Atomic parity violation with radioactive ions
&
the muX experiment

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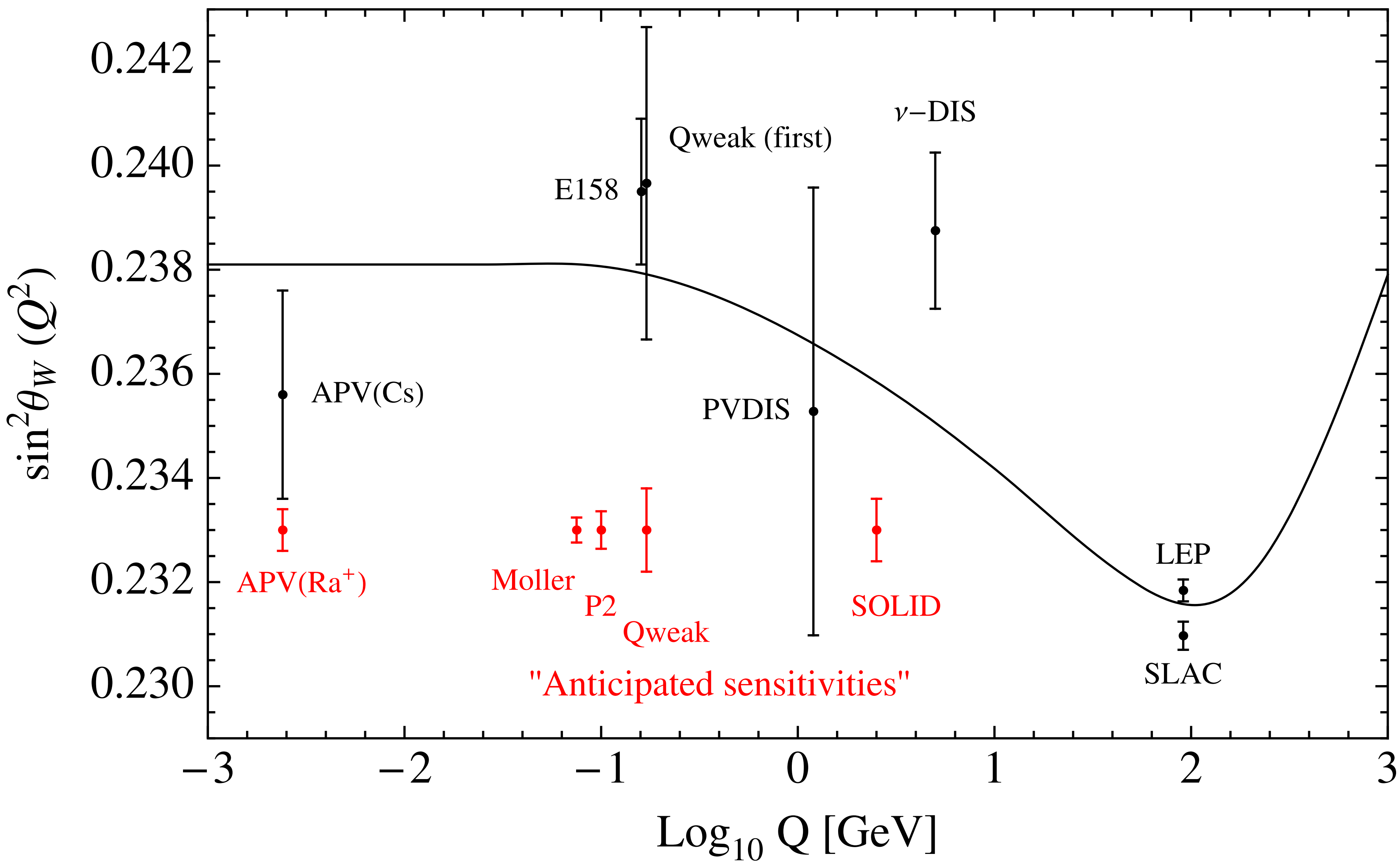
Particle physics & radioactive ions

- Electric dipole moments: Fr-210, Ra-225, Rn
- Weak interaction studies: large range of isotopes
- Atomic parity violation: Fr, Ra

Why atomic parity violation?

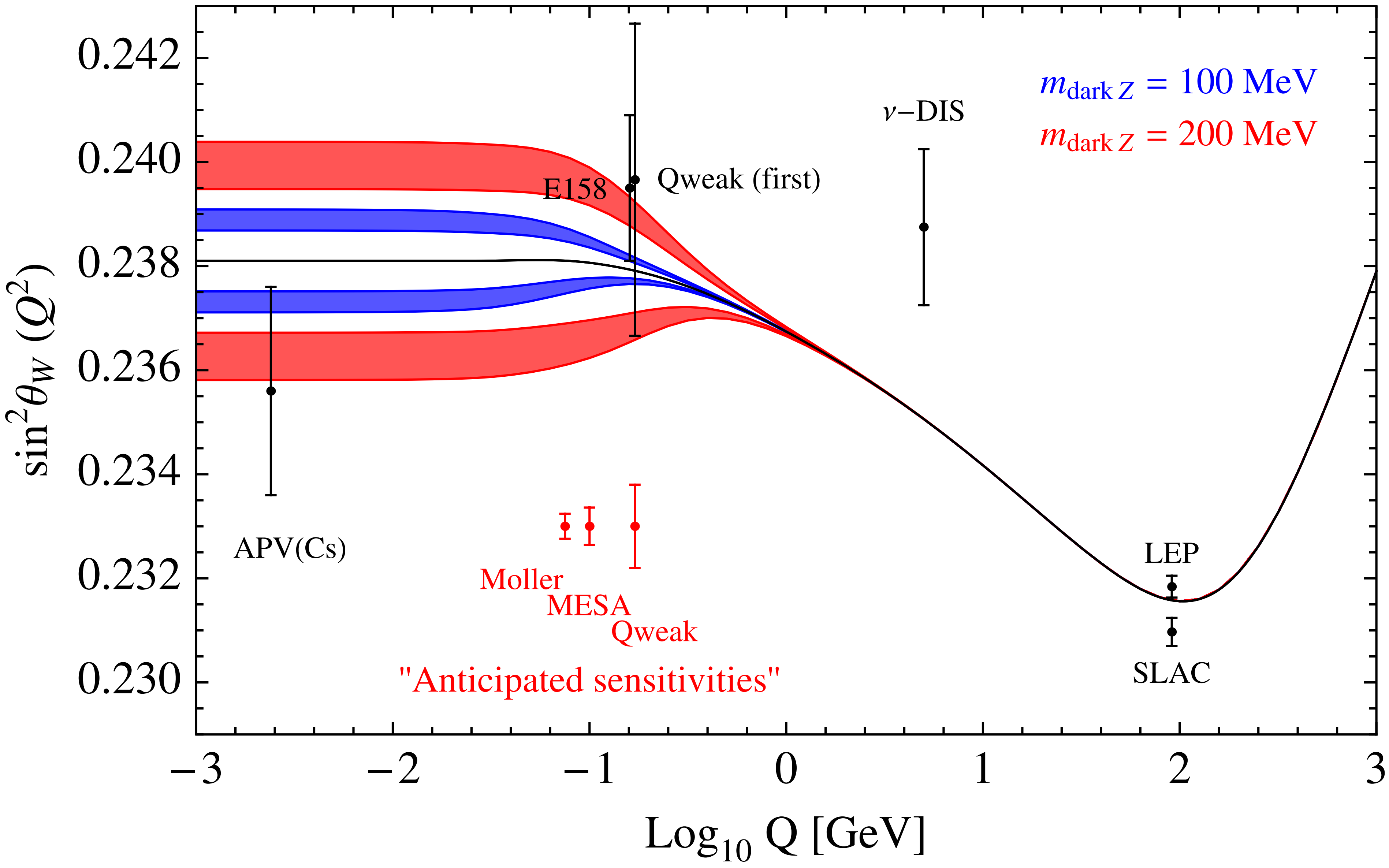
Davoudiasl, Lee, Marciano, Phys. Rev. D **92**, 055005 (2015)



- 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)

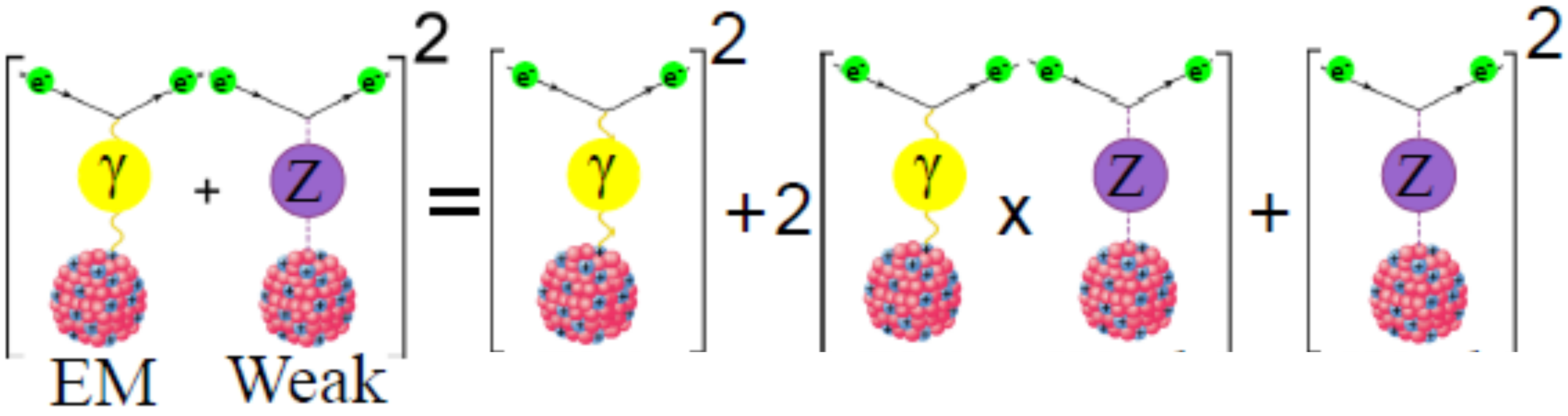


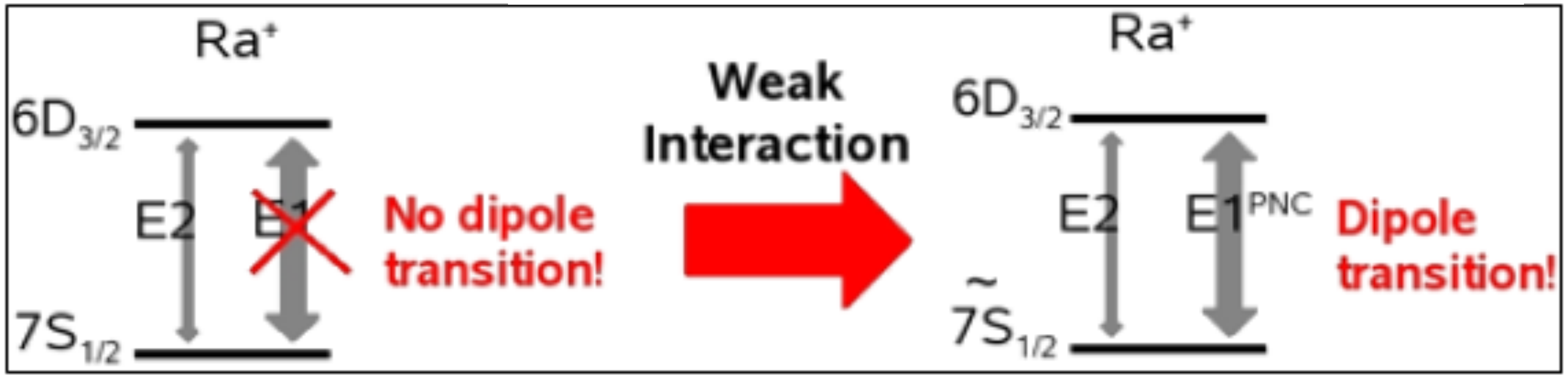
- Possible new physics in the form of a new dark Z boson hides at low momentum!

