The muX Experiment

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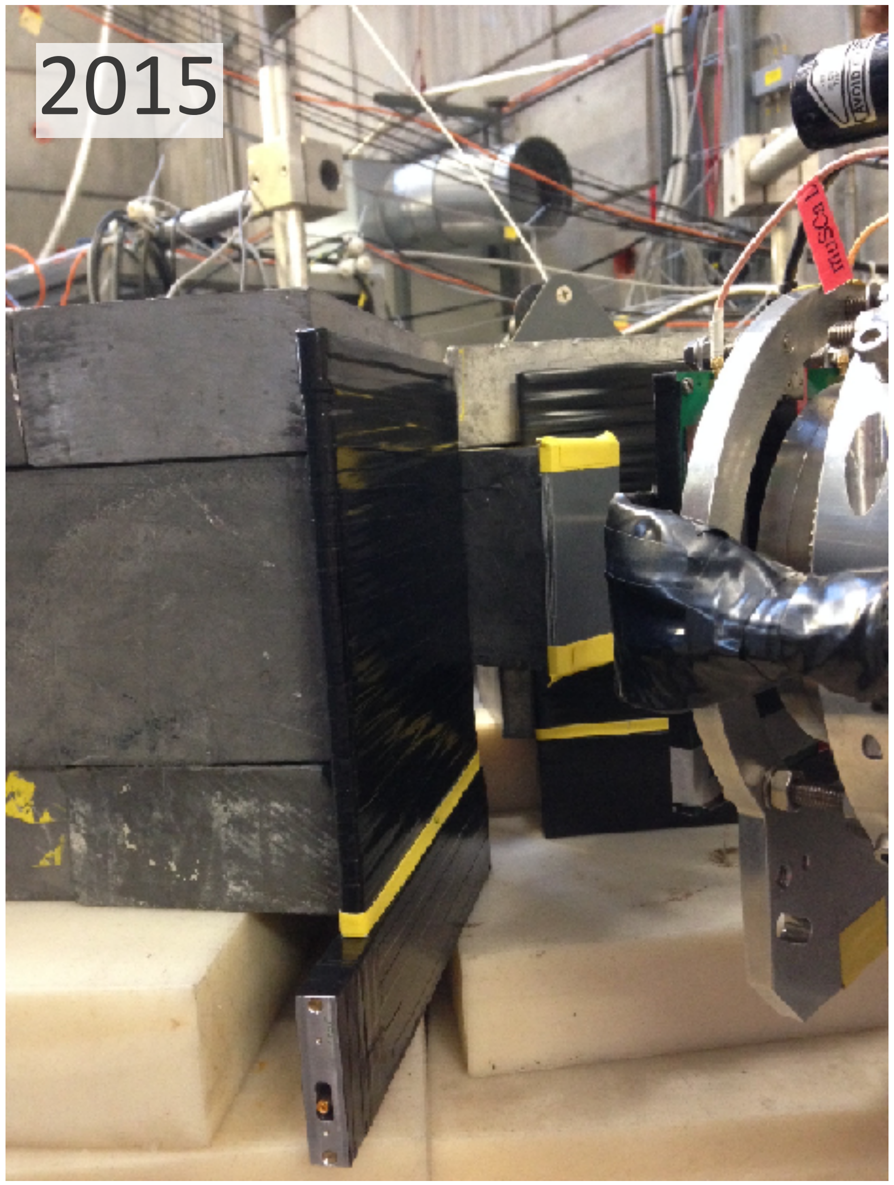
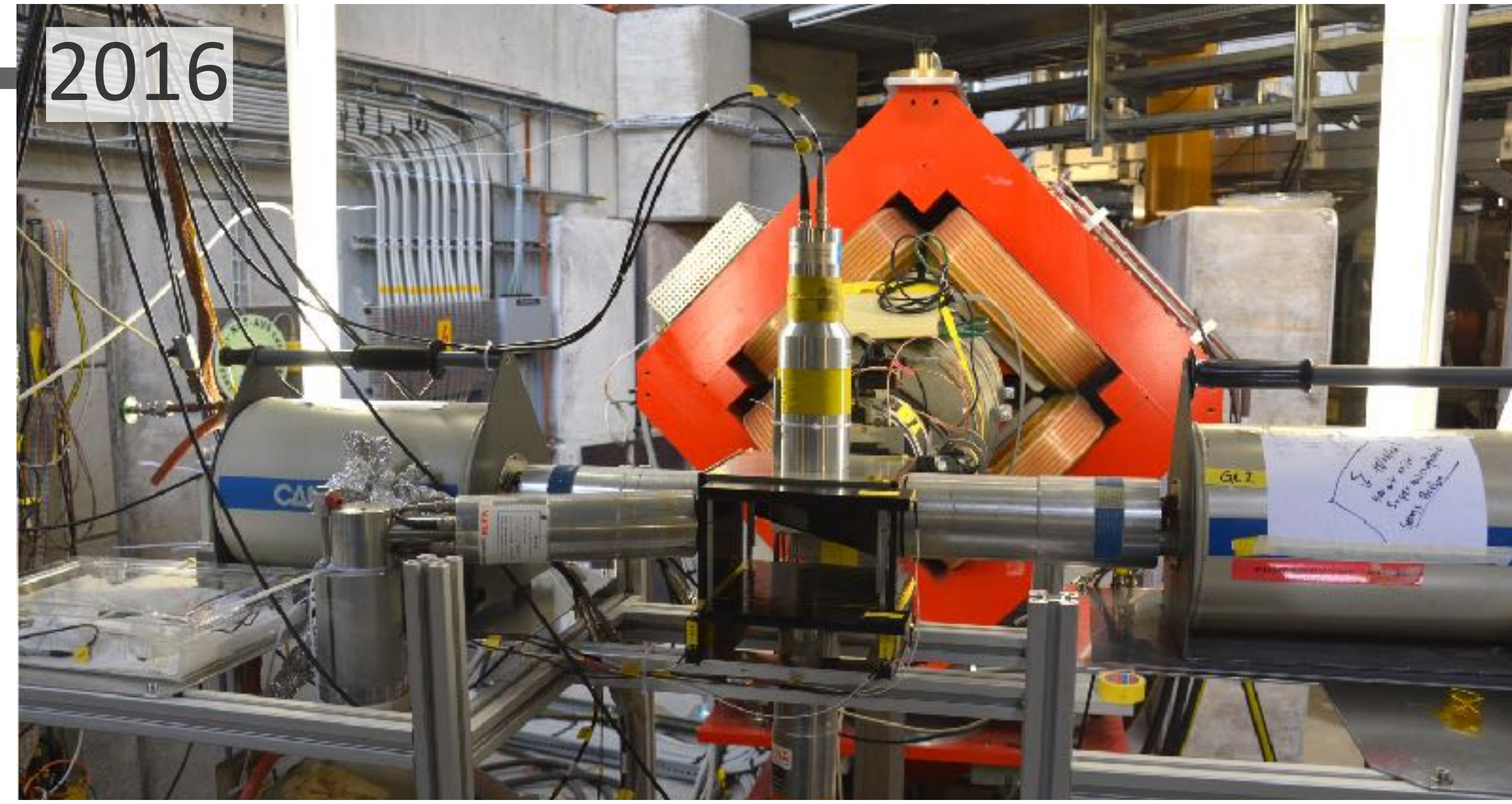
Paul Scherrer Institute

18. 6. 2019
muX collaboration meeting
Mainz

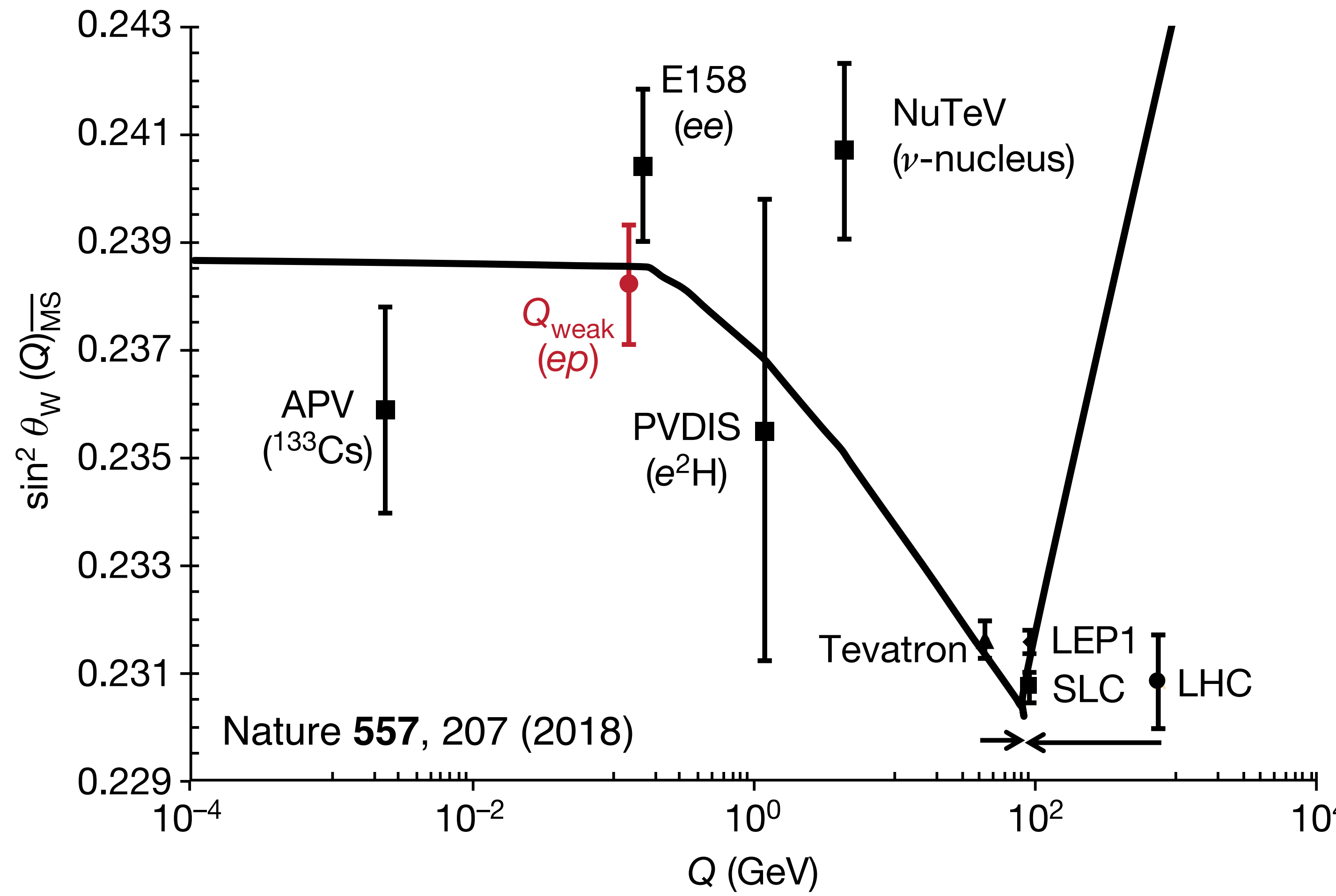
History





Atomic parity violation in radium

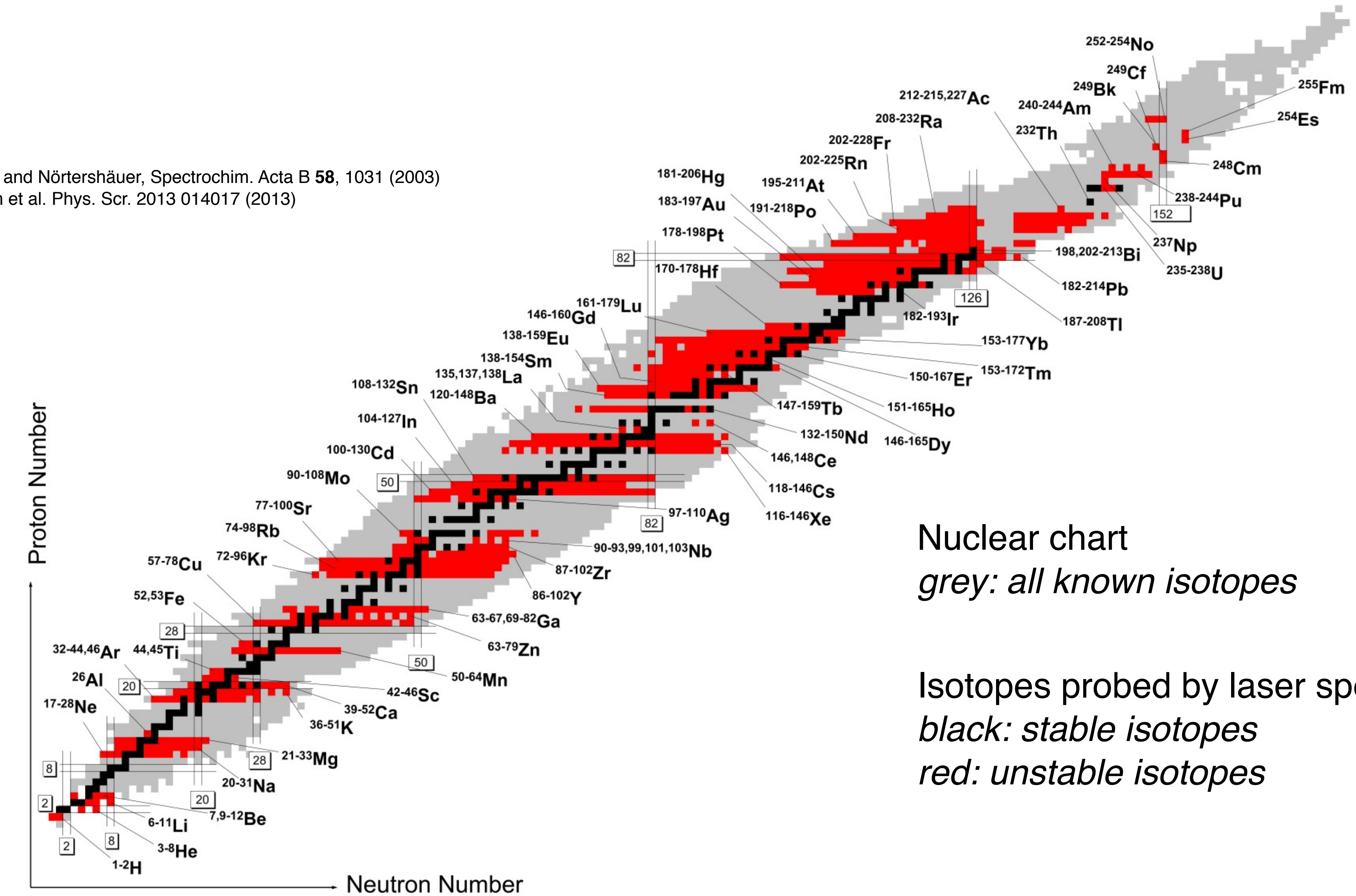
- Weak interaction leads to parity violating effects in atomic transitions
  → enhanced in heavy atoms (∝ Z^3) due to large overlap with nucleus
- Extract Weinberg angle using precision atomic calculations
  → Needs knowledge of the radium charge radius with 0.2% accuracy



⇨ Atomic parity violation fixes weak interaction properties at low momentum

Charge radii in nuclear physics

Kluge and Nörtershäuer, Spectrochim. Acta B **58**, 1031 (2003)
Blaum et al. Phys. Scr. 2013 014017 (2013)



Nuclear chart
grey: all known isotopes

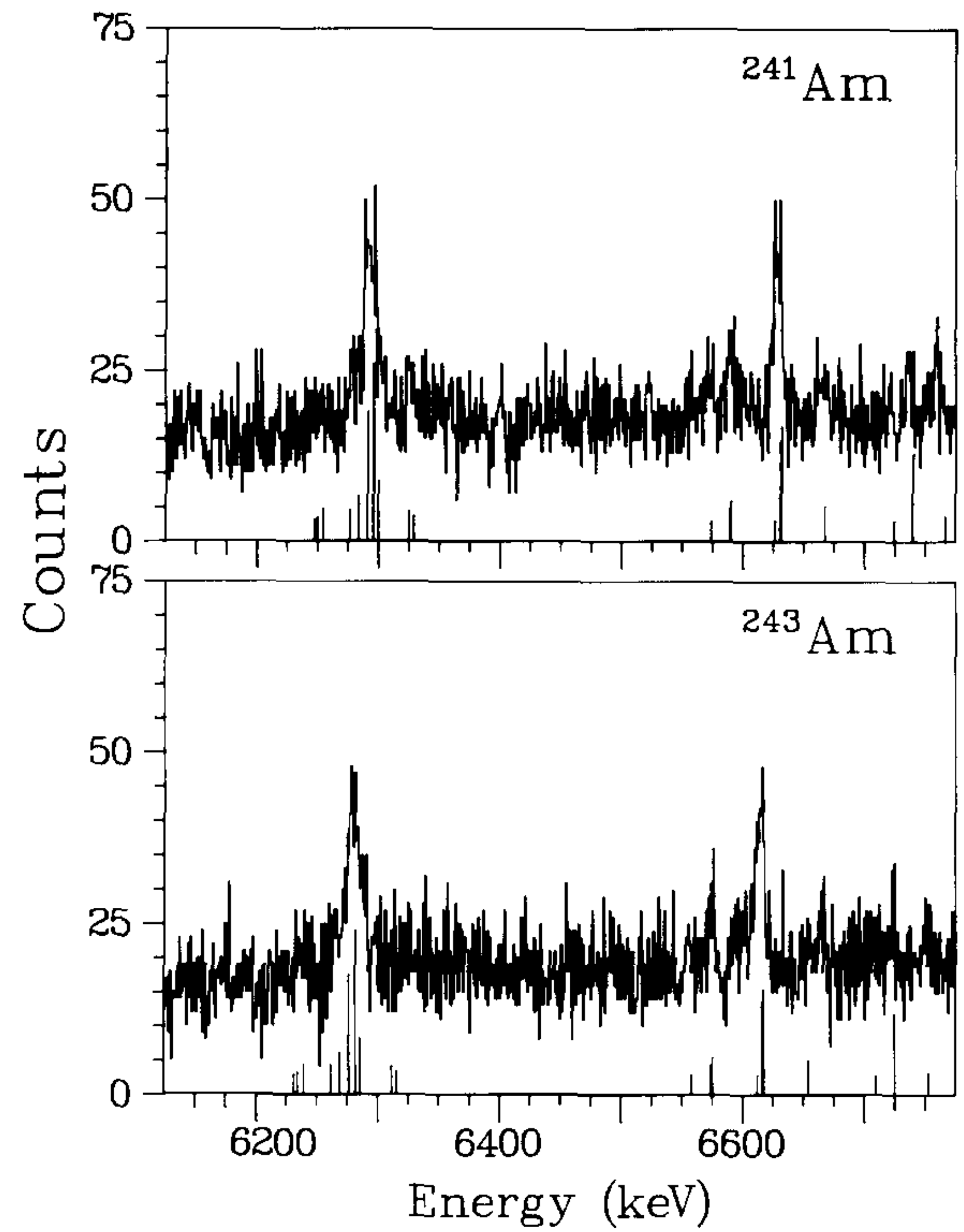
Isotopes probed by laser spectroscopy
black: stable isotopes
red: unstable isotopes

- Large efforts at ion beam facilities to determine charge radii
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

What about radioactive atoms?

- Most of the stable isotopes 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 ^{241}Am allowed in experimental hall…

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



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

Our radioactive targets

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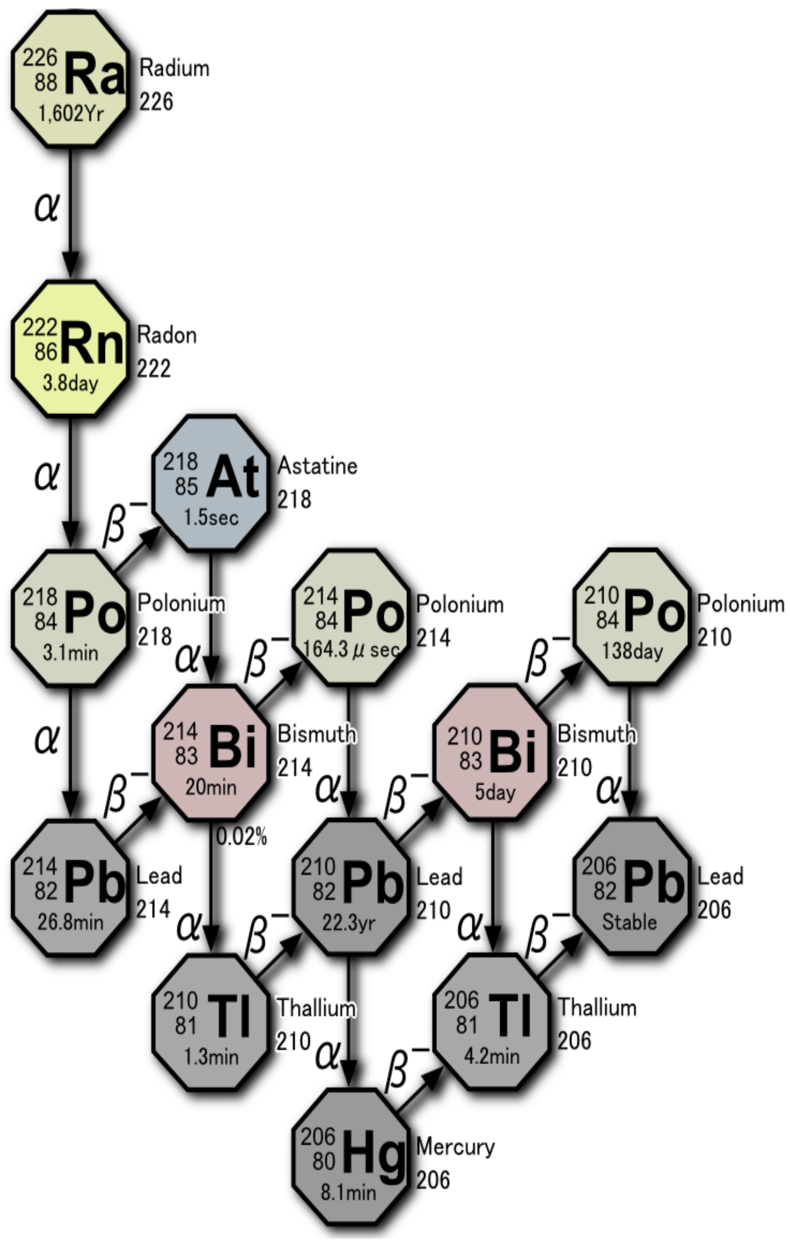
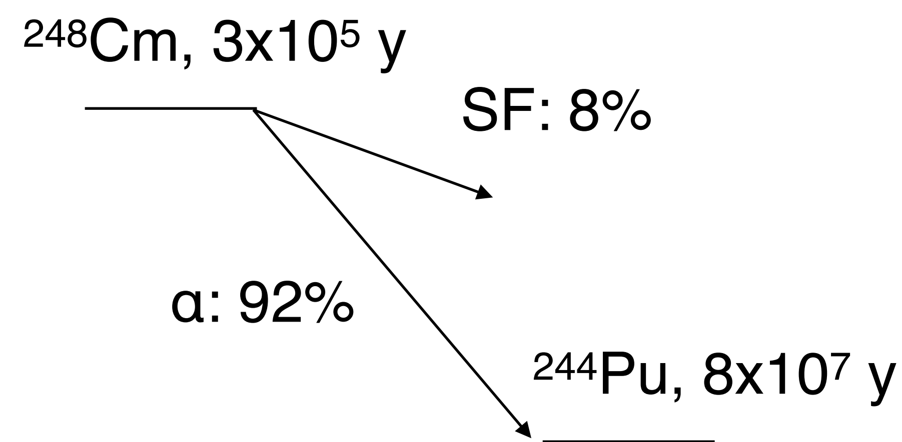


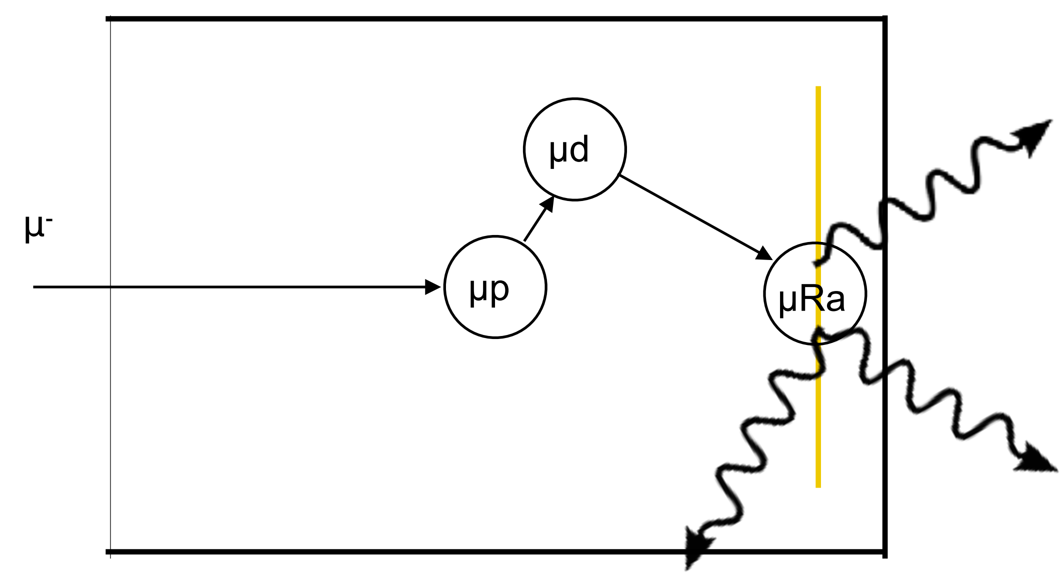


- 5.5 µg target material allowed
- Gamma rate of ~400 kHz from all daughters
- Interest from atomic parity violation

