Experimental Search for LFV Muon Decay

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Topics to Cover

• No Experimental Program exists for $\mu^+ \rightarrow e^+ e^- e^+$

• $\mu^+ \rightarrow e^+ \gamma$ : The MEG Experiment
Transitions Between Generations

- b quark
- s quark
- muon
- electron
- muon neutrino
- electron neutrino

Mass

- GeV
- MeV
- meV

Standard Model CKM matrix verified at B factories

definite proof of “Beyond SM”

a possible hint of new physics (seesaw mechanism?)

\[ \mu \rightarrow e \gamma \]
The MEG Experiment

International Collaboration (~60 collaborators)

LXe Gamma-Ray Detector

Muon Beam

COBRA SC Magnet

Drift Chambers

Timing Counter

π E5 beam line @PSI
The $\mu^+ \rightarrow e^+ \gamma$ process

- clear 2-body kinematics
- need positive muons to avoid formation of muonic atoms
- accidental background limits the experiment

- DC beam, rather than pulsed beam, gives lowest instantaneous rate and thus lowest background
Accidental coincidence of $\gamma$ and $e^+$ is the main background

$\gamma$ ray measurement is most important!

must manage high rate $e^+$

radiative decay

Michel $e^+$
1.2MW Proton Cyclotron at PSI

Provides world’s most powerful DC muon beam
“Surface Muon” Beam Transport System

- $3 \times 10^7$ muons/sec stopped in 18mg/cm$^2$ polyethylene target (slanted by 20.5° from the beam) with 10mm spot size at the center of the spectrometer
- He environment inside the spectrometer to minimize scattering and background
The MEG Experiment

COBRA Magnet
Drift chamber

Muon Beam
Stopping Target
e^+
Timing counter

Liquid Xenon Scintillation Detector

Drift chamber
COBRA Positron Spectrometer

- thin-walled SC solenoid with a gradient magnetic field: 1.27 - 0.49 Tesla
Solenoid

$\mu^+$ beam

DC

emitted $e^+$

Uniform B-field

Gradient B-field

Low energy positrons quickly swept out

Constant bending radius independent of emission angles
Low-Mass Drift Chambers (DC)

- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5um thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- \(~2.0 \times 10^{-3} X_0\) along the positron trajectory
A Drift Chamber Module
A DC Module
Timing Counters

- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing
Liquid Xenon Photon Detector

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- fast response & high light yield provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- gas/liquid circulation system to purify xenon to remove contaminants

assembling the detector

placed at the beam line
Detector Performance Verified by Prototype

Position Resolution (σ in mm)

Energy Resolution

Timing Resolution (FWHM)
Pile-up Photon Removal

- Good position/timing resolutions enable to remove pile-up photons
- All the PMTs are read out by waveform digitizers (DRS2)
The 2008 Physics Run

• After the successful commissioning run at the end of 2007, the MEG detectors were started up again after the winter accelerator shut down.

• Physics run started in September after a long calibration run using pion charge-exchange reaction (CEX) in the summer.

• During physics run, special runs were frequently conducted to monitor and calibrate the detectors (CW, RMD).

• Another CEX calibration run was performed in December.
Pion Charge Exchange Reactions (CEX)

\[ \pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n \]

- negative pions stopped in liquid hydrogen target
- Tagging the other photon at 180° provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution: \[ \pi^0 \rightarrow \gamma e^+ e^- \]
- Conducted in August and December
Photon Detection Efficiency

- ~55MeV photon tagged by another photon measured by NaI on the opposite side
- agree well with simulation < 5%
- 66% within positron acceptance for 46 - 60 MeV
- CR/pile-up selection -9%

photon interacted before LXe
Monochromatic Photons from Nuclear Reactions

- Sub-MeV proton beam produced by a dedicated Cockcroft-Walton accelerator (CW) are bombarded on Li$_2$B$_4$O$_7$ target.

