Muonic atom spectroscopy with radioactive targets

Stella Vogiatzi

On behalf of the muX collaboration*

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Annual Meeting of the Swiss Physical Society

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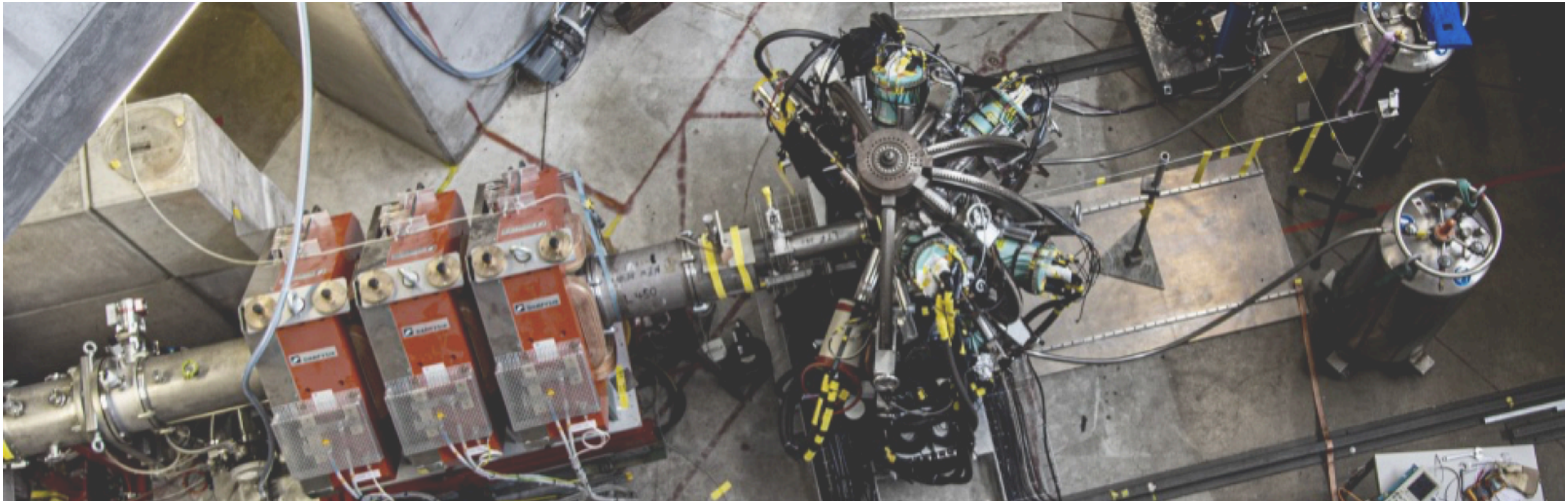


Muonic atom spectroscopy

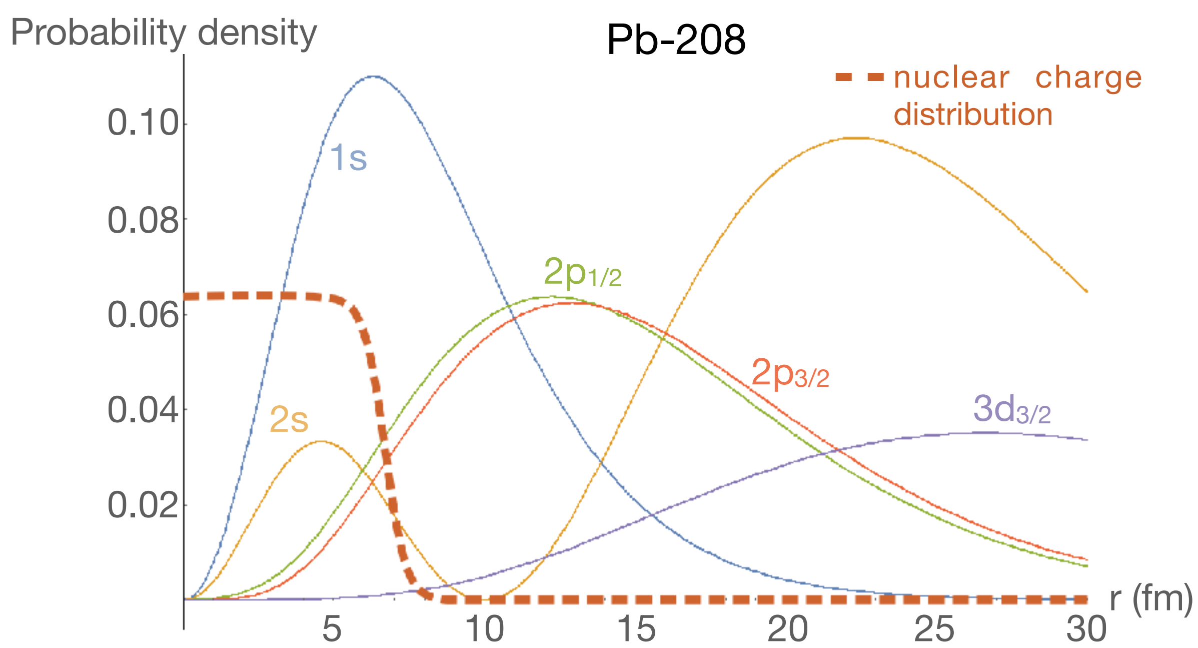
- Large overlap of the low-lying muonic states with the nuclear charge distribution.

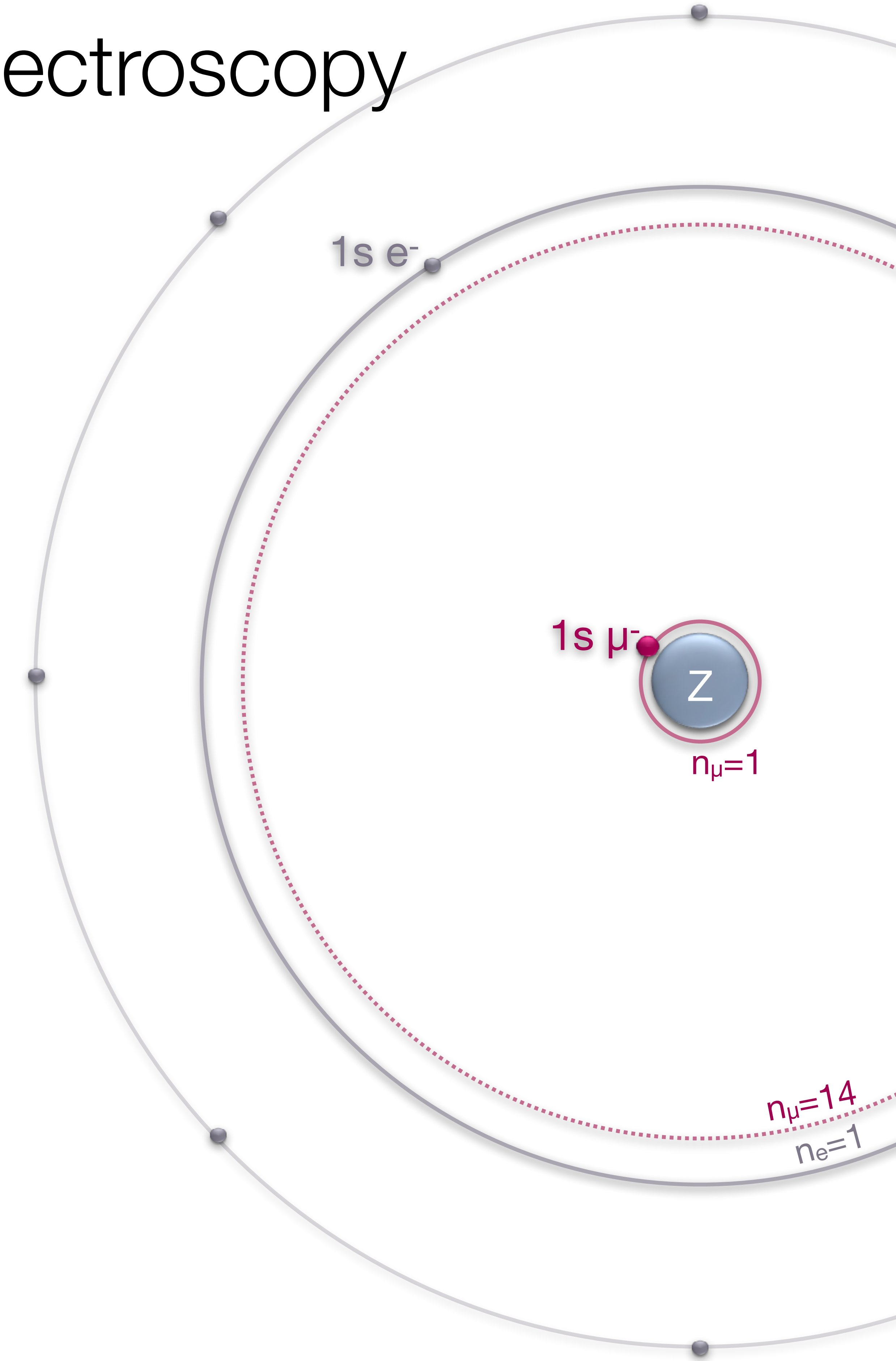
- The measurement of the muonic energy levels allows to extract properties of the nucleus such as the charge radius R_N:

2p-1s transition most sensitive to R_N

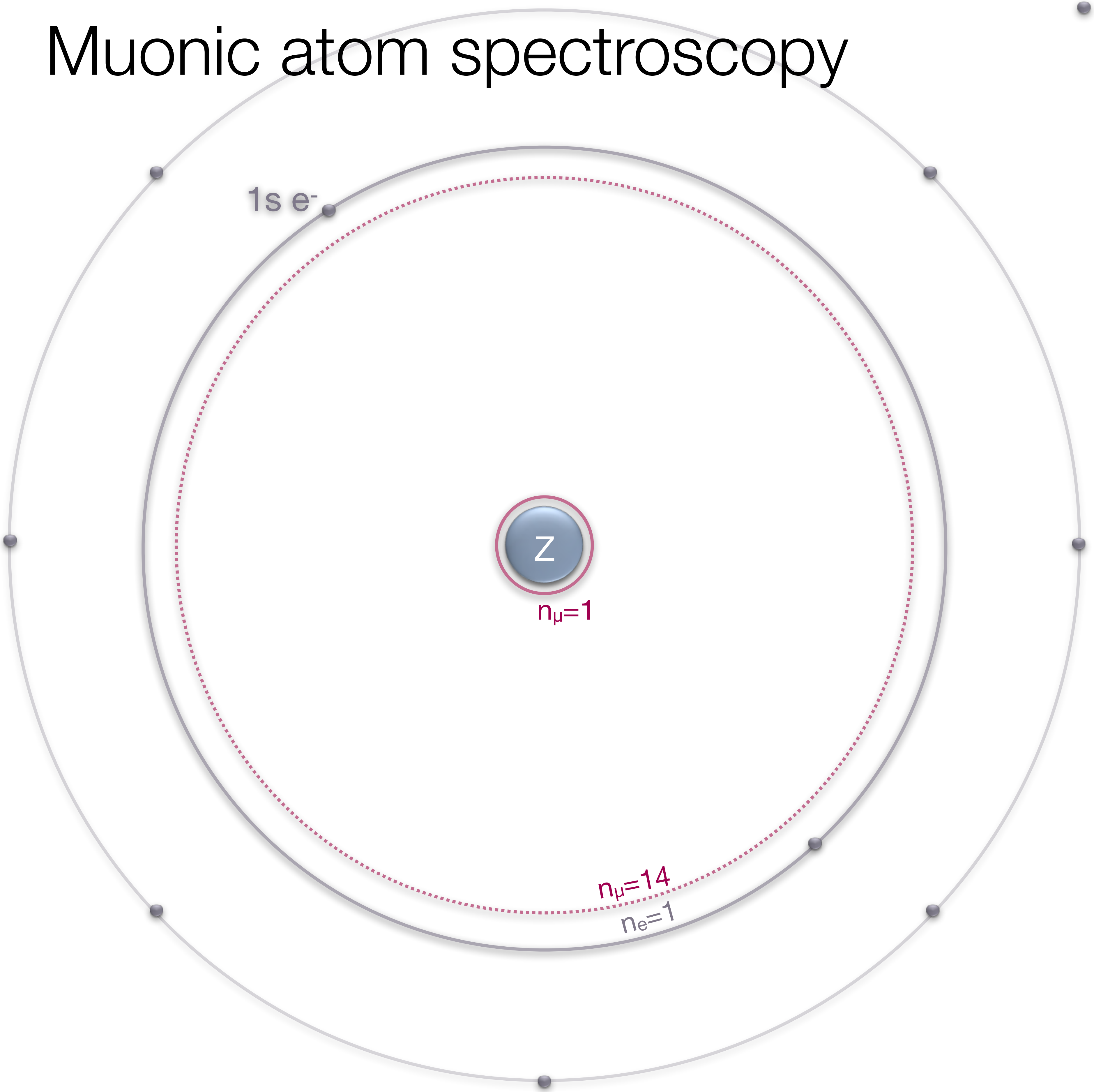
$$R_N^2 = \langle r^2 \rangle = \frac{1}{Ze} \int d^3\vec{r}\, \rho(\vec{r})\, r^2$$

nuclear charge distribution

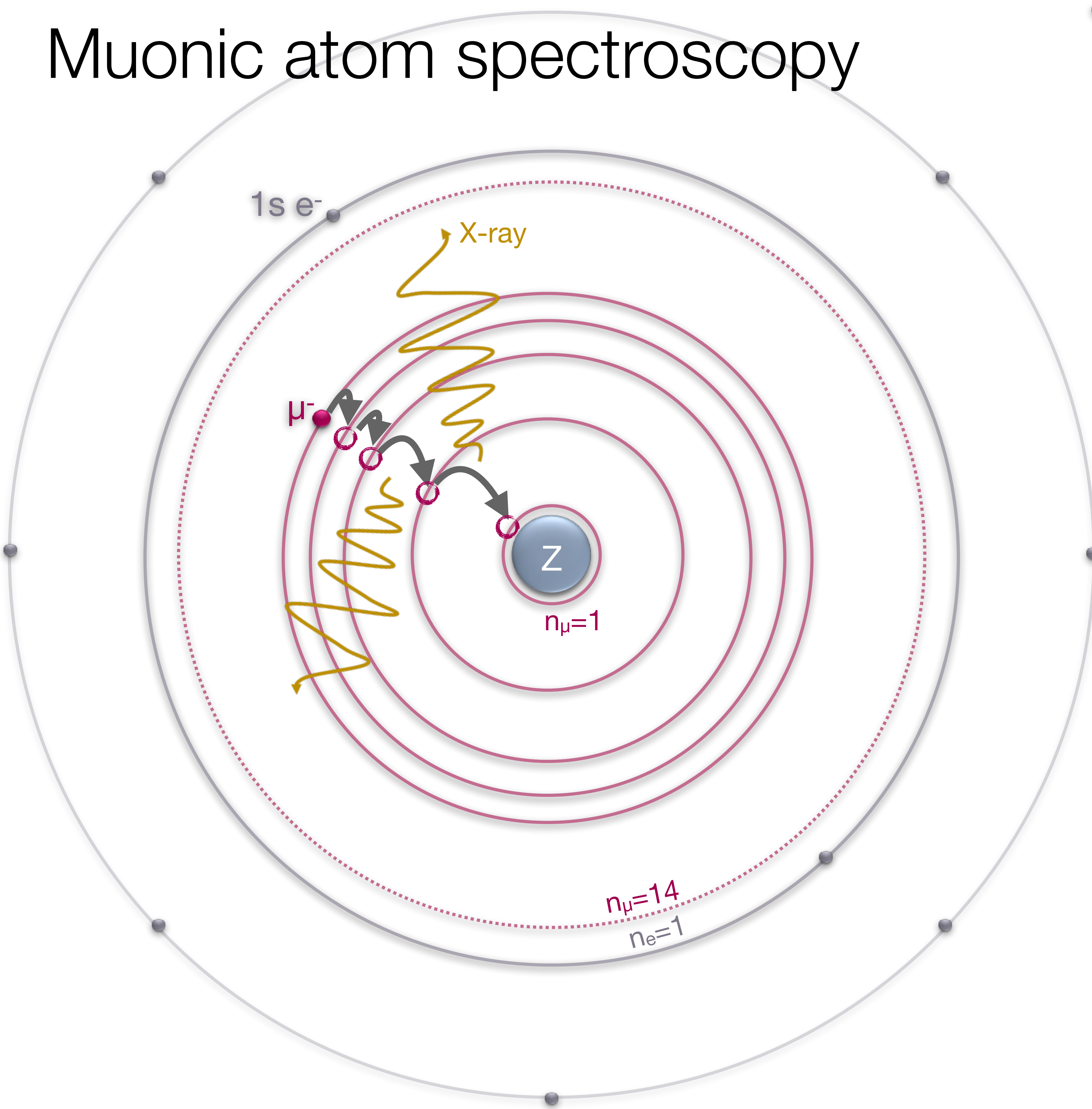




Muonic atom spectroscopy



Muonic atom spectroscopy



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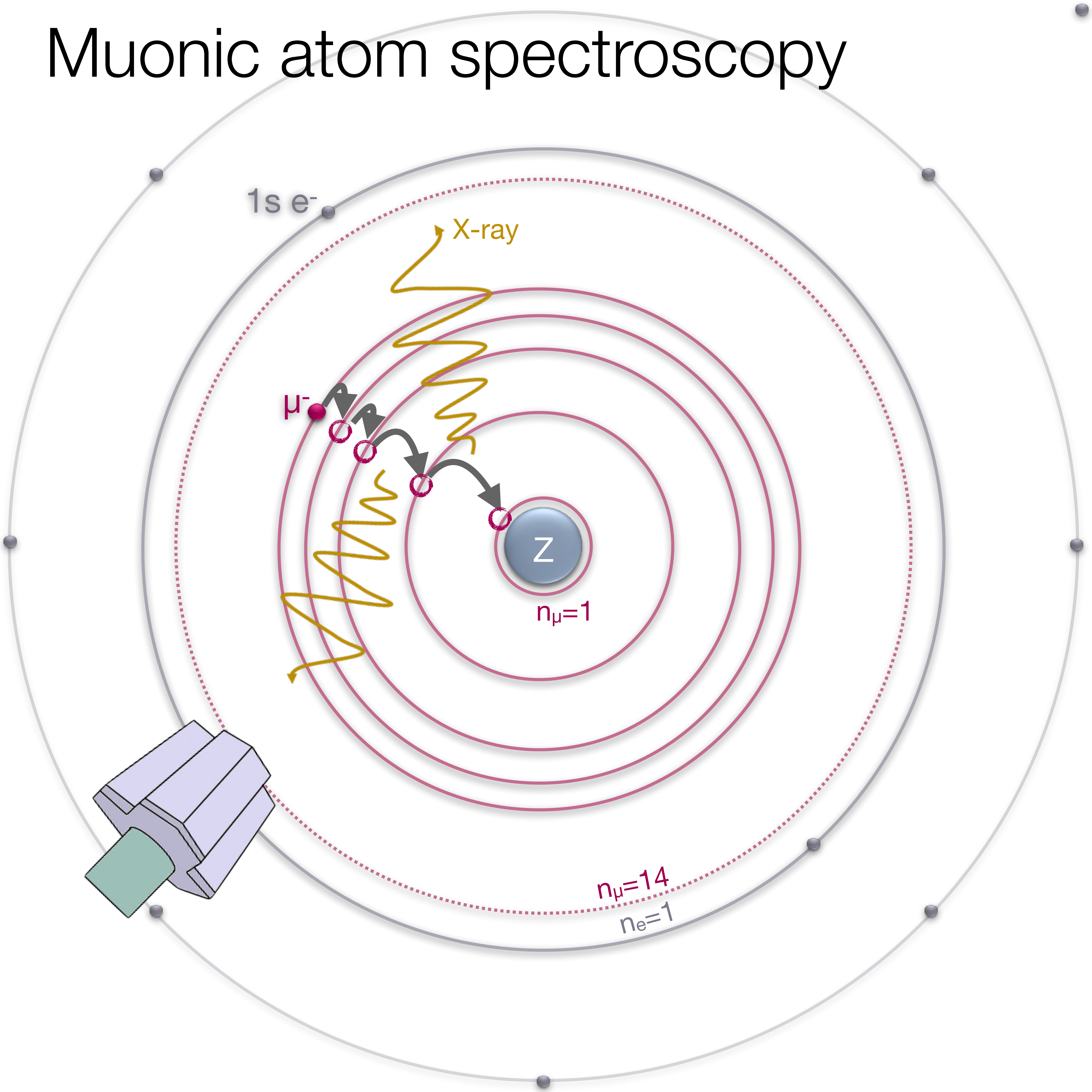

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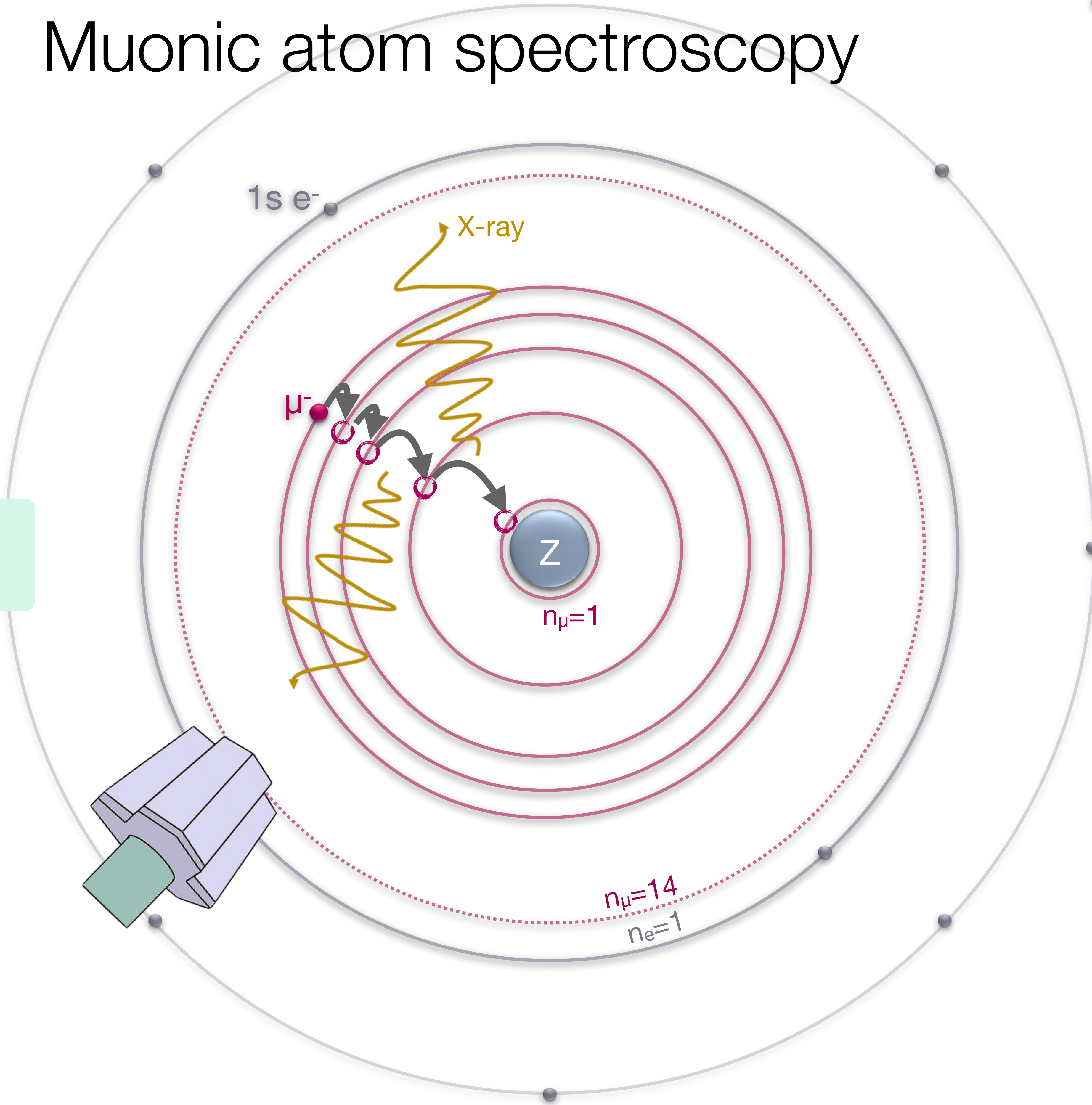
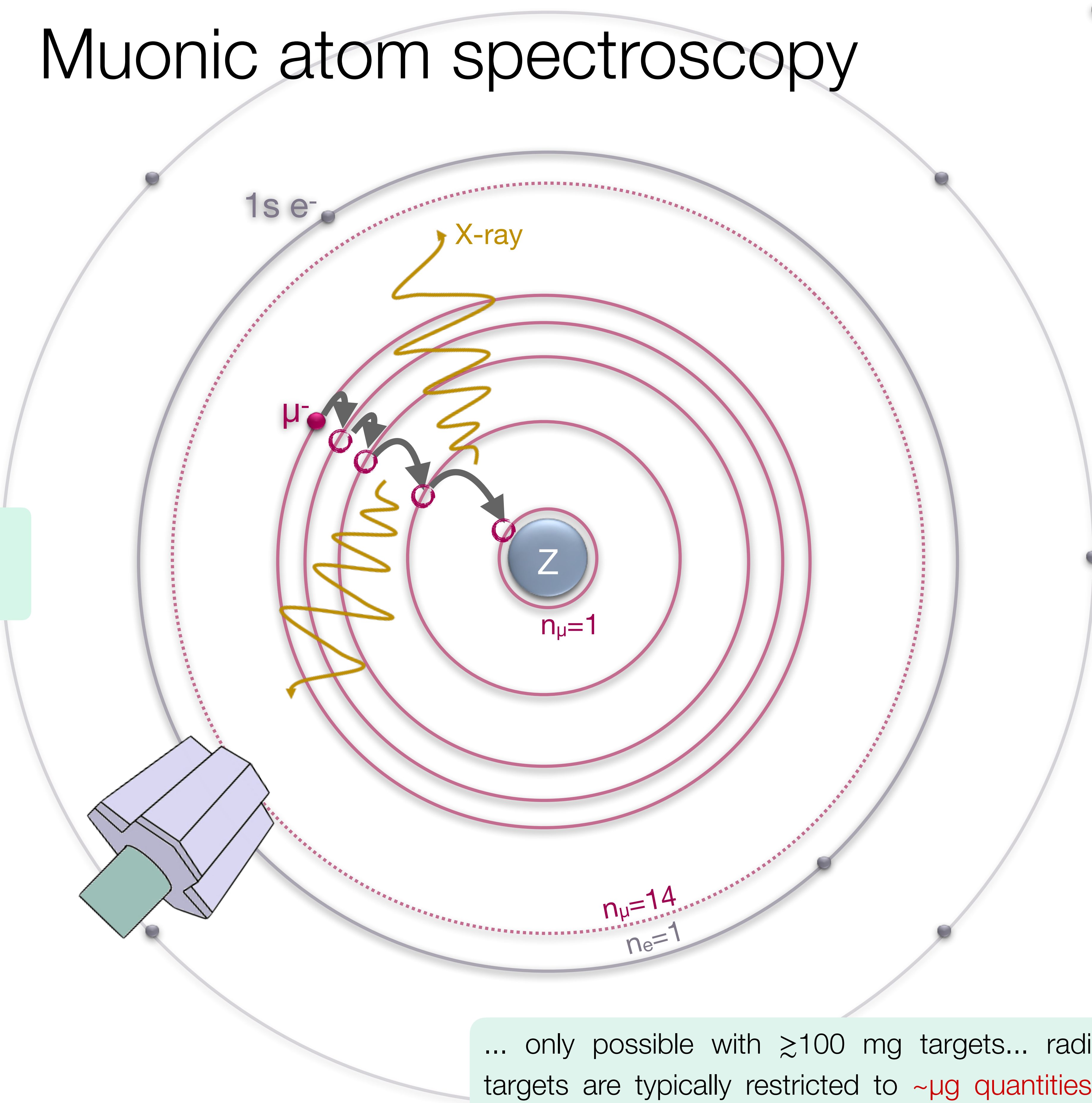


What to measure?

