BVR 49: Progress Report R-16-01.1

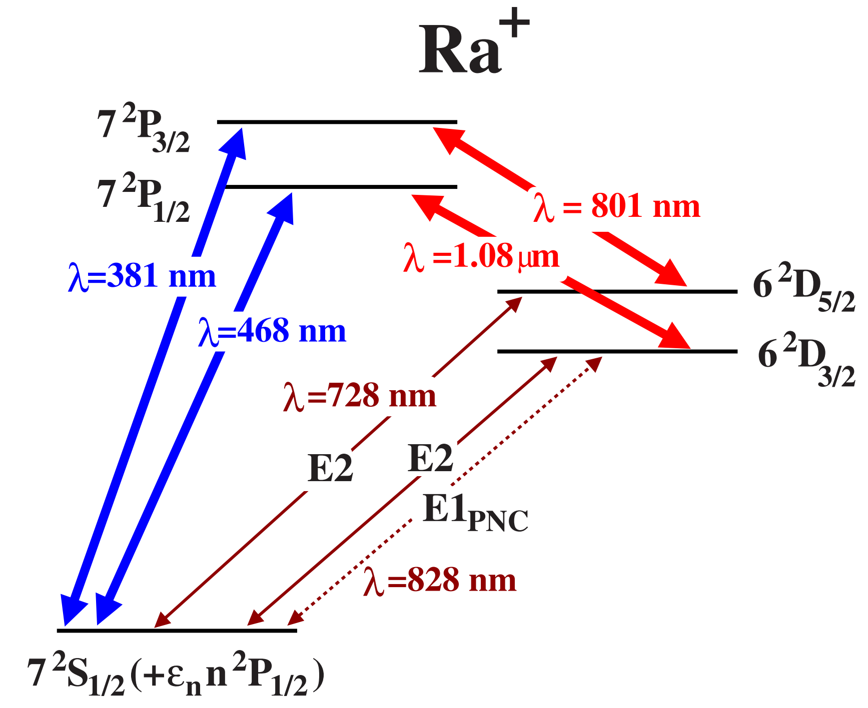
Measurement of the charge radius of radium

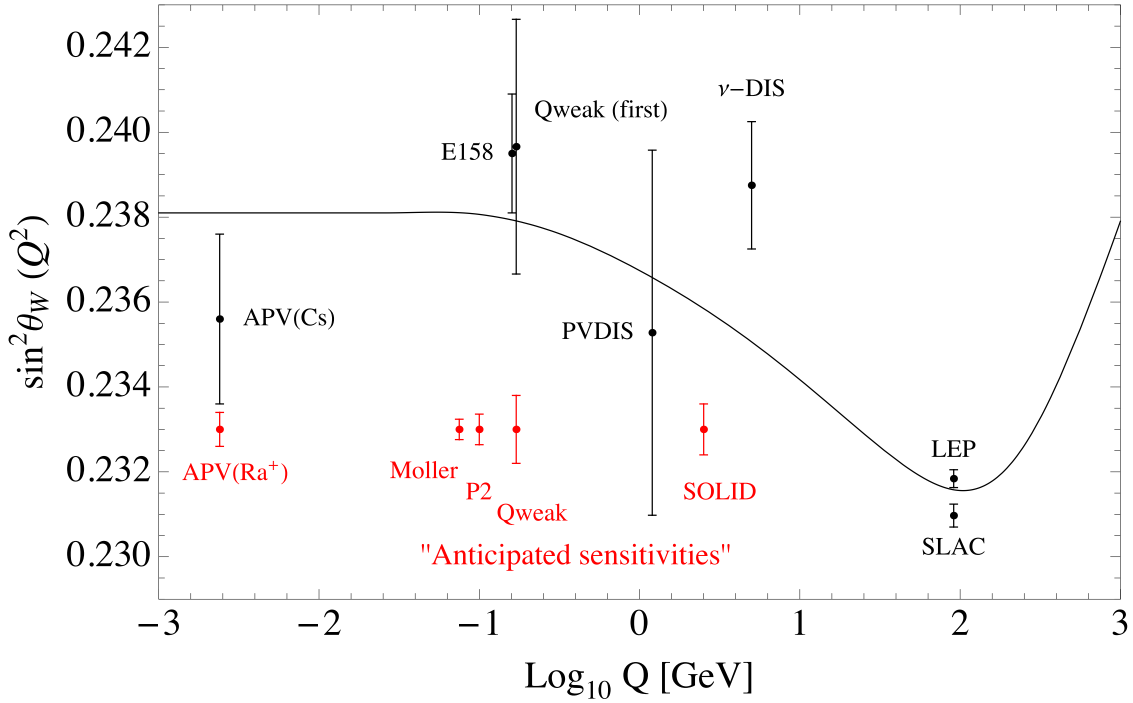
A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], R. Dressler[2], R. Eichler[2], P. Indelicato[6], K. Jungmann[7], K. Kirch[2,3], A. Knecht[2], J. Krauth[4], J. Nuber[2], A. Papa[2], R. Pohl[4], M. Pospelov[8,9], E. Rapisarda[2], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[11], N. Severijns[5], A. Skawran[2,3], F. Wauters[4], and L. Willmann[7]

[1]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[2]Paul Scherrer Institut, Villigen, Switzerland
[3]ETH Zürich, Switzerland
[4]University of Mainz, Germany
[5]KU Leuven, Belgium
[6]LKB Paris, France
[7]University of Groningen, The Netherlands
[8]University of Victoria, Canada
[9]Perimeter Institute, Waterloo, Canada
[10]Institut für Kernphysik, Universität zu Köln, Germany
[11]CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France

Atomic parity violation in radium

- Electron-quark neutral weak interaction mixes states of opposite parity
- Measure E1$_{PNC}$ admixture in E2 transition and extract weak charge using precision atomic calculations
- Needs knowledge of the radium charge radius with 0.2% accuracy
- Potential of improving Cs result by factor 5



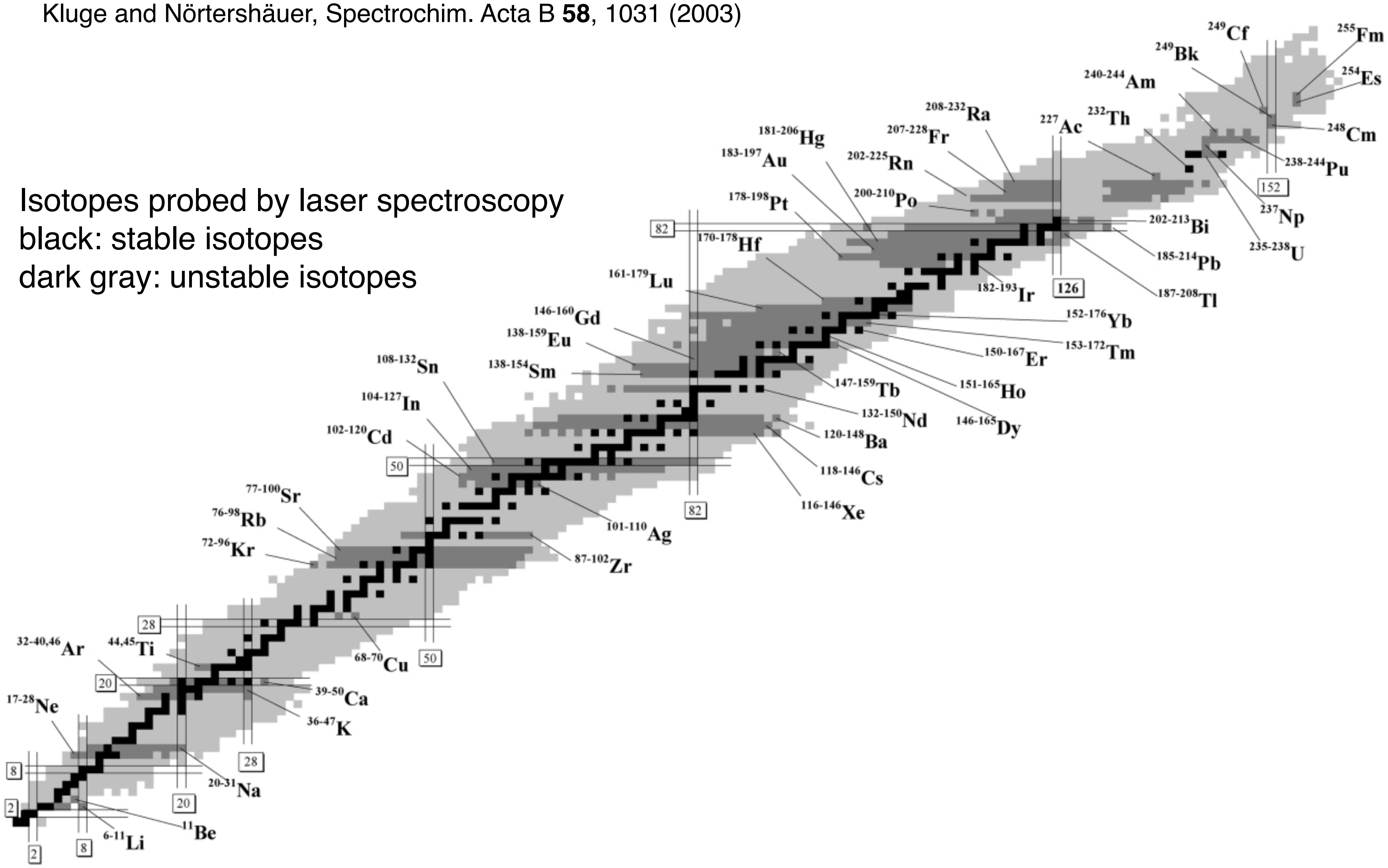


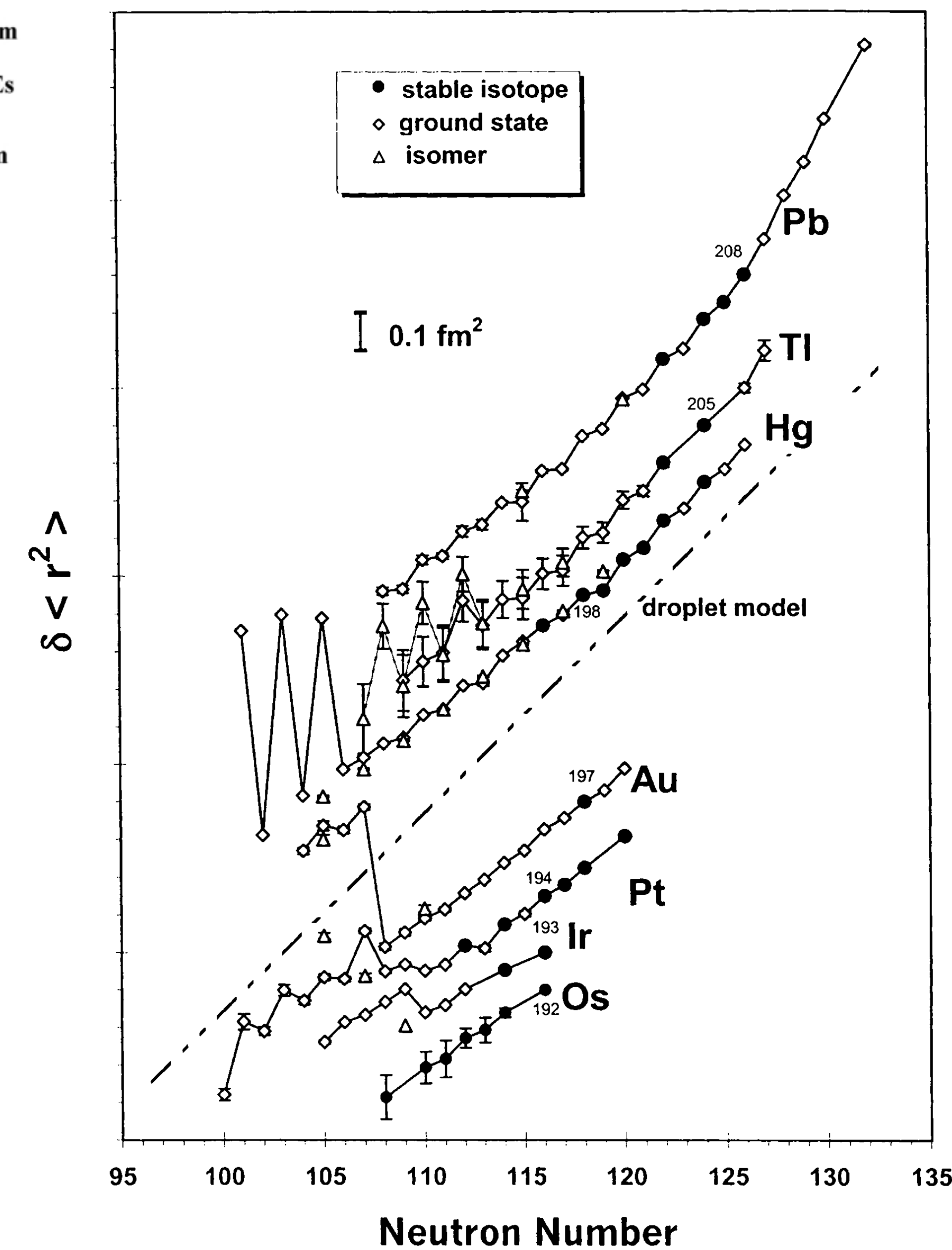
Wansbeek et al., PRA **78**, 050501 (2008)
Wood et al., Science **275**, 1759 (1997)
Davoudiasl, Lee, Marciano, Phys. Rev. D 92, 055005 (2015)

Charge radii from laser spectroscopy

Kluge and Nörtershäuer, Spectrochim. Acta B **58**, 1031 (2003)

Isotopes probed by laser spectroscopy
black: stable isotopes
dark gray: unstable isotopes





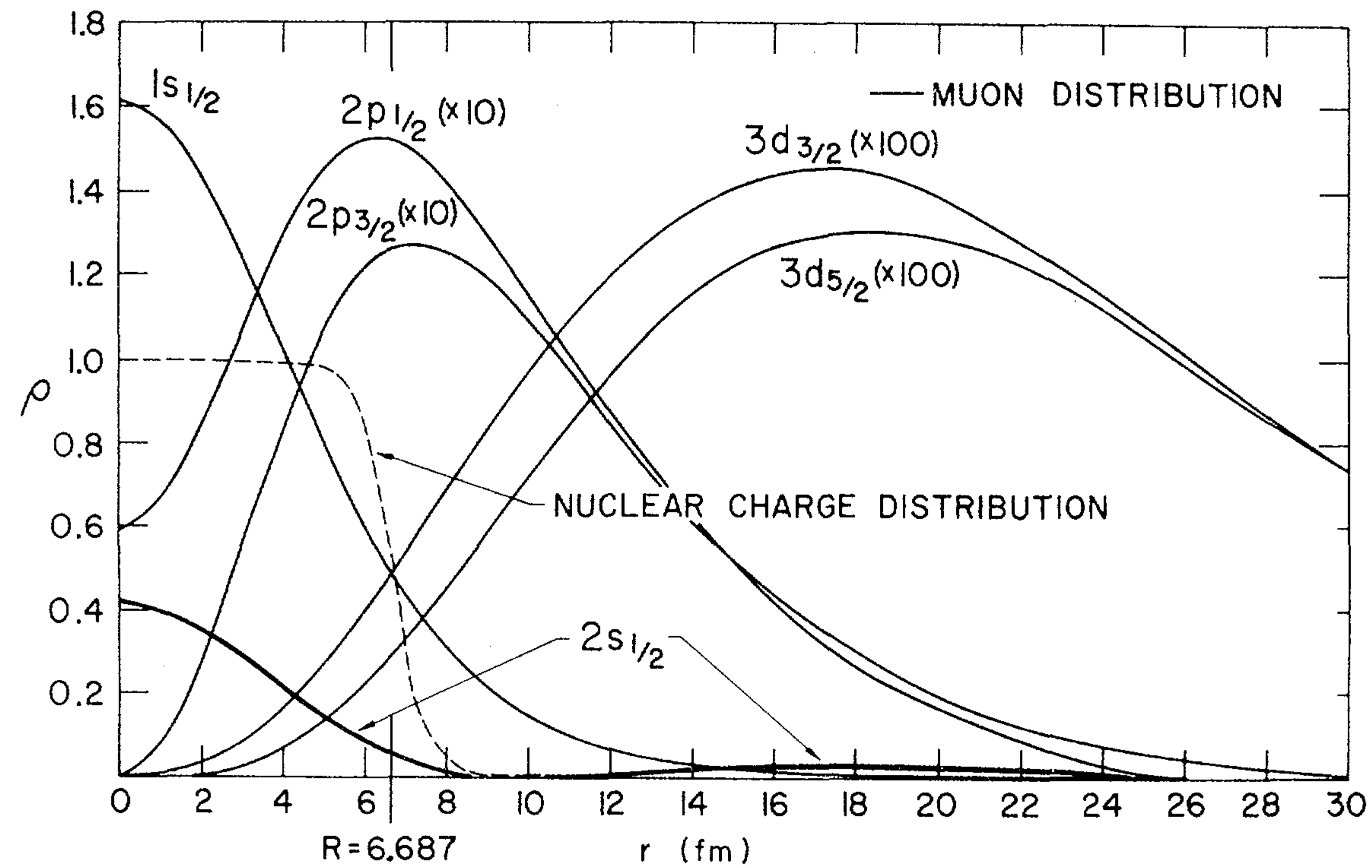
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

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

Kessler et al., PRC **11**, 1719 (1975)



Large effect:

