The muX experiment

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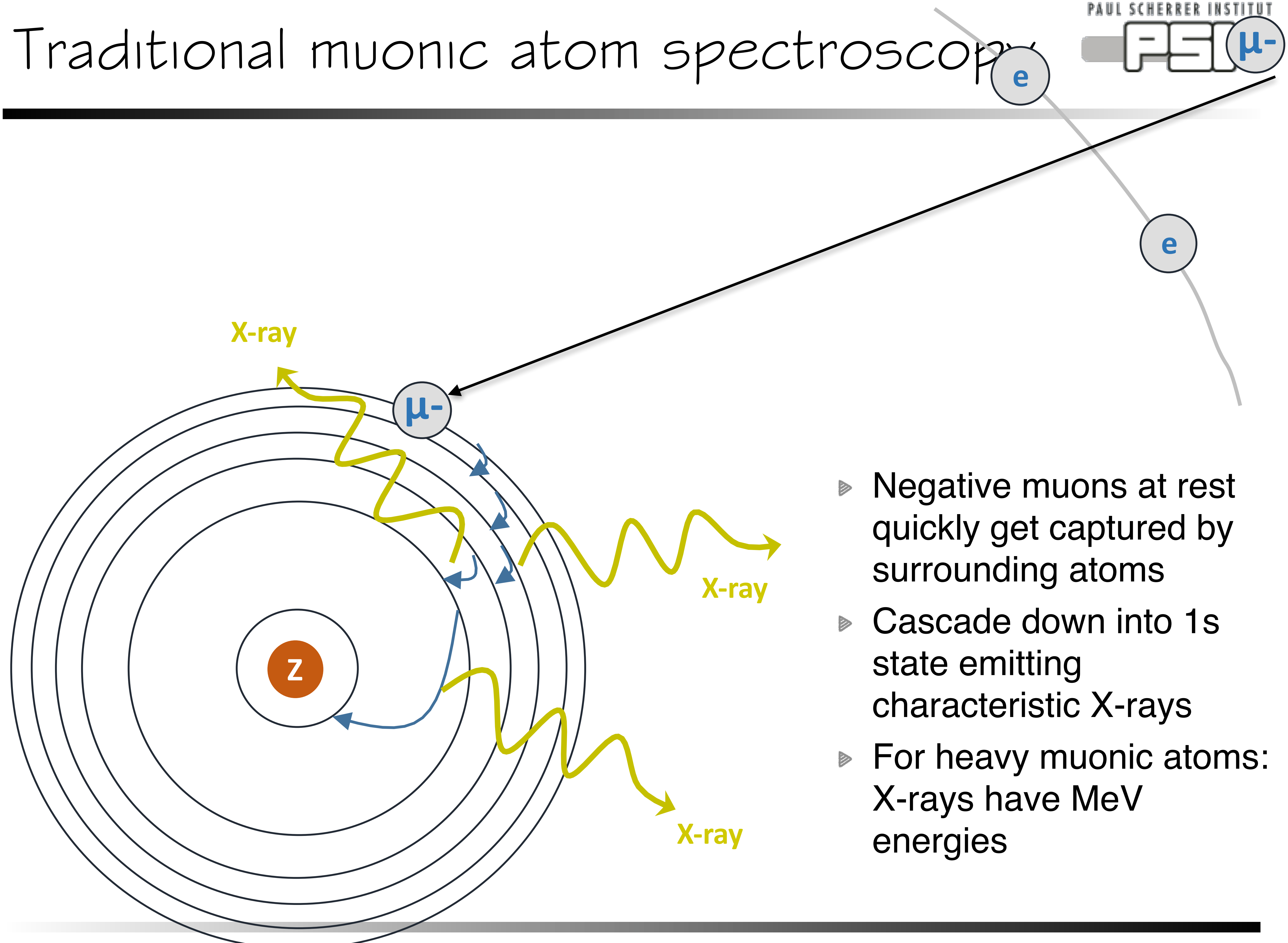
Traditional muonic atom spectroscopy

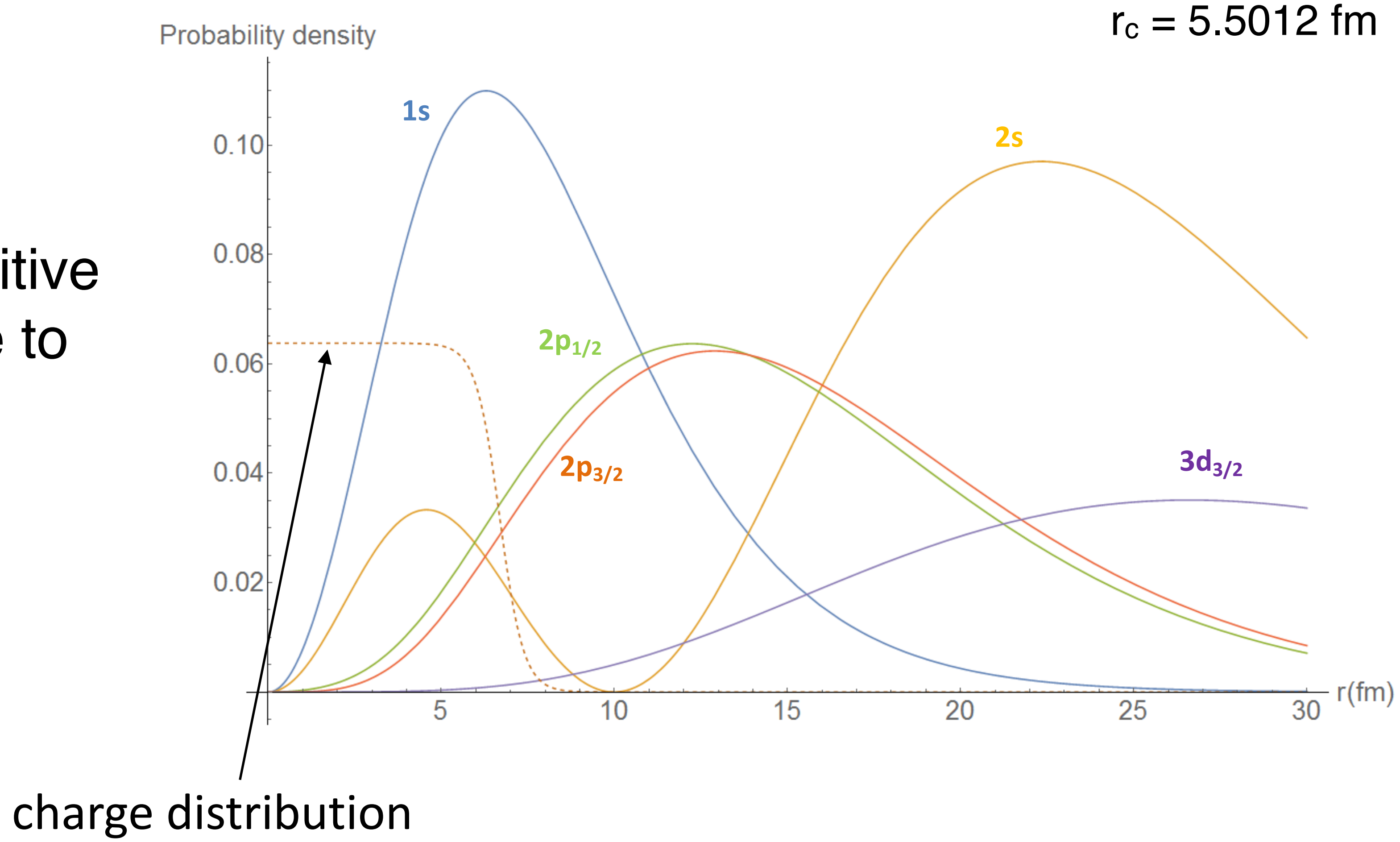


- Negative muons at rest quickly get captured by surrounding atoms
- Cascade down into 1s state emitting characteristic X-rays
- For heavy muonic atoms: X-rays have MeV energies

Muonic atom spectroscopy

- Muonic energy levels highly sensitive to nuclear charge distribution due to large overlap

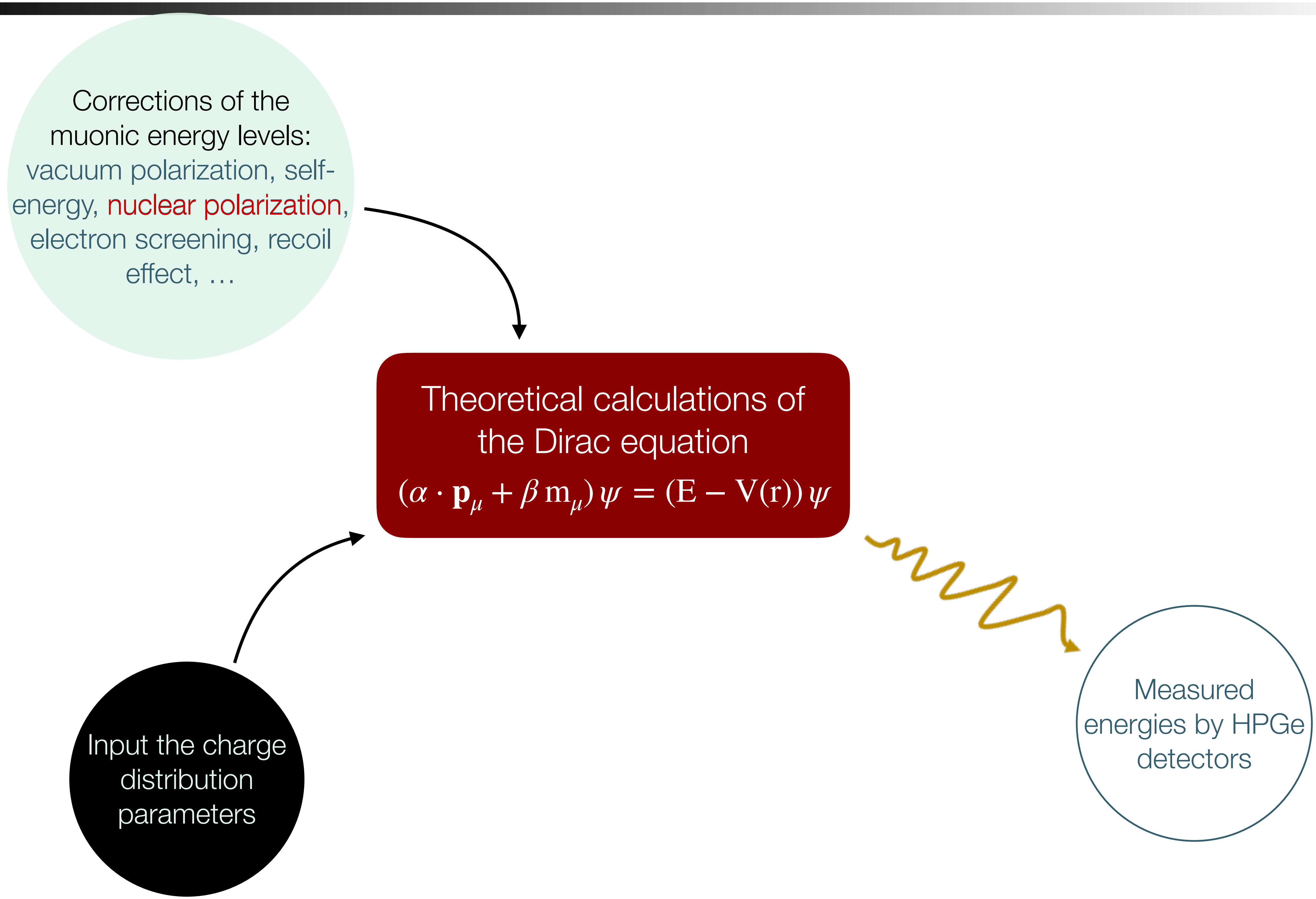
Lead Z=82
r_c = 5.5012 fm



Large effect:

E_{1s} (Z=82) ~ 19 MeV (point nucleus)
→ 10.6 MeV (finite size)

How to extract nuclear charge parameters from measured muonic energies



How to extract nuclear charge parameters from measured muonic energies

Corrections of the muonic energy levels: vacuum polarization, self-energy, nuclear polarization, electron screening, recoil effect, …

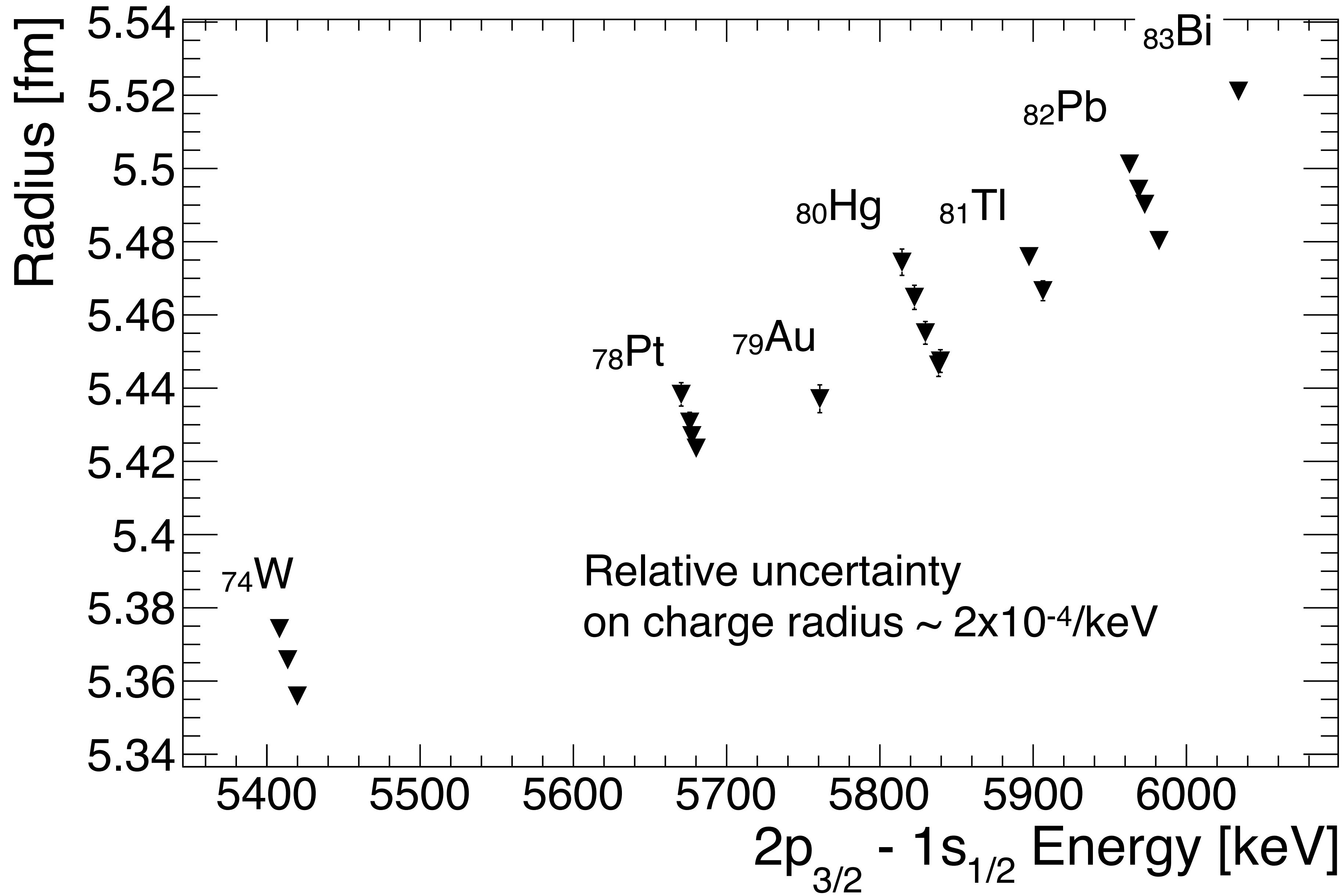
Theoretical calculations of the Dirac equation

$$(\alpha \cdot \mathbf{p}_\mu + \beta\, \mathrm{m}_\mu)\, \psi = (\mathrm{E} - \mathrm{V(r)})\, \psi$$

