The final result of $\mu^+ \rightarrow e^+ + \gamma$ decay with the MEG experiment

Daisuke Kaneko
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2. MEG Instruments
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1. What is $\mu \rightarrow e\gamma$ Decay
Flavor of Particles

Quark
1
2
3
u
c
t
d
b

Lepton
1
2
3
e
μ
τ

CKM Matrix

NOBEL PRIZE
2008

NOBEL PRIZE
2015

Oscillation

Ve
Vτ
Charge: -e
Spin: 1/2
Rest mass: 105.6 MeV
Mean life: 2.197 µs

Decay:
mode (branching ratio)
\[ e^+ \bar{\nu}_\mu \nu_e \ (\approx 100\%) \]
\[ e^+ \bar{\nu}_\mu \nu_e \gamma \ (1.4\% \ (E\gamma > 10\text{MeV})) \]

Lepton flavor violating modes have never been observed!
Forbidden in Standard Model (Lepton flavor conservation law)

It is possible, with neutrino oscillation, probability is $< 10^{-50}$
no exist practically

New theories beyond the SM predict sizable probability
- see-saw mechanism
- SUSY-GUT
- etc.

$\mu \rightarrow e \gamma$ via $\nu$-oscillation

$\mu \rightarrow e \gamma$ via SUSY particle
History of $\mu \rightarrow e \gamma$ search

1936
Discovery of $\mu$

1947
First search with cosmic-ray
"$\mu$ is not an excited state of $e$"

1950s
$\mu \rightarrow e\gamma$ search with accelerator

1970s
Search with meson factories
"Concept of lepton flavor"
Rumor of discovery, but not true

Crystal Box: $1.7 \times 10^{-10}$ 1984 @ LAMPF

MEGA: $1.2 \times 10^{-11}$ 1999 @ LAMPF
$10^{-12} \sim 10^{-14}$ is predicted

Antusch et al.,

SUSY SU(5) + seesaw
different colors correspond
different $\theta_{13}$ value
(already discovered to be $\sim 9^\circ$)

L. Calibbi et al.

SO(10) + seesaw
green : PMNS case, red : CKM case
tan$\beta = 10$, as function of $M_{1/2}$

before MEG

MEG(2013)
Signal & BackGround

★ Signal
52.8 MeV = m_μ /2, back-to-back, at the same time.

● BackGrounds
  ○ Radiative Muon Decay (RMD) \( \mu^+ \rightarrow e^+\bar{\nu}_\mu \nu_e \gamma \)
  ○ ACCidental BG (ACC)
    - e^+ from normal \( \mu^+ \) decay
    - γ from RMD or annihilation of e^+

<table>
<thead>
<tr>
<th>Type</th>
<th>Eγ</th>
<th>Ee+</th>
<th>Time</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>52.8 MeV</td>
<td>52.8 MeV</td>
<td>( T_e = T_\gamma )</td>
<td>180°</td>
</tr>
<tr>
<td>RMD</td>
<td>&lt;52.8 MeV</td>
<td>&lt;52.8 MeV</td>
<td>( T_e = T_\gamma )</td>
<td>≤180°</td>
</tr>
<tr>
<td>ACC</td>
<td>&lt;52.8 MeV</td>
<td>≤52.8 MeV</td>
<td>uniform</td>
<td>no correlate</td>
</tr>
</tbody>
</table>
2. MEG Instruments
Location of experiment
PSI experimental hall

Main proton ring cyclotron
590 MeV, 2.4 mA (@2013)
Inside of the detector

Characteristics

- Total 900 l liquid Xe
- C-shaped cryostat
- 846 PMTs on 6 faces
- Honey-comb window at γ-ray entrance face
- Cooled with pulse tube refrigerator
- 2 kinds of purification systems equipped

200 W pulse tube refrigerator

Liquid purifier
COBRA magnet

Design
- Gradient field
- NbTi/Cu SC magnet
- Thin for γ-ray transmission
- Cooled by GM refrigerator

\[ e^+ \text{ emitted in } \theta \sim 90 \]

\[ \theta \text{ vs radius of track} \]

Gradient B-field
- Reduce pile up
- Low momentum \( e^+ \)s are isolated

Compensation coil (NC)
- Central coil
- Gradient coil
- Inner-end coil
- Outer-end coil
- GM cooler
Drift chamber: e^+ tracker

Interaction of e^+ and matter:
- Multiple scattering → Worsens angular resolution
- Pair annihilation → Generate γ-ray background

High-rate tolerance:
- High rate μ^+s in beam eventually decay into e^+s.

