THE NUCLEAR CHARGE RADIUS OF RADIOACTIVE ISOTOPES BY MUONIC X-RAYS MEASUREMENTS

Alexander Albert Skawran, PSI
For the muX Collaboration
MUON

- “Big brother” of the electron
- 200 times heavier than an electron
- Lifetime of 2.2 µs
- Same electric charge as electrons
- Pion decay is used for muon creation at PSI

Scheme of pion production at PSI
“TRADITIONAL” MUONIC ATOM SPECTROSCOPY

Example of standard setup for muonic atom spectroscopy

Incoming muon beam

Ge Detectors

Target, $m = \mathcal{O}(100\text{mg})$

Simple target setup for unlimited target amount

Muonic atom cascade

$X \text{ ray} \ O(\text{MeV})$

$e^-$

$\mu^-$
Muonic atom energy spectrum is highly sensitive to nuclear charge distribution due to larger overlap.

Charge radius is extracted by QED calculations and model for nuclear charge distribution.

Precise radius extractions are possible.

Example: For $^{208}$Pb was achieved a RMS radius of $5.5031(11)$ fm with $2 \times 10^{-4}$ relative precision.

$E_{1s} (Z=82) \sim 19$ MeV (point nucleus), $10.6$ MeV (finite size)

(Kessler et al., PRC 11, 1719 (1975); Bergem et al., Physical Review C 37.6 (1988): 2821)
A planned atom parity violation experiment requires the radium charge radius with 0.2% accuracy.

E1 transition between $6^2D_{3/2}$ and $7^2S_{1/2}$ is forbidden.

Due to weak interaction a small admixture of E1 in E2 is possible.

Using precise calculations the admixture can be used to extract weak charge.
RADIUM TARGET

- So far only a few radioactive isotopes measured with muonic atom spectroscopy
- In the paper they describe the target weight as “modest weight of 1 g”
- The radium-226 target is allowed to have only several µg due to radioactivity safety regulations
- To stop enough muons O(100 mg) of radium are required
- New target set up required to increase event rate

Energy spectrum of Americium-241 and -243
Gas cell is filled with 100 bar hydrogen and 0.25% deuterium admixture.

Muon collides with $H_2$ molecules in gas cell.
Muon in gas cell is captured by a proton of a $H_2$ molecule. Muonic hydrogen $\mu p$ is produced.
Gas cell is filled with 100 bar hydrogen and 0.25% deuterium admixture.

Muonic hydrogen collides with $D_2$. The muon is transferred to a deuteron. The transfer results in $\mu d$ with a kinetic energy boost of several eV.
The gas is almost transparent to the $\mu d$ atom due to the Ramsauer-Townsend effect. $\mu d$ can move to target.
The \( \mu d \) atom transfers the muon to the target. Muonic X-rays are emitted.
PRESSURE TEST GAS CELL

➤ Gas cell has to resist a pressure of 100 bar

➤ Tested different setups

➤ Final set up includes a carbon fibre window with two support grid layers containing carbon fibre and titanium

➤ Window withstands a pressure of more than 350 bar, some screw threads could not take the increasing pressure
To estimate the efficiency of the muon transfer to the target and to detect coincidences, a thin scintillator is used to detect incoming muons.

Other scintillators are used as veto detectors for anti-coincidence with decay electron.
During 2017 an array of 11 Ge detectors were used.

It was the first time that an array was used for muonic atom spectroscopy.
GOLD SPECTRUM

➤ Used gold to test muon transfer

➤ Observed gold spectrum with 5 µg target

➤ Used lead for energy calibration

➤ Observed also muon catalysed fusion

Energy spectrum of 5 µg gold target
**Detected gammas per muon fraction in gold targets (preliminary)**

- Detected 2p-1s gammas per incoming muon for various target sizes and amounts
- Type of backing layer seems to have negligible influence
- Even a sufficient number of photons is achieved in the 5 $\mu$g target

