Muonic Radioactive Atoms

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&
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Contents:
(1) Muonic atoms
(2) Muonic X-ray spectroscopy
(3) Formation of muonic radioactive atom
(4) Feasibility study at RIKEN-RAL Muon Facility
(5) Future perspectives
## Collaborators

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Taniguchi</td>
<td>(Kyoto)</td>
</tr>
<tr>
<td>T. Matsuzaki, K. Ishida, M. Iwasaki</td>
<td>(RIKEN)</td>
</tr>
<tr>
<td>Y. Matsuda</td>
<td>(Tokyo)</td>
</tr>
<tr>
<td>S. Ohya</td>
<td>(Niigata)</td>
</tr>
<tr>
<td>K. Nagamine</td>
<td>(UCR)</td>
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</table>

*Surface Ionization Ion Source:*

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
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<tbody>
<tr>
<td>S. Ichikawa</td>
<td>(JAEA)</td>
</tr>
<tr>
<td>H. Miyatake</td>
<td>(KEK)</td>
</tr>
</tbody>
</table>
Muonic Atom

Muon Catalyzed Fusion

\[ a_0 = \frac{n^2 \eta^2}{m_e e^2} \frac{1}{Z} \approx \frac{5.3}{Z} \times 10^4 \text{ fm} \] 
(for n=1)

\[ a_\mu = \frac{m_e}{m_\mu} a_0 \approx \frac{1}{207} a_0 \]
Fig. 15.8  The probability densities of finding a muon in the state indicated, at a distance $r$ from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons and Duerdoth 1969).
Muonic Atom Spectroscopy

**X-RAY SPECTROSCOPY** of **MUONIC ATOMS**!

- Precision tool to measure **NUCLEAR CHARGE DISTRIBUTION** and **DEFORMATION PROPERTIES** of nuclei.
- Usefully complement the knowledge obtained from elastic electron scattering and laser spectroscopy.

**Combined Analysis**

- Successfully used since more than 30 years to study **STABLE ISOTOPES** in condensed or gaseous states!

**RI**: Tritium, $^{235}\text{U}$, $^{238}\text{U}$, $^{237}\text{Np}$, $^{239}\text{Pu}$, $^{242}\text{Pu}$

(muon-induced fission experiment)
Nuclear Charge Radii of Tin Isotopes from Muonic Atoms
C. Piller et al., Phys. Rev. C 42 (1990) 182,
(Fribourg Univ. / Mainz Univ.; Exp. PSI μE1)

Fig. 3. Prompt muonic x-ray spectra showing the $2p_{1/2} - 1s$ and $2p_{3/2} - 1s$ transitions in the two tin isotopes at the extreme ends of stability, $^{112}\text{Sn}$ and $^{124}\text{Sn}$ (ref.2). The isotopic purity of $^{112}\text{Sn}$ was 68%, which explains the appearance of further tin isotopes in the upper half of this figure.
Methods for Nuclear Charge Radii

- **Elastic Electron Scattering**
  yields the radial dependence of the nuclear charge distribution, \( \rho(r) = f(r) \)

- **Optical Laser Spectroscopy**
  measures changes of rms radii (isotope shifts), \( \delta(r^2)^{A,A'} \)

- **Muonic Atoms**
  sensitive to nuclear charge moments, specifically to the Barrett moment,
  \( <r^ke^{-\alpha r}> \) with \( 2 \leq k \leq 2.3, 0 \leq \alpha \leq 0.15 \)
  (if \( k=2, \alpha=0 \): Barrett moment \( \approx \) rms radius)

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**Combined Model-Independent Analysis**

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**Nuclear Ground State Charge Radii from Electromagnetic Interactions**


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**Sensibilities of the different methods**

- Optical \( (5p^2\, ^1S_0-5p\, ^1P_1) \) transition
- Electron \( (2p-1s) \) transition
- Muonic \( (2p-1s) \) transition
- Atomic radius \( R_{Sn} \)
- Nuclear radius \( R_{Sn} \)

---

**Note the logarithmic scale!**

---

**from L.A. Schaller**

Muon Lifetime and Free Decay Branch

**Muon Capture:**

\[
\frac{A}{Z}X_N + \mu^- \rightarrow \frac{A}{Z-1}X_{N+1} + \nu_\mu
\]

2.2 μsec for free muon

μ-e Decay Telescope Counter

- Ag
- \( \tau = 2.195 \mu s \)
Why Radioactive Muonic Atoms?

