Study of nuclear properties with muonic atoms

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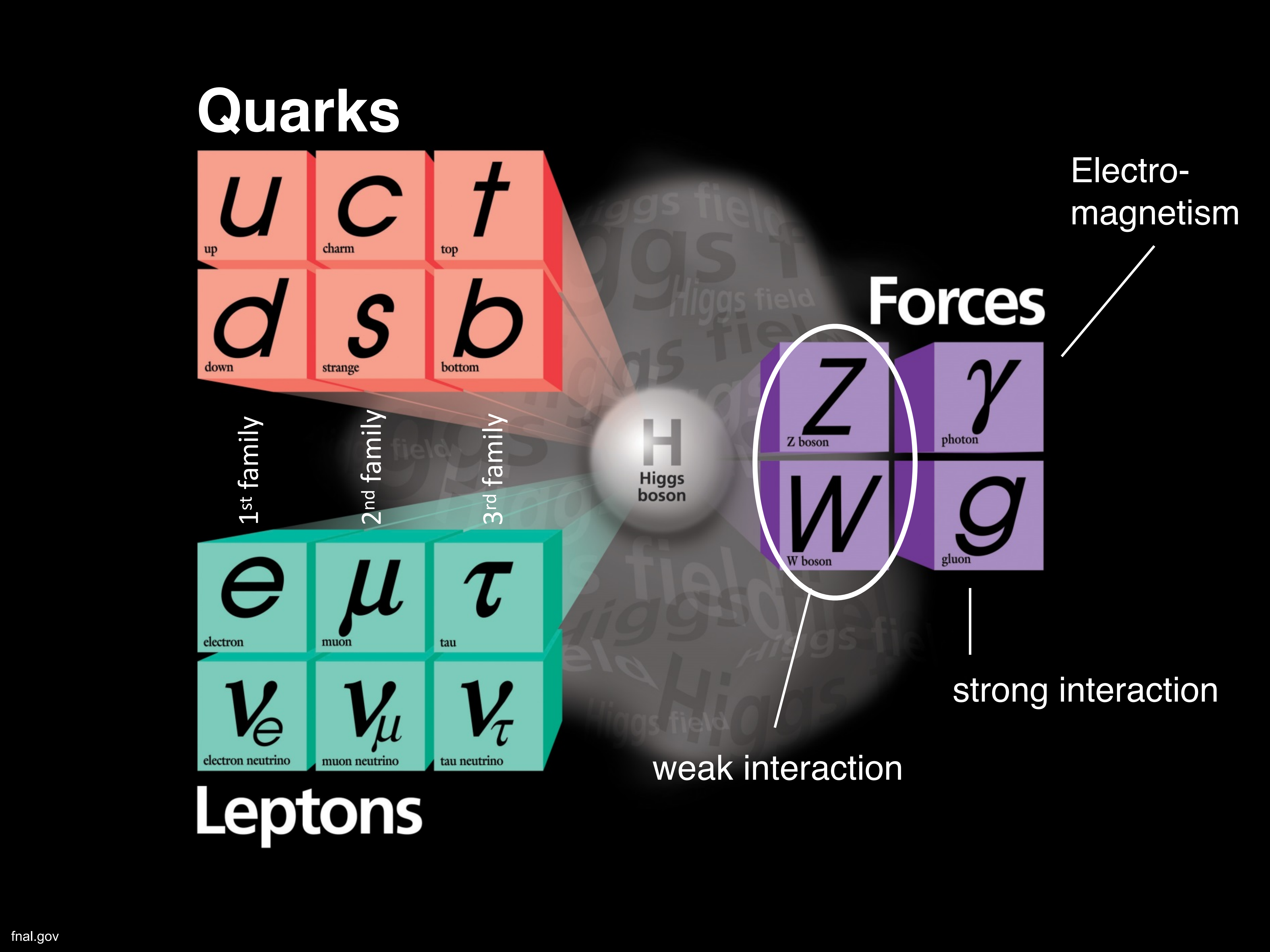
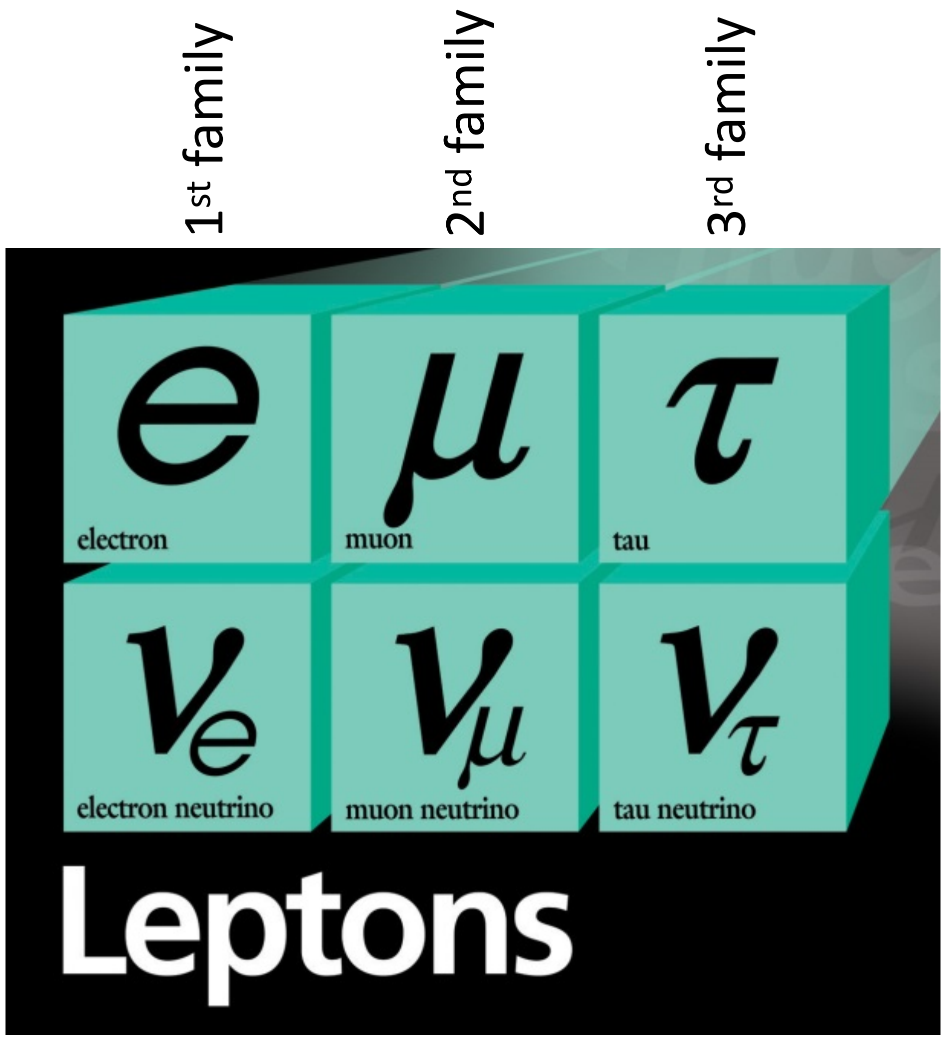
Overview

- Muons and muonic atoms
- Muonic atom spectroscopy
- The muX experiment: Stable isotopes
- The muX experiment: Radioactive isotopes
  - Test of transfer reactions with gold and uranium targets
  - Towards ^{226}Ra and ^{248}Cm measurements

Muons and muonic atoms


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
1st family
2nd family
3rd family
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
H
Higgs boson
Higgs field
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
Electro-
magnetism
strong interaction
weak interaction
fnal.gov

Muons



μ

$J = \frac{1}{2}$

Mass $m = 0.1134289257 \pm 0.0000000025$ u
Mass $m = 105.6583745 \pm 0.0000024$ MeV
Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s
$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$
$c\tau = 658.6384$ m
Magnetic moment anomaly $(g-2)/2 = (11659209 \pm 6) \times 10^{-10}$
$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}} = (-0.11 \pm 0.12) \times 10^{-8}$
Electric dipole moment $d = (-0.1 \pm 0.9) \times 10^{-19}$ e cm

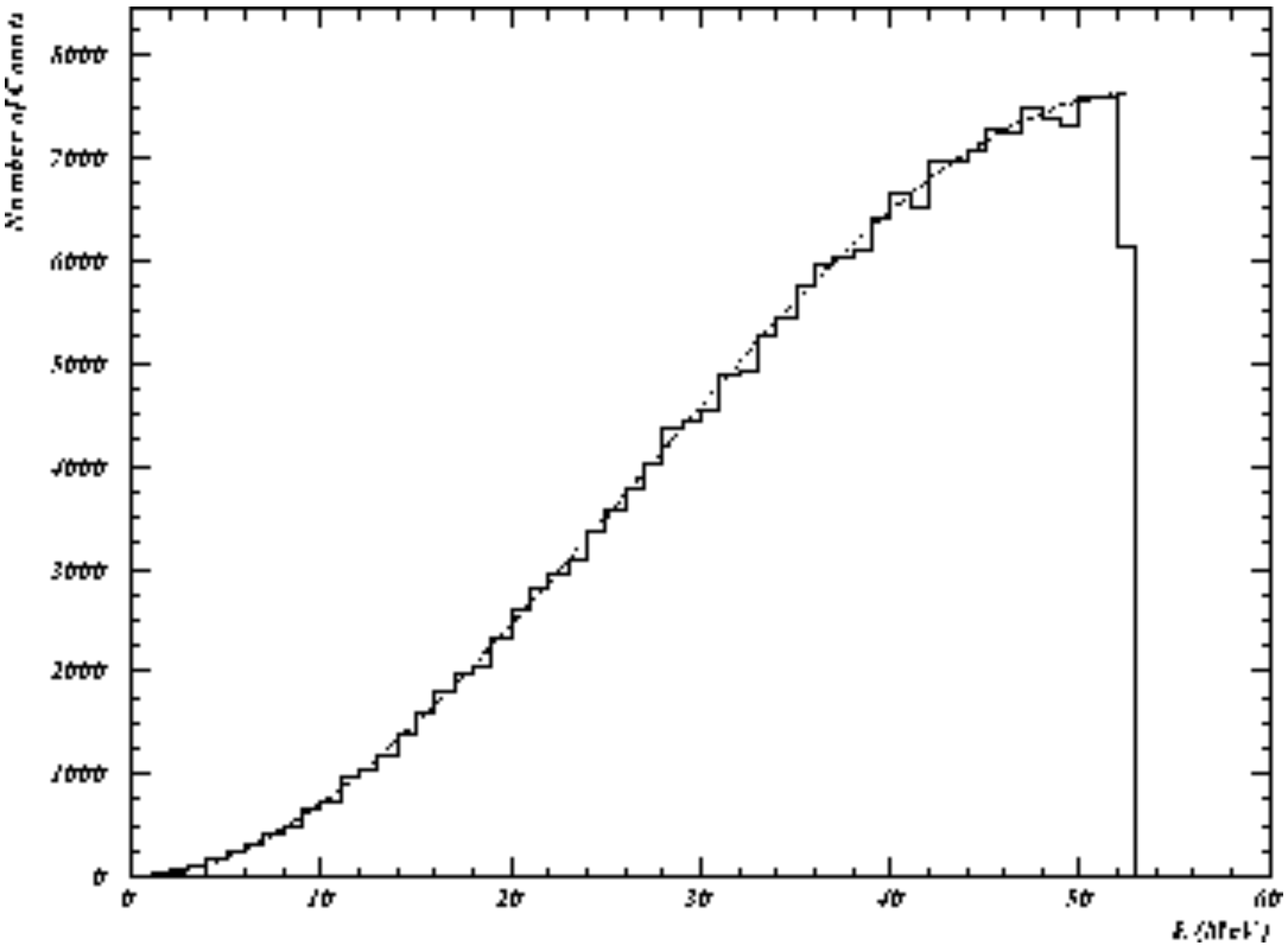
μ^- **DECAY MODES**		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	(1.4 ± 0.4) %		53
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4\pm0.4) \times 10^{-5}$		53

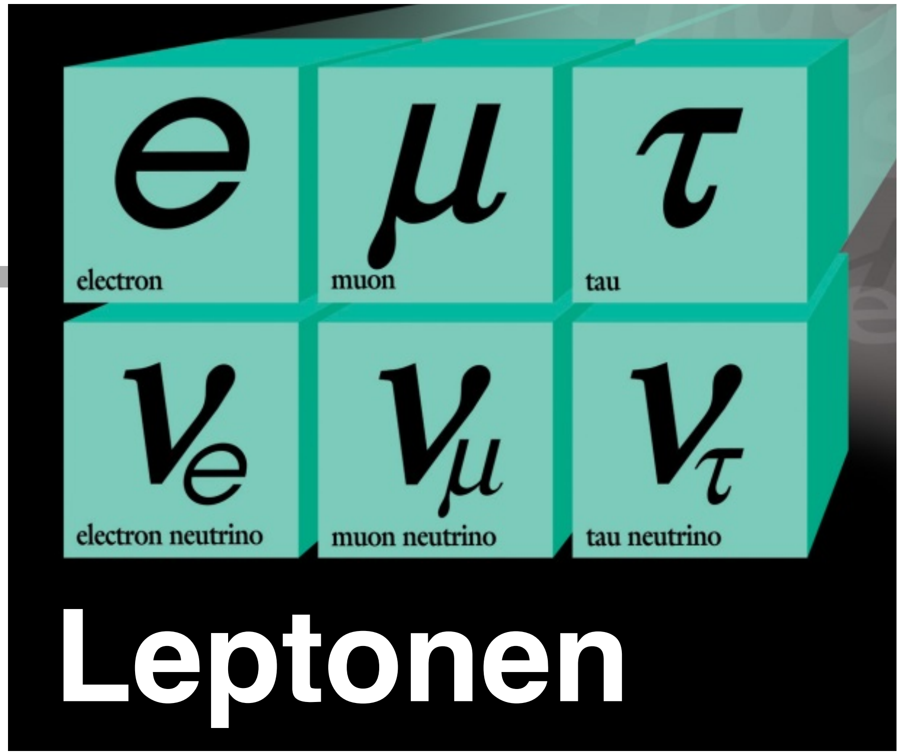
Lepton Family number (*LF*) violating modes

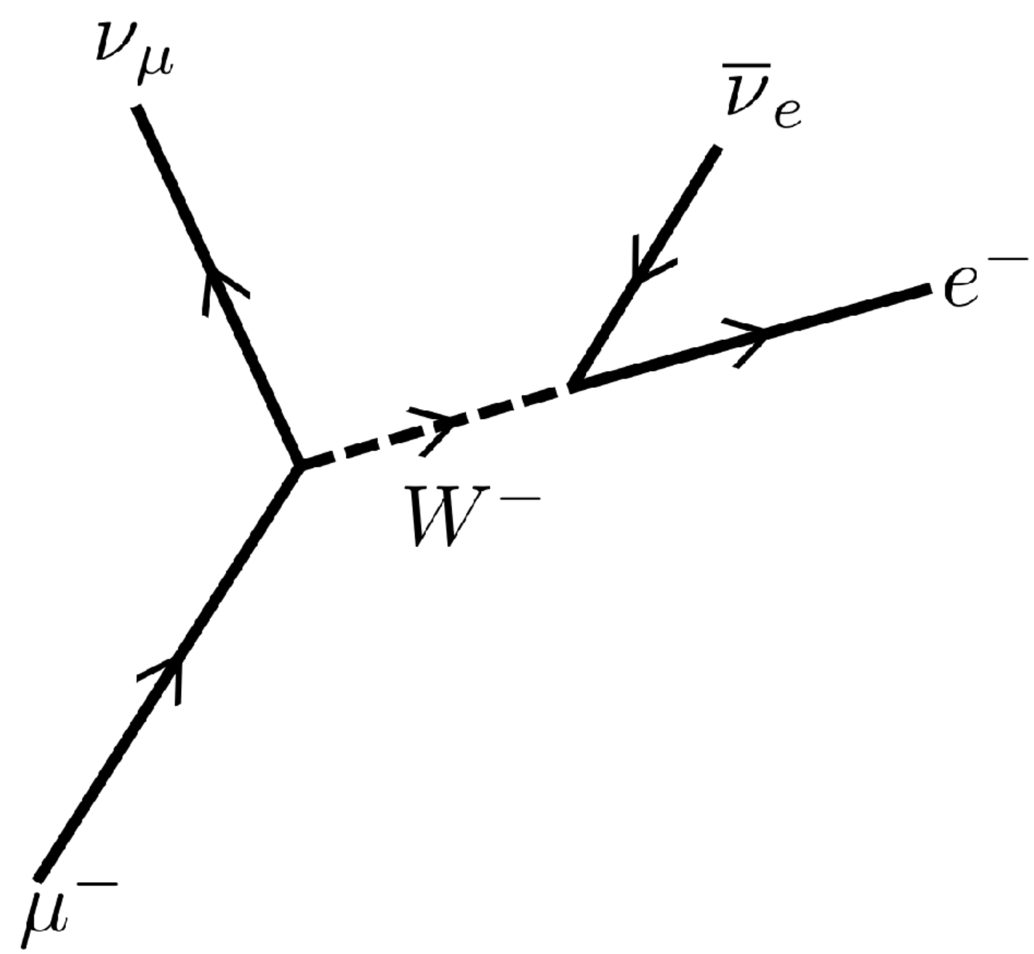
$e^- \nu_e \overline{\nu}_\mu$	*LF*	[f]	< 1.2 %	90%	53
$e^- \gamma$	*LF*		$< 5.7 \times 10^{-13}$	90%	53
$e^- e^+ e^-$	*LF*		$< 1.0 \times 10^{-12}$	90%	53
$e^- 2\gamma$	*LF*		$< 7.2 \times 10^{-11}$	90%	53

- Muons are the heavy siblings of the electrons (m_μ=207m_e)
- Decay within 2.2 µs into electrons

Muon decay



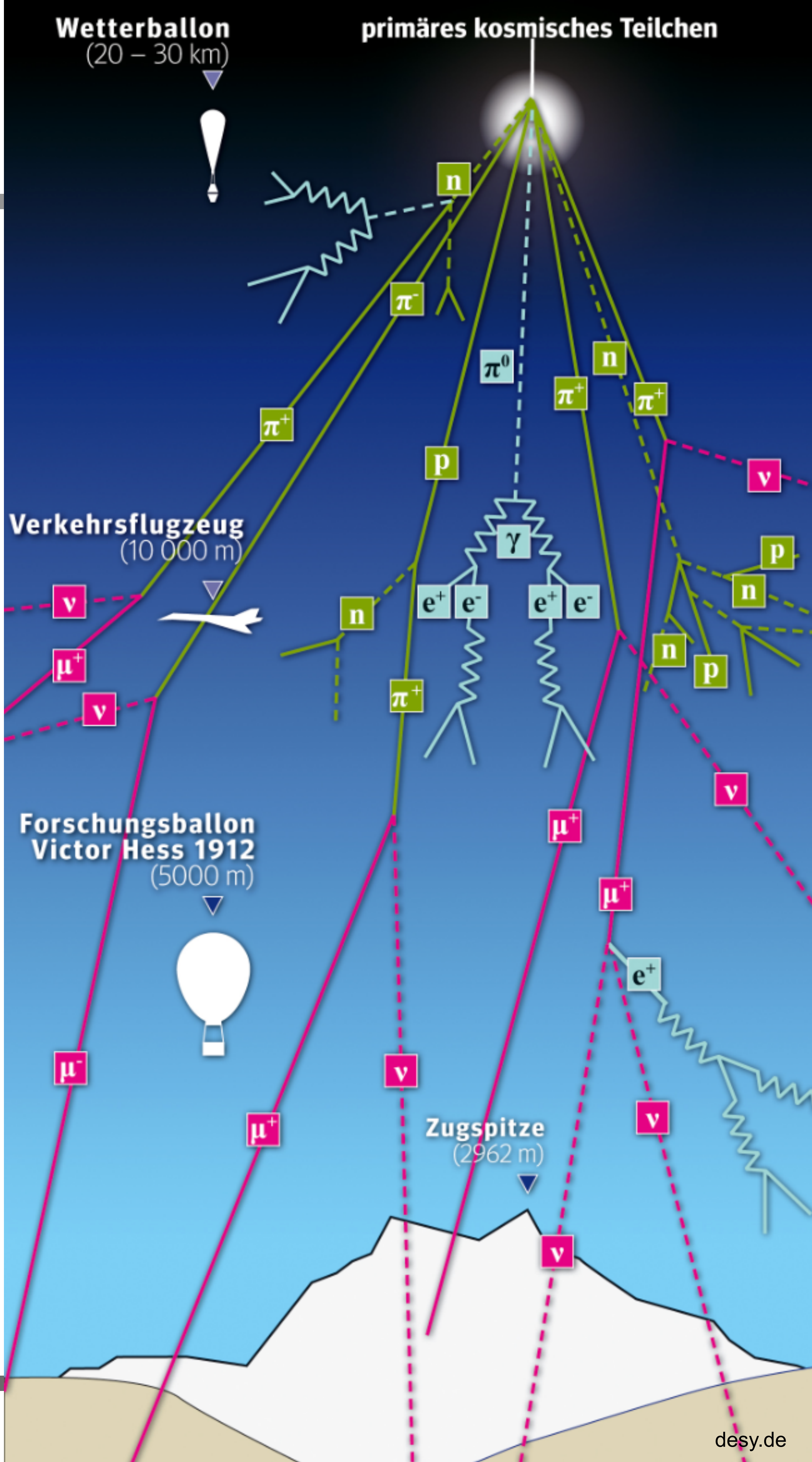




- Decay mediated through W exchange
- Decay into electron and two neutrinos (conservation of lepton number)

Muons in nature

- Muons are created in the upper atmosphere by impact of cosmic rays on gas molecules
- Flux at sea level of about 1 muon/cm²/minute



desy.de

Muons at PSI

Ring cyclotron at PSI

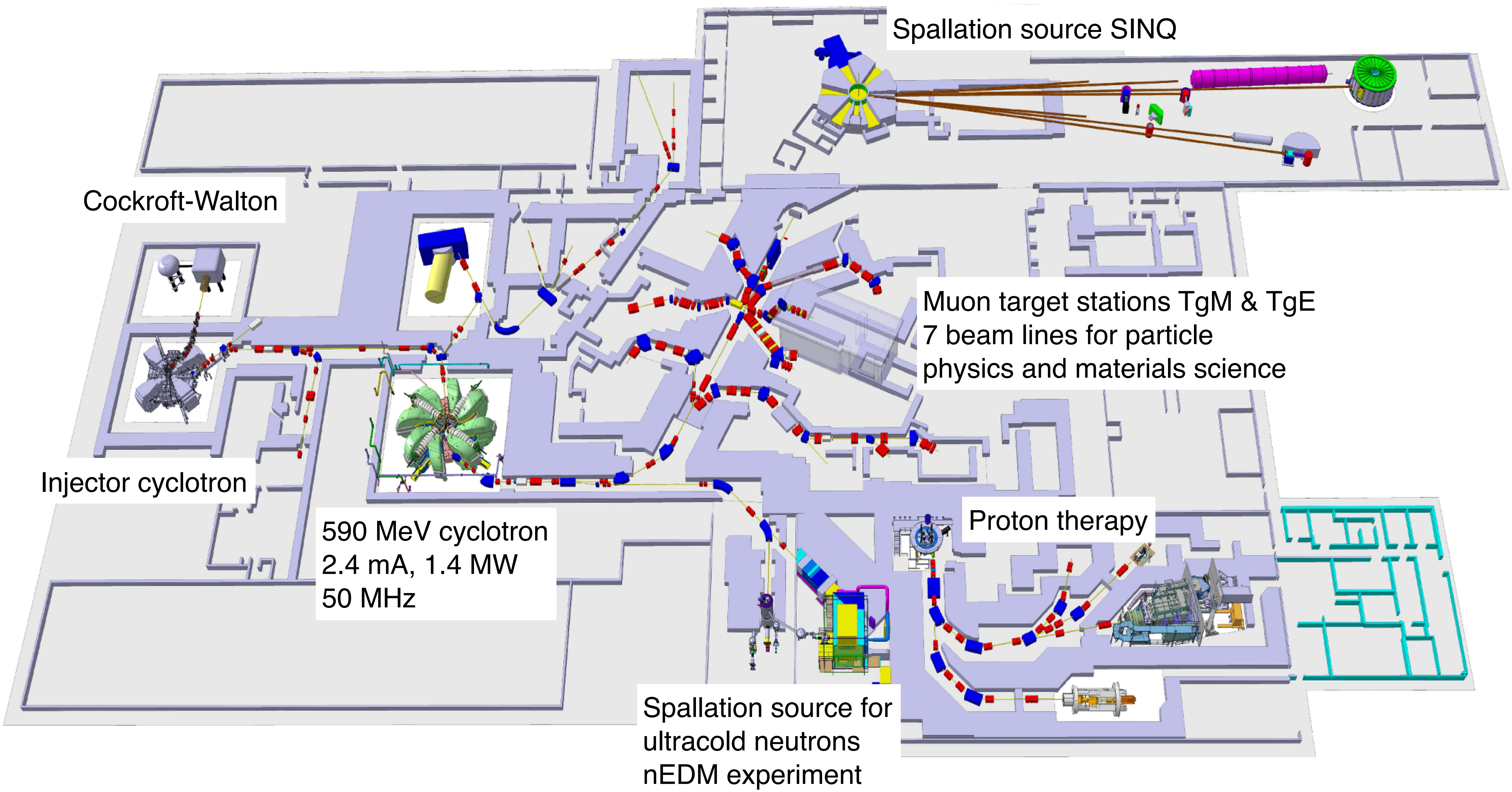
590 MeV energy with 1.4 MW beam power

→ Most powerful accelerator in the world

Location of Paul Scherrer Institute

Location of Paul Scherrer Institute

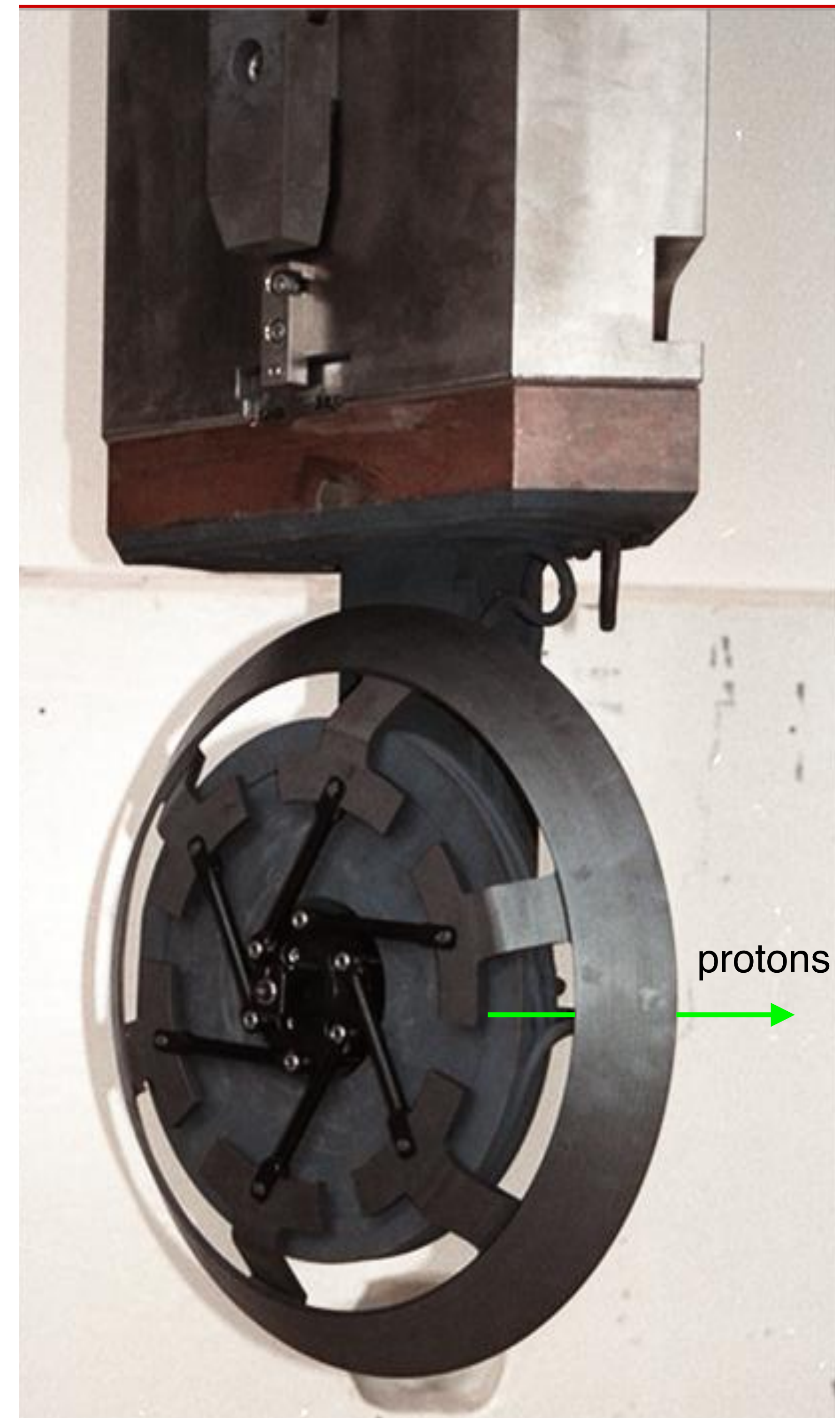
PSI Proton Accelerator HIPA



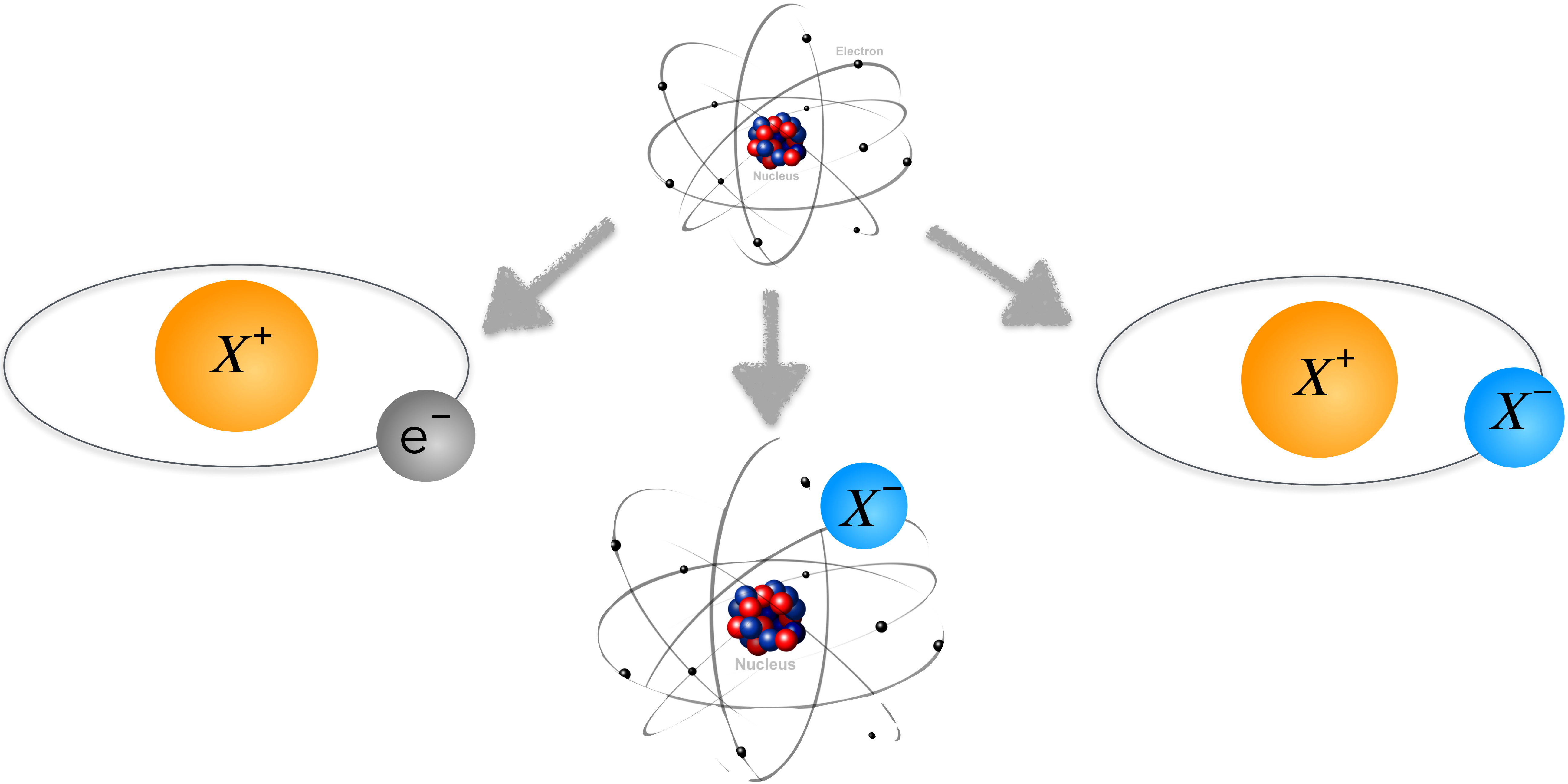
Muon Production Target TgE

- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiatively cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)

⇨ Up to 5×10^8 μ^+/s (depending on beam line)



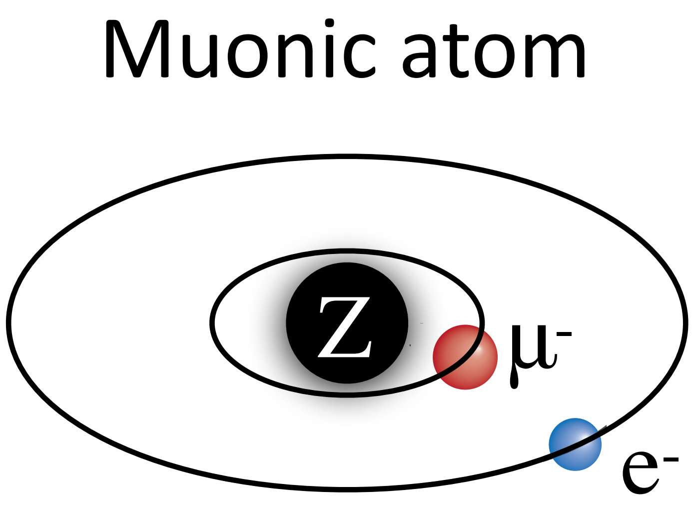
Exotic Atoms



- A system bound by the Coulomb (electromagnetic) interaction that contains subatomic particles other than electrons, protons or neutrons.

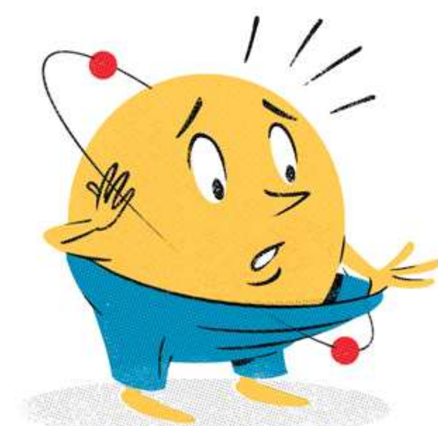
Muonic atoms

- Muon as a tool to measure properties of the nucleus
- Enhanced sensitivity due to small radius
- E.g.: finite-size effects go as m^3 → 10^7 enhancement!



A famous muonic atom

- Measure the 2s - 2p splitting in μp → determine the proton rms radius r_p with improved accuracy (10 x better)
- Large discrepancy observed compared to electron based measurements

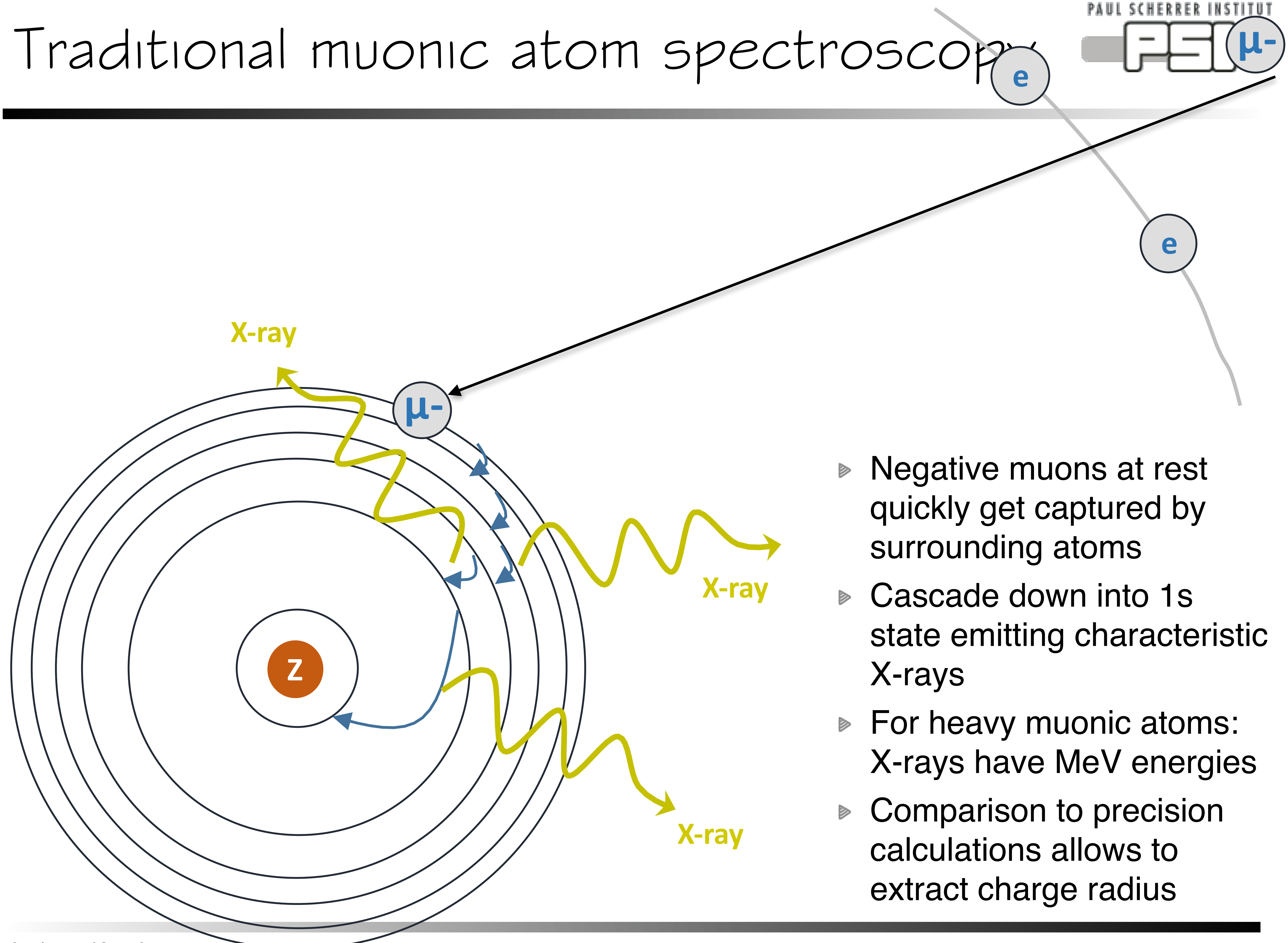


NYT, 12 July 2010

⇨ Proton radius puzzle

Muonic atom spectrocsopy

Traditional muonic atom spectroscopy

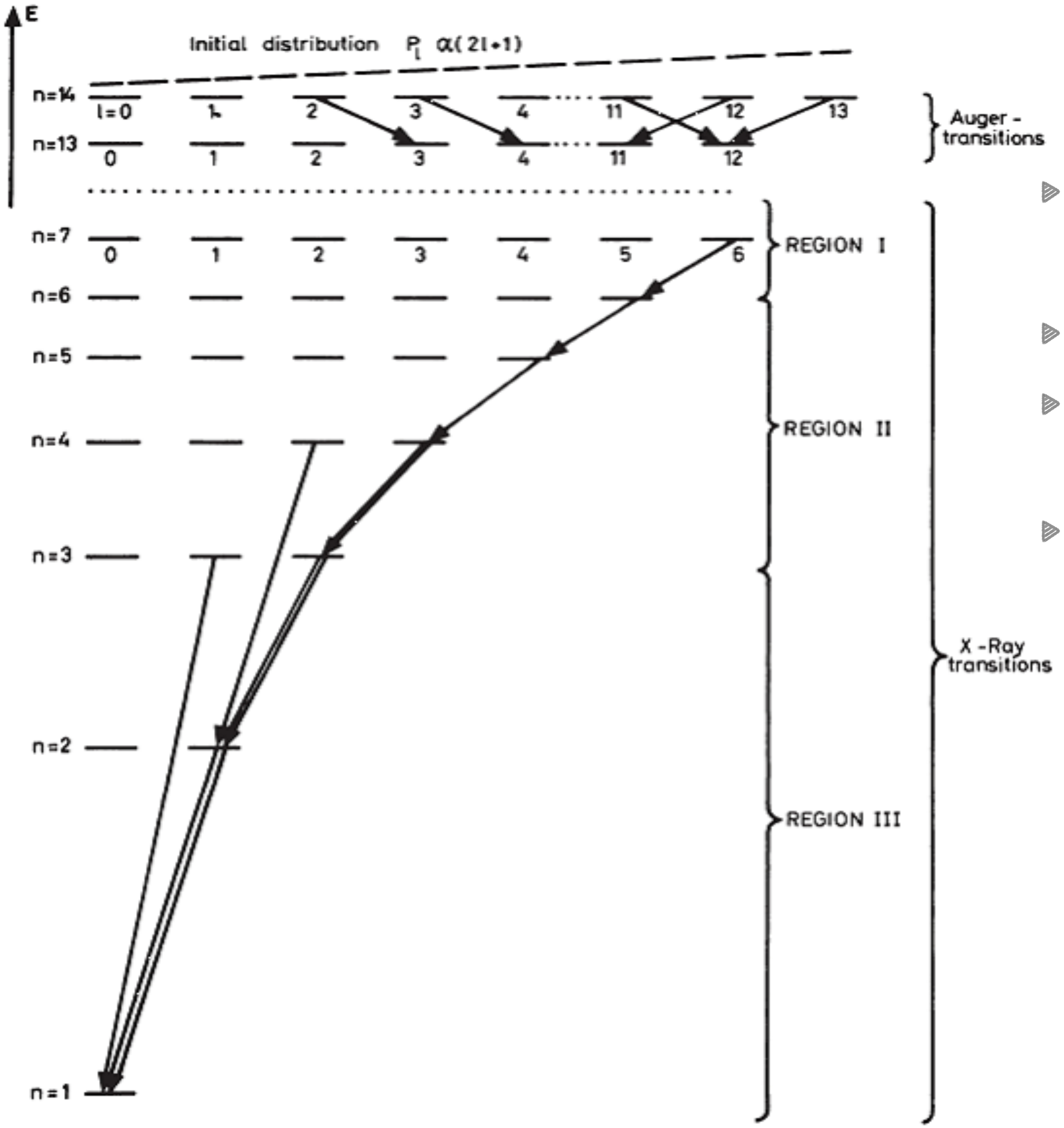


- Negative muons at rest quickly get captured by surrounding atoms
- Cascade down into 1s state emitting characteristic X-rays
- For heavy muonic atoms: X-rays have MeV energies
- Comparison to precision calculations allows to extract charge radius

Bohr radii and energies

- Bohr energies: $$E_n = \frac{mc^2}{2}\frac{\alpha^2 Z^2}{n^2}$$
- Bohr radii: $$r_n = \frac{n^2}{mc^2}\frac{\hbar c}{\alpha Z}$$
- Neglecting finite size effects
  - Energies are ~200 times larger
  - Radii are ~200 times smaller

