Muonic atom spectroscopy with radioactive targets

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On behalf of the muX collaboration


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Muonic atom spectroscopy

- Due to the higher muon mass, there is large overlap of the low-lying muonic states with the nuclear charge distribution.
- The energy of the low-lying muonic levels is highly affected by the nuclear structure details.
- The measurement of the muonic energy levels allows to extract properties of the nucleus such as the charge radius.

muX aims to measure the nuclear charge radius of $^{226}\text{Ra}$ and $^{248}\text{Cm}$ radioactive isotopes.

$E_{1s}(Z = 82) \sim 19 \text{ MeV (point nucleus)}$
$\sim 10.6 \text{ MeV (finite size)}$
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Experimental setup evolution of muX

2015 first test of muonic atom spectroscopy with natural Re, Pb, W
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2016 Measurement of $^{185,187}$Re
Spectroscopic quadrupole moment of $^{185,187}$Re

- In 2016, a 500 mg $^{185,187}$Re target was measured with two HPGe detectors

- The spectroscopic quadrupole moment describes the effective shape of the nucleus

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Fine splitting

$
\vec{J} = \vec{s} + \vec{l}
$

$5g_{9/2} 
5g_{7/2} 
4f_{7/2} 
4f_{5/2}$
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![Spherical Prolate Oblate](image)

Spherical $Q = 0$
Prolate $Q > 0$
Oblate $Q < 0$

5g-4f muonic X-ray spectrum in $^{185}$Re

Theoretical predictions by N. Michel and N. Oreshkina, Max Planck Institute for Nuclear Physics, Heidelberg

First physics result!
$^{185}$Q = 2.07(5) b
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Fine splitting $\vec{J} = \vec{s} + \vec{l}$

Hyperfine splitting $\vec{F} = \vec{I} + \vec{J}$

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Outlook: charge radius of $^{185,187}$Re

- Currently ongoing analysis of the 2p-1s hyperfine transitions in $^{185,187}$Re for the extraction of its nuclear charge radius (has not been measured)
- Admixture of ground and excited hyperfine states due to the dynamic effect — very complicated muonic energy spectrum

Master thesis project of Jérémy Layan

2p-1s muonic X-ray spectrum in $^{185}$Re

Theoretical calculations by N. Oreshkina, MPI
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Preliminary fit of the 2p-1s muonic X-ray transitions in $^{185}$Re

Theoretical calculations by N. Oreshkina, MPI
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2015 first test of muonic atom spectroscopy with natural Re, Pb, W

2016 measurement of $^{185,187}$Re

2017 first measurement with μg targets
Muon transfer to microgram target

… moving to measurement of radioactive targets (mass in μg)…

… technique to transfer muons to μg targets involves a gas cell with H₂/D₂ admixture in 100 bar…

… inspired by the work of Strasser et al. and Kraiman et al…

1. μ⁻ stops in 100 bar of H₂ + 0.1-1.5% D₂ & forms muonic hydrogen μp

2. transfer to deuterium μp → μd

3. μd moves almost freely in the H₂ gas (Ramsauer-Townsend effect [1])

4. transfer to high-Z element μd → μZ when hitting target & emission of X-rays during the atomic cascade

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muX detectors

The gas cell

The muon and electron counters

Schematics of detector setup

$\mu$-beam

electron veto

gas cell

muon entrance

~30 MeV/c muon beam

$\mu$Pb X-ray

Pb-208

target

gas cell

muon entrance

HPGe

$\mu$Z X-ray

HPGe

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Schematics of detector setup

Demonstration of principal in a 5 µg gold target in 2017, 18.5 h of measurement

Measurement of $^{248}\text{Cm}$ and $^{226}\text{Ra}$

- In 2019 we measured $^{248}\text{Cm}$ and $^{226}\text{Ra}$ with the Miniball germanium detectors array

- 8 Miniball germanium clusters and 2 standalone germanium detectors making a total of 26 HPGe detectors were operating
Measurement of $^{248}\text{Cm}$ and $^{226}\text{Ra}$

- We measured 15 μg of $^{248}\text{Cm}$ and 1.4 μg of $^{226}\text{Ra}$ for 6 and 5 days, respectively.
- Targets were produced by the radiochemistry group of the Institute of University of Mainz.
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...2p-1s muonic X-ray spectrum in $^{248}$Cm...

![Graph showing the 2p-1s muonic X-ray spectrum in $^{248}$Cm with energy on the x-axis and counts on the y-axis.]

Preliminary
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...2p-1s muonic X-ray spectrum in $^{248}$Cm...

...$^{226}$Ra spectrum is still being analysed...
Other measurements muX is involved in

- Measurement of rare 2s-1s transitions in medium Z elements to investigate the reach of a possible APV experiment with muonic atoms
  
  *Frederik Wauters, Mainz*

- Studies of nuclear γ-lines after ordinary muon capture [1], interesting for nuclear matrix element calculations for double beta-decay processes
  
  *Daniya Zinatulina, Dubna*

- Elemental analysis measurements of archaeological artefacts, meteorites, batteries, …
  
  *Alex Amato, μSR group PSI*

Outlook & Future plans

- Extraction of the nuclear charge radius of $^{185}$Re and $^{187}$Re
- Analysis of $^{248}$Cm data for the extraction of its nuclear charge radius
- Potentially remeasure $^{226}$Ra and other isotopes of interest to the nuclear physics community
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THANK YOU
BACKUP SLIDES
Muonic atom spectroscopy

Atomic capture (direct)
- bombard target with $\mu^-$
- $\mu^-$ slow down & is captured @ high principal quantum number $n \sim 14$
  … only possible with $\geq 100$ mg targets … radioactive targets are typically restricted to $\sim \mu g$ quantities in the lab

Cascade
- initially dominated by Auger transitions
- below $n \sim 6$, muonic X-rays become the dominant de-excitation mechanism
- the X-rays are detected with Ge detectors

...at the 1s state, the muon either decays or is captured by the atomic nucleus
Atomic parity violation in radium

... why to measure $^{226}$Ra?

- Atomic parity violation transitions in atoms probe the low transfer momentum $Q$ region in the running of the $\sin^2(\theta_W)$ plot
- $APV$ is magnified proportionally to $\gtrsim Z^3$
  $\Rightarrow$ heavy atoms are good candidates

Ongoing effort to measure $APV$ in a single Ra$^+$ ion [1]:

- Weak interactions mix states of opposite parity in the Ra ion and enable the $APV$ dipole transition $E_{1APV}$
  $$E_{1APV} = k \cdot Q_W$$
  $k$: overlap of nuclear and electronic wave functions
  $Q_W$: weak charge (related to Weinberg angle)

- Extraction of the Weinberg angle is possible using precise atomic calculations
  
- The absolute nuclear charge radius of Ra at the level of 0.2% at least is needed

... we also got interested in measuring other radioactive isotopes such as $^{248}$Cm ...

Curium & Radium targets 2019

- Radiation protection restrictions at PSI allow for 16 μg of $^{248}\text{Cm}$ and 5.5 μg of $^{226}\text{Ra}$
- Targets were produced by the radiochemistry group of the Institute of University of Mainz
- Target production is a difficult process

### Curium target
- Cm-MP3
  - 15.46 μg
  - uniformly distributed

### Radium targets
- Ra-MP1
  - 1.35 μg
  - uniformly distributed
  - rigid

- Ra-MP2
  - 2.50 μg
  - uniformly distributed
  - brittle

- Ra-MP3
  - 4.37 μg
  - ring structure
  - rigid