An Innovative Positron Spectrometer to Search for the Lepton Flavour Violating Muon Decay with a Sensitivity of $10^{-13}$

(μ粒子のフレーバー非保存崩壊を10⁻¹³の感度で探索する高感度陽電子分光計の開発)

西口 創 (高エネルギー加速器研究機構・素粒子原子核研究所)

2009年3月28日, 日本物理学会 第64回年次大会 (於立教大学)
CONTENTS

μ→eγ Decay
  • Muon decay in SM / SUSY
  • Signal & Background

MEG Experiment
  • Beam / Detectors
  • Trigger / DAQ

COBRA Spectrometer
  • Magnet
  • Drift Chamber
  • Timing Counter

Drift Chamber
  • Requirements / Design
  • Construction / Operation

Simulation
  • Monte Carlo Simulation
  • Event Mixing / Electronics

Event Reconstruction
  • Hit / Track Find / Track Fit

Calibration
  • Alignment / Coordinate / Timing / X-T calibrations

Analysis
  • Resolutions / Efficiencies

Discussion
  • Limiting Factors
  • MEG Sensitivity
\( \mu \rightarrow e\gamma \) Decay
# $\mu \rightarrow e \gamma$ Decay

## Muon Decay in SM (1)

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu \rightarrow e \nu \nu \gamma$ (Radiative)</td>
<td>1.4 % ($E_\gamma &gt; 10\text{MeV}$)</td>
</tr>
<tr>
<td>$\mu \rightarrow e \nu \nu + e^+e^-$</td>
<td>$3.4 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mu \rightarrow e \gamma$</td>
<td>$&lt; 1.2 \times 10^{-11}$ (MEGA, 1999)</td>
</tr>
<tr>
<td>$\mu \rightarrow e \nu \nu$ (Michel)</td>
<td>$\sim 100%$</td>
</tr>
</tbody>
</table>

(Michel)
Muon Decay in SM (2)

Michel Decay: $\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e / \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

$$\mathcal{M} = -\frac{4G_F}{\sqrt{2}} \sum_{\gamma=S,V,T} g_{e\mu} \langle \bar{e}_e | \Gamma_\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle$$

$$\frac{d^2\Gamma}{dx d(\cos \theta)} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \times \left[ \mathcal{F}_{IS}(x) + P_\mu \cos \theta \mathcal{F}_{AS}(x) \right] \times \left[ 1 + \tilde{P}_e(x, \theta_e) \cdot \hat{\zeta} \right]$$

$$\mathcal{F}_{IS} = x(1-x) + \frac{2}{9} \rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x),$$

$$\mathcal{F}_{AS} = \frac{1}{3} \xi \sqrt{x^2 - x_0^2} \left[ 1 - x + \frac{2}{3} \delta \left( 4x - 3 - \left( 1 - \sqrt{1-x_0^2} \right) \right) \right]$$

Michel Spectrum

Relative Probability

Momenta (MeV/c)
Muon Decay in SM (3)

- Lepton Flavour Violation (LFV)
- Lepton Family Number Conservation in SM
- Neutrino-Oscillation
- Charged Lepton ???
- Muon Rare Decay Search
  - e.g. $\mu \rightarrow e\gamma$ Decay

$$
\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \sum_i U_{\mu i}^* U_{e i} \frac{m_{vi}^2}{m_W^2} \left| \frac{1}{32\pi} \sum_i U_{\mu i}^* U_{e i} \frac{m_{vi}^2}{m_W^2} \right|^2 \rightarrow 10^{-50} !!
$$
\(\mu \rightarrow e\gamma\) in SUSY (1)

- LFV is expected to be enhanced by SUSY !!
- Brand-New Candidate of LFV Source
- Without Suppression by \(\nu\)-mass
- The First Evidence of SUSY !!
- Muon is Suitable Probe
- e.g. \(\mu \rightarrow e\gamma\) Decay

\[
\mathcal{B}(\mu \rightarrow e\gamma) \sim \frac{\alpha^3 \pi \theta^2}{G_F^2 \bar{m}^4}
\]  \(\sim 10^{-15} \sim 10^{-11} !!\)
Many SUSY-based models predict large $B(\mu \rightarrow e\gamma)$!

**$\mu \rightarrow e\gamma$ in SUSY (2)**

- Many SUSY-based models predict large $B(\mu \rightarrow e\gamma)$!!

![Graphs showing $B(\mu \rightarrow e\gamma)$ for different SUSY models and parameter values.](image)
\( \mu \rightarrow e \gamma \) Search Experiment

- \( \mu \rightarrow e \gamma \) Search Experiment has 60-years history
$\mu \to e\gamma$ Search Experiment

- $\mu \to e\gamma$ Search Experiment has 60-years history
$\mu\to e\gamma$ Decay

$\mu\to e\gamma$ Search Experiment

- $\mu\to e\gamma$ Search Experiment has 60-years history
\( \mu \rightarrow e \gamma \) Decay

\( \mu \rightarrow e \gamma \) Signature & Background (1)

- Signal

\( E_e = E_\gamma = 52.8 \text{ MeV (}=m_\mu/2) \)

- \( e^+ \) and \( \gamma \) coincidence (\( \Delta t=0 \))

- Back-to-Back (\( \theta_{e\gamma} = \pi \))
\( \mu \rightarrow e \gamma \) Decay

\( \mu \rightarrow e \gamma \) Signature & Background (2)

- Physics Background
- Radiative Muon Decay
- Back-to-Back e\(^+\) and \(\gamma\)
- very small \(\nu\)-mass
$\mu \rightarrow e\gamma$ Decay

$\mu \rightarrow e\gamma$ Signature & Background (2)

