3 Search for μ-e Conversion with SINDRUM II

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Various observations on solar and atmospheric neutrinos indicate that neutrino states oscillate (much like neutral kaons) which means that lepton flavor is not a conserved quantity. Since in the standard model neutrino masses are set to zero "by hand", the model would need some minor modifications only. Since this mechanism of lepton flavor violation (LFV) does not lead to any observable effects in LFV decay modes involving charged leptons, their observation would require a much more fundamental extension to the model, such as supersymmetry (between fermions and bosons) and/or grand-unification (of the various gauge couplings).

The SINDRUM II project [1] aims at testing the conservation of lepton flavor by a search for μe conversion in muonic atoms. The process would lead to the emission of mono-energetic electrons with a momentum (depending on the muon binding energy) around 100 MeV/c. It is our goal to reach a sensitivity beyond 10^{-13} for the branching ratio relative to nuclear muon capture. SINDRUM II is a solenoidal magnetic spectrometer with 40% solid angle and 1% momentum resolution.

As discussed in last years annual report a new dedicated beamline was brought into operation towards the end of 1998. The major new element is a 9 m long superconducting magnet. Only very recently, after a series of modifications, reliable operation of this PMC magnet was obtained at its design value of 1.5 T.

One of the main difficulties of the experiment is potential background induced by pions contaminating the beam. Radiative pion capture (RPC), followed by e^+e^- pair production, is a source of electrons and positrons in the interesting momentum range around 100 MeV/c. The process leads to identical kinematical distributions for electrons and positrons with momenta reaching beyond the muon endpoint. Two different processes should be distinguished:

- RPC in the moderator
  A large number of pions stop inside the degrader at the PMC entrance. Electrons and positrons from RPC may reach the setup and scatter off the target into the acceptance of the spectrometer. Our simulation shows that at a PMC field of 0.72 T roughly one out of 10^7 pion stops in the moderator result in an electron reaching the target with an energy above 90 MeV. This background differs from the signal both in momentum and in angular distribution.

- RPC in the target
  A tiny number of pions may reach the target. RPC leads to a background that is isotropic and can be distinguished from the events of interest only by their different momentum distribution. In order to keep the probability to observe an RPC electron in a 5 MeV/c interval around 100 MeV/c below 0.3 at most 3×10^4 pions may reach the target. Assuming a measuring time of 100 days this corresponds to a tolerable rate of one pion every five minutes.

In 1998 it had become clear that the planned mode of operation, injecting a 90 MeV/c π^- beam into the PMC and separating the decay muons from the surviving pions with the help of a beam blocker, could not be used because of a very heavy load on the SINDRUM tracking detectors caused by beam electrons scattering off the target. In this situation it was decided to use muons from the pion cloud around the pion production target and suppress the pion background with the help of the moderator at the PMC entrance. At the momenta of interest muons have a mean range in matter which is about twice longer than the pion range. The remaining purpose of the PMC magnet is to efficiently couple the spectrometer magnet to the πE5 exit and to reduce the pion contamination of the beam by an additional 2-3 orders of magnitude by doubling the distance between the production target and the experimental setup.

3.1 Search for conversion on gold: final result from 1997 run

Already in 1997, at a reduced PMC field of $\approx$ 0.3 T, measurements had been done using a 26 MeV/c cloud μ^- beam on a gold target. Although the data proved to be very clean (no background from pions or scattered electrons) the stop rate was a disappointing $0.5 \times 10^6 \mu^- s^{-1}$. The resulting momentum distribution (see Fig. 3.1) shows no events in the μe