High Precision Measurements of Nuclear Charge Distribution

Provide absolute values to calibrate optical data which are relative along an isotopic chain. Attain elements that are complicated using optical methods.

⇒ MUONIC X-RAY SPECTROSCOPY of RADIOACTIVE ATOMS!

Deformation Properties

Quadrupole hyperfine splitting of muonic X-rays yield precise and reliable absolute quadrupole moment values. Measure the deformation properties of nuclei.

⇒ IMPORTANT ROLE in ESTABLISHING and REFINING NUCLEAR STRUCTURE MODELS!

Muon Capture


⇒ IMPORTANT ASTROPHYSICAL IMPLICATIONS!

Novel nuclear structure effects may exist far off the valley of stability?
Deformation Properties of Nuclei

Quadrupole hyperfine splitting of muonic X-rays yield precise and reliable absolute quadrupole moment values. Measure the deformation properties of nuclei.

$^{144}\text{Sm}$ (N=82, n-magic): stiff spherical nucleus which is very hard to excite.

$^{152}\text{Sm}$: Highly deformed nuclei; muonic X-rays show a 2p hyperfine structure (h.f.s.).

A Muonic X-Ray Study of the Charge Distribution of $^{144, 148, 150, 152, 154}\text{Sm}$

R.J. Powers et al., Nucl. Phys A 316 (1979) 295 (Saclay)
Muon Capture with RIB  (from T. Nilsson poster at RNB6)

- Investigate cross-sections for neutrino scattering through the analogue muon capture process:
  - Contain astrophysics processes like "neutrino post-processing".
  - Improve understanding of neutrino detector response.

- Populate highly excited states in very n-rich nuclei:

  T. Nilsson et al.,
  Nuclear Physics A 746 (2004) 513c–517c

  Possible experiment on $^{78}\text{Ni}$ (doubly-magic).
  Capture rates obtained by RPA calculations.
  Majority of the atoms populate excited states reaching beyond the neutron separation energy.

\[
A Z X_N + \mu^- \rightarrow A Z-1 X_{N+1} + \nu_\mu
\]
μA* Technical Feasibility

- How to produce such exotic μA* atoms?
  - Merging Beams Scenario (M. Lindroos),
  - Combined Cyclotron & Penning Trap (K. Jungmann),
  - Cold Hydrogen Film

RAMA WORKSHOP
- 23 February 2001 at CERN
- 22-26 May 2001 at ETC* (Trento)
Cold Hydrogen Film Method

We propose:

- **SOLID HYDROGEN FILM** used to stop both simultaneously \( \mu^- \) and \( A^* \) beams.
- \( \mu A^* \) ATOMS formed through **MUON TRANSFER REACTION** to higher Z nuclei,

\[
\mu H + A^*_z \rightarrow \mu A^*_z + H
\]

**TRANSFER RATE:**

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

**TRANSFER YIELD:**

\[
Y_X = \frac{\phi \lambda_z}{\lambda_0 + \phi \lambda_z} \quad (\phi = 1 \ \text{for LHD})
\]

**HIGH TRANSFER RATE & HIGH EFFICIENCY**

- e.g., \( Z = 50 \) and \( C_z = 1 \ \text{ppm} \ (5 \times 10^{16} \ \text{nuclei/cm}^3) \)
  
  \[ \lambda_z \approx 5 \times 10^5 \ \text{s}^{-1} \]

Muon disappearance rate: \( \lambda_0 \approx 4.55 \times 10^5 \ \text{s}^{-1} \)
Feasibility Study

- EXPERIMENTAL SETUP for X-ray spectroscopy of muonic atoms formed from implanted ions in solid hydrogen

- TEST EXPERIMENT at RIKEN-RAL Muon facility.

- Establish the feasibility of this method by using STABLE IONS.

- In the future, experiment using LONG-LIVED ISOTOPES.

<<New Surface Ionization type Ion Source>>
Advantages:

**Pulsed muon beams**
- Very good S/N ratio for delayed events.

**ISIS repetition rate is 50 Hz!**
- Higher is better for X-ray measurements.
RIKEN-RAL Muon Facility at ISIS

μA* Setup at Port 4

Muon Source: decay negative muon
Momentum (Δp/p): 27 MeV/c (10 %)
Intensity: 5000 s⁻¹
Beam size: Ø40-50 mm
Stopping rate in 1-mm D₂: 3000 s⁻¹ (60%)
μA* Setup at RIKEN-RAL Port 4

Test Experiment to Implant Stable Ions in Solid Hydrogen Films

μA* Setup

Cold Foil (100-μm Ag)