Measured energies by HPGe detectors

Extract the charge distribution parameters

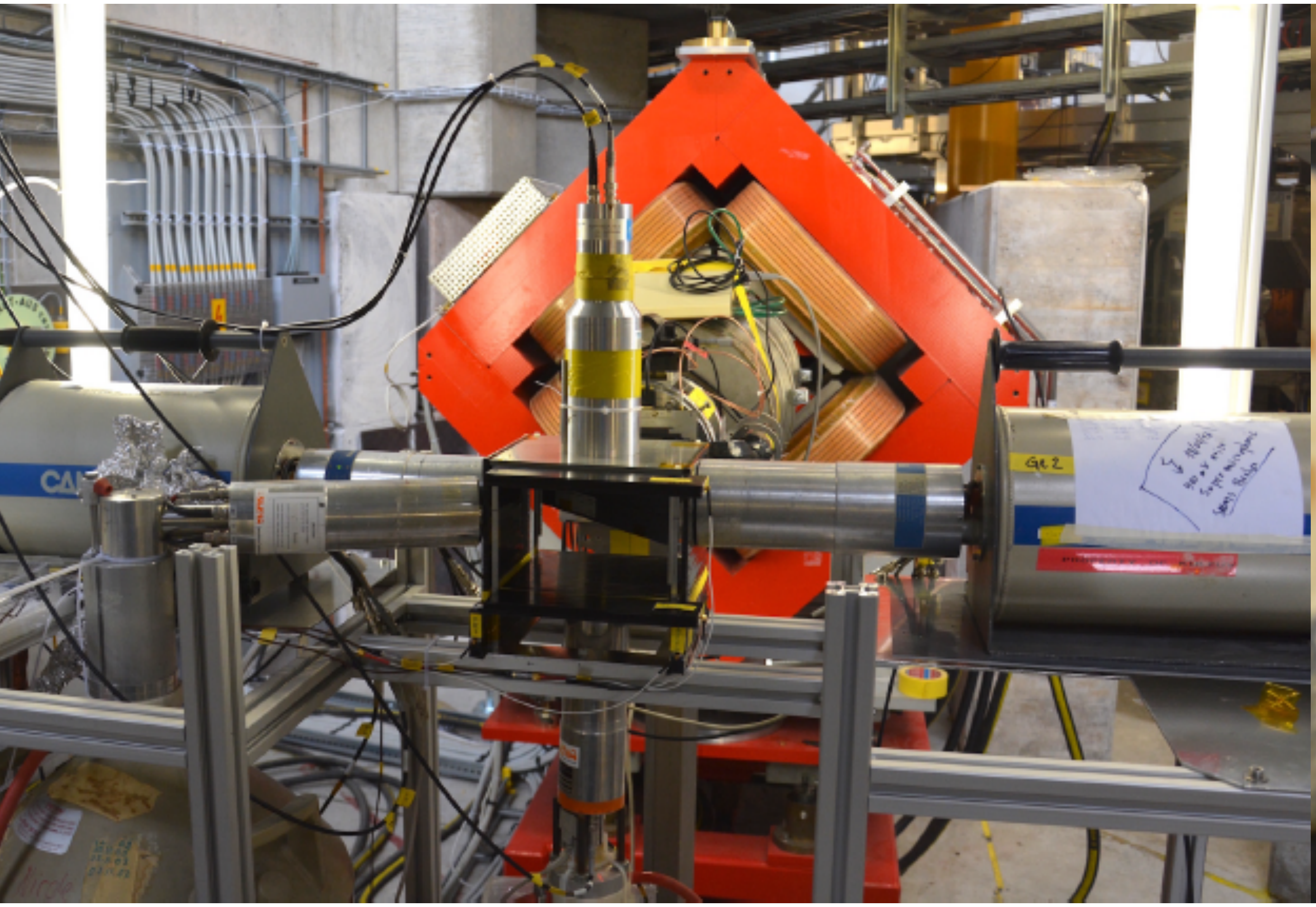
Muonic atom spectroscopy

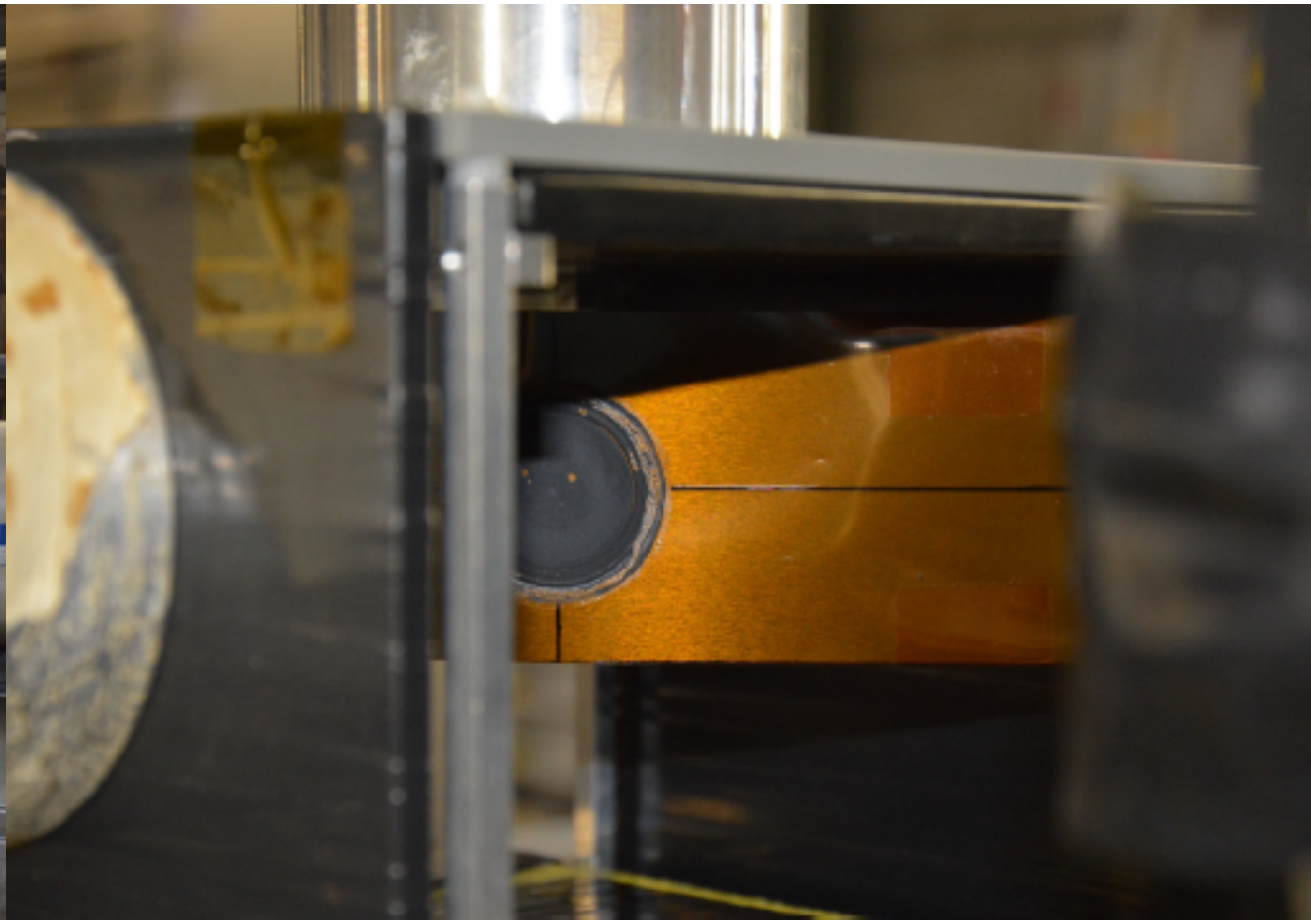


- 2p - 1s energy is highly sensitive to charge radius
- What is the limiting factor? → Typically theoretical modelling, especially calculation of nuclear response to presence of muon (nuclear polarization) and charge distribution model

Rhenium measurements

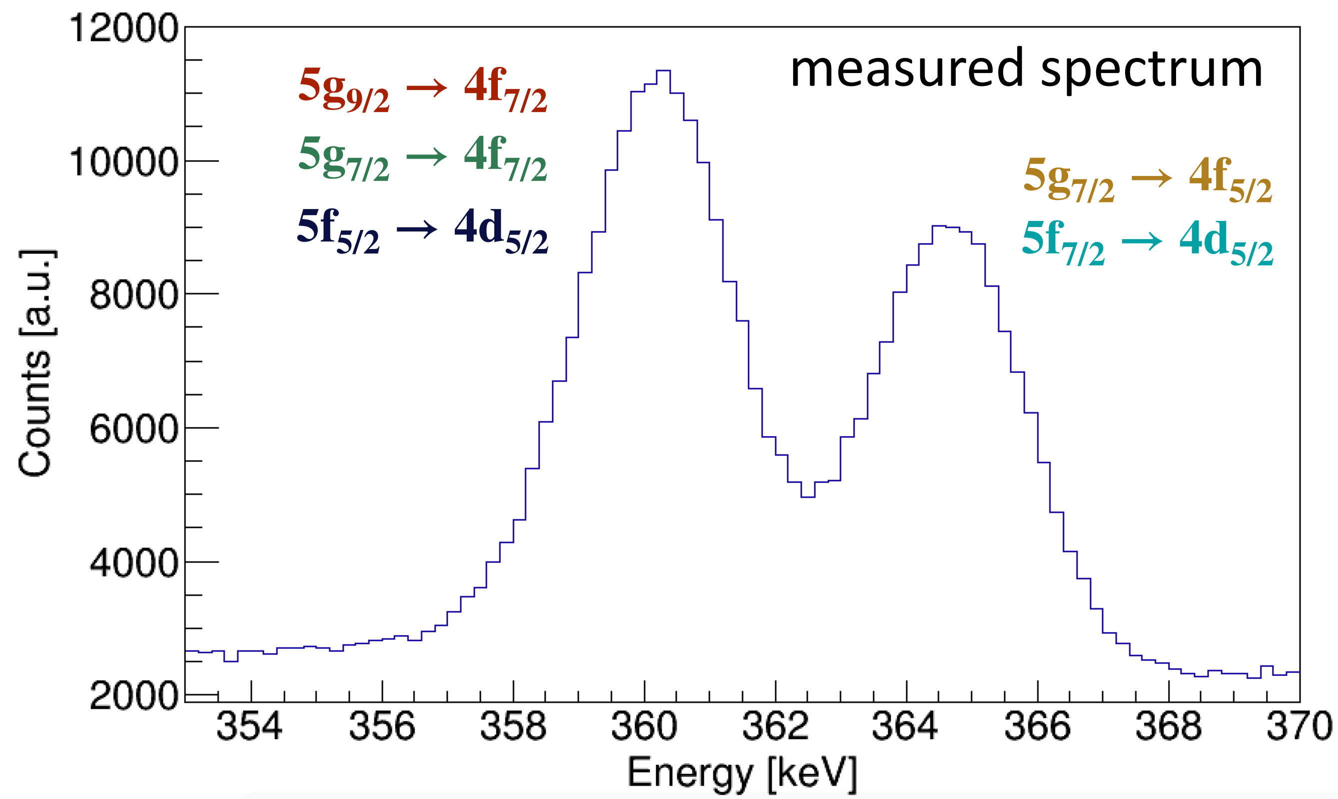
- The two rhenium isotopes ^{185}Re and ^{187}Re are the last stable isotopes without a measured, absolute charge radius

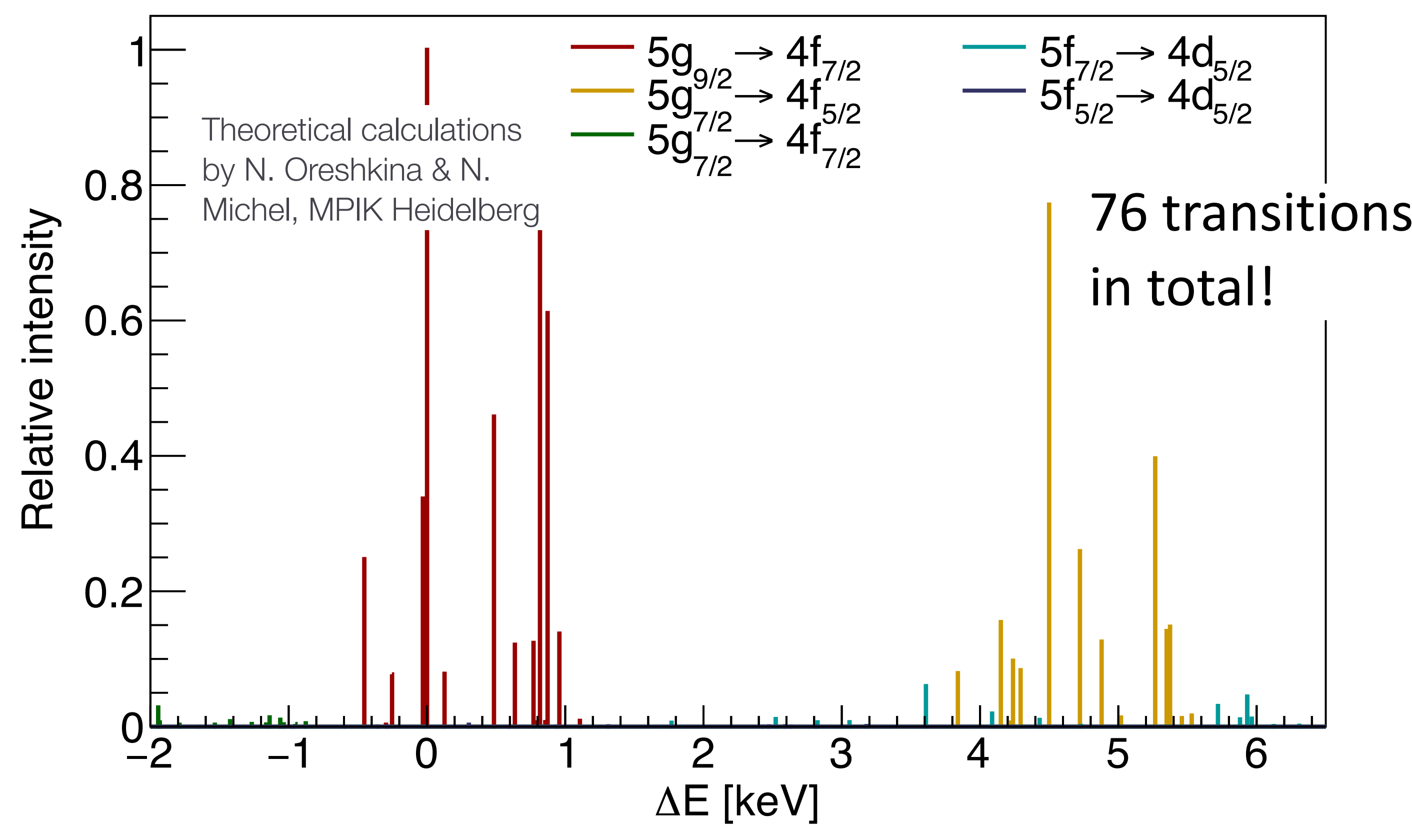




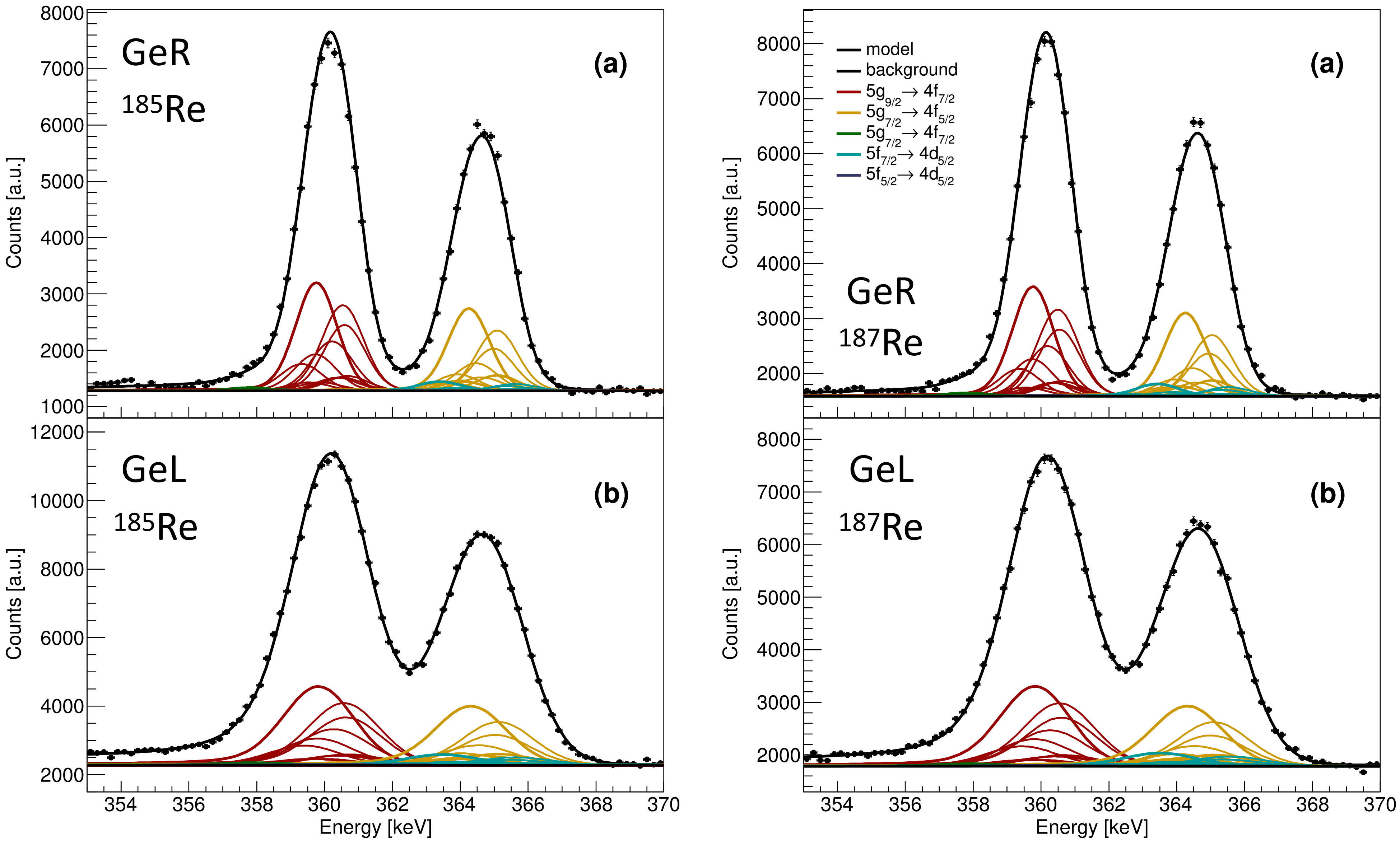
Hyperfine splitting of 5g-4f transitions

