Commissioning of new DC muon beam line, MuSIC-RCNP at Osaka University

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Outline

1. MuSIC beamline
2. Beam commissioning (yield and spin measurement)
3. MuSIC status
4. Summary
MuSIC beamline at RCNP, Osaka University

MuSIC (Muon Science Innovative muon beam Channel) beamline?

- pion capture solenoid + pion collection solenoid + conventional triplet-Q & bends beamline
- world’s most efficient DC muon beam source ( ~ $10^3$ )

Present status
- $10^8$ muons are obtained at the curved solenoid end
- construction of whole beamline is almost completed
- beam commissioning with 20nA proton beam
- prepare experimental port and apparatus
MuSIC Beamline
MuSIC - RCNP by Dai Tomono@PSI2016 19/Oct/2016

Research Center for Nuclear Physics (RCNP), Osaka University

- MuSIC @ RCNP, Osaka Univ.
- Ring Cyclotron ~392MeV (variable)
  - 1uA proton, (0.4kW)
- MuSIC M1 beamline
- MUSE @ J-PARC
  - Pulsed muon source

MuSIC @ RCNP, Osaka Univ.
- DC muon source
- only 100 MeV above pion production threshold (〜2mπ)
- muon source with low proton power (1uA 0.4kW, 5 uA in future)
Experimental port

Triplet-Q

Spin rotator & DC separator

µ/e/π

μon Beam Line @RCNP

MuSIC-M1 Beam Line

ST1 ST2

Triplet-Q

BM1

BM2

+/− 400 kV / 15cm gap
L = 1.8 m

• muon / electron separation
• rotate spin with 80 degree for surface muon
• Now in commissioning

Pion capture solenoid

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Comparison of pion production methods

Conventional muon beamline

- Thin target (~20mmt)
- Small solid angle
- Separate pion and muon momentum selection (obtain highly polarized muon beam)

Ex. J-Parc MUSE
1000 kW proton beam
20mmt graphite target

Proton beam loss ~ 5%

to neutron facility

MuSIC beamline

- Thick target (200mmt)
- Large solid angle, good collection efficiency
- No muon spin selection (no selection of pion/muon momentum)

Ex. MuSIC
0.4 kW proton beam
200 mmt graphite target

Transport solenoid

Capture solenoid

Collect $\pi / \mu$
with 3.5T solenoidal field

to dump
Pion capture solenoid & Pion transport solenoid

- Pion capture solenoid (3.5T)
  - pion production target inside (1.5 interaction length)
  - pion collection with large solid angles
- Pion transport solenoid (2.0T)
  - Curved solenoid to capture and transport pion/muon
  - Momentum selection with dipole collection field

Graphite target

Beam Profile by G4beamline simulation

Surface muon
Inflight-decay muon

Pion Capture Solenoid

exit of the 36° curved solenoid
~ 3x10^8 positive muons
~ 1x10^8 negative muons

~ 10^3 pion production efficiency
Beamline Commissioning
Experimental port (at the beamline end)

Now commissioning is in progress
**Muon yield measurement**

**Inflight-decay muons (μ±)**

- Negative muon
  - ~$1 \times 10^5 \mu^-/s$ @60MeV/c with 1μA proton beam

- Positive muon
  - ~$7 \times 10^5 \mu^+/s$ @60MeV/c with 1μA proton beam

**Surface muon (μ⁺)**

- Succeed in observing surface muons (~28 MeV/c)
  - ~$3 \times 10^4 \text{ surface } \mu^+/s$ @ 28 MeV/c with 1 mA proton beam

**Inflight-decay muons**

**Note:**
- Muon yield (vertical axis) is scaled for 1μA proton beam operation.
- 20nA (2016 run) -> 1μA (2017 run)

**Beam counter (plastic scintillator)**
- (10cmx 10cm)

**Succeed in observing surface muons (~28 MeV/c)**

- Target position tuned for surface muon

**TOF Setup**
- Beamline ~ 20m
- $\Delta t = t_{\text{counter}} - t_{RF}$
Beam profile measurement

Beam profile at the beamline end (beam focusing position) \( p = 28 \text{ MeV/c} \)

- slit fully opened \( 80 \text{ mm x 80 mm} \)
- slit \( \pm 30\text{mm} \) opened \( 50 \text{ mm x 50 mm} \)

Profile monitor

- 1mm\( \phi \) thin scintillation fiber + MPPC readout
- Separate e / \( \mu \) by their energy deposit difference
- 8mm~2mm interval (dense around the center)