Muonic atom level scheme

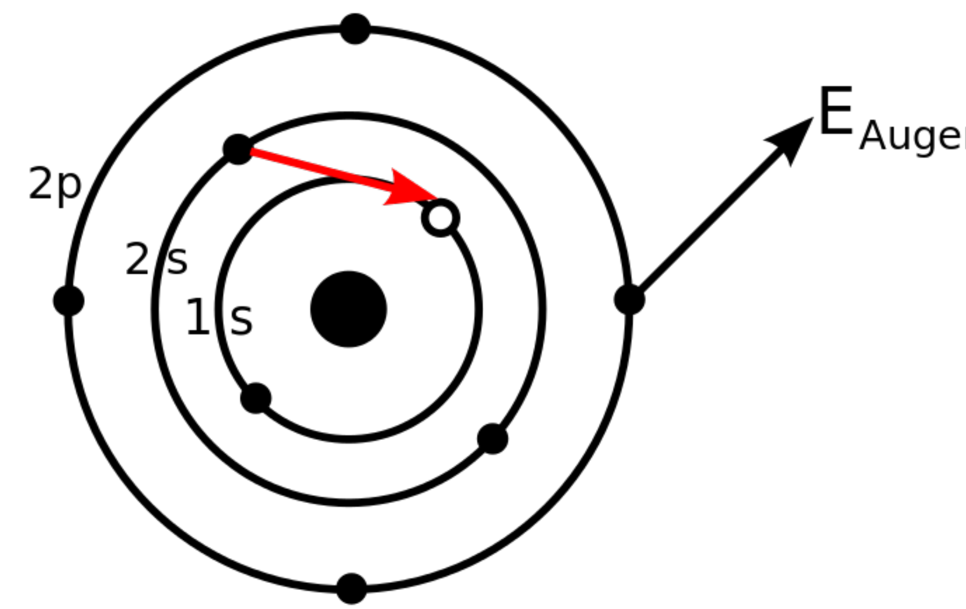


- Level scheme as in a hydrogen atom!
- Capture happens at around n~14
- Radiative transitions start to dominate after n~7 for high-Z atoms
- Mostly circular transitions, but almost any other allowed transition can be seen with enough statistics

Auger transition

- Energy released in cascade from higher to lower energy level is used to eject bound electron
- Refilling of electron shells if available

- Possible transitions: $\Delta l = 0, \pm 1$
  Favored: $\Delta l = 0, -1$ and $\Delta n \sim 1$



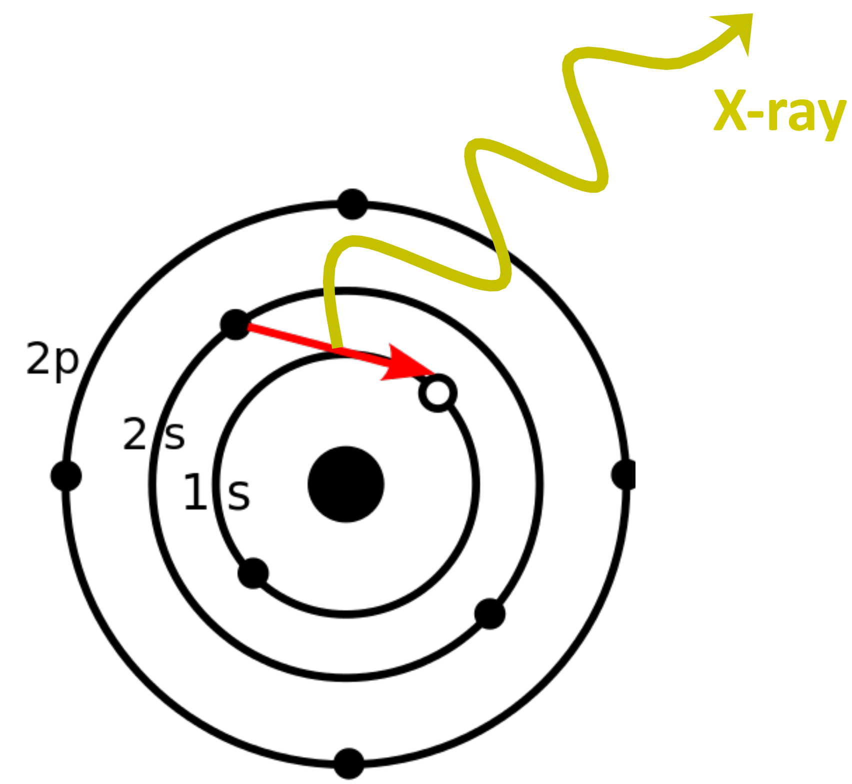
Auger electron emission

Radiative transition

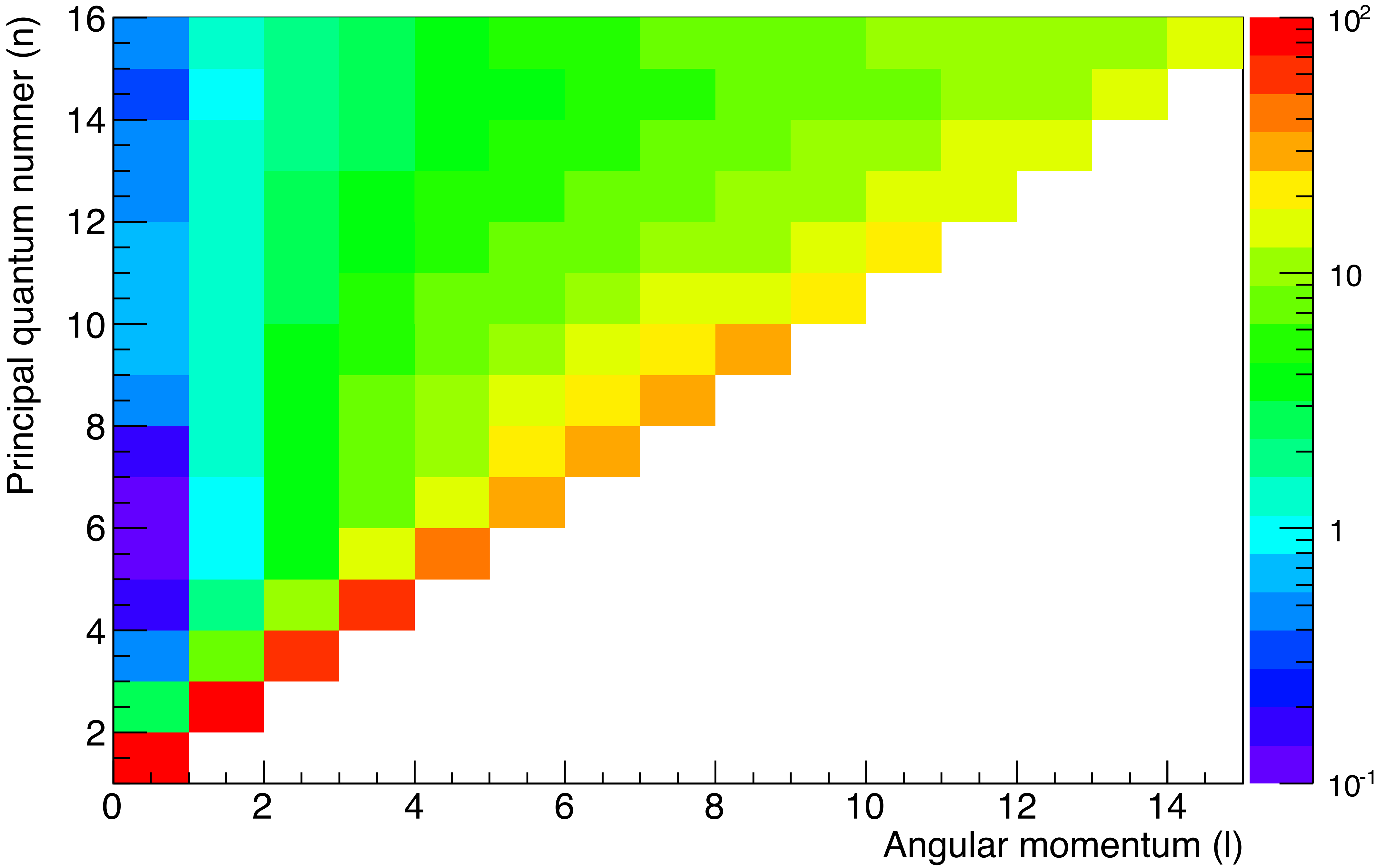
- Energy released in cascade from higher to lower energy level is in the form of a photon

- Possible transitions: $\Delta l = \pm 1$
  Favored: $\Delta l = -1$ and high Δn

- Decay rates are very high for large Z
  - Finite width of energy levels: $\Delta E \sim \frac{\hbar}{\tau}$
  - 2p levels for lead have 1.4 keV width
    → measurable!



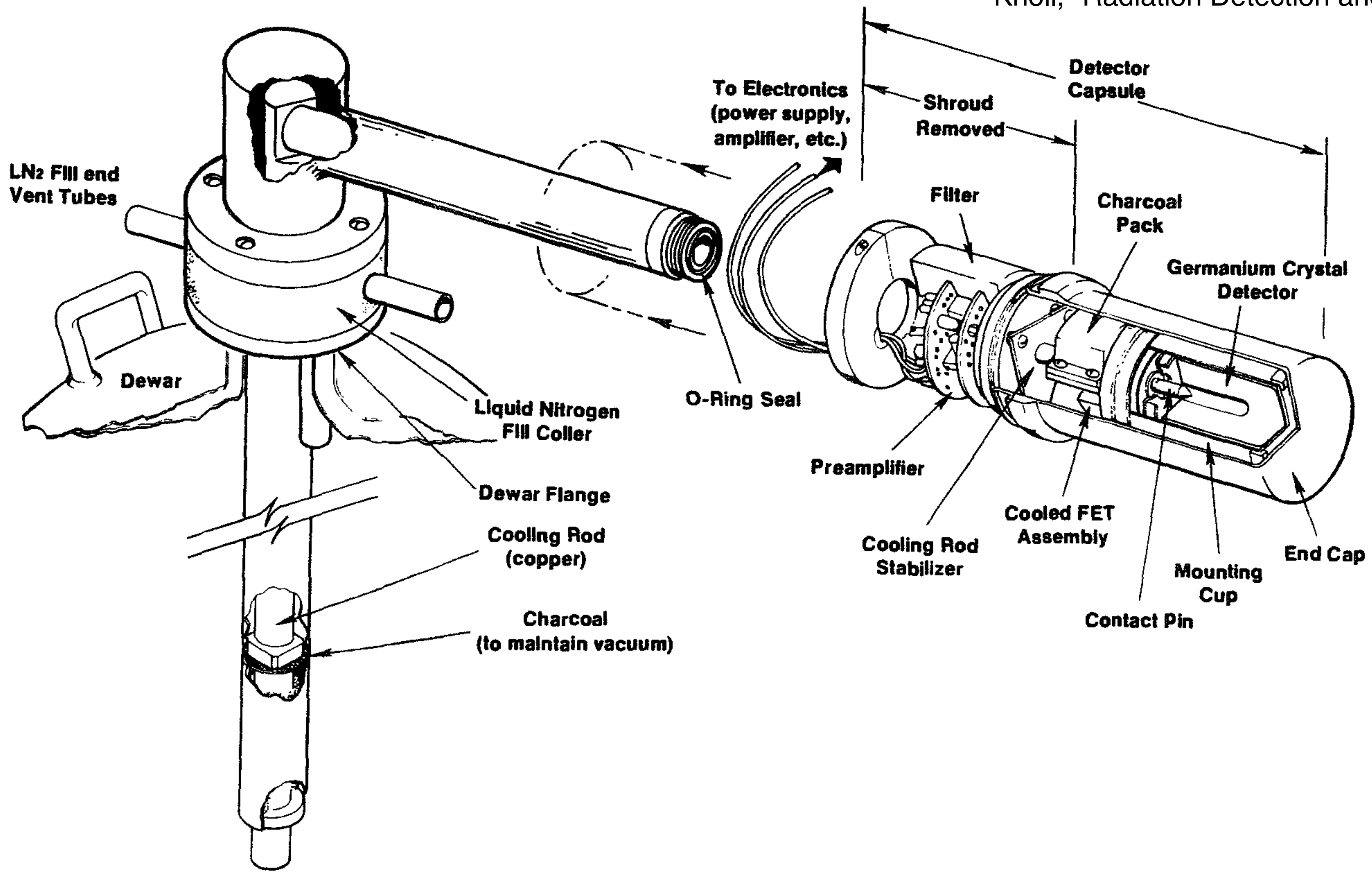
Muonic cascade calculation



- Population of states from full cascade calculation

Germanium detectors

Knoll, “Radiation Detection and Measurement”

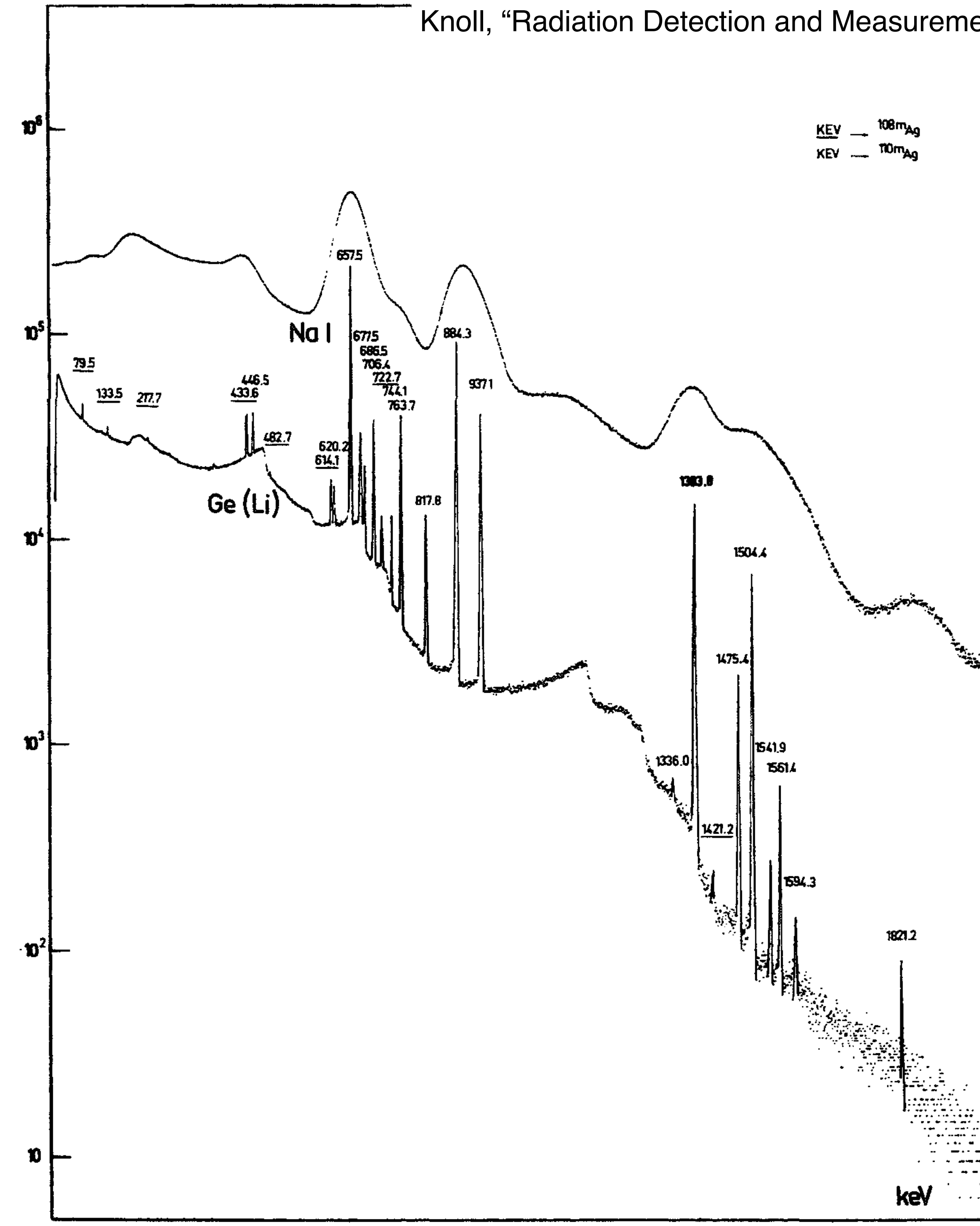


- Germanium detectors quite old technology, but still the best choice for high resolution measurements of X-rays or gammas of a few MeV
- Works as a semiconductor diode: charge deposited in depletion layer between P-N junction is drifted to contact and read out

Why high resolution?

- Possibility to distinguish peaks
- Less statistics needed to determine energy of peak with precision

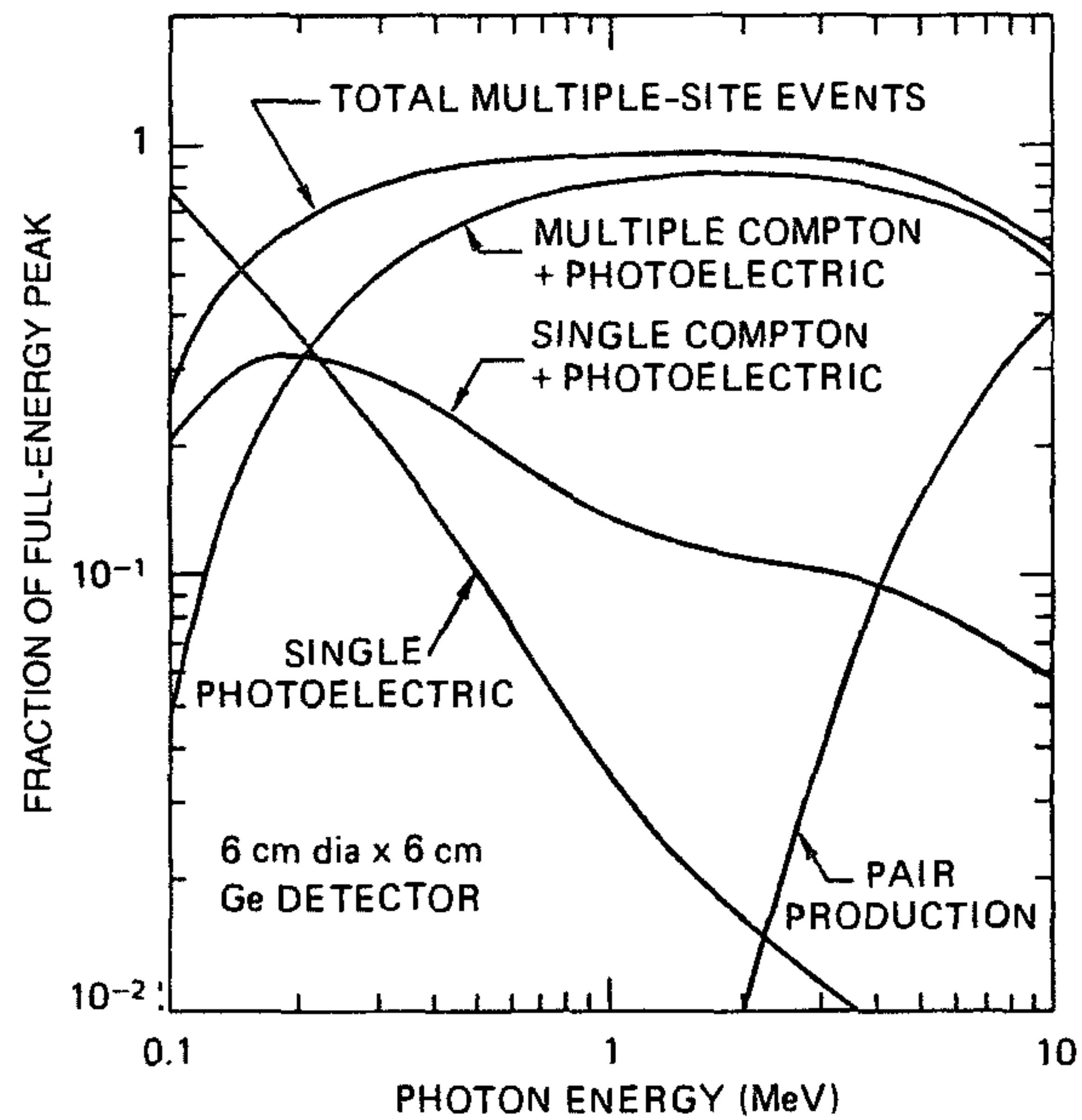
Knoll, “Radiation Detection and Measurement”



Features of a gamma spectrum

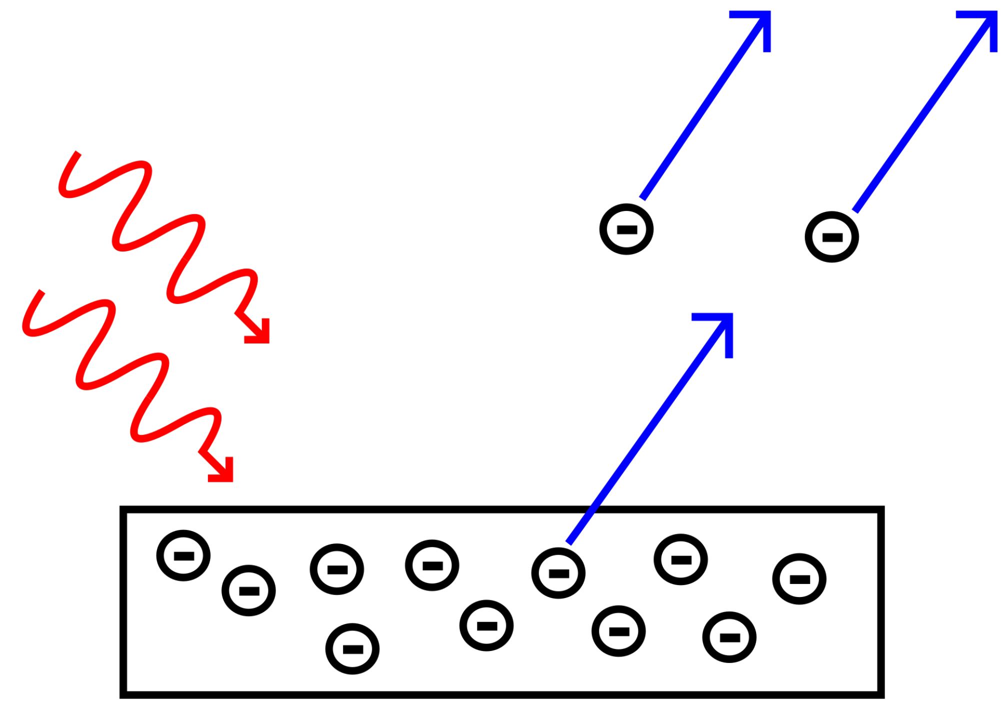
Knoll, “Radiation Detection and Measurement”

- Possible interactions of the photon with the detector
  - Photoelectric effect
  - Compton scattering
  - Pair production



Photoelectric effect

- Photon is absorbed by atom and electron is emitted instead



Compton scattering

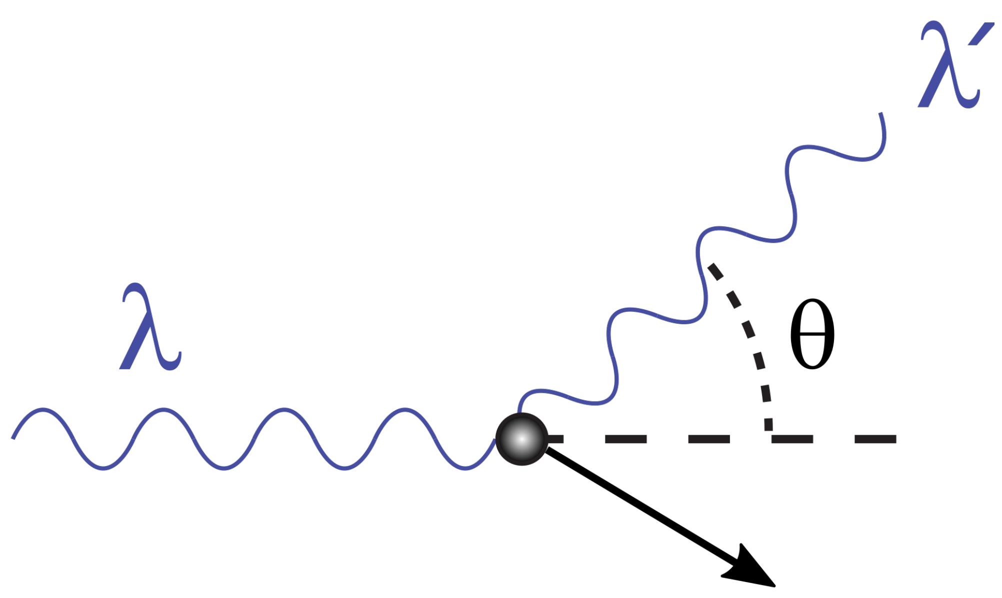
- Inelastic scattering of photon with electron
- Energy of outgoing photon:

$$E_{\gamma'} = \frac{E_\gamma}{1 + (E_\gamma / m_e c^2)(1 - \cos\theta)}$$

- Compton edge: Maximum energy deposition in detector

$\cos\theta = -1 \rightarrow$

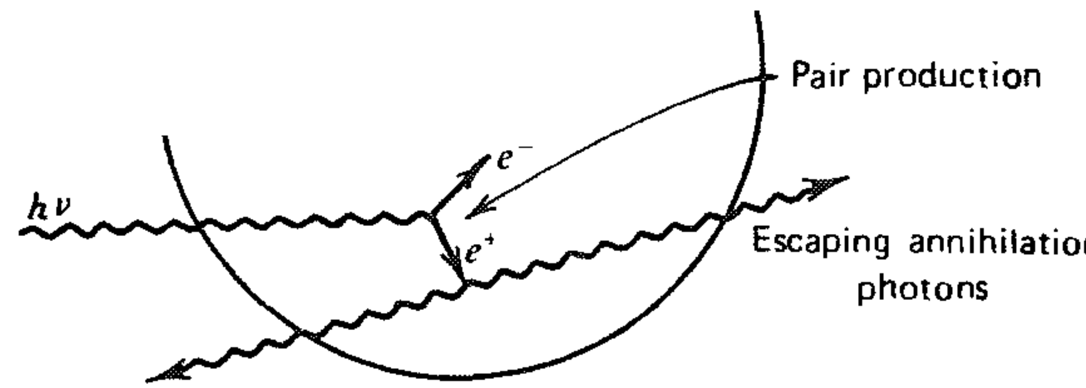
$$E_{\gamma'} \sim \frac{m_e c^2}{2}, E_{dep} \sim E_\gamma - \frac{m_e c^2}{2}$$



Pair production

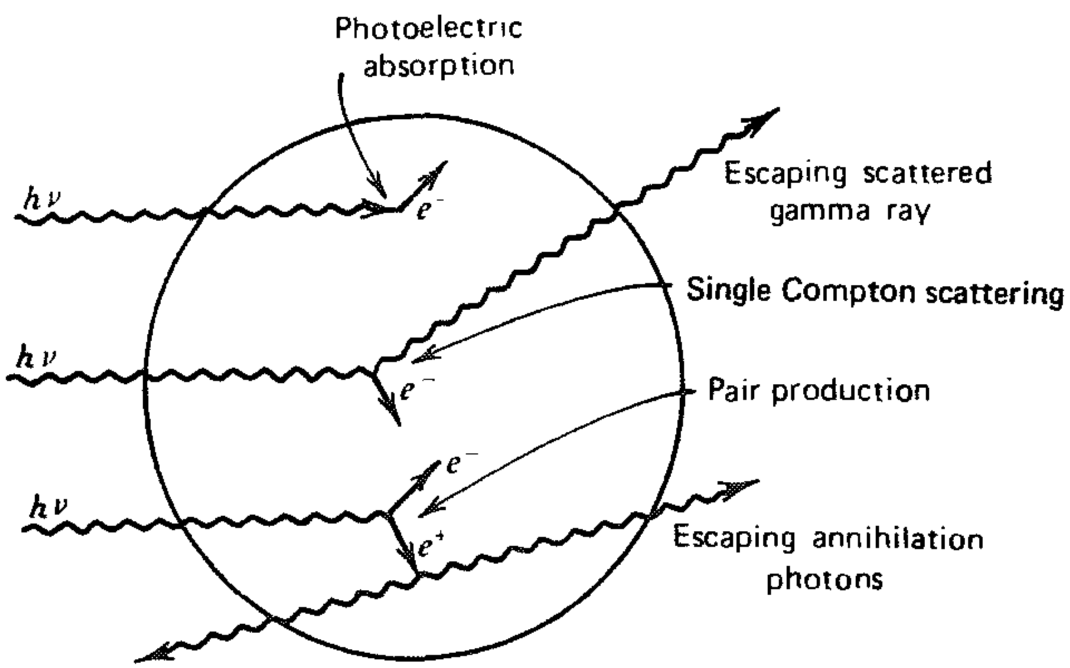
Knoll, "Radiation Detection and Measurement"

- Photon is converted into electron/positron pair
- Minimum energy of photon: 2 x 511 keV
- After stopping: Positron annihilates into two 511 keV photons

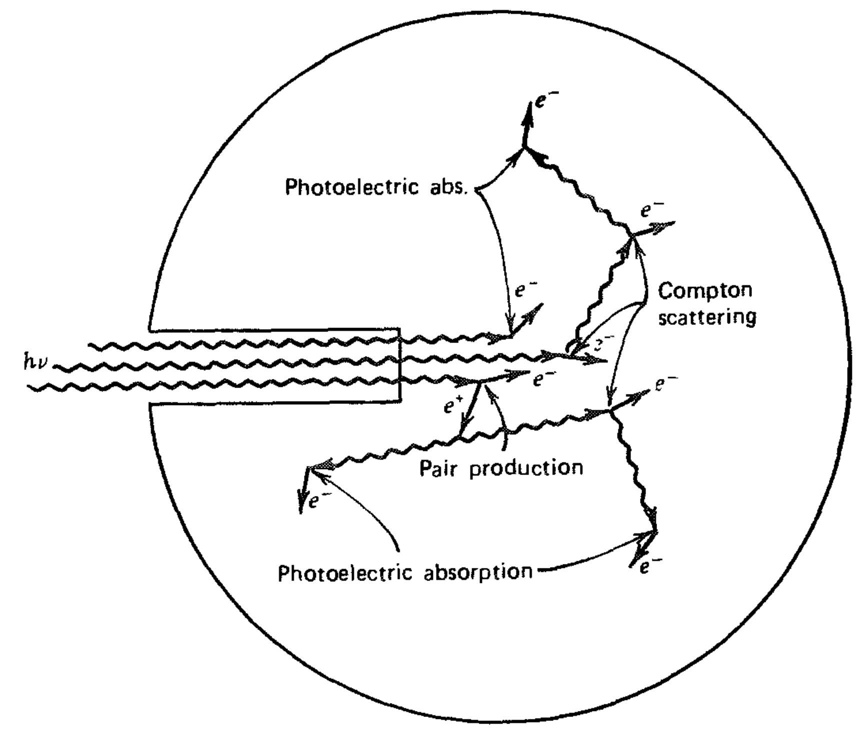


Size matters!

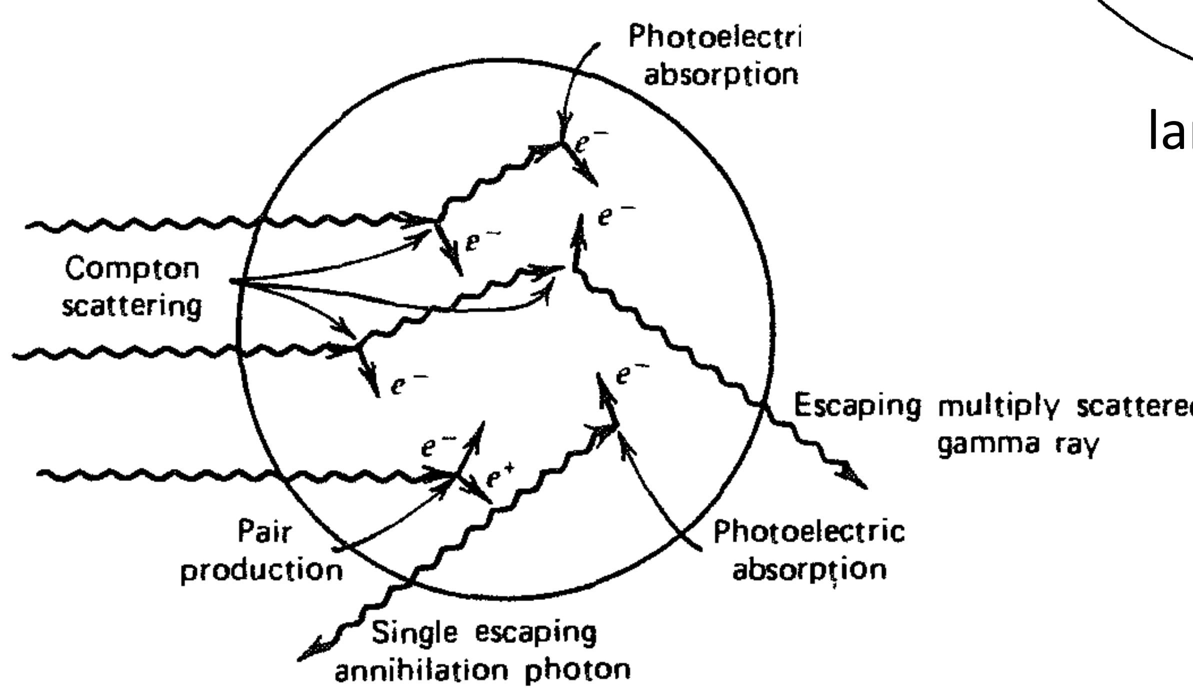
- Resulting spectrum depends on geometry of the detector



small detector



large detector



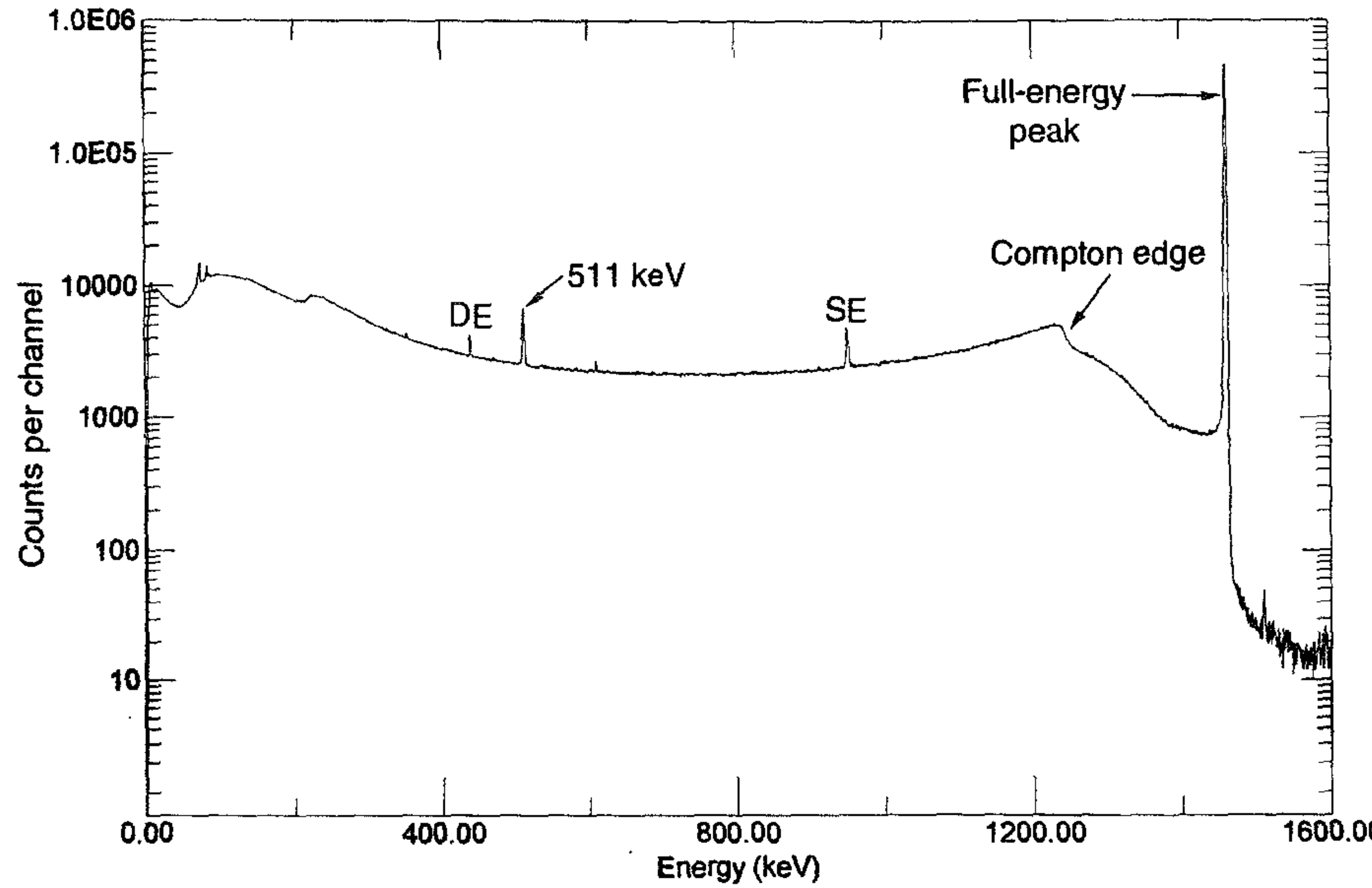
Knoll, "Radiation Detection and Measurement"

medium detector

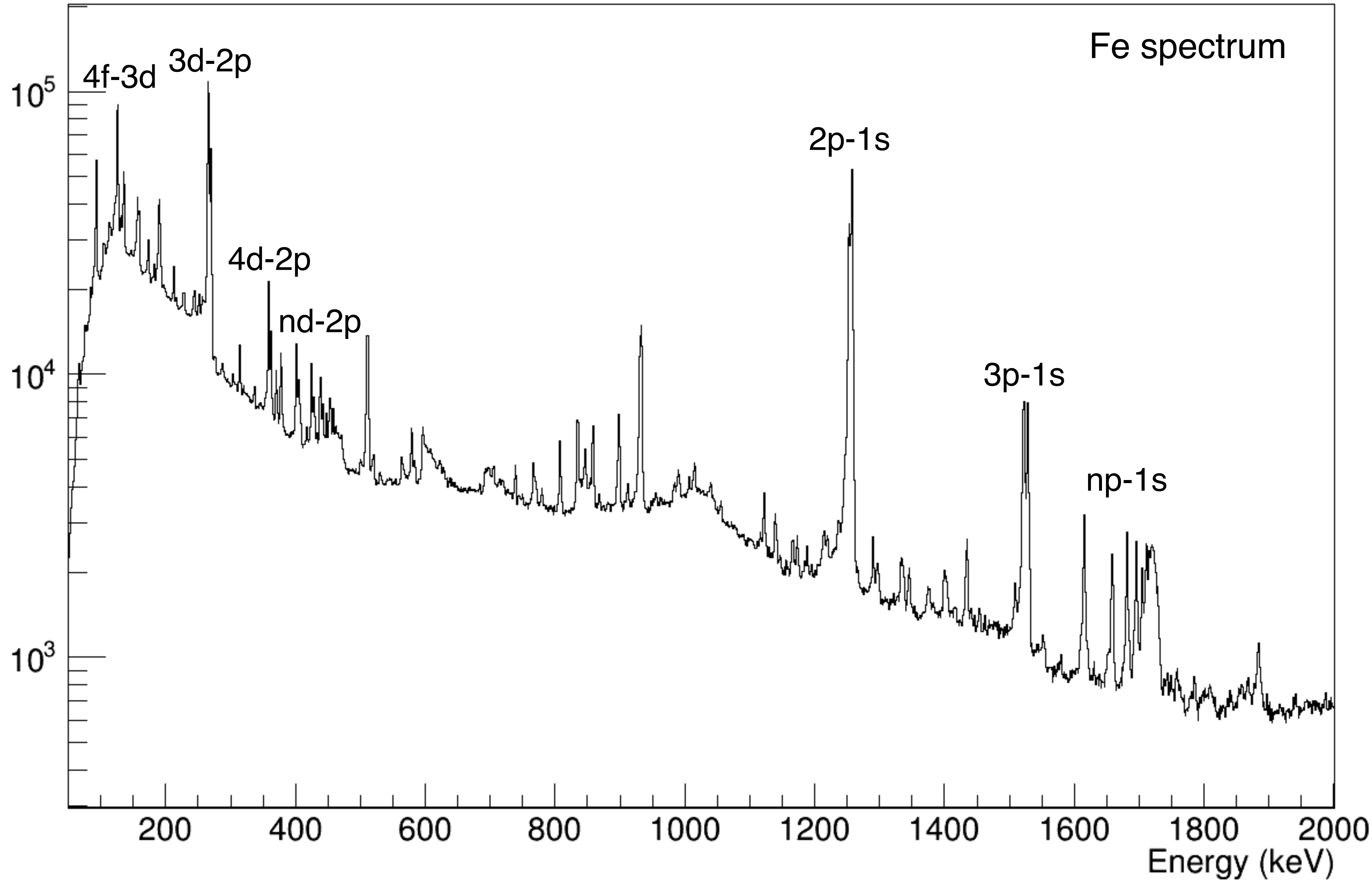
Features of a gamma spectrum

Knoll, "Radiation Detection and Measurement"

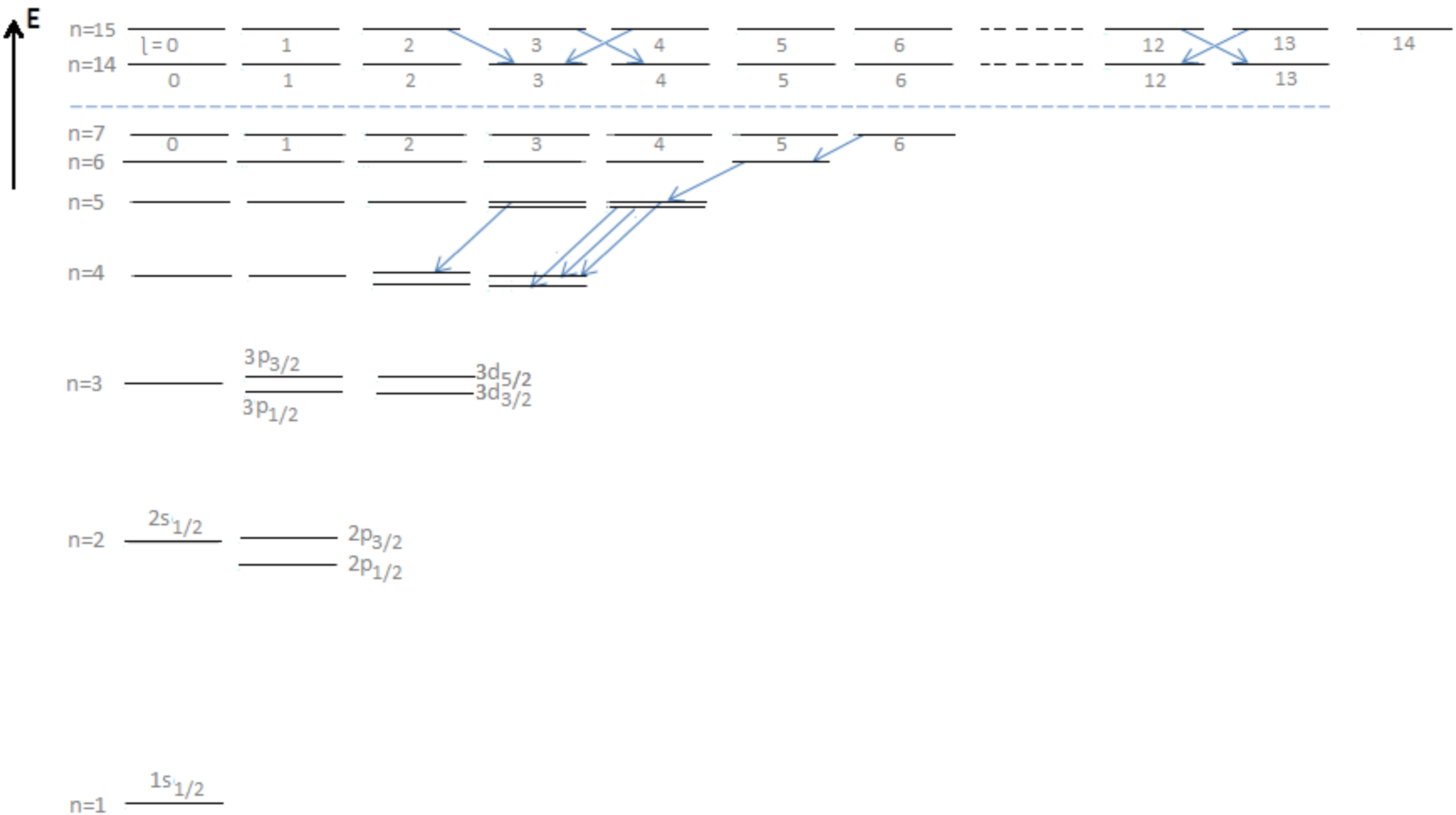
- General features:
  - Full-energy peak
  - Compton edge
  - Single and double escape peaks