- 17.67MeV from $^7$Li

- 2 coincident photons (4.4, 11.6) MeV from $^{11}$B: synchronization of LXe and TC

- Short runs three times a week
Drift Chamber Instability

• DC started to show frequent HV trips after 2-3 months of operation
  ➡ Increasing # DCs had to be operated with reduced HV settings

  • Reduced efficiency & resolution for positron measurement
  • Problem due to long-term exposure to helium (no gas aging)

  • The DC instability uncertainty cancels out in the $\mu^+ \rightarrow e^+\gamma$ analysis:
    \[ \text{BR} = \frac{\# \mu^+ \rightarrow e^+\gamma}{\# \text{Michel}} \]

• The DC modules have now been modified and showed no problem; two of them have been successfully operated for 6 months

HV trip reproduced in the lab
We continued to purify the LXe during the run, carefully monitoring the increasing light yield with various calibration tools (CW, alpha sources, LED, cosmic ray).

Resulting overall energy scale uncertainty during the whole run period: ~0.4%

The light yield at the end of run was still ~70% of the expectation. (Fully recovered this year)
Blind & Likelihood Analysis

- Events falling into a pre-defined “Blinding Box” were written to a separate stream and not used to study the background and optimize analysis.

- “Analysis Box” was also defined for likelihood analysis.

All the preselected events are shown.
Photon Energy

- absolute energy scale determined by CEX runs (55MeV photons)

- average upper tail resolution for deep conversions (> 2cm):
  \[ \sigma_R = 2.0 \pm 0.15\% \]

- systematic uncertainty on energy scale: 0.5%

scale & resolutions verified by RMD (+AIF) spectrum
Position Dependence of Energy Resolution

position dependent response before calibration
Positron Momentum

- Positron energy scale and resolution are evaluated by fitting the kinematic edge of the Michel positron spectrum at 52.8MeV

- Resolution function of core and tail components:
  - core = 374keV (60%)
  - tail = 1.06MeV (33%), 2.00MeV (7%)

Table 5: Results of the fit of the positron spectrum in data events for the range of 51 < E < 55 MeV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{acc}}$ (MeV)</td>
<td>51.3 (fixed)</td>
</tr>
<tr>
<td>$\sigma_{\text{acc}}$ (MeV)</td>
<td>3.32 (fixed)</td>
</tr>
<tr>
<td>$\mu_{\text{core}}$ (MeV)</td>
<td>0.206 ± 0.005</td>
</tr>
<tr>
<td>$\sigma_{\text{core}}$ (MeV)</td>
<td>0.371 ± 0.010</td>
</tr>
<tr>
<td>$f_{\text{core}}$</td>
<td>0.607 ± 0.018</td>
</tr>
<tr>
<td>$\mu_{\text{tail}}$ (MeV)</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>$\sigma_{\text{tail}}$ (MeV)</td>
<td>1.07 ± 0.03</td>
</tr>
<tr>
<td>$f_{\text{out}}$</td>
<td>0.07 (fixed)</td>
</tr>
<tr>
<td>$\mu_{\text{out}}$ (MeV)</td>
<td>0.0 (fixed)</td>
</tr>
<tr>
<td>$\sigma_{\text{out}}$ (MeV)</td>
<td>2.0 (fixed)</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f</td>
<td>88/95</td>
</tr>
</tbody>
</table>

Figure 10: Result of the fit of the positron spectrum in data events for the range of 51 < E < 55 MeV.
• Angular resolutions were evaluated by the double turn tracks inside the DC

Angular resolution is estimated by doubly curling track. Subtracted angular residual of each turn gives intrinsic angular resolution.

Taking the $z$-axis as the beam-axis, $\theta$ is defined as the polar angle, while $\phi$ is the azimuthal angle.