• simulation (turtle)
• measured
Spin measurement

- Muon beam at the solenoid end (G4 beamline output)
- Separate forward and backward decay muons to investigate beam polarization
- Calculate the expected polarization geometrically and compare the experimental results

Setup

\[
A_{asy}(t) \equiv \frac{N_u(t) - \alpha N_d(t)}{N_u(t) + \alpha N_d(t)}
\]

TF = 40 Gauss

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Spin precession results

Typical observed asymmetry spectra

$\propto A \cos(\gamma_{\mu} Bt + \delta_0)$  $\gamma_{\mu}$ : Lamor frequency

$p = 28$ MeV/c

$p = 60$ MeV/c

Measured polarization

<table>
<thead>
<tr>
<th>Momentum [MeV/c]</th>
<th>Polarization (G4 simulation)</th>
<th>Polarization (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 (surface $\mu$)</td>
<td>48</td>
<td>57</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>50</td>
<td>45</td>
<td>59</td>
</tr>
<tr>
<td>60</td>
<td>55</td>
<td>57</td>
</tr>
</tbody>
</table>

Positive muon momentum

Preliminary (simulation with G4 beamline)

Cancel

Polarization (spin←)
Muon Science at MuSIC

● **Stage 0**
  — proof-of-principle for muon capture and transport solenoid (also for COMET experiment)
  — high efficiency (~ $10^3$) muon production was achieved (measured at the capture solenoid end)

● **Stage 1(2012-16)**
  — Conventional triplet-Q and bend magnets were installed successively to the collection solenoid.
  — Beam commissioning is now in progress
  — Physics programs start
    • Muonic X-ray analysis and non-destructive analysis
      • Chemistry on muonic and pionic atoms
      • non-destructive element analysis (ex, from asteroid explorer, Hayabusa-II)
    • Probes for condensed matter physics (DC-µSR), Feasibility tests are now in progress

● **Next stage and future**
  — Muonic X-ray analysis
  — DC-µSR study for users
  — Nuclear physics
    • Nuclear muon capture for 0νββ study (for nuclear matrix element determination, proposed)
    • Gamma-ray measurement from nuclear capture with heavy nuclei
    • Nuclear physics combined with the high resolution / acceptance spectrometer in RCNP (prospects)
  — Improvement of the beamline
  — new physics programs

We are now in this stage (2016)
First experiment ($\mu^-$): muonic X-ray & gamma-ray measurement

First MuSIC beamline experiment for users (E411)

9th – 11th Nov., 2015

Fundamental study for non-destructive elemental analysis with muon for analyzing planetary materials brought by ”Hayabusa2”

From: K. Terada (Osaka U.) MXG16 slide
Demonstration of fast spin precession with DC muon beam

- muon spin precession spectra

![Setup diagram](image)

TF = 40, 580 Gauss

Asymmetry, $A(t) = \frac{N_u(t) - \alpha N_d(t)}{N_u(t) + \alpha N_d(t)}$

- **Spin asymmetry**

**Setup**

- Trigger counter (0.5mmt)
- Upstream counters (4mmt) x2
- Test sample (Ag plate)
- Downstream counters (4mmt) x2

Time resolution ~ 1ns

T~80 ns (typical magnetic order)

$B = 40G$ (slow precession)

$B = 580G$ fast precession was observed

- possibility of DC μSR (proof for high time resolution precession)
Summary

- New innovative DC muon source with solenoid system has been developed at RCNP, Osaka University
  - good pion production efficiency of $\sim 10^3$
  - pion capture & transport solenoid + triplet-Q and bend magnets beamline

- Beamline commissioning is now in progress
  - 28 MeV/c – 110 MeV/c muon beam
  - inflight-decay $\mu^+ 10^5-10^6 \mu^- 10^5-10^6$ surface $\mu^+ 3 \times 10^4$ [count/sec/1uA proton beam]
  - beam size ($<80\text{mm}\phi$), momentum bite ($<10\%$) and polarization ($\sim 60\%$) were measured
  - start feasibility study
  - Improvement of muon beam (especially, solenoid and triplet-Q connection)

- Physics program in MuSIC
  - nuclear physics (muon capture)
  - radio-chemistry and non-destructive evaluation of elements
  - positive muon for $\mu$SR measurement (feasibility study to practical physics program)
  - MuSIC beamline will be a highly intense DC muon source. has possibility to perform DC muon source