The Mu-MASS experiment
LTP colloquium - 2nd of November 2023
Paolo Crivelli, Institute for Particle Physics and Astrophysics, ETH Zurich

https://www.psi.ch/en/ltp/mu-mass
Motivations to study leptonic atoms - Positronium and Muonium

- Being **purely leptonic**, they can be described very precisely by **bound state QED calculations** **devoid of uncertainties from nuclear size effects** present in normal atoms. Therefore, any deviation between theory and measurements could be a signal of **New Physics**.

- Moreover, from these measurements very important values of **fundamental constants** can be extracted such as the **muon mass and muon magnetic moment**.
The muonium (M)

M (positive muon-electron bound state)
Predicted in 1957 (Friedmann, Telegdi, Hughes)
Unstable with lifetime of 2.2 μs
Main decay channel: \( \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \)

Discovered in 1960 (Hughes) by detecting muonium spin (Larmor) precession in an external magnetic field perpendicular to the spin direction.

Actually M is not a real -onium atom (particle-antiparticle system). The true muonium bound state would be \( \mu^+\mu^- \) yet to be discovered…
Muonium spectroscopy Theory and Experiments until recently


Meyer et al. PRL84, 1136 (2000)
K. Woodle et al., PRA 41, 93 (1990)

Liu et al. PRL82, 711 (1999)

HFS (LAMPF 1999) 1S-2S (RAL 1999)
LS (TRIUMF/LAMPF) FS (LAMPF 1990)

EXP. THEORY

UNCERTAINTY (LEFT EDGE)
MEASURED QUANTITY (RIGHT EDGE)

10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9}

Energy [GHz]

UNCERTAINTY DUE TO UNCALCULATED $b$-QED TERMS (LEFT EDGE)
UNCERTAINTY FROM KNOWLEDGE $m_\mu/m_e$ (RIGHT EDGE)
Muonium spectroscopy current status of Theory and Experiments

Karshenboim et al. PRA 103, 022805 (2021)

Adkins et al. PRL130, 023004 (2023)
I. Cortinovis et al., EPJD 77, 66 (2023)

M. Heides et al. PRA 105 (2022) 1, 012803
G. Janka et al. EPJ Web Conf. 262, 01001 (2022)

Some models postulate the suppression of the V+A weak interaction by a heavy W boson such that parity would be restored at high energies [256]. An alternative solution is the one already discussed by Lee and Yang in their original paper. In order to save parity conservation, they suggested that the transformation in the particle space corresponding to the space inversion \( x \rightarrow x \) should not be the usual transformation \( P \) but \( PR \), where \( R \) corresponds to the transformation of a particle (proton) into a reflected state in the mirror particle space.

The idea that for each ordinary particle, such as photon, electron, proton and neutron, there is a corresponding mirror particle of exactly the same mass and properties as the ordinary particle, was further developed over the years [257]. \( R \)-parity interchanges the ordinary particles with the mirror particles. Parity is conserved because the mirror particles experience V+A (i.e. right-handed) mirror weak interactions while the ordinary particles experience the usual V+A (i.e. left-handed) weak interactions.

Doubling the content of the Standard Model to solve some problems might seem un-natural, however it has worked in the past. From the union of quantum mechanics and relativity, anti-matter has been postulated. Moreover, mirror matter being stable and massive is an excellent candidate for Dark Matter (DM). In fact, even though the existence of DM has...
Muonium Spectroscopy - ongoing experiments

S. Kanda et al. PLB 815 (2021) 136154
I. Cortinovis et al., EPJD 77, 66 (2023)
G. Janka et al. EPJ Web Conf. 262, 01001 (2022)

Energy [GHz]

10^{-12} 10^{-9} 10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9}

HFS

1S-2S

LS

FS

EXP.

