崩壊分岐比感度 10^{-15} の
新しい μ^+ → e^+γ 探索
実験の検討

18/September/2014
日本物理学会2014年秋季大会@佐賀大学
Abstract

1. A project to make a new muon beamline is progressing at PSI to provide \( 10^{-100} \) times higher continuous muon beam.

2. Study possibilities of carrying out a new \( \mu \rightarrow e\gamma \) experiment with a sensitivity of \( 10^{-15} \), an order of magnitude better than MEG-II.

3. Consider converting photon spectrometer for the gamma-ray detector.
Paul Scherrer Institut

World’s most powerful proton beam to targets:

\[ 590 \text{ MeV} \times 2.4 \text{ mA} = 1.4 \text{ MW} \]

Proton accelerator complex

World’s highest intensity \( \pi \) & \( \mu \) beams
HiMB project

- Next generation High intensity Muon Beam project

- Extract muon produced at the target of spallation neutron (SINQ)
  - High intensity proton (70% of primary proton stop here)
  - Wide pion energy-range (<150MeV)
  - Large production volume (9000 times larger than E-target at PiE5)

- $O(10^{10})$ surface $\mu^+$/s (estimate)

- Feasibility study in 2013 – 2014

- Operation from ~2019 (?)

Some concrete numbers will come later this year
μ→eγ status (from MEG to MEG II)

- MEG completed data taking
  - Set limit $\mathcal{B}(\mu\rightarrow e\gamma) < 5.7 \times 10^{-13} @ 90\% \text{CL}$
  - Final result with ~40% improved sensitivity coming soon.

- MEG II construction has been started
  - Aim at x10 better sensitivity ($< 5 \times 10^{-14}$)
  - By exploiting full beam intensity available today
    - $\sim 10^8 \mu^+/s$ at the PSI πE5
  - By upgrading the MEG detector
    - Keep experimental concept
    - In short (~5 years), at low cost
Next decade

- Belle II
- 7–8 TeV
- 13–14 TeV
- 14 TeV
- HL-LHC
- PSI/HiMB
- FNAL/PIP II
- Mu2e
- PRISM?
- MEG phase II
- Mu3e phase I
- COMET phase I
- DeeMe
- Mu3e phase II
- COMET phase II
- new $\mu \rightarrow e\gamma$?
Two-body decay
- Clear signature
- Easy to gain acceptance (solid angle & momentum)

Neutral particle ($\gamma$)
- Difficult in high precision & high efficiency detection
- No (or very little) info of direction
- Not able to test vertex matching

Physics BG
- Time coincident
- But highly suppressed at signal region by energies & angle

Accidental BG
- Time, direction & energies are random
- But dangerous at high intensity

Dominant in MEG
\[ N_{BG} \propto (R_\mu)^2 \cdot \epsilon \cdot (\delta E_e)^2 \cdot (\delta E_\gamma)^2 \cdot (\delta \theta_{e\gamma})^2 \cdot (\delta t_{e\gamma}) \]

2009 – 2011 data
No excess of signal-like events observed

\[ |t_{e\gamma}| < 0.244 \text{ns}; \cos \theta_{e\gamma} < 0.9996 \]

\[ 51 < E_\gamma < 55.8 \text{MeV}; \quad 52.4 < E_e < 55 \text{MeV} \]
1. LXe $\gamma$-ray detector
2. Gradient field $e^+$ spectrometer
MEG features

1. Liquid xenon γ detector
   - High eff. γ detection ($\varepsilon > 50\%$)
   - Total absorption w/o any dead material, with good uniformity and high light yield ($\sigma_E \sim 1\%$)
   - High time resolution ($\sigma_t \sim 60 \text{ ps}$)
   - Difficult operation, need massive cryostat
   - Weak to pileup due to single volume
   - No power of direction reconstruction

2. Gradient B-field for efficient $e^+$ measurement

3. Relatively small solid angle (geometrical acceptance) $\sim 10\%$
From MEG II

- To improve x10 (a few dozens?) sensitivity, we need at least x10 statistics. How to gain?