- Physics Background

- Radiative Muon Decay
- Back-to-Back $e^+$ and $\gamma$
- Very small $\nu$-mass

good $\sigma_E$ and $\sigma_\theta$
$\mu^+ \rightarrow e^+ \gamma$ Decay

$\mu^+ \rightarrow e^+ \gamma$ Signature & Background (3)

- Accidental Background

- Accidental Coincidence
  - from Radiative Muon Decay
  - from AiF of Michel $e^+$
  - high rate $e^+$
\( \mu \rightarrow e \gamma \) Decay

\( \mu \rightarrow e \gamma \) Signature & Background (3)

- Accidental Background

\begin{align*}
\mu^+ & \rightarrow e^+ + \nu + \bar{\nu} + \gamma \\
\nu & \rightarrow \gamma \\
e^+ & \rightarrow \text{good Resolutions}
\end{align*}

- Accidental Coincidence
- from Radiative Muon Decay
- from AiF of Michel \( e^+ \)
- high rate \( e^+ \)
MEG Experiment
MEG Experiment

- Liquid Xenon Photon Detector
- Muon stopping target
- Muon Beam Transport Solenoid
- Timing Counters
- COBRA Solenoid
- Drift Chambers

Scale: 1m
MEG Experiment

Liquid Xenon Photon Detector

muon stopping target

COBRA Solenoid

Drift Chambers

Timing Counters

(1) World’s Most Intense DC Muon Beam
MEG Experiment

(1) World’s Most Intense DC Muon Beam

(2) Specially Graded Solenoidal Magnet
MEG Experiment

(1) World’s Most Intense DC Muon Beam

(2) Specially Graded Solenoidal Magnet

(3) Very LIGHT and Sensitive DC, and Very Fast TC
MEG Experiment

(1) World’s Most Intense DC Muon Beam

(2) Specially Graded Solenoidal Magnet

(3) Very LIGHT and Sensitive DC, and Very Fast TC

(4) Liquid Xenon Scintillation Photon Detector
MEG Experiment

(1) World’s Most Intense DC Muon Beam
(2) Specially Graded Solenoidal Magnet
(3) Very LIGHT and Sensitive DC, and Very Fast TC
(4) Liquid Xenon Scintillation Photon Detector

Main Subject
Photon Detector

- Liquid Xenon Scintillation Photon Detector
- Very Heavy (2.98g/cc)
- High Light Yield (80% NaI)
- Good Resolutions (E, x)
- Fast Decay Time
- Good Timing Resolution
- Operational @ High Rate
- Liquid
- Uniform, Easy Design
Trigger and DAQ (1)

- Trigger based on FADC and FPGA

**Type-1 board**
(100MHz FADC, Q and T reconstruction)

- PMTs @ LXe (216+160)
- PMTs @ TC (60)
- APDs @ TC (64)

- Anodes @ DC (32+32)
- APDs @ NaI (9)
- PMTs @ Cosmic-counter

**Type-2 board**
(Online reconstruction for Trigger)

- MEG : Q(Xe)$_{\text{high}}$ & θ$_{\text{narrow}}$ & T$_{\text{narrow}}$ 4 Hz
- MEG-q : Q(Xe)$_{\text{low}}$ & θ$_{\text{narrow}}$ & T$_{\text{narrow}}$ 6 Hz
- MEG-d : Q(Xe)$_{\text{high}}$ & θ$_{\text{wide}}$ & T$_{\text{narrow}}$ 20 Hz
- MEG-t : Q(Xe)$_{\text{high}}$ & θ$_{\text{narrow}}$ & T$_{\text{wide}}$ 10 Hz
- RD-narrow : Q(Xe)$_{\text{low}}$ & & T$_{\text{narrow}}$ 40 Hz
- RD-wide : Q(Xe)$_{\text{low}}$ & & T$_{\text{wide}}$ 70 Hz

**Ancillary Triggers** (calibration for sub-detectors)

- All PMTs and APDs (LXe and TC) are sampled with 100MHz by Type-1 board and converted to Charge and Timing information.
- Type-2 receives Q/T from Type-1 and completes reconstruction. Energy / Angle / Time.
- μ→eγ Trigger is provided by “Q(LXe)” && “e+-γ Direction” && “e+-γ Coincidence”
- In the engineering run 2007, expected trigger rate has been confirmed.
MEG Experiment

Trigger and DAQ (2)

- Waveform Digitizer

**DRS**
(Domino Ring Sampler)

- ALL OUTPUTS are Recorded in Sampler
- 1024 capacitive sampling cells
- 1024 cells SCA
- 0.5 - 4 GHz sampling is available
- 1.8GHz for Xenon/TC and 500MHz for DC
Positron Spectrometer
e\textsuperscript{+} Spectrometer

Requirements

- **Very high counting rate**
  - the most intense DC muon beam in the world
  - muon stopping rate: \(3 \times 10^7\) muons/sec

- **Good momentum/position/timing resolution**
  - aiming excellent sensitivity
  - 0.4-1\% momentum resolution, 500\(\mu\)m position resolution for both direction (r,z) and 40 ps timing resolution

- **Low-mass material**
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - \(\gamma\) background generation should be suppressed as much as possible
Requirements

- **Very high counting rate**
  - the most intense DC muon beam in the world
  - muon stopping rate: $3 \times 10^7$ muon/sec

- **Good momentum/position/timing resolution**
  - aiming excellent sensitivity
  - 0.4-1% momentum resolution, 500µm position resolution for both direction (r,z) and 40 ps timing resolution

- **Low-mass material**
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - $\gamma$ background generation should be suppressed as much as possible
Requirements

• **Very high counting rate**
  - the most intense DC muon beam in the world
  - muon stopping rate: $3 \times 10^7$ muon/sec