- 32.6 µg target material allowed
- Heaviest nucleus accessible

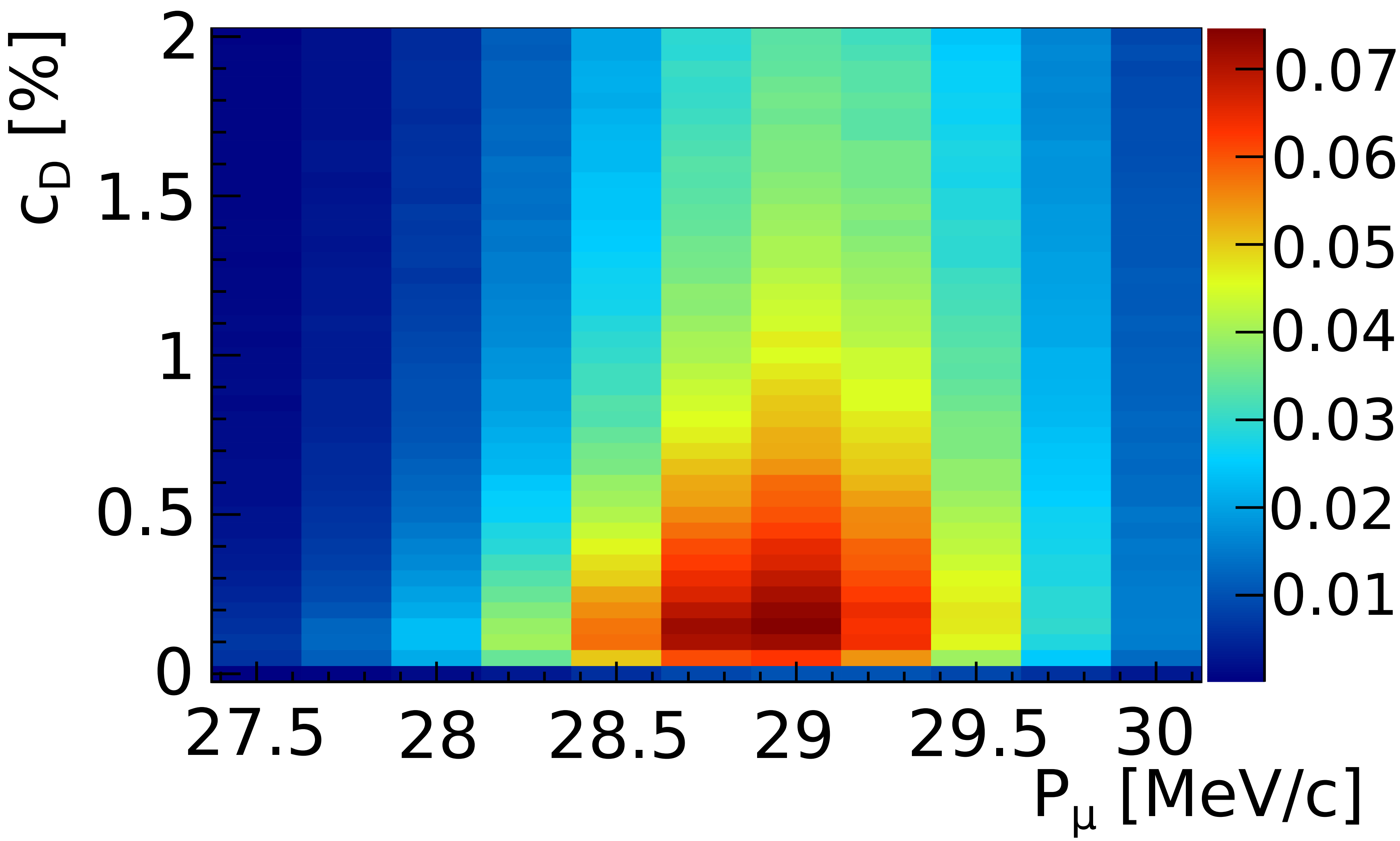
Transfer reactions

- 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



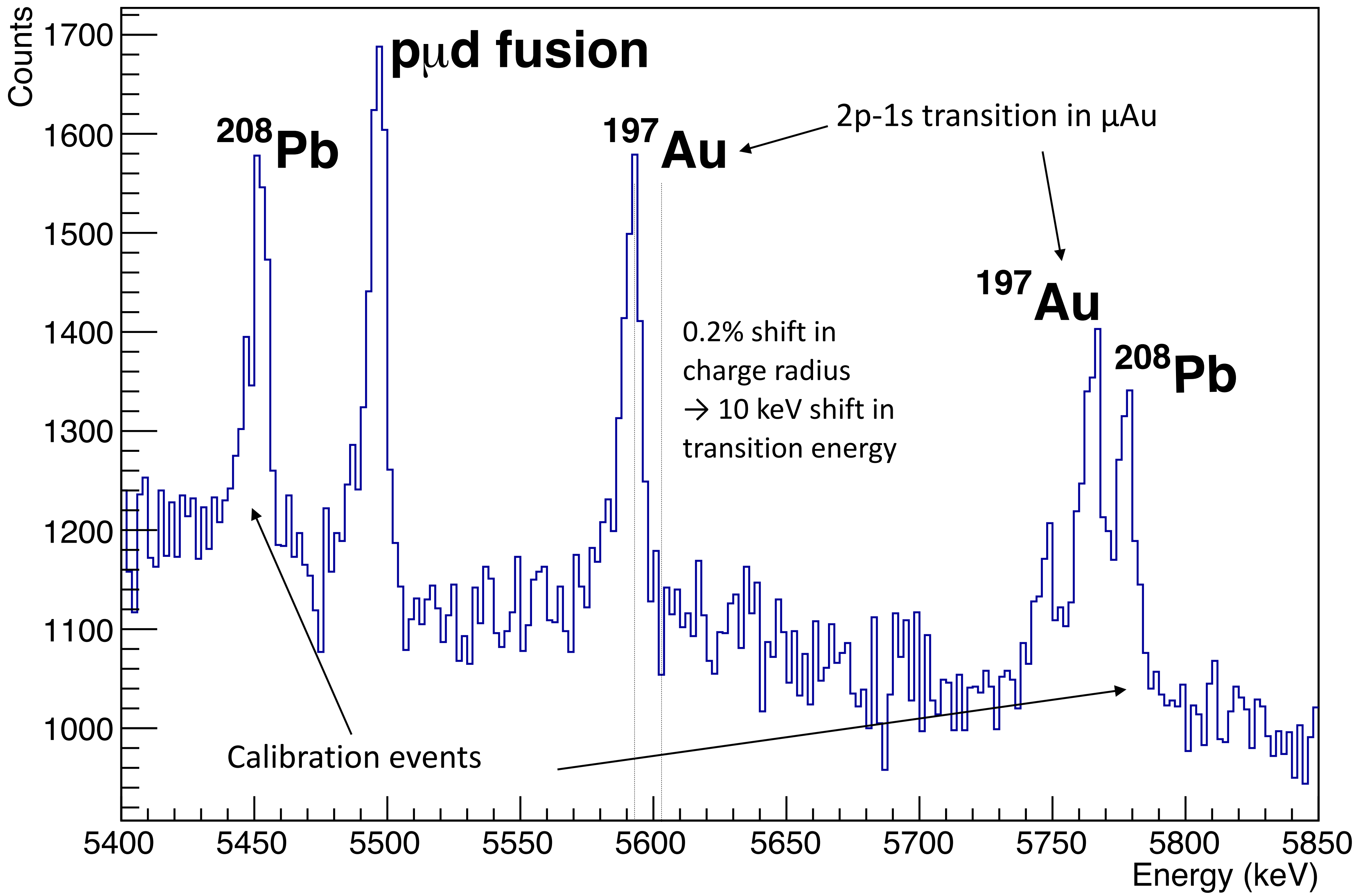
Inspired by work of Strasser et al. and Kraiman et al.

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 μd+D_2 scattering
- ~1% efficiency for 5 μg radium target expected

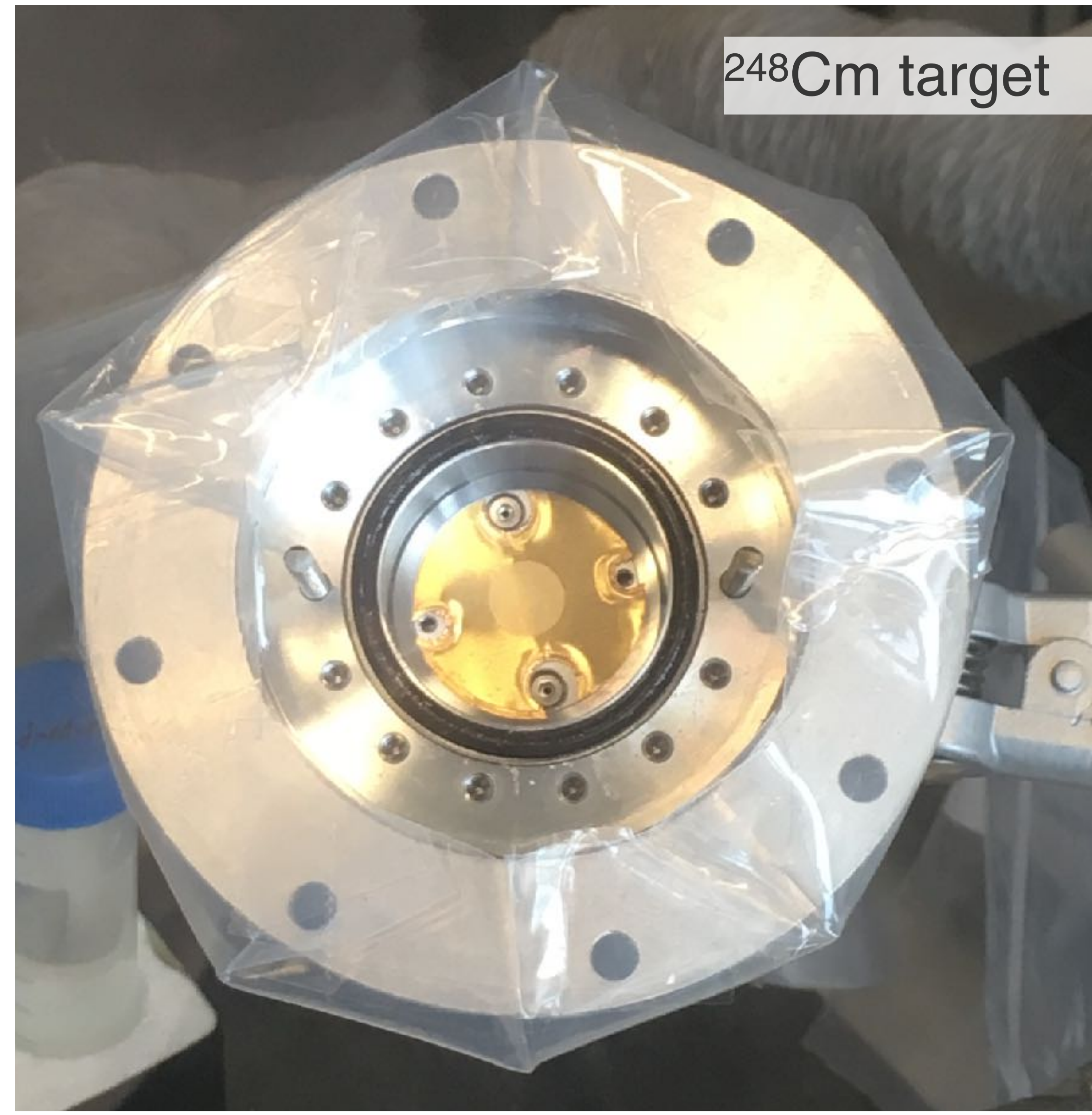
Results 2017



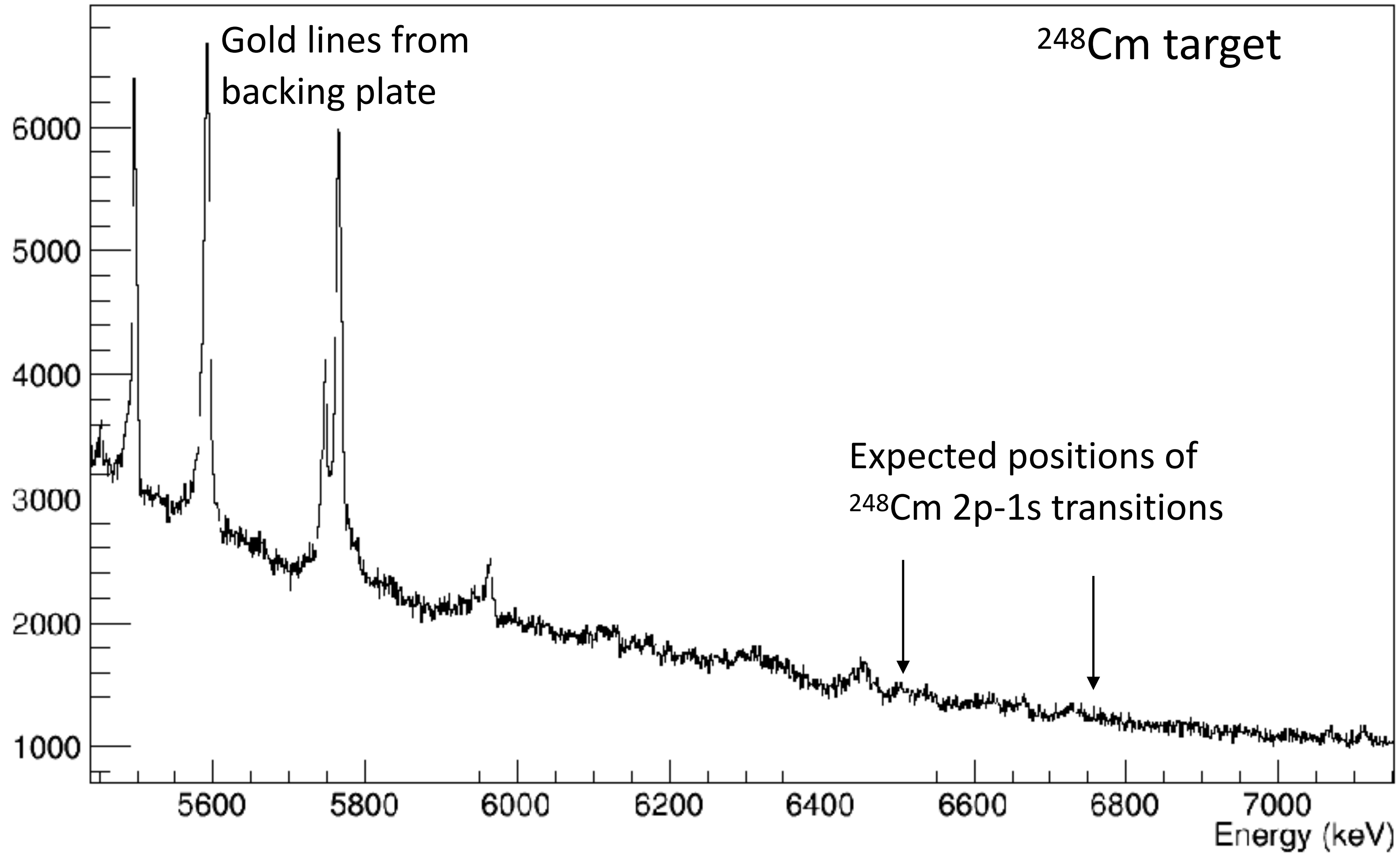
- Measurement with 5 μg gold target as proof-of-principle
- Spectrum taken over 18.5 h
- Setup tested with high-rate gamma sources and uranium targets of a few mg

Radioactive targets 2018

- Curium-248 target was made in Mainz by molecular plating method
- Radium-226 target was made at PSI also by molecular plating methods
- Handling and installation of target foils into gas cells was done in a glove box in the laboratories of the radiochemistry at PSI



Measuring radioactive targets



- In the end we did not see any sign of curium x-rays
- Electroplating inherently leads to organic layers on the target
- The fact that we see the outline of the target clearly indicates a reasonably thick layer
- Tried several times to burn away organic layer on curium target, but without success
- For radium there were unexpected issues with the plating
  → only 1% of required target mass on target foil

Carbon coatings on gold

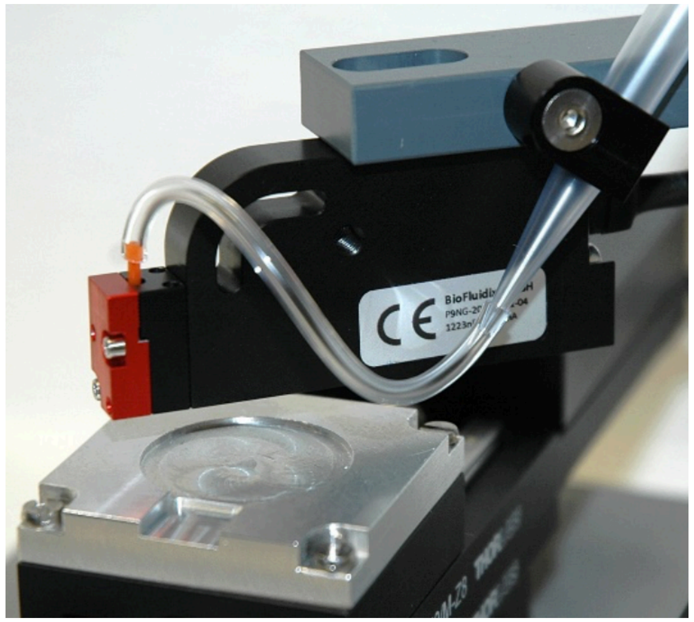
- In order to understand the influence of the organic layer on our measurements prepared gold coatings with 100 and 500 nm carbon coating on top.

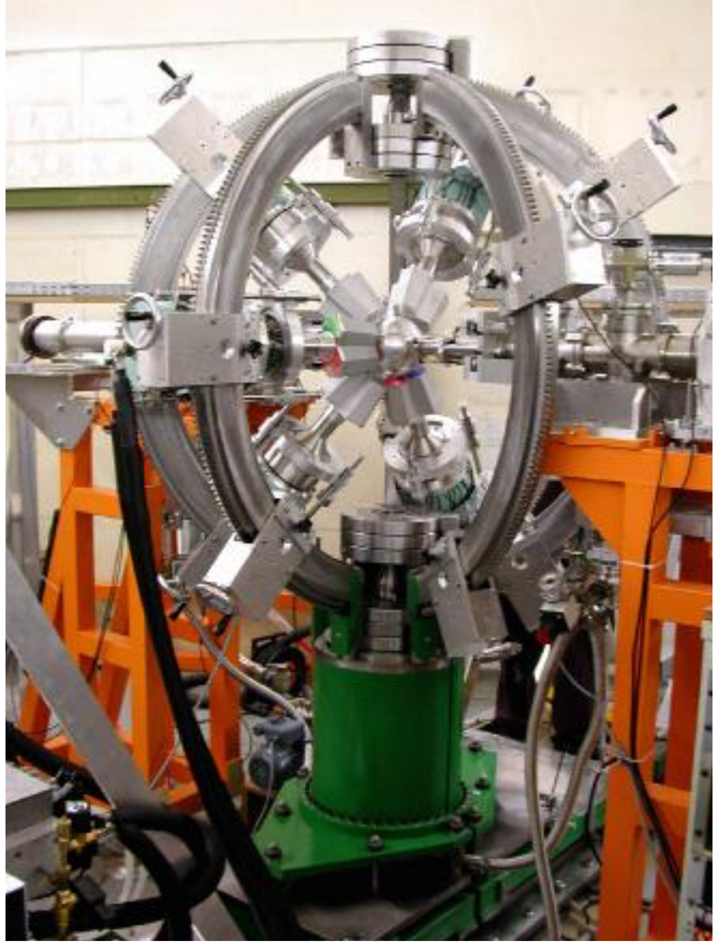
- Results:
  - 100 nm: 27% of gold x-rays left
  - 500 nm: no gold x-rays seen

- We are much more sensitive to organic layers than expected!

Developments for 2019 campaign

- Radioactive target developments:
  - Drop-on-demand technique in Mainz (for curium & radium)
  - Intermetallic targets at PSI (for radium)
  - Offline methods to measure *O*(10 nm) thick layers of organic contamination
- Low-Z target cell to reduce background
- Improved gas handling system to allow pre-mixing of D_2/H_2
- Use of Miniball germanium array





Chemical forms of our targets

- Curium-248
  - There will be contamination from curium-246 (~5%) → limits ^{248}Cm mass to ~16 µg
  - Curium nitrate: $Cm(NO_3)_3$
  - Curium oxide: Cm_2O_3
  - Curium fluoride: CmF_3
  - Transfer properties: oxide > fluoride >> nitrate

- Radium-226
  - Radium nitrate: $Ra(NO_3)_2$
  - Radium oxide: RaO
  - Radium carbonate: $RaCO_3$
  - Radium fluoride: RaF_2
  - Transfer properties: oxide > fluoride > carbonate >> nitrate

Beam request 2019

- 3.5 weeks of beam time for measurement of charge radius of ^{248}Cm and ^{226}Ra
  - 1.5 weeks of setup
  - 2 weeks of data taking
- Beam time for muon capture measurements: 2 weeks of data taking
- Additional test requests using the muX setup:
  - 2s-1s measurements: 1 week
  - Elemental analysis (µSR): 1 week

muX collaboration

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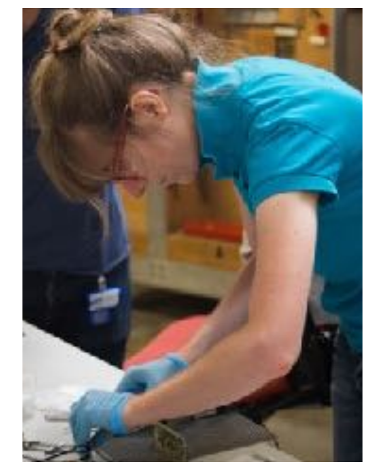
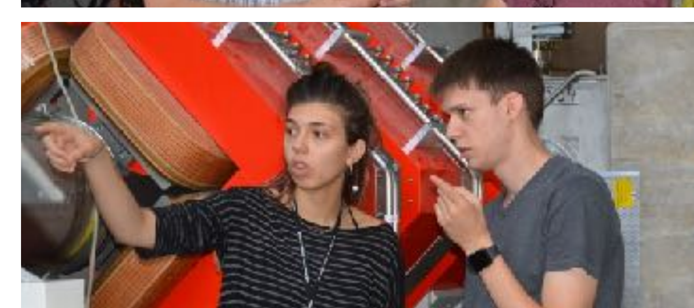
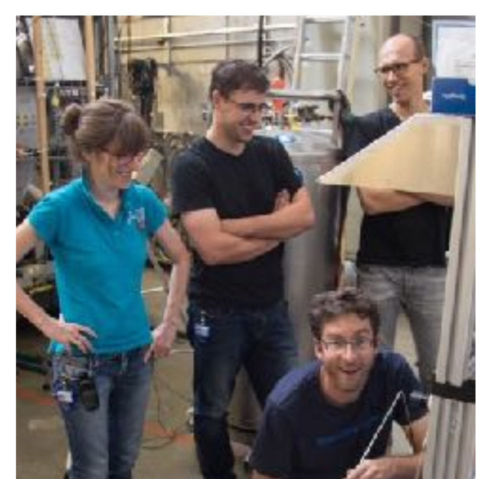


