Performance of the MEG detector

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Outline

- Introduction
- MEG experiment
- MEG detector
- Performance in 2010
- Improvement in 2011 and later
- Summary
Lepton Flavor Violation

- $\mu \rightarrow e\gamma$ decay
  - Lepton flavor violating decay
  - In the SM with neutrino oscillation, the branching ratio is tiny ($\sim 10^{-50}$)
  - Previous experimental upper limit (before MEG experiment)
    - $1.2 \times 10^{-11}$ (1999, MEGA)
  - Well motivated new physics (SUSY-GUT, SUSY seesaw,...) predict the branching ratio around $10^{-11} - 10^{-13}$ region

- MEG experiment
  - Explore down to $10^{-13}$ level

![Graph showing branching ratio over time]
Signal & background

► Signal
  ► μ⁺ decay at rest
  ► 52.8MeV (half of Mμ) (Eγ,Ee)
  ► Back-to-back (θeγ,φeγ)
  ► Timing coincidence (T_{eγ})

► Accidental background
  ► Michel decay e⁺ + random γ
  ► Dominant background for us
  ► Random timing, angle, <52.8MeV

► Radiative muon decay
  ► μ -> eννγ
  ► Timing coincident, not back-to-back, <52.8MeV
Background spectra

Good detector performance (especially $E_\gamma$)
High rate positron measurement
Pileup identification

\[ N_{acc} \propto R^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \theta_{e\gamma})^2 \cdot \delta t_{e\gamma} \]
MEG experiment

Most intense DC muon beam (>1x10⁸µ⁺/s) possible

Requirement:

- Need many muon decays
- Detectors(e⁺) should be working in high rate environment
- Good energy, timing, and position resolutions
MEG detector

COBRA Magnet

Drift chamber

Muon Beam

Stopping Target

Liquid Xenon Scintillation Detector

2.7 ton of liquid xenon Homogeneous detector Good time, position, energy resolution

Special gradient magnetic field Sweeps out high rate e+ quickly Constant bending radius of e+

Ultra thin material Precise e+ tracking

Precise e+ timing Plastic scintillator + PMTs

Waveform digitizer for all detectors (pileup ID)
Positron spectrometer

Uniform B-field

\[ \text{Compensation coil} \]
\[ \text{Superconducting solenoid} \]

Gradient B-field

\[ \mu^+ \text{ beam} \]
\[ e^+ \]
\[ \text{DC compensation} \]

Special gradient magnetic field
1.27T at center
0.49T at each end

Low energy positron quickly swept away

\[ \text{CO} \text{ntant Bending RA} \text{adius} \]

independent of emission angles
Drift chambers

- Positron tracking
  - Momentum, emission angle $(\theta, \varphi)$
- 16 radial drift chambers
  - Only high momentum $e^+$ ($>40\text{MeV}$, $19.3\text{cm}<r<27.9\text{cm}$)
- Chamber gas $\text{He}:C_2H_6 = 50:50$
- Low material budget
  - Open frame at the target side
  - Low MS, low $\gamma$ background
Track reconstruction

R direction (drift time)

Drift circle

Z direction (charge ratio)

charged particle

induced charge

avalanche

charged particle

sense wire

potential wire

inner cathode foil

outer cathode foil

3.0 mm

3.5 mm

4.5 mm

7.0 mm
Timing counter

- 15x2 (Upstream/Downstream) plastic scintillator bars (4x4x80cm³)
- Fine mesh PMTs at both ends, positron timing measurement (σ~65ps)
- Positron φ, z position reconstruction (~5cm)
- Scintillating fibers (6x6mm²) + APD
  - Precise z position measurement, fast θ emission angle information
2.7t Liquid xenon gamma-ray detector

- 900L liquid xenon
- 846 2” PMTs (Hamamatsu)
  - Submerged in Liquid
- γ energy, position, and timing reconstruction

**Merits**
- High light output (80% of NaI)
- Fast timing response (45ns)
- Heavy (3g/cm³)

**Challenges**
- Low temperature (160K)
  - 200W pulse tube cryocooler
- Short scintillation wavelength (178nm)
- Gas/liquid purification
Reconstruction & Goal of gamma ray detector

Reconstruction

- Energy: weighted sum of all PMTs
- Position: peak of light distribution
- Time: weighted average of time of PMTs

Pileup detection

- Waveform
- Light distribution

Goal

- Energy resolution: 1.2–1.5%
- Vertex (Opening angle): 2–4mm
- Time resolution: 65ps
Calibration methods

