MEG II 実験の現状とその展望

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Lepton Flavor Violation

- The Standard Model is completed after the discovery of the Higgs boson.
- However, many parameters and issues remain in the SM.
- Is there new physics beyond the SM?
- No discovery of new physics from the LHC results (yet).
- Lepton flavor violation
  - Neutrino: Neutrino oscillation is a lepton flavor violating process.
  - Charged lepton: No LFV has been observed yet. Why?

SM+Mν

Many new physics such as SUSY–GUT, SUSY–seesaw, Extra Dimensions etc. predict large BR(μ→eγ)

SUSY–Seesaw

In SM with neutrino mass, BR(μ→eγ)~10^{-54} (No background from SM!)

Observation of μ→eγ decay is a clear sign of new physics beyond SM

Search for new physics with ultimate sensitivity and with not very large experiment quickly!
Muon LFV

History of $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, and $\mu \rightarrow 3e$

- $\mu \rightarrow e\gamma$
  - $5.7 \times 10^{-13}$ @90% CL upper limit from 2009–2011 data
  - analysis ongoing with full statistics
  - MEG II
  - Ultimate $\mu \rightarrow e\gamma$ experiment?

- $\mu \rightarrow e$ conversion
  - COMET, DeeMe in Japan
  - Mu2e in USA

- $\mu \rightarrow 3e$
  - at PSI

- Many experiments will start soon.

- Once LFV process is discovered, other inputs will also be important to know new physics

ArXiv: 1307.5787[hep-ex]
**μ→eγ signal & background**

**Signal**

- Simple two body decay

\[ E_\gamma, E_e \approx 52.8 \text{MeV} \]
\[ \Theta_{e\gamma} = 180^\circ, T_{e\gamma} = T_e \]

**Radiative muon decay background**

- if two neutrinos have low energy and e+ and γ are emitted back-to-back

**Accidental background**

- Usual muon decay Michel e+
  + random γ from RMD/Annihilation in flight (AIF)
- dominant for us
- To get good sensitivity, all the resolutions should be good!

\[ N_{\text{acc}} \propto R_\mu^2 \Delta E_\gamma^2 \Delta E_e \Delta \Theta_{e\gamma}^2 \Delta t_{e\gamma} T \]
MEG experiment
MEG Limitation

• MEG detector worked fine, and improved the previous best limit.

• However, sensitivity improvement is being limited by accidental background.
Upgrade Idea

- We know possible improvement items
  - PSI beam rate can be increased up to $7 \times 10^7 \mu + /s$
  - Important to improve detector performance!
  - Segmented DC -> homogeneous DC with long wires to get more # hits and to reduce material
  - XEC inner face 2" PMTs -> smaller photo sensors (MPPCs)
  - TC -> pixelated scintillation counters
  - Additional radiative muon decay tagging
  - These can be quickly upgraded within reasonable time with our experience
- MEG II target sensitivity $\sim 5 \times 10^{-14}$
- Interested region can be explored with a short time scale.
- Still big chance to discover!
Liquid Xenon Detector

2” PMT

12x12mm² MPPC

Log scale

Linear scale

Wider incident face, different PMT angle at lateral face

Present

Upgraded

Y

Y

$(\text{Radial angle})$
Liquid Xenon Detector

- 600 large area (12x12mm) VUV sensitive MPPCs delivered
- Basic characteristic measurements at room T finished!
- Several MPPCs tested at LXe T., and all MPPCs will be tested at LXe T. with prototype
- Cross talk suppress technique will be applied to our MPPCs this year. Mass production for the final detector will follow.
- Detector construction next year.
Pixelated Timing Counter

- **Present**
  - 2x array of 15 scintillating bars readout by PMTs
  - 40x40x800mm³ scintillator
  - Mean resolution ~ 65ps

- **Upgrade**
  - Higher granularity 2x256 of small scintillator plates (90x(40–50)x5mm³) readout by SiPM
  - Resolution down to 30ps
    - High single pixel resolution
    - Further improvement with multi-counter hits
  - Thin scintillator for less multiple scattering
  - Less pile-up also with higher beam intensity
pTC Schedule

- July 2014 at Frascati
  - AdvanSiD SiPM (unfortunately this time bad timing resolution of these SiPMs. Will be fixed for Oct. 2014 beam test)
  - 12cm scintillator
  - 6 SiPMs in series connection
  - PCBs used as structure
- Oct.-Nov. 2014 at PSI
  - SiPM final configuration (6500 SiPMs are already ordered to AdvanSiD)
  - WaveDREAM readout
  - High rate environment test
  - Study on calibration methods
  - Start counter construction, and ready in 2015
Cylindrical Drift Chamber

- Single volume gaseous detector
- Stereo wires along z
- Finer granularity, better resolution
- Larger acceptance DC + TC
- Resolution check, aging test performed, detector construction by 2015 summer

