The muX experiment: muonic atom spectroscopy with microgram target material

Andreas Knecht
Paul Scherrer Institute

for the muX collaboration

PSI2022 Satellite Workshop
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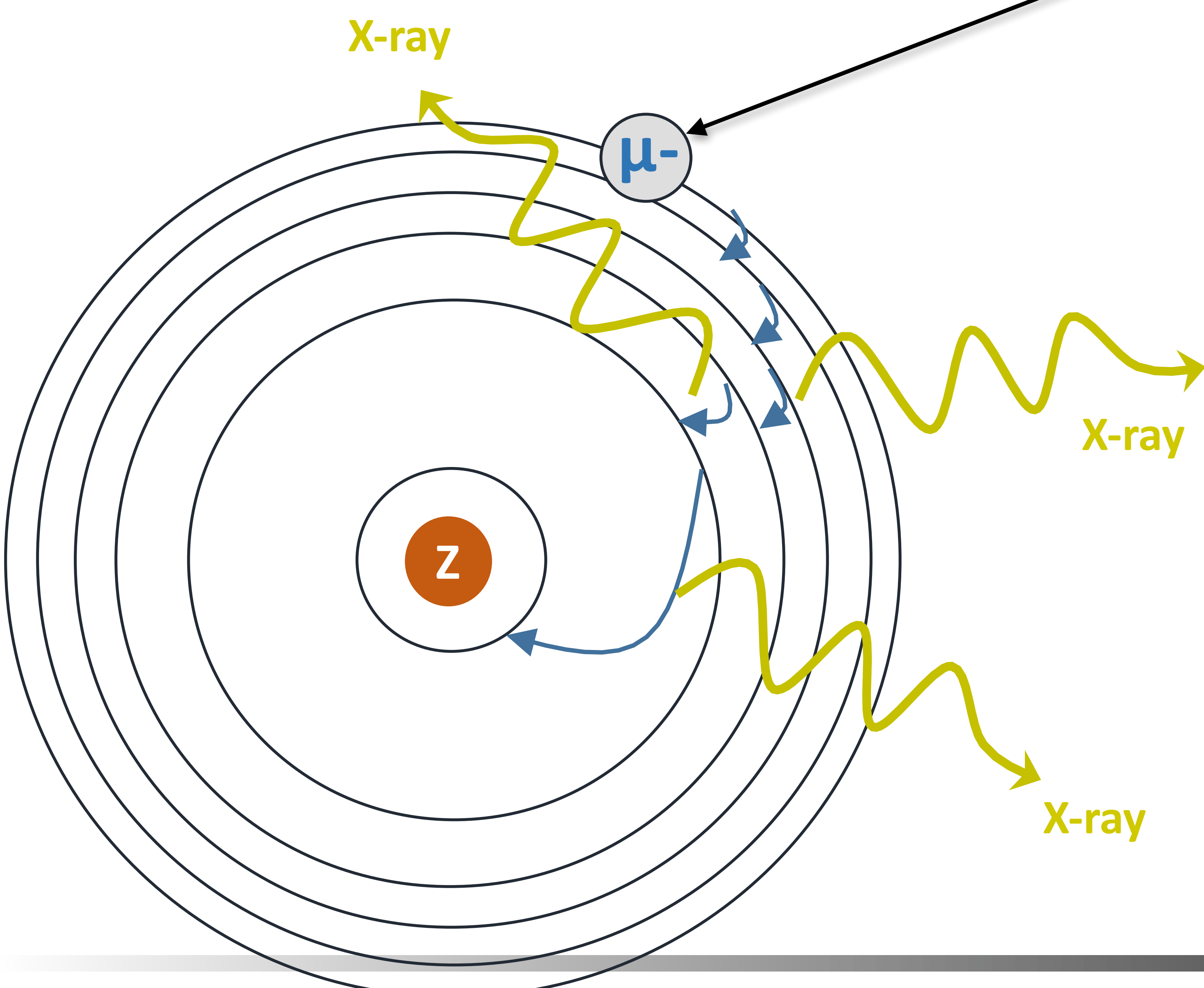
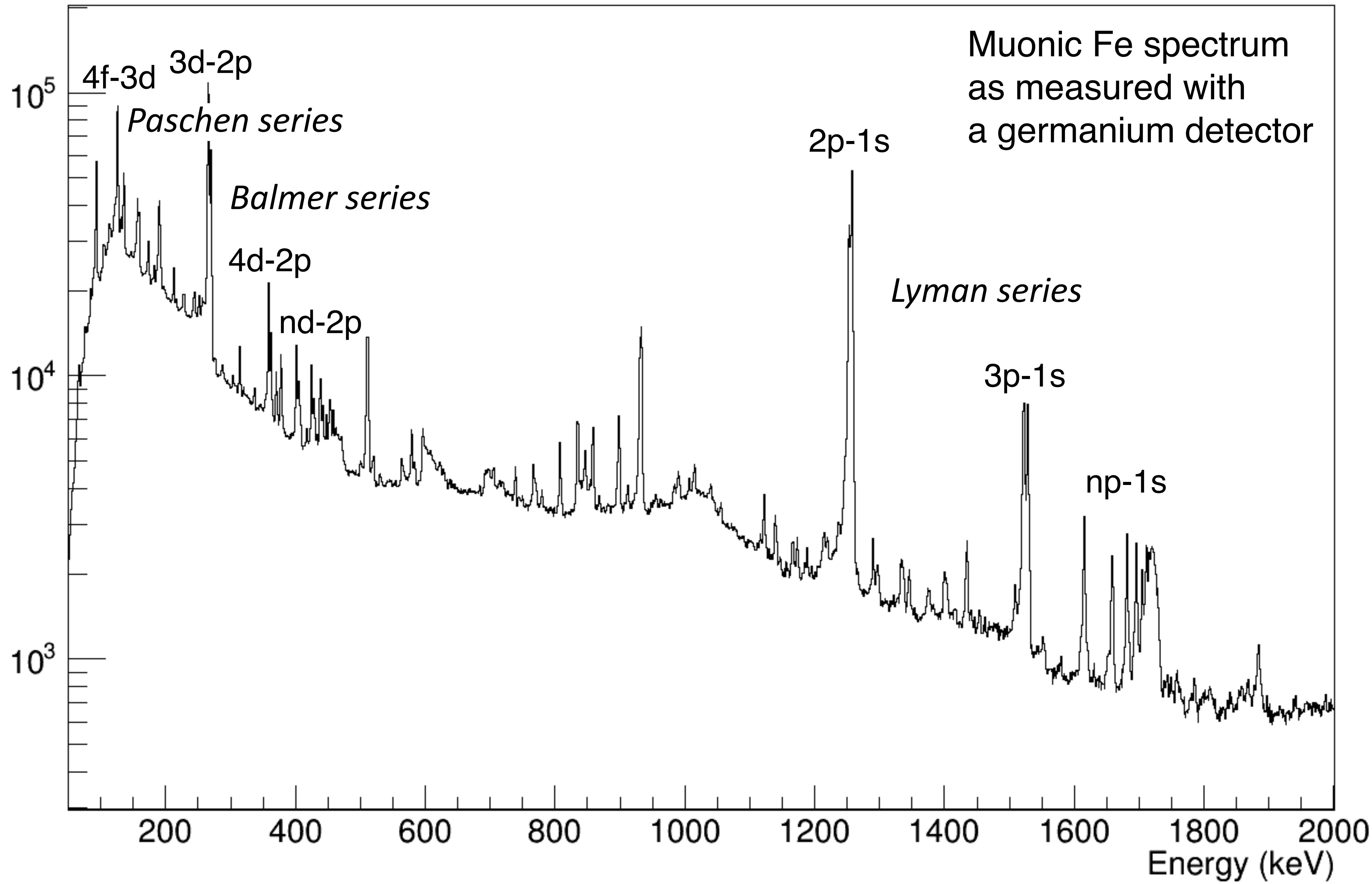
Passive muonic atom spectroscopy



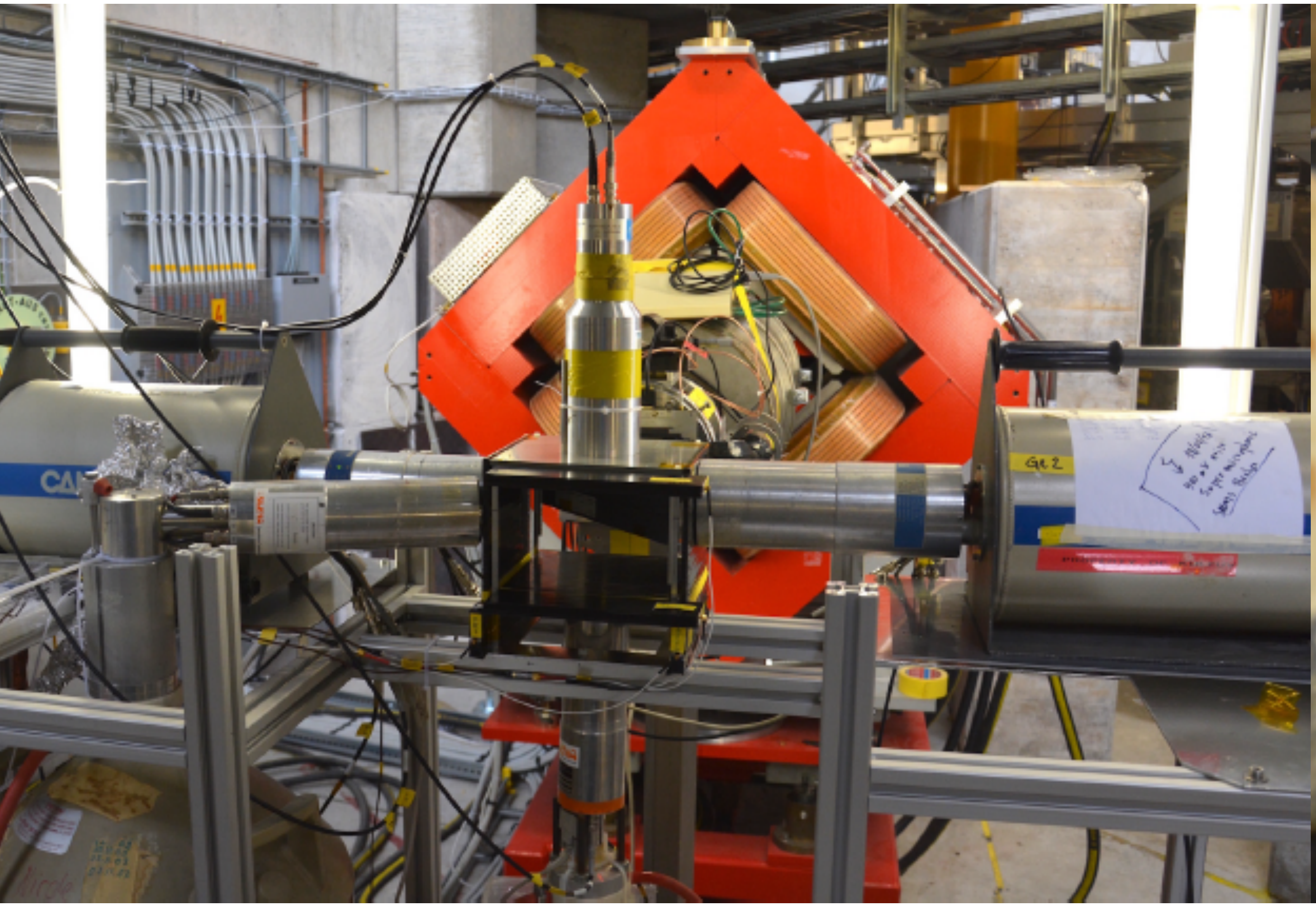
- Negative muons at rest quickly get captured by surrounding atoms
- Cascade down into 1s state emitting characteristic X-rays
- For heavy muonic atoms: X-rays have MeV energies

