Muonium Production in Porous Silica Thin Film

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Muonium

INTRODUCTION
Muonium \textbf{(Mu)}

- Hydrogen-like atom consisting of $\mu^+$ and $e^-$. 
- 1/9 of Hydrogen mass, lifetime $= 2.2 \, \mu s$.
- Main decay channel: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Pure leptonic system governed by QED.
Motivation

Development of new sources for the next generation Mu experiments, with the following requirements:

- High vacuum yield  ← This talk
- Small emission velocities (down to cryogenic temperature)
- Long term stability

An improved Mu source leads to:

- Better result for lepton flavor violation experiment
- More precise test of bound state QED (proton radius puzzle)
- More precise extraction of fundamental constants \((m_\mu, \alpha)\)
Mu and Positronium (Ps) have similar formation mechanisms and yields in vacuum:

<table>
<thead>
<tr>
<th>Source</th>
<th>Ps ((e^+e^-))</th>
<th>Mu ((\mu^+e^-))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Powder</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Silica Porous Material</td>
<td>30-40%</td>
<td>30-40% (?)</td>
</tr>
</tbody>
</table>

[P.Crivelli et al. Phys Rev A81, 052703 (2010)]

Based on this analogy, we thought that Silica Porous material could produce Mu more efficiently. (preselected using the ETHZ slow positron beam)

ETHZ Slow Positron Beam (Will be moved from CERN to ETHZ)
Muonium Production

- $\mu^+$ with 2-30 keV of energy is implanted into the sample.
- $\mu^+$ slows down and stops in the porous bulk material.
- Mu is formed in the porous bulk material.
- Mu drifts to the pore’s wall and is ejected into the pore with energy of a few eV.
- Mu diffuses and is thermalized in the pores.
- Mu can reach the surface and exit into vacuum.

Fraction of Mu that comes out per implanted $\mu^+$ = $F_{\text{vac}}^{\text{Mu}}$
μE4 beam and LEμSR spectrometer

EXPERIMENTAL SETUP
- Experiment was done at Paul Scherrer Institute (PSI) using µE4 beam.
- It is the low energy muon beam (0-30 keV) with the highest intensity in the world. (3000 s⁻¹ on the sample)
LEμSR spectrometer

Surface muon beam
( $E = 4\text{MeV}$ )

Low energy muon beam
0-30 keV

Muon momentum
Muon spin

Positron Counters
Forward (4 parts)
Backward (4 parts)

UHV $\sim 10^{-10}$ mbar

Trigger detector (START)

MCP1 detector
Mirror
L1 Mod.
L2
L3
Helmholtz Coils
Sample or MCP2 detector
Positron counters (STOP)
Cryostat
Backward Det.
Forward Det.

LEμSR spectrometer

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\textbf{\textit{\textmu SR Technique}}

PRINCIPLES OF THE EXPERIMENT
Monitor the evolution of \( \mu \) spin after implantation, under external magnetic field. (Larmor precession frequency, \( \omega = \gamma B \), \( \gamma \) is gyromagnetic ratio, \( \gamma_{\mu} = 13.6 \text{ kHz/G} \) and \( \gamma_{\text{Mu}} = 1.40 \text{ MHz/G} \) \( \Rightarrow \omega_{\text{Mu}} = 103 \omega_{\mu} \) for same B)

Decay positron emitted preferentially in the direction of muon spin, due to the parity violation of weak interaction.
Positron Shielding Technique (PST)

- μ/Mu that decays inside the Porous Silica will have its positron shielded by the material behind the sample.
- In case of zero emission into vacuum, exponential time distributions are expected for both detectors.
- In case of emission into vacuum, there is a deviation from exponential distribution for forward detector. (Position dependent of detection efficiency)

\[ N(t) \]

\[ t \]

\[ \mu^+ \]

\[ e^+ \]

\[ e^+ \]

\[ N(t) \]

\[ t \]


cryostat

29.08.2011

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Summary of the techniques

From $\mu$SR Technique, we can extract

- the residual fraction of $\mu$ that do not convert to Mu.
- the fraction of Mu which do not depolarize.
- the depolarization rates of $\mu$ and Mu in the samples.

From Positron Shielding Technique, we can extract

- the fraction of Mu emitted into vacuum.

