Ultra-slow Muon Source for New g-2

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Ultra-slow Muon Beam as muon source of new g-2 experiment

Brief introduction (see Saito’s presentation WG4)

Progress of slow muon development

see Last talk by Y. Matsuda (NuFact05)

What’s next?

Improvements
Muon g-2 (anomalous magnetic moment) sum rule sensitive to all the new physics beyond the standard model
BNL g-2 experiment result

\[ \Delta a_{\mu}^{(EdR08)} = (29.7 \pm 7.9) \times 10^{-10} \]

shows 3.7 \( \sigma \) deviation from standard model prediction
(talks by L. Roberts
last Nufact08)

BNL g-2 was based on
Muon storage ring with homogeneous magnetic field
Muon focusing by electric quadrupoles
Magic momentum (3.1 GeV/c) cancels E contribution to \( \omega \)
Typical storage ring diameter 14m
The result was statistically limited but systematic error will also contribute
New muon g-2 proposal using ultra-cold muon beam

New g-2 experiment based on ultra-cold muon beam
see N. Saito’s talk -> WG4, this afternoon

Muons with very small transverse momentum can stay in storage ring orbit until they decay even without focusing electric field.

Thus, no need of magic momentum (3.1 GeV/c) though acceleration to reasonably high γ (300 MeV/c) should help statistics (longer dilated lifetime)

Benefits: Compact muon ring, compact detection
Clean muon beam- no pion flash

Essential requirement is high-intensity well-aligned muon beam
Requirement on ultra-cold muon beam

Small beam divergence
\[ \sigma(p_T)/p_L = 10^{-5} \]
will limit vertical spread in storage ring
to 80 mm after 4000 turns (\(\sim 5 \gamma \tau_\mu\))
For \(p_L = 300 \text{ MeV/c}\), \(p_T\) should be < 3 keV/c (\(T \sim 0.045 \text{ eV} = 500K\))

Muons originating from decay of pions produced by high energy protons have too high energies 100 MeV – 4 MeV
Very efficient cooling is required.
We should convert to ultra-cold muons and re-accelerate to achieve above criteria.
Development of cold muon beam at RIKEN-RAL

We have been developing cold muon beam at RIKEN-RAL. (Initial stage was done by 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

   MeV $\mu^+$
   
   Stopping $\mu^+$ at Rear-side of Foil
   
   $\mu^+$ Diffusion and Reaching to Foil Surface
   
   Mu Evaporation
   
   (muonium: $Mu=\mu^+e^-$)

2. MUONIUM IONIZATION AND SLOW $\mu^+$ PRODUCTION

   Laser Ionization of Mu
RIKEN-RAL Muon Facility

Rutherford Appleton Laboratory 200 kW proton source
typical muon intensity : $10^6$/s, pulsed beam @50 Hz
Laser ionization of muonium

Two laser beams necessary for resonant ionization
- required very broad laser bandwidth due to thermal movement of atoms

1S-2P saturation intensity

\( I_{\text{sat}} = 2.3 \text{ W/cm}^2 \) for monochromatic < 100 MHz
\( I_{\text{sat}} = 4.6 \text{ kW/cm}^2 \) for Doppler 200 GHz

Main challenge: to generate VUV @ 122 nm and with 200 GHz (+ 1 ns jitter rel. to ext. trig.)
Transport beamline for slow $\mu^+$

- Electrostatic acceleration to 10 keV

- Cryostat
- Sample chamber vacuum level $1 \times 10^{-7} \sim 8 \times 10^{-10}$ hPa
- Magnetometers
- Sample
- Solenoid magnet
- Positron counters (8 telescope pairs)
- Lead shielding
- Electrostatic deflector
- Retractable MCP
- View port
- 1 m
beam properties measurement

Sharp spot (~10 mm²)

Short pulse

Good S/N ratio

LE-muon at RIKEN-RAL (S/N ~ 250)

LE-muon at PSI (S/N ~ 10)

Thin implantation depth (<40 nm)
present characteristics

<table>
<thead>
<tr>
<th>Low energy $\mu^+$ beam</th>
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<tbody>
<tr>
<td>Intensity at sample $\sim 15$-$20 \mu^+$/s (starting from $10^6$ muons)</td>
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<td>Beam diameter (FWHM): 4 mm</td>
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<tr>
<td>Energy at target region 0.2 eV</td>
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<tr>
<td>Energy after re-acceleration 0.1-18 keV</td>
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<td>Energy uncertainty after re-acceleration $\sim 14$ eV</td>
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<tr>
<td>Pulse repetition rate 25 Hz</td>
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<td>Single pulse structure 7.5 ns (FWHM) at 9.0 keV</td>
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<td>Spin polarisation $\sim 50%$</td>
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<td>Long time background $&lt; 1/250$</td>
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Overall efficiency was $10^{-5}$
Based on hot tungsten (2100 K)
We need lots of improvement in intensity and properties
Improving the ultra-cold muon source at RIKEN-RAL

