A Muon Facility at RISP

Dept. of Physics, Korea University
Eunil Won (원은일)
eunil@hep.korea.ac.kr

for
Muon facility working group
# Muon Science

From basic science to industrial applications

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Compiled from K. Nagamine, Introductory Muon Science (Cambridge)
Contents

- Science with RISP: muon science
  - Muon Spin Rotation/Relaxation/Resonance for condensed matter science
  - Fundamental science with Muon
  - Muon Facility at RISP
Muon
Muon ($\mu$)

- A spin 1/2 charged (+/-e) elementary particle
  
  \[ m_\mu = 0.1 \quad m_{\text{proton}} = 200 \quad m_{\text{electron}} \]

- Can be prepared to have 100% spin polarization

\[ \vec{S}_\mu \quad \leftrightarrow \quad \vec{S}_\nu \]

- Muon decays: mean life time 2.2 micro sec.

\[ \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

- Large magnetic moment: \( \mu_\mu = 3.18 \quad \mu_{\text{proton}} = 8.89 \quad \mu_{\text{neutron}} \)
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*  

Richard L. Garwin,† Leon M. Lederman, and Marcel Weinrich  

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York  

(Received January 15, 1957)

Measurement of  
- parity violation  
- muon spin, g-factor, decay asymmetry and

The 1st muon spin rotation spectrum

Phys. Rev. 105, 1415 (1957)

was there any evidence for an altered moment. It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the \( \mu^- \) decay into electrons\(^9\)), atoms, and interatomic regions.
Range of muons in matter

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)

Great opportunity in condensed matter science

Muons are implanted in the sample (no scattering)

Conventional Surface Muons

Surface muon: muon from the pion that is at rest on the surface of target

Energy [keV]

Cu

LE-Muons

thin films,
multilayers..

Range

[mm] 1

[µm] 10

[nm] 10

7
Condensed Matter Science: $\mu$SR
\[ \muSR \]

- **Muon Spin Rotation/Relaxation/Resonance** = \( \muSR \)

  - Powerful tool for probing magnetic properties of matter
  - Positron is emitted preferentially in the spin direction of the muon

Principle of $\mu$SR

The signal corresponding the time evolution can be directly extracted by looking at the asymmetry function:

$$A(t) \equiv A_0 P(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)}$$

- Asymmetry distribution contains the information about the precessing and relaxing muon spins in the total local field

- Fourier transformation to frequency domain allows measurement of the fields

$$\omega = \gamma \mu B_{\text{loc}}$$
Excellent Science with μSR

- More than 70 papers/year in PRB (dominated by PSI)

Magnetic and non-magnetic phases of a quantum spin liquid

Nature 471 612 (2011)

PRL 103, 147601 (2009)

Li Diffusion in Li$_x$CoO$_2$ Probed by Muon-Spin Spectroscopy

Industrial Applications
Chiral Induction

Chiral Induction in Lyotropic Liquid Crystals: Insights into the Role of Dopant Location and Dopant Dynamics**
Ute C. Dawin, Herbert Dilger, Emil Roduner, Robert Scheuermann, Alexey Stoykov, and Frank Giesselmann*

![Diagram](image)

Figure 1. Schlieren texture and model of the nematic (N) LLC host phase with disk-like micelles (left). Fingerprint texture and model of the chiral nematic (N*) phase; micelles represent the helical modulation of the director n with pitch P induced by doping the host phase with 4.37% R-MA (right).

Science 332, 937 (2011)

Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices

Direct measurement of the electronic spin diffusion length in a fully functional organic spin valve by low-energy muon spin rotation
A. J. Drew1, J. Hoppler1, L. Schulte1, F. L. Pratt1, P. Desai1, P. Shakya1, T. Krounzie1, W. P. Gillin1, A. Suter1, N. A. Morley1, V. K. Malik1, A. Dubroka1, K. W. Kim1, H. Bouzari1, F. Bourqui1, C. Bernhard1, R. Scheuermann1, G. J. Nieuwenhuys1, T. Prokscha1, and E. Morenzoni1

Engineering spin propagation across a hybrid organic/inorganic interface using a polar layer
L. Schulte1, L. Nuccio1, M. Willis1, P. Desai1, P. Shakya1, T. Krounzie1, V. K. Malik1, C. Bernhard1, F. L. Pratt1, N. A. Morley1, A. Suter1, G. J. Nieuwenhuys1, T. Prokscha1, E. Morenzoni1, W. P. Gillin1 and A. J. Drew1,2

