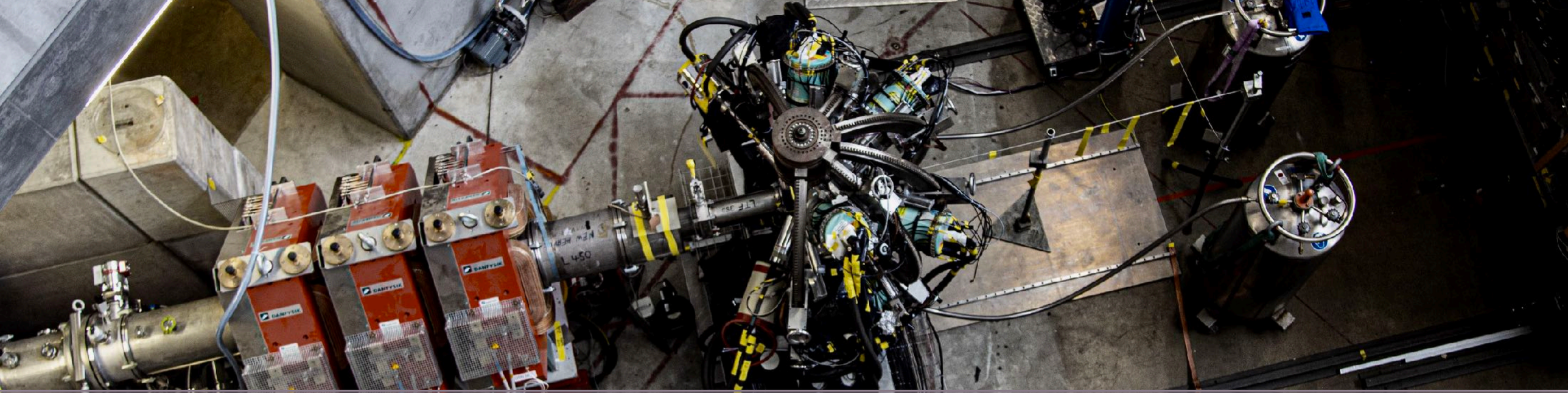


Muonic atom spectroscopy with radioactive targets

Stella Vogiatzi
SPS/ÖPG meeting
02.09.2021

On behalf of the muX collaboration

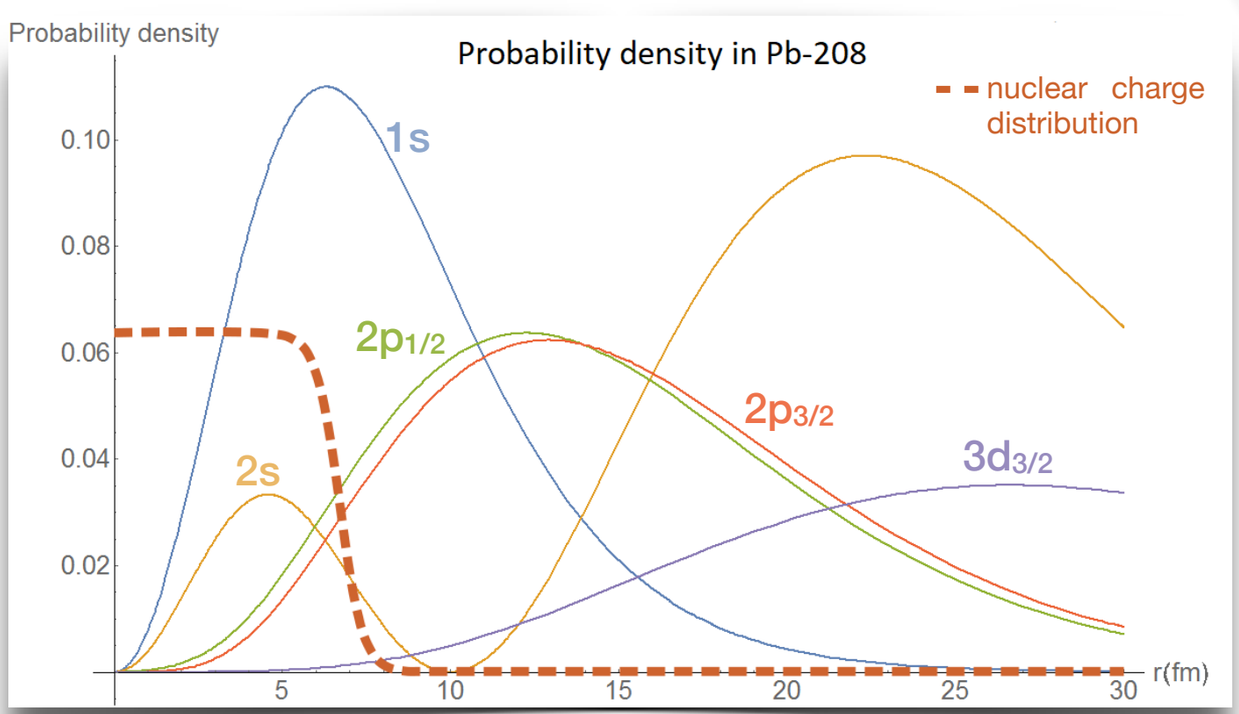
A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], N. Deokar[4], R. Dressler[2], Ch.E. Düllmann[4,6,7], R. Eichler[2], H. Hess[8], P. Indelicato[9], K. Jungmann[10], K. Kirch[2,3], A. Knecht[2], J. Nuber[2,3], A. Ouf[4], A. Papa[2,11], N. Paul[9], R. Pohl[4], M. Pospelov[12,13], D. Renisch[4,7], P. Reiter[8], N. Ritjoho[2,3], S. Roccia[14], M. Seidlitz[8], N. Severijns[5], A. Skawran[2,3], S.M. Vogiatzi[2,3], N. Warr[8], F. Wauters[4], and L.Willmann[10]

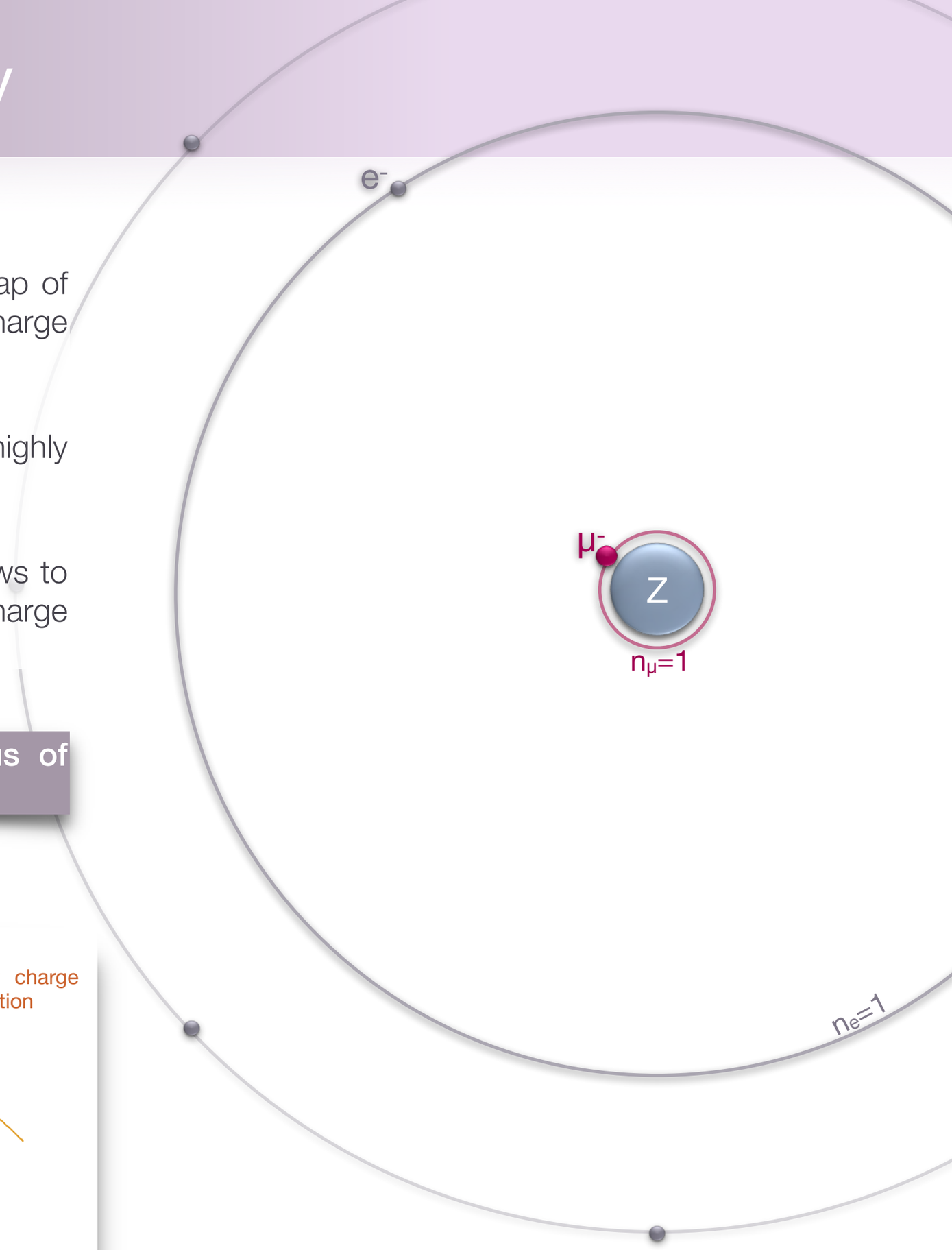
[1]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland,
[2]Paul Scherrer Institut, Villigen, Switzerland,
[3]ETH Zürich, Switzerland,
[4]Johannes Gutenberg University Mainz, Germany,
[5]KU Leuven, Belgium,
[6]GSI Helmholtzzentrum für Schwerionenforschung Darmstadt, Germany,
[7]Helmholtz Institute Mainz, Germany,
[8]Institut für Kernphysik, Universität zu Köln, Germany,
[9]LKB Paris, France,
[10]University of Groningen, The Netherlands,
[11]University of Pisa and INFN, Pisa, Italy,
[12]University of Victoria, Canada,
[13]Perimeter Institute, Waterloo, Canada,
[14]CSNSM, Université Paris Sud, CNRS/IN2P3, Université Paris Saclay, Orsay Campus, France

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}Ra and ^{248}Cm radioactive isotopes





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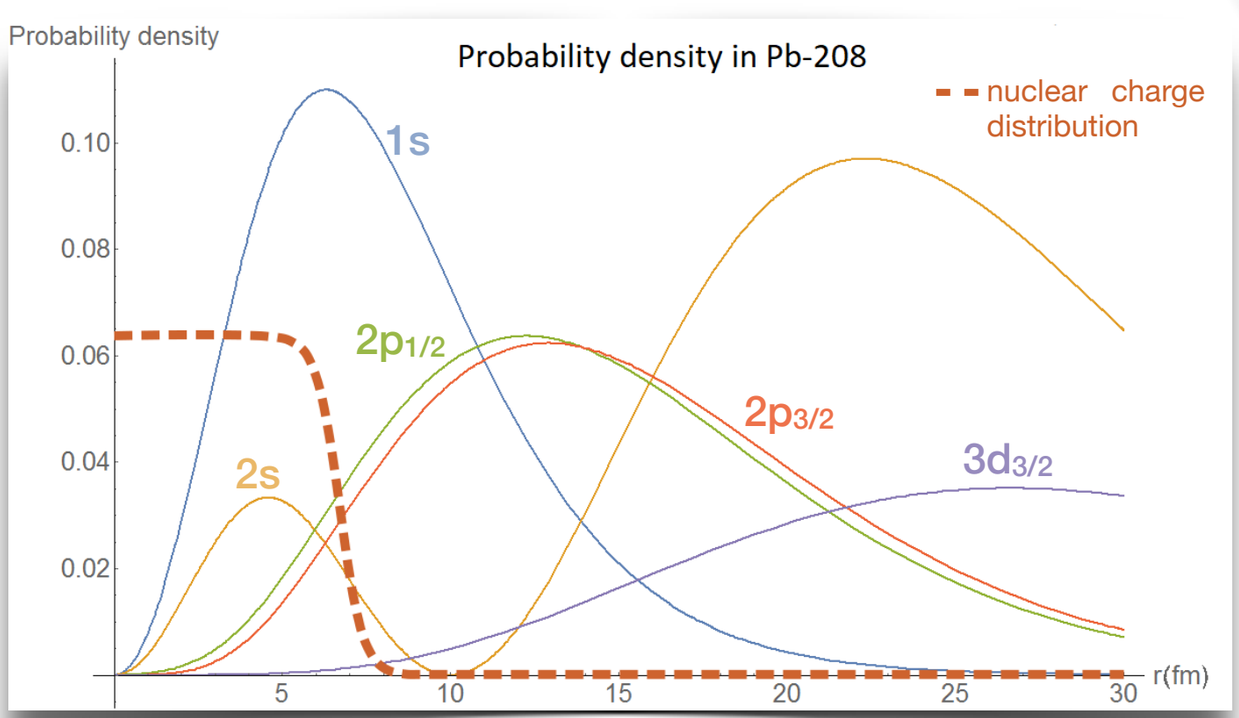

