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Muonium Emission into Vacuum from Mesoporous Thin Films at Cryogenic Temperatures

[Phys. Rev. Lett. 108, 143401 (2012)]
This work is supported by the SNSF grant #200021_129600.

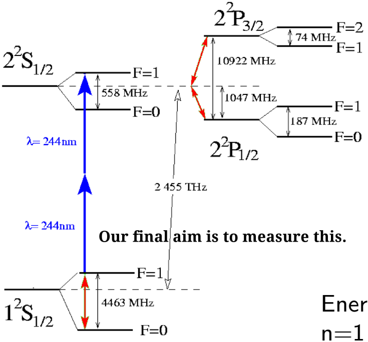
Kim Siang Khaw[1], A. Antognini[1], P. Crivelli[1], T. Prokscha[2], K. Kirch[1,2] *et al.*

[1] **Institute for Particle Physics, ETH Zurich, Switzerland**
[2] Paul Scherrer Institute, Villigen, Switzerland

Zurich PhD Seminar 2012
University of Zurich, Irchel
28th August 2012

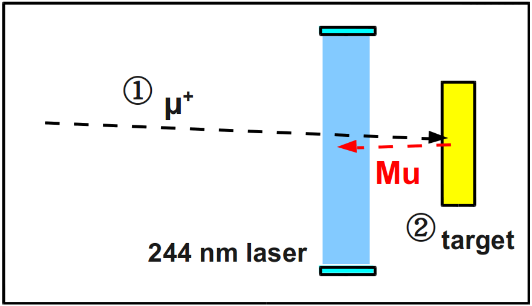
What is muonium (Mu)?

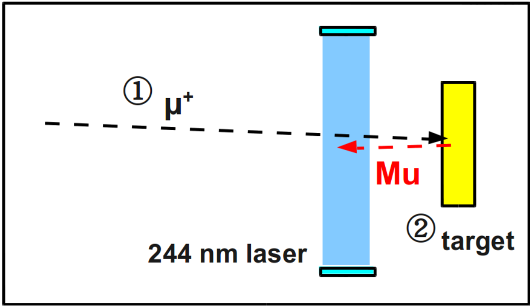
- Purely leptonic atom consisting of μ^+ and e^-.
- An ideal object for testing bound state QED.
- Muonium's hyperfine splitting (HFS) (12 ppb)[PRL 82, 711] and 1S-2S transition frequency (4 ppb)[PRL 84 1136] provided the best determination of $\frac{m_\mu}{m_e}$ (0.8 ppb), $\vec{\mu}_\mu$ (120 ppb) and $\frac{q_\mu}{q_e}$ (2.1 ppb).
- Can probe new physics such as lepton flavor violation via Mu-$\overline{\mathrm{Mu}}$ oscillation.



Our final aim is to measure this.

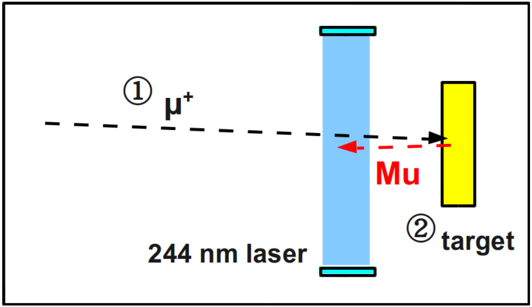
Energy levels of Mu atom for n=1 and n=2.


① μ^+
Mu
② target
244 nm laser



What is needed for the next generation Mu experiments?

The quality of the Mu source was a limiting factor (low vacuum emission, high velocity). Therefore, for next generation experiments, we must



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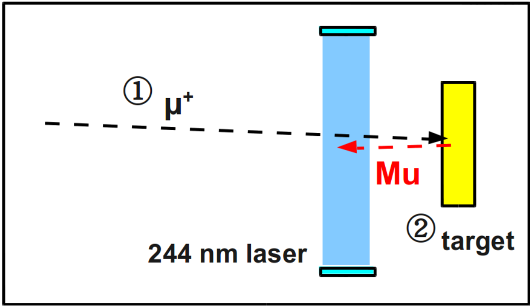
- **improve the μ^+ beam (smaller phase space, low energy and high intensity).** [Longitudinal spatial compression of a slow muon beam (analysis on going)]