Spatially homogeneous ferromagnetism of (Ga, Mn)As
S. R. Dunsiger1, J. P. Carlo1, T. Goke1, G. Nieuwenhuys1, T. Prokscha1, A. Suter1, E. Morenzoni1, D. Chiba1, Y. Nishitani1, T. Tanaka1, F. Matsukura1, H. Ohno1, J. Ohe1, S. Maekawa1 and Y. I. Uemura1

ZF
World-wide $\mu$SR Facility


One continuous, one pulsed $\mu$SR in Asian region will be a crucial step forward (Y. Miyake: J-PARC)
Fundamental Science with Muon
Electric Dipole Moment

- Permanent EDM for an elementary particle: P and T violation (also CP violation under CPT invariance)

- Non-zero EDM measurement: evidence of physics beyond Standard Model

History of EDM Searches

electron EDM limit < $8.7 \times 10^{-29}$ e cm
scaled by $m_\mu/m_e$

Science 343, 269 (2014)

SM prediction (< $10^{-36}$)

J-PARC & Fermilab g-2 exp. target sensitivity ($10^{-21}$ e cm)
Muon EDM Efforts

Spin precession vector in static E and B fields with $\vec{\beta} \cdot \vec{B} = 0, \vec{\beta} \cdot \vec{E} = 0$

$$\vec{\omega} = -\frac{e}{m} \left\{ a\vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\}$$

Three approaches

- Magic momentum (g-2+EDM): BNL E821, Fermilab
  Less sensitive to EDM ($10^{-21}$ e cm level)

$$\vec{\omega} = -\frac{e}{m} \left\{ a\vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right\}$$

- Zero E-field (g-2+EDM): J-PARC E34

$$\vec{\omega} = -\frac{e}{m} \left\{ a\vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} \right) \right\}$$

- Spin frozen (EDM only): introduce radial E to remove g-2 term (Phys. Rev. Lett. 93, 052001 (2004))

$$\vec{\omega} = -\frac{e \eta}{m 2} \left\{ \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right\}$$

So far, only proposals exist
Muon EDM Efforts

“Spin frozen” technique: for future prospect

\[
\begin{align*}
\frac{1}{1 - a} \beta \times \vec{E} + \eta \left( \frac{\vec{E}}{c} + \beta \times \vec{B} \right)
\end{align*}
\]

Apply radial E-field to eliminate this term

As solely by EDM: better sensitivity

\[
\chi = \frac{P \sqrt{N}}{1 - a}
\]

Vertical component of electron decay asymmetry of electron polarization in muon

Time

Vertical component
Spin frozen μ-EDM


- $p = 500, 350 \text{ MeV/c}$
- $B = 0.25 \text{ T}$
- $E = 2 \text{ MV/m}$
- $R = 7 \text{ m (w/ PRISM FFAG)}$

Sensitivity $\sigma(d_\mu) = 8 \times 10^{-25} \text{ e cm}$

Up-down asymmetry

$\eta = 5 \times 10^{-7}$

$d_\mu = 2.4 \times 10^{-20} \text{ e cm}$
Spin frozen \( \mu \)-EDM


- \( p = 125 \text{ MeV/c} \)
- \( B = 1 \text{ T} \)
- \( E = 0.64 \text{ MV/m} \)
- \( R = 0.42 \text{ m} \)
- \( N = 2 \times 10^5 /\text{s} \)

Sensitivity: \( \sigma(d_\mu) = 5 \times 10^{-23} \text{ e cm/year} \)

A “compact storage ring” concept

http://amas.web.psi.ch/projects/muonedm/

Artist’s impression (A. Streun)
Spin frozen $\mu$-EDM

- Planned g-2 exp. (Fermilab, J-PARC) aim at sensitivity of $\sigma(d_\mu) \sim 10^{-21}$ e cm

- Spin frozen technique seems the way to go (?)

- If one sticks with linear mass scaling: $\sigma(d_\mu) \sim 10^{-26}$ e cm at least desired (?)

