Development of a Muon Entrance Detector for the muEDM Experiment at PSI

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25th August 2023
• Why measure (mu)electric dipole moment (EDM)?
• The muEDM experiment
• Prototype entrance trigger design
  • Beamline test fall 2022
  • Photons received
• Simulation results
• Summary
Physics Motivation of (μ)EDM

- Free from SM backgrounds
  - CKM phase contribution: $d_\mu \sim 10^{-42} \text{ e} \cdot \text{cm}$
    PRL 125 (2020) 241802
  - Hadronic long distance contribution: $d_\mu \sim 10^{-38} \text{ e} \cdot \text{cm}$
    PRD 89 (2014) 056006

- Various BSM models predicts enhanced EDM
  - EDMs are good probes for BSM physics

Current experimental limits and model predictions

$|d_\mu| < 1.8 \times 10^{-19} \text{ e} \cdot \text{cm}$

$|d_\mu| < 6 \times 10^{-23} \text{ e} \cdot \text{cm}$
muEDM Measurement at PSI

Projected sensitivities

Phase-1: $3 \times 10^{-21} \, e \cdot cm$

Phase-2: $6 \times 10^{-23} \, e \cdot cm$

$$\sigma(d_\mu) = \frac{h y^2 a_\mu}{2P E_f \sqrt{N} \tau_\mu \alpha}$$

$P$ := initial polarization
$E_f$ := Electric field in lab
$\sqrt{N}$ := number of positrons
$\tau_\mu$ := lifetime of muon
$\alpha$ := mean decay asymmetry

Details at Lily’s talk

Physics Motivation | muEDM | Entrance Trigger | Beam Time 2022 | Simulation Results | Summary
Entrance Trigger

- Fast entrance trigger to trigger magnetic pulse kicker
  - Selects muons within storage acceptance phase space
  - Stops longitudinal motion of muon
  - “Kicks” muons into stable storage orbit for measurement

Requirements and challenges

- Thin scintillators (50 $\mu m$ to 100 $\mu m$) to minimise multiple scattering effect
  - Low number of photons to produce trigger anti-coincidence signal

- Timing requirements
  - Time delay between trigger and pulse kick, $t_{\text{delay}} < 150$ns

We focus on this part
Preliminary Studies of Prototype

- A minimal setup to demonstrate anti-coincidence trigger
- Composed of gate and telescope
- Gate thickness studied for its relation with energy deposition and scattering angle
Preliminary Studies of Prototype

- Geometry constraining the scattering angle $\theta \leq 1.4\, \text{deg}$
- 0.1 mm thickness give optimal results
Prototype Entrance Trigger Design

- Demonstrate anti-coincidence logic
  - Muons passing thru gate but not hitting telescopes
- Scintillator bars have same dimensions and symmetrical in placement
- Compactly placed in 3D-printed rack
  - Expect optical crosstalk between telescope channels

4 x GNKD HND-S2

4 x NDL EQR15 11-6060D-S

Optical grease BC 630
\textbf{πE1 Beamline Test}

- \textbf{πE1 beamline}
  - Surface muons
  - Tuned to 27.5 MeV/c ($\frac{\Delta p}{p} \sim 0.8\%$)
- \textbf{Test efficiency of muons selection within storage acceptance with anti-coincidence scheme}

1D profile scans with pill counter

Beam profile measurements $\rightarrow$ Extract Twiss parameters $\rightarrow$ Simulated beam with Twiss parameters

Details from Jun Kai’s poster
Full-setup Prototype Entrance Trigger

Trigger modes defined using hit coincidence of scintillators
- Only gate trigger
- Gate & Exit trigger

Details from Jun Kai’s poster

DRS4 based WaveDAQ for signal digitisation and powering SiPM
Photons Received

Right vs Top

Muons hitting top channel

Physics Motivation | muEDM | Entrance Trigger | Beam Time 2022 | **Simulation Results** | Summary
Photons Received

Right vs Top

Muons hitting right channel

Physics Motivation | muEDM | Entrance Trigger | Beam Time 2022 | Simulation Results | Summary
Photons Received

- Correlation patterns of detected optical photons
  - Scintillating channels in full contact
  - Optical crosstalk as expected (scintillators in full contact)
  - 4 bumps from correlation of adjacent channels
  - 3 bumps from correlation of opposite channels

Overlaps due to symmetric config
Reproducing Measured Results with Simulation

- Photon transmittance between scintillators not known
  - Measured photon distribution used as simulation input

- By reproducing optical crosstalk to understand transmittance
  - Using extracted beam characteristic
  - Detector geometry and material properties

- Several cases of transmittance found from simulation study
  - With opt. crosstalk
    - optPhot signals from $\mu^+$ and $e^+$
  - Without opt. crosstalk

SiPM:
- Optical sensitive volumes
- Some parameters set based on NDL 6060 datasheet:
  - Photon detection efficiency
  - Photosensitive area

Scintillator to Scintillator:
- Material properties based on HND-S2
- Parameters tuned:
  - Reflectivity (R)
  - Transmittance (T)
  - Surface type
  - Surface finish