Detection of APV

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

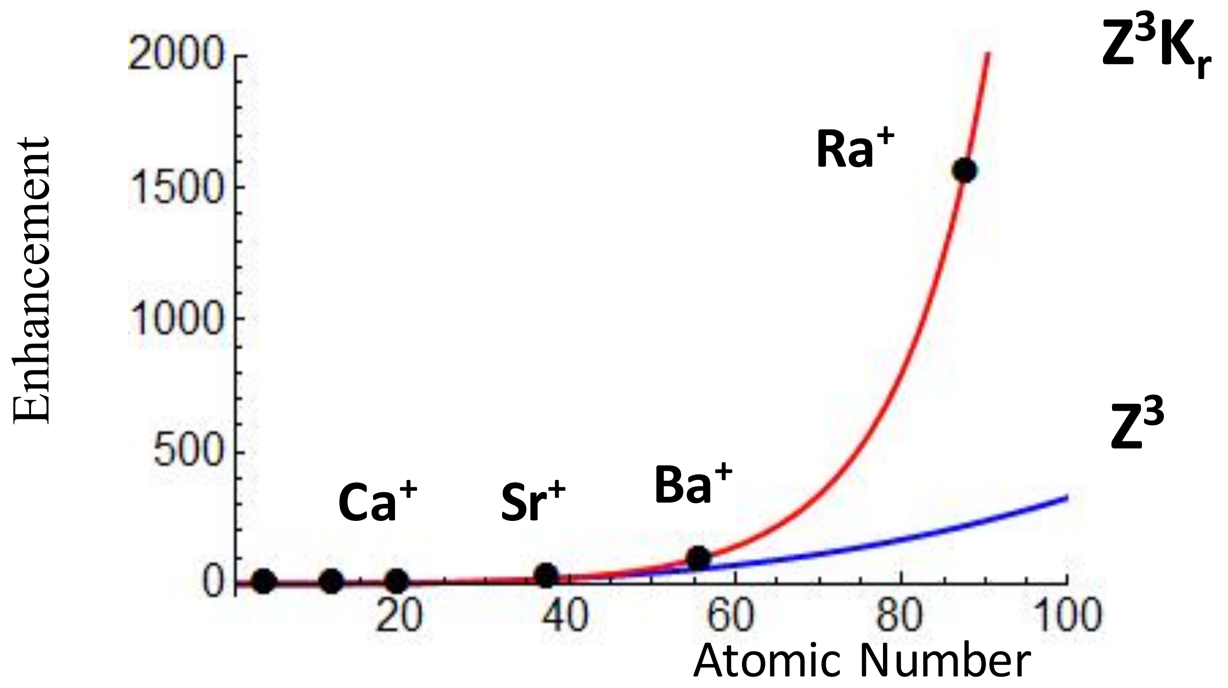
K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

Benefit of Fr, 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^+

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

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

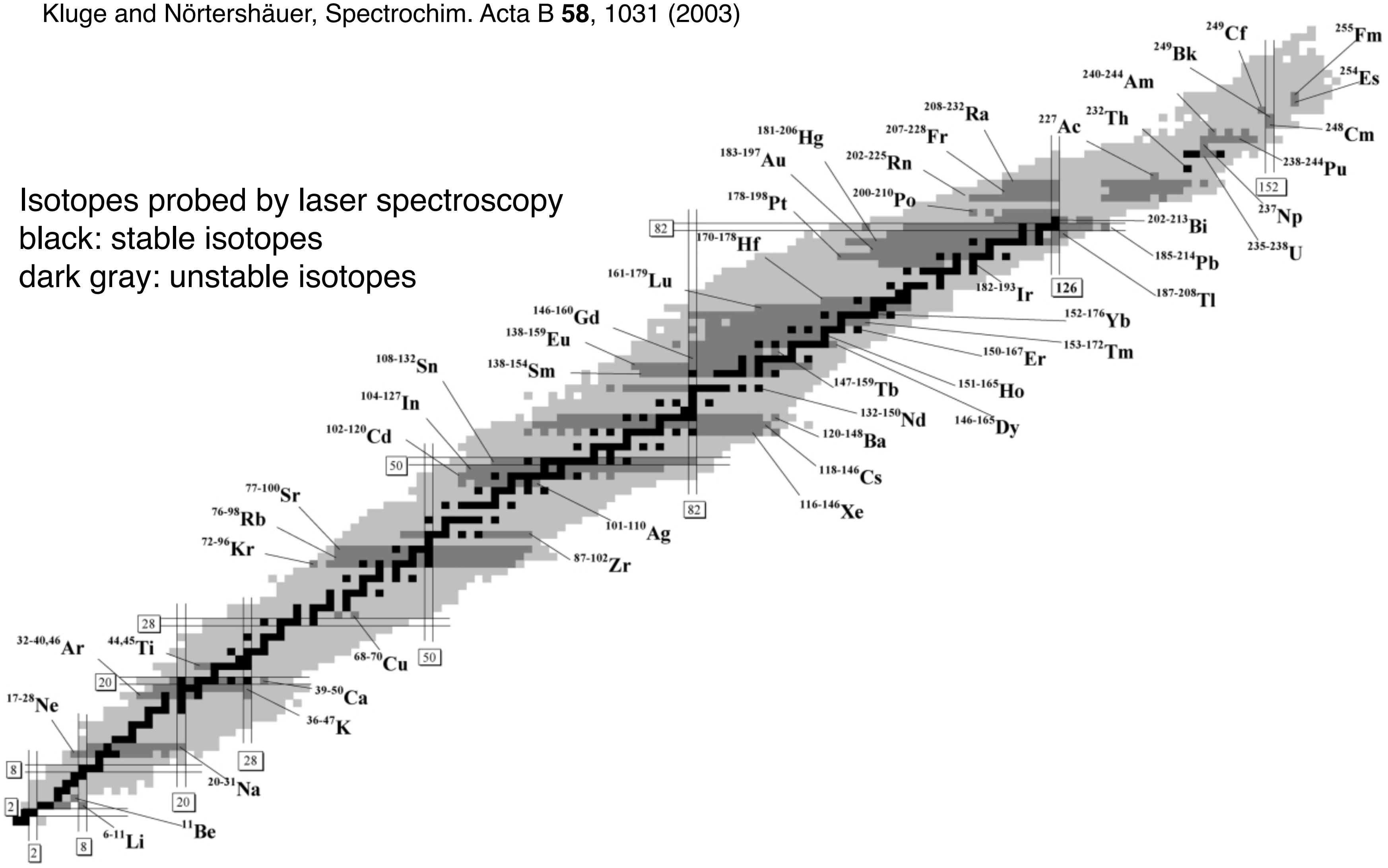
Other results:

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

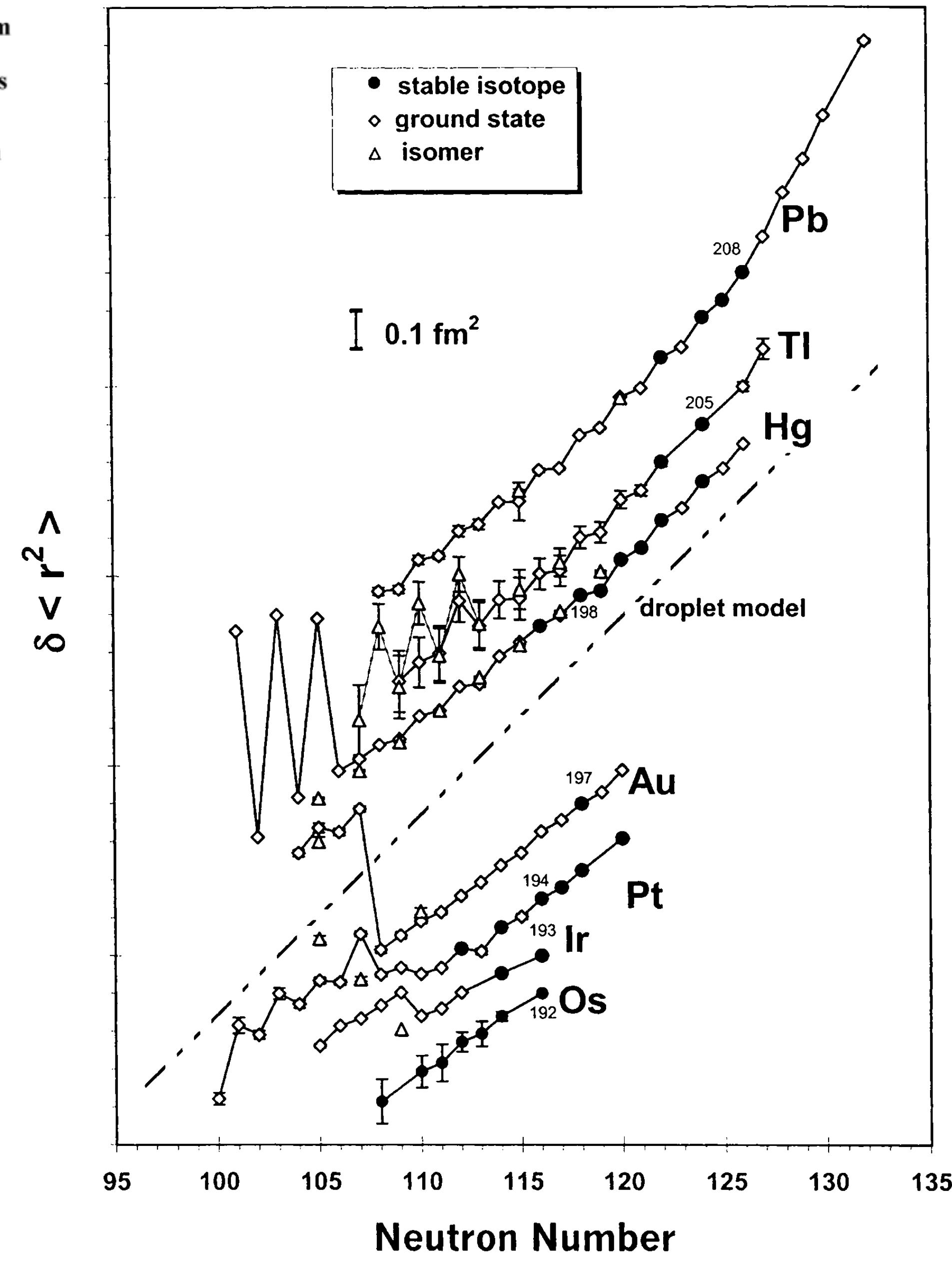
- Need reliable charge radius at <0.2% accuracy for atomic theory