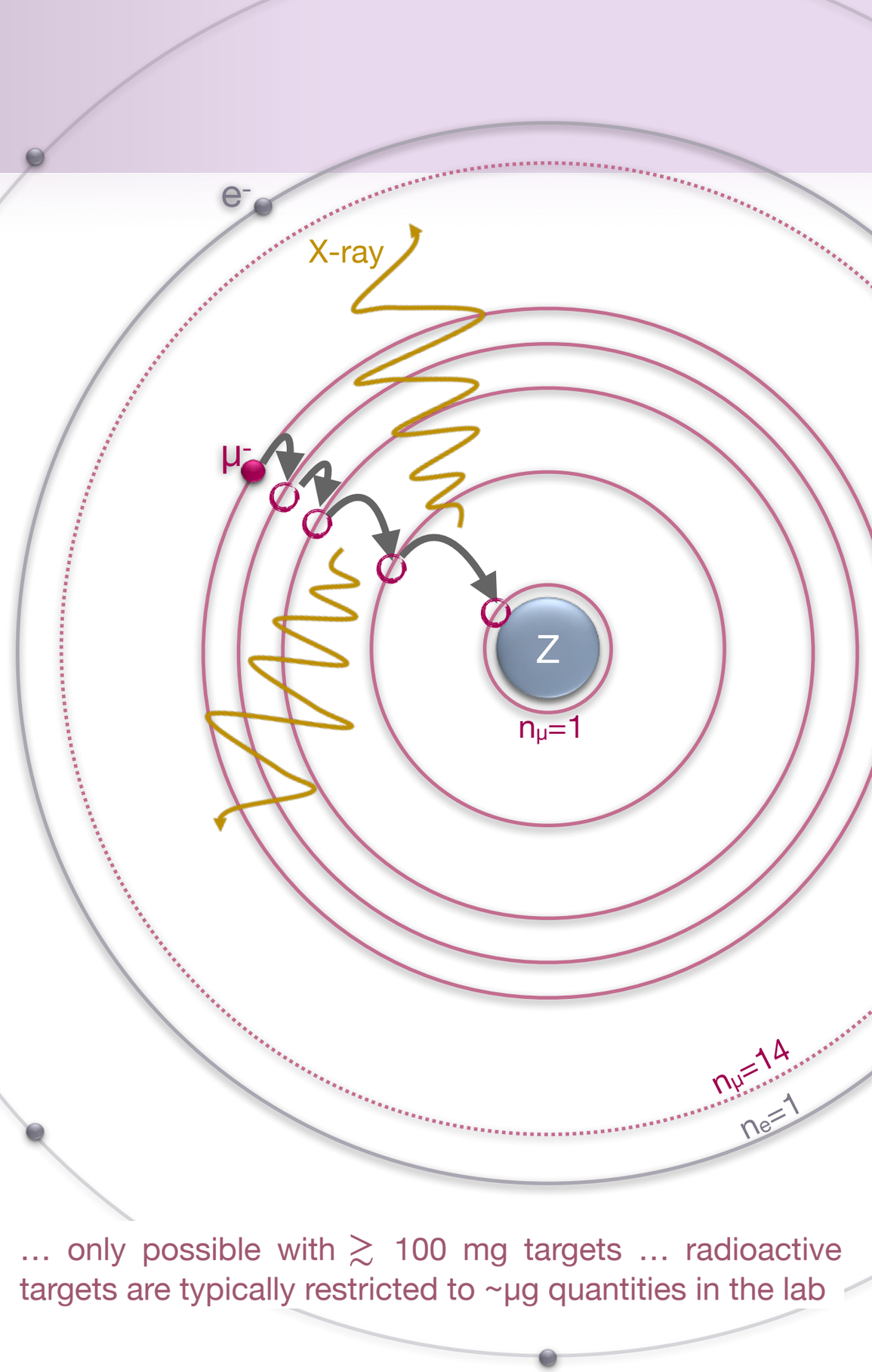

... only possible with $\gtrsim$ 100 mg targets ... radioactive targets are typically restricted to ~μg quantities in the lab

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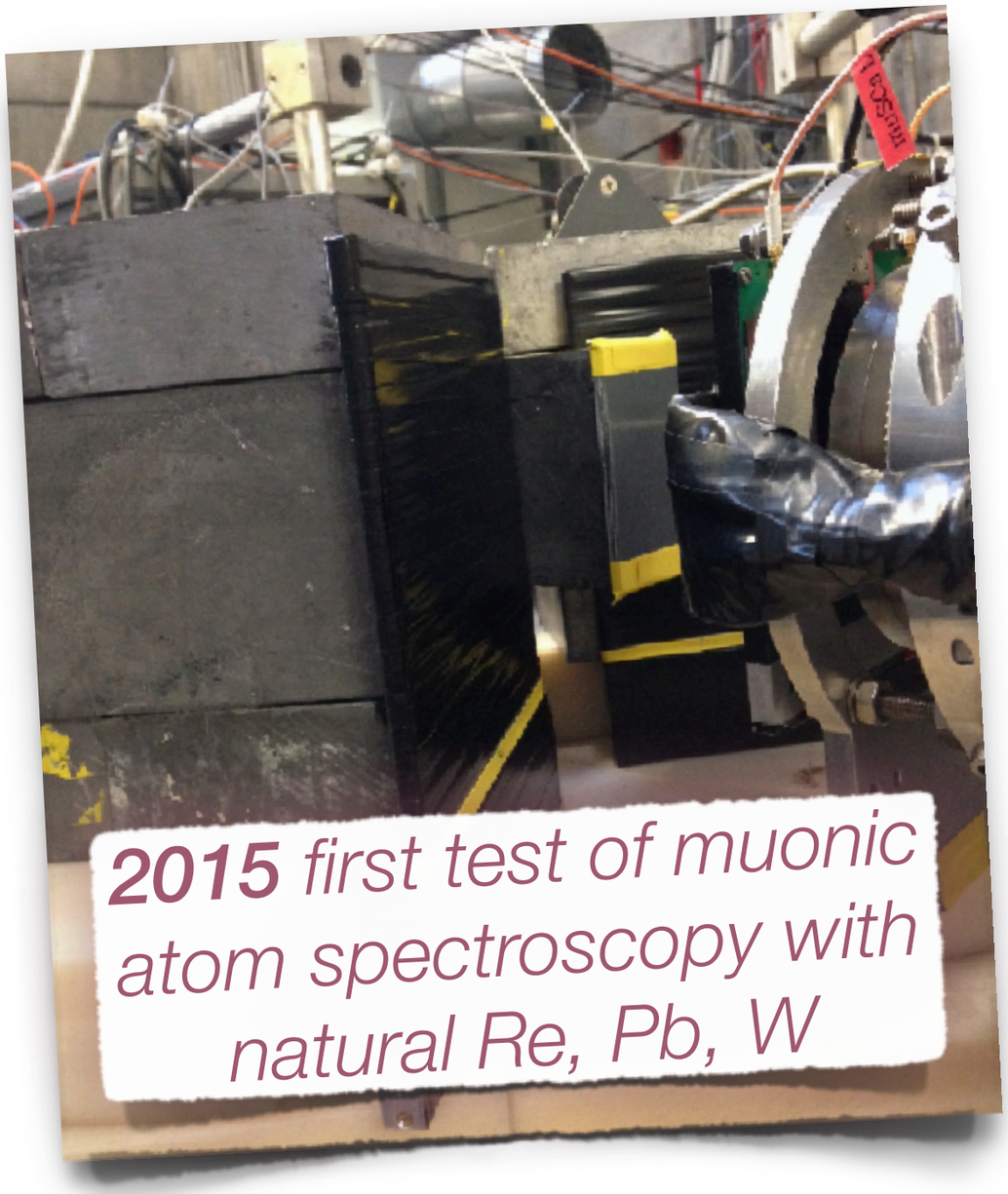
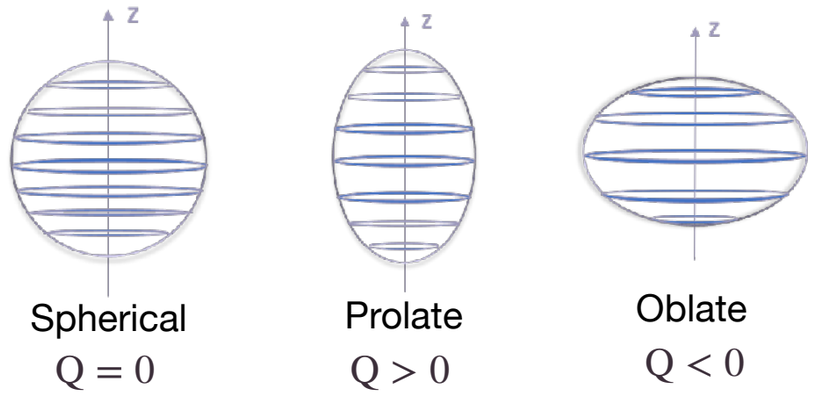
Experimental setup evolution of muX



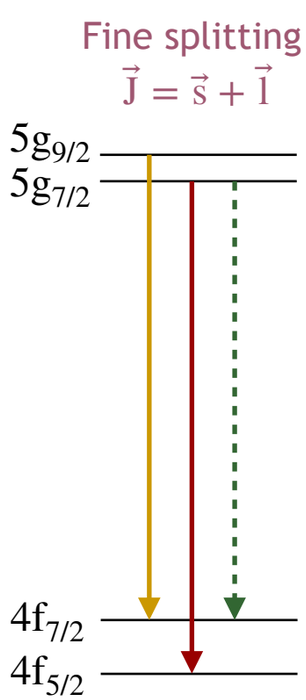
Experimental setup evolution of muX

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



- 5g-4f transitions are not sensitive to the details of the charge distribution so we can extract the spectroscopic quadrupole moment



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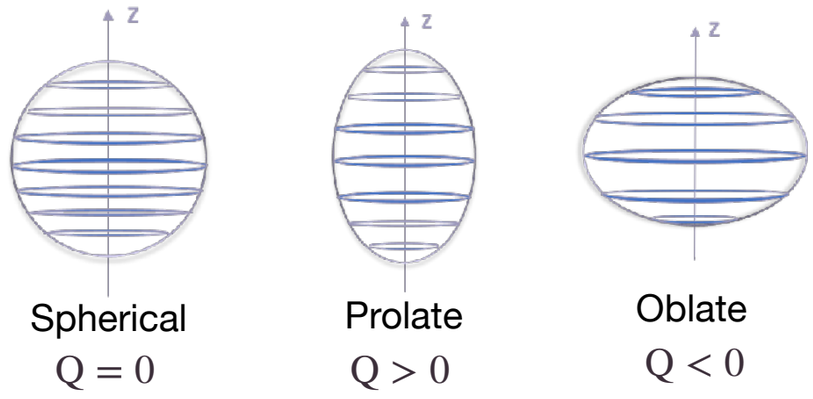

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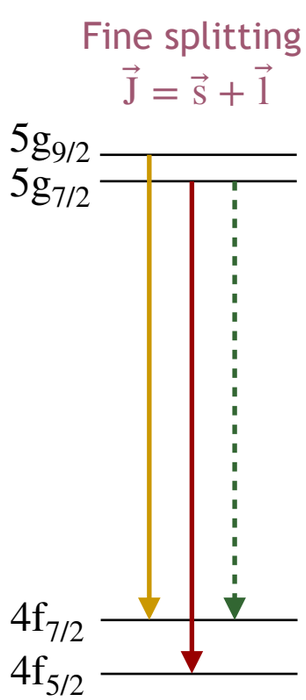

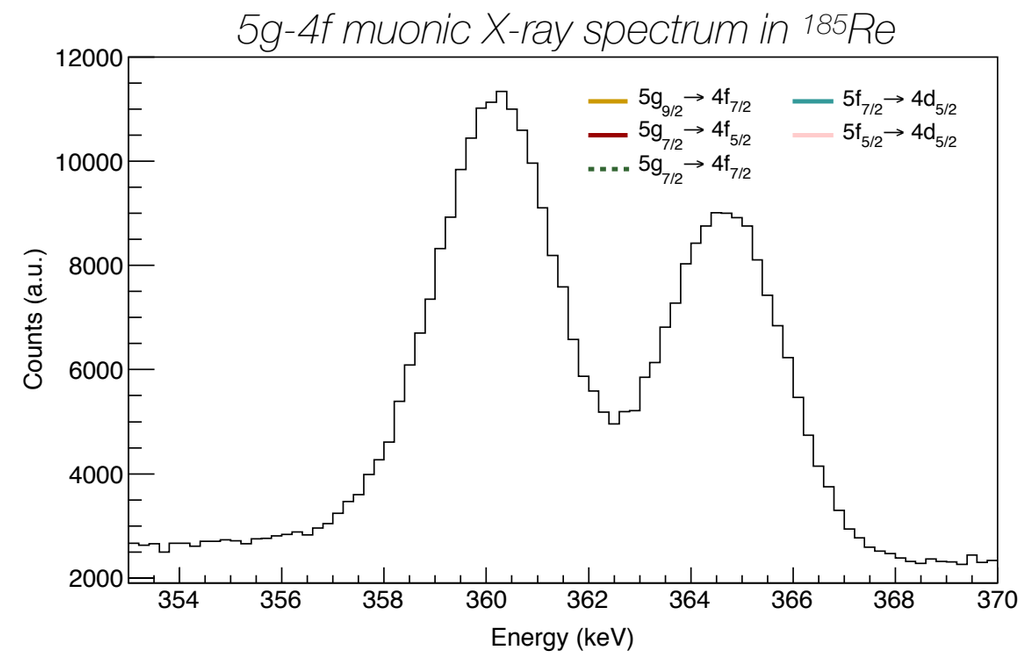

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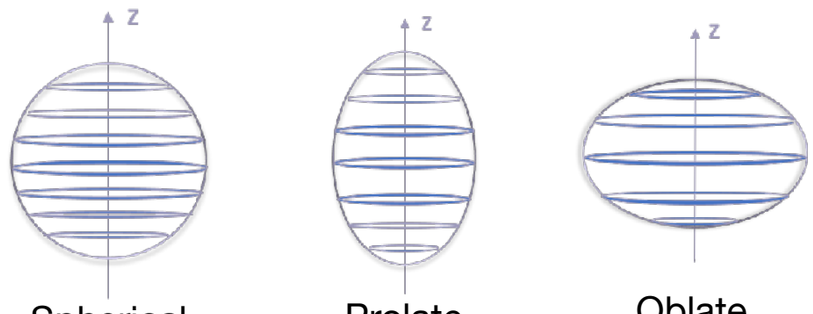

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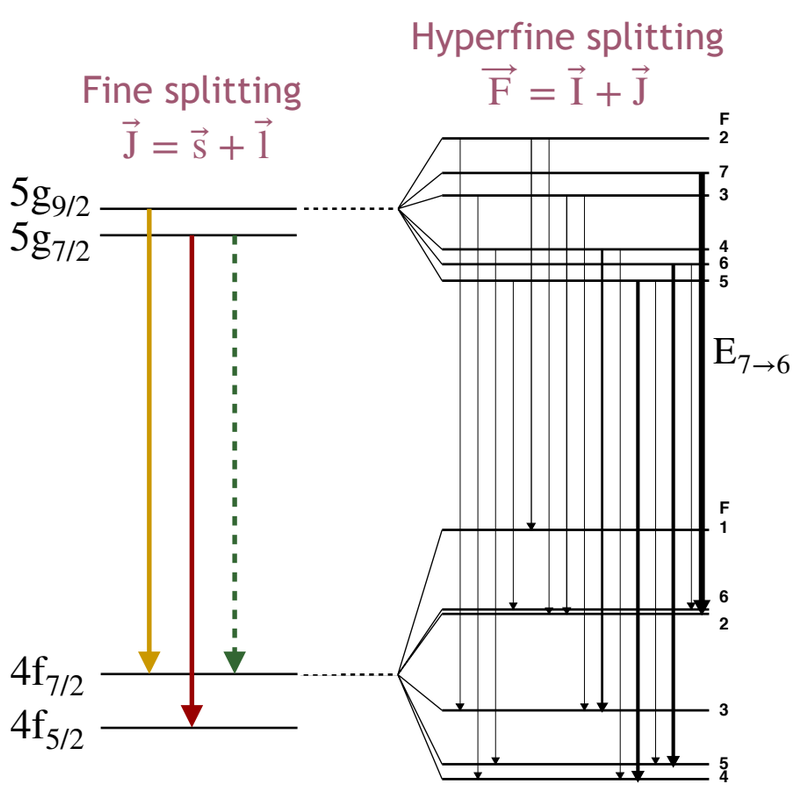

