate drops much faster, to about one per minute after 600 ns which is sufficiently low to keep the background from radiative pion capture under control. Since muonic atoms at medium Z have lifetimes of several 100 ns a large fraction of them is still “alive” when the time window opens. For aluminum which is the first choice for the target 50% of the muonic atoms decay in the time window. Assuming a measuring time of 10^7 s the expected single-event sensitivity is 2×10^{-17} .

6. SINDRUM II: a new limit for μe conversion on gold

In the past decade in a series of searches with the SINDRUM II spectrometer limits on the conversion rates on medium and heavy nuclei have improved significantly (see Table 1). This program was finished in the year 2000 with an effective 81 days measurement on gold. Figure 4 shows a vertical cross section through the spectrometer. Pions are removed with the help

Figure 4. SINDRUM II; typical trajectories of a beam μ^- and a hypothetical conversion electron are indicated.

of an 8 mm thick CH_2 degrader at the entrance of a 9 m long solenoid (“beam solenoid” in Fig.4) which is coupled directly to the spectrometer. At 50 MeV/c pions stop in the degrader and muons go through. The range distributions depend mainly on the momentum distribution of the beam. By carefully adjusting the fields in the various beam elements the required steeply falling range distribution was obtained.

$4.37 \pm 0.32 \times 10^{13}$ muonic gold atoms were formed in the target as monitored by observing muonic X-rays with a Ge(Li) detector positioned outside the spectrometer coil. Given the overall detection efficiency for μe conversion (including the 97% capture probability) of 7.0% this leads to a single-event sensitivity of $3.26 \pm 0.22 \times 10^{-13}$.

Figure 5. The measured energy distribution is compared with simulated distributions for muon decay in orbit and μe conversion. No events are found above 100 MeV.

Figure 6. $L(N_{\mu e})$ and $\int_0^{N_{\mu e}^{\max}} L(N_{\mu e}) dN_{\mu e}$.

Figure 5 shows the resulting e^- energy distribution. The steep drop below 74 MeV reflects the requirement that the electron moves at least 46 cm from the spectrometer axis. The measured spectrum is in reasonable agreement with the prediction for decay in orbit. One event is observed around 96.4 MeV which is marginally compatible with the energy distribution expected for μe conversion. We performed a likelihood analysis of the energy distribution including a flat background from cosmic rays and radiative pion capture in addition to the distributions shown in Fig. 5.

Figure 6 shows the resulting likelihood function $L(N_{\mu e})$ for the expectation value of the number of μe conversion events. The 90% C.L. upper limit is $N_{\mu e}^{\max}(90\% \text{ C.L.}) = 2.45$ deduced from $\int_0^{2.45} L(N_{\mu e}) / \int_0^{\infty} L(N_{\mu e}) = 90\%$. Combined with the single event sensitivity quoted above this leads to:

$$B_{\mu e}^{\text{gold}} < 8 \times 10^{-13} \quad 90\% \text{C.L.} \quad (2)$$

7. Summary and Outlook

Forty years after Pontecorvo's original proposal of neutrino oscillations²⁸ (and five years after his death) Super-Kamiokande found strong evidence for oscillations in the signals from atmospheric neutrinos²⁹. When neutrinos oscillate lepton flavor is not conserved just as quark flavor isn't. Still, due to the tiny neutrino mass splittings on the scale of m_W neutrino mixing can not be observed in processes involving charged leptons such as $\mu^+ \rightarrow e^+\gamma$, μe conversion or $K \rightarrow \mu e$. This situation changes dramatically in many extensions of the Standard Model, such as supersymmetry or left-right symmetry and in many cases experimental bounds on charged lepton flavor violation give the best constraints.

The sensitivities reached in experimental searches for muon number violation have improved steadily in the past fifty years. Presently, the upper limits on the branching ratios are $O(10^{-12})$ and even better searches have been initiated recently. After a first signal would be found "precision" experiments (i.e. Z -dependence of μe conversion, decay asymmetries of $\mu^+ \rightarrow e^+\gamma$ and $\mu \rightarrow 3e$ relative to the μ spin direction) would be needed to discriminate between the various options. Such program would require both better detection systems and better muon beams, like those discussed within the framework of Neutrino Factories³⁰.