Germanium γ-Ray Detector

Muonic Silver X-rays from the Cold Foil

μA* Target System
Argon Ion Range in Solid Deuterium

**ION RANGES**

<table>
<thead>
<tr>
<th>Ion Range</th>
<th>Straggles</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>2560 Å</td>
</tr>
<tr>
<td></td>
<td>295 Å</td>
</tr>
</tbody>
</table>

Skewness: -0.0140, Kurtosis: 2.7506

**Calculation performed with SRIM-2000, by J.P. Biersack and J.F. Ziegler.**

**Non-Uniform Implantation in a Solid D₂ Layer**

**Implanted Argon Ions**

**X-Rays**
Target: 1-mm D$_2$(Ar-multi)

<table>
<thead>
<tr>
<th>Implantation:</th>
<th>20x</th>
<th>10x</th>
<th>5x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance:</td>
<td>50μm</td>
<td>100 μm</td>
<td>200 μm</td>
</tr>
</tbody>
</table>

Single D$_2$ Layer

distance between implantation

Total/Delayed γ-Ray Energy Spectra

Delayed events from 250 ns to 32 μs after the 2nd muon pulse.

~ 2 ppm
~ 1 ppm
~ 0.5 ppm
**dμ Atom Diffusion in Solid D$_2$**

**Mean-Free-Path in Solid D$_2$**

**Implantation**

Limitation on the minimum film thickness!

**Deceleration of Muonic Hydrogen Atoms in Solid Hydrogens**


**Cross-Sections for dμ Scattering in Solid D$_2$**

**dμ Mean-Free-Path in Solid D$_2$**
Comparison between $\text{H}_2$ and $\text{D}_2$

2-mm Pure $\text{H}_2$ (1 ppm Ar)

1-mm Pure $\text{D}_2$ (1 ppm Ar)

“Short” delayed events: from 75 ns to 250 ns
“Long” delayed events: from 250 ns to 32 $\mu$s after the muon pulse.
Towards Radioactive Muonic Atoms

Elements heavier than Bismuth:

There are no stable isotopes for good measurements of nuclear parameters like the nuclear charge radius.

**Calibration data** from muonic atoms measurement.

Example: Radium, Francium

Nuclear parameters like nuclear charge radius needed to exploit the full potential of the radium atom for atomic parity non-conservation studies.
New Surface Ionization Ion Source

In collaboration with: A. Taniguchi (Kyoto), S. Ichikawa (JAEA), H. Miyatake (KEK)

Good for alkali, alkaline-earth, and rare-earth elements!

At first stable isotopes: Ba, Sr, ...
Then maybe long-lived radioactive isotopes.
Surface Ionization Ion Source

New Surface Ion Source
Muonic Strontium X-rays

Target Summary

<table>
<thead>
<tr>
<th>Ion current on target</th>
<th>Sr-88</th>
<th>Sr-86</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 µA</td>
<td>140 nA</td>
<td></td>
</tr>
<tr>
<td>160 min.</td>
<td>900 min.</td>
<td></td>
</tr>
<tr>
<td>6.7x10^{16} (1.1 ppm)</td>
<td>4.7x10^{16} (0.8 ppm)</td>
<td></td>
</tr>
<tr>
<td>11,515 kspills (~63 hrs)</td>
<td>13,139 kspills (~72 hrs)</td>
<td></td>
</tr>
</tbody>
</table>

RIKEN-RAL Port 4
Nov.-Dec. 2006

Solid D₂ Target
Thickness: 1-mm
Implantation: 20x
Spacing: 50 µm
Muonic Strontium X-rays ($\mu^{87}\text{Sr}$)

Muonic Strontium X-rays ($\mu^{87}\text{Sr}$)

Target Summary

<table>
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<tr>
<th>Ion current on target</th>
<th>101 nA</th>
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<tr>
<td>Implantation time</td>
<td>1080 min.</td>
</tr>
<tr>
<td>Ion implanted in D$_2$</td>
<td>4.1x10$^{16}$ (0.7 ppm)</td>
</tr>
<tr>
<td>Data Taking</td>
<td>5,343 kspills (~30 hrs)</td>
</tr>
</tbody>
</table>

Solid D$_2$ Target

<table>
<thead>
<tr>
<th>Thickness</th>
<th>1-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implantation</td>
<td>20x</td>
</tr>
<tr>
<td>Spacing</td>
<td>50 µm</td>
</tr>
</tbody>
</table>
New Ge Detector & Energy Calibration

