The muX project
Measuring muonic X-rays at PSI with a germanium detector array

Frederik Wauters on behalf of the muX collaboration
Johannes Gutenberg University Mainz
Muonic atoms

Particle physics with muons

The Muon g-2 experiment at Fermilab: Overview and status update

20 Oct 2019, 19:00
30M
8M0/801 - Auditorium (PS)

Speaker

Particle reconstruction algorithms for MES II (Electron Cooling) Gantry

22 Oct 2019, 17:00
8M0/801 - Auditorium (PS)

Speaker

Calibration of WC/W ceramic WPCs of MES II Liquid Xenon Gamma-Ray Detector

22 Oct 2019, 17:00
8M0/801 - Auditorium (PS)

Speaker

Overview of New Muon g-2/EDM Experiment J-PARC with Ultra-Cold Muon Beam

Muon beam injection and storage

< 1 ns (<< μ lifetime)
Muonic atoms

- 'Nuclear' physics? → negative muons

Stopped negative muon:
- Atomic capture @ $n \approx 14$

$< 1 \text{ ns } (<< \mu \text{ lifetime})$
Muonic atoms

- 'Nuclear' physics? → negative muons

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- Atomic capture @ $n \approx 14$
- At high $n$: Auger transitions

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Muonic atoms

• 'Nuclear' physics?

negative muons

Stopped negative muon:

• Atomic capture @ n ≈ 14
• At high n: Auger transitions
• At lower n radiative transitions dominate:

Muonic X-rays

< 1 ns ( << μ lifetime )
Muonic atoms

- 'Nuclear' physics?

negative muons

Stopped negative muon:
- Atomic capture @ $n \approx 14$
- At high $n$: Auger transitions
- At lower $n$ radiative transitions dominate:

Muonic X-rays

Cascade

$< 1 \text{ ns} \ (<< \mu \text{ lifetime})$
Muonic atoms

- 'Nuclear' physics? → negative muons

Stopped negative muon:
- Atomic capture @ \( n \approx 14 \)
- At high \( n \): Auger transitions
- At lower \( n \) radiative transitions dominate: **Muonic X-rays**
- Decay in orbit
Muonic atoms

- 'Nuclear' physics?

\[ Z^- \] negative muons

Stopped negative muon:

- Atomic capture @ \( n \approx 14 \)
- At high \( n \): Auger transitions
- At lower \( n \) radiative transitions dominate:
  **Muonic X-rays**
- Decay in orbit
- Muon capture + excited nucleus
Muonic atoms

- 'Nuclear' physics?

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- Atomic capture @ n ≈ 14
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Muonic atoms

- Why (nuclear) physics with muonic atoms?

Very much like the H atom, but:

Bohr energies:

$$E_n = \frac{mc^2 \alpha^2 Z^2}{2n^2}$$

Bohr radii:

$$r_n = \frac{n^2 \hbar c}{mc^2 \alpha Z}$$

Energies 200 higher:
$$\rightarrow 100 \text{ keV, few MeV range}$$

Radii 200 times smaller:
$$\rightarrow \text{significant overlap with the nucleus}$$
Muonic atoms

- Why (nuclear) physics with muonic atoms?

The muon spends quite some time inside the nucleus:

**Laboratory for (short range) muon-nucle(ar)(on) interactions**

Very much like the H atom, but:

Bohr energies:

$$E_n = \frac{mc^2 \alpha Z^2}{2 \, n^2}$$

Bohr radii:

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Energies 200 higher:

\[ \rightarrow 100 \text{ keV, few MeV range} \]

Radii 200 times smaller:

\[ \rightarrow \text{significant overlap with the nucleus} \]
MuX

What is muX?

- A renewed effort for precision muonic X ray measurements at the Paul Scherrer Institute with germanium detectors
- Particle physics / neutral currents main motivation
  - Measuring 2P1S in $^{226}$Ra to determine charge radius of radioactive atom
    Support electric APV measurement
  - Detecting 2S1S transitions motivated by APV
- Measuring muonic X-rays in $\mu$g of materials
- Nuclear physics as it comes along:
  - Quadrupole moment of $^{185/187}$Re
  - $\gamma$’s after muon capture, motivated by double $\beta$-decay searches
- 2019: Miniball high-purity germanium array @ PSI (thank you LHC/CERN shutdown!)
Experimental setup

2015

- Operate high-purity germanium detectors (HPGe) at a muon beam line
Experimental setup

- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with $D_2/H_2$ gas cell
- Measure muonic X-ray spectrum of Re

$\gamma's @ 100 \text{ keV} - \text{few MeV}$
Operate high-purity germanium detectors (HPGe) at a muon beam line

First tests with D$_2$/H$_2$ gas cell

Measure muonic X-ray spectrum of Re

- Quadrupole moment of $^{185/187}$Re from 5g $\rightarrow$ 4f transitions
  - i. Nuclear ground-state hyperfine splitting
  - ii. Fit E(7-6) and two intensities
  - iii. Line shape from neighboring γ transitions
  - iv. Convolute with finite width transition
  - v. Calculate all other energies and intensities in terms of Q

**First physics results!**
Experimental setup

- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with $D_2/H_2$ gas cell
- Measure muonic X-ray spectrum of Re

**2015**

**2016**

- Quadrupole moment of $^{185/187}\text{Re}$ from $5g \rightarrow 4f$ transitions (only nuclear ground state hyperfine splitting)
  - i. Fit $E(7-6)$ and two intensities
  - ii. Line shape from neighboring $\gamma$ transitions
  - iii. Convolute with finite width transition
  - iv. Calculate all other energies and intensities in terms of $Q$

- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with $D_2/H_2$ gas cell
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First physics results!