<table>
<thead>
<tr>
<th>Target</th>
<th>Size</th>
<th>Backing</th>
<th>$N_\gamma / N_\mu$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 nm Au</td>
<td>4.9 cm$^2$</td>
<td>Cu</td>
<td>$(10.9 \pm 0.3) \times 10^{-5}$</td>
<td>10.0%</td>
</tr>
<tr>
<td>10 nm Au</td>
<td>4.9 cm$^2$</td>
<td>Cu</td>
<td>$(6.9 \pm 0.2) \times 10^{-5}$</td>
<td>6.3%</td>
</tr>
<tr>
<td>3 nm Au</td>
<td>4.9 cm$^2$</td>
<td>Cu</td>
<td>$(3.6 \pm 0.1) \times 10^{-5}$</td>
<td>3.3%</td>
</tr>
<tr>
<td>3 nm Au</td>
<td>4.9 cm$^2$</td>
<td>kapton</td>
<td>$(3.2 \pm 0.1) \times 10^{-5}$</td>
<td>2.9%</td>
</tr>
<tr>
<td>3 nm Au</td>
<td>1 cm$^2$</td>
<td>Cu</td>
<td>$(1.3 \pm 0.1) \times 10^{-5}$</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
A 5 µg radium-226 target leads to 200 kBq of all daughter.

Highest gamma emitters are lead-214 and bismuth-214.

The corresponding gamma rate is about 400 kHz.

Decay chain of Radium-226
TIME AND ENERGY RESOLUTION RADIOACTIVE TARGETS

➤ Performed measurements of a high rate 420 kHz yttrium-88 gamma source

➤ The radium source has a similar activity

➤ Offline analysis improves time and energy resolution

➤ DAQ can handle high data rate

---

*Preliminary* 

Effect of offline analysis on energy resolution

*Preliminary*

Time resolution of all Ge detectors at 898 keV

**Sum of all detectors at 898 keV**

**FWHM ~17 ns**
FIRST EXPERIENCES WITH CURIUM-248 AND RA-226 TARGETS

During July 2018 the first attempt to observe muonic curium-248 and radium-226 happened.

The production of appropriate targets was unsuccessful.
FIRST TRY WITH CURIUM-248

▷ A 100 μm copper plate is used as a substrate for curium-248. The copper is covered by a 50 nm thin gold film to avoid unwanted oxidation.

▷ Curium-248 was fixed on the gold layer by electrolysis.

▷ The activity of the curium-248 probe was 2,448 kBq (≈37 μg).

▷ The probe included an admixture of curium-246 with an activity of 8,978 kBq (≈2 μg).

Curium gas cell prepared for sealing
The estimated $2p \rightarrow 1s$ transitions for Cm-248 are:

- $2p_{1/2} \rightarrow 1s_{1/2} \approx 6500$ keV
- $2p_{3/2} \rightarrow 1s_{1/2} \approx 6754$ keV

No Cm lines were observed.

Cm was plated on the Au-Cu plate. Hence, a disturbing organic layer could cover the Cm target.

A flame treatment was applied to reduce the thickness of the organic layer. This resulted in no improvement of the gamma spectrum.
The observed alpha spectrum of the target shows two lines corresponding to $^{248}\text{Cm}$ and $^{246}\text{Cm}$.

- Due to the organic layer:
  - The two lines of each isotope smear out
  - Peak shift of $\sim 10$ keV
  - Huge tails on the left side
- Tested effect of organic layer with carbon covered gold disks

Energy (keV)

Counts

Alpha spectrum of $^{248}\text{Cm}$ and $^{246}\text{Cm}$

Carbon covered gold plate

$^{248}\text{Cm}$

5034.89(25) keV

5078.41(25) keV

$^{246}\text{Cm}$

5343.5(10) keV

5386.5(10) keV

(Nuclear Data Sheets 146, 387 (2017))

(Nuclear Data Sheets 96, 177 (2002))
FIRST TRY WITH RADIUM-226

- Ra-226 with an activity of 201.8 kBq is solved in acid
- During the first try it is plated on Cu-Au-Plate
- The plating destroyed the Au layer
- For a second plating the Ra-226 has to be removed from the Cu-Au-Plate
- During the separation occur many impurities in the solution
- The impurities have to be removed from the solution
- After all separations and the final plating only 1% of the original Ra-226 amount is left in the target
- A measurement in a reasonable time is not possible anymore
SUMMARY & OUTLOOK

