Ultra slow muon generation and applications

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Contents

Part 1 : Development of low energy muon source at RIKEN RAL

- Method of low energy muon (LE-\(\mu^+\)) generation
- Beam and spectrometer characteristics
- Control over the implantation energy
- Efficiency of LE-\(\mu^+\) generation
- Summary of the current status and comparison with LE-\(\mu^+\) beam at PSI

Part 2 : Laser applications at RIKEN RAL beamlines

- Applications for LE-\(\mu^+\) beam
- \(\mu\)SR experiments with laser irradiated samples
- Construction of new laser laboratory at Port 2
- Looking back over past 10 years and looking forward to the future laser experiments at RIKEN RAL
µSR with low energy muons

For “surface muons” with energy of 4 MeV the stopping range in a solid varies from 0.1 - 1 mm with a straggling of about 20% of the mean value. Beam size 40-50 mm (FWHM)

For “low energy muons” with energy 0.01-30 keV the stopping range in a solid varies from 1 - 200 nm. Implantation depth easily controlled on nm scale. Beam size is small 4-5 mm (FWHM)

- allows investigations of near-surface regions, thin films, interfaces and multi-layers, nanomaterials and of samples which can be grown only as thin films.
- allows to make depth resolved measurements.
Methods of LE-muon generation

1) Cold Moderator Method (@PSI)
   - ideal for continuous muon source
   - layer of solid rare gas as a moderator
   - conversion efficiency up to $10^{-5}$
   - 92 % Polarization
   - 10-100eV Kinetic Energy
   - DC, Requiring a start trigger (->5 ns resolution)
   - Time structure determined by initial muon beam

2) Laser Resonant Ionization of Muonium (@RIKEN-RAL)
   - ideal for pulsed muon source
   - 1% efficiency of conversion to thermal muonium i.e. potentially much higher conversion efficiency to LE-muons
   - 50 % Polarization reduction
   - potentially 0.2eV Monochromatic beam
   - Time structure determined by laser pulse (~10 ns) synchronized with pulsed muon beam
   - external trigger allows synchronisation with sample excitation
Principle of ultra low energy muon generation

4 MeV muons $\Longrightarrow$ 0.2 eV thermal Mu $\Longrightarrow$ 0.2 eV $\mu^+$

- 2% thermal reaction
- 0.2 eV thermal muon
- Two laser beams necessary for resonant ionization
- Required very broad laser bandwidth due to thermal movement of atoms

**1S-2P saturation intensity**

$I_{sat}=2.3$ W/cm$^2$ (monochromatic < 100 MHz)

$I_{sat}=4.6$ kW/cm$^2$ (Doppler 200 GHz)

Main challenge: to generate VUV at 122 nm and with 200 GHz (+1 ns jitter relative to external trigger)
Lyman-α generation
(sum-difference frequency mixing in Kr gas)

- **212.55 nm** (single longitudinal mode) tuned to a resonance in Kr - yield resonantly enhanced
- **820 nm** (844 nm for H or D) broadband to match Doppler broadening of 200 GHz
- Tuneable VUV output ~ **122 nm** (with 200 GHz bandwidth)

- Short laser pulses required to increase intensity (~4 ns)
- Scheme requires relative timing of all laser pulses ~ 1 ns with external trigger (!)
  ⇒ possible with **OPO lasers pumped by YAG**
Schematic diagram of the laser system

25 Hz operation
Output synchronised to 1 ns (!)
High stability: 20 days continuous 24/7 operation

Solid State Laser parameters:
212.55 nm (single mode, tuned to Kr resonance):
Energy: 10-15 mJ/pulse x 2 beams
Pulse duration: 4 ns

800-880 nm (tunable broadband output)
Energy: 25 mJ
Pulse duration: 8 ns
Bandwidth: 160 GHz

355 nm (multimode output)
Energy: 380 mJ, 10 ns
Transport beamline for low energy $\mu^+$
Laser beam overlap with muonium

**In laser beam (per pulse):**
Mu: 1-10 atoms  
Deuterium: $10^3$-$10^4$ atoms
µSR setup for LE-muon experiment

Diamagnetic asymmetry in Ag sample:
10.1% ± 0.2%

Solenoid type magnet (transverse field < 60 mT)

Iwatani two-stage cryostat cooling power 0.5W @4K

Scintillation counters (8 telescope pairs) solid angle coverage 80% of 4π sr.

TF measurement to 60 mT ZF compensation to 0.1 μT
LE-$\mu^+$ decay spectrum

Background suppressed below 0.01 counts over 15 $\mu$s period after slow $\mu^+$ arrival.

Background further reduced by subtracting “laser off” events.