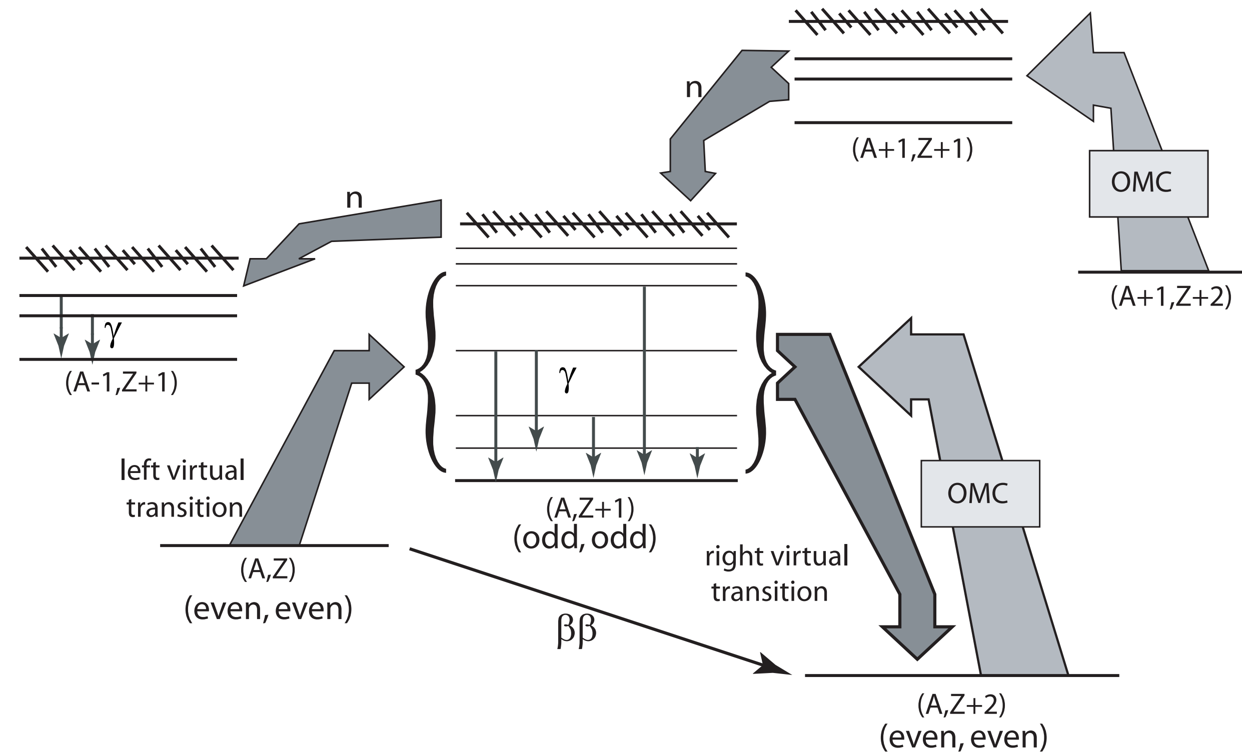



Backup

Addendum to Proposal

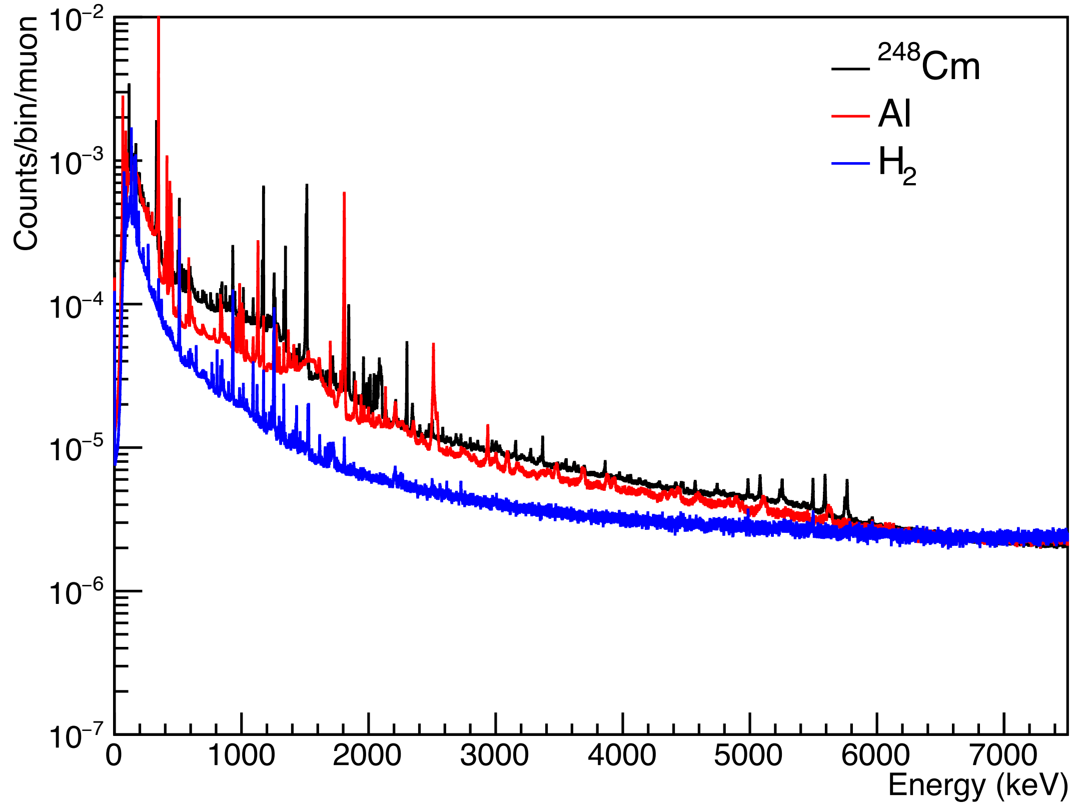
Zinatulina et al., arXiv:1803.10960 (2018)



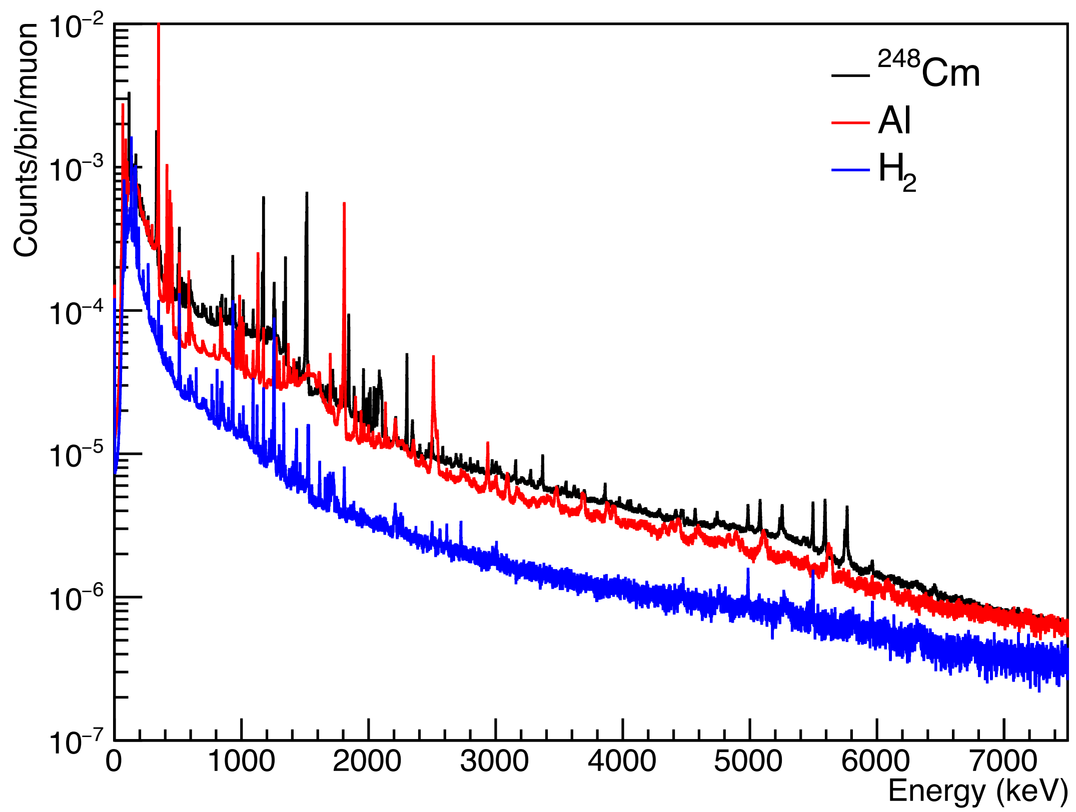
- Muon capture measurement on nuclei relevant for double beta decay (^{82}Kr, ^{130}Xe)
- Compare measurements to nuclear shell model predictions for ^{24}Mg as a benchmark for NSM to calculate higher mass nuclei
- Measure muon capture rates and branches to the different daughter isotopes

target	enr-ment	composition	element mass	thickness mg/cm^2
^{82}Kr	99.9%	Kr gas	1.0 l (1 atm.)	37.3
^{nat}Kr	–	Kr gas	1.0 l (1 atm.)	37.3
^{130}Xe	99.9%	Xe gas	1.0 l (1 atm.)	58.1
^{nat}Xe	–	Xe gas	1.0 l (1 atm.)	58.1
^{24}Mg	99.89%	MgO powder	1.0 g	250

Background Measurements

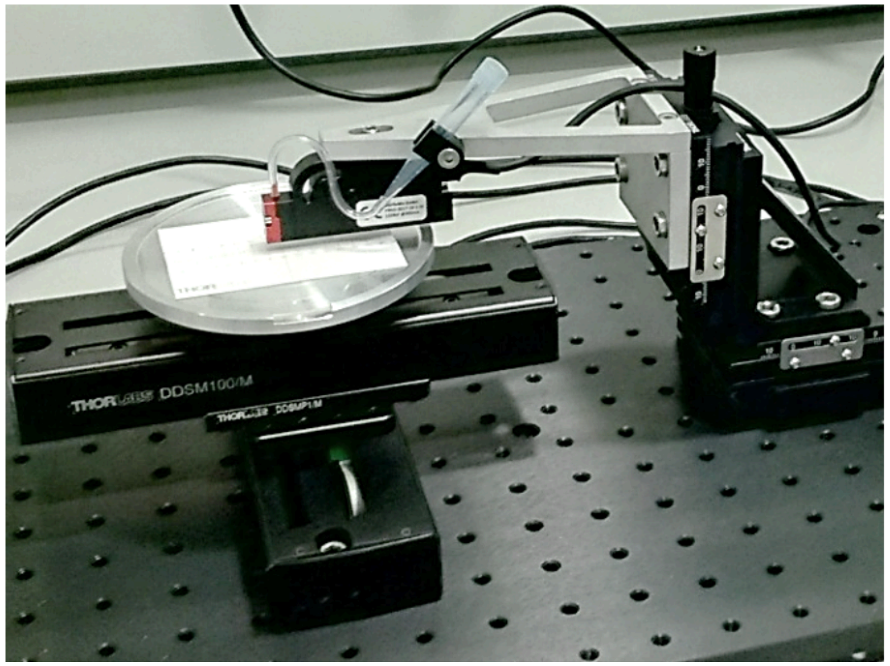


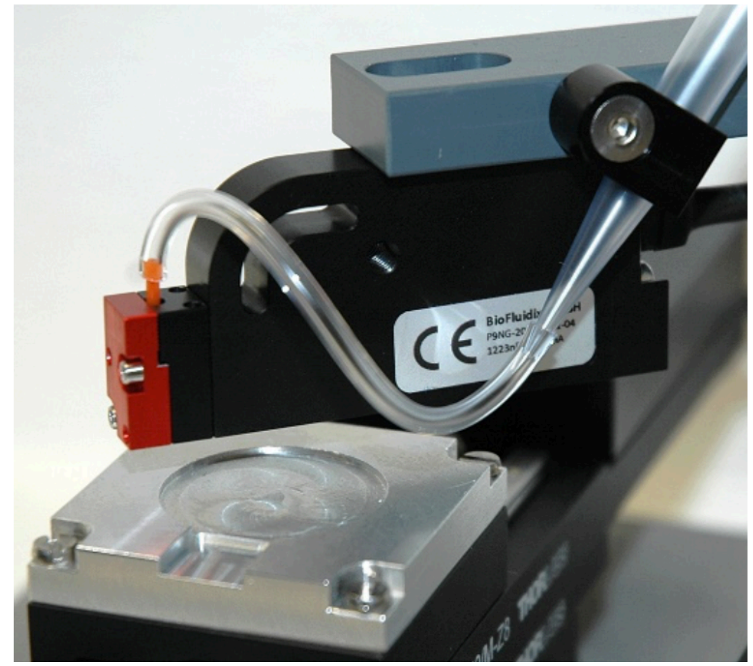
No electron veto



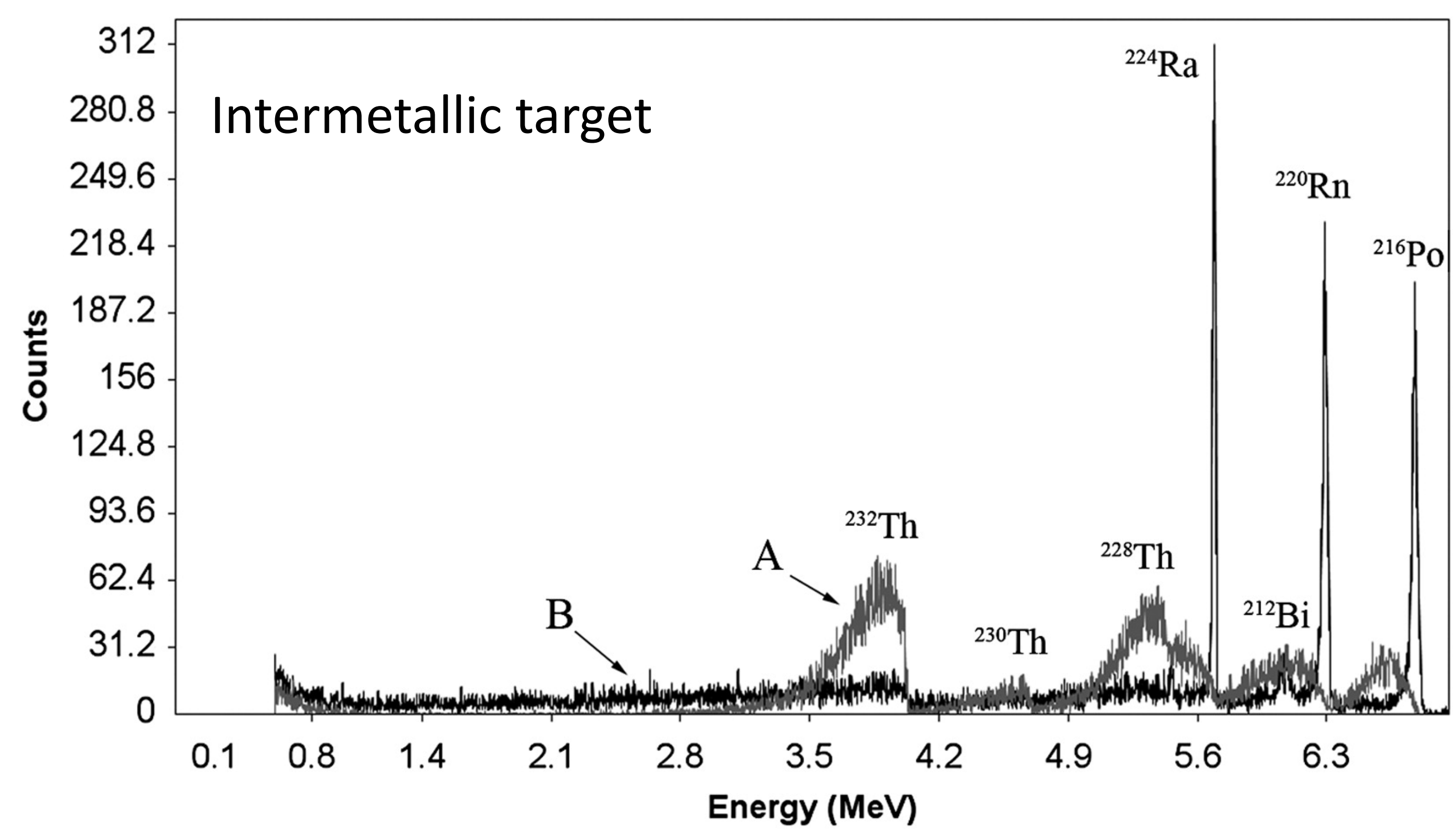
With electron veto

Developments for radioactive targets

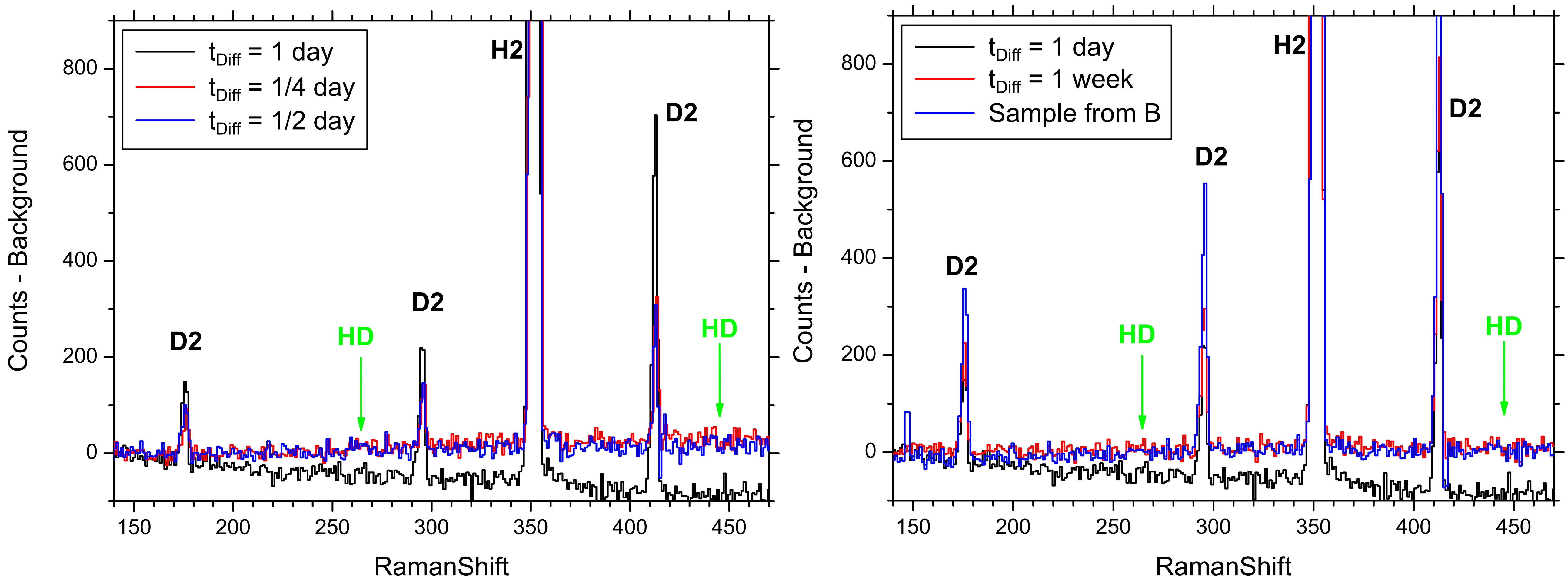




Printer for drop-on-demand

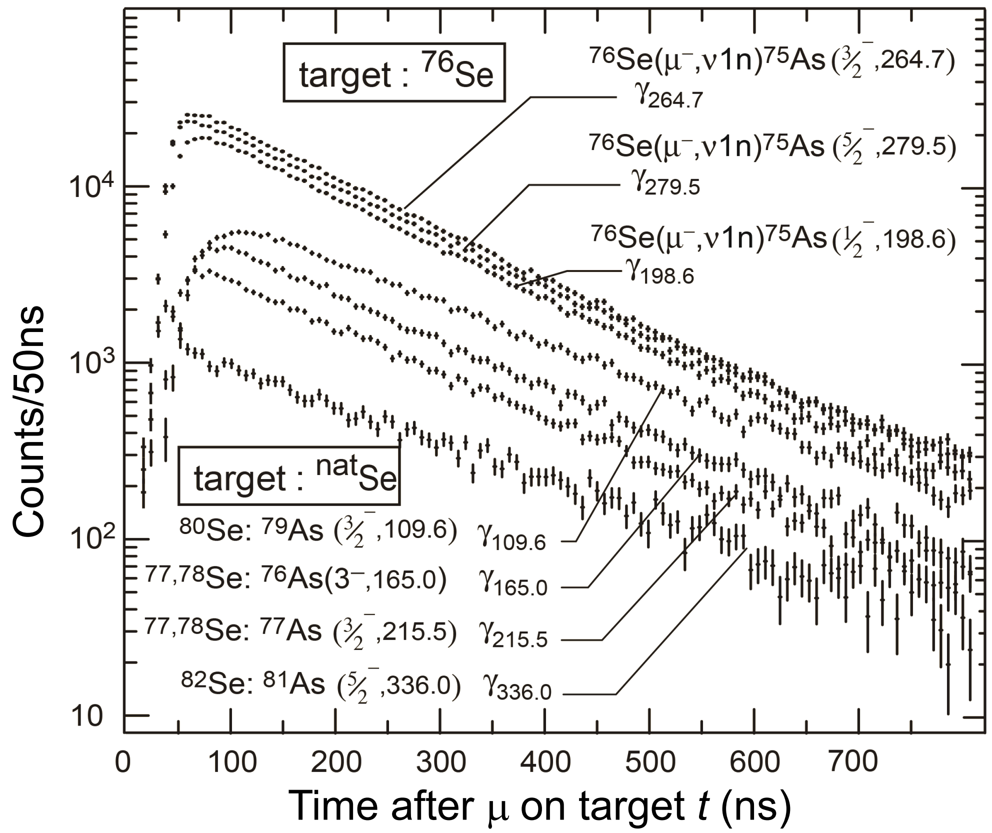


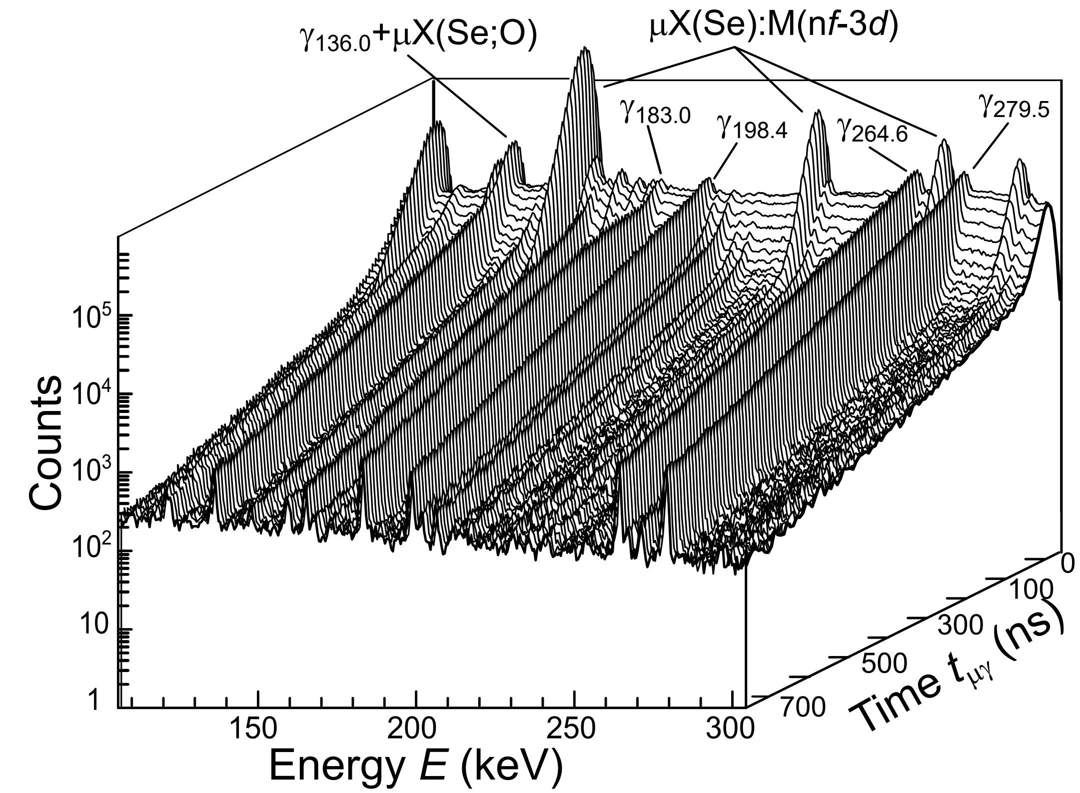
Raman spectroscopy



- Equilibration of D_2 in gas systems takes days/weeks!