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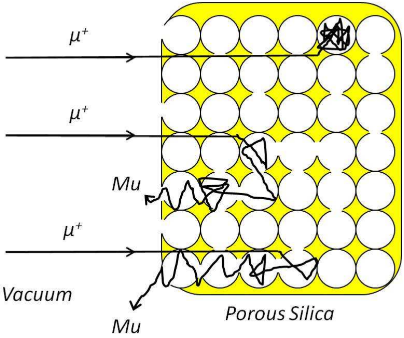
- **improve the μ^+ beam (smaller phase space, low energy and high intensity).** [Longitudinal spatial compression of a slow muon beam (analysis on going)]
- **improve the $\mu^+ \rightarrow \mathrm{Mu}$ conversion rate (using new material).** [This talk]

Motivation of using mesoporous silica thin film

- 40% of Ps (e^+e^-) vacuum yield has been measured [PRA **81**, 052703].
- Both have similar formation mechanism → it should work for Mu as well.

How do we produce Mu in vacuum?

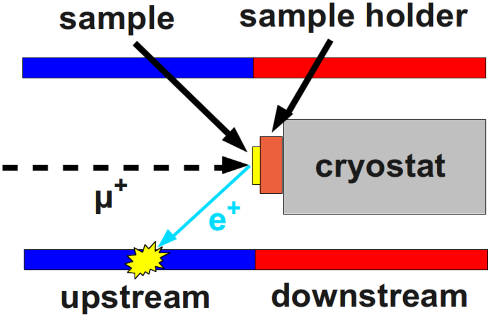
- μ^+ is implanted in the porous silica film (implantation depth = 75 nm for an implantation energy of 5 keV).
- μ^+ rapidly thermalize in the bulk material.
- A fraction of them forms Mu and diffuse until they are ejected in the pores with energies of a few eV.
- Mu diffuses in the interconnected pores and lose its energy via collisions with the pore walls.
- If Mu reaches the film surface before decaying, it is emitted into vacuum.



Porous film of 1 μm thickness, a pore size of (5.0±0.5) nm, and a density of 1.1 g/cm^3

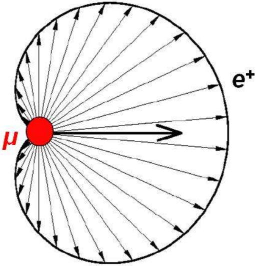
Muon Beam and Positron Detectors

- We have used the low energy positive muon beam (LEM) [T. Prokscha, NIM A 595, 317 (2008)] at PSI. (3000 s^{-1} μ^+ on the sample, 1-30 keV tunable energy)
- It is a dedicated facility for μSR (muon spin rotation) measurements.
- Positron from muon decay is detected by segmented plastic scintillators (Upstream and downstream).
- Each of them is additionally segmented in top, bottom, left and right detectors. (8 in total)

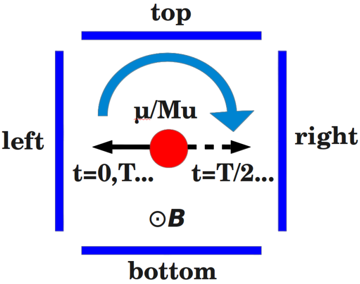


Muon Spin Rotation Technique (μSR)

- Monitor the evolution of μ spin after implantation, under external magnetic field.
- Larmor precession frequency $\omega_{\mathrm{Mu}} = 103 \cdot \omega_{\mu^+}$. (Because gyromagnetic ratio of Mu in the triplet state ($F{=}1, M{=}\pm1$) is $\gamma_{\mathrm{Mu}} = 103 \cdot \gamma_{\mu^+}$).
- It is then possible to distinguish if an implanted μ^+ remains unbound or forms Mu.
- Decay positron emitted preferentially in the direction of μ^+ spin, due to the parity violation of weak interaction.



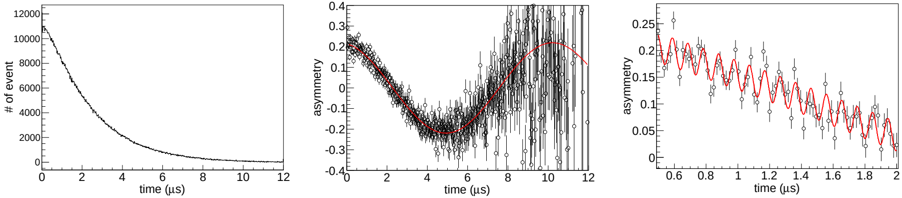
(a) Angular distribution of decay positron



(b) Larmor precession

μSR Method

- Time spectrum of each individual segment = exponential muon decay + Larmor precession of μ^+ and Mu
- $N(t) \propto N_0 e^{-t/\tau}[1 + A_{\mu^+}\cos(\omega_{\mu^+}t + \phi_{\mu^+}) + A_{\mathrm{Mu}}\cos(\omega_{\mathrm{Mu}}t + \phi_{\mathrm{Mu}})]$.
- Fraction of μ^+ and Mu formation (F_{μ^+}, F^0_{Mu}) are obtained from the fitted amplitudes.
- We obtained $F^0_{\mathrm{Mu}} = (60 \pm 2)\%$ for porous SiO$_2$.