- **55MeV γ (CEX)**
  - Energy (MeV) diagram
  - Opening angle
  - Nal
  - 83MeV
  - 55MeV
  - $\pi^- + p \rightarrow \pi^0 + n$
  - $\pi^0 \rightarrow \gamma \gamma$ (55, 83MeV)
  - $\pi^- + p \rightarrow n \gamma$ (129MeV)

- **9MeV γ**
  - Timing resolution
  - PMT calibration
  - Muon radiative decay events

- **17.6MeV γ**
  - Li(p,γ)Be reaction
  - CW accelerator
  - Published in NIMA641(2011)19-32

- **4.4MeV γ**
  - LED for gain

- **PMT calibration**
  - Gain = 1.49 x 10^6

19/Sep./2011
## MEG experiment 2008-2010

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan-Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
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<tbody>
<tr>
<td>2008</td>
<td>Detector preparation</td>
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<td>Physics run</td>
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<td></td>
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</tr>
</tbody>
</table>

**PSI accelerator Shutdown period**

**Physics run (less DC eff., lower LXe LY)**
Current Status of MEG

Physics data taking started in 2008

2008 data
- $\text{Br(}\mu^-\rightarrow\text{e}^-\gamma)<2.8\times10^{-11}$ at 90\%C.L., published in Nucl.Phys.B834:1–12, 2010
- Sensitivity: $1.3\times10^{-11}$

2009 data
- $\text{Br(}\mu^-\rightarrow\text{e}^-\gamma)<1.5\times10^{-11}$ at 90\%C.L. (preliminary)
- Sensitivity: $6.1\times10^{-12}$ (preliminary)

2010 data
- 1.9x statistics of 2009
- 2009+2010 combined analysis result was presented this year
- $\text{Br(}\mu^-\rightarrow\text{e}^-\gamma)<2.4\times10^{-12}$ at 90\%C.L.
- Sensitivity: $1.6\times10^{-12}$

MEG Collaboration

- ~55 Collaborators from Japan, Italy, Switzerland, Russia, and USA
What's new in 2010

- 2010 data = 2 x 2009 data
  - There was a problem of beam transport solenoid, and 2010 beam time finished prematurely.
- Timing improvement by waveform digitizer
- Positron tracking performance and efficiency slightly worse
  - due to noise problem and more unstable DC layers
- Better calibrations of data
  - Alignments inside/among detectors
Waveform digitizer upgrade

- DRS chip developed at PSI
- Fine tuning of DRS4 digitization board (introduced in 2009)
  - Noise reduction on digital board & time jitter minimization
  - Contribution of timing resolution from electronics
    - 130ps in 2009 -> 50ps in 2010
Alignment inside/among detectors

- Optical surveys
  - DC - target
  - double-checked by target hole
- Alignment by CR
  - DC - XEC
  - DC
- LXe
  - Pb collimators
  - AmBe
Performance
Energy resolution

- Energy resolution is evaluated with 55MeV $\gamma$ in CEX data

  $\pi^- + p \rightarrow \pi^0 + n, \pi^0 \rightarrow \gamma\gamma$

- Resolution map on incident position is measured by moving NaI detector

  ![Resolution map graph]

  - Result of resolution in 2010
    - 1.9% (depth > 2cm), 2.4% (depth < 2cm)
Linearity

The graph shows the relationship between reconstructed energy and truth energy. The factor is given as $0.9992 \pm 0.000264$. The data points are plotted on a linear scale, indicating a strong linear relationship between the two variables.
Position resolution is evaluated CEX data with lead collimator.

Resolution in 2009:
- XY direction: 5mm
- Depth: 6mm
- MC expectation: 4.5mm (due to insufficient Q.E. Estimation?)
Timing resolution

Time difference between XEC and reference counter in CEX

Result

- 119ps at 55MeV (171ps in 2009, thanks to electronics improvement)
- XEC resolution: ~67ps
- 119ps – beam spread(58ps) – resolution of reference counter(81ps)

Breakdown

- XEC intrinsic(36ps), ToF(20ps), DRS(24ps), and 46ps

Further improvement only possible by new detectors and higher Q.E. PMT etc.
Performance of the MEG detector

Background rejection

Cosmic ray rejection

Pileup elimination

Inner/Outer charge Ratio

1. Find pileup
2. Reconstruct energy w/o pileup region, calculate expected charge
3. Replace these charge
Background spectrum