Muon Capture Measurements



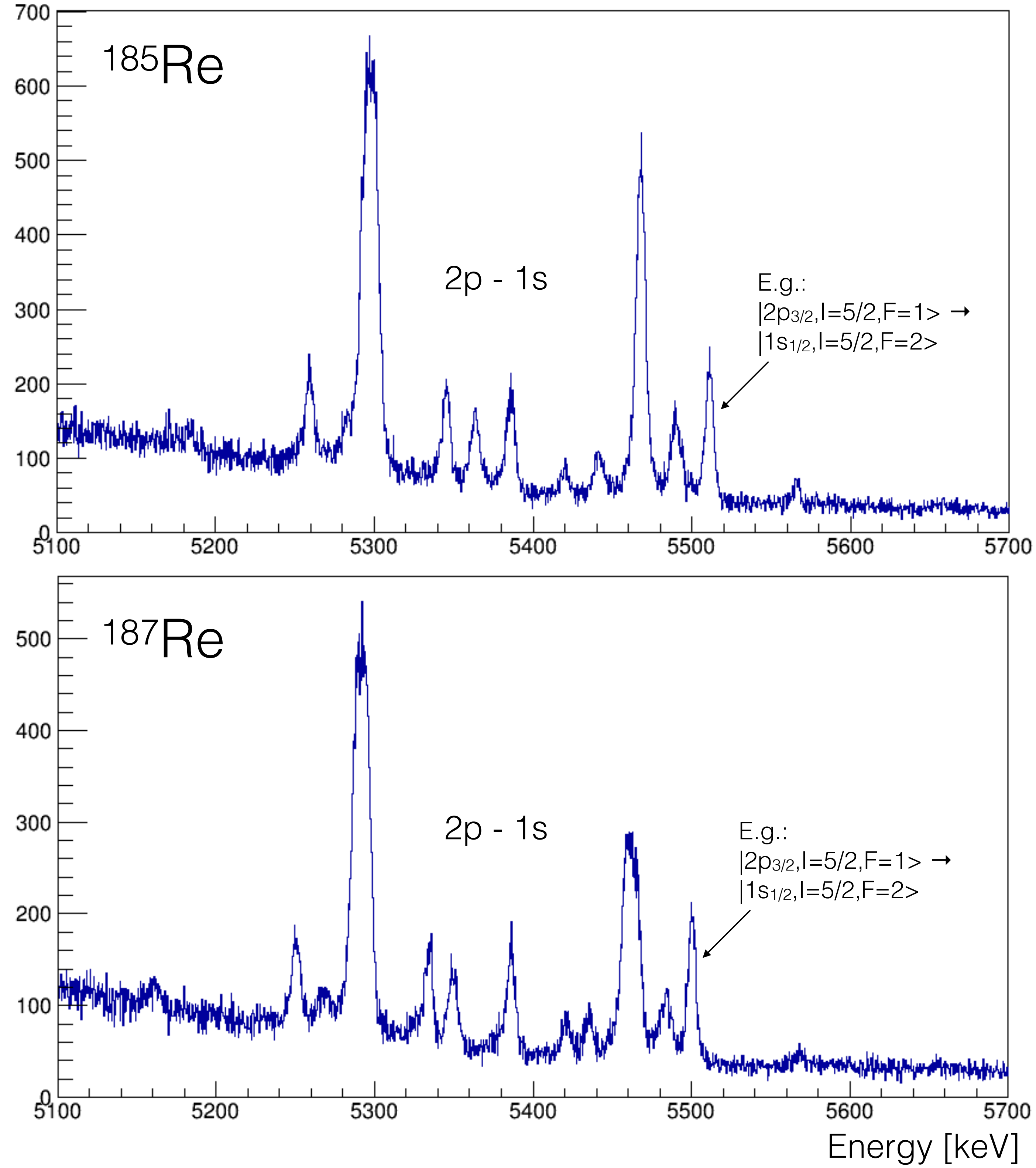


D. Zinatulina et. al *arXiv:1801.06969v2* [nucl-ex]

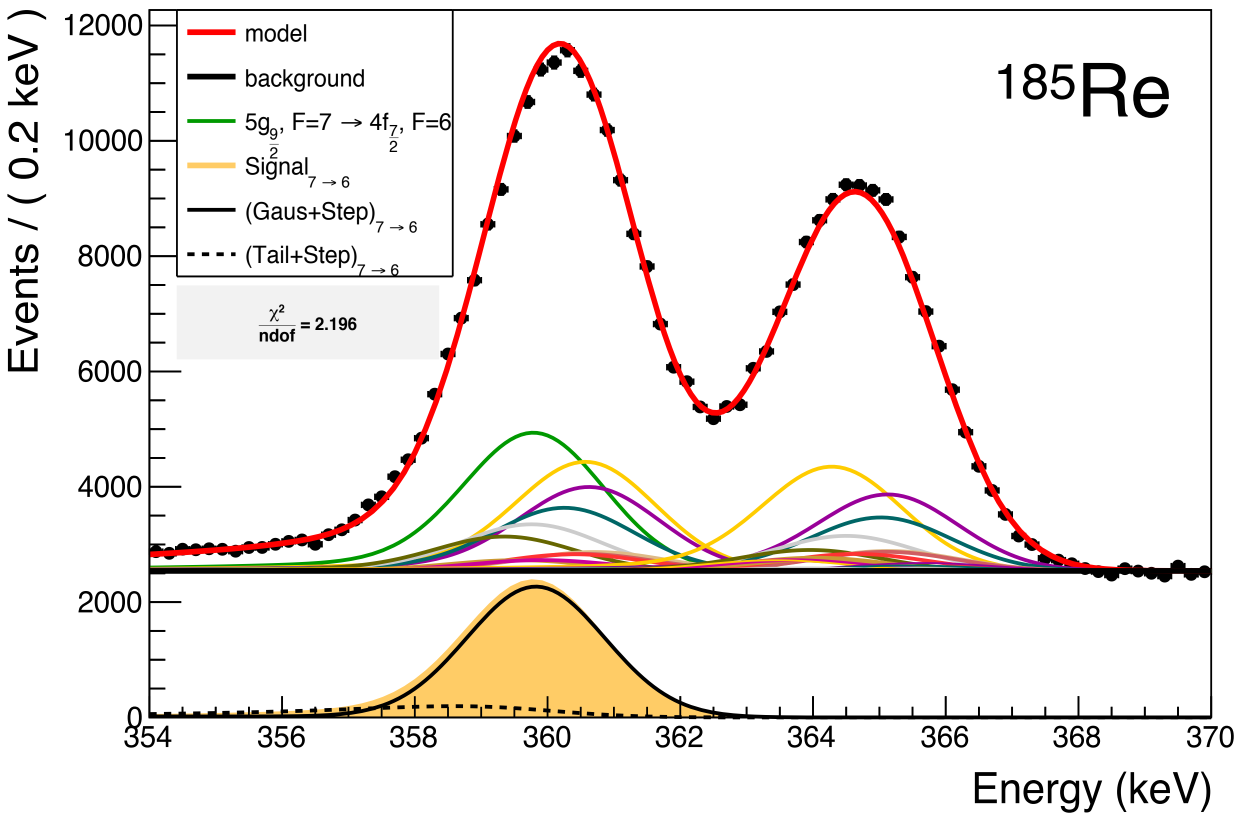
E_j [keV]	J^π	P_j^μ [%]	E_j [keV]	J^π	P_j^μ [%]	E_j [keV]	J^π	P_j^μ [%]
0.0	2^-	g.s.	499.6	$[1^+,2^-]$	0.99(36)	802.4	$(1^-,2^-,3^+)$	0.17(10)
120.3	1^+	0.32(12)	505.2	$(2,3)^+$	0.25(6)	863.3	1^+	0.27(20)
122.2	$(1)^-$	0.21(11)	517.6	$(1,2^+)$	0.24(11)	893.2	$(1^-,2^-,3^+)$	0.23(10)
165.0	$(3)^-$	0.54(31)	544.0	$(2,3)^-$	0.39(24)	924.7	$(\leq 3)^-$	0.24(10)
203.5	$(0,1)^+$	0.08(4)	610.0	$(1,2,3^-)$	0.68(20)	939.7	$(1,2,3)$	0.33(25)
280.3	$(1,2)^+$	0.11(5)	640.1	$(1^-,2^-)$	0.18(9)	958.4	≤ 3	0.13(8)
292.6	$(2,3,4)^-$	0.05(1)	669.1	$(1^+,2^+)$	0.64(20)	985.5	$(1,2,3)^+$	0.21(12)
328.5	$(3,4)^-$	0.09(4)	681.1	$(1-4)$	0.33(10)	1026.2	$[1^+,3^+]$	0.96(24)
352.4	$(3)^-$	0.05(2)	734.4	$(\leq 4)^-$	0.08(4)	1034.2	$(1,2,3)^+$	0.13(8)
401.8	$(1,2)^+$	0.41(26)	751.8	$(0^-,1,2)$	0.37(19)	1064.5	1^+	0.23(15)
436.8	$(1,2,3)^-$	0.28(13)	756.6	$(0^+,3^+)$	0.26(10)			
447.2	$(1,2)^+$	0.46(23)	774.4	$[1^+,3^+]$	0.23(11)			
471.0	$(2)^-$	0.05(4)	793.6	$(1,2,3)^+$	0.20(15)			$\sum = 11.99(105)$

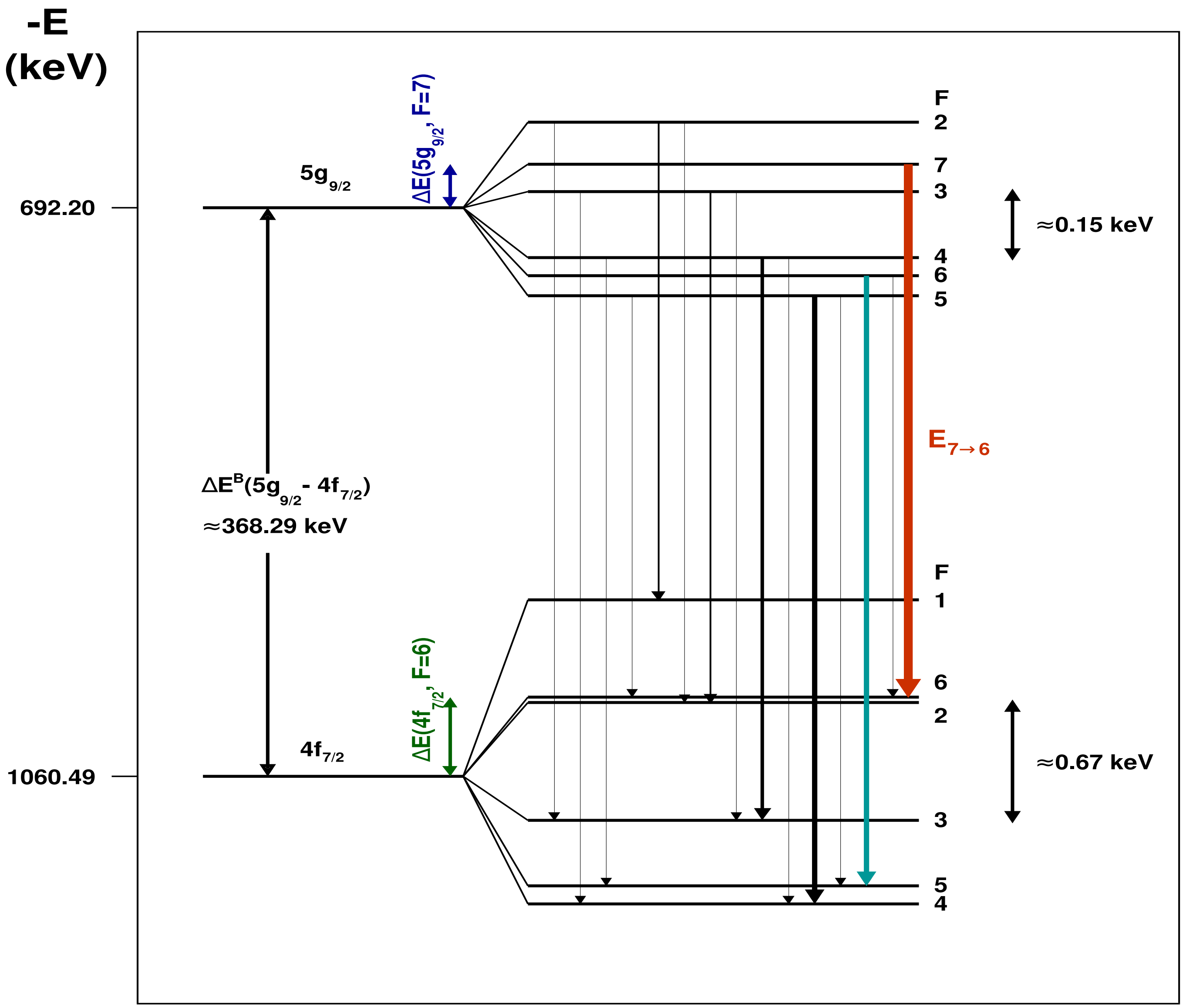
^{185}Re & ^{187}Re spectra

- Hyperfine structure + low-lying nuclear levels
- Highly complicated spectra
- Need very detailed theoretical calculations to extract nuclear properties

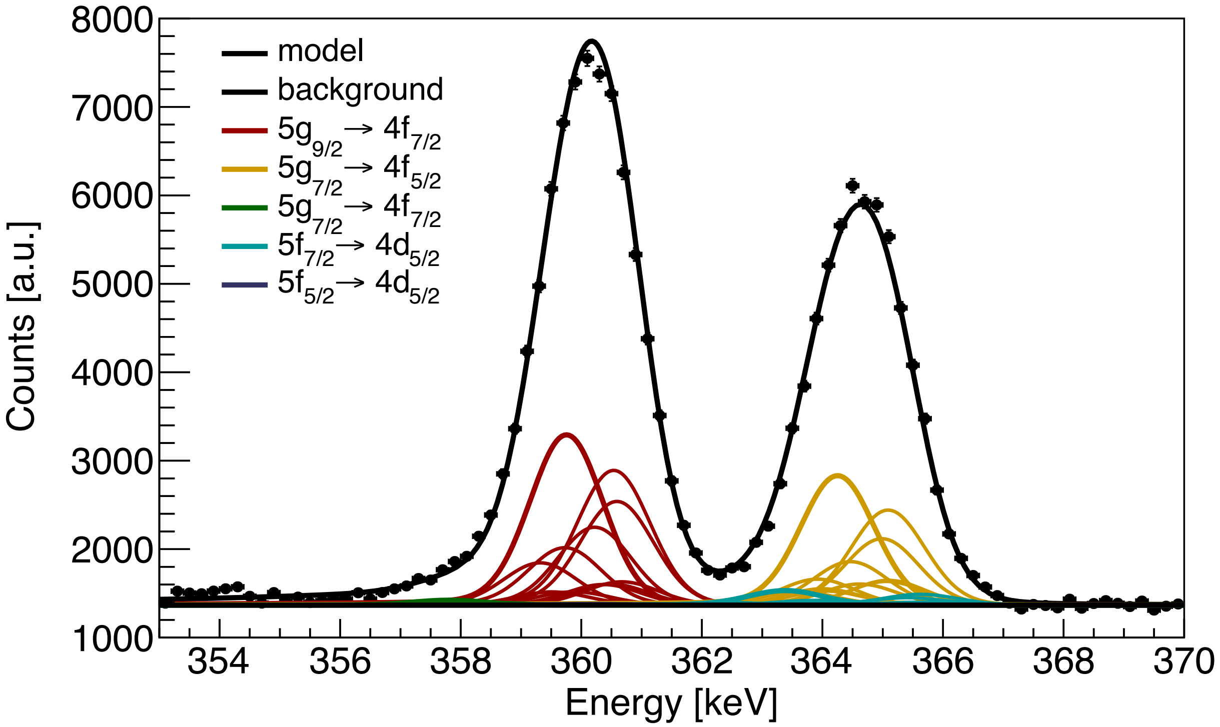


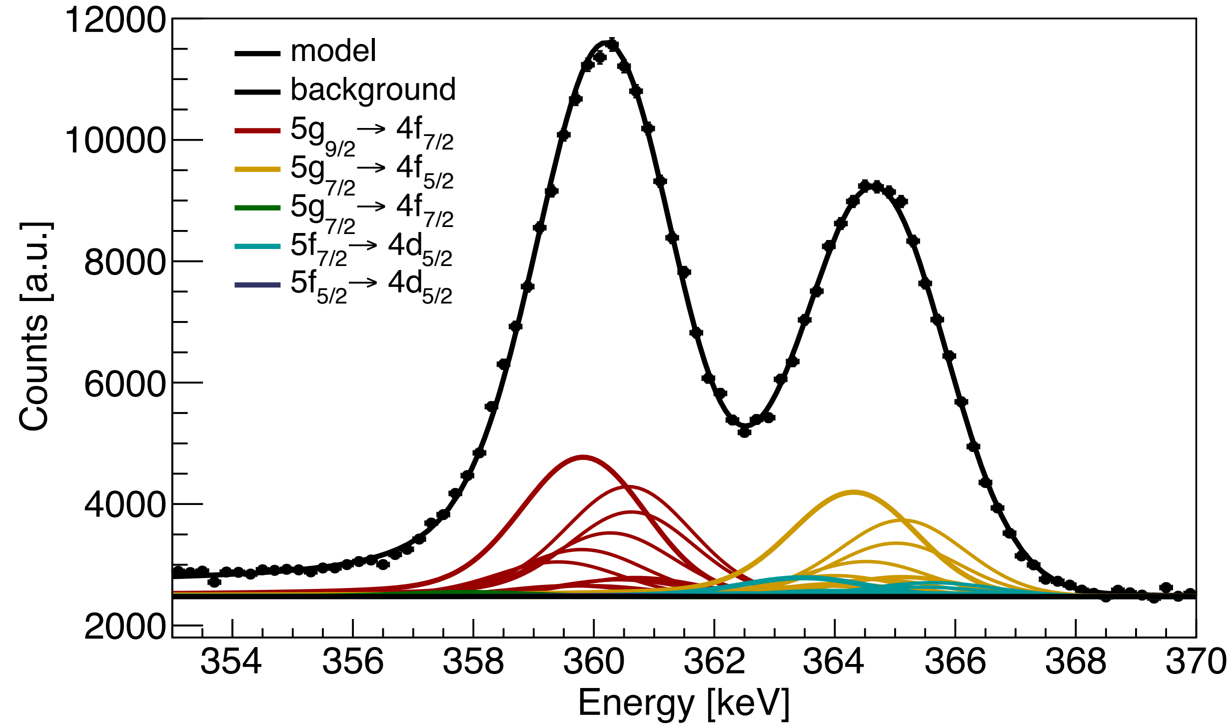
Extraction of quadrupole moments





Quadrupole Moments of ^{185,187}Re

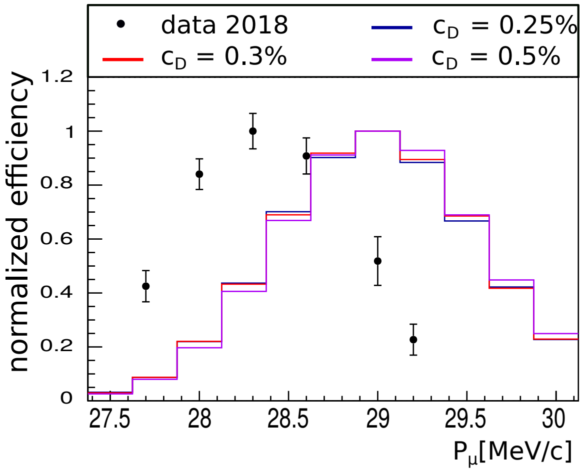




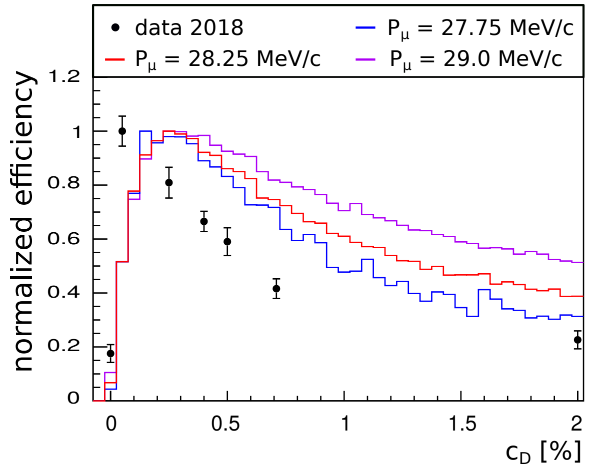
- Preliminary result on quadrupole moments of ^{185,187}Re

Nucleus	detector	Q (barn)	χ^2_{red}	Relative intensity (%)
^{185}Re	GeR	2.12(2)	2.45	9.0(8)
	GeL	2.03(4)	1.50	14.1(7)
^{187}Re	GeR	1.97(2)	1.83	12(1)
	GeL	1.93(4)	1.14	17.0(7)

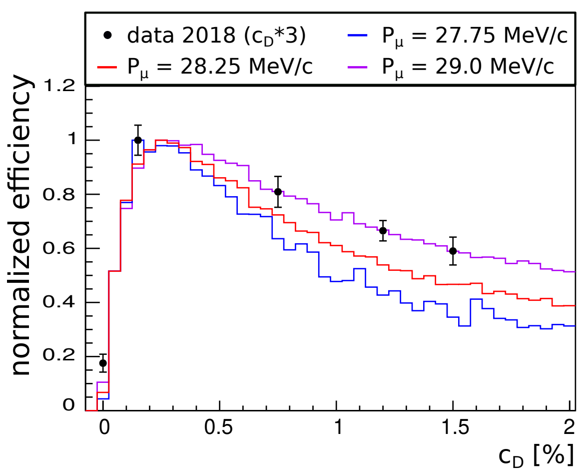
Simulations



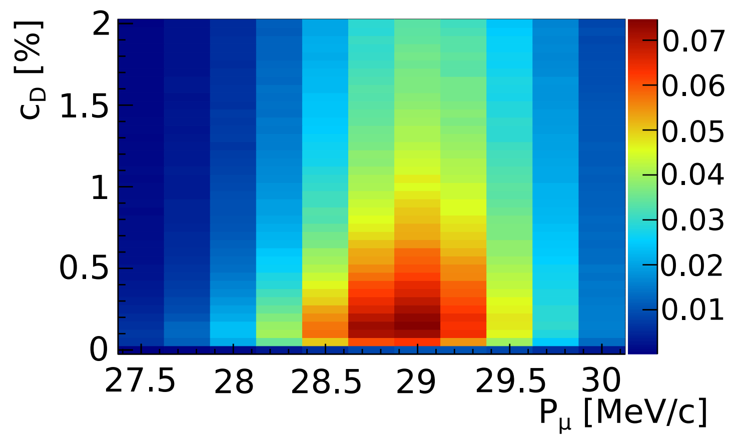
a) P_μ scan (nominal c_D=0.25%)



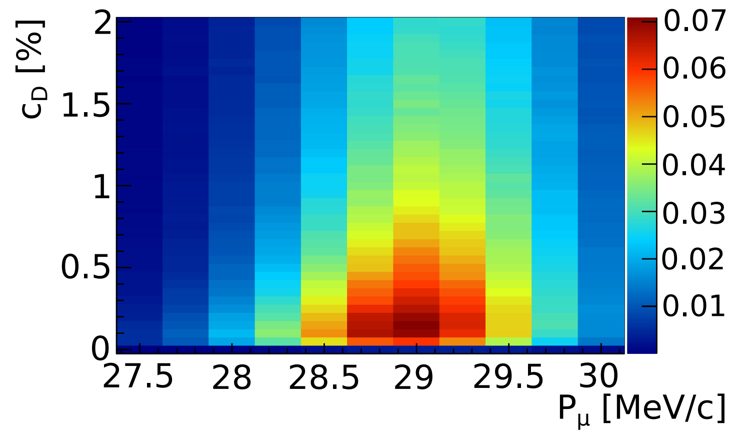
b) c_D scan (P_μ=28.6 MeV/c)



