Muonic future

Atoms for nuclear physics and metrology

Randolf Pohl for the CREMA and muX collaborations
Experiments

Muonic atoms
- Laser spectroscopy
  - Lamb shifts → charge radii
  - Hyperfine splittings → Zemach radii
- X-ray spectroscopy
  - Charge radii of heavy-Z atoms
(1a) Muonic atoms with Lasers

- So far: **Laser spectroscopy** of **Lamb shifts** of
  \( \mu \text{H}, \mu \text{D}, \mu ^3 \text{He}^+, \mu ^4 \text{He}^+ \)
  \[ \rightarrow \text{CHARGE radii of p, d, } ^3 \text{He, } ^4 \text{He} \]

- Next (approved @ PSI):
  Laser spectroscopy of **Hyperfine splittings (1S)**
  \( \mu \text{H}, \mu ^3 \text{He} \)
  \[ \rightarrow \text{ZEMACH (magnetic) radii of p, } ^3 \text{He} \]

Beam time 2016 (test), data in 2018 ff. (??)
similar projects in Japan and Italy/RAL (Vacchi)
Proton Zemach radius

\[ R_Z \text{ [fm]} \]

\[ \mu H, \text{ Antognini et al. 2013} \]

\[ e-p, \text{ Mainz 2011} \]

\[ H, \text{ Volotka 2005} \]

\[ H, \text{ Dupays 2003} \]

\[ e-p, \text{ Friar 2004} \]

Our goal.
Principle of the $\mu_p$ HFS experiment

- $\mu^-$ of 10 MeV/c are detected $\rightarrow$ trigger the laser
  - $\mu^-$ stops in H$_2$ gas (500 mbar, 50 K) $\rightarrow$ $\mu_p(F=0)$ formation

- Laser pulse: $\mu_p(F=0) \rightarrow \mu_p(F=1)$
  - Collision: $\mu_p(F=1) + \text{H}_2 \rightarrow \text{H}_2 + \mu_p(F=0) + E_{\text{kin}}$
  - Diffusion: the faster $\mu_p$ reach the target walls

- At the wall: $\mu^-$ transfer to high-Z atom $\rightarrow (\mu Z)^*$ formation
  - $(\mu Z)^*$ de-excitation $\rightarrow$ MeV X-rays, e$^-$ and $\mu^-$ capture

- Resonance: Number of X-rays/e$^-$/capture signals after laser excitation versus laser frequency

Signal events:
- Laser excited $\mu_p$
  - reach wall in $t \in [t_{\text{laser}}, t_{\text{laser}} + \Delta t]$

Background events:
- Thermalized $\mu_p$
  - reach wall in $t \in [t_{\text{laser}}, t_{\text{laser}} + \Delta t]$
  $\Rightarrow$ Cool target to 50 K
**Principle of the $\mu^3$He + HFS experiment**

- $\mu^-$ of 10 MeV/c are detected $\rightarrow$ trigger a laser
  - $\mu^-$ stop in $^3$He gas (50 mbar, 300 K) $\rightarrow$ $\mu^3$He +

- Laser pulse: drives F=0$\rightarrow$F=1 and F=1$\rightarrow$F=0 transitions
  $\Rightarrow$ change of the avg. muon polarization

- Detect electron from muon decay
  - Decay asymmetry: $N_e(left)$ increases, $N_e(right)$ decreases
  - Resonance: $N_e(left) - N_e(right)$ vs. laser frequency

![Diagram of the experiment setup](image)

![Graph showing electron counts vs. time](image)
\( \mu^3 \text{He} + \) resonance search

Number of frequency points:
Time needed for a 4\( \sigma \) effect over BG
Beam time needed for resonance search (70\% uptime)
Beam time needed for resonance scan

\[ \tau(\mu^3 \text{He}^+) = 1.8 \, \mu s \] (50 mbar)

\( (\mu^3 \text{He})^+ + \text{He} \rightarrow \text{He}(\mu^3 \text{He})^+ + \text{He} \)
(1b) Muonic atoms: X-rays

- MuX collab. approved @ PSI (with N. Berger)
  x-ray spectroscopy of **RADIOACTIVE** muonic atoms
  → CHARGE radii of $^{226}$Ra, $^{248}$Cm, $^{209}$Po, ...
- Challenge: max. masses in the μg range
  → stop μ- in μg/cm$^2$ targets
- Low-energy muon beam line developed for μH
  Beam times: 2016 (Re), radioactive data 2017/18 ff.
  Extension to many more nuclei possible
Proposal for BVR 47

