Ultra Cold Muon Production for New Muon g-2 Experiment

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Requirement on ultra cold muon for new g-2

Search for thermal muonium emission target
(S1249 Experiment @ TRIUMF)

Related developments at RIKEN (laser etc)
Small beam divergence

\[ \sigma(p_T)/p_L = 10^{-5} \]

will limit vertical spread in muon g-2 storage ring to 80 mm after 4000 turns (~5 \( \gamma \tau_\mu \)).

For \( p_L = 300 \, \text{MeV/c} \) (storage in 3T compact ring ~80 cm), \( p_T \) should be < 3 keV/c (\( T \sim 0.045 \, \text{eV} = 500 \, \text{K} \)).

Slow muon from hot tungsten (2100 K) is not cold enough without additional beam cooling.
We should start with muonium emission at room temperature.
Development of cold muon beam at RIKEN-RAL

We have been developing cold muon beam at RIKEN-RAL in collaboration with KEK muon group.

Original motivation was application to materials surface/sub-surface study by muon spin relaxation (μSR) method.

1. THERMAL MUONIUM PRODUCTION IN VACUUM
   - Stopping $\mu^+$ at Rear-side of Foil
   - $\mu^+$ Diffusion and Reaching to Foil Surface
   - Mu Evaporation

2. MUONIUM IONIZATION AND SLOW $\mu^+$ PRODUCTION
   - Laser Ionization of Mu

(muonium: $\text{Mu} = \mu^+\text{e}^-$)
RIKEN-RAL Muon Facility

Rutherford Appleton Laboratory 200 kW proton source

typical muon intensity : $10^6$/s, pulsed beam @50 Hz
present characteristics

Achievement at RIKEN-RAL Port3 by KEK-RIKEN Collaboration

<table>
<thead>
<tr>
<th>Low energy ( \mu^+ ) beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity at sample ( \sim 15-20 \mu^+/s ) (starting from ( 1.5 \times 10^6 ) muons)</td>
</tr>
<tr>
<td>Beam diameter (FWHM): 4 mm</td>
</tr>
<tr>
<td>Energy at target region 0.2 eV</td>
</tr>
<tr>
<td>Energy after re-acceleration 0.1-18 keV</td>
</tr>
<tr>
<td>Energy uncertainty</td>
</tr>
<tr>
<td>( \sim 14 ) eV</td>
</tr>
<tr>
<td>Pulse repetition rate 25 Hz</td>
</tr>
<tr>
<td>Single pulse structure</td>
</tr>
<tr>
<td>7.5 ns (FWHM) at 9.0 keV</td>
</tr>
<tr>
<td>Spin polarisation ( \sim 50% )</td>
</tr>
<tr>
<td>Long time background ( &lt; 1/250 )</td>
</tr>
</tbody>
</table>

Overall efficiency was \( 10^{-5} \) based on hot tungsten (2100 K)
We need lots of improvement in intensity and properties
Increasing the ultra-cold muon intensity by orders

We aim to have $10^6 /s$ ultra cold muon beam for muon g-2.

1. Stopped muon intensity (density) in muonium emission target
   -> Super omega & J-PARC (x300), Tapered tube (Tomono) => $1 - 4 \times 10^8$

2. Muonium emission efficiency (x1 ?)
   0.04 ?????

3. Laser ionization & repetition
   S. Wada, Norihito Saito, K. Yokoyama, O. Louchev (x100 x2) => 0.2

4. Ultra-cold muon extraction optics
   M. Iwasaki, K. Tsukada (~1)
   => $10^6 /s$

The muonium emission efficiency from room temperature generator should be as good as 4 %. 
Searching for best Mu production target for muon g-2

- **Muonium production rate** in vacuum
  one of the uncertain factor
  determining the ultraslow muon beam intensity
  huge impact on new muon g-2 experiment
  (twice yield -> halves the beam time)

- **Requirement**
  - High yield (of course!)
  - room temperature (strong requirement for g-2)
  - stable (absorption/de-absorption, contamination)
  - ease of handling, mounting
Previous measurement for SiO2 powder

- SiO2 Powder had best yield (~3% for 27 MeV/c muon)
- Vacuum chamber + Target + Ion chamber
  - analysis based on 4 regions (each 10mm thick)
  - model: diffusion to surface layer, Boltzman velocity dist. (~300K)

![Diagram of setup](image)

