Cryogenic detector system for background-free Muonium observation at temperatures below 200 mK

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Muonium gravity experiment

Test weak equivalence principle using second generation leptonic antimatter

Mu beam
- $\mu^+$ to vacuum Mu conversion
- low emittance
- narrow momentum distribution

Interferometry
- 3-grating interferometer
- gravitational interaction shifts interference pattern

Detection
- coincidence signal of $e^+$ from $\mu^+$ decay and atomic $e^-$
Novel atomic Mu beam from SFHe

- Mu source based on SFHe
  - Mu gravity experiment requires novel Mu beam with low emittance and narrow momentum distribution

- Mu detection
  - Triple coincidence of horizontally emitted e⁺ in two e⁺ detectors plus signal in atomic e⁻ detector:
  - e.g.: LC4 && LF4 && atomic

Detector requirements:
- Fast timing
- High efficiency
- High background rejection
- Operation in cryogenic setup at T < 200 mK
SiPM operation in dilution cryostat

- SiPM: Hamamatsu S13370-3075CN/-6075CN
  - Pixel pitch: 75 \( \mu \text{m} \), active area: 3x3 / 6x6 mm\(^2\)
  - originally for LXe, LAr scintillation (UV sensitive)
  - no window

- wiring with \(~ 7\) m long micro coax cable
  - AWG-38, \( \phi \) 0.4 mm, 50 \( \Omega \)
  - comprising between heat load & signal quality
  - thermalized at 3 temperature stages
  - 40dB pre-amplifier
  - DRS4 digitizer

- \( \dot{Q} \sim 100 \mu\text{W} \)
- Cu blocks for thermalization of cable

- cryostat cold finger
- \(~ 100\) K
- \(~ 10\) K
- \(~ 2\) K
- \(< 0.2\) K
- \(1.7\) K
- pre-amplifier
- digitizer
Cryogenic SiPM: Electrical characterization

- Measure reverse IV curve under low light condition
  - linear increase up to $V_{bd}$, then quadratic increase
  - steeper increase after $V_{bd}$ at low temperature
- Determine $V_{bd}$ from
  - logarithmic derivative: Landau fit
  - gain v.s bias: linear fit
Cryogenic SiPM: Operating range

- Non-linear $V_{bd}$ at cryogenic temperatures
- explained by Baraff’s model:
  - see C. R. Crowell et al., Appl. Phys. Lett. 9, (1966)

- No proper operation between 20 K and 40 K
- $V_{\text{over}}$ limited to ~ 2 V at ultra low temperatures
Cryogenic SiPM: Single photon detection

- Measure charge spectrum under low light condition
  - Photon from WLS fibre coupled to pulsed LED
- Poisson fit to estimate detected of photons
- Compare low temperature measurement to room temperature measurement

Single photon counting possible at ultra low temperatures
Commissioning with $\mu^+$ beam

- Test detectors with muon beam at PSI
- $e^+$ energy from Michel spectrum

![Diagram showing detector components and Michel decay spectrum](image.png)
Positron detectors

- Plastic scintillator bars
  - Eljen EJ-204, l: 20 mm, h: 3 mm, w: 2-4 mm
  - wrapped with Teflon
  - no optical cement (teared wire bonds)
  - 3D printed acrylic sleeves

- Energy deposition in thin absorber: Landau distributed
- Lower gain in cryogenic but full peak visible
Atomic $e^-$ detector: Design

- **Goal:**
  - Remove muon background in positron detectors
  - Coincidence detection of $e^+$ from $\mu^+$ decay and atomic $e^-$

- **Method:**
  - Use HV electrode to accelerate $e^-$ to scintillator pill
  - Detect low energy ($< 10$ keV) electrons
Atomic \( e^- \) detector: Energy and time spectrum

- Operate atomic \( e^- \) detector w/ and w/o acceleration electrode ring
- Detection of high energetic \( e^+ \) from Michel decay
- Detection of accelerated \( e^- \) liberated from Cu walls
- Atomic \( e^- \) can be detected in the cold

Michel \( e^+ \) and low energy \( e^- \) detection feasible at ultra low temperatures
Summary & Outlook

- Muonium gravity experiment aims to measure gravitational interaction of second generation, leptonic antimatter
- Novel Mu beam is being developed together with cryogenic detection scheme

- Hamamatsu VUV4 SiPMs found to be operational at $T > 40$ K and $T < 20$ K
- SiPMs can be operated in dilution cryostat, at < 200 mK temperatures
- Single photon counting possible at $T < 1$ K
- Commissioned positron detector with muons

- Stable operation of atomic $e^-$ detector and physics run in September 2021
Backup
Mu formation in SFHe

present state-of-art Mu source
- porous SiO₂ structures
- 3 - 30 % vacuum Mu conversion
- thermal beam
  - large momentum distribution
  - wide angular distribution

proposed SFHe Mu source
- superfluid ⁴He
- based on high chemical potential of H isotopes Mu expected to be ejected with ~7 mm/μs velocity

high quality Mu beam
- with SFHe source: fast atomic beam with defined direction and energy
Cryogenic SiPM: Signal shape at low temperatures

- waveform has two main components
  - fast rising: cell capacitance
  - slow falling: quenching resistor $R_Q$
- Metallic quenching resistor with lower temperature dependence
  - Maintain pulse shape
- Increase of $R_Q$ below 80 K leads to narrower waveform
# Hamamatsu S13370 series (VUV4)

<table>
<thead>
<tr>
<th></th>
<th>S13370-3075 CN</th>
<th>S13370-6075 CN</th>
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</thead>
<tbody>
<tr>
<td>Sensitive area / mm²</td>
<td>3.0 x 3.0</td>
<td>6.0 x 6.0</td>
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<tr>
<td>Pixel pitch / μm</td>
<td>75</td>
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<tr>
<td>Geo. fill factor / %</td>
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<tr>
<td>package</td>
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<td>ceramic</td>
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<td>window</td>
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<td>unsealed</td>
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<tr>
<td>Response range / nm</td>
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<tr>
<td>Photon detection efficiency / %</td>
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<td></td>
</tr>
<tr>
<td>Operating voltage / V</td>
<td>V_{bd} + 4</td>
<td></td>
</tr>
<tr>
<td>Dark count / Mcps</td>
<td>1.0 - 3.0</td>
<td>4.0 - 12.0</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td>5.8 x 10^6</td>
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See: [www.hamamatsu.com](http://www.hamamatsu.com), S13370 series product datasheet (2017)