(a) Raw spectrum

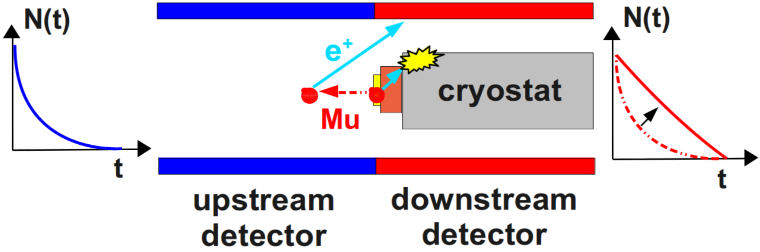
(b) μ^+ precession

(c) Mu precession

μSR method → initial Mu formation rate
fraction of Mu emitted into vacuum = ???

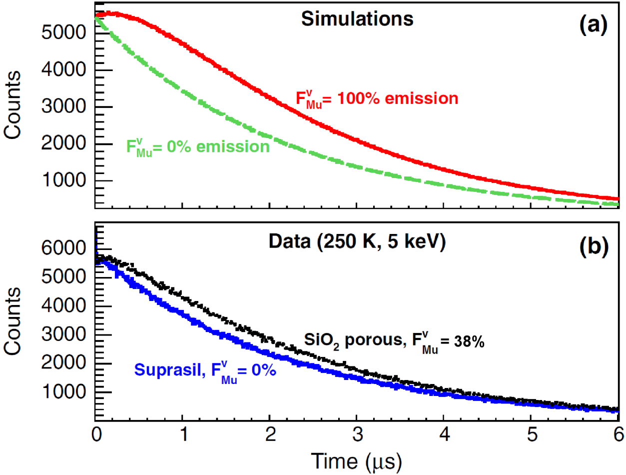
Positron Shielding Technique (PST)

- No Mu emission into vacuum → exponential time distributions.
- Mu emission into vacuum → deviation from exponential function for the downstream detector (Position dependent detection efficiency)
- Detection probability : Mu decaying outside of the sample > decaying in the sample.



Time Spectra Fitting

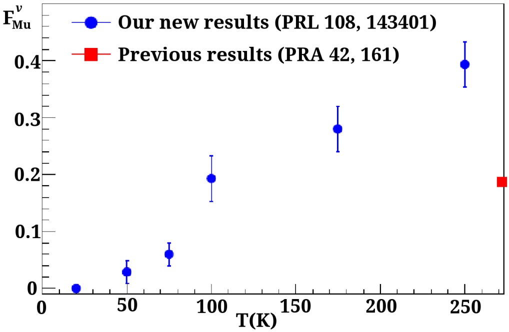
- GEANT4 simulation for 0%($f_0(t)$) and 100%($f_{100}(t)$) Mu emission into vacuum.
- Fit the data with $f_{fit}(t) = n[(1 - F^v_{\mathrm{Mu}})f_0(t) + F^v_{\mathrm{Mu}}f_{100}(t)] + n_{pp}f_{pp}(t)$



Results

We have found that a sizable fraction of thermalized muonium is emitted into vacuum from SiO_2 thin film at 5 keV implantation energy:

- At 250 K, the yield (38%) is more than a factor of two higher than previously found in SiO_2 powder at room temperature (RT).
- At 100 K, the yield (20%) is still as large as previously found at RT.



Summary and Future Plan

Summary

- We have studied the $\mu^+ \rightarrow \mathrm{Mu}$ conversion rate using $\mathrm{SiO_2}$ mesoporous films.
- The yield is more than twice higher than previously found at RT.
- First observation of Mu in vacuum at cryogenic temperatures (20% at 100 K).

