RIKEN-RAL Muon Facility

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Facility and Beam Characteristics

Research
with Negative Muons
with Positive Muons
RIKEN (RIkagaku KENkyujo, The Institute of Physical and Chemical Research) is one of the largest basic research institute in Japan covering physics, chemistry as well as biology with ~3,000 staffs. RIKEN was established in 1917. The second cyclotron in the world was built there in 1937. The world largest SC cyclotron (8300 ton) has started operation in Dec 2006. It provides heavy ion (450 MeV/u) and RI beam for nuclear physics research.

RIKEN muon group is now in the RIKEN Nishina Center for Accelerator-Based Science.
Agreement on muon science collaboration between RIKEN and SERC was signed in 1990.

- **RIKEN** provides, maintains and operates the muon channel.
- **RAL** provides the proton beam and the production target for muon production.

The beam time is shared between **RIKEN** and **RAL**.

RIKEN and RAL each has their own PAC.
History of the RIKEN-RAL Muon Facility

1990 April: Budget Approval by STA (Science and Technology Agency)
1990 September: The first agreement between RIKEN and SERC (term: 10 years)
1991: Beginning of the facility construction
1994 November: Observation of the first muon beam
1995 April: Inauguration of “RIKEN Facility Office at RAL”
    Beginning of condensed matter studies by μSR methods
1996 June: Completion of the RIKEN-RAL Muon Facility
    Beginning of muon catalyzed d-t fusion experiments
2000 September: The 2nd agreement between RIKEN and CCLRC (term: 10 years)
2006 April: Organized in RIKEN Nishina Center for Accelerator-Based Science
Uniqueness of RIKEN-RAL Beam-line

Backward decay muon beam as well as surface muon beam can be chosen at RIKEN-RAL Muon, because of the solenoid decay section.

Compared with surface-muon beam, backward decay muon beam has advantages
- higher momentum (deeper injection)
- choice of positive/negative muon

Disadvantages
- lower muon stopping density (difficulty with small sample)
- smaller polarization (~90%)
Beam structure

Pulsed proton beam with 50 Hz repetition double pulse with 100 ns width, 320 ns peak to peak on Graphite Target 10 mm thick

RIKEN-RAL Muon

Kicker waveform calc.
(SPICE)

Pulsed Magnetic Kicker for single pulse operation (<60 MeV/c)
Beam profile monitor
4 mm x 100 mm scintillator bars
With ADC readout

σ_x = 1.5 cm, σ_y = 1.6 cm
(~10cm^2, FWHM)

measured beam size
(Surface μ^+ Port4)
About muon beam intensity

Muon intensity measurement is not a straightforward thing with pulsed beam

1) From muon decay
   (solid angle, threshold, stopping position)

2) Direct beam
   using profile monitor

   decay $\mu -$ (28 MeV/c)
   typically 5 muons per detector
   $\rightarrow$ 40 muons in 40 x 40 mm$^2$ area

   surface $\mu +$ (28 MeV/c)
   PM gain reduced 1/100 by decreasing bias
   to cope with $>$2 orders intensity increase

   ADC ratio (including x100 bias effect correction)
   $\sim$ 380

   Gives 15000 $\mu+$ /single pulse
   1.5 M $\mu^+$ /s in 4 x 4 cm$^2$/s (50Hz, double pulse)
Muon Beam at RIKEN-RAL

Beam properties

- surface $\mu^+$ (20~30 MeV/c) and
decay $\mu^+/\mu^-$ (20~120 MeV/c)

- choice of double or single pulse
  - with magnetic kicker (<60 MeV/c)
- $\Delta p/p$ FWHM 10%(decay), 5%(surf)
- typical beam size 10 cm$^2$
Muon Science at RIKEN-RAL Muon Facility
- Present Status -

4 Beam Ports with Dedicated Experimental Setups

Port 1: **MuCF** (Muon Catalyzed Fusion)

Port 4: **MuA*** (Muonic atom spectroscopy)

Port 2: **µSR**

Port 3: Development of ultra slow muon beam for µSR etc
Negative Muon

Positive muon mostly stays at interstitial site or makes chemical bonding like a hydrogen while

Negative muon behaves as “a heavy electron” \((m_\mu = 207 \ m_e)\).
\(\mu^-\) is attracted by the positive charge of a nucleus and forms a muonic atom

The muonic atom typically has 1/200 times smaller size than a normal atom, and its binding energy is 200 times larger.

