MEG 実験の最新結果

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Outline

- Motivation
- MEG Experiment
- MEG Detector
- Calibration & monitoring
- Performance in 2009
- Result in 2009
- Plan and prospects
Motivation

- LFV is forbidden in the Standard Model, and even if the neutrino mass is taken into account, the charged LFV branching ratio ($\mu \rightarrow e\gamma$) is almost zero.
- Charged lepton flavor violation is a clear evidence of physics beyond the SM.
- New physics like SUSY-GUT, SUSY-seesaw predicts measurable LFV just below the current limit.

![Diagram showing LFV process]
Motivation

- Current experimental bound is set by MEGA
  - $\text{Br}(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11}$
- MEG goal: $\text{Br}(\mu \rightarrow e\gamma) \sim \text{a few } x \times 10^{-13}$
- Real chance to discover new physics
Signal and Background

- Positive $\mu$ decay at rest
- Clear two body kinematics
- Back to back ($\theta_{\text{e}\gamma}=180^\circ$)
- $E_e \approx E_\gamma = 52.8\text{MeV}$
- Coincident ($T_{e\gamma}=0$)

Background

Accidental background is dominant
Michel $e^+ + \text{random } \gamma$

$\gamma$ BG

Good detector performance is essential (especially, $E_\gamma$)
High rate $e^+$ measurement with intense $\mu$ beam
Pileup rejection is necessary

$B_{\text{acc}} \propto \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \theta_{e\gamma})^2 \cdot \delta t_{e\gamma}$

$11aSA-6$: MEG 実験 背景ガンマ線の研究 澤田龍
PSI accelerator and MEG beamline

- 1.3MW most intense proton accelerator at PSI in Switzerland
- DC muon beam $3 \times 10^7 \mu/s$ (possible up to $\sim 1 \times 10^8 \mu/s$)
  - DC beam is suitable to reduce accidental background
MEG Experiment

- High precision low mass positron spectrometer
  - SC magnet and low mass drift chamber, timing counter
- High performance photon detector
  - 900 liter liquid xenon + 846 PMTs
- Waveforms of all detectors are recorded by waveform digitizer
  - Essential for pileup reduction
MEG history

- 1999: Proposal to PSI
- 2007: all detectors ready
- 2008: 78 days physics runs
  - Positron detection efficiency (~1/3), sensitivity ~1.3x10^{-11}
  - $\text{Br}(\mu^+ \rightarrow e^+\gamma)<2.8x10^{-11} (90\% \text{C.L.})$, Nucl.Phys.B834(2010)1-12
- 2009: 43 days physics runs
  - Other experiment used our beamline, repair work for positron spectrometer
- 2010: physics run restarted in August
  - 10 days CEX calibration at the end of August, 117 days physics run expected

MEG Collaboration
~70 physicists from Japan, Switzerland, Italy, Russia and USA
MEG Detector
Liquid Xenon Detector

- 900 liter liquid xenon
- 846 2” PMTs (Hamamatsu R9869)
  - immersed in LXe directly
- Good uniformity (homogeneous, liquid)
- High light output (~75% of NaI)
- Short decay time (45ns)
- High density (3g/cm³)
- Short scintillation wavelength ~ 175nm
  - Quartz window for PMT
- Low temperature 165K
  - pulse tube cryocooler developed by KEK
- Purification to remove H₂O, O₂, N₂ etc.

13pSM-3: MEG 実験 液体キセノン検出器の性能：白雪
Positron spectrometer

- SC magnet produces special gradient magnetic field, 1.27(at z=0) ~0.49Tesla
  - To sweep out low momentum e^+
- Timing counter (T_e, \sigma_T < 50ps)
  - Plastic scintillator + fine-mesh PMTs
  - Scintillating fiber + APD

- Drift chamber (E_{e^+}, \theta_{e^+}, \phi_{e^+})
  - 16 segmented chambers radially
  - Position resolution ~ 200\mu m(r), 500\mu m(z)
  - Momentum resolution ~ 1%
  - Low material budget (low multiple scattering, low \gamma background)
Drift chamber

- **2008**
  - Discharge problem reduced $e^+$ detection efficiency and resolution for positron measurement
    - $\varepsilon \sim 14\% (~1/3)$, $\sigma_\varepsilon$, $\sigma_{\theta\phi}$ were worse
  - The problem was long term exposure to helium, fixed before physics run in 2009

- **2009**
  - $e^+$ detection efficiency ($30\sim40\%$, including TC matching) and resolutions improved
Timing counters

- Two layers of scintillators at each end of spectrometer
  - outer: plastic scintillator + PMT ($\phi$, $z$)
  - Inner: scintillating fiber + APD ($z$)
- Measure the positron impact position and the precise timing for both trigger and physics analysis
Electronics and trigger

• Waveform digitizer(DRS4)
  - Up to 5GHz sampling speed, 12bits resolution
  - Essential to remove pileup events
  - 1.6GHz sampling for XEC, TC
  - 0.8GHz sampling for DC