PROJECTED UNCERTAINTY (LEFT EDGE)
MEASURED QUANTITY (RIGHT EDGE)

THEORY

UNCERTAINTY DUE TO UNCALCULATED b-QED TERMS (LEFT EDGE)
UNCERTAINTY FROM KNOWLEDGE $m_\mu/m_e$ (RIGHT EDGE)
The PSI low energy muon beam (LEM) https://www.psi.ch/en/low-energy-muons

Paolo Crivelli | 02.11.2023 | 7

Designed in the 1960’s to deliver 100 mA, first mA beam in Feb 1974, 1 mA in 1994; 2.4 mA: ~1.5x10^16 protons/sec @ 590 MeV (highest beam power proton machine in the world): 1.4 MW on 5x5 mm^2 = 50 kW/mm^2, stainless steel melts in ~0.1 ms; Electric power demand of 3000 households; A MW proton beam allows to generate 100% polarized 4-MeV m^+ beams with rates >10^8/sec.

Cyclotron frequency of protons: q/(2p) = 15.25 MHz/T

n_rf = n_0

PSI cyclotron: B_0 = 0.554 T, n_0 = 8.45 MHz, n = 6, → n_rf = 50.7 MHz

Up to 5x10^3 μ+/s

Low energy muon beam 0-30 keV

Helmholtz coil

TARGET

Cryostat

Positron counters (STOP)

Surface muon beam (E = 4 MeV )

Solid Ne/Ar 500 nm film

“Surface” Muons
~ 4 MeV
~ 100% polarized

Ar

Epithermal component

E~15eV

UHV ~10^-10 mbar

Muon momentum Muon spin

https://www.psi.ch/en/low-energy-muons
Muonium (keV beam) formation with a C-foil

Carbon-foil

Extension

Rejection electrode

Rejection off
Rejection on

μ^+

M(1S,2S)

e^−

Quench field

4x Ly-α MCP, CsI-coated

Tag-MCP, Start signal

Stop-MCP, Stop signal

M

μ^+ + M
Muonium (keV beam) formation with a C-foil

Carbon-foil Extension

\[ \mu^+ \rightarrow \text{M(1S,2S)} \]
\[ \text{e}^- \]

Quench field

\[ \text{Ly-}\alpha \]

\[ \text{M(1S)} \]

Rejection electrode

\[ \text{M+} \]

\[ \text{M} \]

Rate [1/min]

Time [ns]

Mean Residual Energy [keV]

M Fraction

\[ 10 \text{ keV dataset} \]
\[ 7.5 \text{ keV dataset} \]
\[ 5.0 \text{ keV dataset} \]

2S Muonium keV beam

Quenching efficiency and geometrical acceptance from MC + detection efficiency -> 1/n^3 naive scaling confirmed

\[ f_M(n=2)/M(n=1) = (10 \pm 2)\% \]