Two examples

- Muon Catalyzed Fusion
- Probing Nuclear Charge Distribution
μCF (Port 1)

Muon catalysis of dt nuclear fusion
MuCF: Introduction

Muon Catalyzed Fusion

=> A **negative muon** can catalyzes nuclear fusions via the formation of muonic atoms and molecules

\[ \text{E}_{1s}(p\mu^-) = -2.5 \text{ keV} \]

\[ \beta_{g.s.}(pp\mu^-) = 520 \text{ fm} \]
\[ \text{E}_{g.s.}(pp\mu^-) = -250 \text{ eV} \]
dt fusion in muonic molecule

thermo nuclear (plasma) fusion

muonic molecule

high temperature overcome the Coulomb barrier

1) Coulomb barrier is largely shielded by muon’s negative charge
no need for high temperature
2) dt encounter increased due to confinement in molecule
=> dt fuse in $10^{-12}$ s in molecule
After injection of muons into D/T mixture (or other hydrogen isotopes)
Formation of muonic atoms and molecules
  d-t fusion in small $dt\mu$ molecule
 Muon released after d-t fusion
    - muon works as catalyst -
$\mu$CF represents a series of processes repeating while the muon is active
  nuclear physics, atomic physics, condensed matter physics,...
Exotic atomic Physics
atomic physics in small scale
few-body problems

Applications
Fusion Energy
~40% the scientific break-even
= ~120 fusions per muon (2 GeV)
/ muon production cost ~5 GeV
“Pure” Fusion Neutron Source
(Material irradiation, Hybrid reactor, Accelerator Driven System)
Maximizing $\mu$CF efficiency

Observables

1. Cycling rate $\lambda_c$ (↑) (vs $\lambda_0$: muon life)
   
   $dt\mu$ formation: $t\mu + D_2 \rightarrow [(dt\mu)dee]$

2. Muon loss per cycle $W$ (↓)
   
   muon sticking to $\alpha$-particle, etc

Emission neutron time spectrum

Fusion neutron disappearance rate:

$\lambda_n = \lambda_0 + W\phi\lambda_c$

Number of fusion per muon:

$Y_n = \phi\lambda_c/\lambda_n = 1 / [(\lambda_0/\phi\lambda_c)+W]$ (↑)
Dedicated μCF facility with safe tritium handling
MuCF target and detectors

2.4T magnets for strong focusing of muon beam in 1 c.c liquid D/T target

NE213 neutron detector

Si(Li) X-ray detector (muonic atom X-ray)

µe decay detector
Muon Catalyzed d-t Fusion

\[
\begin{align*}
    d + t + \mu^- & \rightarrow (dt\mu^-) \\
    & \rightarrow ^4\text{He} + n + \mu^- + 17.59 \text{ MeV}
\end{align*}
\]

120 d-t fusions / muon

(Scientific break even:
300 d-t fusions / muon)

10000 muon stops/s in 1cc liq. D/T target

10^6 fusions /s generated by muCF
Key process of $\mu$CF(1)

- $dt\mu$ formation

Key to improving $\mu$CF efficiency (1)
reaction rates $>>$ muon decay rate
slowing down and capture
muonic atom cascade
muon transfer
$dt\mu$ molecular formation
cascade in molecule, fusion
**Resonant dtµ formation**

Formation of dtµ “bound” state needs energy release mechanism

Auger electron emission is usually slow ($10^6$/s).