➤ Muonic atom spectroscopy can be used for nuclear charge radius measurement

➤ Developed and tested a muon transfer method for tiny amount targets

➤ An improvement and quality assurance of the target production is required

➤ 2019 - Next try to observe muonic radium and curium X-rays
BACKUP SLIDES
RAMSAUER–TOWNSEND EFFECT

\[ E\Psi = -\frac{1}{2m} \frac{\partial^2}{\partial x^2} \Psi + V\Psi \]

\[ V(x) = \begin{cases} 
0 & x < 0 \\
V_0 & 0 < x < a \\
0 & x > a 
\end{cases} \]

\[ \Psi(x) = \begin{cases} 
e^{ikx} + Re^{-ikx} & x < 0 \\
Ae^{ikx} + Be^{-ikx} & 0 < x < a \\
Te^{-ikx} & x > a \end{cases} \]

\[ T = |T|^2 = \frac{1}{1 + \frac{V_0^2}{4E(E-V_0)} \sin^2 Ka} \quad Ka = 2\pi \frac{a}{\lambda} = n\pi \]
BASELINE CORRECTION

Counts

1st Signal

2nd Signal

Baseline (raw) vs Baseline (maw)

Base (raw) [ADC] vs Base (raw) [ADC]

<table>
<thead>
<tr>
<th>Entries</th>
<th>5266301</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean x</td>
<td>1135</td>
</tr>
<tr>
<td>Mean y</td>
<td>-14.03</td>
</tr>
<tr>
<td>Std Dev x</td>
<td>318.3</td>
</tr>
<tr>
<td>Std Dev y</td>
<td>27.59</td>
</tr>
</tbody>
</table>

$t$
ELET TIME CORRECTION

- Avoid threshold activation due to noise (jitter effect)
- Avoid walk effect due to varying time signal shape
- Assume that rising slope is almost linear at the beginning

\[ \Delta t = t_1 - t_0 \]
\[ \Delta t = t_2 - t_1 \]
\[ t_0 = 2t_1 - t_2 \]
\[ p\mu d \rightarrow (\mu^3\text{He})_{nl} + \gamma, \quad Q_{1s} = 5.502 \text{ MeV}, \]
\[ d\mu d \rightarrow (\mu^3\text{He})_{nl} + n, \quad Q_{1s} = 3.277 \text{ MeV}, \]
\[ d\mu t \rightarrow (\mu^4\text{He})_{nl} + n, \quad Q_{1s} = 17.598 \text{ MeV}. \]
Scaling of the APV

(Bouchiat & Bouchiat, 1974)

\[ \langle nS_{1/2} | H_w | nP_{1/2} \rangle \propto K_r Z^3 \]

- \( K_r \) relativistic enhancement factor

Ra\(^+\) effects larger by:
- 20 (Ba\(^+\))
- 50 (Cs)


\( Z^3 K_r \)

→ 5-fold improvement over Cs feasible in 1 day

Relativistic coupled-cluster (CC) calculation of \( E1_{APV} \) in Ra\(^+\)

\[ E1_{APV} = 46.4(1.4) \cdot 10^{-11} \text{iea}_0 \left( -\frac{Q_W}{N} \right) \quad (3\% \text{ accuracy}) \]

Other results:

\[ 45.9 \cdot 10^{-11} \text{iea}_0 \left( -\frac{Q_W}{N} \right) \quad (R. Pal et al., Phys. Rev. A 79, 062505 (2009), Dzuba et al., Phys Rev. A 63, 062101 (2001).) \]

- Need reliable charge radius at <0.2% accuracy for atomic theory
ESTIMATION RADIUS PARAMETER

\[
\rho(r) = \frac{\rho_0}{1 + \exp \left( \frac{r-c}{a} \right)} = \frac{\rho_0}{1 + \exp \left( 4 \log(3) \frac{r-c}{t} \right)}
\]

\[
r_{RMS} = \frac{\int \rho(r)r^2dV}{\int \rho(r)dV}
\]

\[
t = 2.3 \text{ fm} \approx \text{const}
\]

\[
rms = 5.6841 \text{ fm}
\]

I. Angeli/
Atomic Data and Nuclear Data Tables 87 (2004) 185\[Dash]206