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

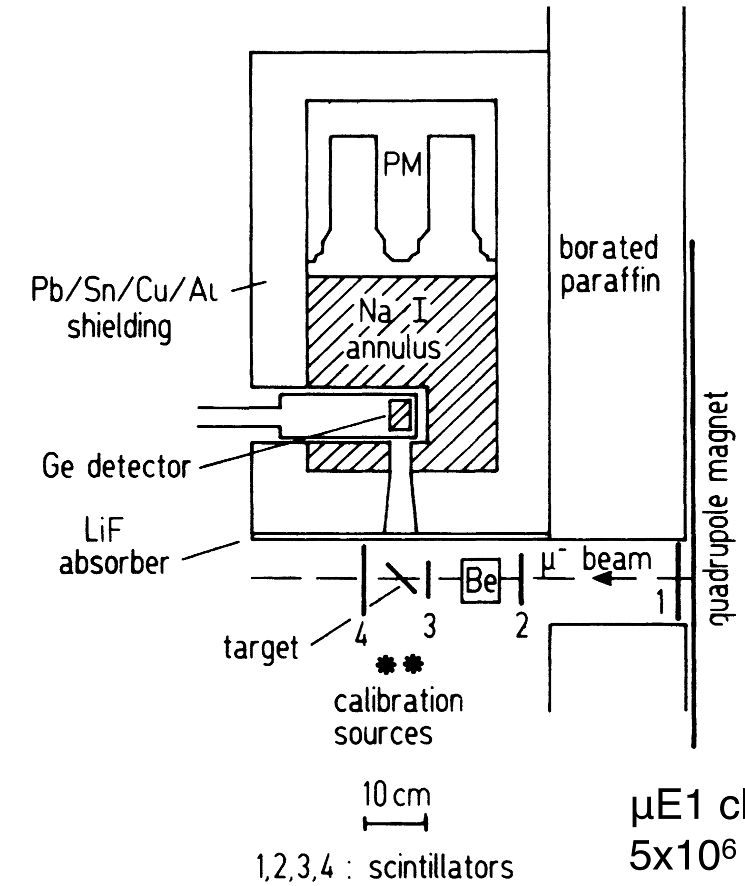
Muonic atom spectroscopy

PAUL SCHERRER INSTITUT PSI

- Impressive precision in the extracted charge radius can be achieved

- For ^{208}Pb: $<r^2>^{1/2}$ = 5.5031(11) fm
  2×10^{-4} relative precision

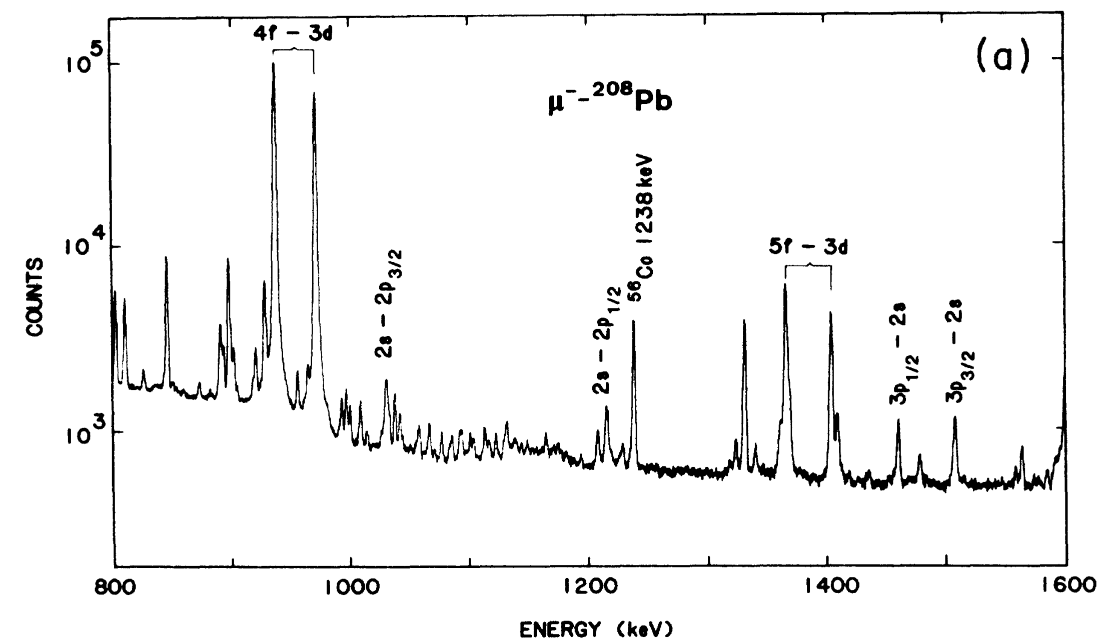
Bergem et al., PRC **37**, 2821 (1988)



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

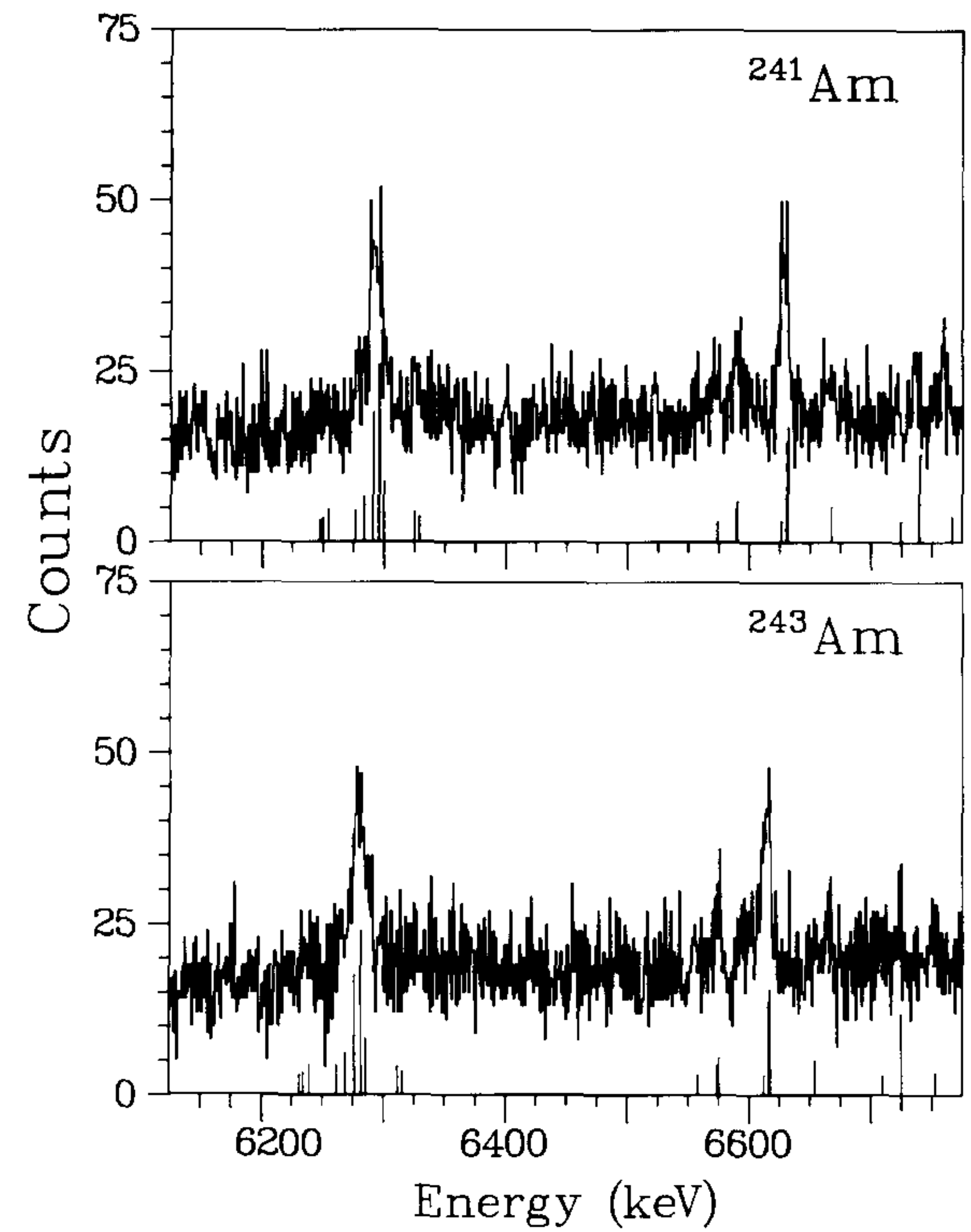
TABLE V. Experimental muonic transition energies (keV) in ^{208}Pb (recoil corrected).

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)



What about radioactive atoms?

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



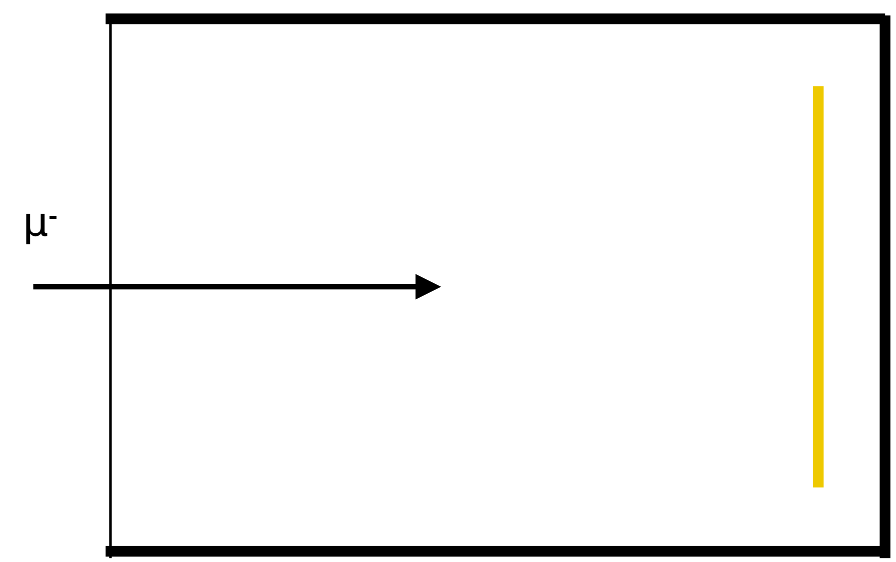
- Most of the stable isotopes have been measured with muonic atom spectroscopy
- In a few special cases also radioactive isotopes, e.g. americium
  - The paper describes the americium target as “modest weight of 1 gram”

Measurements in ultra-thin targets

- Radioprotection laws more strict nowadays
  - Can only use 0.2 µg of (open) ^{241}Am in PSI's experimental hall
  - Can use 5 µg of ^{226}Ra
- For direct stopping need O(100 mg)
- Use the "magic" of muonic hydrogen/deuterium atoms and transfer reactions!

Transfer reactions

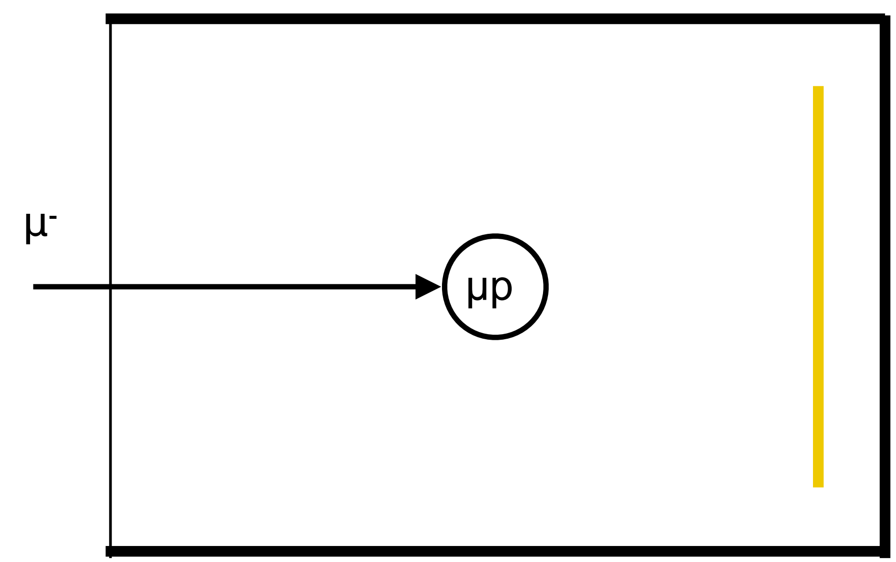
- Stop in 100 bar hydrogen target with 0.25% deuterium admixture
- Form muonic hydrogen μp
- Transfer to deuterium forming μd, gain binding energy of 45 eV
- Hydrogen gas quasi transparent for μd at ~5 eV (Ramsauer-Townsend effect)
- μd reaches target and transfers to μRa
- Measure emitted X-rays from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



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

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

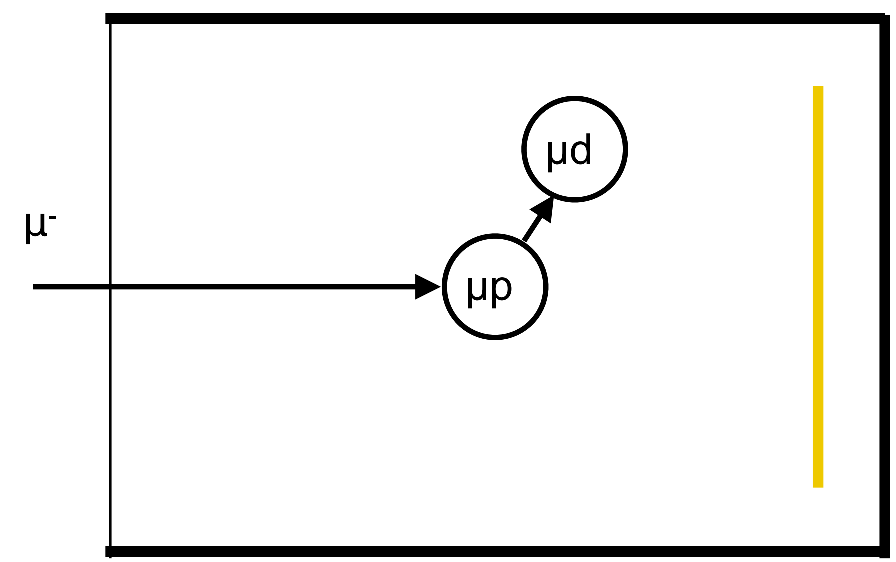


Inspired by work of Strasser et al. and Kraiman et al.

Transfer reactions

PAUL SCHERRER INSTITUT

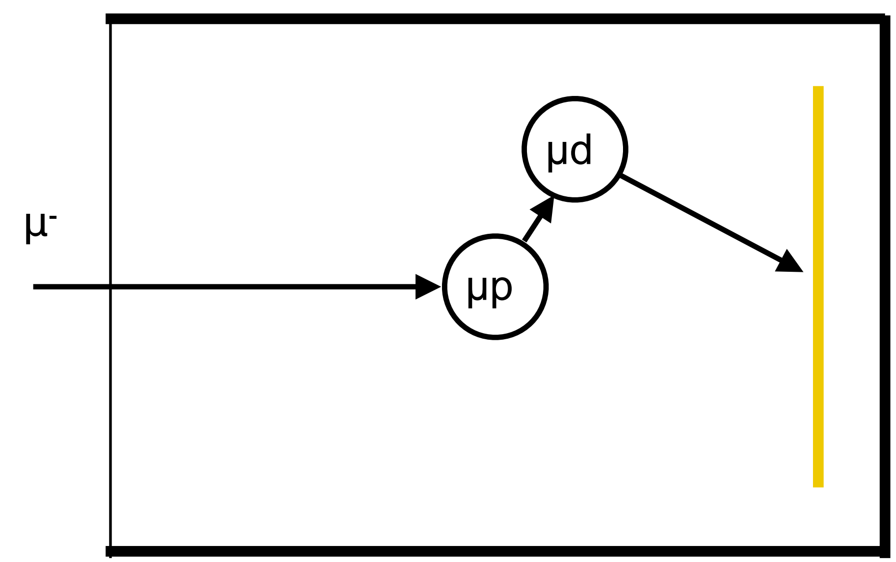
- Stop in 100 bar hydrogen target with 0.25% deuterium admixture
- Form muonic hydrogen µp
- Transfer to deuterium forming µd, gain binding energy of 45 eV
- Hydrogen gas quasi transparent for µd at ~5 eV (Ramsauer-Townsend effect)
- µd reaches target and transfers to µRa
- Measure emitted X-rays from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



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

Transfer reactions

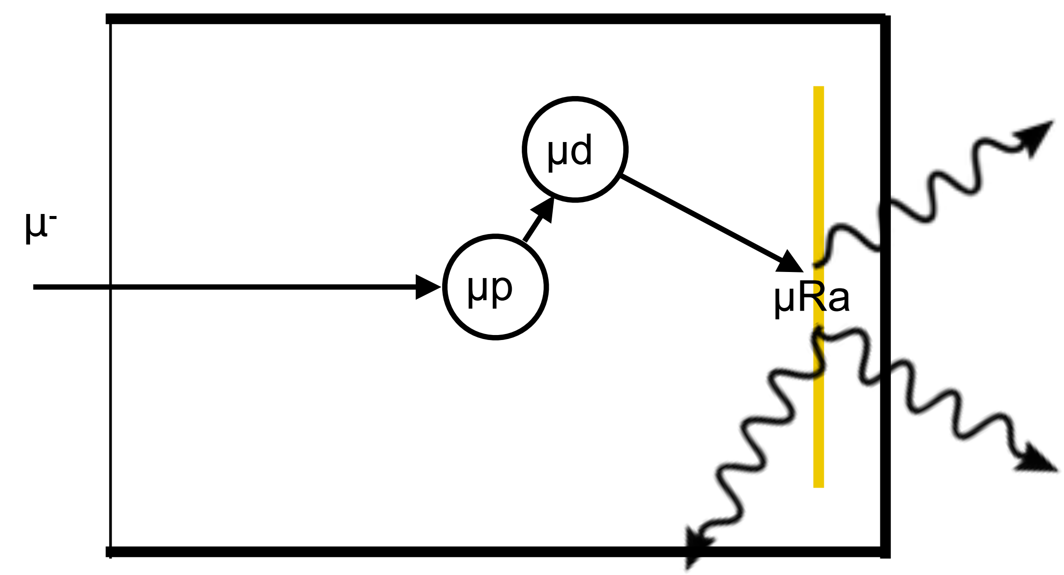
- Stop in 100 bar hydrogen target with 0.25% deuterium admixture
- Form muonic hydrogen μp
- Transfer to deuterium forming μd, gain binding energy of 45 eV
- Hydrogen gas quasi transparent for μd at ~5 eV (Ramsauer-Townsend effect)
- μd reaches target and transfers to μRa
- Measure emitted X-rays from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