Measurement of the charge radius of radium

A. Antognini¹,², N. Berger³, D. vom Bruch³, R. Dressler¹, R. Eichler¹, P. Indelicato⁴, K. Jungmann⁵, K. Kirch¹,², A. Knecht¹, A. Papa¹, R. Pohl⁶, M. Pospelov⁷,⁸, E. Rapisarda¹, N. Severijns⁹, F. Wauters³, and L. Willmann⁵

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³University of Mainz, Germany
⁴LKB Paris, France
⁵University of Groningen, The Netherlands
⁶Max Planck Institute of Quantum Optics, Germany
⁷University of Victoria, Canada
⁸Perimeter Institute, Waterloo, Canada
⁹KU Leuven, Belgium

Open Users Meeting BV47, 9. 2. 2016
Atomic Parity Violation in Radium

- Electron-quark neutral weak interaction mixes states of opposite parity

- Measure $E_{1PNC}$ admixture in $E2$ transition and extract weak charge using precision atomic calculations

- Potential of improving Cs result by more than factor 5

- Needs knowledge of the radium charge radius with 0.2% accuracy

Wansbeek et al., PRA 78, 050501 (2008)
Wood et al., Science 275, 1759 (1997)
Impressive precision in the extracted charge radius can be achieved.

For $^{208}$Pb: $\langle r^2 \rangle^{1/2} = 5.5031(11)\text{ fm}$

2x10^{-4} relative precision

<table>
<thead>
<tr>
<th>Transition</th>
<th>Kessler (Ref. 9)</th>
<th>Hoehn (Ref. 27)</th>
<th>This experiment</th>
</tr>
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<tbody>
<tr>
<td>$2p_{1/2}$-$1s_{1/2}$</td>
<td>5 962.770(420)</td>
<td>5 962.854(90)</td>
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</tr>
<tr>
<td>$2p_{1/2}$-$1s_{1/2}$</td>
<td>5 777.910(400)</td>
<td>5 778.058(100)</td>
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</table>
Impressive precision in the extracted charge radius can be achieved

For $^{208}\text{Pb}$: $\langle r^2 \rangle^{1/2} = 5.5031(11)$ fm

$2 \times 10^{-4}$ relative precision

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**TABLE V.** Experimental muonic transition energies (keV) in $^{208}\text{Pb}$ (recoil corrected).

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<th>Transition</th>
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<td>5 777.910(400)</td>
<td>5 778.058(100)</td>
<td></td>
</tr>
<tr>
<td>$3d_{3/2}-2p_{1/2}$</td>
<td>2 642.110(60)</td>
<td>2 642.292(23)</td>
<td>2 642.332(30)</td>
</tr>
<tr>
<td>$3d_{3/2}-2p_{3/2}$</td>
<td>2 500.330(60)</td>
<td>2 500.580(28)</td>
<td>2 500.590(30)</td>
</tr>
<tr>
<td>$3d_{3/2}-2p_{3/2}$</td>
<td>2 457.200(200)</td>
<td>2 457.569(70)</td>
<td></td>
</tr>
<tr>
<td>$3p_{1/2}-2s_{1/2}$</td>
<td>1 507.480(260)</td>
<td>1 507.754(50)</td>
<td></td>
</tr>
<tr>
<td>$3p_{1/2}-2s_{1/2}$</td>
<td>1 460.558(32)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2s_{1/2}-2p_{1/2}$</td>
<td>1 215.430(260)</td>
<td>1 215.330(30)</td>
<td></td>
</tr>
<tr>
<td>$2s_{1/2}-2p_{3/2}$</td>
<td>1 030.440(170)</td>
<td>1 030.543(27)</td>
<td></td>
</tr>
<tr>
<td>$5f_{5/2}-3d_{5/2}$</td>
<td>1 404.740(80)</td>
<td>1 404.659(20)</td>
<td></td>
</tr>
<tr>
<td>$5f_{5/2}-3d_{3/2}$</td>
<td>1 366.520(80)</td>
<td>1 366.347(19)</td>
<td></td>
</tr>
<tr>
<td>$5f_{5/2}-3d_{3/2}$</td>
<td>1 361.748(250)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4f_{7/2}-3d_{5/2}$</td>
<td>971.850(60)</td>
<td>971.974(17)</td>
<td></td>
</tr>
<tr>
<td>$4f_{7/2}-3d_{3/2}$</td>
<td>937.980(60)</td>
<td>938.096(18)</td>
<td></td>
</tr>
<tr>
<td>$4f_{7/2}-3d_{3/2}$</td>
<td>928.883(14)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4d_{5/2}-3p_{1/2}$</td>
<td>920.959(28)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4d_{5/2}-3p_{1/2}$</td>
<td>891.383(22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4d_{5/2}-3p_{1/2}$</td>
<td>873.761(63)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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μE1 channel at PSI
$5 \times 10^{6}$ μ/s at 125 MeV/c
Most of the stable isotopes have been measured with muonic atom spectroscopy.