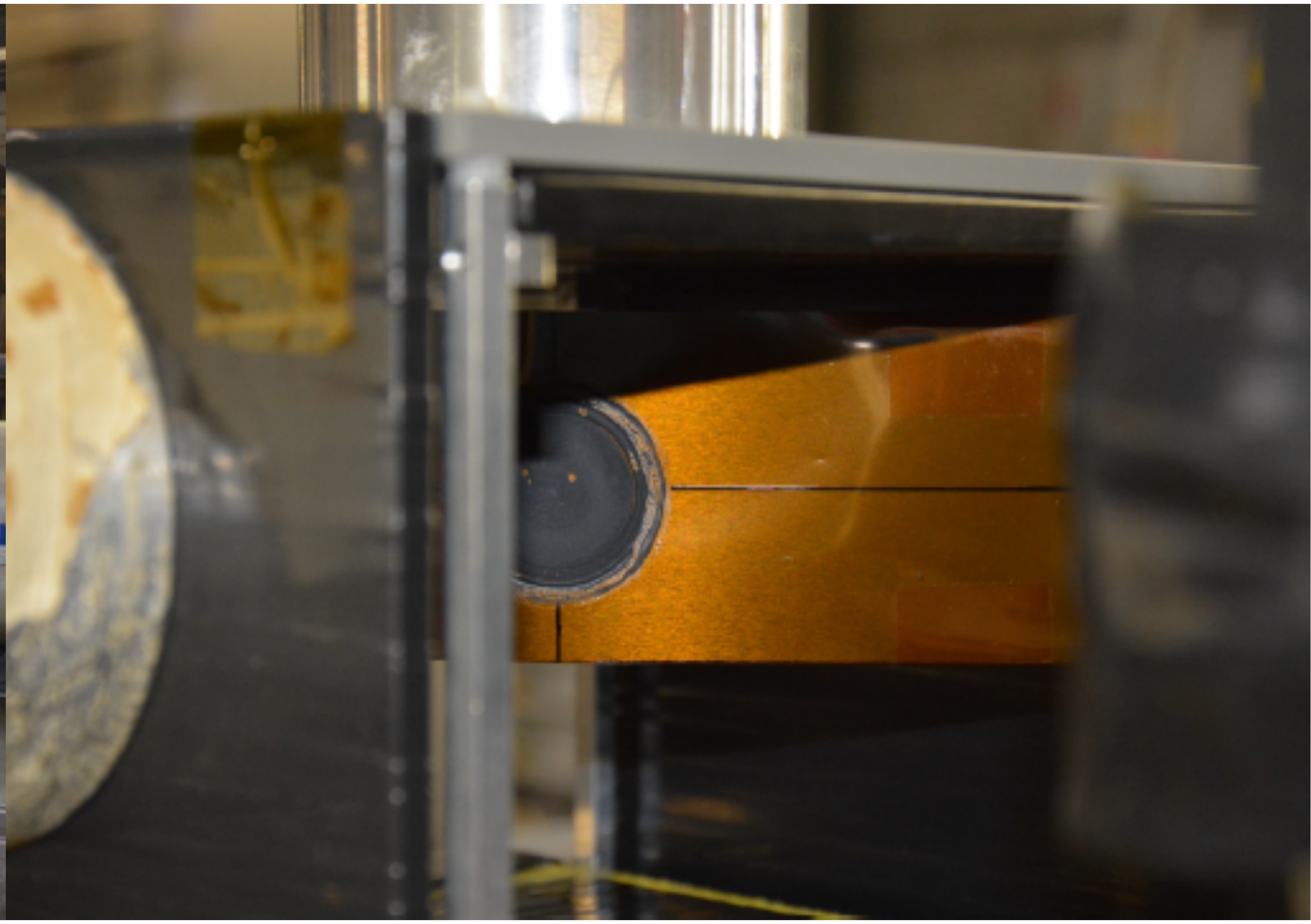
Muonic atom level scheme



Rhenium measurements

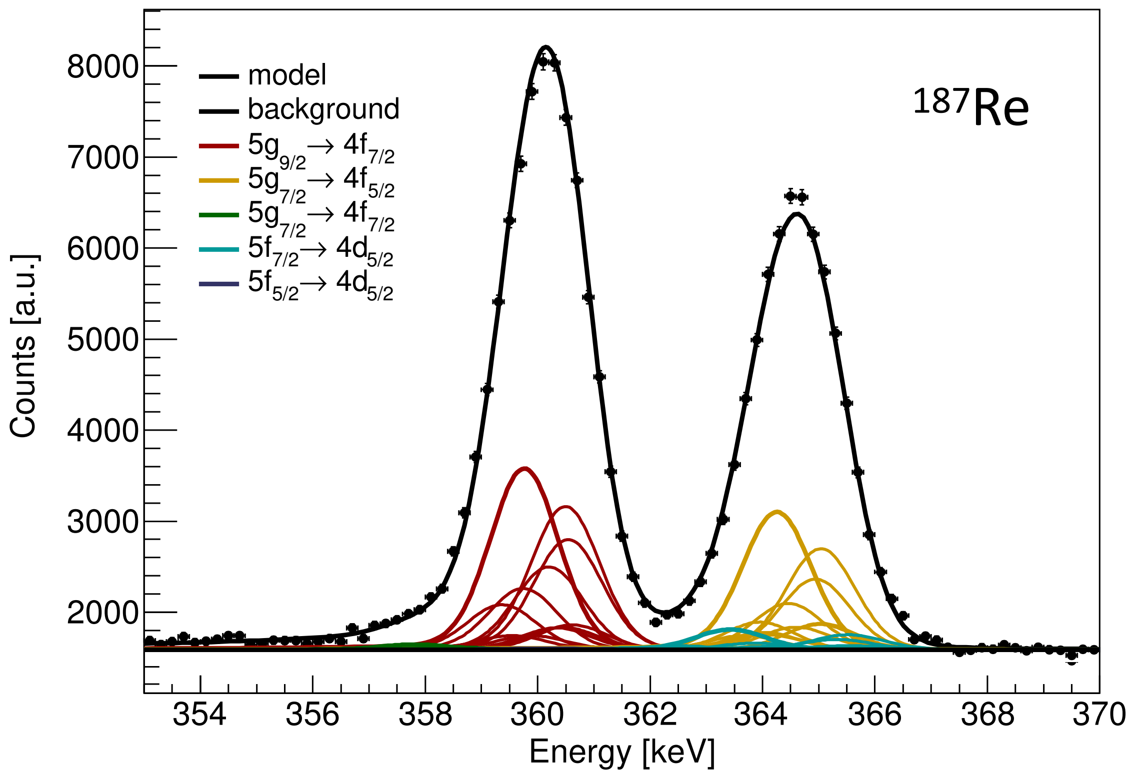
- The two rhenium isotopes ^{185}Re and ^{187}Re are the last stable isotopes without a measured, absolute charge radius
- Their ground states have spin I=5/2 → also have access to their quadrupole moment

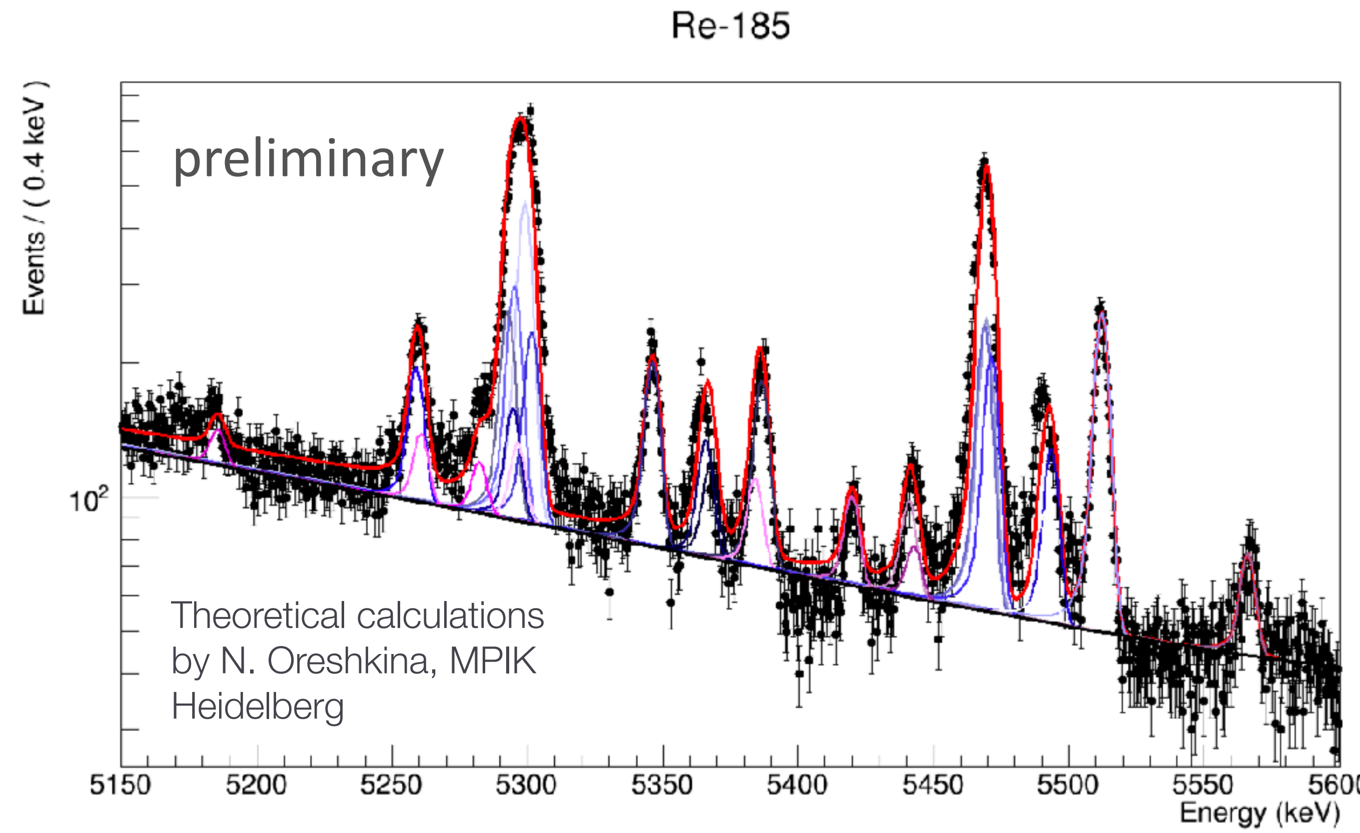




Rhenium results

Antognini et al., PRC **101**, 054313 (2020)





- Quadrupole moments of ^{185,187}Re extracted from the widening of muonic the 5g->4f transitions
- Working on the extraction of the charge radii from the 2p->1s transition

What about radioactive atoms?

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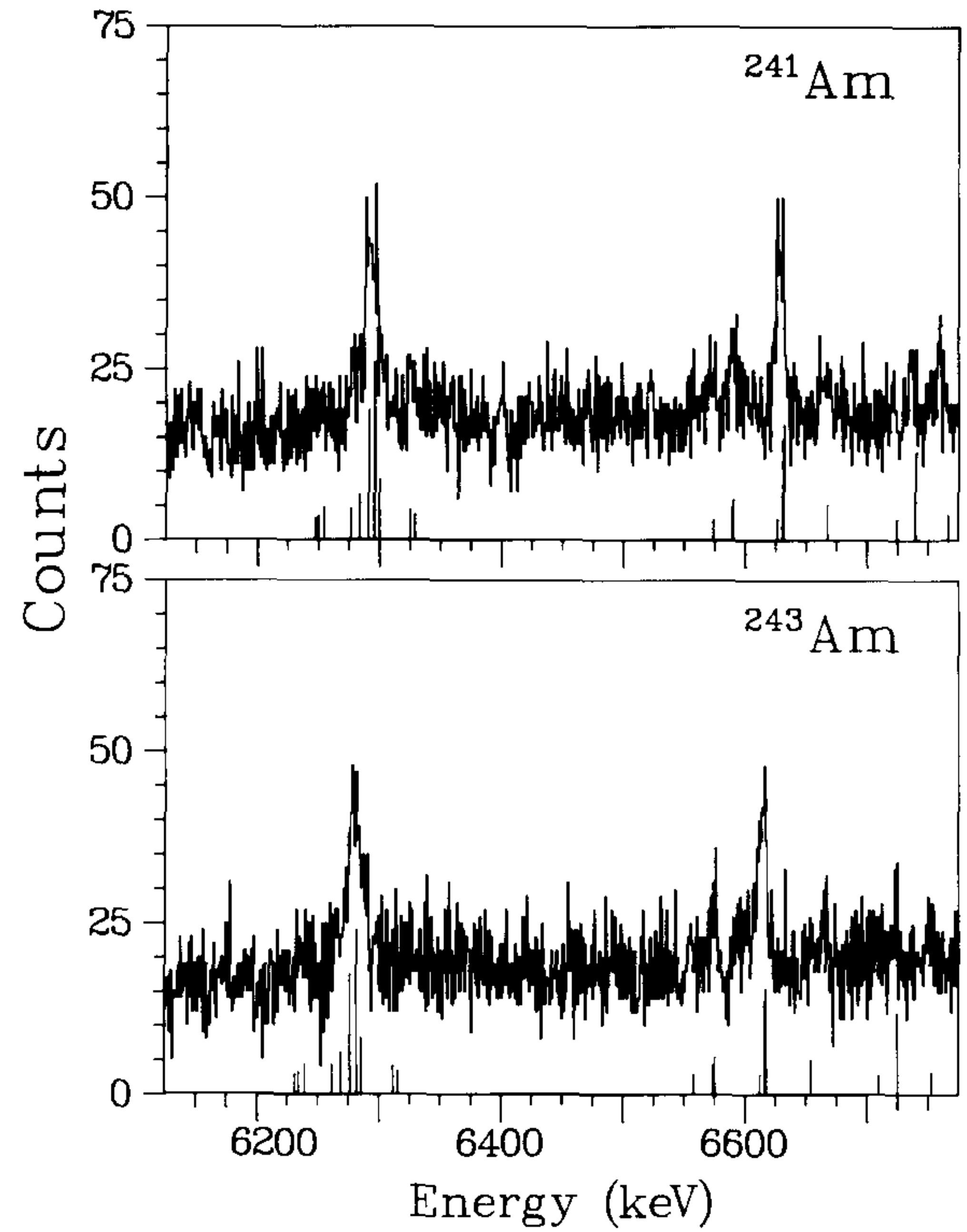
Johnson et al., Phys. Lett. **161B**, 75 (1985)

- 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…

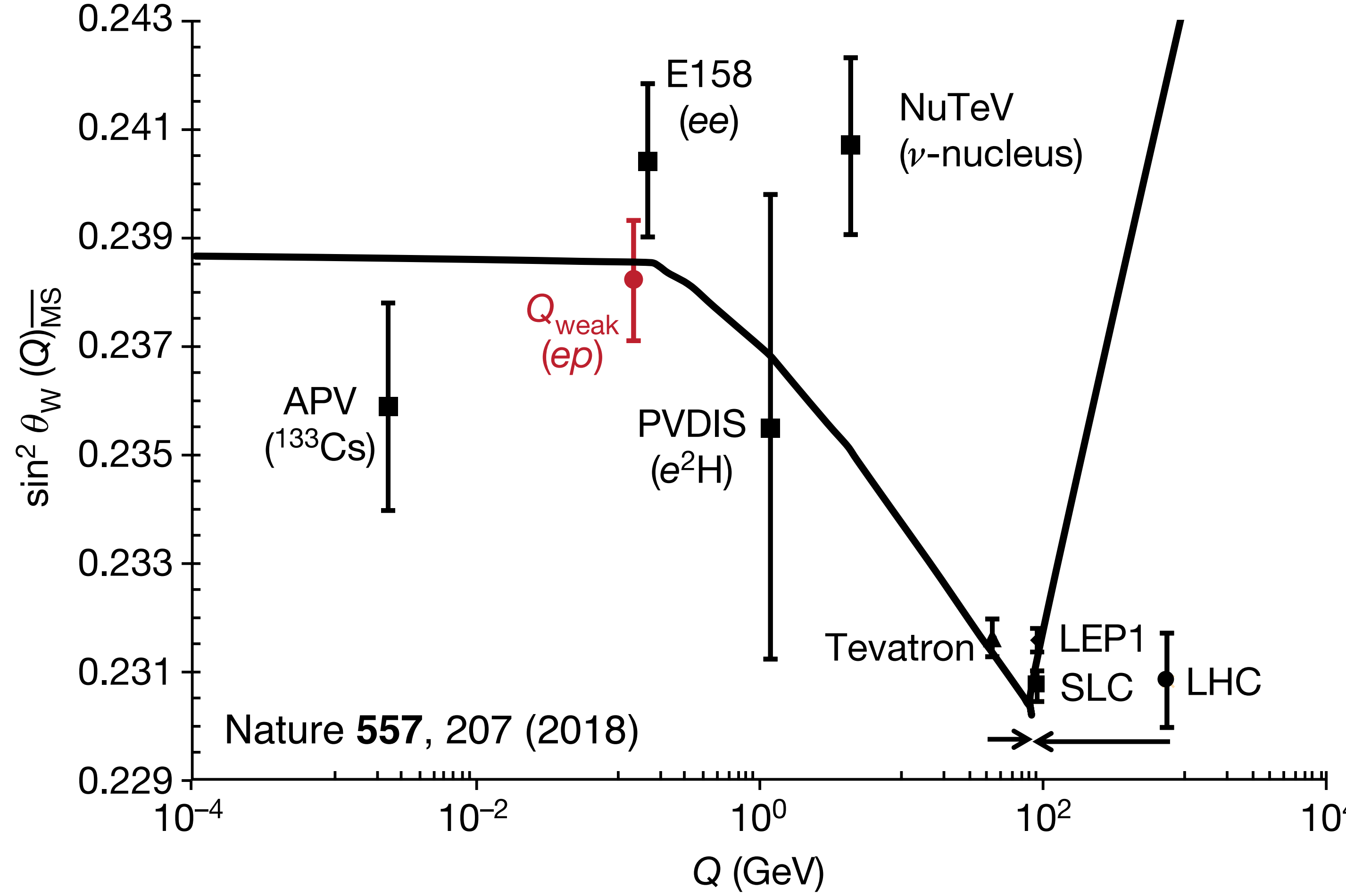


⇨ Cannot stop muons directly in microgram targets
Need new method!

