1 Tests of Lepton-Flavor Conservation at PSI

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One of the great mysteries in present-day particle physics is the origin of the generation pattern of quark and lepton states. Transitions between the generations, as observed in charged weak interactions among quarks, can be attributed to mixing of the quark eigenstates. Within the framework of the minimal Standard Model the mass degeneracy of the neutrino states precludes this mechanism in the leptonic sector, in accordance with the apparent conservation of leptonic generation number (lepton-flavor conservation, LFC).

Although various anomalies in the fluxes of solar, atmospheric and beam dump neutrinos may be interpreted in terms of neutrino oscillations, no convincing signal for the violation of LFC has been found so far. Searches for LFC-violating decay modes of charged leptons, mesons and Z^0 have resulted in upper limits only.

Most extensions of the Standard Model allow neutral interactions between the generations. Whereas higher order charged interactions among quarks lead to effective flavor-changing neutral currents (FCNC), i.e. responsible for the decay $b \to s\gamma$, FCNC's among leptons would yield an unambiguous signal for new physics.

Which LFC-violating mode gives the best constraints is model-dependent. For this reason many different searches are done in parallel and at PSI, for example, three different processes are studied:

- A search for muonium-antimuonium conversion with the SINDRUM I spectrometer resulted in an improvement in sensitivity by almost four orders of magnitude.
- A search for $\mu \to e$ conversion on titanium with the SINDRUM II spectrometer resulted in an upper limit on $B_{\mu e}$ of $6.1 \cdot 10^{-13}$, the lowest upper limit on any decay mode reached so far. A further improvement of the sensitivity by another order of magnitude depends on the question whether the PMC magnet will reach the required field of 1.2 Tesla.
- A letter of intent has been submitted to PSI describing a new search for $\mu \to e\gamma$ at the level of a few times 10^{-14}. This would be an improvement of the present sensitivity by three orders of magnitude.

1.1 $\mu \to e$ conversion in muonic atoms: the SINDRUM II project

Neutrinoless $\mu^- \to e^-$ conversion in muonic atoms, $\mu^-(A,Z) \to e^-(A,Z)$ with A mass number and Z atomic number, gives the best constraints on LFC violation in a large variety of models. For conversions leaving the nucleus in its ground state the nucleons act coherently, which boosts the conversion probability relative to the rate of the dominant process of nuclear muon capture.

Muonic atoms mostly reach their ground state before decaying by muon decay in orbit $\mu^-(A,Z) \to e^-\overline{\nu}_e\nu_\mu(A,Z)$ or nuclear muon capture $\mu^-(A,Z) \to \nu_\mu(A,Z-1)$. In the case of muonic titanium the capture probability amounts to $f^{\mathrm{Ti}}_{\mathrm{capt}} = 85.3\%$, which corresponds to a lifetime of 329 ns. In the usual convention the branching ratio for $\mu \to e$ conversion is quoted relative to the rate for nuclear muon capture:

$$B_{\mu e} \equiv \frac{\Gamma_{\mu^-(A,Z) \to e^-(A,Z) g.s.}}{\Gamma_{\mu^-(A,Z) \mathrm{capture}}} \, . \tag{1.1}$$

Earlier calculations predicted a steady rise of the branching ratio until $Z \approx 30$, from where on it was expected to drop again. For this reason most experiments have been performed on medium-heavy nuclei. More recently it has been estimated that $\mathrm{B}_{\mu e}$ may keep increasing with Z. The dependence of $B_{\mu e}$ on the normalized neutron excess $(N - Z)/(N + Z)$, with $N \equiv A - Z$, depends on the nature of the LFC-violating propagator. A model-independent analysis requires at least two measurements with significantly different values for $(N - Z)/(N + Z)$.

The signature of coherent $\mu^- \rightarrow e^-$ conversion is a monoenergetic electron which is emitted at the kinematical endpoint for bound muon decay, i.e. with an energy equal to the muon mass minus the muon binding energy and the kinetic energy of the recoiling atom.

There are several sources of electron background in the energy region around 100 MeV, involving either beam particles or cosmic rays. Beam-related background may originate from muons, pions or electrons in the beam. Muons may produce background by *muon decay in flight* or, after the formation of a muonic atom, by *muon decay in orbit* or *radiative muon capture*. Pions may produce background by *radiative pion capture*. Capture gammas produce electrons mostly through e^+e^- pair production inside the target. Electrons in the beam may produce background through scattering off the target.