INTENSE 2S M BEAM -> POSSIBILITY TO IMPROVE THE M LAMB SHIFT

Muonium Lamb shift

**Muonium**

**THEORY** \( (E(2S_{1/2}) - E(2P_{1/2}))_{\text{Mu}}^{\text{th}} = 1047.498(1) \text{ MHz} \)

G. Janka et al. EPJ Web Conf. 262, 01001 (2022)

**EXPERIMENT** \( (E(2S_{1/2}) - E(2P_{1/2}))_{\text{Mu}}^{\text{exp}} = 1042(22) \text{ MHz} \)


**Summary of calculated contributions**

<table>
<thead>
<tr>
<th>Largest Order</th>
<th>Hydrogen (MHz)</th>
<th>Muonium (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{SE} ) ( \alpha (Z\alpha)^4 L )</td>
<td>1084.128</td>
<td>1070.940</td>
</tr>
<tr>
<td>( E_{VP} ) ( \alpha (Z\alpha)^4 )</td>
<td>-26.853</td>
<td>-26.510</td>
</tr>
<tr>
<td>( E_{VPu+had} ) ( \alpha (Z\alpha)^4(m_e/m_\mu)^2 )</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
<tr>
<td>( E_{2ph} ) ( \alpha^2(Z\alpha)^4 )</td>
<td>0.065</td>
<td>0.065</td>
</tr>
<tr>
<td>( E_{3ph} ) ( \alpha^3(Z\alpha)^4 )</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( E_{BKG} ) ( (Z\alpha)^4 (m_e/m_n)^2 )</td>
<td>-0.002</td>
<td>-0.168</td>
</tr>
<tr>
<td>( E_{rec,S} ) ( (Z\alpha)^5 L (m_e/m_n) )</td>
<td>0.358</td>
<td>3.138</td>
</tr>
<tr>
<td>( E_{rec,R} ) ( (Z\alpha)^6 (m_e/m_n) )</td>
<td>-0.001</td>
<td>-0.012</td>
</tr>
<tr>
<td>( E_{rec,R2} ) ( (Z\alpha)^6 (m_e/m_n)^2 )</td>
<td>-0.000</td>
<td>-0.001(1)</td>
</tr>
<tr>
<td>( E_{RR} ) ( (Z\alpha)^5 (m_e/m_n) )</td>
<td>-0.002</td>
<td>-0.014(1)</td>
</tr>
<tr>
<td>( E_{RR2+e} ) ( (Z\alpha)^5 (m_e/m_n)^2 )</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( E_{RR3} ) ( \alpha^2(Z\alpha)^5 (m_e/m_n) )</td>
<td>-0.000</td>
<td>-0.000</td>
</tr>
<tr>
<td>( E_{SEN} ) ( Z^2 \alpha (Z\alpha)^4 (m_e/m_\mu)^2 )</td>
<td>0.001</td>
<td>0.041</td>
</tr>
<tr>
<td>( E_{HFS} ) ( \alpha^2(Z\alpha)^2 (m_e/m_n)^2 )</td>
<td>0.002</td>
<td>0.019</td>
</tr>
</tbody>
</table>

**Sum** | 1047.498(1)
Muonium Lamb shift

**Muonium**

**THEORY** \( (E(2S_{1/2}) - E(2P_{1/2}))^{th}_{\text{Mu}} = 1047.498(1) \text{ MHz} \)

G. Janka et al. EPJ Web Conf. 262, 01001 (2022)

**EXPERIMENT** \( (E(2S_{1/2}) - E(2P_{1/2}))^{\exp}_{\text{Mu}} = 1042(22) \text{ MHz} \)


---

**Recoil corrections are enhanced for M** *(9 times lighter than H)*

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<td>-0.002</td>
<td>-0.014(1)</td>
</tr>
<tr>
<td>( E_{RR2e+p} )</td>
<td>( (Z\alpha)^5 (m_e/m_\mu)^2 )</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>( E_{RR3} )</td>
<td>( \alpha^2(Z\alpha)^5 (m_e/m_\mu) )</td>
<td>-0.000</td>
<td>-0.000</td>
</tr>
<tr>
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<td>( Z^2 \alpha (Z\alpha)^4 (m_e/m_\mu)^2 )</td>
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</tr>
</tbody>
</table>

**Sum** | 1047.498(1)

Paolo Crivelli | 02.11.2023 | 12
Measurement of $M$ the Lamb shift

**LEM beamline**

$10 \text{ kHz/10 keV}$

$\mu^+ \rightarrow M(1S, 2S) \rightarrow L_{\gamma} \rightarrow M(1S)$

$\tau_{2S} = 2.2 \mu s$

not allowed
Measurement of M the Lamb shift

\[ \tau_{2S} = 2.2 \, \mu s \]

\[ \tau_{2P} = 1.6 \, \text{ns} \]

RF field \( \sim 1\text{GHz} \)

\( 2S \) not allowed
Measurement of $M$ the Lamb shift

RF field $\sim 1$GHz

$\tau_{2S} = 2.2 \mu s$

$\tau_{2P} = 1.6$ ns

Lyman alpha photon (121 nm) NOT DETECTED
Measurement of the Lamb shift

Electric field (Stark mixing)

\[ \tau_{2S} = 2.2 \mu s \]

not allowed

\[ \tau_{2P} = 1.6 \text{ ns} \]