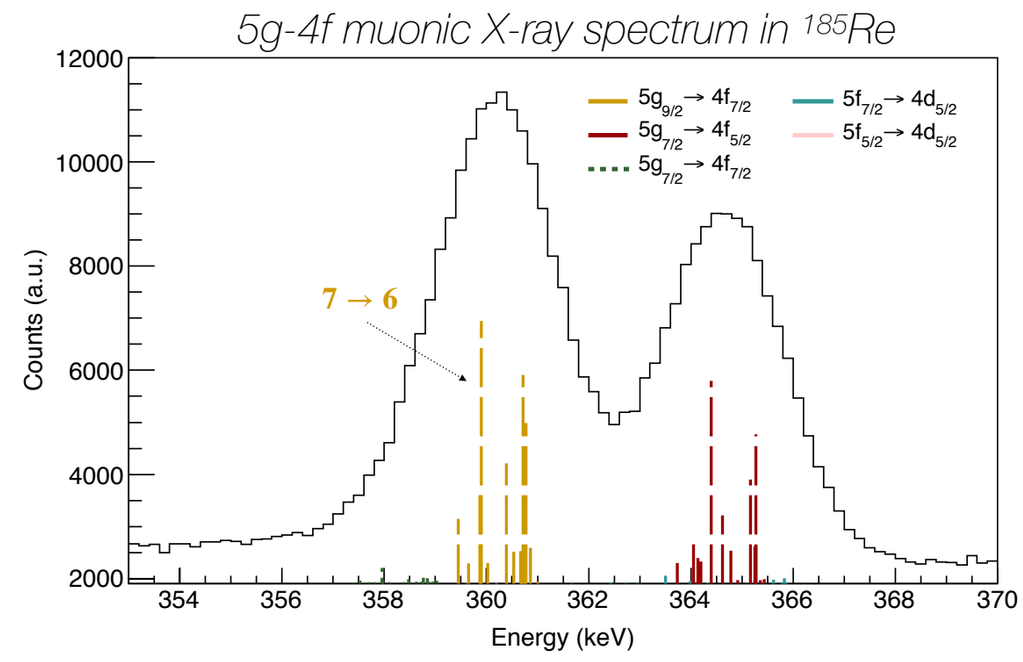

Theoretical predictions by N. Michel and N. Oreshkina, Max Planck Institute for Nuclear Physics, Heidelberg

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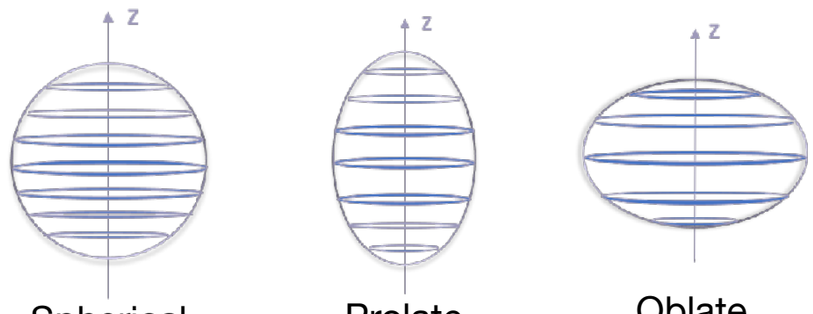

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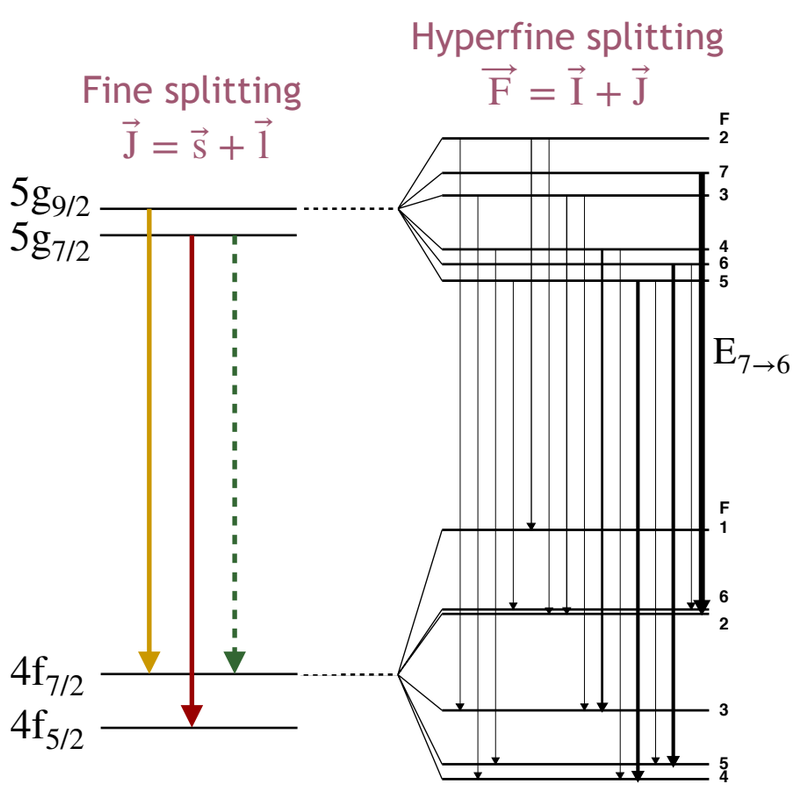

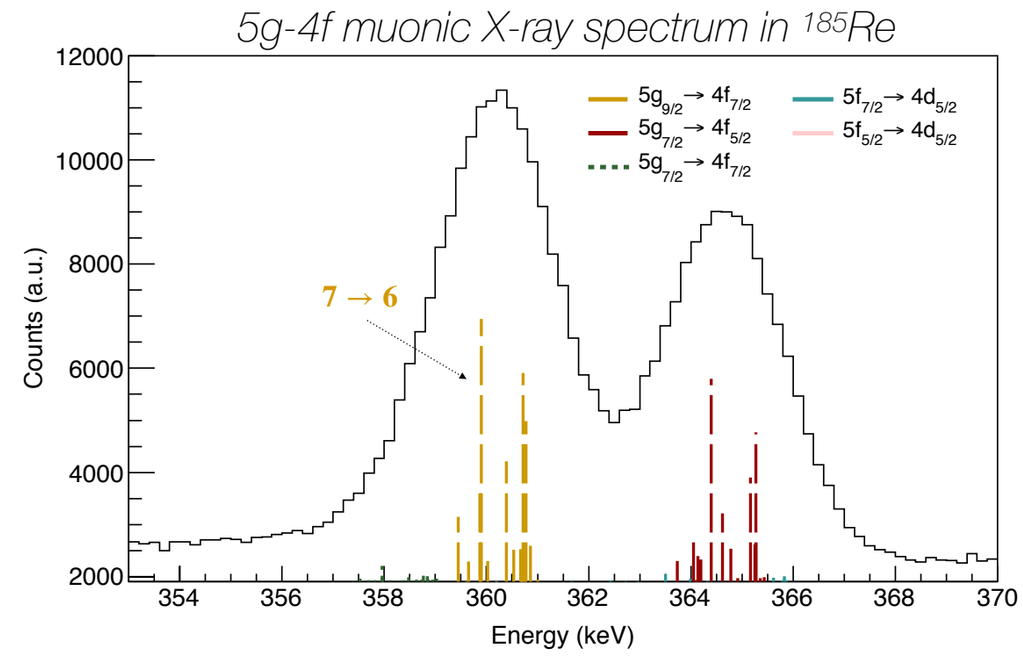

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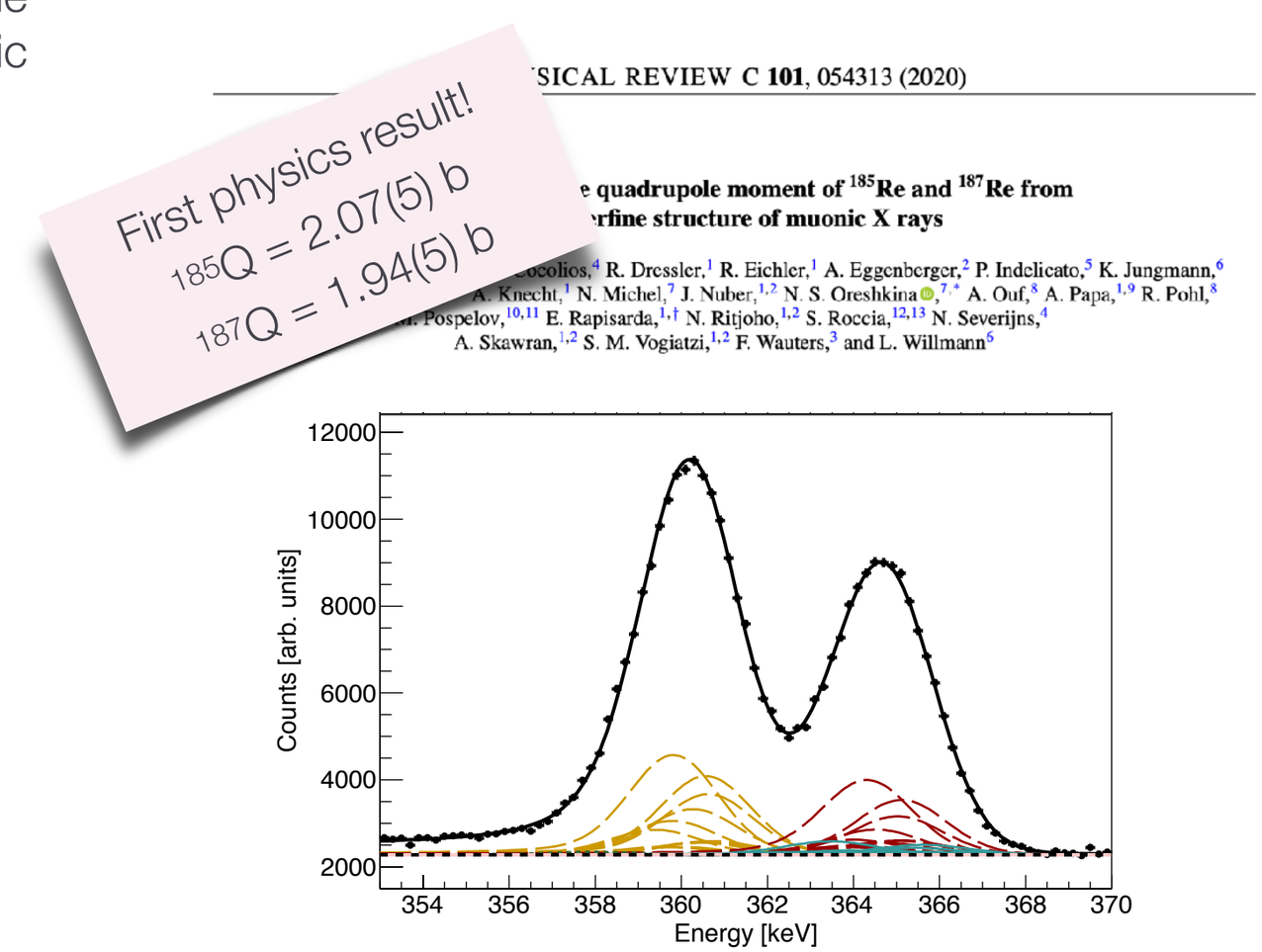
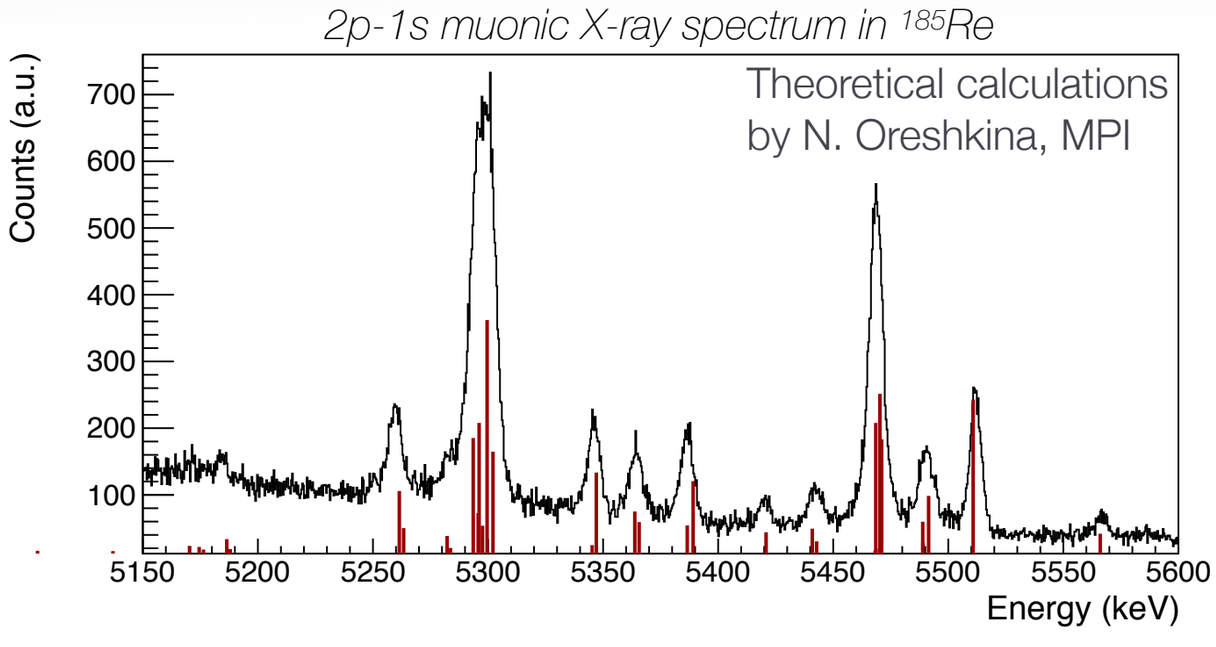