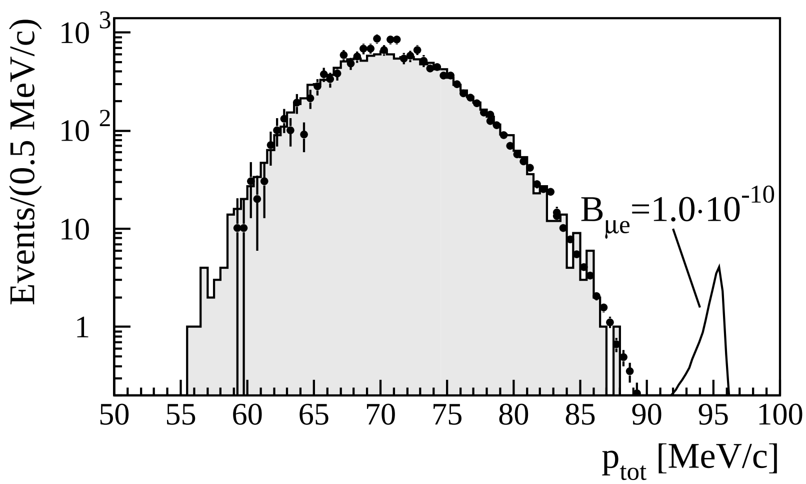

Figure 3.1: *Momentum distributions of electrons emitted in the decay of muonic gold: (i) full histogram: measured data, (ii) data points: simulated data for decay in orbit* $\mu^-\mathrm{Au} \rightarrow e^-\nu\bar{\nu}\mathrm{Au}$, *(iii) peak around 95 MeV/c (i.e. muon rest mass reduced by* $\approx$ *10 MeV atomic binding energy): simulated* μe *data. The steep drop in intensity towards lower momenta reflects the* $p_\perp$ *threshold imposed by the spectrometer field.*

signal region and can be attributed, both in shape and in magnitude, to muon decay in orbit. The analysis [2] has resulted in:

$$\mathrm{B}_{\mu e}^{\mathrm{Au}} < 1.9 \times 10^{-11} \qquad (90\% \text{ C.L.}),$$

which improves over the best previous limit on a heavy target (our own result on lead [3]) by a factor 2.4.

In order to increase the stop rate beyond $10^7 s^{-1}$ the beam momentum has to be raised. At the other hand beam-related background may set in. As will become clear below we are still in the process of optimizing the various parameters that affect stop rate and pion contamination.

3.2 Search for conversion on lead: first results from 1998 run

In 1998 the beam was tuned to 75 MeV/c and data were taken on lead. The target had the shape of a tube with a length of 60 cm, a diameter of 70 mm and a wall thickness of 0.5 mm. By using an additional moderator at the position of the first focus inside the ASC magnet (*double-degrader method*), the electron load could be reduced to an acceptable level with a μ^- stop rate around $0.6 \times 10^7 s^{-1}$. Figure 3.2 shows the distribution of the polar angle,