Fortunately, the existence of a shallow bound state of dtµ allows the small energy to be absorbed by vib-rotational excitation of composite molecule

-> Final states are only in discrete levels

selection on initial state: resonant formation tµ

=> rate is largely dependent on target condition

similar mechanism works for ddµ formation also
Quite interesting dependence of $dd\mu$ formation rate on the initial ortho-para $D_2$ state and temperature was observed. The effect is reversed when the density is increased from gas to solid.
Recent Result

MuCF with controlled molecular states - Non-equilibrium effect

\[ D_2 + T_2 \rightleftharpoons 2DT \]

For muCF in liq. D/T, resonant \( dt\mu \) formation condition is more well matched by D2 rather than DT

\[ t\mu + D_2 \rightarrow [(dt\mu)\text{dee}] \text{ and } t\mu + DT \rightarrow ((dt\mu)\text{ tee}) \]

And further by ortho-D2 \((J=0,...)\) rather than para-D2 \((J=1,...)\) in liquid D/T

\( C_{\text{ortho}} = 28\%, 66\%, 99\% \)

- while any existing theoretical prediction favors para-D2 could be effect of 3-body effect (first sub-threshold resonance for ortho-D2?)

![Graph showing the non-equilibrium effect over time after D/T mixing](image)
Key processes of µCF (2)

µ-to-α sticking

Some of the muons may follow the recoiling α-particle after dt-fusion with small but non-negligible probability $\omega_s^0$,

$$\omega_s = (1-R) \omega_s^0$$

$\omega_s^0$ is an intrinsic value

$$\omega_s^0 (nl) = \sum |F(nlm)|^2, \quad F(nlm) = \int \phi_{nlm}(r) e^{-iqr} \psi_{in}(r) \, dr$$

with powerful few body calculations $\omega_s^0 = 0.9\%$

$R (~0.3)$ can be dependent on target condition

$\omega_s$ place limit on the number of fusions
Status of μ-to-α sticking study (before RIKEN-RAL)

Discrepancy between theory and experiment

**Theory**: two step calc. \( \omega_s = \omega_s^0 (1-R) \)

**Experiment**: \( \omega_s = W(\text{total loss}) - (\text{other losses}) \) by global fit

Some result show significantly low \( \omega_s \) at high density

\( \Rightarrow \) enhanced reactivation ?

wrong calibration ? unknown loss?

direct observation of sticking

\( (\alpha\mu)^+ / \alpha^{++} \) ion (PSI, ISIS RAL)

x-rays (PSI, RIKEN-RAL)

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![Diagram showing initial sticking, ionization, reactivation, and effective sticking.](image-url)
Muon-to-alpha sticking

Precise determination of sticking process

Initial sticking $\omega_s^0$ and recoiling ($\alpha\mu$) atomic process (regeneration, R) determines $\omega_s$

observation of $K\alpha, K\beta$ X-rays from ($\alpha\mu$)$^+$

(pulsed muon can compete strong tritium decay brems background)

$Y(K\alpha) \sim$ theory, $Y(K\beta) \ll$ theory,

final sticking $< \text{theory}$

$n \geq 3$ process should be checked

The sticking still gives severe upper limit $Y_n < 200$
muCF plans at RIKEN-RAL

muCF in D/T targets with controlled molecular states
to better understand the basic process
to achieve higher rate

muCF in high density/high temperature target
muCF under unexplored condition,
large increase is expected

Many other issues on basic processes
  Muon transfer between isotopes (d, t)
  Muon transfer to helium
  muCF of other isotopes
Development towards Muonic Atom Spectroscopy of Unstable Nuclei
Development towards Muonic Atom Spectroscopy of Unstable Nuclei

- Nuclear Charge Distribution of short-lived Nuclei
- **SOLID HYDROGEN FILM** to stop both $\mu$ and $A^*$
- **MUON TRANSFER**

\[ \mu H + A_z^* \rightarrow \mu A_z^* + H \]

\[ \lambda_z \approx C_z Z 10^{10} \text{ s}^{-1} \]

