Precision muon lifetime at PSI

*MuLan Experiment*

Françoise Mulhauser, University of Illinois at Urbana–Champaign (USA)
and Paul Scherrer Institute (Switzerland)

On behalf of the MuLan Collaboration
Motivation: Theory and actual experimental situation

Experimental Principle: How will we reach 1 ppm precision

Kicker: Principle and results

Detectors: Scintillators and Wire chamber

First Results: Run December 2004

Future: This year and the next ones
Science Questions

What are the fundamental electroweak parameters?

\(G_F, \alpha(Z), m_Z\)

Precision \(\mu^+\) lifetime
Scientific Questions

What are the fundamental electroweak parameters?

\[ G_F, \alpha(Z), m_Z \]

Precision \[ \mu^+ \) lifetime

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu \]

Current World average

\[ \tau_{\mu^+} = 2197.03 \pm 0.04 \text{ ns} \quad (18 \text{ ppm}) \]

\[ \downarrow \]

\[ \pm 0.002 \text{ ns} \quad (1 \text{ ppm}) \]
The muon lifetime $\tau_\mu$ is closely related to the Fermi coupling constant $G_F$, which sets the basic strength of the weak interaction:

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} \left(1 + \delta q \right)$$

QED radiative corrections: Two-loop diagrams finished in 1999 by Stuart and van Ritbergen*; now known to $< \pm 0.3$ ppm (previously $\pm 30$ ppm)

Extraction of $G_F$ is now limited by the muon lifetime a truly fundamental parameter of the standard model that should be measured as precisely as possible with today’s technology.

Experiments mostly statistics limited

PDG: $\tau_\mu = 2.19703 \pm 0.00004 \mu s$ (18 ppm)

Our goal: 1 ppm uncertainty in $\tau_\mu$ (0.5 ppm in $G_F$)

$$\frac{\delta G_F}{G_F} = 4 \frac{m_{\bar{\nu}_\mu}^2}{m_\mu^2} (< 25 \text{ ppb}) - \frac{5}{2} \frac{\delta m_\mu}{m_\mu} (75 \text{ ppb}) - \frac{1}{2} \frac{\delta \tau_\mu}{\tau_\mu} (9 \text{ ppm})$$
10^{12} Statistics: more than one muon at a time

✓ 1 ppm measurement → at least 10^{12} stopped muons.

✓ Each muon (or pion) enters target individually with pre– and post–quiet periods. Watch for decay positron and record its time.

✓ For 10^{12} muon, one need about $4 \times 10^7$ s . . . several years !

✓ To be practical, we need to observe several muons at once:
10^{12} Statistics: more than one muon at a time

- 1 ppm measurement → at least 10^{12} stopped muons.
- Each muon (or pion) enters target individually with pre– and post–quiet periods. Watch for decay positron and record its time.
- For 10^{12} muon, one need about $4 \times 10^7$ s . . . several years !
- To be practical, we need to observe several muons at once:

<table>
<thead>
<tr>
<th>Spatial separation: FAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$ arrive continuously into highly segmented timer/tracker; several events can overlap</td>
</tr>
</tbody>
</table>
10^{12} Statistics: more than one muon at a time

✓ 1 ppm measurement $\rightarrow$ at least $10^{12}$ stopped muons.
✓ Each muon (or pion) enters target individually with pre– and post–quiet periods. Watch for decay positron and record its time.
✓ For $10^{12}$ muon, one need about $4 \times 10^7$ s $\ldots$ several years!
✓ To be practical, we need to observe several muons at once:

<table>
<thead>
<tr>
<th>Spatial separation: FAST</th>
<th>Bunched muons: MuLan</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$ arrive continuously into highly segmented timer/tracker; several events can overlap</td>
<td>Many muons arrive “at once” and decay into segmented detector</td>
</tr>
</tbody>
</table>
Muon Lifetime Techniques

✓ Burst of $N$ muons arrives during accumulation period $T_{acc}$
  ◇ Observe muon decays during measuring period of length $T_{meas}$
  ◇ No other muons arrive during this time
  ◇ Get another burst

✓ Ideally:
  ◇ A small $N \implies$ Reduces pileup
  ◇ $T_{acc} + T_{meas} \sim 32 \mu s \implies$ Cycles fast
Pulsed Muon Beam

✓ Collect handful of muons in a few $\mu s$

Accumulation Period

Kicker
$E = 0$

$\mu^+$

$\mu$ in target

Accum. Period

Time
Pulsed Muon Beam

✓ Turn off beam and watch them decay

$\mu^+$

Kicker
$E = 25 \text{ kV}$

Measurement Period

$e^+$

Accum. Period
Measurement Period

Time

$\mu$ in target
A Beam Rate > 12 MHz; Spot at target, only few cm$^2$.
Separator leaves about 5–10% positron background.
Many elements to tune. Tricky to have a straight beam.
Extinction fraction looks reasonable.
The Final transport through helium.
Kicker Time-line

Collection period ≈ 5 μs

RT ≈ 45 ns risetime

FT ≈ 45 ns falltime

Observation Period = 10 τ ≈ 22 μs
Fast Kicker

✓ TRIUMF-built kicker

Extinction factor is quite subtle (seems momentum dependent) during Run 2004 > 1000 in during Beam test in 2005.