Position dependent $\gamma$ background spectra --> PDF for likelihood analysis
These can be extracted directly by time sideband data
Detector response (energy resolution, energy scale) can be double checked by this,
And the result is consistent with CEX data

Contribution of background events in signal region (51-55MeV)

<table>
<thead>
<tr>
<th>Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD+AIF (single gamma)</td>
<td>93%</td>
</tr>
<tr>
<td>Cosmic ray</td>
<td>1%</td>
</tr>
<tr>
<td>Remaining (pileup, tail etc.)</td>
<td>6%</td>
</tr>
</tbody>
</table>
Positron spectrometer performance

2009: almost all drift chamber working correctly after fixing 2008 HV discharge problem

2010: 5 DC chambers are replaced before 2010 run
more bad planes and slightly worse noise situation

- Momentum resolution is extracted from a fit to Michel edge spectrum
- Detector response
  - triple gaussian + acceptance
  - 2009
    - $\sigma_p = 310\text{keV} (80\%) + 1.0\text{MeV}(13\%) + 2.0\text{MeV}(7\%)$
  - 2010
    - $\sigma_p = 330\text{keV} (79\%) + 1.0\text{MeV}(14\%) + 2.0\text{MeV}(7\%)$
Positron spectrometer performance, cont.

Muon decay point, angular resolution: from tracks with two turns inside the drift chambers

2009

Vertex $z/y = 1.5/1.1$mm

$\sigma_\theta = 9.4$ mrad

$\sigma_\phi = 6.7$ mrad ($\phi=0$)

2010

Vertex $z/y = 2.0/1.1$mm

$\sigma_\theta = 11.0$ mrad

$\sigma_\phi = 7.2$ mrad ($\phi=0$)
Positron - photon timing

- Radiative muon decay peak
  - In a normal physics run
  - Corrected by small energy dependence
- Timing resolution of $T_{e\gamma}$
  - 122ps in 2010
  - Breakdown
    - Photon $T_{\gamma}$ : 67 ps
    - $T_e$ : 107 ps
    - $T_{TC}$ : 65 ps (measured by double TC Michel events)
    - $Le/c$ : 75 ps (MC scaled, x1.5)
    - TC calib: 40 ps
## Performance summary

<table>
<thead>
<tr>
<th>Performance parameter</th>
<th>2009</th>
<th>2010</th>
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<tbody>
<tr>
<td>Gamma energy (w&gt;2cm)</td>
<td>1.9 %</td>
<td>1.9 %</td>
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<tr>
<td>Gamma timing</td>
<td>96 ps</td>
<td>67 ps</td>
</tr>
<tr>
<td>Gamma position</td>
<td>5(xy)/6(depth) mm</td>
<td>5(xy)/6(depth) mm</td>
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<td>Gamma efficiency</td>
<td>58 %</td>
<td>59 %</td>
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<tr>
<td>e^+ momentum</td>
<td>310keV (80% core)</td>
<td>330keV (79% core)</td>
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<tr>
<td>e^+ θ</td>
<td>6.7 mrad</td>
<td>7.2 mrad</td>
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<td>e^+ vertex Z/Y</td>
<td>9.4 mrad</td>
<td>11.0 mrad</td>
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<td>1.5/1.1 mm (core)</td>
<td>2.0/1.1 mm (core)</td>
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<td>e^+ efficiency</td>
<td>107 ps</td>
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<td>T_eν</td>
<td>40 %</td>
<td>34 %</td>
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<tr>
<td>Trigger efficiency</td>
<td>146 ps</td>
<td>122 ps</td>
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<tr>
<td>Trigger efficiency</td>
<td>91</td>
<td>92</td>
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<tr>
<td>Stopping Muon Rate</td>
<td>2.9x10^7 / sec</td>
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<td>DAQ time/real time</td>
<td>35/43 days</td>
<td>56/67 days</td>
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<td>Expected 90% C.L. Upper Limit</td>
<td>3.3x10^-12</td>
<td>2.2x10^-12</td>
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**2009+2010 Combined**

Expected 90% C.L. Upper Limit : 1.6x10^-12
# 2011 run

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<td>2011</td>
<td>BTS repair work</td>
<td>7 DC repair work</td>
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<td>PSI accelerator Shutdown period</td>
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Performance of the MEG detector
What can improve our result?

- **Statistics**: still the most important thing
  - 2011 data = 2 x 2010 data (124 days expected)
  - 2012 data ≥ 2011 data

- **Multi-buffer scheme for DAQ**
  - Livetime improved, wider direction match table can be used

- **Better e⁺ resolution & detection efficiency**
  - One of noise sources (HV distributor) is removed in 2011.
  - Thinner DC cables, preamplifiers, rearrangement of cable layout etc.