In a few special cases also radioactive isotopes, e.g. americium
  - The paper describes the americium target as “modest weight of 1 gram”
Radioactive Isotopes in Experiment Hall

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Max. Activity</th>
<th>Max. Mass</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}\text{Ra}$</td>
<td>1600 y</td>
<td>200 kBq</td>
<td>5 µg</td>
<td>~ 1 µg/cm²</td>
</tr>
<tr>
<td>$^{248}\text{Cm}$</td>
<td>350’000 y</td>
<td>5 kBq</td>
<td>32 µg</td>
<td>~ 7 µg/cm²</td>
</tr>
<tr>
<td>$^{209}\text{Po}$</td>
<td>102 y</td>
<td>200 kBq</td>
<td>0.3 µg</td>
<td>~ 0.1 µg/cm²</td>
</tr>
<tr>
<td>$^{185,187}\text{Re}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- Isotopes without measured charge radius that will be addressed in this proposal
- Maximum activity based on current regulations and without major modifications to experimental area infrastructure (100 x approval limit)
Setup for Proposed Measurements

- Radioactive targets and germanium detector in fringe field of 5T-magnet
- Target and detector at \( \sim 1 \text{ T} \)
- Expansion of beam by factor 2 acceptable
Natural lead, tungsten and rhenium measured

Free-running spectra without any background reducing cuts

Additional lines in rhenium due to low-lying nuclear levels
- Preliminary data allows to tune our simulations
- Work in progress but decent agreement so far
Muonic atoms: Future

- Muonic Li, later Be, maybe B
  CHARGE radii from Lamb shift (laser spectroscopy)
Lamb shifts and fine-structure splittings for the muonic ions $\mu^{-}$-Li, $\mu^{-}$-Be, and $\mu^{-}$-B:
A proposed experiment

G. W. F. Drake and Louis L. Byer*

Department of Physics, University of Windsor, Windsor, Ontario, Canada N9B 3P4
(Received 28 February 1985)

TABLE VII. Calculated absorption wavelengths (in Å) for transitions in muonic ions. The first uncertainty listed for the wavelengths is that due to nuclear polarization and the second is that due to the rms nuclear radius $R$.

<table>
<thead>
<tr>
<th>Ion</th>
<th>$R$ (fm)</th>
<th>$\lambda(2s_{1/2}-2p_{1/2})$</th>
<th>$\lambda(2s_{1/2}-2p_{3/2})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4$He</td>
<td>1.674$\pm$0.012</td>
<td>8978.0$\pm$ 4$\pm$27</td>
<td>8118.0$\pm$ 3$\pm$22</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>2.56$\pm$0.05</td>
<td>10097.0$\pm$ 33$\pm$1072</td>
<td>6275.0$\pm$ 13$\pm$414</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>2.39$\pm$0.03</td>
<td>7473.0$\pm$ 18$\pm$334</td>
<td>5147.0$\pm$ 9$\pm$159</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>2.520$\pm$0.012</td>
<td>$-9520.0\pm116\pm703$</td>
<td>$11512.0\pm173\pm1048$</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>2.45 $\pm$0.12</td>
<td>$-1393.0\pm 3\pm354$</td>
<td>$-4033.0\pm 27\pm2947$</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>2.42 $\pm$0.12</td>
<td>$-1481.0\pm 4\pm397$</td>
<td>$-4887.0\pm 46\pm4286$</td>
</tr>
</tbody>
</table>

Visible wavelengths!
Muonic atoms: Future

- Muonic Li, later Be, maybe B
  - CHARGE radii from Lamb shift (laser spectroscopy)
- Challenges: Stop μ- in Li gas
  - Thick Jet / MOT / Penning trap ??
  - Advanced low-energy μ- beam line:
    - 3keV → 100 eV or less.
- Lasers: Advanced CREMA lasers
- Time frame: 2018 ff. Long project.
- Synergies: muX with even less material
Muons!

... have a bright future!

PostDoc and PhD positions available in Mainz!