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



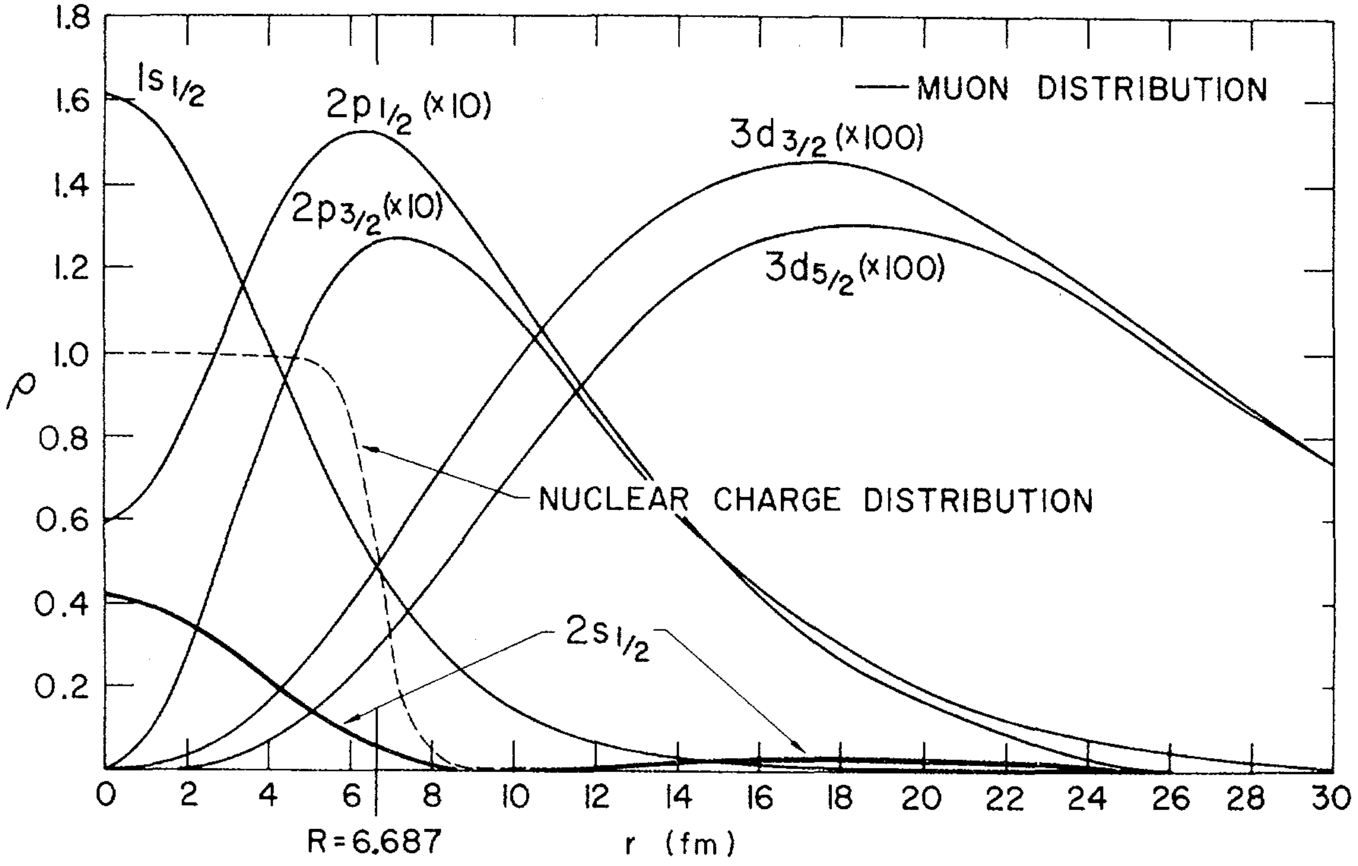
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

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)

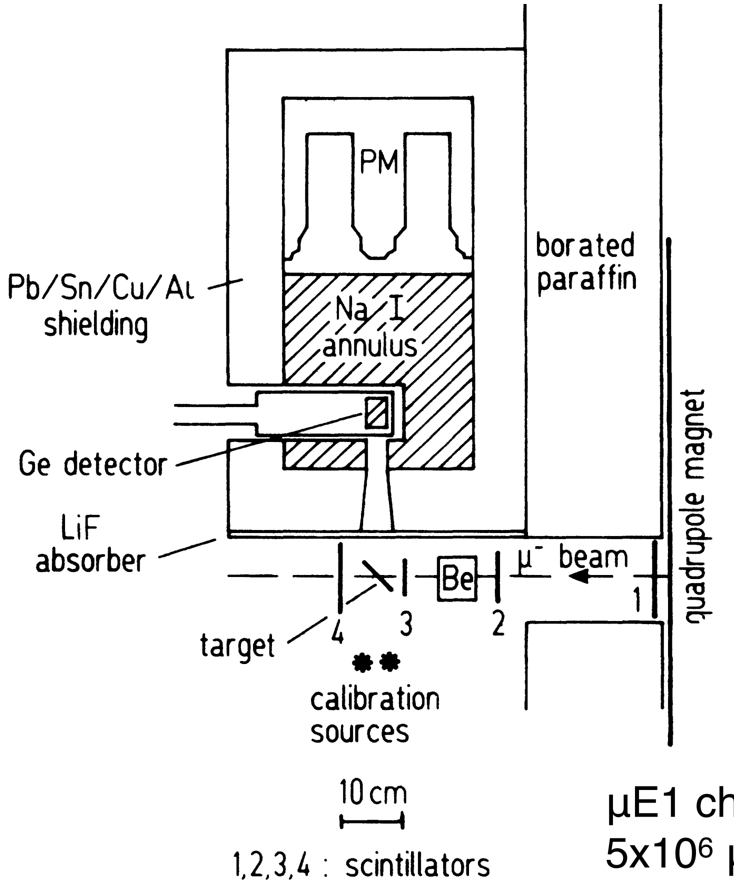
Muonic Atom Spectroscopy

- Impressive precision in the extracted charge radius can be achieved
- For ^{208}Pb: $\langle r^2 \rangle^{1/2}$ = 5.5031(11) fm
  2x10^{-4} relative precision

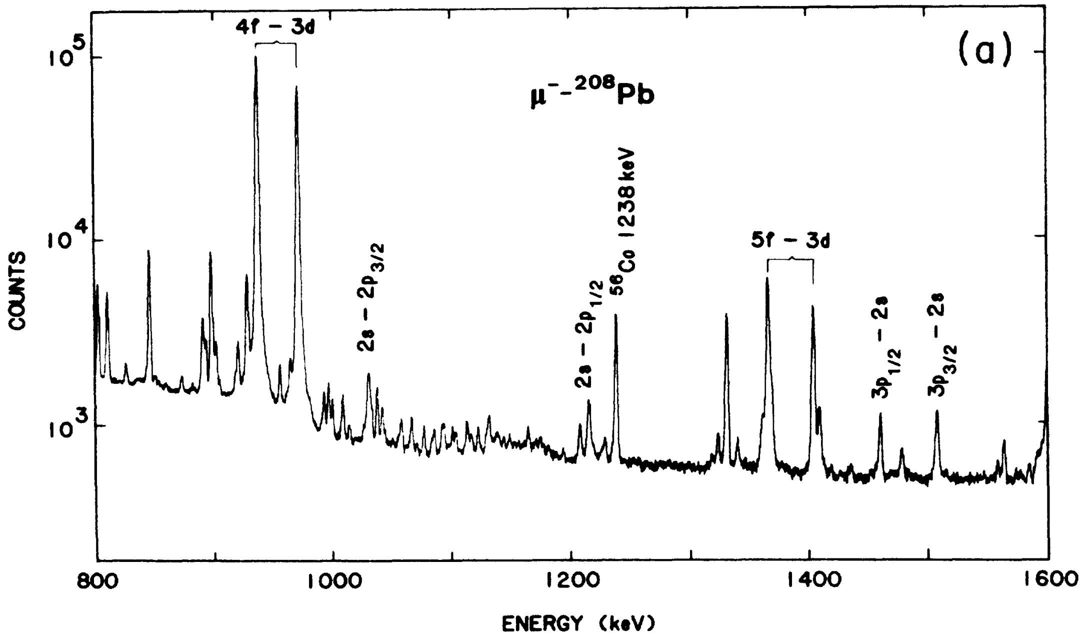
TABLE V. Experimental muonic transition energies (keV) in ^{208}Pb (recoil corrected).

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)

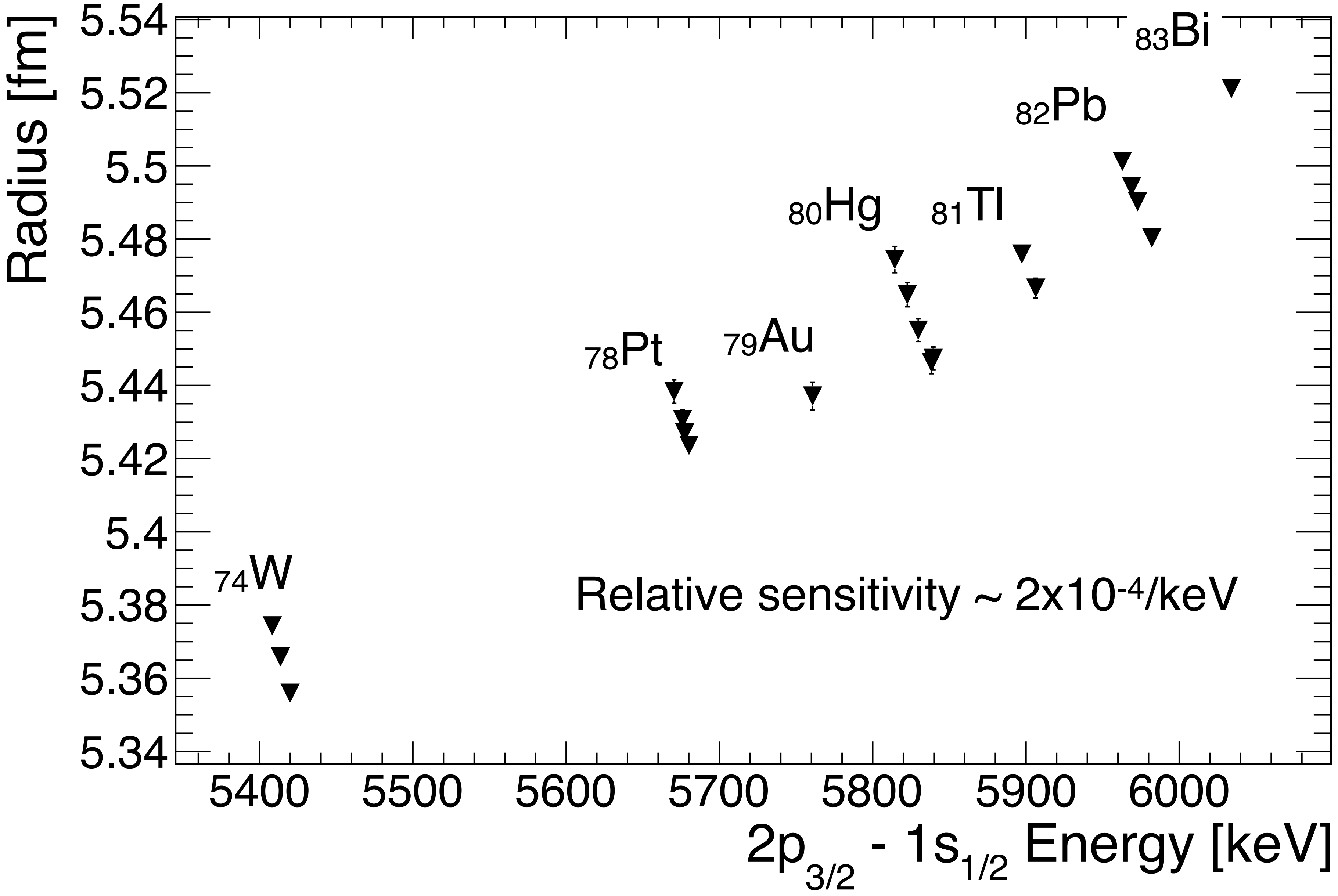
Bergem et al., PRC **37**, 2821 (1988)