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

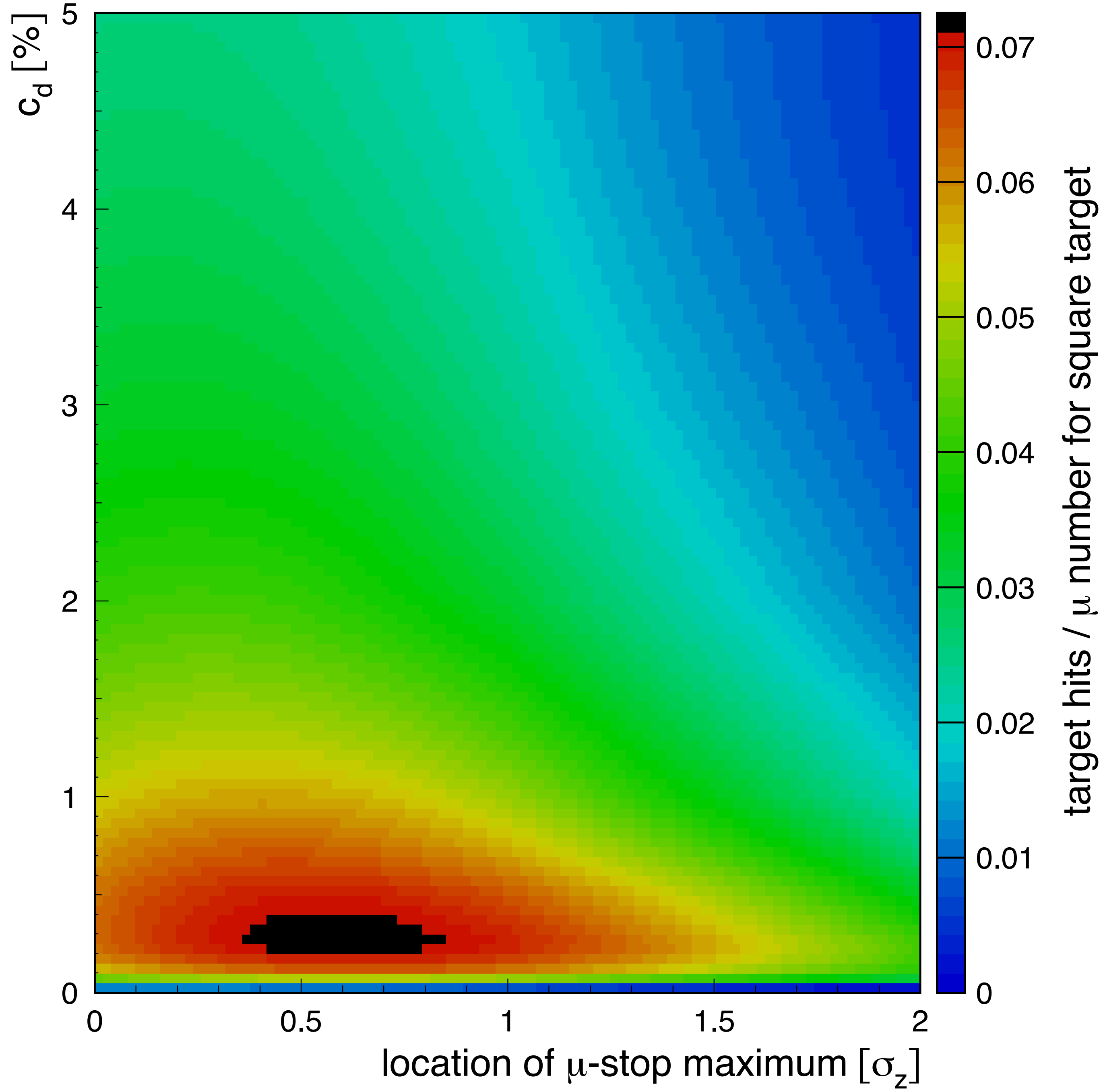
Transfer reactions

- 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.

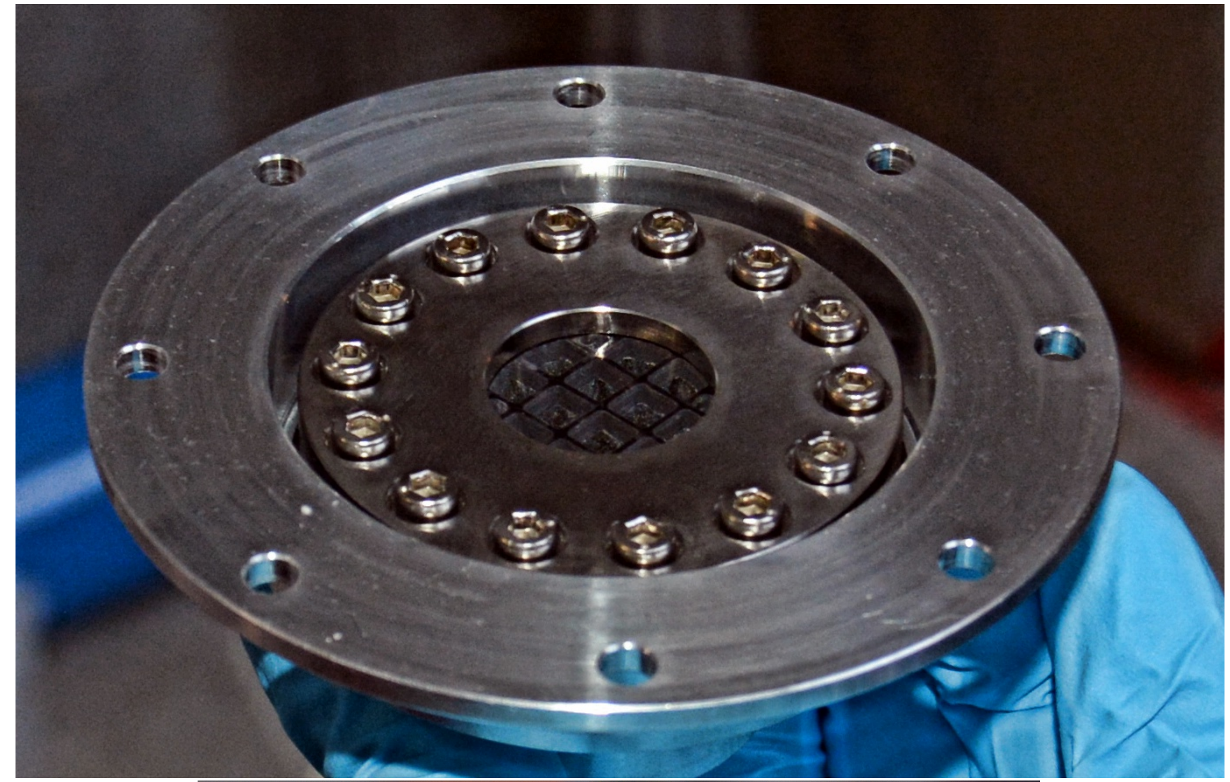
Optimize conditions

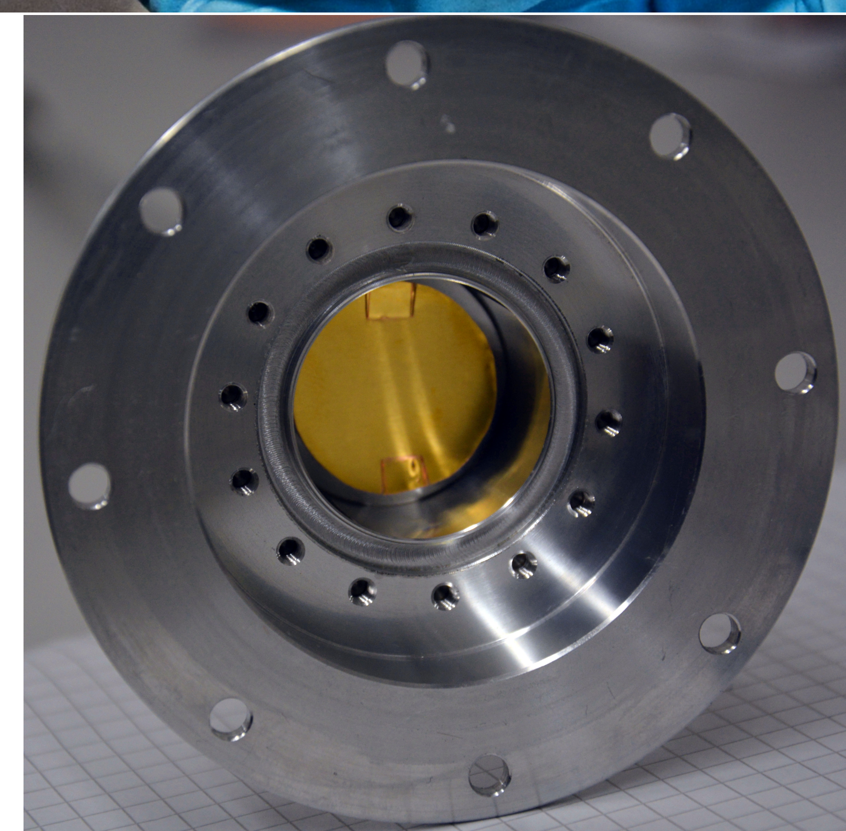


- Maximum efficiency at 0.25% deuterium concentration and a stopping point with part of the stopping distribution inside the target
- Reach an efficiency of around 7% of incoming muons hitting the target as µd atom

100 bar hydrogen target

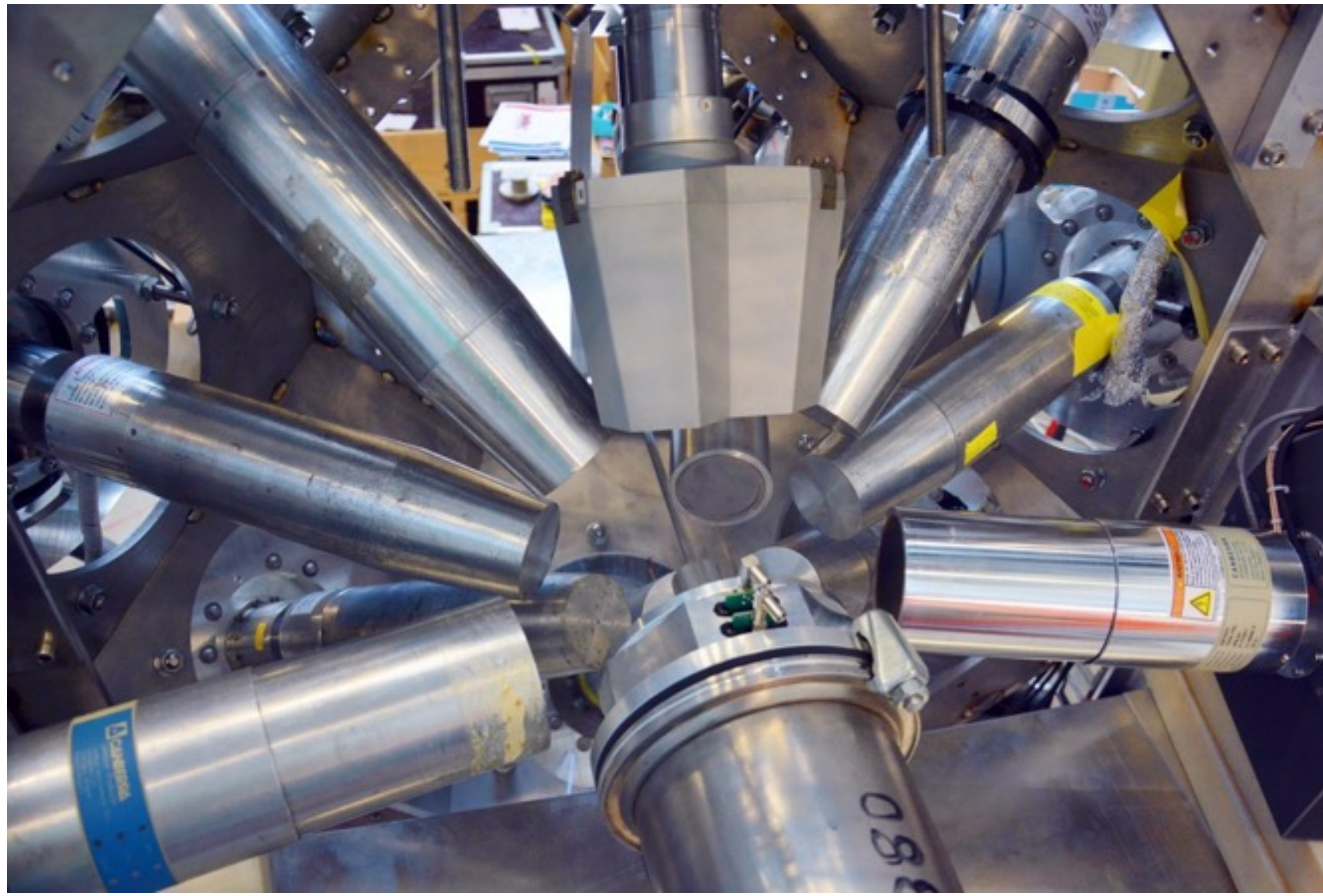
- Target sealed with 0.6 mm carbon fiber window plus carbon fiber/ titanium support grid
- Target holds up to 350 bar
- 8 mm stopping distribution (FWHM) inside 15 mm gas volume
- Target disks mounted onto the back of the cell