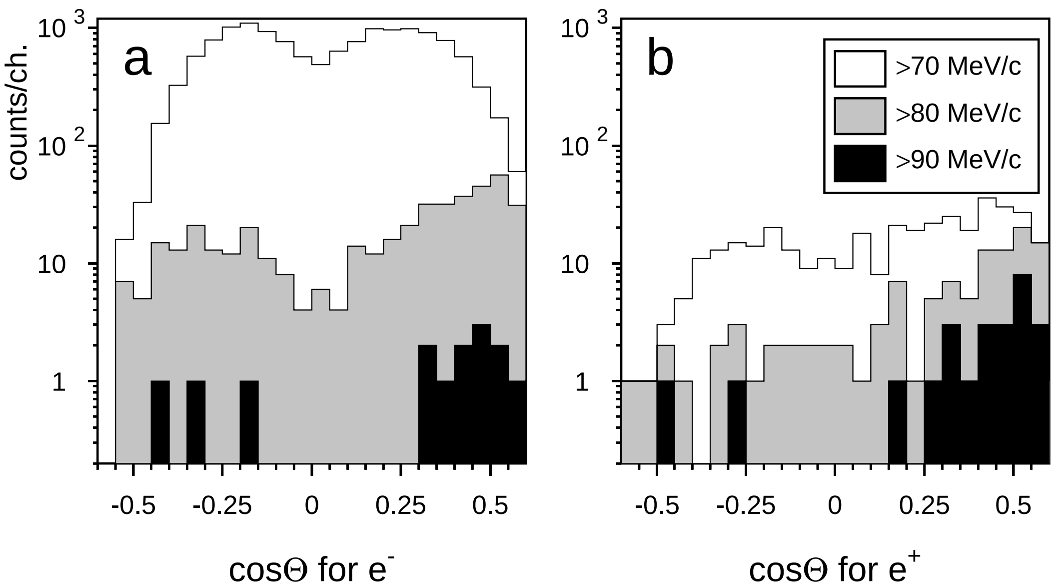

Figure 3.2: *Distributions of* $\cos\theta$, *with* θ *the emission angle relative to the beam direction, for various momentum thresholds. The loss in acceptance around zero* ($\theta = 90^o$) *is explained by energy loss in the target before the endcap trigger counters could have been reached. For momenta above 80-85 MeV/c there appear pronounced peaks in forward direction with roughly equal yields for both charges. See the text for a discussion.*

both for electrons and positrons, at various lower thresholds on the momentum of the decay particle. For relatively low thresholds the distributions are symmetric about 0, as should be expected for e^- from μ decay in orbit and e^+ from radiative μ^- capture followed by $\gamma \to e^+e^-$ pair production. For momenta above $\approx$ 80 MeV/c one notices enhancements in the forward direction ($\cos\theta$ around 0.5) of roughly equal strength for both charges. These events are attributed to radiative pion capture in the moderator at the PMC entrance. A few electron and positron events are found in the backward hemisphere. Presently we are still studying their nature. The most likely explanation would be radiative pion capture in the target. In this case $\approx 10^5$ pions would have reached the target, corresponding to a pion contamination of 10^{-8} in the target stops.

3.3 Results from 1999

In 1999 a systematic study of the rate of cloud muons at different beam momenta was performed. Table 3.1 shows the values measured at the exit of the PMC, which show a steeper momentum dependence than expected.

Based on these results we installed an 8 mm CH_2 degrader inside the collimator at the PMC entrance and selected a beam momentum of 50 MeV/c. The rate observed at the center of the spectrometer was $2 \times 10^7 \mu^-$/mA.s, 70% of which could be stopped in a titanium

Table 3.1: *Particle yields at $\pi E5$*

beam momentum	μ^- yield at PMC exit		π^- yield at PMC entrance	π/μ ratio
	measured	calculated [4]	calculated [4]	calculated [4]
MeV/c	10^6/mA.s	10^6/mA.s	10^6/mA.s	
28	2.6[a]	4	0.03	0.008
35	7.7	6.5	0.3	0.05
40	13	8	1	0.13
45	19	10	3	0.3
55	36	15	23	1.5
65	54	28	90	3.2

[a]this value may have suffered from an additional 0.5 mm mylar foil in the last bending magnet

target of length 50 cm, radius 15 mm and total weight 60 g. During several weeks data were taken at 50 MeV/c beam momentum. These data were scanned on-line and found free of π background. In an attempt to raise the stop rate beyond $2 \times 10^7 s^{-1}$ we increased the beam momentum. However, as can be seen in Fig. 3.3 we did not succeed to keep the pion background under control. Unfortunately, we only realized this after the measurements were finished. The main problem is that it is not obvious how to monitor a pion stop rate around one per minute among $10^7 \mu^- s^{-1}$.