First physics result!
$^{185}Q = 2.07(5)$ b
$^{187}Q = 1.94(5)$ b

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

Master thesis project of Jérémy Layan

- 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



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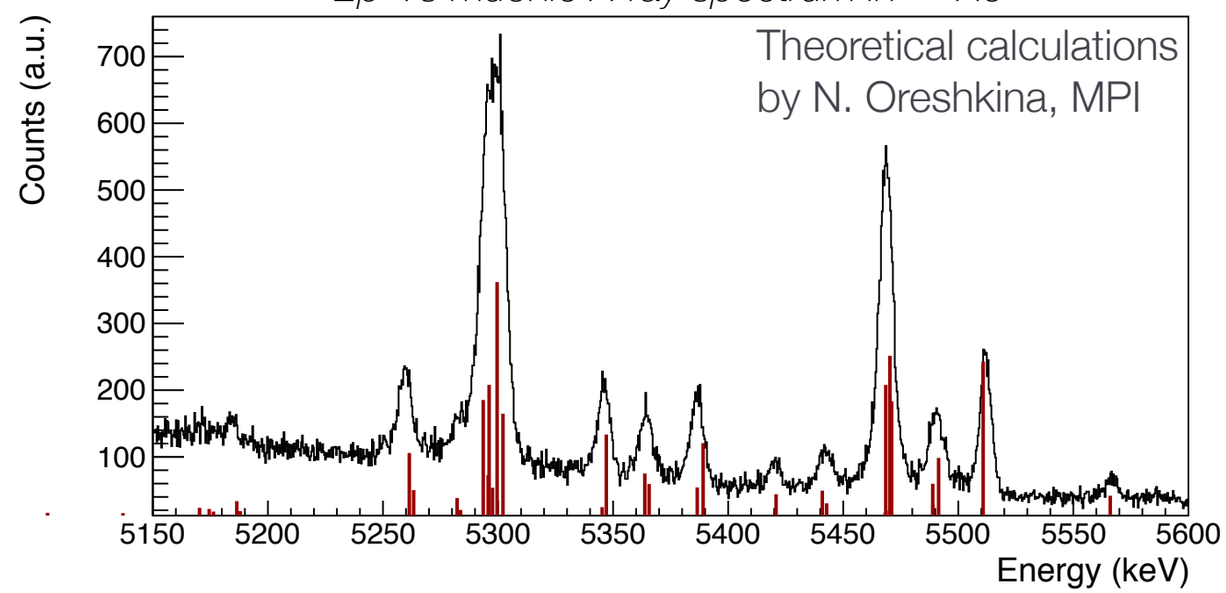
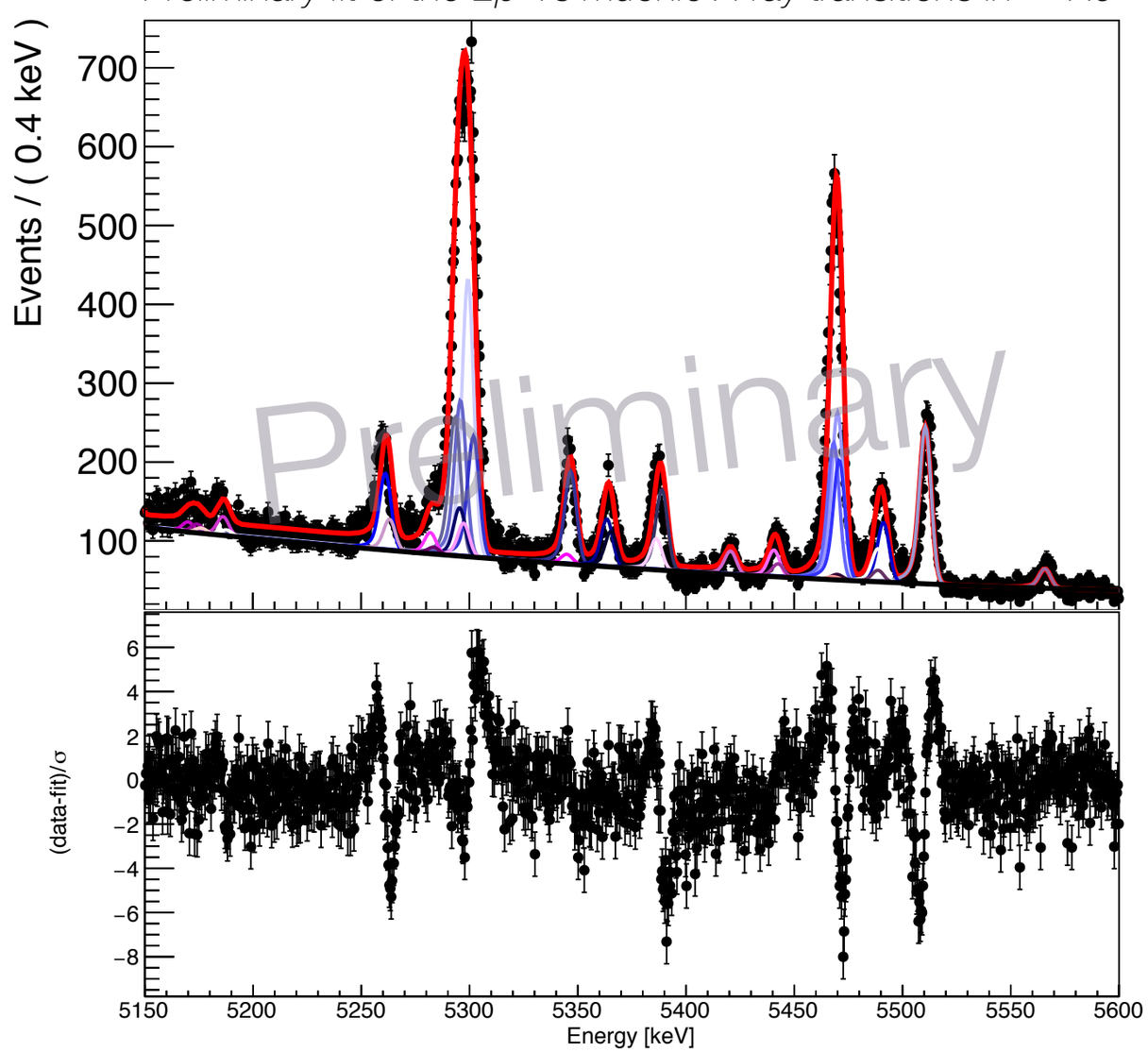
2p-1s muonic X-ray spectrum in ^{185}Re



Preliminary fit of the 2p-1s muonic X-ray transitions in ^{185}Re



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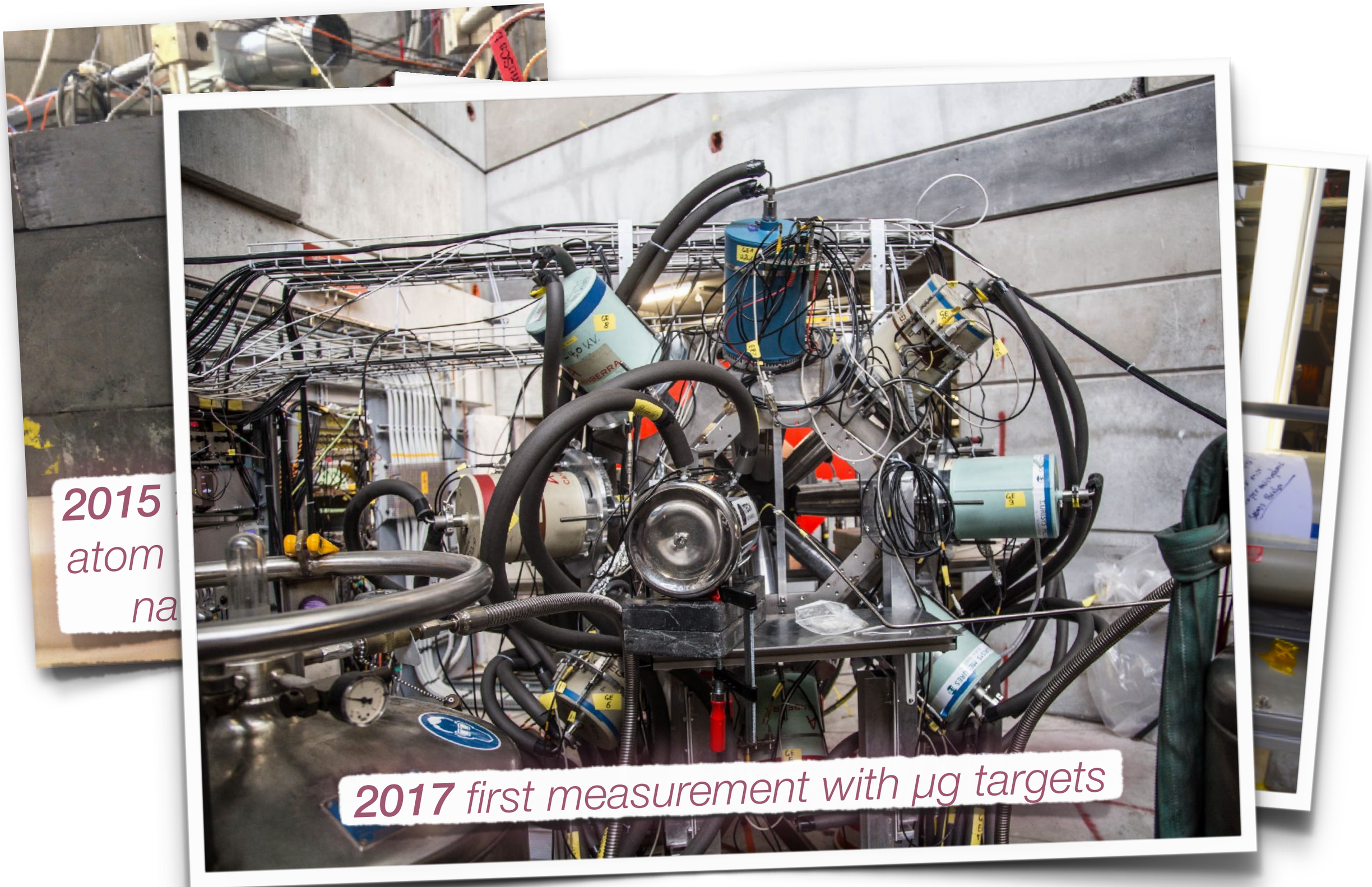
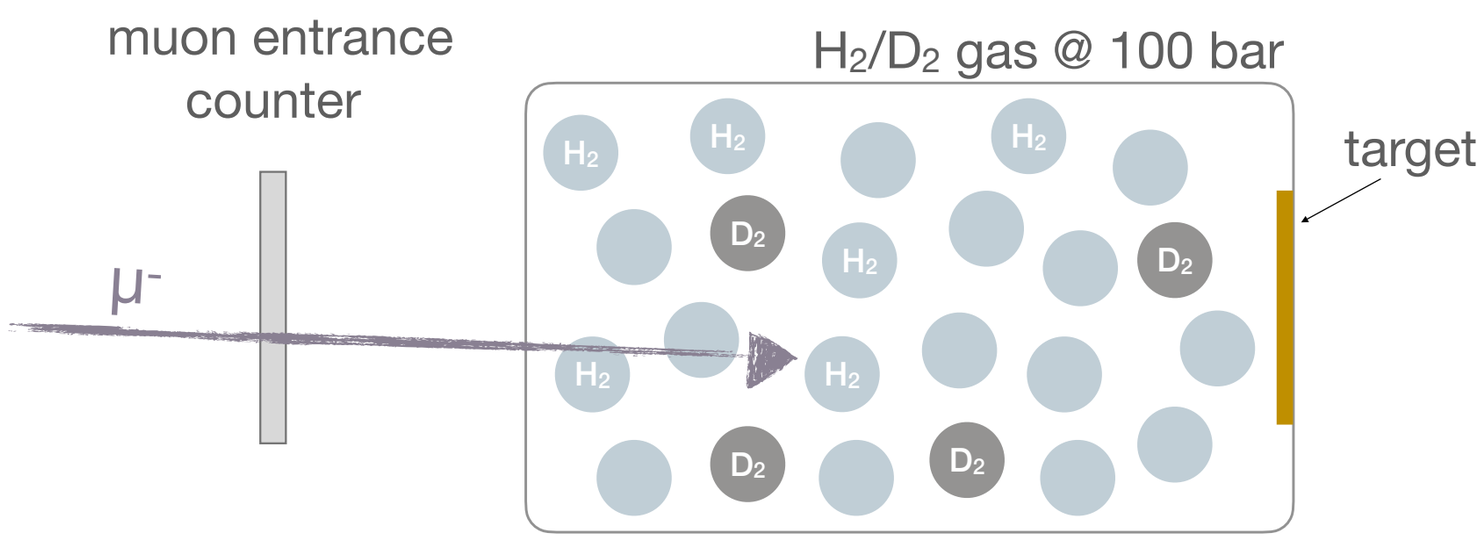


Muon transfer to microgram target

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

…technique to transfer muons to μg targets involves a gas cell with H_2/D_2 admixture in 100 bar…

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



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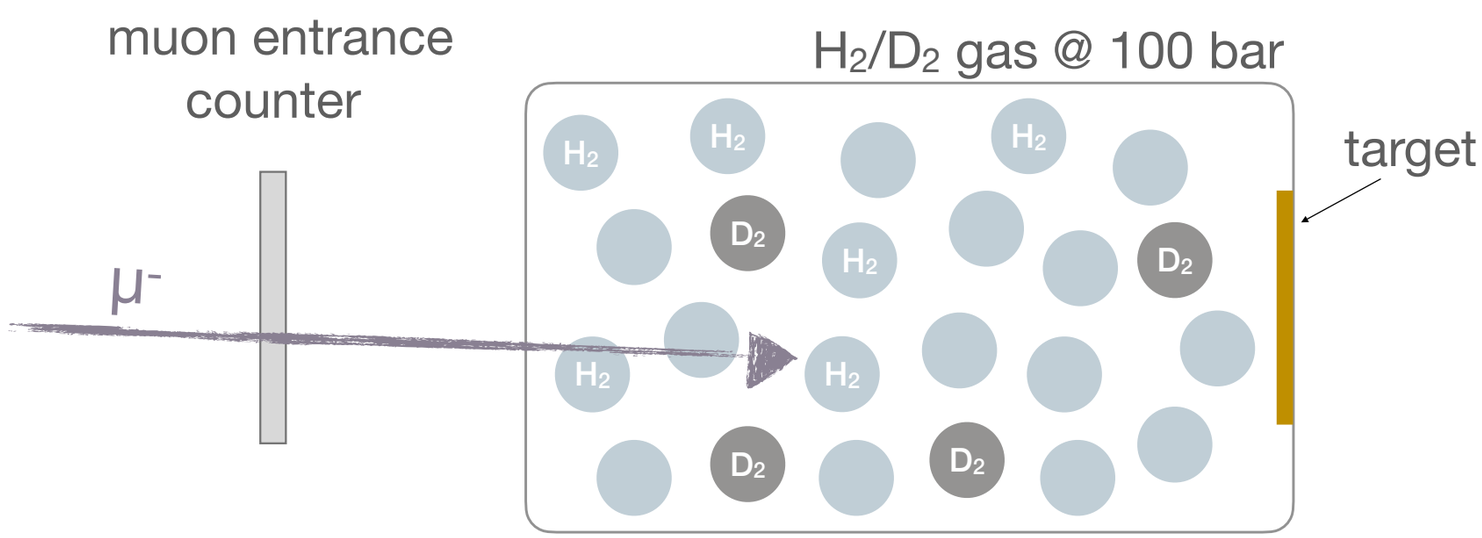