• **Good momentum/position/timing resolution**
  - aiming excellent sensitivity
  - 0.4-1% momentum resolution, 500µm position resolution for both direction (r,z) and 40 ps timing resolution

• **Low-mass material**
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - $\gamma$ background generation should be suppressed as much as possible
**COBRA Spectrometer**

**Solenoid**
- superconducting solenoid gradient B-field (0.5-1.7 T)
- very thin conductor and cryostat wall (0.2X₀)

**Drift Chamber**
- segmented radially (16 sectors)
- helium:ethane (50:50)
- opened-frame
- very thin cathode foil with pads

**Timing Counter**
- 2-layers of scintillators
  - scintillator bars (outer)
  - scintillator fibres (inner)
COBRA Concept (1)

Uniform Field

COBRA Field

e^+ Spectrometer
COBRA Concept (1)

• Michel $e^+$ can be swept away very quickly
• Wire-chamber based tracker is operational
COBRA Concept (2)
COBRA Concept (2)

Uniform Field

COBRA Field

e^+ Spectrometer
• **CO**nstant **B**ending **R**A**d**ius is Possible
• DC is placed at larger-radii region only
• DC is sensitive to high-p region only, blind to most of Michel $e^+$
COBRA Concept (3)

\[ \begin{align*}
\text{rate (Hz/cm}^2) \quad \text{Uniform B-field} \quad \text{COBRA B-field} \\
10^5 & \quad \text{green triangle} & \quad \text{orange dot} \\
10^4 & \quad \text{green triangle} & \quad \text{orange dot} \\
10^3 & \quad \text{green triangle} & \quad \text{orange dot} \\
10^2 & \quad \text{green triangle} & \quad \text{orange dot} \\
10 & \quad \text{green triangle} & \quad \text{orange dot} \\
1 & \quad \text{green triangle} & \quad \text{orange dot} \\
\end{align*} \]

radius (cm)

DC region
COBRA Magnet

e+ Spectrometer
COBRA Field
COBRA Field
COBRA Field

$e^+$ Spectrometer
Positron Detection (DC)
Positron Detection (TC, Inner)

- 256 Plastic Scintillation Fibres (6x6mm², BCF-20)
- Both-end APDs (S8664-55), called z-counter
- Used for z-trigger
Positron Detection (TC, Outer)

- 30 Plastic Scintillator Bars (4x4x90cm³, BC404)
- Both-end PMTs (R5924), called phi-counter
- Used for Trigger and Timing Measurement
Global Coordinate System

e⁺ Spectrometer
Drift Chamber
Drift Chamber

Requirements

• **Very high counting rate**
  - muon stopping rate: \( 3 \times 10^7 \) muon/sec

• **Good Spacial Resolution without Increasing Mass**
  - 500µm position resolution for both direction, R and Z
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - \( \gamma \) background generation should be suppressed as much as possible
Drift Chamber

Requirements

- Very high counting rate
  - muon stopping rate: $3 \times 10^7$ muon/sec
- Good Spacial Resolution without Increasing Mass
  - 500µm position resolution for both direction, R and Z
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - $\gamma$ background generation should be suppressed as much as possible

- COBRA field
- restricted region
- small cell
Drift Chamber

Requirements

- **Very high counting rate**
  - muon stopping rate: $3 \times 10^7$ muon/sec

- **Good Spacial Resolution without Increasing Mass**
  - 500µm position resolution for both direction, R and Z
  - 52.8MeV/c positron can be affected by multiple Coulomb scattering easily
  - $\gamma$ background generation should be suppressed as much as possible

- COBRA field
- restricted region
- small cell

- Ultimate-Low-mass
- Thin-cathode foil with Vernier pads
- Min.- readout channel
Overview

- 16 Segmented Module Structure
- Helium-Ethane gas mixture
- 2 Layers of axial wires
  - staggered sense and potential
  - without stereo wire
- carbon-fibre frame
  - open-structure
  - trapezium shape
- ultra-thin cathode foil
  - vernier-pad mechanism
Drift Chamber

Chamber Design (1)
Chamber Design (2)
Vernier Pad

Drift Chamber
Drift Chamber

Vernier Pad

\[ \varepsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}} \]

\[ \varepsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}} \]
Vernier Pad

\[ \varepsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}} \]

\[ \varepsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}} \]

\[ \alpha = \tan^{-1} \frac{\varepsilon_2}{\varepsilon_1} \]
Vernier Pad

\[ \varepsilon_1 = \frac{Q_{iu} - Q_{id}}{Q_{iu} + Q_{id}} \]

\[ \varepsilon_2 = \frac{Q_{ou} - Q_{od}}{Q_{ou} + Q_{od}} \]

\[ \alpha = \tan^{-1} \frac{\varepsilon_2}{\varepsilon_1} \]
Cathode Foil

• 12.5 μm UPILEX with 400 nm Aluminum Deposition
• Uniform Resistivity and Ultra-thin foil are incompatible
• Excellent Print Accuracy is also incompatible
• 250 nm of effective thickness
Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Assembly (1)  - anode -
Drift Chamber

Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Drift Chamber

Assembly (1) - anode -
Assembly (2) - cathode -
Assembly (2) - cathode -
Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Assembly (2) - cathode -
Assembly (2) - cathode -
Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (2) - cathode -
Drift Chamber

Assembly (3)
Drift Chamber

Assembly (4)
Drift Chamber

Mounting / Installation
Drift Chamber

Material Amount

- Total Radiation Length in Tracker Fiducial Volume: $0.002 \times X_0$
“6 channel / cell” x 288 wires = 1728 channels
Drift Chamber

Pressure Equalization System
Drift Chamber

Pressure Equalization System

COBRA He Gas Volume

DC Inlet Manifold

DC Gas Volume (DC00)