Muonic atom level scheme

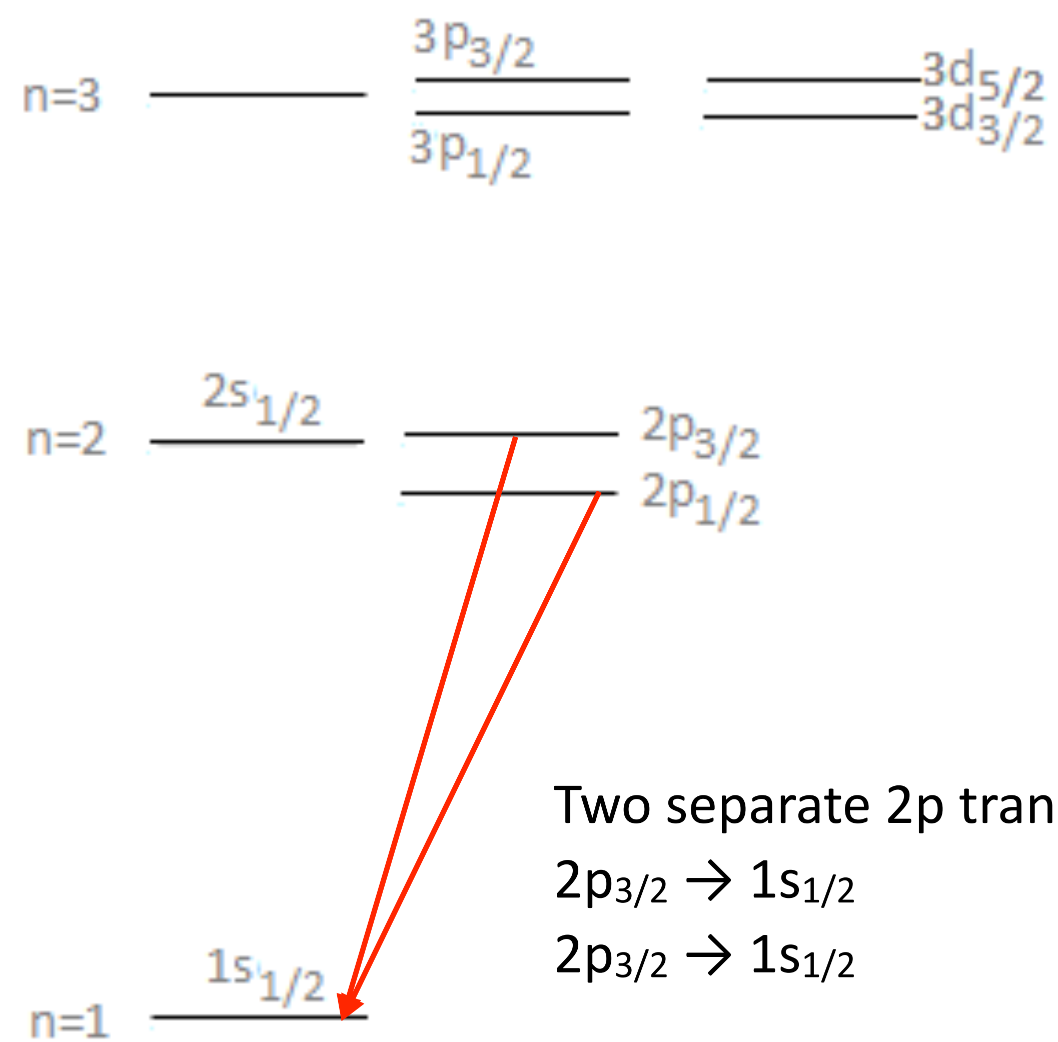


Muonic atom level scheme



Additional level splitting

- So far only talked about *n* and *l* of the muonic energy levels
- Fine structure:
  - Coupling of orbital angular momentum *l* with spin of the muon *s*=1/2
  - New quantum number total angular momentum *j* with **j=l+s**
  - For l=0 → j=1/2; For l≠0 → j=l±1/2
  - Notation of levels: np_j



Two separate 2p transitions:

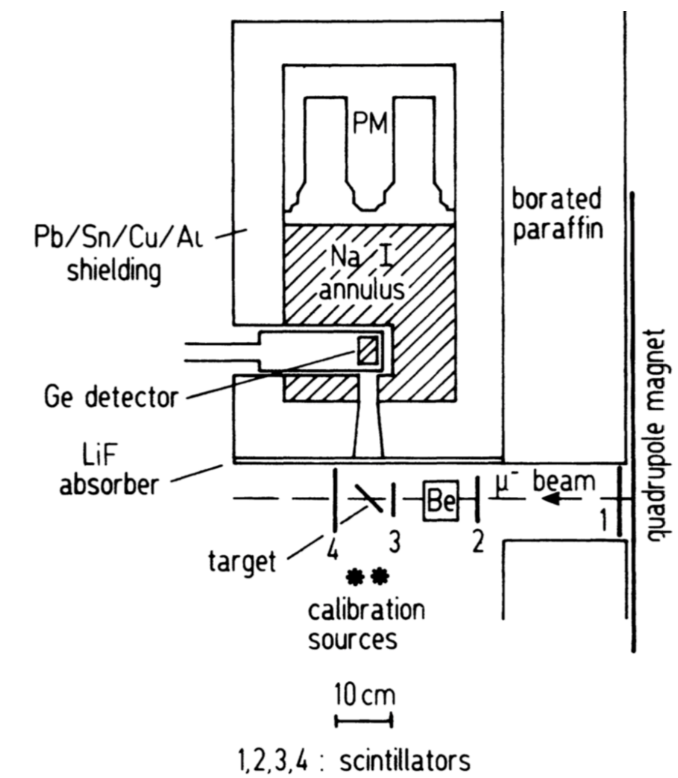
$2p_{3/2} \rightarrow 1s_{1/2}$

$2p_{3/2} \rightarrow 1s_{1/2}$

Muonic atom spectroscopy

- Measurement of ^{208}Pb as an example

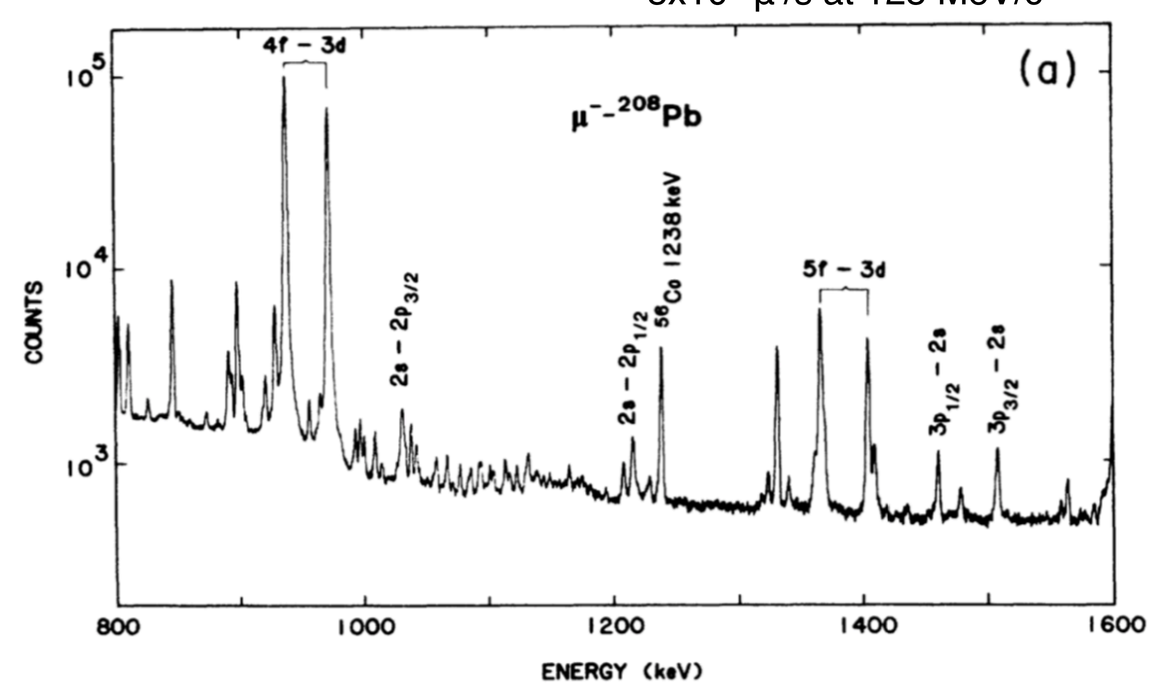
Bergem et al., PRC **37**, 2821 (1988)



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

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

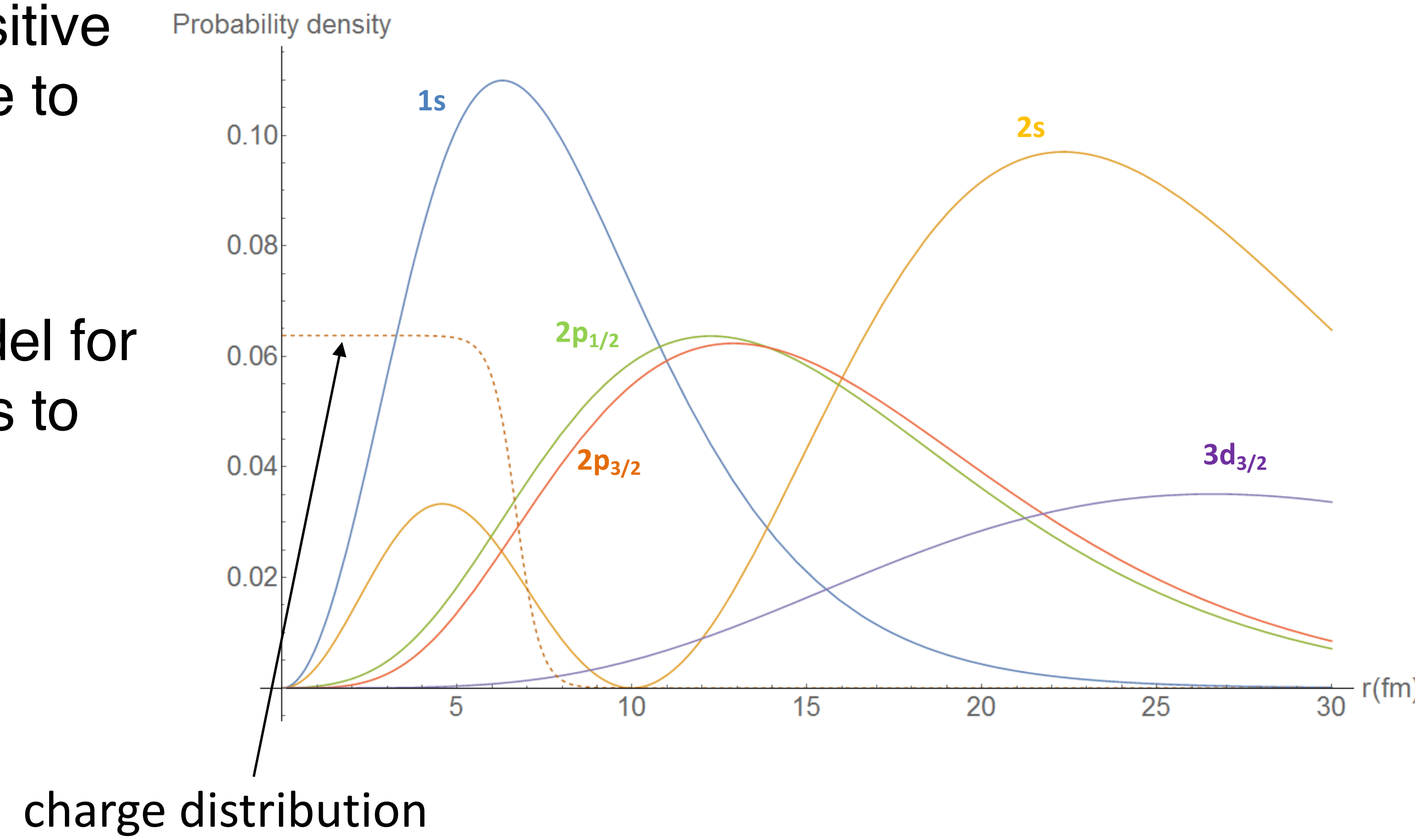
Transition	Kessler (Ref. 9)	Hoehn (Ref. 27)	This experiment
$2p_{3/2}$-$1s_{1/2}$	5 962.770(420)		5 962.854(90)
$2p_{1/2}$-$1s_{1/2}$	5 777.910(400)		5 778.058(100)
$3d_{3/2}$-$2p_{1/2}$	2 642.110(60)	2642.292(23)	2 642.332(30)
$3d_{5/2}$-$2p_{3/2}$	2 500.330(60)	2500.580(28)	2 500.590(30)
$3d_{3/2}$-$2p_{3/2}$	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

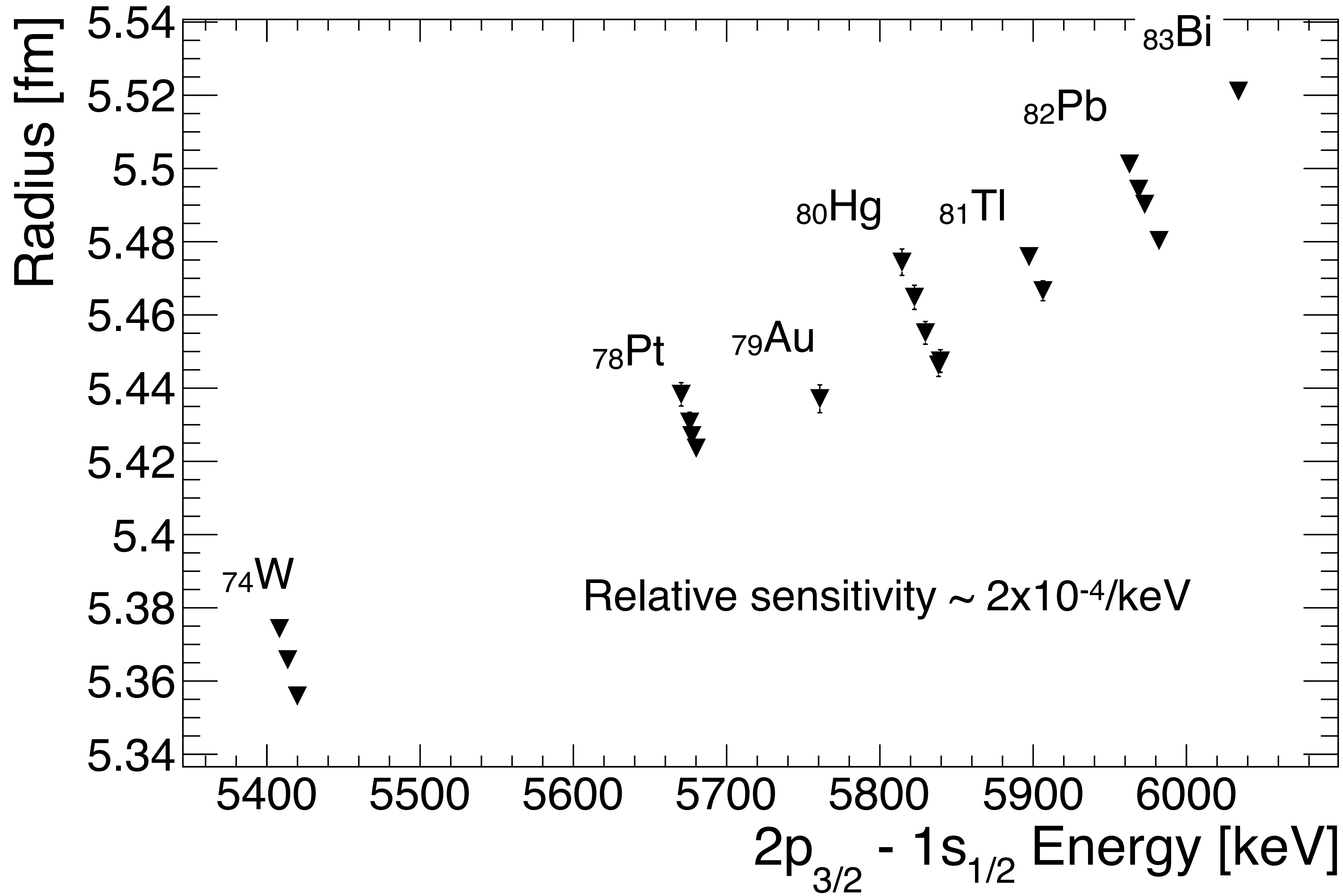
Lead Z=82



Large effect:

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

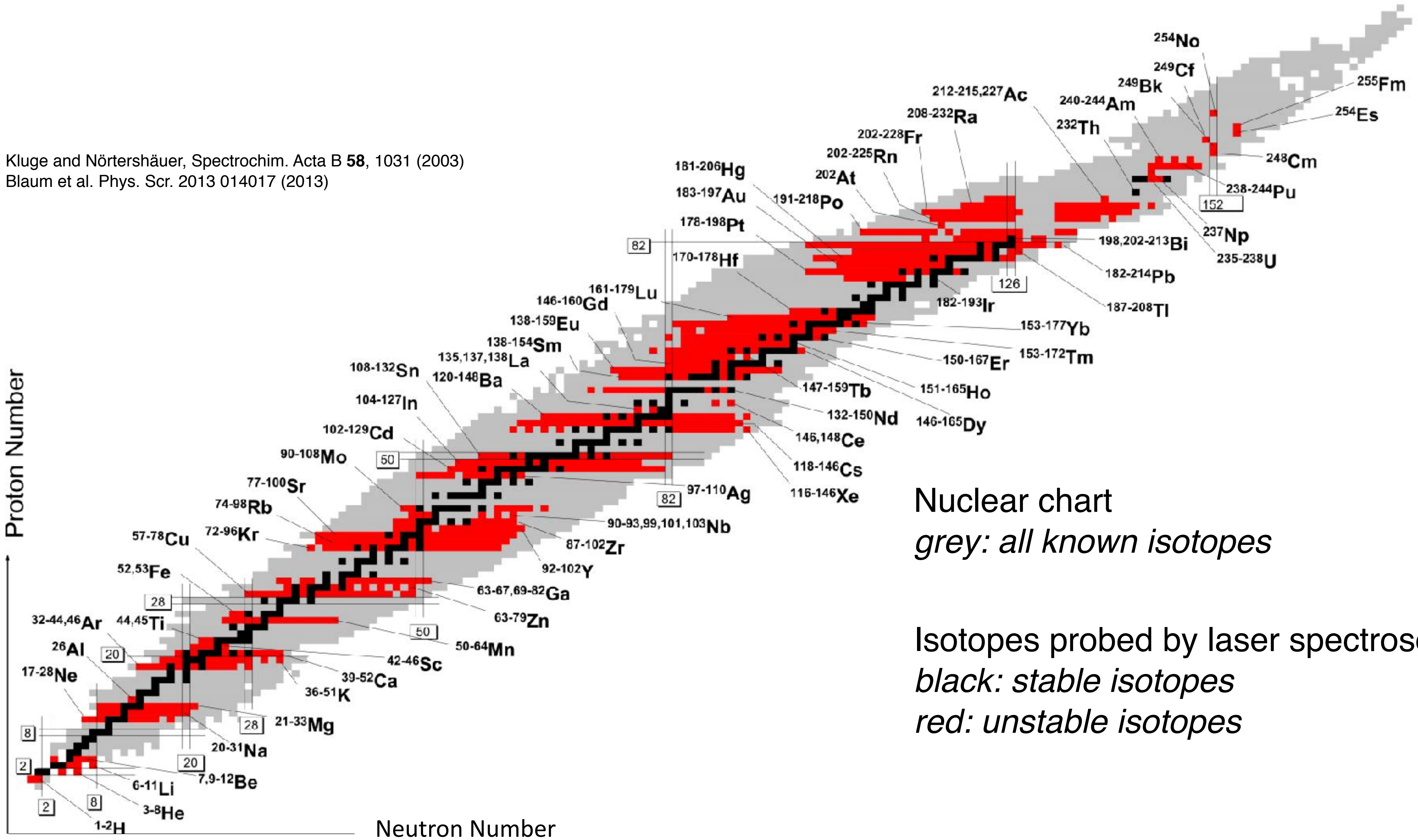
Muonic atom spectroscopy



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

Charge radii in nuclear physics

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



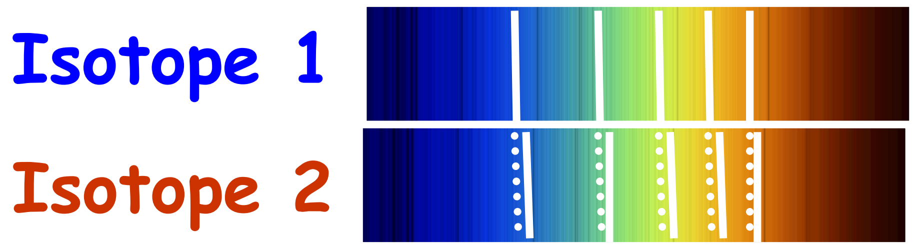
Nuclear chart
grey: all known isotopes

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

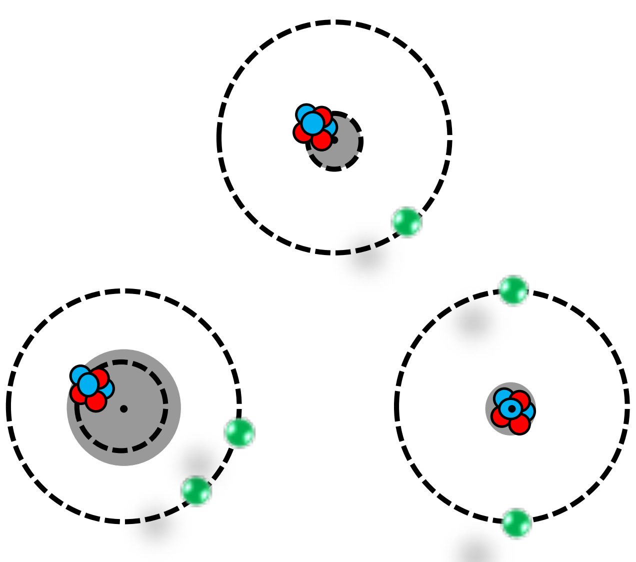
Laser spectroscopy

- Laser spectroscopy of specific transition
- Measure shift of transition energy for different isotopes
- Extract differences in charge radii along isotopes
- Needs good measurements of masses and good atomic calculations

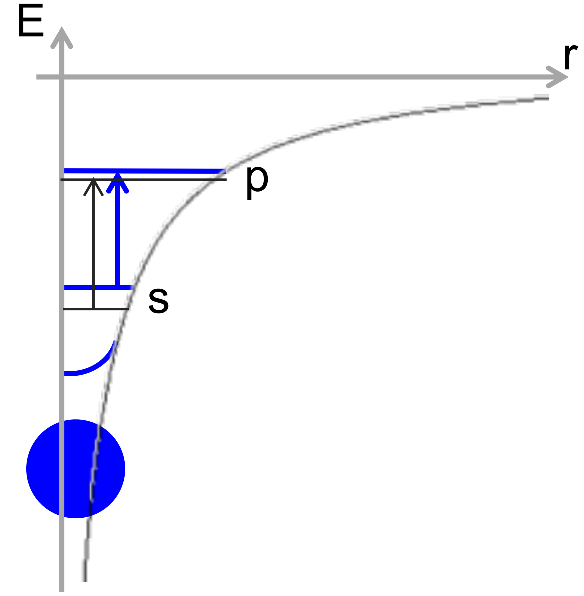


$$\delta\nu_{\mathrm{IS}}^{AA'} = K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + \frac{2\pi Ze}{3} \Delta \left|\Psi(0)\right|^2 \, \delta \left\langle r^2 \right\rangle^{AA'}$$

Mass Shift (center-of-mass motion)



Field Shift (finite size)

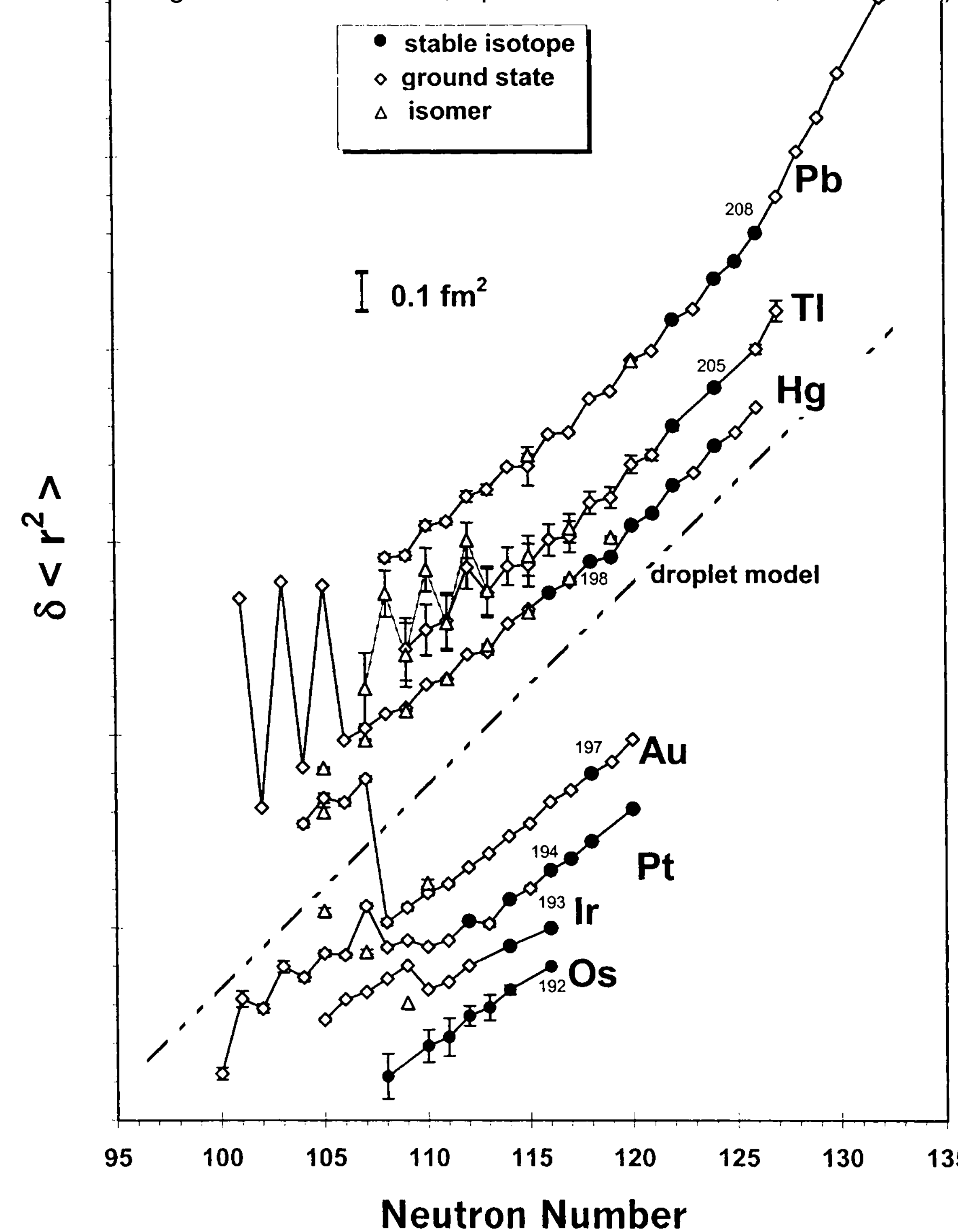


K. Blaum, Workshop on Muonic Atom Spectroscopy (2016)

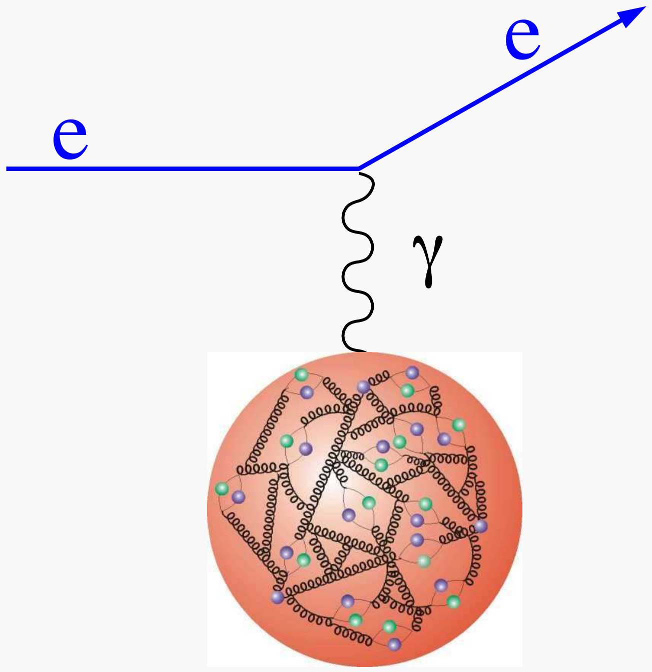
Laser spectroscopy

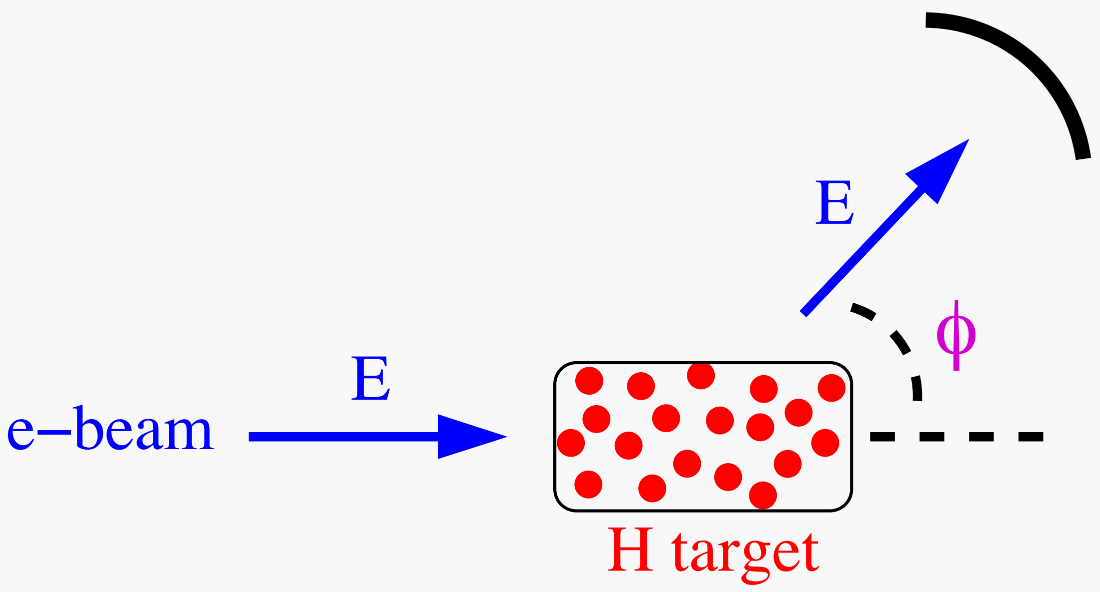
- Large chains of charge radii differences have been measured

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



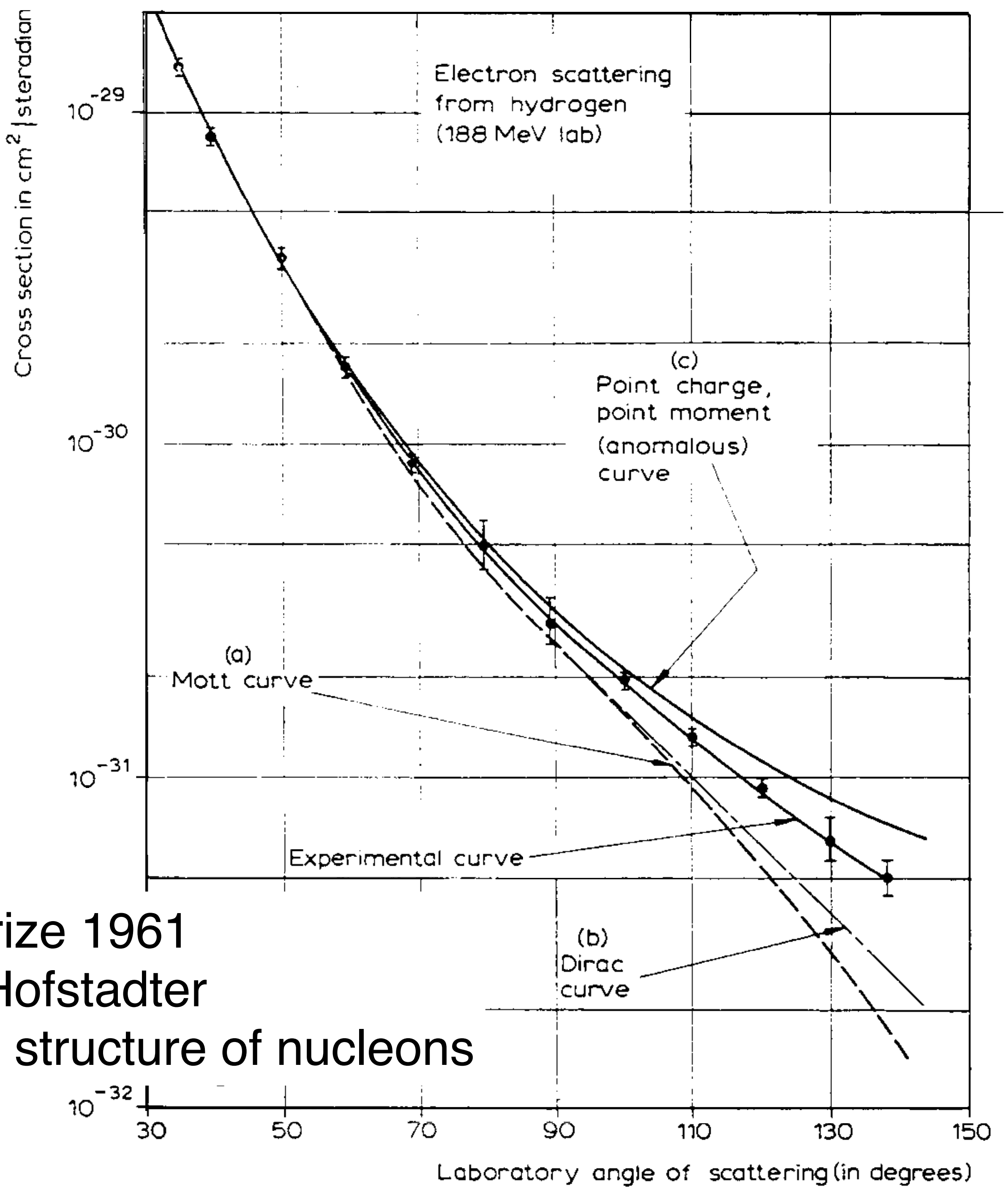
Electron scattering



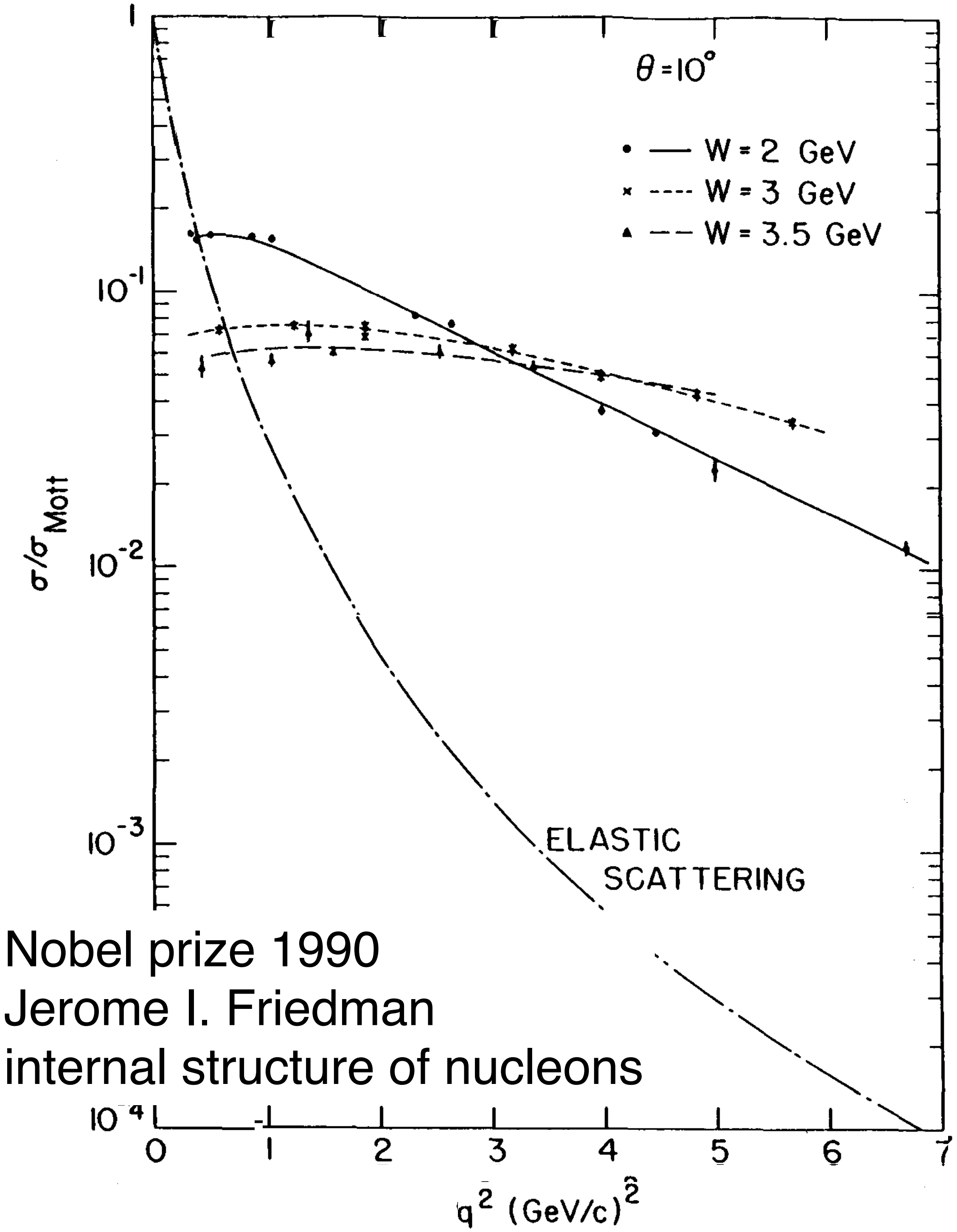


Mainz A1 spectrometer

Electron scattering



Nobel prize 1961
Robert Hofstadter
size and structure of nucleons

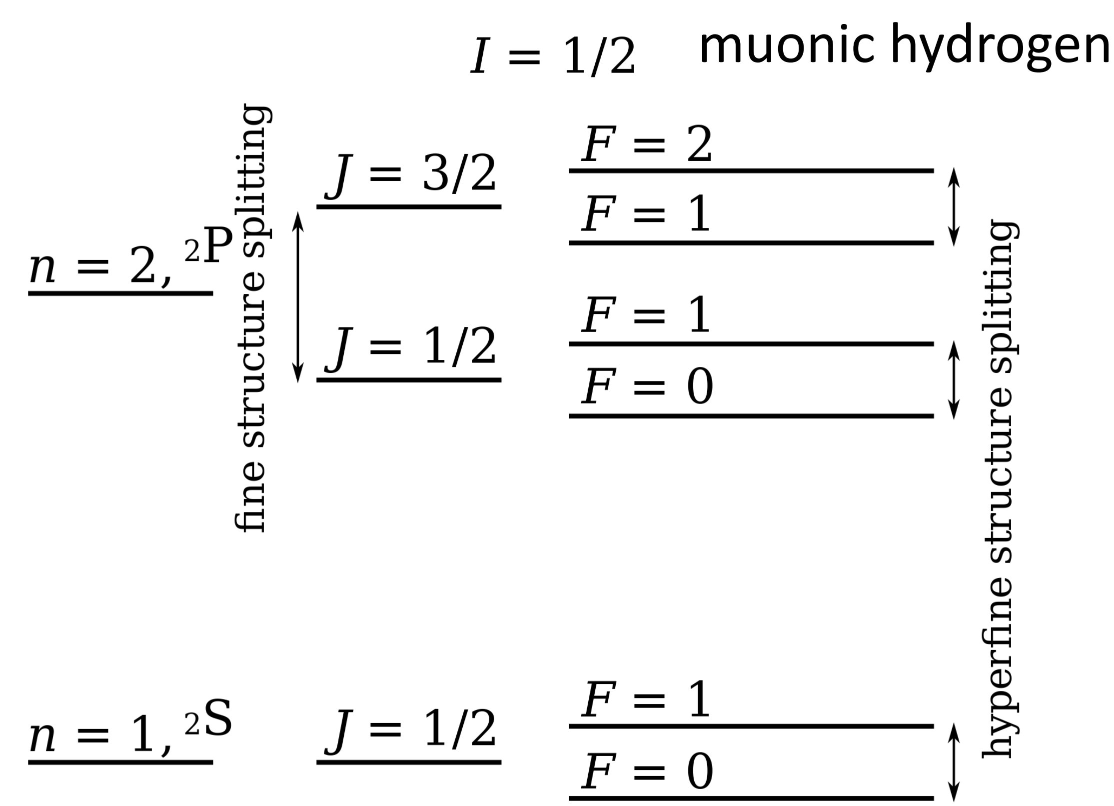


Nobel prize 1990
Jerome I. Friedman
internal structure of nucleons

Additional level splitting

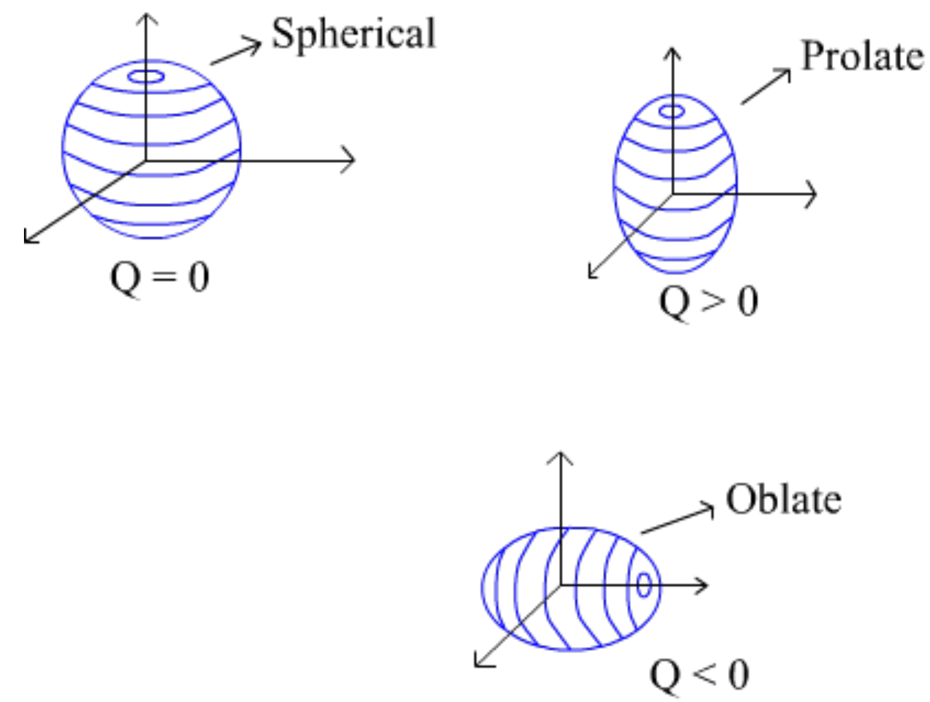
- So far only talked about *n* and *l* of the muonic energy levels
- Defined total angular momentum *j*