The SINDRUM II experiment aims at a sensitivity of a few times 10^{-14} for the branching ratio of $\mu^- \rightarrow e^-$ conversion in muonic atoms. In a first stage data were taken on titanium and lead at the old μE1 beam line at PSI. Below we report on the results of the third and final measurement at the μE1 beam line, a renewed search for $\mu^- \rightarrow e^-$ conversion on titanium with a sensitivity below 10^{-12}. The result of a search in this data-set for $\mu^- \rightarrow e^+$ conversion was presented in last years annual report and was published recently [3].

The sensitivity of the experiment is limited by beam flux and purity. A dedicated beam was designed, aiming at $10^8\,\mathrm{s}^{-1}$ stopped μ^- and a π^- contamination below 10^{-10}. The major beam element, an 8.5 m long solenoid, reached superconductivity by the beginning of 1997, but could not yet be operated at fields above 0.75 T, which is 50% of the design value. For this reason it was decided to change the beam concept temporarily and tune the πE5 channel to stop 20-30 MeV/c cloud muons which require a field around 0.2 T only.

Presently a number of improvements is made to the magnet which may allow operation at the full field after the 1998 six months shutdown period.

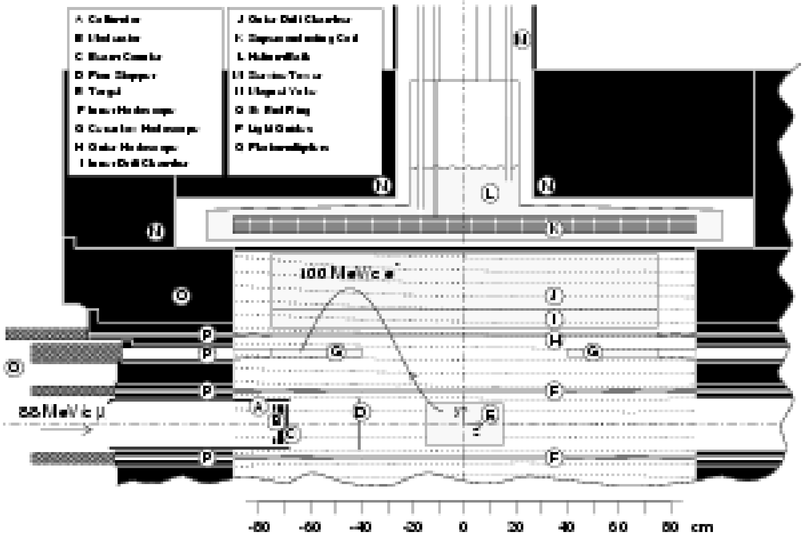

Figure 1.1: SINDRUM II

1.1.1 Search for $\mu \to e$ conversion on titanium

The SINDRUM II spectrometer (see Fig.1.1) consists of a set of concentric cylindrical detectors inside a superconducting solenoid. The muon beam enters the setup on the axis and traverses a CH_2 moderator and a plastic beam counter before reaching the target at the center. The particles of interest make 1-3 full turns before reaching a Čerenkov hodoscope. Two radial drift chambers are used for tracking.

The experiment was performed at the μE1 beam line at PSI. During a measurement life time of 50.4 days with beam switched on $(3.09 \pm 0.14) \times 10^{13}$ muons stopped in the target. Cosmic background was recorded during 44 days without beam.

Figure 1.2 shows an example of a reconstructed trajectory of an electron making two turns before reaching a Čerenkov hodoscope. The particle momentum and the origin of its trajectory are determined from a fit to the first revolution of the reconstructed helix. The events are then checked for additional detector signals characteristic for prompt and cosmic ray background.

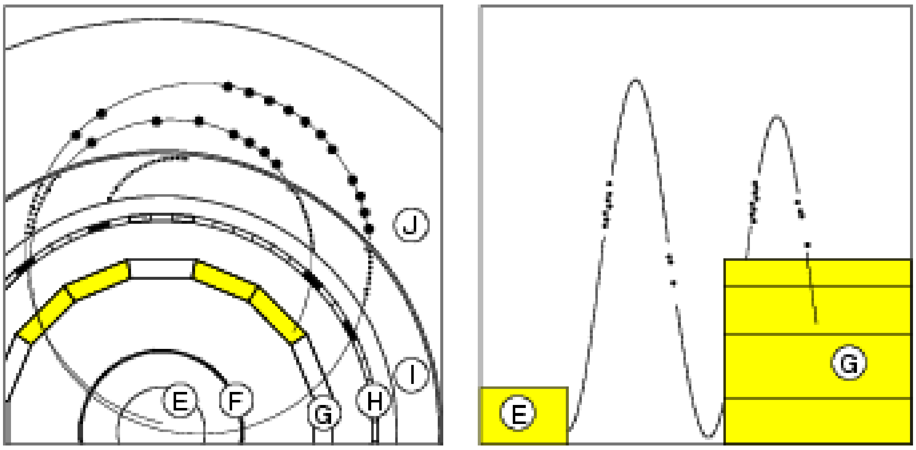

Figure 1.2: *Tracks left in the spectrometer by a 100 MeV/c e^-. The labeling of the detector components is as in Fig. 1.1.*

In the spatial distribution of the point of closest approach, shown in Fig. 1.3, one easily recognizes the contours of the various objects in the beam.