1. Stopped muon intensity (density) in muonium emission target

2. Muonium emission efficiency and temperature

3. Laser ionization

4. Ultra-cold muon extraction optics
1. Stopping more muons

We will eventually need J-PARC
(x5 proton beam) (x2 production target) straightforward comparison
(x~10 curved solenoid beamline) talk by K. Nakahara, WG4, Friday

while it will take several more years to develop

At RAL we can test,

Stronger muon focusing at stopping target
optics, additional device
Using muon guide (it will work!)
Muonium production Target

Muon should diffuse to the surface, emitted to vacuum, and better avoid re-absorption.
Diffusion rate, or large surface area, small work function ...
We have used 2000K tungsten.
Cold (room temperature) muonium source is preferred for g-2.
Room temperature target such as SiO2 powder is equally efficient (~2% emission)
muonium spread less spatially in vacuum but enough away from the surface and also automatic ionization gain (x3) with less Doppler broadening.
Handling of fine powder is a problem.
We will test several other candidates in more solid form: high-density silica aerogel, etc.
Laser development in RIKEN

Collaboration with RIKEN Laser Group
S. Wada, N. Saito, T. Ogawa, O. Louchev and K. Midorikawa

1. Supreme expertise
   Guide star for Subaru Observatory in Hawai, ...
   stable and maintenance free laser...

2. In house technique of special crystal growing
   wave length matching our requirement
   Nd:GdVO4 (1062.75 nm->212.55nm)

3. Compact laser system
   and energy efficient

4. Simulation of 4-wave mixing
Proposed laser system

We are confident we can improve pump laser powers by at least x10 (estimated intensity of present laser system ~1 μJ). Lyman α intensity would bi-linearly or linearly increase with the pump laser intensity. However, saturation effect of 4-wave mixing by phase mismatch should be checked if necessary, saturation could be avoided by multiple focusing optics.
Ultra-cold muon extraction

Initial stage of muon acceleration affects the size and pulse width of the re-accelerated muon beam. Einzel lens and electric muon channel (+mass analyzer) We need improvement (stability, alignment,...) to understand ultimate good quality of the ultra-cold muon. To be studied:
- laser irradiation area and timing (matching to muonium spread)
- initial acceleration field gradient

Geant4 simulation has started. Completely new system may be designed.
Expected cold muon yield (very preliminary)

At RIKEN-RAL
At present 20 /s
Laser x100
Cold muon source x3
Muon density x2
600 x 16 = 10000 mu+

At J-PARC
Proton beam and target x10
New muon channel x10
\(10^6\) /s
Summary

A new g-2 experiment is proposed based on ultra-cold muon source.
We have been developing a cold muon source at RIKEN-RAL for materials application. A few more improvements are necessary for the beam properties to match the new g-2 requirement.
We have plans for further study:
- Room temperature target should be developed
- Intense laser is likely to promise x100 improvement
- To fully understand cold muon beam extraction
Collaborators on new g-2 source development

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W. Higemoto (JAEA)
A. Olin, L. Lee (TRIUMF)
G. Beer (Univ. Victoria)
**Pump Laser 1**

**Pump Laser 2**

**Schematic Diagram**

- **Pump Laser 1**: 2-photon resonance at 212.55 nm
  - DFB-LD
  - LD pump Nd:GdVO₄ Multistage
  - 0.1 mJ
  - 1 J

- **Pump Laser 2**: Tunable from 815-850 nm
  - DFB-LD
  - LD pump Cr:LiSAF Multistage-amp. system
  - 100 mJ

- **Additional Cr:LiSAF MultiAmplifier**
  - Examination
    - Single-pass
    - Double-pass
    - Regenerative amplifier

- **DFB Laser System**
  - Voltage Ramp
  - Current Driver
  - DFB Diode Laser
  - Tapered Pulse
  - Pockels Cell
  - Thin Film Polarizer
  - Faraday Isolator
  - Cr:LiSAF (Cr:LiSAF)
  - 100 mJ

- **Nonlinear Frequency Conversion**
  - 212.55 nm (5ω)
  - 100 mJ
  - Beam Splitter
  - CLBO
  - ω + 4ω
  - 4ω
  - 2ω + 2ω
  - 2ω
  - ω + ω