- Hyperfine splitting:
  - Coupling of total angular momentum *j* with spin of the nucleus *i*
  - New quantum number f with **f=j+i**
  - f follows the relation $|i - j| \leq f \leq i + j$
  - Notation of levels: (np_j, f)



Quadrupole moment

- Energy levels affected by the size and shape of the nucleus
  - Size → charge radius
  - Shape → quadrupole moment
- Effect of quadrupole moment shows up in the hyperfine splitting of muonic energy levels due to dependence on nuclear spin
- Note: also magnetic moment leads to splitting, but effect very small as $\mu_\mu \ll \mu_e$



Nuclear capture

- After the cascade there are two possibilities for the muon:
  - Muon decay with a lifetime of 2200 ns
  - Muon capture with a lifetime of ~80 ns for high-Z atoms
- Nuclear capture strongly dominating for high-Z atoms
- Nuclear capture rates and accompanying neutrons, gammas etc. explore the nuclear structure

Muon decay:

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

Nuclear capture:

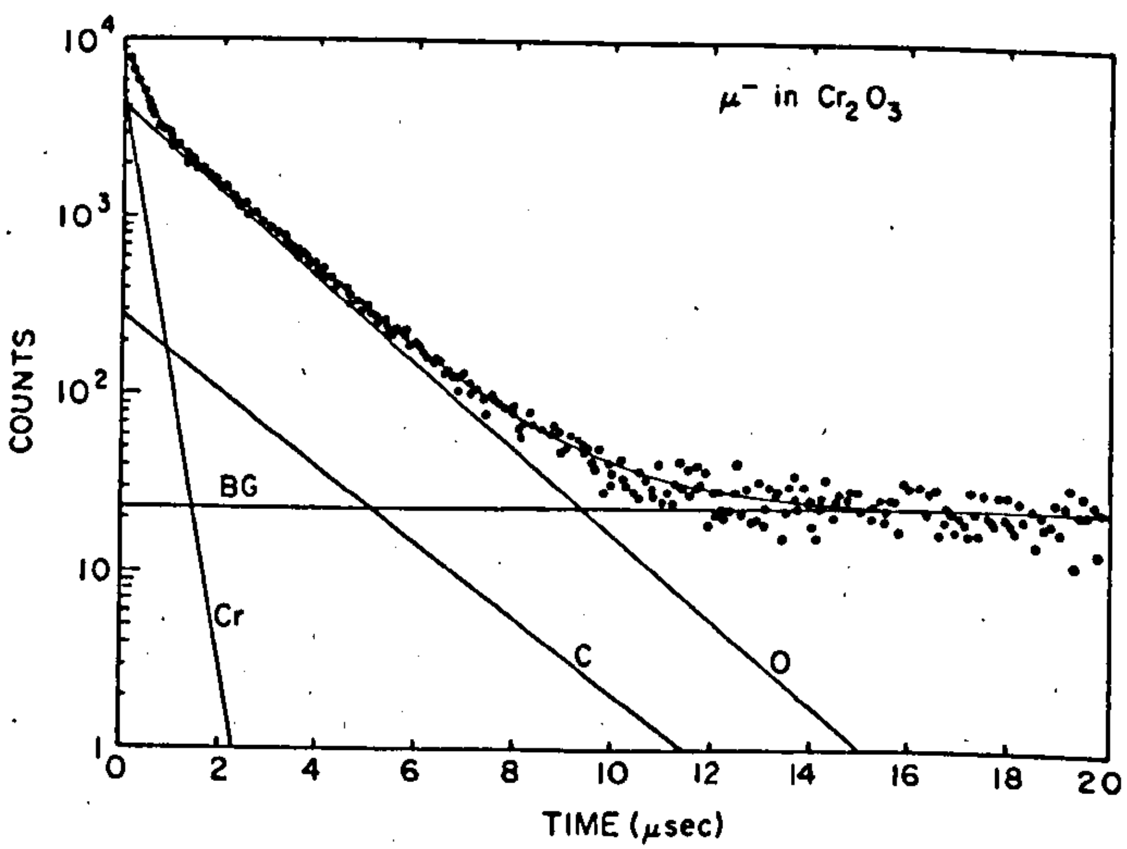
$$\mu^- + p \rightarrow n + \nu_\mu$$

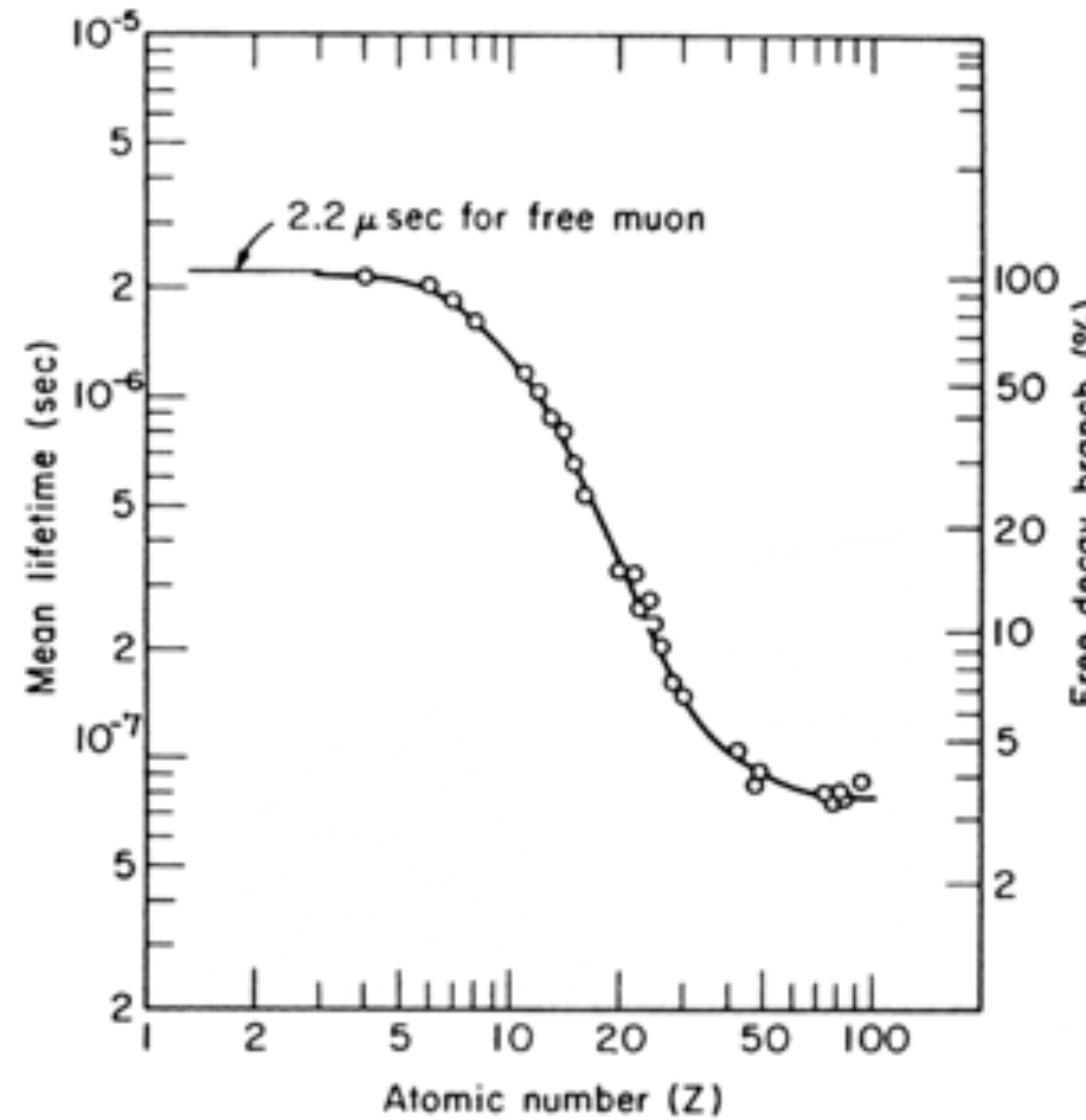
$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{free}} + \frac{1}{\tau_{cap}}$$

Total lifetime

- Total lifetime can be measured by detecting decay electrons
- Extract capture rate by subtracting free muon lifetime

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{free}} + \frac{1}{\tau_{cap}}$$

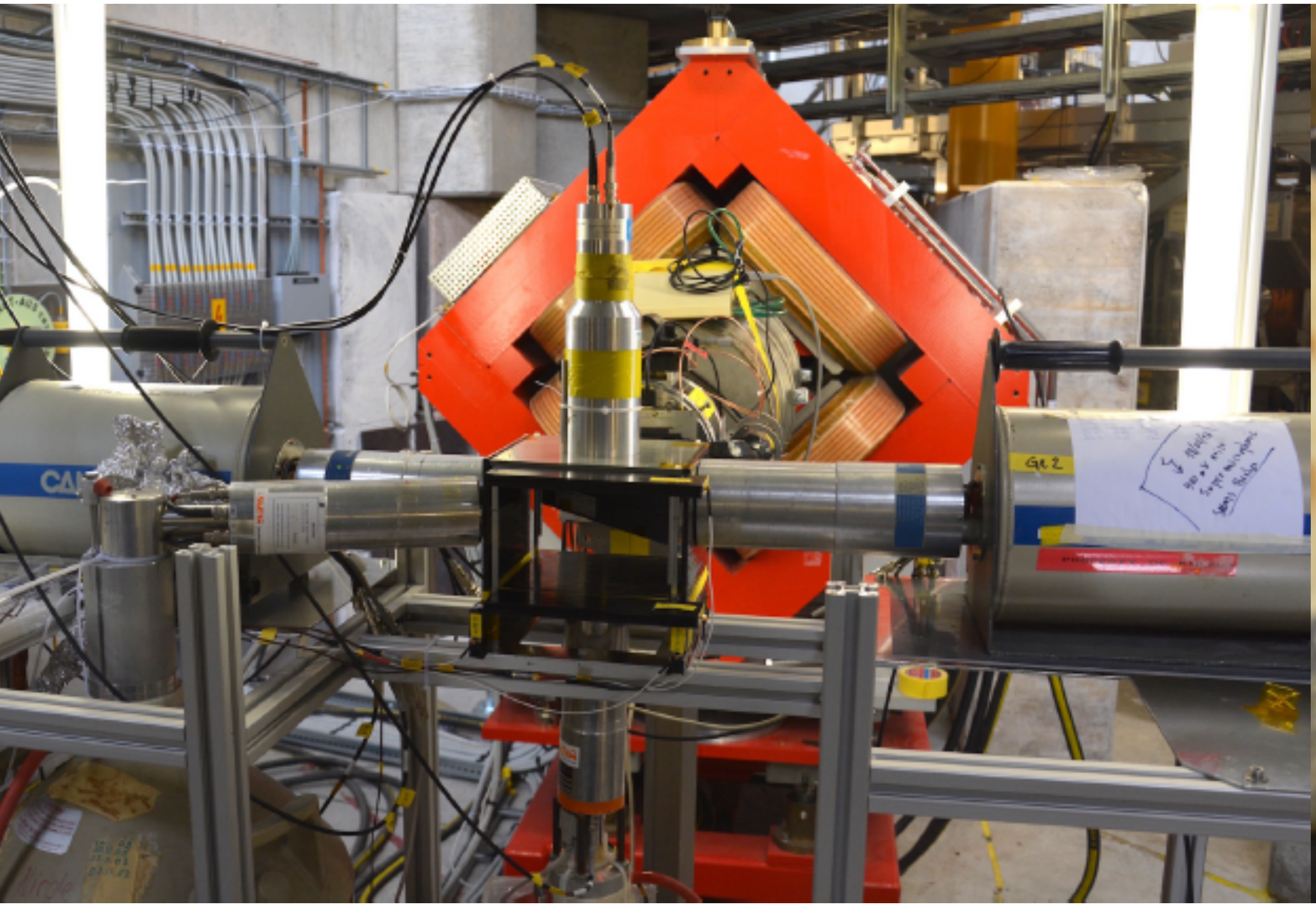
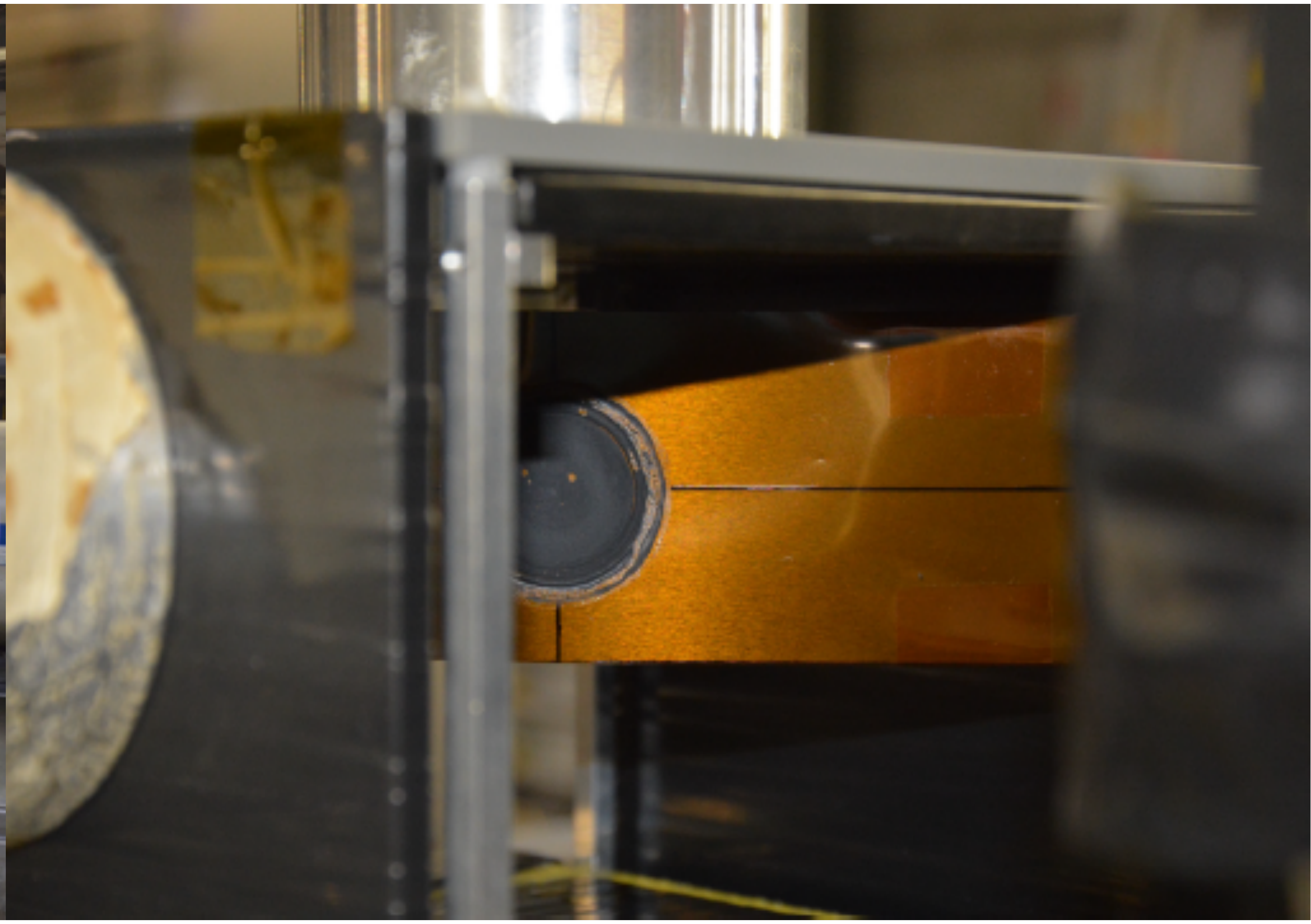




The muX experiment:
Stable isotopes

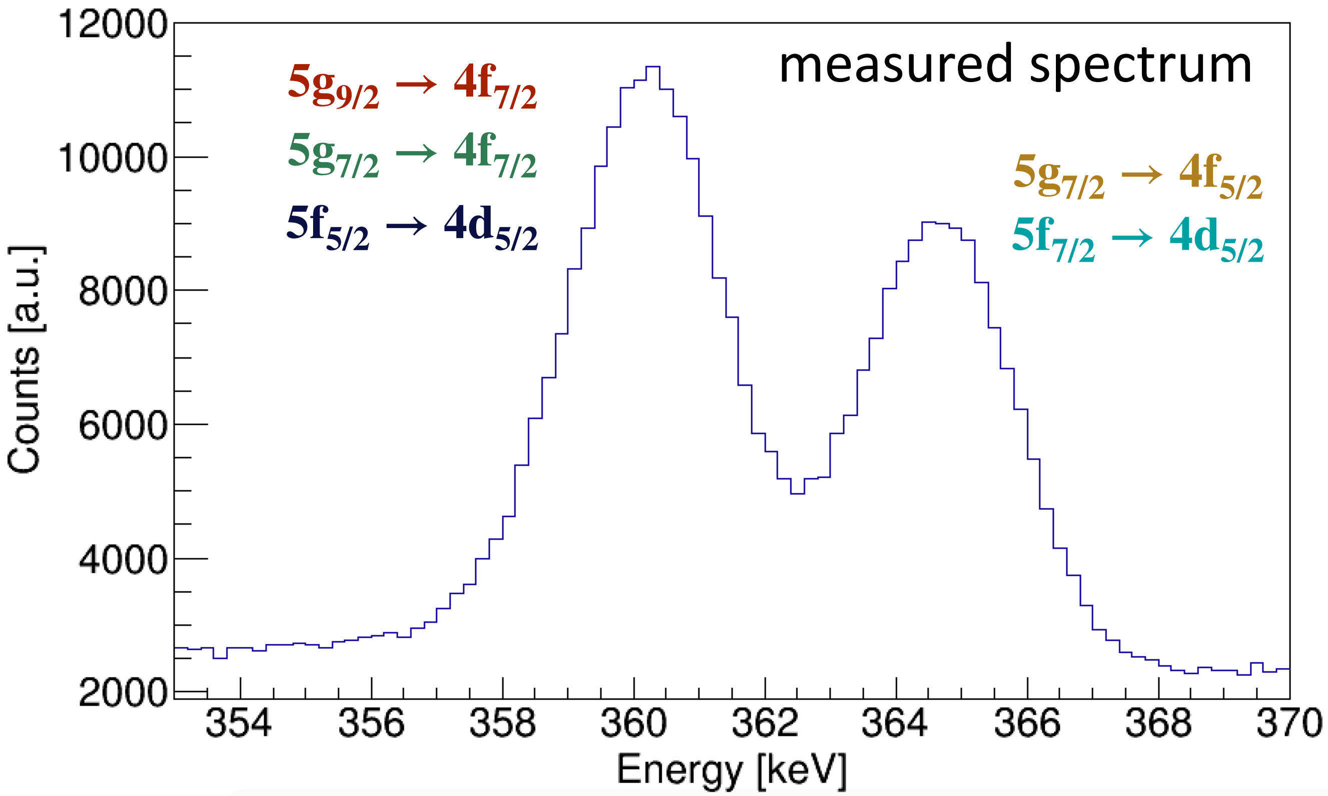
Case of rhenium

- 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

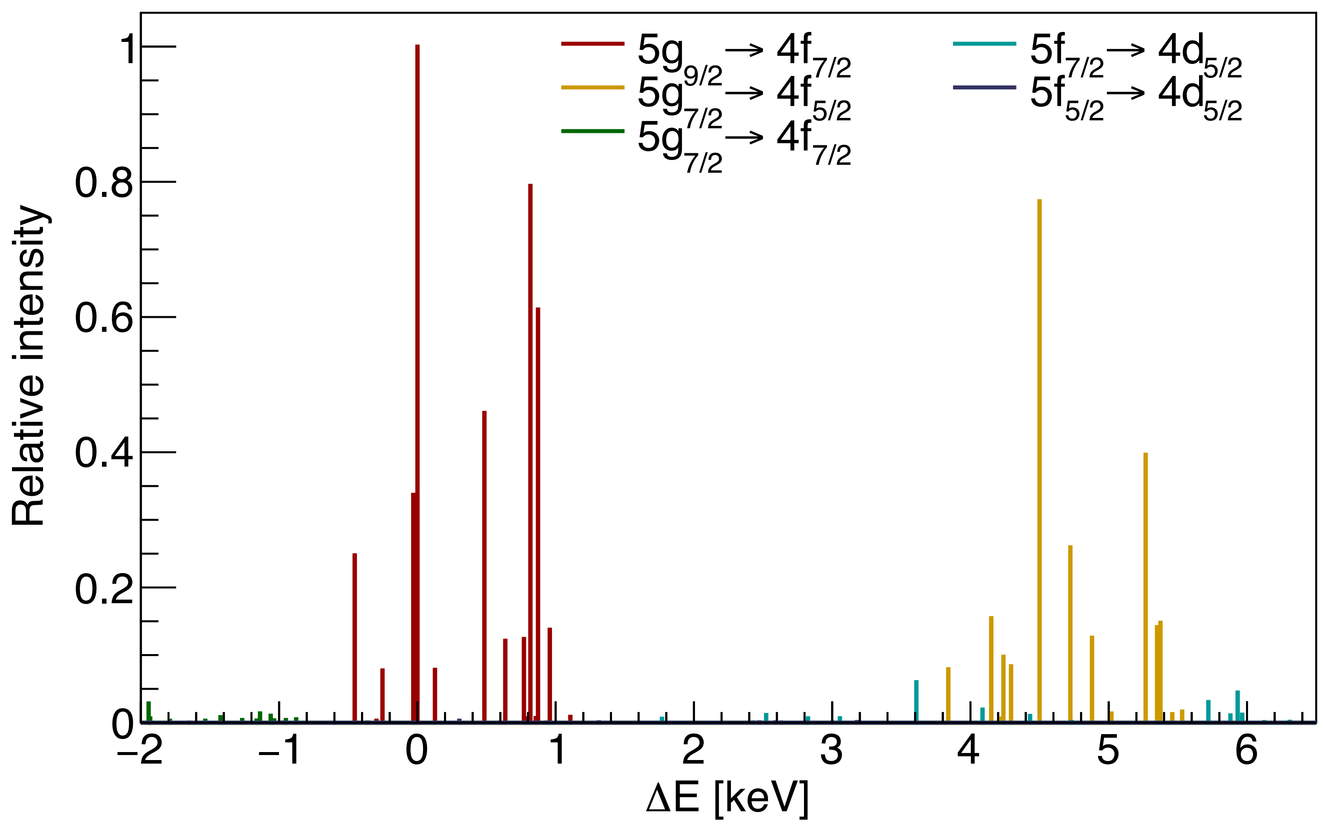
Hyperfine splitting of 5g-4f transitions

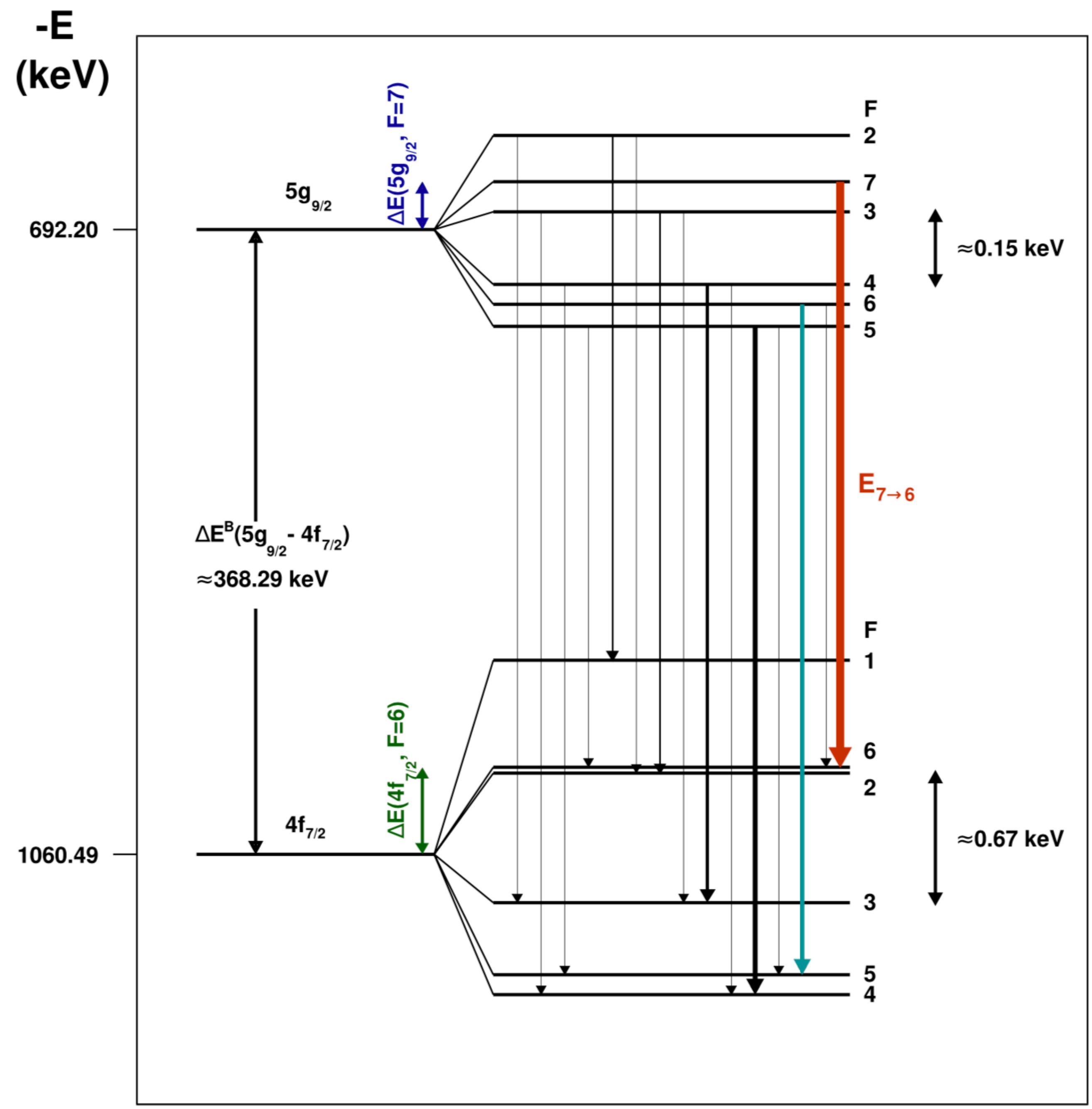
- For higher muonic transitions measure full quadrupole moment → typically chosen: 5g-4f transition
- Drawback:
  - Transitions not separated
  - Effect only through widening of peaks



Hyperfine splitting of 5g-4f transitions

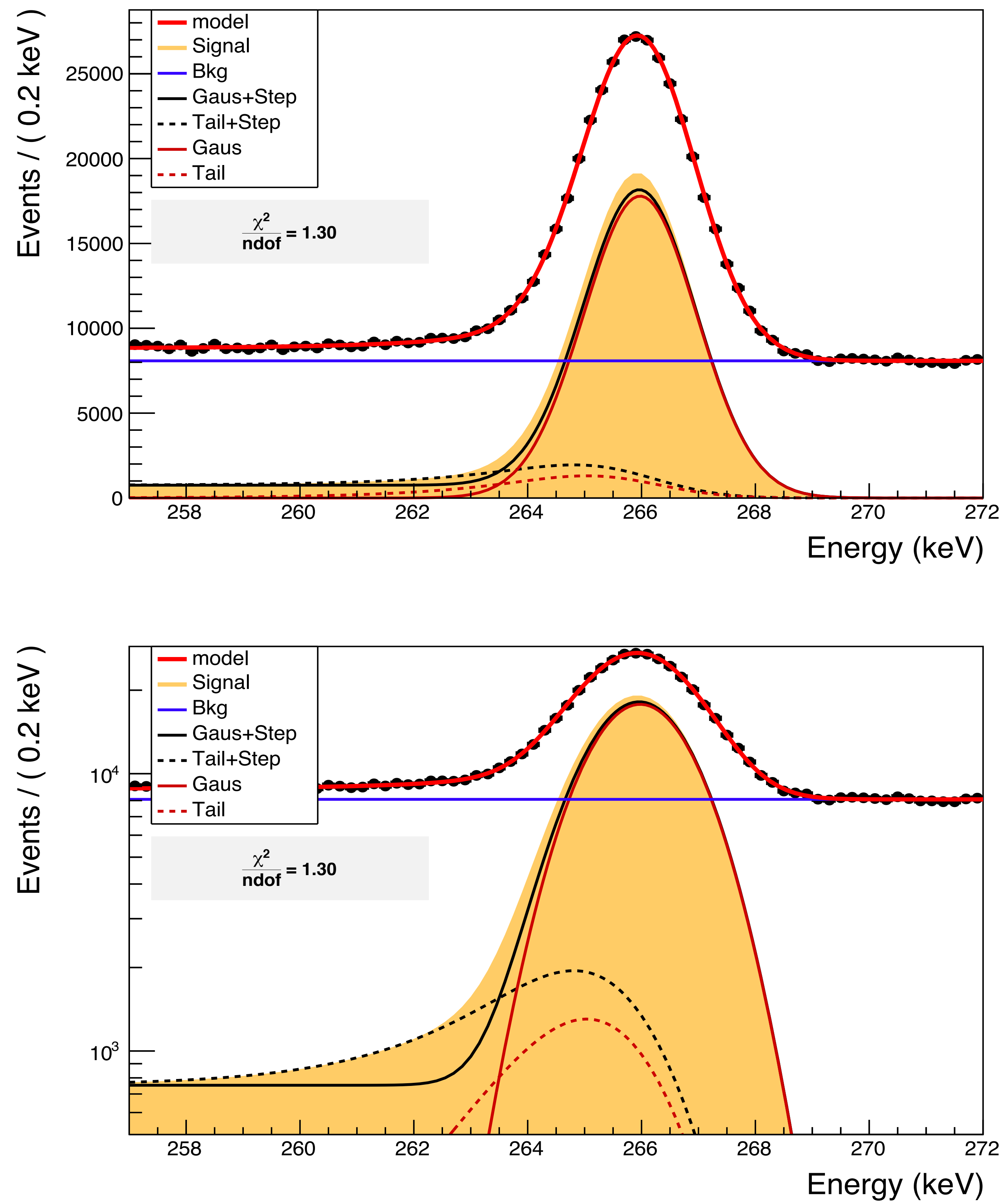
- 5 transitions split into 76 transitions between hyperfine multiplets
- Quadrupole moment changes spacing and intensity of the various lines



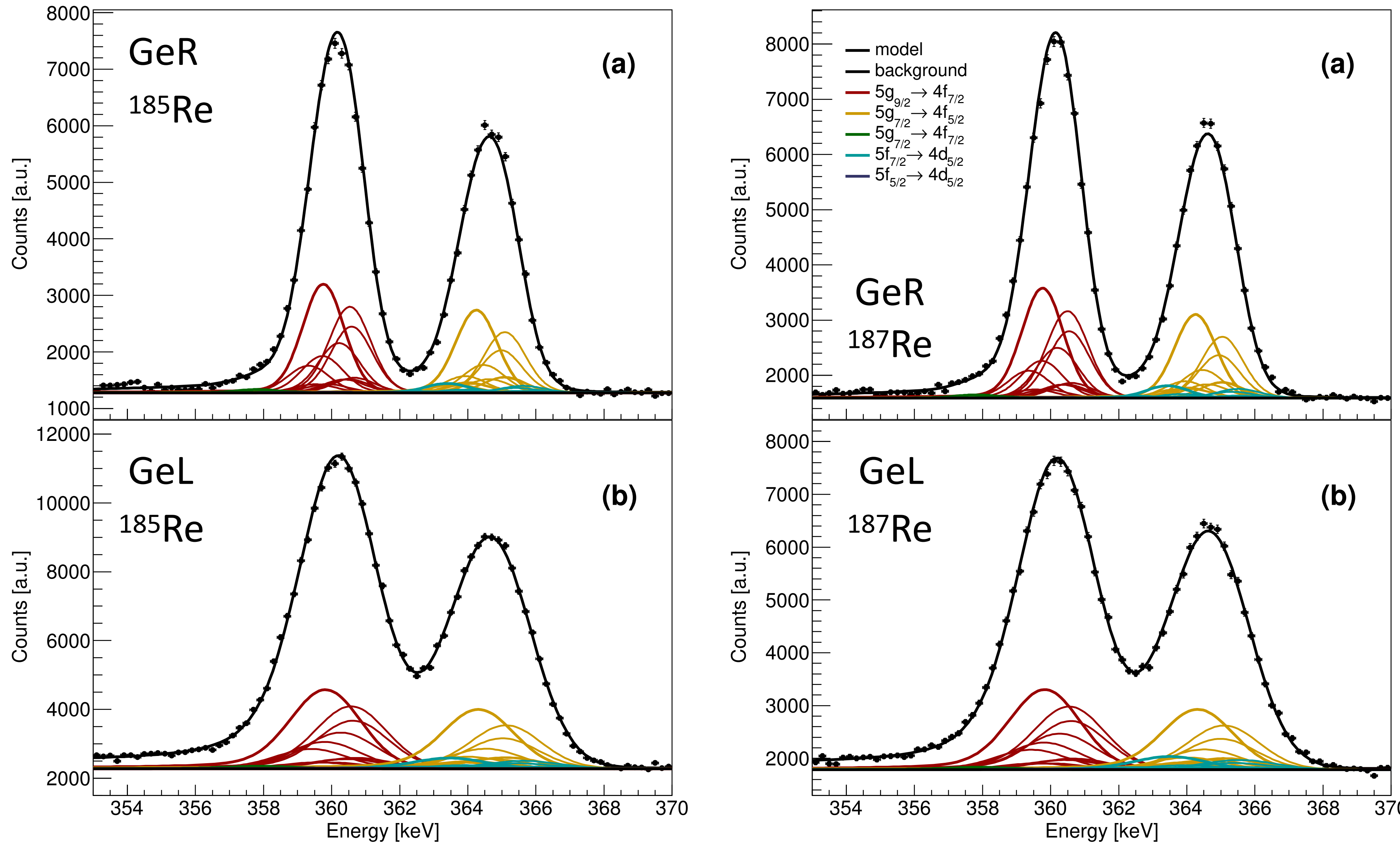


Need to understand line shape!

- Using various lines in the muon and background spectra to fix line shape parameters



Fitting experimental spectra



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

Results on quadrupole moment

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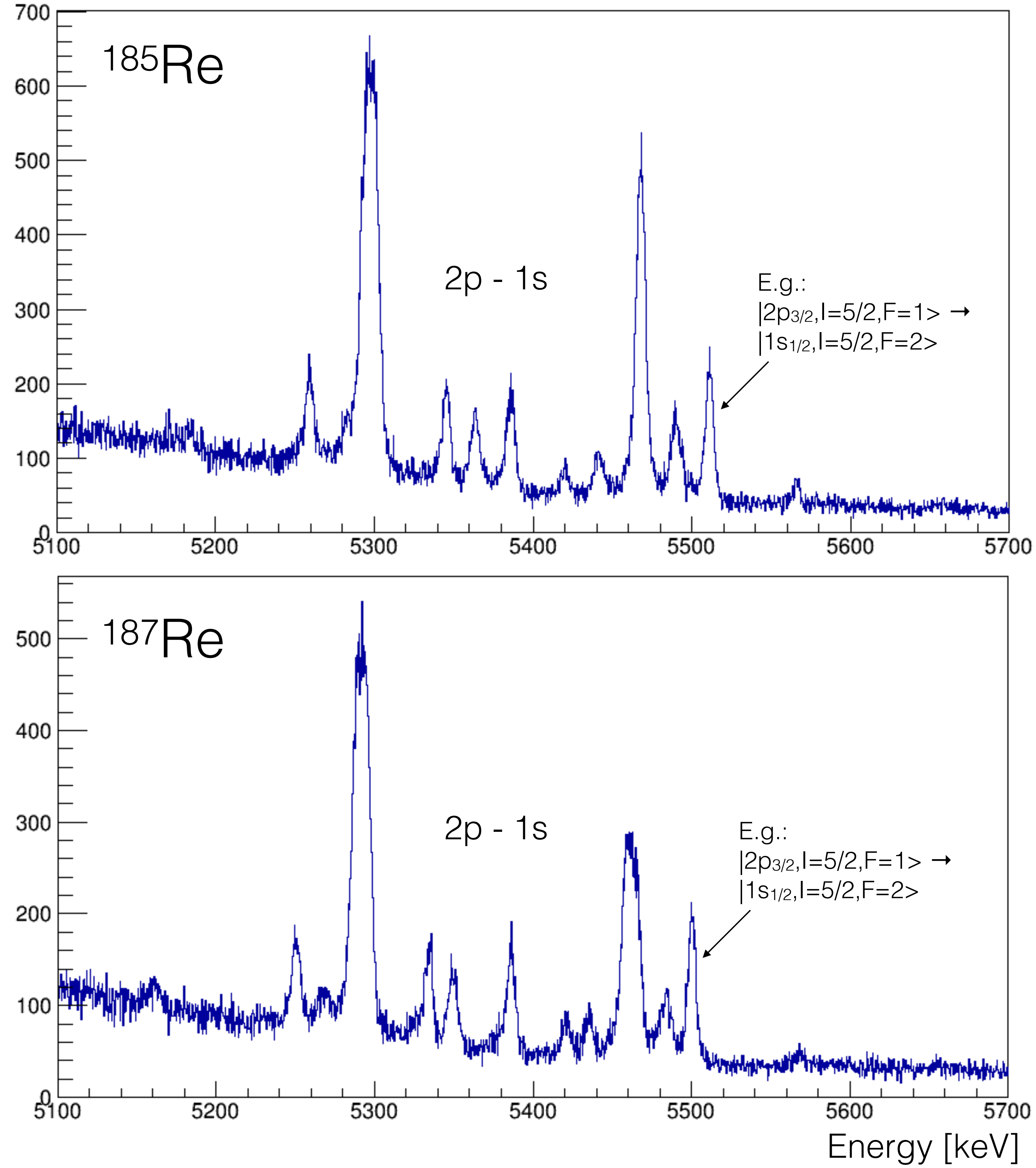
- Extracted quadrupole moments for the two isotopes
- Comparison with existing results reveals some difference. However: performed with natural rhenium, some errors in reported values, weak transitions not included
- Systematic uncertainties: Background shape, line shape model, energy resolution, cascade

	Q [barn]
^{185}Re ^{187}Re	2.07 ± 0.02 ± 0.05 1.94 ± 0.02 ± 0.05
^{185}Re ^{187}Re Konijin et al.	2.21 ± 0.04 2.09 ± 0.04
^{185}Re ^{187}Re our result, no weak transitions	2.14 ± 0.02 ± 0.05 2.02 ± 0.02 ± 0.05

Konijin et al., Nucl. Phys. A **360**, 187 (1981)

Rhenium charge radius

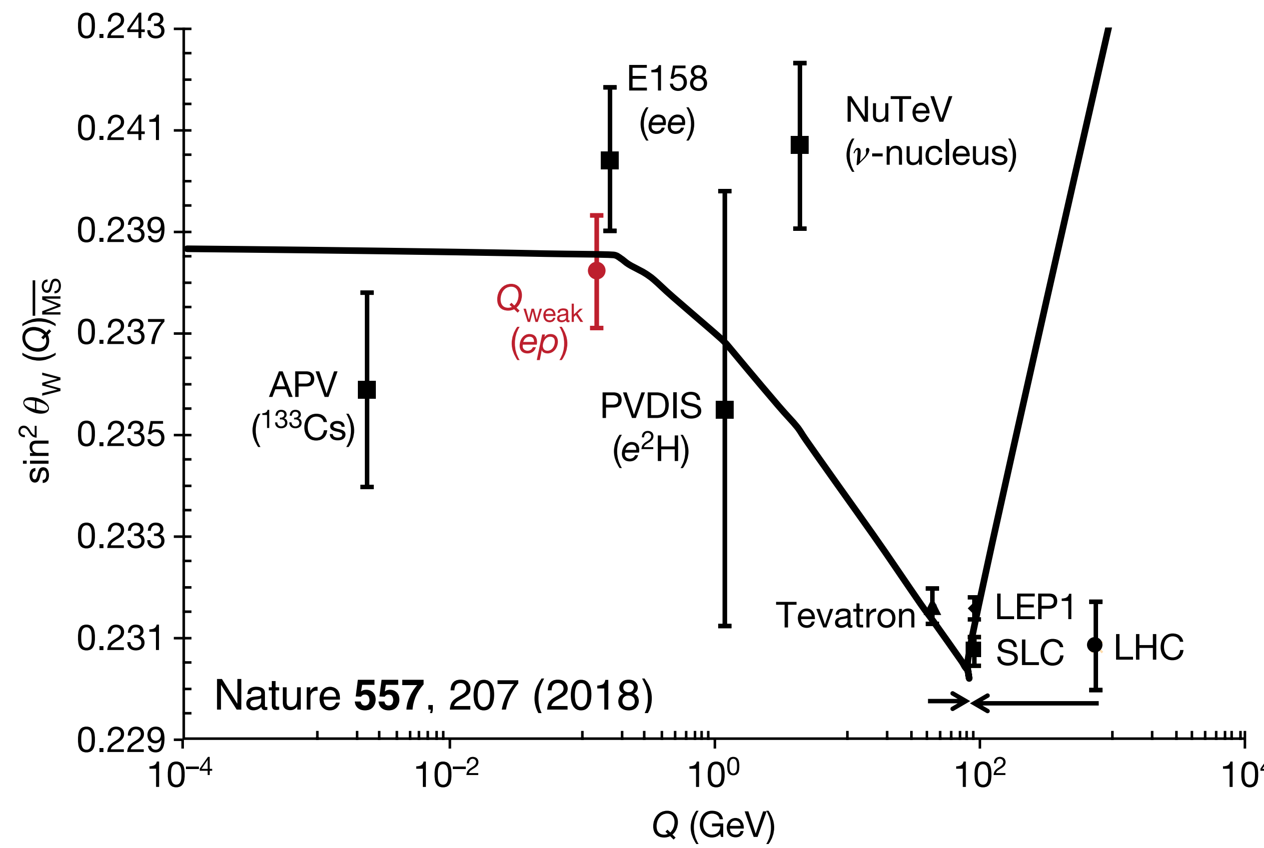
- 2p-1s lines used to extract charge radius
- Hyperfine structure (+low-lying nuclear levels) clearly seen and more resolved than for 5g-4f transitions
- Work in progress…



The muX experiment:
Radioactive isotopes

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

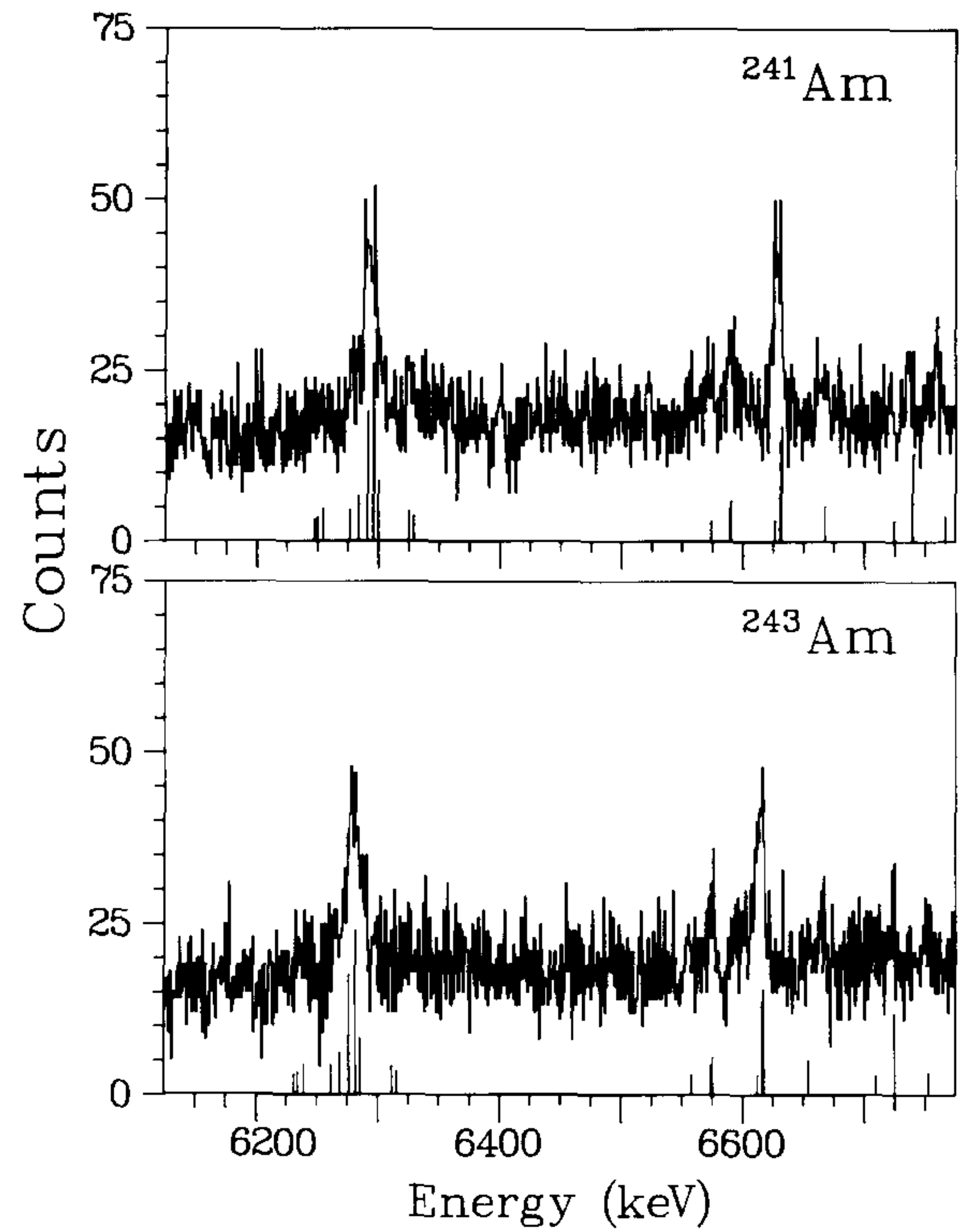


⇨ Atomic parity violation fixes weak interaction properties at low momentum

What about radioactive atoms?