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



Atomic parity violation fixes weak interaction properties at low momentum

Our radioactive targets

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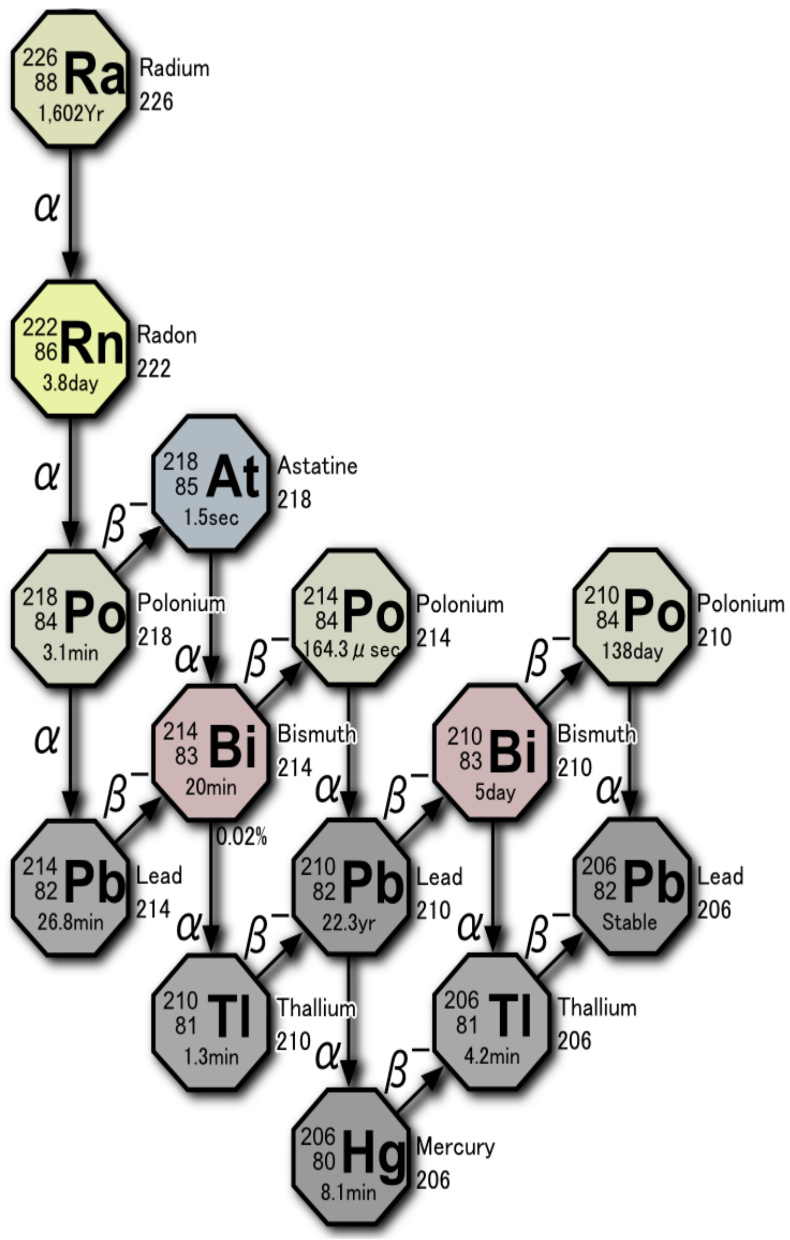
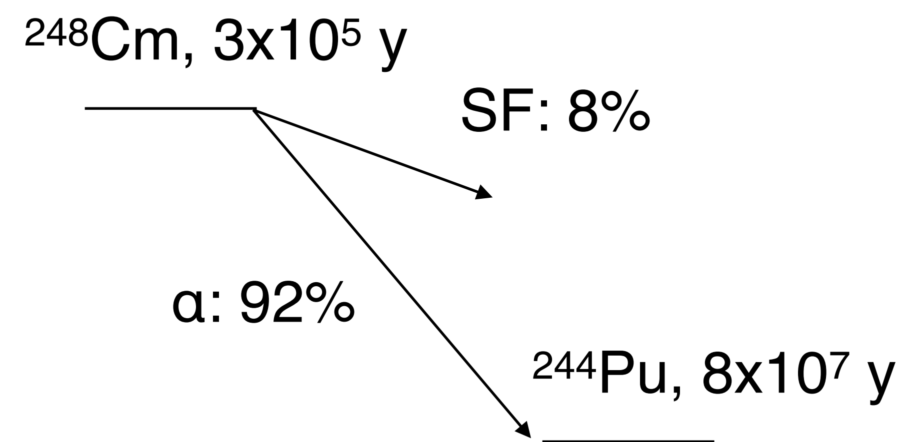


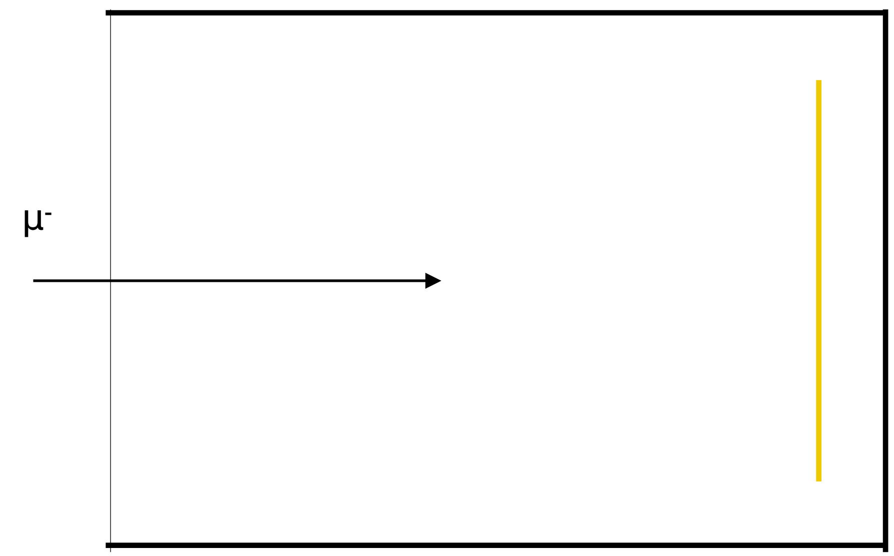


- 5.5 µg target material allowed
- Gamma rate of ~400 kHz from all daughters
- Interest from atomic parity violation

- 32.6 µg target material allowed
- Heaviest nucleus accessible

Transfer reactions

- Stop in 100 bar hydrogen 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.

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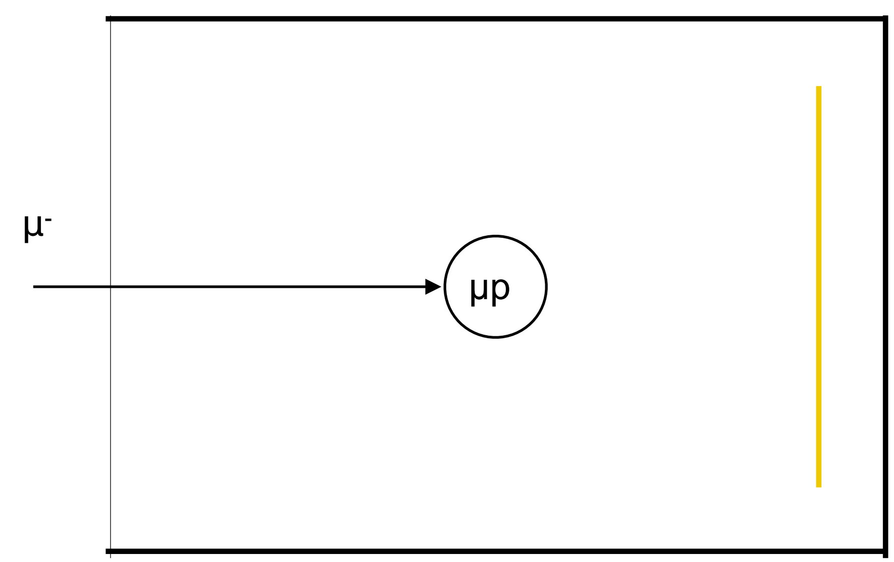

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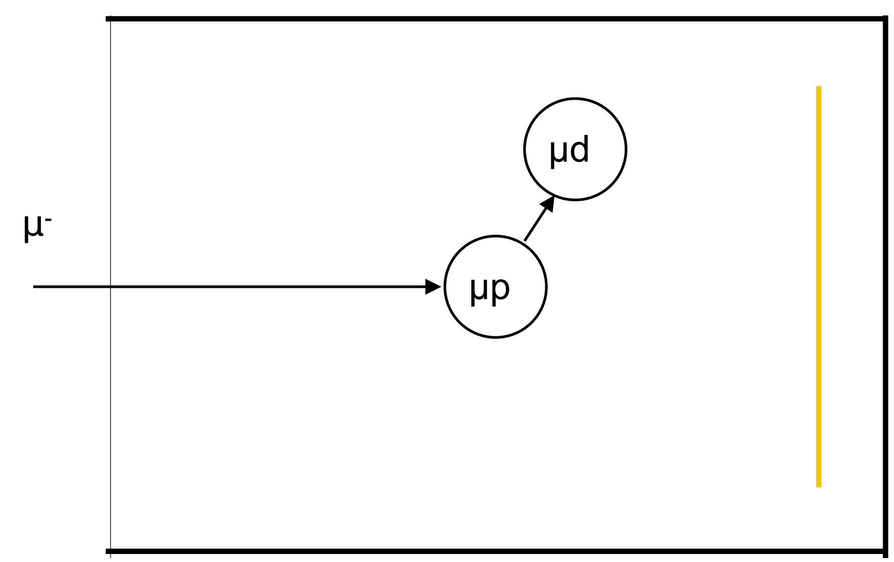

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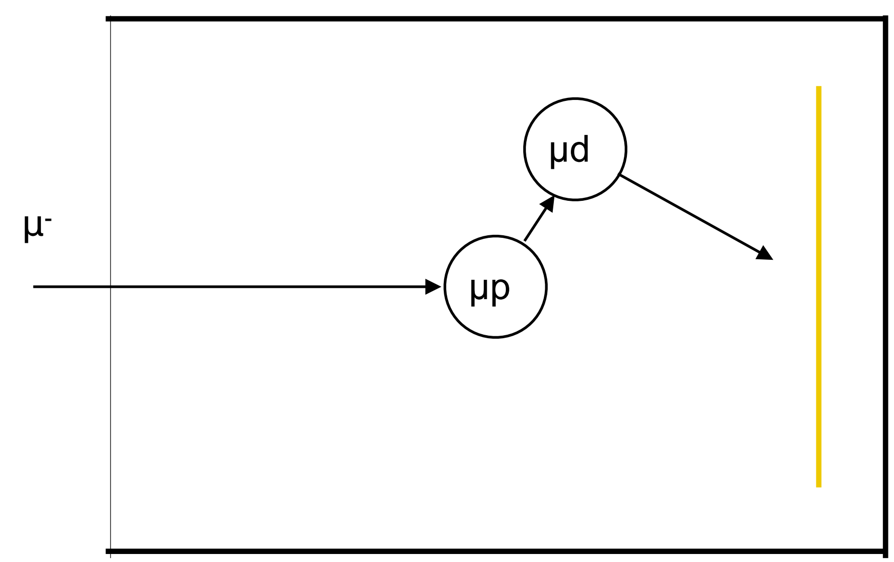

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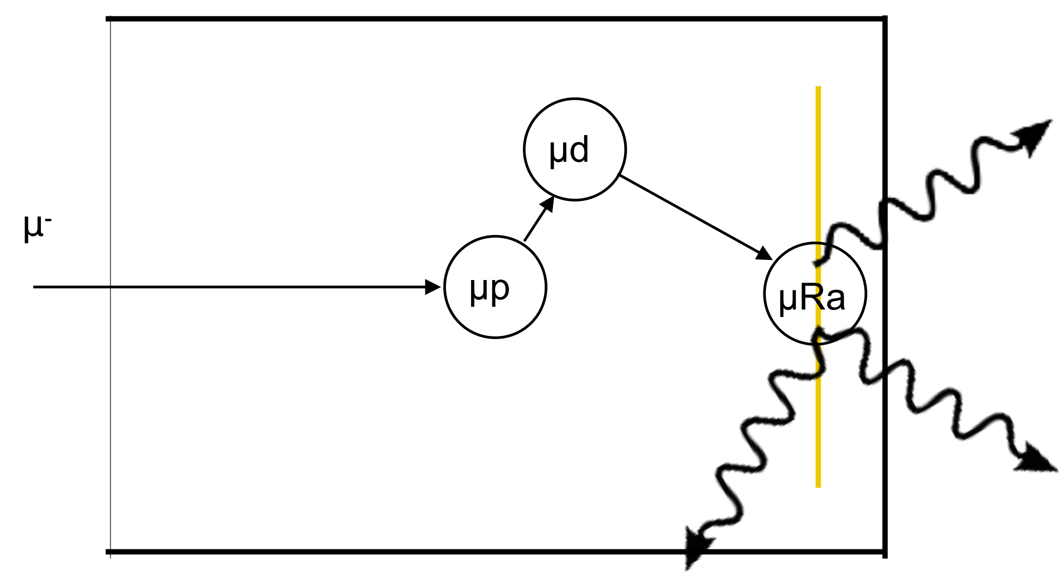

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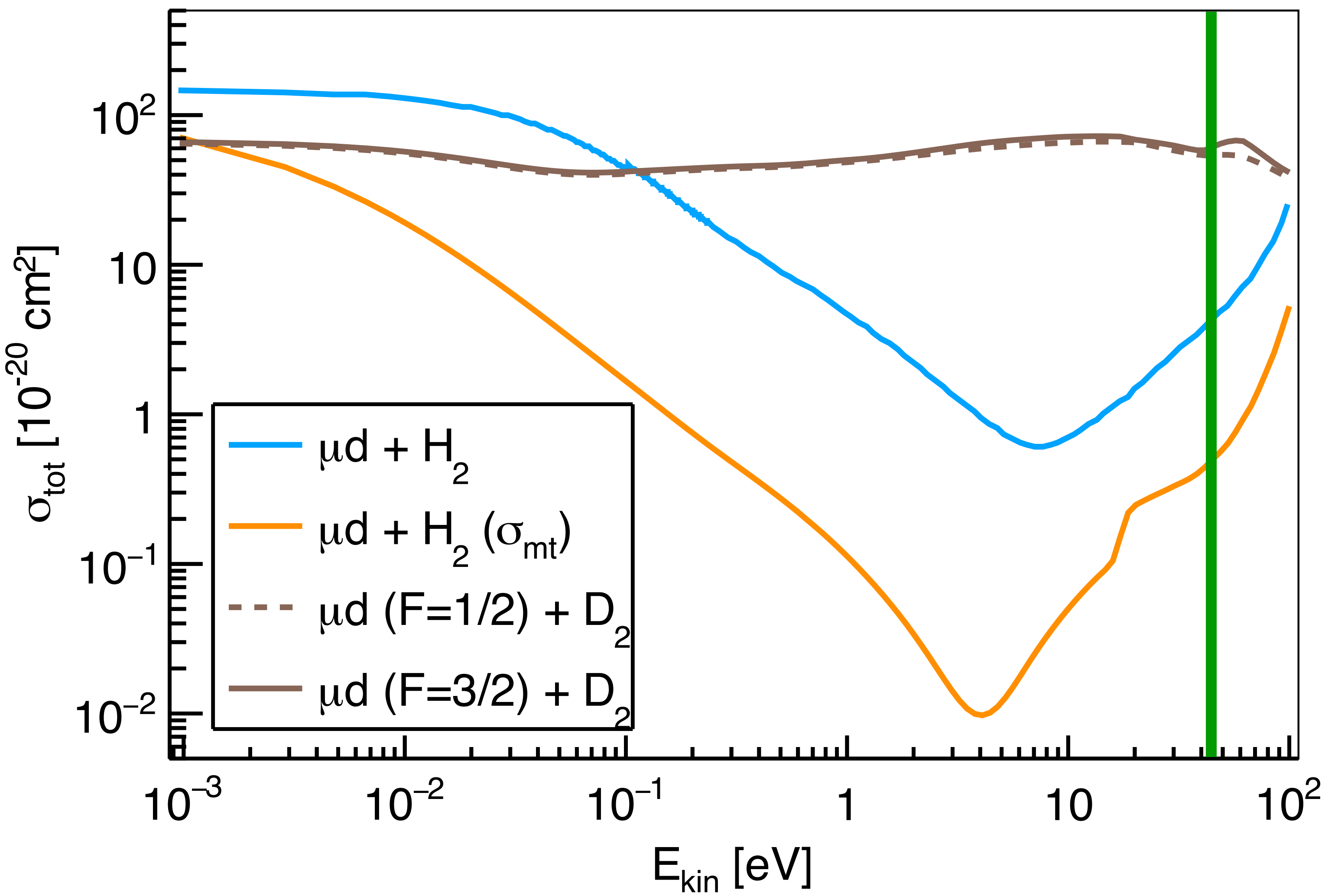
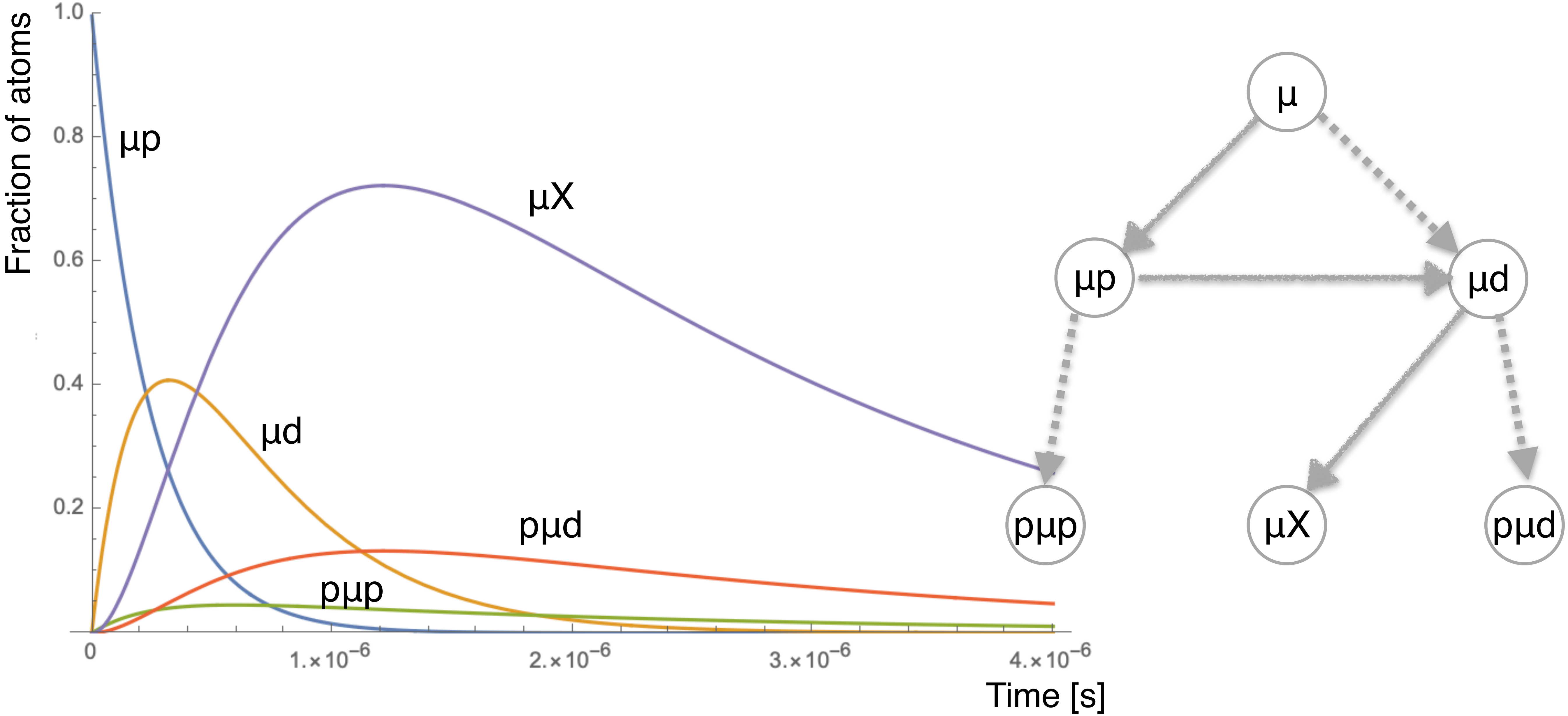
Ramsauer-Townsend effect