**FIG. 2.** Density plot of position of muon decays in space along with definitions of regions. R1, R2, and R3. Yield

**FIG. 3.** Muon decay times for various spatial regions.
Comparison of Mu production from Hot W and Silica powder

<table>
<thead>
<tr>
<th></th>
<th>Hot W</th>
<th>Silica Powder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy spread</td>
<td>0.2 eV</td>
<td>x 1/7</td>
</tr>
<tr>
<td>Transverse momentum</td>
<td>6 keV/c</td>
<td>x 1/2.6</td>
</tr>
<tr>
<td>Doppler width</td>
<td>20 GHz</td>
<td>x 1/2.6</td>
</tr>
<tr>
<td>Mu area</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Mu separation</td>
<td>large</td>
<td>small</td>
</tr>
<tr>
<td>Yield</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>Purity</td>
<td>High &amp; stable</td>
<td>?</td>
</tr>
<tr>
<td>Heat emission</td>
<td>Large</td>
<td>none</td>
</tr>
<tr>
<td>Shape stability</td>
<td>could bend</td>
<td>need settle</td>
</tr>
</tbody>
</table>
Mechanism of muonium emission into vacuum
1. muon stopping (~1mm) in a grain and make muonium
2. muon diffuses ($D_1$) out from the grain (~50nm)
3. muon migrates ($D_2$) through voids between grains (~0.3mm)
4. muon coming out from surface with thermal velocity (~10mm)
Hints for high Mu yield

While the understanding is far from complete, material with large surface area seems essential.

1. Diffuse out of muon from substance
   - fine particle (size $a$), diffusion in bulk ($D_{\text{bulk}}$)
     - yield $\sim D_{\text{bulk}}^{0.5}/a$

2. Mu diffusion in void channels
   - target thickness ($b$), diffusion through voids ($D_{\text{void}}$)
     - yield $\sim D_{\text{void}}^{0.5}/b$

   - large mean free path ($l$) & interconnecting void channels
     - high void/material ratio
     - free interacting gas model ($D = 1/l \sim \rho^{-1/3}$)

whereas high muon stopping density ($\sim \rho$)
Plan for Muonium Production Target Study

Cold (room temperature) muonium source is required for g-2

Room temperature target such as SiO2 powder
  is as efficient (~3% emission) as hot W
but it’s very fluffy and we need some gravitational way to hold
  Build beamline going up vertically?
Search of self standing solid target worth doing for more flexibility

Test several candidates with Mu tracking using DC muon@TRIUMF
in time for irradiation at RIKEN-RAL with new laser (under construction).
Three weeks beam time was approved in the last TRIUMF EEC.
Members of S1249 TRIUMF Experiment

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H. Ohnishi, Y. Fujiwara** (RIKEN)
T. Mibe, N. Saito*, H. Iinuma, S. Hirota** (KEK/IPNS)
Y. Miyake, K. Shimomura, P. Strasser, N. Kawamura (KEK/IMSS)
P. Bakule (RAL)
Y. Matsuda (Univ. Tokyo)
G. Marshall, A. Olin (TRIUMF)
G. Beer (Univ. Victoria)

* contact person for the new J-PARC muon g-2 experiment
** graduate students
Target to be studied(1): Silica Powder

Silica powder: reference sample (well studied before)
several grain sizes (3~10 nm)
Test emission mechanism with better resolution

We may hold nanogel™ vertically (with sample size as large as ~1mm)
Target to be studied(2): Silica Aerogel

Silica aerogel: promising candidate in solid plate form
low Mu rate (<1%) in measurements ~1990 - structure defect in production?
recent developments for Cerenkov counter (Chiba/JAXA)
various densities (0.03 – 1 g/cm²), for optimization of muon stopping vs diffusion
Target to be studied(3): Porous Alumina

channel size is 20-400nm
thickness: 100 μm available
area: 20 mm x 50 mm as standard

how muon diffuses through thin channel?
aspect ratio 1:1000
Mu depolarization in alumina: holding field ~100G?
Other materials to be considered.
Plan for Measurement at TRIUMF (1)

Tracking with MWPC, DC beam@TRIUMF, to measure
1) Thermal muonium yield for various target
2) Spatial distribution of Mu vs timing (laser)

We use MuoinumSR for quickly screening bad samples in June 2010
1) good Mu production probability
2) Mu polarization

We plan Mu yield and spatial distribution measurement by the end of this year.
Plan for Measurement at TRIUMF (2)

Design of tracking experiment
1. Beam counter
2. MWPC - tracking of $\mu$e-decay with better resolution
3. MCP - detection of $e^-$ from Mu
   new equipment to reduce background from muon decay in sample
Plan for Measurement at TRIUMF (3)

MCP: for better tracking resolution and S/N

3-D tracking using MCP

Electric field for electron to drift

Complete reconstruction of 3D coordinates of decay vertex from $e^+$ in coincidence with $e^-$

Detection of electron also rejects a huge BG from $\mu$ decay in target without forming $Mu$.