Lyman alpha photon (121 nm) DETECTED!
Measurement of M the Lamb shift

Lya detection region

Muonium

2S detected

Frequency

Scanning RF field

Carbon foil

Tag MCP

M(1S, 2S)

HFS selector

Microwave

Quenching grids

Lya detector

M(2S → 1S + γ)

M(1S)

Stop MCP

μ+

e−

μ−
Measurement of $M$ the Lamb shift

LEM beamline  T. Prokscha et al., NIMA 595, 317 (2008)

LYMAN-ALPHA DETECTOR

TAGGING+M(2S) FORMATION

MW REGION (HFS SELECTOR + MW TRANSITION)

STOP DETECTOR
Results of the M Lamb shift


48 HOURS DATA TAKING (100x statistics compared to previous measurements)

<table>
<thead>
<tr>
<th>Source</th>
<th>Central Value</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting</td>
<td>1139.9</td>
<td>2.3</td>
</tr>
<tr>
<td>4S contribution</td>
<td></td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>MW-Beam alignment</td>
<td></td>
<td>&lt; 0.32</td>
</tr>
<tr>
<td>MW field intensity</td>
<td></td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>M velocity distribution</td>
<td></td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>AC Stark 2P_{3/2}</td>
<td>+0.26</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>2^{nd}-order Doppler</td>
<td>+0.06</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Earth’s Field</td>
<td></td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>Quantum Interference</td>
<td></td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>2S_{F=1} - 2P_{1/2,F=1}</td>
<td>1140.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Hyperfine</td>
<td>-93.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Lamb Shift</td>
<td>1047.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Theoretical value</td>
<td>1047.47</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Results in **agreement with theoretical calculations**. Precision is not enough to test b-QED but can be used to constrain new physics.
Constraints on Lorentz- and CPT violation


\[ \mathcal{L}_{\text{SME}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{GR}} + \mathcal{L}_{\text{LV}} \]

Conventional physics  Lorentz violation

- SME: Framework for comparing tests of Lorentz and CPT symmetry

Additional energy term for Muonium Lamb Shift:

\[ 2\pi \delta \nu_{\text{Lamb}} = -\frac{2}{3} (\alpha m_r)^4 (a_{4}^{\text{NR}} + c_{4}^{\text{NR}}) \]


- Our results improve an order of magnitude the previous limits

\[ < 1.7 \times 10^5 \text{ GeV}^{-3} \]

Lorentz and CPT  Only Lorentz
Muonium spectroscopy as a probe for new muonic forces

- Perturbations

\[
\Delta E_{ss}(2S^0 \rightarrow 1S^0) = \frac{g_1^S g_2^S}{4\pi} \left( \frac{4}{a_0(Ma_0+2)^2} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4} \right)
\]

\[
\Delta E_{ss}(2S^0 \rightarrow 2P^0) = \frac{g_1^S g_2^S}{4\pi} \left( \frac{1}{4a_0(Ma_0+1)^4} - \frac{2M^2a_0^2+1}{4a_0(Ma_0+1)^4} \right)
\]

Bands: region suggested by \((g-2)_\mu\)


\[\begin{array}{c}
\text{SM} \\
\mu^+ \rightarrow \mu^- + 2\gamma
\end{array}\]

\[\begin{array}{c}
\text{NP} \\
\mu^+ \rightarrow \mu^- + \text{X} + \gamma
\end{array}\]

combined with bound from \((g-2)_e\)

Measurement of $2S_{1/2}, F=0 \rightarrow 2P_{1/2}, F=1$ transition in Muonium

First time:
Measurement of $2S_{1/2}, F=0 \rightarrow 2P_{1/2}, F=1$: 580.6(6.8)MHz
Extraction of $2S$ HFS: 559.6(7.2)MHz
Detection of M(3S) LS at 1045.5(6.8) MHz