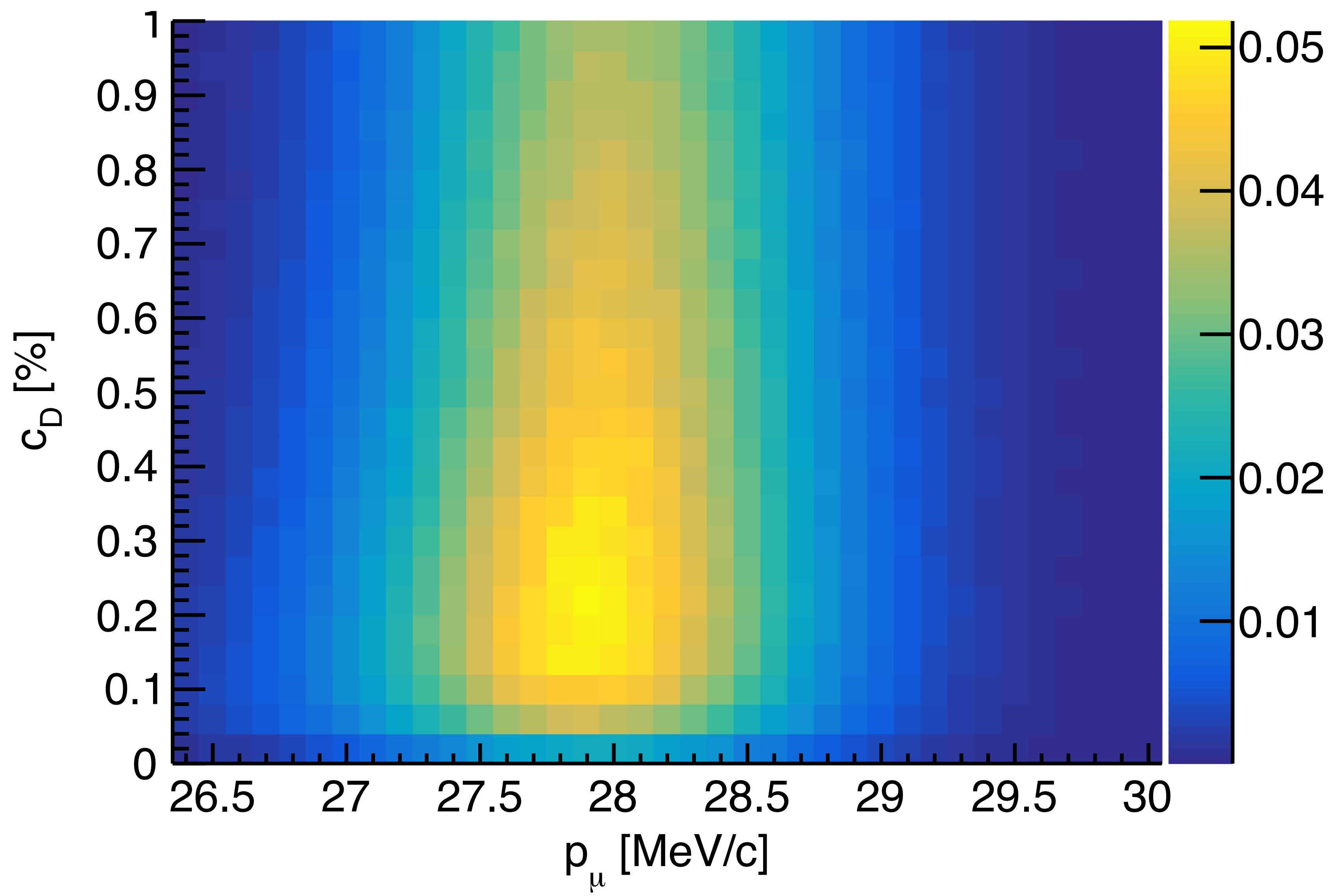
- Quantum mechanical effect in the scattering transitions due to matching of muonic atom wavelength and scattering potential
- Hydrogen gas quasi-transparent for μd at 4 eV
- No minimum in scattering on D_2 -> need to limit total D_2 concentration

Processes in gas cell



- Simplified time evolution of muonic atoms in gas cell by solving coupled differential equations
- Assumes single production rate of μX production → need Monte Carlo to take geometry and scattering into account

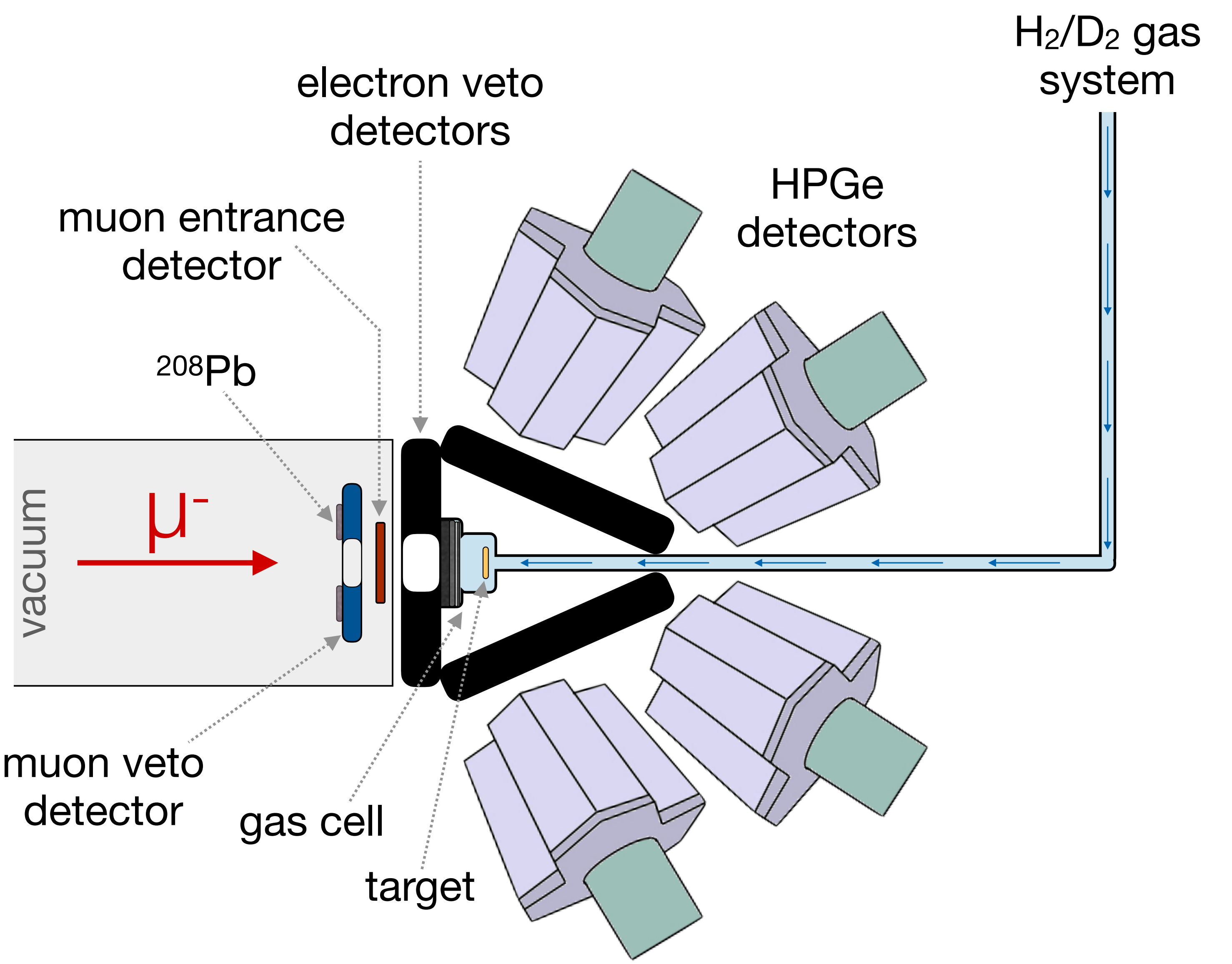
Simulation of transfer



- Developed simulation to predict efficiency of transfer
- Momentum of beam determines stopping distribution with respect to the target
- Deuterium concentration determines speed of transfer but limits range due to $\mu d + D_2$ scattering

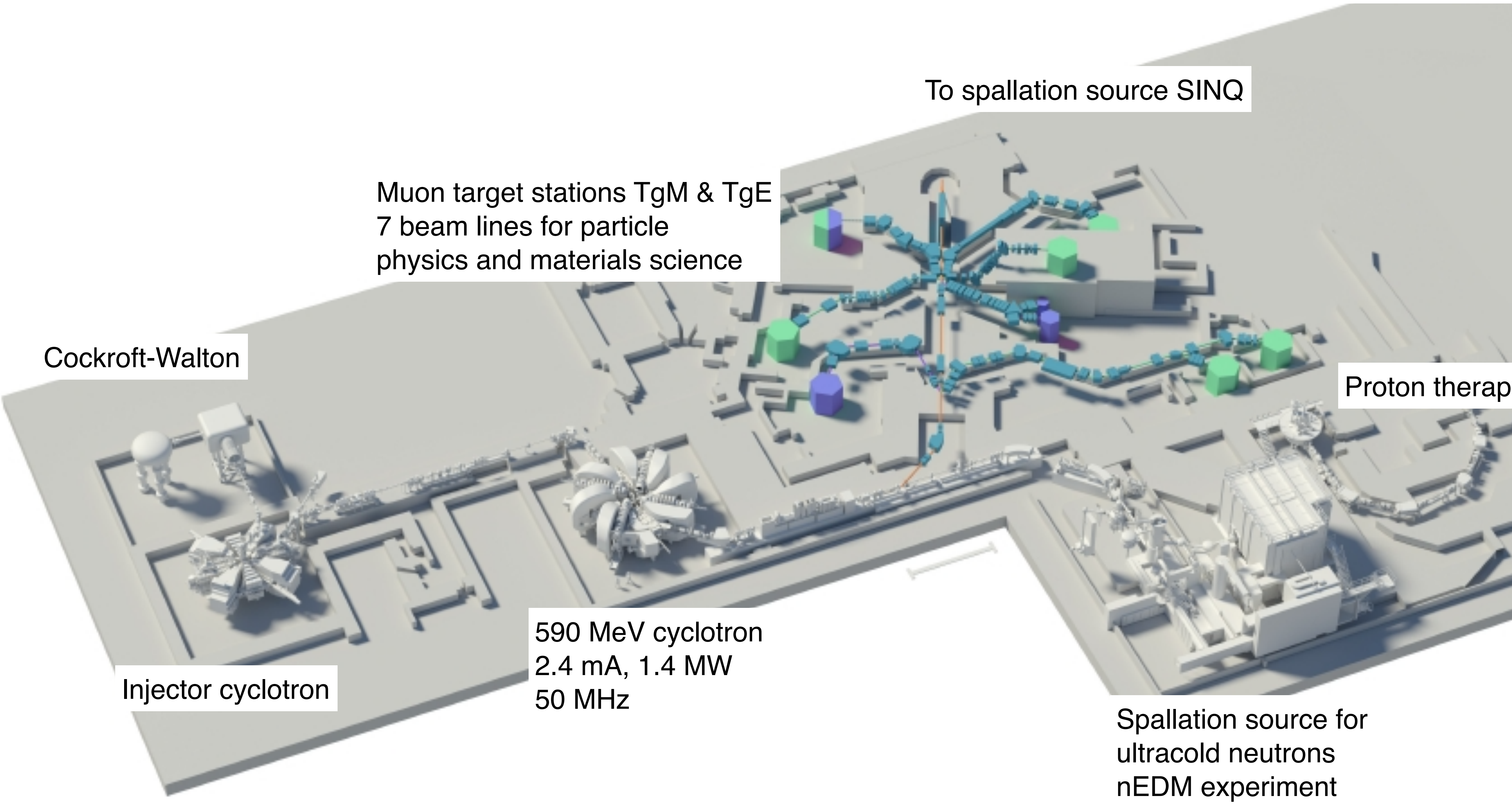
Setup

- Developed setup to perform muonic atom spectroscopy with microgram target material



