荷電レプトンフレーバーを破る
\[ \pi^0 \rightarrow \mu\text{e} \] 崩壊探索実験の提案

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Outline

• $\pi^0 \rightarrow \mu e$ decay
  • Overview
  • P0EM experiment
  • Signal and BG

• Expected experimental setup
  • MEG II experiment
  • Detector: CDCH
  • Target: LH2 target

• Current status of P0EM experiment

• Detection efficiency
  • Optimize LH2 target size
  • Signal selection
  • Trigger DAQ

• Summary & prospects
$$\pi^0 \rightarrow \mu e$$ decay

- $$\pi^0 \rightarrow \mu^+ e^-$$ decay violates charged lepton flavour
- The decay is similar to $$\mu - e$$ conversion, which is one mode of charged lepton flavour violation (cLFV)
- Present upper limit on the decay: $$3.63 \times 10^{-10}$$ (90% C.L.) [1]
- This limit is given by KTeV experiment at Fermilab in 2008 as a by-product of kaon rare decay search [2]

References:
[1] 2018 PDG
P0EM experiment

- P0EM experiment: Experiment to search for $\pi^0 \rightarrow \mu^+ e^-$ decay at Paul Scherrer Institut (PSI) in Switzerland

- The advantages over previous searches are:
  - **High statistics**
    - $1.4 \times 10^6 \pi^- /s$ are incident on liquid hydrogen (LH2) target
    - $\sim 60\% \pi^-$ generates $\pi^0$ by charge exchange (CEX) process ($\pi^- + p \rightarrow \pi^0 + n$) in LH2
      - $\rightarrow \sim 10^{11} \pi^0$ are generated in one day
  - **Low background**
    - Source of $\mu^+$ would not exist
Signal & Background

**Signal**

- $\pi^0 \rightarrow e^+ e^- \gamma$ decay, or pair production
- $\mu^-$ from $\pi^-$ decay in flight
- $p$ from $\pi^-$ interaction with nuclei
  - Elastic or inelastic scattering: $\pi^- + N \rightarrow \pi^- + N$ (or $N'$)
  - Absorption: $\pi^- + N \rightarrow N' +$ several nuclei

**Background**

- $e$ from scattering, $\pi^0 \rightarrow e^+ e^- \gamma$ decay, or pair production

Distinguish signal $\mu^+$ from BG by energy deposit and trajectory

**Hist**

<table>
<thead>
<tr>
<th>Entries</th>
<th>100000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>32.72</td>
</tr>
<tr>
<td>Std Dev</td>
<td>11.42</td>
</tr>
</tbody>
</table>

**Momentum (MeV/c)**

- $\mu^+$ momentum

- Initial $\pi^-$ momentum:
  - 4.076 MeV/c
  - 49.30 MeV/c
Expected experimental setup

- High-intensity $\pi^-$ beam at PSI
- Target is liquid hydrogen
- Detector for signal $\mu^+$ from $\pi^0 \rightarrow \mu^+ e^-$ decay is cylindrical drift chamber (CDCH) used in MEG II
- COBRA magnet used in MEG II is used for bending charged particles
MEG II experiment

- MEG II searches for $\mu \rightarrow e\gamma$ decay which is one of cLFV
- Use the most intense $\mu$ beam
- P0EM experiment will be a parasite on MEG II
- P0EM will use CDCH and COBRA magnet w/ 0.8 magnetic field scale factor
- COBRA magnet is developed for bending MEG II signal $e^+$ w/ constant radius
- Charge can be identified by particles’ trajectory bent by magnetic field

Reference:
Cylindrical drift chamber (CDCH)

- CDCH has been developed for measuring trajectory and momentum of MEG II signal $e^+$
- The features are the following:
  - 1,728 sense wires (= 192 wires/layer x 9 layers)
  - Stereo wires configuration
  - Gas choice: He:isobutane = 90:10
- Readout from 2/3 wires
- The performance study is in progress
Liquid hydrogen (LH2) target

- Most signal $\mu^+$ stop at target frames due to their low momentum (<50 MeV/c)
  → Thin Mylar windows

- Scintillators for trigger in front of LH2 target and at both sides

- Target size is optimized by $\mu^+$ detection efficiency in CDCH

![Diagram of Liquid Hydrogen (LH2) target with labels for Collimator, Inner box (LH2), Side trigger scintillators (250 µm), Copper for cooling, Thin Mylar window (355.6 µm), Flange, Front trigger scintillator, Outer box (vacuum), 50 mm, 70 mm, 70 mm]
Current status

- Plan to start P0EM experiment
  - Examine $\pi^0 \to \mu e$ decay
  - Experimental setups

- Estimate sensitivity ⇐ Need to know efficiency
  - Optimize LH2 target
  - Signal selection
  - Trigger DAQ
  - Sensitivity

- Prepare LH2 target
- Construct analysis method
- Do beam test at PSI
Optimize target size

Collimator window is smaller

More $\pi^-$ stop at collimator
More $\mu^+$ stop in LH2

- 36.0% $\pi^-$ generate $\pi^0$ by CEX
- 14.9% signal $\mu^+$ exit from LH2 target out of $\pi^0$
- 45.9% signal $\mu^+$ are detected in CDCH out of exiting $\mu^+$

Detection = 3 or more hits in CDCH

X length of LH2 target = 36 mm
$\rightarrow$ $\mu^+$ detection efficiency = 2.46% out of all the $\pi^-$ beam

Less $\pi^-$ interact in target frames
Signal selection in analysis (1/2)

• Cut tracks whose initial position is out of LH2 target

← It has no influence on $\mu^+$ detection efficiency due to no cut of signal $\mu^+$ tracks

• $dE/dx$ is calculated by energy deposit in CDCH divided by track length

• Uncertainty of track length and of energy deposit?