G. Janka, P. Crivelli, et al., NC 13, 7273 (2022)
Summary & Outlook - Muonium Lamb shift

\(2S_{1/2}, F=1 \rightarrow 2P_{1/2}, F=1\) transition: most precise determination limited by statistics

\(2S_{1/2}, F=0 \rightarrow 2P_{1/2}, F=1\) transition:
- Not competitive yet with most precise determination due to statistics but isolated transition seems most promising for high precision measurements as for hydrogen

![Figure 1. The experimental sketch of the muonium Lamb shift measurement within the Mu-MASS experiment at PSI.](image)

The M Lamb shift was determined to be 1047.2(25) MHz \[27\], where the uncertainty is almost completely of statistical origin. This result is an improvement of an order of magnitude compared to the last best determinations \[28, 29\]. As a next step, the foil thickness will be reduced from 10 nm to a few layers of graphene \[30, 31\] (\(\sim 1\) nm), which will increase our detectable \(M(2S)\) rate by a factor ranging from 15 to 25.

### 4 Conclusions

Calculating each contribution separately shows that when reaching an uncertainty of around 160 kHz in muonium, one becomes sensitive to higher-order recoil effects such as \(E_{BKG}\), which cannot be resolved yet with hydrogen. In the context of Mu-MASS, by replacing the 10 nm-thick carbon foil for producing muonium with a few layers of graphene, an uncertainty of 160 kHz would be feasible within around a week of beamtime. Lowering the uncertainty further to 40 kHz, the effect coming from the nucleus self energy \(E_{SEN}\) can be studied, which is also not in reach right now with hydrogen. The ongoing development of the muCool project \[32\] at PSI will improve the beam quality and provide an order of magnitude larger muon flux, allowing us to achieve such uncertainty. The realization of the High Intensity Muon Beam (HIMB) project at PSI \[33\] would allow to push this even further as summarized in Tab. 3.

**Table 2.** Summary of possible upgrades to the Mu-MASS setup and which contributions of the M LS could be probed.

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Target</th>
<th>Timeline</th>
<th>M(2S) (Hz)</th>
<th>LS Uncertainty (kHz / 10 d)</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PiE4/LEM</td>
<td>C-Foil</td>
<td>2023</td>
<td>20</td>
<td>&lt;1000</td>
<td>(E_{SE}, E_{VP}, E_{rec,S})</td>
</tr>
<tr>
<td>PiE4/LEM</td>
<td>Graphene</td>
<td>2025</td>
<td>100</td>
<td>200</td>
<td>(E_{BKG})</td>
</tr>
<tr>
<td>PiE1/muCool</td>
<td>Graphene</td>
<td>2026</td>
<td>1000</td>
<td>70</td>
<td>(E_{2ph})</td>
</tr>
<tr>
<td>HiMB/muCool</td>
<td>Gas</td>
<td>2029</td>
<td>100 000</td>
<td>10</td>
<td>(E_{RR}, E_{HFS}, E_{rec,R}, E_{SEN})</td>
</tr>
</tbody>
</table>


[HiMB] M. Aiba et al. (2021), 2111.05788
Now to the laser experiment....
Thermal Muonium formation in porous SiO$_2$ films at LEM

A. Antognini, P. Crivelli, T. Prokscha et al., PRL 108, 143401 (2012)

- Muon implanted with keV energies (Requires low energy muon beam)
- Rapidly thermalises in the bulk (~ps)
- M formation and diffusion in the interconnected pore network
- Up to 20(40)% @100(250)K muonium in vacuum per incoming muon

\[
\text{Vacuum yield} = \text{Muon yield} \times \frac{1}{250} \approx 0.004
\]

\[
F_{\text{Mu}}^v = \text{Mu} \text{ yield} \times 20(40)\% \rightarrow 0.8(1.6)\%
\]

\[
F_{\text{Mu}}^v = \text{Muon yield} \times \frac{1}{250} \times \frac{1}{2} \approx 0.004
\]

\[
\text{Vacuum yield} = \text{Muon yield} \times \frac{1}{250} \approx 0.004
\]

\[
F_{\text{Mu}}^v = \text{Muon yield} \times \frac{1}{250} \times \frac{1}{2} \approx 0.004
\]
Implications for laser spectroscopy