- First extract quadrupole moment
- For higher muonic transitions measure full quadrupole moment
  → typically chosen: 5g-4f transition
- Drawback:
  - Transitions not separated
  - Effect only through widening of peaks





Fitting experimental spectra



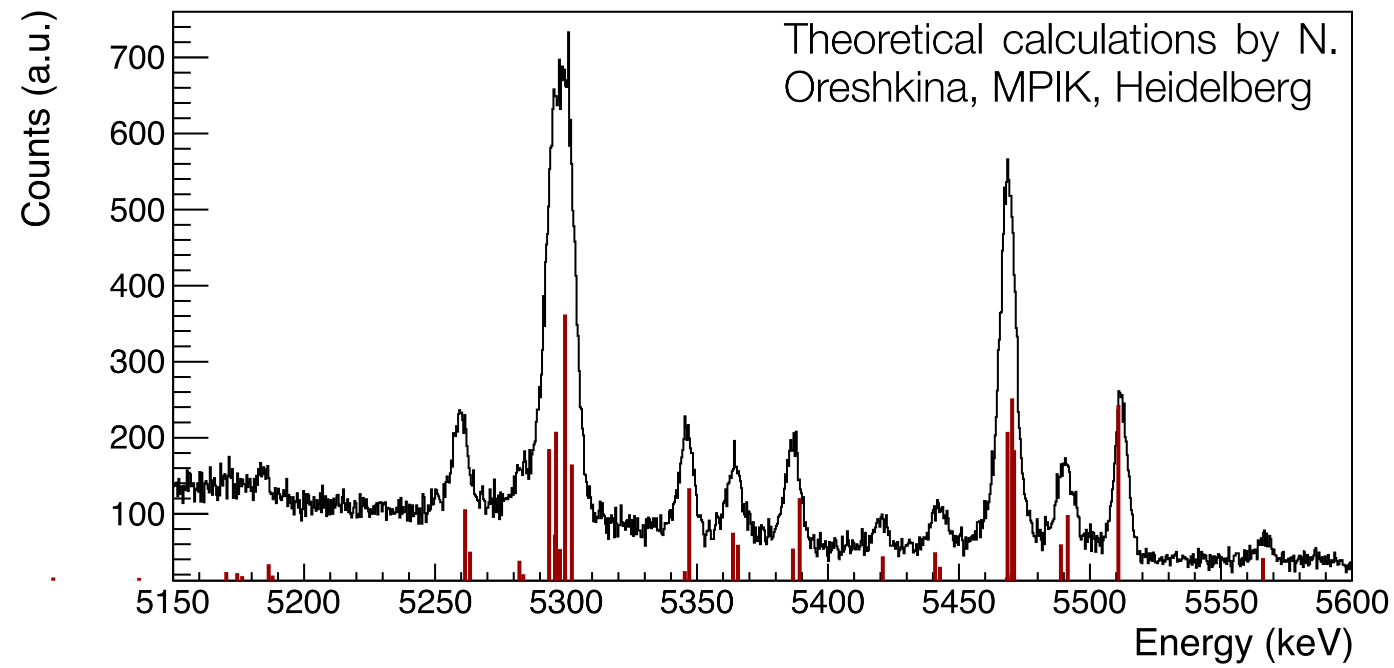
	Q [barn]
^{185}Re	2.07 ± 0.02 ± 0.05
^{187}Re	1.94 ± 0.02 ± 0.05

- Fitting the experimental spectra with the quadruple moment as a free parameter
- Two germanium detectors as cross-check

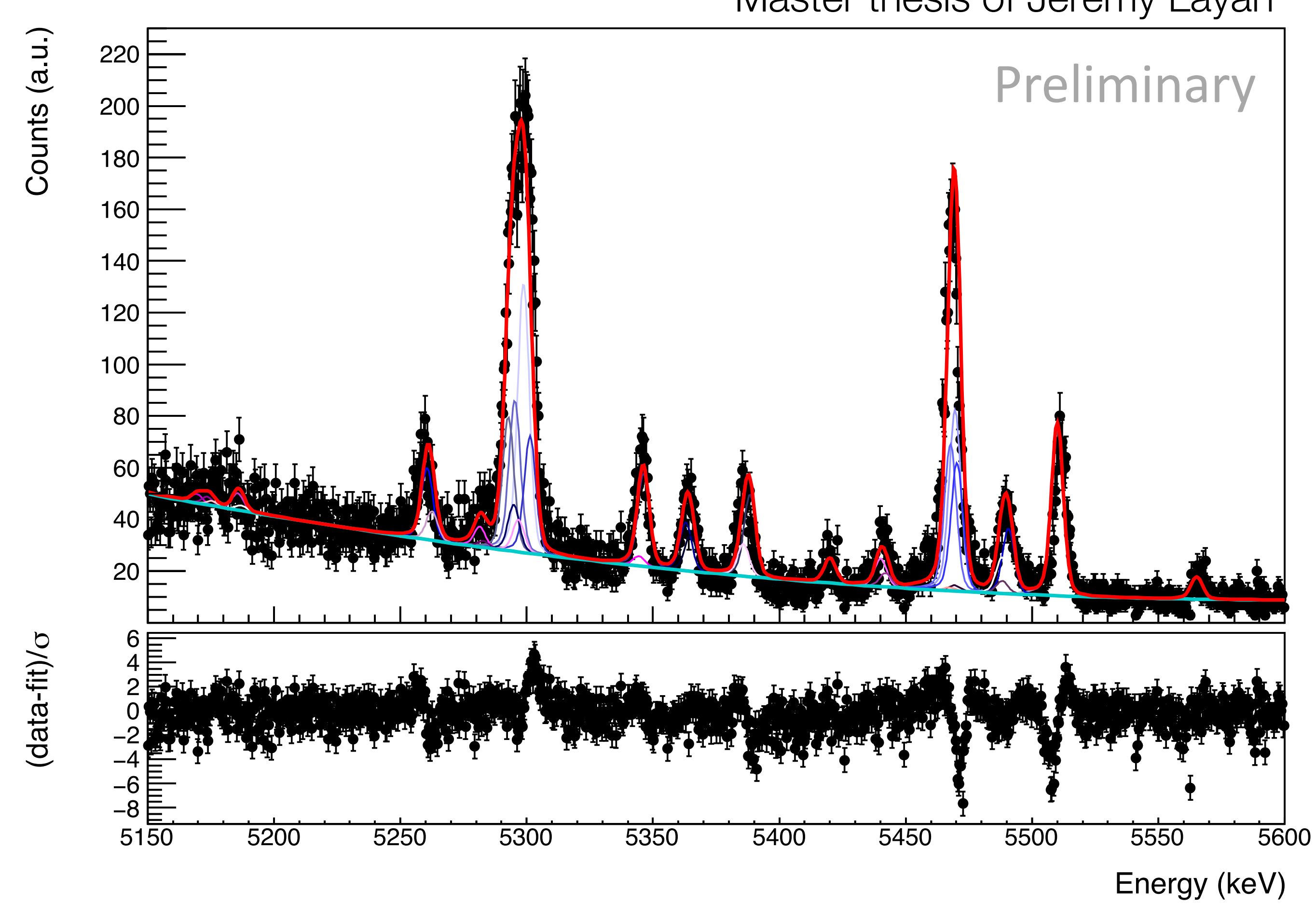
Konijin et al., Nucl. Phys. A **360**, 187 (1981)
Antognini et al., PRC **101**, 054313 (2020)

Rhenium charge radius

- 2p-1s lines used to extract charge radius
- Hyperfine structure clearly seen and more resolved than for 5g-4f transitions
- Work in progress



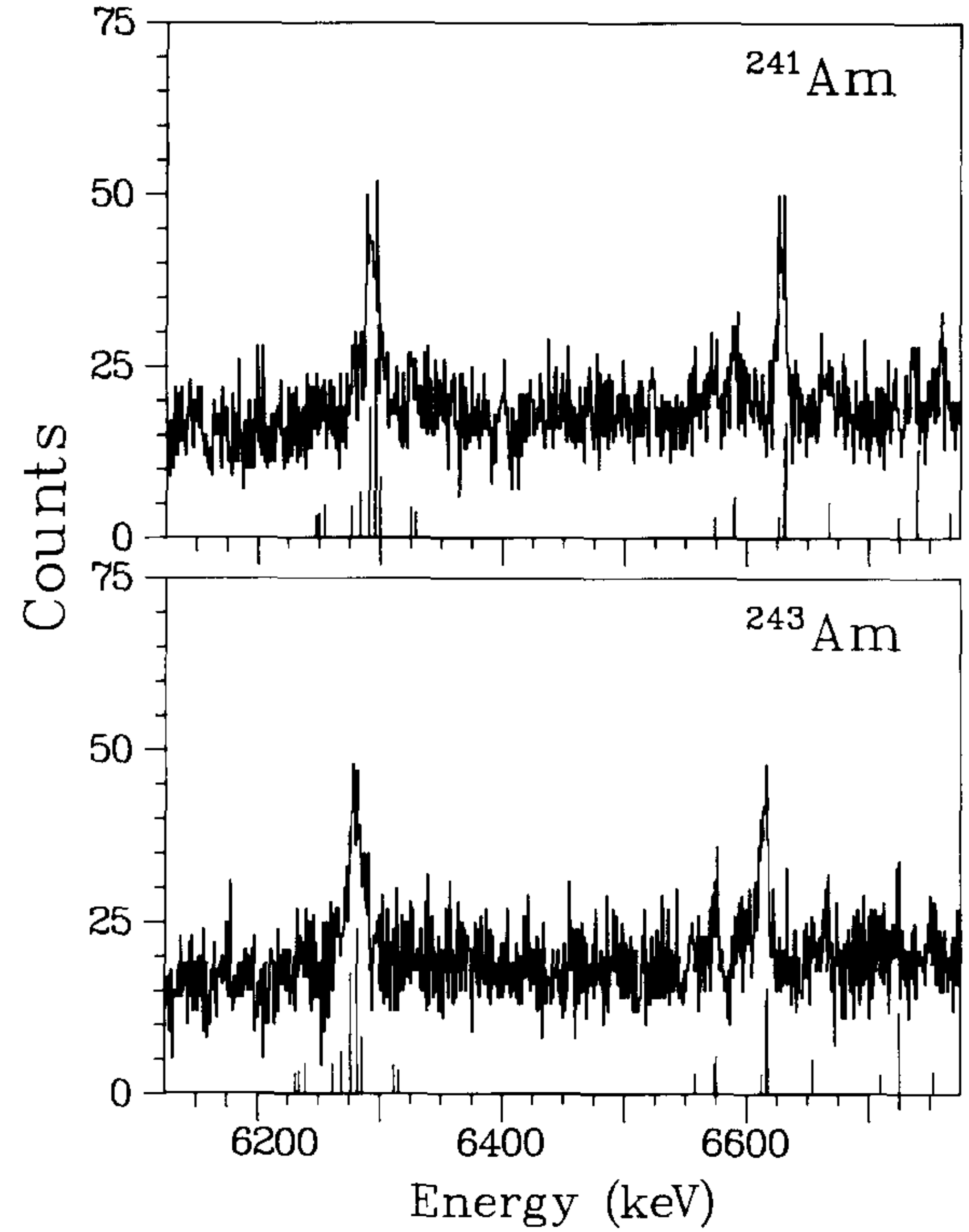
Master thesis of Jérémy Layan



What about radioactive atoms?

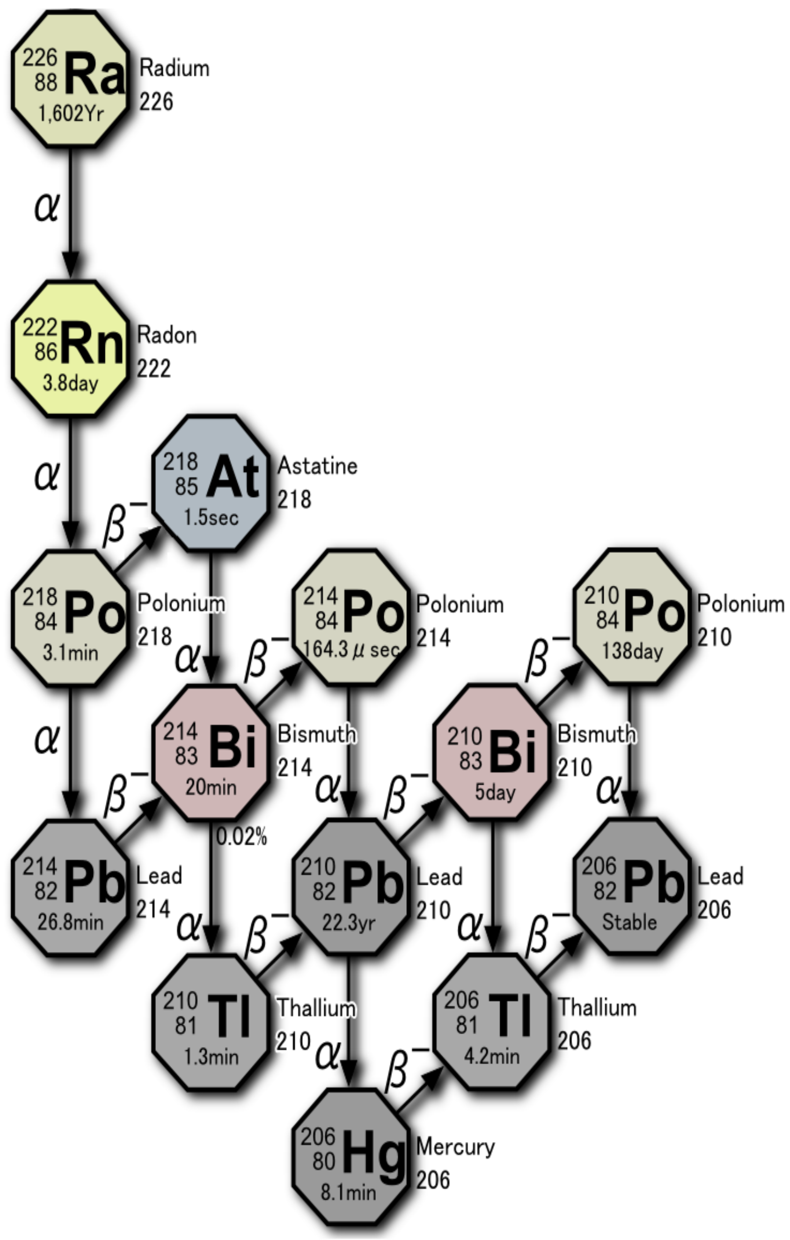
- All stable isotopes (except rhenium) have been measured with muonic atom spectroscopy
- In a few special cases also radioactive isotopes, e.g. americium
  - The paper describes the americium target as "modest weight of 1 gram"
- Nowadays: 0.2 µg of open ^{241}Am allowed in muon experimental area…

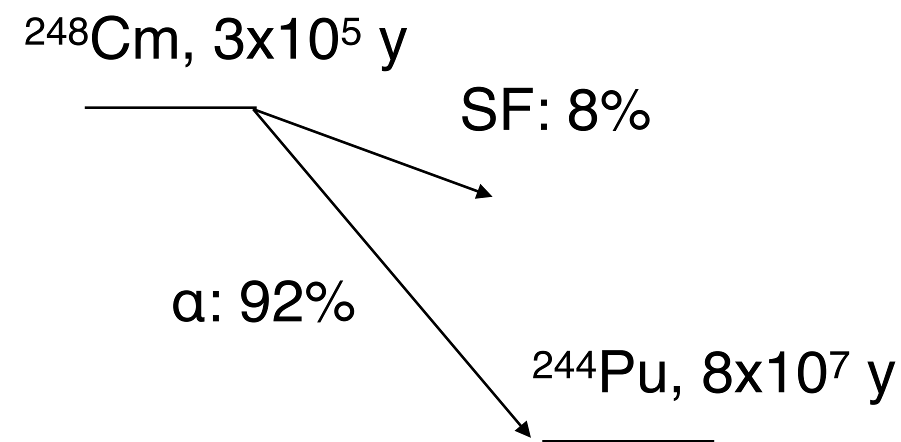
Johnson et al., Phys. Lett. **161B**, 75 (1985)



Cannot stop muons directly in microgram targets
Need new method!