^{248}Cm & ^{226}Ra

Muonic atom spectroscopy



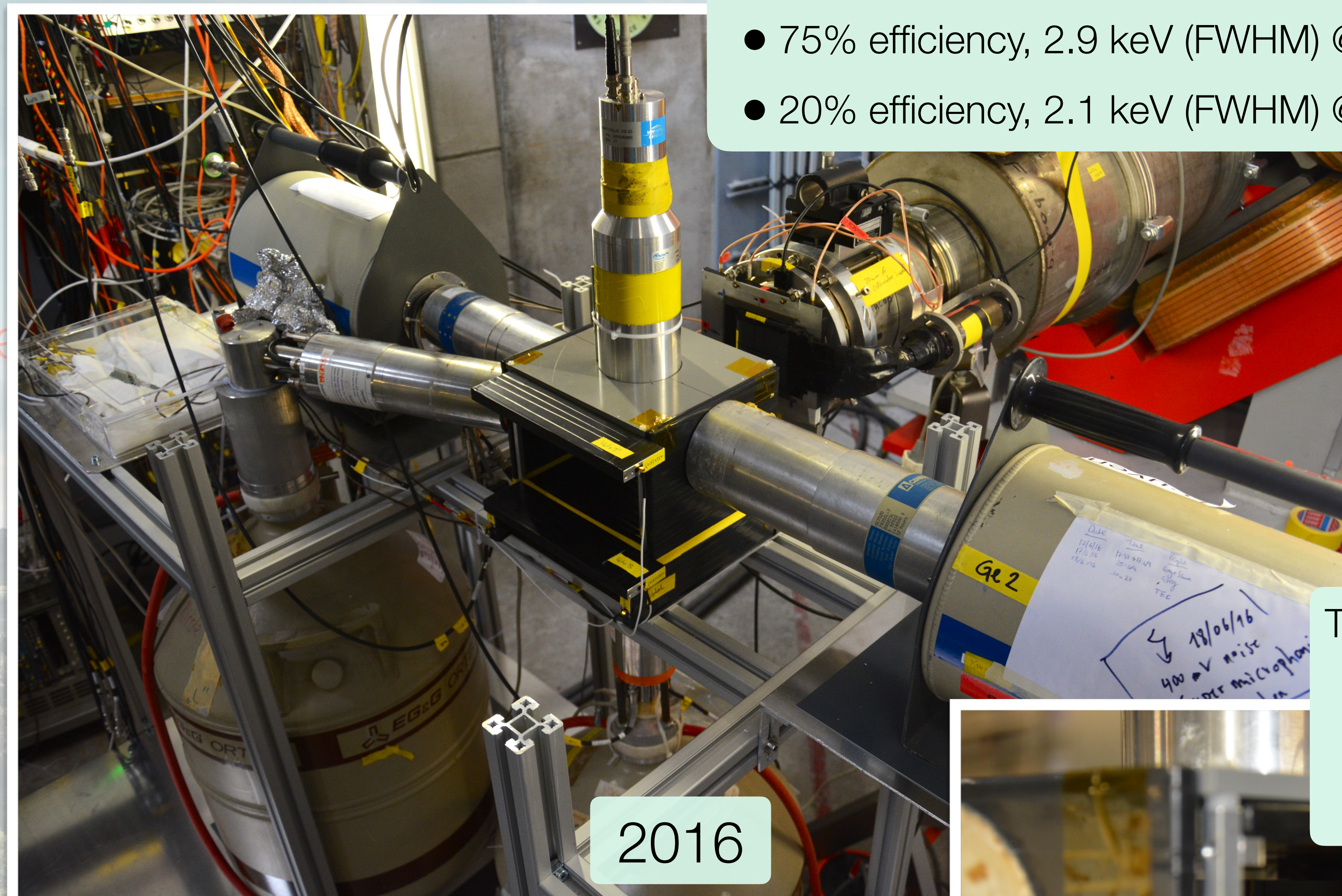
What to measure?

^{248}Cm & ^{226}Ra

... only possible with ≳100 mg targets... radioactive targets are typically restricted to ~μg quantities in the experimental areas

Where does this happen?

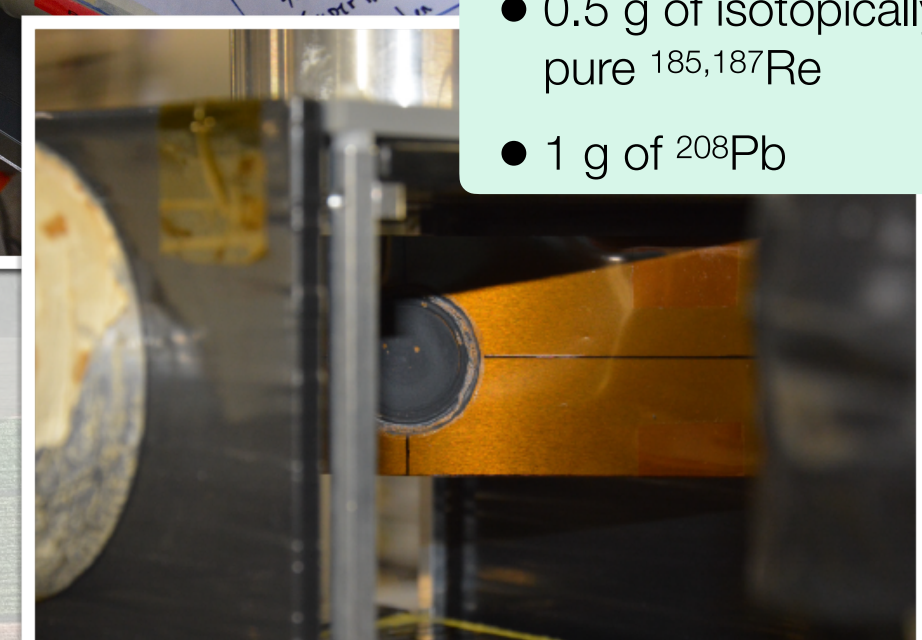
Where does this happen?



2016

2 x HPGe detectors:

- 75% efficiency, 2.9 keV (FWHM) @1.3 MeV
- 20% efficiency, 2.1 keV (FWHM) @1.3 MeV

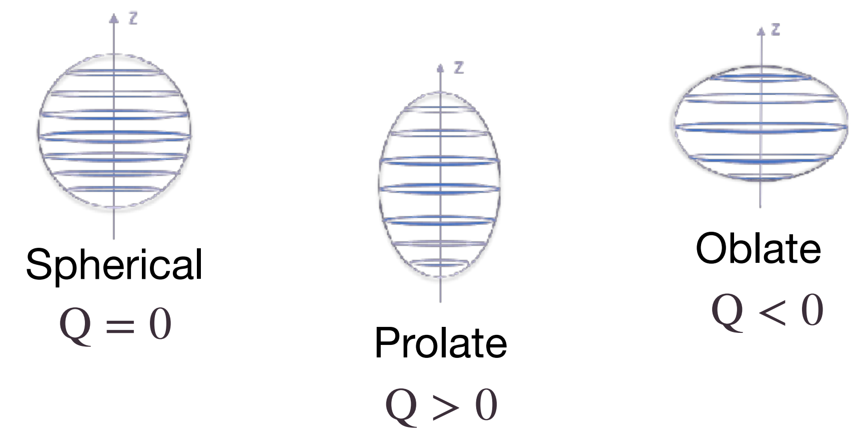


Targets:

- 0.5 g of isotopically pure $^{185,187}Re$
- 1 g of ^{208}Pb

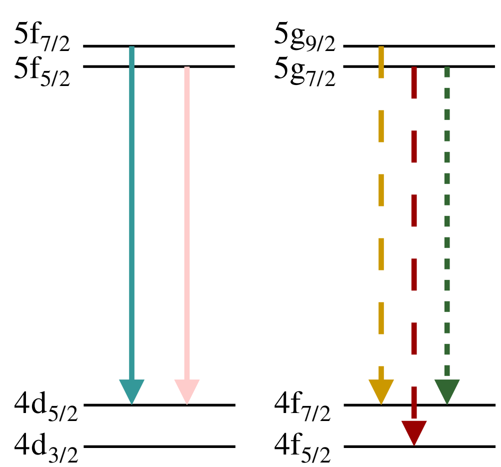
Spectroscopic quadrupole moment in ^{185,187}Re

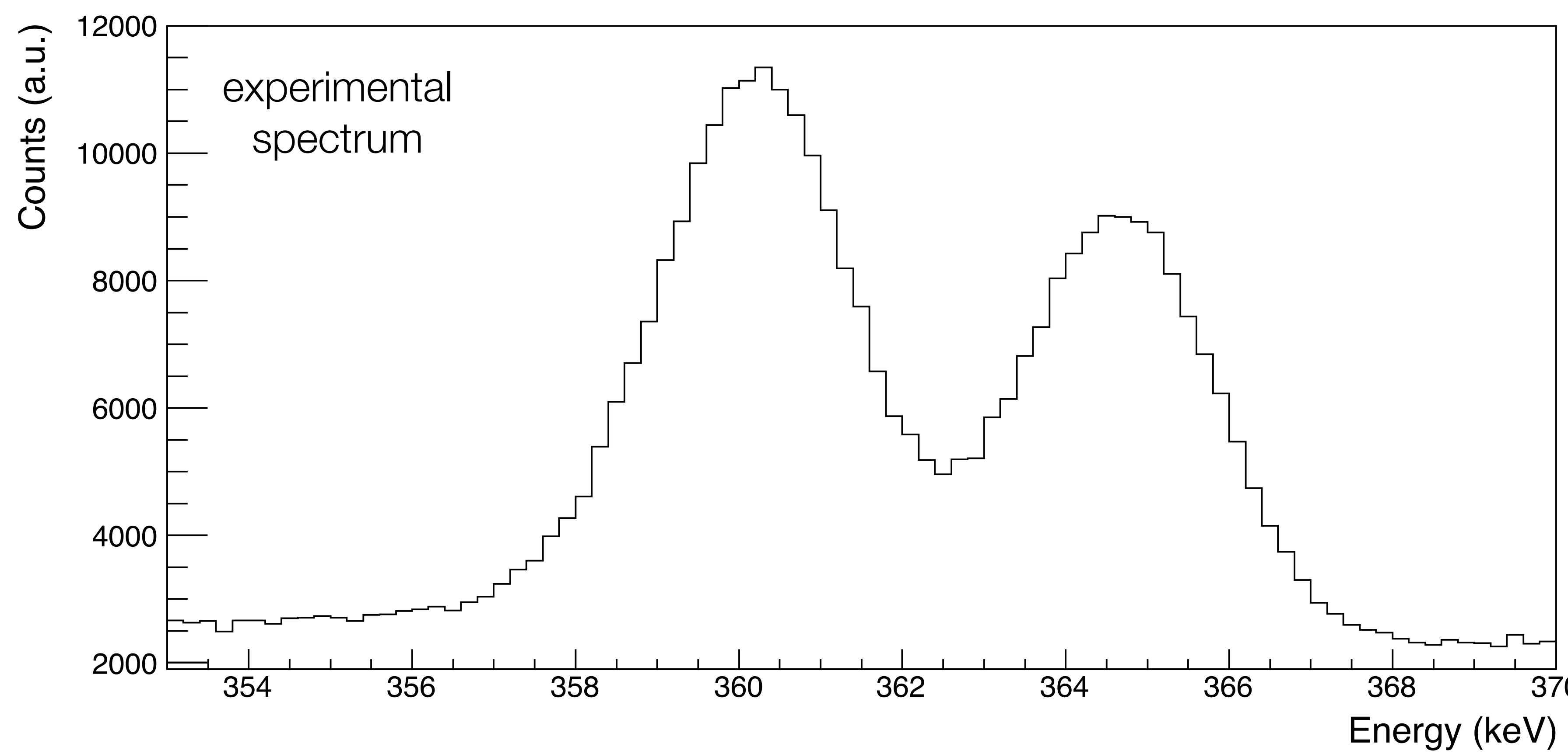
The spectroscopic quadrupole moment $\mathbf{Q}$ is extracted from the 5→4 transitions being not sensitive to the details of the nuclear charge distribution



To extract the quadrupole moment:

- Theoretical predictions of hyperfine transitions
- Good knowledge of the instrumental response is required





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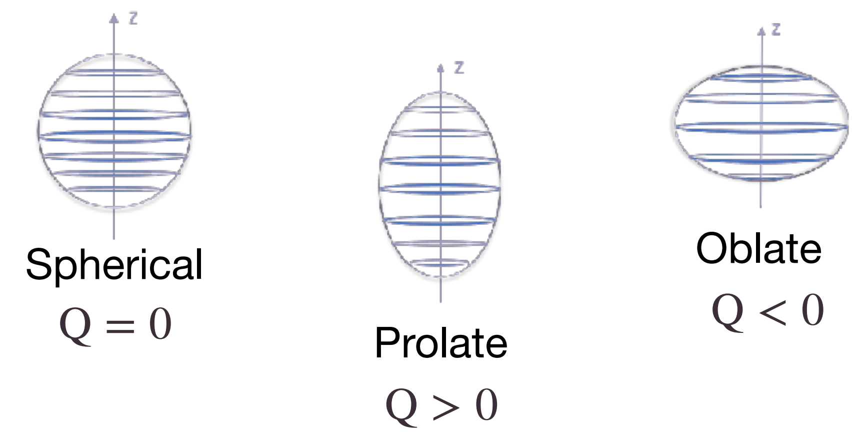

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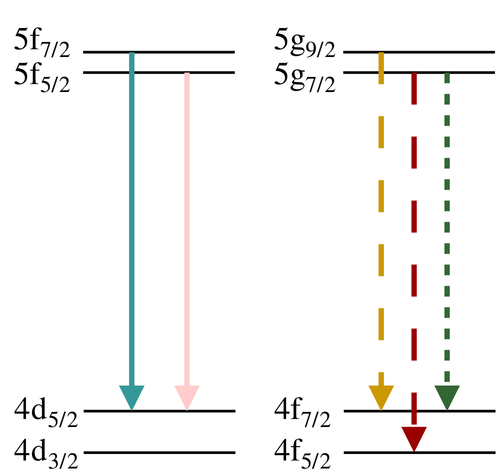
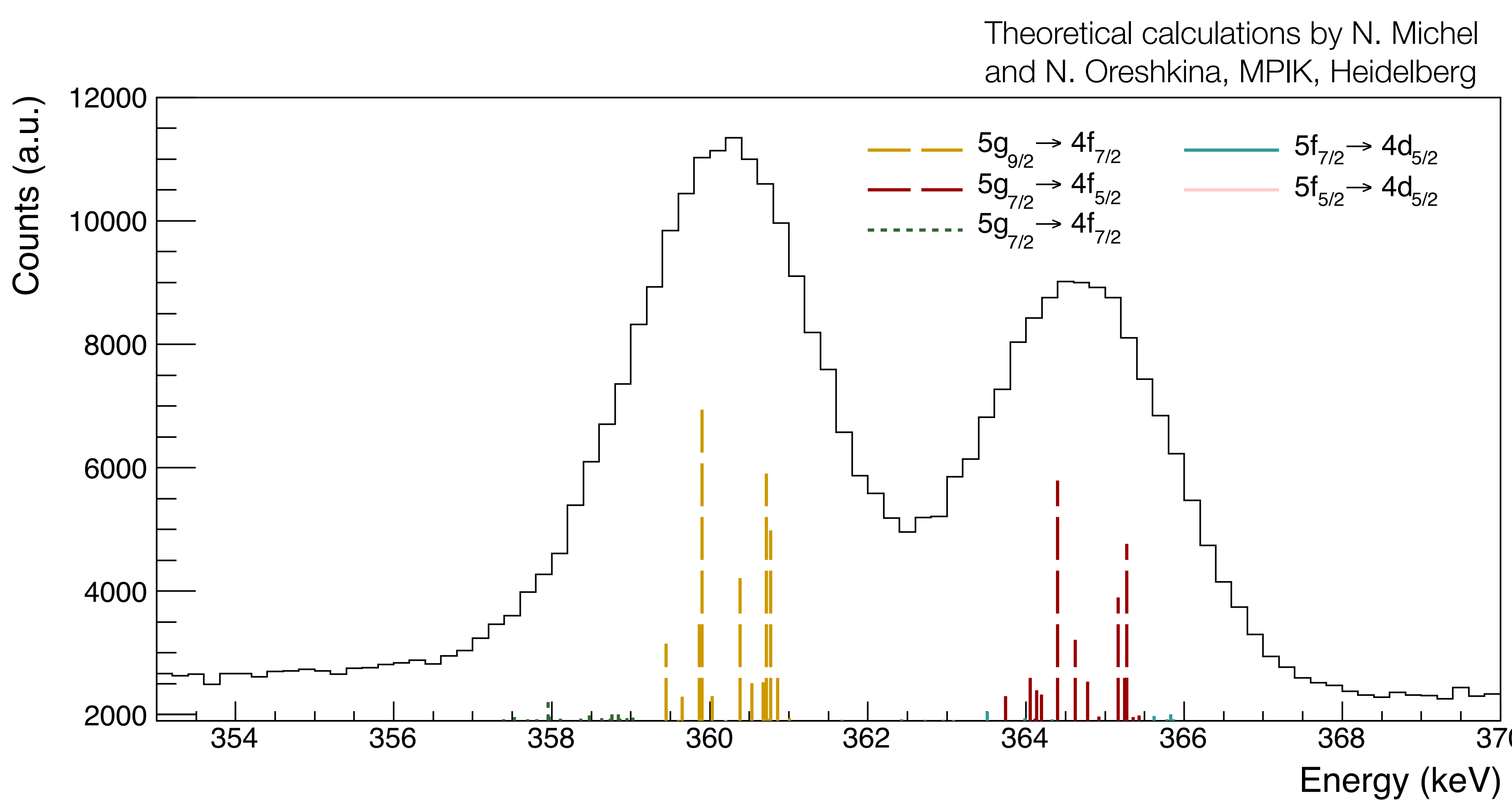
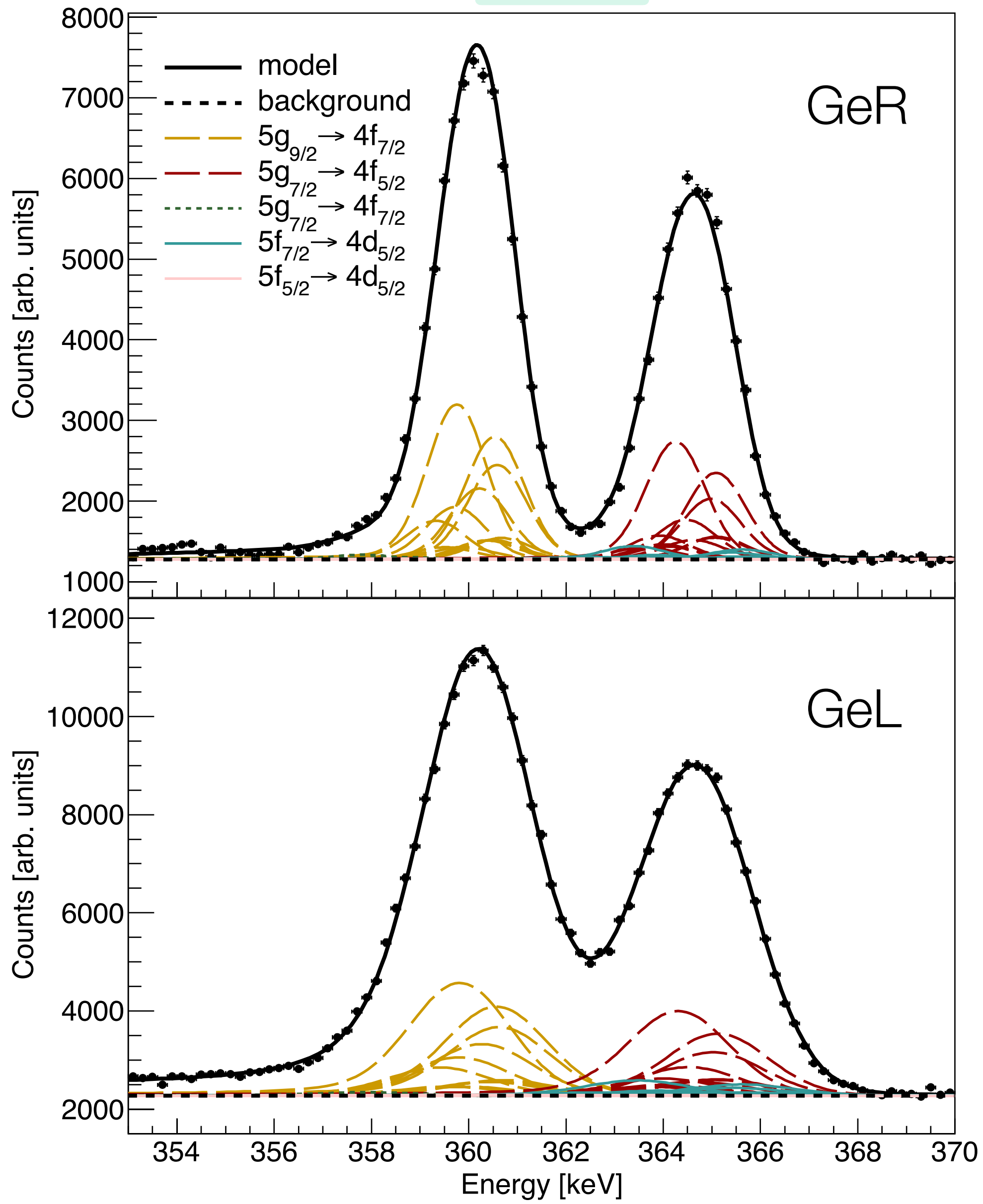