Muonic Copper 2p→1s X-rays

2p\textsubscript{3/2}→1s\textsubscript{1/2} 0.487 keV/ch

2p\textsubscript{1/2}→1s\textsubscript{1/2}

Muonic Silver 2p→1s X-rays

2p\textsubscript{3/2}→1s\textsubscript{1/2} 0.487 keV/ch

2p\textsubscript{1/2}→1s\textsubscript{1/2}

New ORTEC Detector
GMX Series HPGe
Crystal Type: GMX20
Relative Efficiency: 20%
Volume: 117 mm\textsuperscript{3}
Window: 0.50-mm Be
Resolution: 1.8 keV@1.33MeV

Nuclear Ground State Charge Radii from Electromagnetic Interactions
G. Fricke et al.,
### Muonic Strontium X-Ray Energies

**Nuclear Ground State Charge Radii from Electromagnetic Interactions**


TABLE IIIA. Muonic $2p \rightarrow 1s$ Transition Energies and Barrett Radii for $Z < 60$ and $Z > 77$

See page 194 for Explanation of Tables

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$^{86}\text{Sr}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2p_{3/2} \rightarrow 1s_{1/2}$</td>
<td>2323.151</td>
<td>2323.154</td>
<td>0.920</td>
<td>4.8503</td>
<td>4.231</td>
<td>0.0946</td>
<td>2.1678</td>
<td>-6.274</td>
<td>5.4183</td>
<td>(1;17)</td>
</tr>
<tr>
<td></td>
<td>2340.660</td>
<td>2340.658</td>
<td>0.929</td>
<td>1</td>
<td></td>
<td>0.0943</td>
<td>2.1671</td>
<td>-6.240</td>
<td>5.4184</td>
<td>(1;17)</td>
</tr>
<tr>
<td>$2p_{1/2} \rightarrow 1s_{1/2}$</td>
<td>2324.412</td>
<td>2324.396</td>
<td>0.724</td>
<td>4.8403</td>
<td>4.224</td>
<td>0.0947</td>
<td>2.1676</td>
<td>-6.272</td>
<td>5.4093</td>
<td>(4;14)</td>
</tr>
<tr>
<td></td>
<td>2342.009</td>
<td>2342.019</td>
<td>0.843</td>
<td>3</td>
<td></td>
<td>0.0943</td>
<td>2.1669</td>
<td>-6.234</td>
<td>5.4095</td>
<td>(3;16)</td>
</tr>
<tr>
<td>$^{87}\text{Sr}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2p_{3/2} \rightarrow 1s_{1/2}$</td>
<td>2324.673</td>
<td>2324.677</td>
<td>0.929</td>
<td>4.8399</td>
<td>4.224</td>
<td>0.0947</td>
<td>2.1676</td>
<td>-6.272</td>
<td>5.4090</td>
<td>(1;17)</td>
</tr>
<tr>
<td></td>
<td>2342.192</td>
<td>2342.190</td>
<td>0.937</td>
<td>1</td>
<td></td>
<td>0.0943</td>
<td>2.1669</td>
<td>-6.233</td>
<td>5.4092</td>
<td>(1;18)</td>
</tr>
<tr>
<td>$2p_{1/2} \rightarrow 1s_{1/2}$</td>
<td>2324.37(16)</td>
<td>2324.47(26)</td>
<td>0.724</td>
<td>4.8403</td>
<td>4.224</td>
<td>0.0947</td>
<td>2.1676</td>
<td>-6.272</td>
<td>5.4093</td>
<td>(4;14)</td>
</tr>
<tr>
<td></td>
<td>2342.04(13)</td>
<td>2342.04(25)</td>
<td>0.843</td>
<td>3</td>
<td></td>
<td>0.0943</td>
<td>2.1669</td>
<td>-6.234</td>
<td>5.4095</td>
<td>(3;16)</td>
</tr>
</tbody>
</table>


Muonic Barium X-rays

Target Summary

<table>
<thead>
<tr>
<th>Ion current on target</th>
<th>Ba-138</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion implantation time</td>
<td>1.0 μA</td>
</tr>
<tr>
<td>Ion implanted in D₂</td>
<td>220 min.</td>
</tr>
<tr>
<td>Data Taking</td>
<td>8.5x10¹⁶ (1.4 ppm)</td>
</tr>
<tr>
<td></td>
<td>10,140 kspills (≈56 hrs)</td>
</tr>
</tbody>
</table>