Background much lower than at continuous muon source -> much wider time window for measurement 10ns – 15$\mu$s
Size of low energy muon beam at sample

Measured with Roentdek position sensitive MCP (0.8 mm resolution)

~ 100 times smaller cross-section than incident surface muon beam.

Allows us to measure small samples of 10-20 mm diameter with excellent S/N ratio
Muon implantation with external trigger

- The timing between muon injection to the tungsten film and laser ionization was scanned to find optimum timing.
- Proportional to muonium density as a function of time.
- Double-pulsed structure of initial muon beam visible from this chart.
Comparison of muonium ionization and cryogenic moderator methods on ISIS pulsed source

- Laser resonant ionization method makes slow muon beam with good timing resolution.

- Time resolution is 7.5 nsec (FWHM). When cryogenic moderator method was used in ISIS, the time resolution was about 100ns.

- Laser ionization allows to trigger LE muon generation by external trigger with nanosecond resolution → synchronization with pulsed fields
Measured using muonium spin precession

LE-μSR: frequency response plot

Higher frequency limit for pulsed μSR is significantly extended.
Muon implantation energy

Implantation energy range of 0-18 keV controlled by applying potential on sample

Implantation depth in
- Au: 0-55 nm
- Cu: 0-73 nm
- Al: 0-135 nm

-9.0 kV to +9 kV

Energy resolution of the LE-μ⁻ beam

Initially only 0.2eV (thermal energy)

Energy resolution at sample determined by extraction i.e. differences in potential seen by individual muons:
- Width of the laser ionization region ($\sigma_E \approx 13$ eV)
- Uneven distance between W and S1 ($\sigma_E \approx 4$ eV)
- Differences due to laser beam alignment ($\sigma_E \approx 4$ eV)

\[ \sigma_E = 14 \text{ eV} \quad (33 \text{ eV at FWHM}) \]
Energy dependence of $A_{\mu}$ in Al(40 nm) on SiO$_2$

We have demonstrated that we can control muon implantation range within 10nm resolution by changing energy of LE-muons.
→ provides magnetic probe with depth resolution on nm scale

The LE muons are transported through the LE muon beamline at 9 keV. Muon energy is controlled by applying a potential on the sample in the range of 9.0 kV to -9.0 kV giving control over the implantation energy in the range of 0 – 18 keV.
Muon implantation at very low energies

At low incident energies (E < 3 keV):
- large fraction is reflected
- nearly all reflected muons form muonium

E. Morenzoni et al., NIM B 192 (2002) 254–266
Efficiency of LE muon generation

<table>
<thead>
<tr>
<th></th>
<th>RIKEN-RAL</th>
<th>PSI</th>
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<tbody>
<tr>
<td></td>
<td>(muonium ionization)</td>
<td>(cryogenic moderator)</td>
</tr>
<tr>
<td>Surface muon beam</td>
<td>1.2x10^6 µ⁺/sec (50 Hz)</td>
<td>2x10^8 µ⁺/sec (new beamline)</td>
</tr>
<tr>
<td>intensity</td>
<td>6x10^5 µ⁺/sec (25 Hz)</td>
<td></td>
</tr>
<tr>
<td>LE µ⁺/ intensity at</td>
<td>20 µ⁺/sec</td>
<td>8000 µ⁺/sec</td>
</tr>
<tr>
<td>sample</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall efficiency</td>
<td>3x10⁻⁵</td>
<td>4x10⁻⁵</td>
</tr>
</tbody>
</table>

Muonium ionization method is capable of much higher efficiency – potentially up to 10⁻³ level!
Dependence of yield on laser pulse energy

VUV energy is currently in µJ range. While one of the brightest Lyman-α sources available there is still large scope for improvement!
Muonium ionization efficiency

1) Increase VUV laser pulse energy
We expect modest improvements to VUV energy: 50% (In principle muonium can be ionized with close to 100% efficiency, with ~ 100 µJ at 122 nm)

2) Increase muonium density
- Tighter focusing of the incident muon beam would allow better overlap with laser
- Increasing W target surface area (laser drilled or porous W, tungsten coated aerogel)
- SiO2 aerogel

Other factors increasing the number of LE muons available at sample:
- Planned upgrade of ISIS proton current from 200 µA to 300 µA → immediate 50% increase
- Increasing the thickness of muon production target from 10 to 15 mm
- Increasing the acceleration voltage in LE muon beamline from 9.0 kV to 18.0 kV (TOF reduced by ~400 ns i.e. 16% increase in µ+ on sample)
More intense VUV?

Can we get more intense 122 nm beam from different laser system?


**Generation of 100 µJ pulses at 82.8 nm by frequency tripling of sub-picosecond KrF laser radiation**

Non-linear conversion efficiency in gases is typically $10^{-4}$ to $10^{-7}$ but in this case it is claimed to be 0.7%

100 µJ pulses at 82.8 nm generated by frequency tripling (249 nm) in Ar gas jet.