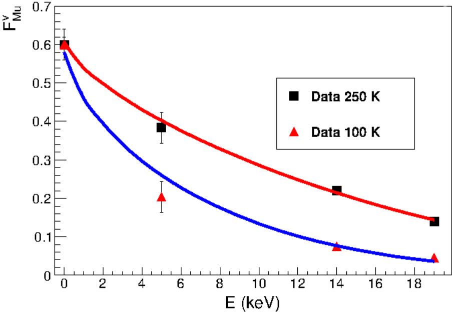
Future Plan

We are particularly interested in the **1S-2S energy interval measurement** of muonium. Since the 1S-2S signal rate is proportional to

$$N_{\mathrm{Mu}} \cdot I^2 \cdot t^2 \quad \text{where} \begin{cases} N_{\mathrm{Mu}}: & \text{Muonium vacuum yield} \\ I: & \text{Laser intensity} \\ t \propto v^{-1}: & \text{Interaction time} \end{cases}$$

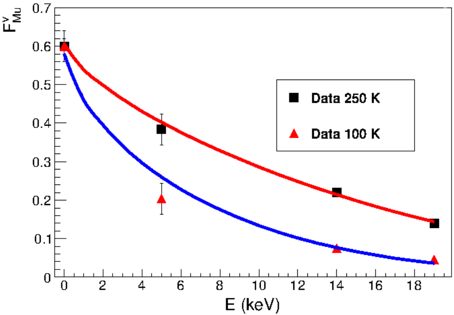
With our new source,

- $N_{\mathrm{Mu}} \uparrow$, $t \uparrow$ (20% at 100 K).
- First time continuous wave laser spectroscopy of this transition is possible.



One-Dimension Diffusion Model

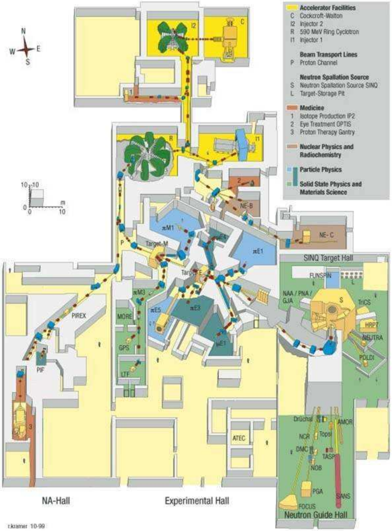
- F^v_{Mu} versus E at 100 K and 250 K are fitted using one-dimensional diffusion model originally developed for Ps.
- The Mu fraction diffusing into vacuum is given by $F^v_{\mathrm{Mu}}(E) = F^0_{\mathrm{Mu}}(E)J(E)$, with $J(E) = \int_0^l e^{-\beta x} P(x,E)\mathrm{d}x$, l is the film thickness, $\beta = 1/\sqrt{D_{Mu}\tau}$ is the inverse diffusion length and D_{Mu} is the diffusion coefficient.
- The resulting values determined from the fits are $D_{Mu}^{250\ \mathrm{K}} = (1.6 \pm 0.1) \times 10^{-4}\mathrm{cm}^2/\mathrm{s}$ and $D_{Mu}^{100\ \mathrm{K}} = (4.2 \pm 0.5) \times 10^{-5}\mathrm{cm}^2/\mathrm{s}$



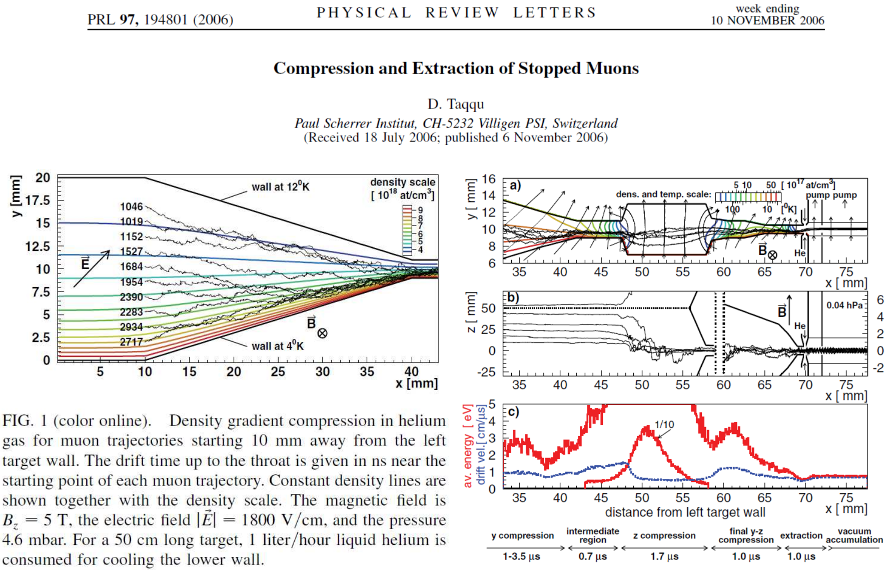
Optimization of the Mu vacuum yield

- We physicists always pushing ourselves towards the limit.
- Try to see if we could achieve 40% at 2 keV at 100 K.
- Measurements were done 1 month ago, the data are still fresh ...
- Very preliminary results - non-thermalized Mu emitted hence not suitable for spectroscopy (Quantitative analysis still on going).