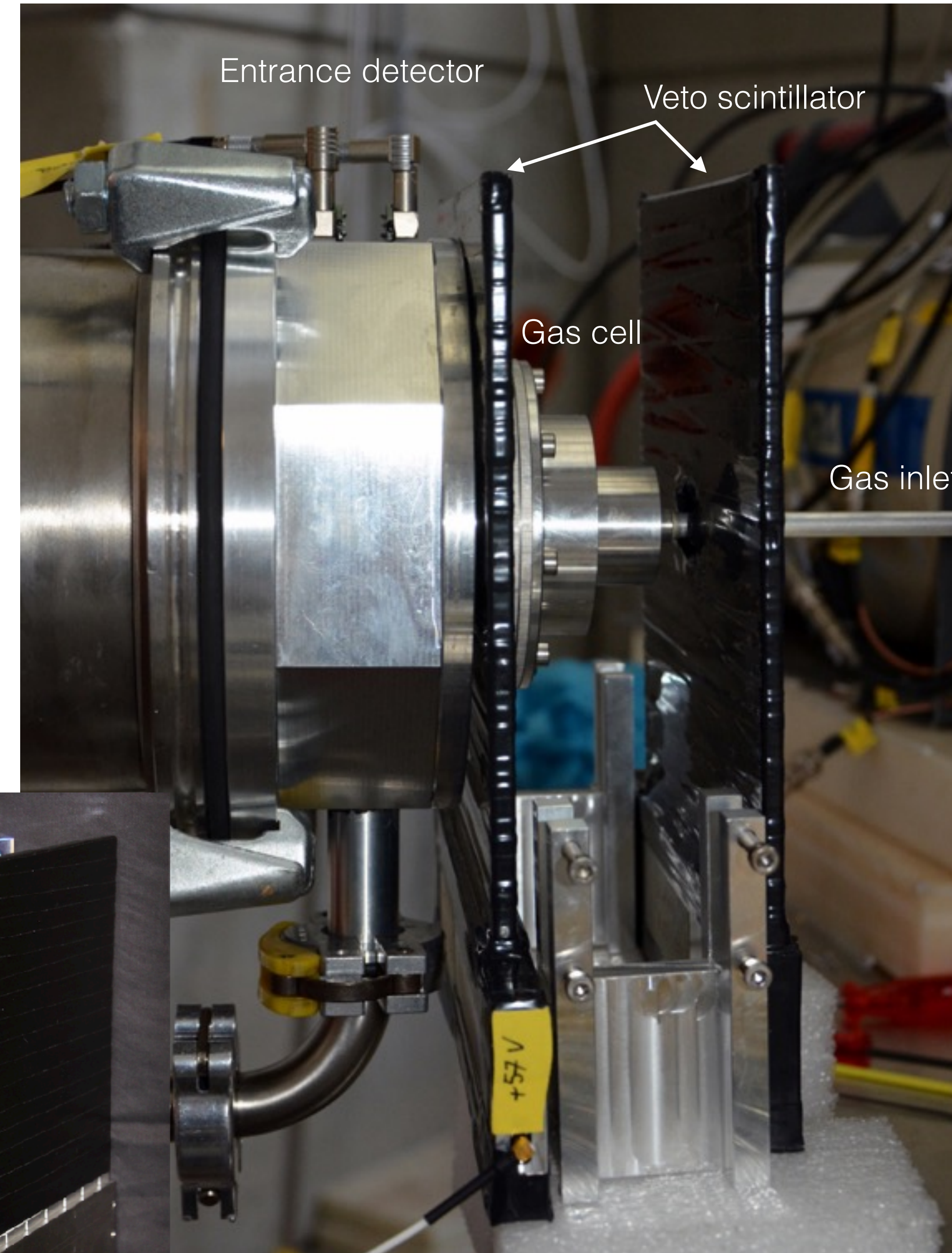
Adamczak et al., arXiv:2209.14365 (2022)

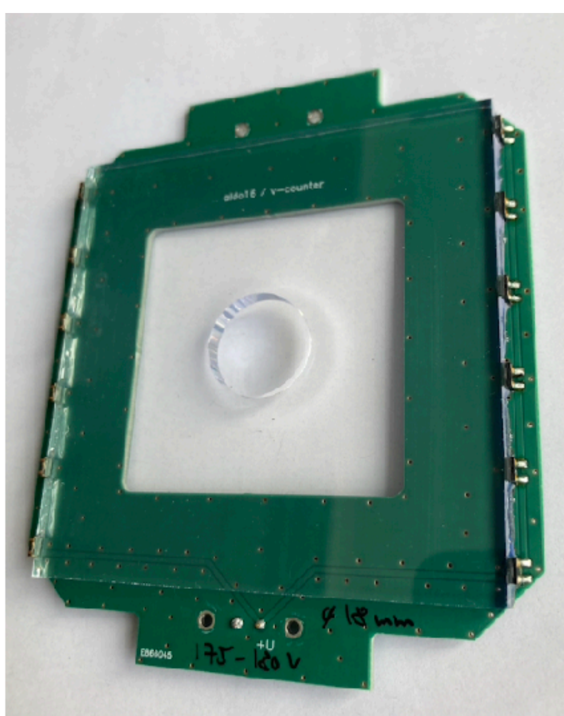
PSI Proton Accelerator HIPA

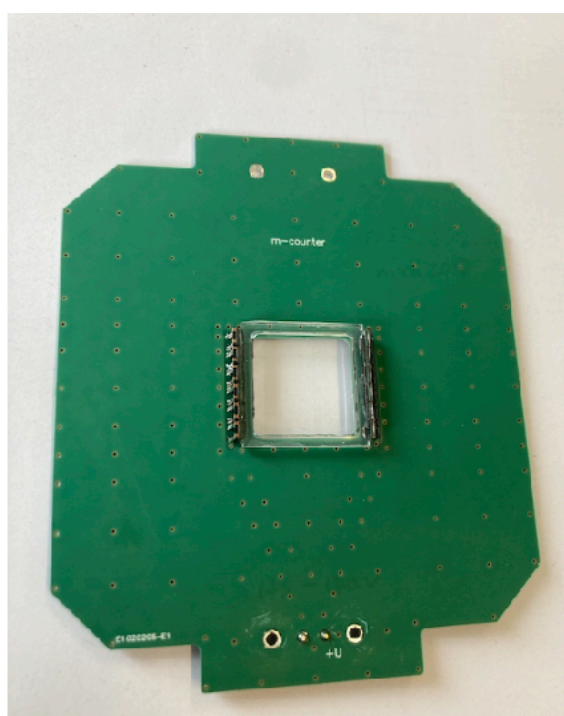


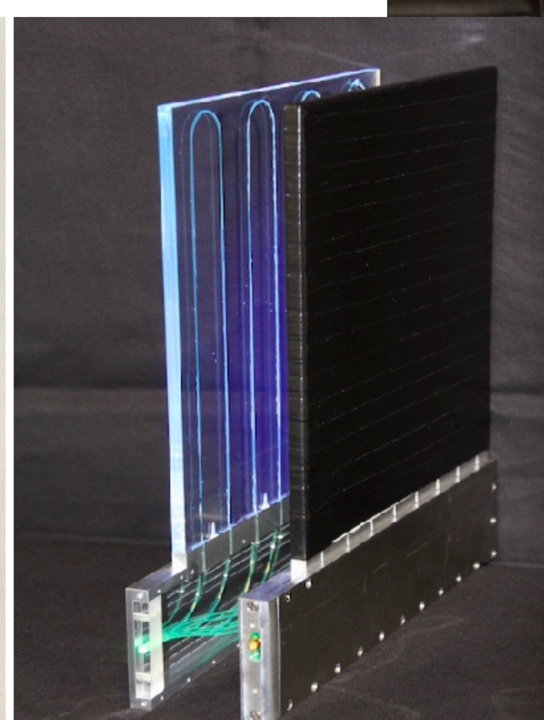
Entrance & veto scintillators

- Plastic scintillators used for entrance and veto detectors



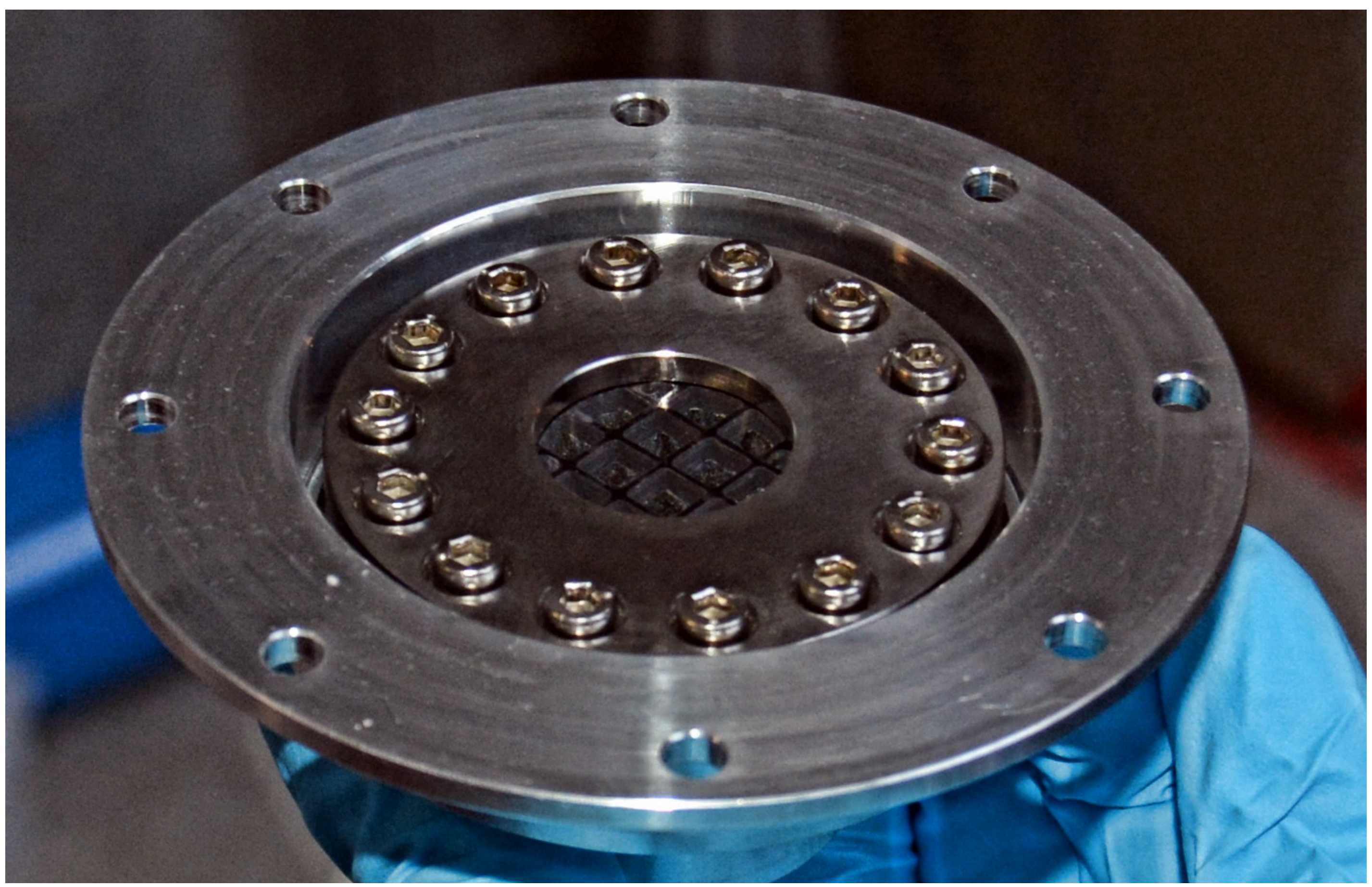


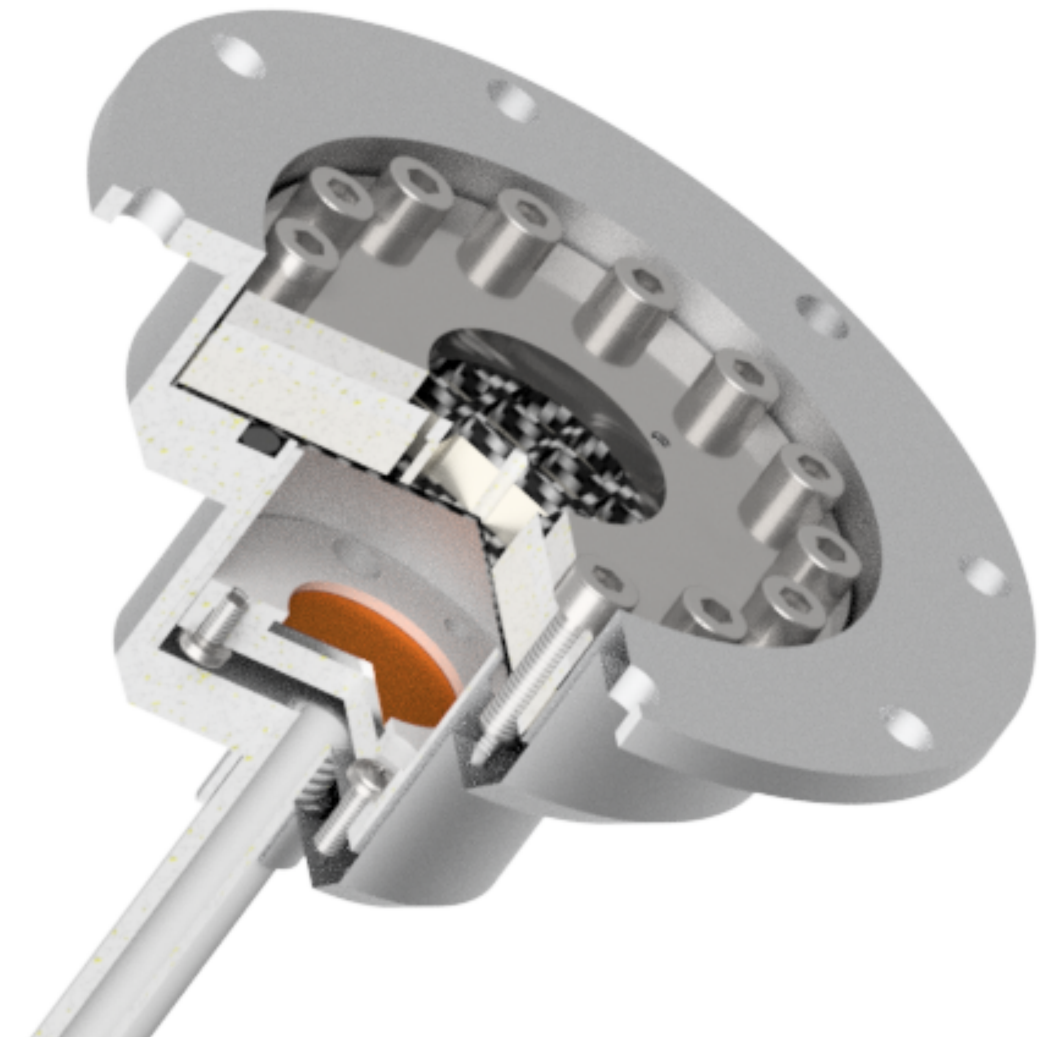




100 bar hydrogen target

- Target sealed with 0.6 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 at the back of the cell