• MEG trigger
  - Built on FADC-FPGA architecture
  - LXe total charge & TC total charge
  - Direction match & timing coincidence
  - 6Hz DAQ rate during MEG run
Calibration and Monitoring
XEC detector

- PMT gain monitored by LED, QE by $\alpha$
- Light yield monitoring (CW, CR, AmBe etc.)
- Cockcroft-Walton proton accelerator
  - 17.6MeV $\gamma$ by Li(p,$\gamma$)Be reaction
  - Light yield monitoring & $\sigma_E$ at 17.6MeV

2008 physics run and shutdown:
gaseous purification to increase light yield
Light yield became as much as expected
And decay time of $\gamma$ waveform changed

2009 physics run: no purification
Light yield monitoring: < 1% level
CEX calibration ($E_\gamma, T_\gamma, XY_\gamma$)

- $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$ (CEX reaction)
  - 55, 83MeV $\gamma$s are available once back-to-back photons are selected
  - Energy close to our signal (52.8MeV)
- Tagging detector - NaI + APD array
- LH$_2$ target
- $\pi^0 \rightarrow e^+e^-\gamma$ (Dalitz decay) for absolute time offset measurement

- Energy, timing, and position resolution
  - 2.1%(depth>2cm), >68ps, 5mm(XY), 6mm(depth)
- Position dependence by moving NaI
- Signal response function
- $\gamma$ efficiency: 58%
Positron resolution

- Resolution and signal response can be extracted from residuals of two turn tracks
  - Momentum resolution
    - $\sigma_E \sim 0.74\%$ core
  - Angle resolution
    - $\sigma_\phi \sim 7.1\text{mrad (core)}$
    - $\sigma_\theta \sim 11.2\text{mrad}$
- Background spectrum
  - Michel spectrum fit smeared by detector resolution
  - Double Gaussian plus acceptance
Radiative muon decay ($T_{e\gamma}$)

- Relative timing resolution can be estimated directly by physics data (RMD)
  - Coincident, not back-to-back, $\gamma$ low energy
  - $\sigma_{Te\gamma}$ consists of each detector resolution, tracking ambiguity etc.
  - Good test to detect $\mu \rightarrow e\gamma$ events, and possible to measure $\sigma_{Te\gamma}$ directly
  - Can be also used to check overall detection efficiency

- $\sigma_{Te\gamma} \sim 142$ ps (core)
Relative angle \((\theta_{e\gamma}, \phi_{e\gamma})\)

- Relative angle resolution is combination of each detector resolution
- Xenon detector position resolution
  - \(x, y\) : 5mm
  - Depth: 6mm
- In total,
  - \(\theta_{e\gamma} \sim 14.6\text{mrad}\)
  - \(\phi_{e\gamma} \sim 12.5\text{mrad}\)
- Positron angle resolution
  - \(\theta\): 11.2mrad
  - \(\phi\): 7.1mrad (core)
- Vertex resolution on the target
  - Extrapolation from the track
  - Resolution by two turn tracks
  - \(R\): 2.3mm
  - \(Z\): 2.8mm
In 2008, sensitivity was $1.3 \times 10^{-11}$, and our result was the BR UL $2.8 \times 10^{-11}$ (90% C.L.).

2009 DAQ time is shorter than 2008.

e$^+$ efficiency, resolutions improved.

Trigger efficiency improved.

Statistics in 2009: $\sim x2$
MEG 2009 Results
Analysis procedure

- **Blind analysis to avoid human bias**
  - \( T_{\gamma} (-1\text{ns}<T_{\gamma}<1\text{ns}), E_{\gamma}(48<E_{\gamma}<57.6\text{MeV}) \)

- **Optimization of analysis algorithms and background study using sideband data**

- **Open the box**

- **Likelihood fit** for data, and calculate confidence intervals with toy MC simulation

- **\( N_{\text{sig}} \) normalized** to the number of observed Michel decays

- **\( \text{BR}(\mu^+\rightarrow e^+\gamma) = N_{\text{sig}} / (\text{Normalized factor}) \)**

13aSK-1: MEG 実験 \( \mu^+\rightarrow e^+\gamma \) 探索の最新結果 西村康宏

E\( _{\gamma} \) vs T distribution without any selection.
Analysis Method

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

- Extended unbinned maximum likelihood analysis
- Fitting parameters \((N_{\text{BG}}, N_{\text{RMD}}, N_{\text{signal}})\)
- PDF preparation
  - \((S, R, B)\) : PDF for \((\mu \rightarrow e\gamma, \text{RMD}, \text{Background})\)
  - Product of PDFs for the five observables \((E_{\gamma}, E_{e}, t_{\gamma}, \theta_{\gamma}, \phi_{\gamma})\)
- Most PDFs can be obtained by data
- Position, time, and positron tracking quality dependence etc. included
Number of Michel decay

\[ BR(\mu^+ \rightarrow e^+ \gamma) = \frac{N_{sig}}{N_{evv}} \times \frac{f_{evv}^E}{P} \times \frac{\varepsilon_{trig}}{\varepsilon_{e\gamma}} \times \frac{A_{TC}^{TC}}{A_{e\gamma}^{TC}} \times \frac{\varepsilon_{evv}^{DCH}}{\varepsilon_{e\gamma}^{DCH}} \times \frac{1}{A_{e\gamma}^g} \times \frac{1}{\varepsilon_{e\gamma}} \]