Fig. 1.4 shows an example of a waveform trace taken from an radiative pion capture (RPC) event. In addition to the 700 ns history of the beam counter signal, a time marker and some periods of the cyclotron rf signal are recorded. The marker has a fixed time relation with the start signal of the hodoscope TDC's.

$\mu \to e$ conversion would lead to an enhancement of the number of events at the endpoint of the energy distribution for muon-induced electrons. Fig. 1.5 shows energy distributions for three stages in the event selection. The energy distribution of the final sample, which contains 3580 events with an energy above 85 MeV, falls steeply towards zero with an endpoint below 100 MeV. Both prompt and cosmic ray background could be removed completely. No candidate events have been found.

The upper limit on the branching ratio is calculated using:

$$\frac{\Gamma(\mu^- \mathrm{Ti} \to e^- \mathrm{Ti}^{g.s.})}{\Gamma(\mu^- \mathrm{Ti}_{\mathrm{capture}})} < \frac{n^{\mu e}_{\max}(1 + n^{\mu e}_{\max}\sigma_r^2/2)}{f_{\mathrm{capt}} N_{\mathrm{stop}} \mathcal{E}^{\mu e}_{99\,\mathrm{MeV}}} , \qquad (1.2)$$

where $n^{\mu e}_{\max} = 2.3$ is the upper limit on the number of candidate events, $f_{\mathrm{capt}} = 0.853$

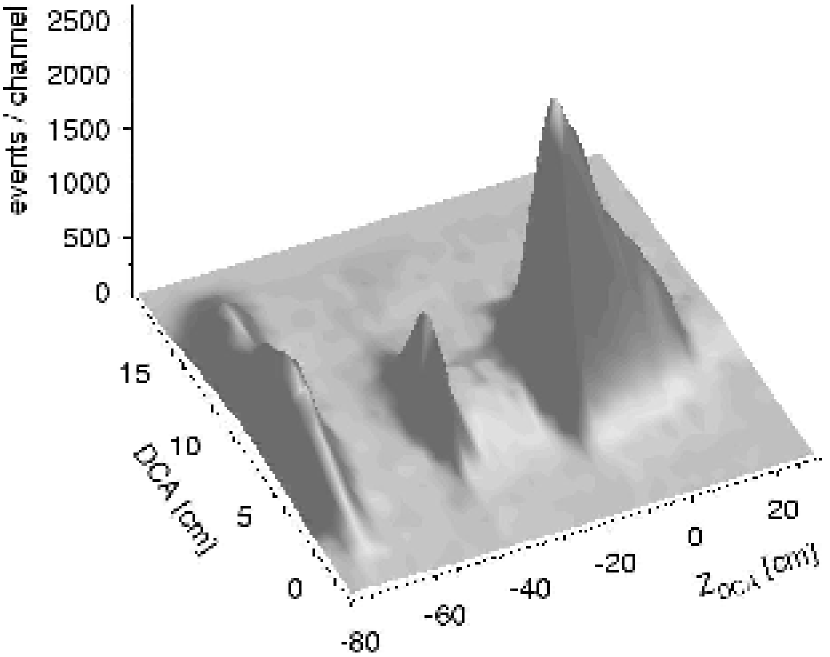

Figure 1.3: *Spatial distribution of the point of closest approach to the beam axis of the reconstructed trajectories showing event accumulations at the locations of the beam counter and collimator, the second moderator and the target (from the left).*

is the probability for nuclear muon capture on titanium, $N_{\rm stop} = (3.09 \pm 0.14) \times 10^{13}$ is the total number of muons stopping in the target during the life time of the experiment, $\mathcal{E}^{\mu e}_{99\,\rm MeV} = 0.146 \pm 0.012$ is the overall probability that a $\mu - e$ conversion in the target leads to the observation of an e^- event with energy above 99 MeV and σ_r is the relative uncertainty