μE1 channel at PSI
5x10^6 μ^-/s at 125 MeV/c



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

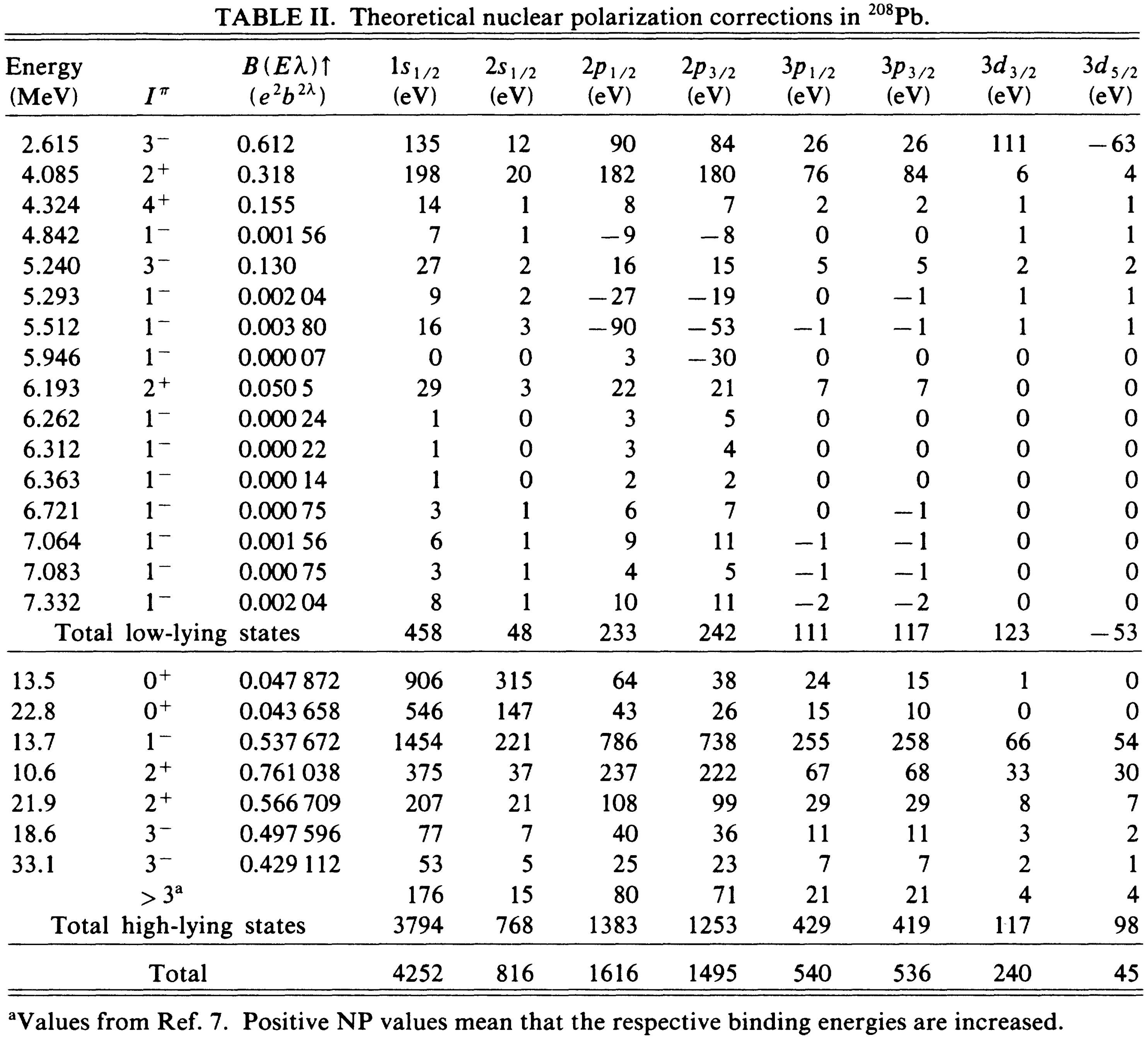


TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

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

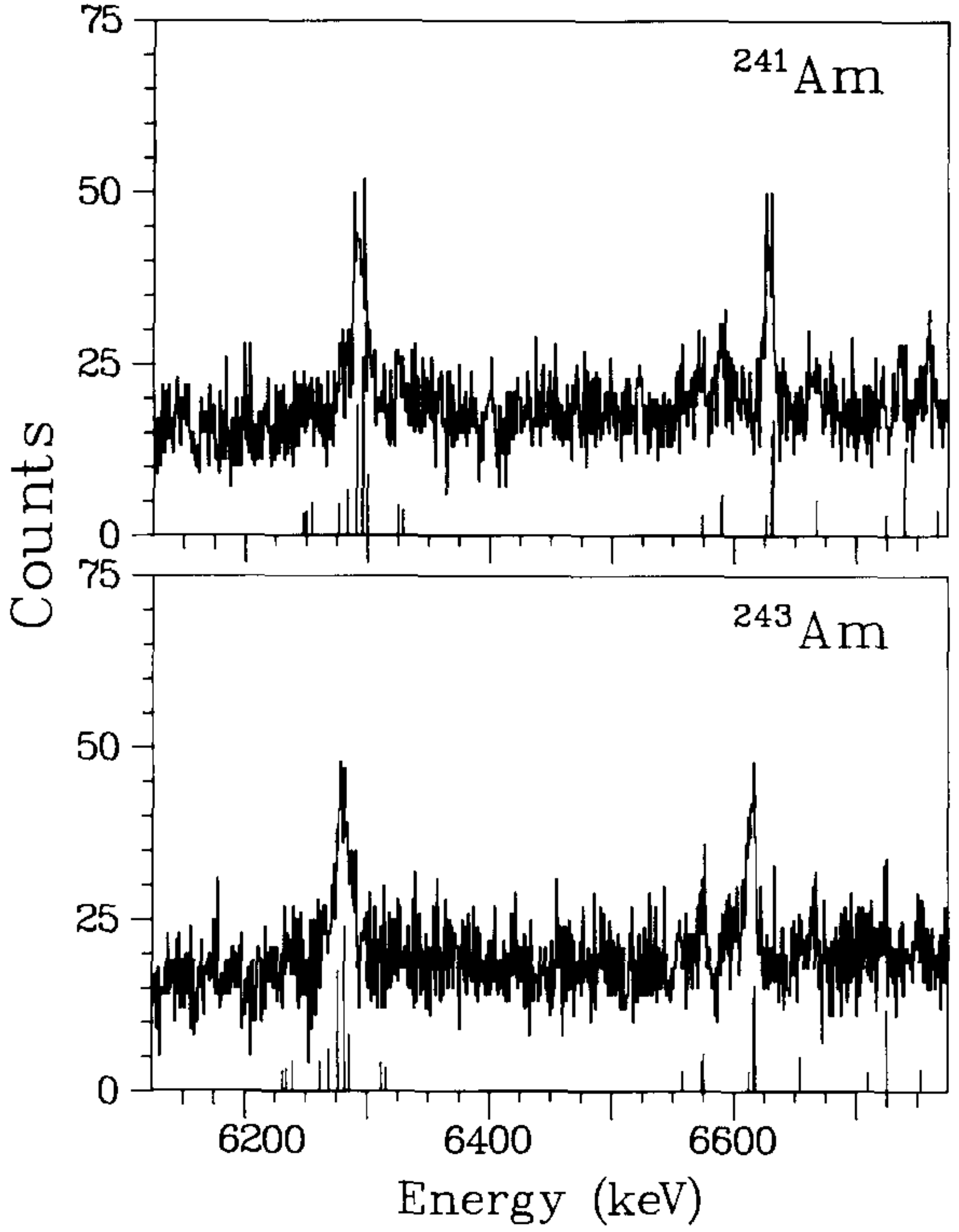
[a] Values from Ref. 7. Positive NP values mean that the respective binding energies are increased.

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

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”

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



Measurements in ultra-thin targets

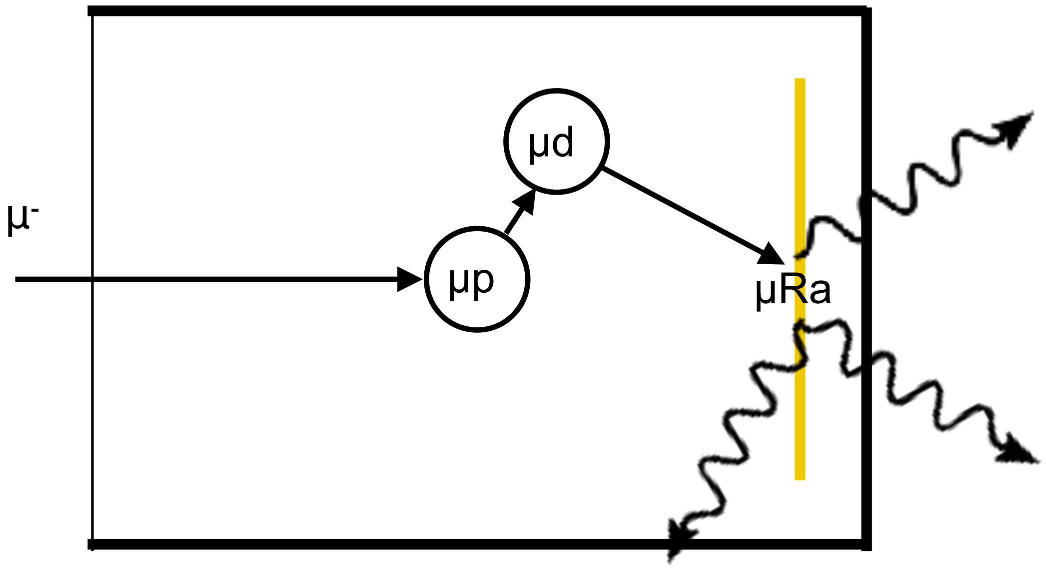
- Radioprotection laws more strict nowadays
  - Can only use 0.2 µg of 241-Am in PSI experimental hall
  - Can use 5 µg of 226-Ra

- For “normal” stopping need *O*(100 mg)