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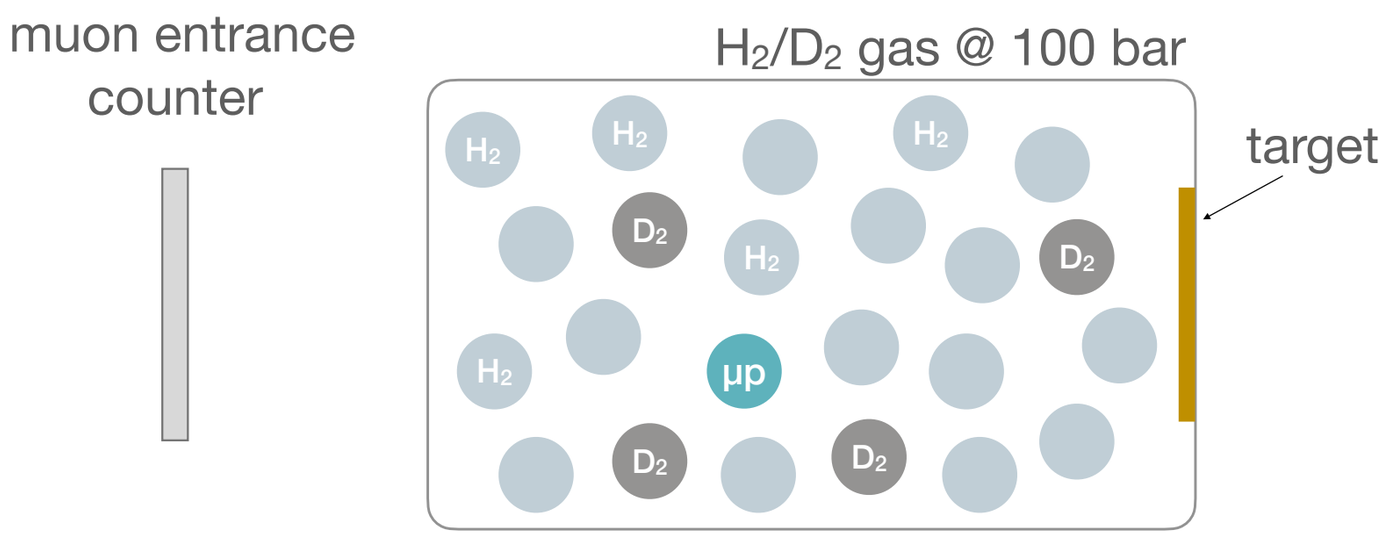

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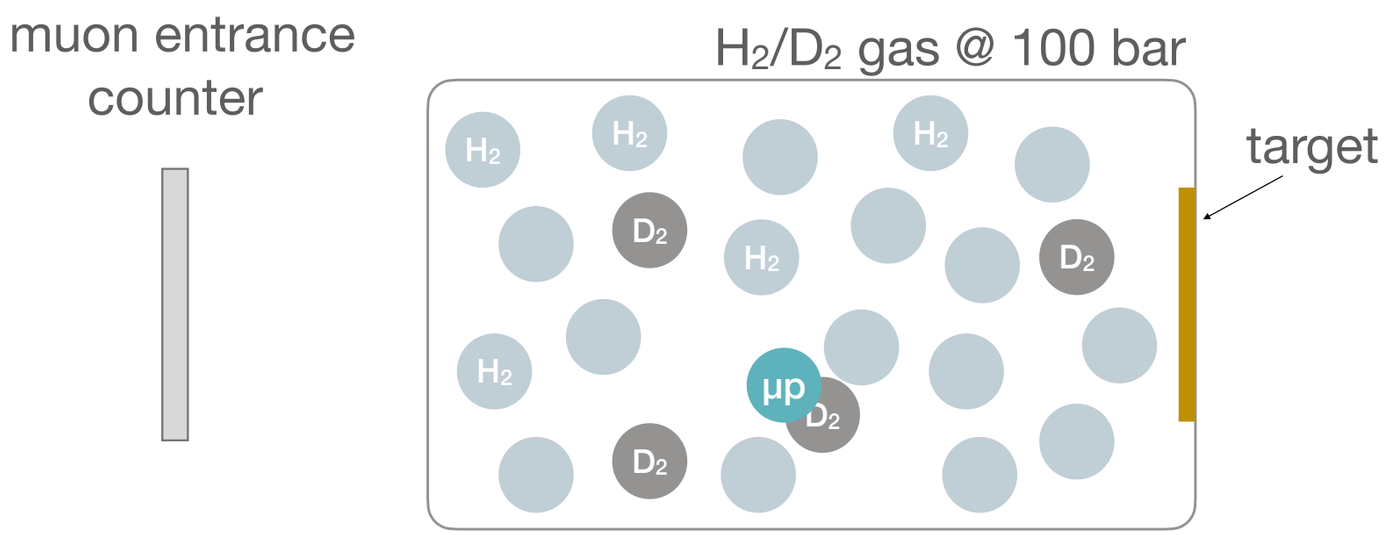

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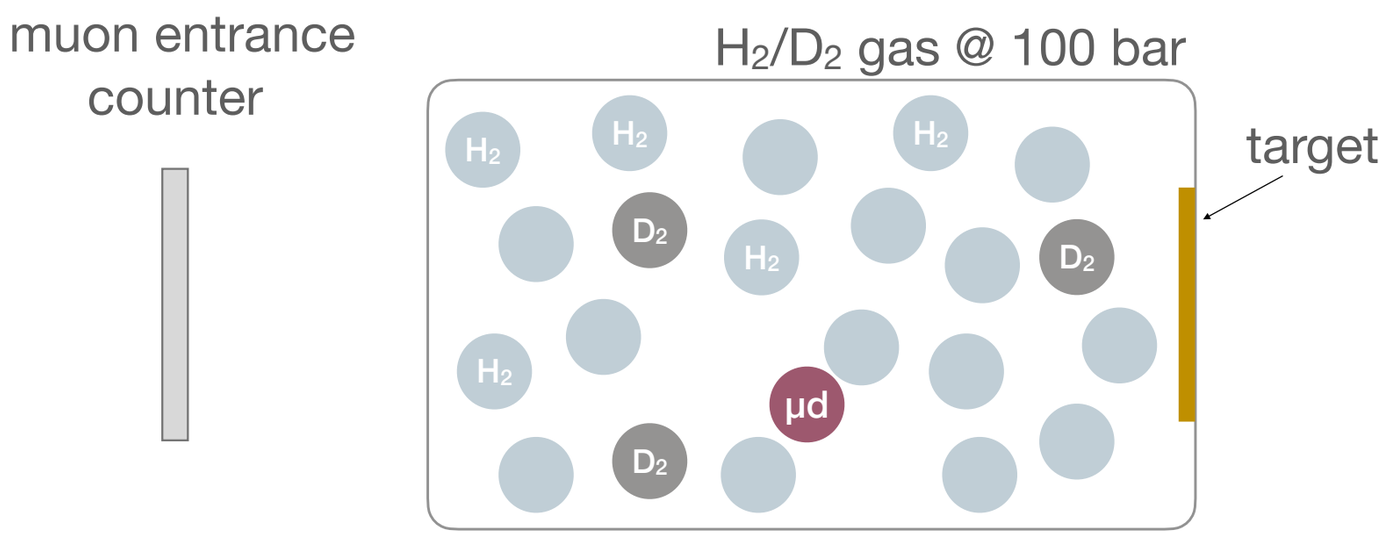

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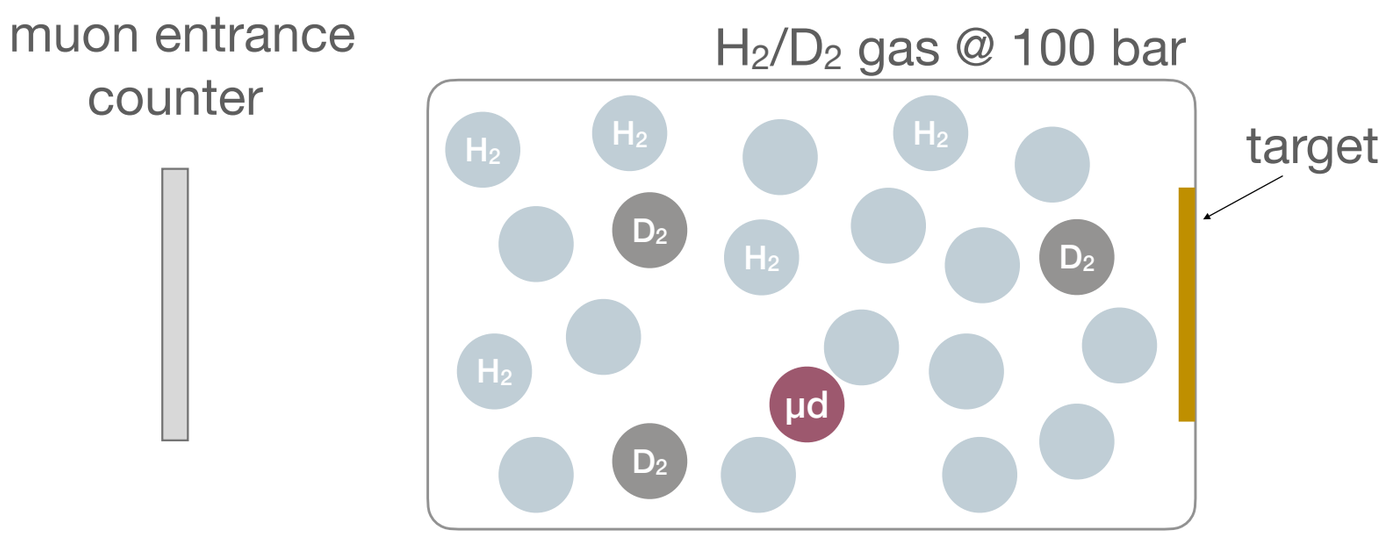

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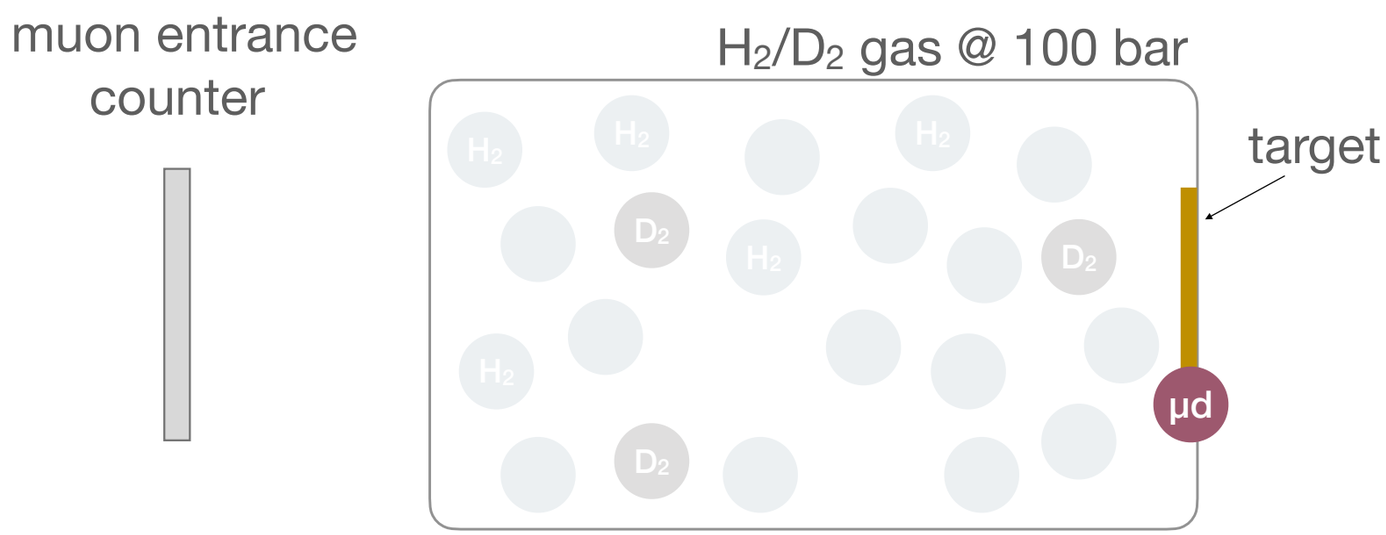

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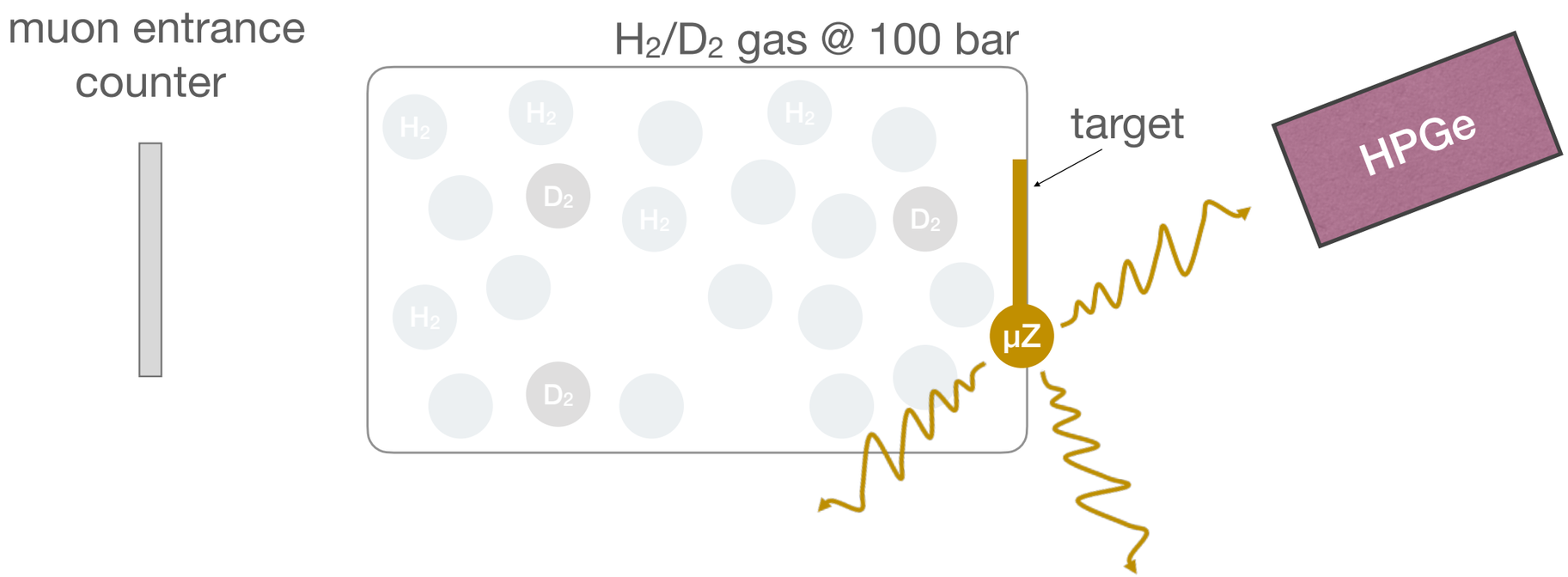