Germanium detector array

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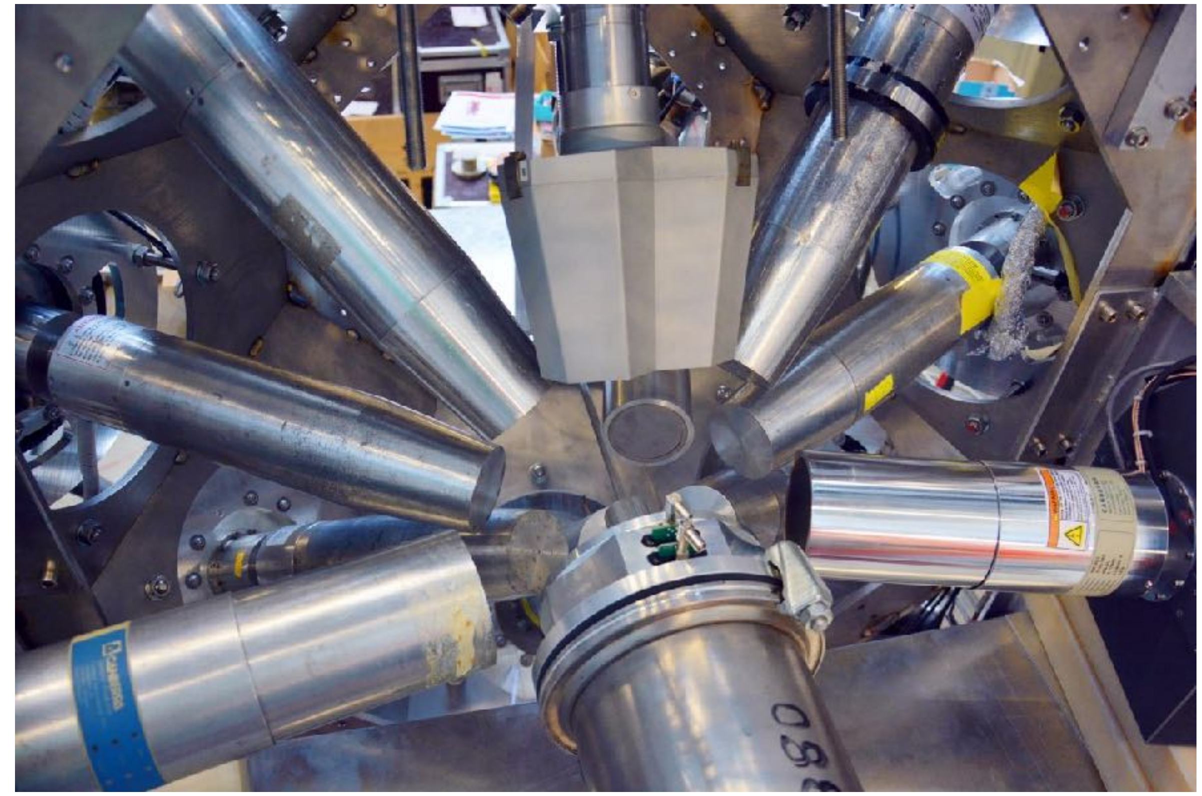
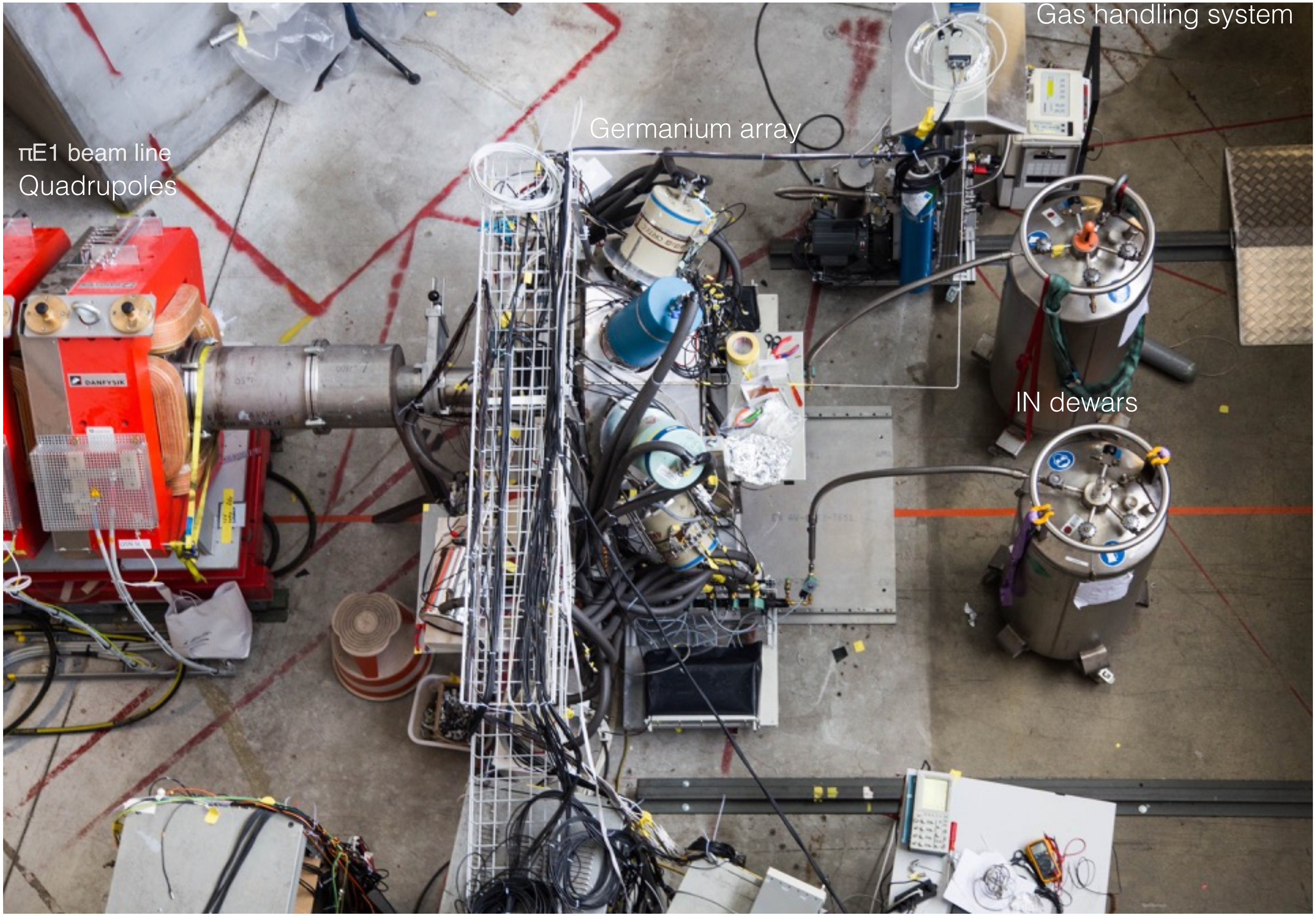
- 2017/2018
  - 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
  - First time a large array is used for muonic atom spectroscopy



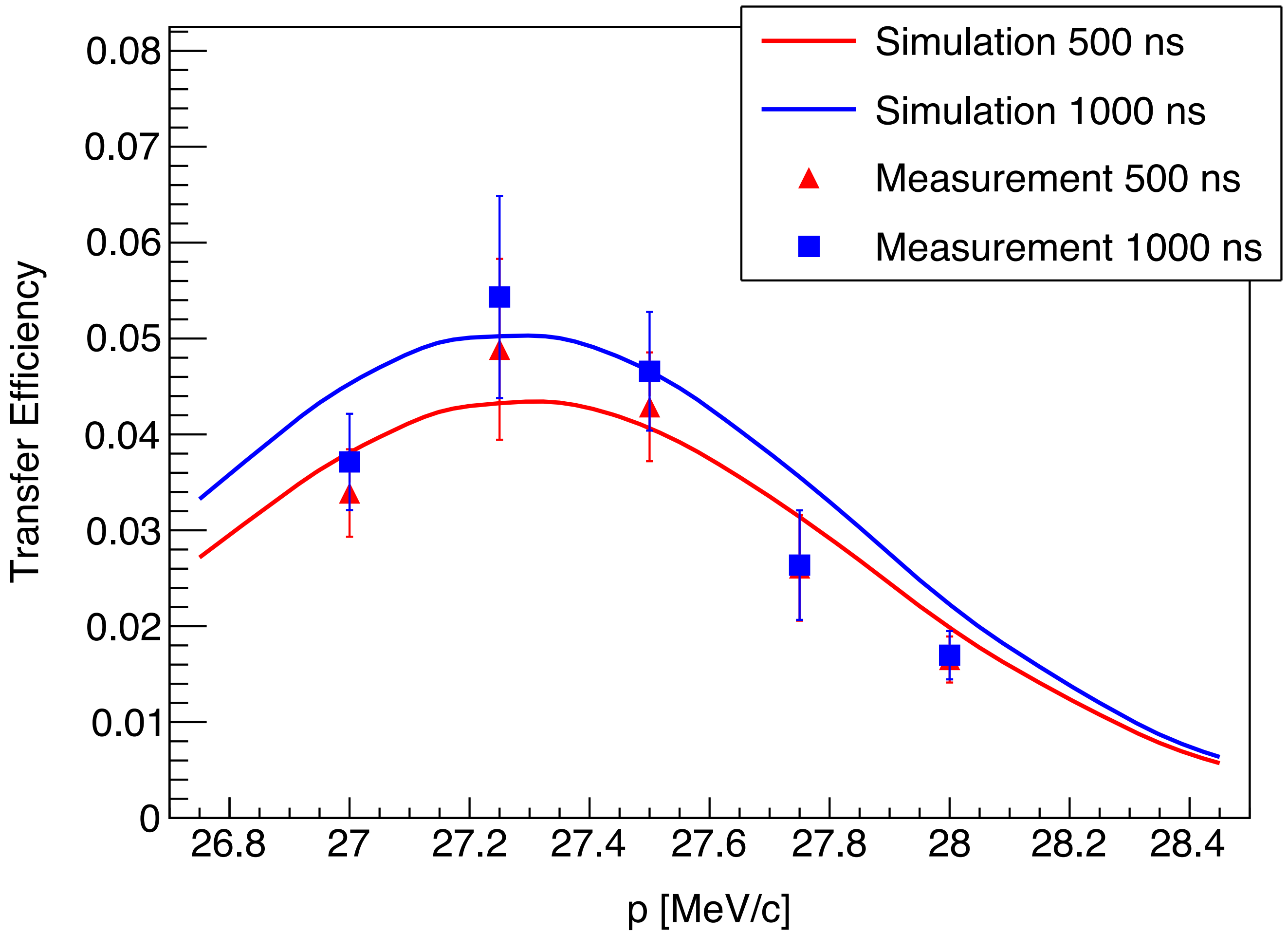
- 2019
  - Miniball germanium detector array from CERN
  - 26 germanium crystals in total

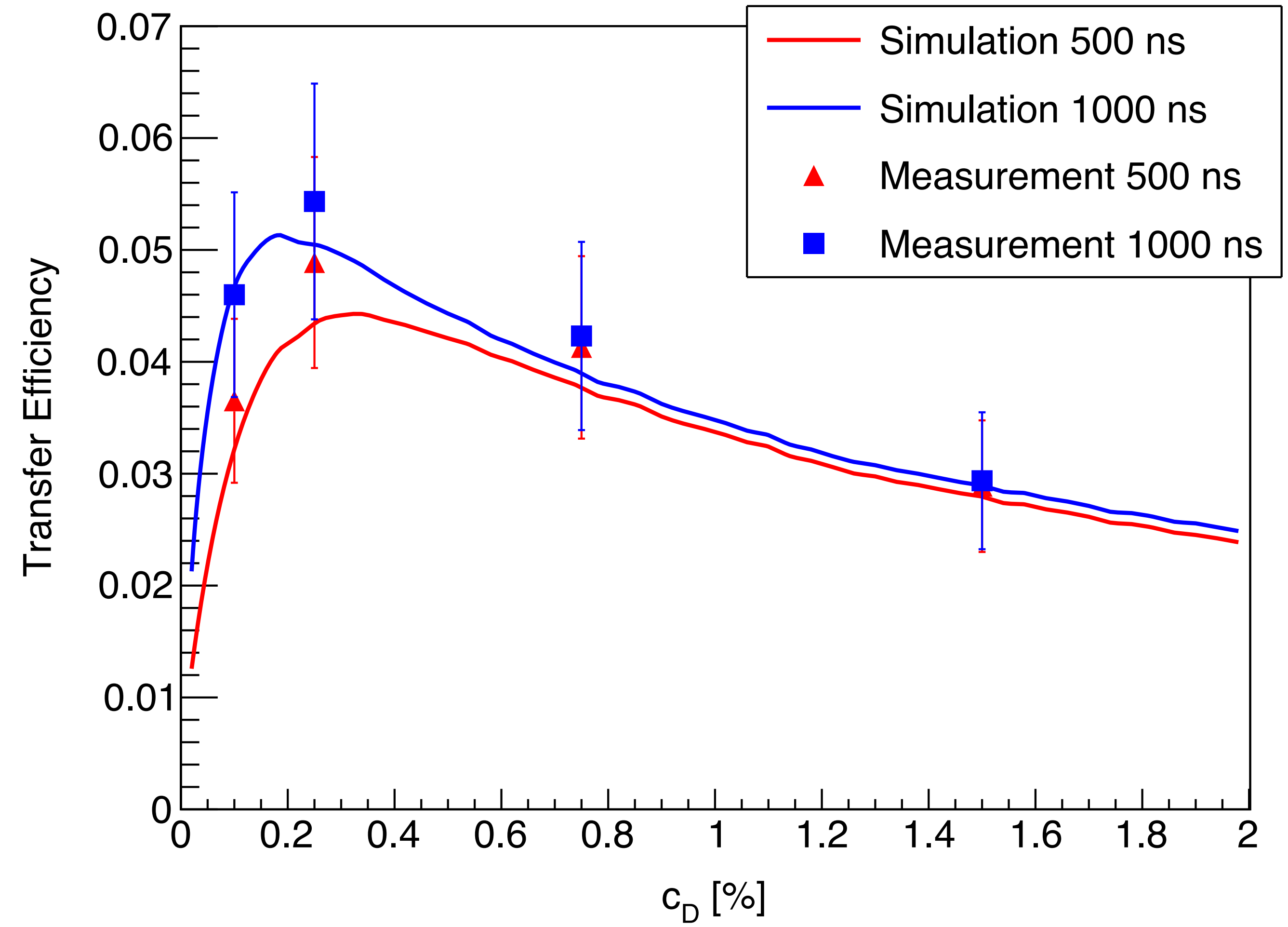
Warr et al., Eur. Phys. J. A **49**, 40 (2013)

Experimental setup 2017/2018



Optimisation of transfer

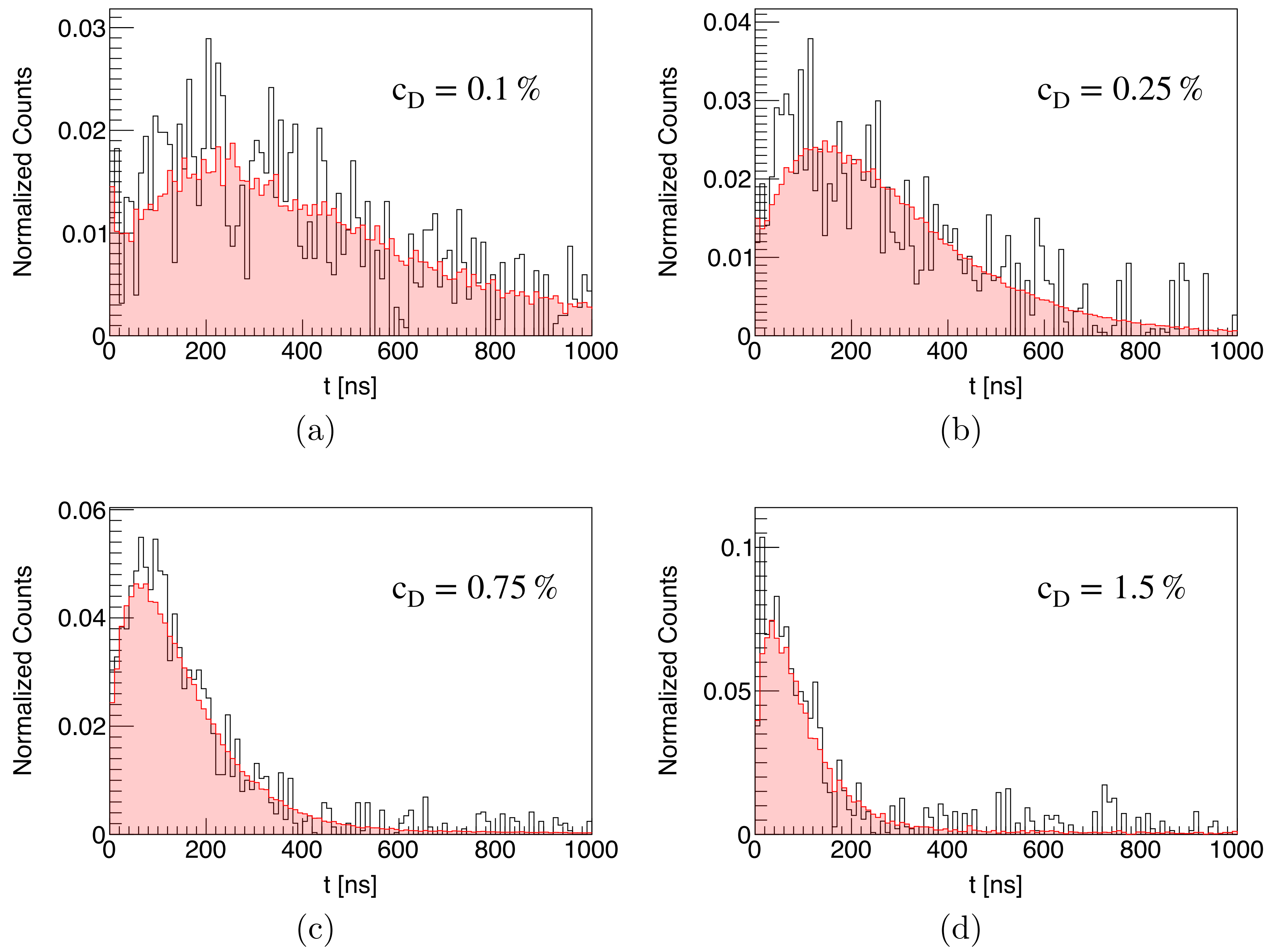




- Optimisation of transfer process inside gas cell using a 50 nm thick gold target
- Good understanding of all processes
- Good matching of simulation and data