Some bad news too: We killed many MOSFETS in 2004. We ran with half of them, at lower voltage.
Fast Kicker

✓ TRIUMF-built kicker
  ◇ ~45 ns rise/fall time,
  ◇ ± 25 kV swing,
  ◇ two 75 cm plates

Some bad news too:
- We killed many MOSFETs in 2004.
- We ran with half of them, at lower voltage.
Fast Kicker

- TRIUMF-built kicker
  - ~45 ns rise/fall time,
  - ± 25 kV swing,
  - two 75 cm plates

- Extinction factor
  - is quite subtle (seems momentum dependent)
  - ~ 300 during Run 2004
  - > 1000 in during Beam test in 2005.
Fast Kicker

✓ TRIUMF-built kicker
  ◊ ≈ 45 ns rise/fall time,
  ◊ ± 25 kV swing,
  ◊ two 75 cm plates

✓ Extinction factor
  ◊ is quite subtle (seems momentum dependent)
  ◊ ≈ 300 during Run 2004
  ◊ > 1000 in during Beam test in 2005.

✓ Some bad news too . . .
  ◊ We killed many MOSFETS in 2004.
  ◊ We ran with half of them, at lower voltage.
Scintillators: 32-sided, soccer-ball geometry

The complete detector has 30 active “houses”, with 170 tile pairs
The Crew
Impact of muon spin rotation ($\mu$SR)

- The muon beam is polarized $\Rightarrow$ muon precesses in magnetic field
- Decay $e^+$s are preferentially emitted in the direction of the $\mu^+$ spin.
- Residual polarization effects will produce direction-dependent distortions in the $\mu^+$ lifetime histograms.
- Pointlike symmetric geometry
  - Fit $F + B$
  - Monitor $F - B$
The muon beam is polarized

$\mu^+$ precesses in magnetic field

Decay $e^+$s are preferentially emitted in the direction of the $\mu^+$ spin.

Residual polarization effects will produce direction-dependent distortions in the $\mu^+$ lifetime histograms.

Pointlike symmetric geometry

- Fit $F + B$
- Monitor $F - B$
Impact of muon spin rotation ($\mu$SR)

- **Silver**
  - Preserves muon polarization (100%)

- **Sulfur**
  - Residual polarization (8%)

- **Arnokrome-3 (AK3)**
  - (30% chromium, 10% cobalt, 60% iron)
  - Internal Field $\approx 1$ T
  - No observable precession frequency up to 320 MHz or $<B> = 2.4$ T
Double-Pulse Resolution - Hit Pileup

detector modularity:
170 tile pairs

new electronics:
500 MHz wave form digitizers
During beam-off period sneaky muons lead to time dependent background

high rate (MHz), thin, fast (30 ns FWHM) wire chamber
Efficiency >95%, stable within 5%
Active Area $94 \times 100$ mm
First physics fits

(the clock timescale is only approx in ns . . . and they don’t know the offset)

All kicked data summed up without too much screening

\[ N(t) = N_0 e^{-\frac{t}{\tau}} + B \]

Better than 10 ppm and good, stable fits (so far)
Stability of fit parameters versus fit start time is a good barometer of fit quality.
Fit Stability

Also important, behavior of different detectors . . .
Fit Stability

... and by run number, but ...
Fit Stability

... These fits started about $1.8 \mu s$ after kicker off because of a nasty ripple in the data, probably from the kicker, but we are not sure yet ... we will figure it out

**Conclusion on data:**

We are hoping for a 5–10 ppm result by the end of the summer
MuLan Future plans

✓ June 2005:
  ◊ Beam Tuning:
    → Improve Rate
    → Improve Extinction Factor
  ◊ Many combinations were studied. Improvement achieved.

✓ Fall 2005:
  ◊ First Run with waveform digitizers
  ◊ New Run with the improved kicker

✓ 2006:
  ◊ Major production run with waveform digitizers
  ◊ Full proposed $O(10^{12})$ statistics
MuLan Collaboration

University of Illinois at Urbana-Champaign, USA (UIUC)
Boston University, USA (BU)
University of California, Berkeley, USA (UCB and LBNL)
University of Kentucky, Lexington, USA
James Madison University, USA (JMU)
KVI Groningen, Netherlands
Istanbul Technical University, Turkey
Paul Scherrer Institute, Villigen, Switzerland (PSI)