References

1. Äystö *et al.*, CERN Stopped Muons Working Group, *Preprint* CERN-TH/2001-231, hep-ph/0109217 (2001).
2. Y. Kuno and Y. Okada, *Rev. Mod. Phys.* **73**, 151 (2001).
3. M. Ahmed *et al.*, MEGA Collaboration, *Phys. Rev.* **D65**, 112002 (2002).
4. U. Belgardt *et al.*, SINDRUM Collaboration, *Nucl. Phys.* **B229**, 1 (1988).
5. L. Willmann *et al.*, *Phys. Rev. Lett.* **82**, 49–52 (1999).
6. P. Wintz, Proc. *Lepton-Baryon 98* (Trento), eds. H.V. Klapdor-Kleingrothaus and I.V. Krivosheina (Bristol and Philadelphia: Institute of Physics Publishing), p 534 (1998).
7. J. Kaulard *et al.*, SINDRUM II Collaboration, *Phys. Lett.* **B422**, 334–38 (1998).
8. W. Honecker *et al.*, SINDRUM II Collaboration, *Phys. Rev. Lett.* **76**, 200 (1996).
9. F. Riepenhausen, Myon-Elektron-Konversion in Gold, *Ph.D thesis* Zurich University (1999).
10. K.W. Edwards *et al.*, CLEO Collaboration, *Phys. Rev.* **D55**, R3919–23 (1997).
11. S. Ahmed *et al.*, CLEO Collaboration, *Phys. Rev.* **D61**, 071101(R) (2000).
12. K. Abe *et al.*, Belle Collaboration, Search for $\tau \rightarrow \mu\gamma$ decay at Belle, *LP 01*

- (Rome), KEK-PREPRINT-2001-79 (2001).
13. M. Roney, Search for $\tau \rightarrow \mu\gamma$ at BaBar, *ICHEP02* (Amsterdam), July 24-31 2002, to appear in the proceedings (2002).
 14. D.W. Bliss *et al.*, CLEO Collaboration, *Phys. Rev. D* **57**, 5903–07 (1998).
 15. R. Appel *et al.*, *Phys. Rev. Lett.* **85**, 4482 (1999).
 16. D. Ambrose *et al.*, *Phys. Rev. Lett.* **81**, 5734 (1998).
 17. L. Bellantoni, KTEV Collaboration, Proc. *36th Rencontres de Moriond* (Les Arcs, France), 10-17 Mar 2001, hep-ex/0107045 (2001).
 18. G. Tong G, Lepton flavour violation at e^+e^- colliders, *ICHEP02* (Amsterdam), July 24-31 2002, to appear in the proceedings (2002).
 19. R. Ammar *et al.*, CLEO Collaboration, *Phys. Rev. D* **49**, 5701–04 (1994).
 20. R. Akers *et al.*, *Z. Phys. C* **67**, 555 (1995).
 21. E. Gabrielli, *Phys. Rev. D* **62**, 055009 (2000).
 22. A. de Gouvêa *et al.*, *Phys. Rev. D* **63**, 035004 (2001).
 23. L. Barkov *et al.*, Search for $\mu^+ \rightarrow e^+\gamma$ down to 10^{-14} branching ratio, available at <http://www.icepp.s.u-tokyo.ac.jp/meg>.
 24. T.S. Kosmas, *Progress in Particle and Nuclear Physics* **48**, 307–16 (2002).
 25. R. Kitano *et al.*, *Phys. Rev. D* **66**, 096002 (2002).
 26. R. Watanabe *et al.*, *Atom. Data and Nucl. Data Tab.* **54**, 165 (1993).
 27. M. Bachman *et al.*, MECO, *BNL proposal E 940* (1997).
 28. B. Pontecorvo, *Sov. Phys. JETP* **6**, 429 (1958).
B. Pontecorvo, *Sov. Phys. JETP* **7**, 172 (1958).
B. Pontecorvo, *Sov. Phys. JETP* **26**, 984 (1968).
 29. Y. Fukuda *et al.*, Super-Kamiokande Collaboration, *Phys. Rev. Lett.* **81**, 1562 (1998).
 30. <http://muonstoragerings.web.cern.ch/muonstoragerings/>