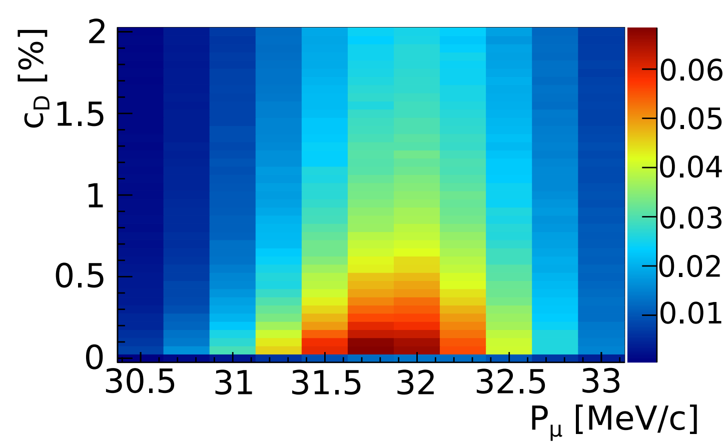
c) c_D scan, modified data



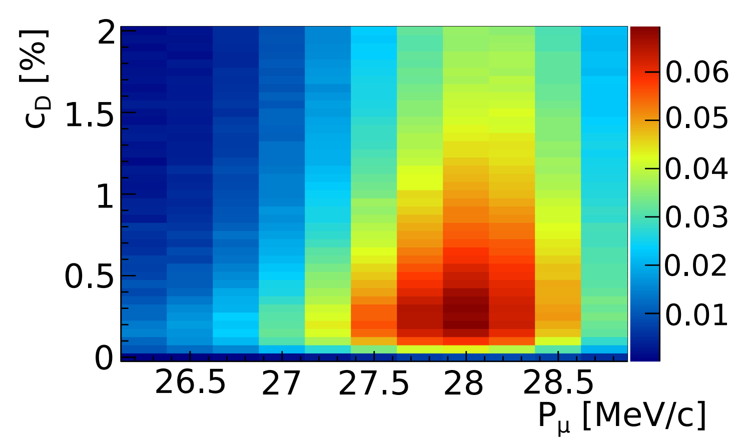
a) original muX 2018



b) T = 50 K, p = 17 bar



c) higher pressure p=300bar

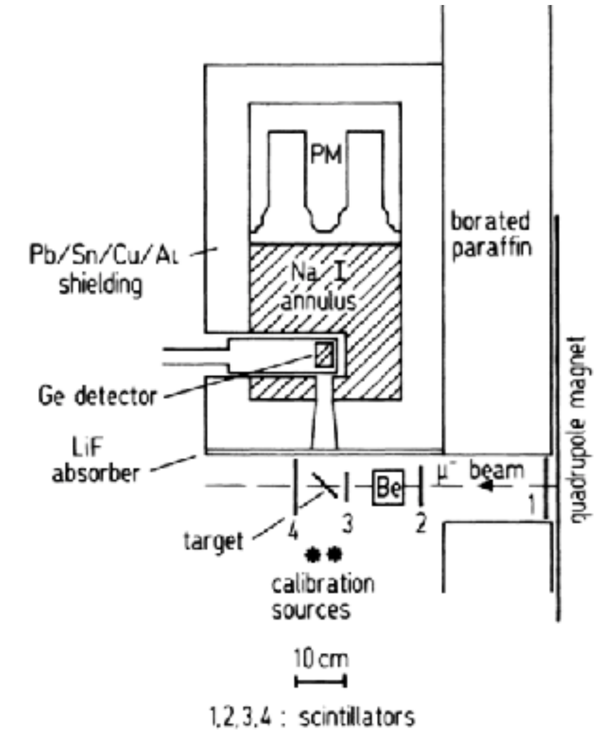


d) lower pressure p=50bar

Muonic atom spectroscopy

- Impressive precision in the extracted charge radius can be achieved
- For ^{208}Pb: $\langle r^2 \rangle^{1/2}$ = 5.5031(11) fm
  2×10^{-4} relative precision

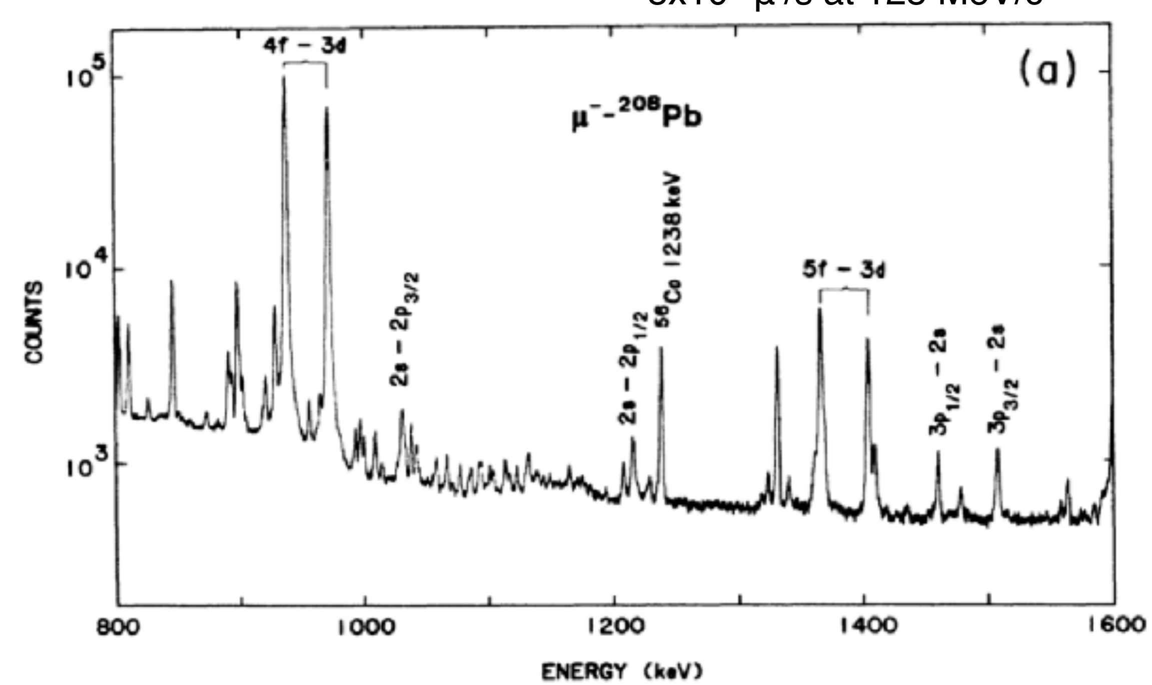
Bergem et al., PRC **37**, 2821 (1988)



μE1 channel at PSI
5×10^6 μ^-/s at 125 MeV/c

TABLE V. Experimental muonic transition energies (keV) in ^{208}Pb (recoil corrected).

Transition	Kessler (Ref. 9)	Hoehn (Ref. 27)	This experiment
$2p_{3/2}$-$1s_{1/2}$	5 962.770(420)		5 962.854(90)
$2p_{1/2}$-$1s_{1/2}$	5 777.910(400)		5 778.058(100)
$3d_{3/2}$-$2p_{1/2}$	2 642.110(60)	2642.292(23)	2 642.332(30)
$3d_{5/2}$-$2p_{3/2}$	2 500.330(60)	2500.580(28)	2 500.590(30)
$3d_{3/2}$-$2p_{3/2}$	2 457.200(200)		2 457.569(70)
$3p_{3/2}$-$2s_{1/2}$	1 507.480(260)		1 507.754(50)
$3p_{1/2}$-$2s_{1/2}$			1 460.558(32)
$2s_{1/2}$-$2p_{1/2}$	1 215.430(260)		1 215.330(30)
$2s_{1/2}$-$2p_{3/2}$	1 030.440(170)		1 030.543(27)
$5f_{5/2}$-$3d_{3/2}$	1 404.740(80)		1 404.659(20)
$5f_{7/2}$-$3d_{5/2}$	1 366.520(80)		1 366.347(19)
$5f_{5/2}$-$3d_{5/2}$			1 361.748(250)
$4f_{5/2}$-$3d_{3/2}$	971.850(60)	971.971(16)	971.974(17)
$4f_{7/2}$-$3d_{5/2}$	937.980(60)	938.113(13)	938.096(18)
$4f_{5/2}$-$3d_{5/2}$			928.883(14)
$4d_{3/2}$-$3p_{1/2}$			920.959(28)
$4d_{5/2}$-$3p_{3/2}$			891.383(22)
$4d_{3/2}$-$3p_{3/2}$			873.761(63)

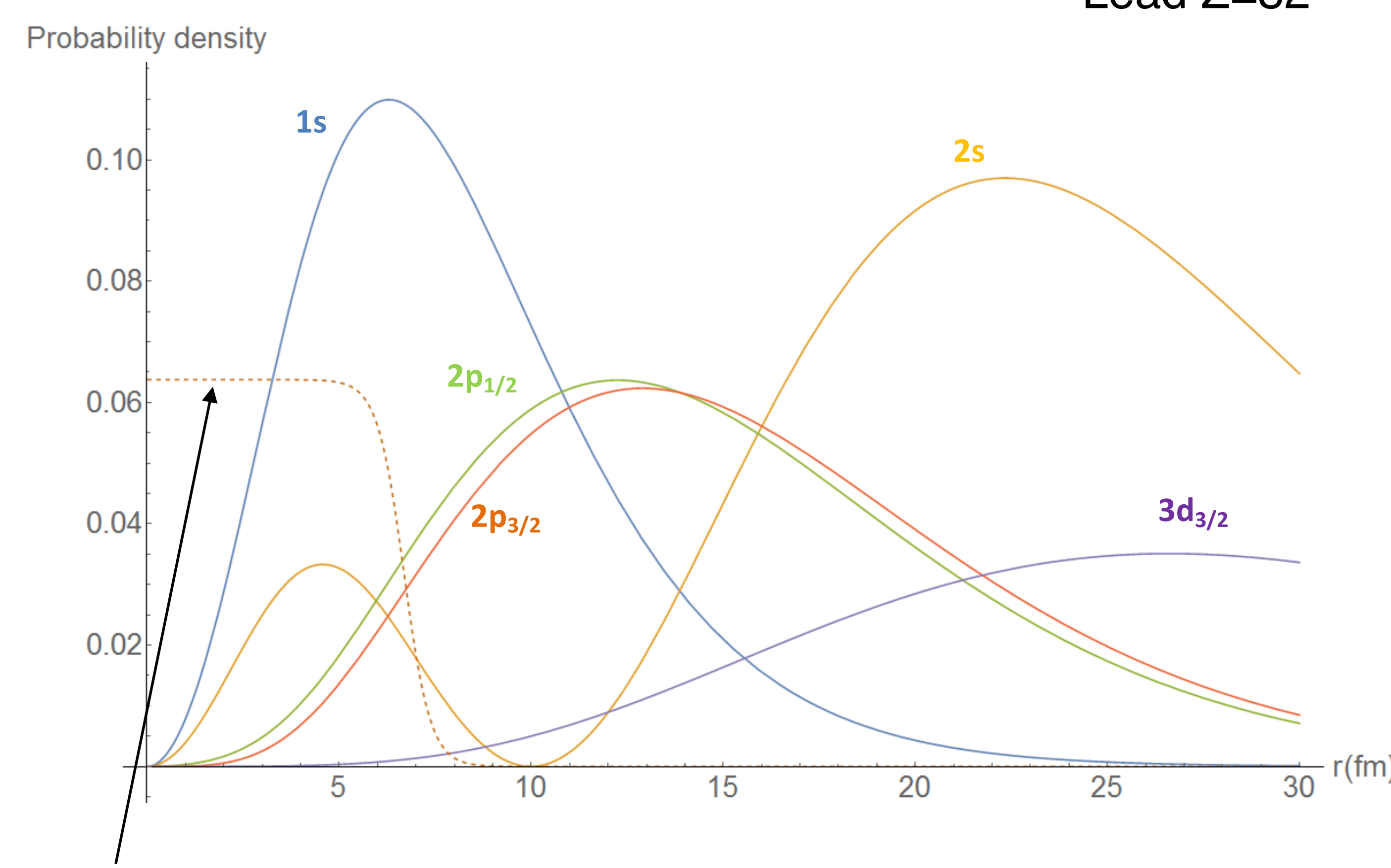


Muonic atom spectroscopy

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

- Using QED calculations and model for nuclear charge distribution allows to extract charge radius

Lead Z=82

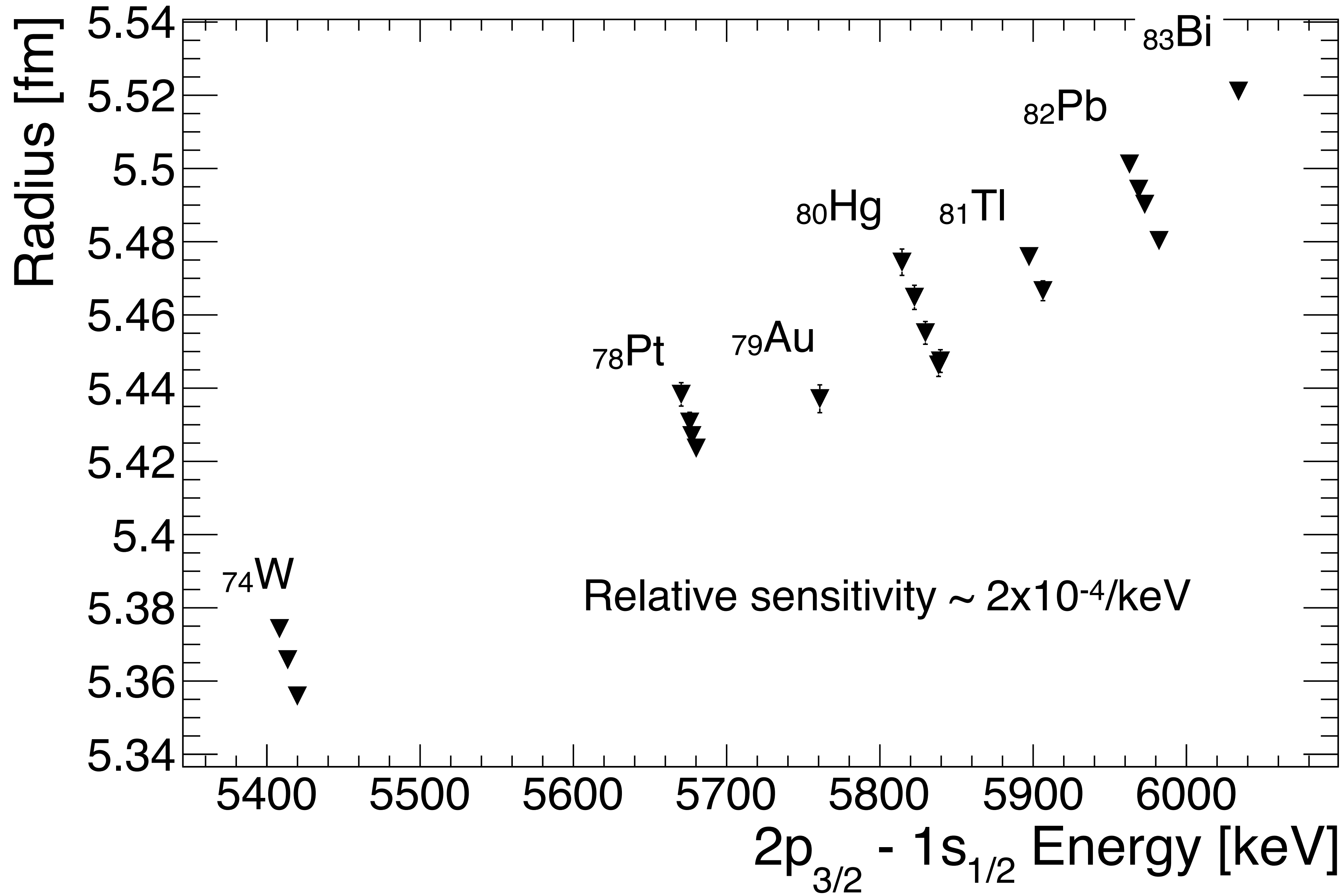


charge distribution

Large effect:

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

Muonic atom spectroscopy



- 2p - 1s energy is highly sensitive to charge radius
- What is the limiting factor?

Muonic atom spectroscopy

PAUL SCHERRER INSTITUT

- 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

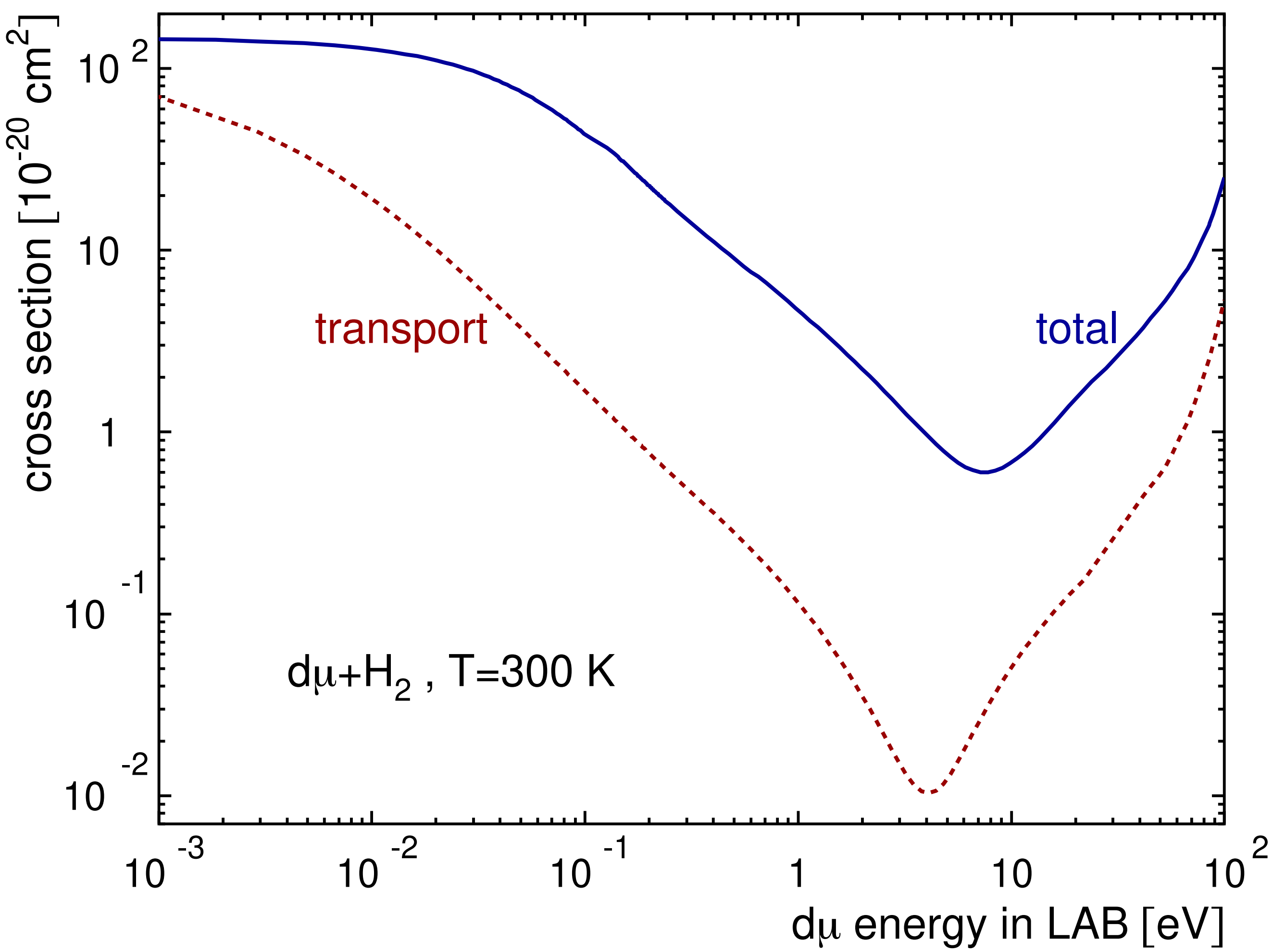
TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

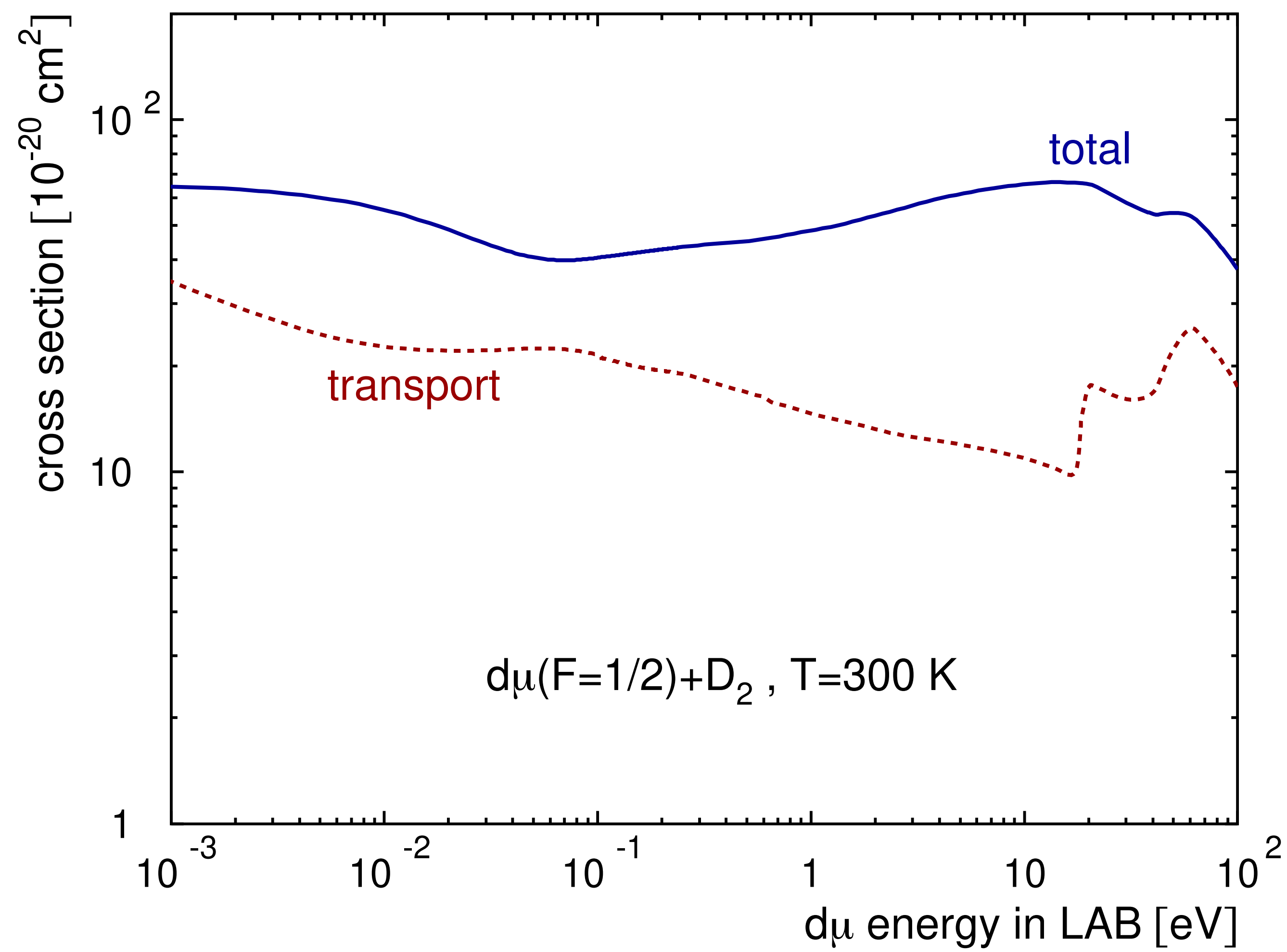
Energy (MeV)	I^{π}	$B(E\lambda)\uparrow$ ($e^2b^{2\lambda}$)	$1s_{1/2}$ (eV)	$2s_{1/2}$ (eV)	$2p_{1/2}$ (eV)	$2p_{3/2}$ (eV)	$3p_{1/2}$ (eV)	$3p_{3/2}$ (eV)	$3d_{3/2}$ (eV)	$3d_{5/2}$ (eV)
2.615	3^-	0.612	135	12	90	84	26	26	111	−63
4.085	2^+	0.318	198	20	182	180	76	84	6	4
4.324	4^+	0.155	14	1	8	7	2	2	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)

Scattering cross sections

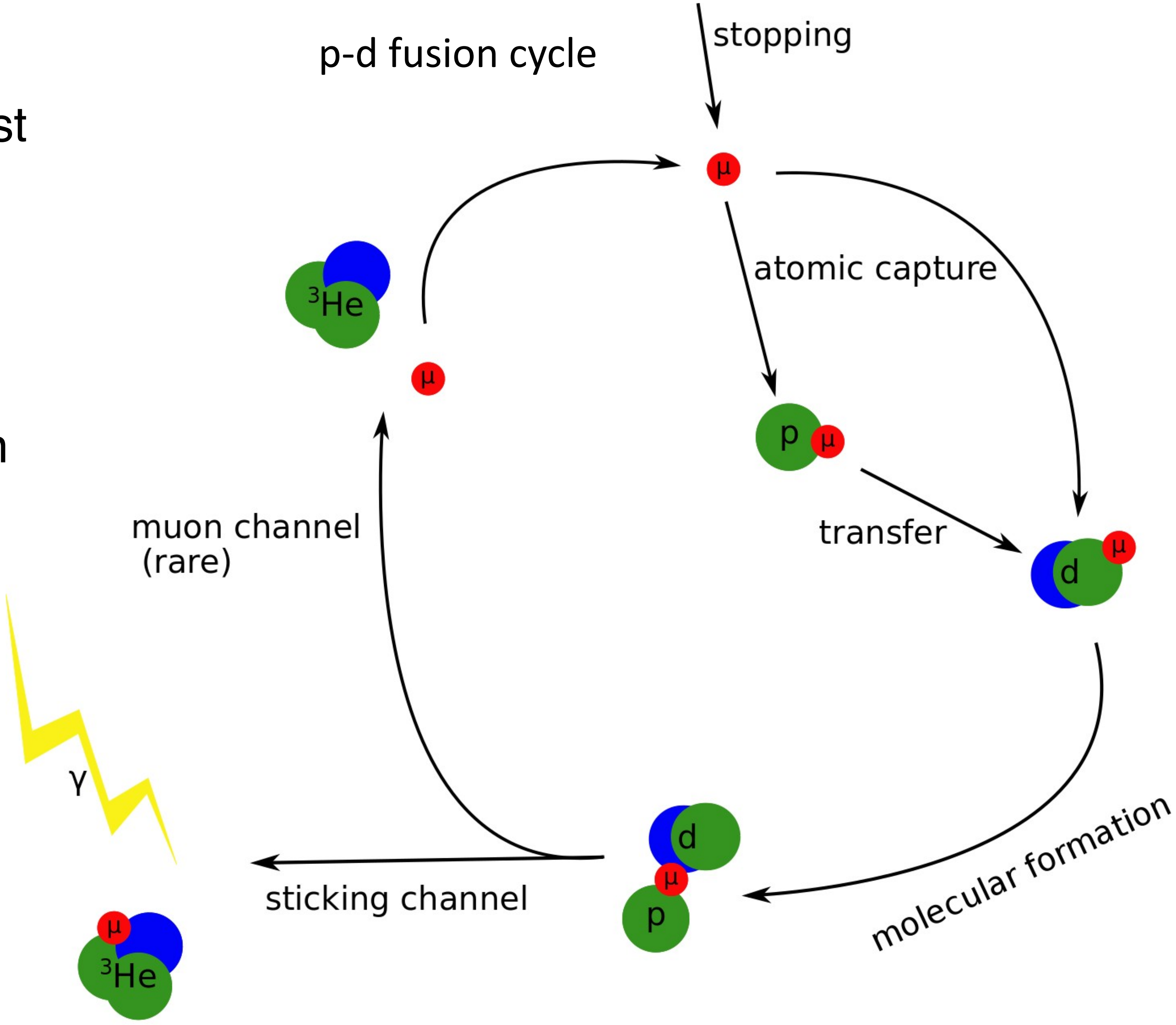




- Scattering on deuterium does not show a Ramsauer-Townsend minimum
- Need to be careful to not have too much deuterium in the gas mixture

