Nuclear Structure with radioactive muonic atoms

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for the muX collaboration
Muonic Atom Spectroscopy:
unique laboratory for precision measurements

- Muonic energy levels highly sensitive to nuclear charge distribution due to large overlap
- Using QED and model for nuclear charge distribution allow to extract charge radius

Finite Size Effect

$$E_{1s} (Z=82) \sim 21 \text{ MeV (point nucleus)} \rightarrow 10.6 \text{ MeV (finite size)}$$

Atomic energies: keV-MeV ≥ Nuclear energies

Elisa Rapisarda

Fission Workshop 20th-24th March 2017
Nuclear muon capture and neutrons

Once in the 1S state the muon can:
- decay (lifetime = 2.2 us) $\mu^- \rightarrow e + \nu_e + \nu_\mu$
- be captured by the nucleus $\mu^- + (N,Z) \rightarrow (N+1,Z-1)^* + \nu_\mu$

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**MUON CAPTURE**
- $m_\mu c^2 \sim 105$ MeV
- $<E^*> \sim 15-20$ MeV but wide distribution
- Populate several multipoles

$Q_{\beta} \leq 20$ MeV
Mainly one multipole

**β-decay**

Total muon capture rate, $<n>$ to compare with theory
Detailed spectroscopy

RAMA workshop, ECT Trento, May 2001
Muonic Atom Spectroscopy in the past

- Impressive precision in the extracted charge radius can be achieved
- For $^{208}\text{Pb}$: $<r^2>^{1/2} = 5.5031(11)$ fm
  - $2 \times 10^{-4}$ relative precision

$\mu$E1 channel at PSI
- $5 \times 10^6 \mu^-/s$ at 125 MeV/c

Muonic atom and electron scattering investigations require at least tens of milligrams of target material.
Our first steps

- Preliminary beam time in October 2016
- Measured with 500 mg $^{185}\text{Re}$, $^{187}\text{Re}$ and 1000 mg $^{208}\text{Pb}$ for calibration
Our first steps

A lot of information are contained in the spectra:

- Energy first excited states
- Diagonal matrix elements
- Transitional matrix elements

Rhenium is the last stable element without absolute charge radius

Complicated spectrum due to hyperfine structure and low-energy nuclear excitations

Prompt muon induced fission in actinide elements

*D.F. Measday/Physics Reports 354 (2001) 243–409*
What about radioactive targets?

*Johnson et al., Phys. Lett. 161B, 75 (1985)*

- 1 gram targets of $^{241,243}\text{Am}$ ("a modest weight of 1 g") (!)
- Partially stop of the muon beam

**Radioactive isotope in Experimental Hall of PSI**

| Isotope | Half-life | Max. Activity | Max. Mass | Density     |
|---------|-----------|---------------|-----------|-------------|
| $^{226}\text{Ra}$ | 1600 y    | 200 kBq       | 5 µg      | ~ 1 µg/cm² |
| $^{248}\text{Cm}$ | 350'000 y | 5 kBq         | 32 µg     | ~ 7 µg/cm² |
| $^{209}\text{Po}$ | 102 y     | 200 kBq       | 0.3 µg    | ~ 0.1 µg/cm² |

**Challenges:**

- the high energy muon beam
- small amount of material

**Methods for limited mass of the target**

- Low-energy muon beam (5 keV) that can be stopped in ~ µg/cm² target thickness
  → Beam developed for the Lamb shift measurement of muonic hydrogen

- Stop muons in a D2/H2 mixture and exploiting transfer reactions
  → Method pioneered at RIKEN-RAL

*P. Strasser, et al. Nucl. Phys. B, Proc. Suppl. 149 (2005) 390-392*
Alternative experimental approach

- stopping muons in gaseous hydrogen
- Transfer from muonic hydrogen to muonic deuterium $\mu H + D \rightarrow \mu D + H$ (45eV energy gain)
- $\mu D$ decelerates in $H_2$ down to $\sim 1$ eV (Ramsauer-Townsend effect)
- it reaches the wall
- Transfer to heavier elements
Test the technique(I)

Constructed a cell with 10 bar H₂/D₂ mixture

10 cm long, 3 cm diameter

Wall covered with Cu coated with Au
Optimization of the technique(II)

- need compactness to maximize the efficiencies
  - Walls coated with the radioactive element of interest (at least 10 nm → 2 cm²)
  - Muon range: 2-3 mm
  - Expected efficiency (GEANT4) of μZ formation ≈ 3% of incoming muon rate (15 kHz)

- need high detection efficiency

**Beam time in 2017**

Stop muons in a gas cell at 100 bar pressure (3 cm diameter, 1.5 cm long)

9 HpGe detectors: 6 from UK-FR loan pool + 1 Miniball spare cluster (KULeuven) + 2 from PSI

U-238 in the quantity of 5 µg
Conclusions and Perspective

• Muonic X-rays Spectroscopy
  - Experimental programme at PSI starts with $^{226}$Ra
  - Possibility to develop the method for several radioactive sample

• Interests:
  - Nuclear structure effects other than nuclear charge radii
  - Physics of muon capture
The muX Collaboration

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