DC Gas Volume (DC01)

DC Gas Volume (DC02)

DC Gas Volume (DC15)

DC Outlet Manifold

ΔP (COBRA-Air)

Exhaust

ΔP (DC-COBRA)

Relief lines

DC-He bypass

Exhaust

He inlet (COBRA)

He inlet (DC)

C₂H₆ inlet (DC)

2~4 L/m

Normally Closed Valve

Mass Flow Controller

Temperature Sensor

One-direction Relief Valve

ΔPressure Transducer

Rotary Pump
Slow-Control Stability

ΔP (DC-COBRA)

High Voltage
Simulation
Simulation and Analysis Flow

- Experiment -
  - MIDAS
    - .mid file
    - * Data Acquisition
    - * RAW data

- Simulation -
  - megmc
    - .rz files
    - * event generation
    - * detector simulation
    - * physics background
    - * ZEBRA format data

  - megbartender
    - .root file
    - * event mixing
    - * electronics simulation
    - * digitization
    - * trigger simulation
    - * ROOT format data

  - meganalyzer
    - .root file
    - * event reconstruction
    - * event display
    - * ROOT format data
Simulation and Analysis Flow

- Experiment -
  - MIDAS
    - .mid file
      - Data Acquisition
      - RAW data

- Simulation -
  - megmc
    - .rz files
      - event generation
      - detector simulation
      - physics background
      - ZEBRA format data
  - megbartender
    - .root file
      - event mixing
      - electronics simulation
      - digitization
      - trigger simulation
      - ROOT format data

megmc

megbartender

Event Generator Geant3-base → Detector Simulation Geant3-base → Gas Detector Simulation Garfield9-base

Event Mixing Rate/Distribution → Waveform Simulation Avalanche/Electronics → Trigger Simulation File Converting
Simulation

Event Generation and Detector Simulation

- one DC module -

- cross-sectional view -

generated e⁺
cells
energy depositions
Simulation

Event Generation and Detector Simulation

generated e^+
cells
energy depositions
Garfield-based precise simulation
Simulation

Gaseous Detector Simulation
Event Mixing

3×10^7 muon/sec

Simulation

x-y view

x-z view
Waveform Simulation (1)

- Simulation from X ray
- Template
- Data
- Simulation from MC
- Filtered
Simulation

Waveform Simulation (2)

- Waveform Reproducibility
- “Charge” ~ “Height”, “Charge/Amplitude” ~ “Width” or “Shape”
Event Reconstruction
Event Reconstruction Flow

1. Start from Waveform
2. Hit Reconstruction
3. Pattern Recognition
4. Track Fitting

Reconstruction
Hit Reconstruction

baseline fitting

leading-edge fit
Track Finding (x-y view)
Track Finding (x-y view)

raw hit map
Track Finding (x-y view)
Track Finding (x-y view)
Track Finding (x-y view)

- Raw hit map
- Time-window
- Delta-z in single plane
- Delta-z in different planes
- Delta-z vs absolute-z
Track Finding (x-y view)

Reconstruction

raw hit map

time-window

cluster finder
Track Finding (x-y view)

Reconstruction
Track Finding (x-y view)

- Raw hit map
- Time-window
- Track seed

Reconstruction
Track Finding (x-y view)
Track Finding (x-y view)

Reconstruction
Track Finding (z-x view)

- Waveform Information Available
- 3-dimensional hit coordinates help a lot
- without adaptive filtering, very effective, very fast
Track Fitting Requirement

- Global Fit vs. Adaptive Fit
- Speed, Accuracy, Experimental Circumstances
Track Fitting Requirement

- Global Fit vs. Adaptive Fit
- Speed, Accuracy, Experimental Circumstances
Reconstruction

Kalman Filter Implementation

![Diagram of Kalman Filter Implementation](diagram.png)

- Measurement
- Predicted
- Filtered
- State Vector with errors
- Predicted Position for "k+1"-th step
- Predicted Position for "k"-th step
- Process Error Projection
- State Prediction "k-1" to "k"
- Filtered Position for "k"-th step by weighted mean of "k"-th and "k-1"-th
Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???
Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???

\[
\frac{dp}{dt} = qv \times B
\]
Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???

\[
\frac{d}{dz} \begin{bmatrix} z \\ x \\ y \\ x' \\ y' \\ \rho \end{bmatrix} = \begin{bmatrix} 1 \\ x' \\ y' \\ \rho' \end{bmatrix} - \frac{\rho\sqrt{1 + x'^2 + y'^2}((r' \times B)_x - x'(r' \times B)_z)}{\rho\sqrt{1 + x'^2 + y'^2}((r' \times B)_x - y'(r' \times B)_y) - \rho'(r' \times B)_z}
\]

\[
\frac{dp}{dt} = qv \times B
\]
Track Fitting

- Fitting is done by Kalman filter
- Interpolation is required, Circle Projection ???

\[ \frac{dp}{dt} = qv \times B \]
Calibration
Calibration Runs (1)

- Cosmic-Ray Trigger (w/o B-field)
- Wire Alignment, z-Coordinate Calibration, (Timing Pedestal)
Calibration Runs (2)

- Michel Positron Trigger (DC self-trigger)

- Time-to-Distance Calibration, (z-Coordinate Calibration)

- Detector Performance Estimation
Calibration Runs (3)

- For the Run 2007, several chamber was badly conditioned

- “Feed-through Problem”
- “Discharge” Problem
- All problems are repaired during winter shutdown 2007-2008
Wire Alignment
Wire Alignment

• relatively aligned with 47.3\(\mu\)m of accuracy
z-Coordinate Calibration (1)

