3 A New Upper Limit on the Branching Ratio for μe Conversion on Gold

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the measurements discussed here were performed in the year 2000 by:
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(SINDRUM II)

Lepton flavour violation as observed in neutrino oscillations[1] automatically leads to charged lepton flavour violation (CLFV), i.e.

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i |V^*_{\mu i} V_{ei} \frac{m^2_{\nu_i}}{M^2_W}|^2.$$

Since neutrino masses are so small this leads to a branching ratio of $O(10^{-50})$ which is out of reach of any experiment. The same mechanism in the quark sector gives $B(b \to s\gamma) \approx 10^{-4}$ due to the large top mass. The observation of CLFV would thus be an unambiguous sign of physics beyond the Standard Model and indeed, numerous extensions can be probed [1]. Neutrino-less μe conversion of μ^- bound in muonic atoms is a very sensitive probe of CLFV. The process results in mono-energetic electrons at the kinematic endpoint of normal muon decay $\mu^- \to e^- \overline{\nu_e} \nu_\mu$ which constitutes the only intrinsic background. Other potential background results from pions contaminating the beam or cosmic rays.

In the year 2000 SINDRUM II raised the sensitivity to neutrino-less μe conversion on heavy targets by two orders of magnitude. See [2] for a description of the setup and [3] for a discussion of the data below 90 MeV which are dominated by muon decay in orbit. Recently we finished the analysis and we present the resulting upper limit for the first time.

Muon stops were monitored with a germanium X-ray detector. The detection efficiency was measured with calibrated ^{137}Cs and ^{60}Co sources at three positions along the target. $4.37 \pm 0.32 \times 10^{13}$ muonic gold atoms were formed during the 81 days of data taking. Given the overall detection efficiency (including the 97% capture probability) of 7.0% this leads to a single event sensitivity of $3.26 \pm 0.22 \times 10^{-13}$.

Events were selected with electron trajectories originating in the target. Cosmic ray background was recognised by the occurence of additional prompt detector signals. Figure 3.2 shows the distibution of the decay time w.r.t. the 50 MHz cyclotron rf signal v.s. longitudinal momentum.

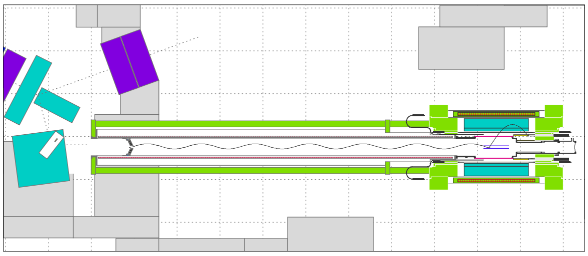

Figure 3.1: *Plan view of the experiment. The 53 MeV/c μ^- beam entering from the left is focused on a degrader situated inside a collimator at the entrance of the 9 m long transport solenoid. Whereas most muons cross the degrader only very few pions enter the solenoid. Shown is a background event in which a high-momentum e^- emitted from the degrader reaches the gold target from where it scatters into the acceptance of the SINDRUM II spectrometer.*

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[1] Raymond Davis and Masotoshi Koshiba received the 2002 Nobel prize in physics for their contributions to these results.

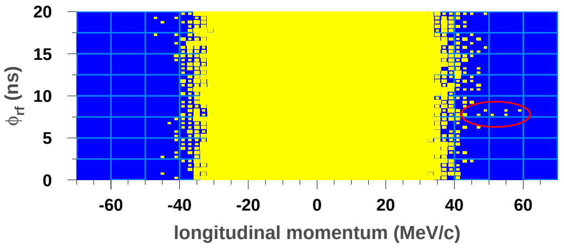

Figure 3.2: *Distribution of the phase of the track time w.r.t. cyclotron r.f. signal v.s. longitudinal momentum. The bulk of the events have a flat phase distribution as expected for muon decay in orbit which has a decay time of* ≈ 70 *ns. The red contour indicates events induced by radiative* π^- *capture in the moderator (see also Fig.3.1 and the discussion in the text).*

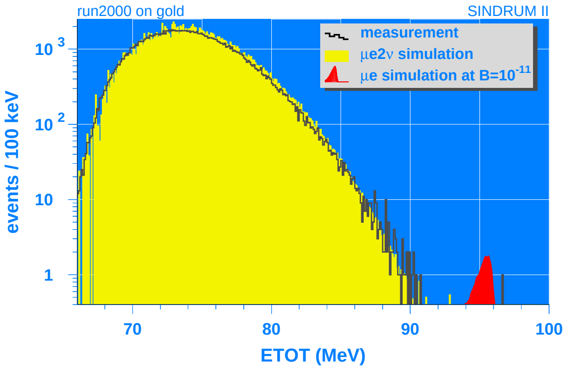

Figure 3.3: *The measured energy distribution is compared with simulated distributions for muon decay in orbit and* μe *conversion. No events are found above 100 MeV.*

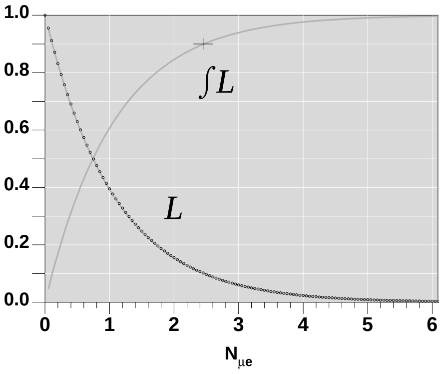

Figure 3.4: $\mathcal{L}(N_{\mu e})$ *and* $\int_0^{N_{\mu e}^{\max}} \mathcal{L}(N_{\mu e}) dN_{\mu e}$.

Indicated are some events from radiative π^- capture in the moderator followed by asymmetric $\gamma \rightarrow e^+e^-$ conversion and large-angle e^- scattering in the gold target, a process that keeps memory of the 50 MHz time structure of the proton beam. The observed rate for this background process is in rough agreement with the predictions from the GEANT simulation. Figure 3.3 shows e^- energy distribution after removal of the events in the indicated region. 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. 3.3

Figure 3.4 shows the resulting likelihood function $\mathcal{L}(N_{\mu e})$ for the expectation value of the number of μe conversion events. The 90% C.L. upper limit deduced from $\int_0^{2.45} \mathcal{L}(N_{\mu e}) / \int_0^{\infty} \mathcal{L}(N_{\mu e}) = 90\%$ is $N_{\mu e}^{\max}(90\% \text{ C.L.}) = 2.45$. Combined with the single event sensitivity quoted above this leads to:

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

This final SINDRUM II result lowers the best previous limit on μe conversion on a heavy target[4] by two orders of magnitude.

[1] Y. Kuno and Y. Okada, Rev. Mod. Phys. **73** (2001) 151.
J. Ellis, PSI Summer School, Zuoz, 2002, hep-ph/0211168.

[2] SINDRUM II Collab., Annual Report 2000-2001, Physik-Institut, Zurich University, p.8.

[3] SINDRUM II Collab., Annual Report 2001-2002, Physik-Institut, Zurich University, p.7.

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