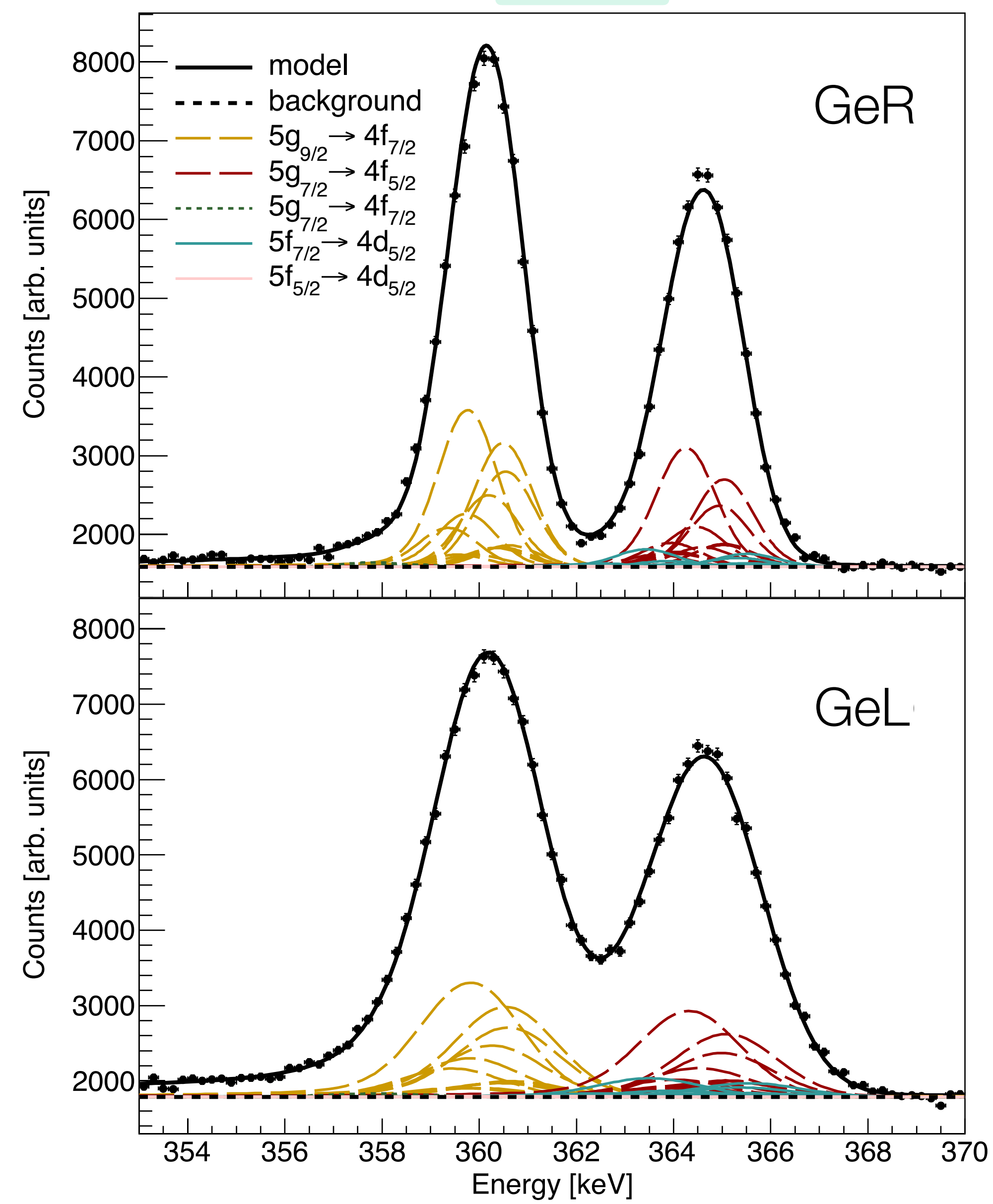
Fit the 5→4 transitions in ^{185,187}Re

- Fit of the theoretical predictions in the experimental spectrum with the quadrupole moment as a free parameter

^{185}Re



^{187}Re



Fit the 5→4 transitions in ^{185,187}Re

- Fit of the theoretical predictions in the experimental spectrum with the quadrupole moment as a free parameter

- First physics result:

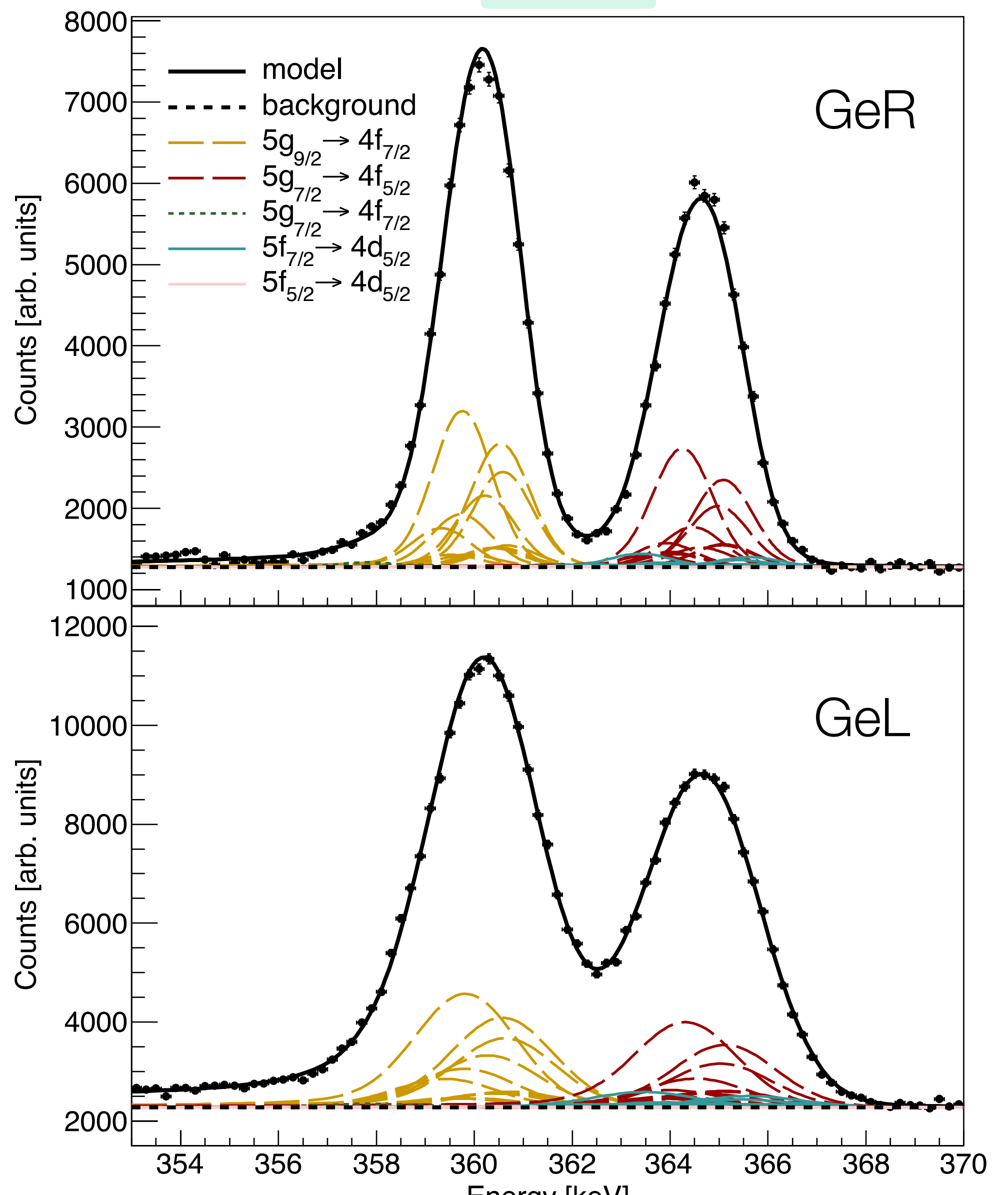
$Q(^{185}Re) = 2.07(5)$ b
$Q(^{187}Re) = 1.94(5)$ b

PHYSICAL REVIEW C **101**, 054313 (2020)

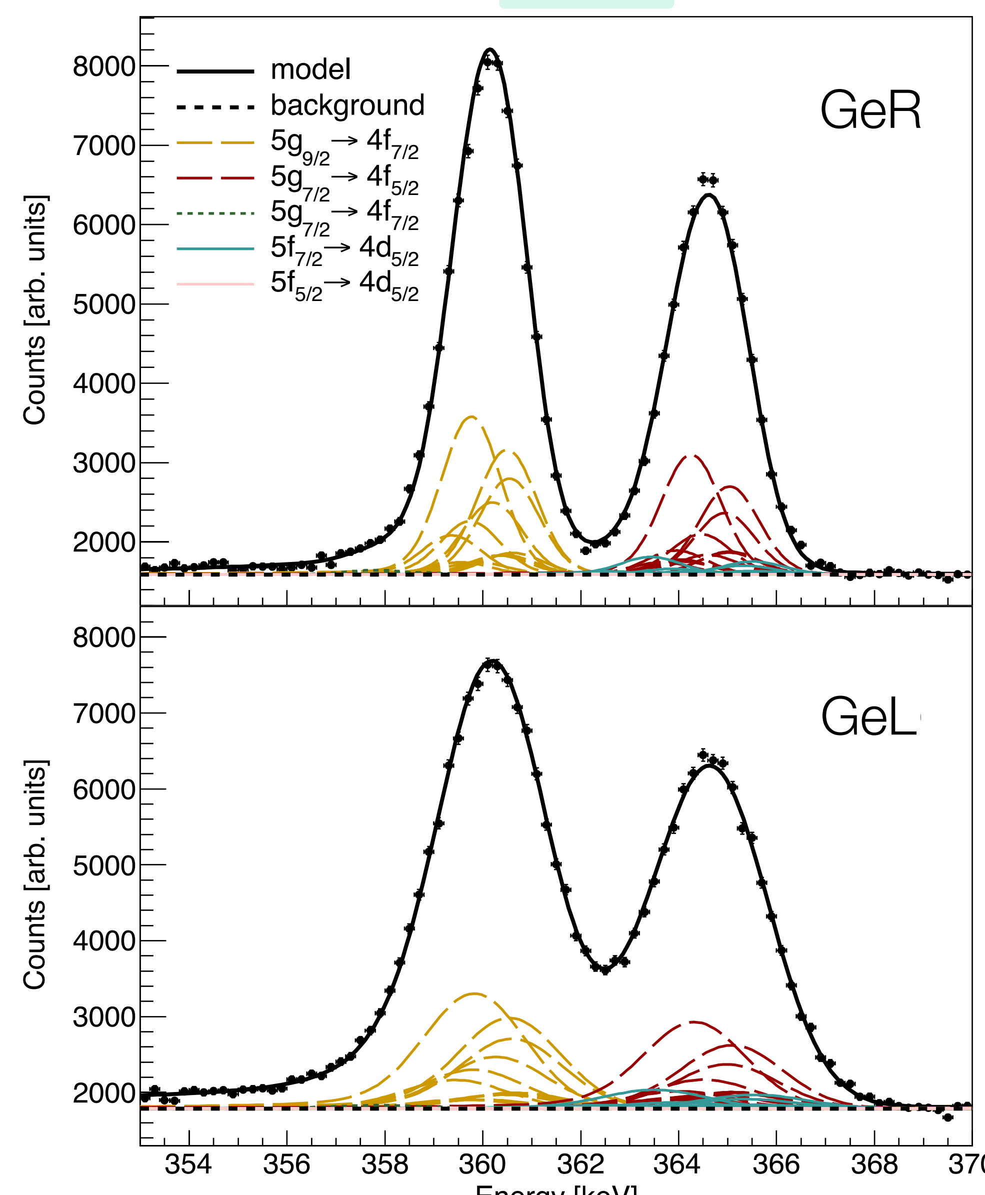
Measurement of the quadrupole moment of ^{185}Re and ^{187}Re from the hyperfine structure of muonic X rays

A. Antognini,[1,2] N. Berger,[3] T. E. Cocolios,[4] R. Dressler,[1] R. Eichler,[1] A. Eggenberger,[2] P. Indelicato,[5] K. Jungmann,[6] C. H. Keitel,[7] K. Kirch,[1,2] A. Knecht,[1] N. Michel,[7] J. Nuber,[1,2] N. S. Oreshkina,[7,*] A. Ouf,[8] A. Papa,[1,9] R. Pohl,[8] M. Pospelov,[10,11] E. Rapisarda,[1,†] N. Ritjoho,[1,2] S. Roccia,[12,13] N. Severijns,[4] A. Skawran,[1,2] S. M. Vogiatzi,[1,2] F. Wauters,[3] and L. Willmann[6]

^{185}Re

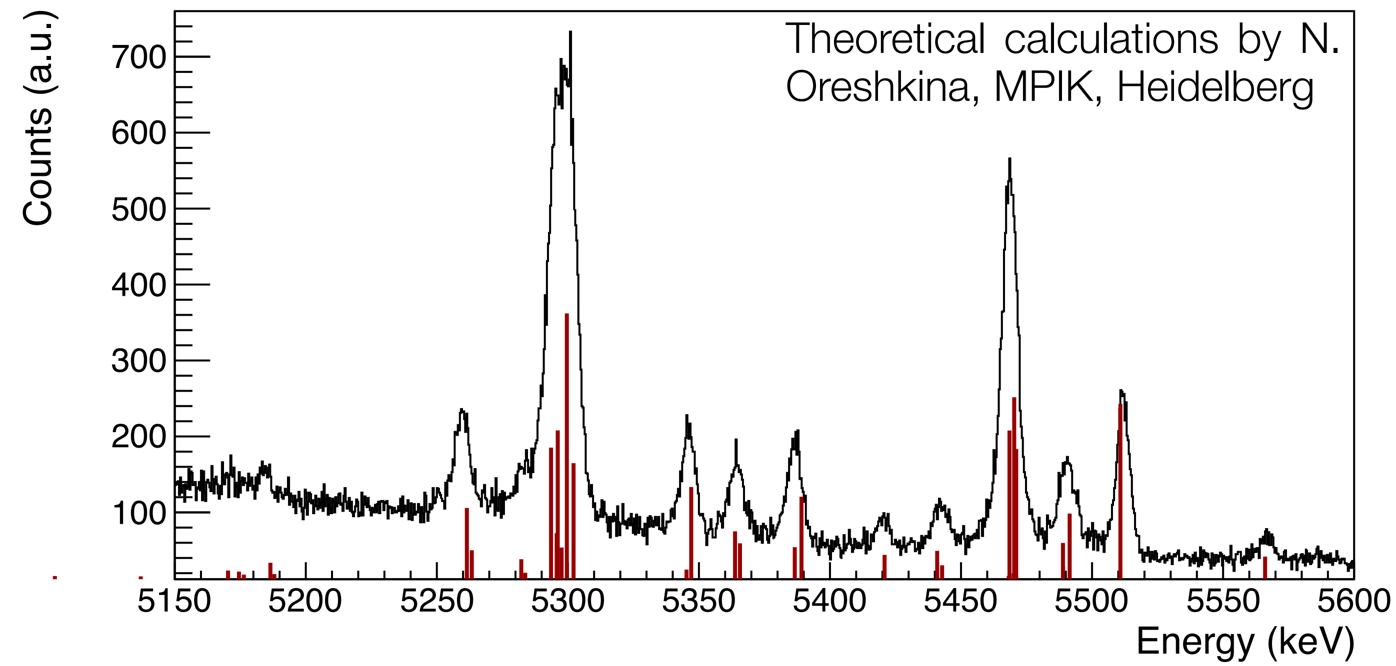


^{187}Re



Nuclear charge radius in $^{185,187}Re$

The extraction of the nuclear charge radius from the analysis of the 2p→1s hyperfine transitions



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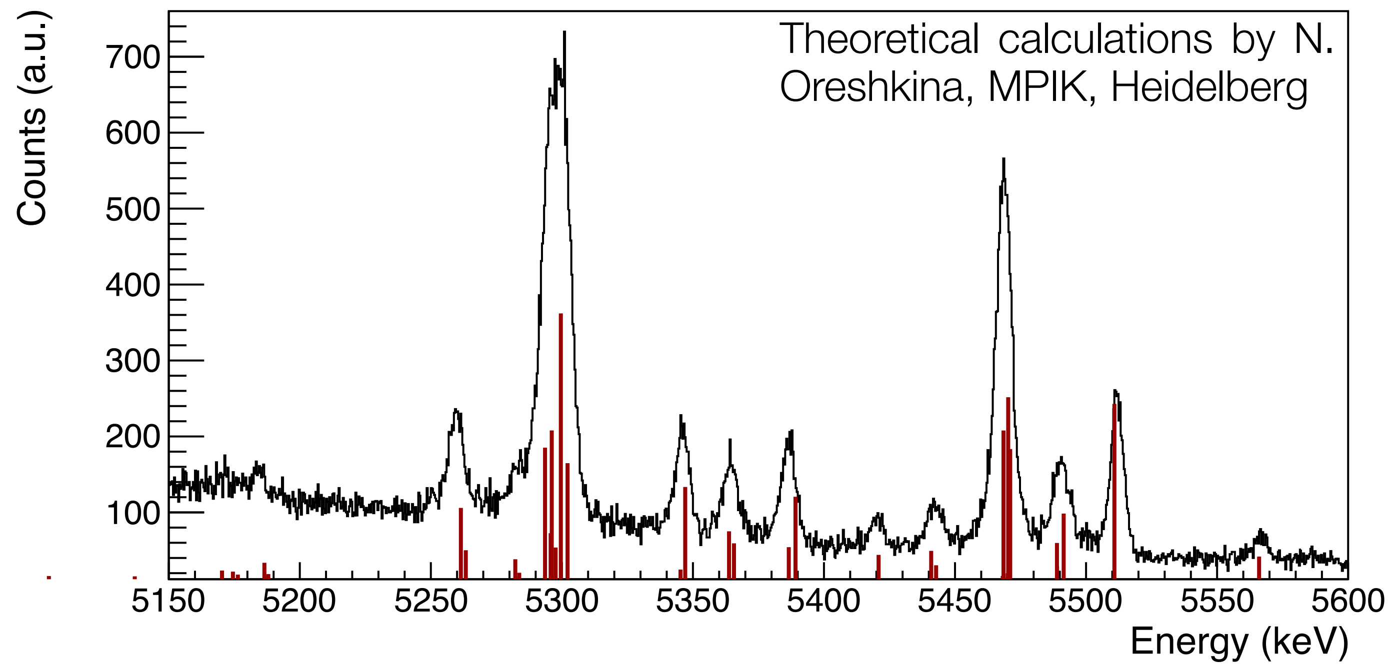


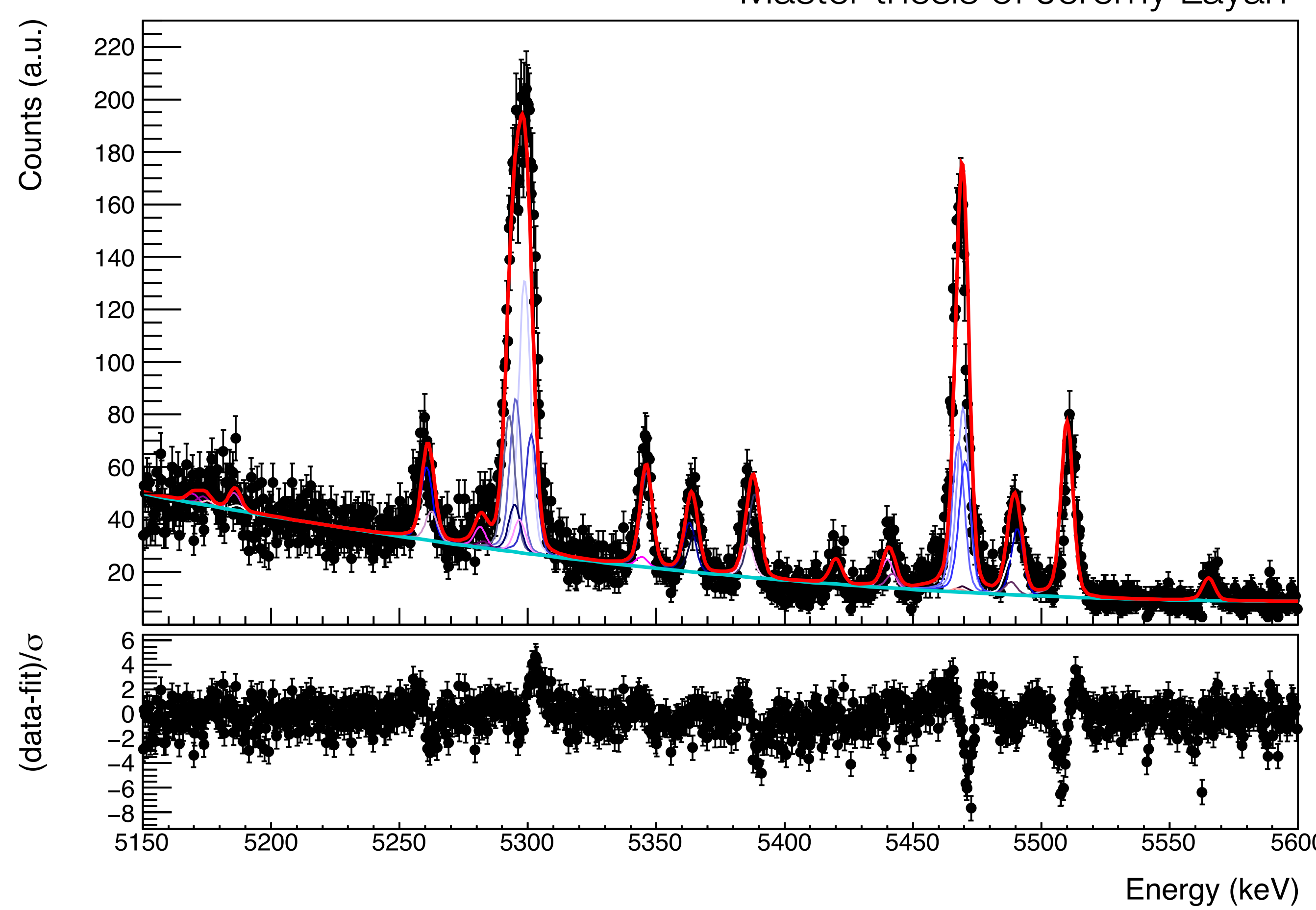
Preliminary results on the nuclear charge radii:

$$R(^{185}\mathrm{Re}) = 5.297(2)_{stat}(6)_{sys}\ \mathrm{fm}$$

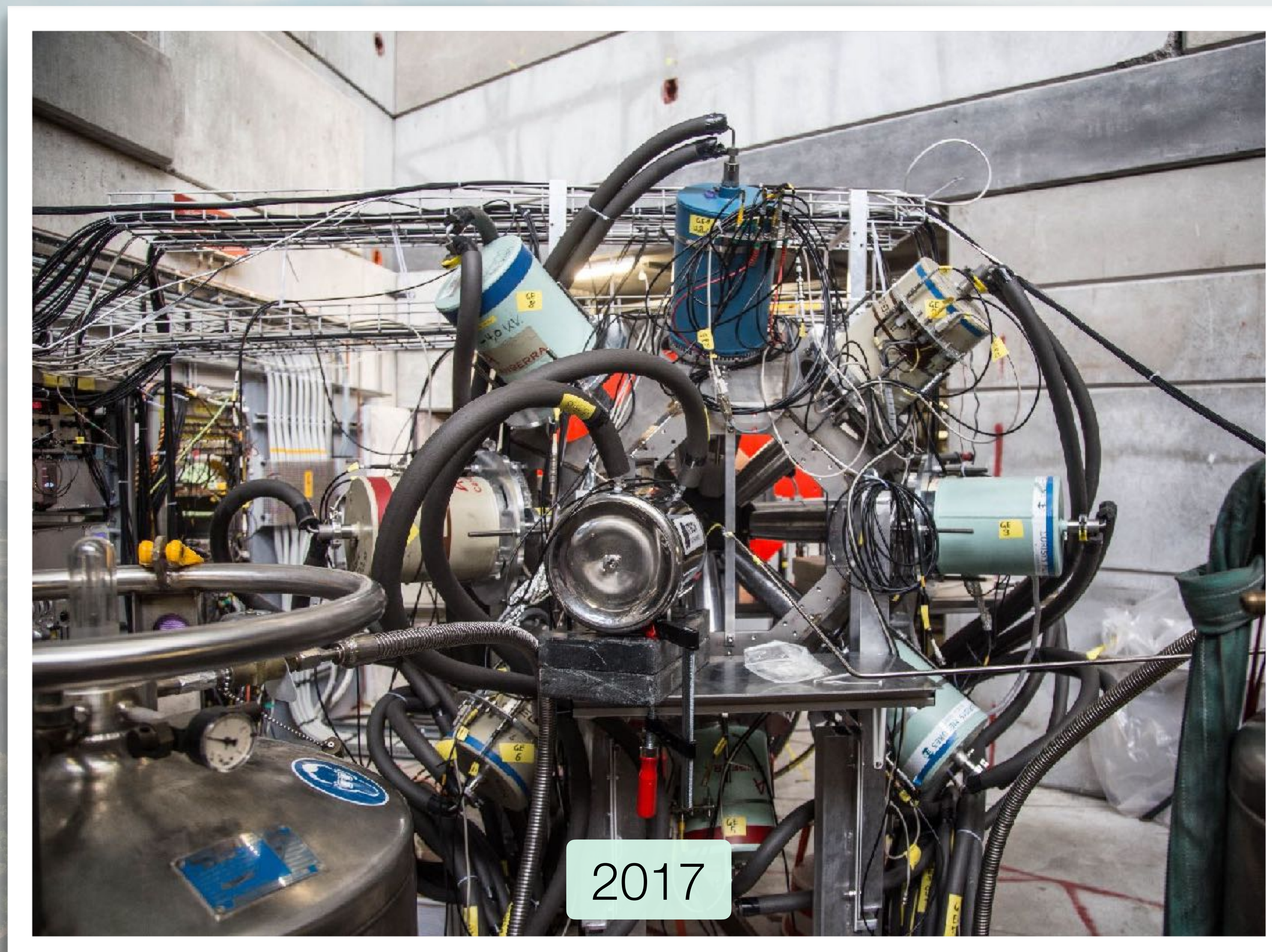
$$R(^{187}\mathrm{Re}) = 5.288(2)_{stat}(4)_{sys}\ \mathrm{fm}$$

Not all the systematics are taken into account.