<table>
<thead>
<tr>
<th></th>
<th>$Q$ (Barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{185}\text{Re}$</td>
<td>2.07(2)(5)</td>
</tr>
<tr>
<td>$^{187}\text{Re}$</td>
<td>1.94(2)(5)</td>
</tr>
</tbody>
</table>

Our result

<table>
<thead>
<tr>
<th></th>
<th>$Q$ (Barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{185}\text{Re}$</td>
<td>2.21(4)</td>
</tr>
<tr>
<td>$^{187}\text{Re}$</td>
<td>2.09(4)</td>
</tr>
</tbody>
</table>

Konijn et al. (neglecting $5f_{5/2} \rightarrow 4d_{5/2}$ \& $5g_{7/2} \rightarrow 4f_{7/2}$ transitions)

**Master thesis Stella Vogiatzi**

**Analysis of the hyperfine splitting of the $5 \rightarrow 4$ transitions in muonic Re-185 and Re-187**

**Theoretical prediction of the fine and hyperfine structure of kaonic Re-185 and Re-187 atoms**

Niklas Michel, Natalia S. Oreshkina, and Christoph H. Keitel
Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
(Received 19 August 2017; published 28 September 2017)
Experimental setup

- Develop *triggerless* DAQ and analysis
- 11 HPGe detectors from various collaborators & French/UK Ge Pool
- Muon counters, Electron counters, BGO shield
- Physics:
  - Stop muons in µg of material
  - Measure 2s1s transition in Zn and Kr

2015 - 2016

Got serious, no longer a side project
Experimental setup

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**Bread and butter spectrum**

- 60Co calibration lines
- Nuclear capture
- Kr 3D2P
- Balmer series
- Lyman series
- Michel electrons and neutrons
- 10 ns time resolution on HPGe detectors
Experimental setup

- Move the MiniBall HPGe array from ISOLDE/CERN to PSI
- Measurements with radioactive targets
- Extended 7 week program
  - Ra and Cm measurements (A. Knecht & Co)
  - γ’s after muon capture (Dubna)
  - Elemental analysis
  - 2s1s measurements in Zn (F. Wauters & Co)

Running right now
MuX physics results & plans

- Measuring 2P1S in 226Ra → Input for a APV experiment on a single trapped Ra ion.

\[ E_{1PNC} = K_r \ Z^3 \ Q_w \]

- Determine \( E(2P1S) < 10 \text{ keV} \) to determine charge radius < 0.2% needed to calculate \( K_r \)

- All Ra isotopes are radioactive! → < 5 μg of 226Ra
• Measuring 2P1S in 5 μg of radium

  ○ Stop 30 MeV/c muons in a small amount of material

    1. Stop in 100 Bar of H₂ + 0.25% - 1% of D₂
    2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy
MuX physics results & plans

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    3. μD moves freely through H₂ gas at ca. 5 eV

Ramsauer-Townsend effect in muonic atom scattering

F. Mulhauser,1,A. Adamczak,2,A. G. A. Beer,3 V. M. Bystritsky,4 M. Filipowicz,5 M. C. Fujiwara,6 T. M. Huber,7 O. Huot,1 R. Jacot-Guillarmod,1,4 P. Kammei,8,S. K. Kim,9 P. E. Knowles,1 A. R. Kunselman,10 G. M. Marshall,6 A. Olin,6 C. Petitjean,11 T. A. Porcelli,6 L. A. Schaller,1 V. A. Stolupin,4 J. Woźniak,12 and J. Zmeskal13

(TRIUMF Muonic Hydrogen Collaboration)
muX physics results & plans

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    4. Upon hitting the chamber walls: μD → μZ transfer

**Ramsauer-Townsend effect in muonic atom scattering**


(TRIUMF Muonic Hydrogen Collaboration)
muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material
  - Demonstrated in 2017, few % efficiency

Small gas cell for 100 Bar of H₂ with a Cu disk + 3-50nm of Au

\[ \mu D + H \rightarrow 3\text{He} + \gamma (5.5 \text{ MeV}) \]

Delay (after transfer)
Au X-rays
Prompt events
muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material
  - Demonstrated in 2017, few % efficiency
  - Measured 248/246Cm & 226Ra 2 weeks ago!