Our radioactive targets of interest





Around 3 neutrons per SF emitted

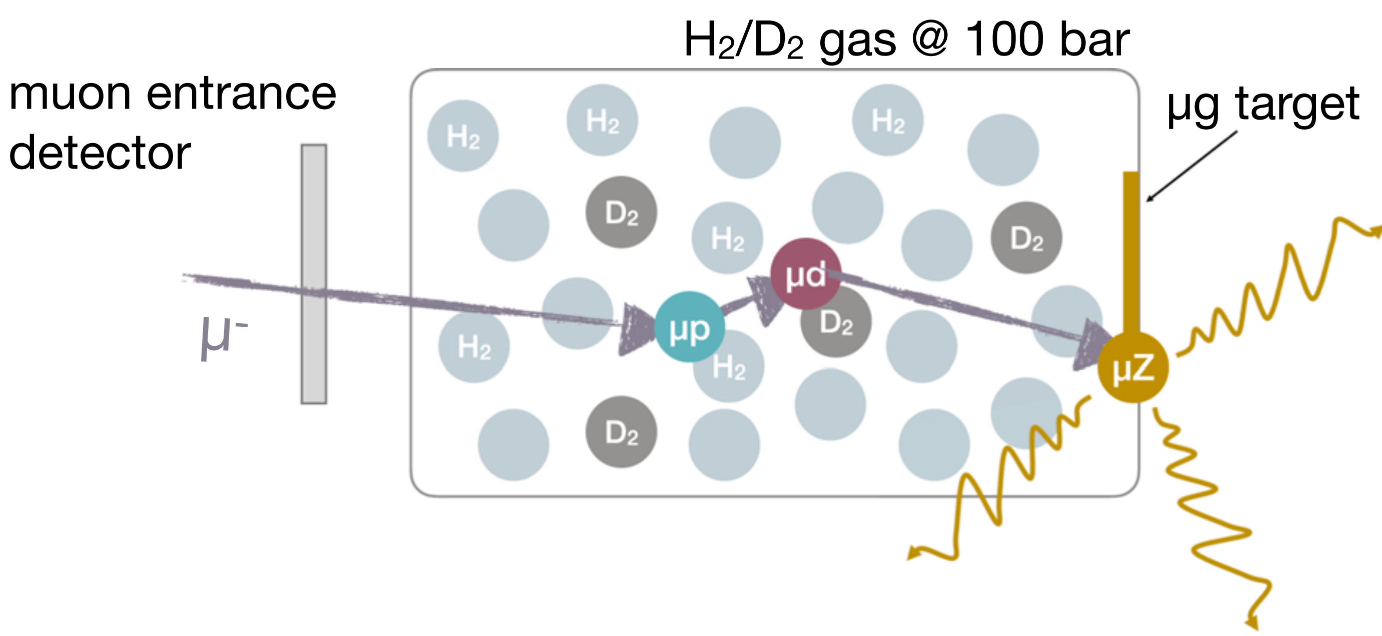
Vorobyev et al., AIP Conf. Proc. **798**, 255 (2005)

- 5.5 µg target material allowed
- Gamma rate of ~400 kHz from all daughters
- Interest from atomic parity violation

- 32.6 µg target material allowed
- Heaviest nucleus accessible

Transfer reactions

- Stop in 100 bar hydrogen (10% liquid density) target with 0.25% deuterium admixture
- Form muonic hydrogen μp
- Transfer to deuterium forming μd, gain binding energy of 45 eV
- Hydrogen gas quasi transparent for μd at ~5 eV (Ramsauer-Townsend effect)
- μd reaches target and transfers to μRa
- Measure emitted X-rays from cascade

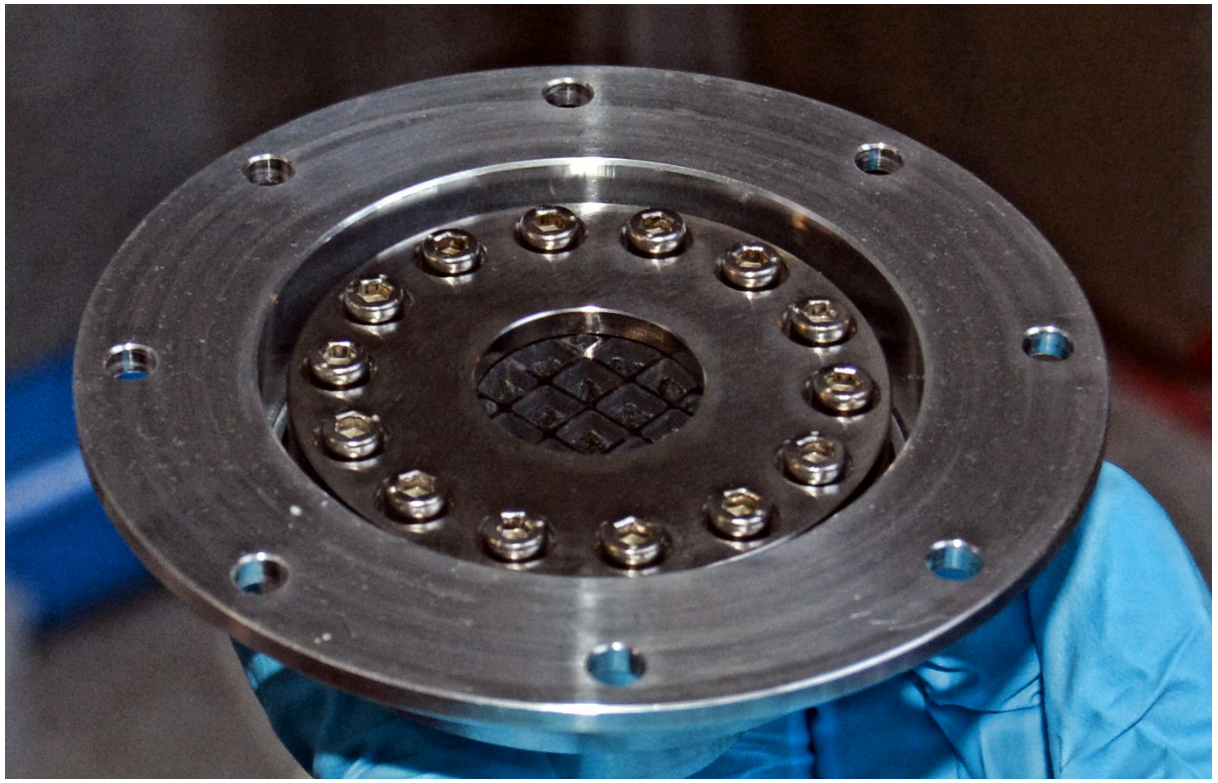


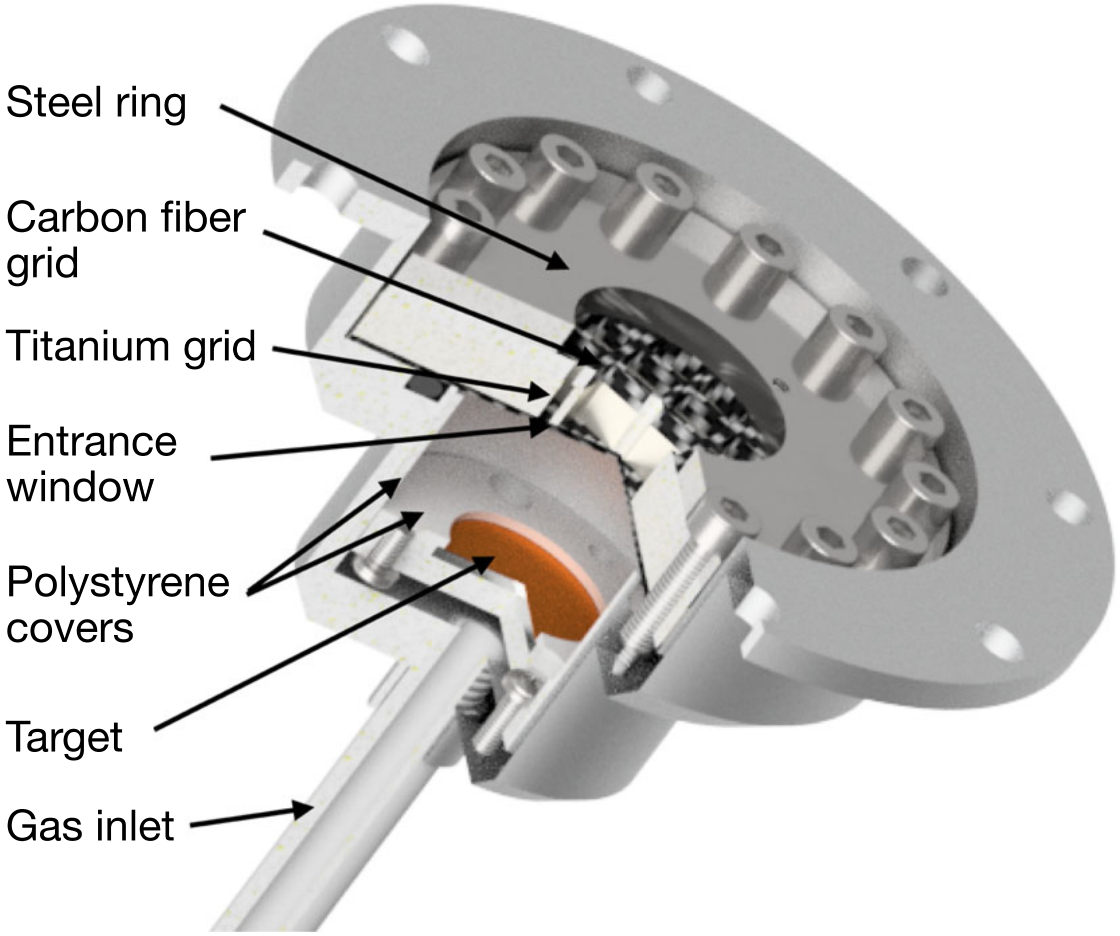
Inspired by work of Strasser et al. and Kraiman et al.

F. Mulhauser et al., Physical Review A 73, 034501 (2006)

100 bar hydrogen target

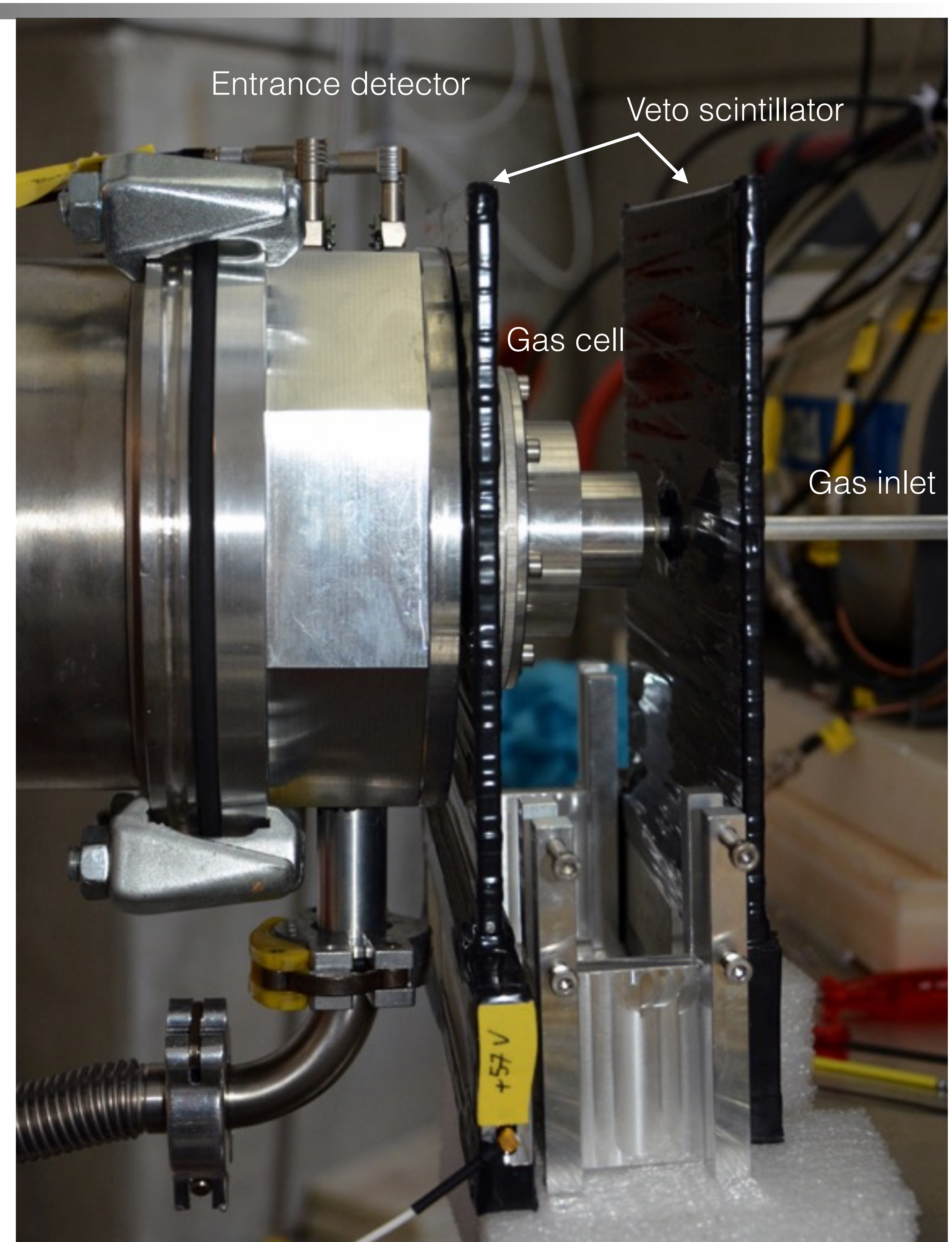
- Target sealed with 0.5 mm carbon fibre window plus carbon fibre/titanium support grid
- Target holds up to 350 bar
- 10 mm stopping distribution (FWHM) inside 15 mm gas volume
- Target disks mounted onto the back of the cell





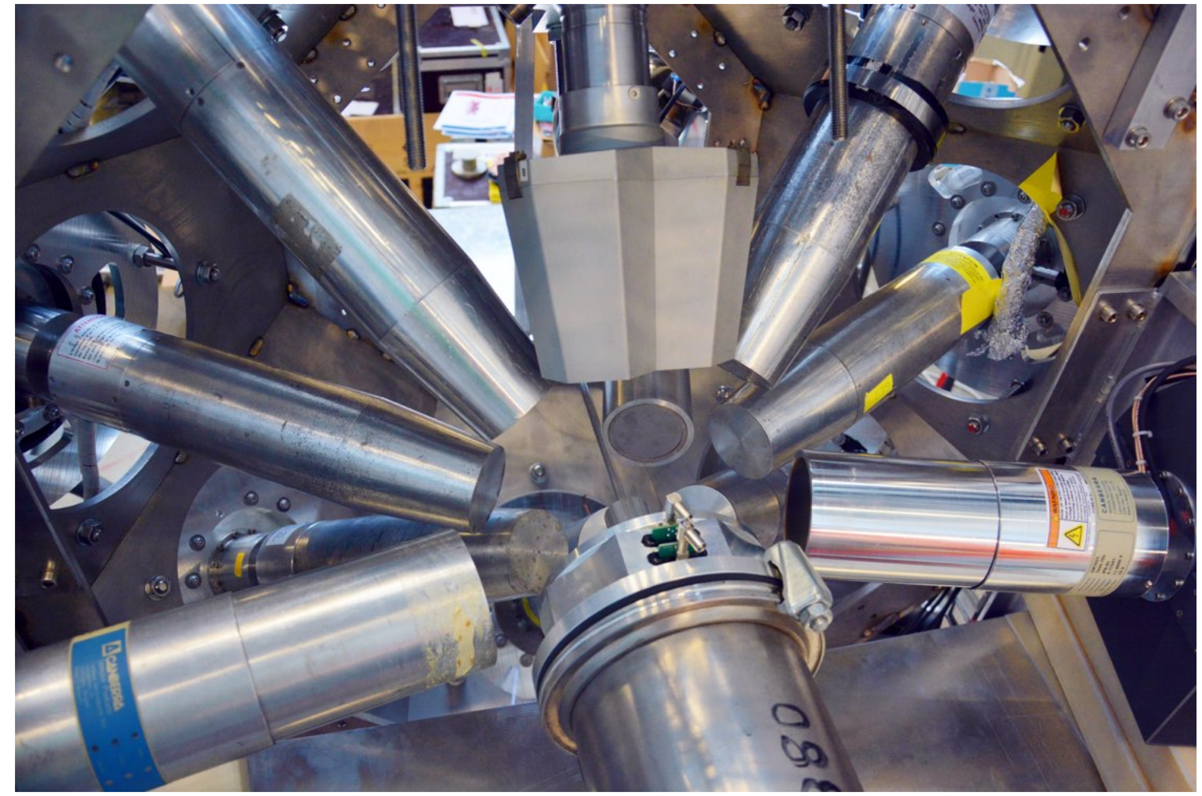
Entrance & veto detectors

- Entrance detector to see incoming muon
- Veto scintillators to form anti-coincidence with decay electron