Master thesis of Jérémy Layan

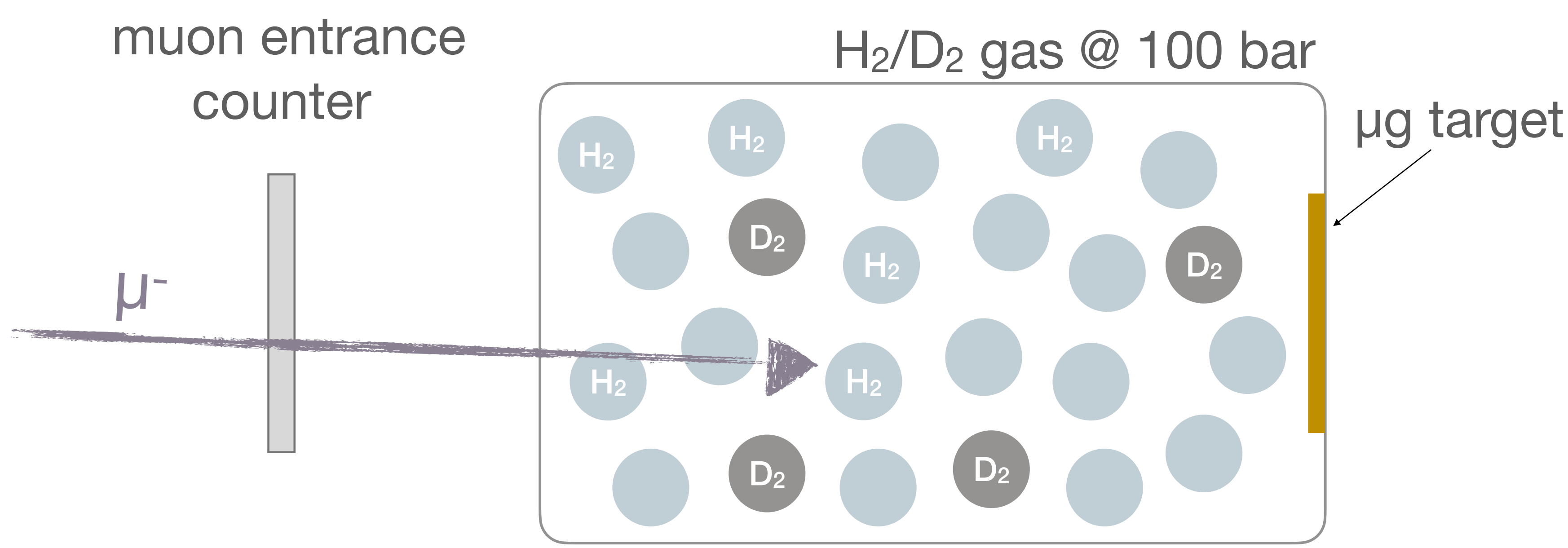


Towards the measurement of μg targets



Muon transfer to microgram targets

Inspired by the work of Strasser *et al.* and Kraiman *et al.*



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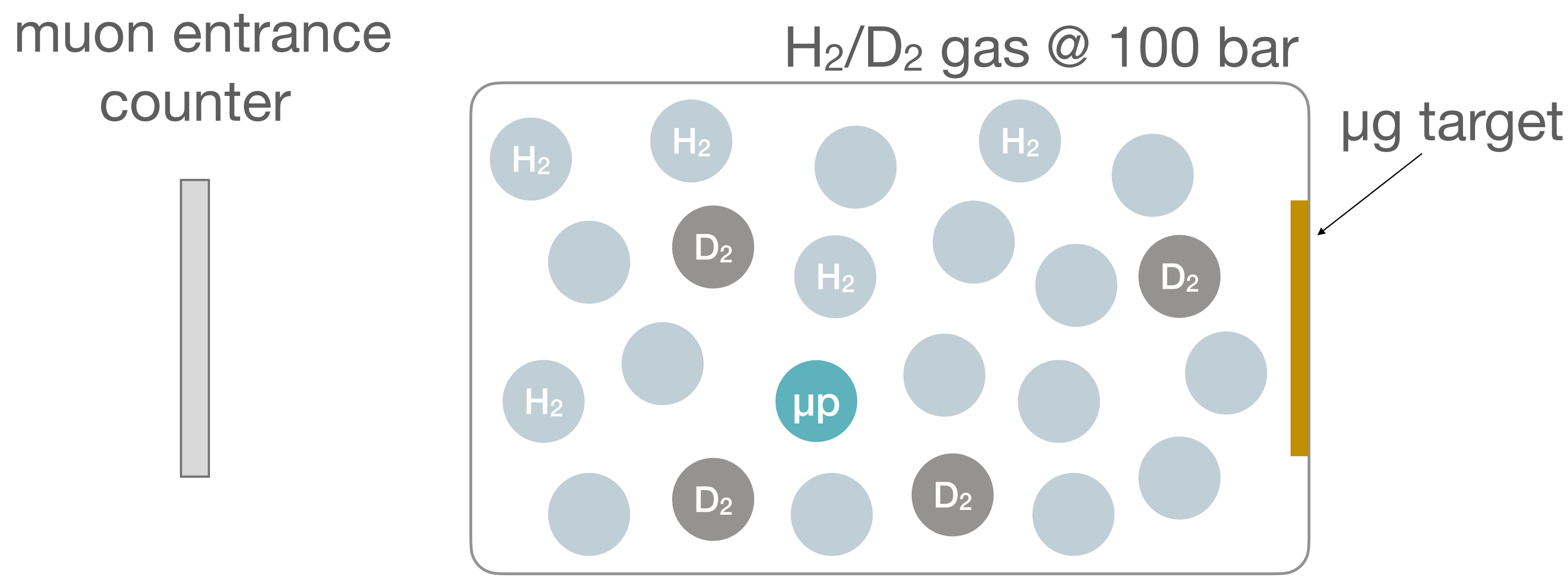

1. μ^- stops in 100 bar of H_2 + 0.25% D_2 & forms muonic hydrogen μp

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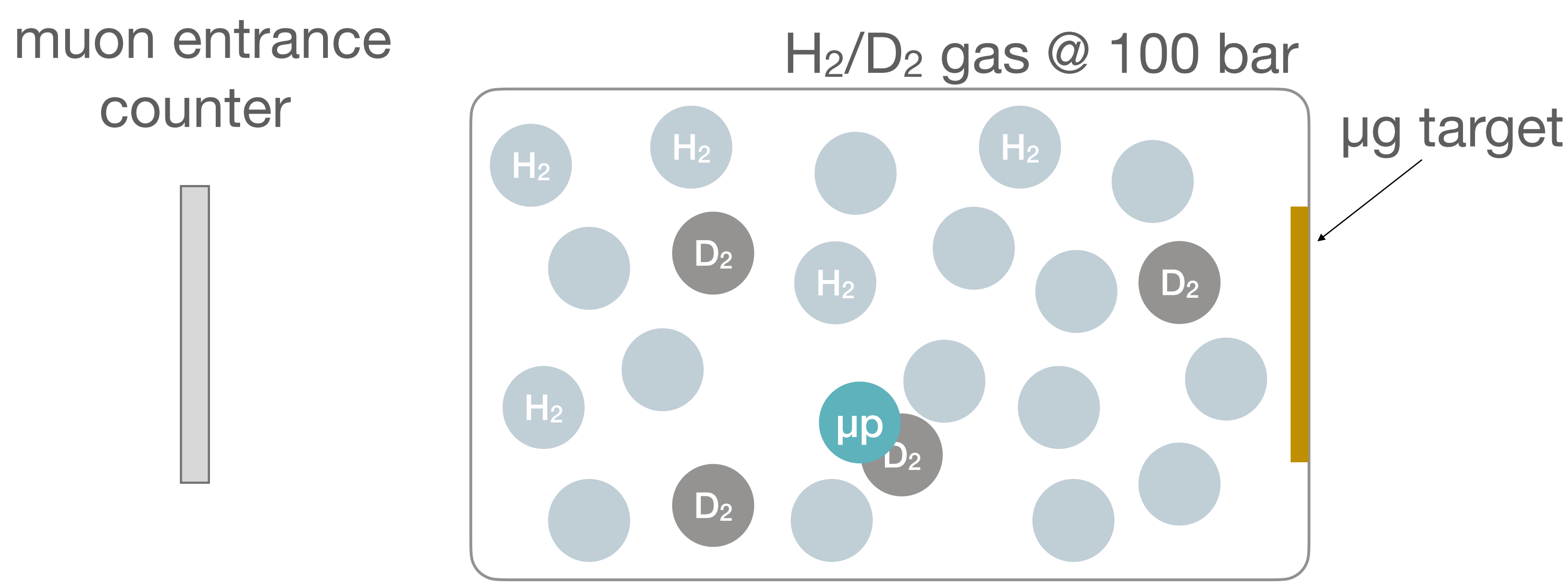

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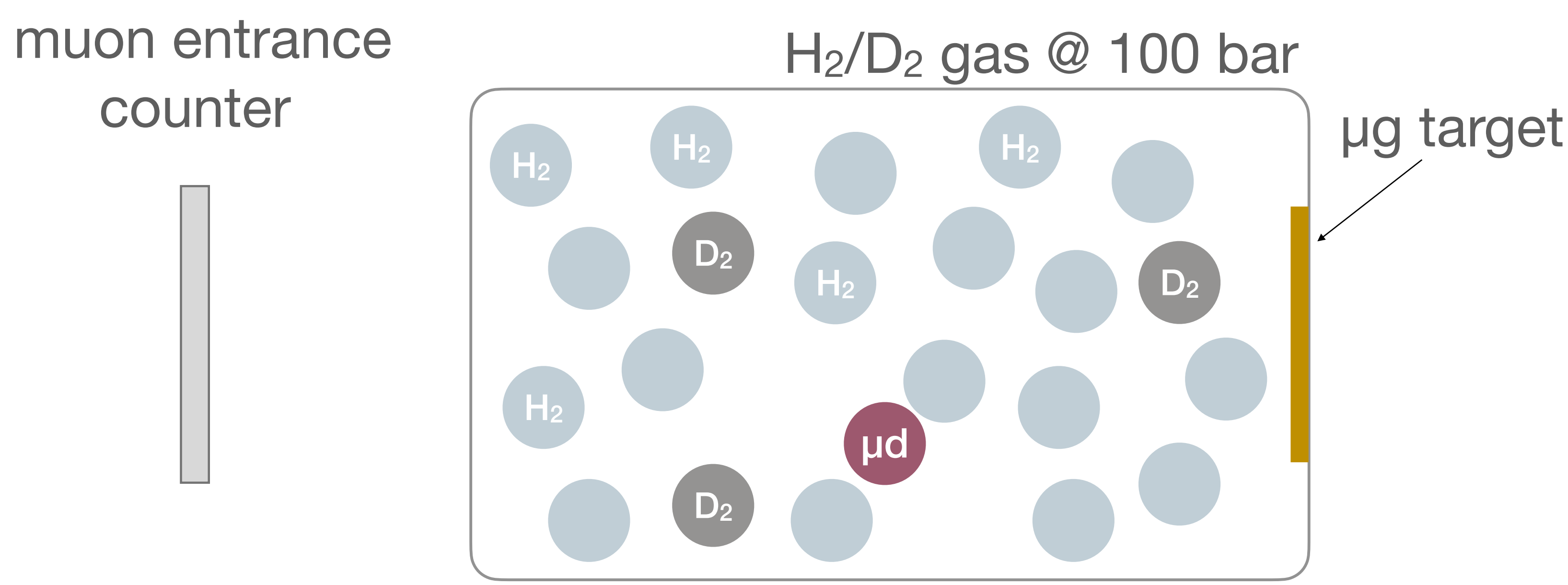

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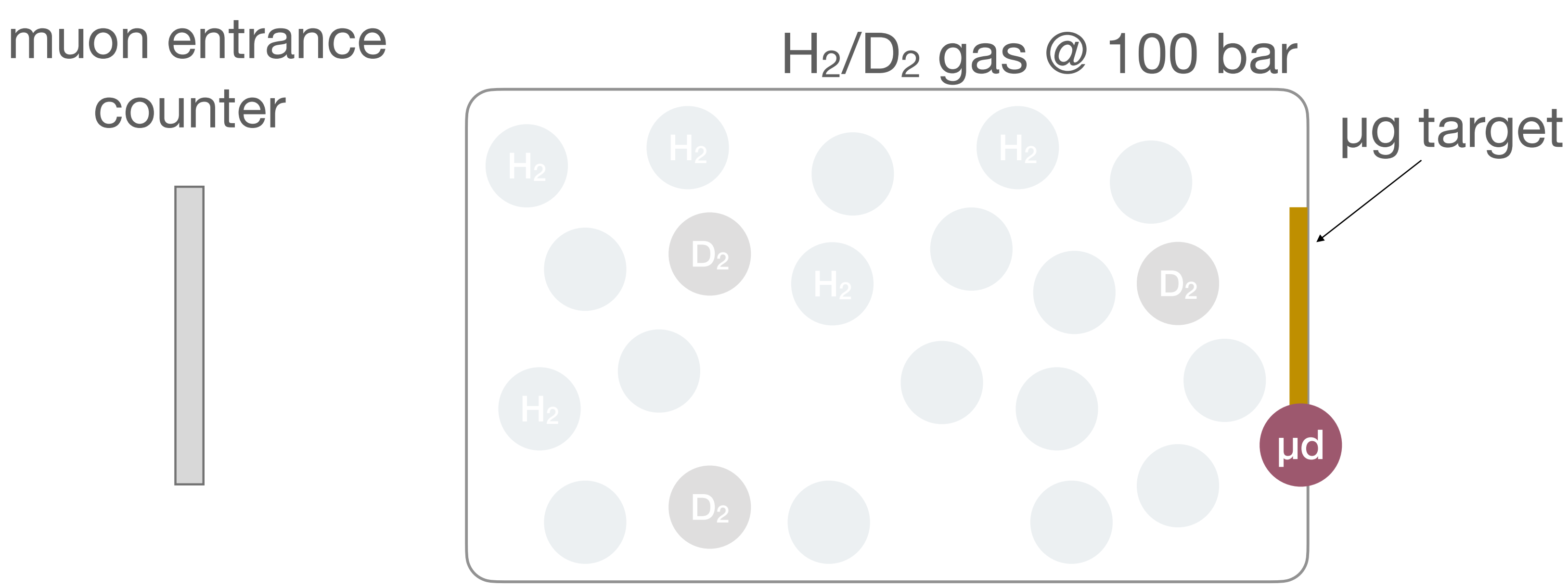

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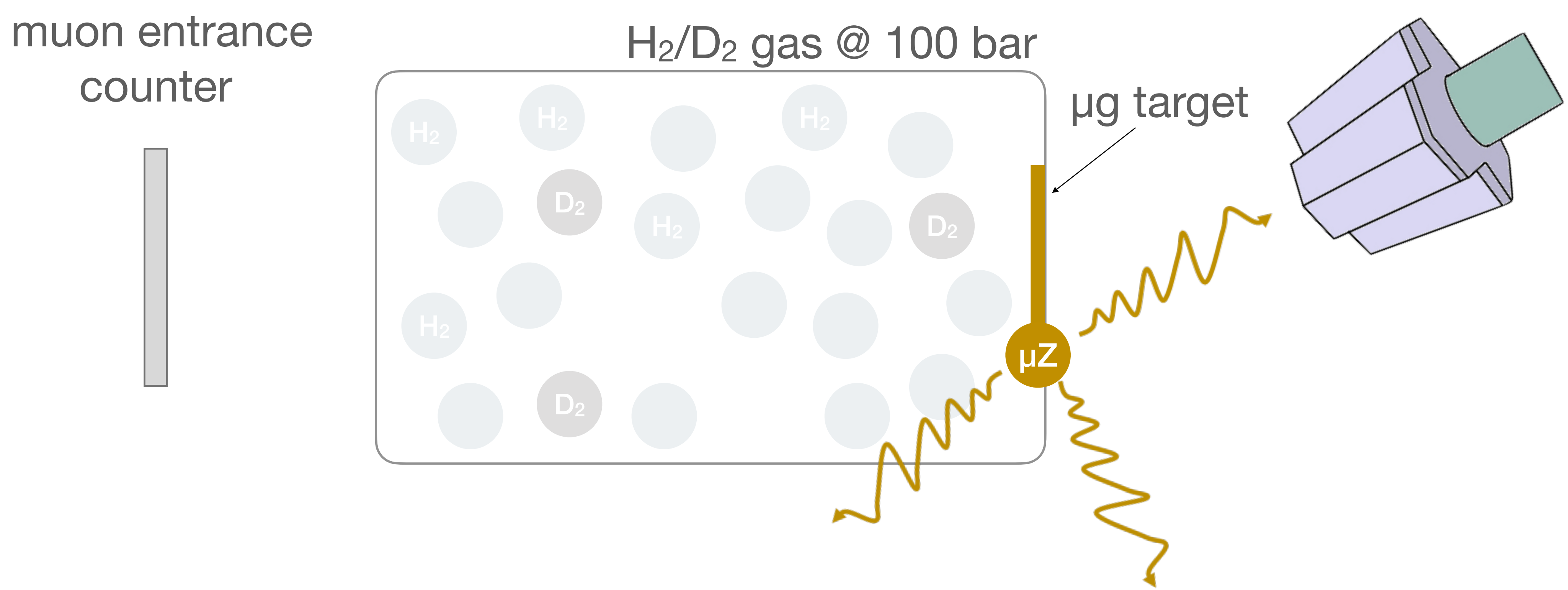

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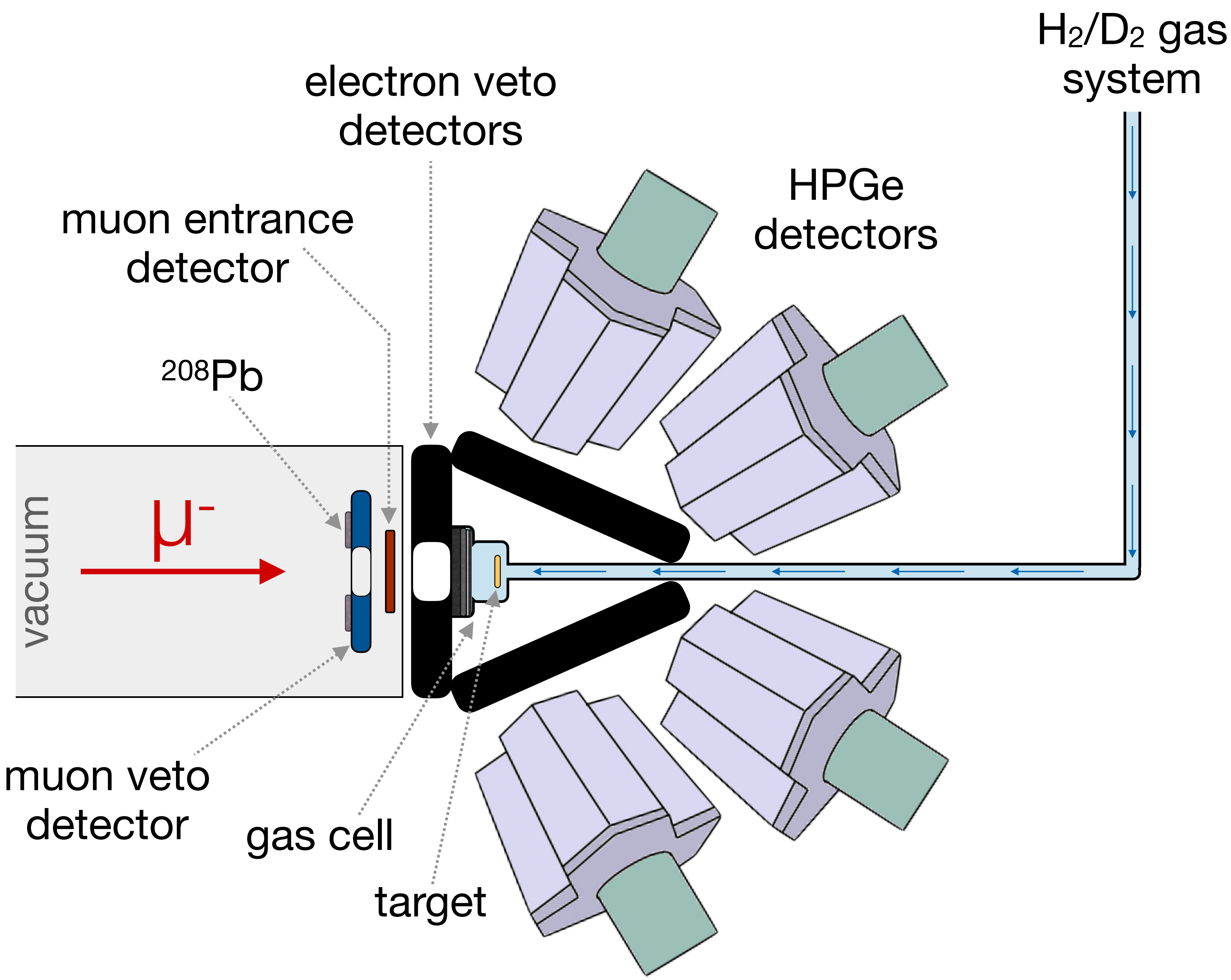
2. transfer to deuterium μp → μd
3. μd moves almost freely in the H_2 gas
4. transfer to high-Z element μd → μZ when hitting target & emission of x rays during the atomic cascade

