Searches for charged lepton flavor violating muon decay, MEG/MEG II experiment

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ICEPP, the University of Tokyo
8 August 2019
Introduction

• Charged Lepton Flavor Violation
  • FV happens in quarks, neutral lepton (neutrinos)
  • Why has charged lepton flavor violation never been observed yet?
• $\mu \rightarrow e\gamma$
  • Long search history since the muon has been discovered.
  • In SM + neutrino oscillation, $\text{Br}(\mu \rightarrow e\gamma) \sim 10^{-50}$
  • Many new physics scenarios (SUSY-GUT, SUSY-seesaw etc.) predict large $\text{Br}(\mu \rightarrow e\gamma)$ through new particles in a loop diagram
MEG/MEG II Experiment

- MEG experiment
  - MEG was designed to search for such regions where new physics like SUSY-GUT, SUSY-seesaw predict
  - Real chance to discover new physics
  - Data taking during 2009-2013
  - MEG final results: \( \text{Br}(\mu \rightarrow e\gamma) \) upper limit \( 4.2 \times 10^{-13} \) @90%CL (sensitivity \( 5.3 \times 10^{-13} \)) (Eur. Phys. J. C 76(8), 434(2016))

- MEG II experiment
  - An order of magnitude better sensitivity with three years data taking than MEG
  - Target sensitivity: \( 6 \times 10^{-14} \)

- CLFV experiments
  - \( \mu \)-e conversion (DeeMe, COMET, Mu2e), \( \mu \rightarrow 3e \) (Mu3e) experiments etc. will also come soon

\[ \mu \rightarrow e\gamma \text{ signal and background} \]

**Signal**

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

**Accidental Background**

- Dominant BG
- Michel $e^+$ + random $\gamma$ from RMD/Annihilation in flight (AIF)

**Radiative Muon Decay (RMD) Background**

- $e^+ - \gamma$ timing coincident
- Good for timing calib.

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

- Lower instantaneous muon beam rate (DC muon beam)
- Better detector resolutions
MEG experiment

- Paul Scherrer Institute in Switzerland
- World most intense 590MeV proton accelerator (2.4mA)
MEG results

- Full dataset: $7.5 \times 10^{14} \mu^+$ stopped on the target
- Blind analysis in $(E_\gamma, t_{e\gamma})$ plane
- Five observables $E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$
- Maximum likelihood analysis
  - All PDFs well consistent with data
  - The fit result was consistent with no signal

- $\text{Br}(\mu^+ \rightarrow e^+ \gamma) < 4.2 \times 10^{-13} @ 90\% \text{ C.L.}$
MEG II Experiment

Liquid Xenon γ Detector
- Better uniformity w/ VUV-sensitive 12x12mm² SiPM

Radiative Decay Counter
- Further reduction of radiative BG

Positron (e⁺)
- ×2 resolution everywhere

Gamma-ray (γ)
- Cylindrical Drift Chamber

Muon (µ⁺)
- COBRA SC Magnet
- Pixelated Positron Timing Counter
  - 7x10⁷/s (×2.3 higher rate)
  - 30ps resolution w/ multiple hits
  - Single volume small stereo cells more hits

×2 resolution everywhere
MEG II positron spectrometer

- Cylindrical Drift Chamber
  - Tracking 52.8MeV e\(^+\) to reconstruct vertex, angle, and momentum
  - Single volume wire drift chamber with 1280 anode wires with less material
  - Higher granularity, increased number of hits per track → better angle/momentum resolution
  - High transparency towards TC → Higher positron detection efficiency

- Pixelated Timing Counter
  - Time measurement of 52.8MeV e\(^+\)
  - 15 scintillator bars → 256 scintillator plates
    - multi-counter hits → better timing resolution down to ~30ps
MEG II liquid xenon γ detector

- Energy, position, time measurement of 52.8MeV γ from μ → eγ decay
- Inner 216 PMTs → 4092 MPPCs (VUV-sensitive large area MPPCs)
- Better granularity, better uniformity → Better energy, position resolution
Radiative Decay Counter

- New device for MEG II
  - To tag high energy $\gamma$ background from radiative muon decay by detecting low momentum $e^+$
- Downstream detector ready, upstream detector under development
  - $\mu^+$ beam goes through US RDC

[Diagram of the detector system with labels for COBRA magnet, $\mu^+$ beam, RDC, $\gamma$ (RMD), $e^+$ (RMD), $e^+$ (Michel), $e^+$ spectrometer, Plastic Scinti.+SiPM for $e^+$ energy, LYSO 2x2x2 cm$^3$+SiPM for $e^+$ energy]
Readout Electronics

- Waveform data crucial for high rate environment
- Number of channels increased
  - For finer granularity
  - More compact boards necessary
- WaveDREAM developed by PSI
  - Waveform digitizer (DRS4), simple trigger, amplifier and bias voltage supply (~200V) are integrated in a board, suitable for SiPM
- Online trigger important to manage high event rate and background suppression.
  - FPGA based trigger system prepared
### Sensitivity

<table>
<thead>
<tr>
<th>Resolution</th>
<th>MEG</th>
<th>MEG II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{e^+}$ (keV)</td>
<td>380</td>
<td>130</td>
</tr>
<tr>
<td>$\theta_{e^+}$ (mrad)</td>
<td>9.4</td>
<td>5.3</td>
</tr>
<tr>
<td>$\phi_{e^+}$ (mrad)</td>
<td>8.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$z_{e^+}/y_{e^+}$ (mm) core</td>
<td>2.4/1.2</td>
<td>1.6/0.7</td>
</tr>
<tr>
<td>$E_{\gamma}$ (%) (w&gt;2cm/&lt;2cm)</td>
<td>1.7/2.4</td>
<td>1.0/1.1</td>
</tr>
<tr>
<td>$u_{\gamma}$, $v_{\gamma}$, $w_{\gamma}$ (mm)</td>
<td>5/5/6</td>
<td>2.6/2.2/5</td>
</tr>
<tr>
<td>$t_{e\gamma}$ (ps)</td>
<td>122</td>
<td>84</td>
</tr>
</tbody>
</table>