Ultra-low mass tracker

16 modularized detector in φ direction

Detector locate only at large R
e$^+$ timing counter

$\phi$ counter
- BC404 scintillator
  4\(\times\)4\(\times\)79.6 cm$^3$
  15 bars on each side
- PMT read-out on both end
  (Fine mesh type)

$z$ counter
- BCF-20 scintillation fiber
  Total 256 pcs.
- APD readout at one end
  (※$z$ counter is not used)

Roll of timing counter
- Precise measurement of e$^+$ hit time
- Provide information for trigger
Electronics

Typical chain:
- Sensor
- Active splitter
- Trigger
- DRS
- Online computers
  - Data size: $\sim 1$ MB/event

Trigger:
- Make trigger information with FPGA by fast event reconstruction
  - $\gamma$ energy
  - Timing $\gamma$-e$^+$
  - Angle $\gamma$-e$^+$
- Trigger rate: $\sim 13$ Hz

DRS:
- Waveform digitizer developed in PSI
- Sampling speed: 1.4GHz (DCH: 0.7GHz, Max. 5GHz)

MIDAS system:
- System to control DAQ and slow-control with Ethernet, by PSI.
3. Analysis and Result
History of MEG

- **2000**
  - design
  - 1999 PSI proposal Approval

- **2004**
  - construction
  - 2007 Detector Complete

- **2008**
  - data taking
  - 2010 Nucl. Phys. B 834 1
  - $2.8 \times 10^{-11}$ (90%CL)

- **2012**
  - $2.4 \times 10^{-12}$ (90%CL)

- **2016**
  - final
  - 2013 Phys. Rev. Lett. 110, 201801
  - $5.7 \times 10^{-13}$ (90%CL)

Data amount 93 TB
DAQ time 288 days
# of run 124156
(~2000 event/run)
# of stopped $\mu^+$ 7.5 $\times 10^{14}$
Firstly, apply pre-selection in order to obviously accidental events.

Then, detailed calibration is done on passed events.

Event selection is defined as,

\[ 48 < E_\gamma < 58 \text{ MeV} \]
\[ 50 < E_e < 56 \text{ MeV} \]
\[ |t_{e\gamma}| < 0.7 \text{ ns} \]
\[ |\theta_{e\gamma}| < 50 \text{ mrad} \]
\[ |\phi_{e\gamma}| < 75 \text{ mrad} \]

Region \( |t_{e\gamma}| < 1.0 \text{ ns} \) is blinded at first. Parameter for physics analysis is determined by outside (sideband) events.
Definition of MEG likelihood function

\[
\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{ACC}}) = \frac{e^{-N}}{N_{\text{obs}}!} C(N_{\text{RMD}}, N_{\text{ACC}}) \times \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}} S(\bar{x}_i) + N_{\text{RMD}} R(\bar{x}_i) + N_{\text{ACC}} A(\bar{x}_i))
\]

extended likelihood
constraint term

\[N = N_{\text{sig}} + N_{\text{RMD}} + N_{\text{ACC}}\]

\[N_{\text{obs}}: \text{Event number in window}\]
\[\bar{x}: (E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}; t)\]
\[S, R, A: \text{(Probability Density Function)}\]
\[C: \text{Constrain } N_{\text{RMD}} N_{\text{ACC}} \text{ around expectation in side band}\]

Best fit value is defined by such that maximized likelihood function
Confidence interval is determined with Feldman-Cousins approach, setting Nsig as the main parameter, and profiling out the others.
PDF

Probability to find the observable to be the value when each type of event happens.

