Positronium and Muonium 1S-2S laser spectroscopy
- SSP2018 Aachen, 13th of June 2018

Paolo Crivelli, ETH Zurich, Institute for Particle Physics and Astrophysics
Leptonic atoms

Precise bound state QED test free from finite size effects

Test fundamental symmetries and search for new physics


**Talk R. Pohl (Thursday)**

**Positronium (Ps)**

**Muonium (Mu)**

Fundamental constants

Test effect of gravity on anti-matter

Applications in material science

**Talk Seo (Friday)**
Energy levels

Ps

\[ n \]
\[ 4 \]
\[ 3 \]
\[ 3S \quad 3P \quad 3D \]

\[ ^23S \quad 1.1 \ \mu s \quad 2P \quad 3.2 \ \text{ns} \]

2 photons transition:
\( \lambda = 486 \ \text{nm} \)

Natural linewidth:
1.2 MHz

\[ ^3S_1 \quad 142 \ \text{ns} \]

Mu

\[ n \]
\[ 4 \]
\[ 3 \]
\[ 3S \quad 3P \quad 3D \]

\[ ^2S \quad 2.2 \ \mu s \quad 2P \quad 1.6 \ \text{ns} \]

2 photons transition:
\( \lambda = 244 \ \text{nm} \)

Natural linewidth:
144 kHz

\[ ^1S \quad 2.2 \ \mu s \]

\[ R_M = R_\infty \left( \frac{1}{1 + m/M} \right) = \begin{cases} R_\infty/2, & \text{for Ps.} \\ 0.995 \cdot R_\infty, & \text{for Mu.} \end{cases} \]
Positronium 1S-2S measurement

New measurement ongoing at ETHZ: goal 0.5 MHz

1) Check QED calculations ($\alpha^7 m$)
2) Stringent test of SME
3) Positron to electron mass ratio

**Theory:**

$$\nu^\text{theory} = 1233607222.2^{(6)} \text{ MHz}$$

Adkins, Kim, Parsons and Fell, PRL 115 233401 (2015)

**Experiments:**

$$\nu^d = 1233607216.4^{(3.2)} \text{ MHz}$$

M. S. Fee et al., Phys. Rev. Lett. 70, 1397 (1993)
Muonium 1S-2S measurement

Experiment:
$$\Delta \nu_{1S2S}^{(\text{expt.})} = 2455528941.0(9.8) \text{ MHz}$$
Meyer et al. PRL84, 1136 (2000)

Theory:
$$\Delta \nu_{1S2S}^{(\text{theory})} = 2455528935.4(1.4) \text{ MHz}$$
Limited by knowledge of muon mass.
QED calculations at 20 kHz

Reduced mass contribution:
1.187 THz (4800 ppm)

$$m_{\mu^+}/m_{e^-} = 206.76838(17)$$

Byproduct:
$$q_{\mu^+}/q_{e^-} = -1 - 1.1(2.1) \times 10^{-9}$$

Improvement by 3 orders of magnitude seems possible!
Fundamental constants in muon sector

Talks Mott, Denig, Stoeckinger (Tuesday)

\[ a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} \]

\[ a_\mu = \frac{\omega_a}{\omega_p} \frac{m_\mu}{m_e} \frac{\mu_p}{\mu_B} \]

Muon g-2

FNAL

\[ \mu_\mu = g_\mu \frac{e\hbar}{2m_\mu} \]

MUSEUM - HFS

\[ \Delta \nu_{\text{HFS}, n=1} \]

\[ \mu_\mu \]

\[ \alpha \]

\[ \text{QED corrections} \]

\[ \text{weak contribution} \]

Mu-MASS

\[ \Delta \nu_{1S-2S} \]

\[ m_\mu \]

\[ \text{QED corrections} \]

\[ \text{Rydberg} \]

Adapted from K. Jungmann, DPG 2017 (Mainz)
Positronium/muonium formation

Porous Silica thin film ~1000nm 3-4 nm pore size

$e^+ / \mu^+ (1-20 \text{ keV})$

Vacuum
Positronium formation

30% of the incident positrons are converted in positronium emitted into vacuum with 40 meV (almost $10^5$ m/s).