  - Quadratic, cubic scenarios exist

- Systematics
Muon Science @ RISP
Reminder

● RISP: 660 uA, 600 MeV for proton

● Note: this is slightly less than half of beam power of PSI cyclotron (1.3 MW)

Muon yield will be less then PSI yield
- New flexible design with ideas is desired
Our Simulation Shows

Muon transport

Muon production

\begin{align*}
\text{Muon production} & \sim 10^{-5} \text{ surface muons/proton} \\
\epsilon(\text{collection}) & \sim O(3 \times 10^{-2}) \\
\epsilon(\text{transport}) & \sim O(1) \\
\epsilon(\text{thermalize}) & \sim 10^{-5}
\end{align*}

\begin{align*}
\text{Surface muon: muon from the pion that is at rest on the surface of target} \\
p_\mu = 29 \text{ MeV/c (for surface muon)}
\end{align*}

4 \times 10^{15} \text{ protons/s} \quad (660 \text{ uA})

\begin{align*}
10^8 \text{ surface muons/s} \\
10^4 \text{ thermalized muons/s}
\end{align*}
Magnetic Field Validation

- Simulated magnetic field maps are compared
- Generally good agreement with CST

E. Won
Transport in Detail

- “solenoid only” option

Integration of magnets

- Capture Solenoid
- Curved Solenoid (45°)
- Straight line (6m)
- Magnetic Dipole (0.15T)
- Axial Focusing Solenoid

Missing parts:

- Positron Separator
- Beam Blocker
- Steering dipole coils?
- cooling materials, etc.

Overall surface muon transportation efficiency ~60%: need further improvement

Transport Efficiency

\[ p = 29 \text{MeV/c} \]

\[ e^- p = 29 \text{MeV/c} \]

\[ e^+ p = 29 \text{MeV/c} \]

\[ \mu^- p = 29 \text{MeV/c} \]

\[ \mu^+ p = 29 \text{MeV/c} \]
Epi-thermal Beam Line

- Einzel lens design simulation (CST)
  Kyungmin Lee, Jihoon Choi/KU

- Result of simulation after field map from CST into Geant4 (using PSI tool)

Moderated muons come in

Momentum smearing (10mm gaussian beam)
  : unit (mm)

ByeongRok Ko/KU

No smearing

1%

5%

10% smearing

2014 AKPA IBS Symposium on Special Topics in Physics, Univ. of Chicago
Recent Developments
(up to previous went into TDR)
Beyond Default Design

- Increase of surface $\mu$ by thinner targets: 1.6 times increase seen

- Targets in solenoid: $O(20)$ increase seen
Can it work? Radiation/heat

MUSIC facility @ RCNP/Osaka
(target inside solenoid)

Graphite target

Target at the center of the capture solenoid.

Note:

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<th>660</th>
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<td>1 uA 400 MeV</td>
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<tr>
<td>200 mm thick</td>
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<td>660 uA 400 MeV</td>
<td></td>
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<tr>
<td>5 mm x 4 thick</td>
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660/40=16.5

: still O(10) higher, can we have
them in the collecting solenoid?

Requires serious radiation/heat study of
course

Note:

My Option 1
thickness (total 20 mm): 5 mm x 4
Muon Facility Working Group

- μSR
  Mansoo Choi, Sanghoon Lee, Jaeho Jeong (KU), W. Higemoto (TBC, JAEA/J-PARC)

- Fundamental science
  E. Won, ByeongRok Ko (KU), Bongho Kim, Seonho Choi (SNU), T. Mibe, N. Saito (KEK)
● Our initial studies
Critical Interfaces explored with μSR

- LAO/STO Interface
  - Insulator + Insulator : metal
  - Ferromagnetism

Topological Matter/Normal Matter
- Topological insulator / Normal superconductor
- Topological superconductor / Magnetic insulator

μSR workshop: KU+J-PARC (Apr. 18, 2014)
To RISP: μSR

- Ultra-slow polarized muon facility
  It has much bigger science impact to the society than with just surface muon facility

- Design to host multiple beam lines/spectrometers (in future)
  PSI has 6 different spectrometers for users.
  Note that world-wide muon beam lines are overbooked:
  : no beam at PSI in 2014 at all
  : call for beam at J-PARC for late 2014 on July 2014
Fundamental Science

Science case we have been developing for example

- Muon EDM
- Muonium oscillation (not today)
- We are not limited to above of course
Fundamental Science

Muon EDM with RISP

- Low emittance beam by re-acceleration of epi-thermal muons
  \[ p = 300 \text{ MeV/c} \text{ (a semi-random number from J-PARC } g-2) \]

- Ideal beam structure: pulsed at 1-10 kHz
  
  Muon lifetime (boosted) + DAQ dead-time

  J-PARC beam is pulsed at 25 Hz and is inefficient for μEDM
Spin frozen technique at RISP?