• No Alternative Position Sensitive Detector (other than DC)
• z-coordinate calibration is very important to guarantee $\sigma_p$, $\sigma_\theta$ and $\sigma_x$ on target
z-Coordinate Calibration (1)

- No Alternative Position Sensitive Detector (other than DC)
- z-coordinate calibration is very important to guarantee $\sigma_p$, $\sigma_\theta$ and $\sigma_x$ on target

- "Vernier Period" (=5cm) can be a good position reference in z-coordinate
Calibration

z-Coordinate Calibration (2)

- Iterative Method: “z_{cathode}” <-> “z_{anode}”
- z-Coordinate Calibration $\approx$ Relative Gain Calibration

- z-alignment is also performed here, 100$\mu$m of z displacement are corrected
Time-to-Distance Calibration

- XT-map are corrected so that the residual is minimized
- All Cells should be calibrated individually due to B-variation
Analysis
Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam

- Calibration Runs (October-November)
  - Cosmic-ray Runs
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity
    - 2M outer trig. with Normal intensity

- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)
Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam

- Calibration Runs (October-November)
  - Cosmic-ray Runs
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity
    - 2M outer trig. with Normal intensity

- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

Analysis
Analysis

Engineering Run 2007

• Conditioning Runs (September-October)
  • without beam, with low-intensity beam, with normal intensity beam

• Calibration Runs (October-November)
  • Cosmic-ray Runs
  • Michel Runs
    • 3M normal and 2M outer trig. with Low intensity
    • 2M outer trig. with Normal intensity

• MEG Rehearsal Run (December)
  • MEG event trigger (TC && Xenon with direction matching)
Analysis

Engineering Run 2007

• Conditioning Runs (September-October)
  • without beam, with low-intensity beam, with normal intensity beam

• Calibration Runs (October-November)
  • Cosmic-ray Runs
  • Michel Runs
    • 3M normal and 2M outer trig. with Low intensity
    • 2M outer trig. with Normal intensity

• MEG Rehearsal Run (December)
  • MEG event trigger (TC && Xenon with direction matching)

efficiency

resolutions

rate dependence
Engineering Run 2007

- Conditioning Runs (September-October)
  - without beam, with low-intensity beam, with normal intensity beam

- Calibration Runs (October-November)
  - Cosmic-ray Runs
  - Michel Runs
    - 3M normal and 2M outer trig. with Low intensity
    - 2M outer trig. with Normal intensity

- MEG Rehearsal Run (December)
  - MEG event trigger (TC && Xenon with direction matching)

Analysis

- efficiency
- resolutions
- rate dependence
- spectrometer performance
Analysis

Single Hit Efficiency

- For Run 2007
  - 1850V is nominal
  - 1800V for discharge DCs
Spacial Resolution (Transverse, “r”)

- Residual “reconstruct - fit”
- Slice by 0.5 mm intervals in drift distance, position dependence of R resolution is studied.
- 170~350 micron in sigma is achieved (good DC).
Analysis

Spacial Resolution (Longitudinal, “z”)

Anode Charge Div. Resolution

<table>
<thead>
<tr>
<th>cell #8</th>
<th>$\sigma_z = 6.786 \pm 0.02$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell #0</td>
<td>$\sigma_z = 11.08 \pm 0.05$ (mm)</td>
</tr>
</tbody>
</table>

Resolution vs Wire Length

- Plane A
- Plane B

- cell #8
- cell #0
Spacial Resolution (Longitudinal, “z”)
Analysis

Spacial Resolution (Longitudinal, “z”)

\[ \alpha = \frac{\pi}{2}, \quad \alpha_z = 499 \pm 9.5 \, (\mu m) \]

\[ \alpha = \frac{3\pi}{4}, \quad \alpha_z = 833 \pm 10 \, (\mu m) \]
Momentum Resolution (1)

- Michel-Edge Fitting
  - Absolute Momentum Calibration
  - Momentum Resolution Estimation

Analysis
Momentum Resolution (2)

- Michel-Edge Deformation
- Radiative Corrections to the Michel Spectrum
- Trigger Condition Dependences

![Graphs showing Michel and Triggered Spectra](image)
Analysis

Momentum Resolution (3)

- Michel-Edge Fitting is done with several angular slices
Momentum Resolution (4)

- Resolution Estimation with monochromatic 52.8MeV $e^+$ by MC

- “Actual MC”
  - Garfield part and Waveform simulation are turned off
  - Only using “Geant-Hit” degraded by each effects
Momentum Resolution (4)

- Resolution Estimation with monochromatic 52.8MeV $e^+$ by MC

- “Actual MC”
  - Garfield part and Waveform simulation are turned off
  - Only using “Geant-Hit” degraded by each effects

Analysis

\[ \sigma_p = (292 \pm 10) \text{ keV/}c \]

\[ \sigma_p = (421 \pm 14) \text{ keV/}c \]

- dead channel
- bad channel
- bad resolution
- air doping

300keV (averaged over acceptance)

458keV (averaged over acceptance)
Momentum Resolution (5)

- Rate Dependence / Trigger Dependence

![Reconstructed Spectrum (Michel Outer Trig.)](image1)

- $E_{\text{edge}} = 52.78 \pm 0.14 \text{ MeV/c}$
- $\sigma_p = 500 \pm 81 \text{ keV/c}$

![Reconstructed Spectrum (MEG Trig.)](image2)

- $E_{\text{edge}} = 52.81 \pm 0.10 \text{ MeV/c}$
- $\sigma_p = 488 \pm 62 \text{ keV/c}$
Vertex Resolution

- Hole on Target can be used

\[ \sigma_x = 1.8 \text{ mm} / \text{MC}_{\text{ideal}}: \sigma_x = 1.1 \text{ mm} \]