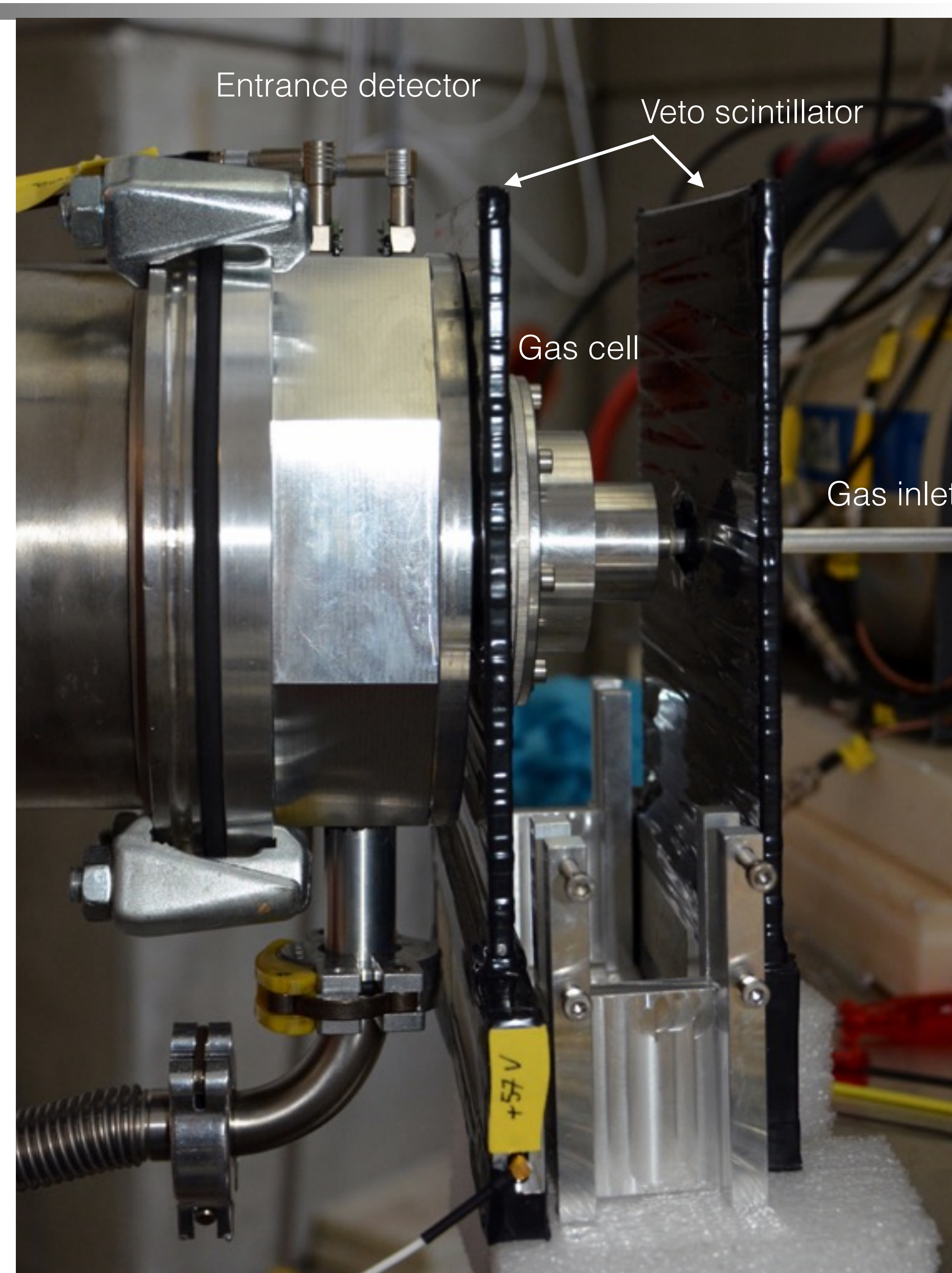
Germanium array

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



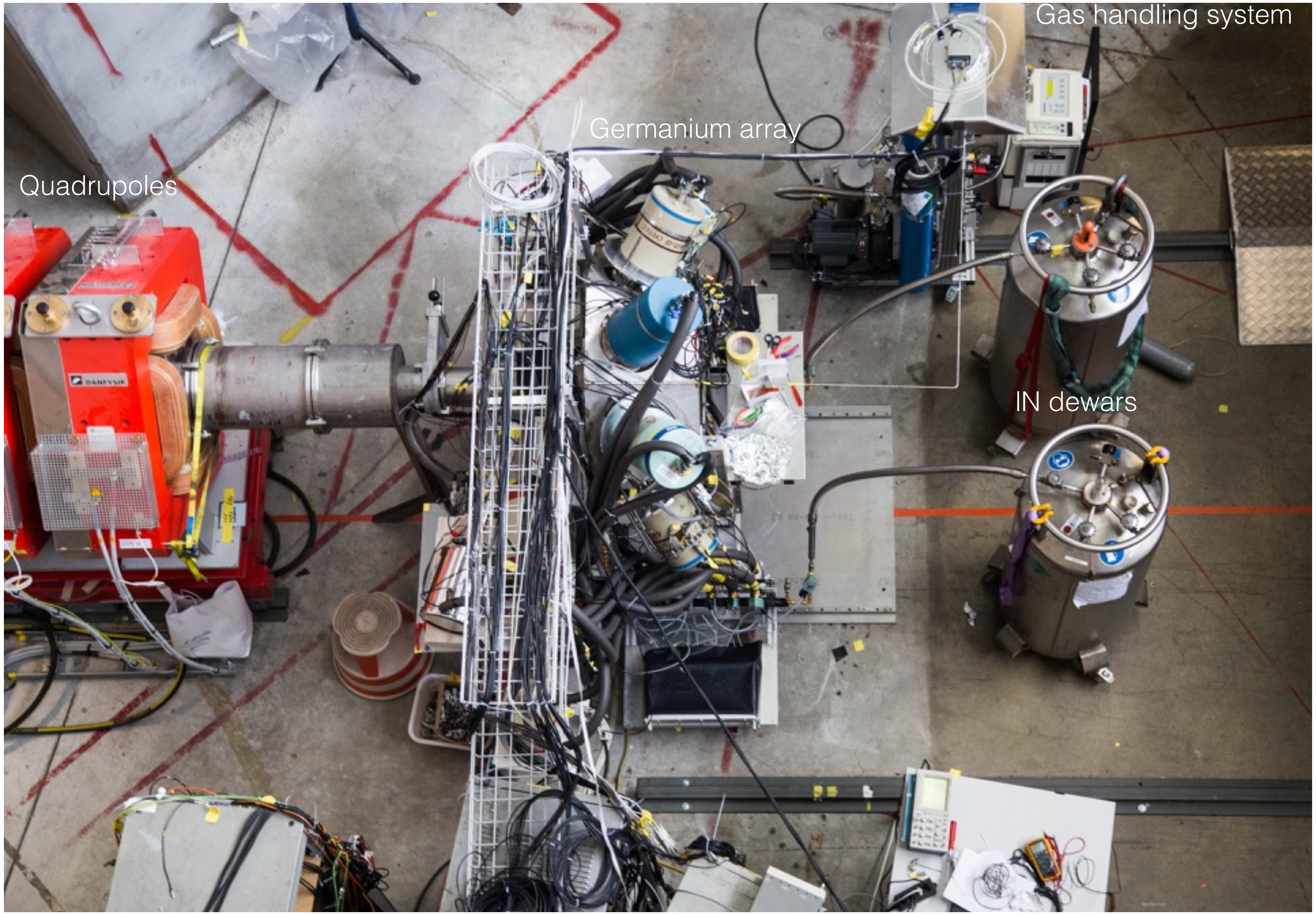
Entrance & veto detectors

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



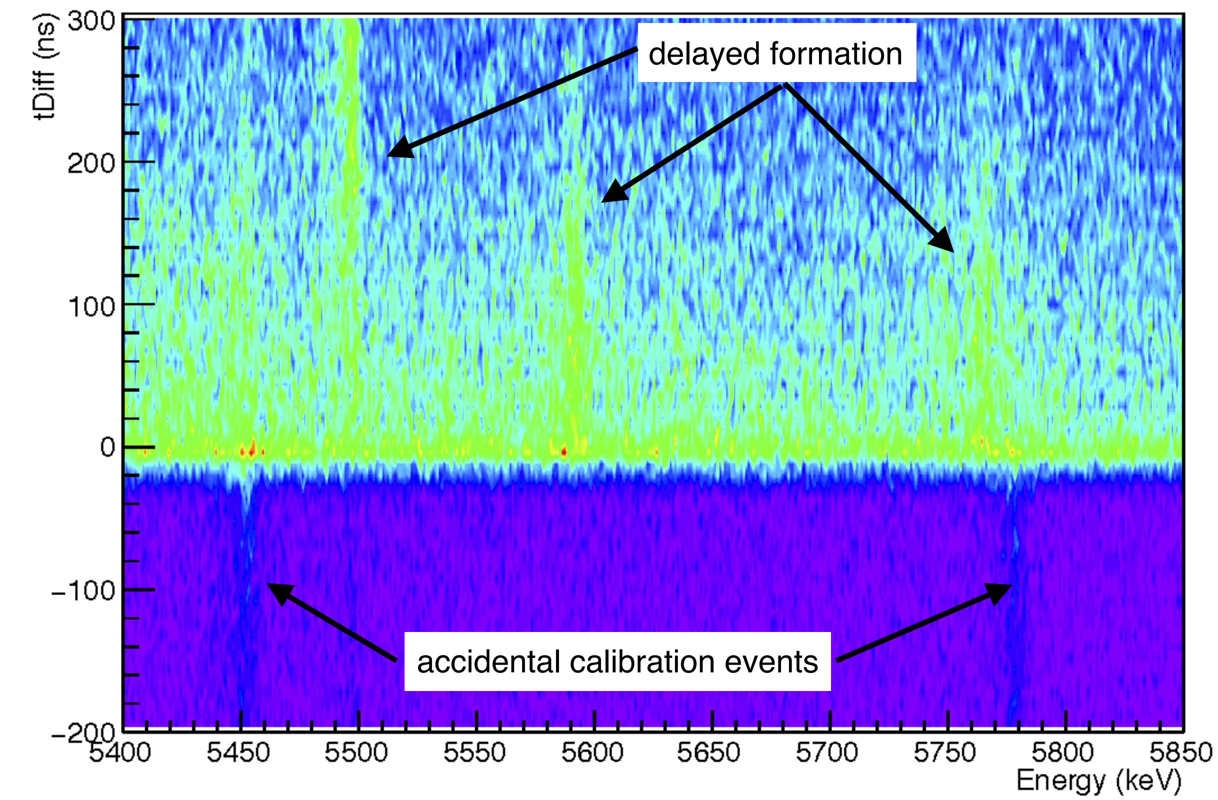
piE1 beam line

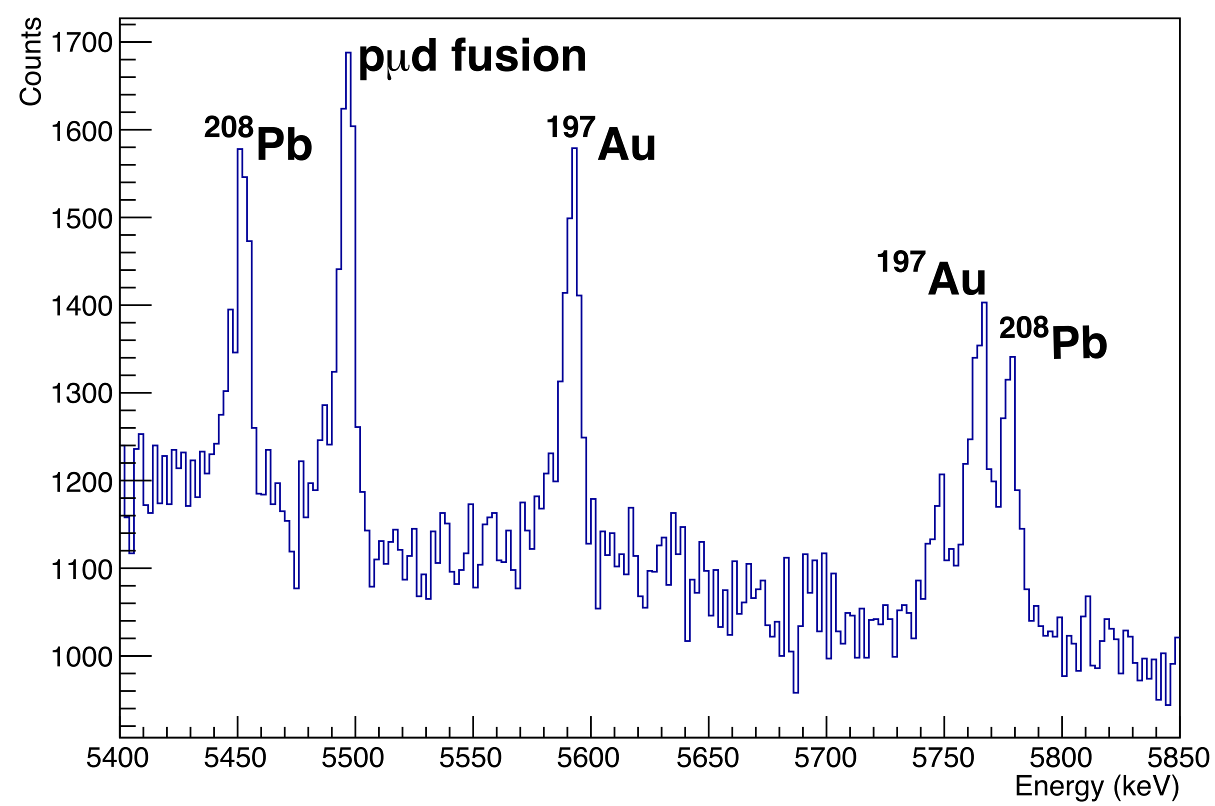
- piE1 beam line
- 9 kHz µ- at 28 MeV/c, 1.5 mA



Measurement with ultra-thin target

- Measurement with 5 μg gold target as proof-of-principle
- Data taken during 18.5 h





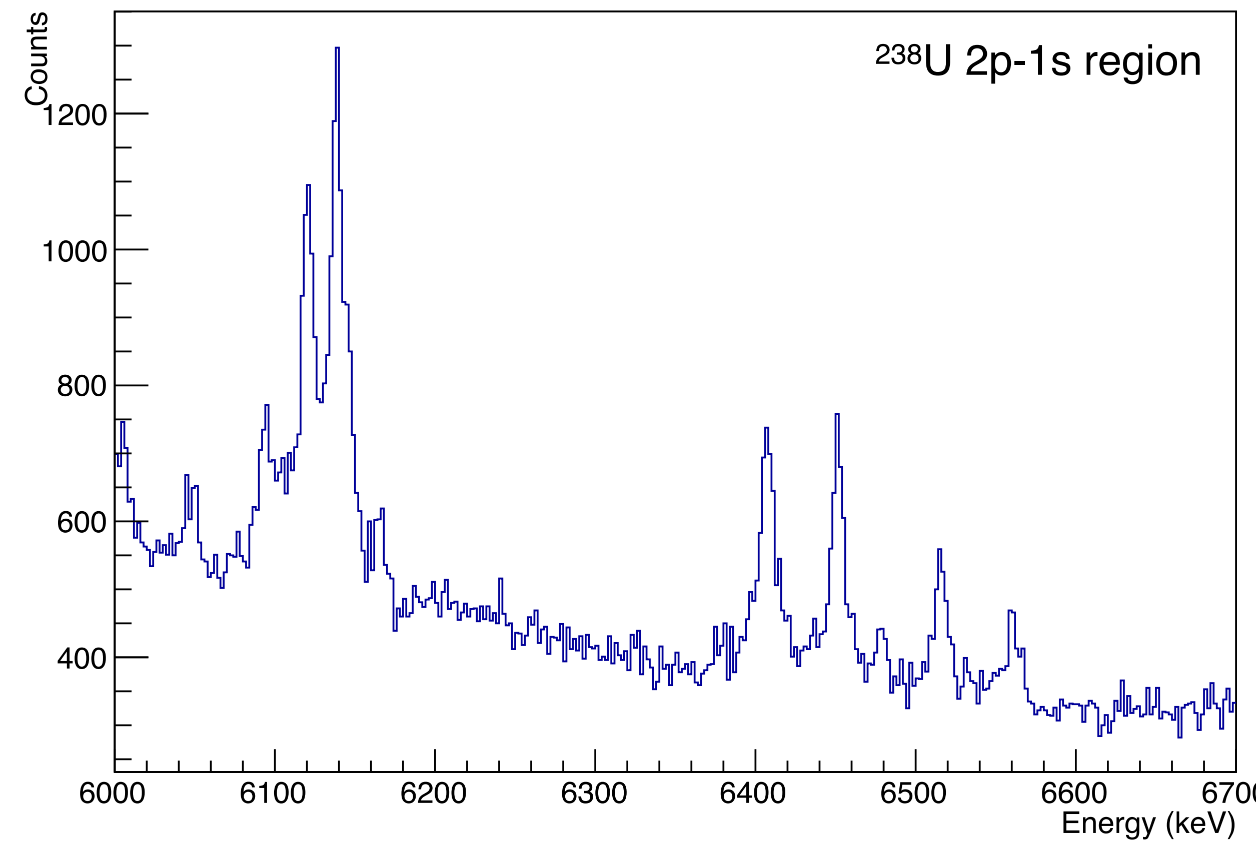
Understanding target conditions

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

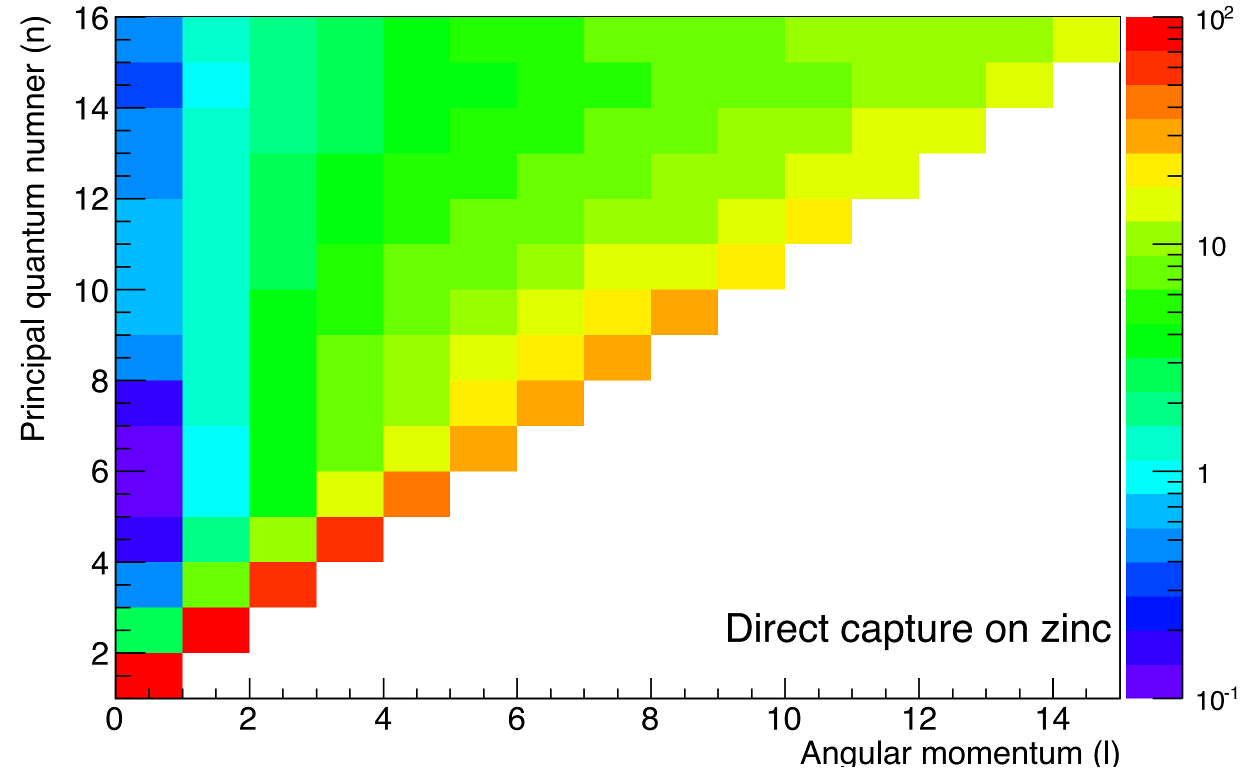
- Measurement with ~5 mg uranium as a test for handling radioactive materials in our setup
- Complicated spectrum due to hyperfine splitting plus low-lying nuclear excitations
- ^{226}Ra will look very similar

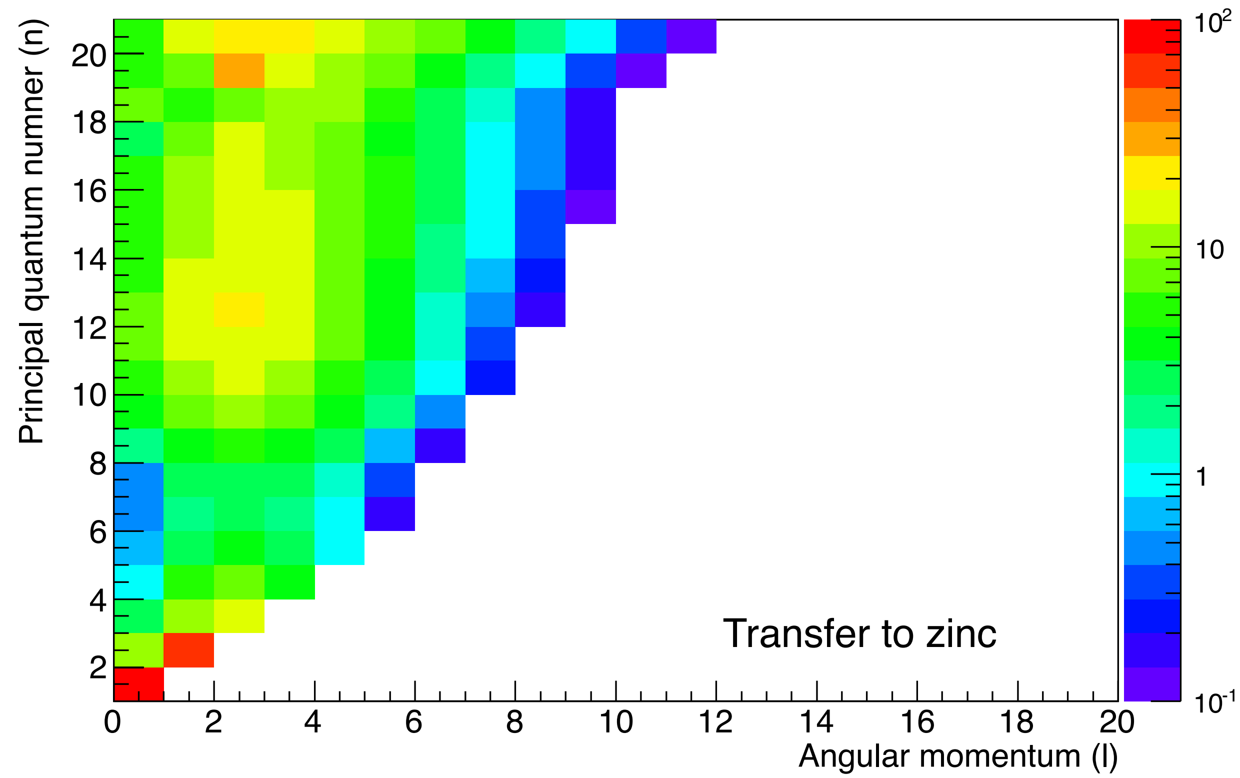


Side note: Muonic cascade

PAUL SCHERRER INSTITUT PSI

- Muonic cascade after transfer favors higher np-1s transitions
- Experimentally confirmed for many low- and medium-Z atoms