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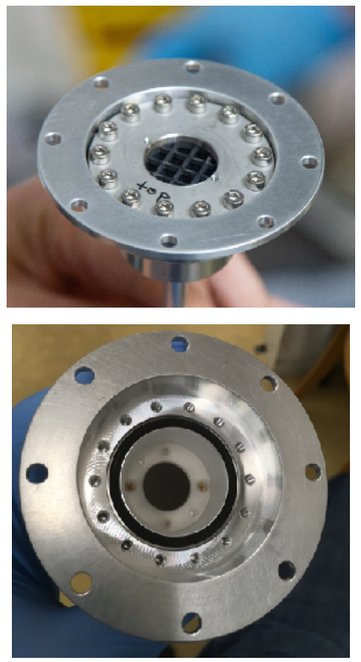
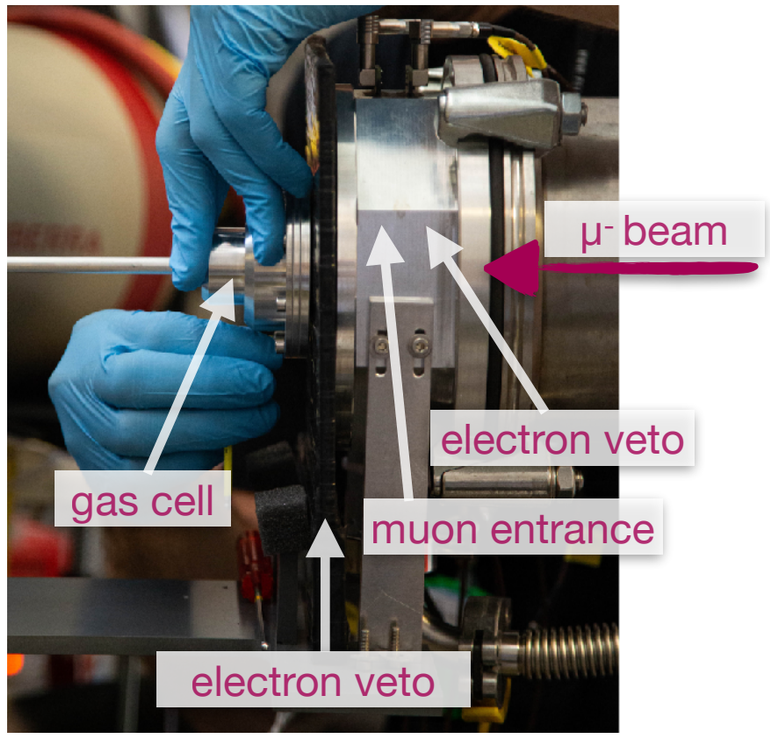
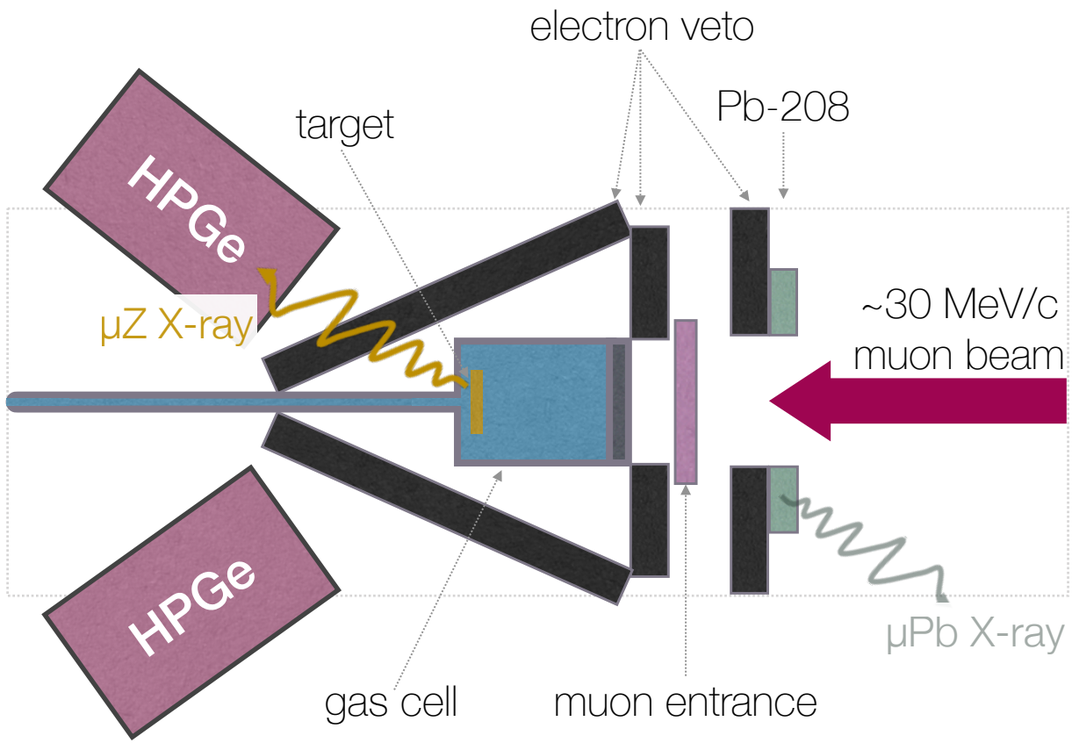
muX detectors



The gas cell

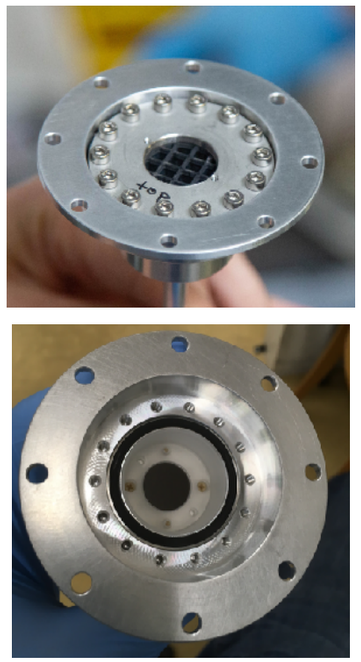


The muon and electron counters



Schematics of detector setup

muX detectors



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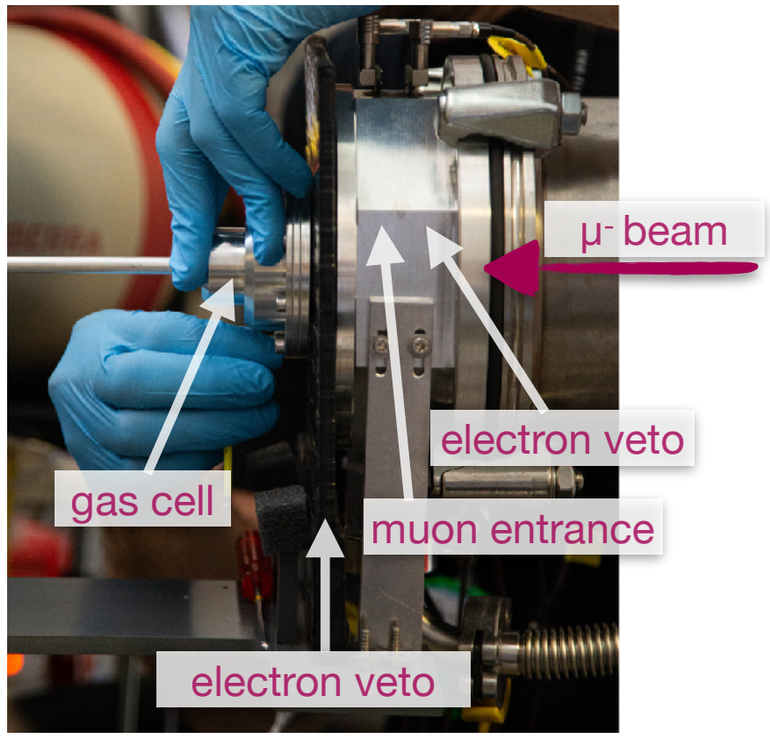

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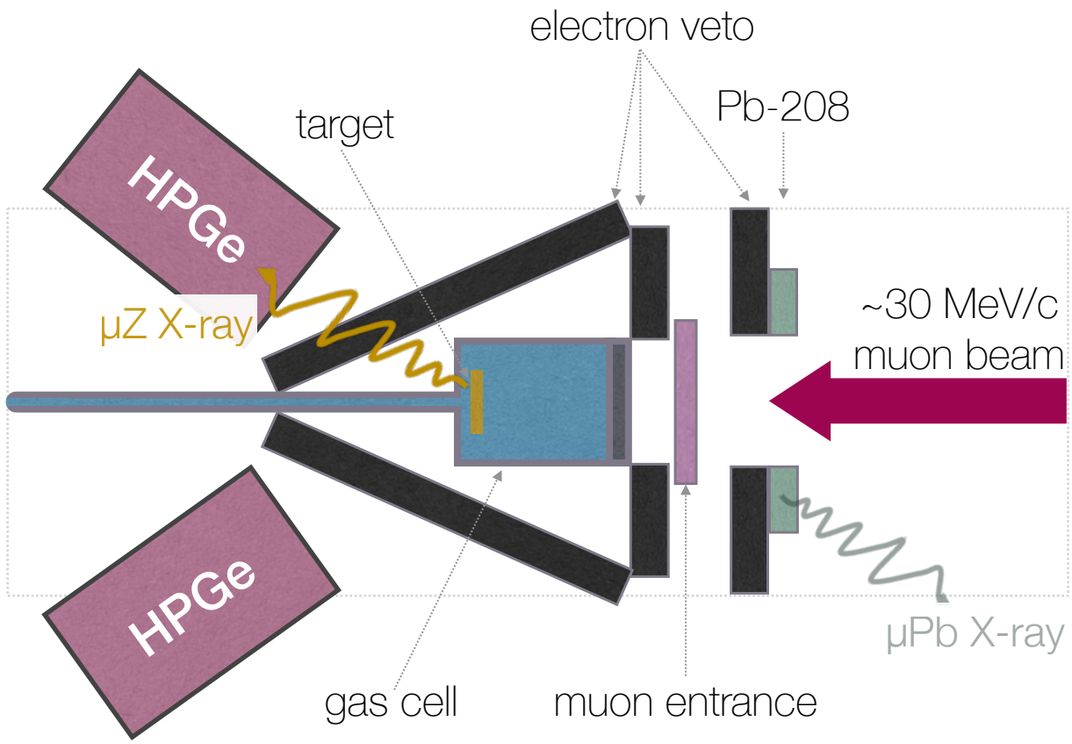
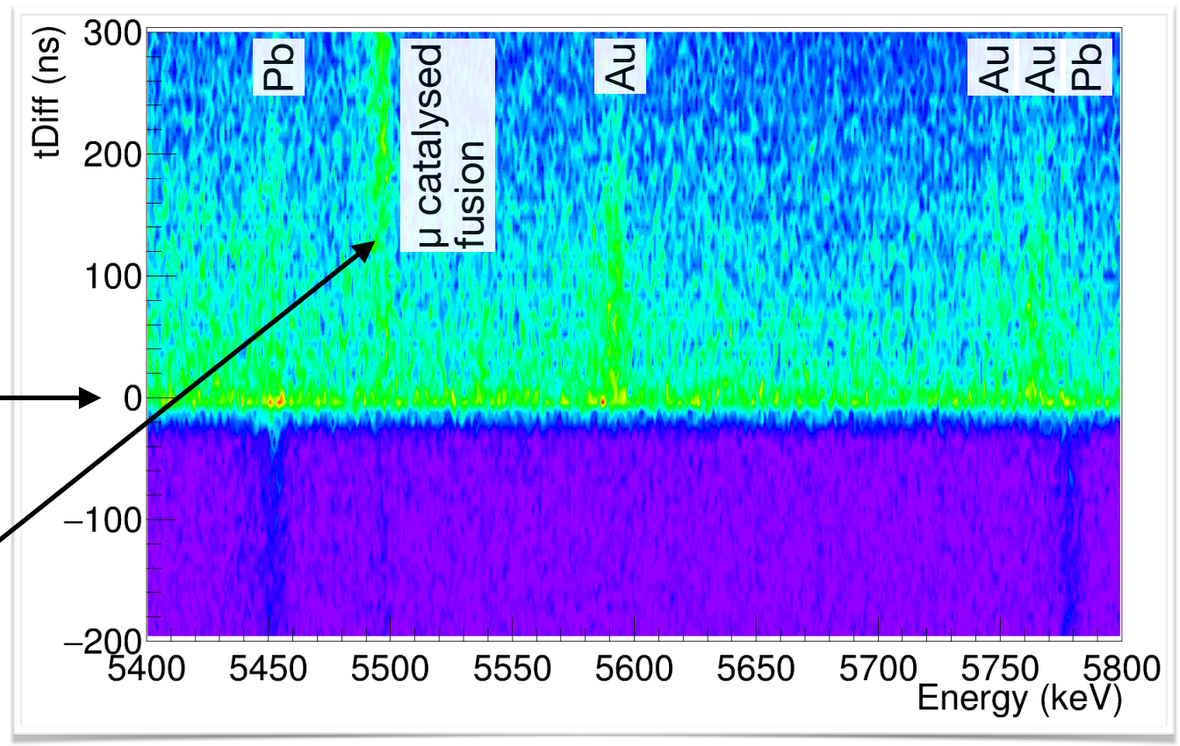


Schematics of detector setup

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

the time the muon enters the gas cell

$$\mu d + p \rightarrow p\mu d \rightarrow \mu^3He + \gamma\,(5.5\,\mathrm{MeV})$$