  Higher beam intensity
  $\times \ 3, \ 5, \ 10, \ 100 \ ?$

  Increase acceptance
  $\times \ 3, \ 5, \ 10 \ ?$

  MEG II $7 \times 10^7 \mu^+/s$

  MEG II ~5%

- Then, we have to reduce increased BG.
  – How much do we have to reduce?
**Statistics & BG**

\[ N_{BG} \propto (R_\mu)^2 \cdot \epsilon \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot (\delta \vartheta_{e\gamma})^2 \cdot (\delta t_{e\gamma}) \]

**S:** Increase factor of the statistics \((\propto R_\mu \cdot \epsilon)\)

**B:** Increase factor of number of BG events \((\propto N_{BG})\)

<table>
<thead>
<tr>
<th>( R_\mu \times )</th>
<th>( \epsilon \times 1 )</th>
<th>( \epsilon \times 3 )</th>
<th>( \epsilon \times 5 )</th>
<th>( \epsilon \times 10 )</th>
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<td>9</td>
<td>15</td>
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<td>( B )</td>
<td>3</td>
<td>27</td>
<td>45</td>
<td>10</td>
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<tr>
<td>( \text{MEG II} )</td>
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<td>( R_\mu \times 3 )</td>
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<tr>
<td>( R_\mu \times 5 )</td>
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<td>15</td>
<td>45</td>
<td>90</td>
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<tr>
<td>( R_\mu \times 10 )</td>
<td>5</td>
<td>15</td>
<td>45</td>
<td>90</td>
</tr>
<tr>
<td>( R_\mu \times 100 )</td>
<td>100</td>
<td>100</td>
<td>500</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Assuming same running time as MEG II*
Converting Photon Spectrometer
Concept

- Measure $e^+e^-$ pair from incident photon converted in conversion layer.

- Previous experiment, MEGA, used this type detector.

**Merits**
- Good position resolution
- Direction of γ reconstructed
- Strong against pileup
- Low cost (?)
- Better energy resolution possible but trade off b/w efficiency

**Challenge: How to gain efficiency**
- ~a few %
- Complicated pattern recognition and tracking
There are a few preceding studies of new $\mu \rightarrow e\gamma$ experiments using the converting photon spectrometer.

- Mainly in US snowmass process for ProjectX
- They conclude that it is possible to go to $O(10^{-15})$

However, there are several points suspicious

- Unreasonable assumptions,
- Not proper (or lack) simulation
Perform simple MC study
- shoot 52.8 MeV γ perpendicular to the Pb plate
- Calculate out-coming e+e- energies

Need to track particle as low as <10 MeV to get good efficiency

Energy loss inside the converter (dominant) was not simulated!

560 μm Pb

1% 0.75%

52.8 MeV ± 200keV * 1.64
• Energy reso. is limited by energy loss in converter
  – Energy loss clearly correlates with path length inside the converter
  – However, reconstruct the depth of conversion seems difficult

• As thin as 100 um necessary.
• Efficiency is <0.75% per layer.

• Able to solve the dilemma by sub-layers
  – Fill the gap with active device, or
  – Just gap
  – can disentangle sub layer
**γ angular resolution**

- γ direction can be reconstructed from momenta of the pair
- Resolution: $\sim 50$ mrad (<10 mrad in ProjectX study)
  - Limited by multiple scattering in the converter
  - Similar to MEGA’s resolution (250 um Pb)

Power of accidental BG discrimination. Compensate increased beam intensity.
In 1.5 T uniform B-field

10 super layers
- first layer from r=26 cm
- at 5 cm radial distance

A super layer consists of
- two 100 um Pb converters
- two Si pixel layers put both outside the conversion double layer

Target
- 100 um plastic sheet
- slant angle of 10° to spread vertex distribution

-15% conversion eff.
assuming 50% rec. eff. ⇒ 7–8% eff.