(a) PSI Proton Accelerator



(b) PSI Experimental Hall



PRL **97,** 194801 (2006) PHYSICAL REVIEW LETTERS week ending 10 NOVEMBER 2006

Compression and Extraction of Stopped Muons

D. Taqqu
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

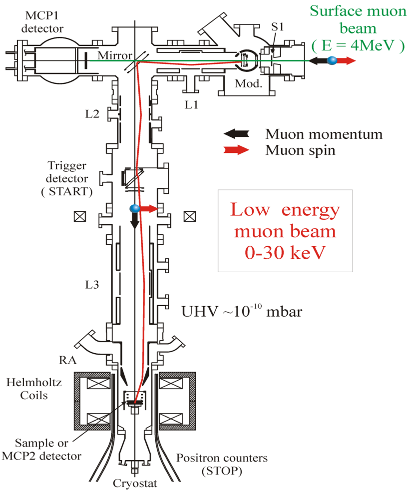
(Received 18 July 2006; published 6 November 2006)

FIG. 1 (color online). Density gradient compression in helium gas for muon trajectories starting 10 mm away from the left target wall. The drift time up to the throat is given in ns near the starting point of each muon trajectory. Constant density lines are shown together with the density scale. The magnetic field is $B_z = 5$ T, the electric field $|\vec{E}| = 1800$ V/cm, and the pressure 4.6 mbar. For a 50 cm long target, 1 liter/hour liquid helium is consumed for cooling the lower wall.

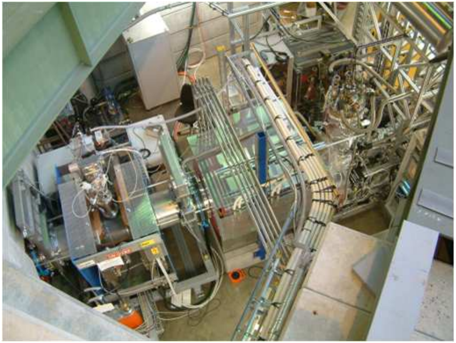
(a) Density gradient compression

(b) Compression and extraction

LEμSR Spectrometer



(a) Schematic view of LEM Spectrometer



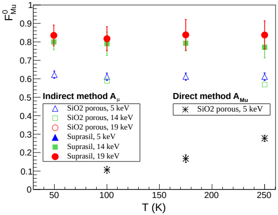
(b) Side view of LEM Spectrometer

Extraction of μ^+ and Mu fraction

- Fraction of μ^+ and Mu (F_{μ^+} ,F_{Mu}) are given by the fitted amplitudes.
- $F_{\mu^+} = \frac{A_{\mu^+}}{A_{tot}}$ and $F_{\mathrm{Mu}} = \frac{2A_{\mathrm{Mu}}}{A_{tot}}$
- The total amplitude, A_{tot}=0.27 was measured from the reference sample of Silica Suprasil. (singlet and M$_s$=0 triplet do not contribute)
- The initial fraction of Mu formed is $F^0_{\mathrm{Mu}} = 1 - \frac{A_{\mu^+}}{A_{tot}}$.
- We obtained $F^0_{\mathrm{Mu}} = (60 \pm 2)\%$ for porous SiO$_2$ and $(80 \pm 4)\%$ for Suprasil.

F_{Mu} and F^0_{Mu}

- Note that direct method $F_{\mathrm{Mu}} = \frac{2A_{\mathrm{Mu}}}{A_{tot}}$ and indirect method $F^0_{\mathrm{Mu}} 1 - \frac{A_{\mu^+}}{A_{tot}}$ are different.
- This is because direct method is sensitive only to the fraction of Mu that does not undergo fast relaxation, e.g., due to spin exchange collisions in the pores.



F^0_{Mu} versus temperature for the mesoporous film and Suprasil for various implantation energies.