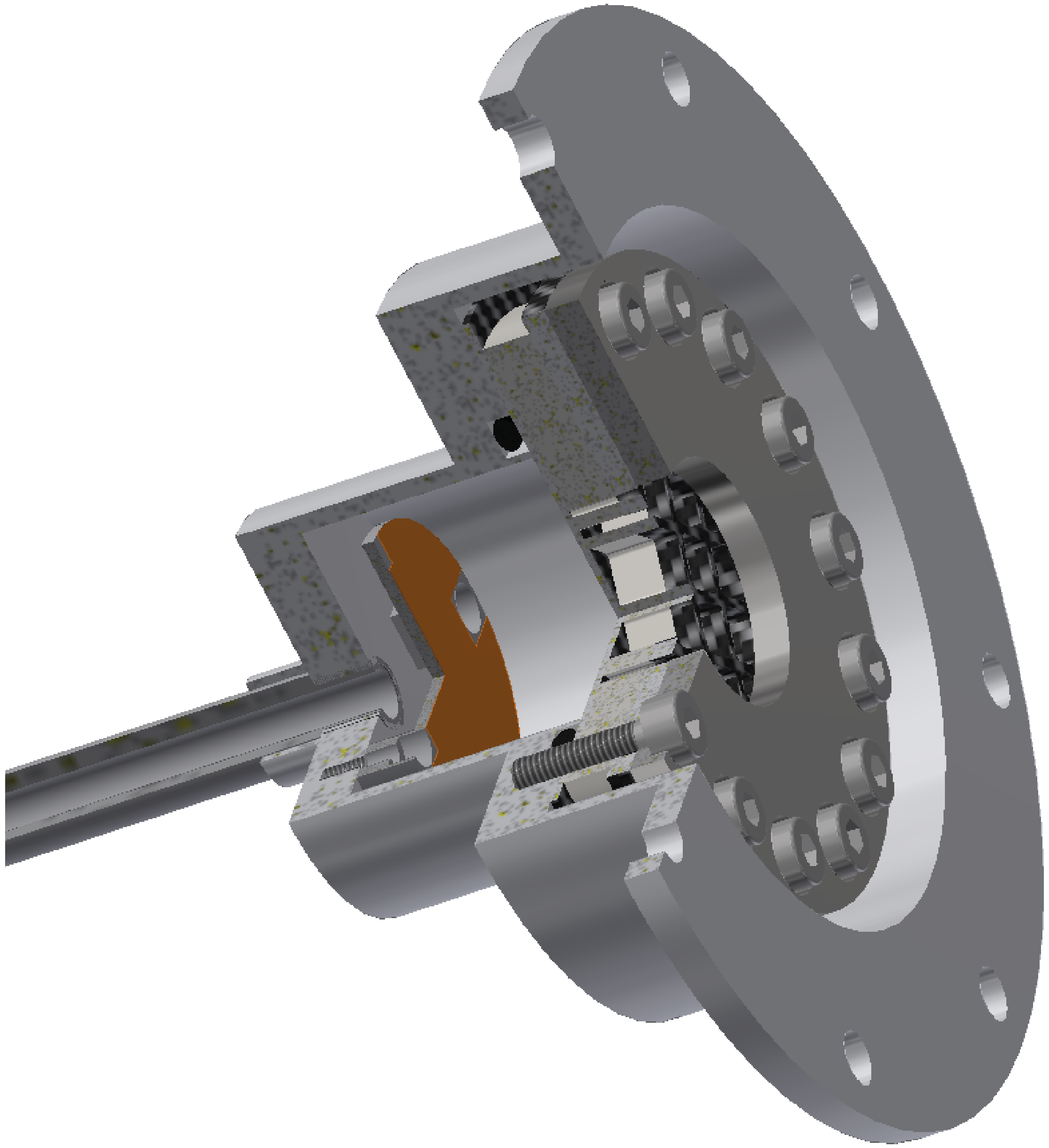
Muon catalysed fusion

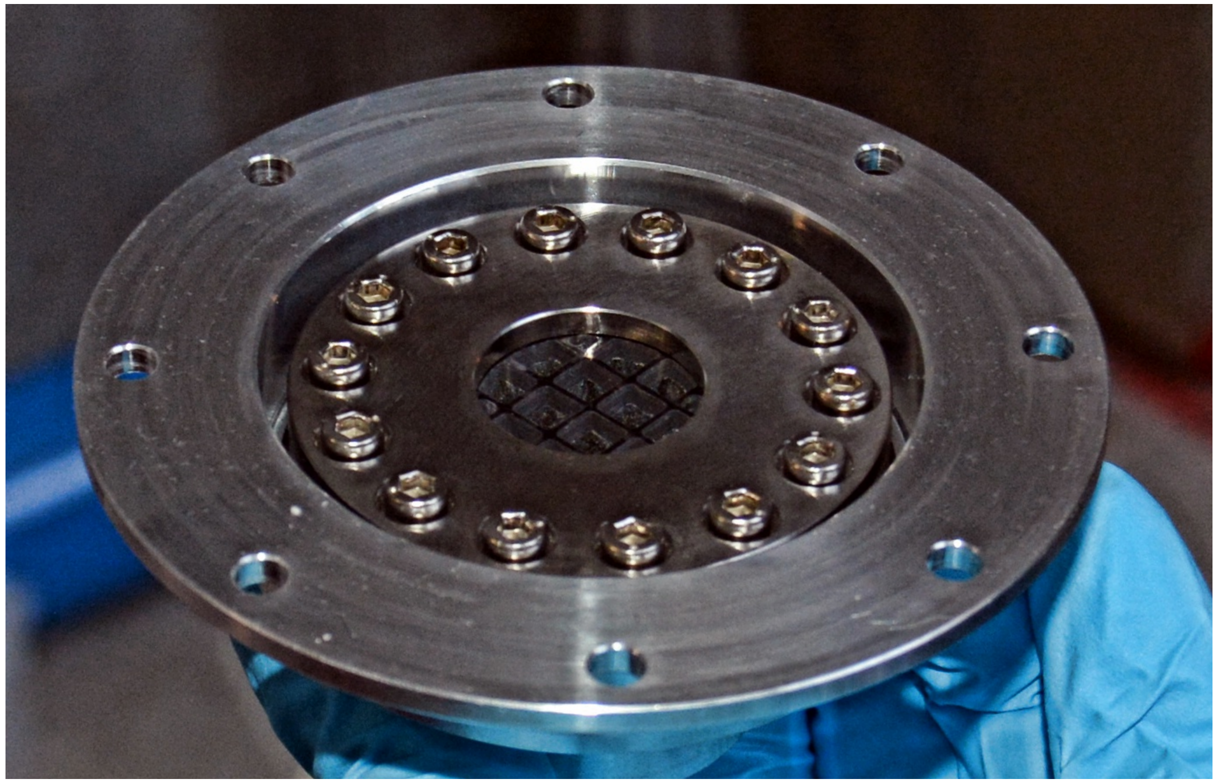
- Lot of experience on behaviour of muons in hydrogen gas due to past work on muon catalysed fusion
- Most efficient cycle:
  d-t fusion, up to 150 fusions per muon
- Not enough for energy break-even



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 onto the back of the cell

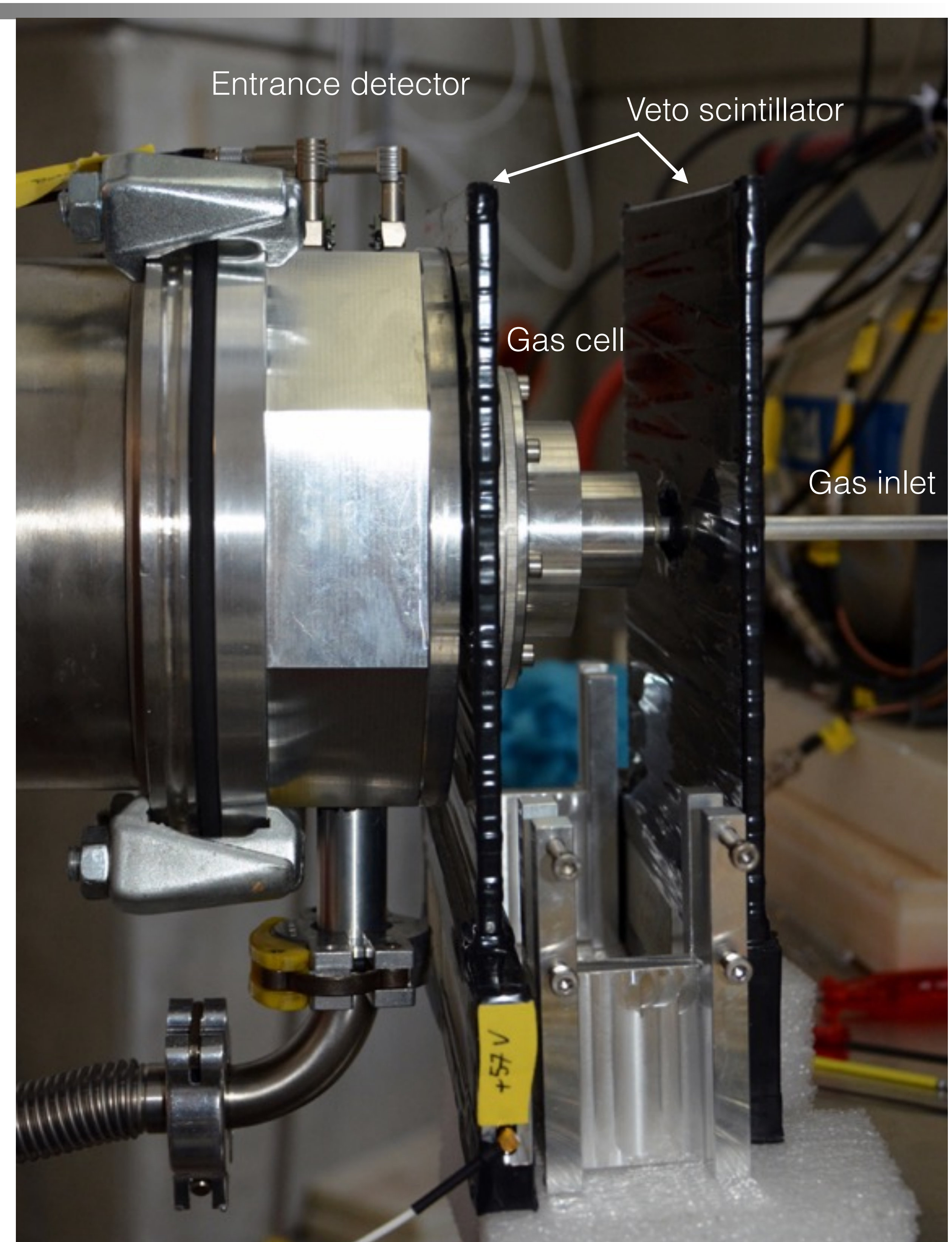




Entrance & veto detectors

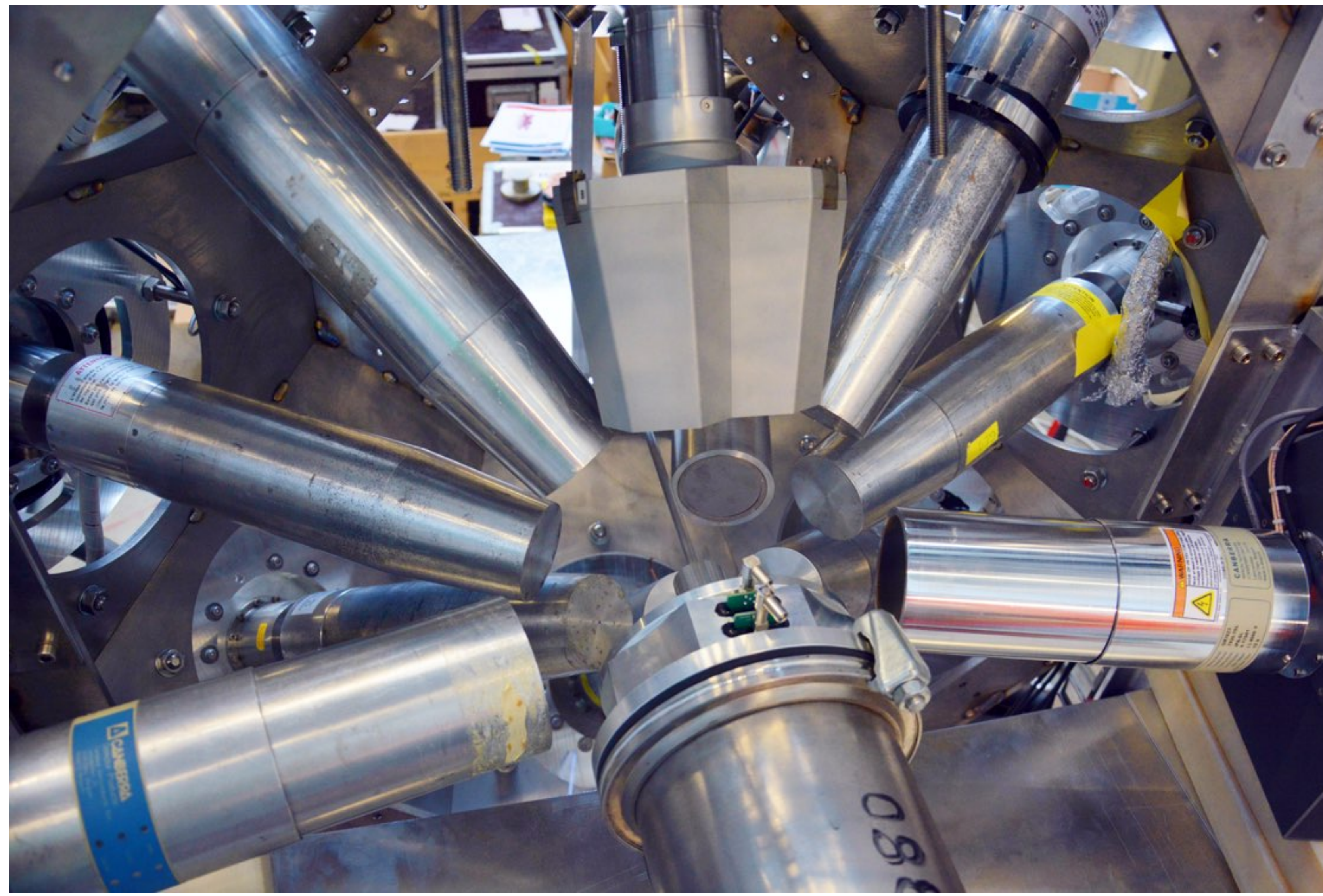
- Entrance detector to see incoming muon

- Veto scintillators to form anti-coincidence with decay electron

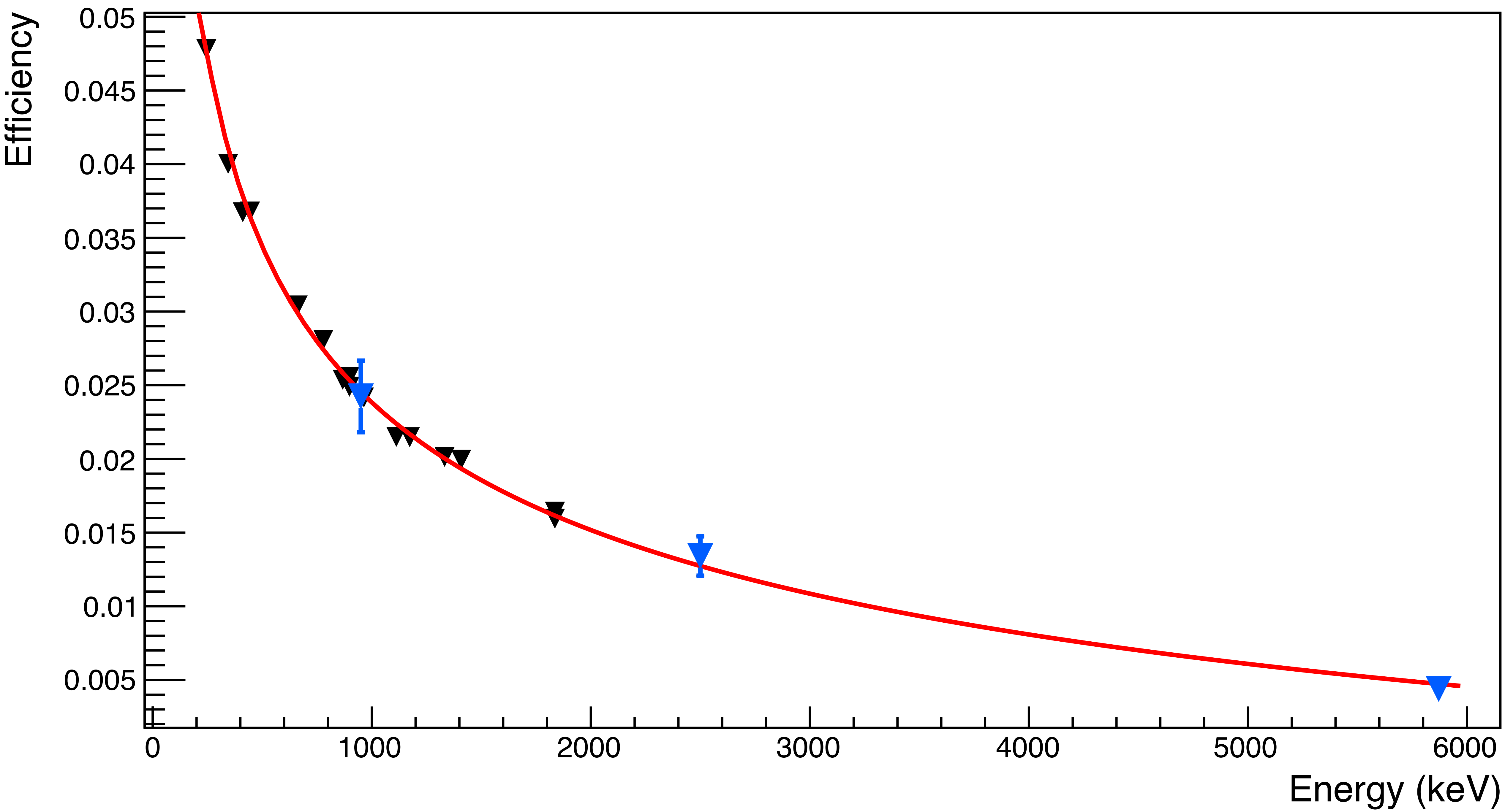


Germanium array

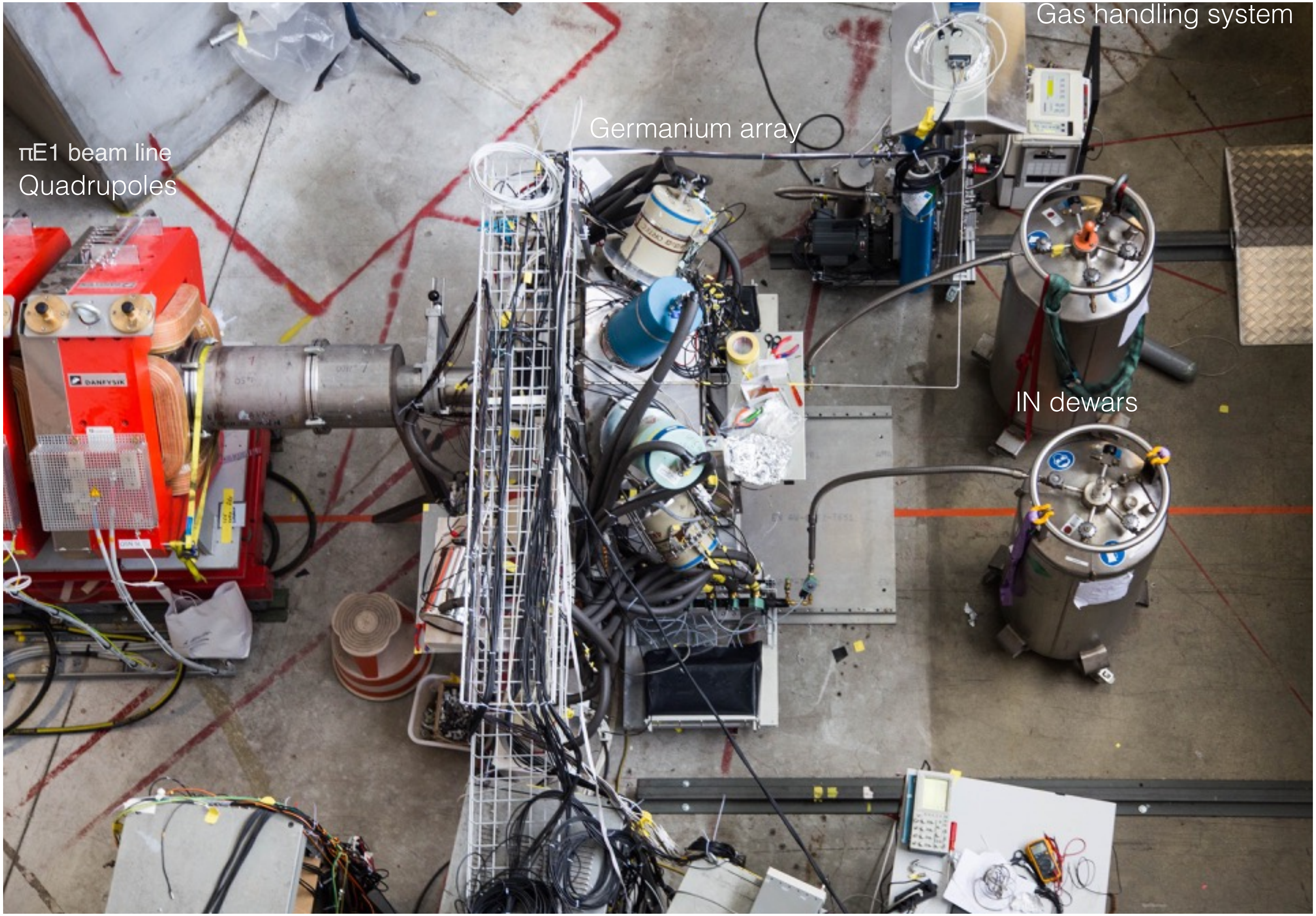
- 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI
- First time a large array is used for muonic atom spectroscopy