• Count the number of detected Michel positrons
  - \( N_{evv} \) obtained simultaneously with the signal

• The upper limit on \( BR(\mu^+ \rightarrow e^+ \gamma) \) is calculated by normalizing \( N_{sig} \) to the \( N_{enn} \)

• Independent of instantaneous beam rate and insensitive to positron acceptance and efficiency

\[ B.R. = \frac{N_{sig}}{1.0 \pm 0.1 \times 10^{12}} \text{ (Preliminary)} \]
Sensitivity

Average 90% C.L. upper limit of toy MC with null signal.

**Sensitivity : 6.1 \times 10^{-12}**

Sideband fit result is consistent. $Br < 4 \sim 6 \times 10^{-12}$

(Current B.R. upper limit is $1.2 \times 10^{-11}$ by MEGA)
Event distribution after unblinding

6/July the blind box was opened

Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.

For each plot, cut on other variables for roughly 90% window is applied.
Fit result

Accidental BG
RMD
Signal
Total

Dashed lines: 90% C.L. UL of Nsig

N_{RMD}=35^{+24}_{-22}
(Expectation from sideband = 32±2)

N_{sig}=0 is in 90% confidence region

Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent (N_{sig} best fit = 3.0-4.5, UL = 1.2-1.5\times10^{-11})
Event display

Calorimeter sum WF

Calorimeter PMT hit map

Spectrometer hits and a track

Each highly ranked event is checked carefully.
Event quality check

High quality $e^+$ track category events

Selected by number of drift chamber (DC) hits, $E_e$, $\theta_e$, $\phi_e$ fitting uncertainties, track fitting $\chi^2$, $r$ and $z$ difference between timing counter hit and extrapolation of a track.

High quality fraction = 59%

Events around signal region do not disappear by selecting high quality track events.
Prospects

- Possible improvements
  - Improvement of synchronization of waveform digitizer (DRS4) improves $\sigma_T$
  - Possible better calibration with monochromatic positron beam and improve positron tracking
  - Noise reduction and electronics modification for DC
  - Refinement in calorimeter analysis
- 3 years physics data (2010-2012)
  - Sensitivity will reach our goal, a few $\times 10^{-13}$
  - Each detector performance could be improved further!

<table>
<thead>
<tr>
<th></th>
<th>2010 (preliminary)</th>
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<tbody>
<tr>
<td>Gamma Energy (%)</td>
<td>1.5 (w&gt;2cm)</td>
</tr>
<tr>
<td>Gamma Timing (psec)</td>
<td>68</td>
</tr>
<tr>
<td>Gamma Position (mm)</td>
<td>5(u,v)/6(w)</td>
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<tr>
<td>$e^+$ Timing (psec)</td>
<td>&lt;95</td>
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<tr>
<td>$e^+$ Momentum (%)</td>
<td>0.7</td>
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<tr>
<td>$e^+$ angle (mrad)</td>
<td>8(\phi )/8(\theta )</td>
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<tr>
<td>$e^+$ - gamma timing (psec)</td>
<td>120</td>
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<tr>
<td>Muon Decay Point (mm)</td>
<td>1.4(R)/2.5(Z)</td>
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<tr>
<td>Stopping Muon Rate (sec$^{-1}$)</td>
<td>2.9x10$^7$</td>
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<tr>
<td>DAQ time / Real time (days)</td>
<td>95/117</td>
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<tr>
<td>Sensitivity</td>
<td>(2.0-2.2)$\times 10^{-12}$</td>
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<td>BR upper limit</td>
<td>-</td>
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Summary

- MEG detector has started operation since 2007, and physics data have been taken in 2008 and 2009.
- Many calibration & monitoring methods have been established to check our detector performance.
- Our result to search for lepton flavor violating $\mu \rightarrow e \gamma$ decay is the branching ratio upper limit $1.5 \times 10^{-11}$ (90% C.L., preliminary) based on 2009 data with the sensitivity $6.1 \times 10^{-12}$ (90% C.L., preliminary).
- We will have three years data taking (2010-2012) to reach our sensitivity, a few $\times 10^{-13}$. Improvement of our detector performance is the most important for us.

13aSK-3: MEG 実験 $\mu^+ \rightarrow e^+ \gamma \gamma$ 探索 名取寛顕
Improve Resolutions, contd.

- New Calibration Source will be implemented.
- Using Mott-Scatt. (coherent elastic) on light nuclei.
- "Variable / Monochromatic" $e^+$ is available.
- Momentum Calibration and Resolution Understanding will be improved.