**Expected Performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>~130 keV (350 keV)</td>
</tr>
<tr>
<td>Angular</td>
<td>~5 mrad ; ~5 mrad (9 mrad ; 11 mrad)</td>
</tr>
<tr>
<td>Vertex</td>
<td>~1.2 mm ; ~0.7 mm (1.8 mm ; 1.1 mm)</td>
</tr>
<tr>
<td>DC-TC matching eff.</td>
<td>~ 90 % (41%)</td>
</tr>
</tbody>
</table>

**End Cap**

**Mechanical design**

**Single full-length wire prototype**
Electronics

- higher granularity -> more # channels
  - LXe 846 -> 4722
  - DC 1730 -> 2760
  - pTC 60 -> ~1000
- DRS4 VME board-> WaveDREAM
  - waveform digitizer
  - higher density
    - bias voltage supply, amplifier for SiPM, and simple trigger are integrated
- Test boards will be ready soon, and will be used in pTC beam test this November
- Mass production in next year
Radiative Decay Counter

- Tagging radiative muon decay events with 
  \(~50\text{MeV} \gamma\) (low energy \(e^+\) is emitted \(\sim 4\text{MeV}\))
- Plastic scintillator + crystal with MPPC readout

\[
\begin{align*}
\text{Energy deposit in LXe} & > 0.9 \times M_{\mu}/2
\end{align*}
\]

\[
\begin{align*}
\text{Opening Angle}
\end{align*}
\]

\[
\begin{align*}
E_\gamma > 48\text{MeV}
\end{align*}
\]

- Plastic scintillator + crystal with MPPC readout

\[
\begin{align*}
\text{RMD} & \\
\text{AIF not from TAR} & \\
\text{AIF TAR 0-th turn} & \\
\text{AIF TAR >1 turn} & \\
\end{align*}
\]

\[
\begin{align*}
\text{E}^+ \text{ momentum}
\end{align*}
\]

- RDC
- \(\gamma\) from RMD
- \(\mu^+\) beam
- \(e^+\) from RMD
- (Accidental \(e^+\) from Michel)
Magnetic field measurement

• 2006 magnetic field was measured with 0.2% precision (sensor position calibration ~800 μm) ~ 150keV momentum resolution

• Momentum resolution in MEG II ~ 130keV, need to reduce the uncertainty of the magnetic field

• In July and August 2014, magnetic field measurements were performed with a new measurement machine which sensor position is more precisely calibrated (<300 μm). If this new field map improves the momentum resolution of the current MEG data, this will be applied to them, too.
• The MEG experiment improved the BR(μ³→e⁺γ) upper limit this year, 5.7x10⁻¹³ at 90% C.L.

• MEG physics run finished in Aug. 2013, and the analysis is ongoing.

• MEG upgrade proposal is approved by PSI in 2013. R&D for detector upgrade is ongoing, and the detector construction will be carried out next year.

• The target sensitivity is 5x10⁻¹⁴, and data taking for three years starting from 2016.
MEG limitation

フレームやプリアンプなどに当たり飛跡が曲げられてしまう。

時間測定器に当たる直前までトラッキング。余分な物質はない。
MEG Experiment

• 1999 Proposal to PSI

• 2008–2013 Physics run

• The latest result based on 2009–2011 data set upper limit of \[ BR(\mu \rightarrow e\gamma) < 5.7 \times 10^{-13} @90\%CL \]

• 2012–2013 data will double the statistics, and the new result with our full statistics would be published at winter conferences

• MEG Collaborator ~ 60 physicists from Japan, Italy, Switzerland, Russia, and USA
MEG II Status

• 2013/Jan- Upgrade proposal presented, and accepted by PSI (arXiv: 1301.7225)
• 2013-2015 Design & Construction
• 2015- Engineering run
• 2016 - 2018 Physics run

PDF parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present MEG</th>
<th>Upgrade MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+ energy (keV)</td>
<td>306 (core)</td>
<td>130</td>
</tr>
<tr>
<td>e+ θ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>e+ φ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>e+ vertex (mm) Z/Y (core)</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>γ energy (%) (w&lt;2cm) / (w&gt;2cm)</td>
<td>2.4/1.7</td>
<td>1.1/1.0</td>
</tr>
<tr>
<td>γ position (mm) u/v/w</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>γ-e+ timing (ps)</td>
<td>122</td>
<td>84</td>
</tr>
</tbody>
</table>

Efficiency

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present MEG</th>
<th>Upgrade MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>trigger</td>
<td>≃99</td>
<td>≃99</td>
</tr>
<tr>
<td>γ</td>
<td>63</td>
<td>69</td>
</tr>
<tr>
<td>e+</td>
<td>40</td>
<td>88</td>
</tr>
</tbody>
</table>
What can be improved?