### Efficiency (%)

| Trigger | 99 | 99 |
| $\gamma$ | 63 | 69 |
| $e^+$ (tracking $\times$ matching) | 30 | 70 |

- Data for a few months exceed the current limit, and reach $6 \times 10^{-14}$ in three years
Current status

**CDCH**
Construction finished in 2018. Detector commissioning after small modification will be restarted this fall.

**TC**

**LXe**

**WaveDREAM**
Tests of Prototype WaveDREAM with 6 crates (~1500ch.) and final version with 2 crates will be carried out this fall.
Mass production next year.

**RDC**
Downstream detector constructed in 2017, and performance test with muon beam finished.
Prospects & Summary

- MEG II Detector integration in August 2019, and muon beam time from September to December with limited no. of electronics

- Mass production of the readout electronics happens next year.
- Engineering run and physics run will follow.
- The sensitivity of the MEG II experiment will exceed the current limit with a few month data statistics, and will be improved by one order of magnitude with three years data.
HIPA operation in 2018-2020

**Betrieb Protonen-Anlagen 2018-2020**

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Feb</td>
<td>Mrz</td>
</tr>
<tr>
<td>Beschleuniger</td>
<td>Resonator 2</td>
<td>Betrieb</td>
<td>Resonator 4</td>
</tr>
<tr>
<td>max. Strahlstrom</td>
<td>2.0 mA</td>
<td>2.0 mA</td>
<td>2.4 mA</td>
</tr>
<tr>
<td>Beamdump</td>
<td>neuem BV1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target E</td>
<td>4 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SINQ Betrieb</td>
<td>Shtdown</td>
<td></td>
<td>Betrieb</td>
</tr>
<tr>
<td>Target Nr.</td>
<td>Target 13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UCN Betrieb</td>
<td>Testexperimente</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Myone (LMU&amp;LTP)</td>
<td>Betrieb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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: Umbau  
: Betrieb

Klaus Kirch, PSI  
BVR Feb 13, 2018 – page 13
Final MEG dataset / Analysis

- Accumulated number of muons stopped on the target as a function of time

- Full dataset: $7.5 \times 10^{14}$ $\mu^+$ stopped on the target

- Blind analysis in $(E_\gamma, t_{e\gamma})$ plane

- Five observables $E_\gamma, E_e, t_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}$

- Maximum likelihood analysis
Event distribution

\[
\cos \Theta < -0.99963 \ (90\% \ \varepsilon_{\text{signal}}) \\
|t_{\gamma\gamma}| < 0.2443\text{ns} \ (90\% \ \varepsilon_{\text{signal}}) \\
51 < E_{\gamma} < 55.5\text{MeV} \ (74\% \ \varepsilon_{\text{signal}}) \\
52.385 < E_e < 55\text{MeV} \ (90\% \ \varepsilon_{\text{signal}})
\]

2009-2013 data

Signal PDF contour (1\(\sigma\), 1.64\(\sigma\), 2\(\sigma\))
Cylindrical Drift Chamber

- Tracking 52.8 MeV $e^+$ to reconstruct vertex, angle, and momentum
- Single volume wire drift chamber with 1280 anode wires
- Higher granularity, increased number of hits per track

<table>
<thead>
<tr>
<th>MEG DCH</th>
<th>MEG II CDCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 modules</td>
<td>single volume</td>
</tr>
<tr>
<td>288 drift cells</td>
<td>1280 drift cells</td>
</tr>
<tr>
<td>40-80cm</td>
<td>2m long, stereo angle</td>
</tr>
<tr>
<td>He:C$_2$H$_6$=50:50</td>
<td>He:iC$<em>4$H$</em>{10}$=85:15</td>
</tr>
</tbody>
</table>
MEG II timing counter

- Time measurement of 52.8MeV $e^+$

<table>
<thead>
<tr>
<th>MEG TC</th>
<th>MEG II TC</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 scintillating bars x 2</td>
<td>256 scintillator plates x 2</td>
</tr>
<tr>
<td>4x4x80 cm$^3$</td>
<td>12x(4or5)x0.5 cm$^3$</td>
</tr>
<tr>
<td>Readout by PMTs</td>
<td>Readout by SiPM</td>
</tr>
<tr>
<td>Single bar hit</td>
<td>Multiple counter hits</td>
</tr>
</tbody>
</table>

Single counter

6 SiPMs array

Resolution (ps)

$\sigma < 30\text{ ps}$
MEG II liquid xenon γ detector

- Energy, position, time measurement of 52.8 MeV γ from μ → eγ decay
- Non uniform response for shallow events
- Replace inner PMTs with MPPCs
- Better granularity, better uniformity → Better energy, position resolution

<table>
<thead>
<tr>
<th>MEG LXe</th>
<th>MEG II LXe</th>
</tr>
</thead>
<tbody>
<tr>
<td>900L LXe</td>
<td>900L LXe</td>
</tr>
<tr>
<td>216 2” PMTs (γ entrance)</td>
<td>4092 12x12mm² MPPCs</td>
</tr>
<tr>
<td>630 PMTs (other faces)</td>
<td>668 PMTs</td>
</tr>
</tbody>
</table>