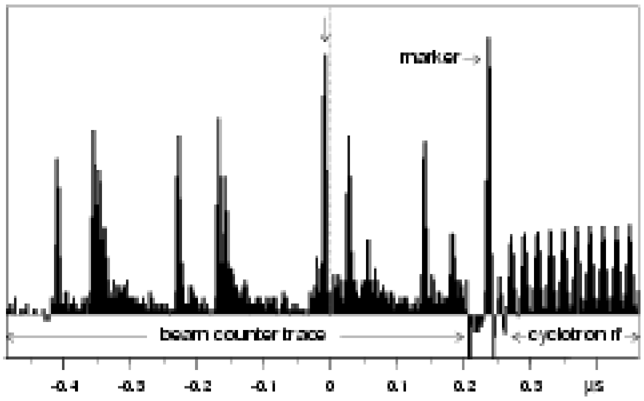

Figure 1.4: *Digitized waveform from a π^- induced event showing the beam counter trace, a time marker indicating the start signal for the hodoscope TDC's and the cyclotron rf signal. The position for prompt events at t=0 is calculated, assuming beam particles traveling between the beam counter and the target at light speed. Since pions move typically at one third of this velocity they cross the beam counter around t=-6 ns, where a large π signal is found.*

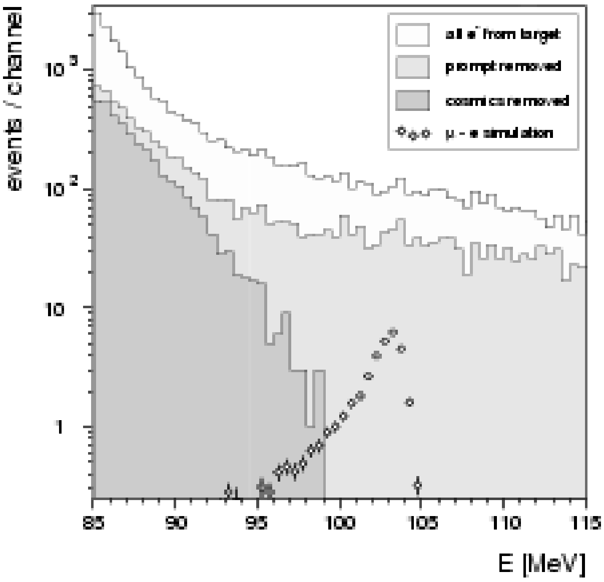

Figure 1.5: *Electron energy distribution at three stages of the event selection and as predicted by a GEANT simulation of* $\mu - e$ *conversion on titanium assuming* $B_{\mu e} = 4 \cdot 10^{-12}$.

of the denominator. One obtains:

$$\frac{\Gamma(\mu^- \mathrm{Ti} \rightarrow e^- \mathrm{Ti}^{g.s.})}{\Gamma(\mu^- \mathrm{Ticapture})} < 6.1 \times 10^{-13} \quad (90\% \text{ C.L.}) \, , \tag{1.3}$$

which improves over the previous results [1] by a factor 7.

1.1.2 Search for $\mu \rightarrow e$ conversion on gold

These measurements were done during the second half of 1997 when it became clear that the PMC magnet could not be operated above 0.75 T. For this reason it was decided to use a cloud muon beam instead with a central momentum around 27 MeV/c. To transport this beam to the experimental target inside the spectrometer vacuum had to be maintained all the way from the pion production target to the exit of the spectrometer.

The only purpose of the PMC magnet was to reduce the pion flux by increasing the length of the πE5 channel. At this low momentum the beam can be stopped in a very thin target, which had a total mass of 10 g only, i.e. 100 times less than foreseen for the PMC mode. The reduced size leads to a reduction of the cosmic background and a better definition of the acceptance and trigger. The low mass has a large number of advantages:

- All background sources which scale with the target mass are reduced correspondingly:
  - radiative π and μ capture followed by asymmetric external e^+e^- production
  - the cosmic background component which requires a target interaction.
- The energy resolution is no longer given by the spread in target energy loss, but by the intrinsic spectrometer resolution of 1%.
- Signal losses by bremsstrahlung (at least 30% for the heavy targets) have become negligible.
- It is not necessary to limit the acceptance to the upstream hemisphere as is necessary in PMC operation due to the large scattering background in forward directions.

- The remaining background will be purely muon decay in orbit, rather than an uncertain mixture of various processes.

During a beam period with $1.6 \cdot 10^{6}$ mA·s about $2 \cdot 10^{12}$ muons stopped in the target. Since the overall efficiency is expected to raise by $\approx 50\%$ compared to the titanium measurement (no prompt veto, better energy resolution) the single-event sensitivity would be around $3 \cdot 10^{-12}$, or six times higher than achieved in our previous measurement on a heavy target [2].

References

[1] SINDRUM II Collab., C. Dohmen *et al.*, Phys. Lett. B **317**, 631 (1993).

[2] SINDRUM II Collab., W. Honecker *et al.*, Phys. Rev. Lett. **76** 200 (1996).

[3] SINDRUM II Collab., J. Kaulard *et al.*, Phys. Lett. B **422**, 334 (1998).