- Higher muon beam rate
  - \(3 \rightarrow 7 \times 10^7 \mu /s\)
- Larger acceptance
- Better resolutions
- Active background suppression
  - Radiative muon decay tagging detector

Upgrade Concept

LXe detector

Small Photon Sensors

Single Volume Tracker

Cylindrical Drift Chamber

Radiative decay counter

Pixelated Timing Counter
PSI Accelerator (muon beam rate)

- PSI also has a plan to upgrade the accelerator
  - Mainly for Mu3e experiment
- MEG experiment doesn’t require the accelerator upgrade
  - We can quickly start whenever the detector upgrade finishes
- $3.0 \times 10^7 \Rightarrow 7.0 \times 10^7 \mu/s$
  - stopped at the target are possible now
Drift chamber

- Single volume gaseous detector
- Stereo wires along z
- Finer granularity, better resolution
- Larger acceptance DC + TC

Challenging

Long wires: ~200 cm
High rate environment

Large number of hits

Red: new tracker
<\textit{N}> \approx 64
(Black: current one)

Expected Performance

- Momentum: \(~130\ \text{keV} \ (350\ \text{keV})\)
- Angular: \(~5\ \text{mrad} \ ; \sim 5\ \text{mrad} \)
  (9\text{mrad} \ ; 11\text{mrad})
- Vertex: \(~1.2\ \text{mm} \ ; \sim 0.7\ \text{mm} \)
  (1.8\text{mm} \ ; 1.1\text{mm})
- DC-TC matching eff.: \sim 90\% \ (41\%)
DC R&D Status

- Many prototypes
- Single hit resolution
- Aging
- Mechanical design & optimize the length etc.

Aging test

Lead shield

X-ray source

Nal x-ray monitor

Single full-length wire prototype

Resolution study

σ ~ 130 μm
New Pixelated Timing Counter

- Array of ultra-fast plastic scintillator counters
- SiPM readout
- High resolution with multiple counter hits
- Expected resolution 30-35ps

15 scintillators \(\times 2\)

\(\langle N_{\text{hit}} \rangle = 6.6\)

\(-250\) counters \(\times 2\) (up/downstream)

Resolution (ps)
Beam tests @ Frascati

- Single counter resolution ~70ps (90x40x5mm, BC418)
- Ultimate resolution with multi-counter hit
  - Reduce electronics, calibration contribution, and counter resolution
  - Eight counters (90x40x5mm, BC418) with MPPC and six counters with AdvanSiD are prepared (still to be optimized)
- Beam test condition @ Frascati
  - Repetition rate: 50Hz
  - Bunch width: 10ns
  - Positron 48MeV
- Resolution improvement as a function of number of counters is confirmed!
  - Measured resolution 30~35ps
LXe $\gamma$-ray detector

- Small photon sensors (12x12mm$^2$ MPPC) at $\gamma$-ray incident face
  - ~4000ch MPPCs instead of 216 PMTs
  - Better position, energy resolutions at shallow events
  - Better identification of pile-up events
- Wider incident face, Change PMT angle at lateral face
  - To reduce shower leakage, better uniformity

Computer Graphic
Possible improvements

Position Resolution

Red: PMT (present)
Blue: MPPC (upgraded)

Distance from entrance (cm)

Energy resolution

Red: present
Blue: upgraded
MPPC R&D Status

- MPPC development in cooperation with Hamamatsu

**Achieved**
- UV (~175nm) sensitivity: PDE > 15%
- Large area (12x12 mm$^2$), single photoelectron peak resolved

**Remaining issues**
- To reduce long tail (~200 ns)
Series or Parallel connection?

- Original plan was a single sensor with 12x12mm² large area, but it had a long tail ~ 200ns

- To reduce a sensor capacitance, one sensor can be segmented into sectors, which will be connected in series.

- To simulate the concept works or not, 4 independent 6x6mm samples are connected differently, and the waveforms are compared.

- Succeeded in obtaining shorter tail (30-50ns)!
• More channels, higher rate
  • XEC MPPC (inner face) : ~4000
  • XEC PMT (other faces) : 630
  • pTC MPPC : ~1200
  • DC : 2760 (1GHz bandwidth)

• WaveDREAM
  • Higher density, compact
  • Waveform digitizer(DRS) +bias voltage supply +amplifier+simple trigger
Background tagging detectors

- Tagging radiative muon decay events with $\gamma \sim 50\text{MeV}$ ($\text{low energy } e^+ \text{ is emitted } \sim 4\text{MeV}$)
- Plastic scintillator + crystal with MPPC readout
- Beam test was performed at the end of MEG beam time in August with prototype
SUSY-Seesaw

Likelihood analysis

- Fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering
New DC parameters

- 90% He + 10% Iso-Butane (iC₄H₁₀)
- Spatial resolution estimate ~130μm
- Momentum resolution ~ 130keV
- Angular resolution ~5mrad
- DC-TC matching eff. ~ 90%
- 10 layers, square projective cells of 0.7 cm, stereo angle of ~8 deg with respect to Z (z resolution ~ 7 times the transverse resolution)
- 25 and 40μm anode and field wires
- Total length 180-190 cm, outer radius 29.2 cm, 1380 anode/7500 field wires
- Positron hit rate density by MC simulation
  - Michel e⁺ generated over 4π at 1x10⁶ μstop/s, max rate 45kHz/cm²
  - At 1x10⁵ gain and 7x10⁷ μstop/s, the maximum current is 6nA/cm(innermost wire), 3 years of running, the maximum integrated charge is 0.4C/cm
  - Free radical polymerization is regarded as the dominating mechanism of wire chamber aging
- Pisa aging up to 0.5C/cm