We can then cross check the consistency of the data.
μSR Spectra

ANALYSIS
\[ N(t) = N_0 e^{-t/\tau} \{1 + A_\mu(t) + A_{Mu}(t)\} \]

\[ A_\mu(t) = A_\mu e^{-\lambda_\mu t} \cos(\omega_\mu t - \phi_\mu) \]

\[ A_{Mu}(t) = A_{Mu} e^{-\lambda_{Mu} t} \cos(\omega_{Mu} t - \phi_{Mu}) \]

\[ A: \text{Amplitude} \]
\[ \tau: \text{Lifetime} \]
\[ \lambda: \text{Relaxation Rate} \]
\[ \omega: \text{Precession Frequency} \]
\[ \phi: \text{Phase} \]
Fraction of $\mu$ and Mu

Fraction of $\mu$ and Mu ($F_{\mu^+}, F_{\text{Mu}}$) are given by the fitted amplitudes. The total amplitude, $A_{\text{tot}} = 0.27$ was measured from the reference sample of Silica Suprasil. $A_{\text{tot}} = A_{\mu^+} + 2A_{\text{Mu}}$ (singlet and $M_s=0$ triplet do not contribute)

$$F_{\mu^+} = \frac{A_{\mu^+}}{A_{\text{tot}}}$$

$$F_{\text{Mu}} = \frac{2A_{\text{Mu}}}{A_{\text{tot}}}$$

Mu formation fraction $= 1 - F_{\mu^+} = 45\%$ and temperature independent.

(Notice that $F_{\mu^+} + F_{\text{Mu}} \neq 1$! This is due to the fast depolarization of Mu due to spin exchange collisions.)
Forward-Backward Asymmetry ($A_{FB}$)

![Diagram of Forward-Backward Asymmetry](image)

\[ A_{FB}(t) = \frac{F(t) - B(t)}{F(t) + B(t)} \]

In case of 0% Mu emission, 
$A_{FB}(t) = \text{constant}$

For non-zero Mu emission, 
$A_{FB}(t) \neq \text{constant}$

- With the help of GEANT4, we simulated the cases of 0% and 100% Mu vacuum emission at different temperatures. 0% is corresponding to Silica Suprasil sample where no emission into vacuum is expected.

- By introducing a free parameter which is the fraction of Mu emitted into vacuum, we fitted the data according to the temperatures.

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\[ A_{FB}(t) \]

- 100% emission
- $F_{\text{vac}}$ emission (linear combination of 0% and 100%)
- 0% emission (Silica Suprasil)
Extraction of Mu Vacuum Emission

Results from Positron Shielding Technique. No systematic errors are included at the moment. Mu vacuum emission is proportional to the temperature.

+ Data (T = 250 K)
-- Simulation (T = 250 K)

The shapes are well reproduced by the simulations.
Preliminary Results

Comparison of results from $\mu$SR and positron shielding techniques.

Notice that values from PST are always higher compared to $\mu$SR Technique. This is due to the emission of depolarized Mu into vacuum that could not be extracted using $\mu$SR technique. Also, higher implantation energy leads to higher fraction of depolarized Mu.
Conclusions and Outlook

- Mu formation in Silica Porous Material is 45% per implanted $\mu^+$, independent on temperature.
- Mu emission in vacuum is as high as 25% per implanted $\mu^+$, at 250 K. (a factor of 2 better than other sources.)
- First measurement of Mu emission in vacuum at low temperature. (10% even at 100 K)
- Temperature dependent of Mu vacuum emission is under investigation $\Rightarrow$ study of diffusion.
Backup

Transport system

- Entrance scintillator (S1)
- Moderator (Mod)
- Einzel lens (L1, LN2 cooled)
- Electrostatic mirror
- Einzel lens (L2), Multi Channel Plate detector (MCP1)
- Trigger detector (Start)
- Einzel lens (L3, LN2 cooled)
- Ring anode (RA)
- Sample, Multi Channel Plate detector (MCP2)
- Positron counters (Stop)
If both spectra are exponential decay, i.e. in case of 0% Mu emission,
\[ F(t) = F_0 \exp\left(-\frac{t}{\tau_\mu}\right), \quad B(t) = B_0 \exp\left(-\frac{t}{\tau_\mu}\right) \]
\[ A_{FB} = \frac{F_0 - B_0}{F_0 + B_0} = \text{constant} \]
For non-zero Mu emission,
\[ F(t) = F_0 \exp\left(-\frac{t}{\tau_\mu}\right) + e(t), \]
\[ A_{FB} \rightarrow A_{FB}(t) \neq \text{constant} \]