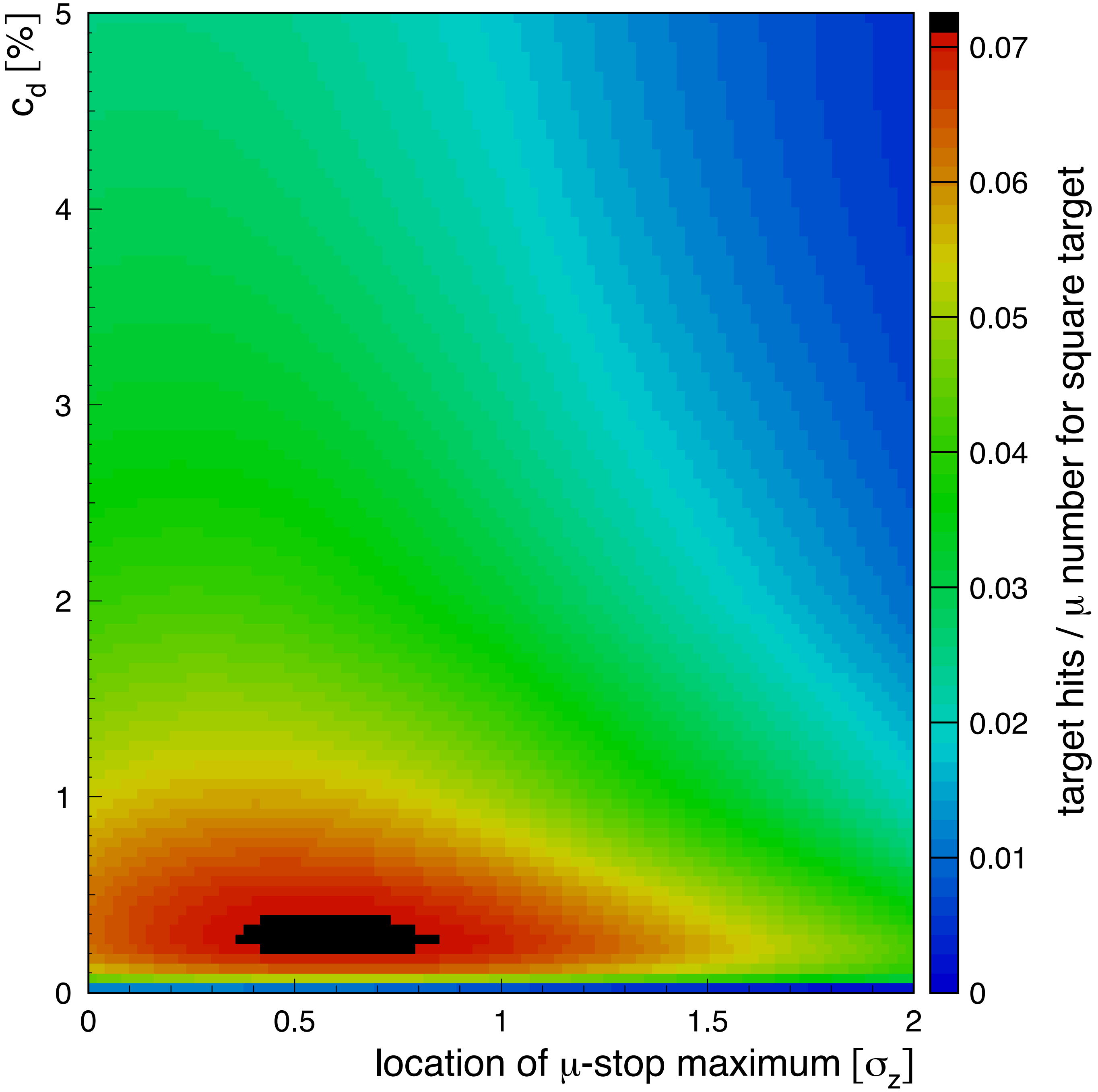
- Use the “magic” of muonic hydrogen/deuterium atoms and transfer reactions!

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

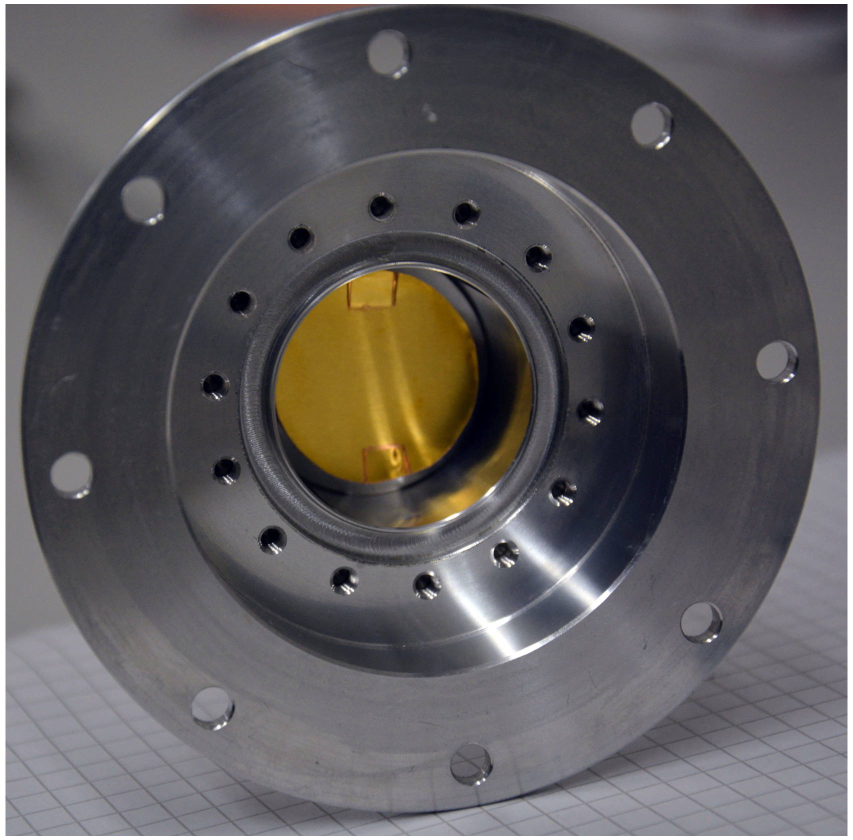


Optimize conditions

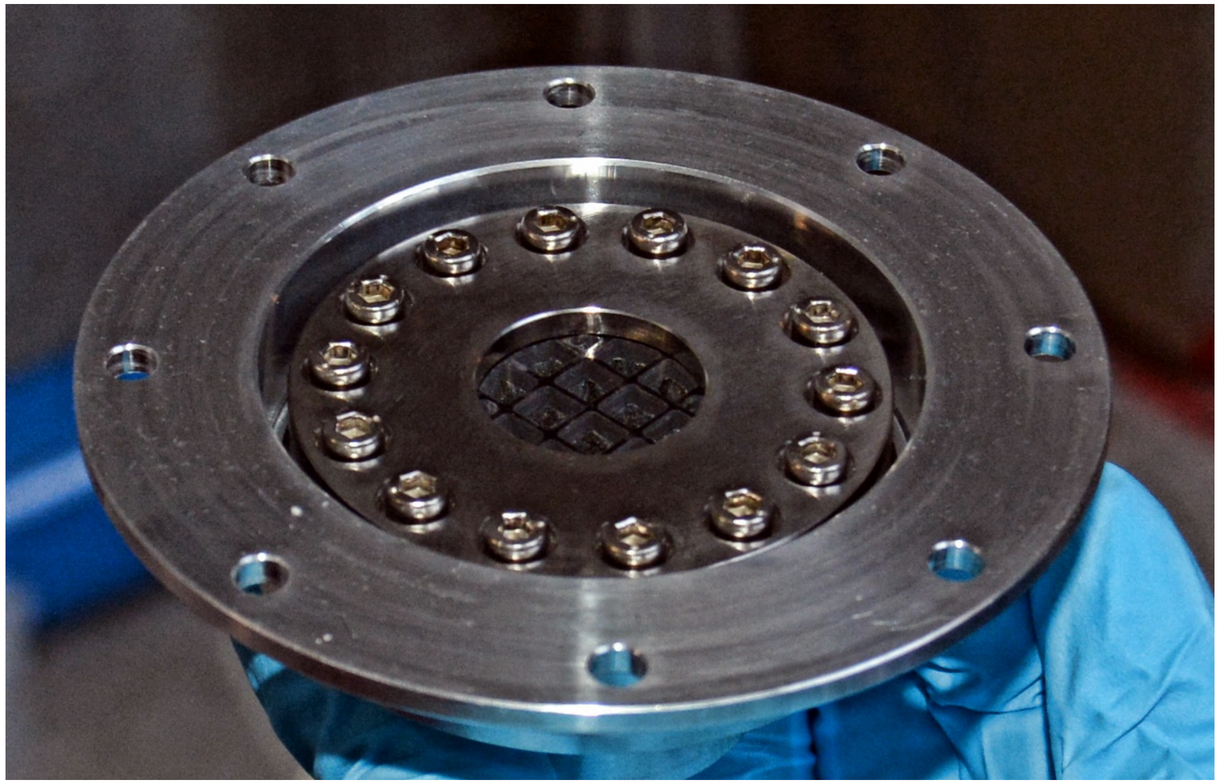


- Maximum efficiency at 0.25% deuterium concentration and a stopping point with part of the stopping distribution inside the target
- Reach a efficiency of around 7% of incoming muons hitting the target as µd atom