*Muons
*Optical photons
Without Optical Crosstalk

- Reflectivity of each telescope channel set to 1.0
  - Optical photons produced in each telescope are confined within
  - Inhibiting optical crosstalk

✓ Trend agrees with measurement from another prototype
  ✓ Similar setup as ours, but with more significant air gaps
  ✓ Material properties in simulation are correctly applied
Optical Crosstalk

- Fine-tuning surface parameters
  - Transmission rate tuned via reflectivity and transmittance
- Reflectivity of each telescope channel set to 0.95
  - ~95% of optical photons produced a particular channels remained within
  - Remaining optical photons are involved in optical crosstalk
- Trend agrees with our measurement
  - The peaks are in the right ballpark
- Higher order fine-tuning required to reproduce exactly the measurement results
Optical Crosstalk

- Measured optical photon signals are from a combination of muons and positron hits
- Muon signals would arrive earlier
  - Distinct peaks from the muon hits
- Positron signals are the later ones
  - Continuous distribution from the Michel decay
Towards Phase-1 Entrance Trigger

Conceptual sketch of the Phase-1 entrance detector

- Active aperture with holes to veto muons out of storage acceptance
- Dual entrance for CW and CCW injection
- ~ 5 ns
- ~ 10 ns (2 m)
- ~ 5 ns (1 m)
- ~ 10 ns
• A prototype entrance detector was constructed with plastic scintillators and SiPMs
• The prototype is characterised by studying the optical process
• Prototype entrance detector achieved designed anti-coincidence function
• Agreement between measurement and simulation results
  • Able to study transmittance of optical photons between scintillators
  • Able to distinguish between positrons and muons
    ○ Higher order fine-tunning of simulation undergoing
• Event topologies and relative event rates to be studied with optical photon signals
• Provides reference to phase-1 entrance detector RnD
In fig. 3 (a) we show an ammonia (NH$_3$) molecule which rotates about its angular momentum $J$. In the state shown the molecule would have an EDM as the charge is asymmetrically distributed. The molecule in this state is not in an eigenstate of parity as the parity-transformed state (fig. 3 (b)) is a different state. However, the two states are degenerate (have identical energies) and can be combined to make other states. The states given by the wave-functions

$$\psi_{\pm} = \psi_I \pm \psi_{II}$$

are eigenstates of parity with the same energy. Thus the reason a molecule can exist in the state $\psi_I$ or $\psi_{II}$ and have an EDM is the degeneracy of the parity eigenstates $\psi_{\pm}$ and $\psi_{-}$.

What prevents a neutron from behaving in the same way? All neutrons are observed to obey the Pauli exclusion principle, that is, a given quantum state can only contain one neutron. If the neutron was observed to have a non-zero EDM either parity is violated or the neutron can exist in two degenerate states. If the neutron existed in two degenerate states we would find two neutrons, rather than one, in each quantum state in atomic nuclei, contrary to observations. Thus we are left with the conclusion that the existence of a neutron EDM would be evidence for the violation of parity, whereas the same is not true for the existence of a molecular EDM.
Back-up

HV → SIPM → AMP(40dB) → DRS4

Dark Box

Test condition:
- HV (41V)
- Trigger: 20mV, 40mV, 80mV

SiPM Signal Area

First, I set three different thresholds to observe the dark noise spectrum, and check the circuit correct.

Then, a set of thresholds to get the SiPM gain and linearity.

SiPM_04

SiPM Signal Area

Trigger Set
- 10 mV
- 20 mV
- 30 mV
- 40 mV
- 50 mV

Courtesy of T Hu
SiPM Linearity

<table>
<thead>
<tr>
<th>Area [mV/μs]</th>
<th>p0</th>
<th>1.6 ± 22.72</th>
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<tbody>
<tr>
<td></td>
<td>p1</td>
<td>328.2 ± 6.852</td>
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</table>

SiPM Response Linearity

<table>
<thead>
<tr>
<th>Area [mV/μs]</th>
<th>p0</th>
<th>3 ± 22.58</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>p1</td>
<td>323 ± 6.807</td>
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</table>

Detector Gain:

$$\frac{328.2 \times 10^{-3} \times 10^{-9}/50}{1.6 \times 10^{-19}} = 4.1 \times 10^7$$

With 40dB, 100 times Pre-amp

SiPM Gain: $4.1 \times 10^5$

Recommended Operation Voltage

- $V_a = 8$ V

Peak PDE @ 420nm

- 45%

Gain

- $4.0 \times 10^2$

Dark Count Rate (DCR)

- $250$ kHz / mm²

<table>
<thead>
<tr>
<th>High Voltage(V)</th>
<th>Gain (e5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiPM_01</td>
<td>4.10</td>
</tr>
<tr>
<td>SiPM_02</td>
<td>4.04</td>
</tr>
<tr>
<td>SiPM_03</td>
<td>4.03</td>
</tr>
<tr>
<td>SiPM_04</td>
<td>4.00</td>
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</tbody>
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The telescope detector PCB (electronic system) is ready