$\sigma = 18 \text{ mrad}$

$\sigma = 10 \text{ mrad}$
Muon Decay Position

- Evaluated by the holes of the muon stopping target and the double-turn tracks: 3.2 - 4.5 mm
Photon Conversion Position

- Resolution for photon conversion position was evaluated by CEX run with PB collimators
- ~ 5mm
Positron - Photon Timing

- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence:
  \[ \sigma_{t_{e\gamma}} = 148 \pm 17 \text{ps} \]
  stable < 20ps
Time Resolution of LXe Detector

- Dependent on the light yield (~energy)
- Has improved during the 2008 run.
Blinding Box was Opened on July 30th

- Several systematic checks are still being carried out - So the following results should be regarded as preliminary.

- “Feldman-Cousins” approach was adopted for likelihood analysis.

  - The average expected 90% CL upper limit on BR assuming no signal: \( \sim 1.3 \times 10^{-11} \)

  - The 90% CL UL obtained for the side-band data (no signal): \( (0.9 - 2.1) \times 10^{-11} \)

  - Sensitivity limited by the data statistics: \( \sim 5 \) times more data expected for data taking 2009

  cf. The present 90% CL UL by MEGA is \( 1.2 \times 10^{-11} \)
Maximum Likelihood Fit

\[
\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}} \exp^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[ \frac{N_{\text{sig}} S + N_{\text{RMD}} R + N_{\text{BG}} B}{N} \right]
\]

\[N_{\text{obs}} = 1189\]

\[N_{\text{sig}} < 14.7 \text{ @90\% CL}\]

\[N_{\text{RMD}} \text{ consistent with sideband estimate: } 25_{-16}^{+17}\]
Normalization to Observed $\#$ Michel Decays

$$\text{BR}(\mu^+ \to e^+ \gamma) = \frac{N_{\text{sig}}}{N_{e\nu\bar{\nu}}} \times \frac{f^E_{e\nu\bar{\nu}}}{P} \times \frac{\epsilon^{\text{trig}}_{e\nu\bar{\nu}}}{\epsilon_{e\gamma}} \times \frac{A^{TC}_{e\nu\bar{\nu}}}{A^{TC}_{e\gamma}} \times \frac{\epsilon^{DC}_{e\nu\bar{\nu}}}{\epsilon_{e\gamma}} \times \frac{1}{A^{LX}_{e\gamma}} \times \frac{1}{\epsilon_{e\gamma}}$$

$\approx 1$

- Nsig normalized to Michel positrons counted simultaneously with the signal.
- Independent of instantaneous beam rate and insensitive to positron acceptance and efficiency.
Various Checks on Normalization

- Expected vs. measured rate of the background photons
The Preliminary 2008 Data Result

\[ \text{BR}(\mu^+ \rightarrow e^+ \gamma) < 3.0 \times 10^{-11} \]

After the selection cuts on the other variables where 90% of the signal events remain after each cut.
Prospects for the 2009 Run

• Sensitivity is limited by data statistics with the expected detector performance

• Up to 5 times more data expected => up to 5 times better sensitivity
  
  • Positron efficiency: the DC modules operating for 6 months - no problem
  
  • Trigger efficiency: TC fiber detector with improved electronics

• More DAQ live time and less time needed for calibration

• Better performance expected also for LXe with the increased light yield and the new wave form digitizer (DRS4)
Summary and Prospects of MEG

• Data taken during the first startup period in 2008 have yielded a 90% CL upper limit
  \[ \text{BR}(\mu^+ \rightarrow e^+\gamma) < 3.0 \times 10^{-11} \]
  while the expected 90% sensitivity was
  \[ 1.3 \times 10^{-11} \].

• The drift chambers have now been modified to solve the problems and two of
  them have been successfully operated for 6 months. Following minor maintenance,
  the LXe detector is now operating and shows improved light yield (x ~1.4).

• MEG will resume data taking in late September; It is expected to reach a ~5
  times better sensitivity (~2.4 x 10^{-12}) by the end of the year. Two more years will
  be required to accomplish a 10^{-13} sensitivity goal.