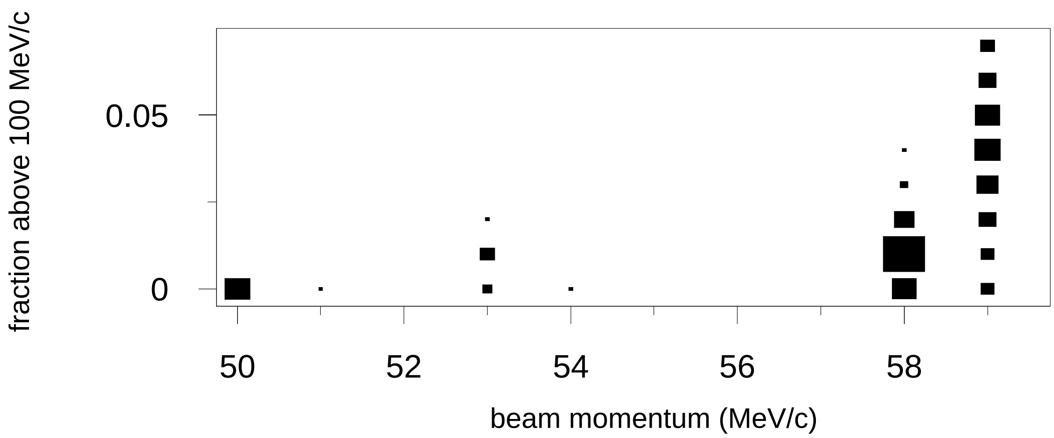

Figure 3.3: *Result of the analysis of the* ≈ 2000 *subsets of the 1999 data. In the spectra the region above 100 MeV/c is completely dominated by* π^- *induced background. Except for the* $\approx 10\%$ *data taken at 50 MeV/c all distributions show significant background contributions.*

The rate of pions reaching the target is equal to the product of the rate of π^- entering the PMC collimator, the probability to penetrate through the moderator and the probability to survive over the distance between moderator and target. As can be seen from Table 3.1 the π^- rate is $O(10^7)\ s^{-1}$ at the entrance of the PMC. Simulation shows that the survival probability is $O(3 \times 10^{-4})$. This means that *only one out of* 10^6 *pions may cross the moderator*. For the momenta of interest the muon range is about twice the pion range. Pions of 60 MeV/c have the same range as muons of 50 MeV/c. From these considerations one finds that *the 50 MeV/c beam may contain at most a* 10^{-6} *component with momenta above 60 MeV/c.*

3.4 Intentions for 2000: gold versus titanium

Presently we are designing better diagnostic tools to handle the high-momentum tails in the beam. Fortunately, there are many parameters (slits, magnet settings) to affect those tails. We plan to make a systematic study, before starting a ≈ 4 months measurement on gold.

In 1999 we achieved a μ^- stop rate of $2\times10^7 s^{-1}$. Given the shorter production target and assuming we will sacrifice $\approx 30\%$ beam intensity in favor of a reduced pion contamination we may have to live with a stop rate of $\approx 10^7\mu^- s^{-1}$ this year. Assuming efficiencies as in 1997, when a $0.5\times10^6 s^{-1}$ stop rate during two weeks resulted in a 2×10^{-11} upper limit [2], we would be able to reach a limit of 2×10^{-13} in ten weeks (no background - no signal). In this situation we decided to take only data on one target and choose gold for the following reasons:

- From a theoretical point of view conversion on gold is up to 3 times more likely than conversion on titanium [5].
- A future experiment, such as MECO, using pulsed beam to fight the beam-related background would not be able to measure a heavy element with less than 100 ns life time. The lifetime of muonic gold is 73 ns.
- On gold we can raise the sensitivity by two orders of magnitude, on titanium the improvement would only be a factor three as compared to our own measurement [6].

References

[1] PSI proposal R-87.03

[2] *Suche nach der Myon-Elektron-Konversion in Gold*, F. Riepenhausen, PhD thesis, Zürich University, 1999.

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[6] P. Wintz, Proceedings of the 29th International Conference on High Energy Physics, ed. A. Astbury, D. Axen, J. Robinson, World Scientific, Singapore (1999).