- 5.3 mm misalignment of target position can be seen
Angular Resolution

**Analysis**
Spectrometer Efficiency (1)

- Counting Efficiency is limited by scattering between DC and TC
Spectrometer Efficiency (1)

- Counting Efficiency is limited by scattering between DC and TC
Spectrometer Efficiency (2)

- $e^+$ scattering should be investigated with material distribution
Analysis

Spectrometer Efficiency (2)

- $e^+$ scattering should be investigated with material distribution

<table>
<thead>
<tr>
<th></th>
<th>reconstruction</th>
<th>spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>data (2007)</td>
<td>65.5%</td>
<td>42.8%</td>
</tr>
<tr>
<td>MC (actual)</td>
<td>65.5%</td>
<td>43.8%</td>
</tr>
<tr>
<td>MC (ideal)</td>
<td>65.5%</td>
<td>63.9%</td>
</tr>
</tbody>
</table>

- Spectrometer Efficiency
  - $\varepsilon^{2007} = 42.8\%$
  - $\varepsilon^{2008} = 63.9\%$
Material Distribution
Discussion
## Limiting Factors (1)

### DC Spacial Resolution

<table>
<thead>
<tr>
<th>Resolutions</th>
<th>Effect</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse Spacial Resolution 169 - 351 μm (data,2007)</td>
<td>High Voltage</td>
<td>± 0.40</td>
</tr>
<tr>
<td></td>
<td>Gas Pressure</td>
<td>± 0.25</td>
</tr>
<tr>
<td></td>
<td>Timing Determination</td>
<td>± 76.4</td>
</tr>
<tr>
<td></td>
<td>Alignment (r)</td>
<td>± 33.5</td>
</tr>
<tr>
<td></td>
<td>Electron Diffusion</td>
<td>± 90.1</td>
</tr>
<tr>
<td></td>
<td>Multiple Scattering</td>
<td>± 125</td>
</tr>
<tr>
<td></td>
<td>Total in quadrature</td>
<td>± 175</td>
</tr>
<tr>
<td>Longitudinal Spacial Resolution 499 - 833 μm (data,2007)</td>
<td>DRS Fake Pulse</td>
<td>± 138</td>
</tr>
<tr>
<td></td>
<td>Alignment (z)</td>
<td>± 92</td>
</tr>
<tr>
<td></td>
<td>Relative Gain Fluctuation</td>
<td>± 199</td>
</tr>
<tr>
<td></td>
<td>Baseline Noise</td>
<td>± 109</td>
</tr>
<tr>
<td></td>
<td>Multiple Scattering</td>
<td>± 175</td>
</tr>
<tr>
<td></td>
<td>Charge Distribution</td>
<td>± 354</td>
</tr>
<tr>
<td></td>
<td>Total in quadrature</td>
<td>± 484</td>
</tr>
</tbody>
</table>
Limiting Factors (2)

- Spectrometer Resolution
- Missing Channels / Spacial Resolutions / Air Doping
Limiting Factors (2)

- Spectrometer Resolution
- Missing Channels / Spacial Resolutions / Air Doping

- Obtained Momentum Resolution: 477 keV (data) and 300 keV (MC_{ideal})
  - Contribution: Spacial Resolution: ± 135 keV (r), ± 164 keV (z)
  - Contribution from Air Contamination: ± 125 keV
  - Contribution from Missing Channels: ± 285 keV
Limiting Factors (2)

- Spectrometer Resolution
- Missing Channels / Spacial Resolutions / Air Doping

- Obtained Momentum Resolution: 477 keV (data) and 300 keV (MC$^{\text{ideal}}$)
- Contribution: Spacial Resolution: ± 135 keV (r), ± 164 keV (z)
- Contribution from Air Contamination: ± 125 keV
- Contribution from Missing Channels: ± 285 keV

461 keV (sum) 458 keV (MC$^{\text{actual}}$)
Limiting Factors (3)

- Is it Reasonable??

\[
(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2
\]

(in uniform B field)

\[
\delta k_{res} = \frac{\epsilon}{L^2} \sqrt{\frac{720}{N + 4}}
\]

\[
\delta k_{ms} = \frac{(0.016)(\text{Gev}/c)z}{Lp\beta \cos^2 \theta} \sqrt{\frac{L}{X_0}}
\]
Analysis

Limiting Factors (3)

• Is it Reasonable ??

\[
(\delta k)^2 = (\delta k_{res})^2 + (\delta k_{ms})^2
\]

(in uniform B field)

\[
\delta k_{res} = \frac{\epsilon}{L^2} \sqrt{\frac{720}{N + 4}}
\]

\[
\delta k_{ms} = \frac{(0.016)(\text{Gev}/c)z}{L \beta \cos^2 \theta} \sqrt{\frac{L}{X_0}}
\]

• Obtained Momentum Resolution : 477 keV (data) and 300 keV (MC_{\text{ideal}})
  • Contribution : Spacial Resolution (factor 1.21) : ± 127 keV (r) (135 keV, MC_{\text{actual}})
  • Contribution from Air Contamination (factor 1.48) : ± 121 keV (125 keV, MC_{\text{actual}})
  • Contribution from Missing Channels (factor 1.88) : ± 224 keV (249 keV, MC_{\text{actual}})
## MEG Sensitivity (1)