muX detectors



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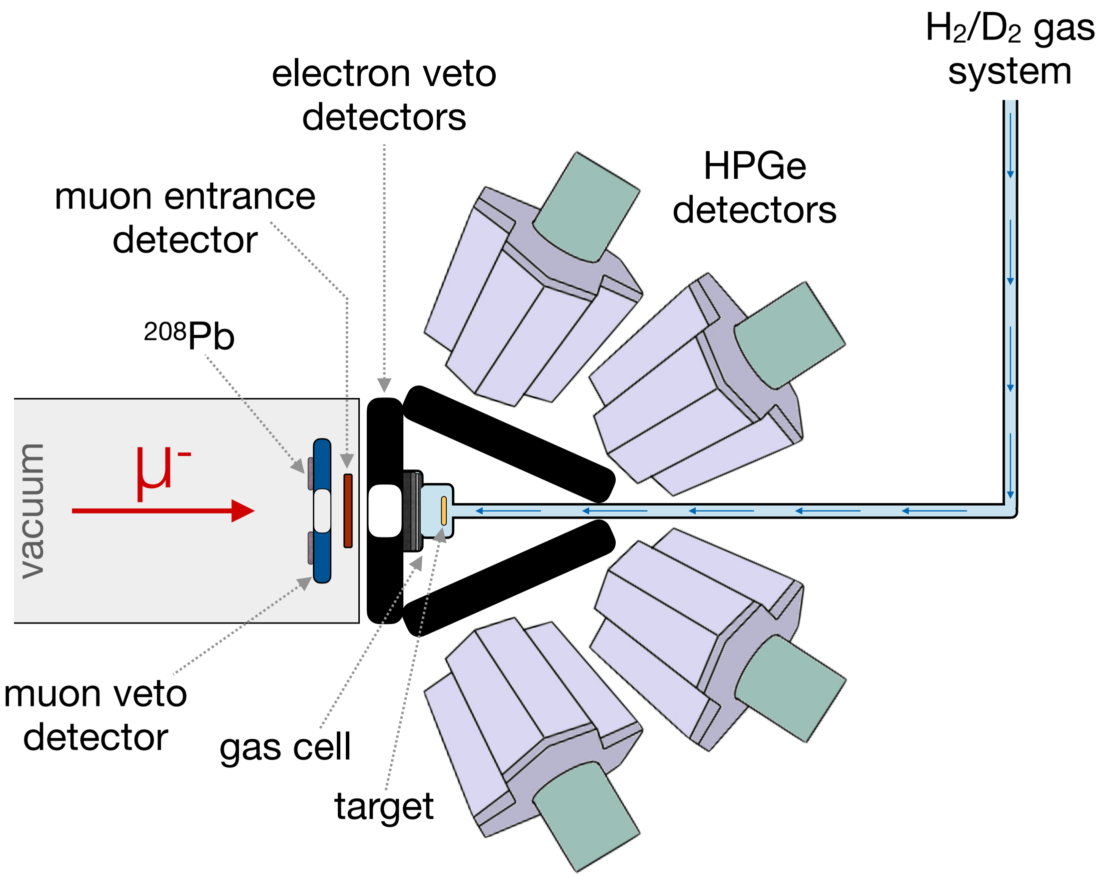
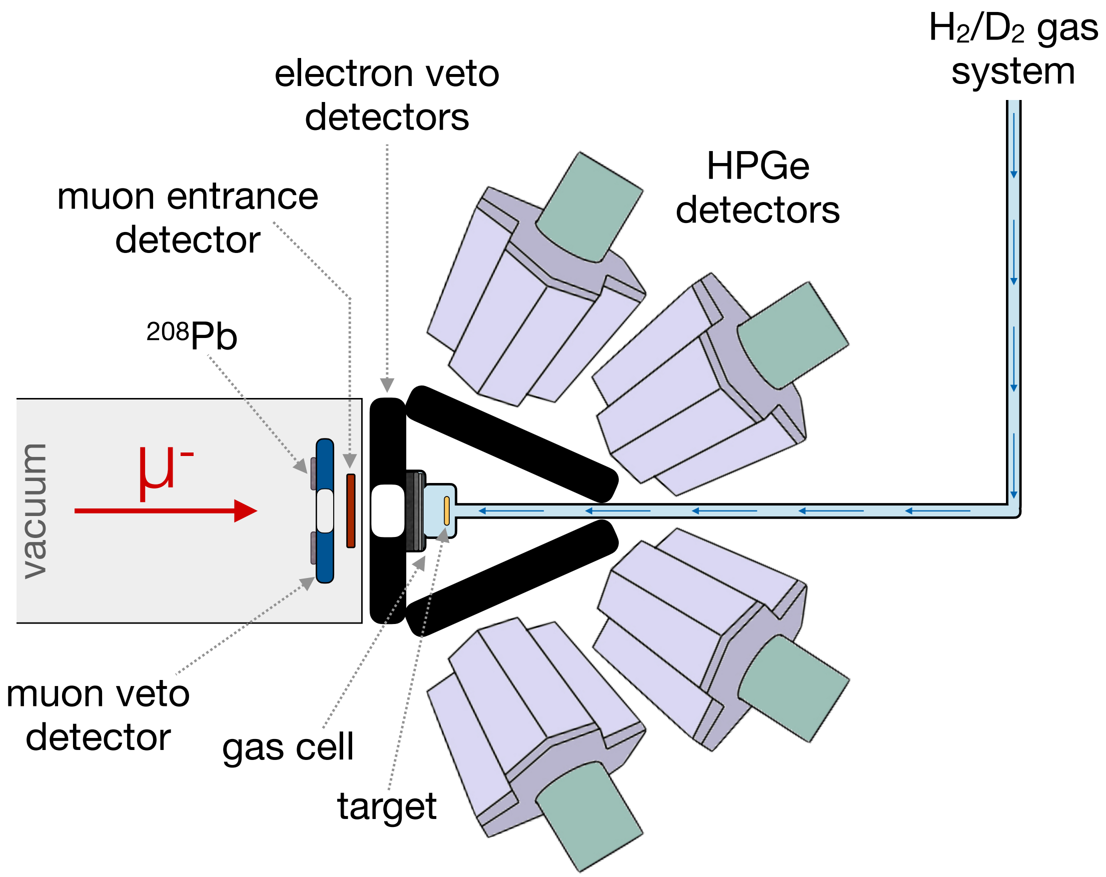


Schematics of detectors setup

muX detectors



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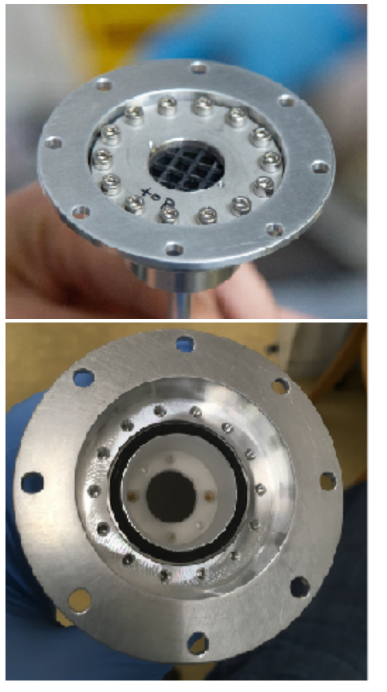
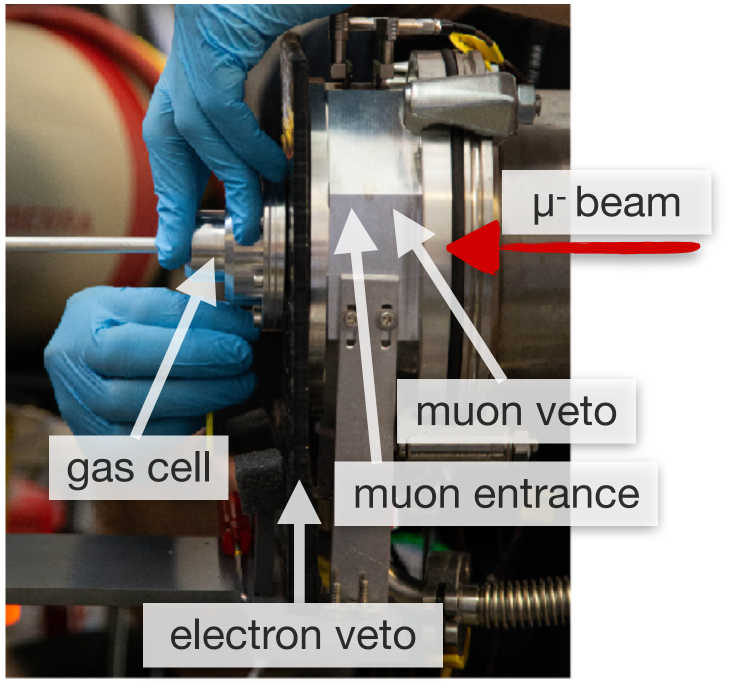
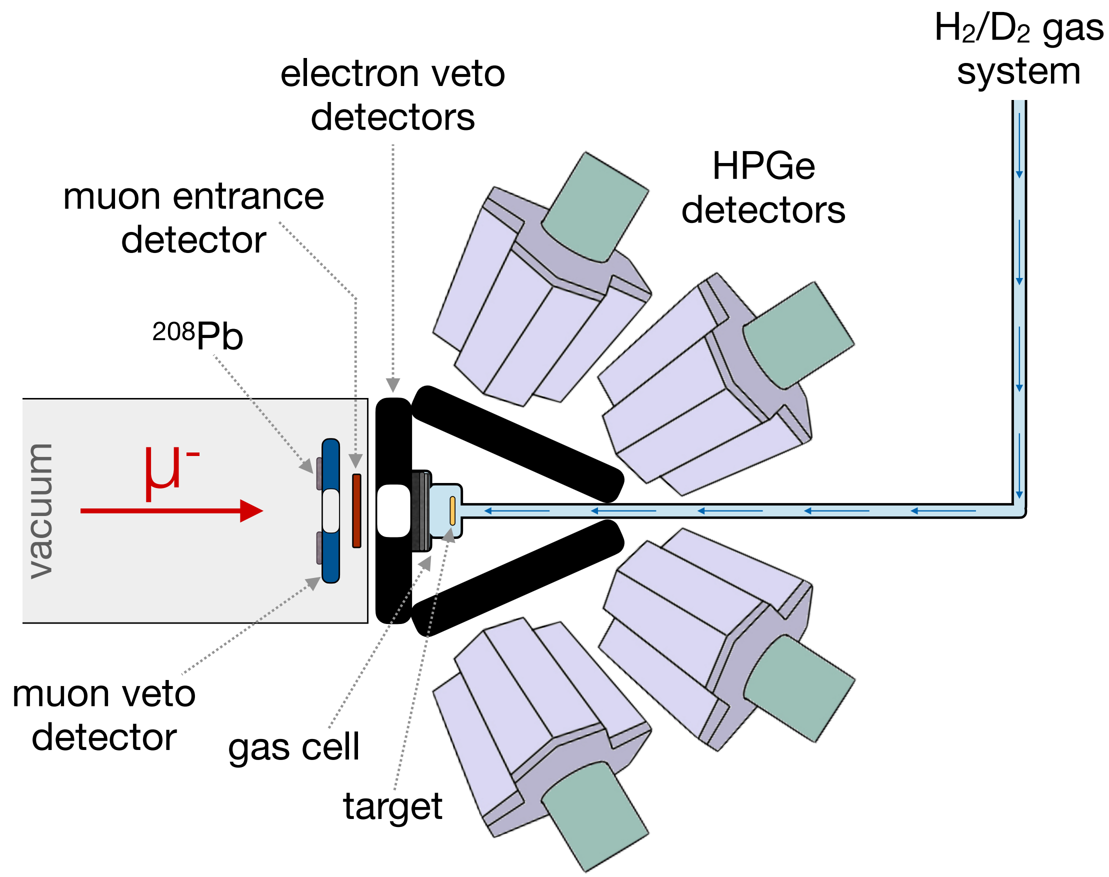

The gas cell



The muon and electron counters

muX detectors



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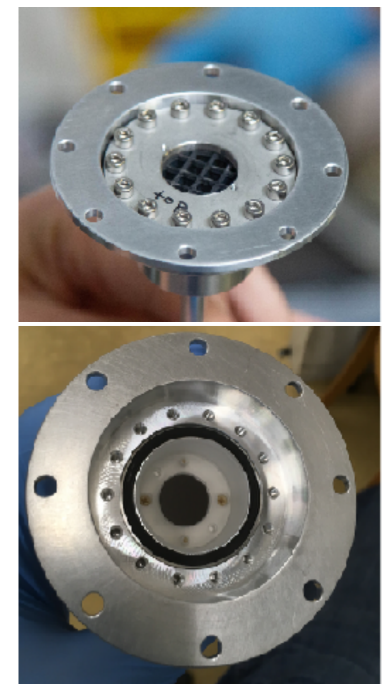

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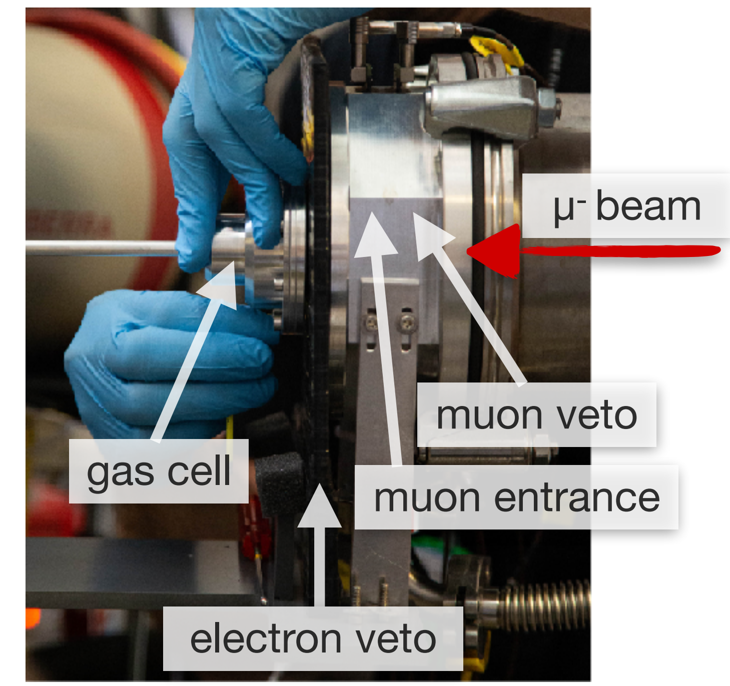
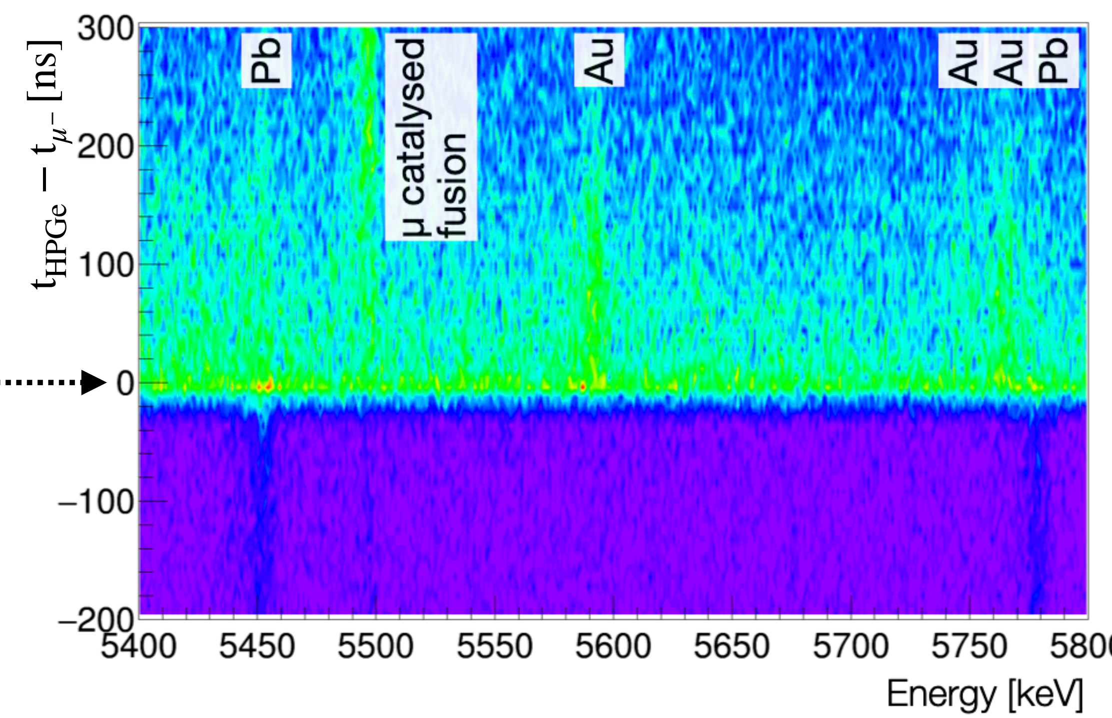


The muon and electron counters

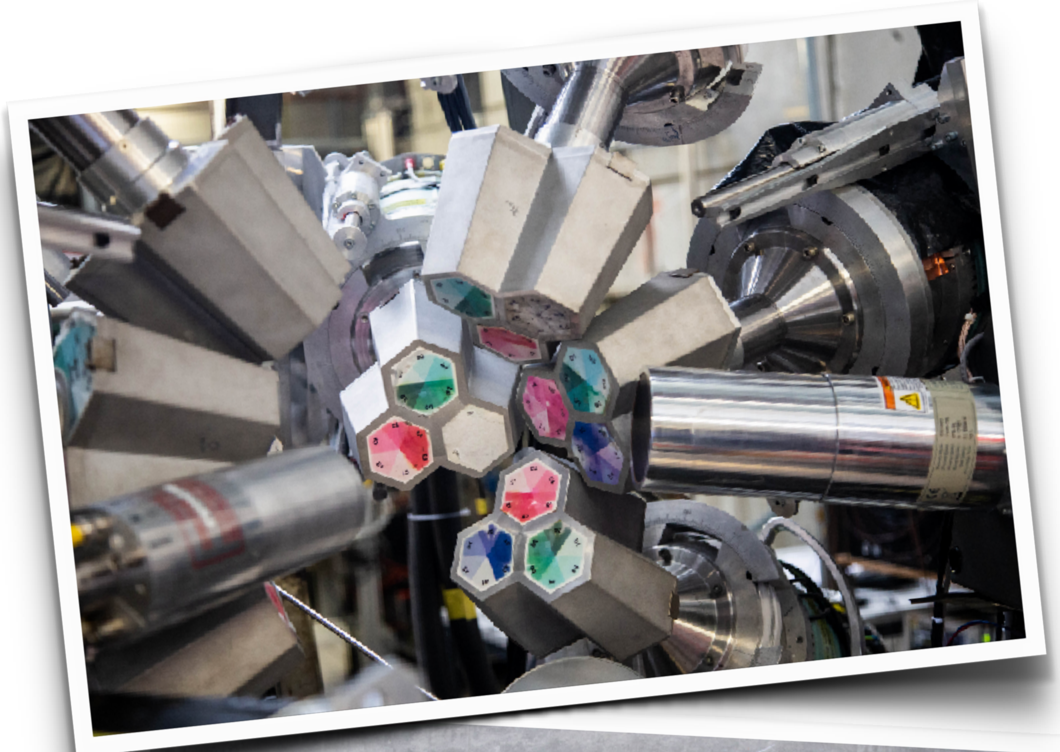
Demonstration of principal in a 5 μg gold target in 2017, 18.5 h of measurement

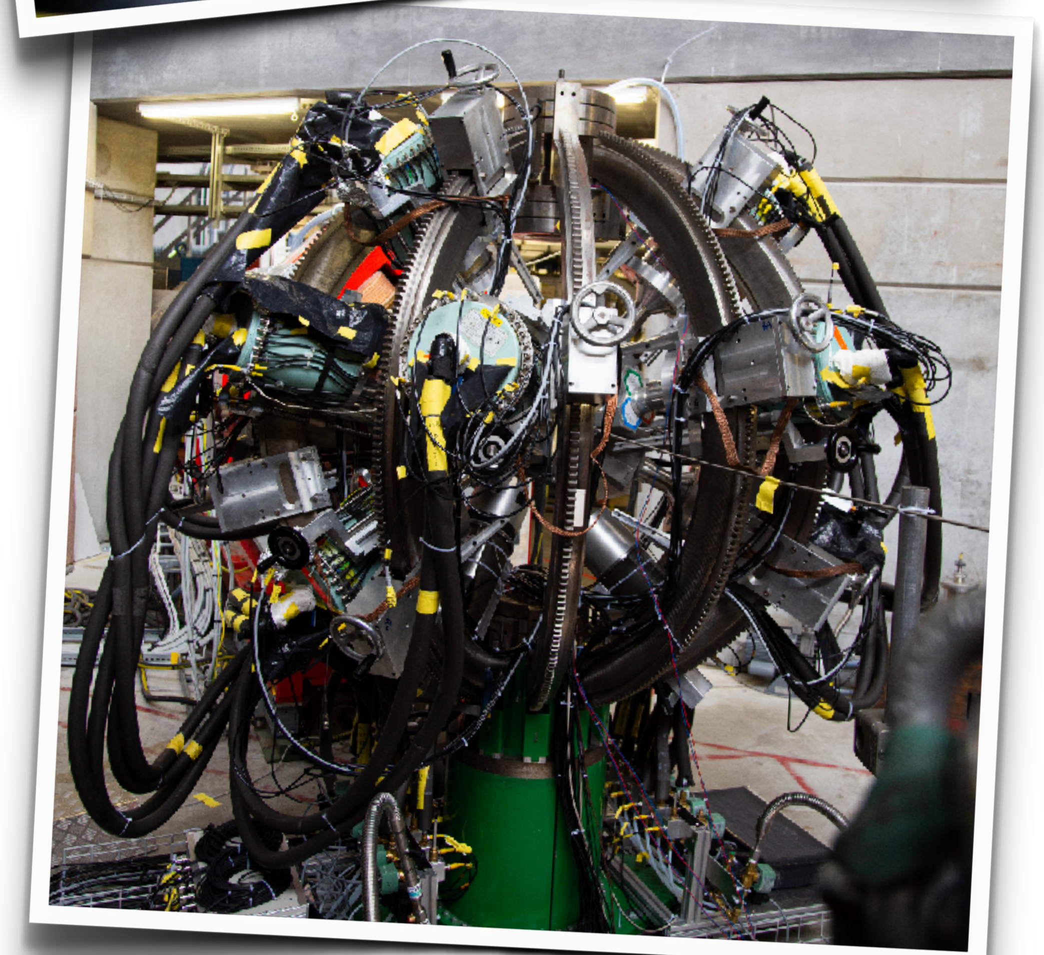
A. Adamczak *et al.*, Eur. Phys. J. A 59, 15 (2023)

the time the muon enters the gas cell



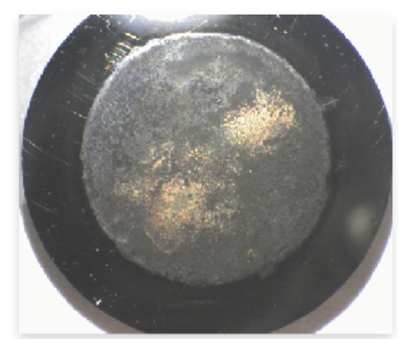
2019 measurement of ^{248}Cm and ^{226}Ra



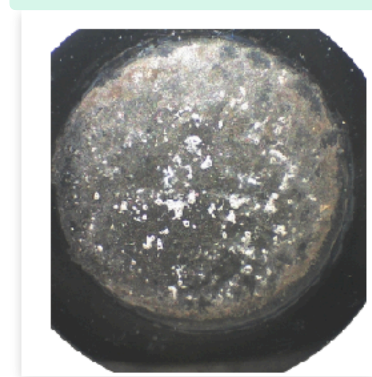


- 8 Miniball[1] germanium clusters and 2 standalone germanium detectors making a total of 26 HPGe crystals were operating
- Radiation protection restrictions at PSI allow for 32.6 μg of ^{248}Cm and 5.5 μg of ^{226}Ra
- Targets were produced by the radiochemistry group of the University of Mainz

15 μg of ^{248}Cm



1.4 μg of ^{226}Ra



[1] Eur. Phys. J. A 49, 40 (2013)

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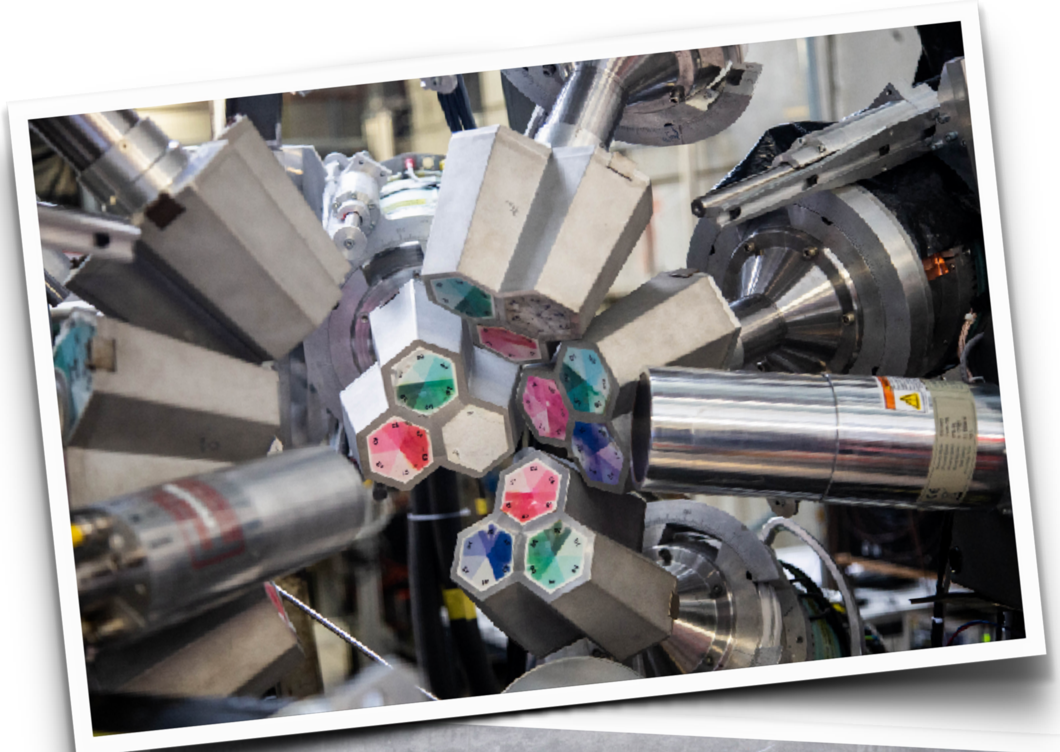