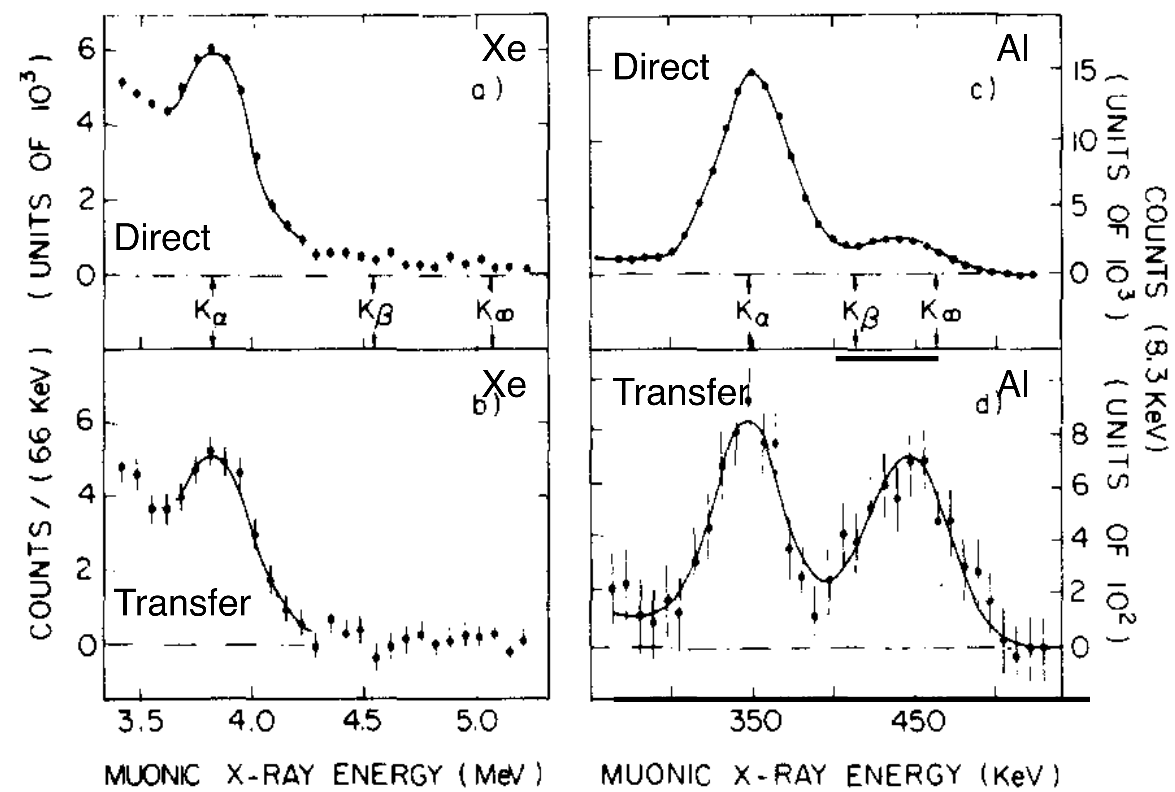


Side note: Muonic cascade

- One publication that claims that enhancement is not seen in high-Z atoms

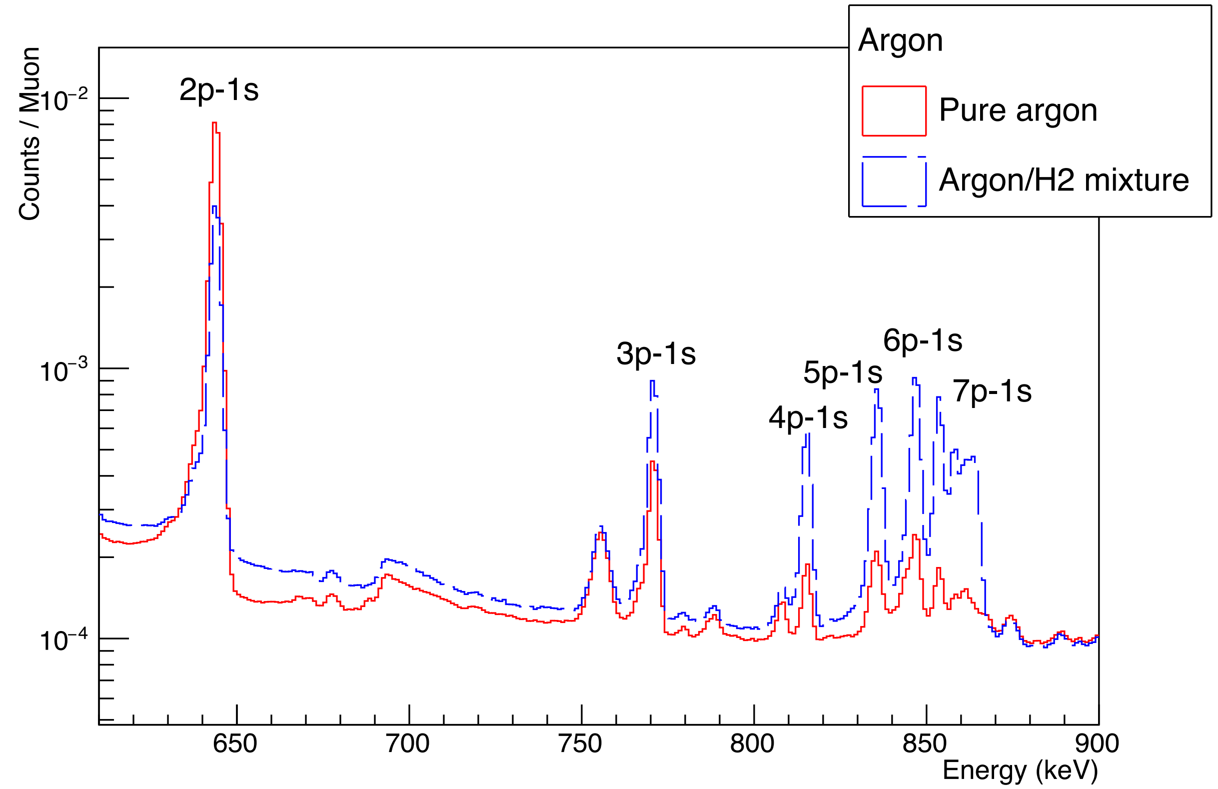
- Troubling as would like to predict our yields
- Additionally need to do a cascade calculation to predict the relative strengths of all the HFS states

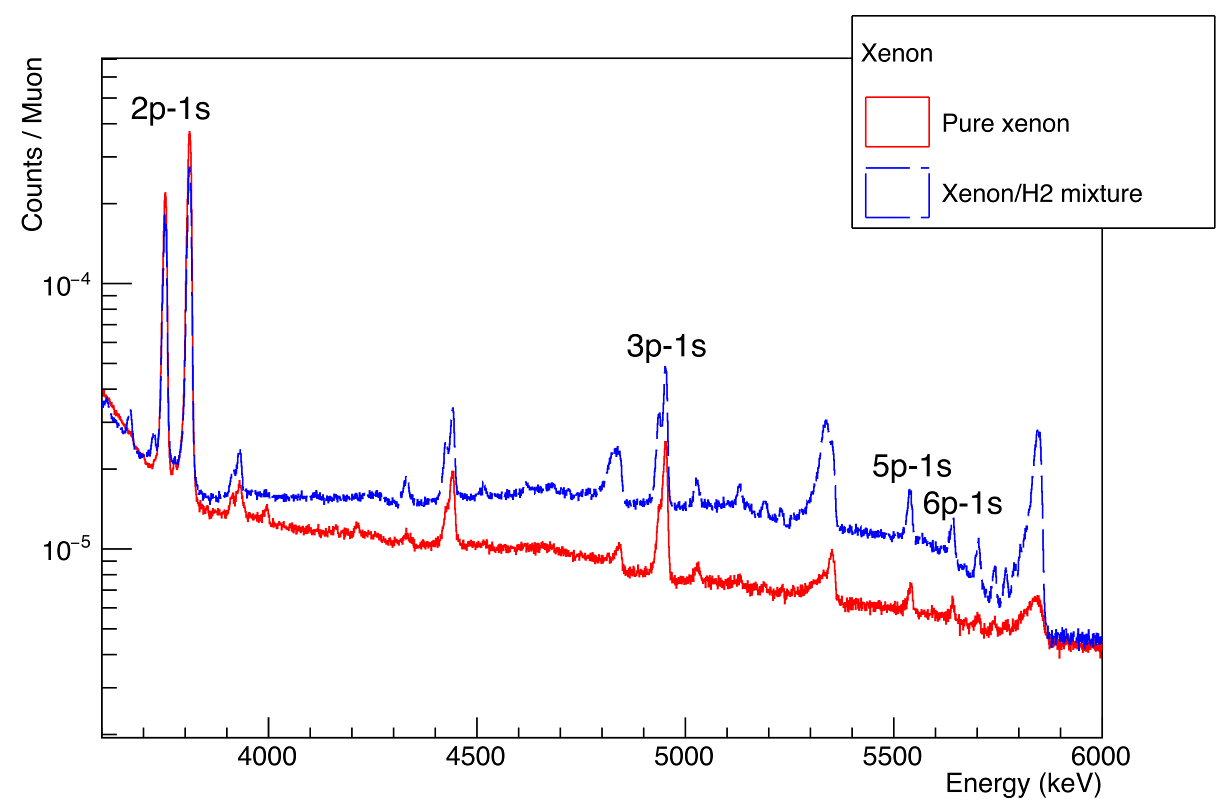
Bertin et al., Phys. Lett. **74A**, 39 (1979)



Measurements with noble gases

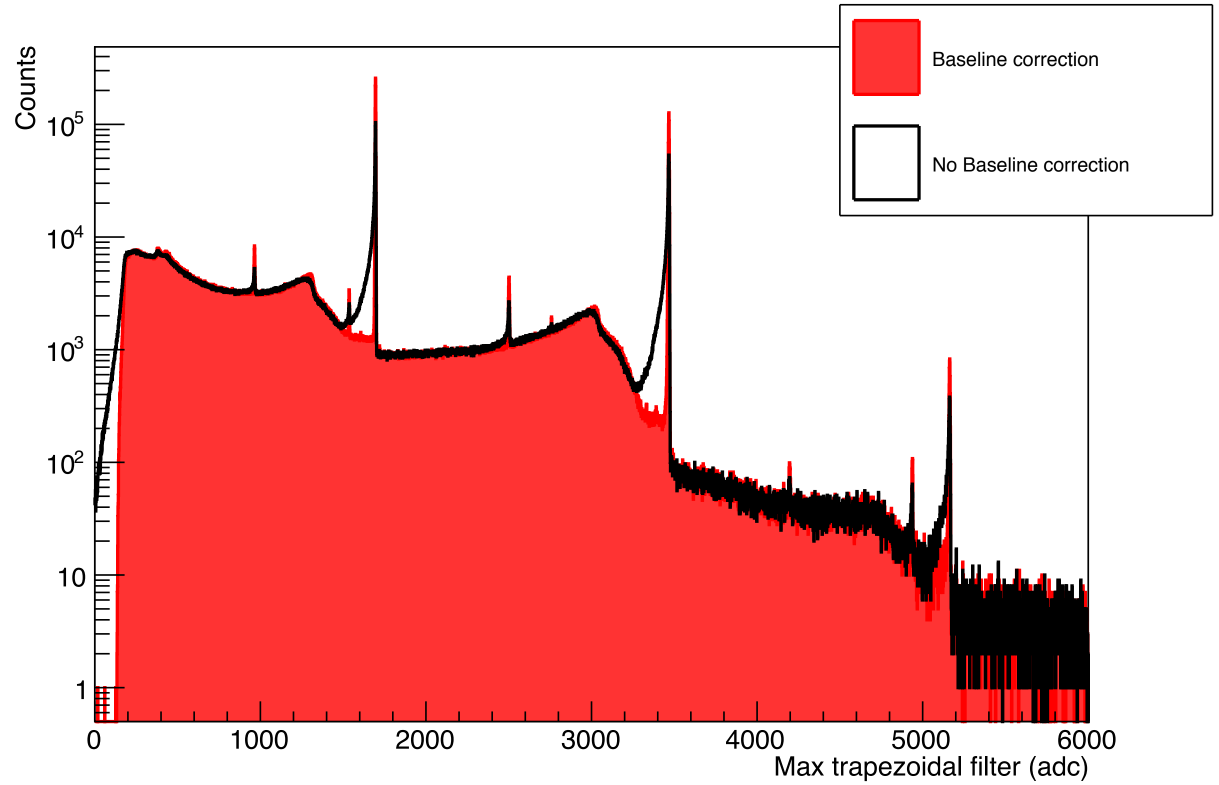
- Performed measurements in pure Ar, Kr, Xe and corresponding mixtures with H_2
- Effect of enhanced np-1s clearly seen also in Xe
- Detailed yields currently under investigation

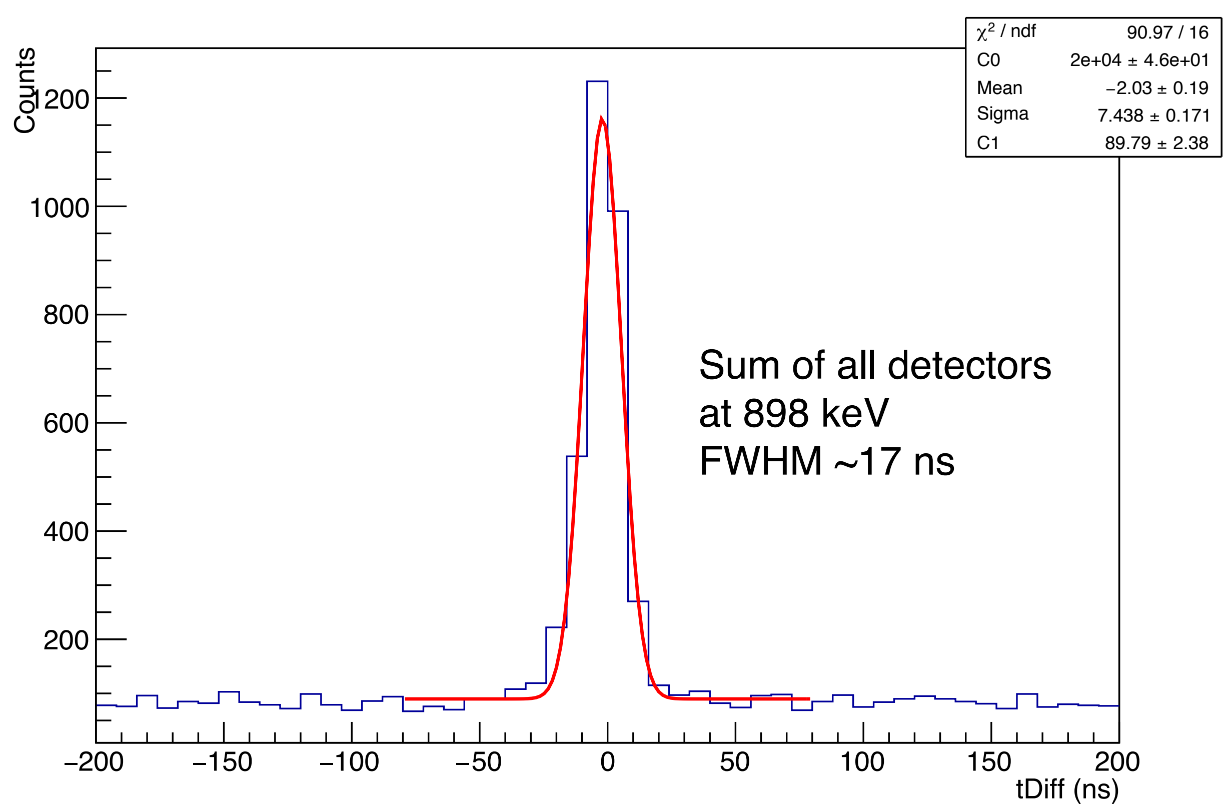




Measurement with high rates

- 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



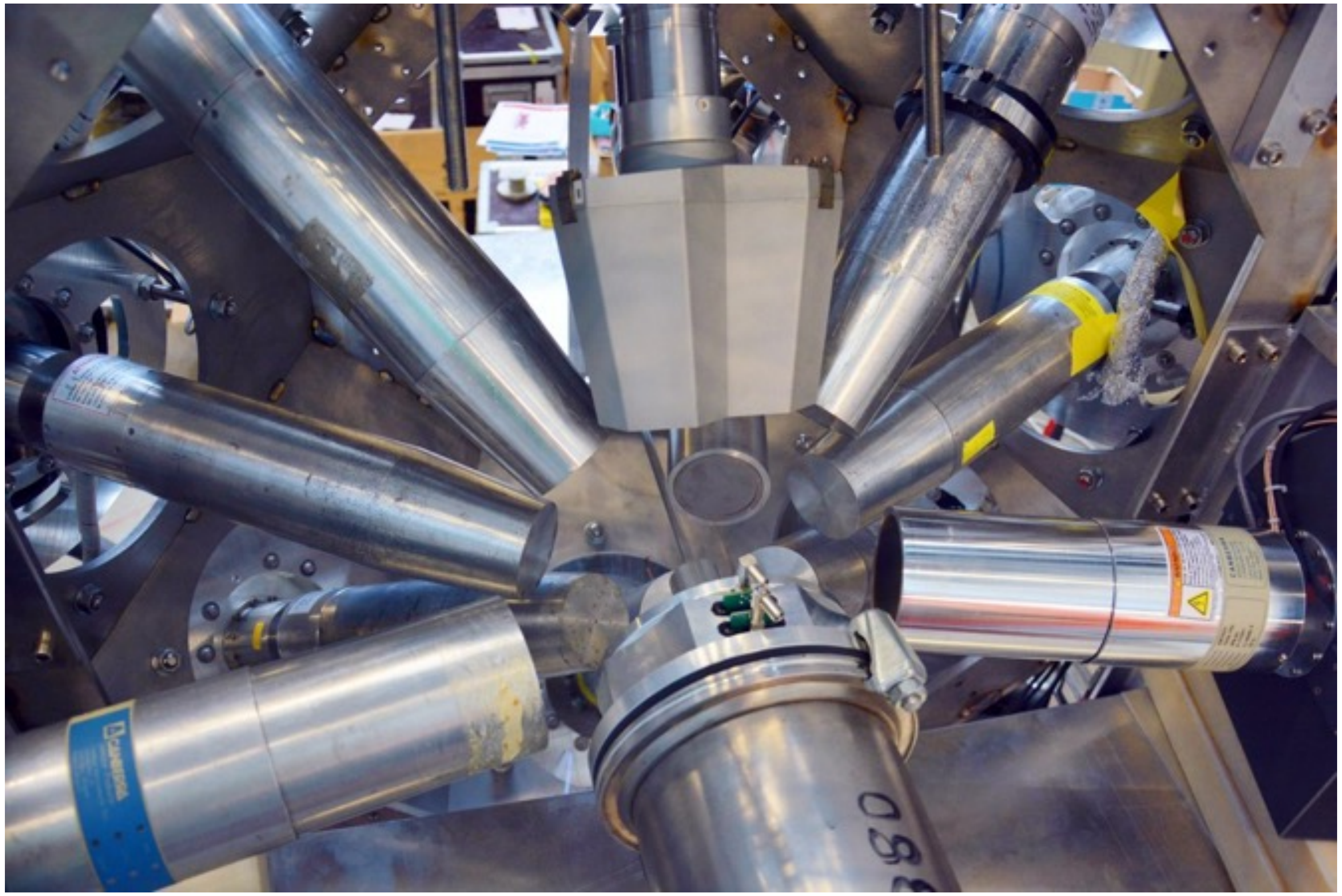


Beam request

- Milestones achieved:
  - Operation of large germanium array during 4 weeks
  - Transfer reactions in high-pressure cell
  - Measurement with 5 µg gold as proof-of-principle
  - High-rate capability of detection system
  - Handling of radioactive material in experimental hall
- We are ready to perform the measurement with an ultra-thin, high-activity target
- ^{226}Ra currently being purchased
- 1 week of setup, 2 weeks of beam