Positronium formation

\[ \lambda_{Ps} = 0.9 \text{ nm} \sqrt{1 \text{ eV}/E_{Ps}} \]

\[ E_{Ps} = \frac{\hbar^2}{2md^2} \approx 0.8 \text{ eV} (1 \text{ nm/d})^2 \]

\[ \langle H \rangle = kT^2 \left( \frac{1}{Z(a)} \frac{dZ(a)}{dT} + \frac{1}{Z(b)} \frac{dZ(b)}{dT} + \frac{1}{Z(c)} \frac{dZ(c)}{dT} \right) \]

\[ Z(a) = \sum_{n=1}^{\infty} e^{-\frac{\hbar^2 n^2}{8ma^2} / kT} \]

Laser spectroscopy
The laser system

**486/488 nm TOPTICA LASER**
- 972 nm diode laser

**Requirements:**
- High power (≈kW) at 486 nm -> detectable signal
- Long term stability (continuous data taking ≈days)
- Scanning of the laser ± 100 MHz

**Tapered Amplifier**
- 2.4 W

**SHG cavity with LBO crystal**
- Light at 486/488 nm 750mW, 200kHz

**Space for 244 nm SHG for Mu spectroscopy**

**Incoming laser beam**
- e+ beam
- oPs
- Ps target

**Vacuum 10^{-9} mBar**

**Mirror 1 mounted in double piezo-actuator**

**Mirror 2**
The laser system

486/488 nm TOPTICA LASER
972 nm diode laser

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Space for 244 nm SHG for Mu spectroscopy

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- Scanning of the laser ± 100 MHz

Incoming laser beam

500 W circulating power
Vacuum $10^{-9}$ mBar

Mirror 1 mounted in double piezo-actuator

High finesse resonator for power build up
500 mW $\rightarrow$ 1 kW

Mirror 2
Detection of Ps annihilation in the 2S state

Use bunched beam (buffer gas trap)
→ Noise from *accidentals* reduced by 2 orders of magnitude
→ Reduction and correction of *systematic* effects


S/N ratio should be improved.
New beamline based on a buffer gas trap

- Solenoid 1kG
- Gamma Detectors
- Positron Source (many thanks to D. van der Werf and the Swansea group of M. Charlton)
- Excitation region
Bunching and extraction to a field free region

\[ e^+ (7 \text{ eV}), \Delta t = 50 \text{ ns}, \sigma = 1 \text{ mm}, B = 120 \text{ G} \]

**ON TARGET (@ground)**: \( \Delta t = 1 \text{ ns}, \sigma = 1 \text{ mm}, B < 0.1 \text{ G}, 90 \% \text{ efficiency} \)
Pulsed laser system for Ps excitation

frequency tripled pulsed Nd:YAG laser - seeded
(Spectra Physics)

wavelength-meter (High Finesse)

Computer PID control

486 nm CW

Optical fiber

355 nm pulsed

Pulsed Dye Amplifier (Radiant Dyes)

energy stabilised 486 nm pulsed

Pockels Cell

PBS

Frequency stabilised diode laser
(Toptica)
Detection schemes for Ps 2S excitation

SiO$_2$ target

PbWO$_4$

486nm

Mu-metal shield

Direct photo-ionization in the exciting laser
Detection schemes for Ps 2S excitation

Ps 2S photo-ionization in separate laser
Detection schemes for Ps 2S excitation

2S $\rightarrow$ Rydberg (e.g. 20P) and field ionization on MCP

allows for correction of second order doppler shift (main systematic!)

$$\Delta \nu_{D2} = \nu_0 \frac{v^2}{2c^2}$$
Detection schemes for Ps 2S excitation


![Graph showing ratio of ionized e+ over backscattered e+ (x10) (%) vs laser detuning (MHz)]

- PbWO4
- SiO2 target
- Mu-metal shield
- MCP
- Rydberg Ps
- e+
“Quasi” Doppler free excitation → velocity distribution

- Camera
- Beam sampler
- Silica thin film target
- Tilt able piezo mount
- Vacuum chamber
- Positrons
- Ring MCP
- Detector
“Quasi” Doppler free excitation → velocity distribution

\[ \Delta v \propto v_{Ps} \cdot \delta \]
Outlook of 1S-2S Ps spectroscopy

**GOAL:** current source (10000 Ps/pulse @ 40 meV)

→ Measurement of 1S-2S of Ps at a level about $5 \times 10^{-10}$

→ Check QED calculation, SME test (sidereal variations)

**NEXT STEPS**

→ Combine CW laser with bunched positron beam.

→ Absolute frequency reference: upgrade with output @ 972 nm frequency comb of Prof. Esslinger group (ETHZ).

**POTENTIAL IMPROVEMENTS**

→ GBAR LINAC

→ Colder Ps source?
Muonium formation
Polarized surface muon generation

\[ 2.2 \, \text{mA} \approx 1.4 \times 10^{16} \, \text{Protons/sec} \]

with 600 MeV

\[ p + C \rightarrow \pi^+ \pi^- p n \ldots \]

~ \(10^7 - 10^8\) \(\mu^+\)/sec

100% pol.