Time evolution

- Speed of transfer depends on D_2 concentration
- Good match between simulation and data



Measurement with microgram gold target

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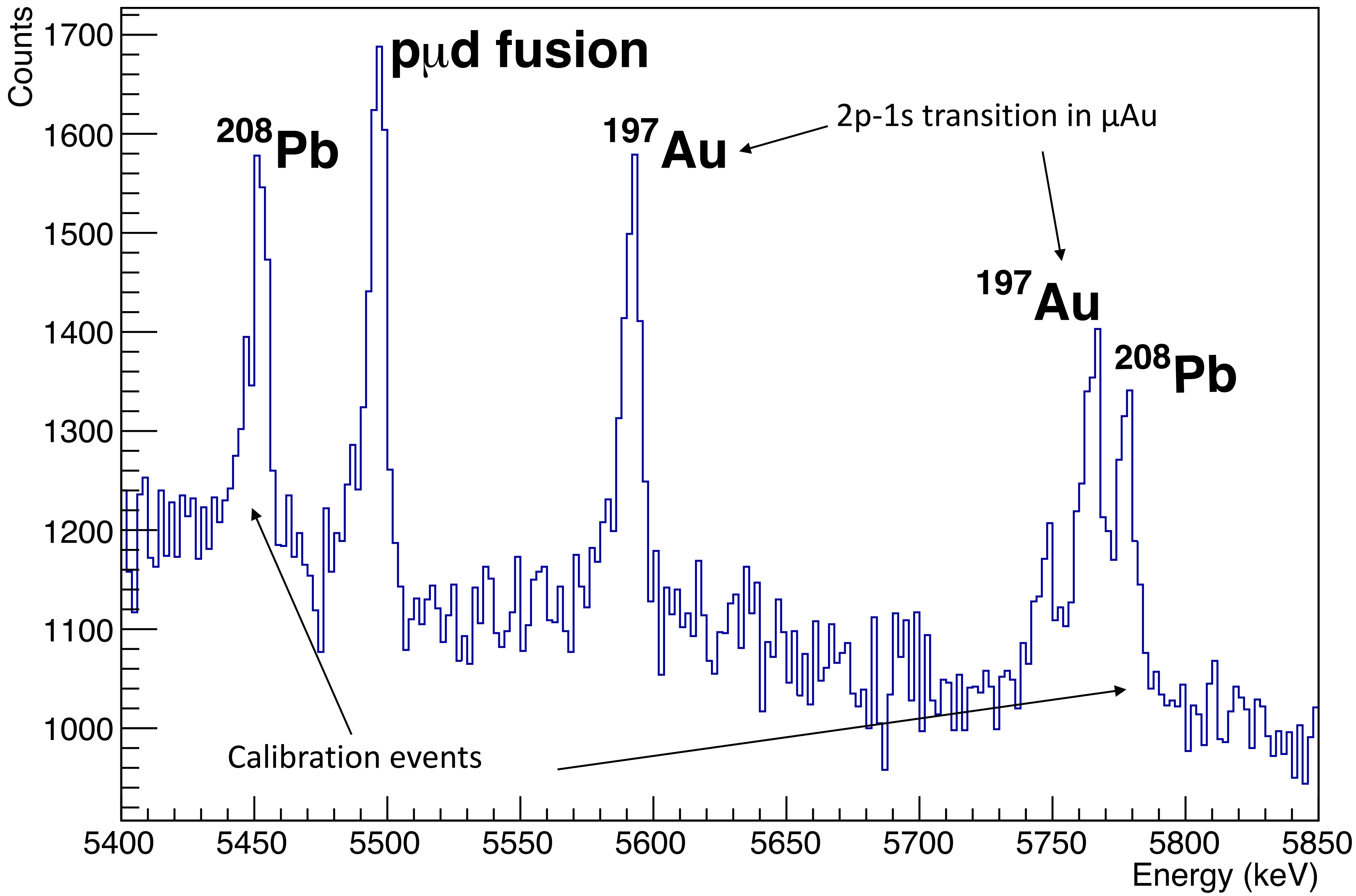
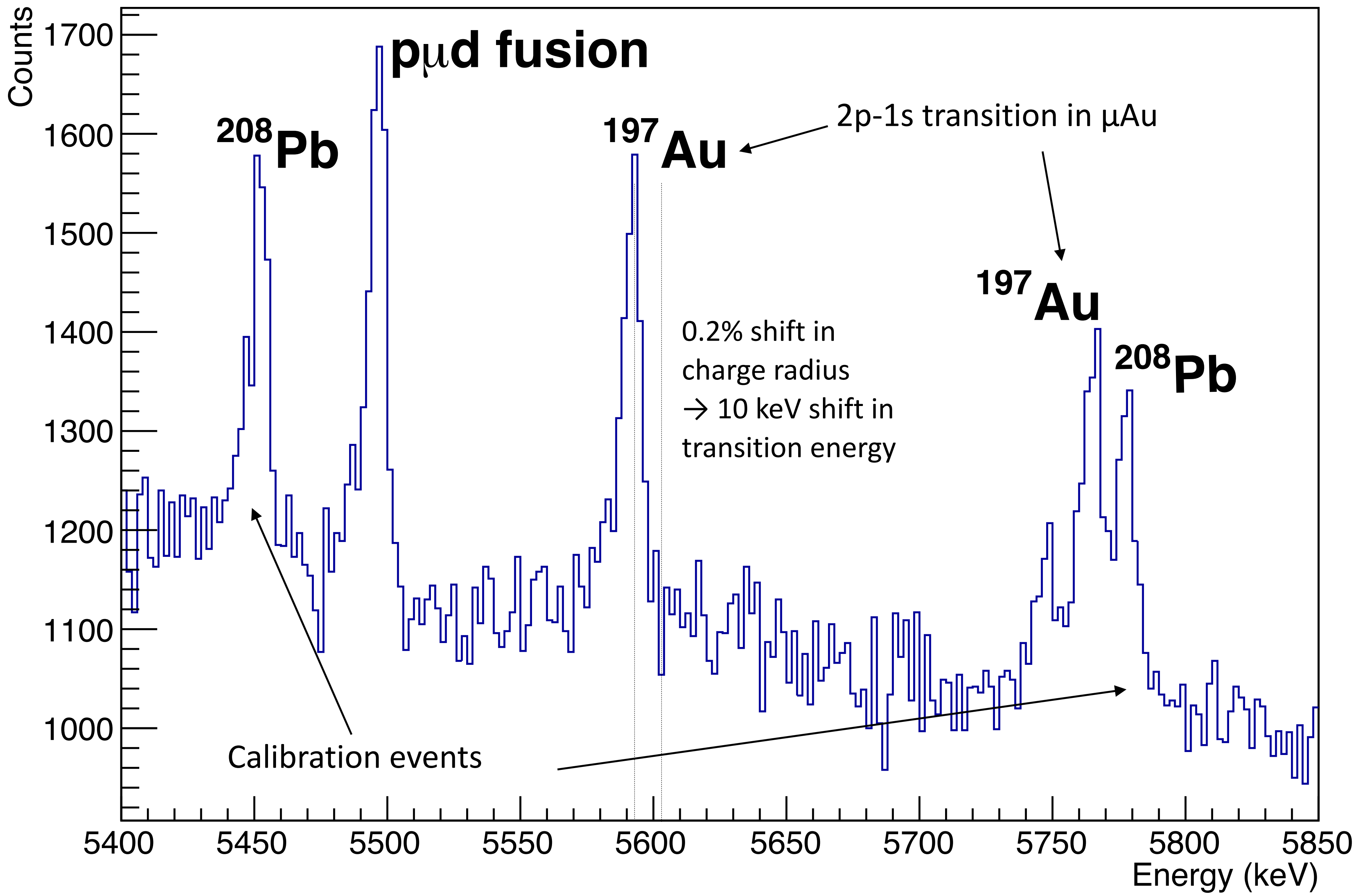


- Measurement with 5 μg gold target as proof-of-principle
- Spectrum taken over 18.5 h

Measurement with microgram gold target



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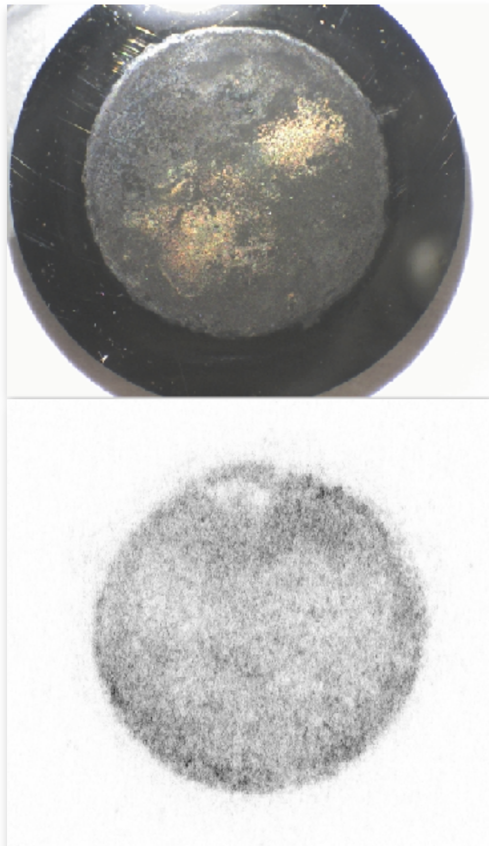
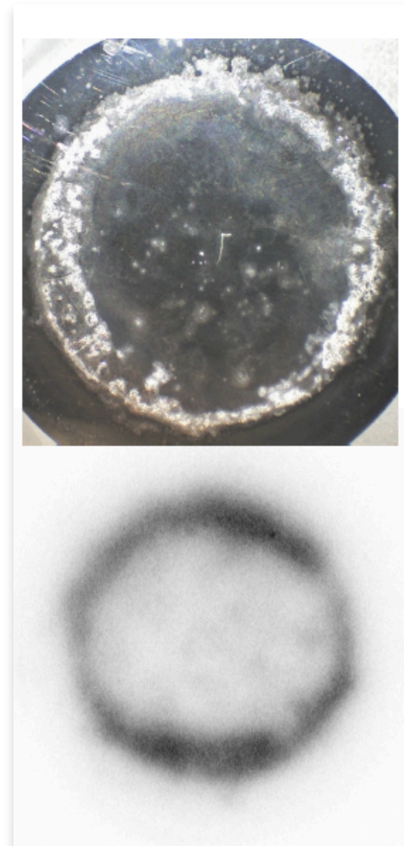
Radioactive targets



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 drop-on-demand 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

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

- Cuts:
  - Electron veto anti-coincidence
  - Clustering of events in Miniball detector
  - Gain stabilisation
  - Baseline correction

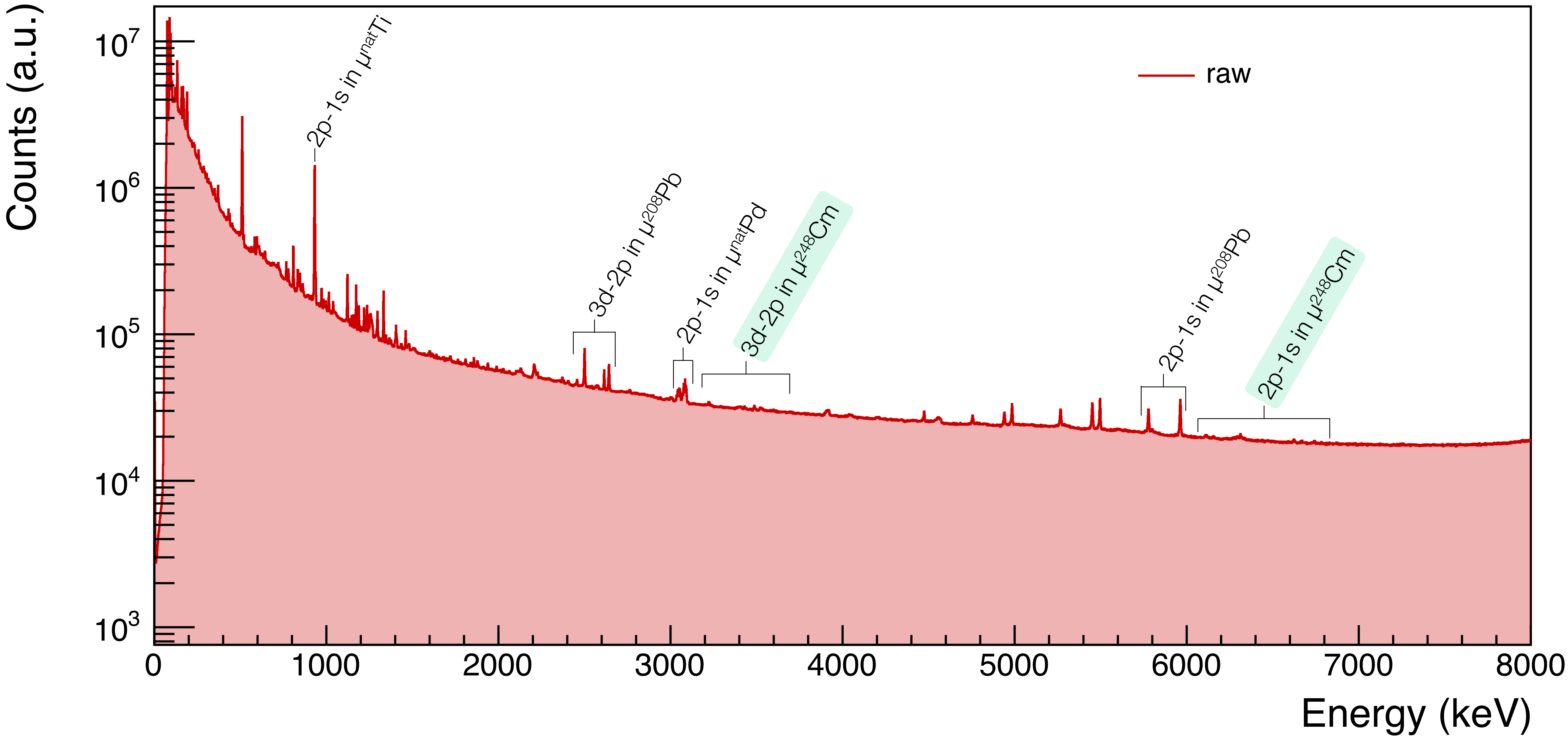
Most electron background is removed

$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Remaining neutron background