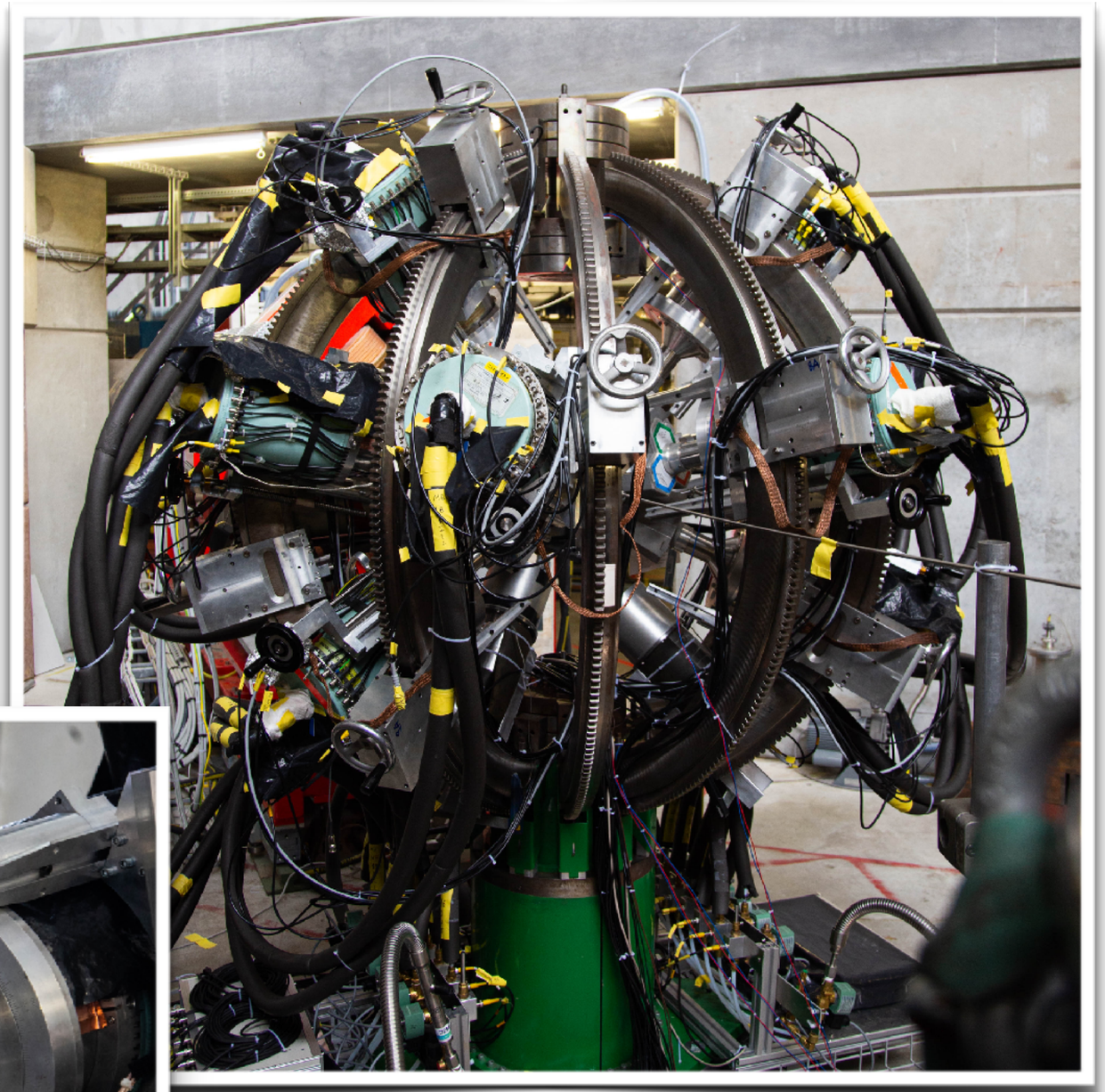


A. Knecht, A. Skawran & S.M. Vogiatzi, *Eur. Phys. J. Plus* **135,** 777 (2020)

Measurement of ^{248}Cm and ^{226}Ra

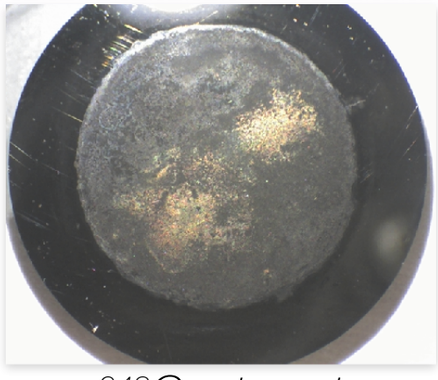
- In 2019 we measured ^{248}Cm and ^{226}Ra with the Miniball germanium detectors array
  [N. Warr et al., “The Miniball spectrometer”, Eur. Phys. J. A 49, 40 (2013)]

- 8 Miniball germanium clusters and 2 standalone germanium detectors making a total of 26 HPGe detectors were operating



Measurement of ^{248}Cm and ^{226}Ra

- We measured 15 μg of ^{248}Cm and 1.4 μg of ^{226}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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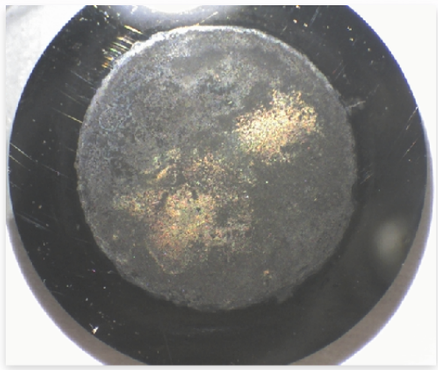

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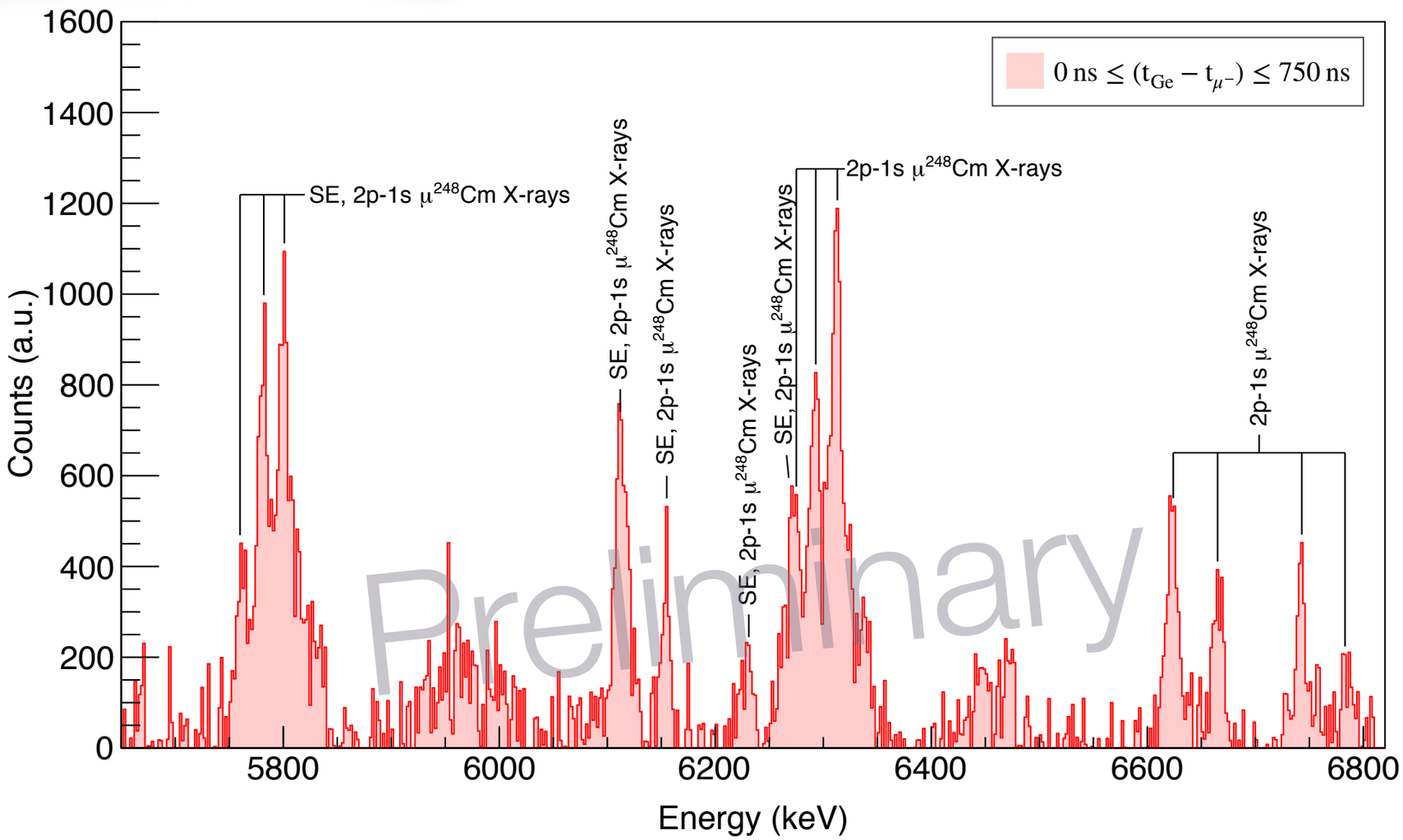
…2p-1s muonic X-ray spectrum in ^{248}Cm…



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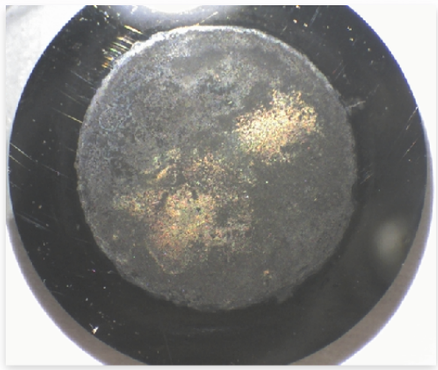

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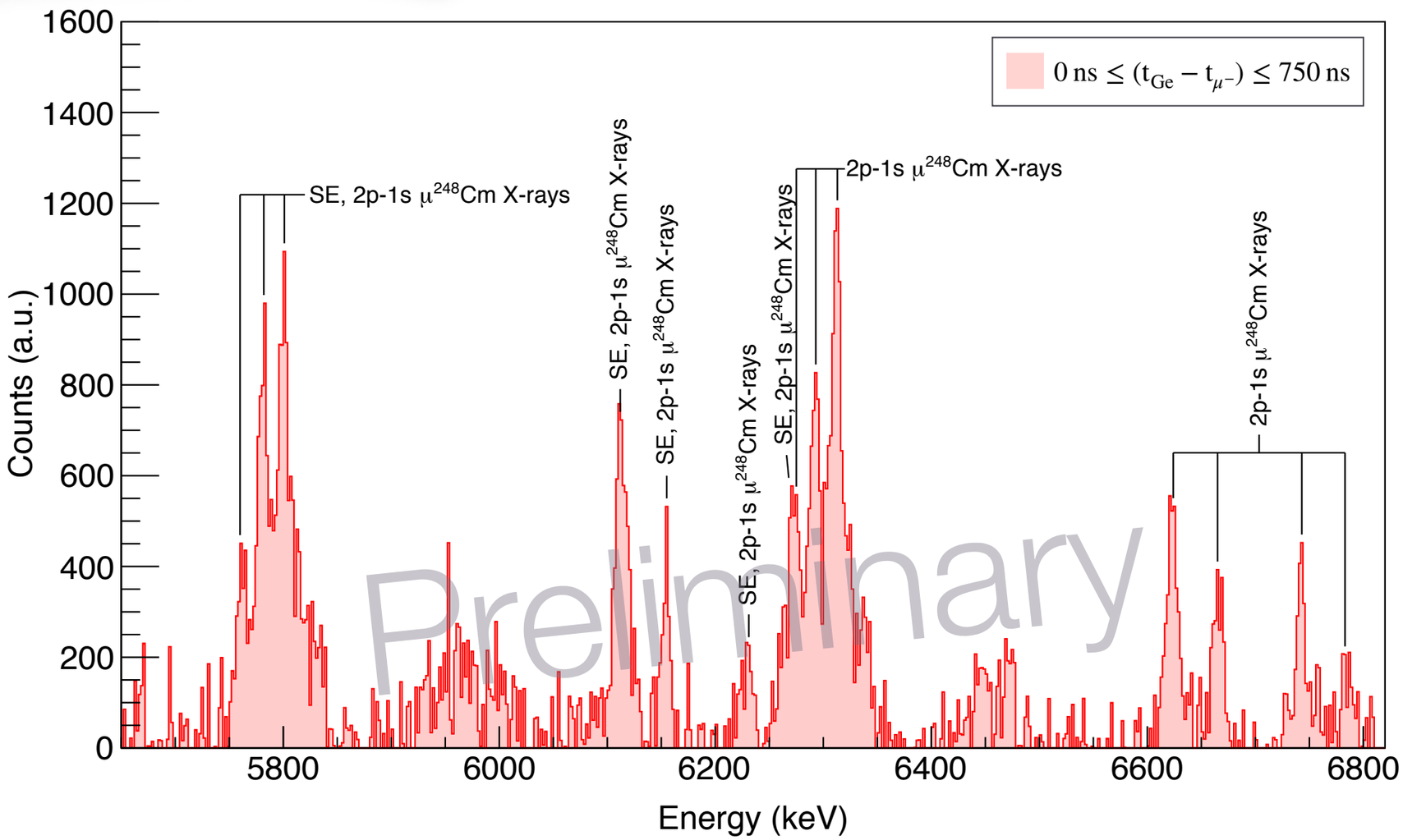
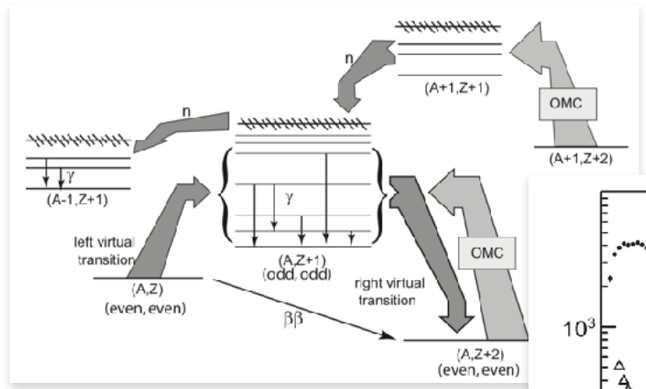


…^{226}Ra spectrum is still being analysed…

Other measurements muX is involved in

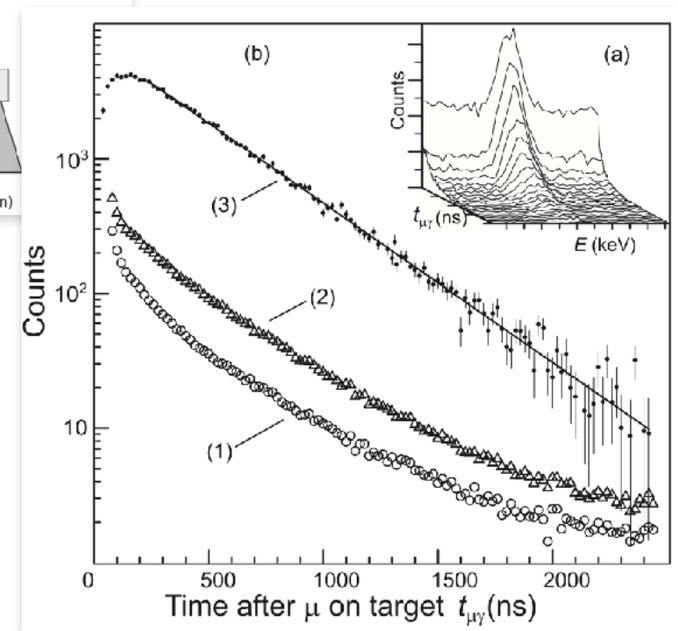
- Measurement of rare 2s-1s transitions in medium Z elements to investigate the reach of a possible APV experiment with muonic atoms