Conclusions

- Large progress over the last two years
- Ready to measure ^{226}Ra this year

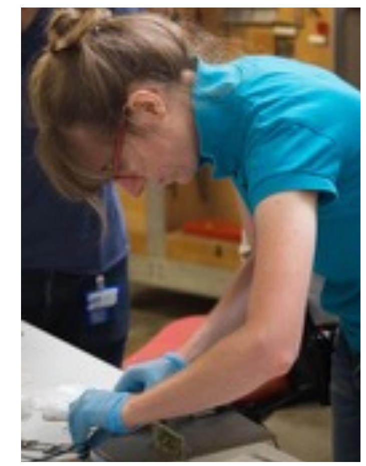


muX collaboration

A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], R. Dressler[2], R. Eichler[2], P. Indelicato[6], K. Jungmann[7], K. Kirch[2,3], A. Knecht[2], J. Krauth[4], J. Nuber[2], A. Papa[2], R. Pohl[4], M. Pospelov[8,9], E. Rapisarda[2], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[11], N. Severijns[5], A. Skawran[2,3], F. Wauters[4], and L. Willmann[7]

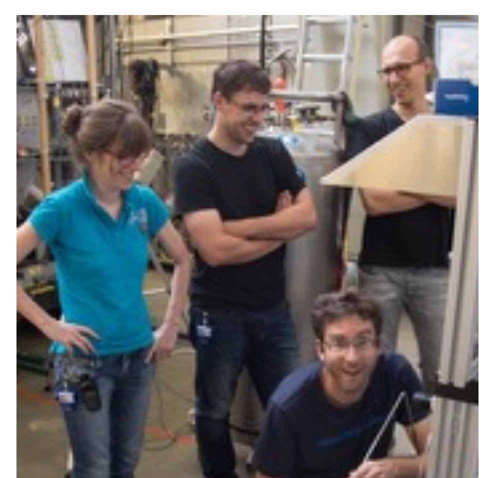
[1]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[2]Paul Scherrer Institut, Villigen, Switzerland
[3]ETH Zürich, Switzerland
[4]University of Mainz, Germany
[5]KU Leuven, Belgium
[6]LKB Paris, France
[7]University of Groningen, The Netherlands
[8]University of Victoria, Canada
[9]Perimeter Institute, Waterloo, Canada
[10]Institut für Kernphysik, Universität zu Köln, Germany
[11]CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France





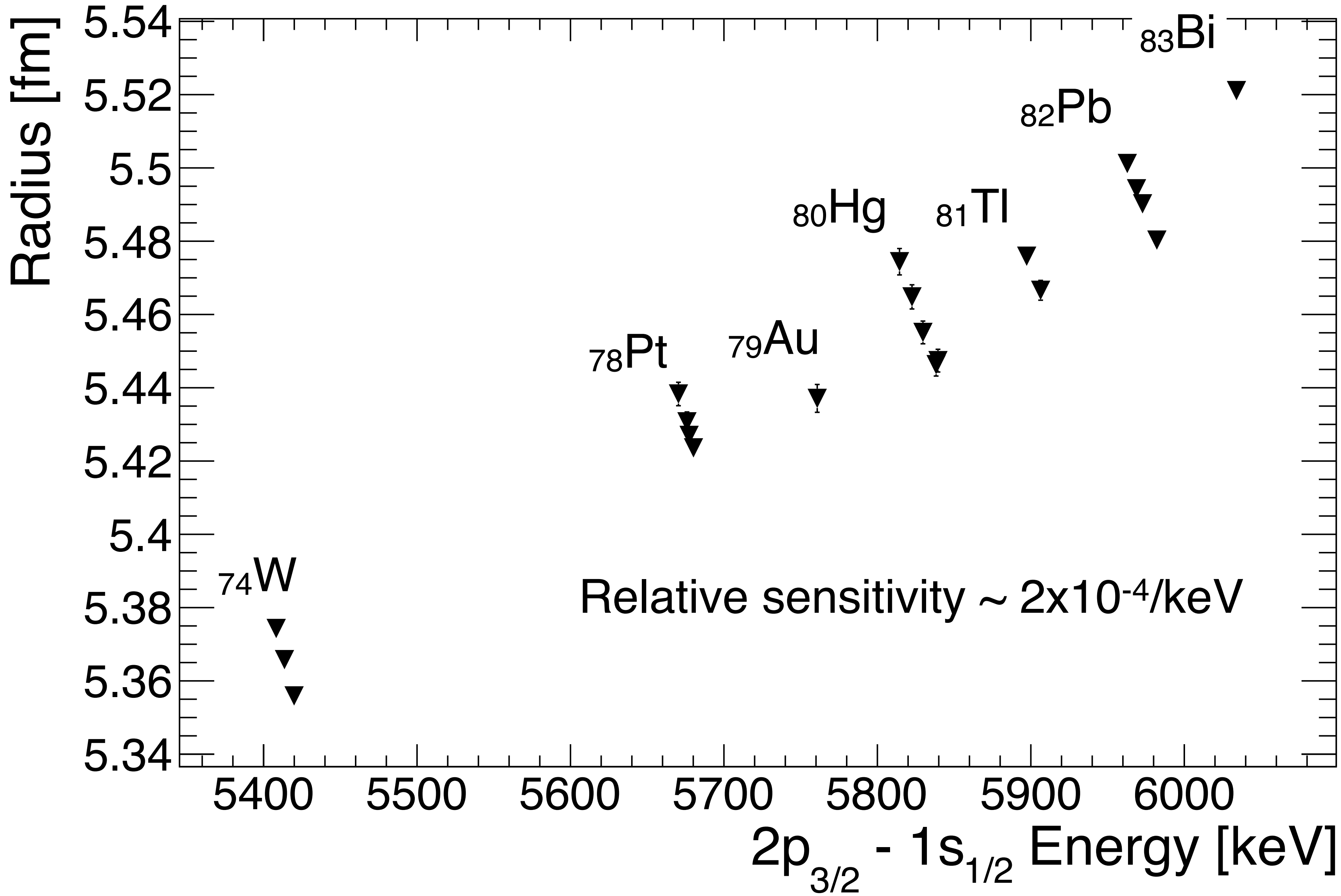






Backup

Muonic Atom Spectroscopy



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

Muonic Atom Spectroscopy

- Nuclear polarization 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

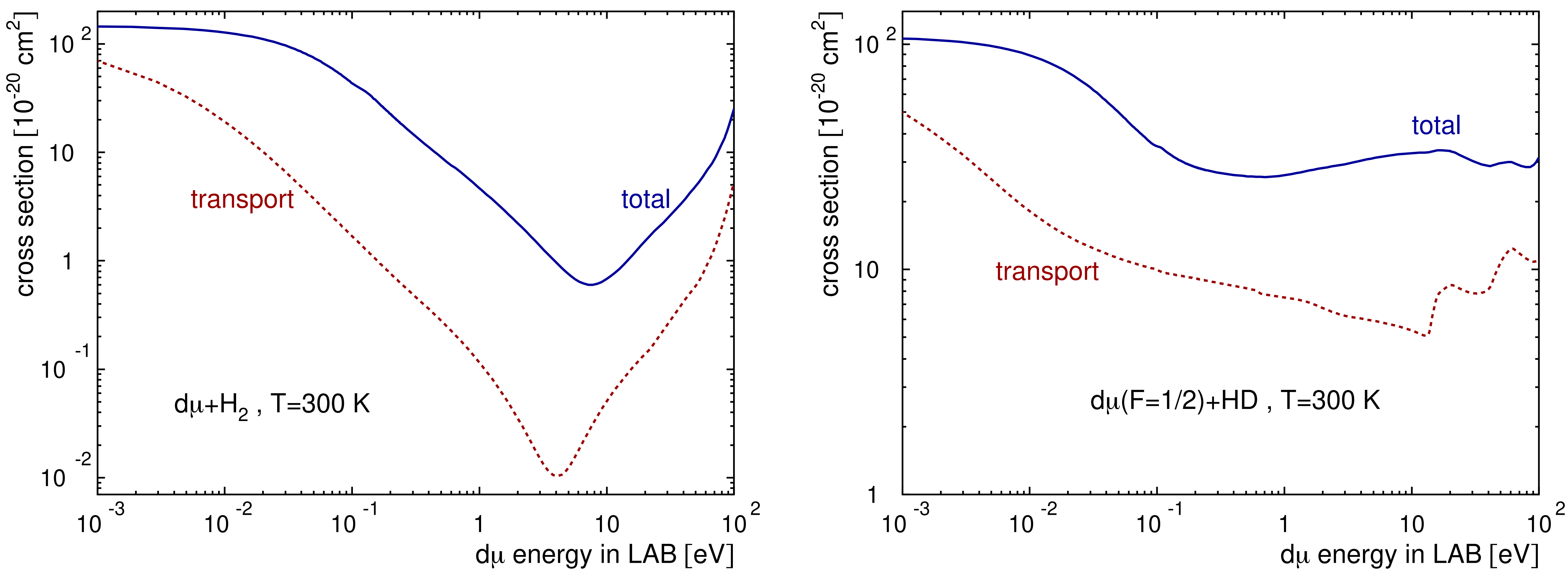
TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

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

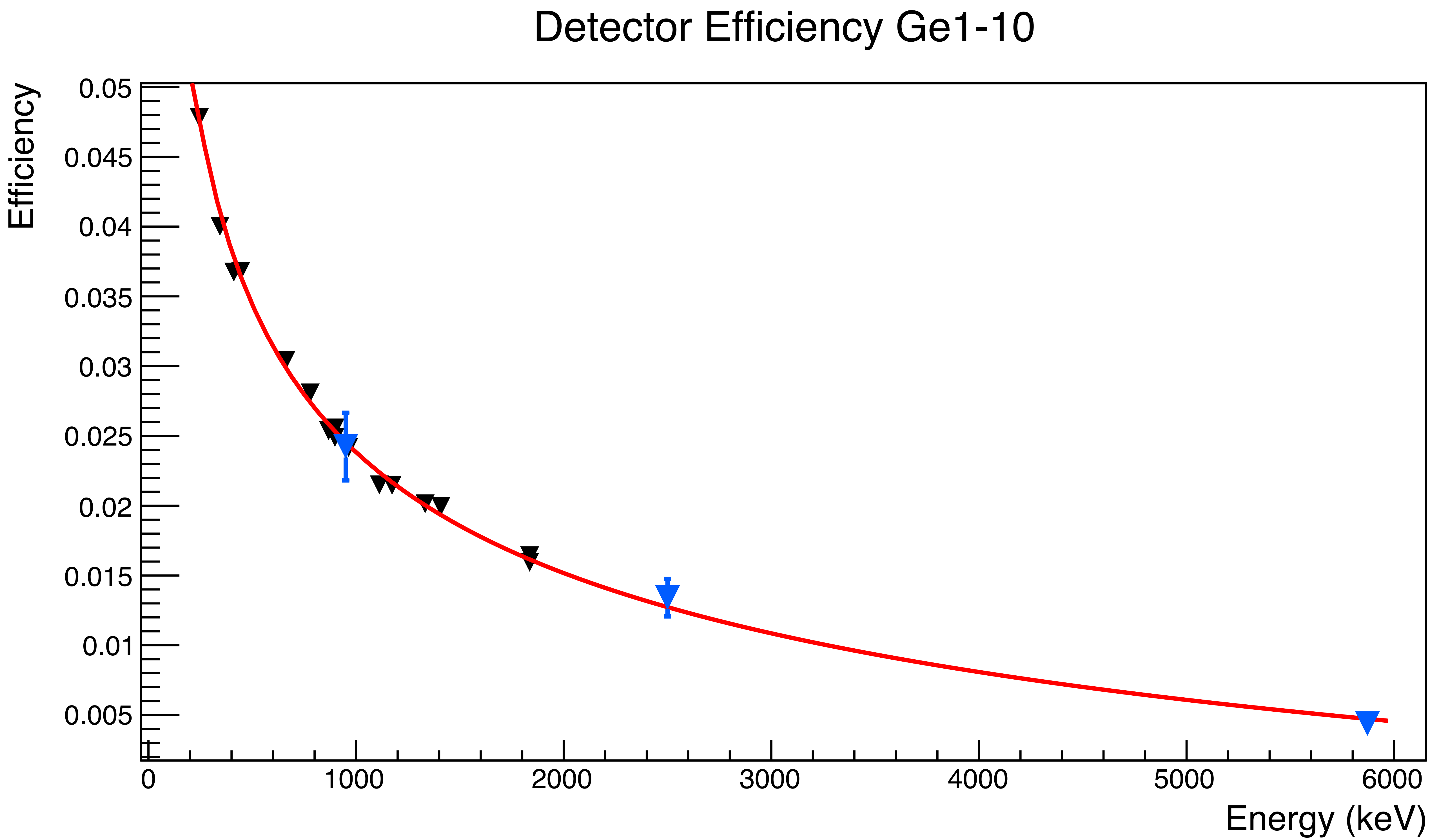
[a]Values from Ref. 7. Positive NP values mean that the respective binding energies are increased.