Germanium array

- 2017/2018
  - 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
  - First time a large array is used for muonic atom spectroscopy

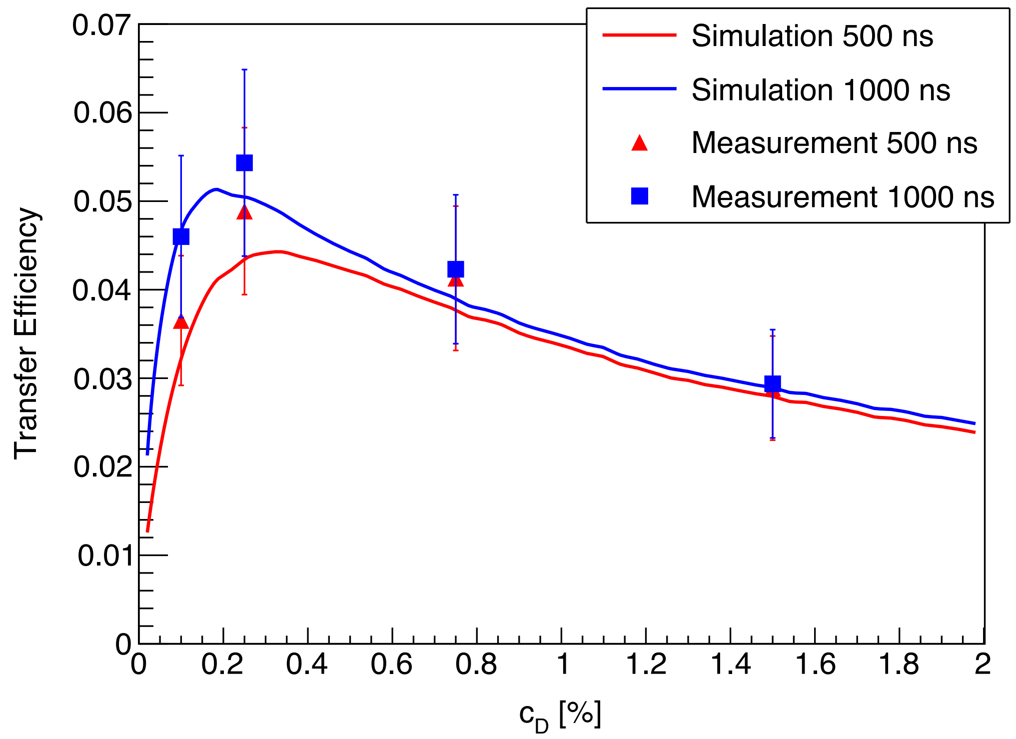


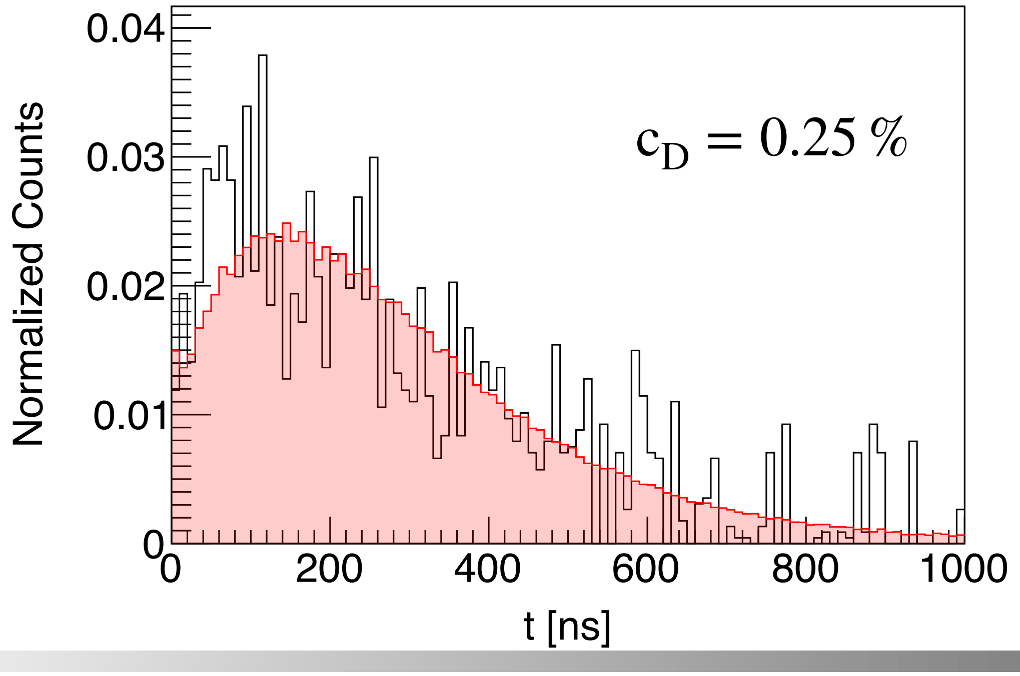
- 2019
  - Miniball germanium detector array from CERN
  - 26 germanium crystals in total

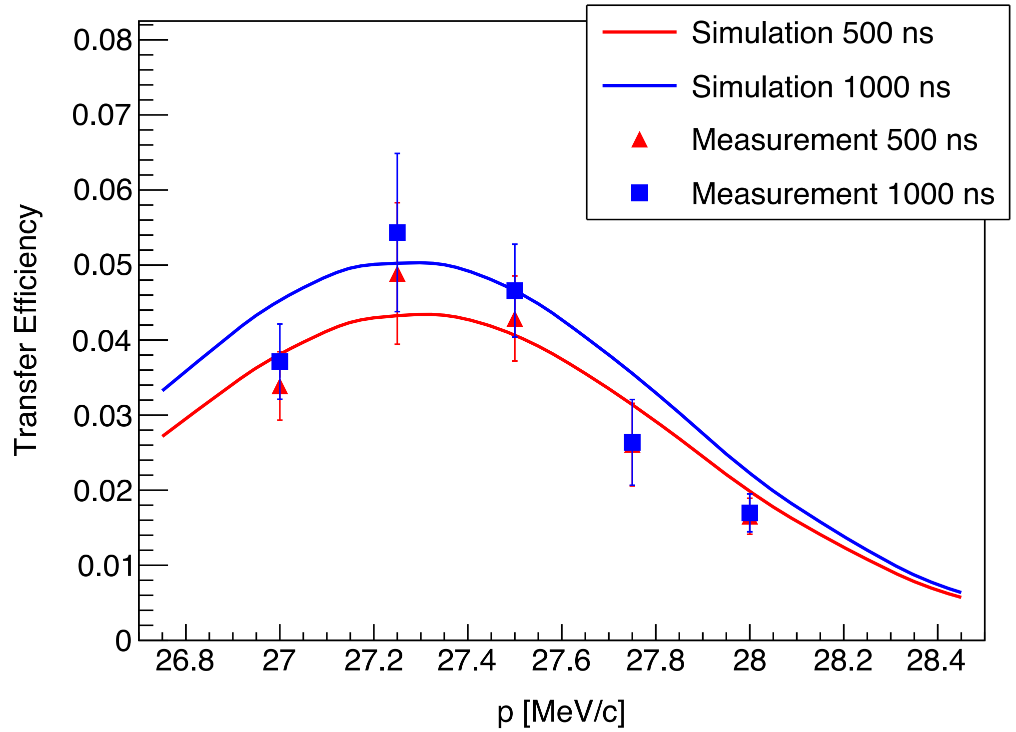
N. Warr et al., "The Miniball spectrometer", Eur. Phys. J. A 49, 40 (2013)

Optimisation of the transfer yield

- A 200 µg Au target was mounted inside the gas cell
- The amount of the 2p-1s µAu X-rays was measured by scanning the:
  - c_D: D2 admixture in H2 gas (cD)
  - p: stopping position of the muon beam
- Good agreement of all observables with simulation

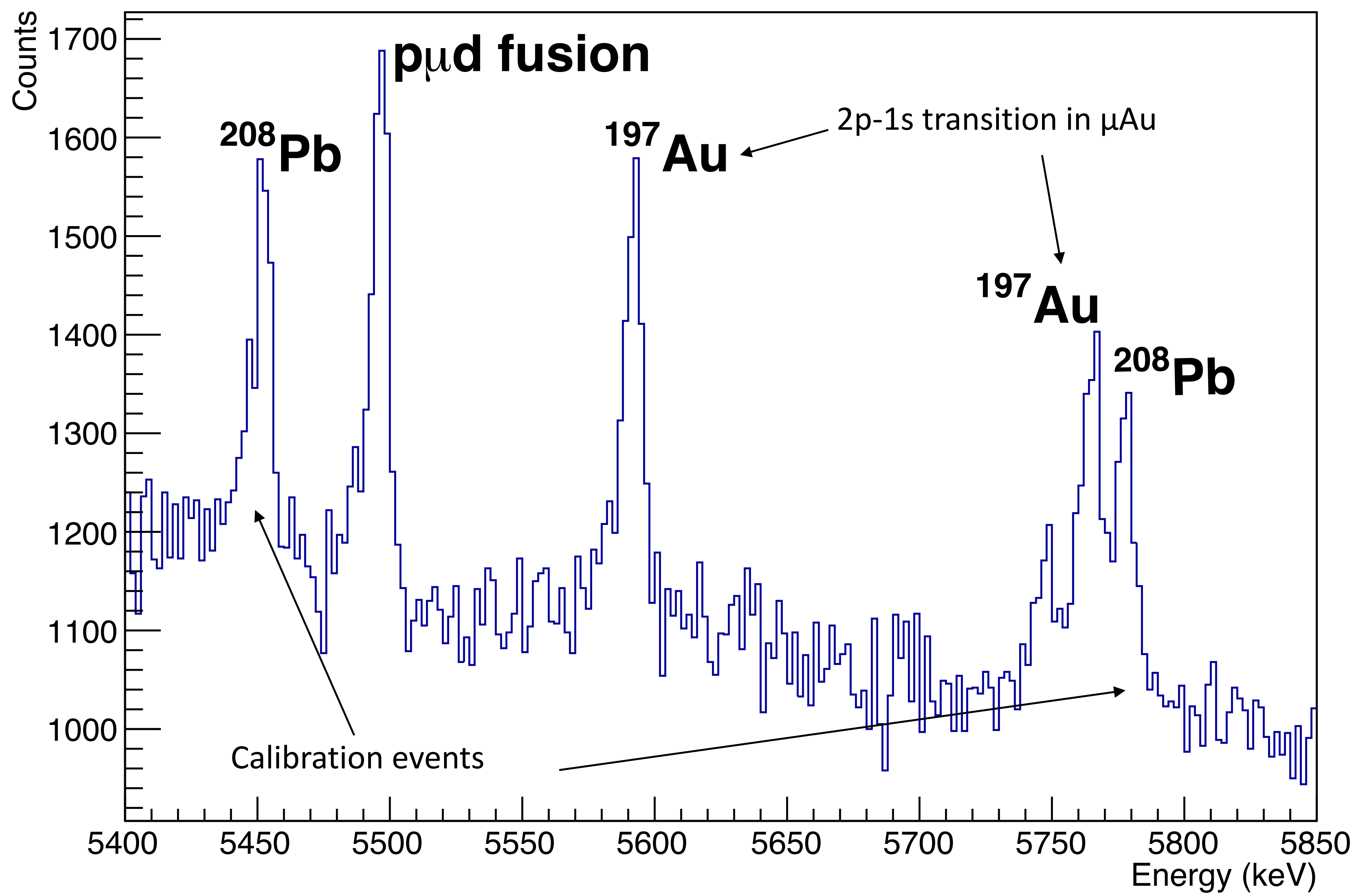






A. Adamczak et al., Eur. Phys. J. A 59, 15 (2023)

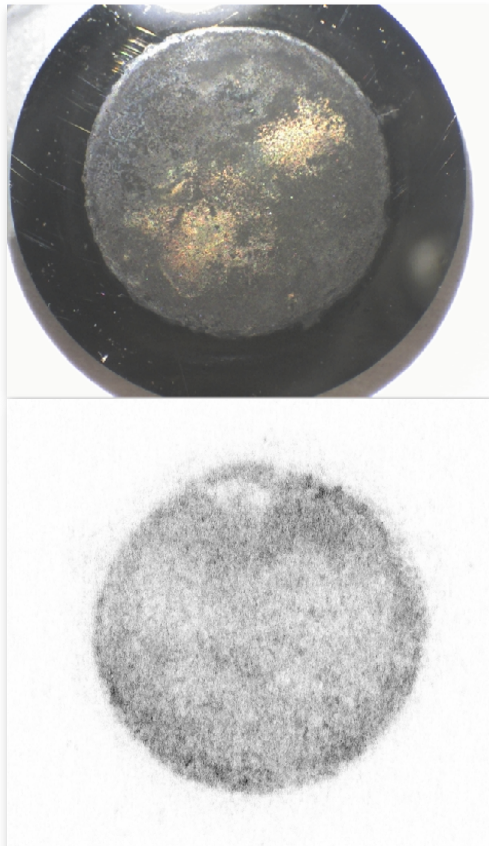
Measurement with microgram gold target



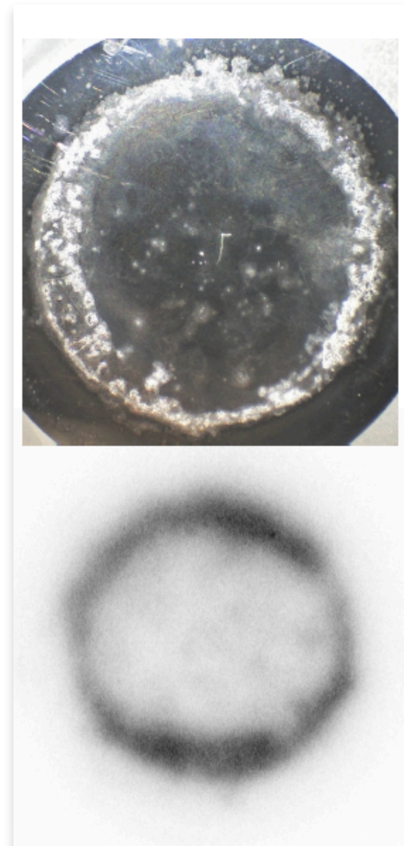
- Measurement with 5 µg gold target as proof-of-principle
- Spectrum taken over 18.5 h

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

Radioactive targets



15.5 µg ^{248}Cm target



4.4 µg ^{226}Ra target

1.4 µg ^{226}Ra target

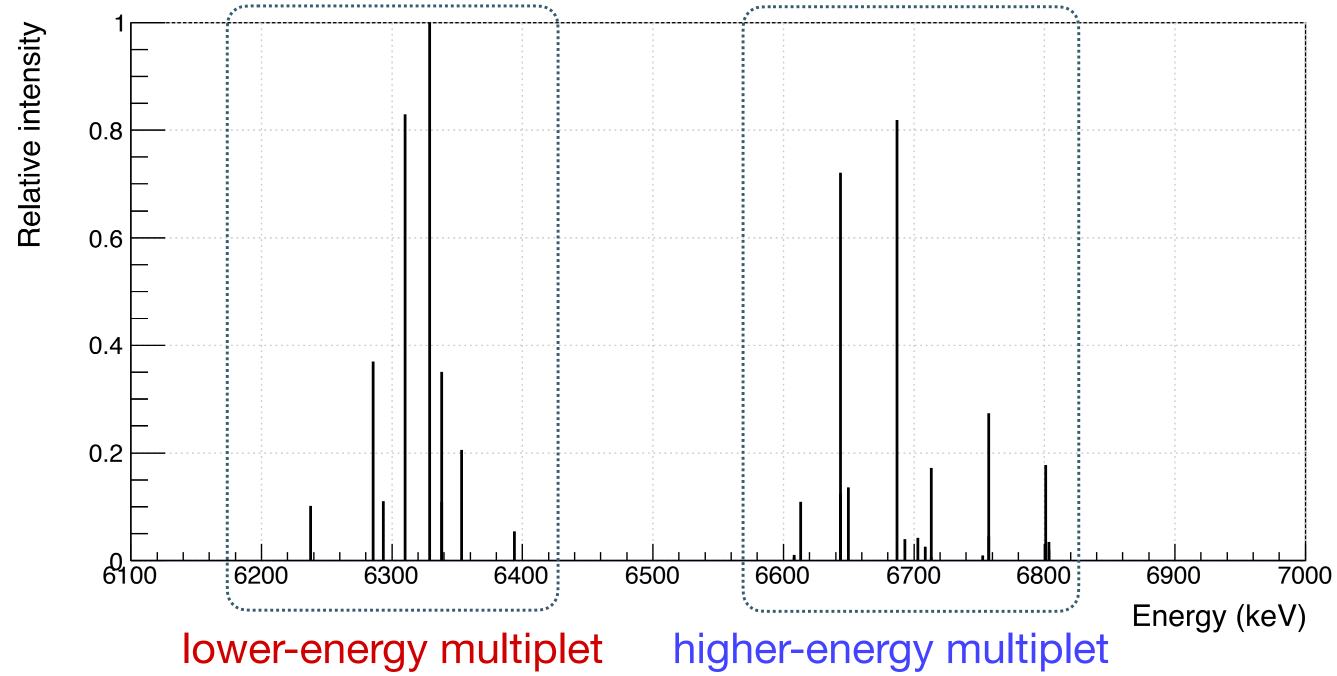
- Made by a combination of electroplating and printing by Institut für Kernchemie, Mainz
- Difficult to make thin targets that have only very little organic contamination
- We did not observe anything from 4.4 µg radium target; only hints from 1.4 µg target
- For both curium and radium target we suffered from palladium contamination —> only about 1/3 of muons went to target material