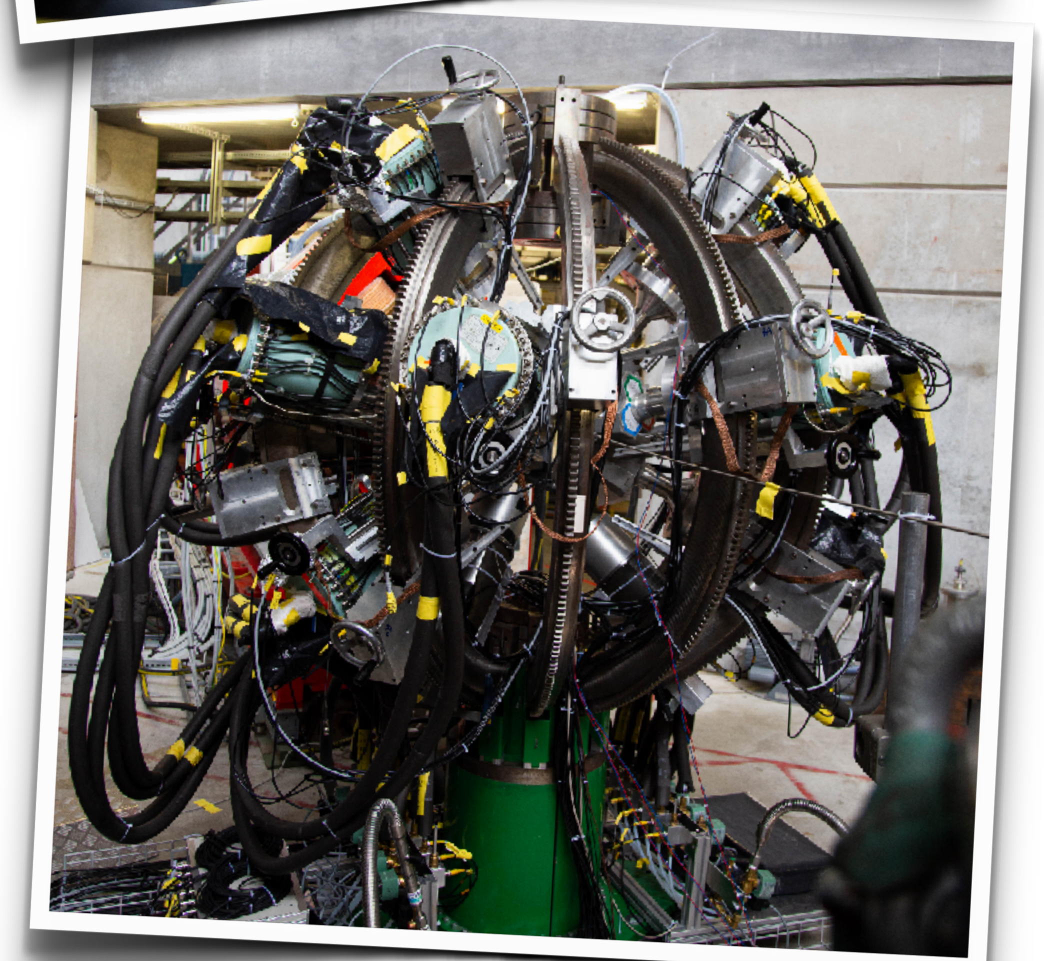

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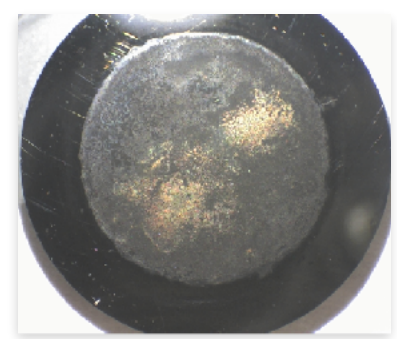

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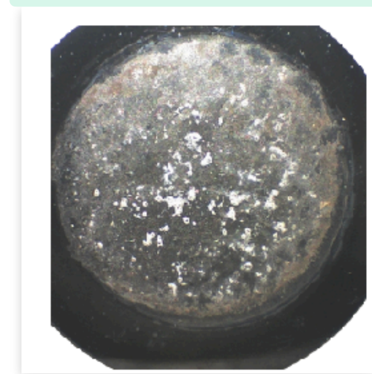
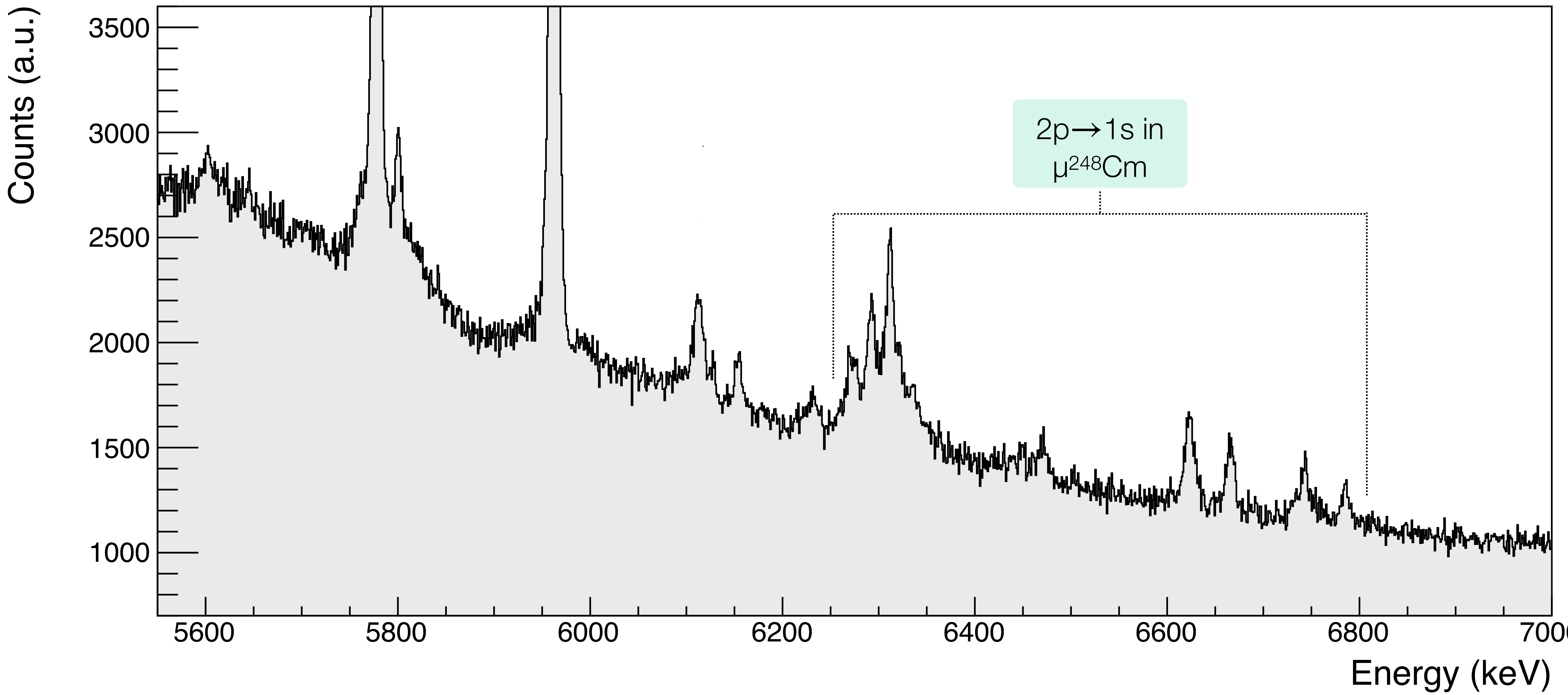


No clear 2p→1s hyperfine transitions are observed in ^{226}Ra ⇒ Radium needs to be remeasured!

[1] Eur. Phys. J. A 49, 40 (2013)

2p→1s transitions in ^{248}Cm



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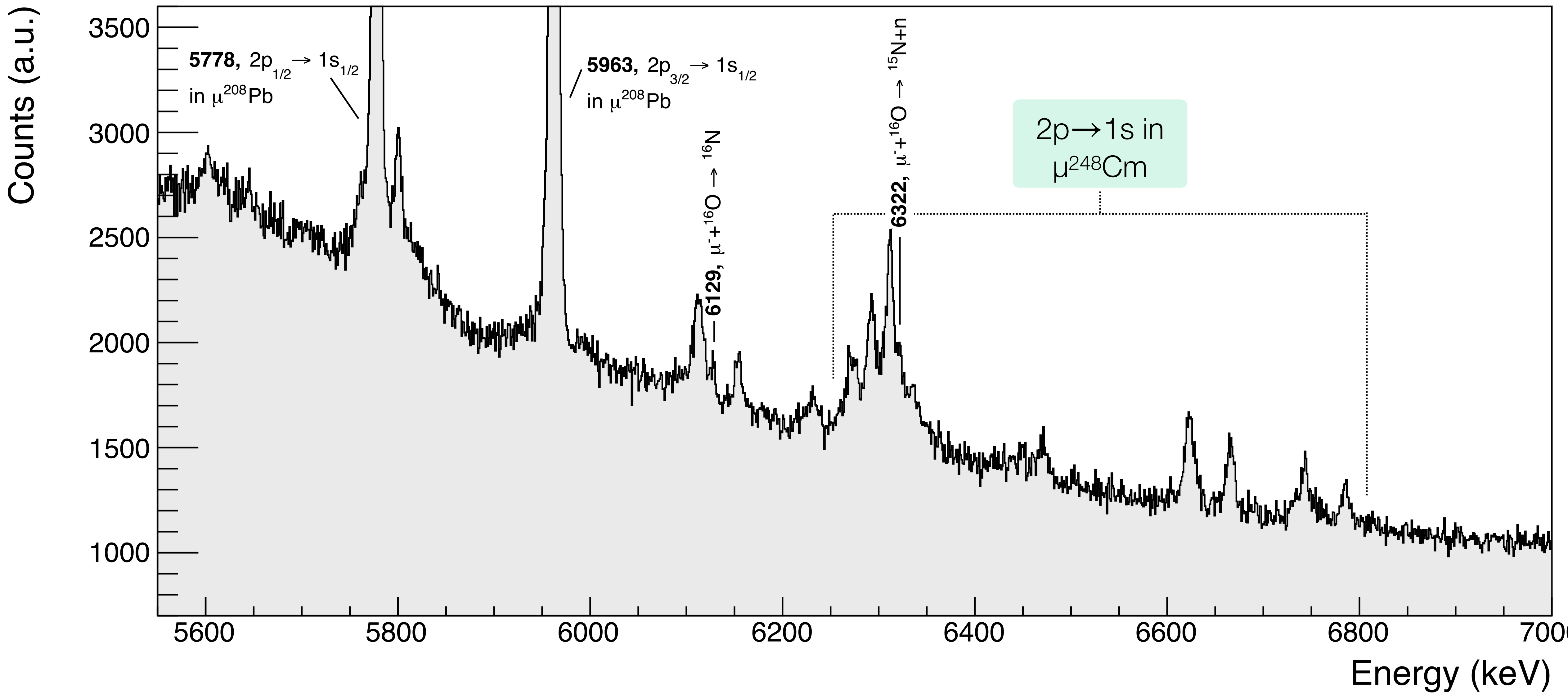

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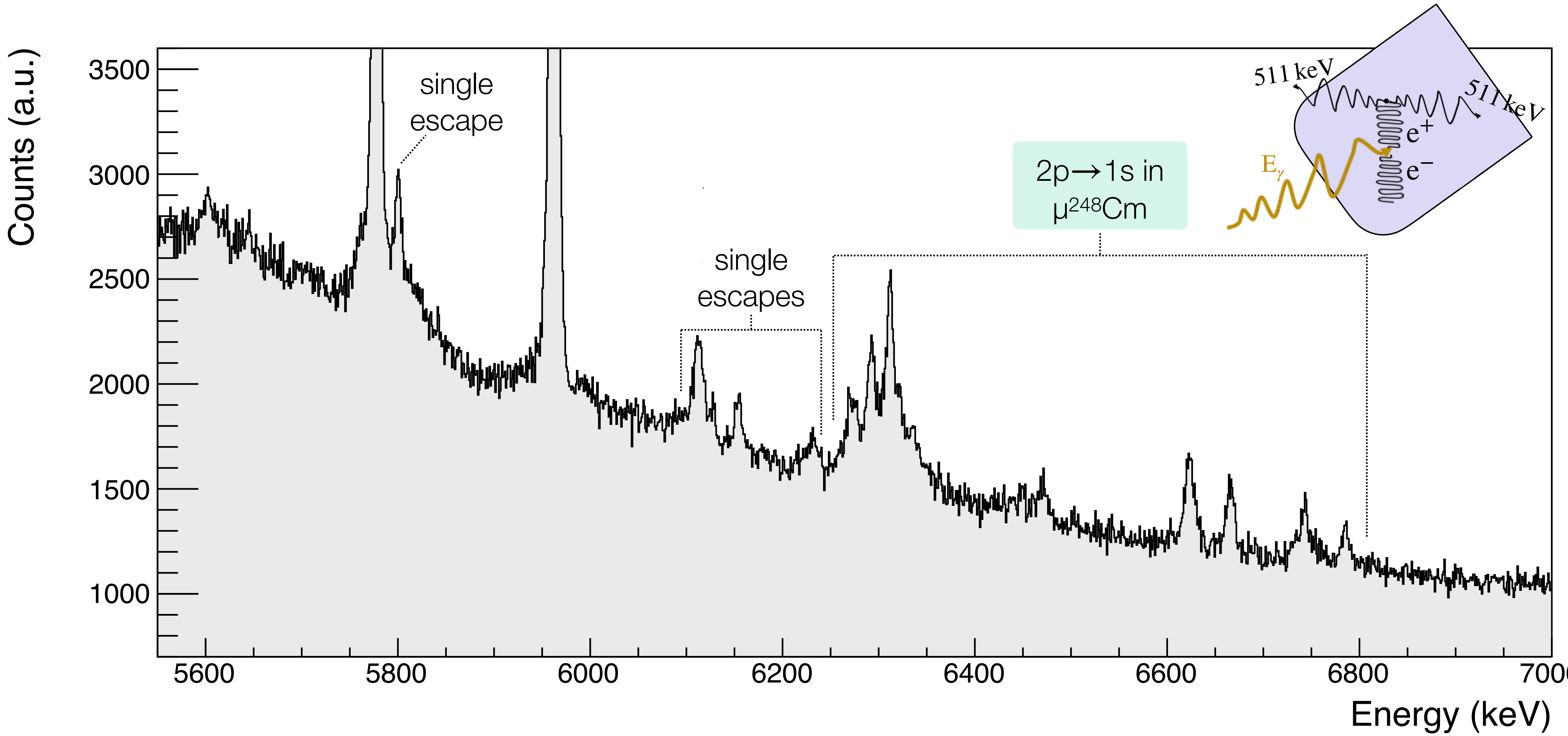

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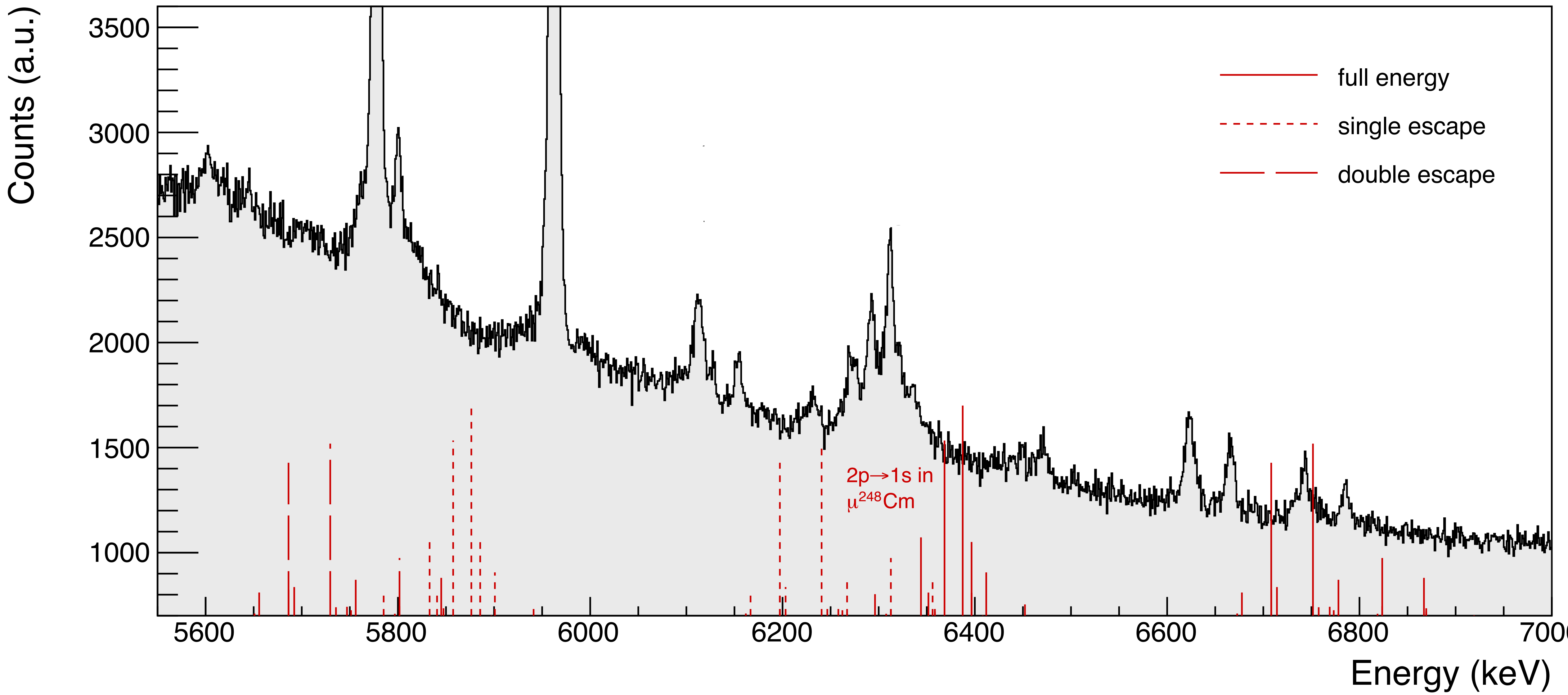

Predictions shown for a charge radius estimated by interpolating the nuclear charge parameters of neighbouring nuclei[1]

$R_N = 5.8687$ fm

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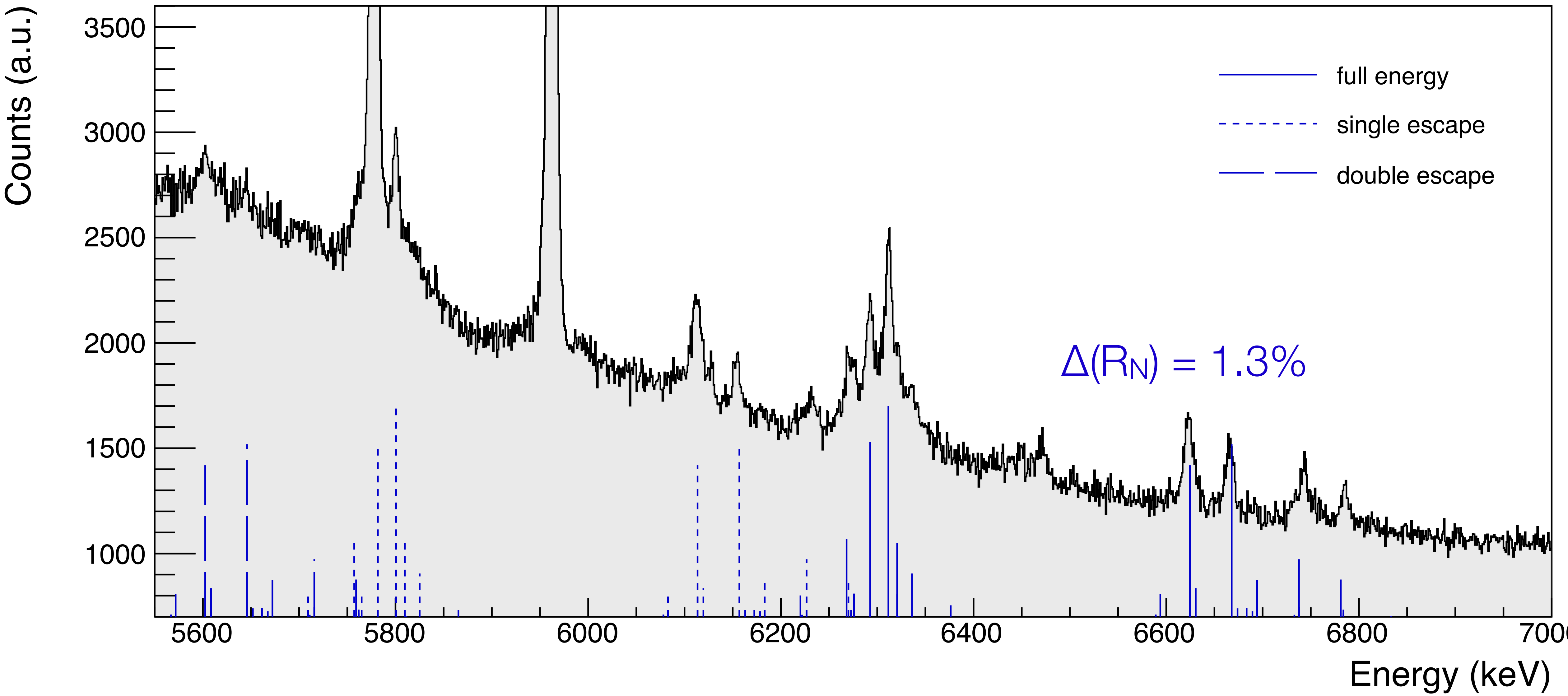

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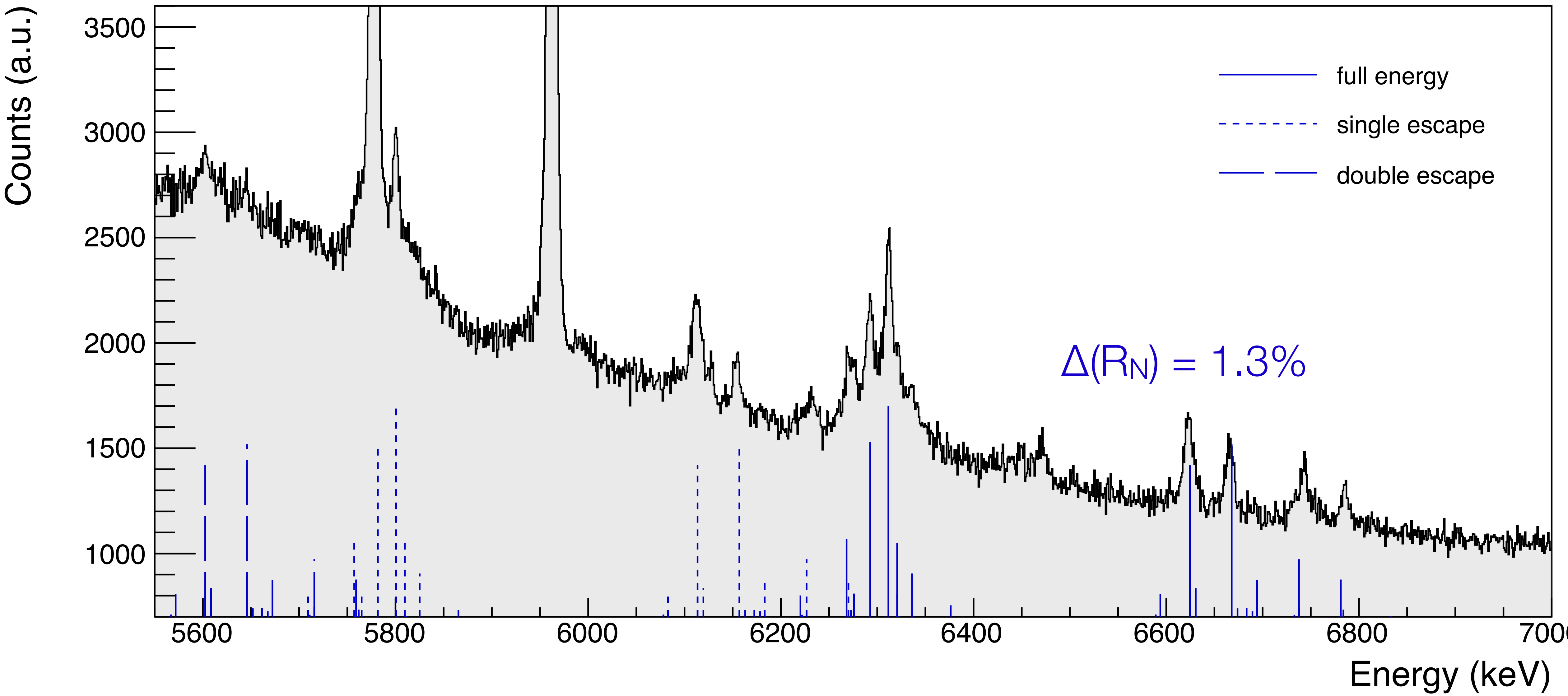