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



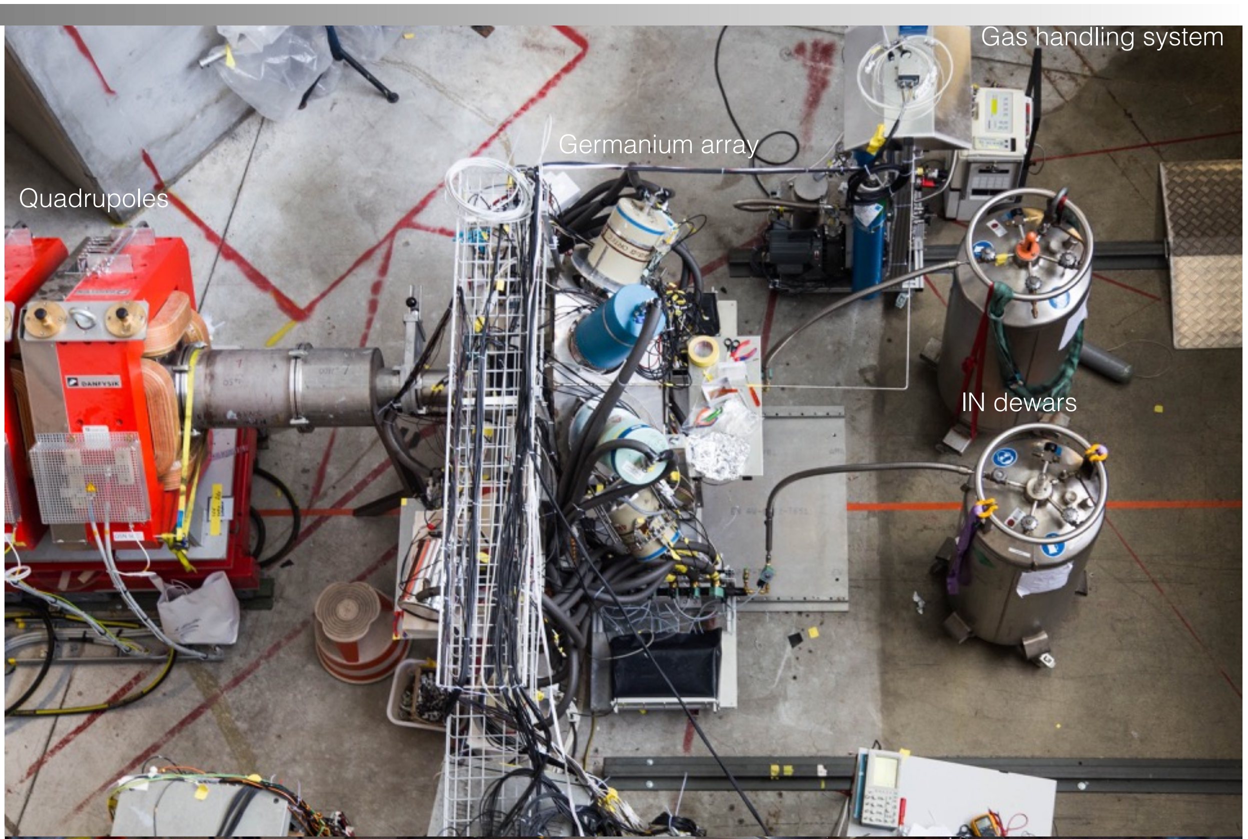
Entrance & veto detectors

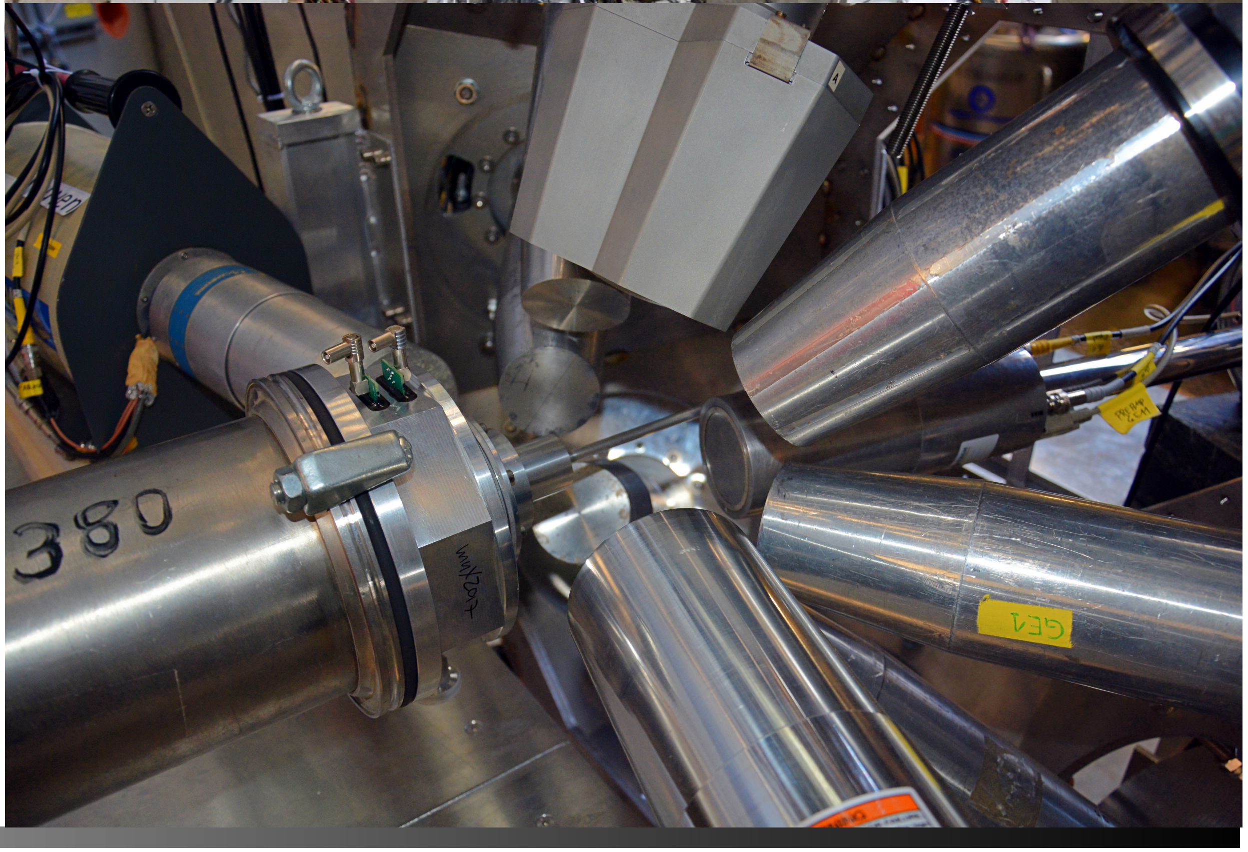
- Entrance detector to see incoming muon
- Veto scintillators to form anti-coincidence with decay electron

Optimize detection efficiency

- piE1 beam line at PSI
- ~10 kHz μ- at 28 MeV/c

- 11 germanium detectors in an array from French/UK loan pool, Leuven, PSI





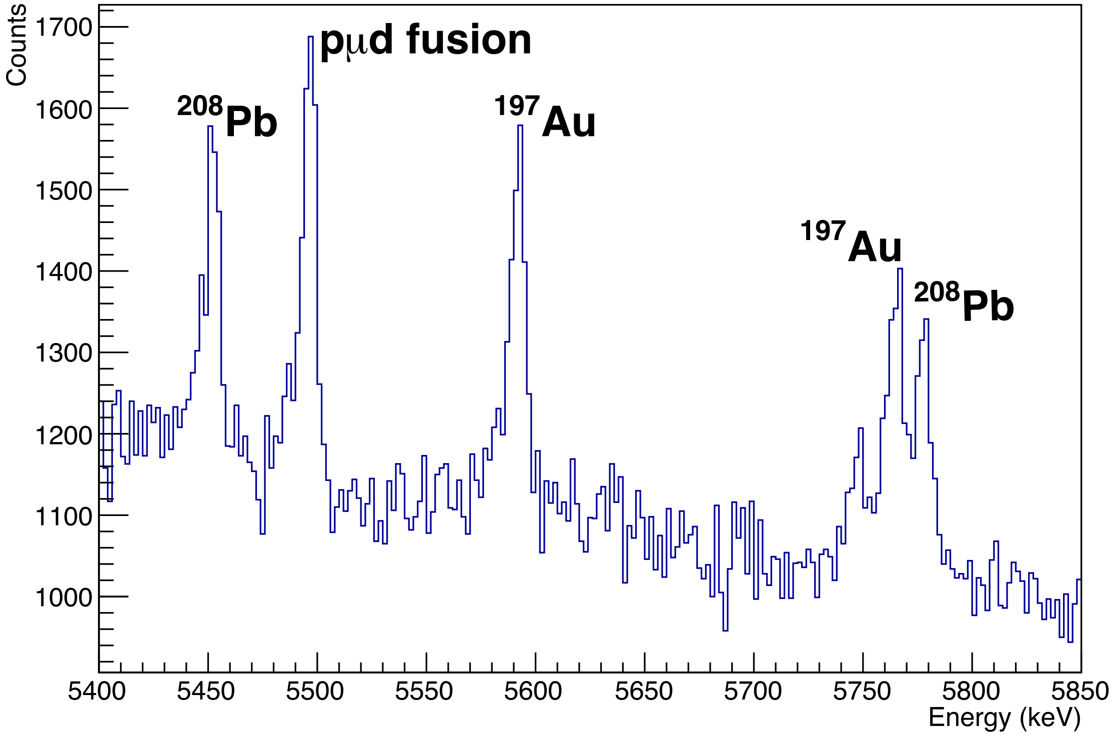
Optimize target conditions

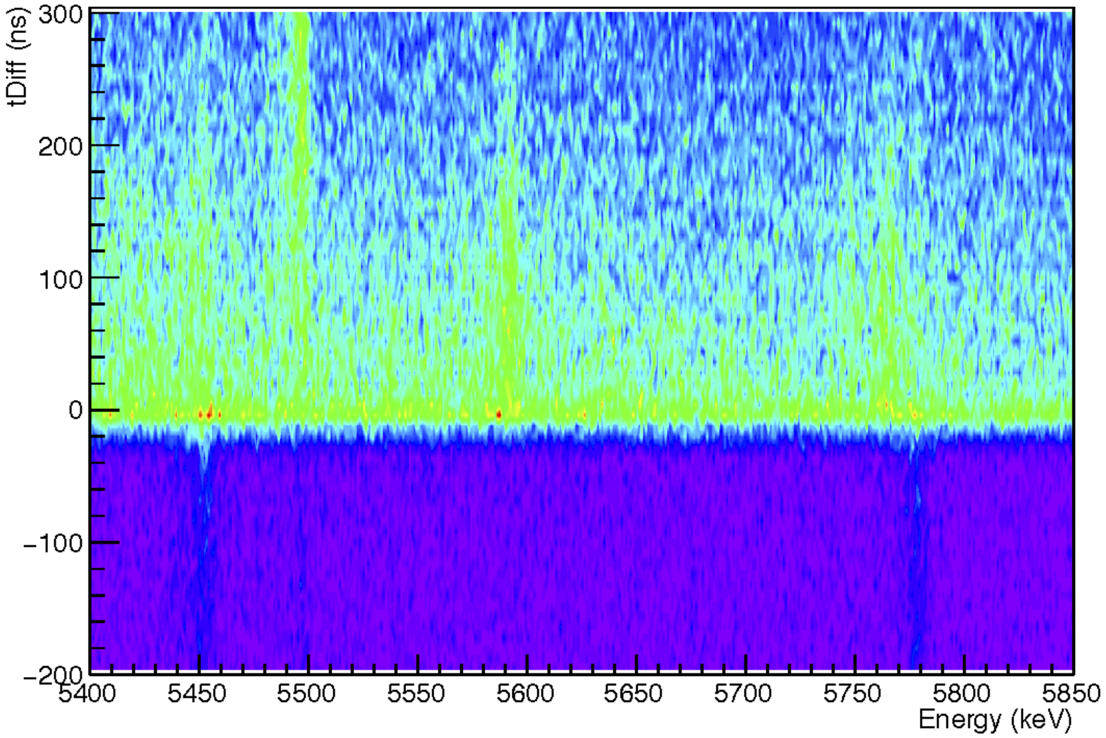
Target	Size	Backing	N_γ / N_μ	ϵ
50 nm Au	4.9 cm^2	Cu	$(10.9 \pm 0.3) \times 10^{-5}$	10.0%
10 nm Au	4.9 cm^2	Cu	$(6.9 \pm 0.2) \times 10^{-5}$	6.3%
3 nm Au	4.9 cm^2	Cu	$(3.6 \pm 0.1) \times 10^{-5}$	3.3%
3 nm Au	4.9 cm^2	kapton	$(3.2 \pm 0.1) \times 10^{-5}$	2.9%
3 nm Au	1 cm^2	Cu	$(1.3 \pm 0.1) \times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

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

Measurement

- Measurement with 5 µg gold target as proof-of-principle
- Data taken during 18.5 h
- Ready for radioactive radium target this year





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)