- \( p = 300 \text{ MeV/c} \)
- \( B = 0.8 \text{ T} \)
- \( E = 2.5 \text{ MV/m} \)
- \( R = 1.3 \text{ m} \)

**RIPS:** \( \sigma_{d_\mu} = 8.5 \times 10^{-17} / \sqrt{N} \text{ e cm} \)

**PSI:** \( \sigma_{d_\mu} = 1.5 \times 10^{-16} / \sqrt{N} \text{ e cm} \)

**J-PARC:** \( \sigma_{d_\mu} = 2.0 \times 10^{-16} / \sqrt{N} \text{ e cm} \)

10 kHz \( \times \) 10^6 muons/s \( \times \) 1 year: \( \sigma_{d_\mu} \sim 10^{-25} \text{ e cm} \)

Don’t get too much excited, I’m just playing with numbers
Summary

- RISP is under construction
- We are considering a muon facility for both condensed matter and fundamental science applications
- A careful design to host both $\mu$SR and fundamental science programs will be great
Particle Physics @ μ Facilities

μ to eγ : MEG experiment (2009-)

MEG upgrade (2016-2018)
: arXiv: 1301.7225

μ to eee proposal:
: arXiv: 1301.6113

J-PARC fundamental science program
- DeeMe (μ to e conversion)
- COMET (μ to e conversion)
- g-2/EDM
- (μe) hyperfine

PSI (Swiss)

S-Line
Surface μ+ (30 MeV/c)
For materials science
Under Construction!
Hopefully first muon this coming March!

J-PARC (Japan)

μ up to 120 MeV/c For μCF
USM for Muon Microscopy

U-Line
Ultra Slow μ+
(0.05-60 keV)
For multi-layered thin foils, nano-materials, catalysis, microbeam, etc.

MUSE Facility @MLF

D-Line
Surface μ+ (30 MeV/c)
Decay μ+/μ⁻ (5-120 MeV/c)
Users’ RUN, in Operation

Korea Univ. Dept. of Physics, Eunil Won
2014 AKPA IBS Symposium on Special Topics in Physics, Univ. of Chicago
A Muon Campus @ RISP

μ-Campus

I believe there is great fundamental science case @ RISP

END Station of SCL2

kicker: controls current to solenoid

TO IF separator

Beam dump
Extra Slides
Ultra-slow Muon Generation

Beam test at TRIUMF: Muonium yield estimation

KEK+RIKEN+TRIUMF + E. Won, W. Lee (KU):
2013 Oct.

Analysis being done by KEK + S. H. Lee (KU)

Comparison: Differences

- Comparison with Kitamura-san’s result $0.00039 \pm 0.00002$

$\mu = 0.00023 \pm 0.00006$

$\sigma = 0.00047 \pm 0.00004$
Muonium Oscillation Exp.

- Some of us have been looking at a muonium oscillation experiment (but not limited to it)

Phys. Rev. Lett. 82, 49 (1999)

- Various new fundamental interaction can cause Mu to anti-Mu transition
- Not updated since 1999
- A new technique to reject accidental and irreducible backgrounds more effectively needed
Muonium Oscillation Exp.

- by R. Bernstein and P. Cooper (Fermilab)
- excellent review of cLFV experiments

- typical counter type
- suffer from rate-dependent background
- < 3x10^{-3} G_F was achieved

- a radiochemical approach
- antimuonium absorbed in tungsten nucleus (μ⁻ W → ν_μ^{184}Ta)
- < 10^{-4} G_F can be possible

arXiv:1307.5787
- improve counter type experiment
- use modern technology
- could reduce limit by 10^{-2} (but with pulsed beam)
Muonium Oscillation Exp.