  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



[1] D. Zinatulina et al., Physical Review C 99, 024327 (2019)

- 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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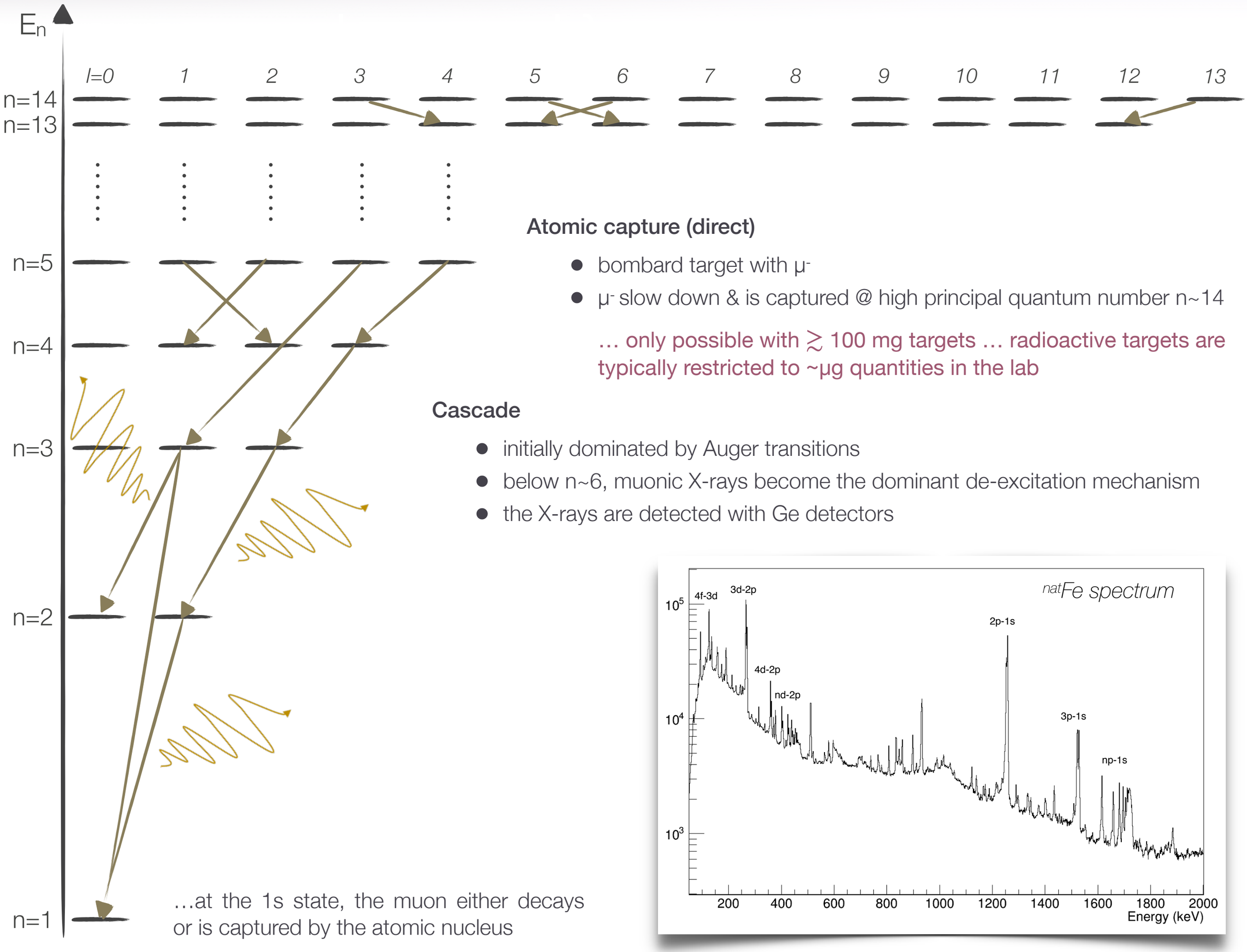
THANK

YOU

BACKUP SLIDES

Muonic atom spectroscopy



Atomic capture (direct)

- bombard target with μ^-
- μ^- slow down & is captured @ high principal quantum number n~14

… only possible with $\gtrsim$ 100 mg targets … radioactive targets are typically restricted to ~μg quantities in the lab

Cascade

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

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 $E1_{APV}$

$$E1_{APV} = k \cdot Q_W$$

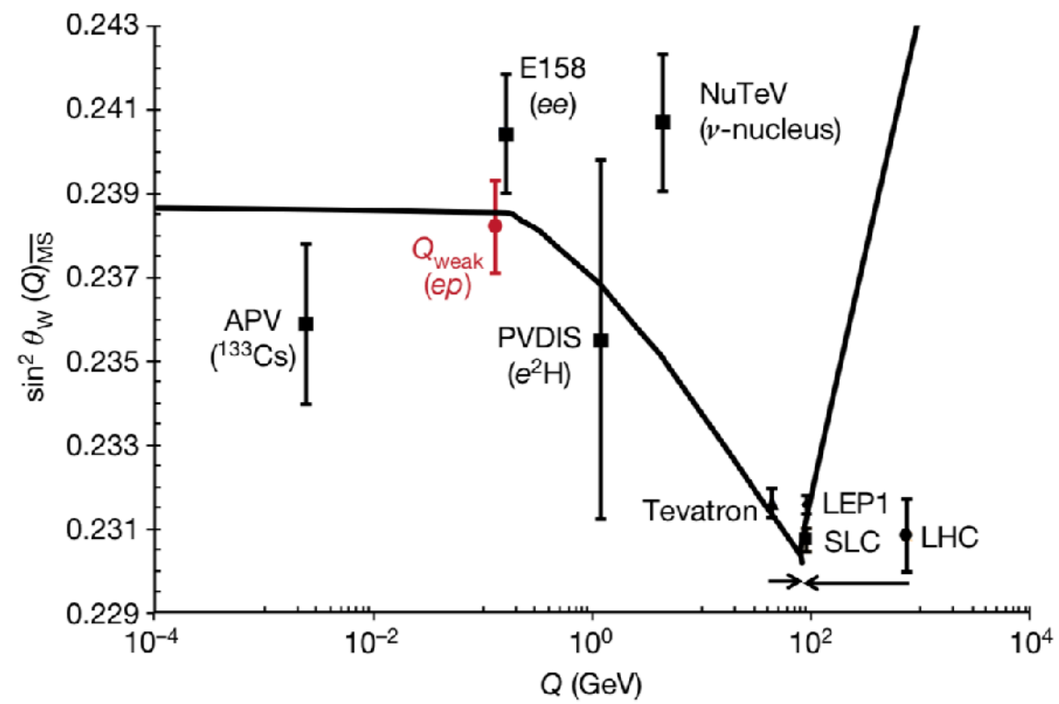
k: overlap of nuclear and electronic wave functions

Q_W: weak charge (related to Weinberg angle)

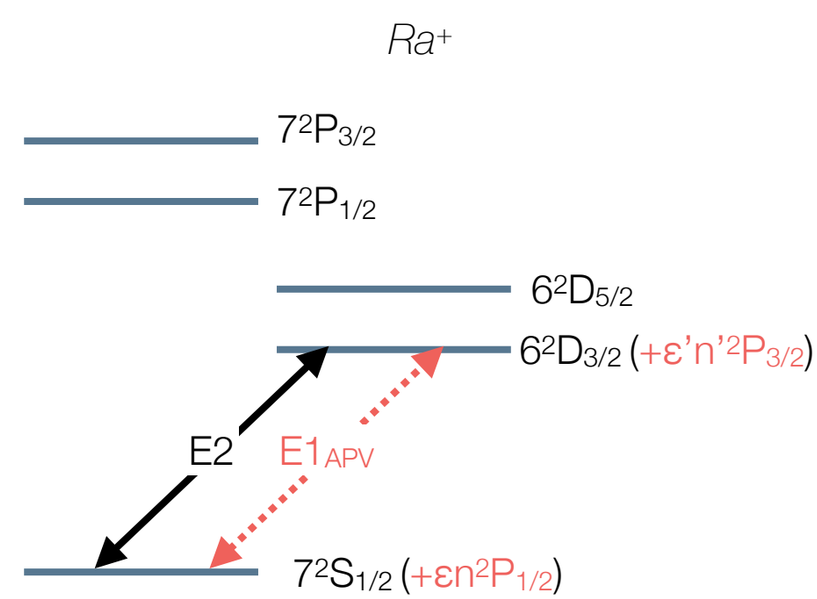
- Extraction of the Weinberg angle is possible using precise atomic calculations

- 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 …



The Jefferson Lab Qweak Collaboration., Androić, D., Armstrong, D.S. *et al., Nature* **557,** 207–211 (2018)

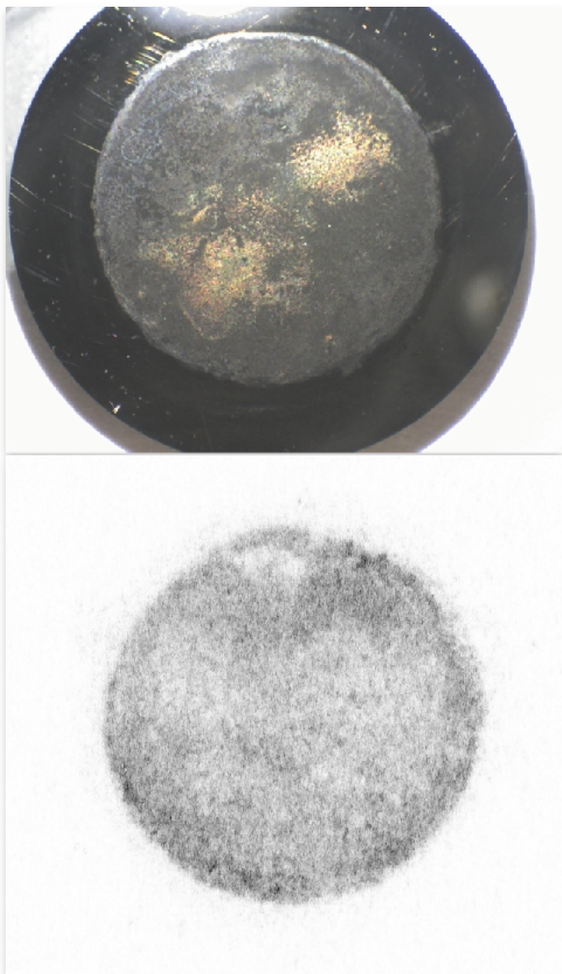


[1] L.W. Wansbeek, *et al., Physical Review* A **78,** 050501(R) (2008)

Curium & Radium targets 2019

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

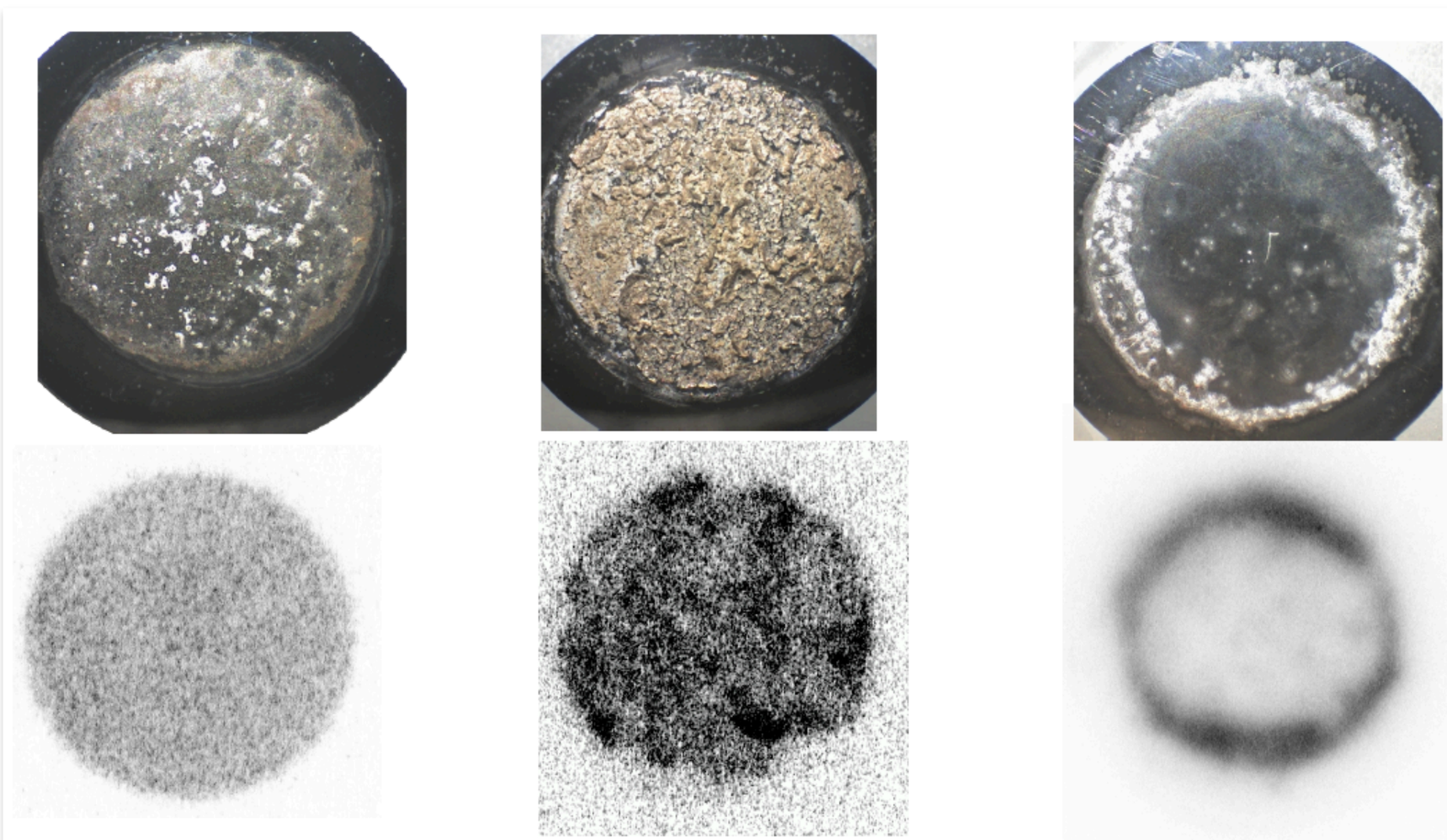
Curium target



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