- **Better gamma resolution & calibration**
  - Stable & better quality data with new detector (BGO) for CEX
  - New reconstruction algorithm, improve Q.E. estimation etc.
Multi buffer DAQ

- **Dead time in 2009–2010**
  - 25ms/event ~ 83% livetime @ 6Hz

- **Multi buffer DAQ**
  - Installed at the end of 2010
  - >99% livetime @ 10Hz
  - Direction match table between positron and photon can be widen (92% -> 96%).
DC performance in 2011

- Found that one of noises (14MHz) coming from DC HV distribution system
  - 1 primary HV power supply (ISEG EHQ 103M) and 16 HV distribution modules with 2 ch. each (PSI)
- 2011 physics run (in a month after starting)
  - 32 different primary HV power supplies (ISEG EHS)
  - dz, dr improved before/after exchange in 2011
  - DC calibration is on-going. θ, φ resolution will be checked after that.
BGO array for CEX in 2011

CEX two weeks for scanning all the XEC inner face, and LH$_2$ target setup, $\mu^-$ -> $\pi^-$ beam change

Improvement of detection efficiency is important to minimize DAQ time

NaI (3.67 g/cm$^3$) : 3x3
(6.5x6.5x33 cm$^3$)

BGO (7.13 g/cm$^3$) : 4x4
(4.6x4.6x20 cm$^3$)

Better detection efficiency > x2
Better position, energy resolutions
position resolution is important to know opening angle of two $\gamma$s, that indicates true energy
Positron detection efficiency

- Positron efficiency ~ 40%

- New design of DC frames
  - Design of a new DC system – is a long term activity

- Feasible starting point for improvements
  - Thinner signal cables (1728ch)
  - Thinner Preamplifier PCB (576 pcb)
  - Expected: (50 +x) %
Summary

MEG experiment has started physics run in 2008, and MEG detector has been working since then, and the performance is still being improved.

The expected 90% C.L. upper limit with 2009+2010 data is $1.6 \times 10^{-12}$, which is already 7 times better than the previous experiment.

MEG physics run has restarted since the end of June 2011, and MEG is accumulating more data 2011–2012 to reach $O(10^{-13})$ sensitivity.

Possible major upgrades of experiment (sensitivity $<\sim 10^{-13}$?) are being discussed.
Linear-Fit

- Linear fit algorithm
  - $E = c + \sum c_i Q_i$
  - The weights are computed with MC
    - $\chi^2 = \text{distance from MC}$
    - Analytical minimization

- Worked well for prototype

- With refinement of MC,
  - Progressing
  - Currently getting comparative to existing algorithm (still slightly worse)
  - Working further improvement of MC

16/Feb/2011

Yusuke UCHIYAMA
BGO

- NaI: 3x3 (6.5x6.5x33 cm$^3$, 3.67g/cm$^3$)
- BGO: 4x4 (4.6x4.6x20 cm$^3$, 7.13g/cm$^3$)
- Efficiency
  - 17% NaI center, 35% center 2x2 BGO
- Position reconstruction
  - NaI: 1.5cm, BGO: 1.1cm
Efficiency

- For normalization, need efficiency conditional on the $e^+$ detection
  - Position-dependent efficiency from MC
  - Weighted by the $e^+$ distribution
- Confirmed with pi0 data (NaI-self)

\[ \varepsilon_{\gamma}(>48\text{MeV}) = \varepsilon_{\text{det}} \times \varepsilon_{\text{ana}} \\
= 0.647 \times 0.893 \\
= 0.58 \pm 0.03 \]

9% decrease from 2008
- Change of analysis window (46→48MeV) : 5%
- Higher pileup level & higher pileup cut threshold
  → rejected events have less significance, almost no effect on sensitivity.