Under study: Electric field, Magnetic field
Laser overlap with Mu: Modeling of Mu emission

- TRIUMF and PSI model of Mu emission from SiO2
- "effective diffusion rate" $D_2$ is one of the parameters
  - time for muon to diffuse to surface layer, delayed emission
  - 500 cm$^2$/s (G. Marshall)
    - 1mm thick -> 20 $\mu$s ! very slow (10% yield)
    - 0.1 mm thick -> 200 ns
- emitted Mu moves with Boltzman velocity of $\sigma_{vz}=0.5$ cm/$\mu$s
  - $z$ distribution is Gaussian with $\sigma_z=0.5$cm after 1$\mu$s,
  - Mu spreads in region $z = 0 \sim 5$ mm
- with this diffusion model and uniform muon stopping, muonium in vacuum increase with $(D_2t)^{1/2}$ (if ignoring muon decay)
  - emission rate is its derivative $(D_2/t)^{1/2}$
- Mu distribution is convolution of these two
  - adding up Gaussian of different width ($\sigma_z(t-t_e) = 0.5(t-t_e)$ cm) with weight $t_e^{-1/2}$
Laser overlap with muonium

Typical calculation on Mu distribution in vacuum

Thermal Mu distribution in vacuum with time

Distance from surface

Laser coverage

We could wait ~0.6 µs and irradiate 1 – 5 mm from surface by laser

More detailed 3-D simulation is in progress

Parameters to describe Mu distribution will be obtained by measurement

Then, we can design the ionizing laser (timing and laser beam size)
Ionization Process

Estimation of ionizing process versus laser intensity based on rate equation & transition rate

Case for $I$(Lyman-$\alpha$) = 1 $\mu$J, $I$(355) = 300 mJ length=4ns ionization 0.11 (??)

Case for $I$(Lyman-$\alpha$) = 100 $\mu$J $I$(355) = 300 mJ length = 1ns gives ionization efficiency = 0.76 after 1 ns
Laser Development at RIKEN

Under development by laser group (S. Wada, Norihito Saito) and K. Yokoyama
Acceleration of muons

We should keep the low transverse momentum spread as much as possible.
Design of system without higher order aberration.

and further ideas ... (though very preliminary)
  Reduction of transverse momentum by phase rotation (churped laser)
  Pulsed extraction field might help to suppress acceleration voltage spread due to ionizing position.
We have started search of best materials for Mu production at room temperature.

Measurement is planned at TRIUMF to study
1. Various samples with good muonium yield
2. Precise information on Mu distribution in vacuum to have better model on the mechanism and also to optimize laser irradiation condition

We also develop laser, muon extraction etc.

These will contribute to muon g-2 measurement as well as microscopic µSR.
Thermal Muonium Emission / 
with Momentum scaling

(based on Shimomura-san’s compilation)

<table>
<thead>
<tr>
<th>name</th>
<th>target</th>
<th>momentum (MeV/c)</th>
<th>mom width</th>
<th>yield (raw)</th>
<th>scale factor</th>
<th>yield (@27MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mills</td>
<td>hot W</td>
<td>23.2</td>
<td></td>
<td>0.04</td>
<td>0.58</td>
<td>0.023</td>
</tr>
<tr>
<td>Matsuhita</td>
<td>hot Ir</td>
<td>24.6</td>
<td></td>
<td>0.05</td>
<td>0.72</td>
<td>0.036</td>
</tr>
<tr>
<td>Matsuhita</td>
<td>hot Pt</td>
<td>24.5</td>
<td></td>
<td>0.04</td>
<td>0.70</td>
<td>0.028</td>
</tr>
<tr>
<td>Janissen</td>
<td>SiO2</td>
<td>28.5</td>
<td>2.85</td>
<td>0.024</td>
<td>1.21</td>
<td>0.030</td>
</tr>
<tr>
<td>Janissen</td>
<td>SiO2</td>
<td>22.2</td>
<td>2.22</td>
<td>0.076</td>
<td>0.49</td>
<td>0.038</td>
</tr>
<tr>
<td>Woodle</td>
<td>SiO2</td>
<td>20.0</td>
<td>1.5</td>
<td>0.100</td>
<td>0.34</td>
<td>0.034</td>
</tr>
</tbody>
</table>

average 0.031

* scale factor is based on p^3.6
({"stopping distribution})
Conclusions on Targets from TRIUMF Experiment

• **Fused Silica Powder** (Cab-O-Sil, powder 7~14 nm)
  – 2.4+-0.5% @ 28.5 MeV/c

• **Compressed fumed silica powder**
  – suppression of the yield

• **Merck Opti-Pur powder**
  – 1.9+-0.5 % @ 28.5 MeV/c (comparable yield)

• **Silica Aerogel** (translucent block) 0.14 g/cm², 520 m²/g
  – more cross-linked chain
  – pore size ~20 nm (could be reduced x1/4 by moisture)
  – 0.7+-0.2 % @ 28.5 MeV/c (poor producer?)

• **Aerogel O₂ cleaning**
  – yield halved

• **Powder surface could be important, but baking did not help**