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$R_N = 5.8687$ fm

sensitivity on the quadrupole moment Q is also observed

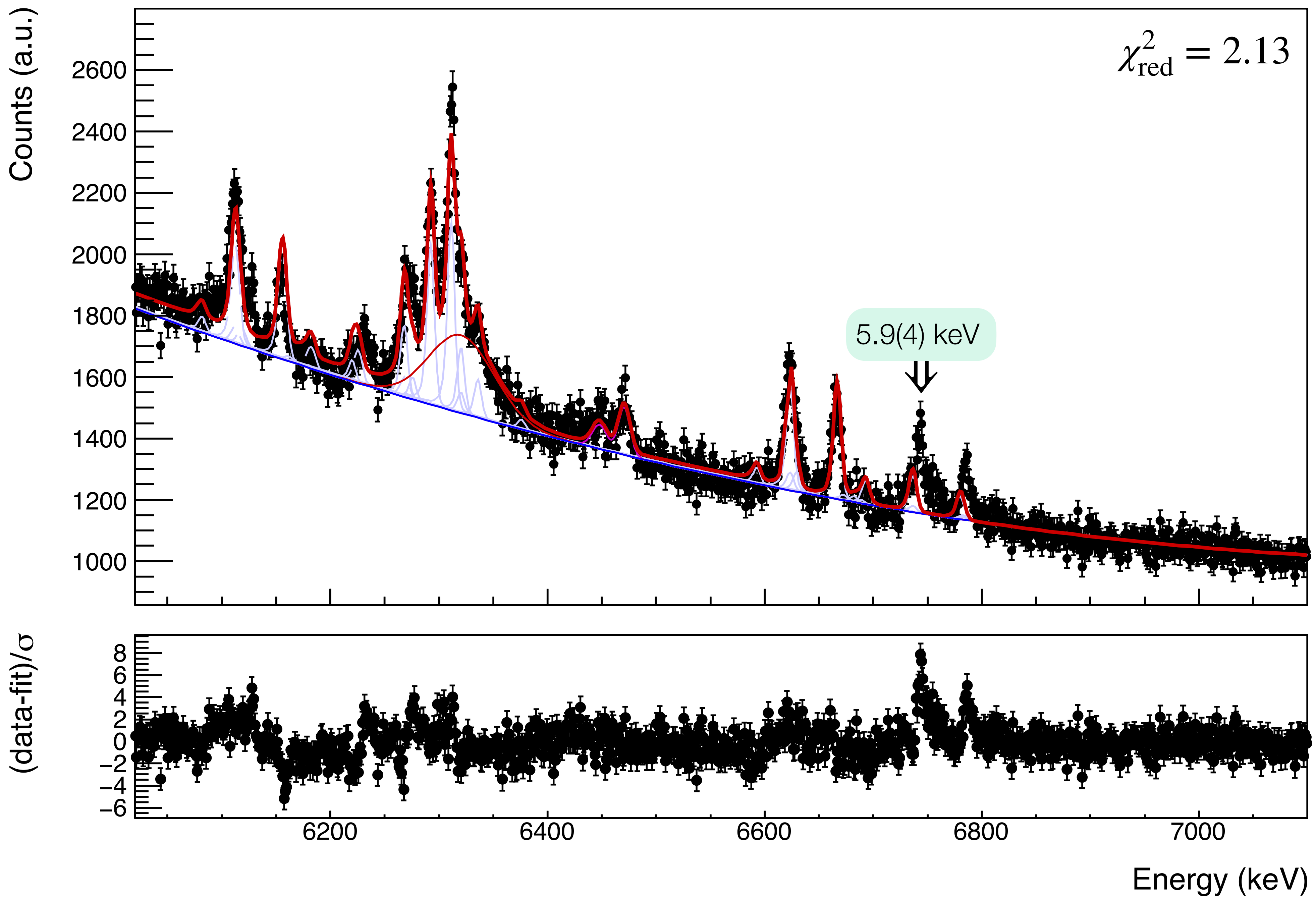
Fit of the 2p→1s transitions in ^{248}Cm

Fit results (only statistical):

$R = 5.94518(9)$ fm

$Q = 12.003(8)$ b

+ full study of systematic uncertainties



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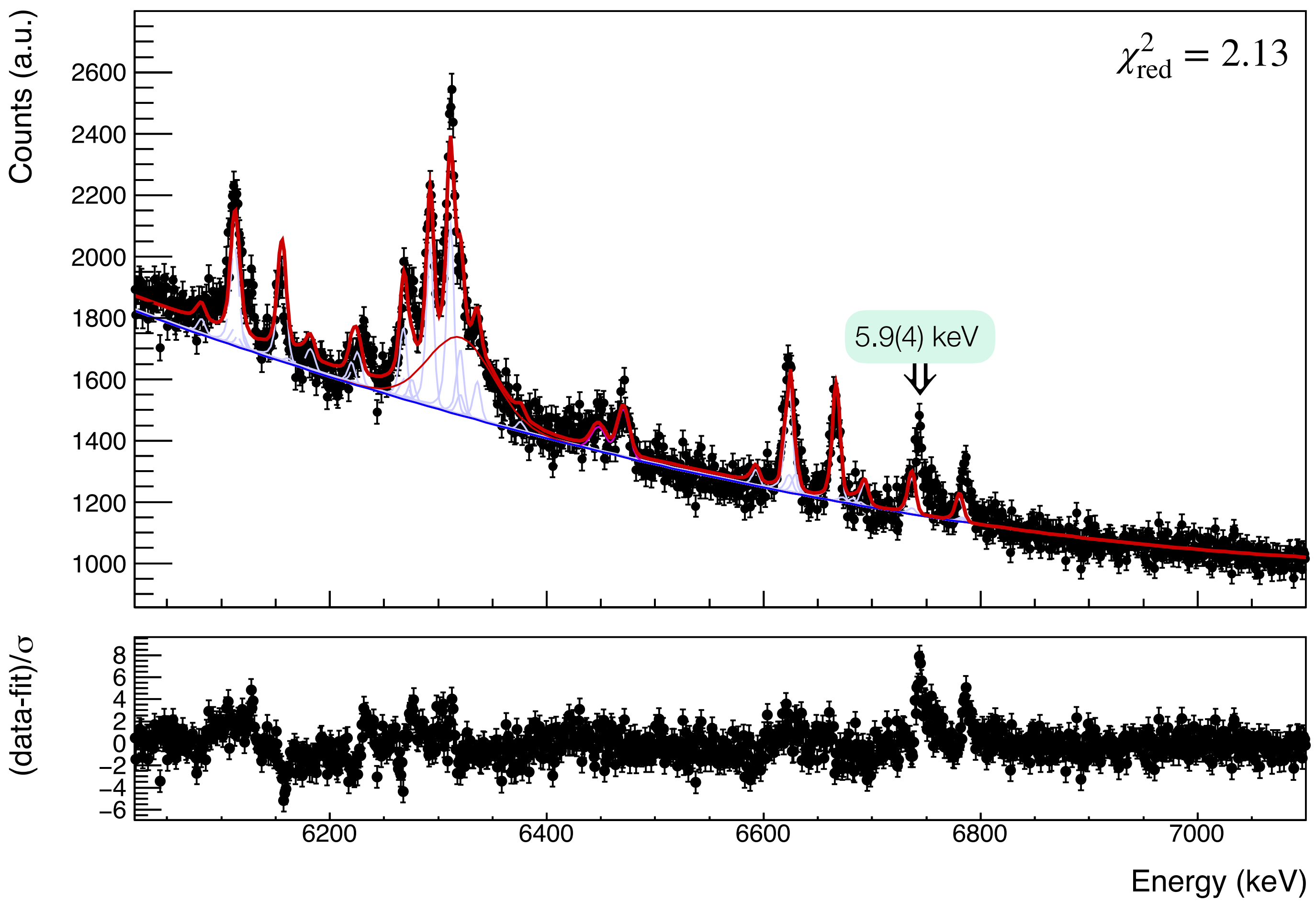


Results on the nuclear charge radius and quadrupole moment:

$R = 5.9455(1)_{stat}(117)_{sys}\ \mathrm{fm}$

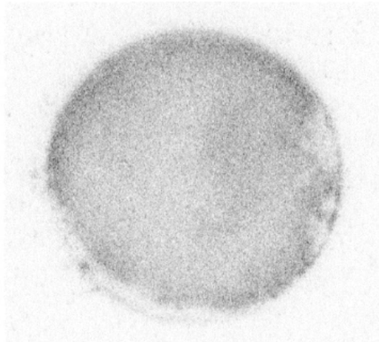
$Q = 12.003(8)_{stat}(361)_{sys}\ \mathrm{b}$

Outlook: Further revision of the theory to resolve the discrepancies between the fitted and measured hyperfine transitions

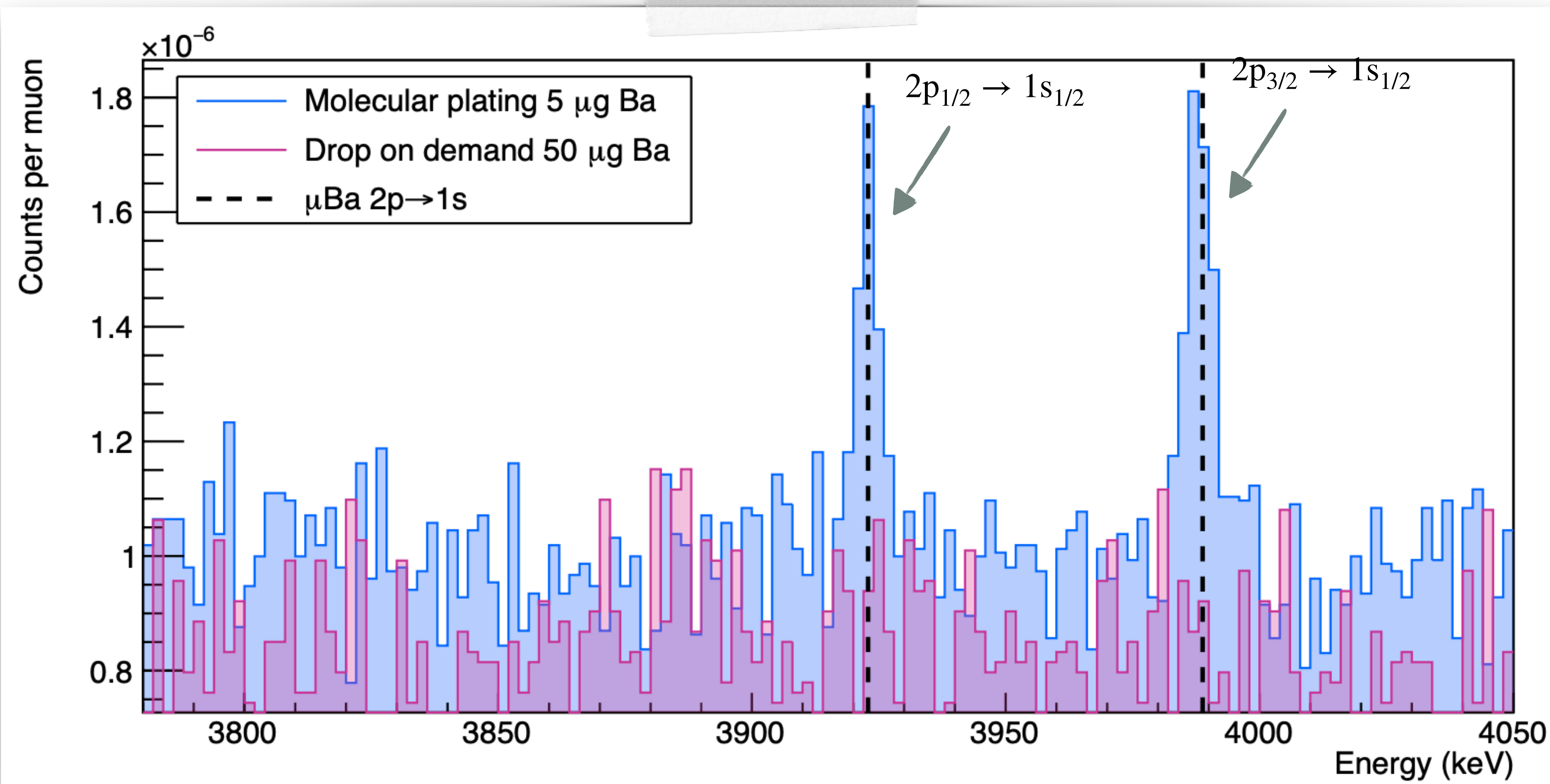
2022 test measurement with ^{nat}Ba

Towards the future measurement of ^{226}Ra

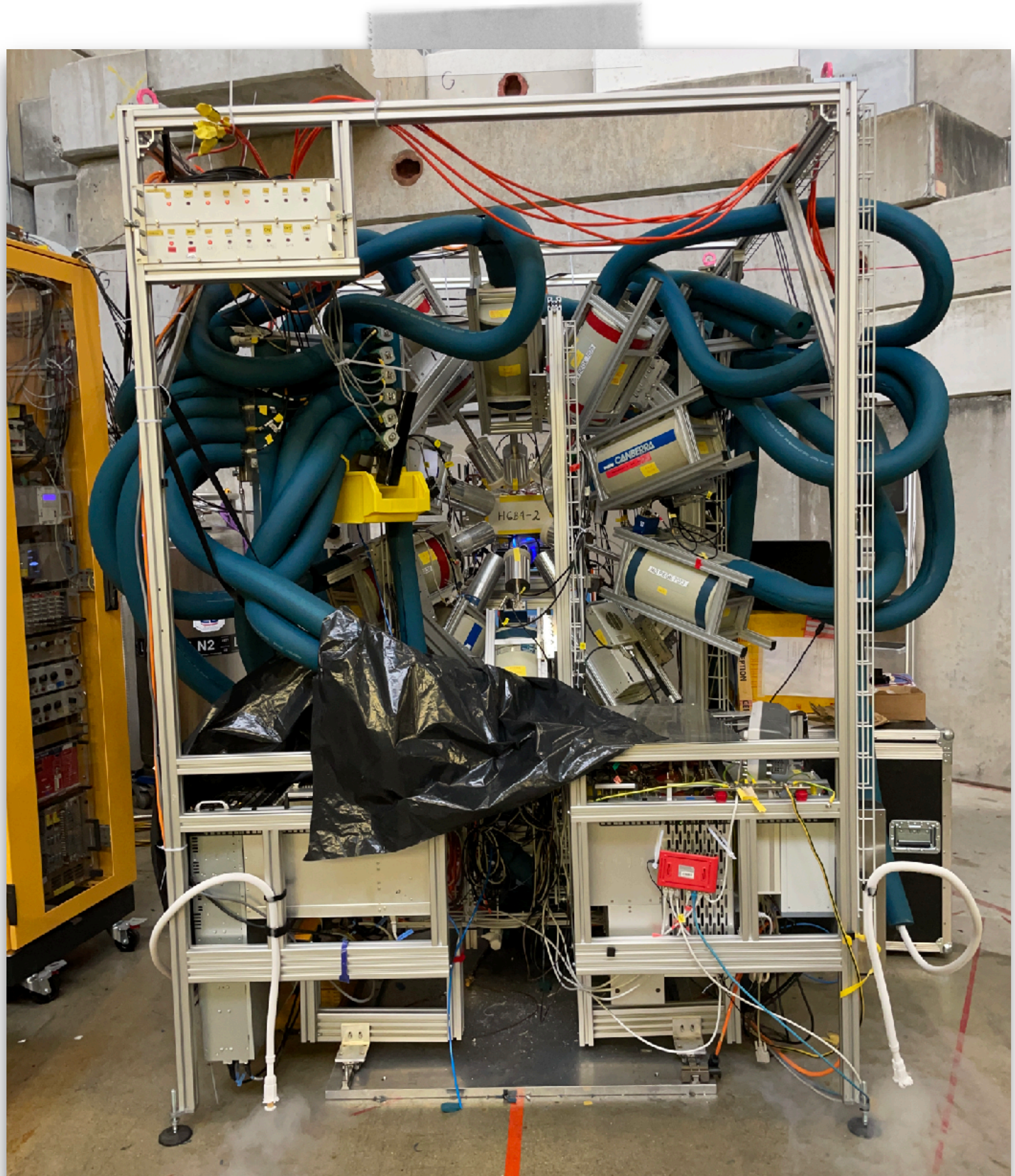
- Measured of barium deposition targets
- Compared two methods: drop-on-demand (DoD) & molecular plating (MP)



^{nat}Ba target with MP

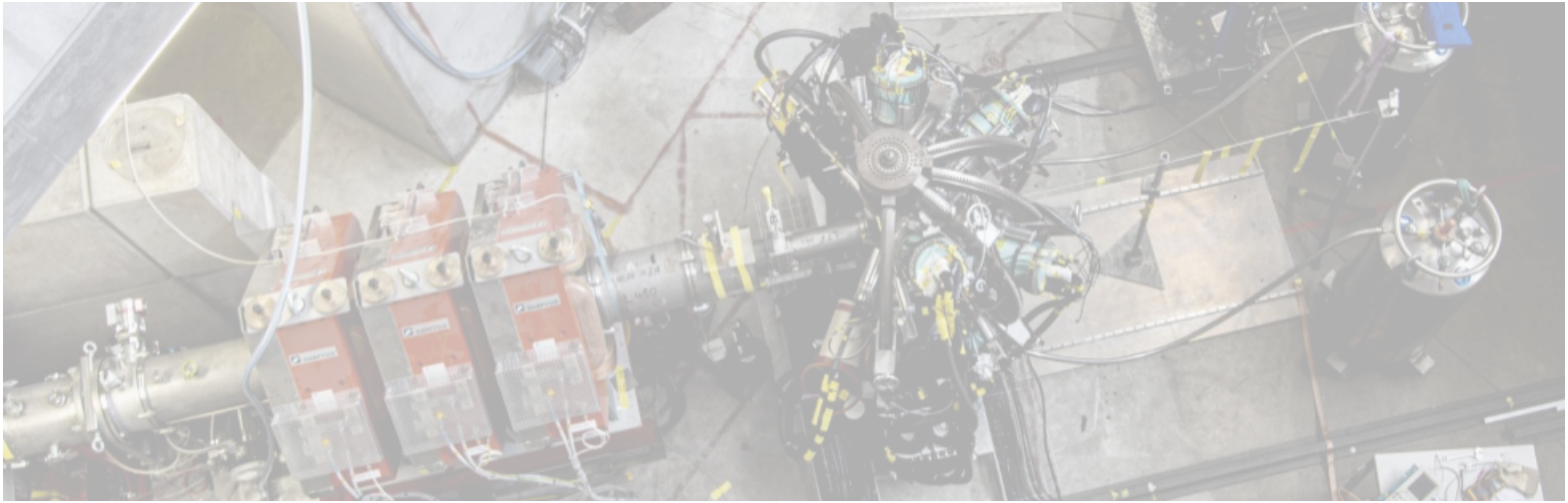


What's next: remeasure ^{226}Ra this September!



- Measure a ^{226}Ra target produced by the MP & DoD method
- Using 20 HPGe crystals in total!

What's next: remeasure ^{226}Ra this September!

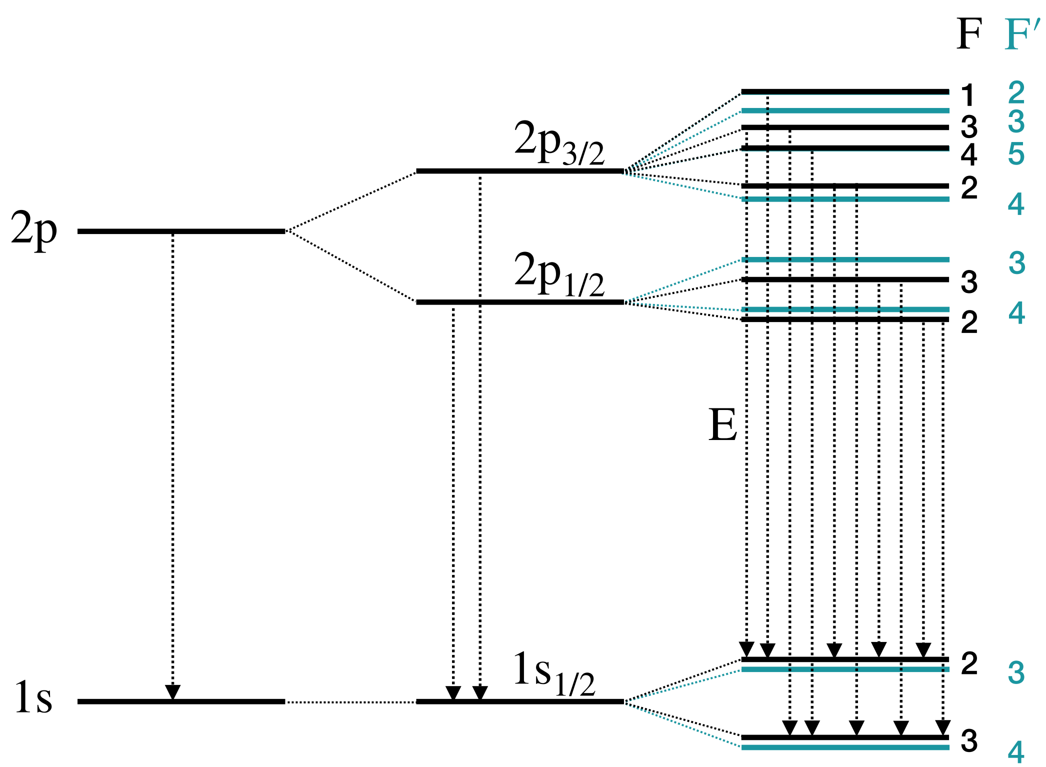


Backup Slides

Fine & Hyperfine splitting in muonic atoms

Fine splitting (FS): $\vec{J} = \vec{l} + \vec{s}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$



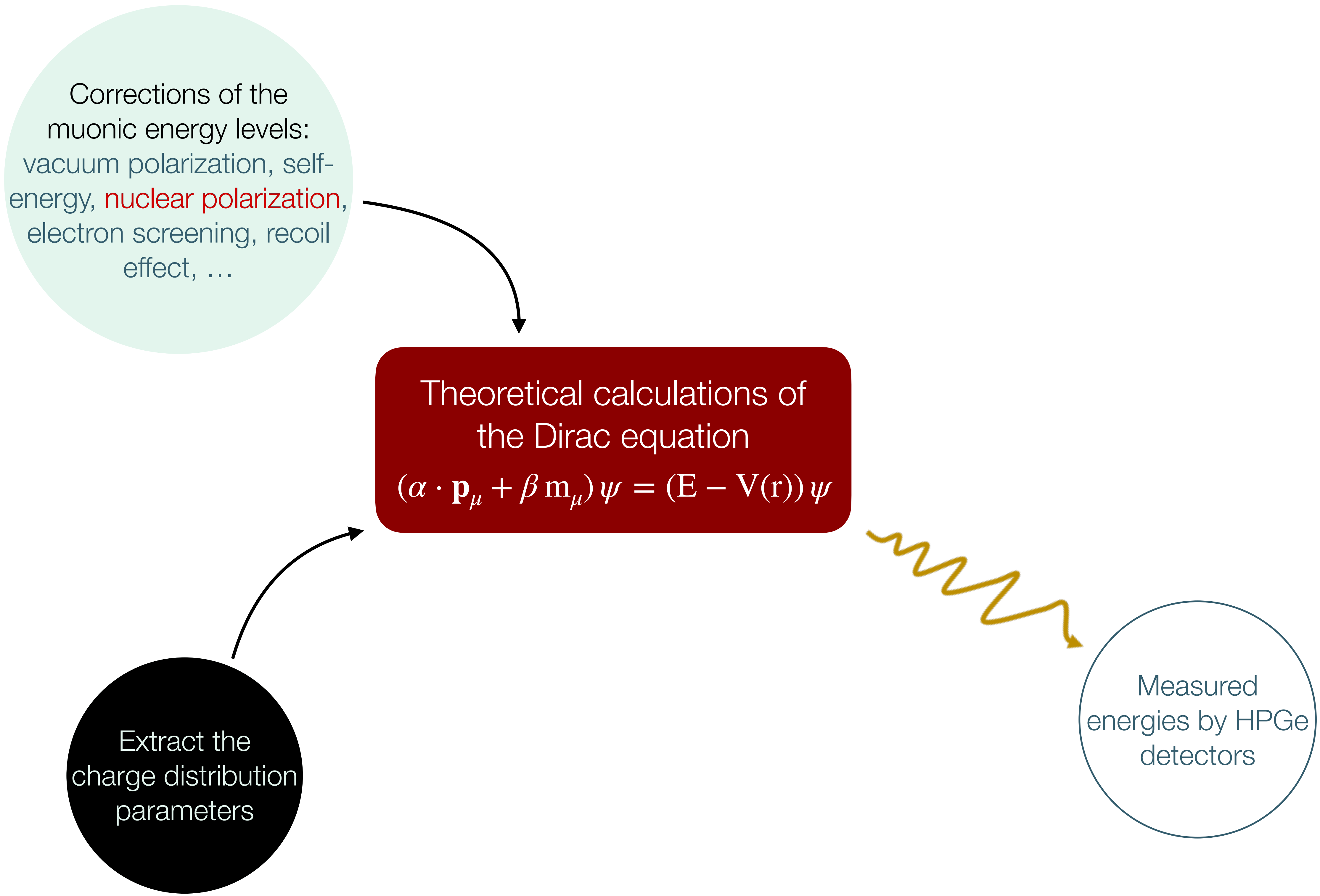
$I_{\text{ground}} = \frac{5}{2}^{+}$ $I_{\text{excited}} = \frac{7}{2}^{+}$