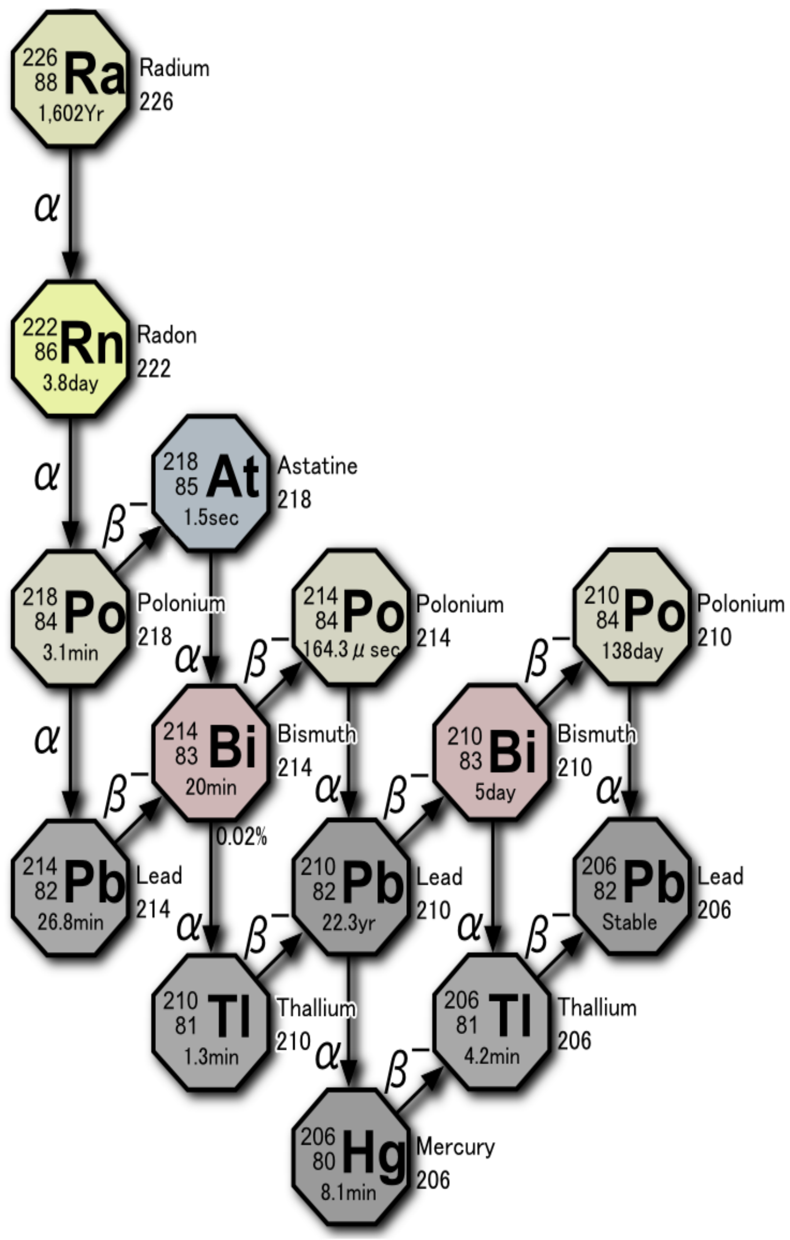
- All stable isotopes (except rhenium) have been measured with muonic atom spectroscopy
- In a few special cases also radioactive isotopes, e.g. americium
  - The paper describes the americium target as “modest weight of 1 gram”
- Nowadays: 0.2 μg of open ^{241}Am allowed in experimental hall…

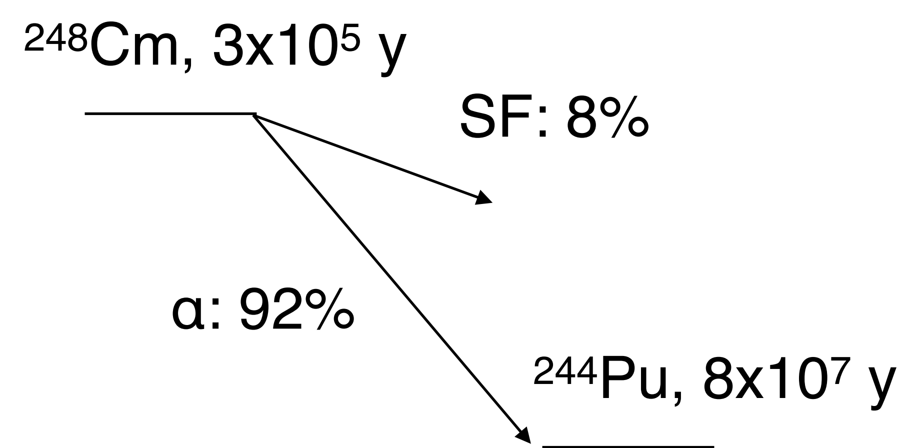
Johnson et al., Phys. Lett. **161B**, 75 (1985)



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

Our radioactive targets





Around 3 neutrons per SF emitted

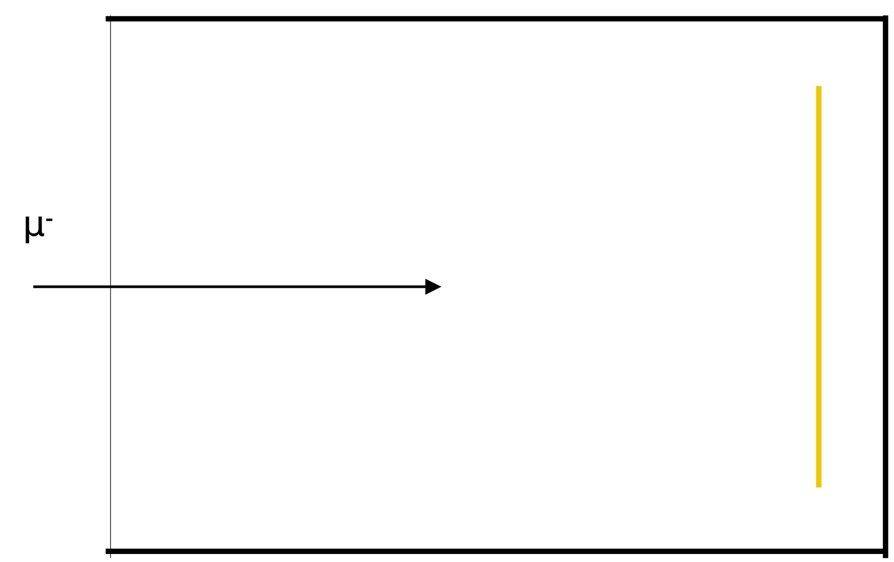
Vorobyev et al., AIP Conf. Proc. **798**, 255 (2005)

- 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.

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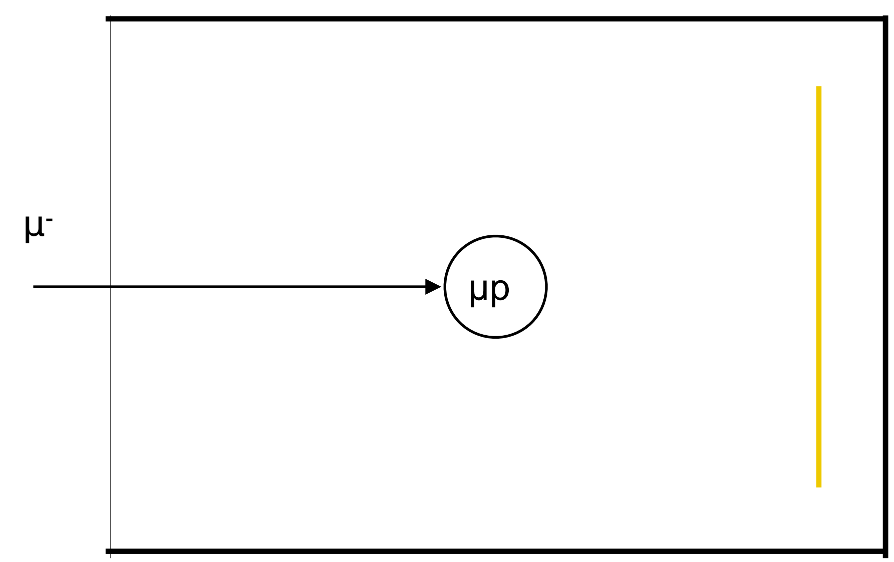

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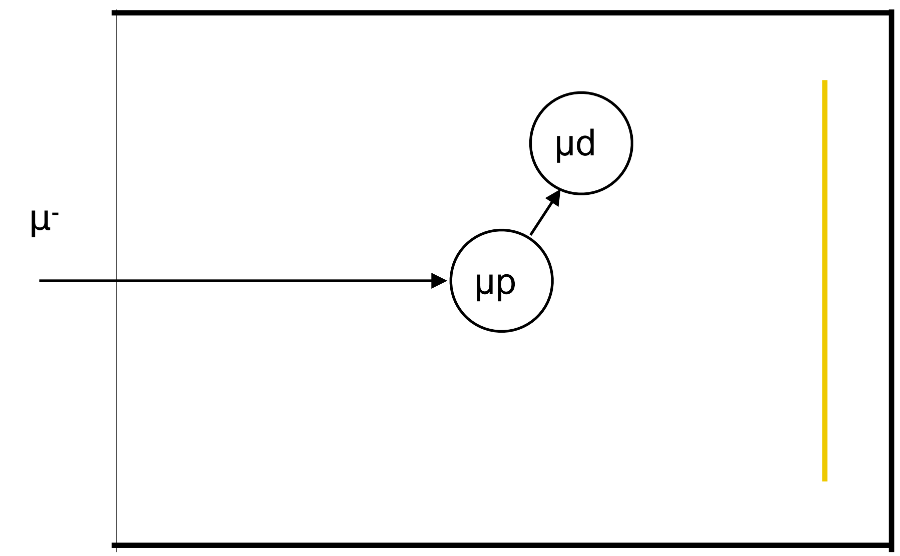

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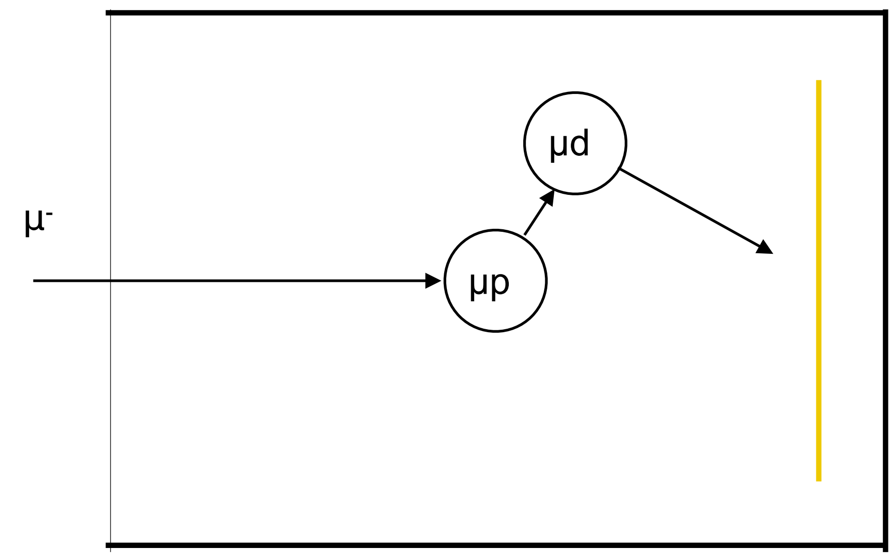

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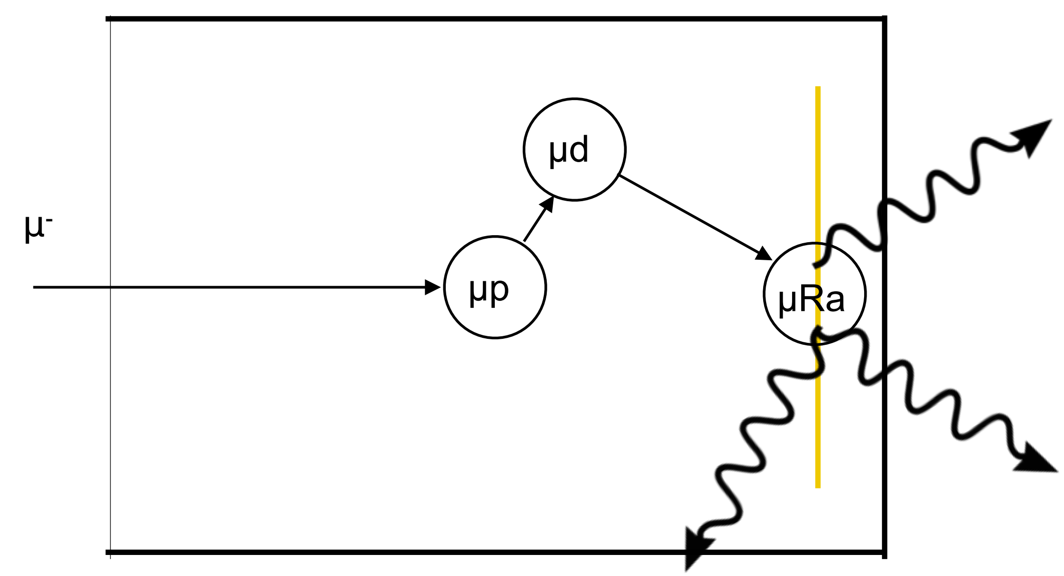
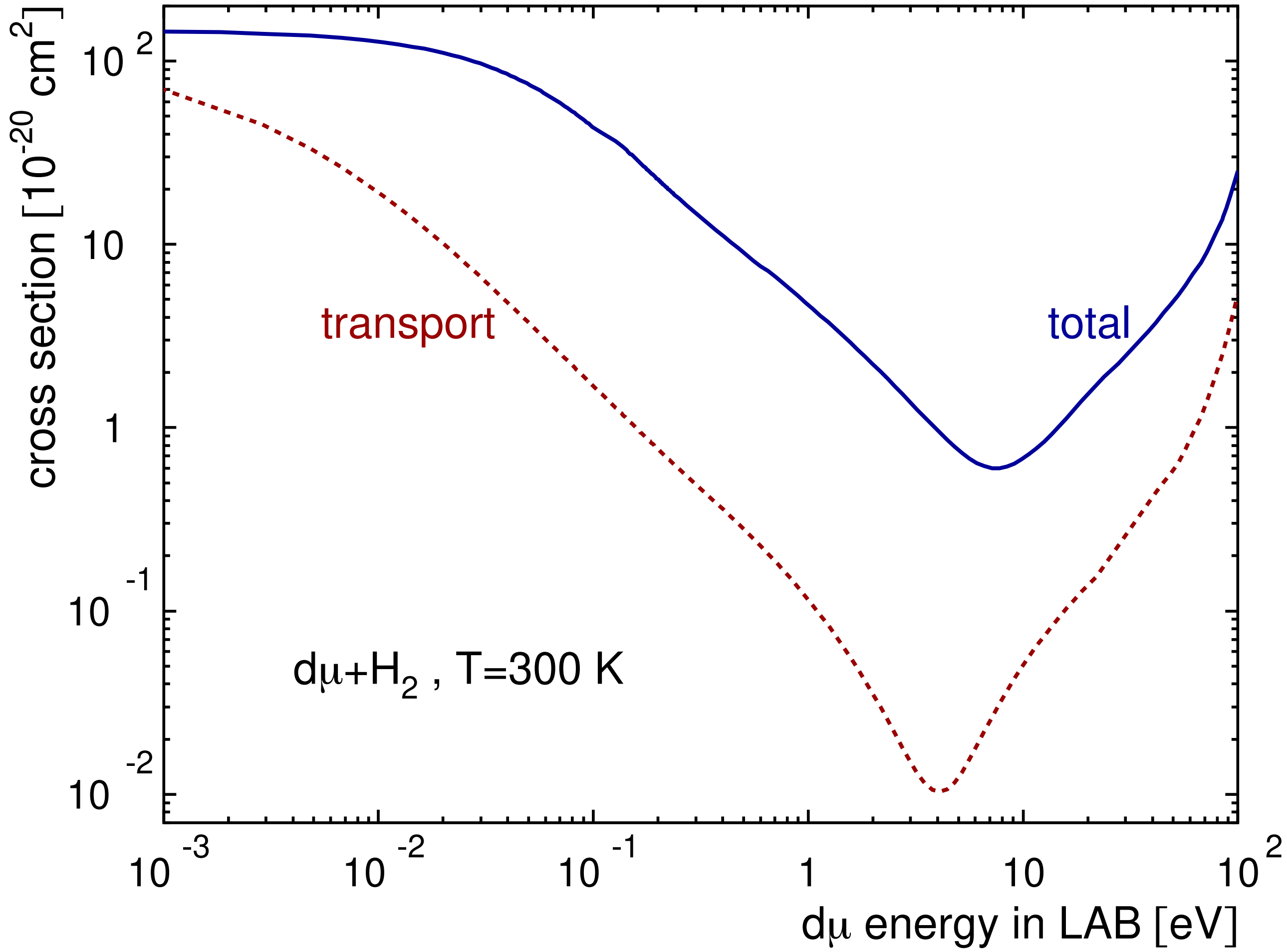


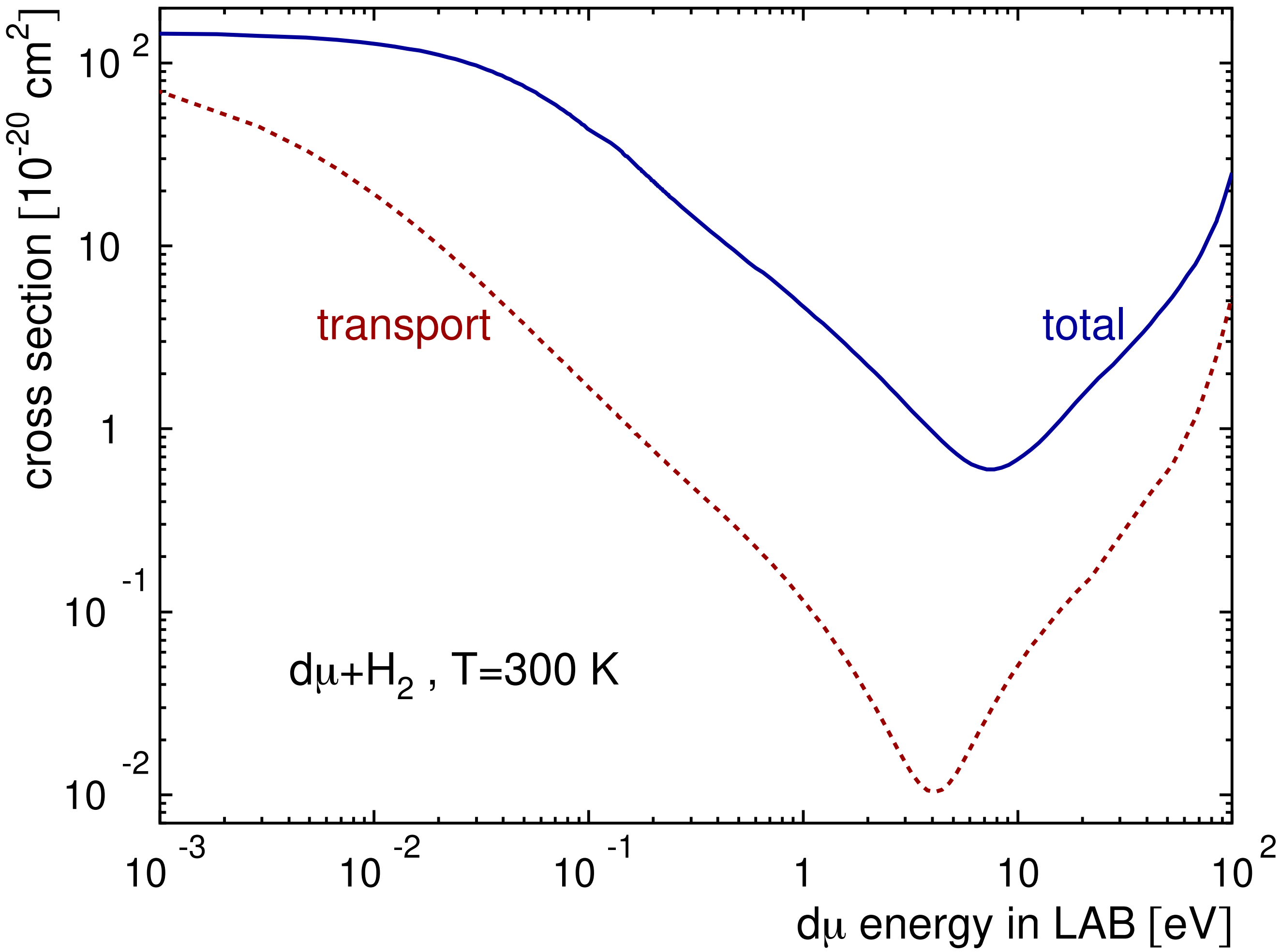
Inspired by work of Strasser et al. and Kraiman et al.

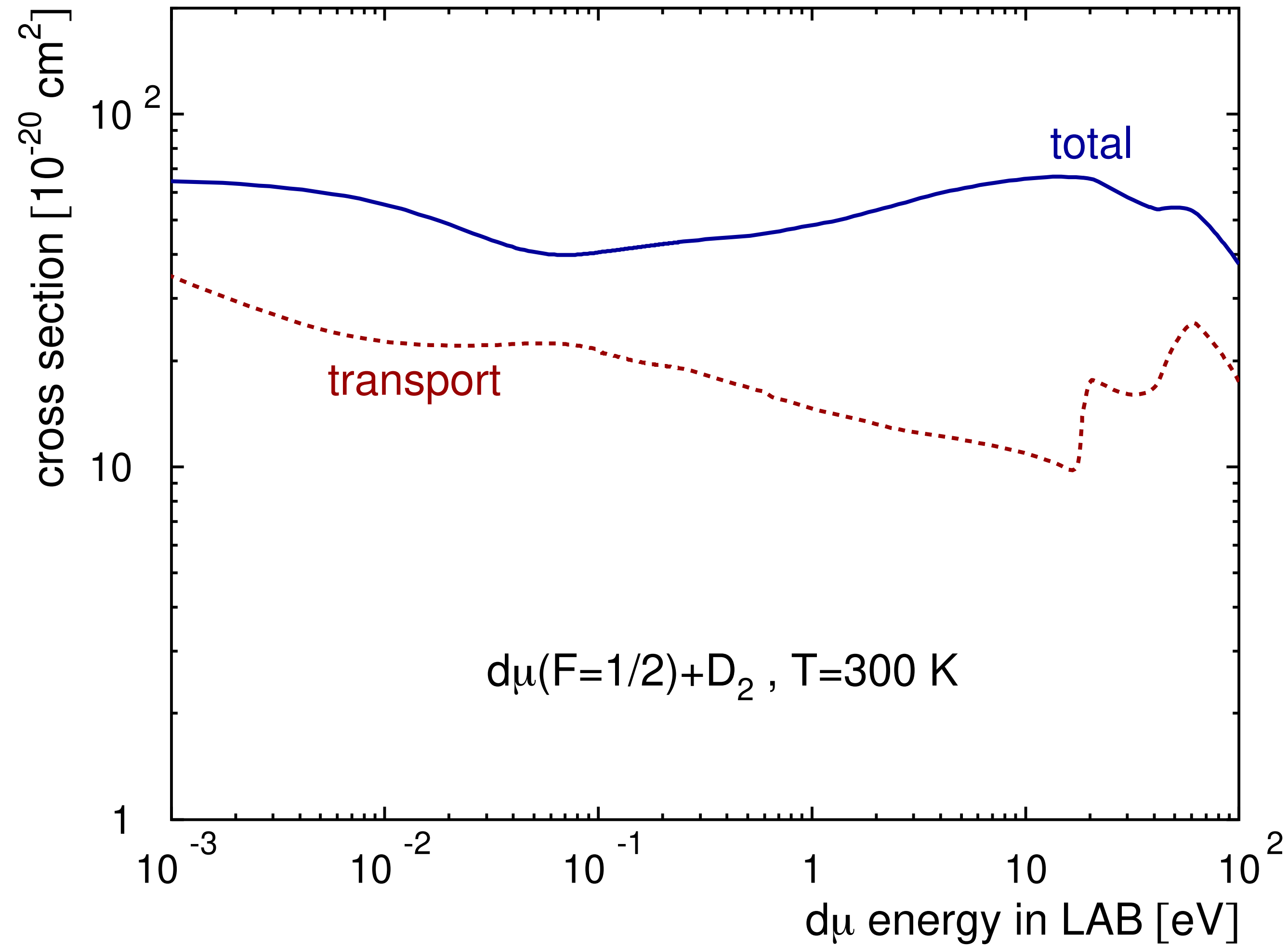
Ramsauer-Townsend effect



- 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

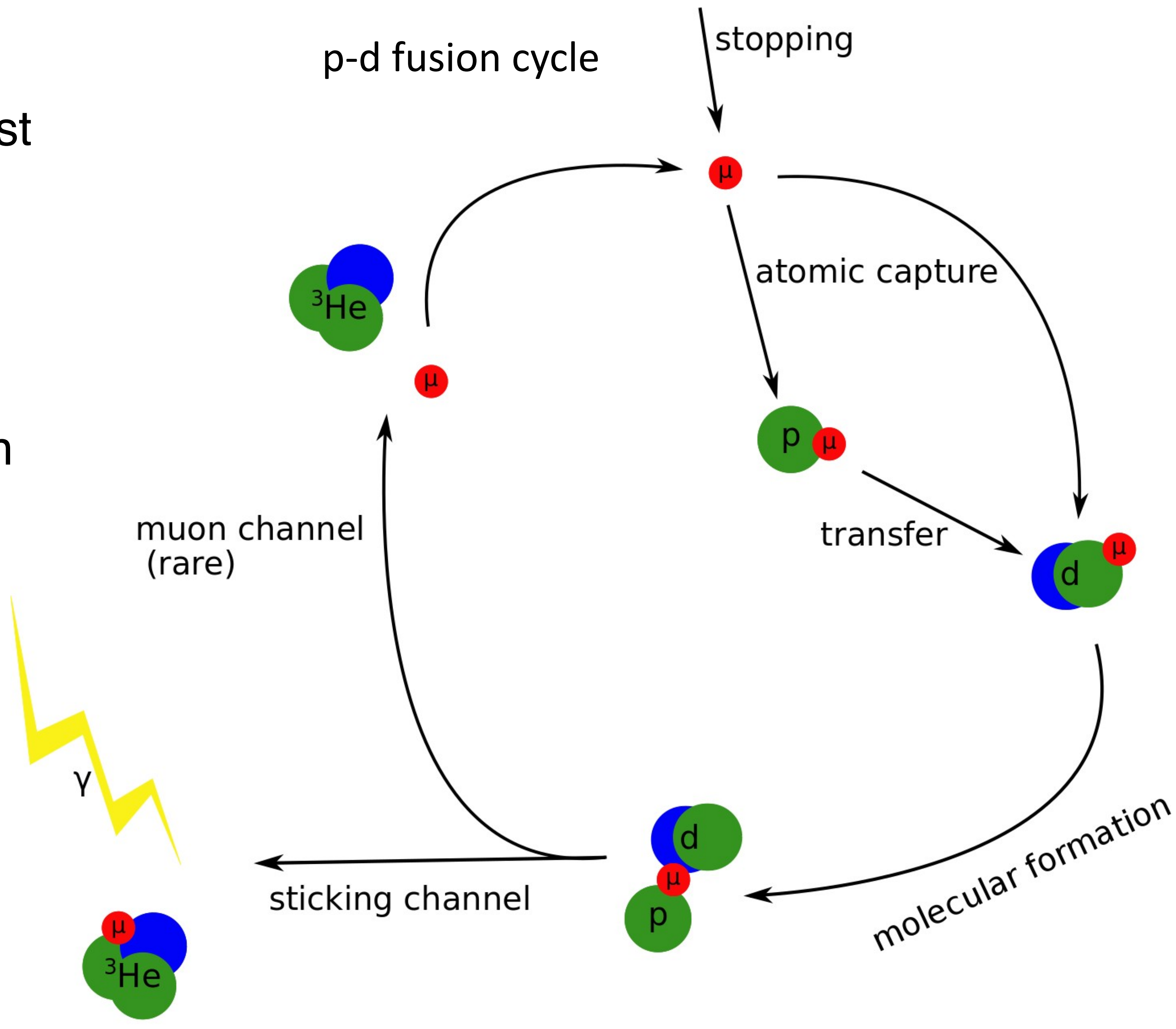




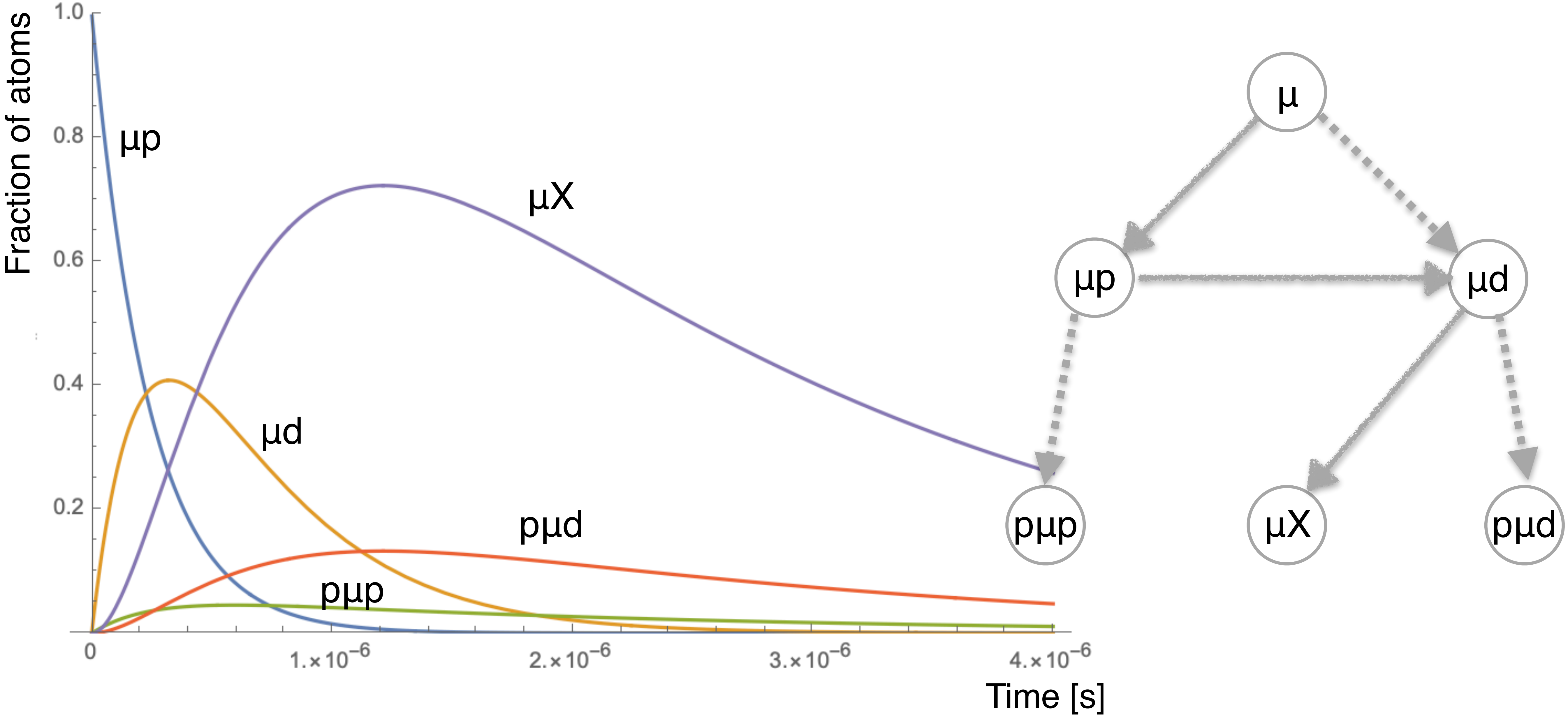
- Scattering on deuterium does not show a Ramsauer-Townsend minimum
- Need to be careful to not have too much deuterium in the gas mixture

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

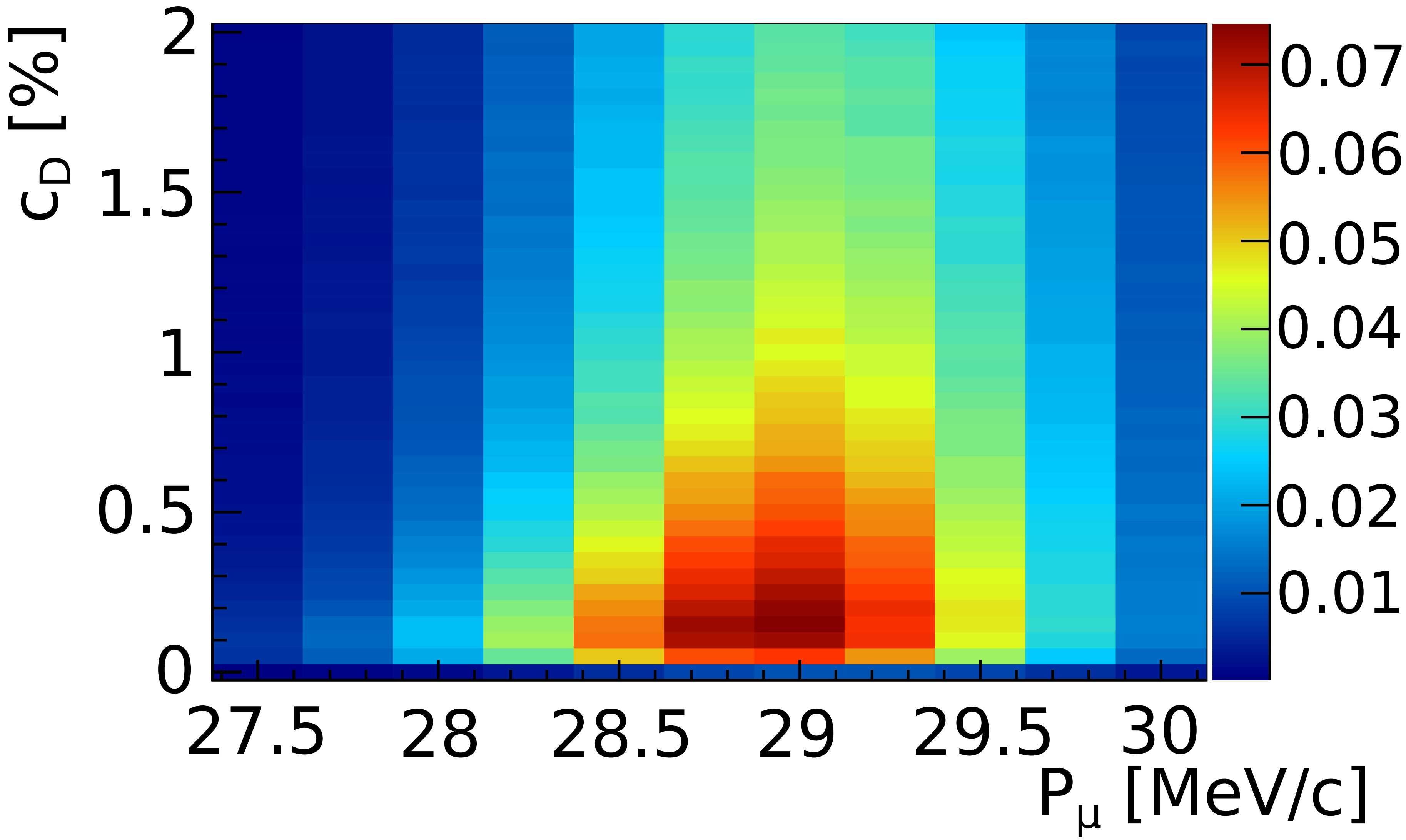


Processes in gas cell



- 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 into account

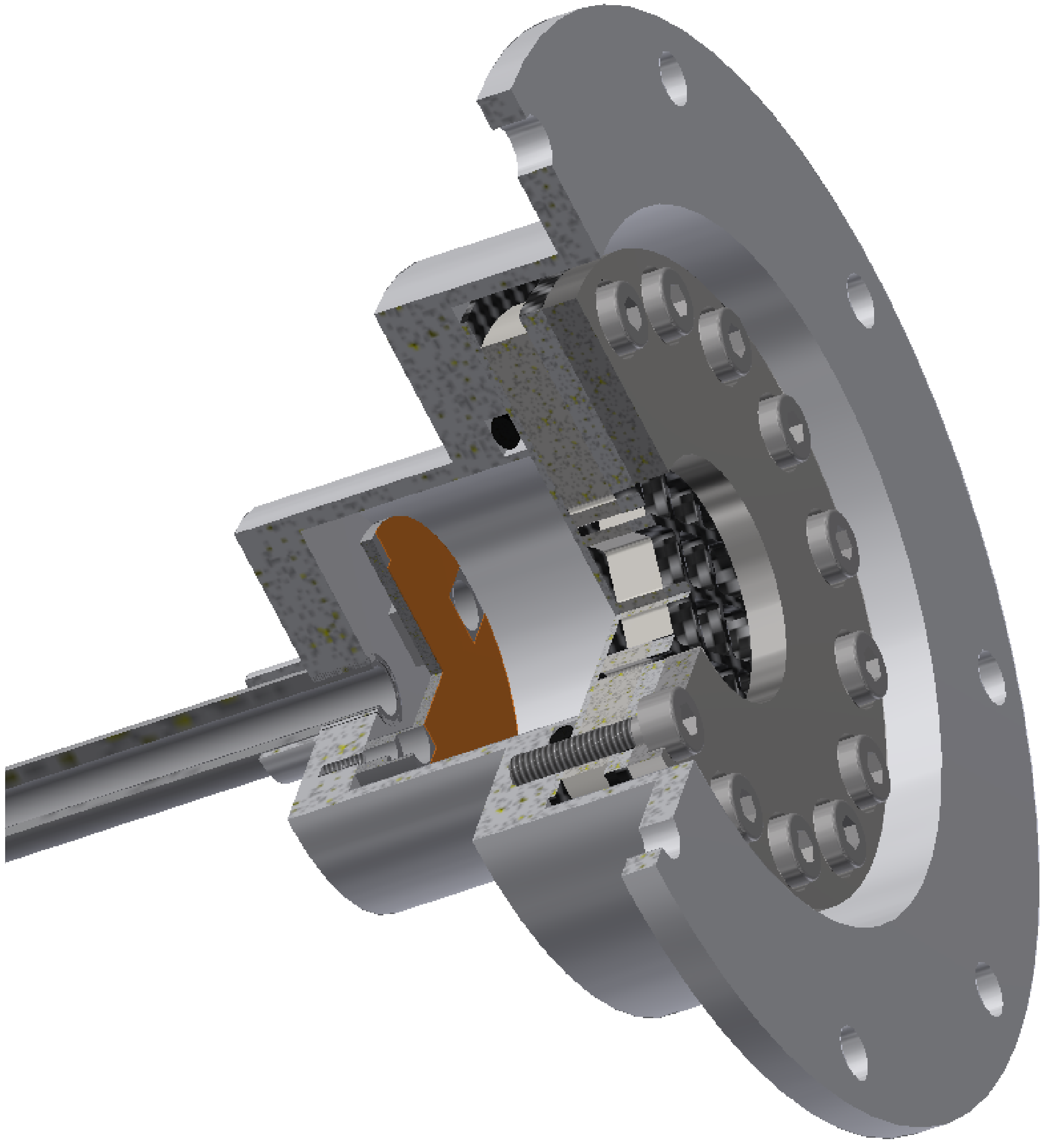
Simulation of transfer

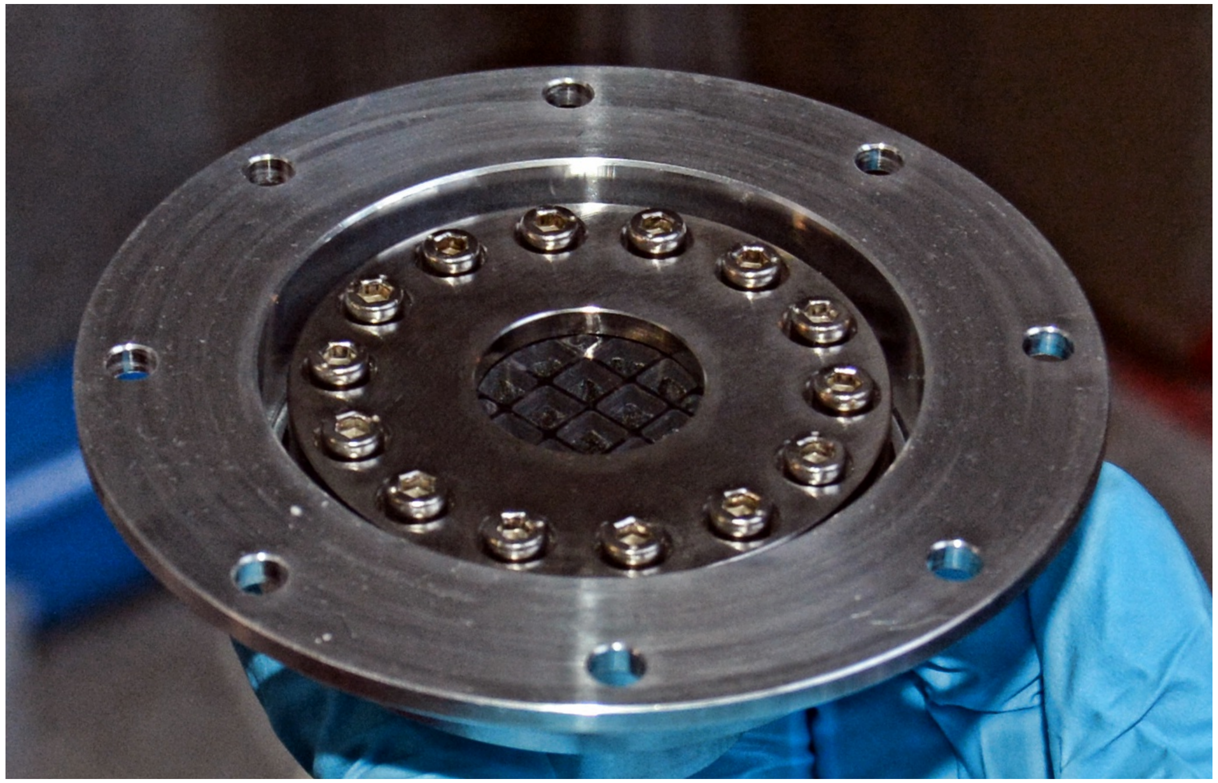


- Developed simulation to predict efficiency of transfer
- Momentum of beam determines stopping distribution with respect to the target
- Deuterium concentration determines speed of transfer but limits range due to $\mu d + D_2$ scattering