- **TRANSFER RATE**

**HIGH TRANSFER RATE & HIGH EFFICIENCY**

**Target System**

- **$\mu$A* Setup at RIKEN-RAL**
- **Cold Foil (100-$\mu$m Ag)**
μA*

Muonic X-ray from 1 ppm Ar implanted in D2
~$10^6$ gain in $\mu + A^*$ encounter

New development

Installation of surface ionization ion source
Sr, Ba, (Ra) with isotope selection
Muonic Strontium X-rays
First muonic X-ray measurement from isotopes separated online

Target Summary

<table>
<thead>
<tr>
<th>Ion current on target</th>
<th>Sr-88</th>
<th>Sr-86</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Implantation time</td>
<td>1.1 µA</td>
<td>140 nA</td>
</tr>
<tr>
<td>Ion implanted in D₂</td>
<td>160 min</td>
<td>900 min</td>
</tr>
<tr>
<td>Data Taking</td>
<td>6.7x10¹⁶ (1.1 ppm)</td>
<td>4.7x10¹⁶ (0.8 ppm)</td>
</tr>
<tr>
<td></td>
<td>11,515 kspills (~63 hrs)</td>
<td>13,139 kspills (~72 hrs)</td>
</tr>
</tbody>
</table>

Solid D₂ Target
Thickness: 1-mm
Implantation: 20x
Spacing: 50 µm

RIKEN-RAL Port 4
Nov.~Dec. 2006
With reduced muon rate (30%)
The new surface ion capable of **rare-earth elements** very high Z nuclei with **deformation properties**.

**Samarium isotopes** from spherical to highly deformed.

- $^{144}\text{Sm}$ (N=82, n-magic) spherical nucleus
- $^{152}\text{Sm}$ and $^{154}\text{Sm}$ highly deformed nuclei

### Sm Natural Abundances:

- $^{144}\text{Sm}$: 3.1%
- $^{147}\text{Sm}$: 15.0%
- $^{148}\text{Sm}$: 11.3%
- $^{149}\text{Sm}$: 13.8%
- $^{150}\text{Sm}$: 7.4%
- $^{152}\text{Sm}$: 26.7%
- $^{154}\text{Sm}$: 22.7%

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**A Muonic X-Ray Study of the Charge Distribution of $^{144, 148, 150, 152, 154}\text{Sm}$**, by R.J. Powers et al., Nucl. Phys **A316** (1979) 295. (Saclay)
and also, of course, $\mu$SR

More than 70% beam time is used for $\mu$SR

There are several unique options for RIKEN-RAL
  • High momentum muon beam
  • Coupling with Laser
  • Ultra slow muon beam
$\mu$SR (Port-2)

$\mu$SR with surface/decay muon beam under various target conditions
μSR at RIKEN-RAL

ARGUS Spectrometer

Highly segmented detector (96+96)
High data rate (70 M/hr)
Magnetic field up to 0.4 T (LF) and 0.015 T (TF)
Various cryostats (dilution, 3He, He, Flow type)
Choice of backward decay or surface muon
  high momentum muon for high pressure chamber
Other capabilities
  coupling with RF, laser excitation
Gas Pressure

6.4 kbar, 1.5 K

Hydrostatic Pressure

10 kbar, 30 mK
A new laser laboratory and light-tight enclosure for Port 2

- Mini-breadboards for additional optical elements e.g. image relay
- Optical breadboards in light-tight box 800x1200 mm
- Optical tables 900x3000 mm
- LASER ROOM
- PORT2 AREA (ARGUS and Sample box not shown)

Tunable laser system with Nd:YG laser and OPO (430 nm – 2500 nm, 10-100 mJ)

- First experiment done in February 2008.
On going laser μSR studies or under preparation