Determined from sideband data (partially Monte Carlo simulation)

All known correlations between observables, detector position etc. are corrected.

event-by-event PDF
Shape of function changes, according to Error in reconstruction
Position in detector
Correlation

Examples in certain events
Normalization

A constant to convert event number into $\mu^+ \rightarrow e^+\gamma$ branching ratio

$$B(\mu^+ \rightarrow e^+\gamma) = \frac{N_{\text{sig}}}{k}$$

$k$ is considered to be a number of events multiplied with detector acceptance and detection efficiency.

There are independent 2 ways, Michel positron way and RMD way. Final value is given by combining two.

Both ways do not need $e^+$ detection efficiency.

For all statistics of MEG data,

$$k = 1.71 \pm 0.06 \times 10^{13}$$
positron AIF recognition
(Annihilation in Flight)

Tag one of the sources of γ-ray, “positron AIF”

A. Recognize interrupted e⁺ track in drift chamber
B. Estimate γ-ray momentum from the track
C. Calculate angle difference between estimation and observation
Sharp peak in $\Delta \theta_{\text{AIF}}, \Delta \phi_{\text{AIF}}$ distribution is really tagged AIF events. Cut events near peak.

**Method:**
1. Fit 2D distribution $\Delta \theta_{\text{AIF}}, \Delta \phi_{\text{AIF}}$ with combination of 2D Gaussian function. (2 peak and 1 base component.)

2. Remove events within 0.7σ from either of the peaks, as they are likely to be AIF Accidental BG.

**Impact:**
No significant improvement in sensitivity. Insurance for AIF event to come near center of window.
Search sensitivity

Histogram of upper limits of many Toy MCs which do not contain signal.

<table>
<thead>
<tr>
<th>Data set</th>
<th>2009-2011</th>
<th>2012-2013</th>
<th>2009-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k \times 10^{12}$</td>
<td>8.15</td>
<td>8.95</td>
<td>17.1</td>
</tr>
<tr>
<td>Sensitivity $\times 10^{-13}$</td>
<td>8.0</td>
<td>8.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Arrows are limit from time sideband (-2.0ns, +2.0ns)
$8.4 \times 10^{-13}$, $8.3 \times 10^{-13}$

Previous publication (2009-2011) Sensitivity was $7.7 \times 10^{-13}$
Understandable, considering the changes in analysis.
Event distribution

Excess of the signal is not seen.

2009-2013 full data

\[ E_\gamma \text{ (MeV)} \]

\[ E_e \text{ (MeV)} \]

\[ t_\gamma \text{ (ns)} \]

\[ \cos\Theta \text{ (e\gamma)} \]

\[ \cos\Theta < -0.99963 \ (90\% \ \varepsilon_{\text{signal}}) \]

\[ |t_{\text{e\gamma}}| < 0.2443\text{ns} \ (90\% \ \varepsilon_{\text{signal}}) \]

\[ 51 < E_\gamma < 55.5 \text{ MeV} \ (74\% \ \varepsilon_{\text{signal}}) \]

\[ 52.385 < E_e < 55 \text{ MeV} \ (90\% \ \varepsilon_{\text{signal}}) \]

Contours show averaged signal PDF (1\(\sigma\), 1.64\(\sigma\), 2\(\sigma\))
Fit result

2009-2013 full data

- data
- ACC
- signal (500 events)
- sum
- RMD

Data and projected PDF agree well.

<table>
<thead>
<tr>
<th>Data set</th>
<th>2009-2011</th>
<th>2012-2013</th>
<th>2009-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>best fit $B$ ($\times 10^{-13}$)</td>
<td>-1.3</td>
<td>-5.5</td>
<td>-2.2</td>
</tr>
</tbody>
</table>

$R_{\text{sig}} = \frac{S(x_i)}{0.07R(x_i) + 0.93A(x_i)}$
Consistent with no signal assumption

<table>
<thead>
<tr>
<th>Data set</th>
<th>2009-2011</th>
<th>2012-2013</th>
<th>2009-2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$ 90% UL ($\times 10^{-13}$)</td>
<td>6.1</td>
<td>7.9</td>
<td>4.2</td>
</tr>
<tr>
<td>Sensitivity ($\times 10^{-13}$)</td>
<td>8.0</td>
<td>8.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>

In previous result, $5.7 \times 10^{-13}$ with 2009-2011 data. Consistent including change in analysis.