100 bar hydrogen target

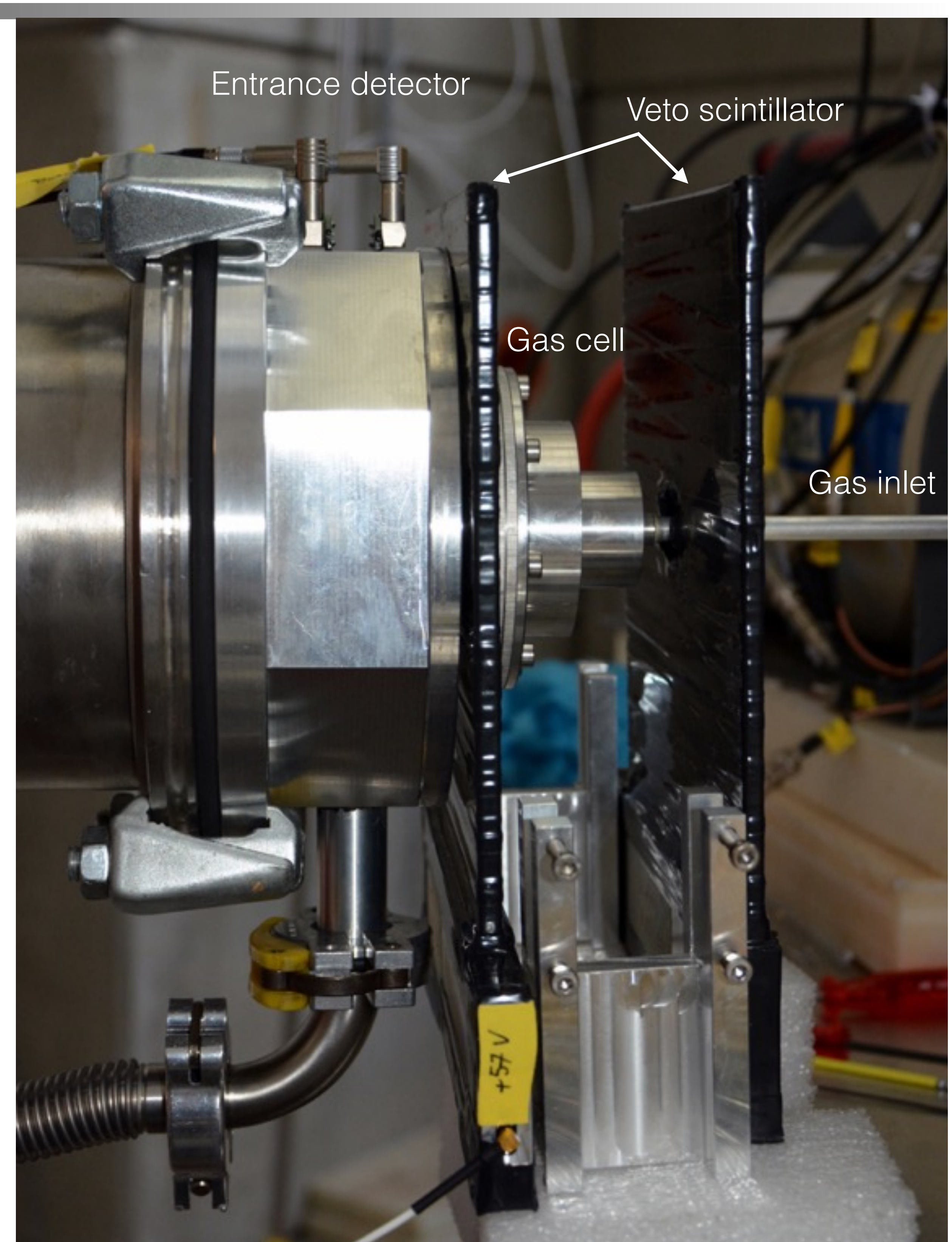
- Target sealed with 0.6 mm carbon fibre window plus carbon fibre/titanium support grid
- Target holds up to 350 bar
- 10 mm stopping distribution (FWHM) inside 15 mm gas volume
- Target disks mounted onto the back of the cell





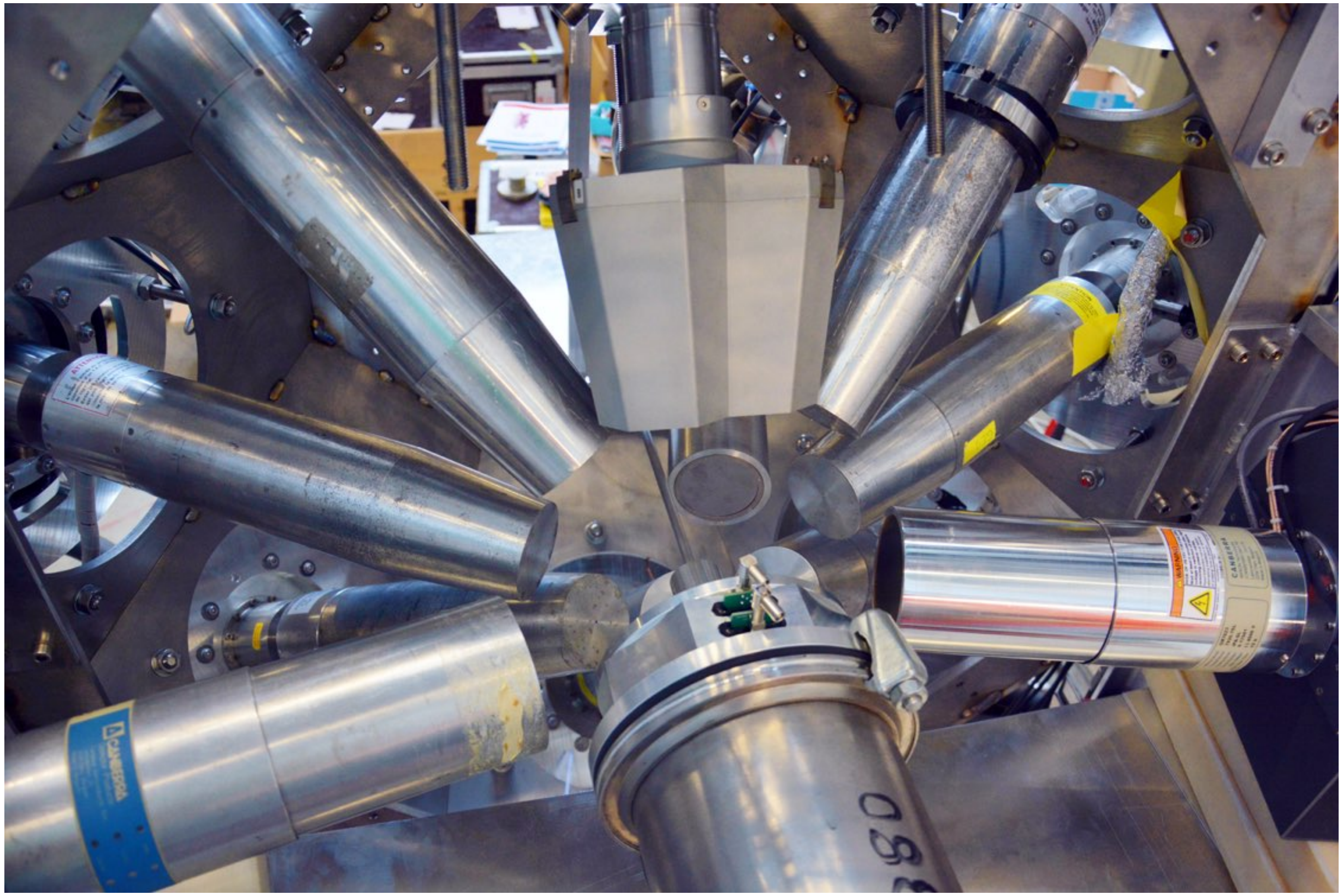
Entrance & veto detectors

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

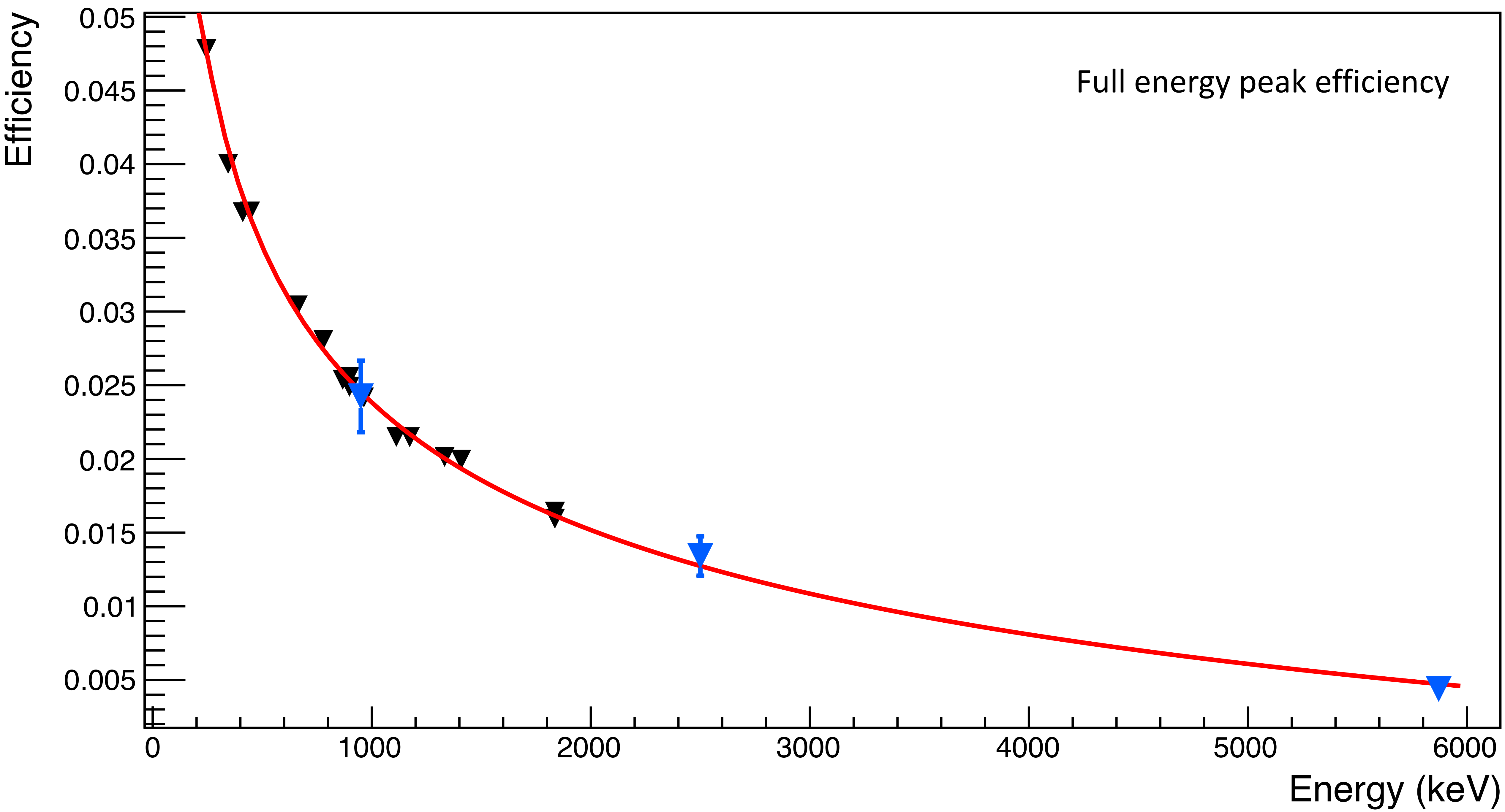


Germanium array

- 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

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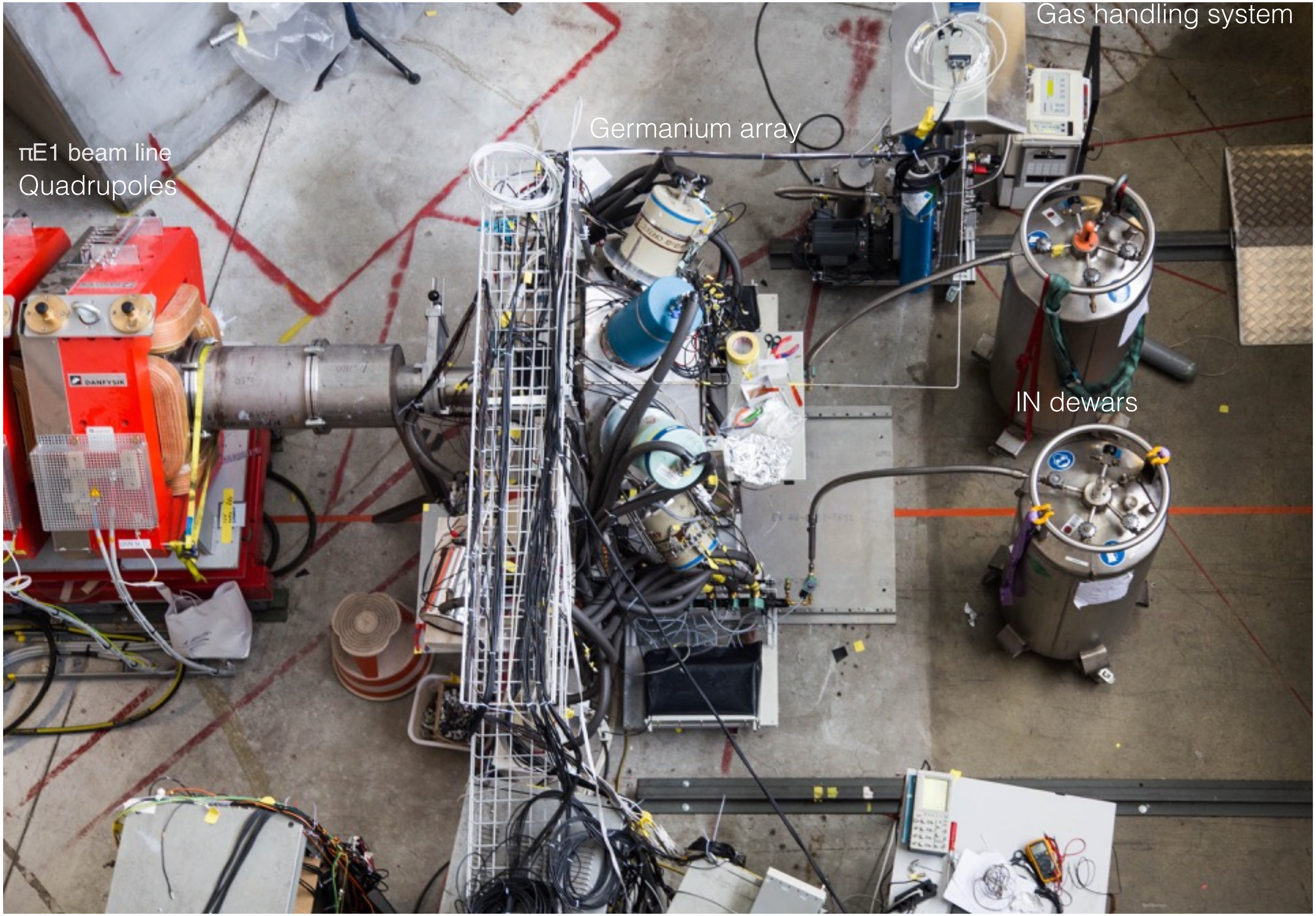
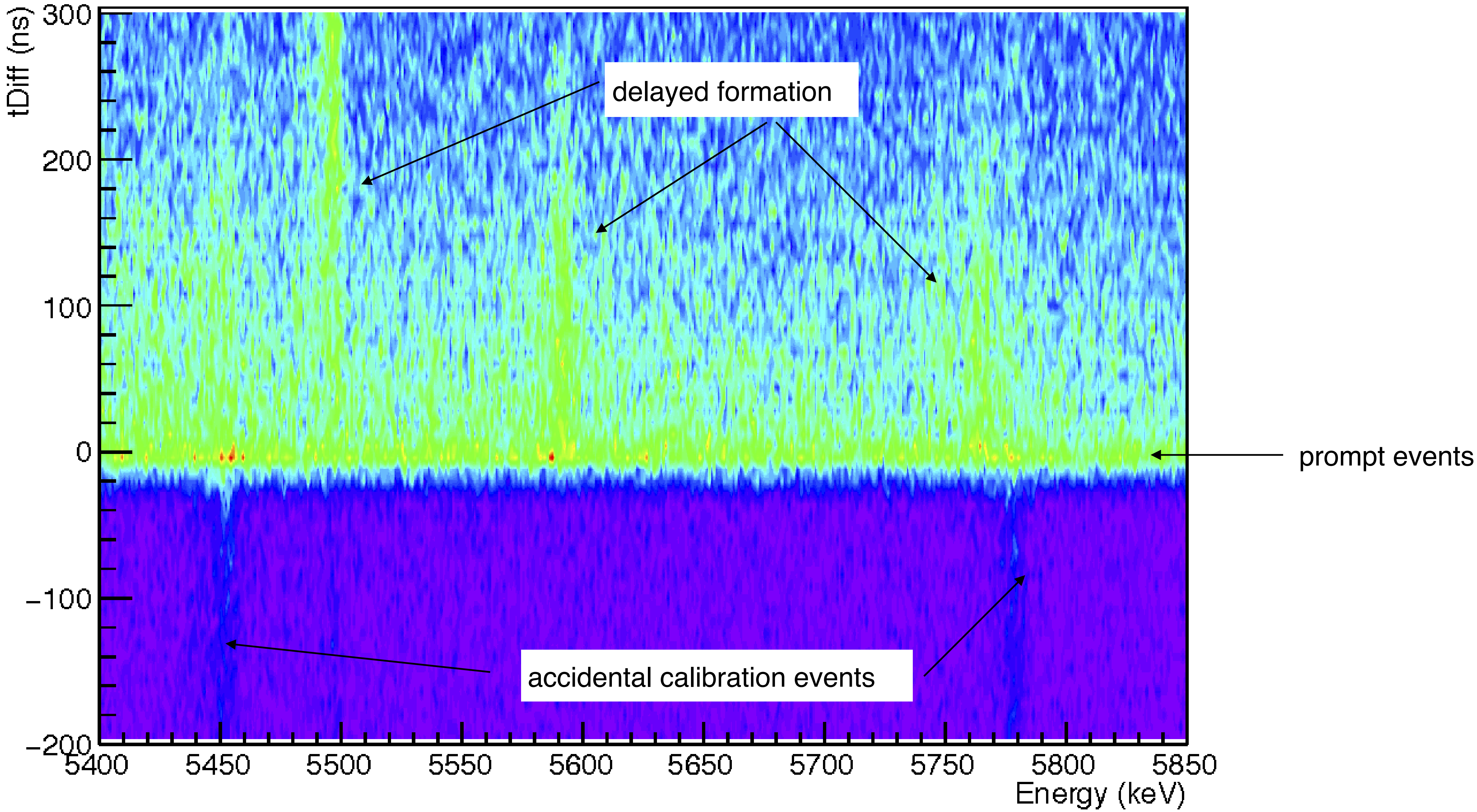


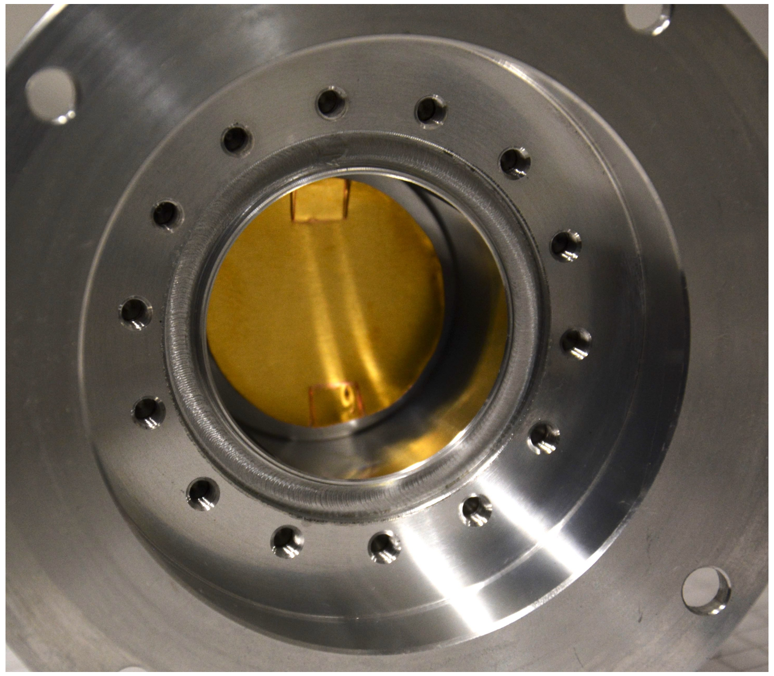
Test of transfer reactions with gold and uranium targets

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

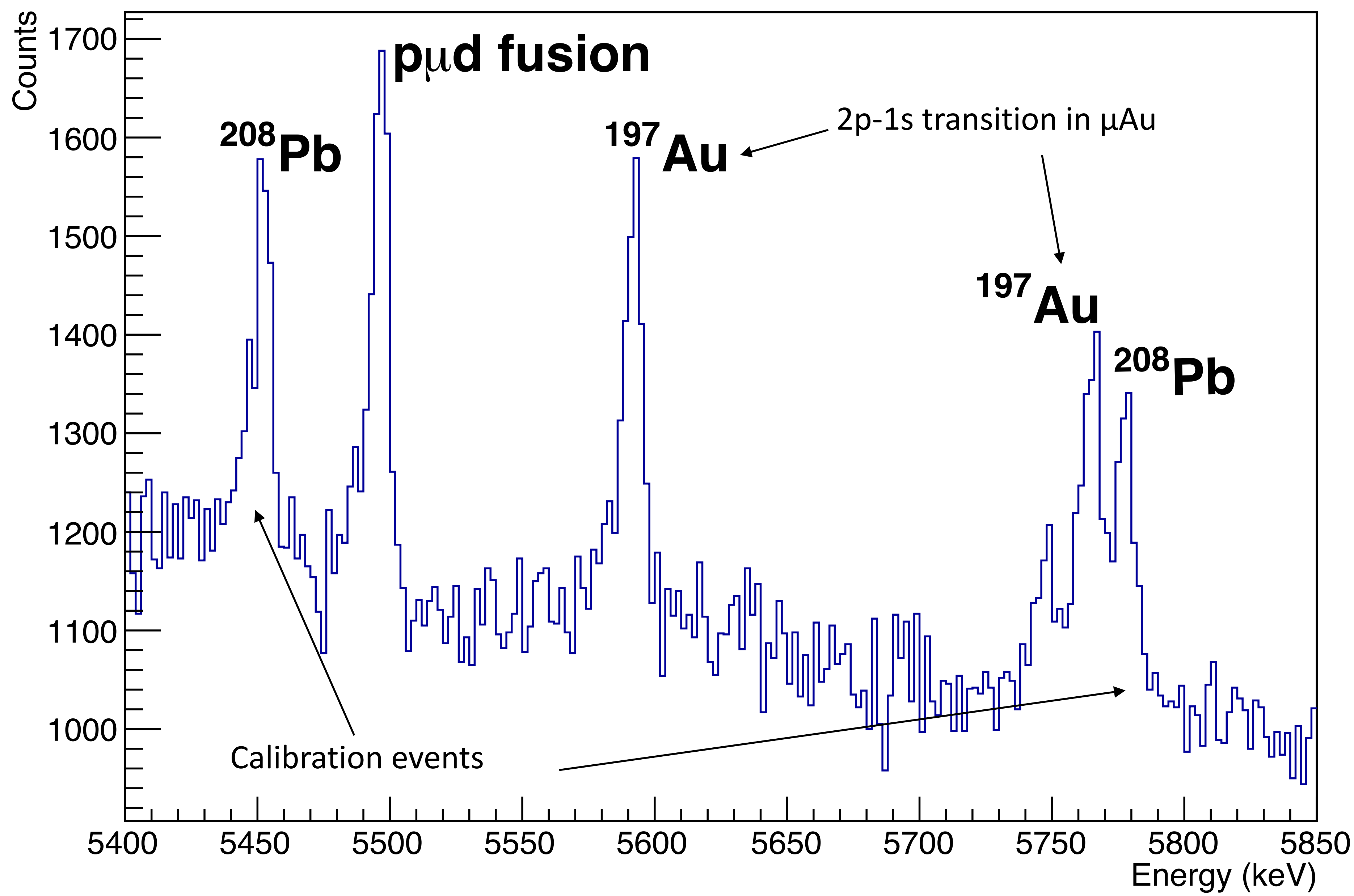
Understanding target conditions



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%

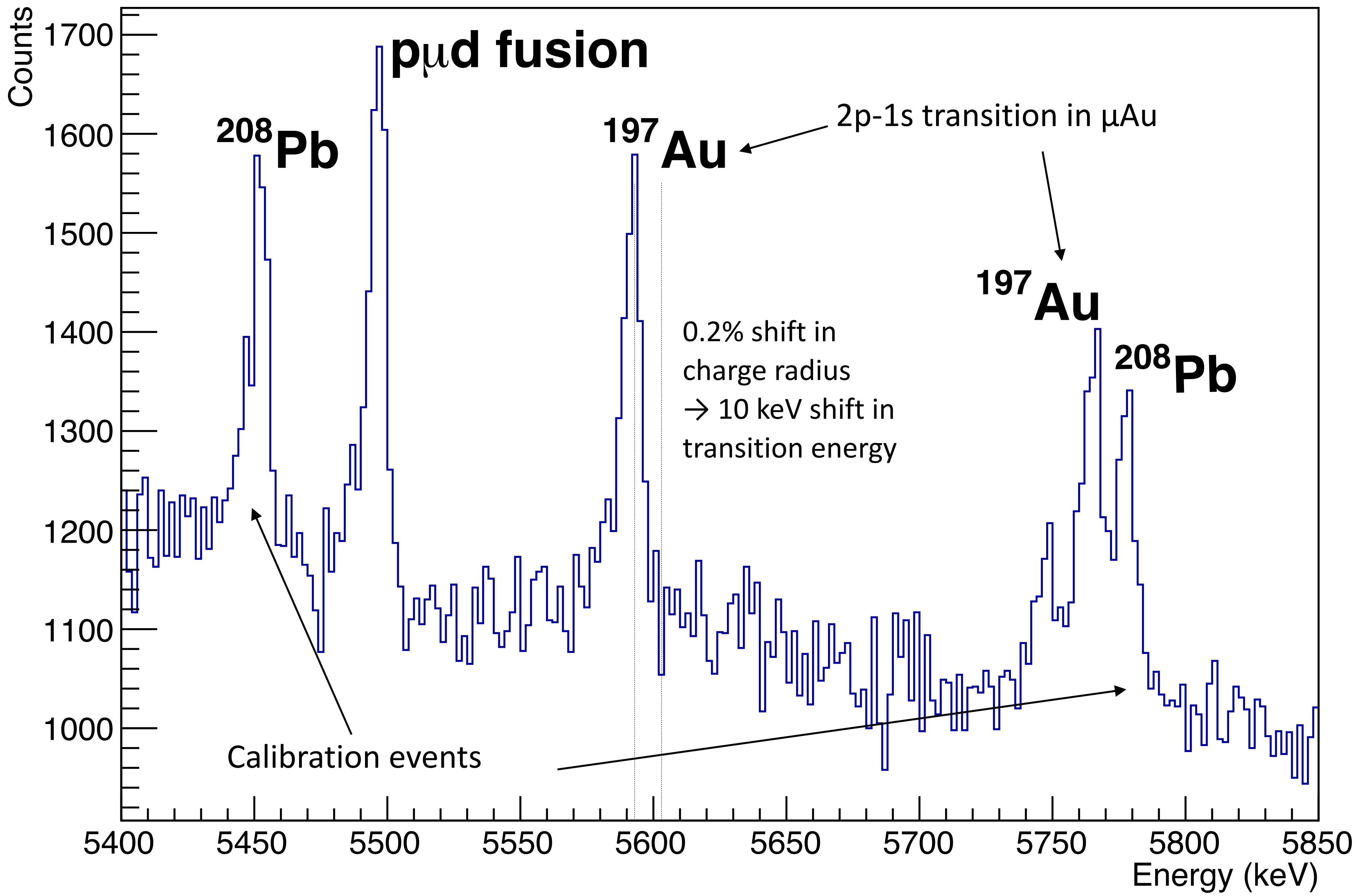
- Detected 2p-1s gammas per incoming muon for various targets
- Not all µd converted in thin targets
- Impact of backing material small
- Can still reliably see gammas from 5 µg gold target (1 cm^2, 3 nm)

Measurement with microgram gold target



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

Measurement with microgram gold target



- Measurement with 5 μg gold target as proof-of-principle
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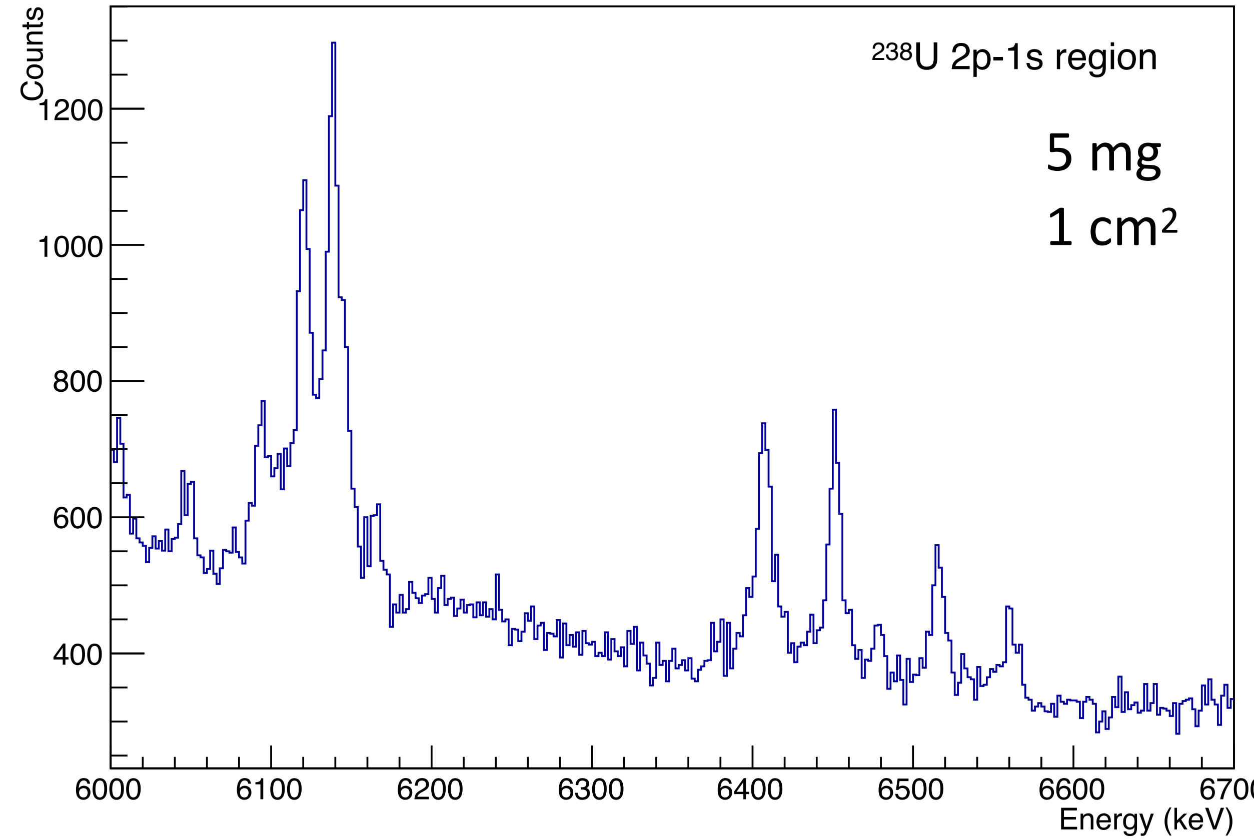
Measurement with uranium

- 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



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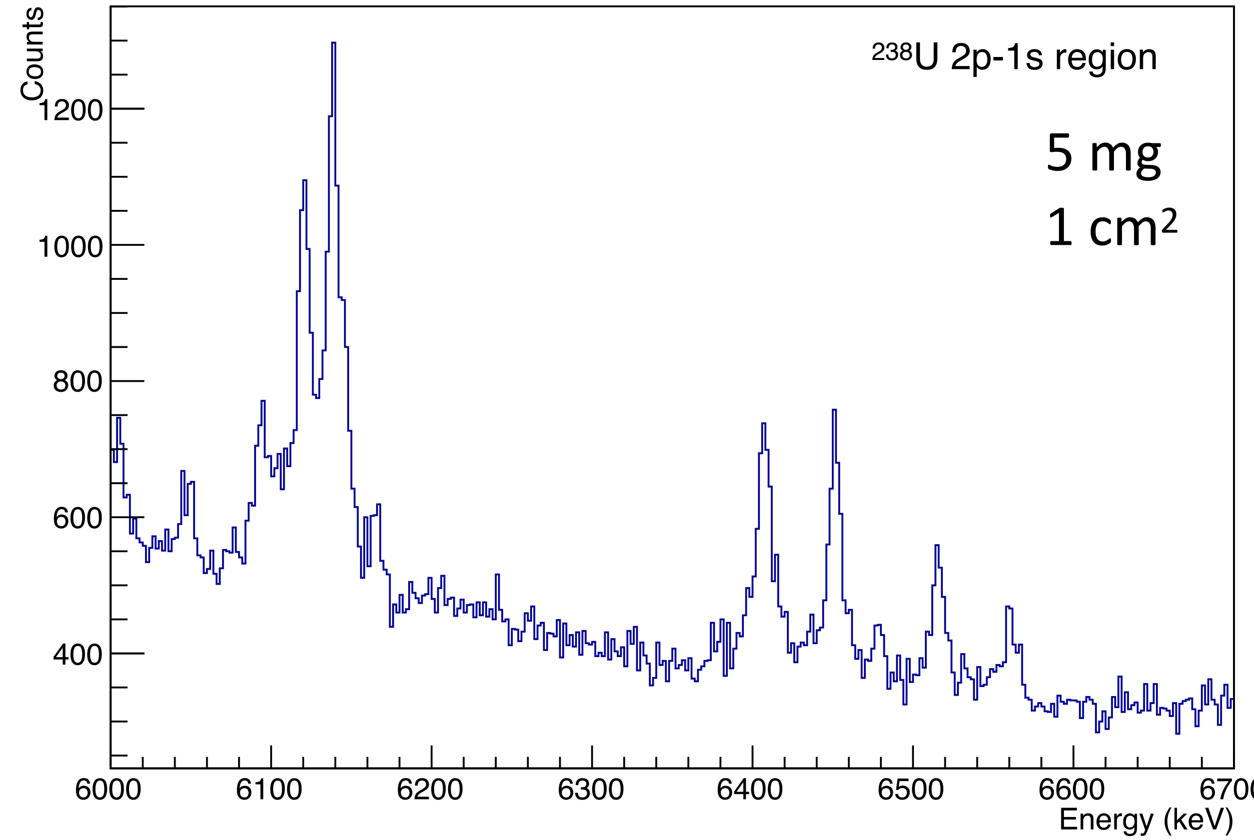
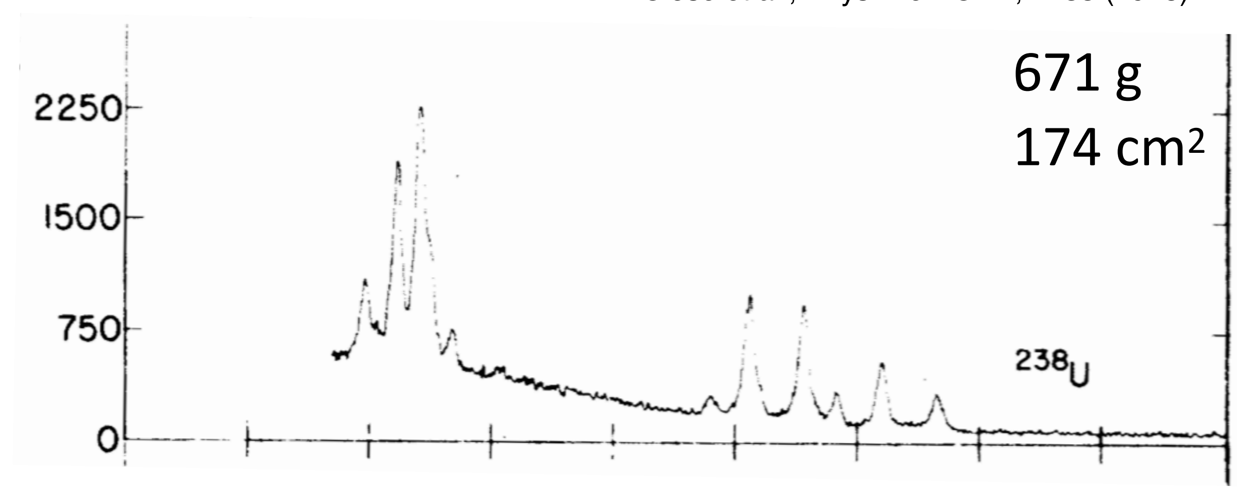


Close et al., Phys. Rev. C **17**, 1433 (1978)



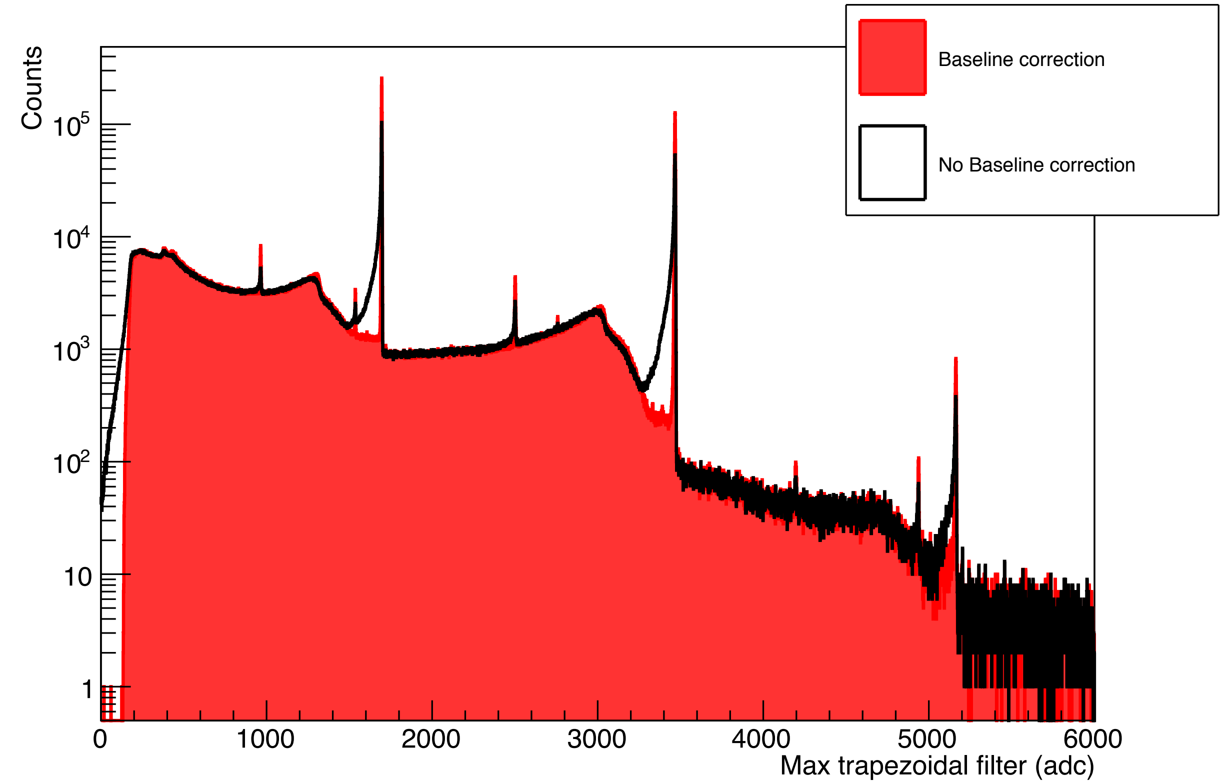
⇨ Similar performance as in the past but a factor 10^5 less target material

