Precision measurement of the positive muon lifetime with a pulsed muon beam

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NP08 workshop Mito, 06.Mar.2008

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Outline

✓ Physics Motivation
✓ Intense pulsed beam method at RIKEN-RAL
✓ Data analysis
✓ Error estimation
✓ results
✓ Future prospects
✓ Summary
Physics motivation

- Precision measurement of $\tau_\mu$
- Precision determination of $G_F$ by the relationship:

\[ T^{-1} \equiv \frac{G_F^2 m_\mu^5}{192\pi^3} F \left( \frac{m_e}{m_\mu} \right) \left( 1 + \frac{3}{5} \frac{m_\mu^2}{M_W^2} \right) \left( 1 + \Delta q \right) \]

relation ambiguity $\rightarrow$ less than 1 ppm

- Determine one of the parameters in the weak sector of the Standard Model

<table>
<thead>
<tr>
<th>$\Delta \alpha / \alpha$</th>
<th>$\Delta G_F / G_F$</th>
<th>$\Delta M_Z / M_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.033 ppm</td>
<td>9 ppm</td>
<td>22 ppm</td>
</tr>
</tbody>
</table>

$\Delta \tau / \tau \sim 18$ ppm (PDG average, 2004)

$\alpha^{-1} = 135.03599911(46)$: electron anomalous magnetic moment, quantum hall effect etc

$M_Z = 91.1876(21)$: $Z \rightarrow l l Z$ lineshape scan at LEP 1
Muon lifetime measurement

✓ How to measure $\tau_\mu$

$\mu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$

~100 %

1. precisely measure positron emission timings (setup)
2. produce time spectrum (analysis)
3. fit by exponential function

→ Determine decay rate ($\tau$)

✓ Difficulty

• Measure timing difference distribution between one event and the next event without missing
• Precisely measure absolute timings
• Suppress systematic errors $< \Delta \tau/\tau$

✓ Status in 2004

✓ World record : 27 ppm (TRIUMF 1984 : when our experiment started)
Our first goal : $10^{10}$ decay observed -> 10 ppm precision in statistics

✓ Recently the World record have been improved -> PSI group (~11 ppm)
Previous measurement at PSI μLan

- Prior – PSI(2007)

**PRL 99(2007)032001**

\[ \tau = 2197.013(24) \text{ nsec (11ppm)} \]

- pulsed 10 counts/time window of ~27 μs (not so intense pulsed beam)
- improved the precision in TRIUMF
- overcome pile-up problem, measured by FADC
- high “constant?” background level
RIKEN-RAL experiment with a intense pulsed muon beam

✓ RIKEN-RAL (1998-)

More statistics with an intense pulsed muon beam (low background)

Establish the intense pulsed beam method

✓ Observe lots of muons at a time

✓ Overcome pile-up problem in the offline analysis

@ RIKEN-RAL

✓ Highly segmented detectors (MWPC)
  RAL: $10^6$ counts/sec*efficiency

✓ Numerical correction in the offline analysis

✓ Low background (Proton synchrotron)

No rate limitation in principle for an intense pulsed muon beam
RIKEN-RAL experiment

Experimental Setup

- setup summary
- setup overview

Data Analysis Procedure:

- MWPC analysis (wire correlation, multi-hit effect) with TDC module
- Background data analysis
- LM data analysis (for time spectrum),
- Count-loss correction
- Time spectrum fitting, fit region determination
- Estimation of statistical error
- Consistency test
- Estimation of systematic errors
New techniques in the RIKEN-RAL experiment

I  Increase of an event rate and reduction of the count-loss
   ✔  high intense pulsed muon beam (50Hz, 10^6/sec surface μ+)
   ✔  detector with the large number of segments : MWPC (192 segments)
   ✔  count-loss correction in the offline analysis

II  Muon stopping target selection (para-magnetic Holmium)
   ✔  minimize muon spin polarization effect, magnetic field dependence
   ✔  target with short relaxation time (rare earth magnet)

III Very accurate clock and data acquisition system (Newly developed)
   ✔  latching Memory synchronized with accurate GPS signal
   ✔  data acquisition system with 4 CAMACs in parallel.
Experimental setup at port-2 area

- Port-2 area
- Surface $\mu^+$
- $\sim 27$ MeV/c
- $\sim 4 \times 10^4$ muons/pulse
MWPC time spectrum analysis (1) – multi-hit effect

- MWPC multi-hit correlation analysis
  - A few MWPC wires are fired by one positron.
  - Real events and fake events are produced.
  - The total statistics becomes larger than the number of real events.

- In this case, two wires are fired

- Estimate this effect from the data
- Take this effect into account when estimating the statistical error

Positrons from the target

MWPC wire (anode wire)

chamber cell structure

Cathode plane

Cathode plane
Estimation of the multi-hit effect

- The hit timing difference between the base and nearest, second, third and fourth nearest neighbor wires are shown.
- Only the nearest neighbor wire has correlation (2 cluster-size).
- Duration of the peak center corresponds to the charge drift time of ~50 nsec.