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

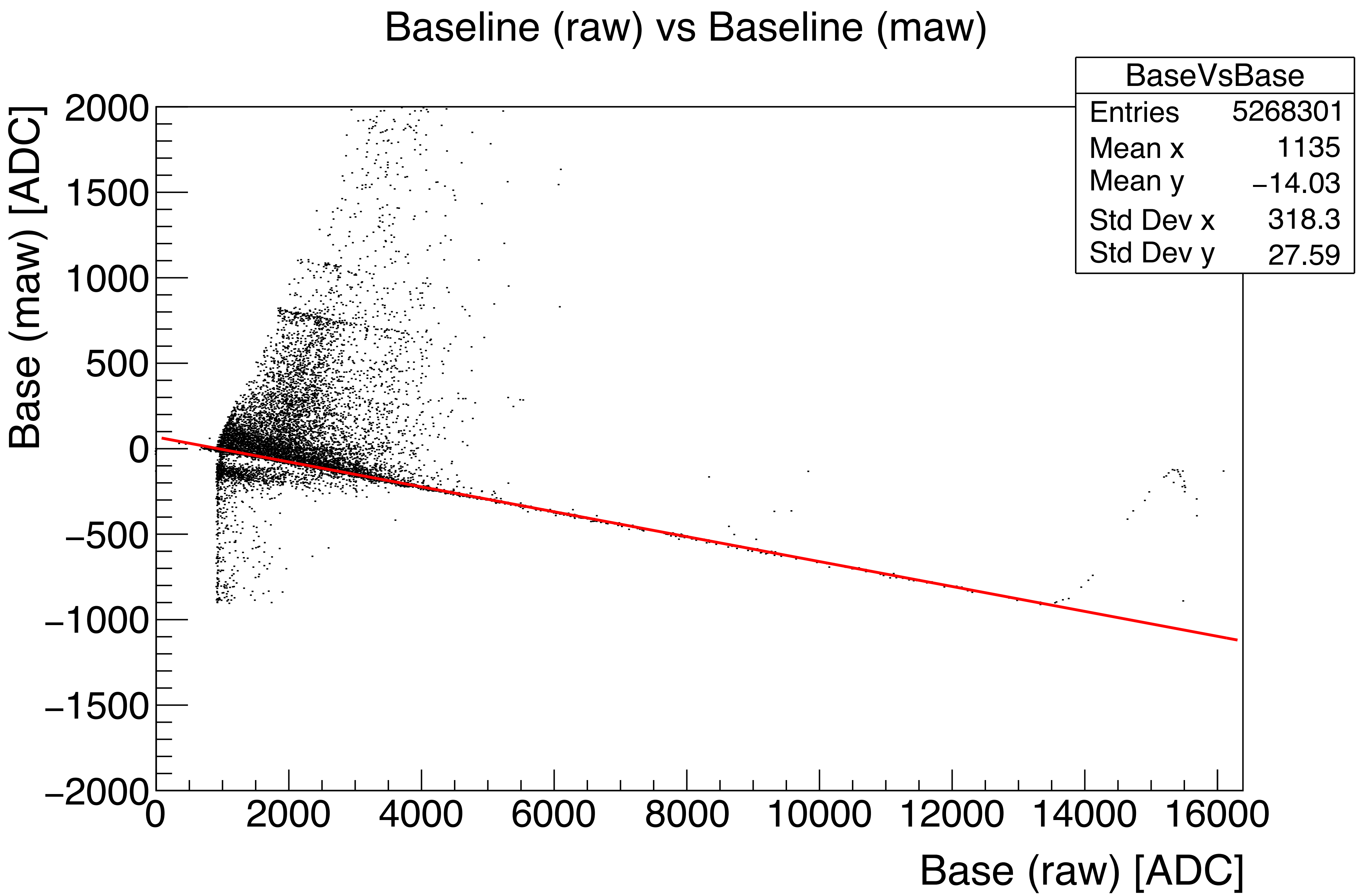
Scattering cross sections



Array Detection Efficiency

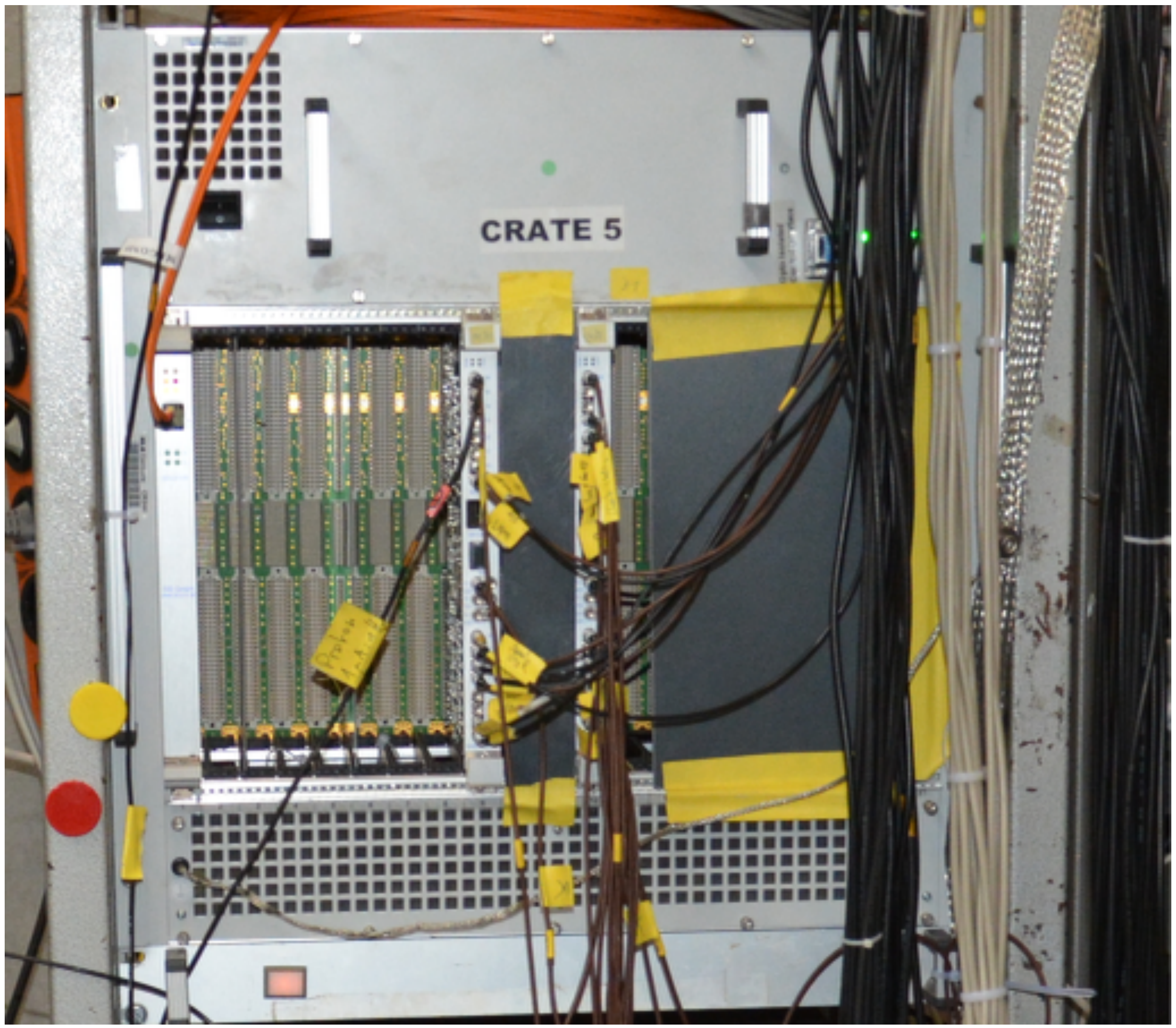


Baseline correction from raw trace



- Can predict maw baseline value from raw baseline amplitude!
- Raw baseline amplitude is a proxy for last pulse's energy, time

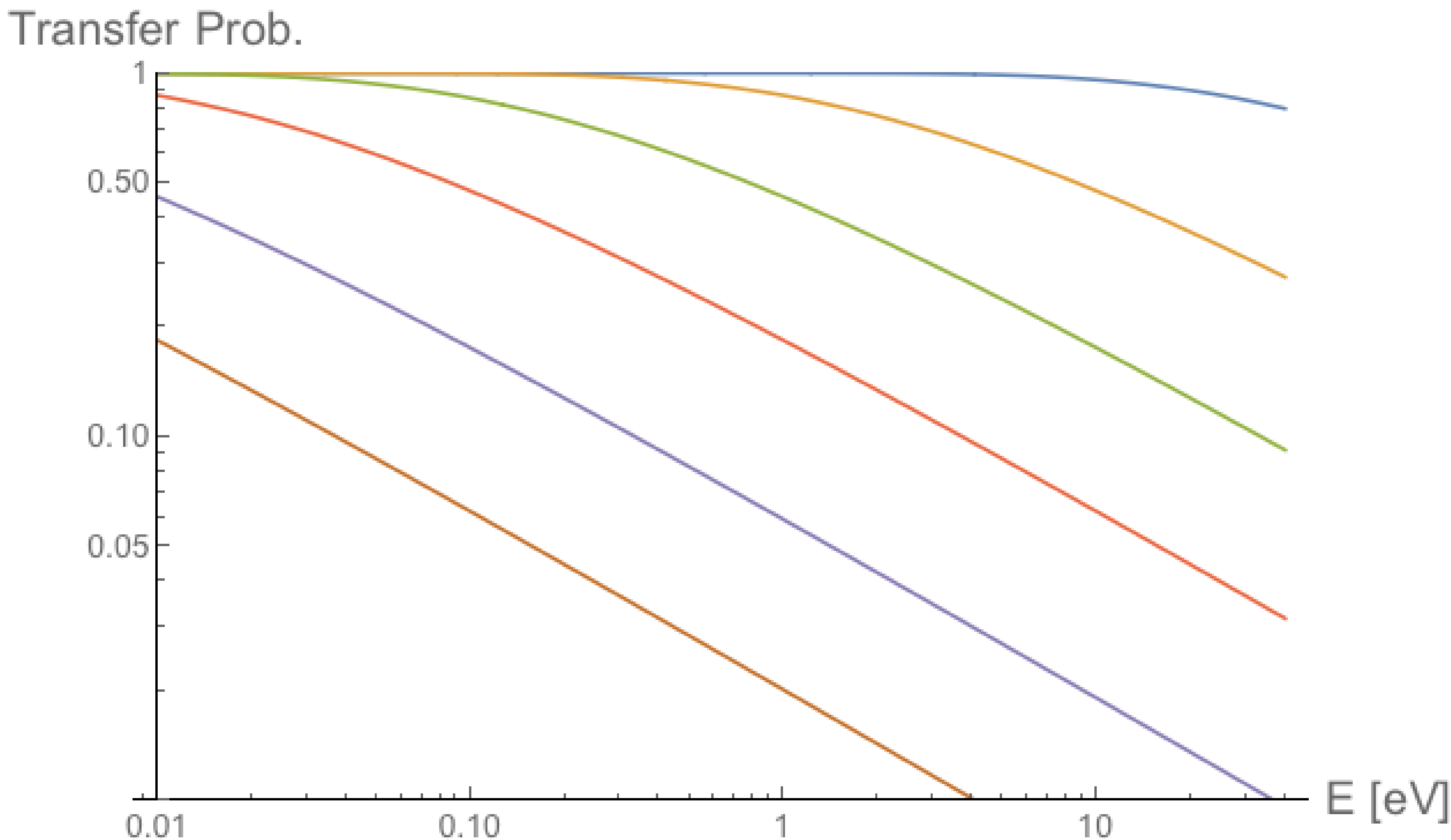
DAQ



http://www.struck.de/sis3316.html

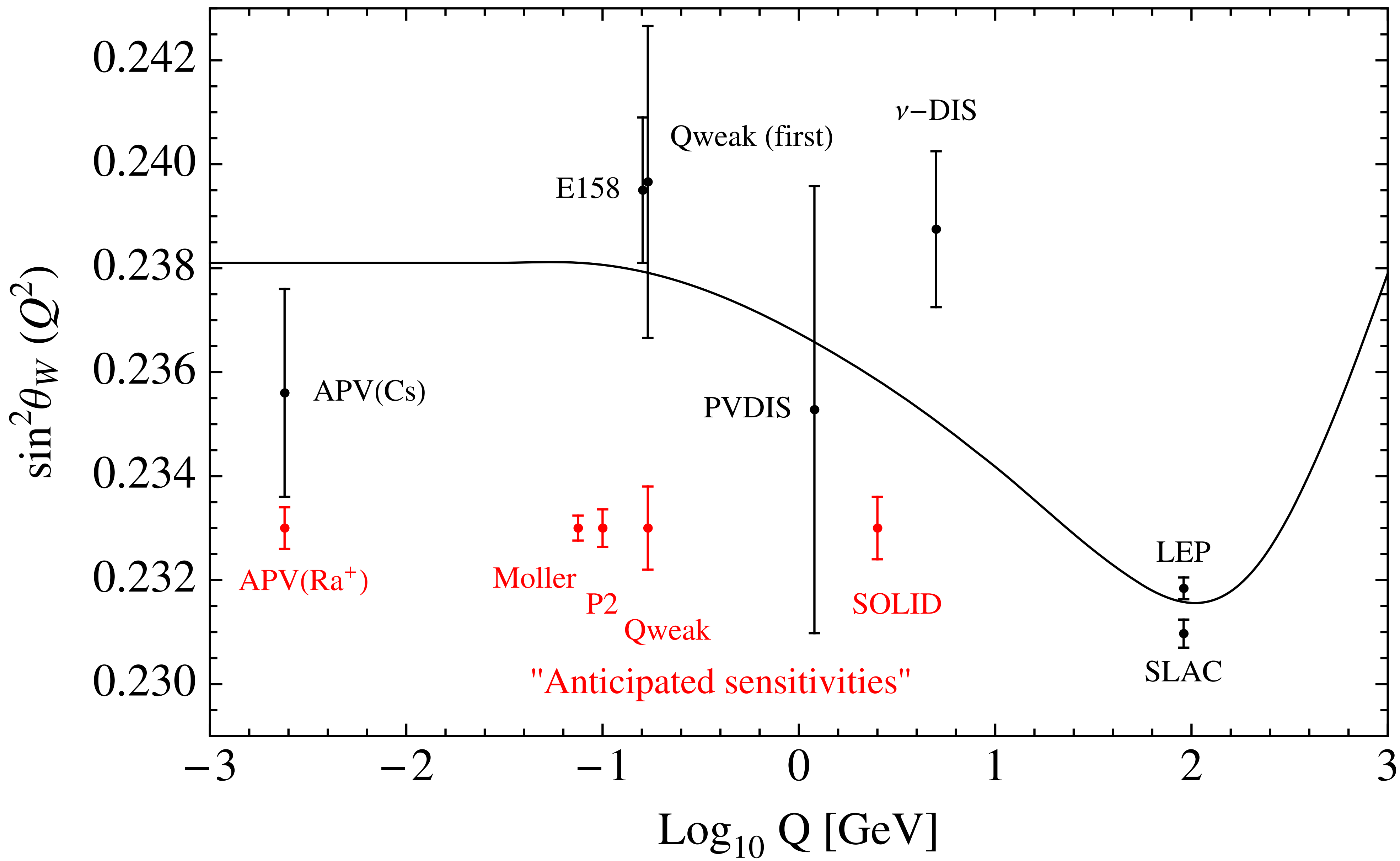
- Struck SIS3316 digitizer: 16 channel, 14 bit, 250 MHz
- Firmware for online pulse processing

Transfer Probability in Gold



Why atomic parity violation?

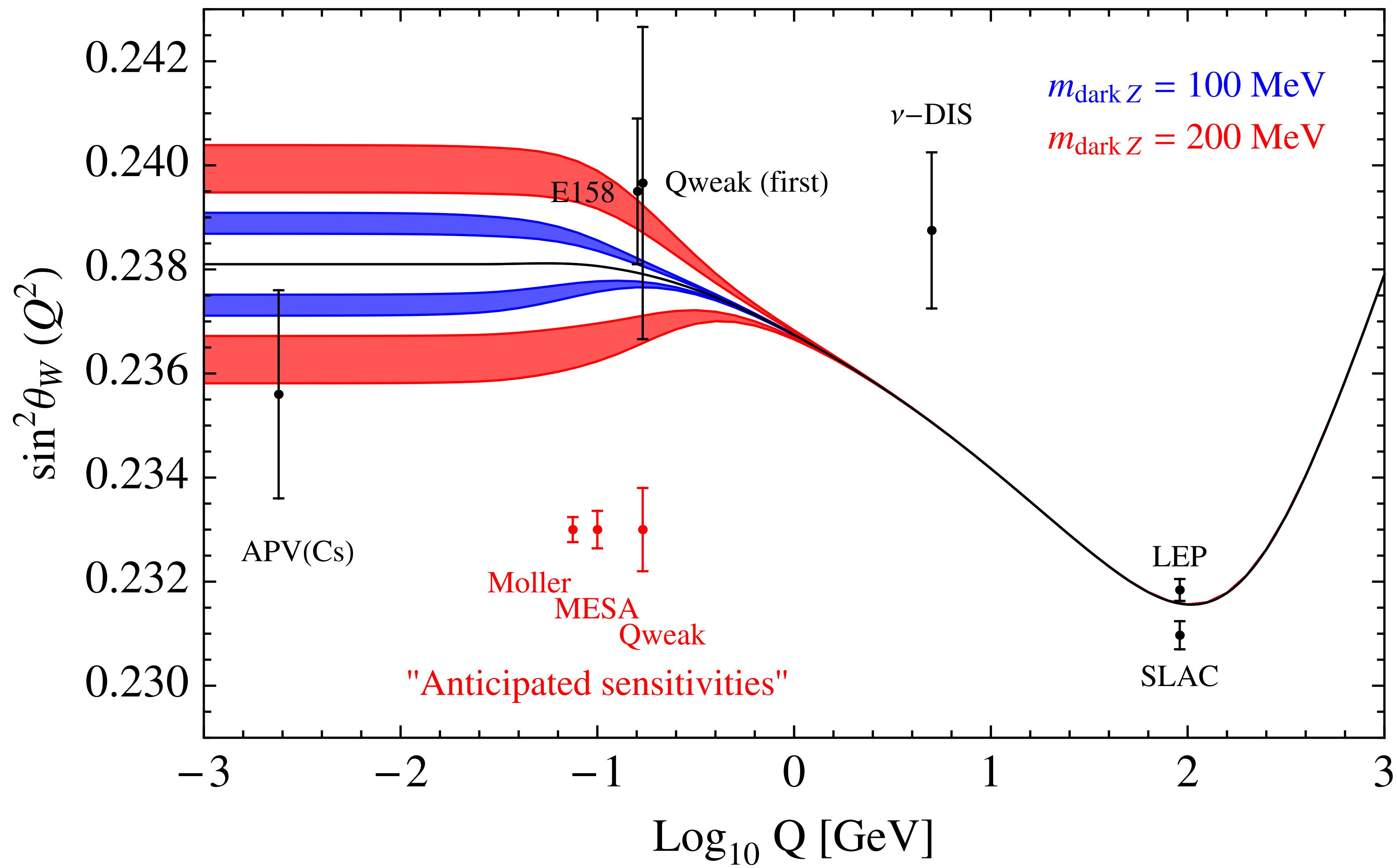
Davoudiasl, Lee, Marciano, Phys. Rev. D **92**, 055005 (2015)



- Running of the Weinberg angle as a function of momentum transfer
- APV fixes the low momentum value

Possible New Physics

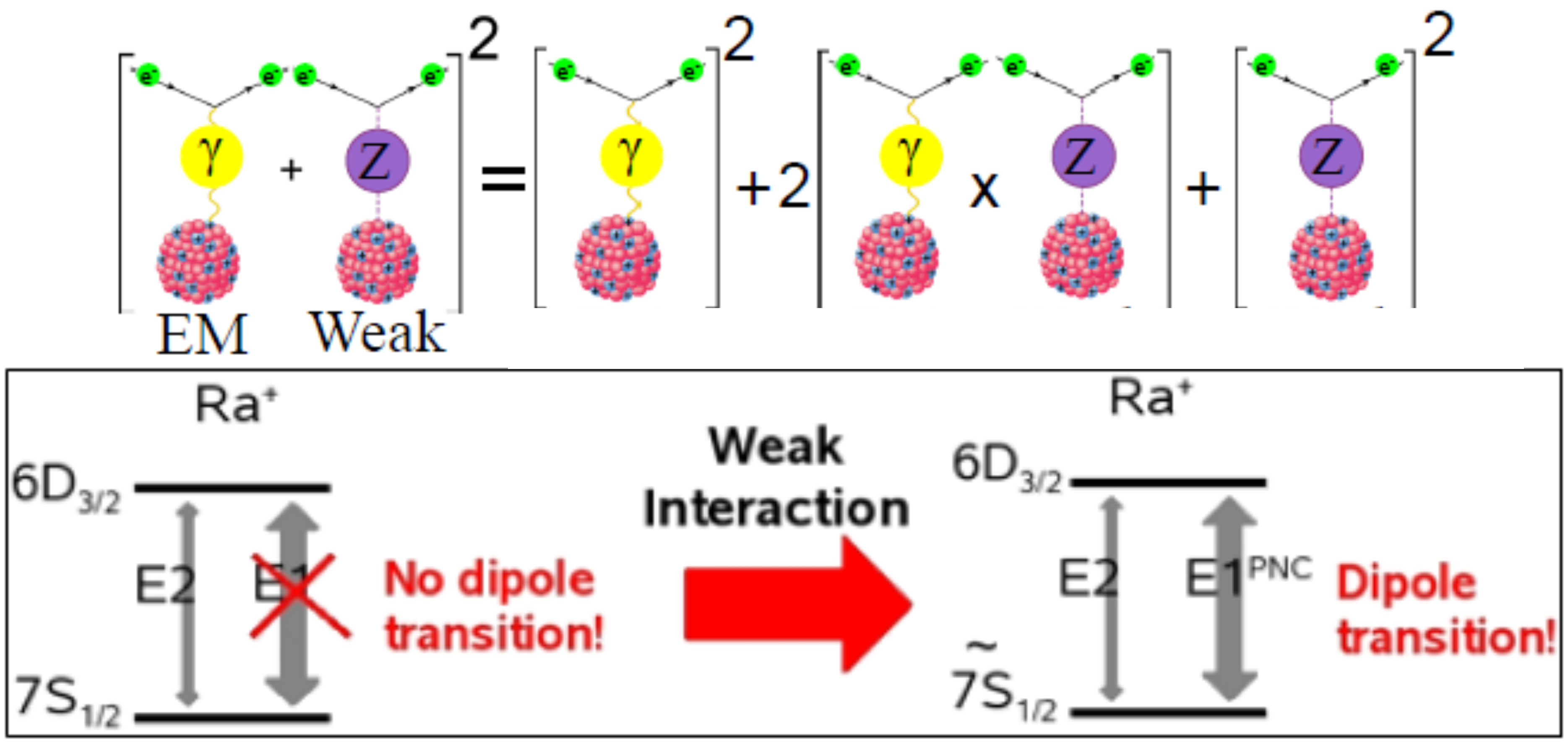
Davoudiasl, Lee, Marciano, Phys. Rev. D **89**, 095006 (2014)



- Possible new physics in the form of a new dark Z boson hides at low momentum!