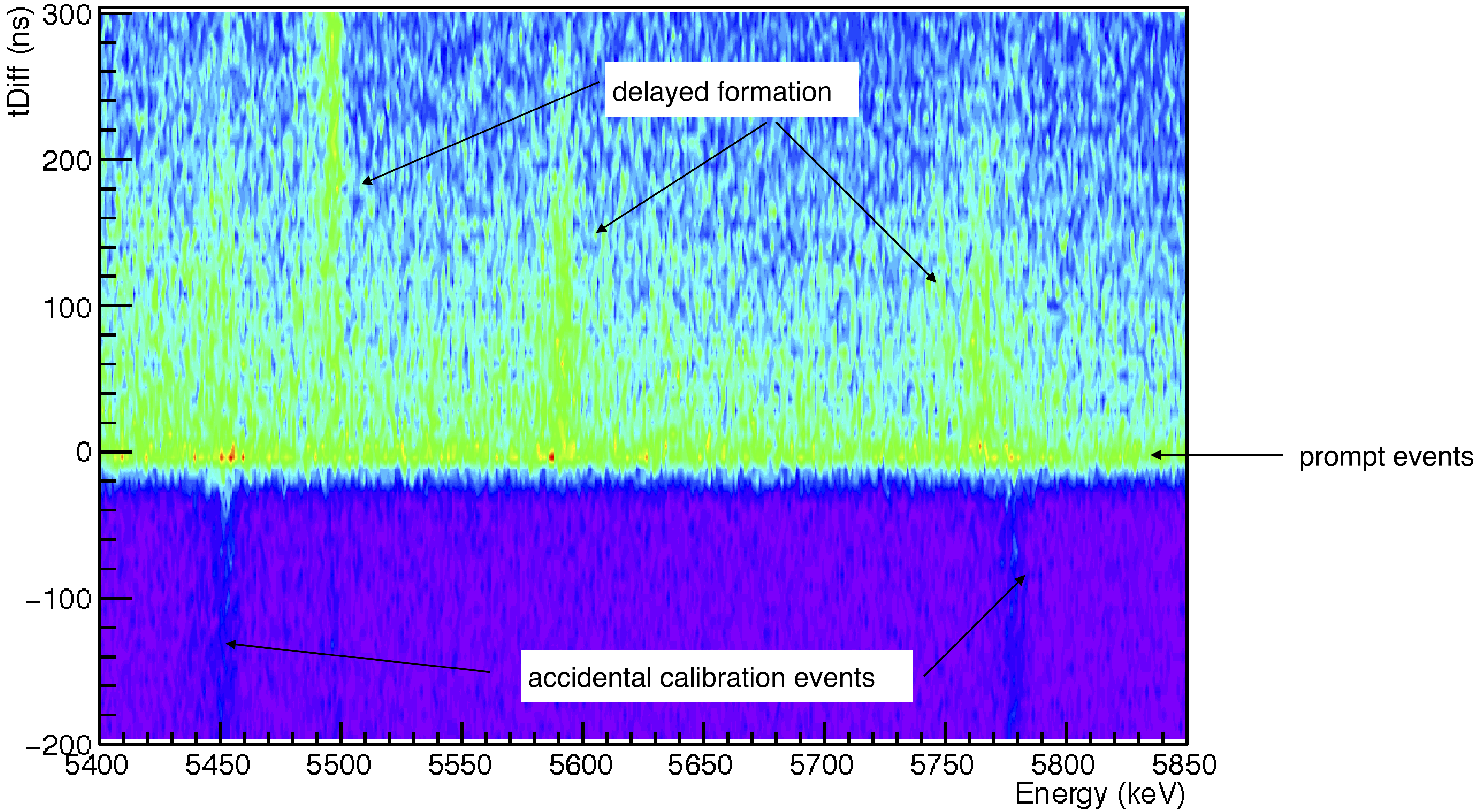
Array Detection Efficiency



Experimental setup 2017/2018

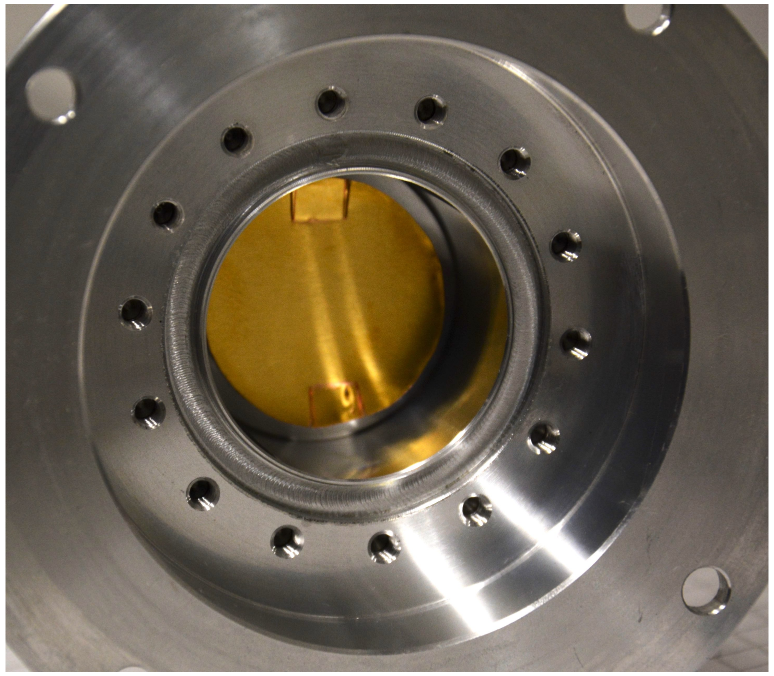


Energy vs. time spectra



- DAQ is free-running and recording every detector with a timestamp
- Sorting germanium detector hits in time after muon entrance hit

Understanding target conditions

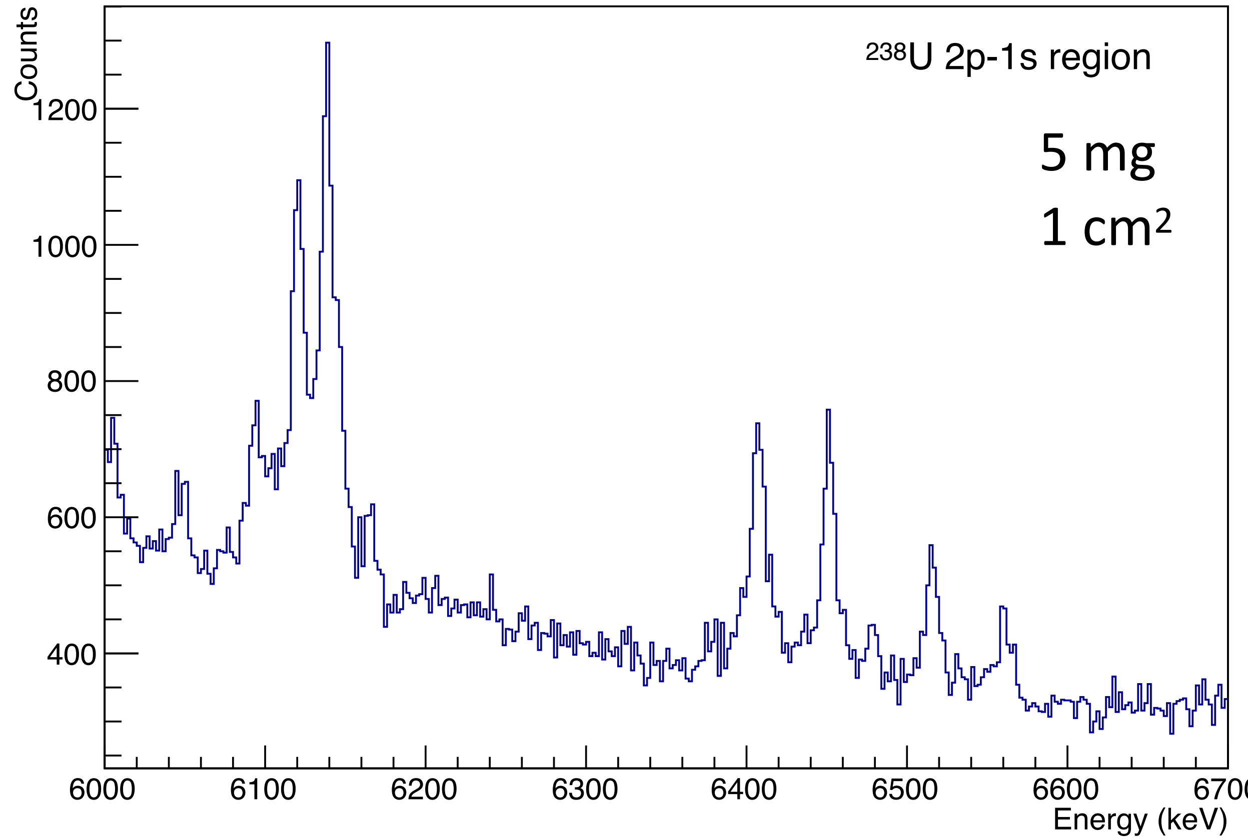


Target	Size	Backing	N_γ / N_μ	ϵ
50 nm Au	4.9 cm^2	Cu	$(10.9 \pm 0.3) \times 10^{-5}$	10.0%
10 nm Au	4.9 cm^2	Cu	$(6.9 \pm 0.2) \times 10^{-5}$	6.3%
3 nm Au	4.9 cm^2	Cu	$(3.6 \pm 0.1) \times 10^{-5}$	3.3%
3 nm Au	4.9 cm^2	kapton	$(3.2 \pm 0.1) \times 10^{-5}$	2.9%
3 nm Au	1 cm^2	Cu	$(1.3 \pm 0.1) \times 10^{-5}$	1.2%

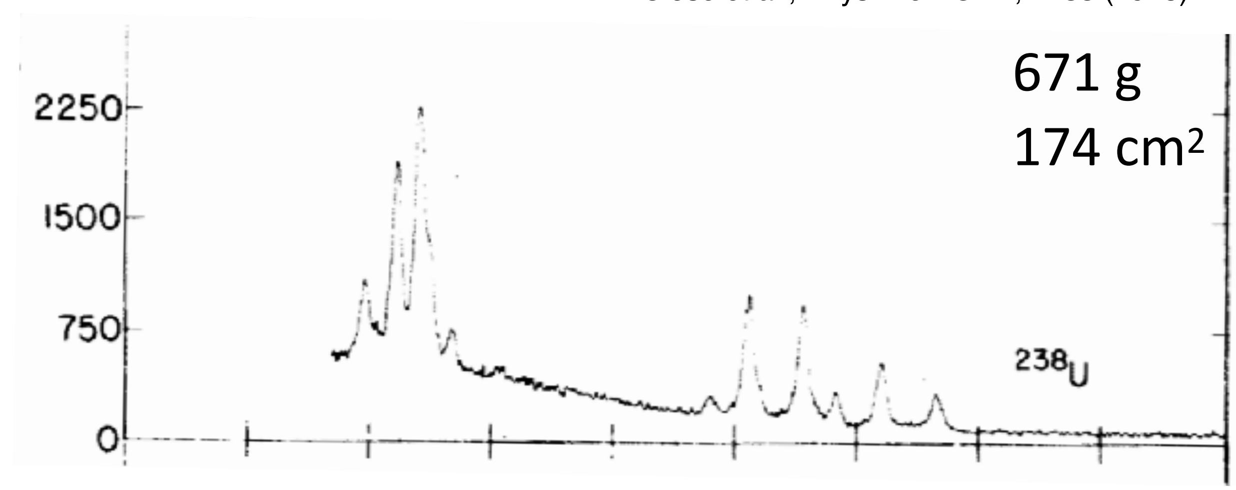
- Detected 2p-1s gammas per incoming muon for various targets
- Not all µd converted in thin targets
- Impact of backing material small
- Can still reliably see gammas from 5 µg gold target (1 cm^2, 3 nm)

Measurement with uranium

- Measurement with ~5 mg uranium as a test for handling radioactive materials in our setup
- Complicated spectrum due to hyperfine splitting plus low-lying nuclear excitations
- ^{226}Ra will look very similar



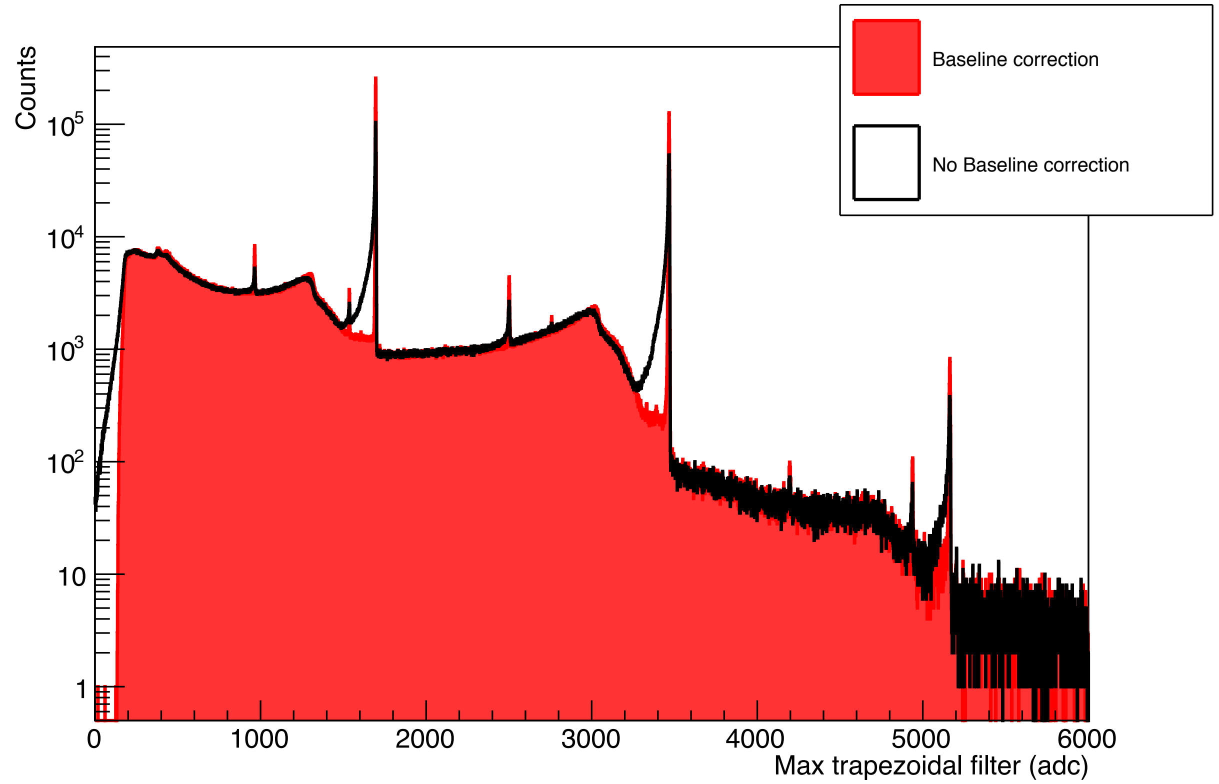
Close et al., Phys. Rev. C **17**, 1433 (1978)

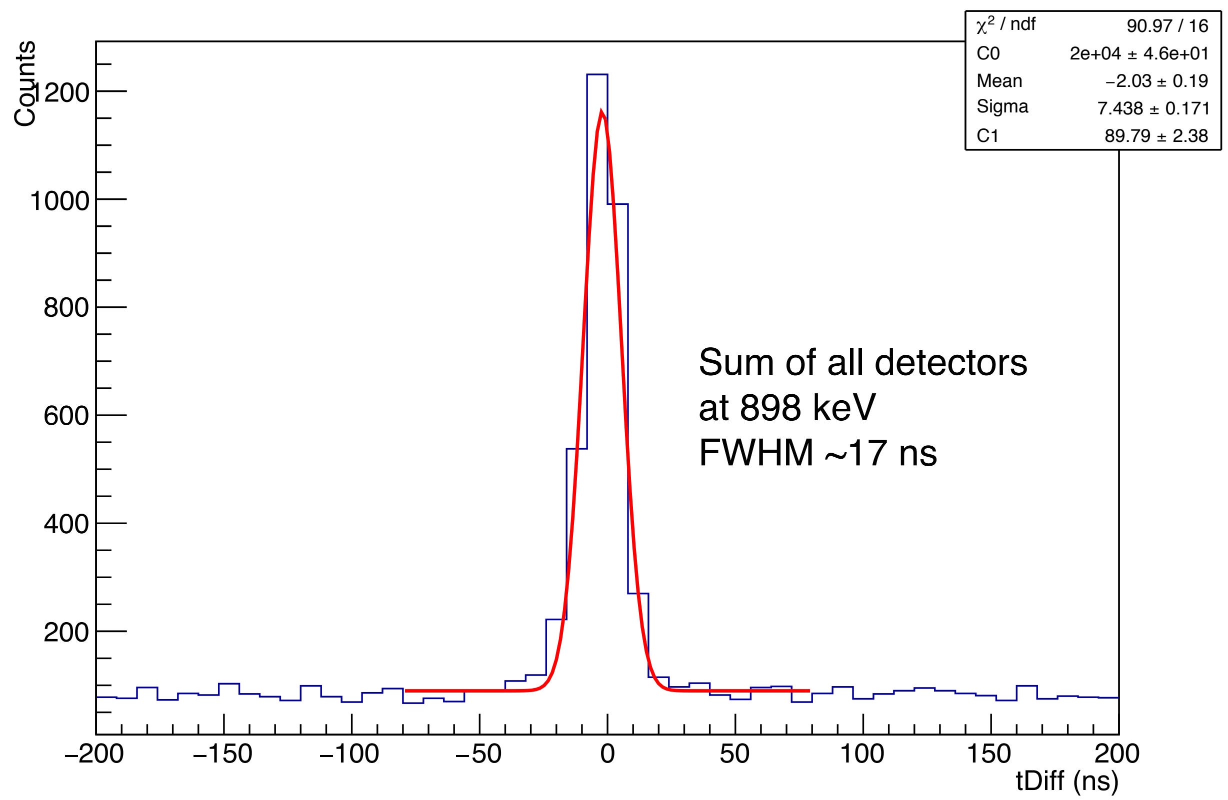


⇨ Similar performance as in the past but a factor 10^5 less target material

Measurement with high rates

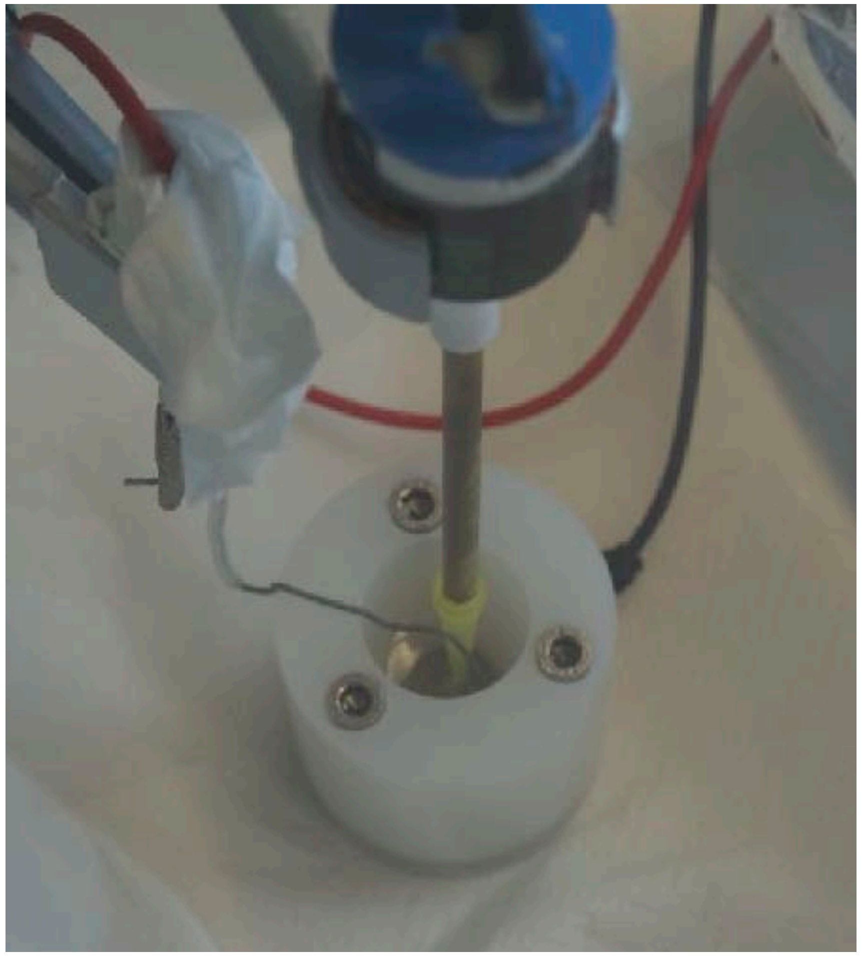
- Performed measurements with strong ^{88}Y source producing 420 kHz gammas comparable to ^{226}Ra target
- Able through offline analysis to improve energy and time resolution
- DAQ able to cope with data rate

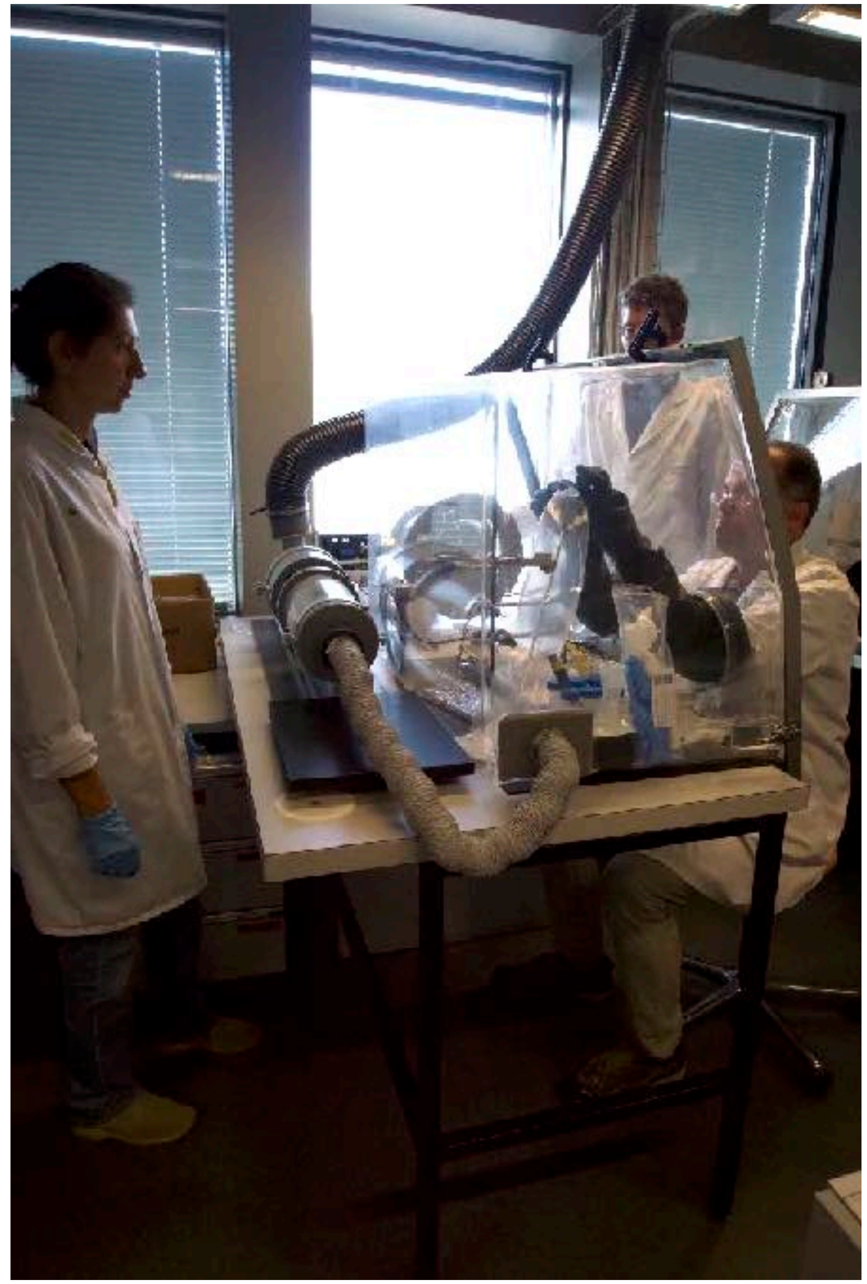


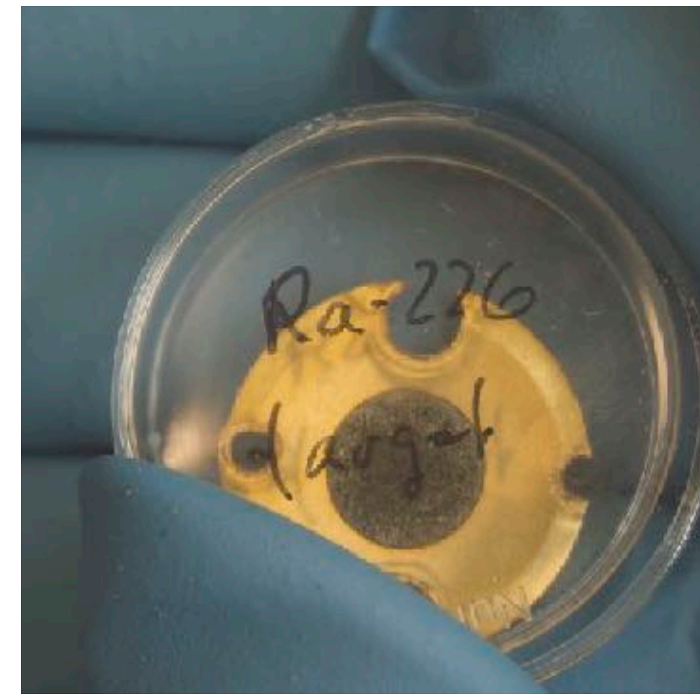


⇒ Experiment is ready for measurements with radioactive targets!