Correlation ratio for all wires
Count-loss correction parameters - counter’s dead-time

Two input parameters from the data:

- mean hit rate: m
- counter’s dead-time: d

- easily calculated the mean hit rate
- dead-time determined by the data
- time difference data was fitted with a function:

\[
f_{\text{dead}}(t) = \left[ 1 - \frac{1}{1 + e^{-\frac{(t-t_0)}{t_z}}} \right] Ae^{-\frac{t}{t_m}}
\]

- dead-time: \( d \sim 150 \) nsec
**Time spectrum fitting**

- **Fit function and fit region**

\[ f(t) = A e^{-\frac{t}{\tau}} + B e^{-\frac{t}{\tau_{bg}}} + C \]

- **Decay positrons**
- **Background**

- **5 parameters fit**
- **Strong correlation**: \( \tau \approx \tau_{bg} \)
  - \( \sim \) worse the lifetime precision

\[ \tau_{bg} \approx 2.9 \times 10^4 \text{ nsec} \]

- **5 \times 10^{-5} \text{ counts/pulse}**
  - (cf. signal 200 counts/pulse)

**Time Spectrum after count-loss correction**

**Background Spectrum**

- **Fit start**
Application of the count-loss scheme to the experimental data

✓ Correct time spectrum for run-by-run for each wire
✓ Use a dead-time and mean event rate in a run

Muon Decay Time Spectrum after Count-loss Correction

Time spectrum after the correction

Fit reduced $\chi^2$ distribution before and after count-loss correction

Reduced $\chi^2$
Systematic error

The most largest systematic error is caused by detectors behavior: minimize sum of systematic and statistical errors

- fit start time $t_{\text{start}} = 3500$ nsec chosen

Data deviation from fit function (data / fit function)

Deviation from the fitting function (Observed spectrum / Fit Function)

Deviation from exponential (translated into relative error)
Fitting result

Muon decay time spectrum

deviation from the fitting function

2005 analysis (statistical)

\[ \tau_\mu = 2197.011 \pm 0.105 \text{ (51 ppm) [nsec]} \]

- fit start time \( t = 3500 \text{ nsec} \)
Estimation of the systematic Error

- unknown detector response (previously discussed -> -15.3 ppm)
- the setup (clock etc)
- residual spin polarization effect
- from the count-loss correction (d and m ambiguity)

<table>
<thead>
<tr>
<th>source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual distortion</td>
<td>-15.3ppm (only negative side)</td>
</tr>
<tr>
<td>Data rejection</td>
<td>&lt;1ppm</td>
</tr>
<tr>
<td>Correction (dead-time)</td>
<td>&lt;1.24 ppm</td>
</tr>
<tr>
<td>Correction (mean hit rate)</td>
<td>&lt;1.99 ppm</td>
</tr>
<tr>
<td>Clock</td>
<td>&lt;1 ppm</td>
</tr>
<tr>
<td>Spin Polarization</td>
<td>0.1 ppm(〜3500 nsec)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-15.3ppm/+2.77ppm</strong></td>
</tr>
</tbody>
</table>
Analysis Result

• Result in 2005

\[ \tau_\mu = 2197.01 \pm 0.11 \text{(Statistical)}^{+0.006}_{-0.034} \text{(systematic)} \]

\[ G_F = (1.166372 \pm 0.000029) \times 10^{-5} \text{ GeV}^2 \text{ (25ppm)} \]

- Obtained 2005 (preliminary) : 51 ppm (mainly statistical error)
- Consistent with a PDG average
- Not improve the PSI result in 2007
- Now, re-analysis of some parts about LM
- Fit start time (possibly earlier) -> improve slightly
- The last stage -> difficult to improve the prior experiment ????
Achievements and Problems at RAL experiment

Achievements
✓ establish the new method with an intense pulsed muon beam high segmented detector (MWPC, 192ch) was employed
✓ new techniques such as target system, clock system, DAQ was successfully worked in this experiment
✓ observed a number of muon decay, $\sim 1.15 \times 10^{10} (t>0)$
✓ solved pile-up problem by the new numerical correction method in the offline analysis
✓ achieved “low background” measurement, S/B $\sim 5 \times 10^{-5}$

This “RIKEN-RAL pulsed method” is an important milestone to the future muon lifetime measurement with a very high intense pulsed muon beam.

Problems in the RIKEN-RAL R77 experiment
✓ multi-hit problem of the wire chamber
✓ Large count-loss due to the long dead-time of $\sim 150$ nsec
✓ LM pattern convert to the time spectrum
✓ detector control, stability for a short range and for a long range
For the future muon lifetime measurement
Beam structure

- expect low background (due to the proton beam accelerator)
- long interval (beam waiting time is long)
- muon lifetime x 50 times is enough

- not so intense pulsed beam, high repetition, high integrated beam intensity
Detector selection

- Short dead-time (reduce pile-up event, less dead-time ambiguity effect)
- Long term stability
- High segments

- naive count-loss estimation

- Assumed short dead-time counters (d=15nsec) scintillator?
- pile-up error can be smaller even if the event rate is 4 times larger.

Pile-up correction
- RIKEN-RAL method
  (numerically corrected, essential to the parameter precision)
- PSI method
  (correction from the pulse height information)

Both method is effective, better to cross-check
Naïve beam time estimation

- Assumed the same event rate at RKEN-RAL exp
- Assumed that solid angle is increased

\[ N \approx (n \cdot \text{events/pulse}) \times (\text{dutyfactor}) \times (\text{beamtime}) \times \exp(-1\,\mu s/\text{lifetime}) \]

0.7

1\,\mu s delay
Summary

RIKEN-RAL R77 experiment
✓ The pulsed method was established
✓ Obtained 2005 (preliminary) : 51 ppm
✓ Consistent with a PDG average
✓ Not improve the PSI result in 2007
✓ This method is available for the future muon lifetime measurement with a pulsed muon beam, upgraded RAL facility and J-PARC etc.

For the future measurement
✓ The possibility of a new measurement of the positive muon lifetime is discussed
✓ detector is the key to improve the statistics at RAL (not a beam !)
✓ But, best condition is high repetition (~ kHz), high intensity (~ $10^5$ counts/spill) stable, short dead-time, quick response, fine segmented counter
✓ If we have a chance to use suitable muon beam for the lifetime measurement, we would like to perform this experiment applying to the pulsed muon beam method.