![dE/dx vs Momentum](image)

**Hist 2D Data**
- Entries: 82823
- Mean x: 41.42
- Mean y: 1.444
- Std Dev x: 27.98
- Std Dev y: 4.93

14 Sep 2020 Proposal for experiment on search for $\pi^0 \rightarrow \mu e$ decay violating charged lepton flavour
• Momentum will be calculated by rotation radius of the track

• Charge of particles can be identified by reconstructed tracks orientation

• **Signal $\mu^+$ can be identified in CDCH**

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**Signal selection in analysis (2/2)**

- Momentum will be calculated by rotation radius of the track.
- Charge of particles can be identified by reconstructed tracks orientation.
- **Signal $\mu^+$ can be identified in CDCH**

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**Proposal for experiment on search for $\pi^0 \rightarrow \mu e$ decay violating charged lepton flavour**

14 Sep 2020
Trigger DAQ

• P0EM plans to use MEG II DAQ system
• MEG II DAQ rate ~ 10 Hz → Rough idea in P0EM

• Trigger conditions requirements:
  • Easy construction of online logic
    ← Reconstructed information cannot be used
  • Selection of more signal-like events
    ← Exit from LH2 target & Large energy deposit
Trigger conditions

Scinti TRG
- Install plastic scintillators for trigger
- Require hits at trigger scintillators
- Require energy deposit over 200 keV threshold at side scintillators

SecLay TRG
- Require hits at inner 3 layers at a sector
  - Signal $\mu^+$ must pass through CDCH from inside

dE/layer TRG
- Require energy deposit over 95 keV threshold at a layer in CDCH
  - Signal $\mu^+$ has larger energy deposit than $e$

~90% signal events were cut at trigger DAQ rate = 9.1 Hz

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\(\mu^+\) detection efficiency

- 36.0% \(\pi^-\) generate \(\pi^0\) by CEX
- 14.9% signal \(\mu^+\) generated by \(\pi^0 \rightarrow \mu^+ e^-\) exit from LH2 target
- 45.9% \(\mu^+\) out of exiting from LH2 target is detected in CDCH
  \(\Rightarrow\) **Signal \(\mu^+\) detection efficiency is 2.46% out of all the \(\pi^-\) beam**

- 10.5% \(\mu^+\) out of detected in CDCH is triggered at 9.1 Hz
  \(\Rightarrow\) **Signal \(\mu^+\) detection efficiency is 0.26% out of all the \(\pi^-\) beam**

- Much lower detection efficiency than we expected
  \(\Rightarrow\) Need to review trigger conditions
Summary

• We propose the P0EM experiment to search for $\pi^0 \rightarrow \mu^+ e^-$ decay which is one of cLFV modes at PSI
• P0EM experiment will be a parasite on MEG II
• The setups use CDCH to detect signal $\mu^+$, COBRA magnet to bend tracks of charged particles, and LH2 target
• LH2 target size is optimized
• Signal $\mu^+$ can be identified in CDCH
• Detection efficiency of $\mu^+$ is 2.46% w/o trigger
• Thinking of trigger DAQ in progress
Prospects

• Review trigger conditions to find detection efficiency
  → Estimate sensitivity

• Make LH2 target
  • Target strength test is on going

• Construct analysis method
  • Online logic in trigger
  • Reconstruction of particles’ tracks
  → Prepare to do beam test
Backups
π⁻ interactions and BG

• π⁻ interacts with nucleus in the following reactions:
  • Elastic or inelastic scattering: π⁻ + N \rightarrow π⁻ + N (or N')
  • Absorption: π⁻ + N \rightarrow N' + several nucleus
  • Charge exchange (CEX): π⁻ + N \rightarrow π⁰ + N'
  • Radiative capture: π⁻ + N \rightarrow γ + N'

• The nuclei generated through scattering will deposit too much energy in CDCH due to its little momentum

→ The nuclei will not be BG candidates

• Absorption does not occur in LH2 because violating energy conservation

• But absorption occurs in materials w/ larger Z than that of hydrogen
Proposal for experiment on search for $\pi^0 \rightarrow \mu e$ decay violating charged lepton flavour

Signal $\mu^+$ momentum distribution

Momentum of all the signal $\mu^+$

Momentum of detected signal $\mu^+$
Proposal for experiment on search for $\pi^0 \rightarrow \mu e$ decay violating charged lepton flavour

**dE/dx vs momentum**

**Signal $\mu^+$**

**BG $p$**

**BG $\mu^-$**

**BG $e^-$**

**BG $e^+$**
Scinti TRG (1/2)

- Install plastic scintillators for trigger
- Front scintillator is installed in front of LH2 target
- The size is 18 mm x 32 mm x 5 mm
- (Collimator hole size is 14.4 mm x 28.4 mm)
- Require hit at front scintillator
- This is for removing CDCH detection of $\mu^-$ generated by $\pi^-$ decay
Scinti TRG (2/2)

- Side scintillators are installed by Mylar windows of outer box
- The size is 60 mm x 80 mm x 250 µm
- (Outer Mylar window size is 60 mm x 80 mm)
- Require hit at side scintillator and energy deposit over 200 keV
- The thickness is 250 µm due to direct detection of signal $\mu^+$
- # of triggered events is 1,764 out of 100,000 $\pi^-$ events

Energy deposit at side scintillator
**dE/layer TRG**

- Signal $\mu^+$ has larger energy deposit per layer than $e$
  
  $\rightarrow$ Cut $e$ tracks w/ small dE/layer

- Threshold is 95 keV/layer to make trigger rate <10 Hz w/ 3 triggers
  
  $\leftarrow$ This results in too large signal loss (Triggered signal $\mu^+$ is $\sim$10% out of detected in CDCH)