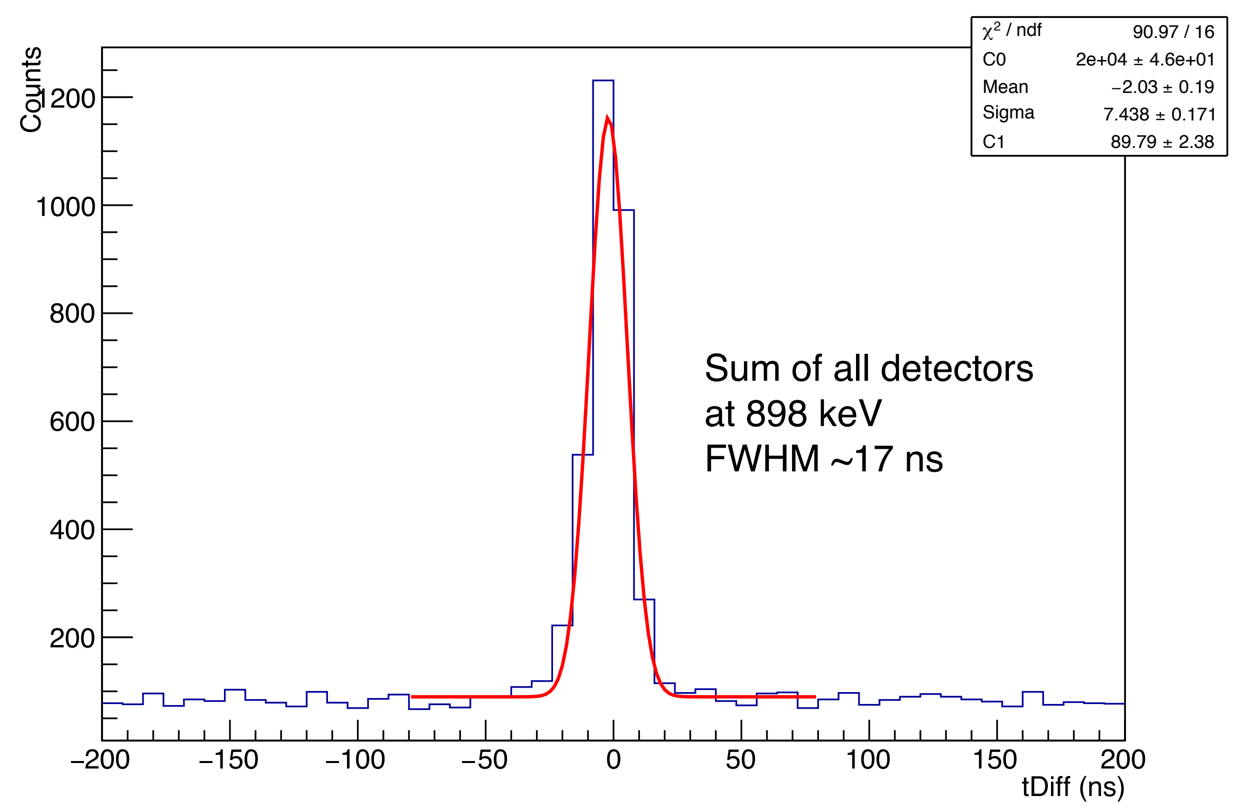
Measurement with high rates

- 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

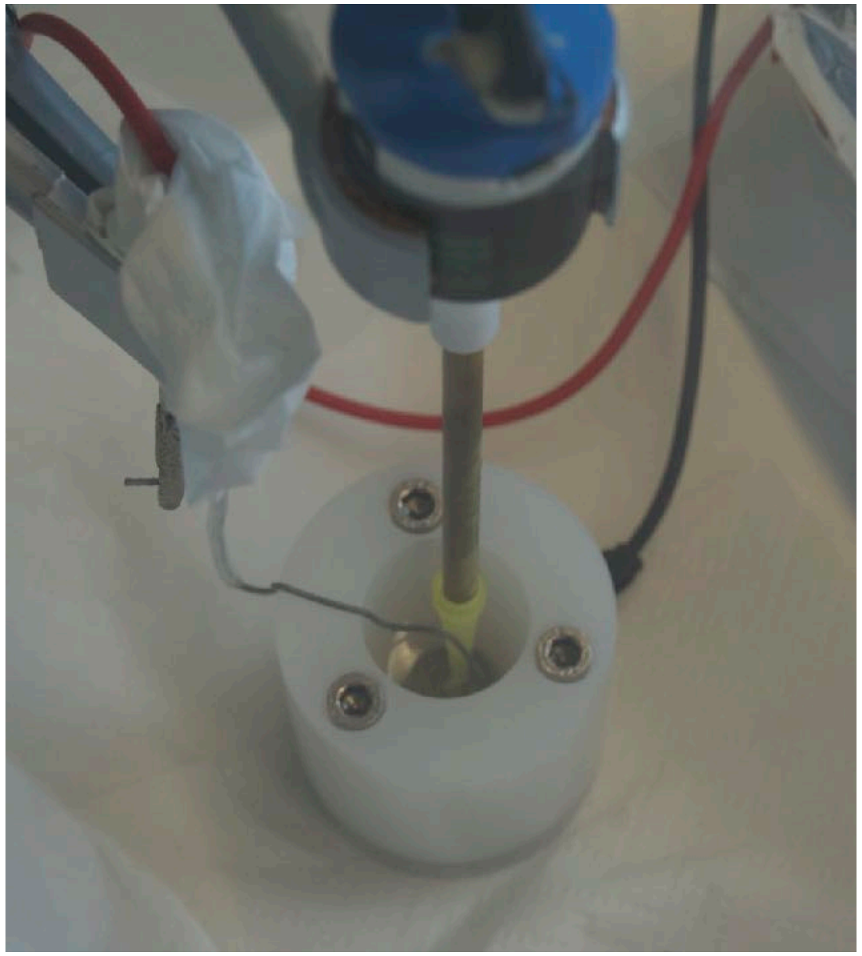


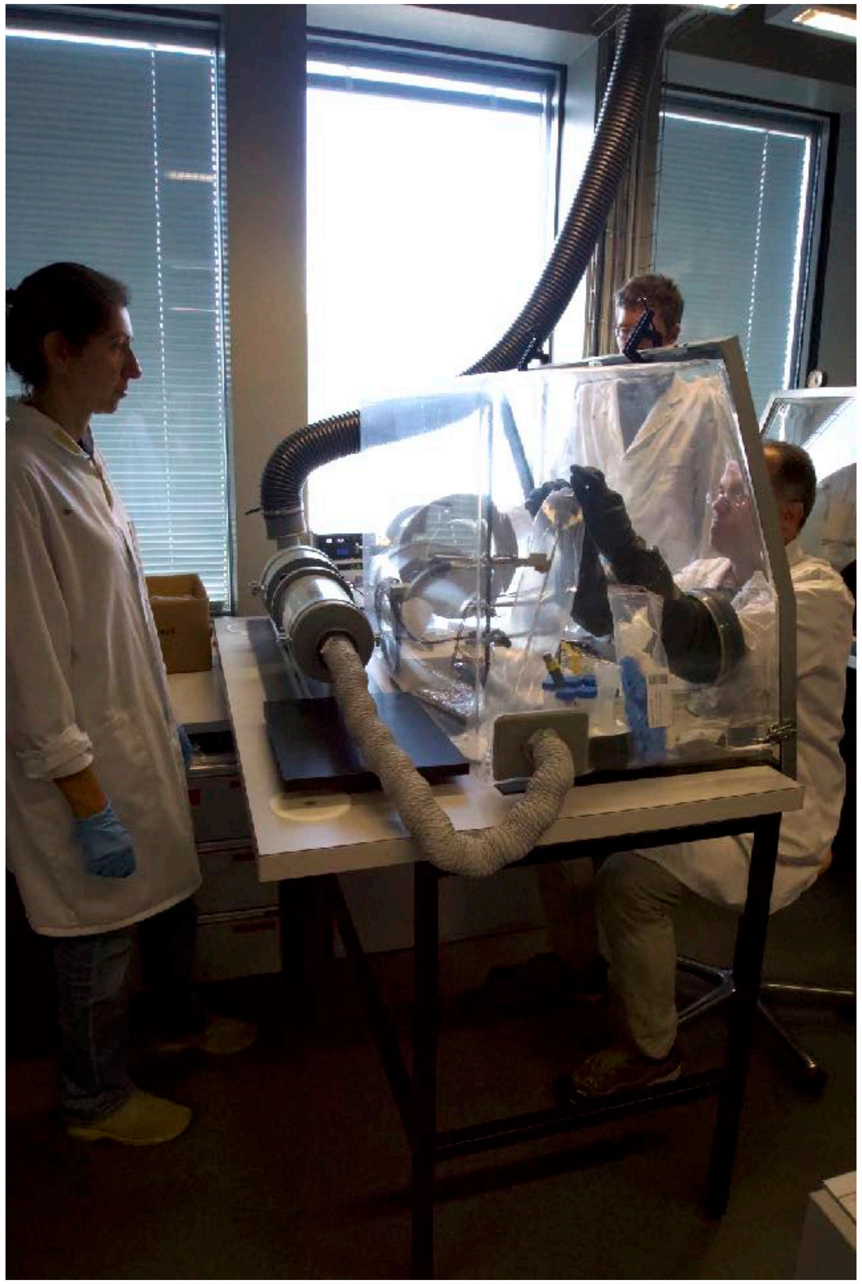


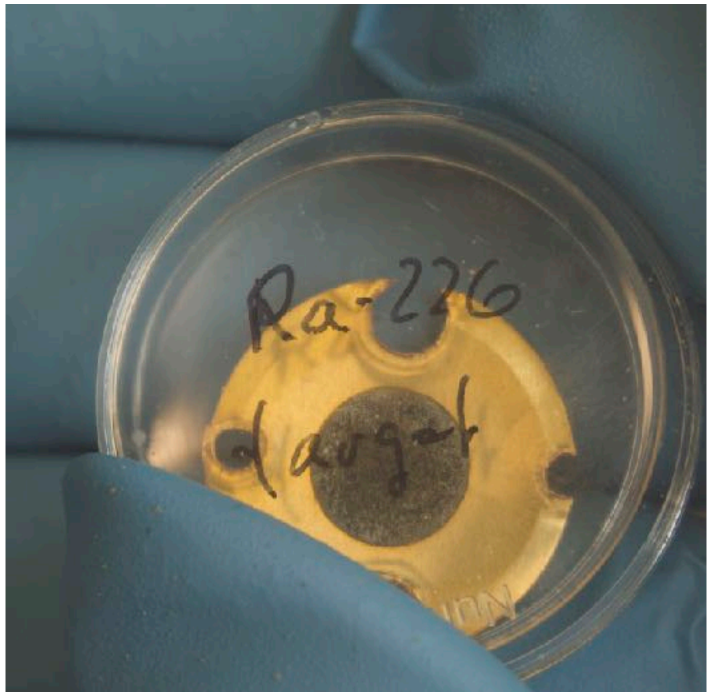
⇨ Experiment is ready for measurements with radioactive targets!

Towards ^{226}Ra and ^{248}Cm measurements

Making radium target

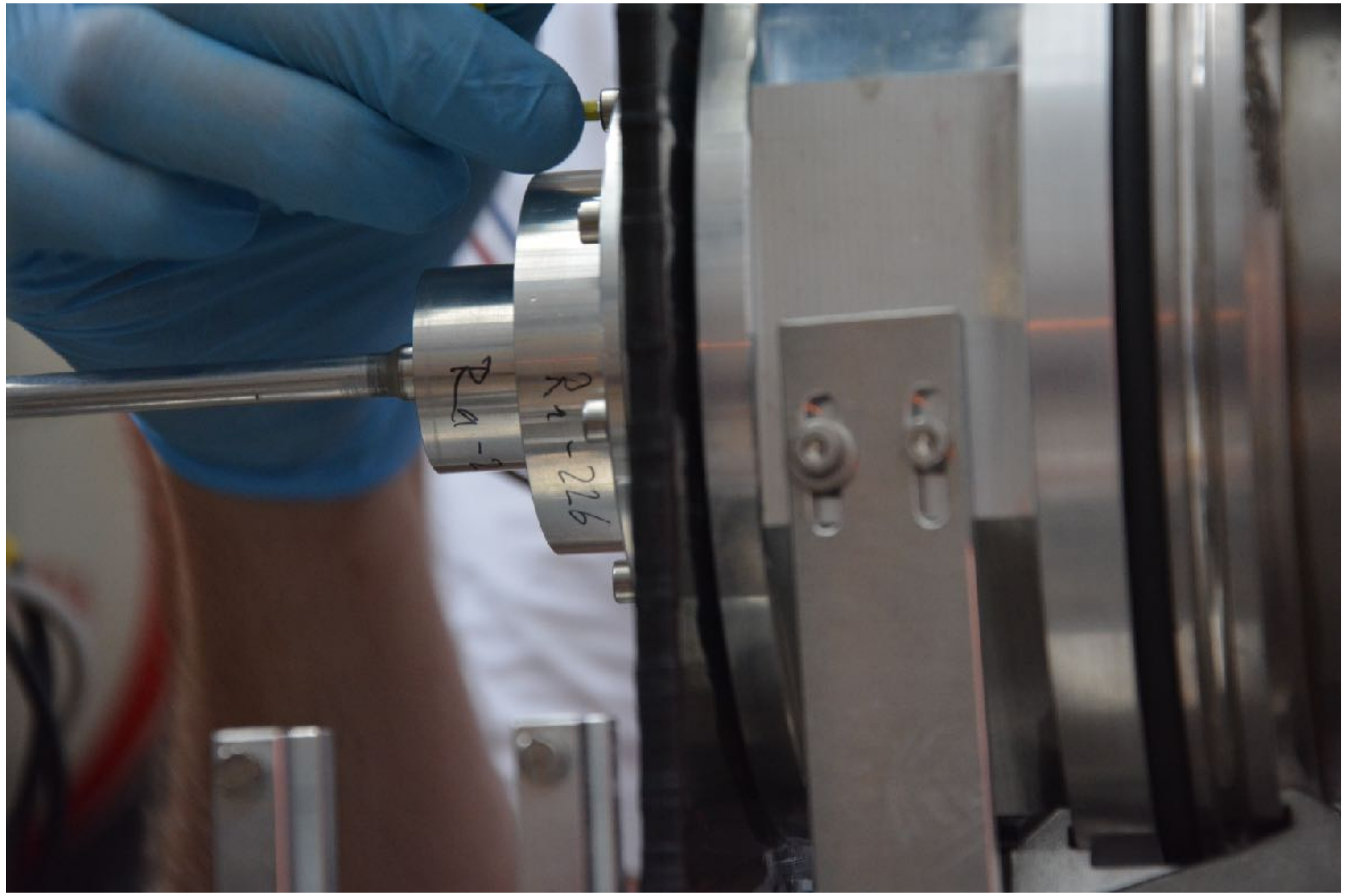






- Attempted a measurement of ^{226}Ra and ^{248}Cm in 2018
- Electroplating the ^{226}Ra out of the isopropanol solution onto gold plated copper foil

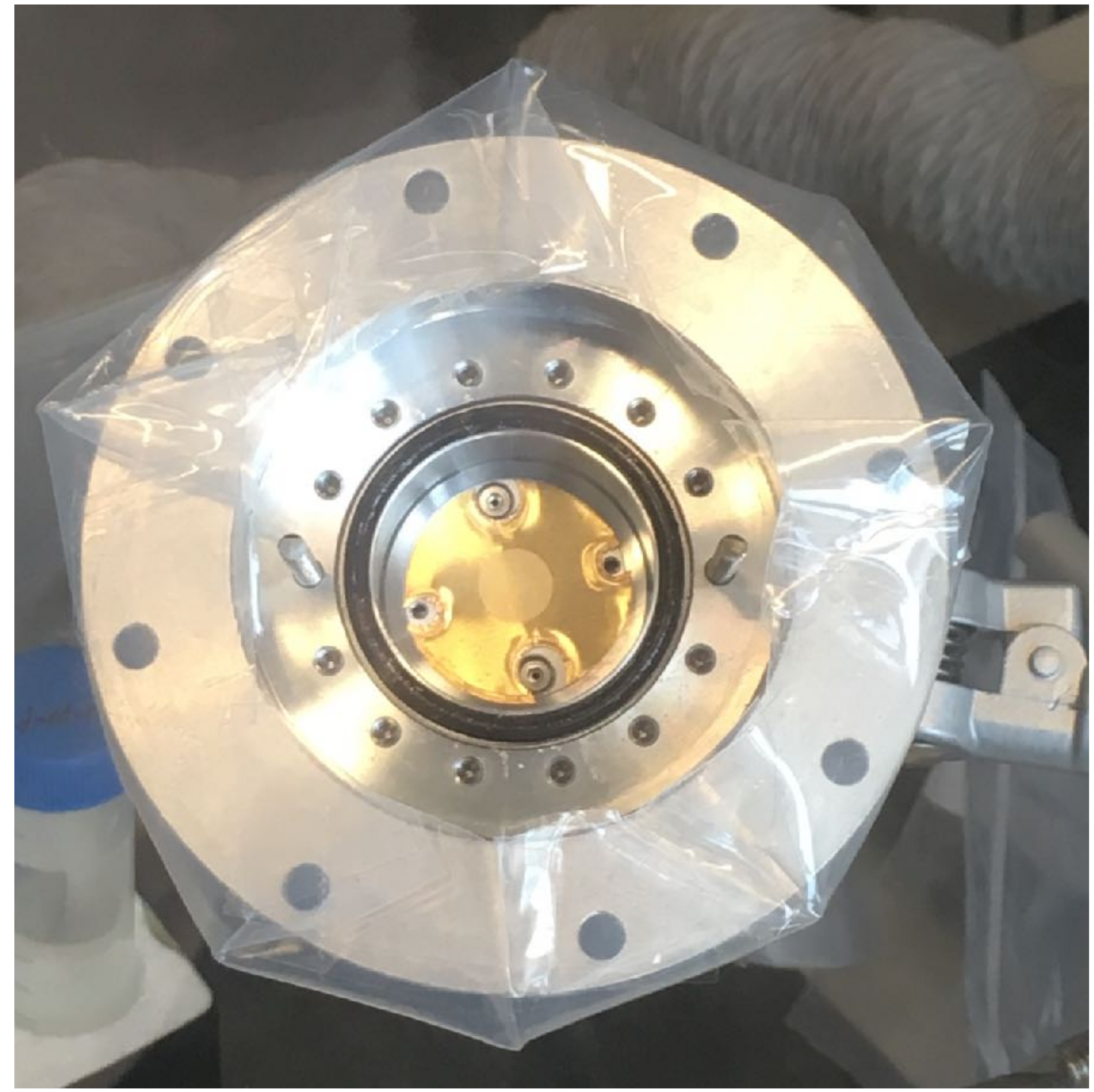
Measuring radium target



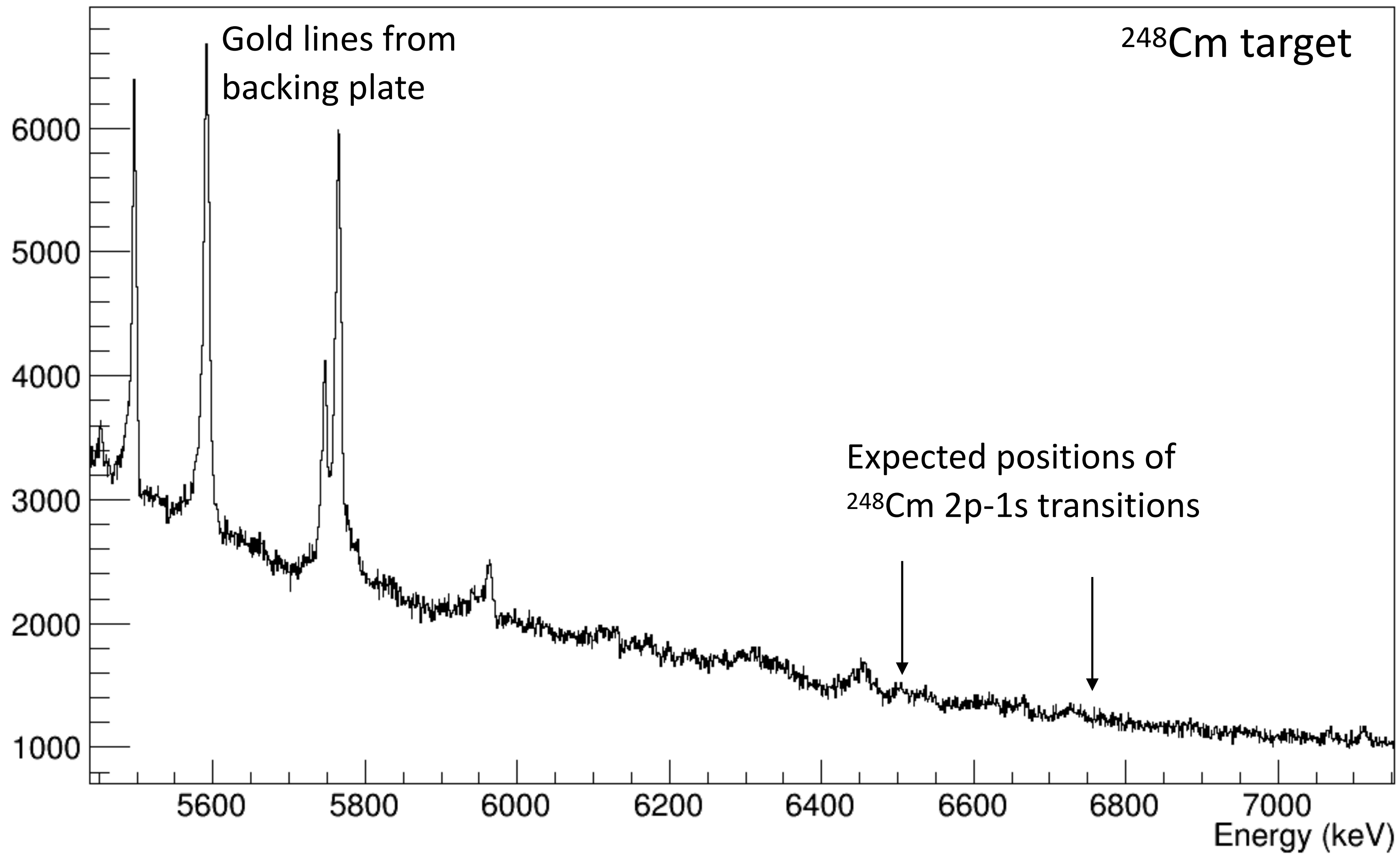
- We knew that we had lost a lot of radium in the target making process plus target had a large organic contamination
- Mounted target anyway but immediately saw that we had only 1% of the required target mass…
- Measured for a while, but clearly saw nothing

Making curium target

- Curium-248 target was made in Mainz
- Some issues with plating too much activity & contamination of Cm-246
- Due to the contamination could not plate as much Cm-248 as planned

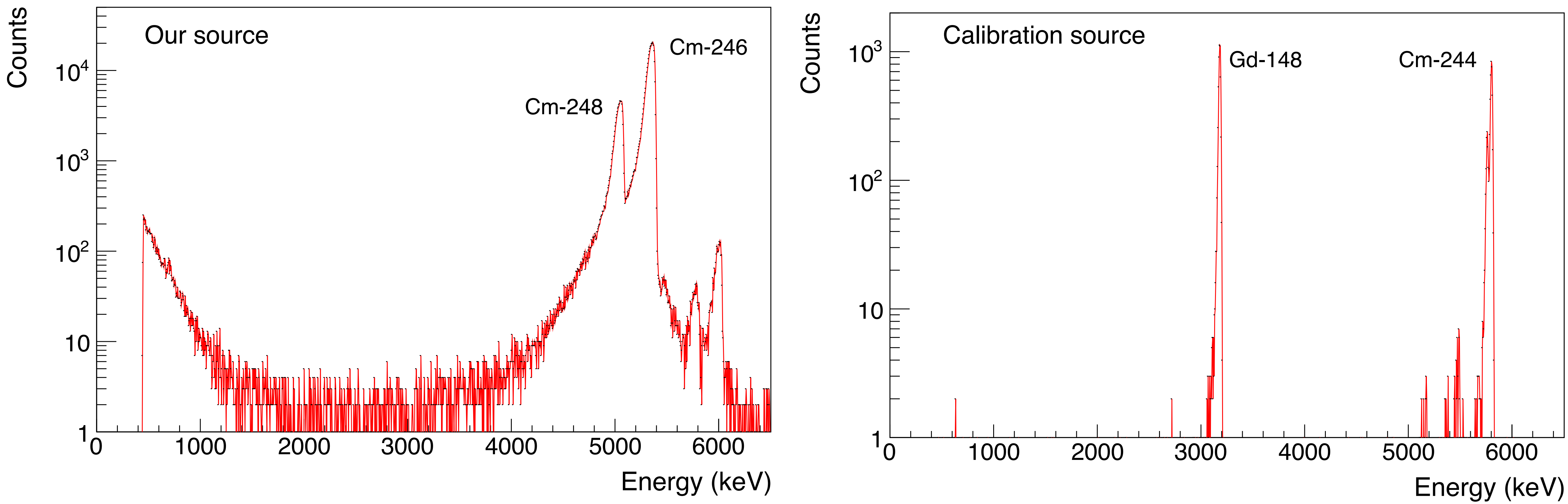


Measuring curium target



- 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

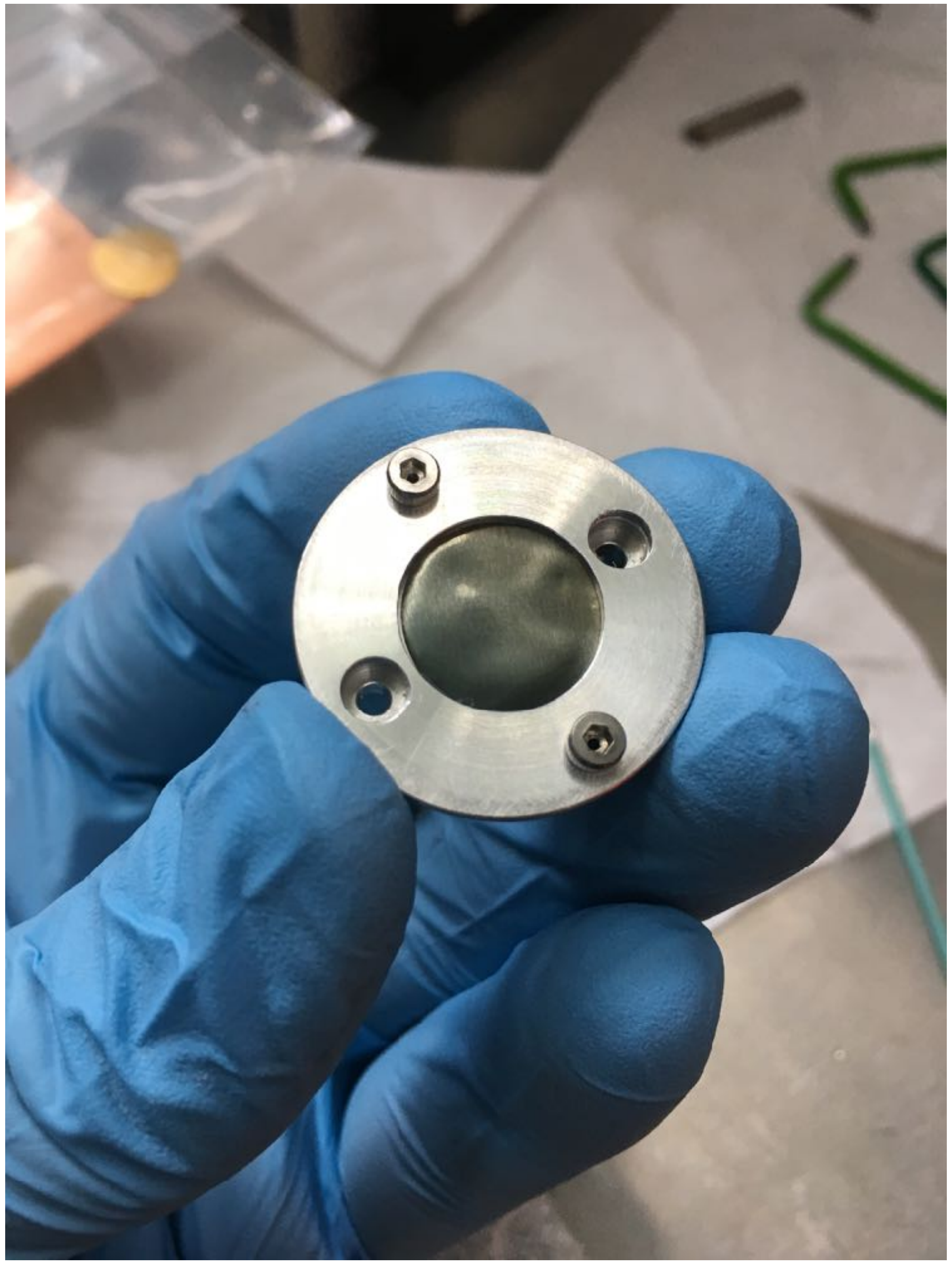
Alpha Spectrum



- 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

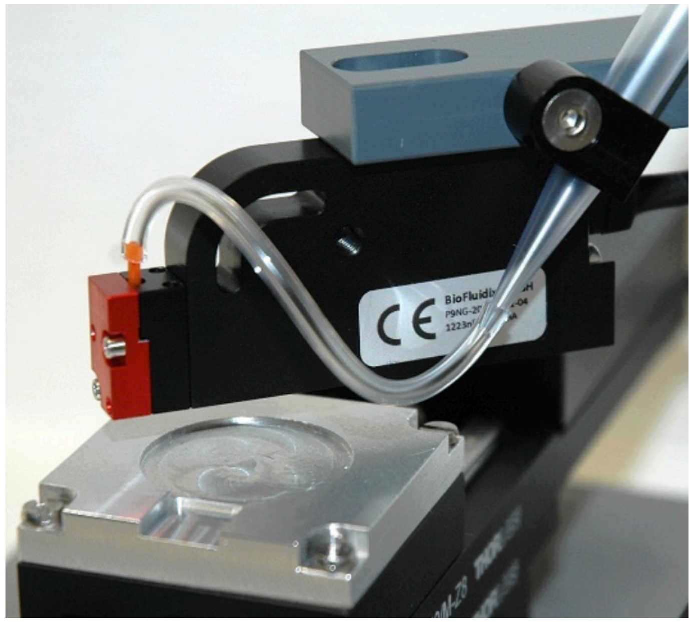
Carbon coatings on gold

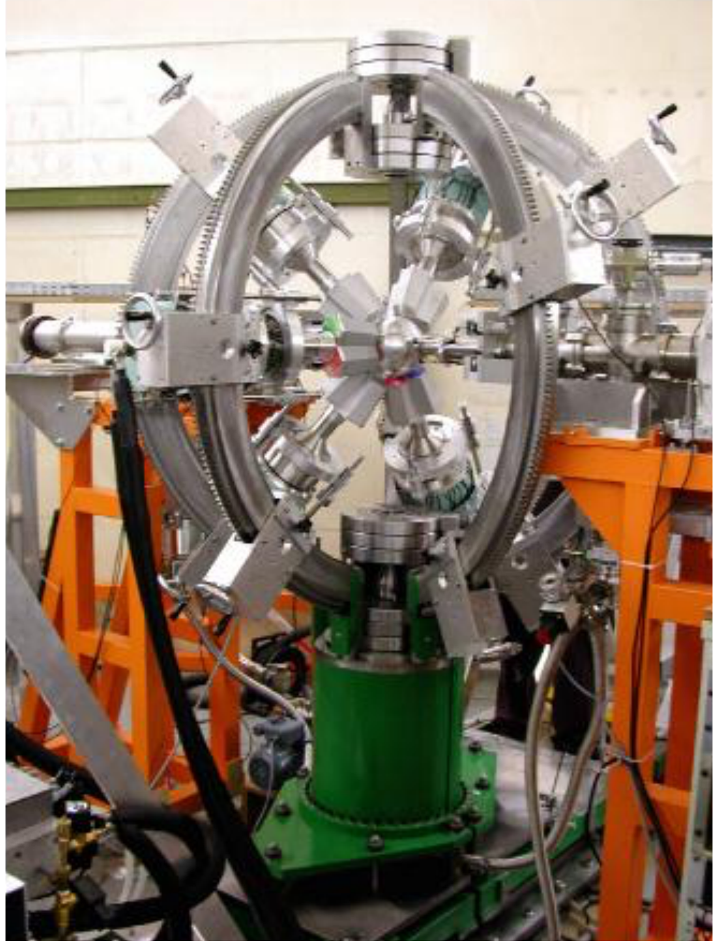
- In order to understand the influence of the organic layer on our measurements prepared gold coatings with 100 and 500 nm carbon coating on top.
- Results:
    - 100 nm: 27% of gold x-rays left
    - 500 nm: no gold x-rays seen
- We are much more sensitive to organic layers than expected!



Developments for 2019 campaign

- Radioactive target developments:
  - Drop-on-demand technique and/or plating at low voltage in Mainz (for curium & radium)
- Low-Z target cell to reduce background
- Use of Miniball germanium array



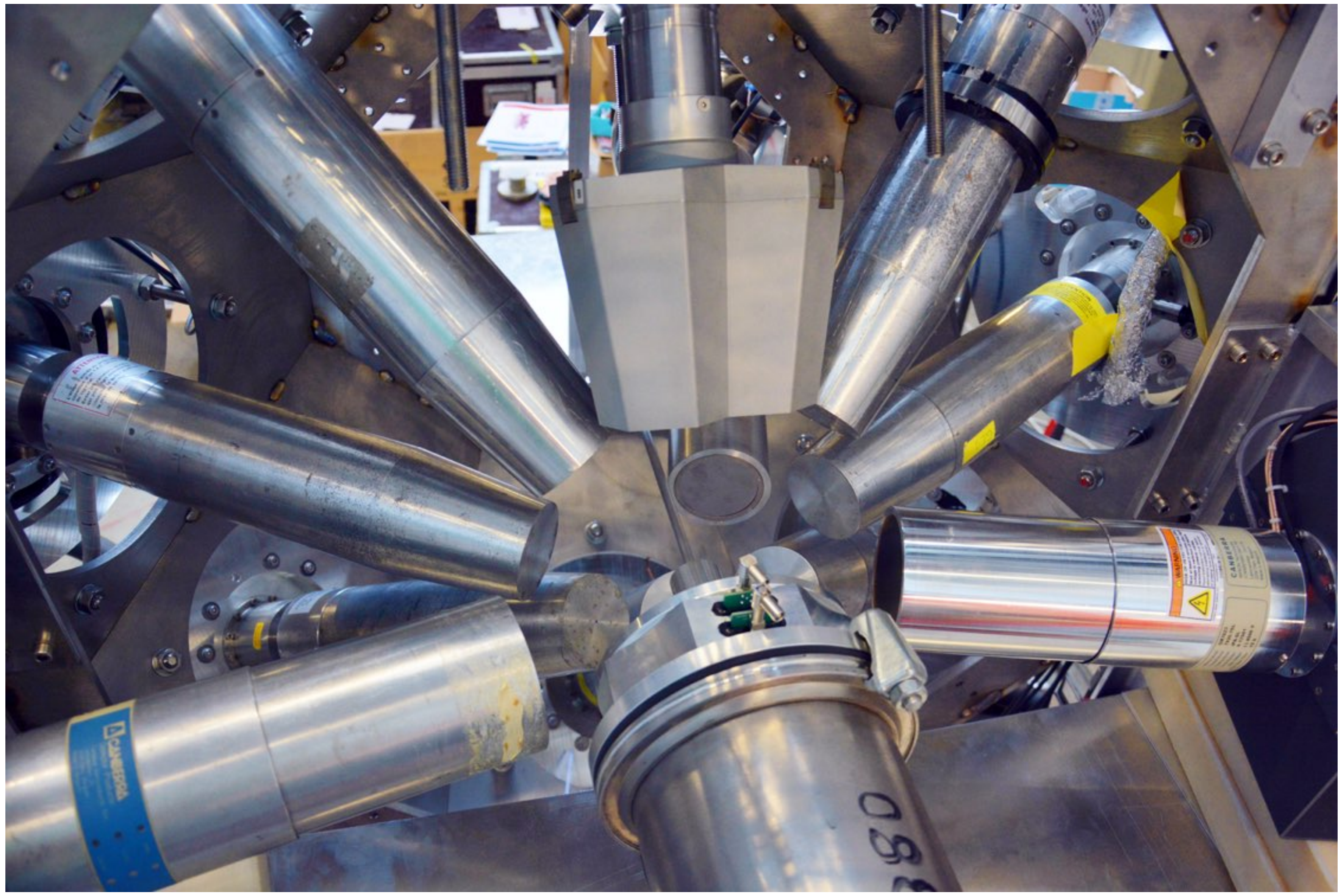


Campaign 2019

- Measurement of charge radius of ^{248}Cm and ^{226}Ra
- Muon capture measurements to obtain input for nuclear matrix element calculations relevant for double-beta decay
- Additional test requests using the muX setup:
  - 2s-1s measurements in muonic zinc: Access to atomic parity violation
  - Elemental analysis: Exploring the use of muons for elemental analysis (non-destructive, possibility to select depth)

Conclusions

- Muonic atom spectroscopy is a powerful tool to study properties of nuclei (charge radius, quadrupole moment)
- muX project developed method based on transfer reactions to perform measurements with microgram target material
- Good progress towards measuring the charge radii of ^{226}Ra and ^{248}Cm



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muX collaboration

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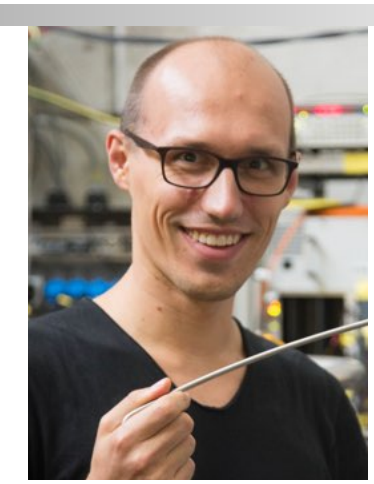
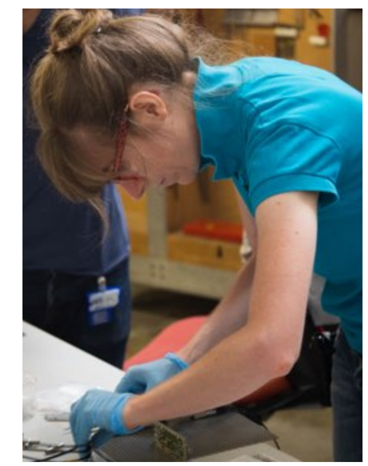
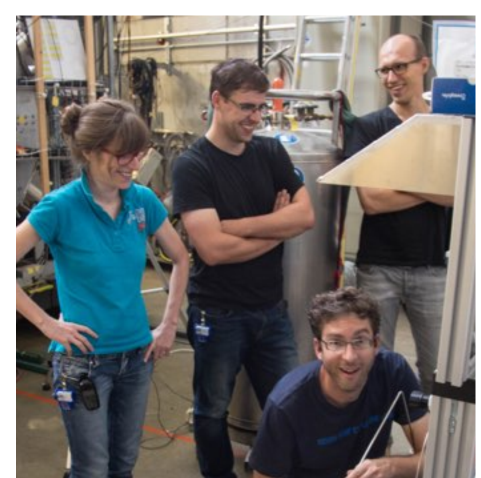
[11]CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France











Backup

Muonic atom spectroscopy

- 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

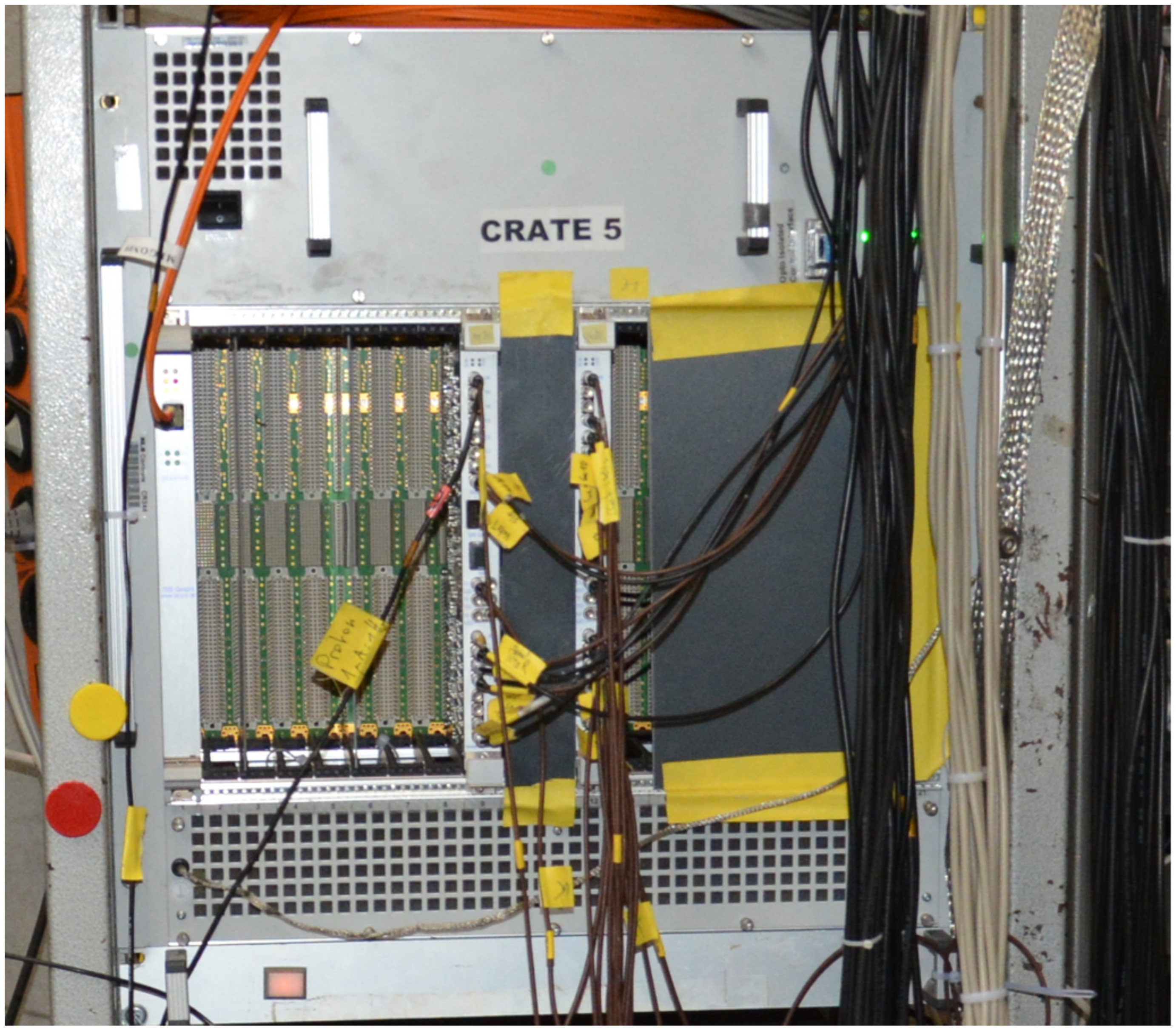
TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

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)

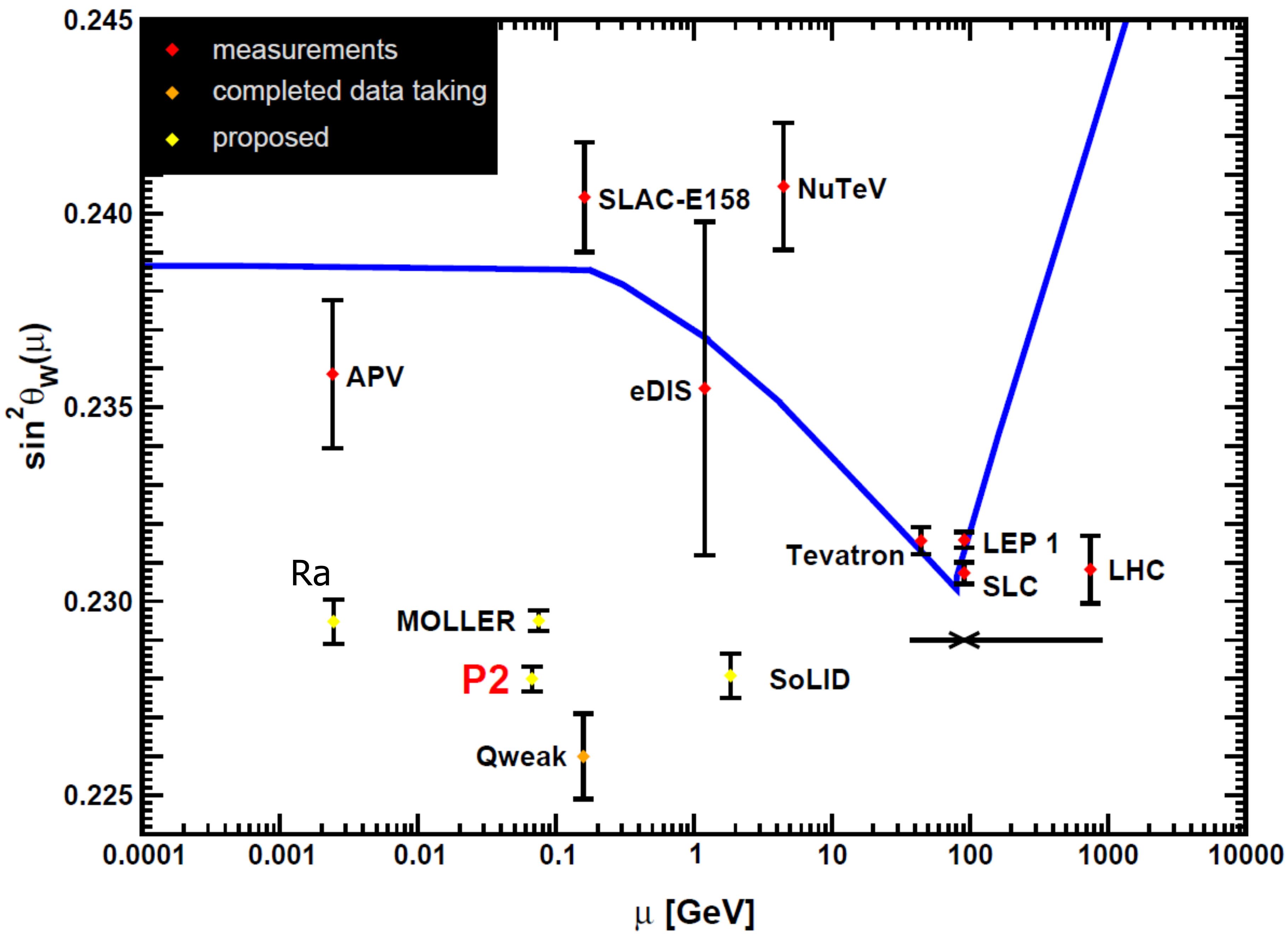
DAQ



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

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

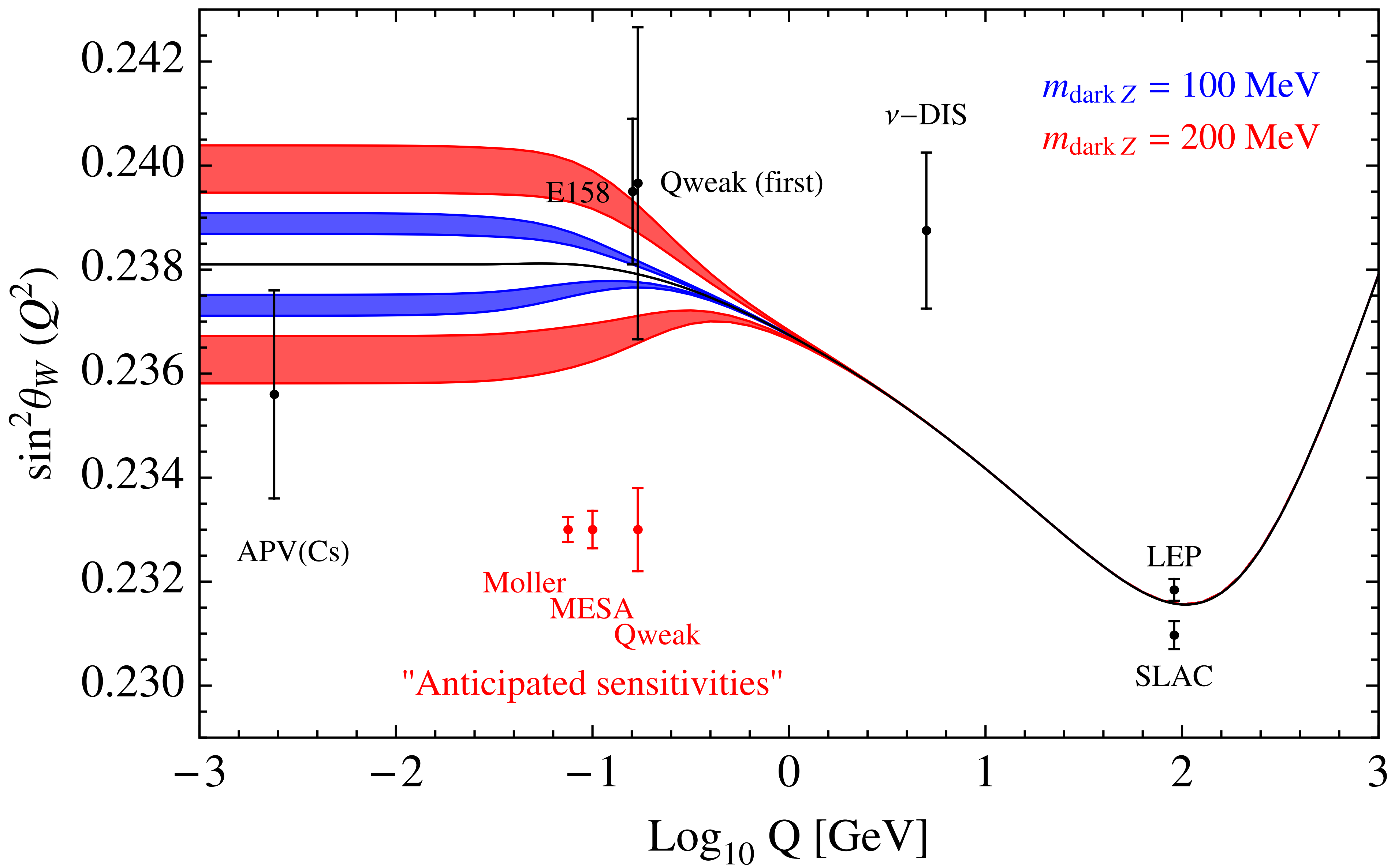
Why atomic parity violation?