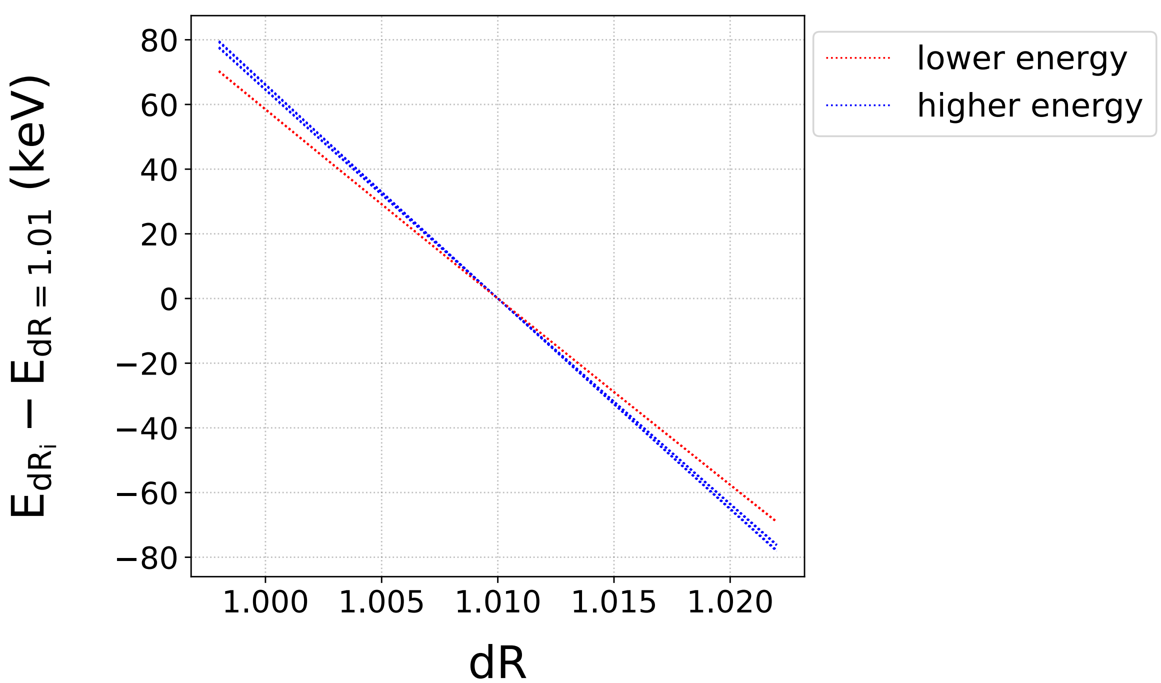
Energy dependence on the charge radius and quadrupole moment

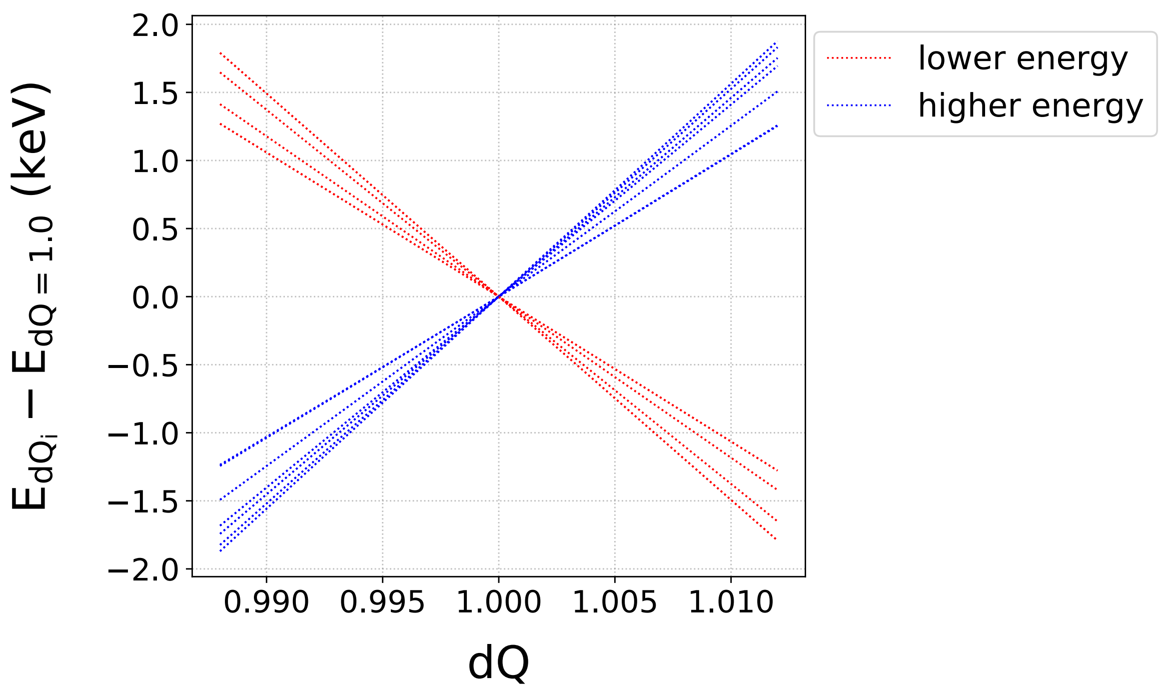
$$dR = \frac{R}{R_N}, \text{ where } R_N = 5.8687\ \text{fm}$$

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

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

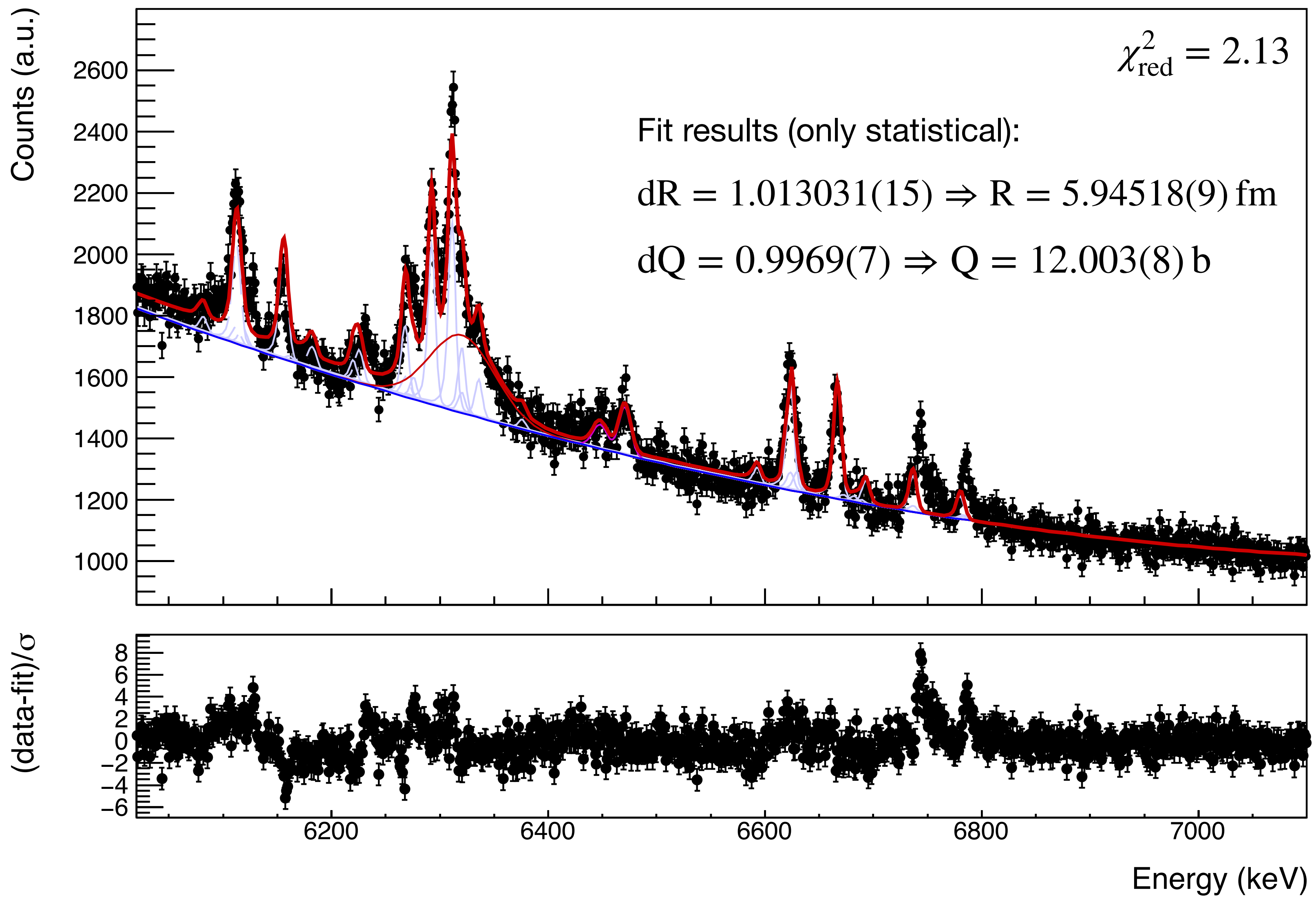






Muonic curium spectrum

- Succeeded to measure muonic curium for the first time
- Effectively a 5 µg target, so no principal show stopper to measure radium as well if the target can be made sufficiently clean and with the required amount



^{248}Cm results

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Systematic effect	Description	$\Delta(dR)$	σ_{dR}	$\Delta(dQ)$	σ_{dQ}
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	Uncertainty of nuclear polarization correction	0	0.000 20	0	0.000 11
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

Results on the nuclear charge radius and quadrupole moment:

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

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

Next steps ^{248}Cm analysis:

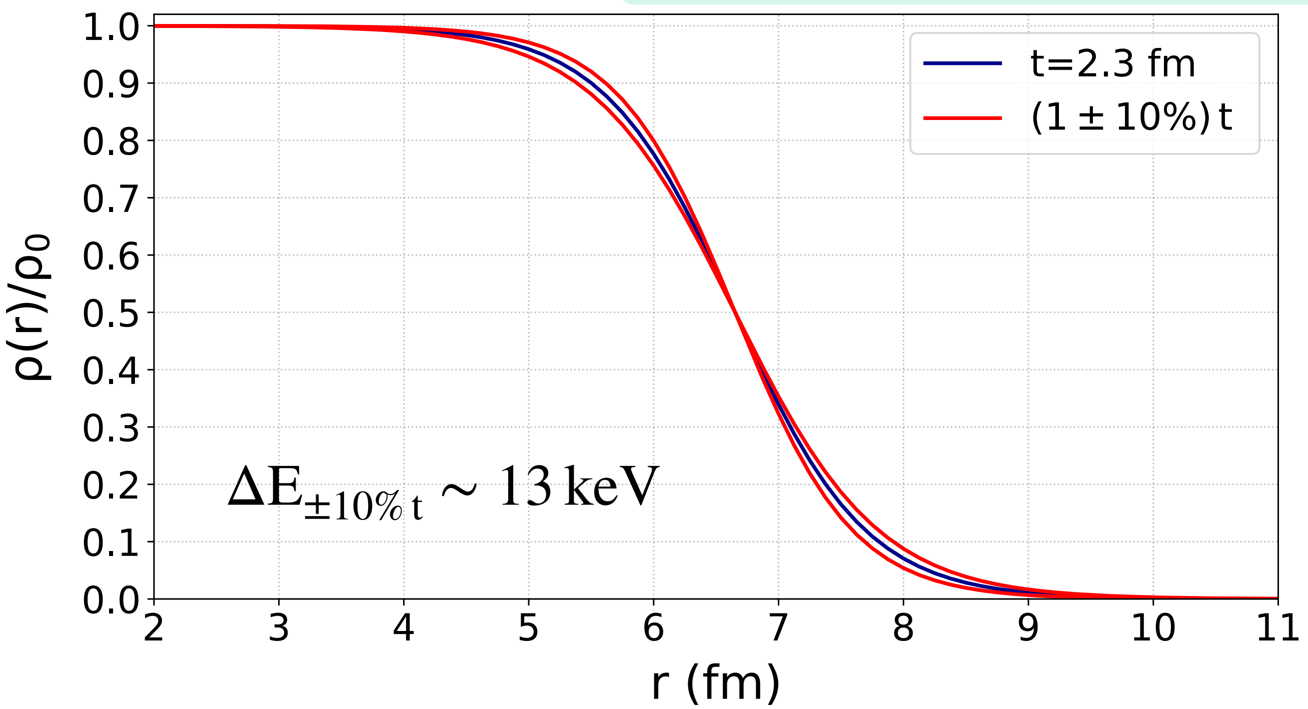
- Understand the discrepancies between the fitted and measured hyperfine transitions
- Then, the systematic effect of the skin thickness can be reduced by fitting the 2p→1s and 3d→2p together

Charge distribution model

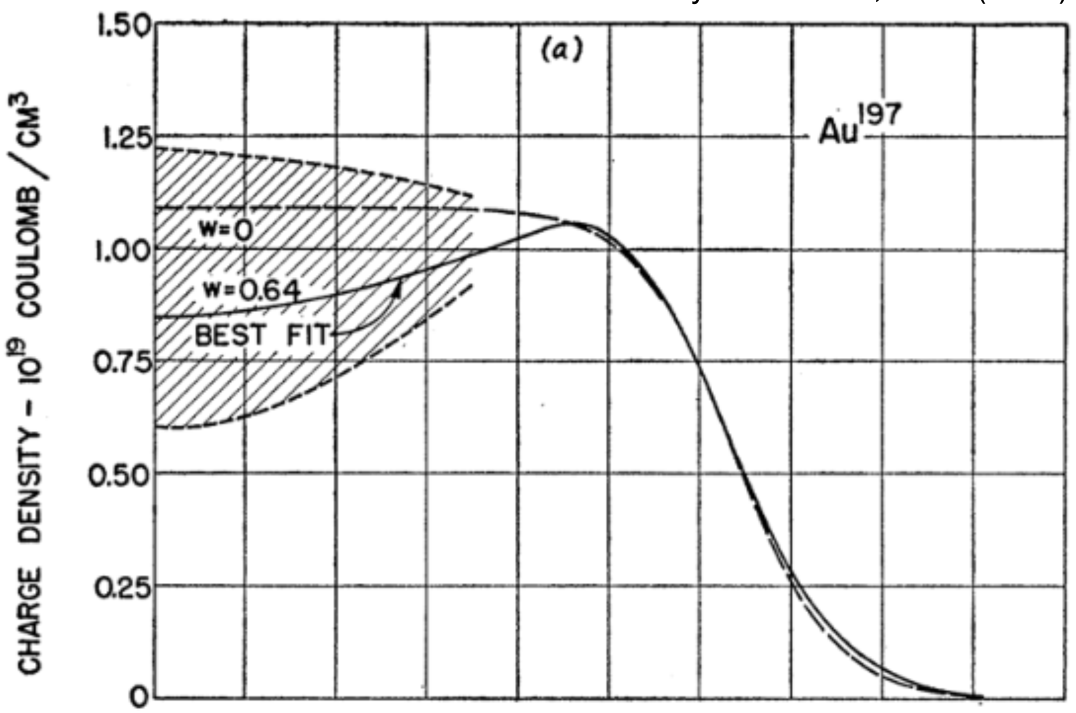
- In the absence of guidance from electron scattering, need to rely completely on model for charge distribution
- Uncertainty on tail (skin thickness) or central depletion (w parameter) or …
- Higher order deformations?
- In the end have ideally several transitions that help to constrain through different moments the shape somewhat
- Need to assign reasonable systematic uncertainty
- Not always treated very rigorously in the past