Need active area of 160 m²
CMS level!
⇒ Increase B-field, increase sub-layers
Detector requirement

- Si pixel tracker with
  - Large area
  - High time resolution ($O(100 \text{ ps})$)
  - Ultra thin (~50 um)
    - If build $e^+$ side as well, <50 um important

- No available device today
  Need device development

Giga-tracker for NA62 about in use

Hybrid pixel
$\sigma t = 200 \text{ ps}$
200 um thick

HV-MAPS for Mu3e
50 um thick
High rate

(High voltage monolithic active pixel sensors)
1. Peric et.al. NIMA 582 (2007) 876

New technologies open new physics!
Summary

● 10 times larger statistics achievable by
  – 5 times higher intensity beam
  – twice higher signal acceptance (compared to MEG II)

● with multi-layer converting photon spectrometer
  – multi layers to gain efficiency
  – sub layers for good resolution retaining efficiency

● Suppress increased BG by
  – Vertex matching (compensate increased beam rate)
  – Better γ energy resolution (3 times better)

◆ However, realization seems really challenging
  – Need further detailed studies
  – Need technological development
  – Need more or completely different idea

2014/Sep/18 @ JPS2014 Autumn
Yusuke UCHIYAMA/ The University of Tokyo
To be studied

- Reconstruction (pattern recognition & tracking)
- Event overlap
- BG study
- e^+ side (no study yet)
Upgraded MEG

1. World’s most intensity DC μ beam @ PSI
2. Innovative liquid xenon γ-ray detector
3. Gradient B-field e⁺-spectrometer

Double beam intensity,
Double efficiency,
Suppress BG factor ~30
• Halve every resolution,
• Add new detector to identify BG (option)

<table>
<thead>
<tr>
<th>TABLE XI: Resolution (Gaussian σ) and efficiencies for MEG upgrade</th>
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<tbody>
<tr>
<td>PDF parameters</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>e⁺ energy (keV)</td>
</tr>
<tr>
<td>e⁺ θ (mrad)</td>
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<tr>
<td>e⁺ φ (mrad)</td>
</tr>
<tr>
<td>e⁺ vertex (mm) Z/Y (core)</td>
</tr>
<tr>
<td>γ energy (%) (w &lt;2 cm)/(w &gt;2 cm)</td>
</tr>
<tr>
<td>γ position (mm) u/v/w</td>
</tr>
<tr>
<td>γ-e⁺ timing (ps)</td>
</tr>
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</table>

Efficiency (%)

<table>
<thead>
<tr>
<th></th>
<th>Present MEG</th>
<th>Upgrade scene</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>

μon rate            3.3x10⁷/sec  7x10⁷/sec
Detector technology

- **Ultra thin** device necessary to suppress multiple scattering.

- **HV-MAPS**
  - Thinned down to 30–50 μm
  - Amp, digitization on chip
  - Fast readout: <50 ns timestamp

2013: Extensive beam test campaign

Mock-up

- HV-MAPS
- Flex print
- Kapton Frame

<1‰ X₀ per layer

(High voltage monolithic active pixel sensors)
I. Peric et. al. NIMA 582 (2007) 876
Mu3e Experiment

Tackle with new technologies

- Geometrical acceptance ~70%

SciFi

$\sigma_t \sim \text{a few 100 psec}$

Cone-shape target

disperse vertices into large surface

HV-MAPS

Ultra-thin Si device

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Yusuke UCHIYAMA/ The University of Tokyo
HV-MAPS Prototypes

Design Specifications

- 80 μm × 80 μm pixel size
- 1 cm × 2 cm active area

MuPix2

- 39 μm × 30 μm pixel size
- 1.8 mm × 1 mm active area
- Proof of Concept

MuPix3/4

- 92 μm × 80 μm pixel size
- 2.9 mm × 3.2 mm active area

MuPix4 HV-MAPS Prototype

- 92 μm × 80 μm pixel size
- Global threshold
- Zero-suppressed digital readout
- Timestamps
- Additional readout FPGA

Timestamp frequency 100 MHz

Efficiency

Effective thickness ~ 1/ cos α

HV = 70V
E = 5 GeV

0.0° incidence angle
22.5° incidence angle
45.0° incidence angle