Benefit from more absolute measurements

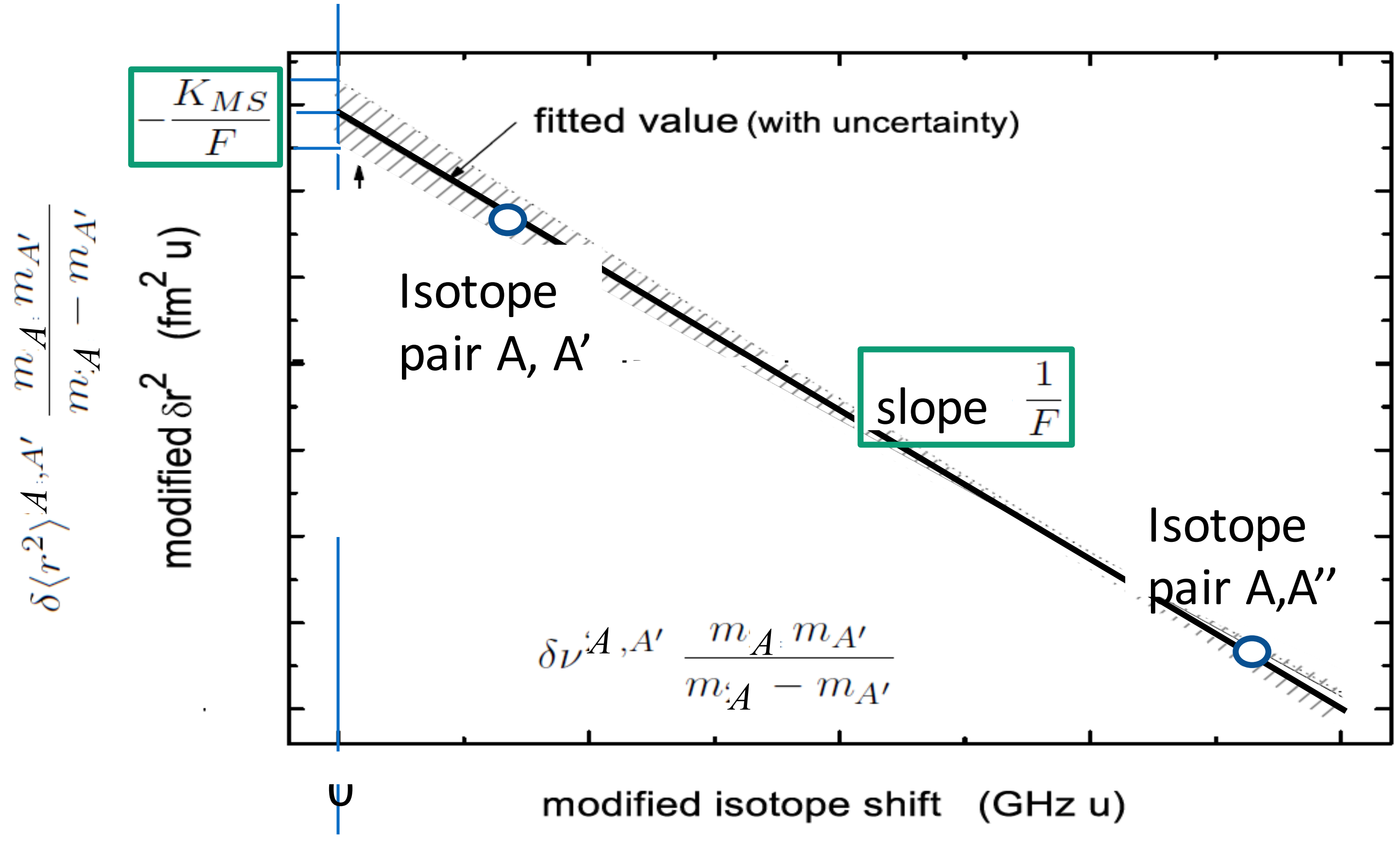
=> Modified King plot

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

- 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 …

Isotopes at SPES

- Isotopes without muonic data with sufficient yield at SPES to reach µg ion numbers in a few days
- Sufficiently long lived for transport
- Need to carefully study activity and regulations for lower half-life isotopes
- We'll continue to develop the method towards lower target masses
  → more radioactive elements can be measured

		Yield (SPES, 200 uA)	Half-life [s]
Sn	123	1.28E+10	1.12E+07
Sn	125	3.5E+10	8.33E+05
Sn	126	4.21E+10	3.16E+12
Te	132	4.21E+10	2.77E+05
I	131	5.47E+10	6.93E+05
I	133	1.89E+11	7.49E+04
Cs	134	4.08E+09	6.52E+07
Cs	135	1.68E+10	7.26E+13
Cs	136	4.96E+10	1.14E+06
Cs	137	1.07E+11	9.49E+08
Ba	140	6.05E+10	1.10E+06

Conclusions

- Particle physics interest in radioactive ions in connection with the study of EDM, weak interaction and atomic parity violation
- Muonic atom spectroscopy able to measure absolute charge radii needed for atomic theory in APV
- muX collaboration developed method of using microgram targets for muonic atom spectroscopy enabling the measurement of high-activity targets
- Several isotopes with sufficient yield at SPES identified that could be measured with our method

muX Collaboration

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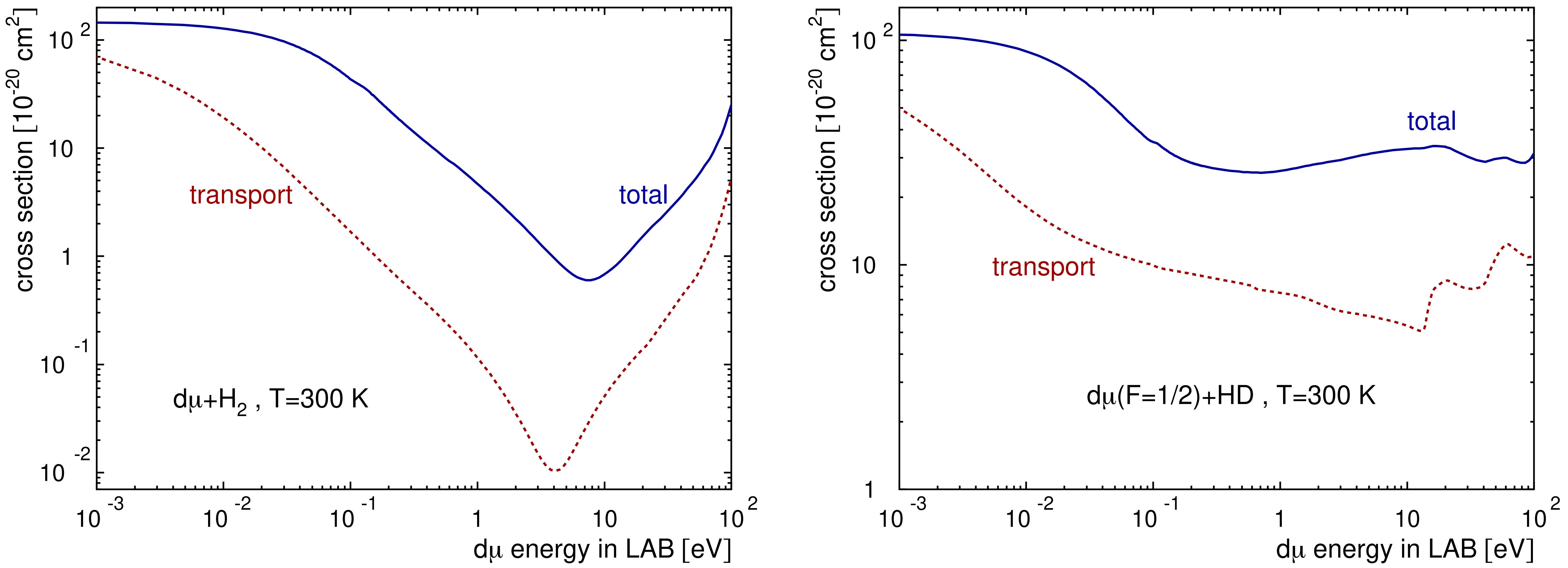
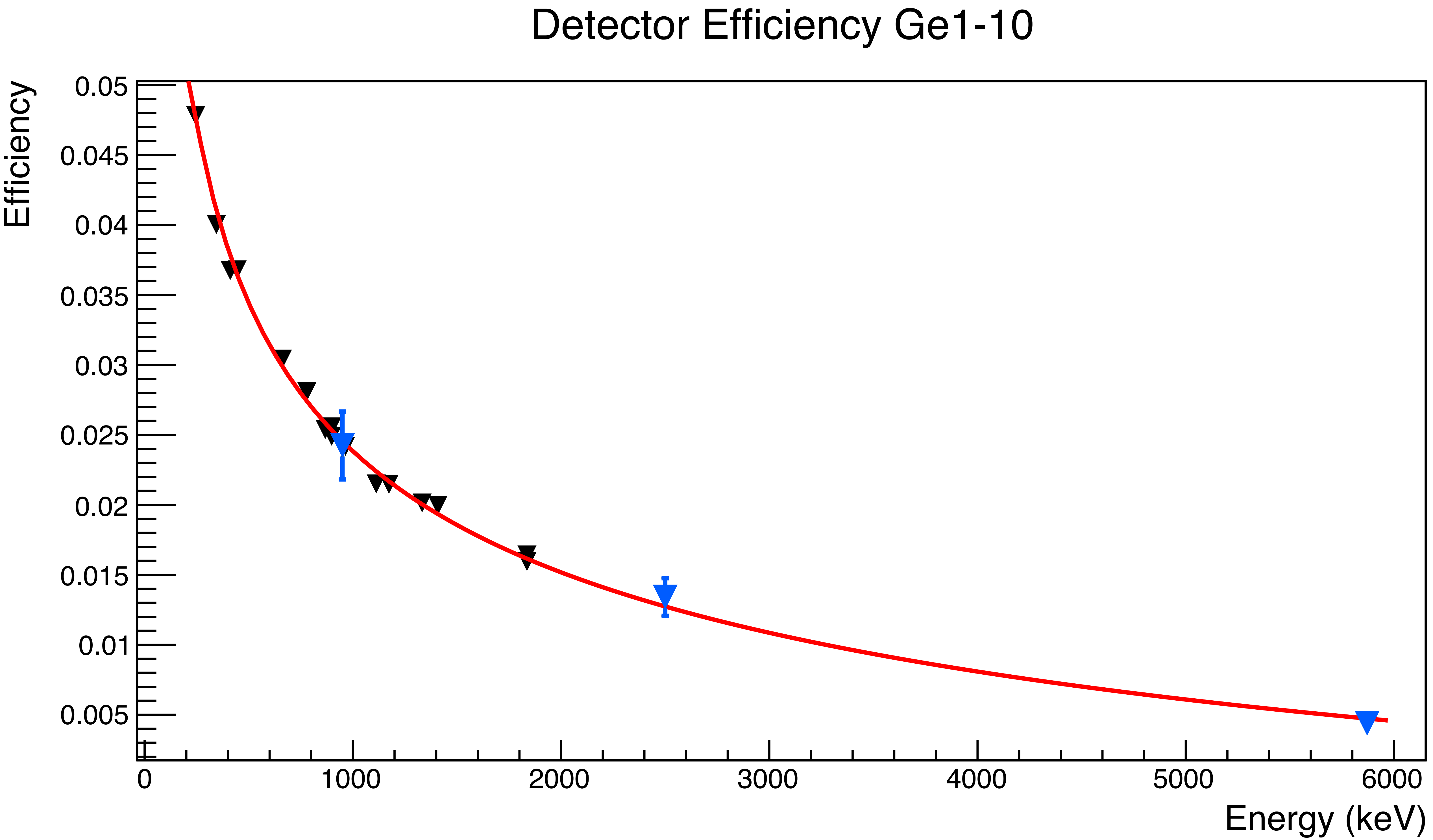
Backup