The 1S-2S signal rate is proportional to

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

where

- \( N_{\text{Mu}} \) : Muonium production rate
- \( I \) : Laser intensity
- \( t \sim v^{-1} \) : Interaction time

Need a Mu source with high yield and low energy

Decrease requirements of laser intensity

Our results on Mu formation at 100K opens the way for the first **CW spectroscopy** of the 1S-2S transition in Mu!
Muonium 1S-2S: current status theory/experiment

**EXPERIMENT**

\[ \Delta \nu_{1S2S} \text{(expt.)} = 2455528941.0(9.8) \text{ MHz} \]

Meyer et al. PRL 84, 1136 (2000)

**THEORY**

\[ \Delta \nu_{1S2S} \text{(theory)} = 2455528935.4(1.4) \text{ MHz} \]


**UNCERTAINTY LIMITED BY OUR KNOWLEDGE OF**

\[ \frac{m_\mu}{m_e} = 206.768277(24)(120 \text{ ppb}) \]

Liu et al. PRL 82, 711 (1999)
Muonium 1S-2S: current status theory/experiment

<table>
<thead>
<tr>
<th>n</th>
<th>4</th>
<th>3S</th>
<th>3P</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2S 2.2 μs</td>
<td>2 photons transition: λ=244 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1S 2.2 μs</td>
<td>Natural linewidth: 144 kHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
\nu_{1S-2S} \approx \frac{3}{4} \frac{R_{\infty} c}{1+m_e/m_\mu}
\]

Summary of different contributions

<table>
<thead>
<tr>
<th>Contr.</th>
<th>Largest Order</th>
<th>Muonium (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{Dirac}})</td>
<td>((Z\alpha)^2)</td>
<td>2455535991.3(1.4)</td>
</tr>
<tr>
<td>(E_{\text{SE}})</td>
<td>(\alpha (Z\alpha)^4)</td>
<td>-7222.771</td>
</tr>
<tr>
<td>(E_{\text{VP}})</td>
<td>(\alpha (Z\alpha)^4)</td>
<td>185.565</td>
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<tr>
<td>(E_{\text{VP,\mu+had}})</td>
<td>(\alpha (Z\alpha)^4(m_e/m_\mu)^2)</td>
<td>0.007</td>
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<tr>
<td>(E_{2\text{ph}})</td>
<td>(\alpha^2(Z\alpha)^4)</td>
<td>-0.627(1)</td>
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<tr>
<td>(E_{3\text{ph}})</td>
<td>(\alpha^3(Z\alpha)^4)</td>
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<tr>
<td>(E_{\text{rec,S}})</td>
<td>((Z\alpha)^5 (m_e/m_n))</td>
<td>-18.104</td>
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<tr>
<td>(E_{\text{rec,R}})</td>
<td>((Z\alpha)^6 (m_e/m_n))</td>
<td>0.056</td>
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<tr>
<td>(E_{\text{rec,R2}})</td>
<td>((Z\alpha)^6 (m_e/m_n)^2)</td>
<td>0.005</td>
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<tr>
<td>(E_{\text{RR}})</td>
<td>(\alpha (Z\alpha)^5 (m_e/m_n))</td>
<td>0.095(6)</td>
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<tr>
<td>(E_{\text{RR2}})</td>
<td>(\alpha (Z\alpha)^5 (m_e/m_n)^2)</td>
<td>-0.001</td>
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<tr>
<td>(E_{\text{SEN}})</td>
<td>(Z^2\alpha(Z\alpha)^4(m_e/m_n)^2)</td>
<td>-0.286</td>
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<tr>
<td>(E_{\text{NVP}})</td>
<td>(Z^2\alpha(Z\alpha)^4(m_e/m_n)^2)</td>
<td>-0.004</td>
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Sum | 2455528935.2(1.4) |
QED only | -7056.065(6) |
Mu-MASS: Goal and Output