In 2010, pileup reduced by beam optimization
  \[ \varepsilon_{\gamma}(>48\text{MeV}) = 60\% \text{ (expected)} \]
Purification system

Gaseous purification

- Metal heated getter
- Mainly H$_2$O rejection
- Diaphragm pump ~1L/h

Liquid purification

- Liquid circulating purifier
- Cryogenic centrifugal pump ~100L/h
Light yield

Monitored by CW Li 17.6MeV γ

- 2008: purification during physics data taking
- 2009, 2010: no purification
- Maximum LY measured by our prototype was already achieved in 2009

RMS 0.2%

2010 CW-Li
Intrinsic resolution

- PMTs are divided into 2 groups (odd, even)
- See difference of rec. time by the two
  - Electronics contribution canceled out
  - $\sigma((T_{\text{odd}} - T_{\text{even}})/2)$

<table>
<thead>
<tr>
<th></th>
<th>55 MeV</th>
<th>83 MeV</th>
</tr>
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<tbody>
<tr>
<td>2008</td>
<td>44.7</td>
<td>36.0</td>
</tr>
<tr>
<td>2009</td>
<td>37.5</td>
<td>30.5</td>
</tr>
<tr>
<td>2010</td>
<td>36.4</td>
<td>28.4</td>
</tr>
</tbody>
</table>

Intrinsic time resolution is dominated by p.e. statistics

$\sigma = 277.8 / \sqrt{E}$

Yusuke UCHIYAMA
TC resolution: intrinsic+DRS

- $\sigma(\Delta T)/\sqrt{2}$ in double bar Michel events $\Rightarrow$ upper limit on TC intrinsic resolution + DRS

$$\Delta T = T_A - T_B$$

M. De Gerone

Estimate of resolution on positron impact point at TC: $\sigma(T_{TC}) \sim 65$ ps

Resolution on average $\sim 5$ ps worse in 2010 with respect to 2009
The Future

Assuming for 2011 the expected noise RMS from the test on the new HV modules (see M. Hildebrandt's talk), we should be able to reach \( \sim 600 \) \( \mu m \) resolution in \( Z \) single hit position and \( \sim 230 \mu m \) in \( R \)

Moreover, with reduced noise, subleading contributions to resolution clearer (and easier to correct for)

\( \theta \) resolution vs \( z \) resolution

\( \phi \) resolution vs \( z \) resolution

\( Z \) hit resolution vs resolution

From MC studies (not taking into account all the other possible improvements described in previous slides) we expected an improvement of:

- \( \sim 15\% \) in \( \theta \)
- \( \sim 5\% \) in \( \phi \)
- \( \sim 10\% \) in momentum (but bigger data/MC discrepancy not yet explained)

Elisabetta Baracchini - MEG DCH Analysis - MEG BVR Meeting 16th February 2011
Alignment

About 15 x 15 x 13 mm

These screws were replaced by plastics

Data

MC

55

57

59

61
Systematics

- Systematic effects are taken into account in the calculation of confidence interval by profiling on \(N_{RD}, N_{BG}\) and by fluctuating PDFs according to the uncertainty values.
  - all the results shown so far already contain systematic effect.
- Size of effect of systematic uncertainty is in total 2% on the UL.
  - \(2.3 \times 10^{-12} \rightarrow 2.4 \times 10^{-12}\) for combined result

<table>
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<th>Relative contributions on UL</th>
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<tr>
<td>Center of (\theta_{e\gamma}) and (\phi_{e\gamma})</td>
<td>0.18</td>
</tr>
<tr>
<td>Positron correlations</td>
<td>0.16</td>
</tr>
<tr>
<td>Normalization</td>
<td>0.13</td>
</tr>
<tr>
<td>(E_{\gamma}) scale</td>
<td>0.07</td>
</tr>
<tr>
<td>(E_e) bias, core and tail</td>
<td>0.06</td>
</tr>
<tr>
<td>(t_{e\gamma}) center</td>
<td>0.06</td>
</tr>
<tr>
<td>(E_{\gamma}) BG shape</td>
<td>0.04</td>
</tr>
<tr>
<td>(E_{\gamma}) signal shape</td>
<td>0.03</td>
</tr>
<tr>
<td>Positron angle resolutions ((\theta_e, \phi_e, z_e, y_e))</td>
<td>0.02</td>
</tr>
<tr>
<td>(\gamma) angle resolution ((u_{\gamma}, v_{\gamma}, w_{\gamma}))</td>
<td>0.02</td>
</tr>
<tr>
<td>(E_e) BG shape</td>
<td>0.02</td>
</tr>
<tr>
<td>(E_e) signal shape</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Contribution of each item was studied with toy-experiment by comparing the result with nominal PDF and that with fluctuated one.
Alternative Energy Reconstruction

- Treat each PMT as a detector and fit energy for each PMT
- Calculate event energy from tube energies
  - weighted mean energy of truncated distribution
- Correction table for gain $\times$ QE is prepared from output of PMT for each event
- Potential advantages:
  - can optimize PMT selection
  - insensitive to vast variations in solid angles subtended by nearby PMTs