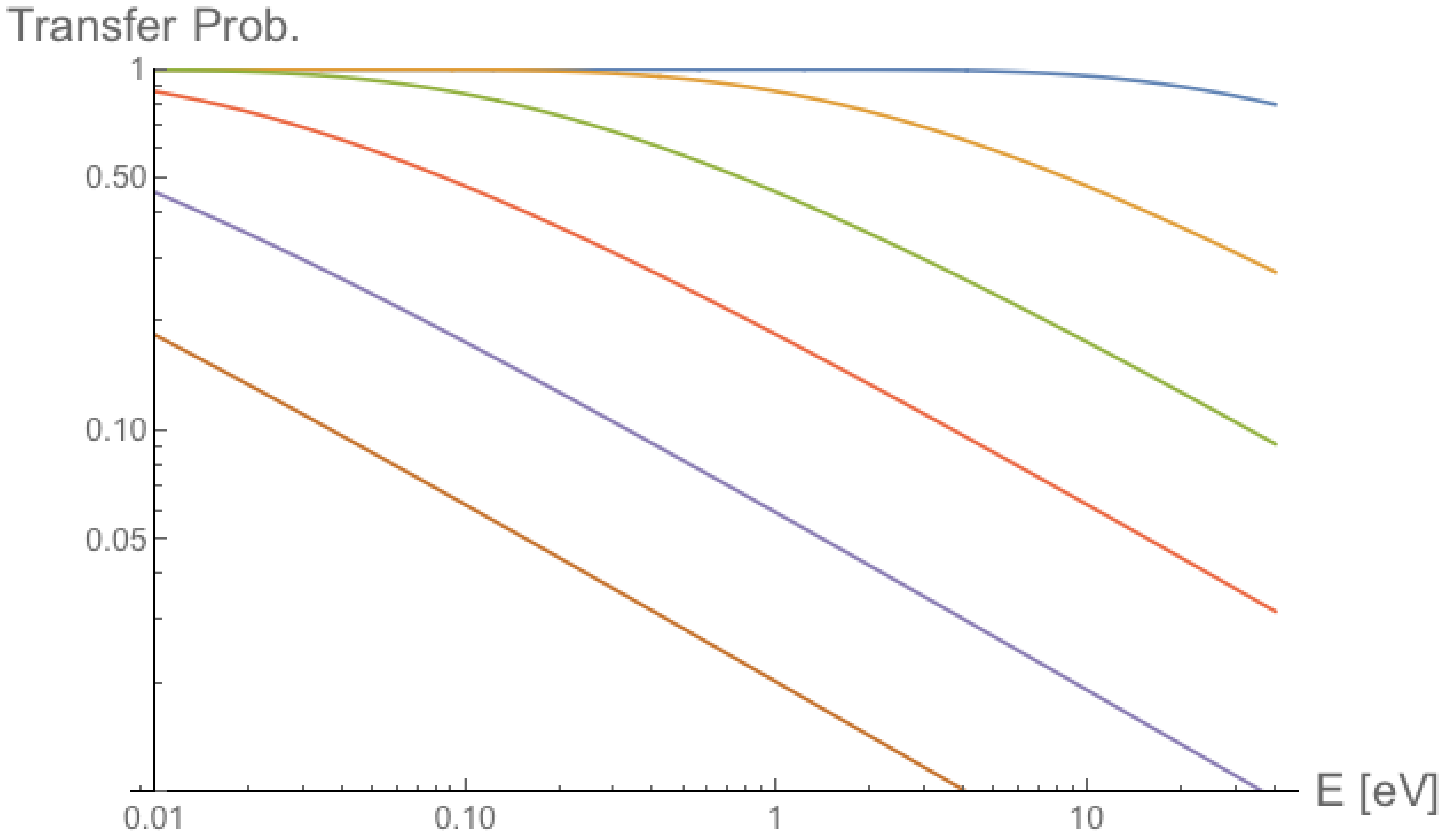
Scattering cross sections



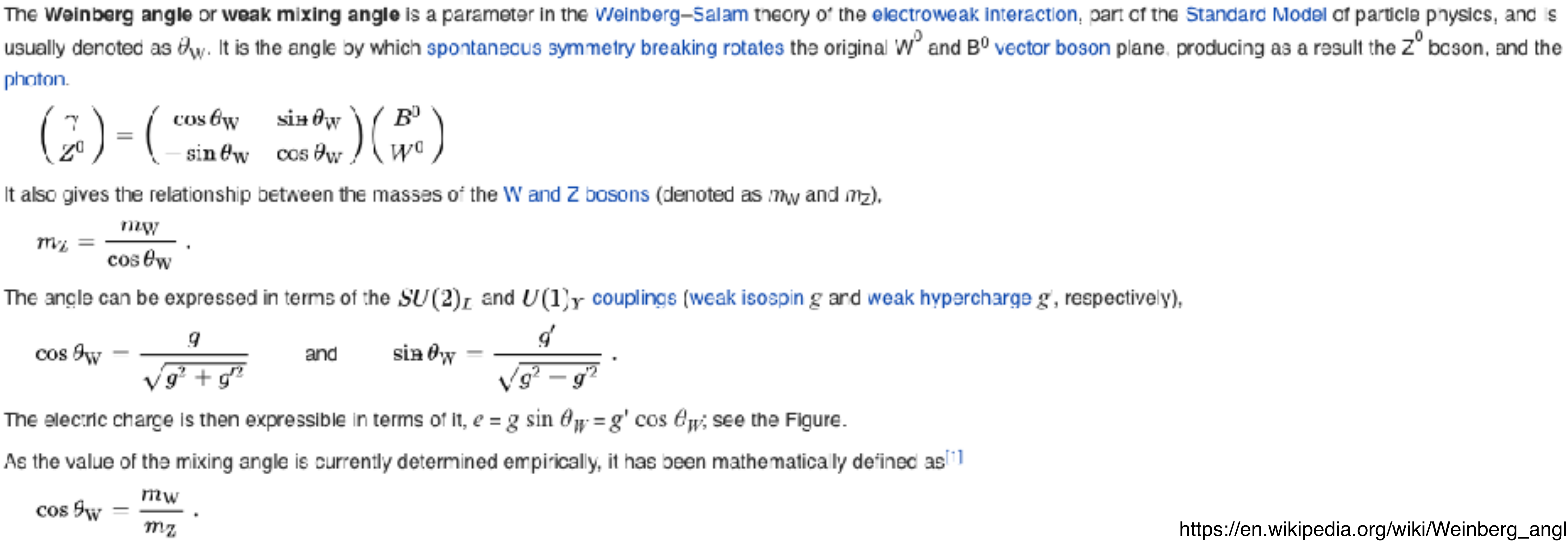
Array Detection Efficiency



Transfer Probability in Gold



Weinberg angle



The **Weinberg angle** or **weak mixing angle** is a parameter in the Weinberg–Salam theory of the electroweak interaction, part of the Standard Model of particle physics, and is usually denoted as θ_W. It is the angle by which spontaneous symmetry breaking rotates the original W^0 and B^0 vector boson plane, producing as a result the Z^0 boson, and the photon.

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

It also gives the relationship between the masses of the W and Z bosons (denoted as m_W and m_Z),

$$m_Z = \frac{m_W}{\cos\theta_W} \, .$$

The angle can be expressed in terms of the $SU(2)_L$ and $U(1)_Y$ couplings (weak isospin g and weak hypercharge g', respectively),

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad \text{and} \quad \sin\theta_W = \frac{g'}{\sqrt{g^2 - g'^2}} \, .$$

The electric charge is then expressible in terms of it, $e = g \sin\theta_W = g' \cos\theta_W$; see the Figure.

As the value of the mixing angle is currently determined empirically, it has been mathematically defined as[1]

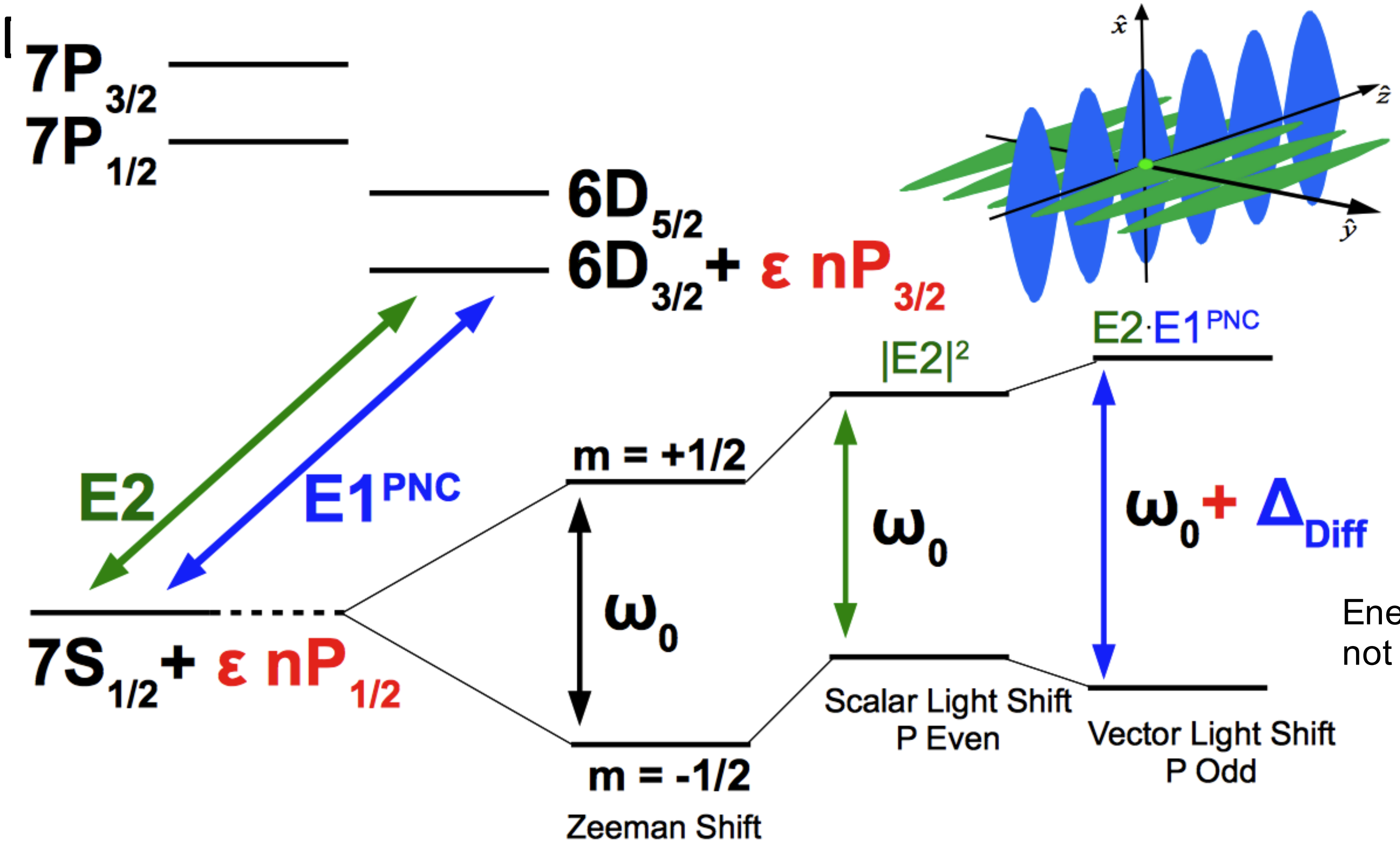
$$\cos\theta_W = \frac{m_W}{m_Z} \, .$$

https://en.wikipedia.org/wiki/Weinberg_angle

Radium Energy Levels

K. Jungmann, L. Willmann

Experimental Method



Energy splittings
not to scale

$$|\Omega|^2 = |\Omega^{E2}_{m'm} + \Omega^{PNC}_{m'm}|^2 \sim |\Omega^{E2}_{m'm}|^2 + 2Re|\Omega^{PNC}_{m'm}\Omega^{E2}_{m'm}|$$

N. Fortson, Phys. Rev. Lett. 70, 2383-2386 (1993)

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