**Mu-MASS**: Measure **1S-2S transition** with Doppler free CW laser spectroscopy

**GOAL**: improve by 3 orders of magnitude (10 kHz, 4 ppt)

**OUTPUT**
- Muon mass @ 1 ppb
- Ratio of $q_e/q_\mu$ @ 1 ppt
- Search for New Physics
- **Test of bound state QED** ($1 \times 10^{-9}$)
- Input to muon g-2 theory
- Rydberg constant @ ppt level
- New determination of $\alpha$ @ 1 ppb

\[
\sigma_{m_e/m_\mu} \approx \frac{\sigma_{\nu_{1S-2S}}}{\nu_{1S-2S}} \cdot \frac{m_\mu}{m_e}
\]
Mu-MASS: experimental scheme

3. 1S-2S laser excitation of Muonium: High power UV CW laser at 244 nm, cavity-enhanced to >20 W of stable intracavity power
4. Photoionization of 2S state with pulsed laser

Opt. Express 29, 27450 (2021)

2. Muonium formation in SiO2 target

PRL 108, 143401 (2012)

7. Coincidence with positron from decay, in scintillators

6. Muon detection in MCP

In parallel: M formation diagnostics system

1. Low energy μ+ beam (LEM beamline at PSI, ~10k μ+/s)

JINST 10, P10025 (2015)

5. Guiding ionized muon further away in a "protected" area

Commissioning with residual hydrogen in vacuum chamber+ pulsed UV laser
Mu-MASS: Laser system

* Many thanks to Tilman Esslinger for lending us his frequency comb

![Diagram of the Mu-MASS laser system](image)

**Stable 1W UV operation**

More than 1.8W UV max. output

Mu-MASS: Enhancement cavity

Development of CaF$_2$ substrate and MgF2/LaF3 dielectric coating in collaboration with Laser Optic to prevent mirror degradation in vacuum compared to standard SiO$_2$, HfO2/Al2O3 coatings.

![Graphs showing enhancement versus time for CaF$_2$ and SiO$_2$ at different oxygen pressures.]

Mu-MASS: enhancement cavity QCW operation

Tagged muon rate \(~ 5\, \text{kHz}\) and M TOF \(~1\, \text{microsecond}\) --> duty cycle 0.5 %

“Laser on demand” reduce average power
Mu-MASS: enhancement cavity QCW operation

Tagged muon rate ~ 5 kHz and M TOF ~1 microsecond -> duty cycle 0.5 %

“Laser on demand” reduce average power

Mu-MASS: detection scheme

@ time to "pulse" cw laser

cw 244 nm, 5 mW

SO₂ [ ] O

μ⁺

e⁻

μ⁻ + e⁻ → Sc
Mu-MASS: detection scheme

@ After ~300 ns IR readout CW laser

\[ \text{CW 244 nm, 20 W} \]

\[ \text{SO}_2 \]

\[ \nu - \text{MCP} \quad e^- - S_{2}^{2-} \]

\[ \text{MCP} \quad \text{Claid} \]

\[ \text{G} \]
Mu-MASS: detection scheme

Pulsed laser 1 mJ @ 5 kHz, triggerable with 500 ns latency
Mu-MASS: detection scheme

@ ~ μ⁺ s, Cμ on, E field on, Pulled PI base

Signal in muon MCP

\( E \sim \text{100 MeV} \)

\( \mu^- \rightarrow \text{MCP} \)

\( \mu^- \rightarrow e^- + \text{Sc} \)