Nuclear charge distribution for spherical nuclei

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

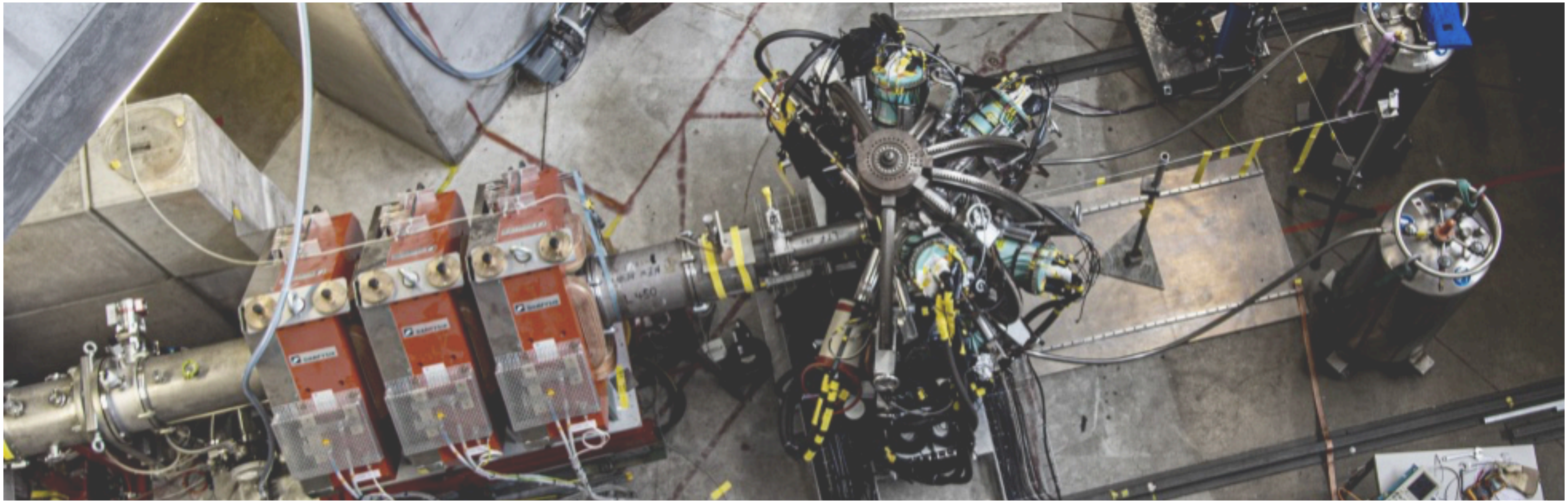


Phys. Rev. **101**, 1131 (1956)



Conclusions

- Muonic atom spectroscopy is a powerful tool to study properties of nuclei (charge radius, quadrupole moment, nuclear structure)
- muX project developed method based on transfer reactions to perform measurements with microgram target material
- Measured muonic curium spectrum for the first time!
- Radium measurements to come; other isotopes being prepared, e.g. $^{39,40,41}K$



muX collaboration

A. Adamczak[1], A. Antognini[2,3], E. Artes[4], N. Berger[4], T. Cocolios[5], N. Deokar[4], R. Dressler[2], Ch.E. Düllmann[4,6,7], R. Eichler[2], M. Heines[5], H. Hess[8], P. Indelicato[9], K. Jungmann[10], K. Kirch[2,3], A. Knecht[2], E. Maugeri[2], C.-C. Meyer[4], 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. Antognini[2,3], K. von Schoeler[3], N. Warr[8], F. Wauters[4], and L. Willmann[10]

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Backup

Muonic atom spectroscopy

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- Nuclear polarisation is the dominating factor that in the end determines the accuracy of the extracted charge radius
- Typically assumed uncertainty: 10 - 30%
- Nuclear excitation spectra important
- Looking for theorists that want to tackle these calculations with modern methods

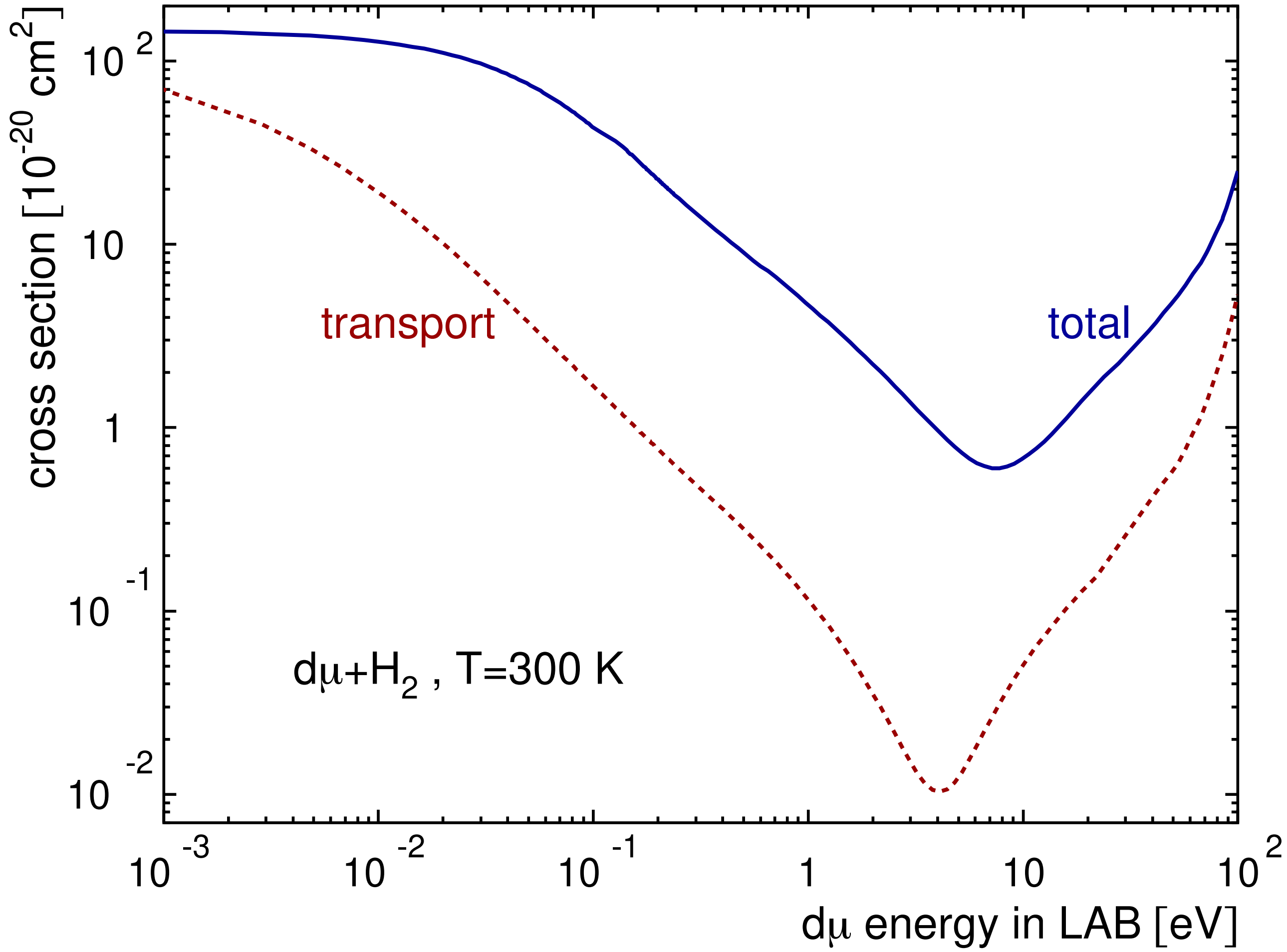
TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

Energy (MeV)	I^π	$B(E\lambda)\uparrow$ ($e^2b^{2\lambda}$)	$1s_{1/2}$ (eV)	$2s_{1/2}$ (eV)	$2p_{1/2}$ (eV)	$2p_{3/2}$ (eV)	$3p_{1/2}$ (eV)	$3p_{3/2}$ (eV)	$3d_{3/2}$ (eV)	$3d_{5/2}$ (eV)
2.615	3^-	0.612	135	12	90	84	26	26	111	−63
4.085	2^+	0.318	198	20	182	180	76	84	6	4
4.324	4^+	0.155	14	1	8	7	2	2	1	1
4.842	1^-	0.001 56	7	1	−9	−8	0	0	1	1
5.240	3^-	0.130	27	2	16	15	5	5	2	2
5.293	1^-	0.002 04	9	2	−27	−19	0	−1	1	1
5.512	1^-	0.003 80	16	3	−90	−53	−1	−1	1	1
5.946	1^-	0.000 07	0	0	3	−30	0	0	0	0
6.193	2^+	0.050 5	29	3	22	21	7	7	0	0
6.262	1^-	0.000 24	1	0	3	5	0	0	0	0
6.312	1^-	0.000 22	1	0	3	4	0	0	0	0
6.363	1^-	0.000 14	1	0	2	2	0	0	0	0
6.721	1^-	0.000 75	3	1	6	7	0	−1	0	0
7.064	1^-	0.001 56	6	1	9	11	−1	−1	0	0
7.083	1^-	0.000 75	3	1	4	5	−1	−1	0	0
7.332	1^-	0.002 04	8	1	10	11	−2	−2	0	0
Total low-lying states			458	48	233	242	111	117	123	−53
13.5	0^+	0.047 872	906	315	64	38	24	15	1	0
22.8	0^+	0.043 658	546	147	43	26	15	10	0	0
13.7	1^-	0.537 672	1454	221	786	738	255	258	66	54
10.6	2^+	0.761 038	375	37	237	222	67	68	33	30
21.9	2^+	0.566 709	207	21	108	99	29	29	8	7
18.6	3^-	0.497 596	77	7	40	36	11	11	3	2
33.1	3^-	0.429 112	53	5	25	23	7	7	2	1
	> 3[a]		176	15	80	71	21	21	4	4
Total high-lying states			3794	768	1383	1253	429	419	117	98
Total			4252	816	1616	1495	540	536	240	45

[a]Values from Ref. 7. Positive NP values mean that the respective binding energies are increased.

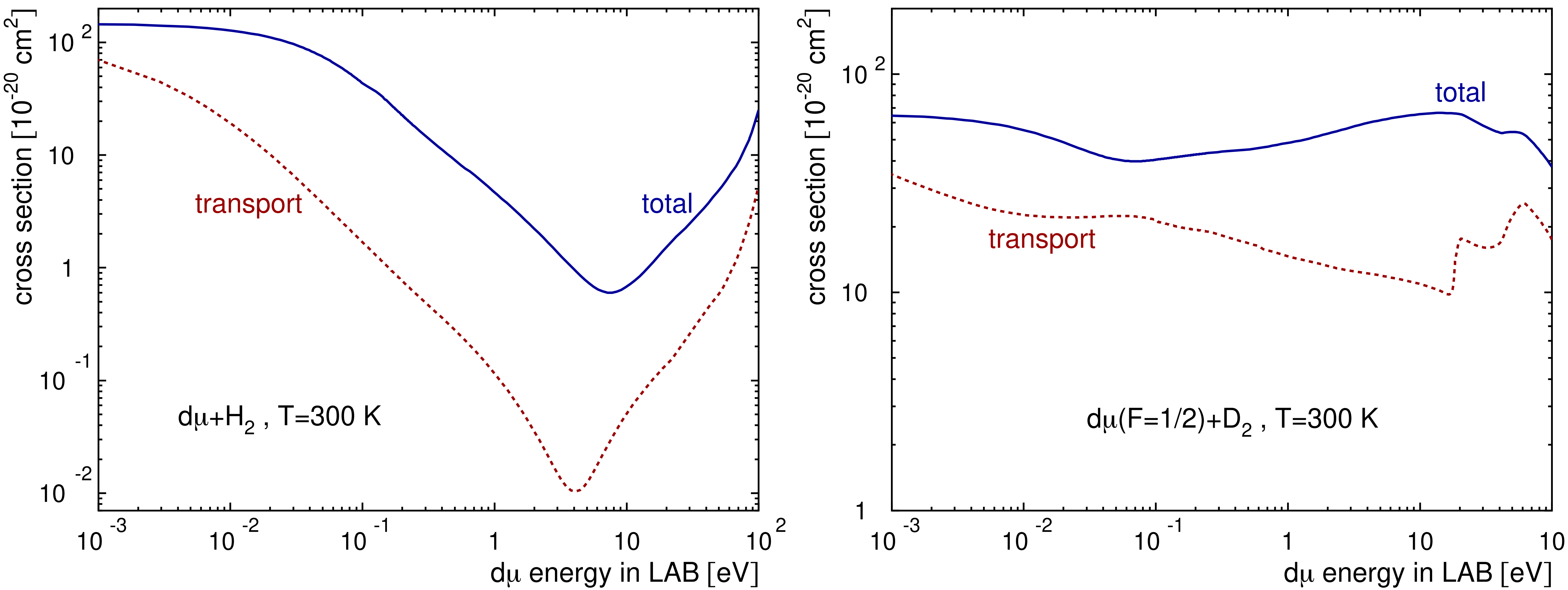
Bergem et al., PRC **37**, 2821 (1988)

Ramsauer-Townsend effect



- Quantum mechanical effect in the scattering transitions due to matching of muonic atom wavelength and scattering potential
- Hydrogen gas quasi-transparent for μd at 4 eV
- Transport cross-section: Taking into account angular dependence of cross-section; change in momentum proportional to transport cross-section