RIKEN-RAL Port 4
Feb. 2008

Solid D₂ Target
Thickness: 1-mm
Implantation: 20x
Spacing: 50 μm
Energy Calibration: μPb X-rays

RIKEN-RAL Port 4
Feb. 2008

μ$_{Nat}$Pb

$^{208}$Pb: 52.4%
$^{207}$Pb: 22.1%
$^{206}$Pb: 24.1%
$^{204}$Pb: 1.4%

Counts / 0.75 keV

Energy [keV]

5700 5750 5800 5850 5900 5950 6000
Muonic Samarium X-rays

RIKEN-RAL Port 4
Oct. 2007

Target Summary

<table>
<thead>
<tr>
<th></th>
<th>Sm-148</th>
<th>Sm-152</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion current on target</td>
<td>140 nA</td>
<td>340 nA</td>
</tr>
<tr>
<td>Implantation time</td>
<td>1080 min.</td>
<td>600 min.</td>
</tr>
<tr>
<td>Ion implanted in D₂</td>
<td>5.7x10¹⁶ (0.9 ppm)</td>
<td>7.7x10¹⁶ (1.3 ppm)</td>
</tr>
<tr>
<td>Data Taking</td>
<td>4,931 kspills (~27 hrs)</td>
<td>12,500 kspills (~69 hrs)</td>
</tr>
</tbody>
</table>

Solid D₂ Target
Thickness:  1-mm
Implantation: 20x
Spacing: 50 μm
Long-lived RI: Possible Candidates

A surface ion source can ionize Alkali, Alkaline-earth and Rare-earth elements.

- **To prove the feasibility of using RI nuclei:**
  - $^{137}$Cs ($T_{1/2}=30.07 \text{y}$), $^{133}$Ba ($T_{1/2}=10.35 \text{y}$), $^{22}$Na ($T_{1/2}=2.67 \text{y}$), $^{134}$Cs ($T_{1/2}=2.06 \text{y}$).

- **Studies following experiments with stable Barium:**
  - $^{133}$Ba ($T_{1/2}=10.35 \text{y}$).

- **Studies following experiments with stable Strontium:**
  - $^{85}$Sr ($T_{1/2}=64 \text{d}$), $^{89}$Sr ($T_{1/2}=50.5 \text{d}$).

- **Rare Earth Region:**
  - Transitional region, nuclei shapes gradually changing from spherical to highly deformed.
  - Measurements of the muonic X-rays of these nuclei would be very effective.
  - Of interest: $^{139}$Ce, $^{144}$Ce, $^{147}$Pm (commercial RI), and $^{151}$Sm, $^{146}$Gd, $^{148}$Gd.

- **Radium:** No stable isotopes!
  - Nuclear parameters like nuclear charge radius urgently needed to exploit the full potential of the radium atom for atomic parity non-conservation studies.
**RI Selection for First Experiment?**

What unique interesting physics can be extracted from which unstable nuclei!

**Physics**
- Safe handling of RI in the ion source and the system.
- Removal of RI after the measurements (cold finger, trap, ...).
- Reduce $\mu^{-}$/RI interaction volume (beam size)! ➔ Fewer nuclei needed!
- X-Ray detection efficiency and dead-time!
  ➔ *More detectors* and reduction of $\mu^{-}$ stopping in surrounding materials.

**High Cost & Human Resources**
- Activity
- Half-Life
- Decay mode
- Energy

**Practicability**

⇒ Need submission of a detailed proposal to RIKEN-RAL and RAL!
Short-lived RI: Practical Considerations

- **SIMULTANEOUS** implantation of unstable nuclei and measurement with $\mu^-$. (at present, only TRIUMF has $\mu^-$ and RI beams, but cw)

- Beam **ENERGY** and **SPREAD** determine implantation **DEPTH** and **THICKNESS**.
  
  Ion range in solid hydrogen: 
  
  \[
  \begin{align*}
  1 \text{ mm} & \Rightarrow \sim 10 \text{ MeV/u} \\
  5 \mu\text{m} & \Rightarrow \sim 30 \text{ keV/u}
  \end{align*}
  \]

- **CONTINUOUS SPUTTERING** of solid hydrogen films.
  
  If proven important, simultaneous hydrogen deposition & ion implantation.

- RI beam **COMPLETELY** stopped in the target!
  