\( \mu^- \rightarrow \text{MCP} \)
Mu-MASS: detection scheme

→ Estimated ~ 1 BGK event per day (laser@ETH + beam@PSI induced)
Status of 1S-2S transition

OUTCOME OF OUR FIRST BEAMTIME WITH LASER IN DEC 2022 (3 days setup/ 5 days beam)

1) No signal detected:
- laser-induced background on tagging detector -> higher threshold to reduce it -> an order of magnitude smaller muon rate
- laser system running stable for 80 hours (conditioning enhancement cavity mirrors with O₂ every 6 hours) but on average only 20W circulating power (noisy/dusty environment of exp. hall)

2) No background: < 1 BKG/day to be compared with about 1 event/hour expected for optimised conditions

PROGRESS in 2023:
- Upgraded mechanical design
- Improved light shielding
- Determination of M diffusion time
When to fire the photo-ionization laser?

1D Diffusion Model (Inspired by Model for Ps)
A. Antognini, P. Crivelli, T. Prokscha et al., PRL 108, 143401 (2012)

\[ F_{\text{Mu}}^v(E) = F_{\text{Mu}}^0 \cdot \int_0^\ell e^{-\beta x} P(x, E)\,dx \]

\[ \beta = \frac{1}{\sqrt{D_{\text{Mu}}\tau}} = l_D^{-1} \]

- \( F_{\text{Mu}}^0 \) is the fraction of muonium formed in the target
- \( F_{\text{Mu}}^v \) is the fraction diffusing into vacuum
- \( P(x, E) \) is the stopping distribution for muons with kinetic energy \( E \).
- \( \ell \) is the target depth
- \( D_{\text{Mu}} \) is the diffusion constant
- \( \tau \) is the muon lifetime
- \( l_D \) the diffusion length

**Diffusion time**

\[ t_D = \frac{l_D^2}{D_{\text{Mu}}} \]

**Assuming QM tunnelling** \( D_{\text{Mu}}(T) \propto T^{3/2} \)

\[ D_{\text{Mu}}(250 \text{ K}) = (1.6 \pm 0.1) \times 10^{-4} \text{ cm}^2/\text{s} \]

\[ D_{\text{Mu}}(100 \text{ K}) = (4.2 \pm 0.5) \times 10^{-5} \text{ cm}^2/\text{s} \]

Large effect of muon implantation depth on diffusion time expected
Mu-MASS: direct measurement of diffusion time (June 2023)

*Big thanks to Aldo, Anna and Malte and Florian for their great help in preparing this setup.

M diffusion time basically independent on implantation depth in contradiction to the simple 1D model.
Outlook of Mu-MASS

muCool and HIMB open great prospects for M spectroscopy

- CURRENT 1S-2S AIMED ACCURACY FROM 10 kHz → 1kHz
  Improve muon mass/test of New Physics/ Rydberg constant, combined with HFS provide one of the most precise b-QED test

- 10 kHz accuracy for LS and FS using SOF technique might be in reach.

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Target</th>
<th>Timeline</th>
<th>1S-2S Uncertainty (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PiE4/LEM</td>
<td>SiO2 @ 300K</td>
<td>2024-2025</td>
<td>100</td>
</tr>
<tr>
<td>PiE1/muCool</td>
<td>SiO2 @ 100K</td>
<td>2026</td>
<td>10</td>
</tr>
<tr>
<td>HiMB/muCool</td>
<td>SFHe</td>
<td>2029-</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.

Summary of possible upgrades to the Mu-MASS 2S Beamline Target Timeline Uncertainty (kHz)

References

[9] A.D. Brandt, S.F. Cooper, C. Rasor, Z. Burkley, D.C. Yost, A. Matveev, Measurement of the \(^2s_1/2 \rightarrow 8d_5/2\) transition in hydrogen (2021), 2111.08554
THIS WORK IS SUPPORTED BY an ERC consolidator grant (818053 -Mu-MASS) and by the Swiss National Foundation under the grant 197346.