Weak Interaction in Atoms

Interference of EM and Weak interactions



$$E1_{PNC} = K_r \; Z^3 \, Q_w = K_r \; Z^3 \, (- N + Z \, (1\text{-}4\sin^2 \theta_W))$$

Measurement

Atomic Theory

Heavy System

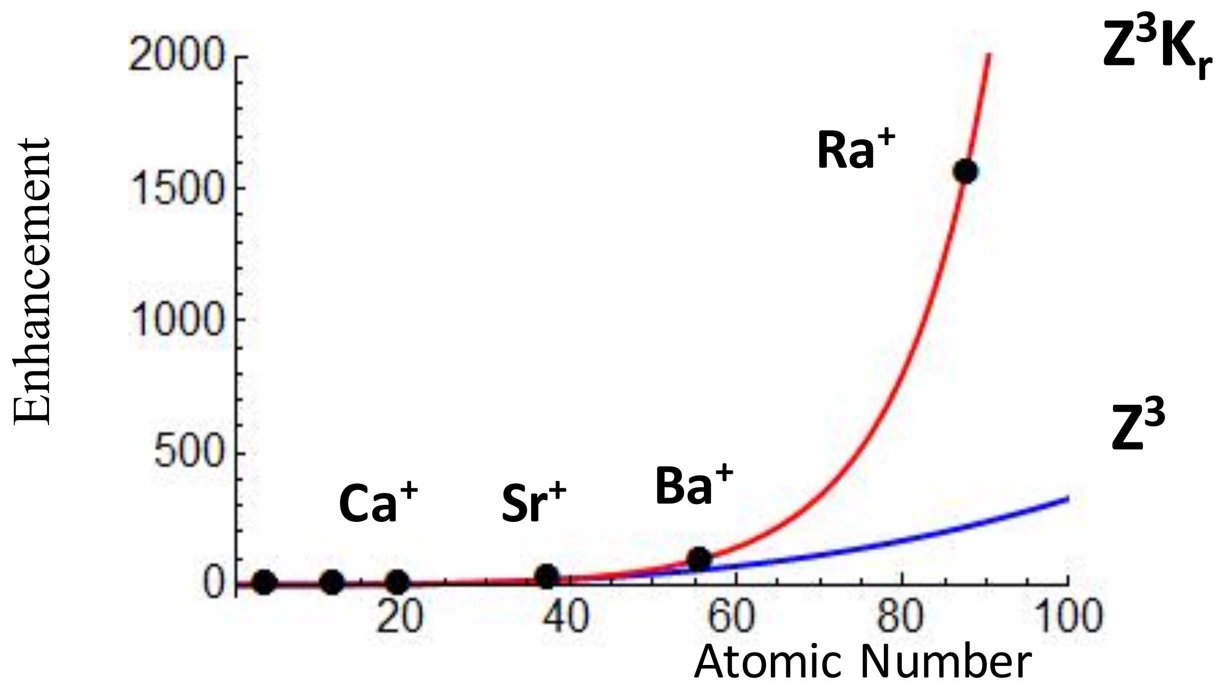
K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

Benefit of Ra

Scaling of the APV

increase faster than Z^3 (Bouchiat & Bouchiat, 1974)

$\langle nS_{1/2}|H_W|nP_{1/2}\rangle \propto K_r Z^3$ K_r relativistic enhancement factor



Ra^+ effects larger by:
20 (Ba^+)
50 (Cs)

L.W. Wansbeek *et al.*, Phys. Rev. A **78**, 050501 (2008)

→ 5-fold improvement over Cs feasible in 1day

Relativistic coupled-cluster (CC) calculation of $E1_{APV}$ in Ra^+

$$E1_{APV} = 46.4(1.4) \cdot 10^{-11}\, iea_0\, (-Q_w/N) \quad \text{(3\% accuracy)}$$

K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

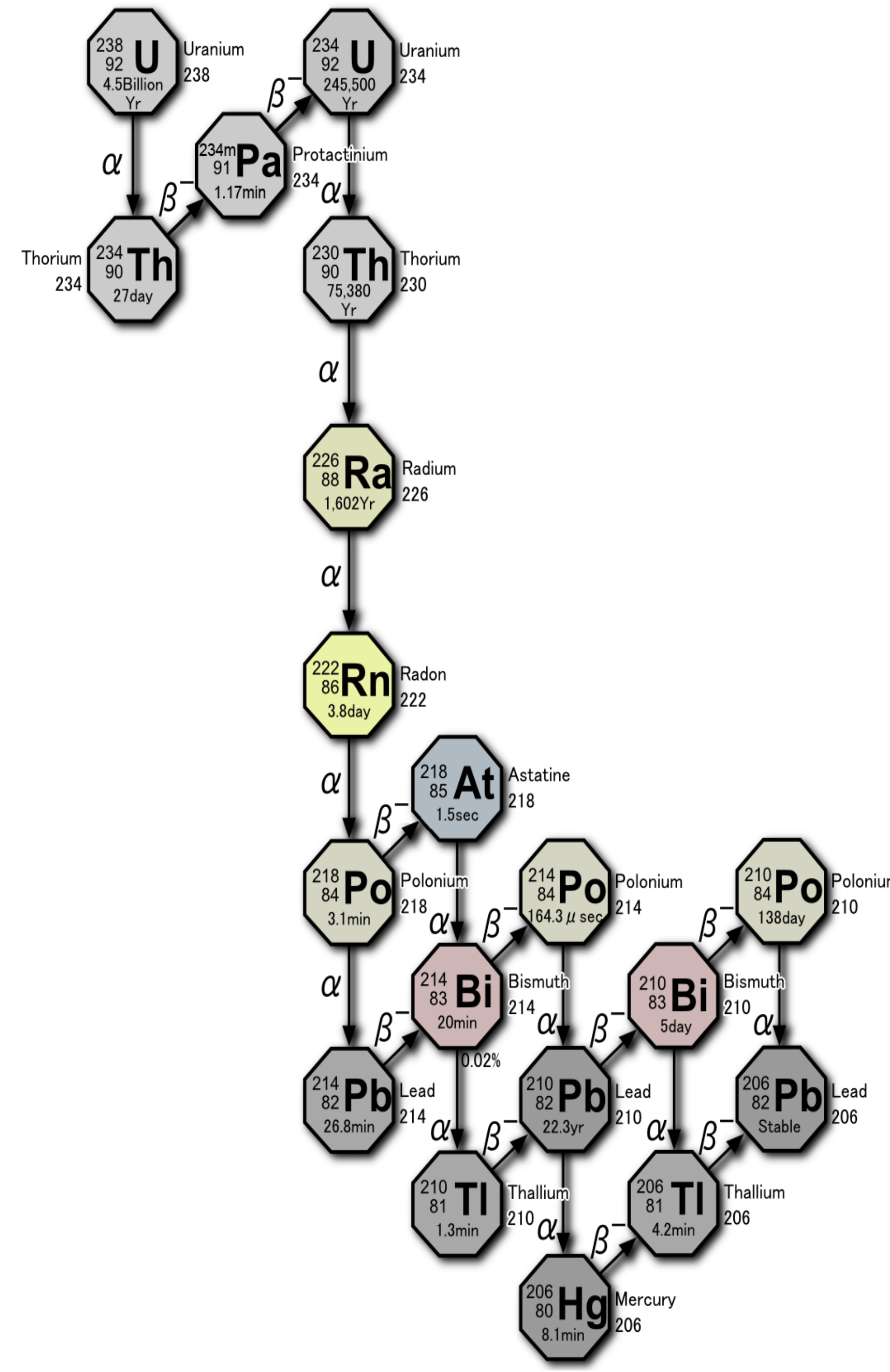
Other results:

$45.9 \cdot 10^{-11}\, iea_0\, (-Q_w/N)$ (R. Pal *et al.*, Phys. Rev. A **79**, 062505 (2009), Dzuba *et al.*, Phys Rev. A **63**, 062101 (2001).)

- Need reliable charge radius at <0.2% accuracy for atomic theory

Radium Activity

- 5 µg corresponds to 200 kBq of 226-Ra and all daughters
- Highest gamma emitters: 214-Pb, 214-Bi
- Gamma rate: ~400 kHz



Other radioactive isotopes

Isotope	Half-life	Max. Activity	Max. Mass
^{226}Ra	1600 y	200 kBq	5 μg
^{248}Cm	350’000 y	5 kBq	32 μg
^{209}Po	102 y	200 kBq	0.3 μg

- Isotopes without measured charge radius
- Maximum activity based on current regulations and without major modifications to experimental area infrastructure (100 x approval limit)

PAUL SCHERRER INSTITUT

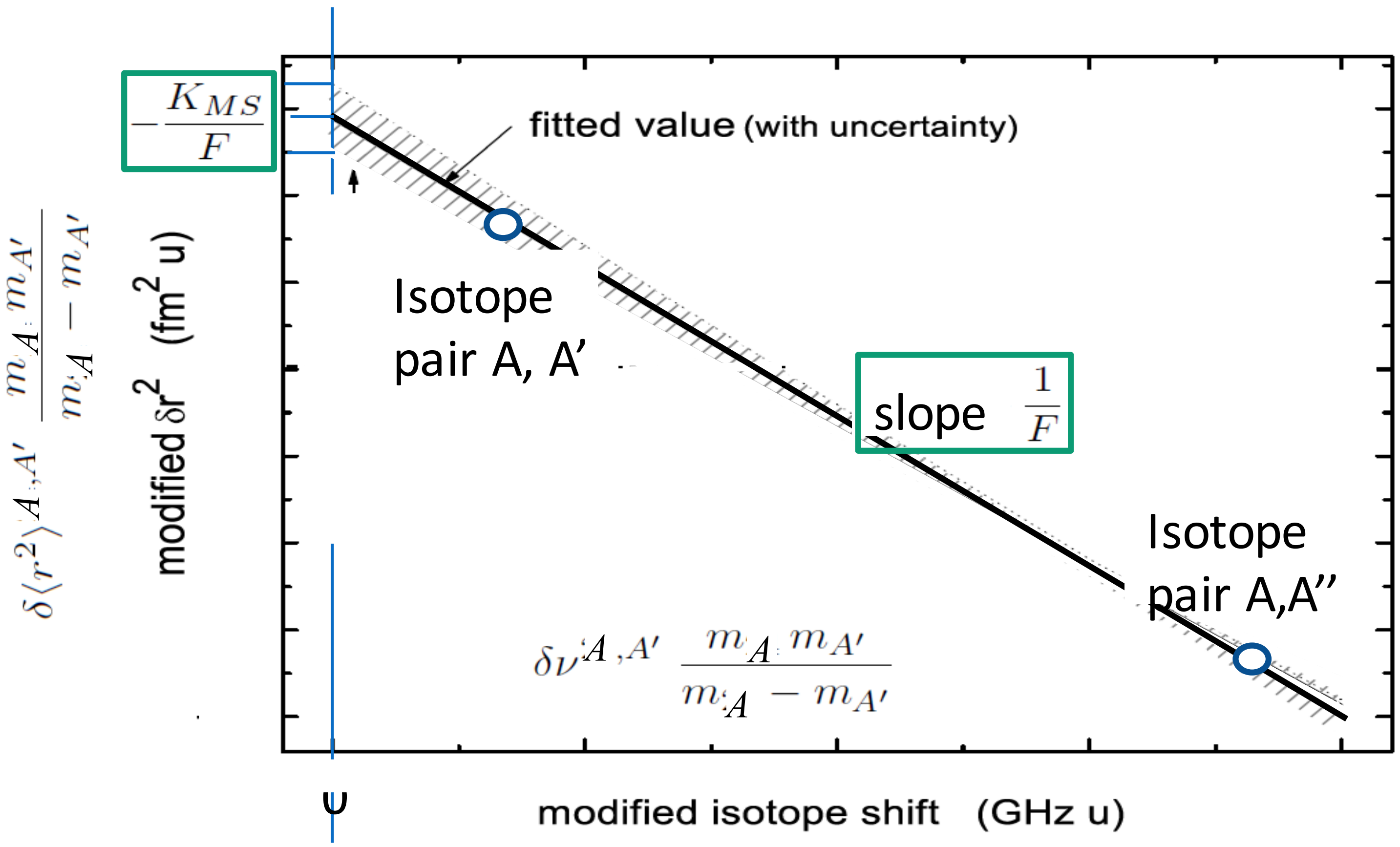
M. Kowalska, Workshop on Muonic Atom Spectroscopy (2016)

=> Modified King plot

- When data for at least 3 isotopes exists (i.e stable isotopes):
  - Combine absolute radii (transitions in muonic atoms and/or electron scattering) and isotope shifts in optical transitions to derive more precise F and K_MS values

$$\delta\nu^{A,A'} \frac{m_A m_{A'}}{m_A - m_{A'}} = K_{MS} + F\delta\langle r^2\rangle^{A,A'} \frac{m_A m_{A'}}{m_A - m_{A'}}$$

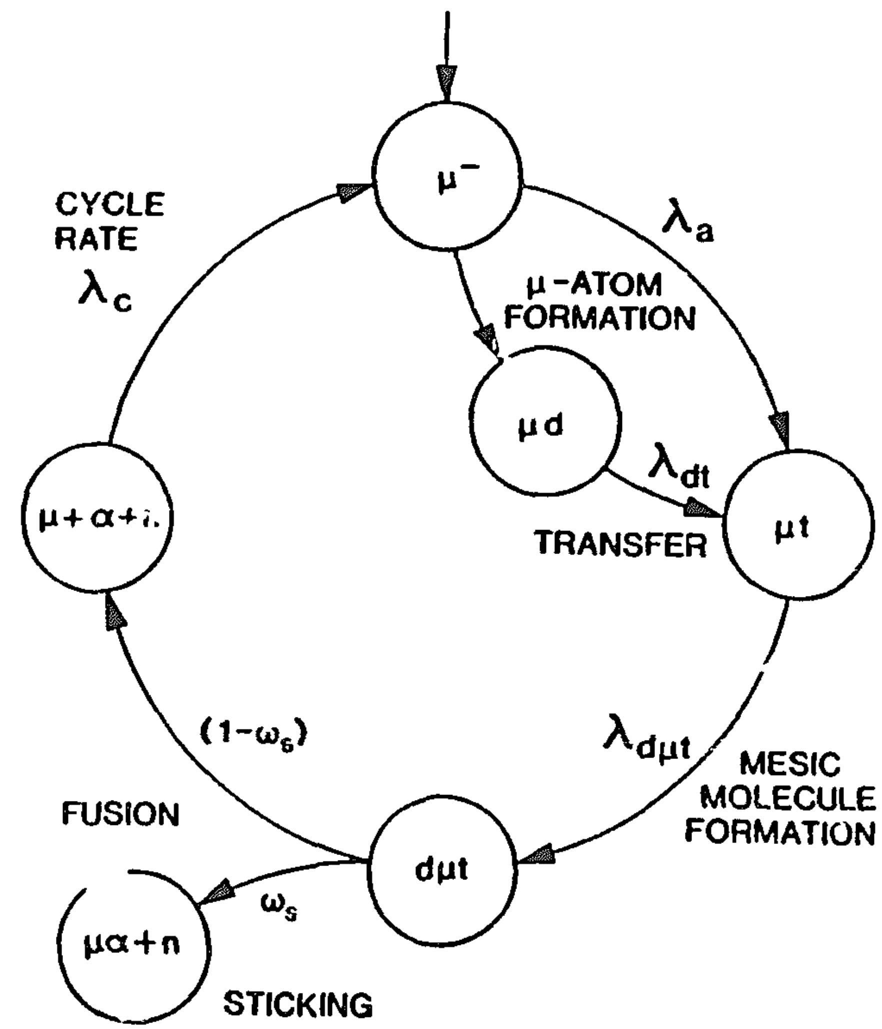
$$\delta\langle r^2\rangle^{A,A'} \frac{m_A m_{A'}}{m_A - m_{A'}} = -\frac{K_{MS}}{F} + \frac{1}{F} \delta\nu^{A,A'} \frac{m_A m_{A'}}{m_A - m_{A'}}$$



But if there are fewer stable isotopes …
See Na, Mn, Cu, Ga …

Muon catalyzed fusion

$$p\mu d \longrightarrow (\mu\, {}^3\mathrm{He})_{nl} + \gamma, \quad Q_{1s} = 5.502\ \mathrm{MeV},$$
$$d\mu d \longrightarrow (\mu\, {}^3\mathrm{He})_{nl} + n, \quad Q_{1s} = 3.277\ \mathrm{MeV},$$
$$d\mu t \longrightarrow (\mu\, {}^4\mathrm{He})_{nl} + n, \quad Q_{1s} = 17.598\ \mathrm{MeV}.$$



Petitjean, Nucl. Phys. **A543**, 79 (1992)