**Detector Performances**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Engineering Run 2007</th>
<th>Physics Run 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$ Momentum Resolution (%)</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$e^+$ Angular Resolution (mrad)</td>
<td>14.5</td>
<td>11.5</td>
</tr>
<tr>
<td>$e^+$ Timing Resolution (ps)</td>
<td>127</td>
<td>103</td>
</tr>
<tr>
<td>$\gamma$ Energy Resolution (%)</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>$\gamma$ Spacial Resolution (mm)</td>
<td>-</td>
<td>9.0</td>
</tr>
<tr>
<td>$\gamma$ Timing Resolution (ps)</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>$e^+$ Detection Efficiency (%)</td>
<td>43.8</td>
<td>63.9</td>
</tr>
<tr>
<td>$\gamma$ Detection Efficiency (%)</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Muon Rate (/sec)</td>
<td>3.00E+07</td>
<td>3.00E+07</td>
</tr>
</tbody>
</table>
## MEG Sensitivity (1)

### Detector Performances

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Engineering Run 2007</th>
<th>Physics Run 2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$ Momentum Resolution (%)</td>
<td>2.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$e^+$ Angular Resolution (mrad)</td>
<td>14.5</td>
<td>11.5</td>
</tr>
<tr>
<td>$e^+$ Timing Resolution (ps)</td>
<td>127</td>
<td>103</td>
</tr>
<tr>
<td>$\gamma$ Energy Resolution (%)</td>
<td>-</td>
<td>5.0</td>
</tr>
<tr>
<td>$\gamma$ Spacial Resolution (mm)</td>
<td>-</td>
<td>9.0</td>
</tr>
<tr>
<td>$\gamma$ Timing Resolution (ps)</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>$e^+$ Detection Efficiency (%)</td>
<td>43.8</td>
<td>63.9</td>
</tr>
<tr>
<td>$\gamma$ Detection Efficiency (%)</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>Muon Rate (/sec)</td>
<td>$3.00\times10^7$</td>
<td>$3.00\times10^7$</td>
</tr>
</tbody>
</table>
MEG Sensitivity (2)

- Physics Background (Radiative Muon Decay)

\[ dB(\mu \rightarrow e\nu\gamma) = \frac{1}{\Gamma(\mu \rightarrow e\nu\gamma)} \int_{1-\delta x}^{1} dx \int_{1-\delta y}^{1} dy \int_{0}^{\min[\delta z, 2\sqrt{(1-x)(1-y)}]} dz \frac{d\Gamma(\mu \rightarrow e\nu\gamma)}{dx dy dz} \]
MEG Sensitivity (2)

- Physics Background (Radiative Muon Decay)

\[
\frac{d B(\mu \rightarrow e\nu\gamma)}{\Gamma(\mu \rightarrow e\nu\gamma)} = \frac{1}{\Gamma(\mu \rightarrow e\nu\gamma)} \int_{1-\delta x}^{1} dx \int_{1-\delta y}^{1} dy \int_{0}^{\min[\delta z, 2\sqrt{(1-x)(1-y)}]} dz \frac{d\Gamma(\mu \rightarrow e\nu\gamma)}{dxdydz}
\]

**Analysis**

- For MEG 2008, Physics Background < 1.1×10^{-14}
MEG Sensitivity (3)

- Accidental Background

\[ B_{acc} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[ \frac{\alpha}{2\pi} (\delta y)^2 (\ln(\delta y) + 7.33) \right] \times \left( \frac{\delta \theta^2}{4} \right) \cdot (2\delta t). \]
MEG Sensitivity (3)

- Accidental Background

\[ B_{\text{acc}} = \mathcal{R}_\mu \cdot (2\delta x) \cdot \left[ \frac{\alpha}{2\pi} (\delta y)^2 (\ln(\delta y) + 7.33) \right] \times \left( \frac{\delta \theta^2}{4} \right) \cdot (2\delta t). \]

**Analysis**

- For MEG 2008, Accidental Background < $1.2 \times 10^{-13}$
MEG Sensitivity (3)

- Accidental Background

\[ B_{acc} = R_{\mu} \cdot (2\delta x) \cdot \left[ \frac{\alpha}{2\pi} (\delta y)^2 (\ln(\delta y) + 7.33) \right] \times \left( \frac{\delta \theta^2}{4} \right) \cdot (2\delta t). \]

- For MEG 2008, Accidental Background < $1.2 \times 10^{-13}$
MEG Sensitivity (3)

- Accidental Background

\[ B_{\text{acc}} = R_{\mu} \cdot (2\delta x) \cdot \left[ \frac{\alpha}{2\pi} (\delta y)^2 (\ln(\delta y) + 7.33) \right] \times \left( \frac{\delta\theta^2}{4} \right) \cdot (2\delta t). \]

**Analysis**

- For MEG 2008, Accidental Background < $1.2 \times 10^{-13}$
- For MEG 2008, Number of Expected Background Event = 0.60
MEG Sensitivity (4)

- Single Event Sensitivity

\[ B(\mu^+ \rightarrow e^+\gamma) = \frac{1}{R_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{sel}}, \]
MEG Sensitivity (4)

- Single Event Sensitivity

\[ B(\mu^+ \rightarrow e^+\gamma) = \frac{1}{R_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{\text{sel}}}, \]

- For MEG 2008, Single Event Sensitivity:

\[ B^{2008}(\mu \rightarrow e\gamma) = 2.2 \times 10^{-13} \]
MEG Sensitivity (4)

- Single Event Sensitivity

\[ B(\mu^+ \rightarrow e^+\gamma) = \frac{1}{R_\mu \cdot T \cdot (\Omega/4\pi)} \times \frac{1}{\epsilon_e \cdot \epsilon_\gamma \cdot \epsilon_{sel}}, \]

- For MEG 2008, Single Event Sensitivity:

\[ B^{2008}(\mu \rightarrow e\gamma) = 2.2 \times 10^{-13} \]

- For MEG 2008, Feasible Upper-limit

\[ B^{2008}(\mu \rightarrow e\gamma) < 7.4 \times 10^{-13} (90\% \text{ C.L.}) \]
Conclusion