~ 4 MeV

generally used for “bulk” condensed matter studies

For thin film studies: eV-30 keV
Low energy muon (LEM) beam line at PSI

~ 5000 μ/s

E~15eV

~ 1.9 x 10^8 μ+/s

„Surface“
Muons
~ 4 MeV
~ 100% polarized

Low energy
muon beam
0-30 keV

UHV ~10^-10 mbar
muSR results for porous and bulk SiO2

Larmor frequency: \( \omega_{Mu} \approx 103 \omega_{\mu^+} \)

\[\begin{align*}
F^0_{Mu} & \quad \text{Indirect method } A_\mu \\
\text{SiO}_2 \text{ porous, 5 keV} & \triangle \\
\text{SiO}_2 \text{ porous, 14 keV} & \square \\
\text{SiO}_2 \text{ porous, 19 keV} & \bigcirc \\
\text{Suprasil, 5 keV} & \blacktriangle \\
\text{Suprasil, 14 keV} & \blacksquare \\
\text{Suprasil, 19 keV} & \bullet
\end{align*}\]

MuSR \(\rightarrow\) Mu is formed but is this emitted in vacuum?
Positron shielding technique (PST)

Upstream detector  Downstream detector

B-field

Sample

Usual $\mu$SR sample position

$\mu^+$ spin

$\mu$ momentum

10 cm

No emission into vacuum

SIMULATIONS
Positron shielding technique (PST)

Upstream detector  Downstream detector

B-field

Cryostat

Usual $\mu$SR sample position

Sample

$\mu^+$ spin

$\mu$ momentum

10 cm

Emission into vacuum

Simulations

$F_{\mu} = 100\%$ emission

$F_{\mu} = 0\%$ emission
PST principle

\[ f_{\text{fit}}(t) = n[(1 - F_{Mu}^V)f_0(t) + F_{Mu}^Vf_{100}(t)] + n_{pp}f_{pp}(t) \]

Vacuum Yield: \( F_{Mu}^V \)
PST results

A. Antognini (ETHZ), P. Crivelli (ETHZ), K. S. Khaw (ETHZ), K. Kirch, (ETHZ/PSI), B Barbiellini (NU Boston), L. Liszkay (CEA), T. Prokscha (PSI), E. Morenzoni (PSI), Z. Salman (PSI), A. Suter (PSI), PRL 108, 143401 (2012)

\[ (38 \pm 4)\% \text{ at } 250 \text{ K and } (20 \pm 4)\% \text{ at } 100 \text{ K for } 5 \text{ keV} \]
Muonium spatial confinement


Factor 5 enhancement in exc. probability
Muonium Laser Spectroscopy (Mu-Mass)
Current (1999) 1S-2S measurement

BKG: 2.5 counts/day

~20 MHz (FWHM)

Meyer et al. PRL 84, 1136 (2000)

3500 mu+/pulse, 50 Hz, 80 Mu/pulse
1S-2S CW laser spectroscopy

The 1S-2S signal rate is proportional to

\[ R \sim N_{\text{Mu}} \cdot I^2 \cdot t^2 \]

where

\[ \begin{align*}
N_{\text{Mu}} &: \quad \text{Muonium production rate} \\
I &: \quad \text{Laser intensity} \\
t &\sim v^{-1} &: \quad \text{Interaction time}
\end{align*} \]

Need a Mu source with high yield and low energy

Decrease requirements of laser intensity

Mu @ 100 K

HP 244 nm laser light

First CW spectroscopy

# Pulsed vs CW spectroscopy

<table>
<thead>
<tr>
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<th>RAL (1999)</th>
<th>Mu-MASS Phase1</th>
<th>Mu-MASS Phase2</th>
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<td>$\mu^+$ beam intensity</td>
<td>3500 $\times$ 50 Hz</td>
<td>5000 s$^{-1}$</td>
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<td>$\mu^+$ beam energy</td>
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<td>M atoms</td>
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For CW reduction of the transition linewidth by a factor >20!
# Pulsed vs CW spectroscopy

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Systematic related to pulsed excitation eliminated
## Pulsed vs CW spectroscopy

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→ Improvement in reach using the LEM beamline at PSI
Outlook – Muonium spectroscopy

NEXT STEPS
- Upgrade Ps laser with fiber amplifier and SHG (CLBO) + UV enhancement cavity.
- Develop laser: Mu(2S) → Mu* enhance the signal and measure atoms velocity.
- Test new targets for Mu production (in collaboration with PSI muon group)

GOAL:
→ Improve muon mass (1 ppb) and $q_\mu / q_e$ (1 ppt)
Combined with HFS:
→ Stringent test of bound state QED (rel. accuracy 1 ppt)
→ Rydberg constant free of finite size effects (few ppt), $\alpha$ (1 ppb)
→ Test of SME

POTENTIAL IMPROVEMENTS:
1S-2S results will be statistically limited
→ New low energy beam lines under development at PSI (Kirch group, ETHZ/PSI) and at JPARC → 2 orders of magnitude more low energy muons expected.
Acknowledgments

Graduate students: M. Heiss and G. Wichmann


Thank you to the organizers for the very kind invitation and you for your attention!