Development of very slow negative muon beam in J-PARC
Introduction: J-PARC MLF

Utilize powerful pulsed proton beam from J-PARC

Extract secondary muon beam

I will focus on one of the beam development,
Slow negative muon beam
Slow negative muon in D2 area

J-PARC MLF employs warm bore no heat shielding window along the beam line

Slow muon can be extracted

Muonic atom characteristic X-ray

Ge detector

※ Efficiency limited by solid angle of the detector

3.5 MeV/c in 2016

number of muon scaled to 1MW operation [muon/s]

Muon momentum [MeV/c]
Update in slow negative muon in J-PARC

Direct muon detection with MCP
Getting rid of loss of efficiency due to solid angle

※ Quantum efficiency for slow muon and its energy dependence are not well known
Update in slow negative muon in J-PARC

Automated beam tuning program with MCP

(magnet current) vs (number of muons)

Direct measurement of incoming muon enables efficient beam tuning.
Primary electron elimination by TOF

Muons

Prompt electrons

600ns

MPO placed at beam focus position
Update in slow negative muon in J-PARC

2.6 MeV/c muon extracted

Issues
- Quantum efficiency for slow muon
- Reproducibility?
  - Stability of power supply in low current? Hysteresis?

--> Continue to work to solve them
Future plan

Sophisticated procedure to make very slow negative muon
How can we make ultra slow negative muon?

① Stop on a material
② Accelerate
If it is possible, it’s ok but …

Difficult issues for \( \mu^- \):
1. Muons stop deep inside
2. Muon is 200 times heavier than electron
   Go deeply inside nuclear

Then,
We plan to utilize

• Ramsauer-Townsend effect
• Muon catalyzed fusion
Ramsauer-Townsend effect

Wave nature of \( \sim 10 \text{eV} \) muonic Deuterium enables it to penetrate H2 w/o scattering

[C. Chiccoli et al., Muon Catal. Fusion 7(1992) 87]
[A. Adamczak et al., Atomic Data and Nuclear Data Tables 62 (1996) 255]
Stopping $\mu^-$ on solid H/D, Muon transfer:
$$p\mu + d \rightarrow d\mu (\sim 45\text{eV}) + p$$
then some $d\mu$ moves to the surface

According to [Forster et al., Hyp. Int. 65 (1990) 1007-1014],
0.1% D concentration is optimum

Mean free path $\sim 0.5\text{mm}$

$$\frac{(# \text{ of transportation to surface})}{(# \text{ of Incident muon})} \sim 10^{-2} \quad [\text{Forster 1990, Marshall 2001}]$$

Next: drag $\mu^-$ away from D
Muon-Catalyzed Fusion

$\mu$-CF (muon-Catalyzed Fusion)

$\mu$- enables D and T come close enough to make D-T reaction

$^4$He and n are emitted by $\mu$CF
Slow $\mu^-$ (~10keV) is left behind

$\mu$- energy after $\mu$CF (calculation)

$M\mu \sim 200 \times Me$
Orbital radius $\sim 1/200$
Make thin T layer on solid H/D mixture as muon stopping target, and slow muon in vacuum is obtained.

$\mu$CF efficiency ~ a few 10%
Collection of $\mu$ from $\mu$CF

- $\mu$- beam ($\sim50\text{MeV/c}$)
- Heat shielding window
- $V=-30\text{kV}$
- Half sphere electrode $V=-100\text{kV}$
- Solid H/D layer $\sim1\text{mm}$
- $T_{\text{surface layer}} \sim1\mu\text{m}$
- Total efficiency is expected to be $<10^{-3}$
Frictional cooling

- Slowing down with thin film
- Acceleration with $\Delta V$ to cool down muon

10 films and $E = \text{a few keV}$, $\Delta E \sim 100\text{eV}$ is expected
Scanning muon microscope

1) Injection of $\mu^-$ from accelerator ~50 MeV
2) Stop $\mu^-$ on Solid Hydrogen and Deuterium (thickness = 1mm)
3) Transportation to the surface by Ramsauer-Townsend effect
4) $\mu$CF D-T reaction
   $\mu^-$ is left aside with ~10 keV
5) Collect $\mu^-$ by electrical field
6) Extracting muon distribute around a few keV
7) Frictional cooling
   $\Delta E \sim 100$ eV
8) Extraction to beam optics
   $E \sim 16$ keV
9) Correct chromatic aberration by Achromatic lens
10) Focus ~ 10um, Scan the sample
    -> Scanning muon microscope
μ⁻ as a tool for non destructive inspection

\[ M\mu \sim 200 \times Me \]

\[ \rightarrow \text{Characteristic X-ray has x200 energy,} \]
\[ \text{Transparent to thick sample material} \]

Electron injection can identify atoms heavier than Na,
μ⁻ can identify Li

Efficiency of characteristic x-ray
Electron injection case < 10⁻⁴
Negative muon injection ~ 100%
Current target is non-destructive inspection of nuclear distribution in a sample material but,

Your ideas for application to particle physics are welcome
Summary

• Updated lowest momentum of $\mu$- delivery from 3.5 MeV/c to 2.6 MeV/c by tuning magnets using MCP
  
  • Study for stabilization of the beam for low momentum will be done

• Brand new way to make very slow negative muon beam is planned
  
  • Stop muon on solid H/D
  
  • Transport muon to surface by Ramsauer-Townsend effect of $d\mu$
  
  • $\mu$CF of D-T reaction and ~10keV bare $\mu$- in vacuum obtained
  
  • Give frictional cooling

• Total efficiency $< 10^{-3}$ expected