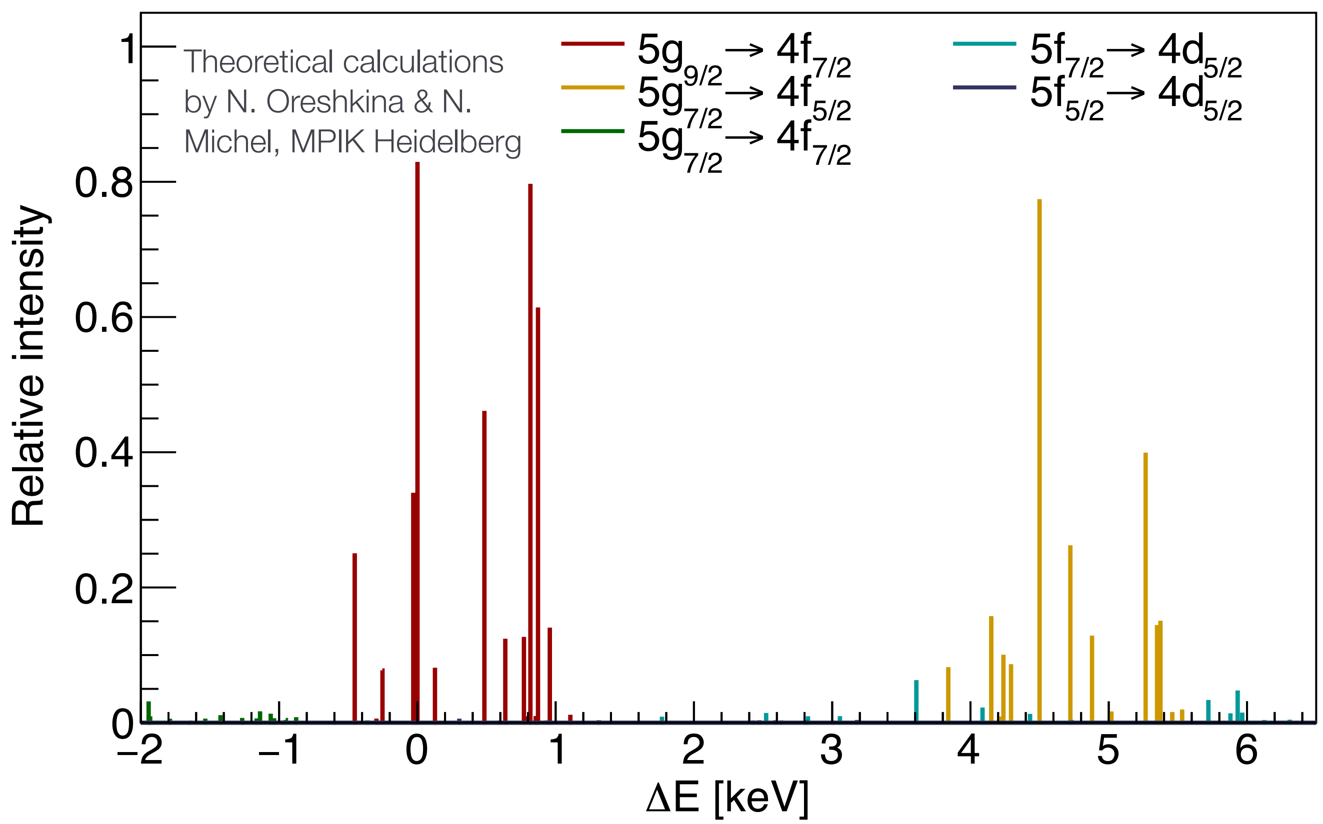
Scattering cross sections

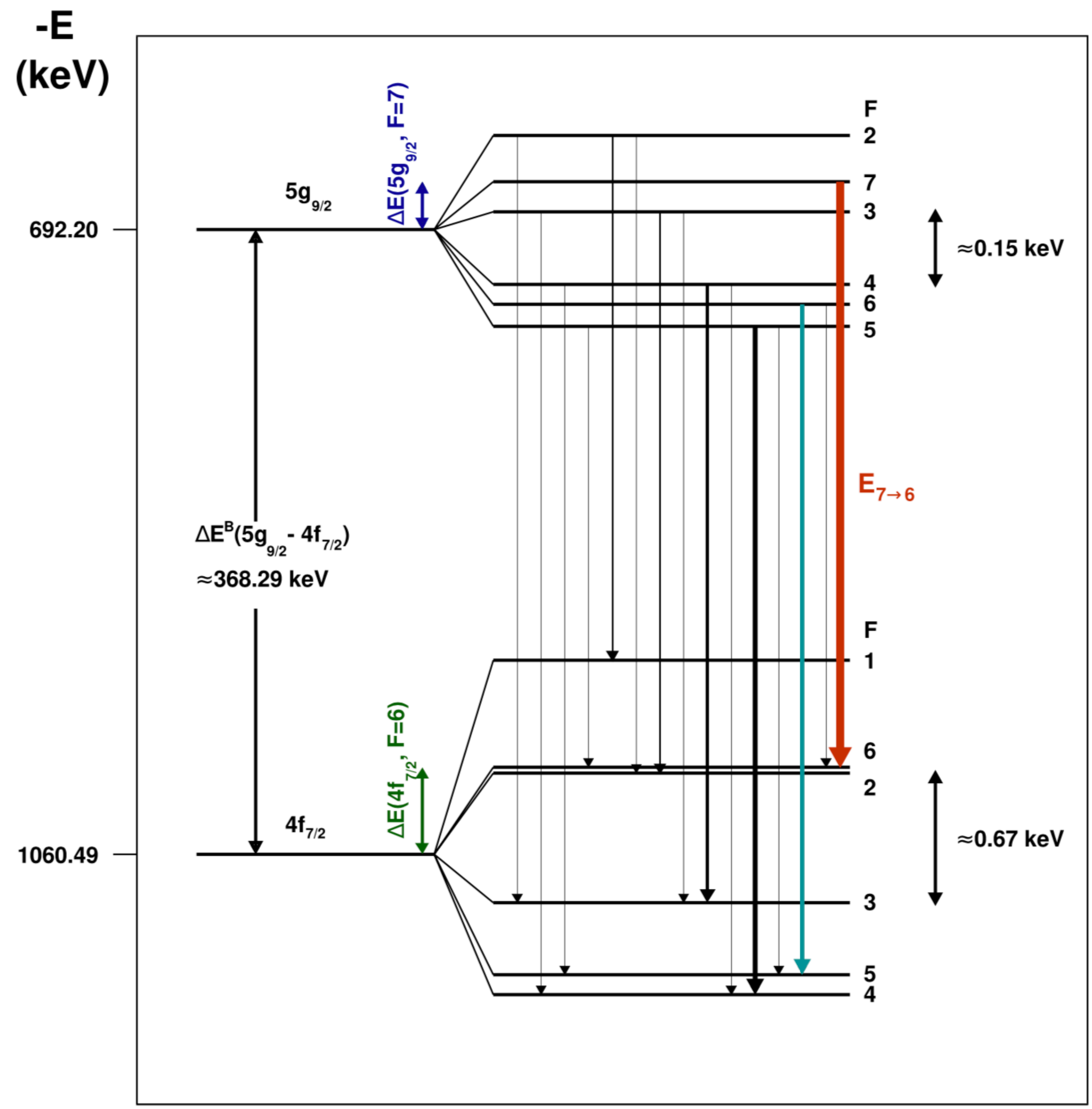


- Scattering on deuterium does not show a Ramsauer-Townsend minimum
- Need to be careful to not have too much deuterium in the gas mixture

Hyperfine splitting of 5g-4f transitions

- 5 transitions split into 76 transitions between hyperfine multiplets
- Quadrupole moment changes spacing and intensity of the various lines



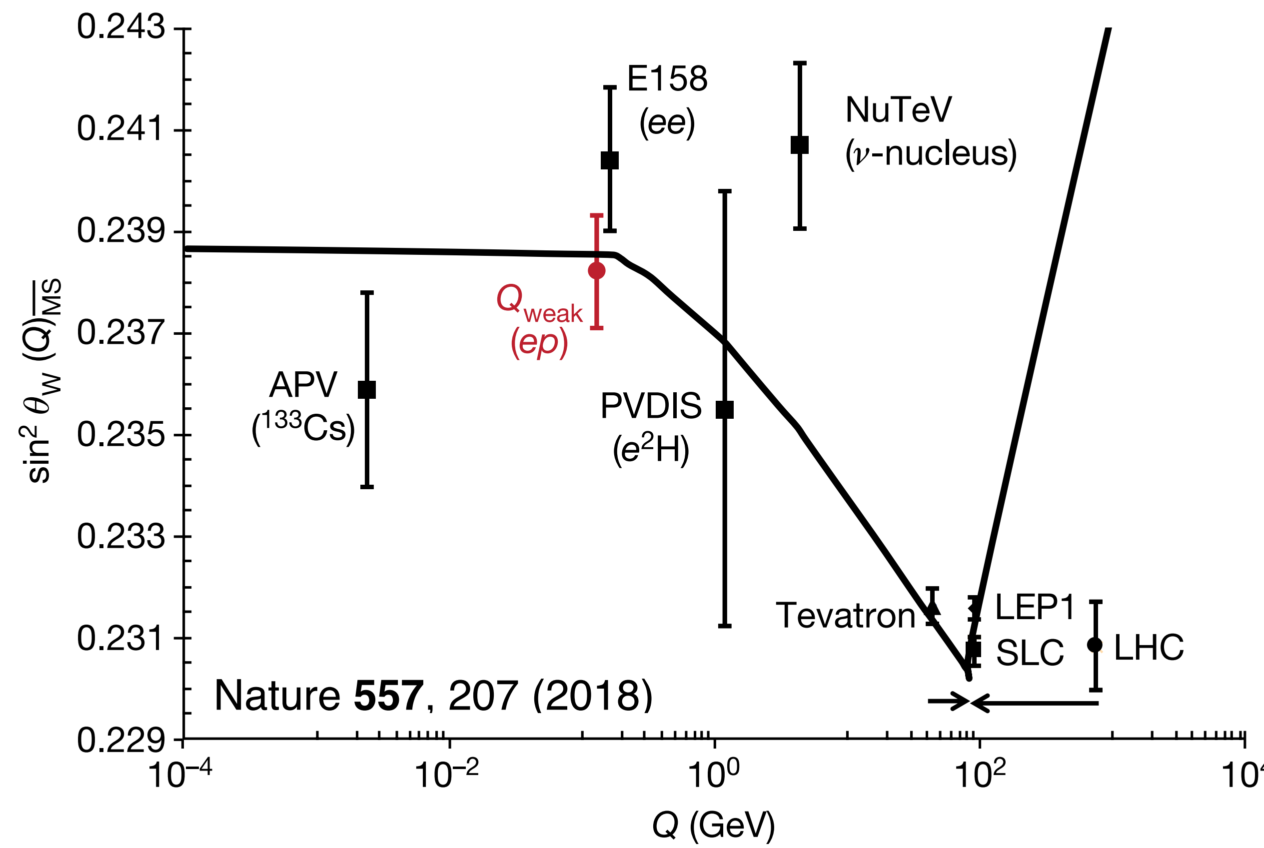


Atomic parity violation in radium

- Weak interaction leads to parity violating effects in atomic transitions
  → enhanced in heavy atoms ($\propto Z^3$) due to large overlap with nucleus

- Extract Weinberg angle using precision atomic calculations
  → Needs knowledge of the radium charge radius with 0.2% accuracy

- Weinberg angle comparable to α and m_e in electromagnetism



Atomic parity violation fixes weak interaction properties at low momentum

Discrepancies between the fitted and the measured transition energies

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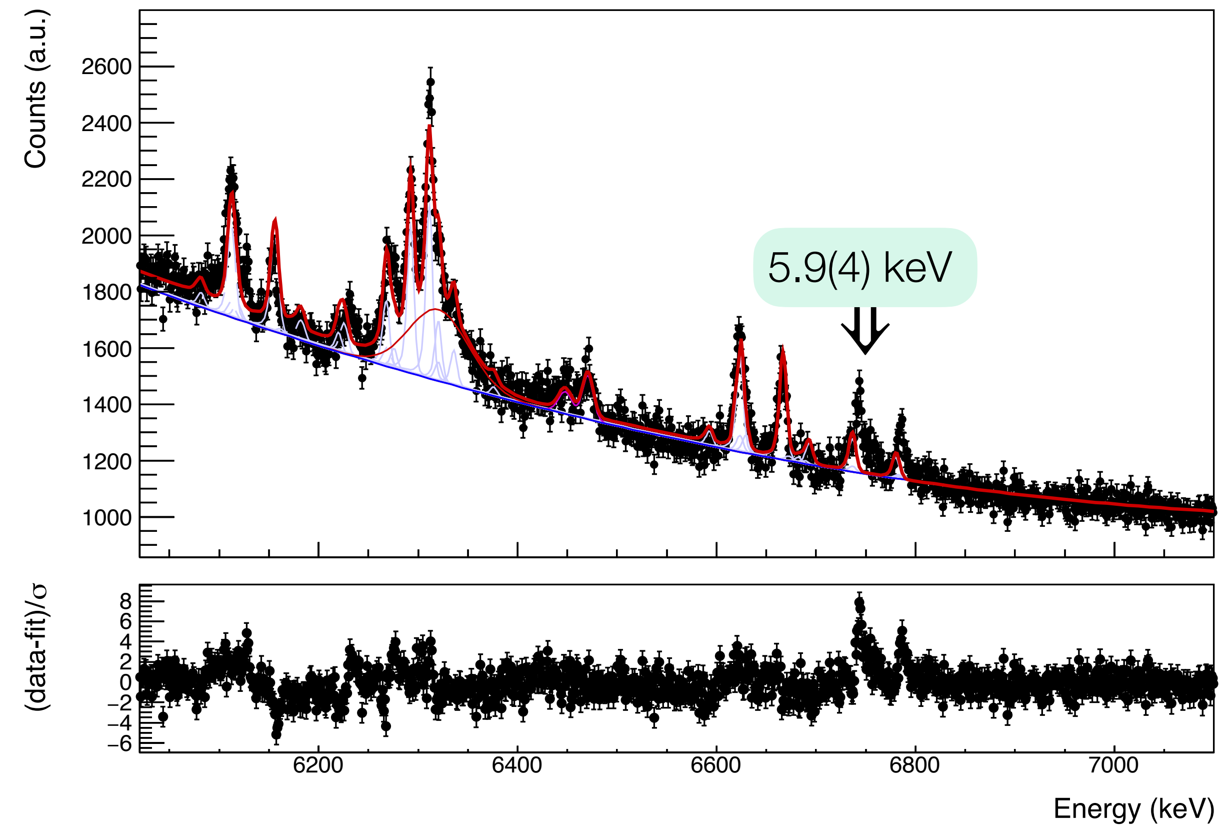
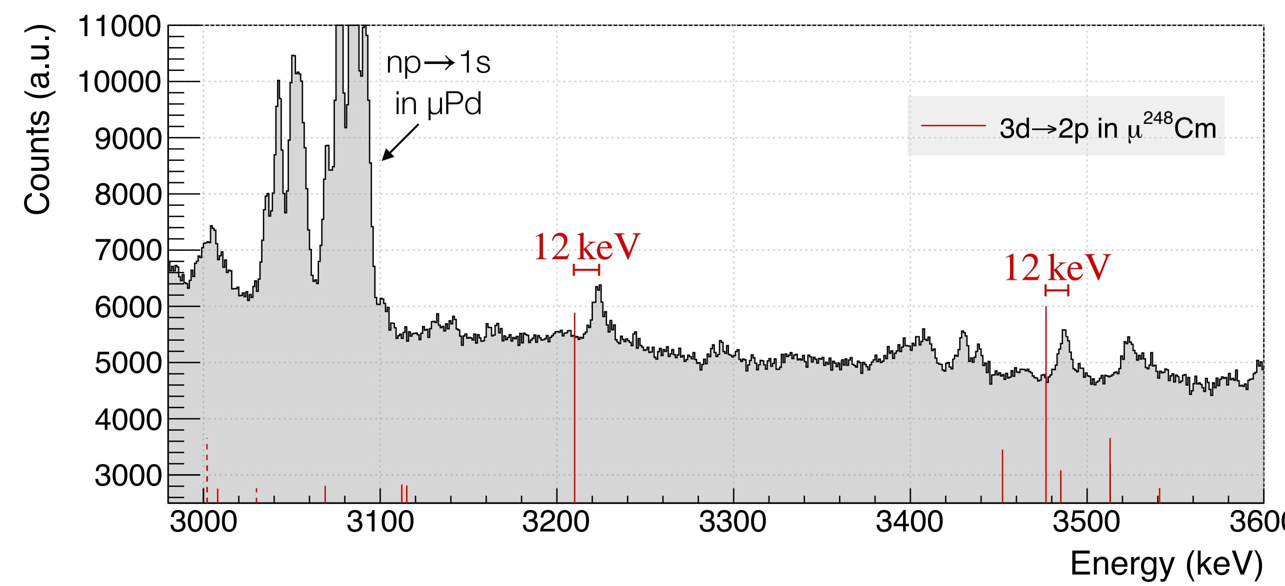
- 2p→1s: discrepancies between the experimentally observed and the fitted transitions on the order of 5.9 keV are observed
- $\frac{R}{E}$ sensitivity $\sim 10^{-6} \frac{\text{fm}}{\text{eV}} \Rightarrow \sigma_{\text{dR}_{5.9\,\text{keV}}} \approx 0.00095$



- 3d→2p: using the dR and dQ results from the 2p→1s fit to plot the 3d→2p transitions

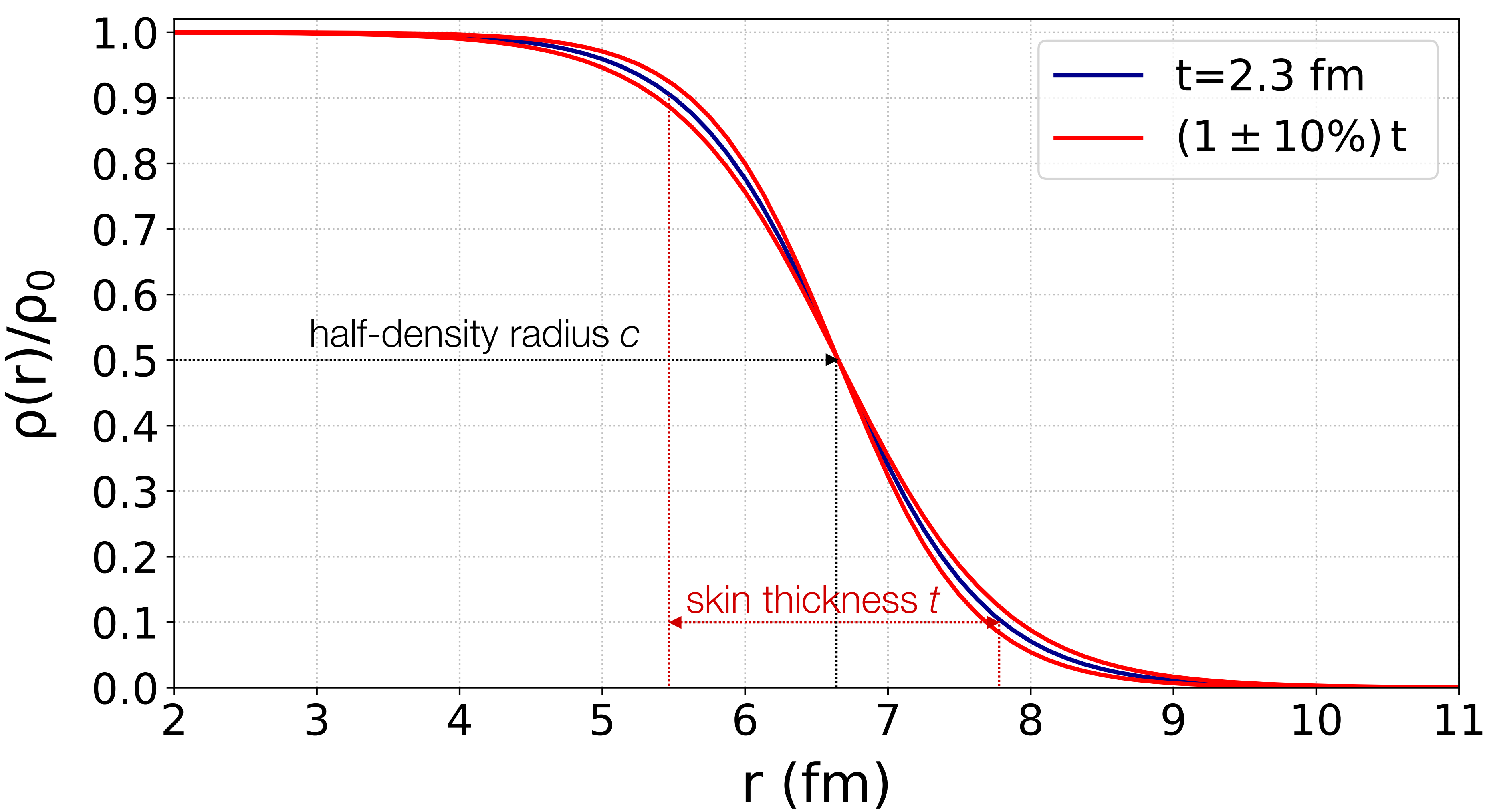
No effect on the charge radius due to the much reduced sensitivity in the 3d→2p



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

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

Charge distribution from nuclear structure calculations

^{248}Cm

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