Making radium target

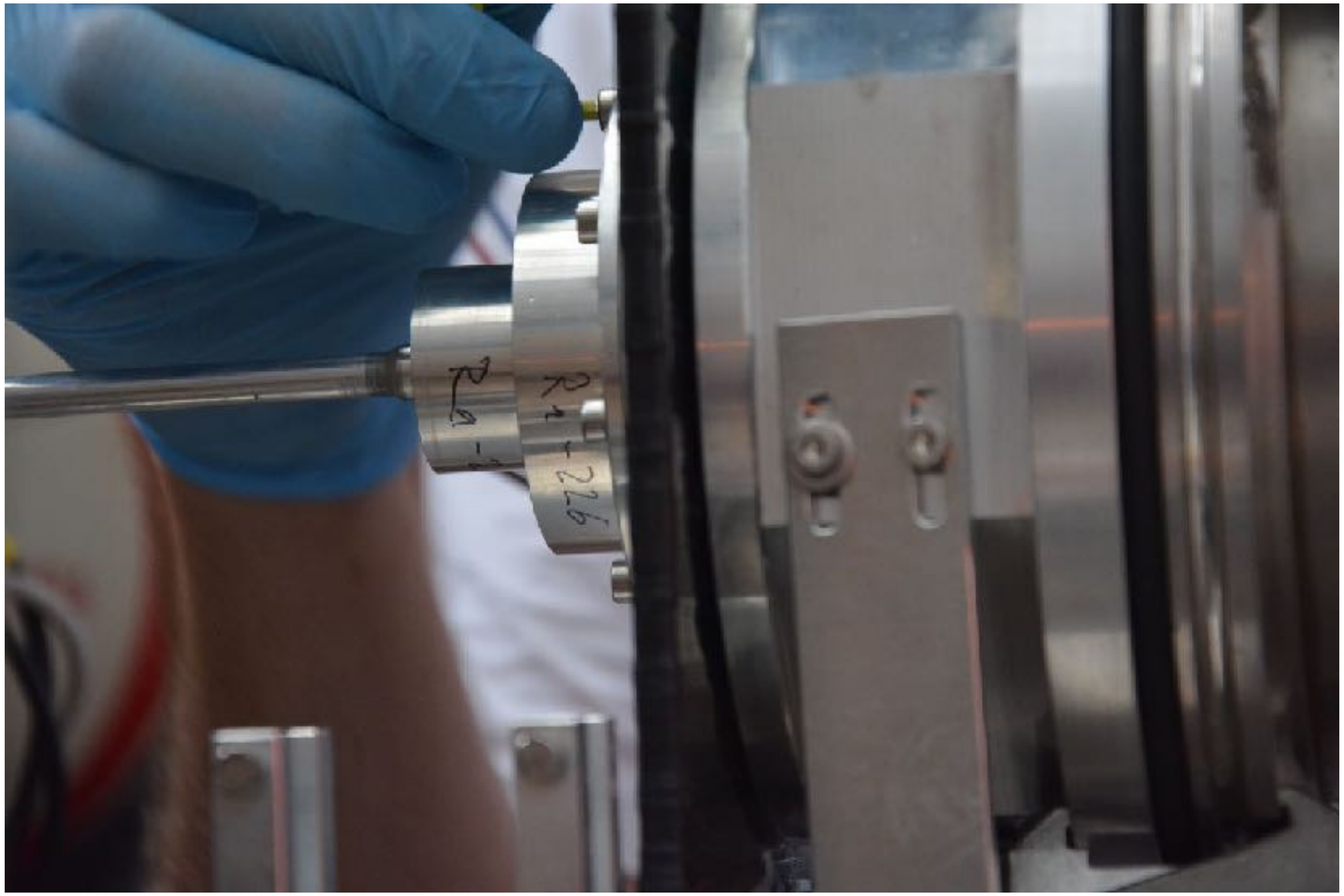






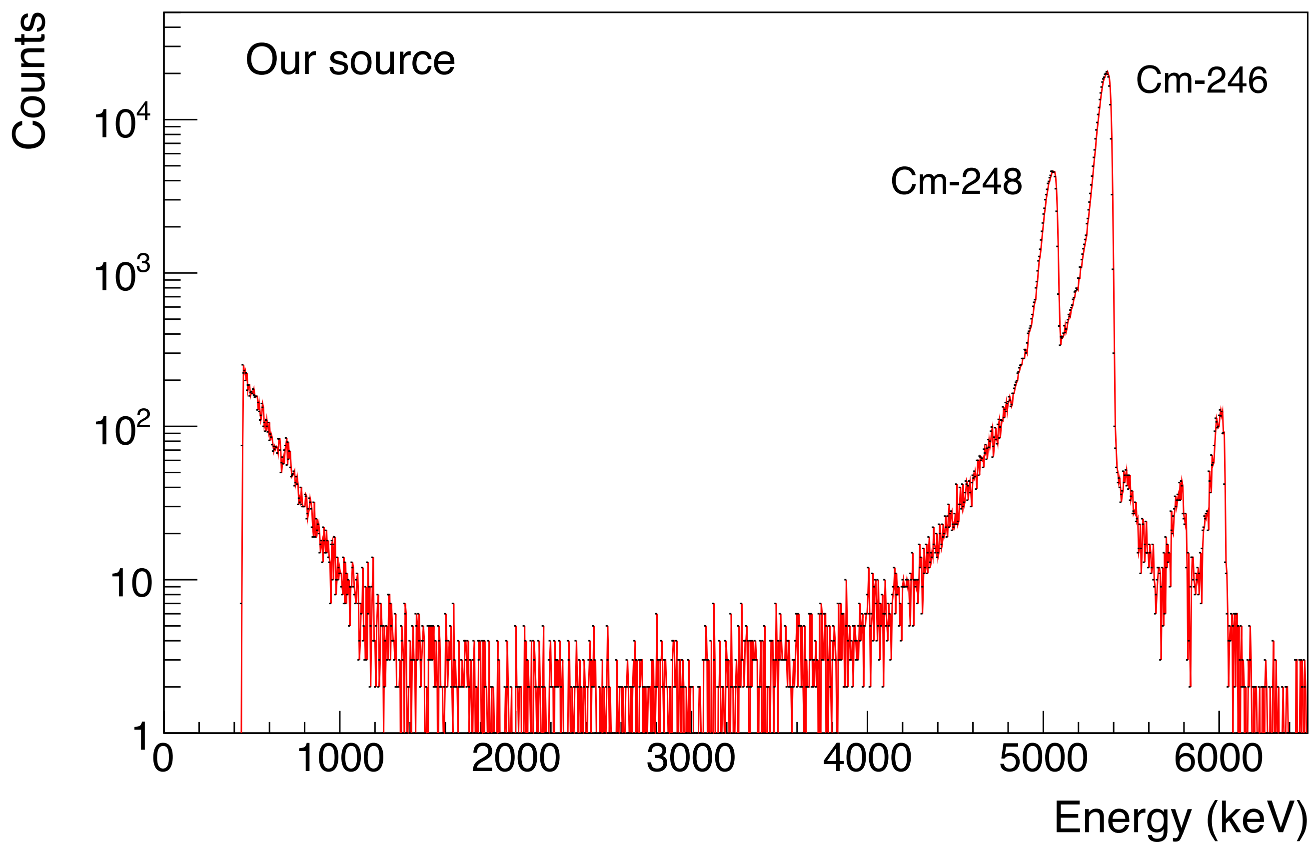
- Attempted a measurement of ^{226}Ra and ^{248}Cm this year
- Electroplating the ^{226}Ra out of the isopropanol solution onto gold plated copper foil

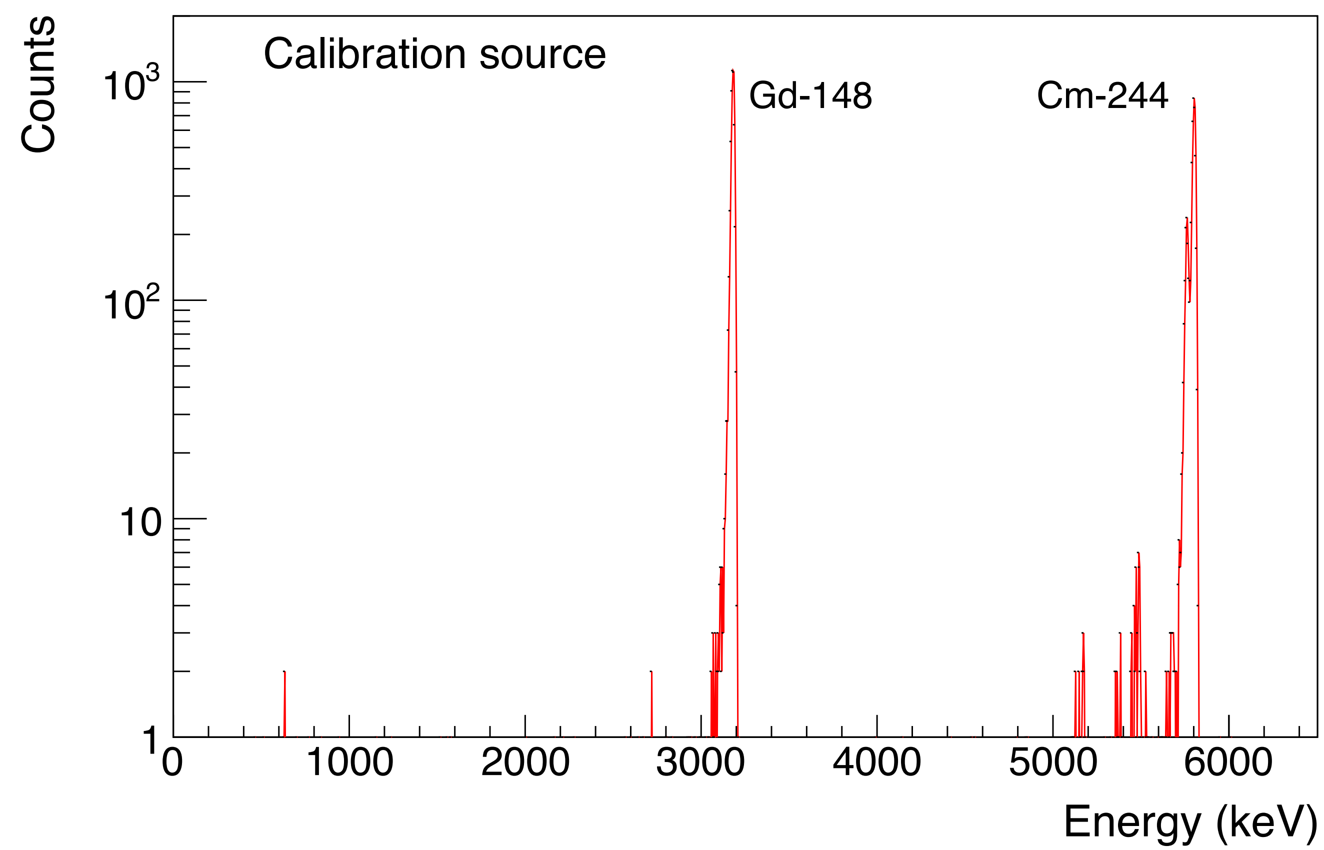
Measuring radium target



- We knew that we had lost a lot of radium in the target making process plus target had a large organic contamination
- Mounted target anyway but immediately saw that we had only 1% of the required target mass…
- Measured for a while, but clearly saw nothing

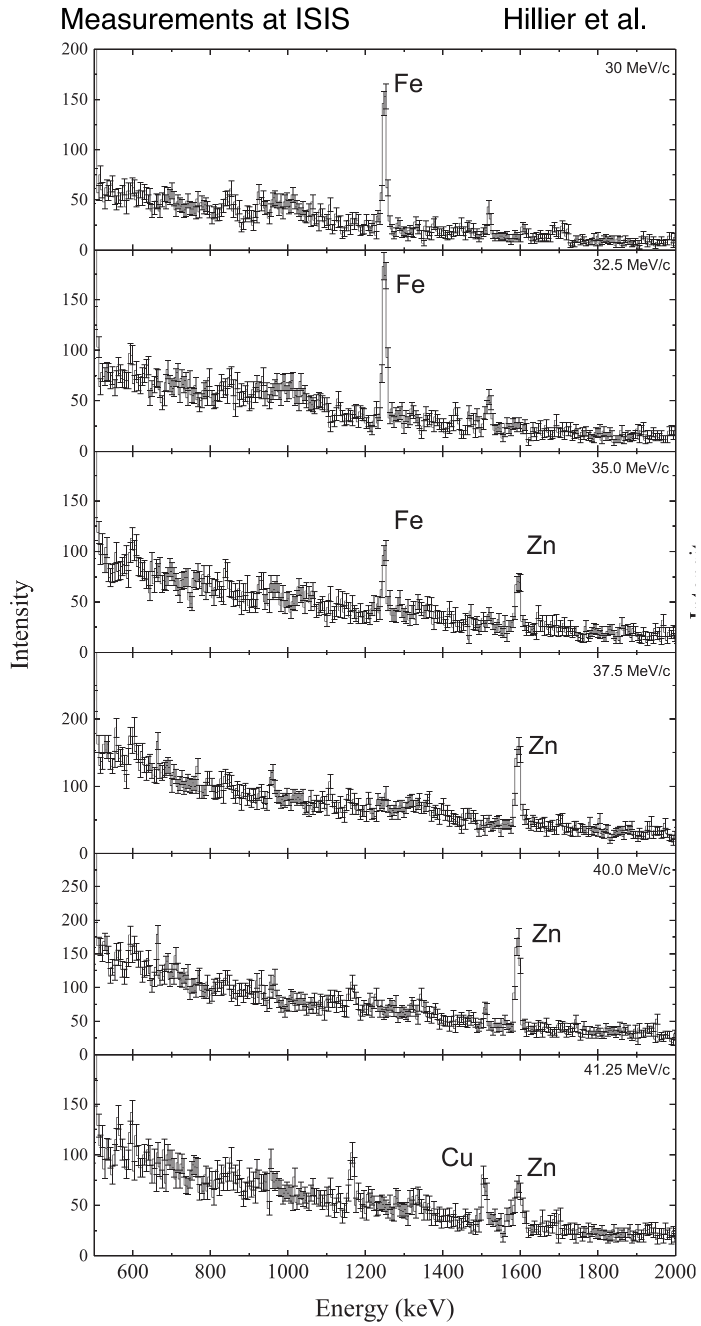
Alpha Spectrum

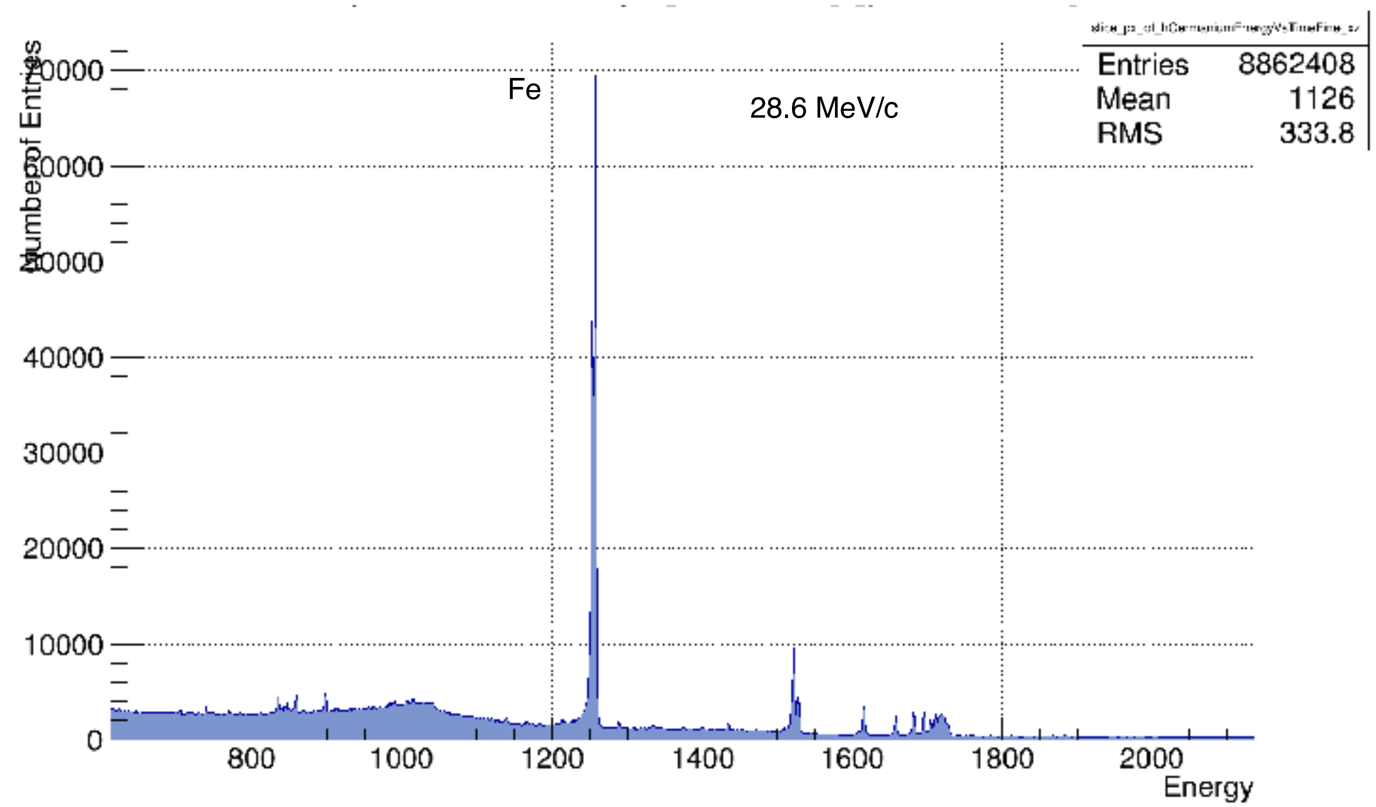


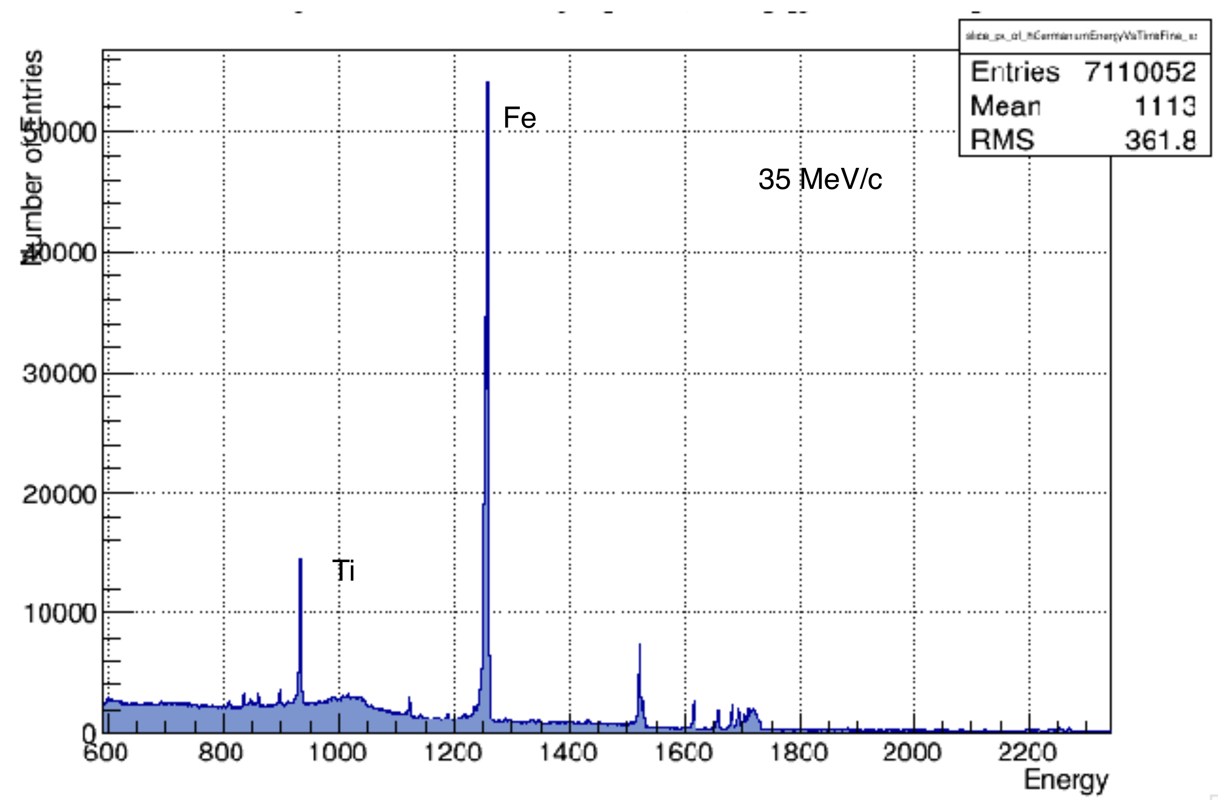


- Alpha spectrum measurements can reveal some hints on source thickness
- Tails and unresolved double peak clearly show that we have a “thick” source
- Performed some alpha spectrum simulations but quite a lot of free parameters
- Simulations tend to point towards organic layer of order 500 nm

Elemental analysis with negative muons

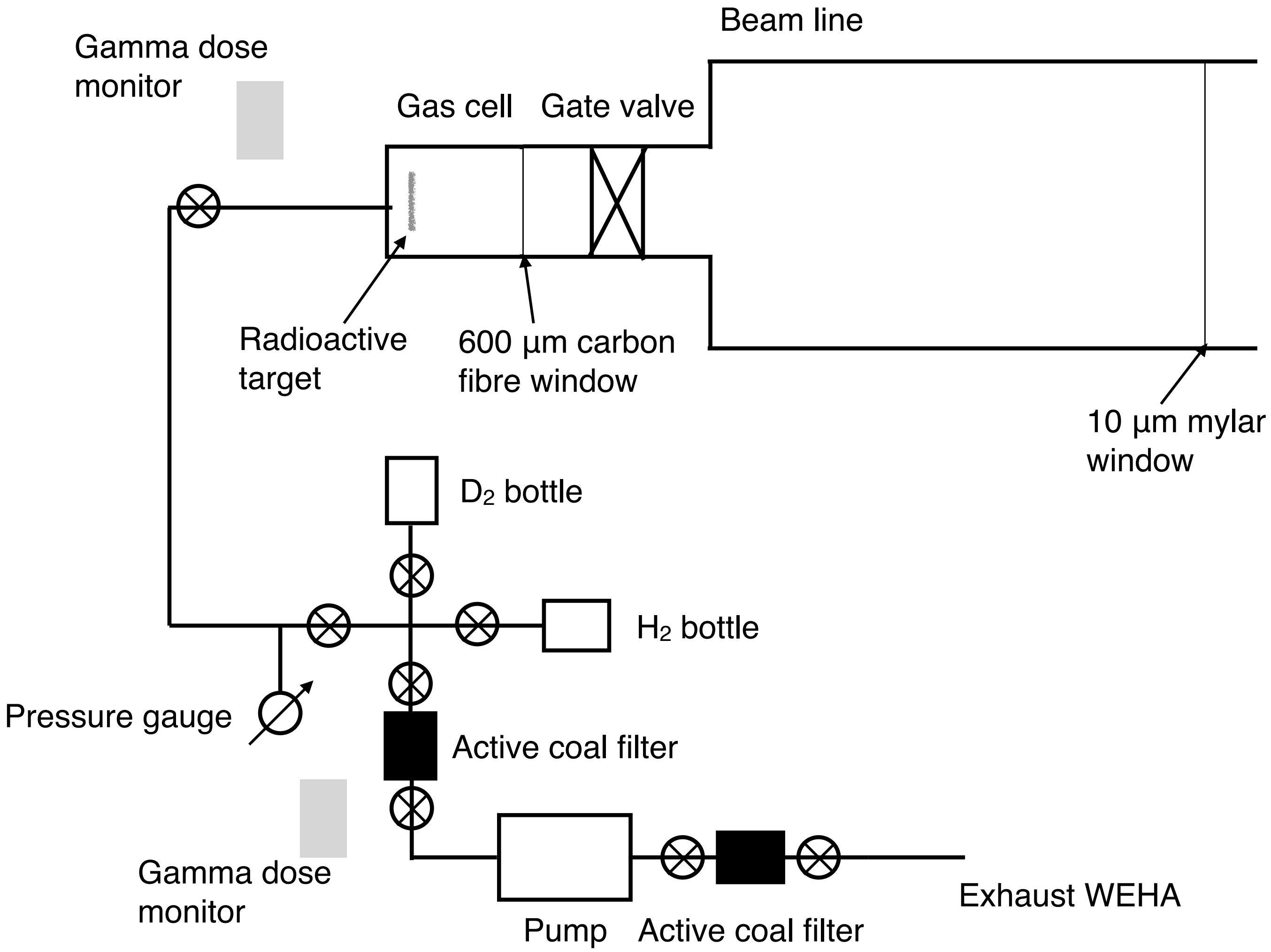






- Elemental analysis with muonic x-rays
- Depth profiling as a function of momentum
- Proof-of-principle with stacks of foils

Safety



- Implemented full safety features for handling radioactive targets