350 nm ps pulses converted to 116.6 nm with $8 \times 10^{-4}$ efficiency (max. 2.4 µJ)

If this conversion efficiency can be reproduced with 0.5 ps pulses at 366.27 nm it could:
- increase the muonium ionization efficiency to nearly 100% (with 100 µJ pulses)
- greatly simplify the laser system (only one wavelength needed & need to overlap several laser beams is eliminated)
- automatically match the Doppler broadened bandwidth of Mu since the transform limit would be about 300 GHz
- time resolution of LE-µ+ would be reduced to ~ 1 ns (limited by extraction ion optics)

366.27 nm generated by SHG solid-state system at 732.54 nm (e.g. Ti:Sapphire)
Main features of the method

- **Positive**
  - Timing determined by laser pulse, which is externally triggered
  - Pulse duration only 7.5 ns (comparable to continuous source) and independent of the surface muon pulse structure
  - Good energy resolution ~ 14 eV – (in principle as low as 0.2 eV)
  - Extremely low background
  - Small beam spot size
  - Efficiency of conversion from surface muon beam can be, in principle, as high as 10^{-3}.

- **Negative**
  - Only suitable for pulsed sources with low repetition rate
  - Inherent loss of muon polarization (50%) - BUT can be recovered
## Summary - Present characteristics

<table>
<thead>
<tr>
<th>Low energy $\mu^+$ beam</th>
<th>$\mu$SR spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity at sample $\sim$ 15-20 $\mu^+/s$</td>
<td>Background: $&lt;0.01$ per 15 $\mu$s after $\mu^+$ pulse</td>
</tr>
<tr>
<td>Beam diameter (FWHM): 4 mm</td>
<td>Count rates: $\sim 50$ kev/hour</td>
</tr>
<tr>
<td>Energy at target region 0.2 eV</td>
<td>(compared to 20-50 Mev/hour @ bulk $\mu$SR at ISIS)</td>
</tr>
<tr>
<td>Energy after re-acceleration 0.1-18 keV</td>
<td>TF : $&lt; 60$ mT</td>
</tr>
<tr>
<td>Energy uncertainty</td>
<td>ZF compensation to 0.1 $\mu$T</td>
</tr>
<tr>
<td>after re-acceleration $\sim$14 eV</td>
<td>Sample temperature: 10K-300K</td>
</tr>
<tr>
<td>Pulse repetition rate 25 Hz</td>
<td>External LE-$\mu^+$ trigger</td>
</tr>
<tr>
<td>Single pulse structure</td>
<td></td>
</tr>
<tr>
<td>7.5 ns (FWHM) at 9.0 keV</td>
<td></td>
</tr>
<tr>
<td>Spin polarisation $\sim$50%</td>
<td></td>
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</table>

### J-PARC facility
- projected muon intensity $\sim 10^8 \mu^+/s$ (comparable to current PSI beam)
- projected smaller diameter of the surface muon beam
- 25 Hz operation (double pulse structure – 600 ns separation)

We can expect more than $10^4$ LE-$\mu^+/s$ in $<10$ ns pulse
Comparison with PSI LE-muon beam

<table>
<thead>
<tr>
<th></th>
<th>PSI</th>
<th>RKEN–RAL</th>
<th>LE-muons @ PSI</th>
<th>LE-muons @ RKEN–RAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>time structure</td>
<td>DC</td>
<td>pulsed</td>
<td>DC</td>
<td>pulsed</td>
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<tr>
<td>beam intensity</td>
<td>5x10^7/sec</td>
<td>10^8/sec</td>
<td>8x10^7/sec</td>
<td>2x10^7/sec</td>
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<tr>
<td>external trigger capability</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>polarization</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
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<tr>
<td>time resolution</td>
<td>2nsec</td>
<td>100nsec</td>
<td>7nsec</td>
<td>7.5nsec</td>
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<tr>
<td>implantation energy</td>
<td>4.1MeV</td>
<td>4.1MeV</td>
<td>1y 30keV</td>
<td>0.1y 20keV</td>
</tr>
<tr>
<td>energy resolution</td>
<td>0.4MeV</td>
<td>0.4MeV</td>
<td>500eV</td>
<td>14 eV</td>
</tr>
<tr>
<td>S/N (=NO/B0)</td>
<td>~150</td>
<td>~100000</td>
<td>~100000</td>
<td>~100000</td>
</tr>
<tr>
<td>observable relaxation time</td>
<td>5y 9000</td>
<td>20y 32000</td>
<td>20y 12000</td>
<td></td>
</tr>
<tr>
<td>beam size (FWHM)</td>
<td>30mm</td>
<td>30mm</td>
<td>15mm</td>
<td>4mm</td>
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</tbody>
</table>