CL curve with 2009-2013 data (Ratio of ToyMC with $\lambda_p^{MC} < \lambda_p^{data}$)
MEG I summary

MEG experiment has searched in regime of new physics.

New upper limit for $\mu \rightarrow e\gamma$ is 30 times better than that before MEG.
4. MEG II experiment
MEG II experiment

MEG was no linger BG-free experiment, how to go further?

A. Increase statistics
   A-1 Increase beam intensity $\times 2$
   A-2 Improve detector efficiency $\times 2$

B. Improve detector resolutions
   $E_\gamma, E_e, \text{Angle, Timing} \div 2$ for all components

Aiming at one order of magnitude higher sensitivity.
Please listen to talks in this JPS meeting!

MEG II general: 22pL402 4 (yesterday)  
内山

LXe detector: 25aK206 1–3  
小川、松澤、小林

Timing counter: 25aL401 2–5  
宇佐美、中尾、西村、恩田
# MEG II prospects

<table>
<thead>
<tr>
<th>Specification</th>
<th>MEG I</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam intensity (/s)</td>
<td>$3 \times 10^7$</td>
<td>$7 \times 10^7$</td>
</tr>
<tr>
<td>Resolutions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E\gamma$ (% w&gt;2 / w&lt;2)</td>
<td>2.4/1.7</td>
<td>1.1/1.0</td>
</tr>
<tr>
<td>$\gamma$ pos. (mm, u/v/w)</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>$Ee$ (keV)</td>
<td>380</td>
<td>130</td>
</tr>
<tr>
<td>$E$ pos. (mm, z/y)</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>$\theta e\gamma/\phi e\gamma$ (mrad)</td>
<td>9.4/8.7</td>
<td>5.3/3.7</td>
</tr>
<tr>
<td>$te\gamma$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
<tr>
<td>Efficiencies (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>trigger</td>
<td>&gt;99</td>
<td>&gt;99</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>$e^+$</td>
<td>30</td>
<td>70</td>
</tr>
</tbody>
</table>

## R&D
- 2013 Upgrade proposal approve
- ←2012

## Assembly
- 2018 upgrade complete
- ←2016

## DAQ
- 3 years
- ←2020

sensitivity $6 \times 10^{-14}$
5. My Current Project
My current project is

Cosmic Microwave Background

If low-\(\ell\) B-mode polarization is found, it’s a decisive evidence of the Inflation theory!

Multiplicity moment \(\ell\)
(Fineness of the patterns)
Upgrading work is proceeded to experiment with 3 POLARBEAR-2 receiver at Atacama, Chile.

6 times more TES detectors
2 frequencies to remove FG

me, working for optical validation tests
## Differences (personal feeling)

<table>
<thead>
<tr>
<th></th>
<th>MEG</th>
<th>PB/SA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Collab. size</strong></td>
<td>~100 people</td>
<td>~100 people</td>
</tr>
<tr>
<td><strong>Goal</strong></td>
<td>Beyond SM (of particle)</td>
<td>Beyond SM (of cosmology)</td>
</tr>
<tr>
<td><strong>Site</strong></td>
<td>Switzerland (German)</td>
<td>Chile (Spanish)</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td>MeV</td>
<td>meV</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>ns</td>
<td>ms</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>100K</td>
<td>100mK</td>
</tr>
<tr>
<td><strong>Data type</strong></td>
<td>Triggered</td>
<td>Continuous</td>
</tr>
<tr>
<td><strong>Coding</strong></td>
<td>C++</td>
<td>python</td>
</tr>
</tbody>
</table>

Many differences, but I hope more people from high-energy.
Summary

MEG experiment is searching for $\mu^+ \rightarrow e^+ \gamma$, evidence of the physics beyond the standard model of particle.

MEG experiment has been finished and we published final result. (Eur. Phys. J. C, 76(8), 1-30) New limit $4.2 \times 10^{-13}$ is 30 times more stringent than previous experiment.

Preparation for MEG II experiment is underway, aiming at one order of magnitude better sensitivity. (arXiv:1801.04688)

Please look forward the results from CMB experiment. Today’s afternoon, 23pK 307
Thank you for your listening