  - **ACCUMULATION** of **DAUGHTER NUCLEI**
    
    **LIMITATION** (static target): $T_{1/2} > 10$ min.

  - **HIGH RADIATION BACKGROUND**
    
    - Pulsed muon beam
    
    - Active BG suppression, detector segmentation, ...
Using Solid Hydrogen Films

◆ Advantages
  ➤ **WINDOWLESS TARGET** in vacuum, with a **WELL-DEFINED** interaction region.
  ➤ **EASY TARGET EVAPORATION** and **REPLACEMENT**.
  ➤ **RI BEAM**: Impurities, Emittance, Energy spread, ... ➤ not critical!
  ➤ Maybe the only method for short-lived RI ➤ no beam cooling needed, but ...

◆ Limitations
  ➤ **ACCUMULATION** of **DAUGHTER NUCLEI** ➤ Dynamic target
    (sputtering against daughter nuclei accumulation)

◆ Possible Improvements
  ➤ Magnetic confinement field ➤ reduce decay e\(^-\) related BG.
  ➤ **Pulsed muon beam** ➤ good S/N for delayed events.
  ➤ **Muon beam intensity** ➤ Super-Omega beamline (J-PARC): \(10^{6-7} \mu^-/s\) ~\(10^3\times\)
    (expected cloud \(\mu^-\) intensity at 27MeV/c at 1 MW)
  ➤ **Low energy \(\mu^-\)**

    PSI cyclotron trap (few ten keV)
    ➤ smaller interaction volume ➤ fewer RI! ~\(10^3\times\)
    \(\phi5cm\times1mm \rightarrow \phi5mm\times100\mu m: 1000\ times\ smaller\)
Muon Beam Requirements

Optimum Muon Beam Requirements for μA* Experiment:
(at a new High Intensity Proton Accelerator)

♦ Muon Stopping in Solid Deuterium

- Momentum: ~ 27 MeV/c
- Width (Δp/p): ≤ 5%
- Beam intensity: > 1 x 10^7–8 s⁻¹
- Beam size: ≤ 1 cm²

♦ X-Ray and γ-Ray Detection System

- Muon beam: pulsed
- Pulse structure: single (double)
- Pulse width: ≤ 20–50 ns
- Repetition rate: ~1 kHz

Muonic Atoms (in brief)

Transfer Rate:

\[ Y_x = \frac{\phi \lambda_z}{\lambda_0 + \phi \lambda_z} \]

We need

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

(approximation)

\[ N_Z N_\mu \approx \frac{10^{17}}{Z} \]

(\(\lambda_z \ll \lambda_0\))

to produce 1 μA* per cm².

NZ, Nμ: Z and μ⁻ in 0.5-mm D₂
Muon Science Facility in J-PARC

Muon Area

Neutron Scattering Area

Experimental Hall No.1

Materials and Life Science Facility

Muon Target

Neutron Source

Experimental Hall No.2
J-PARC “MUSE” Facility (today)

- J-PARC “MUSE” Facility (today)
- JAEA Project
- 3GeV Proton
- Muon Target
- Decay Muon Channel
FUTURE DREAMS at MUSE

RI Muonic Atoms

~5x10^7 \(\mu^-\)

~5x10^8 \(\mu^+\)

30 MeV/c \(\mu^+/\mu^-\)

Ultra-Slow Muon

3GeV Proton

Super-Omega Muon Channel

Muon Target
Muonic Radioactive Atoms at J-PARC?

Radioactive Beam at MLF?

KUR-ISOL

<Specification>
Target: $^{235}\text{U}(50\text{mg})$
  enrichment-93%
Transportation:
  He-N$_2$ mixed gas-jet
  PbI$_2$ aerosol
  O$_2$ for oxidation method
Skimmer:
  2-stage skimmer system
Ion source:
  Surface ionization type
Available elements:
  Alkali, Alkali-earth, Rare-earth
  $T_{1/2} > \sim 1\text{s}$
Beam intensity: $10^8$ /s @$^{140}\text{Cs}$

from A. Taniguchi (KURRI)
**Summary**

- **COMMISSIONING OF THE NEW ION SOURCE SUCCESSFUL !!!**
  - Muonic **Strontium** transfer X-rays clearly observed with trace isotopes.
  - **Barium** and **Samarium** also measured.
  - Isotope shift consistent with previous experiments performed using enriched isotopes in very large quantities.

- **FUTURE PLANS**
  - First experiment with long-lived radioactive nuclei under consideration. Improvements needed to handle RI safely, ...

- **MUONIC RADIOACTIVE ATOMS at J-PARC**
  - This project would bring great opportunities to explore new possibilities of muon science with radioactive isotopes.