$\mu^- + (N, Z) \rightarrow (N+1, Z-1)^* + \nu_\mu$

$(N+1, Z-1)^* \rightarrow (N-x, Z-1)^* + (1+x)\, n$



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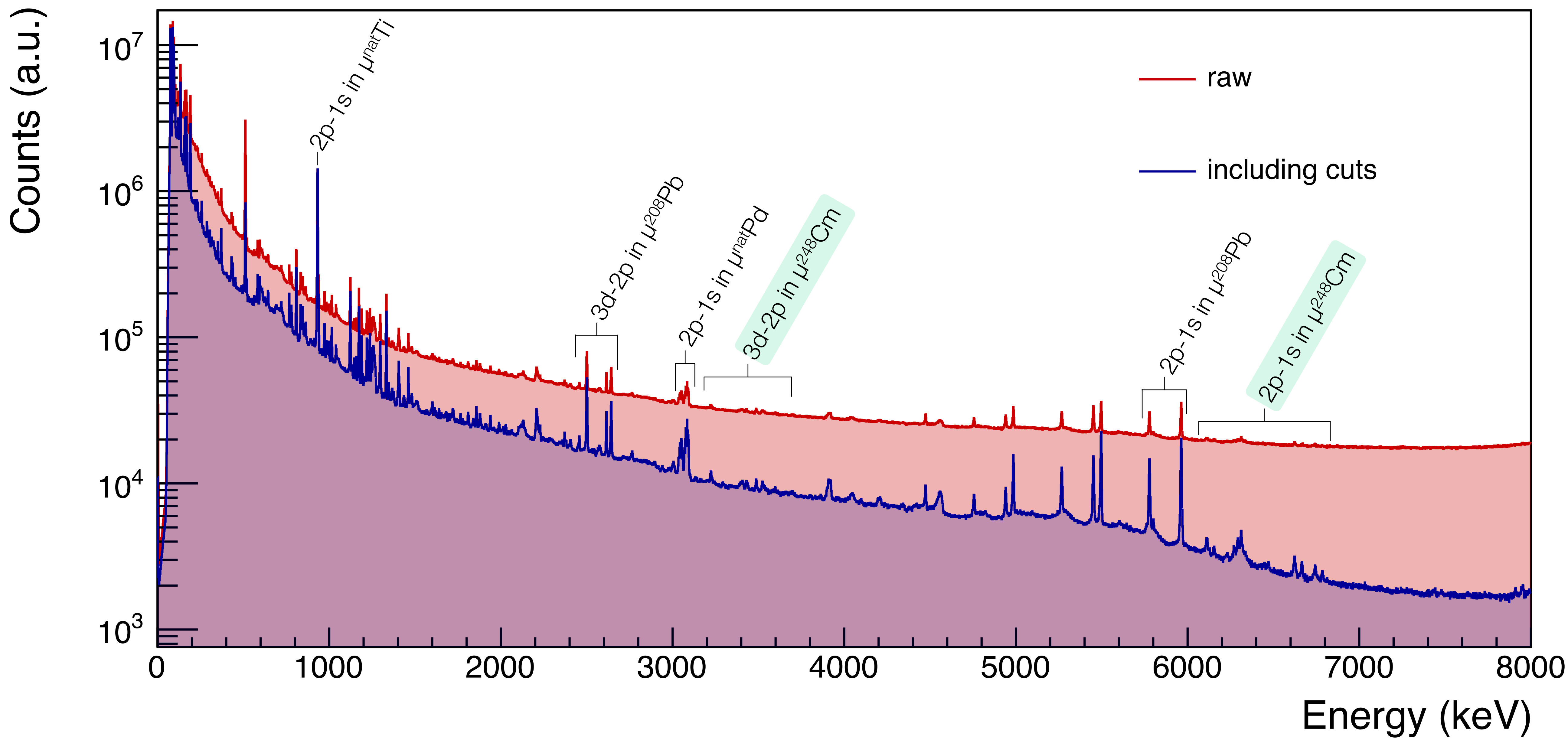

2p→1s hyperfine transitions in ^{248}Cm

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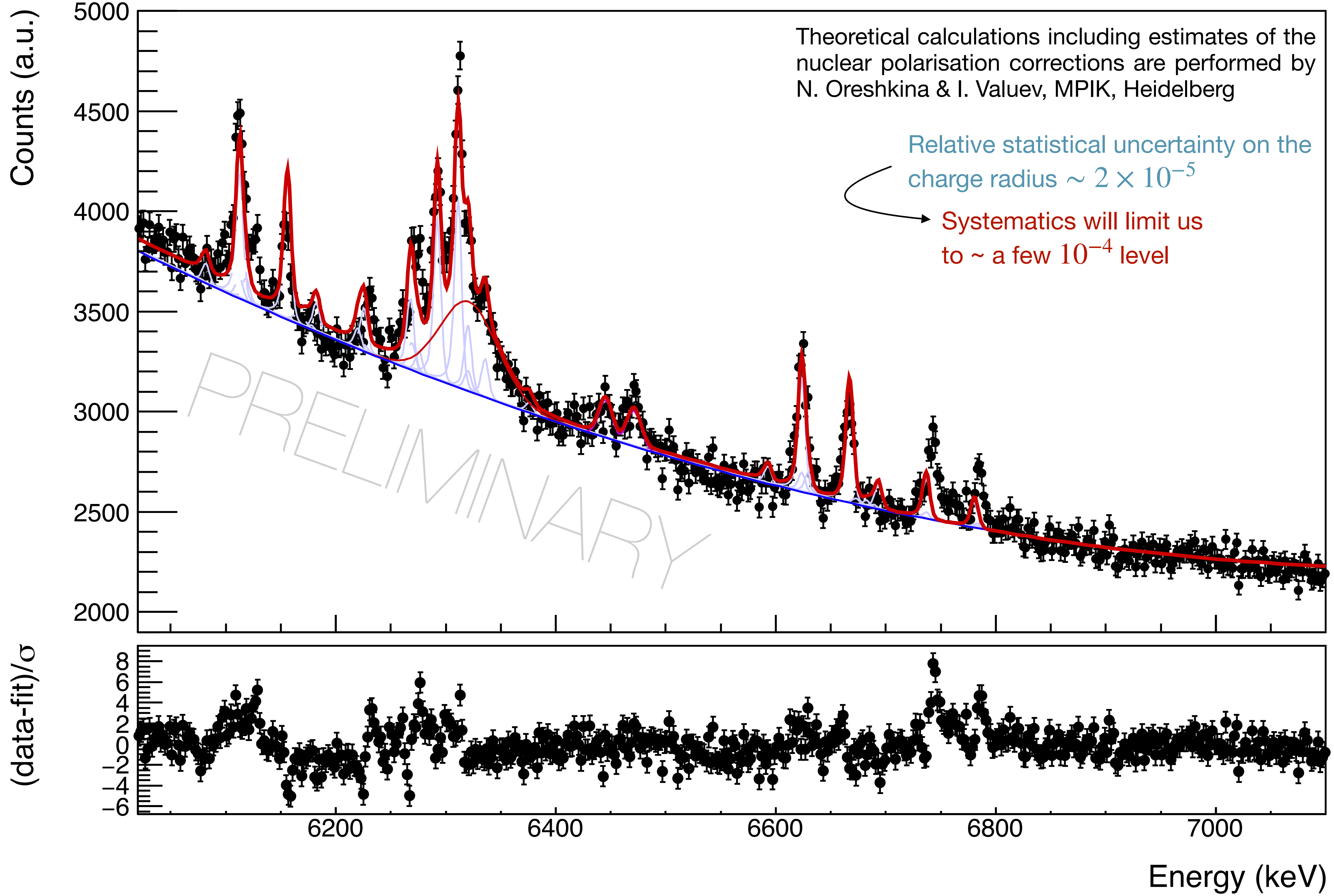
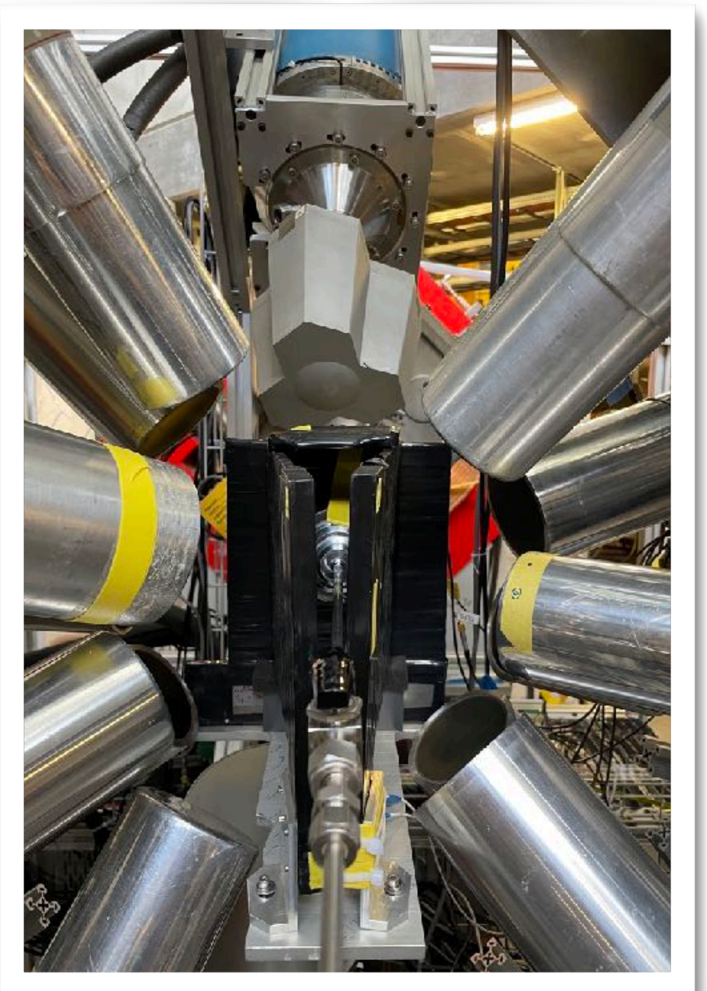


September 2022 measurement



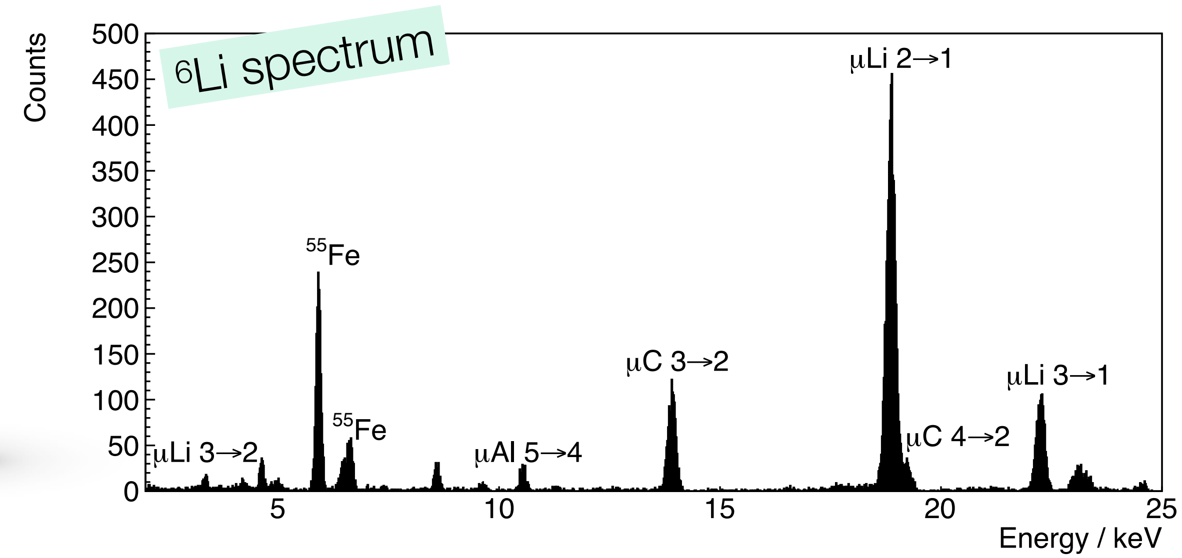
A

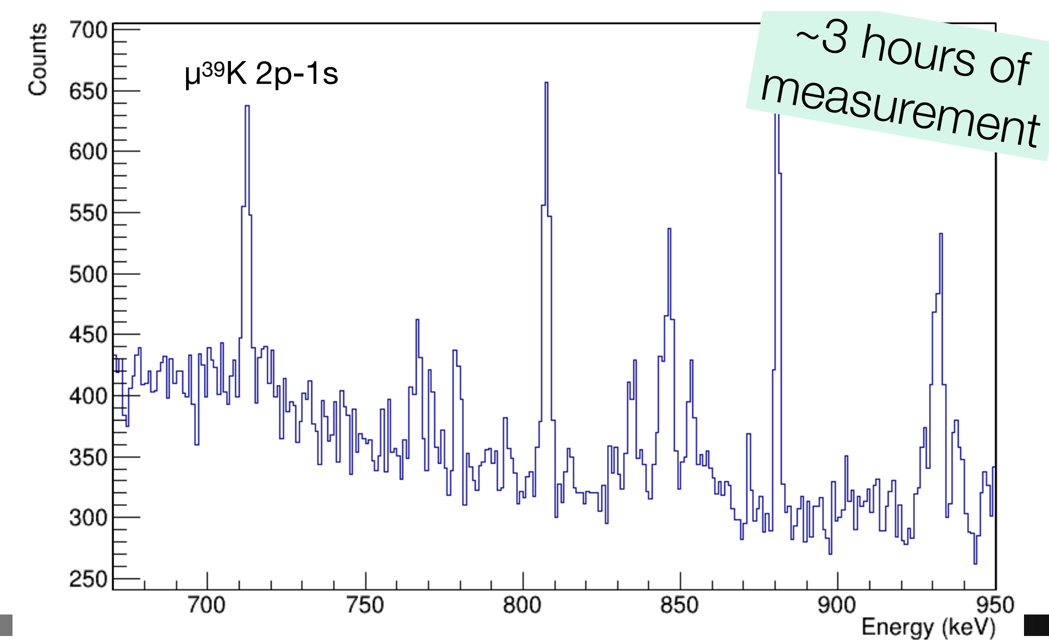
Towards the measurement of ^{226}**Ra**:

- measured implanted gold targets
- measured barium deposition targets (drop-on-demand, molecular plating)

B

First **low-Z** elements tests with enriched ^{6}Li and ^{nat}Li samples using a silicon drift detector





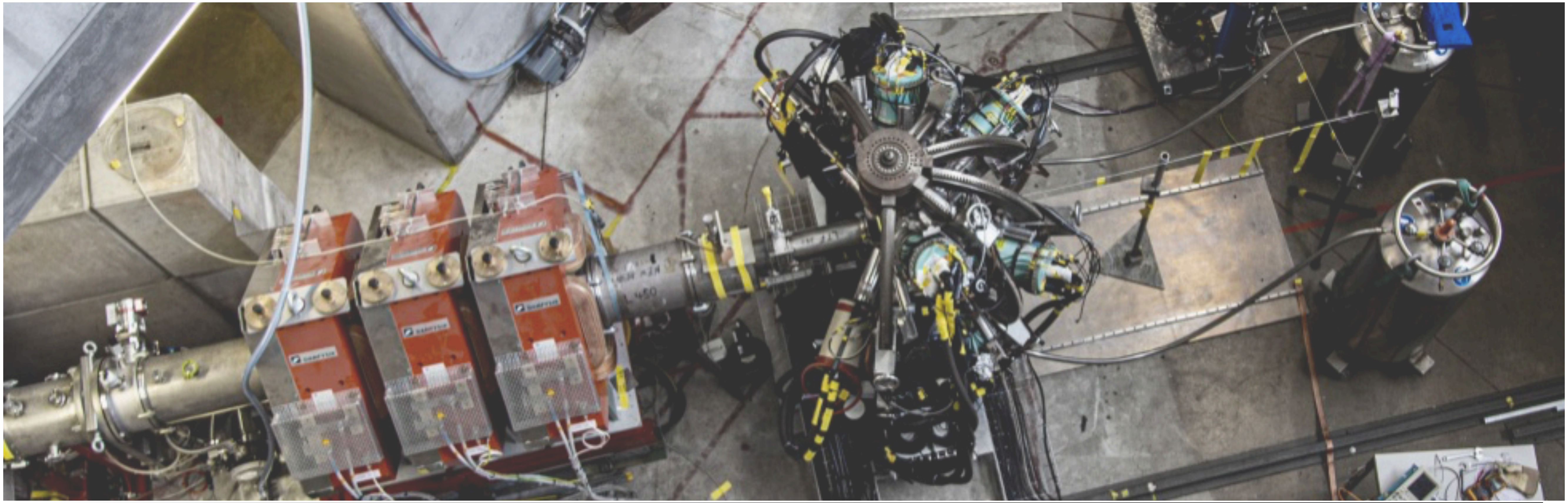
C

Expand towards **medium-Z** elements:

- measured ^{39}K (5.7 μg) using the muX method
- future goal: measure triplet ^{39}K, ^{40}K, ^{41}K
- improve laser spectroscopy results

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 under consideration, e.g. ^{40}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]

[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]Université Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, France.









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)