One slide R&D status

- Geant4 study for tracker is ongoing
- 40 MeV e- in Xenon gas (atm)
- 10 MeV
- 8 MeV
- 4 MeV

- ✓ Muonium production R&D is starting with J-PARC people
- ✓ Improvement from MWPC
- ✓ Improvement from CsI and faster timing
- ✓ Active target?
Continuous vs. Pulsed

**Continuous**

- At RISP the accelerator structure (80 MHz microstructure) and the pion lifetime (26 ns) leads to a practically continuous surface muon beam


- one muon at a time
  (otherwise it is background)

**Pulsed**

- At a pulsed machine all the muons are contained in a pulse (50-100 ns wide) with low repetition rate (25-50 Hz)

- This allows a higher rate (all the decay positrons of a pulse are measured at once)

- But only one positron in a detector or in the case of more than one, you have to get the time stamp on them

This requires a high segmentation of the positron spectrometer (HEP knows how to do it)
Generation of Slow Muons

1) By moderation in thin layers of cryosolids

   - More suitable for “continuous” accelerator such as RISP and PSI

2) By laser resonant ionization of muonium

   - More suitable for “pulsed” accelerator such as J-PARC and Project X
Generation of Slow Muons

1) By moderation in thin layers of cryosolids

Moderator
Generation of Slow Muons

1) By **moderation** in thin layers of cryosolids

This is a 2-step process

i) Put a foil (O(100) μm thick) in the muon’s flight path: this will slow down the muon but the energy spectrum of muons exiting the foil is very broad

Coulomb collisions with target atoms (e-h pair, excitation creation)

ii) Then place some well-selected materials (moderator, usually < 1 μm thick) and it will lead to a preferential emission of muons at energies of a few eV

Surface Muons
~ 4 MeV
~ 100% polarized

~100 μm Ag
< 6 K
~500 nm
s-Ne, Ar, s-N₂

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)
Generation of Slow Muons

2) By laser resonant ionization of muonium

What is muonium? (a μ+μ- bound state? NO): \textit{muonium} = μ+e-

![Diagram of muonium energy levels compared to hydrogen energy levels.](image)

---

**Physics Reports 342 (2001) 63-261**

**Fig. 1.** Hydrogen energy levels.

**Fig. 2.** Muonium energy levels.

Muonium energy levels are somewhat similar to those of hydrogen
Generation of Slow Muons

2) By laser resonant ionization of muonium

Generation of muonium:

PRL 52, 910 (1984)

PRL 47, 1441 (1981)

Incident surface muons to a target generate slower muons and muonium atoms

Observation of Muonium in Vacuum
Ultra-slow Muon Generation

2) By **laser resonant ionization** of muonium

![Diagram showing laser resonant ionization of muonium]

\[ p = 28 \text{MeV}/c \quad 3 \text{keV}/c \]
Ultra-slow Muon Generation

2) By laser resonant ionization of muonium

P. Bakule and Elvezio Morenzoni, Contemporary Physics, 45, 203 (2004)
## Moderator vs. Laser

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<th>Laser Resonant Ionization</th>
<th>Moderator</th>
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<tr>
<td>Location</td>
<td>J-PARC, RIKEN/RAL</td>
<td>PSI, TRIUMF</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>0-30 keV</td>
<td>0-30 keV</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>0.2 eV</td>
<td>10 - 100 eV</td>
</tr>
<tr>
<td>Beam Size</td>
<td>0.5-1 mm</td>
<td>10 - 15 mm</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td>100 ps - ~ ns</td>
<td>10 ns</td>
</tr>
</tbody>
</table>

Kazutaka Nakahara (UMD, JLAB seminar 8/28/2009)
Stopping Range of Ultra Slow $\mu^+$ Generated by Laser Resonant Ionization of Mu

Dot: low energy $\mu^+$ ($100\,\text{eV, }\sigma500\,\text{eV}$)
Solid; Ultra Slow $\mu^+$ ($\sigma\ 13\,\text{eV}$)
Implantation Energy($50,100,200,300,500,1000\,\text{eV}$)

You can control implantation depth
From 1 nm with 1nm width
to 300 nm on the any boundary.

W. Higemoto (J-PARC)
KU workshop

U-Line

Stopping Range of Ultra Slow $\mu^+$
Generated by Laser Resonant Ionization of Mu

Dot : low energy $\mu^+$ (100 eV, $\sigma$500 eV)
Solid; Ultra Slow $\mu^+$ ($\sigma$ 13eV)
Implantation Energy(50, 100, 200, 300, 500, 1000 eV)

You can control implantation depth
From 1 nm with 1nm width
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