Drop on Demand target production at Institut für Kernchemie (Mainz)

<table>
<thead>
<tr>
<th>Method</th>
<th>Activity (kBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{248}$Cm/$^{246}$Cm Plating / Printing(1)</td>
<td>2.5 / 8.4</td>
</tr>
<tr>
<td>$^{248}$Cm/$^{246}$Cm Plating / Printing(2)</td>
<td>2.4 / 8.1</td>
</tr>
<tr>
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<tr>
<td>$^{226}$Ra Plating / Printing</td>
<td>49.5</td>
</tr>
<tr>
<td>$^{226}$Ra Plating</td>
<td>91.6</td>
</tr>
<tr>
<td>$^{226}$Ra Plating / Printing</td>
<td>160.1</td>
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muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material
  - Demonstrated in 2017, few % efficiency
  - Measured 248/246Cm & 226Ra 2 weeks ago!

![Graph showing the Cm 2P1S multiplet](image)

*We have measured 226Ra!"
- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure APV with muons directly?
  - Motivation:
    i. Is the muon special
    ii. Neutral currents at low Q^2 have not yet been measured
  - Goal of muX:
    i. Observe 2S1S transition
    ii. Achieve good S/B for a 10^{-4} B.R. transition

**Not a new idea:**

**Is the muon special?**

- Extending theories on muon-specific interactions
  - Carl E. Carlson and Michael Fried
  - Phys. Rev. D 92, 095024 – Published 30 November 2015

- Constraints on muon-specific dark forces
  - Savely G. Karshenboim, David McKemn, and Maxim Pospelov
  - Phys. Rev. D 90, 075004 – Published 13 October 2014

- Testing Parity with Atomic Radiative Capture of μ^{-}
  - David McKemn and Maxim Pospelov
  - Phys. Rev. Lett. 108, 263001 – Published 29 June 2012
muX physics results & plans

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Level scheme Zn:

MC estimate of signal to background: 0.05

Our current project focuses on:

1. Detecting the 2S1S transition  2017/2018
2. Establishing a signal to BG of O(1)  2019
3. Determine reach of APV experiment  2020+
• Measuring 2P1S in 5 μg of radium
• Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  ○ Increase the 2S population with μH → μKr transfer
muX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  - Increase the 2S population with μH → μKr transfer
    - 3-4 fold increase of 2S population
    - BR ≈ 6 • 10^{-4} for 2S1S
    - Still Compton BG dominated

X-ray spectrum of 1% Kr gas in 100 Bar H2

First observation of 1 photon 2S1S transition

2018 data
MuX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  - Increase the 2S population with μH → μKr transfer
  - Select 2S population by tagging on (n>2)P2S transitions
    i. Loose efficiency
    ii. Potential to achieve S/B of O(1)

Level scheme Zn:

Tag with (n>2)p2S X-rays

(keV)
muX physics results & plans

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    ii. Potential to achieve S/B of O(1)

First attempt in 2017

Gated energy spectra versus Gate, prompt eVeto, PP muon

2019:
- 1 week of beam time in November
- Optimized detector geometry
- >100 counts with conservative analysis cuts

Level scheme Zn:

- tag with (n>2)p2S X-rays

(keV)
muX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
- Nuclear γ transitions after muon capture, of interest for matrix element calculations for double β-decay

- $^{82}$Kr ($^{82}$Se of SuperNemo)
- $^{130}$Xe ($^{130}$Te of Cuore)
muX status

The collaboration:

A. Adamczak¹, A. Antognini²,³, N. Berger⁴, T. Cocolios⁵, R. Dressler², C. Düllmann⁴, R. Eichler⁵, P. Indelicato⁶, K. Jungmann⁷, K. Kirch²,³, A. Knecht², J. Krauth¹, J. Nuber², A. Papa², R. Pohl¹, M. Pospelov⁵,⁹, E. Rapisarda², D. Renisch⁴, P. Reiter¹⁰, N. Ritjoho²,³, S. Roccia¹¹, N. Severijns⁵, A. Skawran²,³, S. Vogiatzi², F. Wauters⁴, and L. Willmann⁷

¹Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
²Paul Scherrer Institut, Villigen, Switzerland
³ETH Zürich, Switzerland
⁴University of Mainz, Germany
⁵KU Leuven, Belgium
⁶LKB Paris, France
⁷University of Groningen, The Netherlands
⁸University of Victoria, Canada
⁹Perimeter Institute, Waterloo, Canada
¹⁰Institut für Kernphysik, Universität zu Köln, Germany
¹¹CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France

Outlook:

- Finish analysis of 2017 → 2019 data
- Determine reach 2S1S APV experiment
- Get $<r^2>$ from 2P1S transition energies

Theoretical predictions for nuclear polarization will limit final precision

+ Jonas Nuber, Narongrit Ritjoho, Julian Krauth, Ahmed Ouf, Madalina Ravar, David Werner, ...
EXTRA
20 x 20 x 0.20 mm beam counter

80 x 80 x 4 mm veto counter with 18 mm hole

SiPM readout
- **SIS3316 digitizer modules**
  - 250 MHz
  - Save every single channel trigger (coincidences & events in software)
  - Save raw waveforms

**Trapezoidal filter**

**Graph**

**Save raw waveforms**

**10 ns time resolution**