Following PAC approved experiments are planned

1) Measurement of conduction electron polarization by muonium
   (first result in Feb 2008)

2) Spin-dependent exchange scattering of conduction electrons
   with Mu in solids

3) Muonium Reactivity from Raman-pumped H₂*
   Laser excites hydrogen (at ground state) to vibrationally excited state,
   where the exchange reaction $\text{Mu}^+ \text{H}_2^* \rightarrow \text{MuH} + \text{H}$ is much faster.
   The rate is sensitive to the potential energy surface as well as quantum effect.

and lots of possibilities
Slow $\mu$ (Port3)

Ultra slow muon beam by laser ionization of thermal muonium
Low energy muons

The surface muon beam make experiments possible with a thin sample (~20 mg/cm²) but still not enough to be used for very thin layer or interface.

To make it possible, ultra slow muon beam is developed with simple moderation, the energy is spread rapidly and we lose beam intensity.
Producing low energy muon with laser

Thermal Muonium
muons stopped in hot W film
diffuse to surface and thermally emitted
(with 4% efficiency)

Laser ionization
Thermal muonium + laser ionization
$1s \rightarrow 2p(122\text{nm}) \rightarrow \text{unbound}$

PSI use other methods for slow $\mu$ production
(rare gas solid moderator)
Laser ionizing Ultra-Slow muon beam

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)

Al (40nm)

SiO₂

Thin implantation depth (<40nm)
Slow $\mu$: Comparison with the PSI method

PSI rare gas solid moderator (Morenzoni et al) emits $\sim15$eV muons during moderation in rare-gas solid, energy loss process terminates below energy gap in solid rare-gas film

RIKEN-RAL laser ionization method has achieved similar $10^{-5} \sim 10^{-4}$ efficiency for the moderation

PSI produce higher intensity low energy muons, mainly because primary muon intensity is about two orders higher

Laser ionization method has several advantages
- smaller energy distribution (thermal)
- smaller spot size after acceleration from thermal energy timing capability (narrow pulsed beam controllable by laser timing)

and potentially higher efficiency
- with improvement of laser power, extraction etc
Possible upgrading works

Improvements continue

- **B magnet**
  - Stabilization with new power supply
- **Upgrading acceleration voltage**
  - 10→20kV
  - 15% less in-flight decay
  - Smaller beam spot size
- **laser beam**
  - More collinearity 122nm, 355nm
- **Muon beam enhancement**
  - Focusing, muon mirror
Near future development at RIKEN-RAL

New μSR spectrometer in Port 4

Beam time is highly crowded by many users request
The capability of the facility had not yet been fully utilized

Simultaneous use of two ports (Port 2 and Port 4) with single pulse will become possible by
1) Installation of DC separator in Port 4
2) Installation of a new μSR spectrometer in Port 4
easily detractable on rail by 1m from beam switchable with μA* setup

New μSR spectrometer is aimed at

μSR with tiny (10 mg) samples
low background
high rate of data acquisition
Large bore magnet 350mm, 0.4 T
600 segmentation scintillation detector with multi-anode Photo tube
Summary

RIKEN-RAL Muon Facility has been operating since 1994. It can deliver both backward decay $\mu^+/\mu^-$ and surface $\mu^+$ beam.

Scientific research
1. The RIKEN-RAL has unique program using negative muons. muCF and $\mu A^*$ (monic atom spectroscopy)

2. For $\mu$SR it has optional features such as
   Use of high pressure
   Use of laser
   and we will double the $\mu$SR capacity with the installation of a new spectrometer in Port 4

The RIKEN RAL Facility is open to users via ISIS and RIEKN PACs.
RIKEN is operated by

Staff in RIKEN
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T. Suzuki, T. Kawamata, Y. Ishii, D. Tomono, K. Ohishi
Y. Okuizumi, H. Miyamoto, A. Tano, Y. Fujita
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Staff in the UK
P. Bakule, H. Takesue, J. Suzuki

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S. Ohira