- An Innovative Positron Spectrometer has been Developed for MEG experiment
  - Highly Graded Magnetic Field
  - Very Light & Sensitive Drift Chamber System
  - Very Fast Timing Counter System
- Challenging Development on Hardware and Software both has been done
- Detector Construction was completed in summer 2007
- Engineering run (detector conditioning, beam commissioning, detector calibration) have been carried out in September - December 2007
- All the Calibration Procedures are established for Positron Spectrometer
- Positron Spectrometer worked well in high intensity muon beam with COBRA
- However, several components were not conditioned well; it made a serious deterioration.
- In consequence, we obtained 0.9% of $\sigma_p$ and 6 mrad of $\sigma_{\theta}$ for 52.8 MeV/c positron
- These performances can be improved up to 0.5% of $\sigma_p$ and 4 mrad of $\sigma_{\theta}$
- MEG Physics Run 2008 can achieve $B(\mu \rightarrow e\gamma) < 7.4 \times 10^{-13}$ (90% C.L.)
Acknowledgements

日本大学

森俊則氏、大谷航氏、岩本敏幸氏、澤田龍氏

KEK

三原智氏、山田秀衛氏、小曽根健嗣氏、春山富義氏、笠見勝祐氏

MEG Students

久松康子氏、内山雄祐氏、名取寛顕氏、西村康宏氏、白雪氏、金子大輔氏

PSI Drift Chamber Group

J. Egger, M. Hildebrandt, M. Schneeberi, A. Hofer, D. Fahrni, F. Barachetti, L. Meyer

Special Thanks to:

近野和夫氏 (林栄精器)、(株)プリント電子研究所
In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.

Successfully all DC modules were operational !!!
In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.

Successfully all DC modules were operational !!!

but...
In winter-spring shutdown 2008, we made the tight helium protection on DC-HV tracer line.
Successfully all DC modules were operational !!!

but...

After 2 months operation, discharge happened again...
At the beginning of physics run, 27 planes (32) were operational, finally only 18 planes were operational at the end of physics run.
宣伝

29pSE01: MEG実験2008 液体キセノン検出器 I, 名取寛顕 (東大)
29pSE02: MEG実験2008 液体キセノン検出器 II, 西村康宏 (東大)
29pSE03: MEG実験2008 光電子増倍管量子効率測定の改良, 白雪 (東大)
29pSE04: MEG実験2008 陽電子スペクトロメータ, 西口創（KEK）
29pSE05: MEG実験2008 $\mu^+ \rightarrow e^+\gamma$崩壊事象探索解析 内山雄祐 (東大)
backup slides
Muon Beam

• Requirements
  • Powerful Proton Driver
  • Pulsed Beam vs. DC Beam
  • Surface Muon vs. Cloud Muon
Muon Beam

• Requirements

• Powerful Proton Driver

• Pulsed Beam vs. DC Beam

• Surface Muon vs. Cloud Muon
Muon Beam

- **Requirements**
  - Powerful Proton Driver
  - *Pulsed Beam* vs. *DC Beam*
  - Surface Muon vs. *Cloud Muon*

**Paul Scherrer Institut (PSI) is the BEST Experiment Site**

1. 1.2 MW proton cyclotron
2. Up to 2mA proton beam
3. World Most Intense Surface Muon Beam

πE5 Beam Channel
10^8 /sec surface muon is available
Muon Stopping Target

- Requirements
  - Light Material
  - Thin
  - (Plastic)
Muon Stopping Target

• Requirements
  Light Material
  Thin
  (Plastic)
Muon Stopping Target

- Requirements
  Light Material
  Thin
  (Plastic)
DC Requirements

**DC Mass and Resolution**

- $\sigma_{p_{MS}} (0.001-0.004X_0)$
- $\sigma_{p_{meas}} (100-700\mu m)$
- $\sigma_{p_{MS+meas}} (0.002X_0 + 100-700\mu m)$

![Graph showing DC mass and resolution with varying momentum resolutions.](diagram.png)
“Intrinsic” Timing Resolution

- Time Difference b/w two \( \varphi \)-counter
- 52 ps of timing resolution
Timing Resolution

- TC impact timing should be converted to $e^+$ time of flight (decay timing)
- Can be evaluated indirectly by the combination of MC and Data

### Spectrometer Timing Resolution
- Spectrometer Timing Resolution = 58.7 ps
- Timing Uncertainty caused by Track Length Error $\approx 27$ ps
Analysis

Spectrometer Efficiency (1)

- Spectrometer Efficiency = Tracking Efficiency \(\otimes\) Counting Efficiency

### Track Finding Eff.

<table>
<thead>
<tr>
<th></th>
<th>Low Rate (5(\times)10^6 /sec)</th>
<th>Normal Rate (3(\times)10^7 /sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cluster finder</td>
<td>track finder</td>
</tr>
<tr>
<td>data (2007)</td>
<td>99.9%</td>
<td>97.9%</td>
</tr>
<tr>
<td>MC (actual)</td>
<td>99.9%</td>
<td>98.1%</td>
</tr>
<tr>
<td>MC (ideal)</td>
<td>100%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

### Track Reconstruction Eff.

<table>
<thead>
<tr>
<th></th>
<th>Low Rate (5(\times)10^6 /sec)</th>
<th>Normal Rate (3(\times)10^7 /sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fitting</td>
<td>(\chi^2) cut</td>
</tr>
<tr>
<td>data (2007)</td>
<td>77.8%</td>
<td>66.1%</td>
</tr>
<tr>
<td>MC (actual)</td>
<td>80.4%</td>
<td>67.2%</td>
</tr>
<tr>
<td>MC (ideal)</td>
<td>99.5%</td>
<td>97.9%</td>
</tr>
</tbody>
</table>