- Energy shift of hyperfine states due to the electric quadrupole (E2) and magnetic dipole (M1) interaction

Dynamic hyperfine splitting

- The hyperfine levels from ground and excited nuclear states are mixed due to the high energy of muonic transitions
- HFS also observed in even-even nuclei with zero spin in the ground state

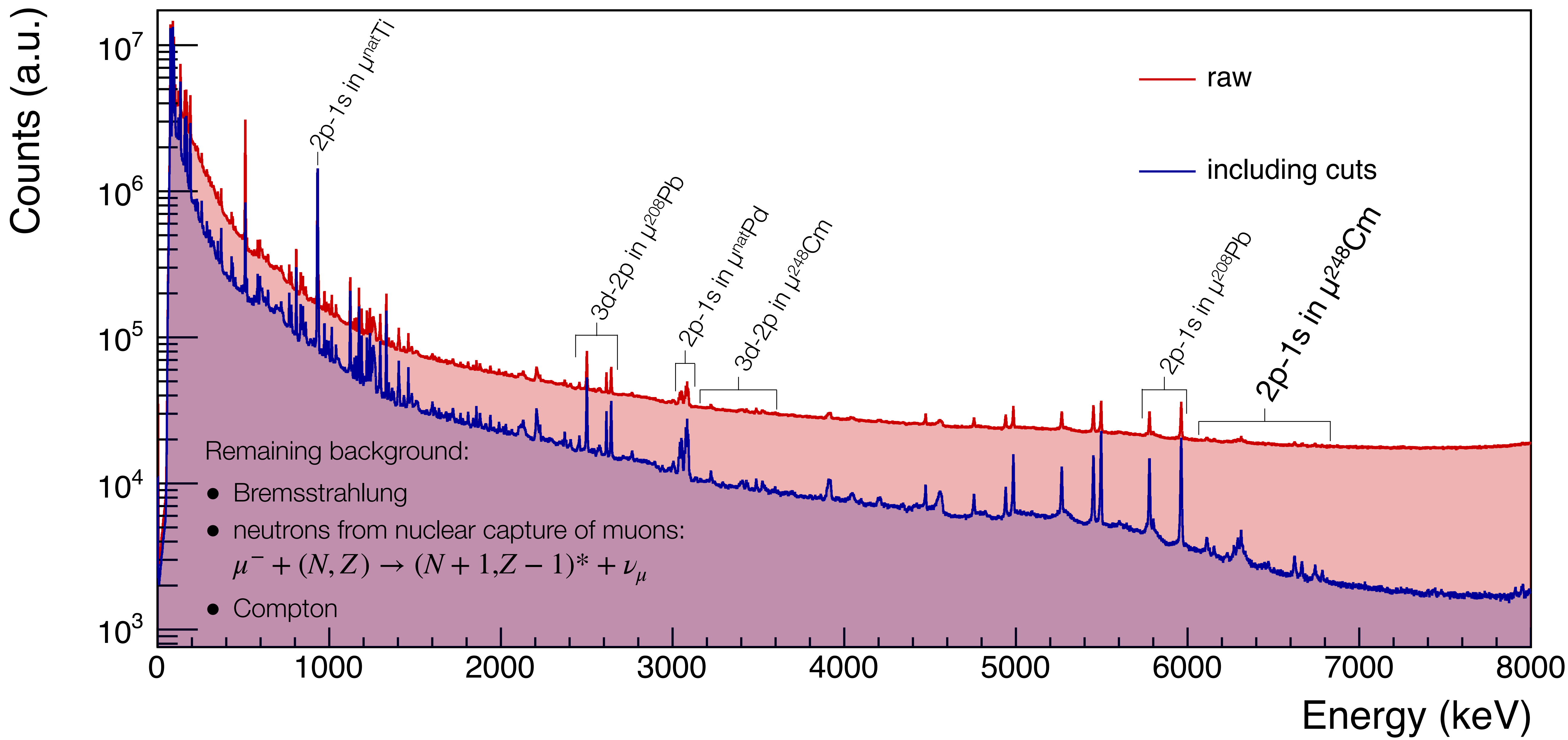
How to extract nuclear charge parameters from measured muonic energies



How to get to good S/B ratio at high energies?

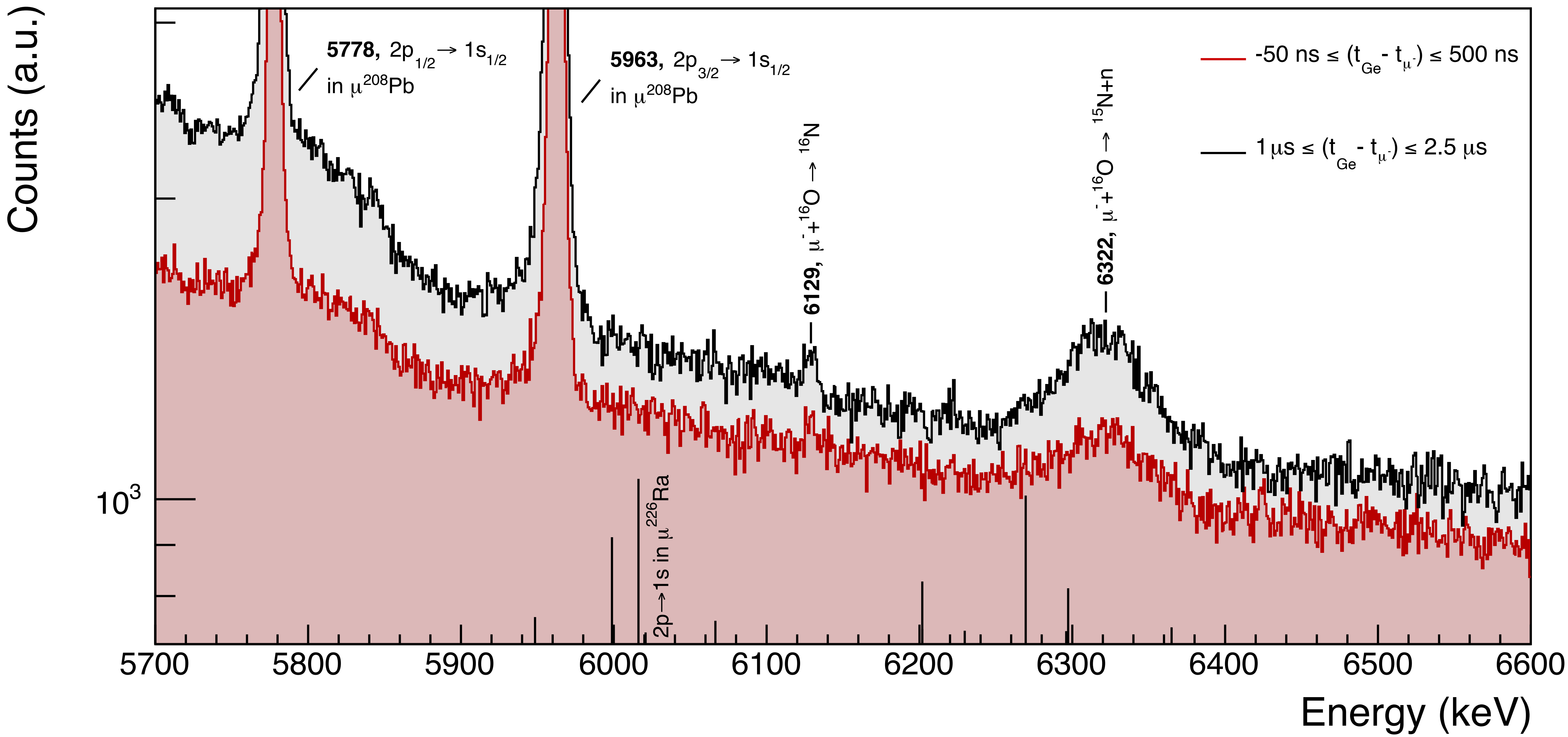
Cuts included:

- Electron veto & HPGe detectors' anti-coincidences
- Clustering of events using the 3-crystal Miniball geometry
- Correction of gain drifts before energy calibration
- Baseline correction to correct for low-energy tails of the peaks



2p→1s transitions in ^{226}Ra?

- No clear 2p→1s hyperfine transitions are observed in ^{226}Ra
- Radium needs to be remeasured

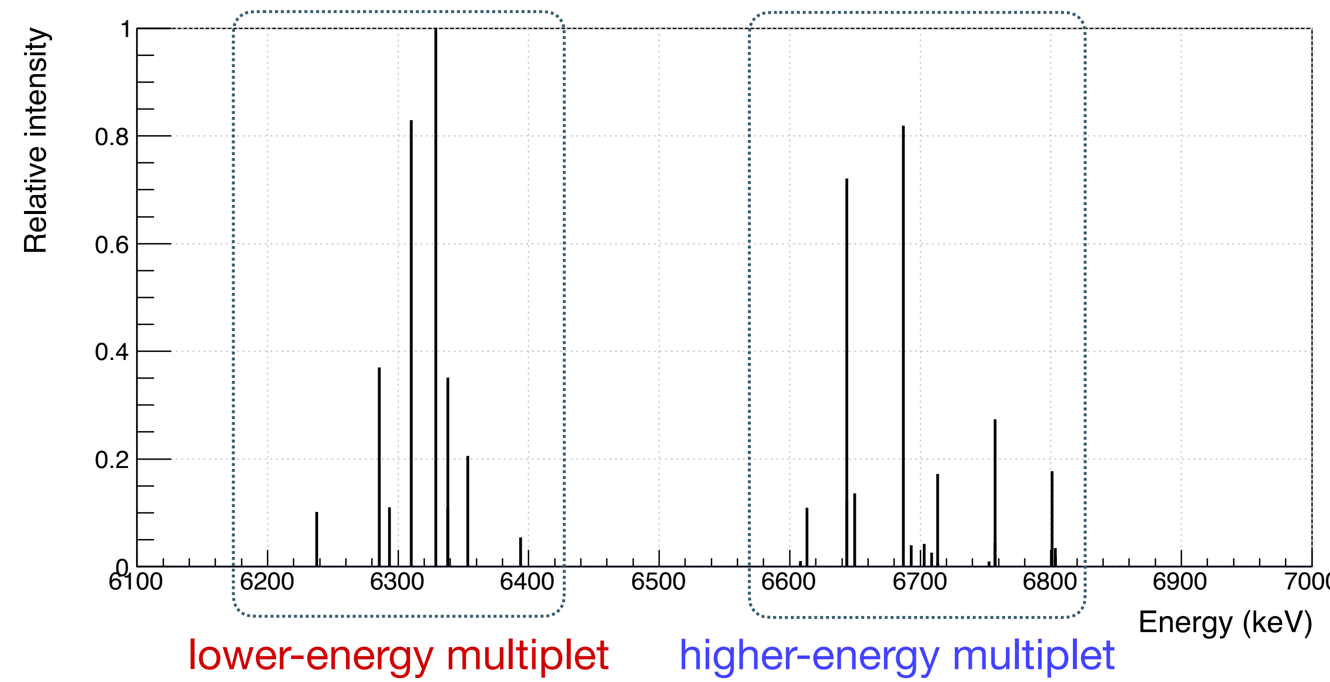


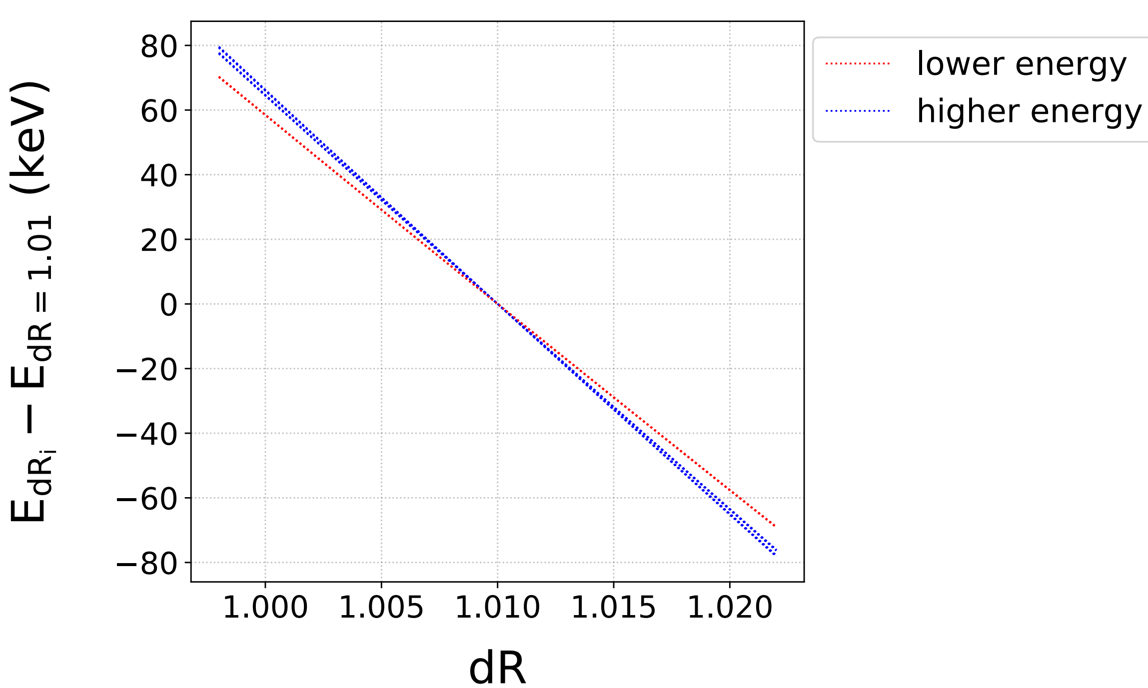
Energy dependence on the charge radius and quadrupole moment

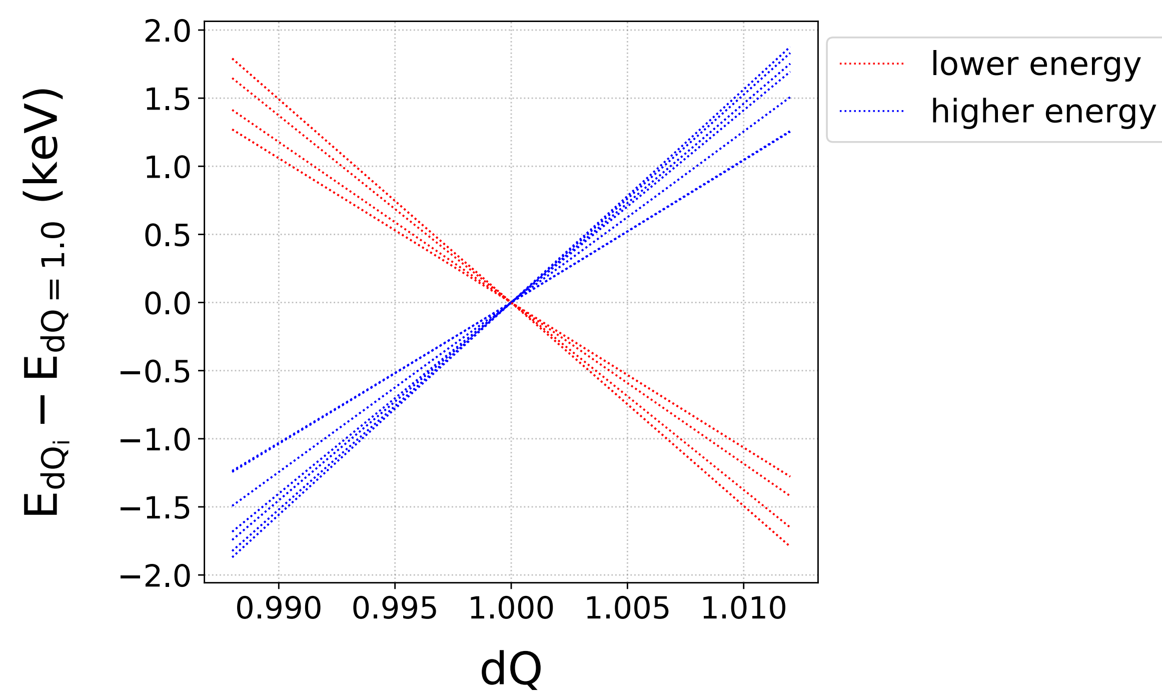
$$dR = \frac{R}{R_N}, \text{ where } R_N = 5.8687\,\text{fm}$$

$$dQ = \frac{Q}{Q_N}, \text{ where } Q_N = 12.04\,\text{b}$$

Theoretical calculations are performed by N. Oreshkina & I. Valuev, MPIK, Heidelberg







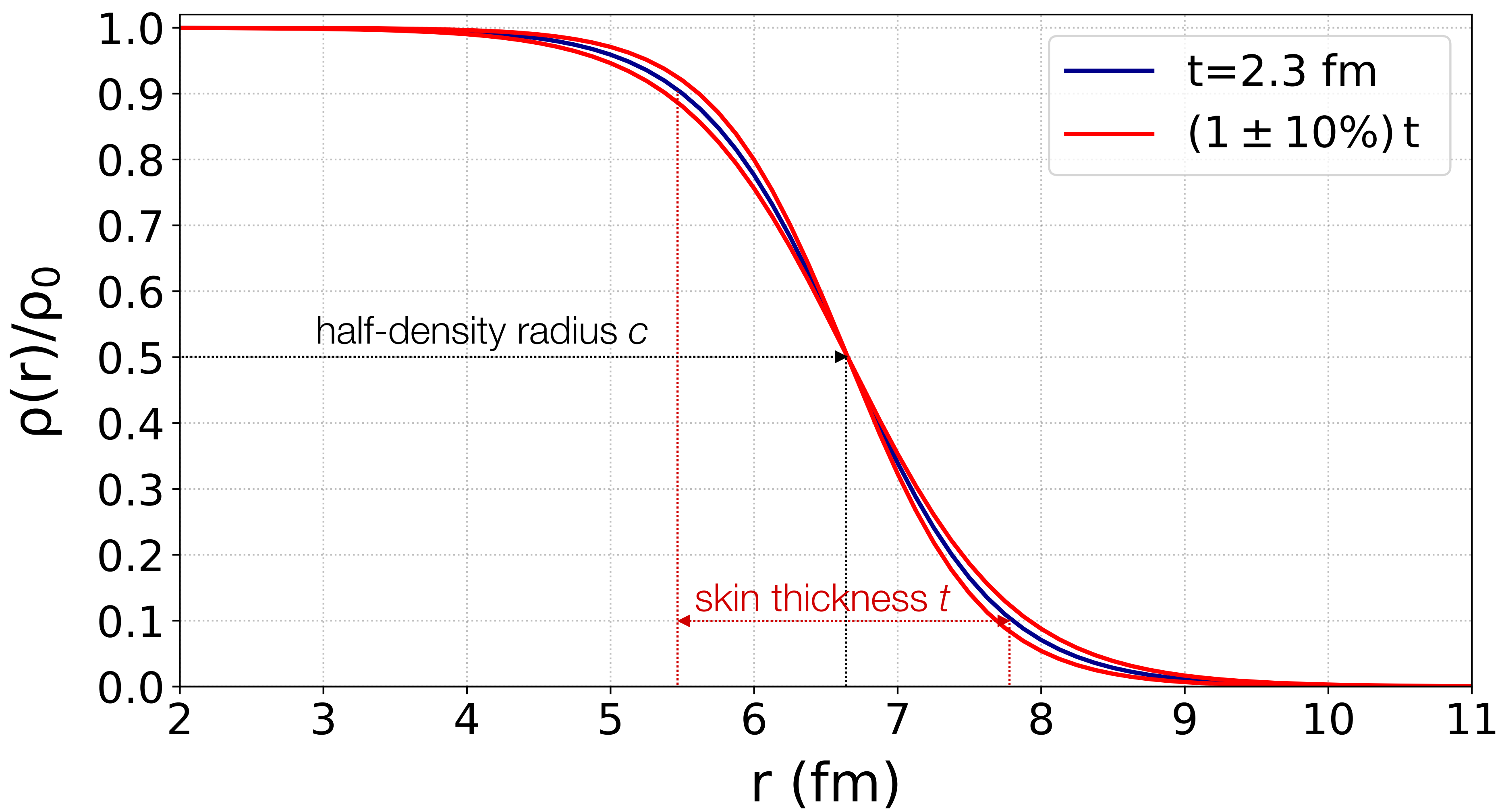
Sources of systematic uncertainties

Category	Systematic effect	Description	Charge radius $\Delta(dR)$	Charge radius σ_{dR}	Quadrupole moment $\Delta(dQ)$	Quadrupole moment σ_{dQ}
Experimental	Fitting features	Instrumental line-shape	0	0.000 032	0	0.001 4
		SE/FE ratio	0	0.000 015	0	0.001 3
		Binning	0	0.000 008	0	0.000 8
		Fitting energy range	0	0.000 033	0	0.001 3
		Background model	0	0.000 042	0	0.004 0
		Free intensities fit	0	0.000 028	0	0.000 4
		Combined	0	0.000 070	0	0.004 7
	Energy calibration	Wrong energy of ^{16}N line	0.000 12	0.000 04	−0.000 82	0.000 55
		Energy calibration scheme	0	0.000 007	0	0.000 67
		Uncertainty of literature energy	0	0.000 018	0	0.002 25
		Line-shape for energy calibration	−0.000 068	0.000 038	0	0
		Combined	0.000 052	0.000 058	−0.000 82	0.002 4
Theory	Theory	Uncertainty of nuclear polarization correction	0	0.000 20	0	0.000 11
Theory input	Charge distribution model	Change of the skin thickness parameter	0	0.002 2	0	0.001 91
	Discrepancies of spectrum and fit	Free Gaussian fits	0	0.000 95	0	0.028 2
	Total		0.000 052	0.002 4	−0.000 82	0.028 8

Charge distribution model systematics: skin thickness

Nuclear charge distribution for spherical nuclei

$$\rho(\mathrm{r}) = \rho_0 \left(1 + \mathrm{e}^{4\ln 3 \frac{\mathrm{r}-\mathrm{c}}{\mathrm{t}}}\right)^{-1}$$



$\frac{\mathrm{t}}{\mathrm{E}}$ sensitivity $\sim 1.8 \times 10^{-5} \frac{\mathrm{fm}}{\mathrm{eV}}$:

$$\Delta \mathrm{E}_{\pm 10\%\,\mathrm{t}} \sim 13\,\mathrm{keV} \Rightarrow \sigma_{\mathrm{dR}} \approx 0.0022$$

Spectroscopic quadrupole moment results

PHYSICAL REVIEW C **101**, 054313 (2020)

Measurement of the quadrupole moment of ^{185}Re and ^{187}Re from the hyperfine structure of muonic X rays

A. Antognini,[1,2] N. Berger,[3] T. E. Cocolios,[4] R. Dressler,[1] R. Eichler,[1] A. Eggenberger,[2] P. Indelicato,[5] K. Jungmann,[6] C. H. Keitel,[7] K. Kirch,[1,2] A. Knecht,[1] N. Michel,[7] J. Nuber,[1,2] N. S. Oreshkina,[7,*] A. Ouf,[8] A. Papa,[1,9] R. Pohl,[8] M. Pospelov,[10,11] E. Rapisarda,[1,†] N. Ritjoho,[1,2] S. Roccia,[12,13] N. Severijns,[4] A. Skawran,[1,2] S. M. Vogiatzi,[1,2] F. Wauters,[3] and L. Willmann[6]

- Thorough study of systematic uncertainty studies is performed:
  - background model
  - line-shape model
  - cascade intensities

- Results are compared with previous analysis using muonic atoms by Konijn *et al.*[1]:
  - natural rhenium
  - weaker multiplets $(5f_{5/2} \rightarrow 4d_{5/2}, 5g_{7/2} \rightarrow 4f_{7/2})$ are not included

Isotopes	Q (b)	
^{185}Re	2.07(5)	our analysis
^{187}Re	1.94(5)	
^{185}Re	2.21(4)	past analysis with muonic atoms by Konijn *et al.*[1]
^{187}Re	2.09(4)	
^{185}Re	$2.18(3)_{stat}$	our analysis without the weaker multiplets
^{187}Re	$2.05(2)_{stat}$	

[1] Konijn et al., Nucl. Phys. A 360, 187 (1981)