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

Possible New Physics

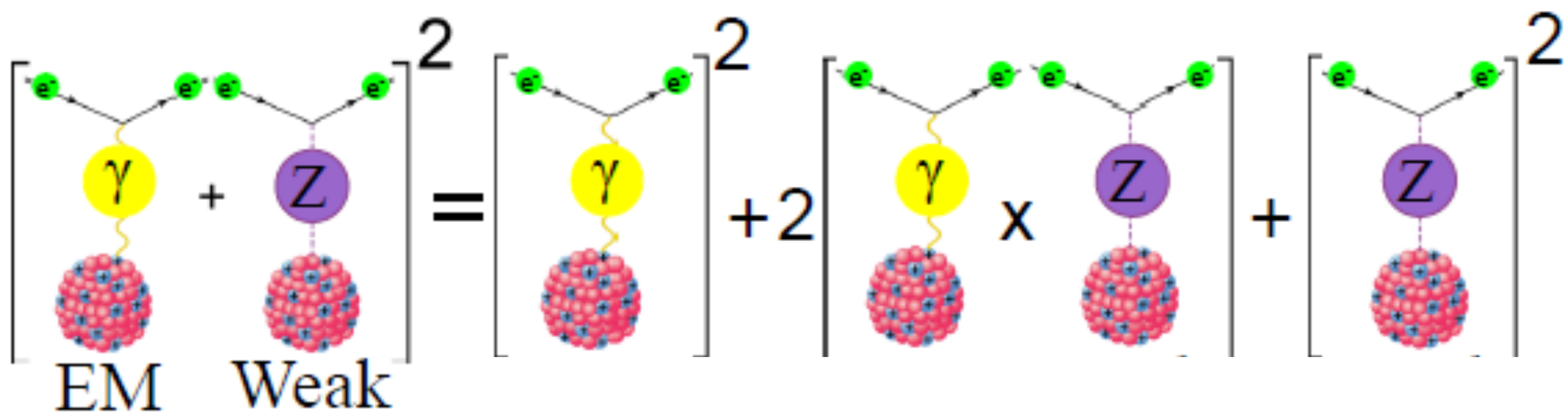
Davoudiasl, Lee, Marciano, Phys. Rev. D **89**, 095006 (2014)

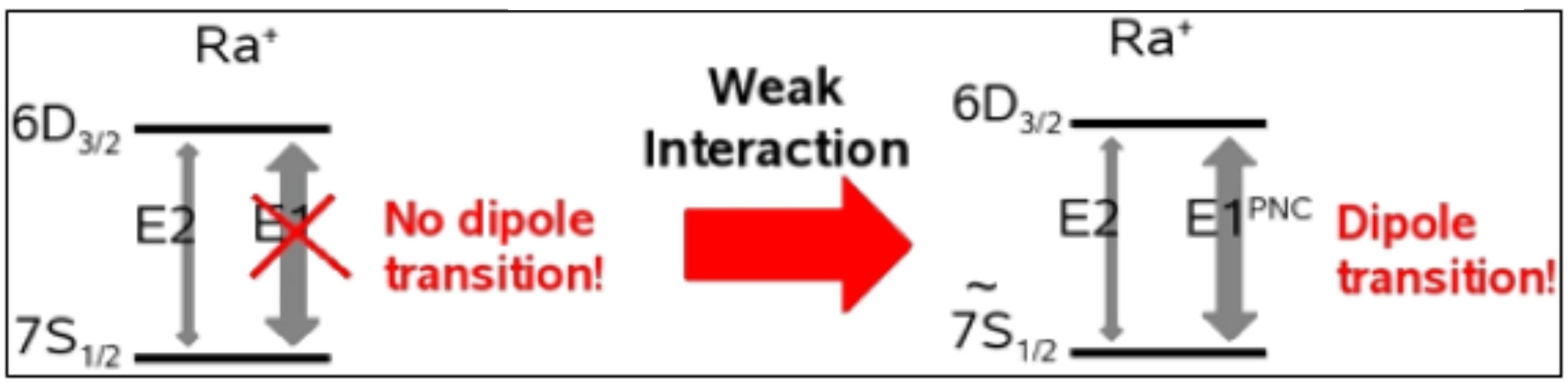


- Possible new physics in the form of a new dark Z boson hides at low momentum!

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 (→ $E1_{PNC}$)

Atomic Theory (→ K_r)

Heavy System (→ Z^3)

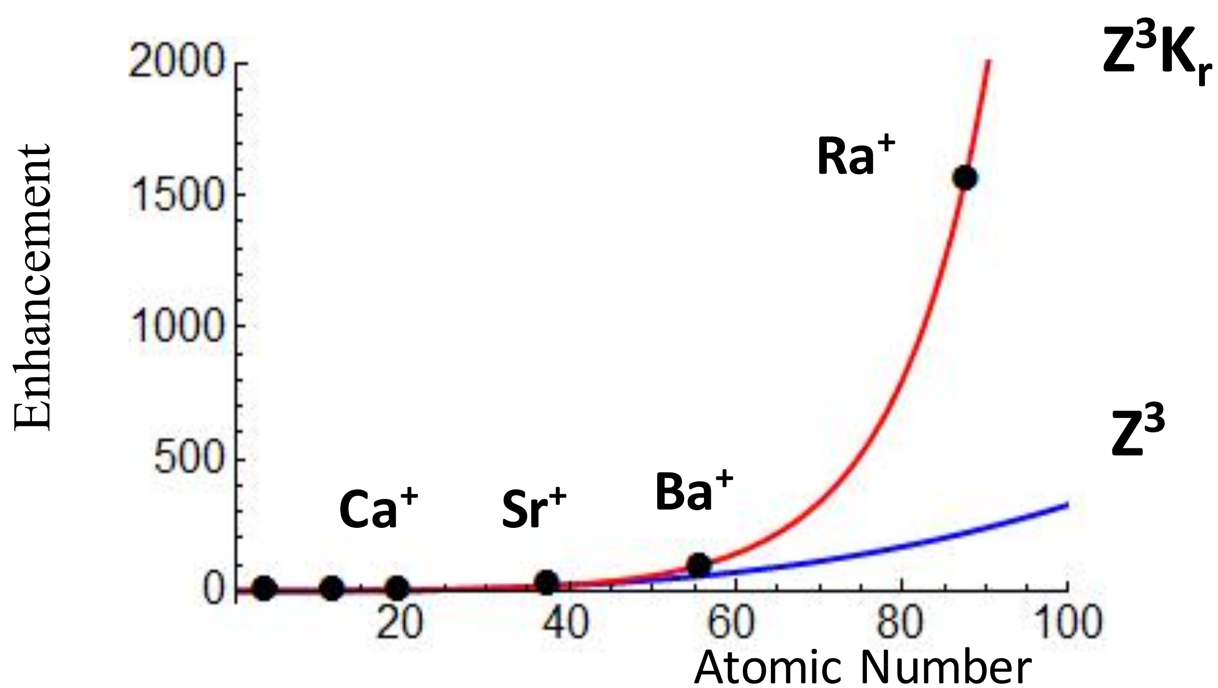
K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

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^+

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

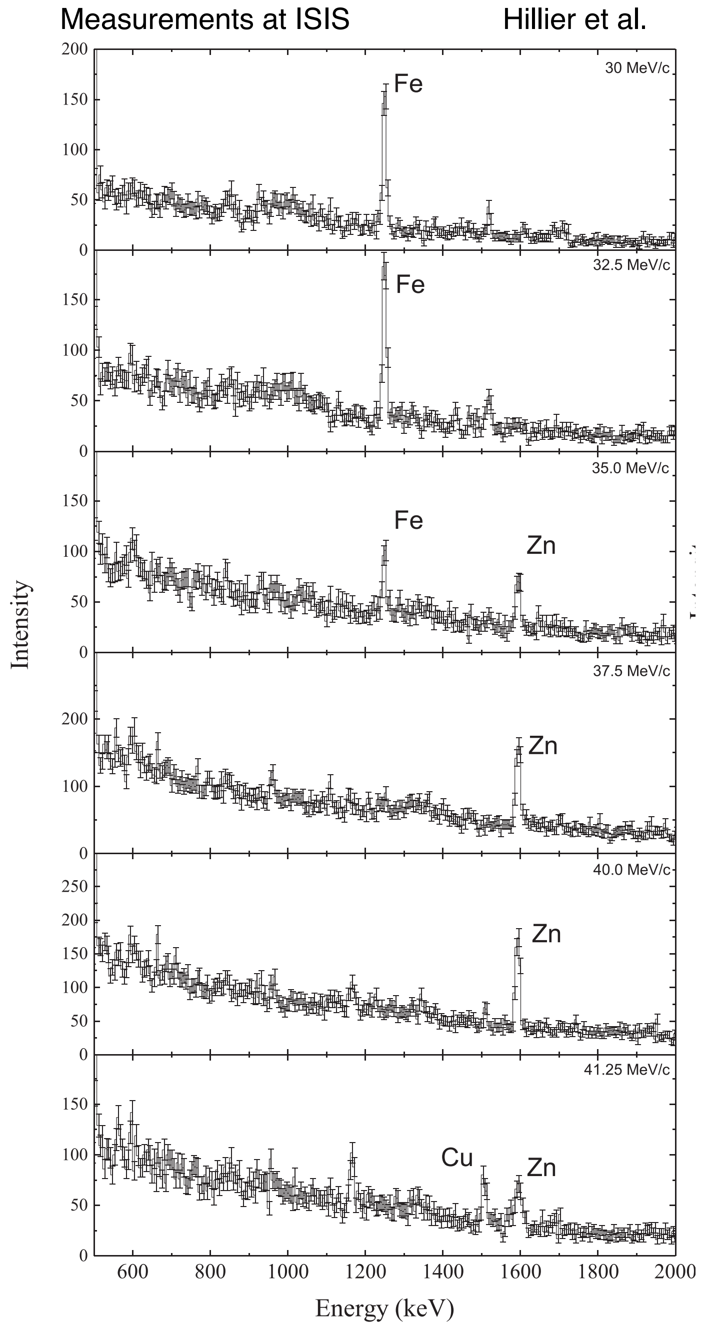
K. Jungmann, L. Willmann, Workshop on Muonic Atom Spectroscopy (2016)

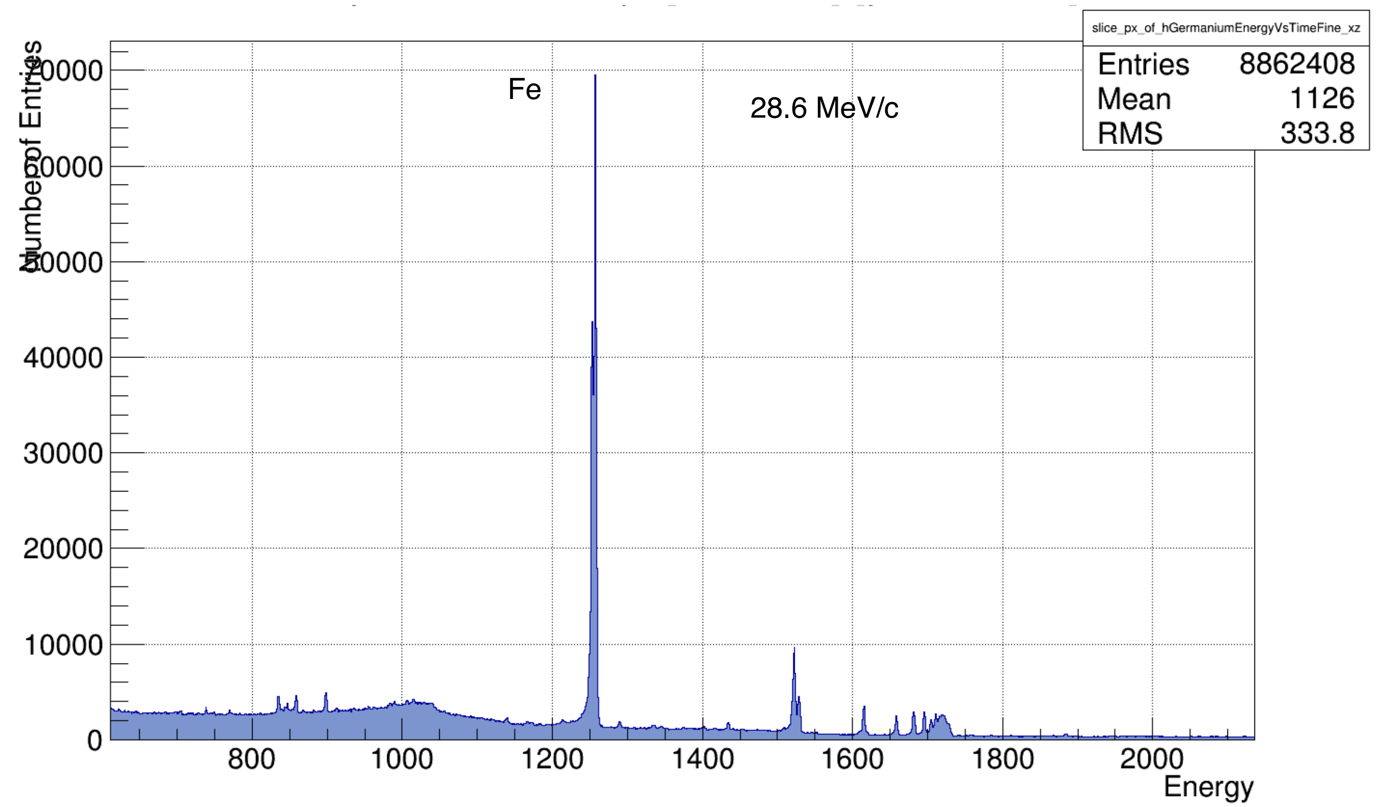
Other results:

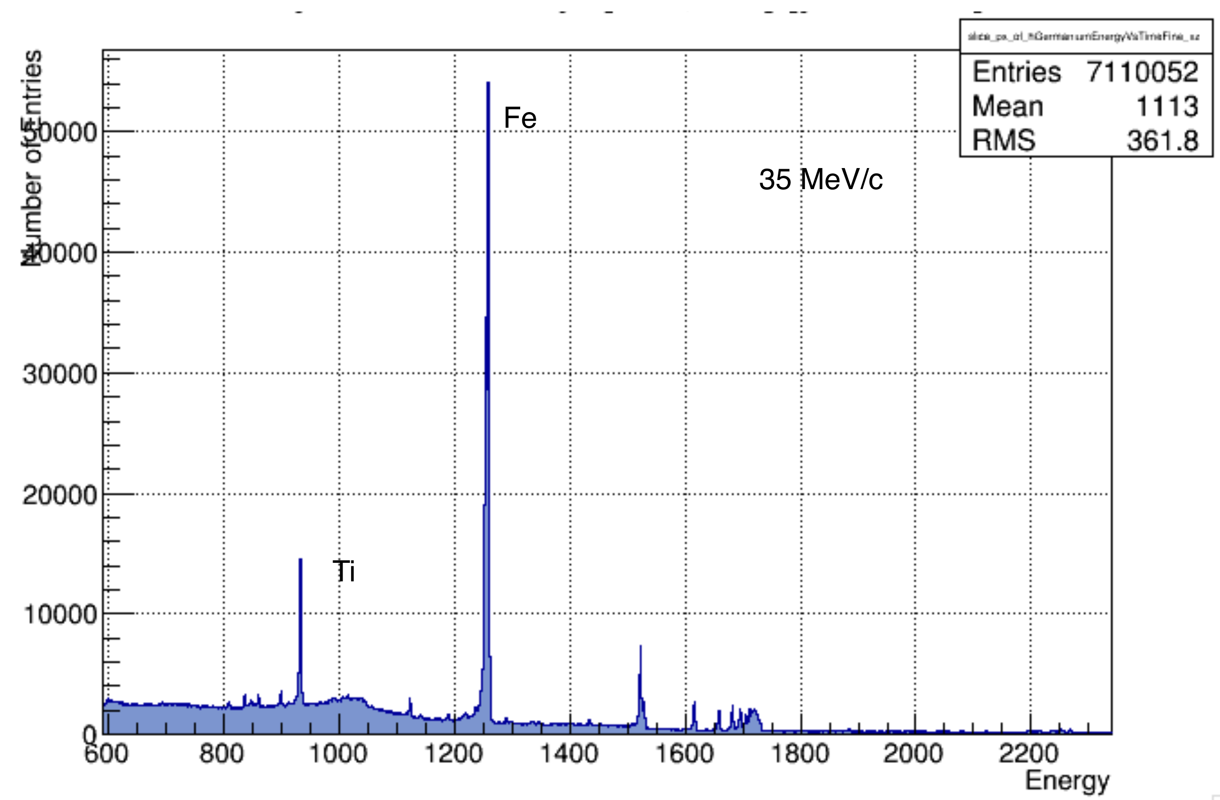
$45.9 \cdot 10^{-11}\, iea_0\, (-Q_w/N)$ (R. Pal *et al.*, Phys. Rev. A **79**, 062505 (2009), Dzuba *et al.*, Phys Rev. A **63**, 062101 (2001).)

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

Elemental analysis with negative muons



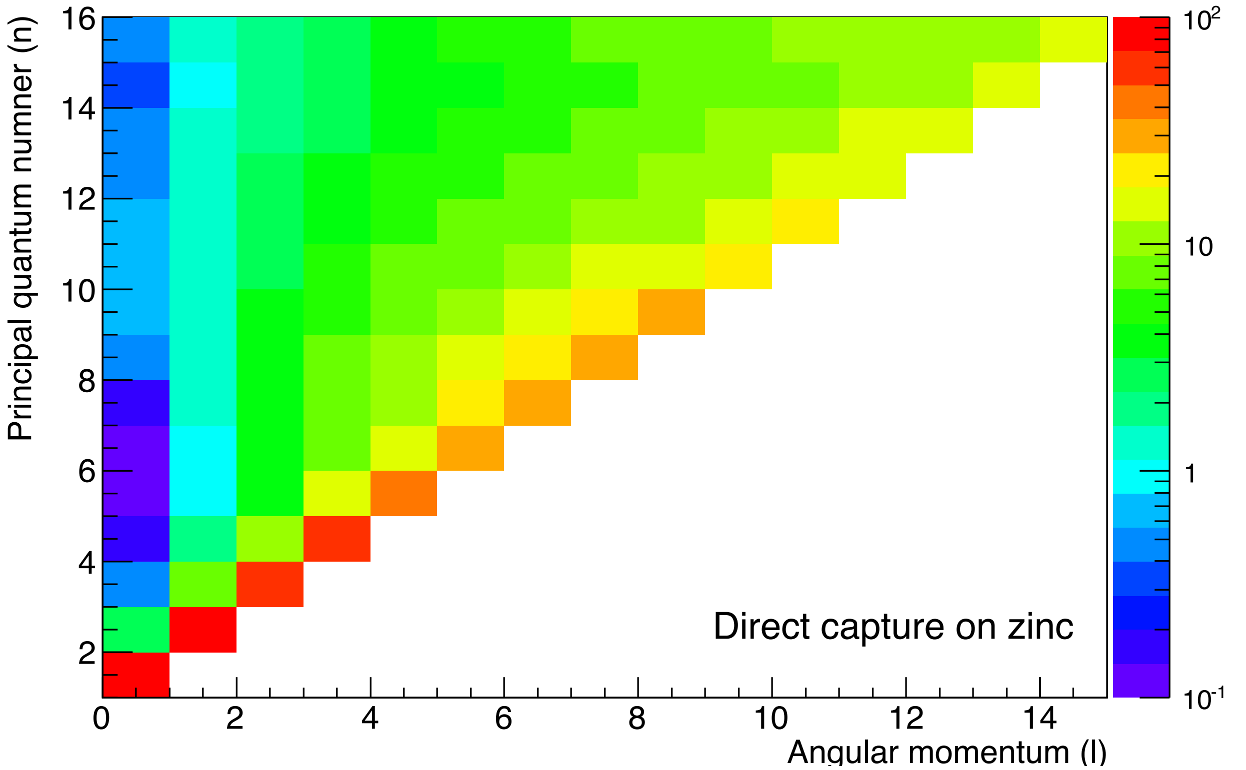


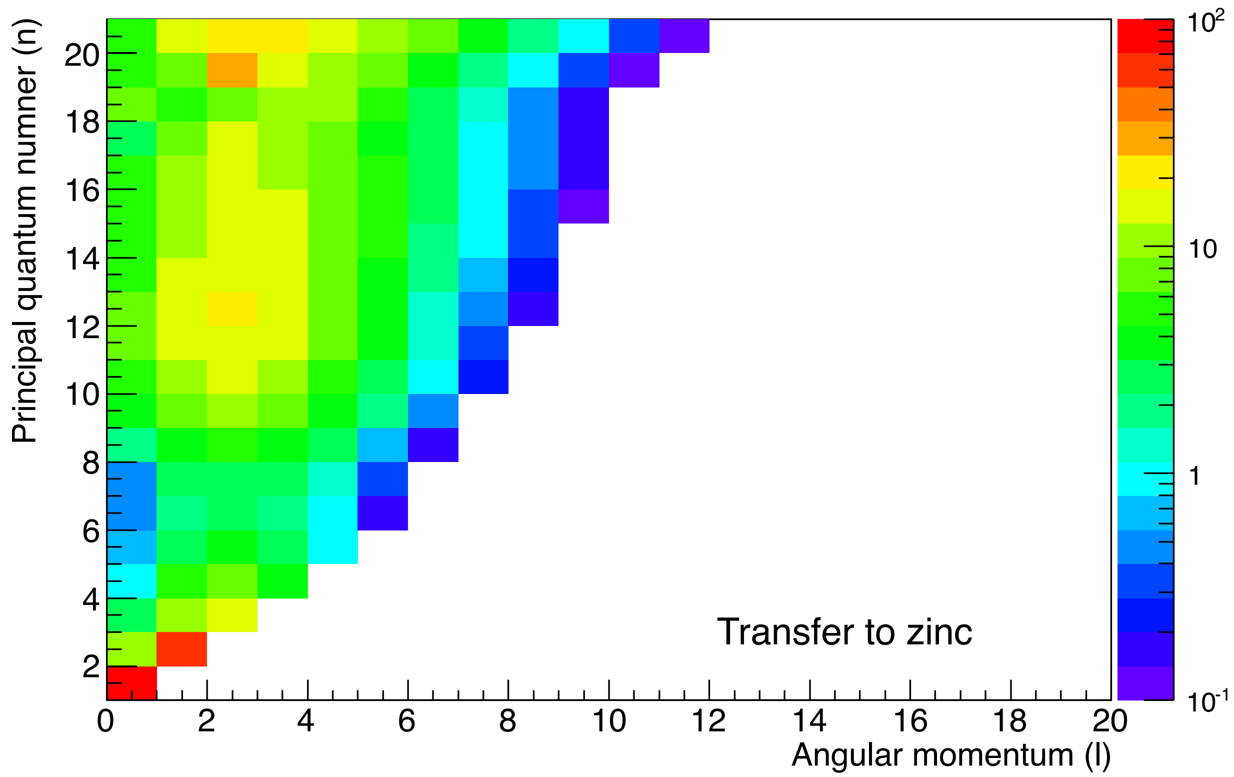


- Elemental analysis with muonic x-rays
- Depth profiling as a function of momentum
- Proof-of-principle with stacks of foils

Muonic cascade

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

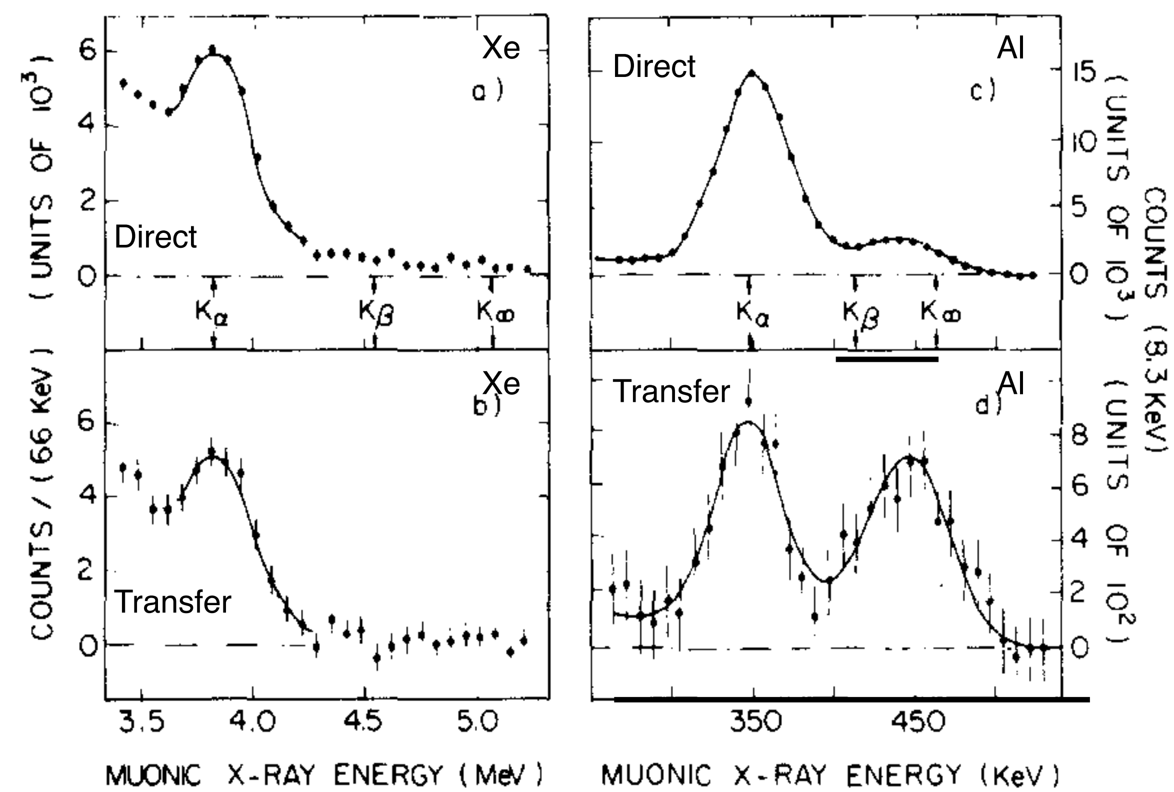




Muonic cascade

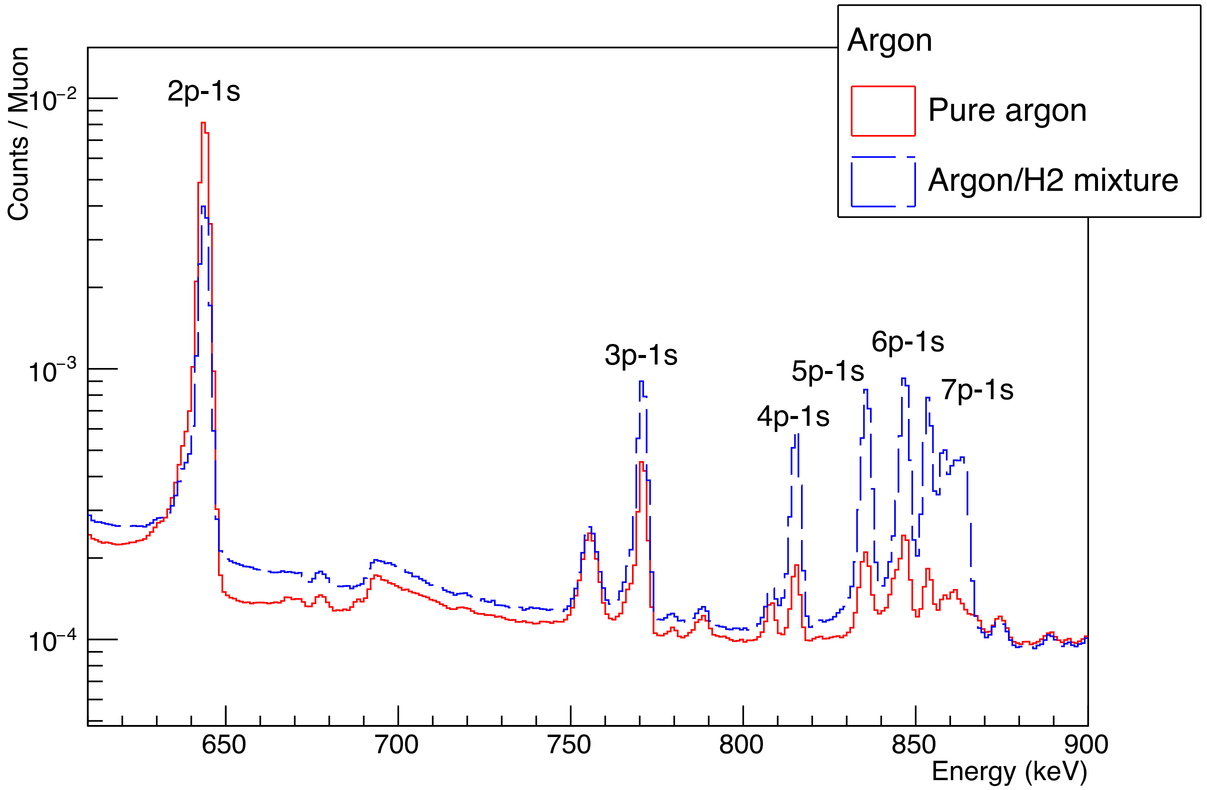
- One publication that claims that enhancement is not seen in high-Z atoms
- Troubling as would like to predict our yields
- Additionally need to do a cascade calculation to predict the relative strengths of all the HFS states

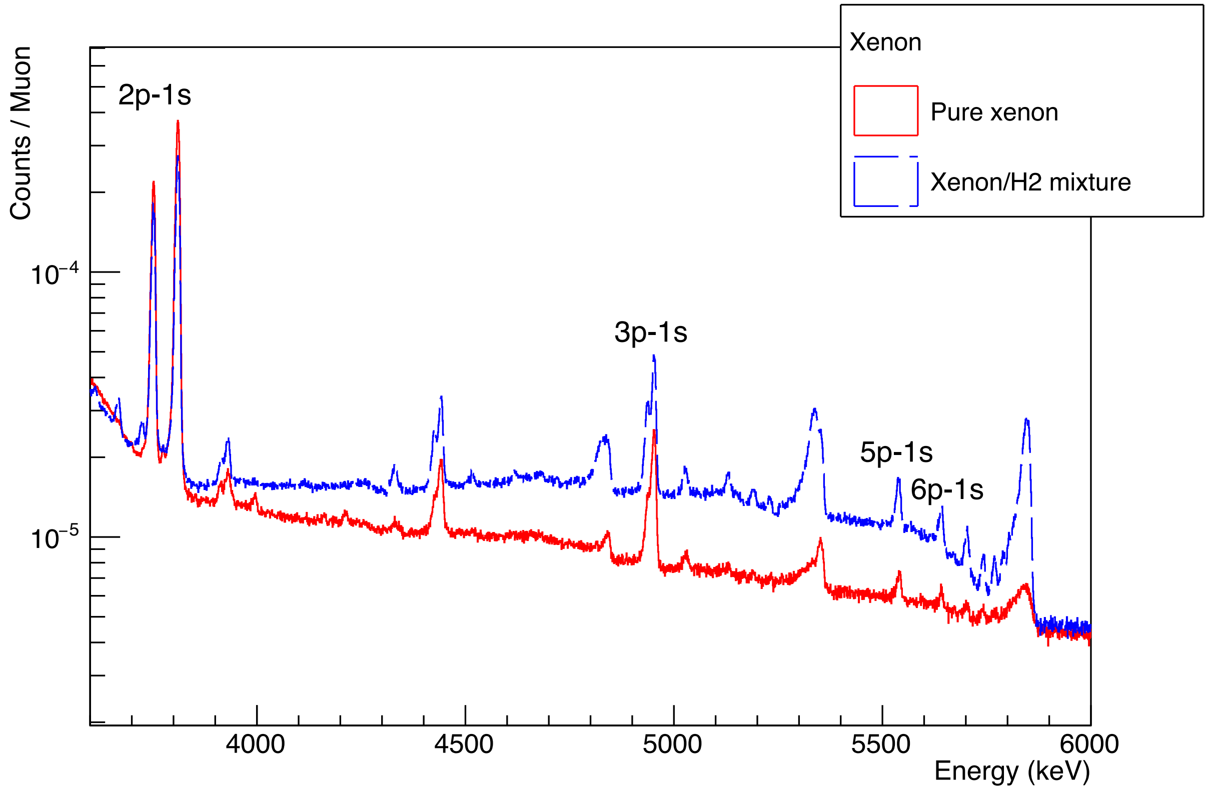
Bertin et al., Phys. Lett. **74A**, 39 (1979)



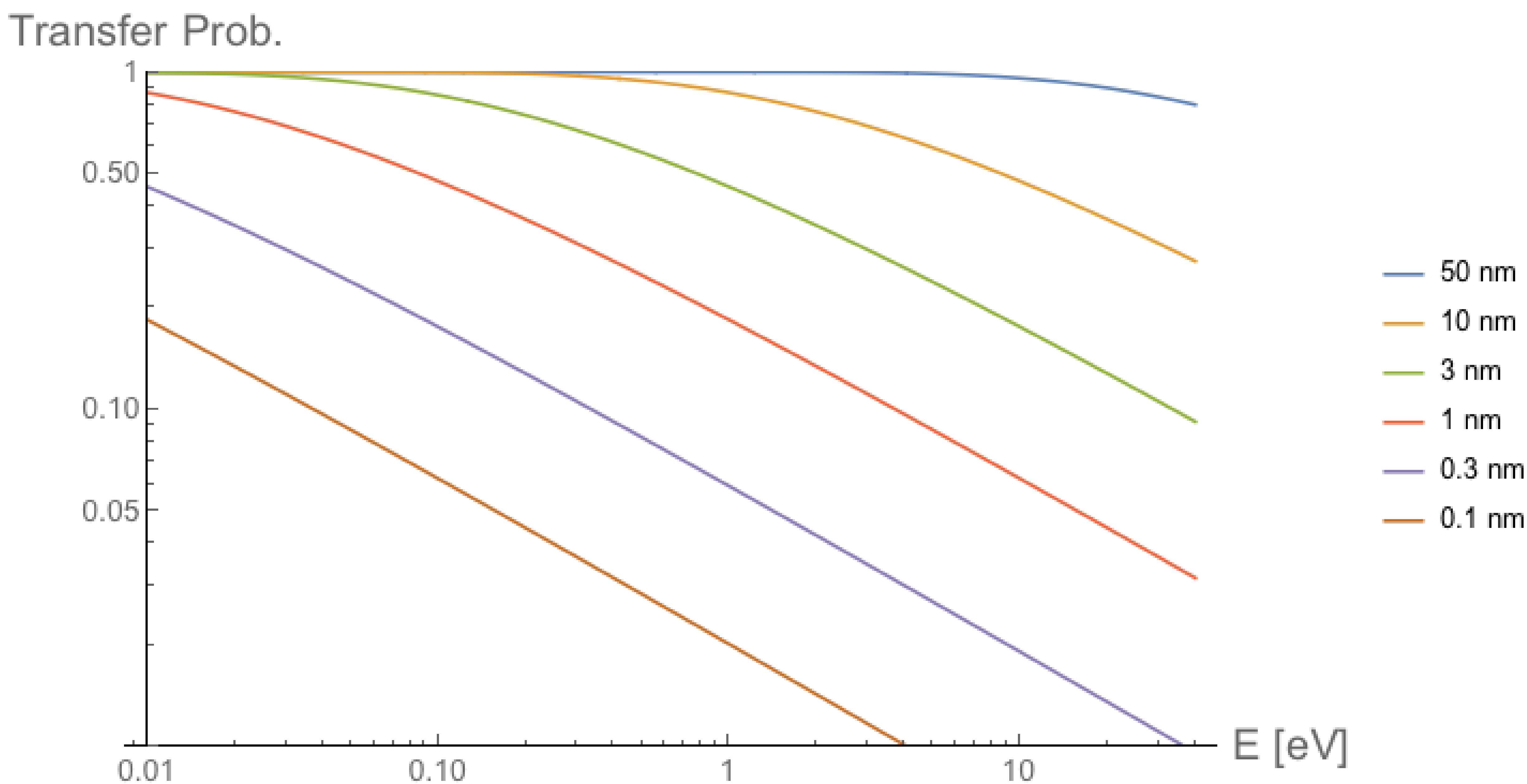
Measurements with noble gases

- 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 under investigation





Transfer Probability in Gold



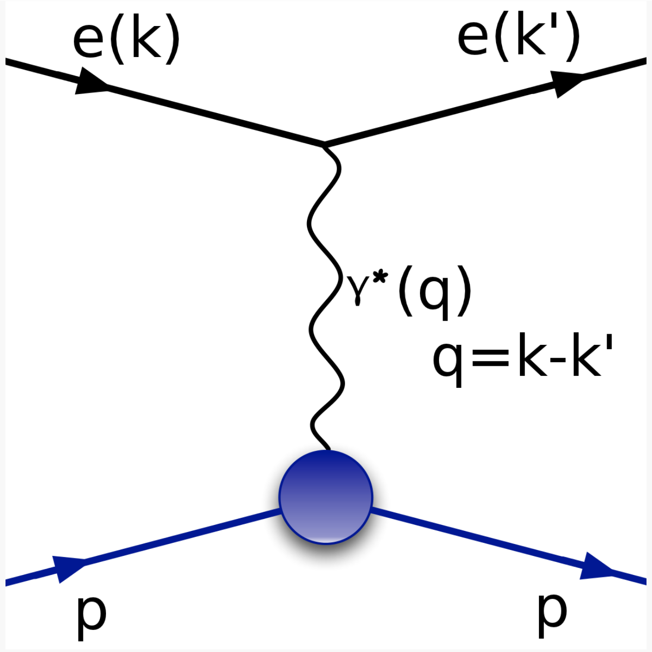
Rosenbluth separation

Cross section measurement

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{el.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} \left(1 + R\right)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Ros.}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{(1+\tau)} \left(\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$

Point-like, s=1/2



$G_E(0) = 1$ (charge)

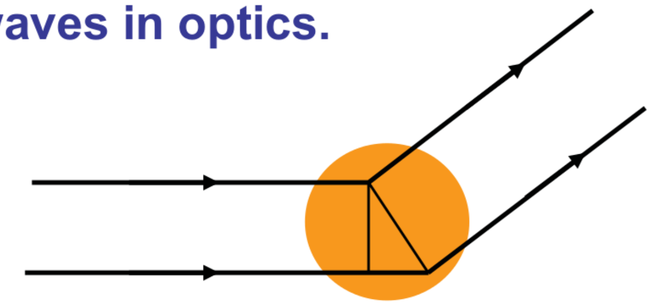
$G_M(0) = \mu_p$ (magnetic moment)

$$\langle r_{\text{p}}^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

extrapolation to $Q^2 \to 0$ required

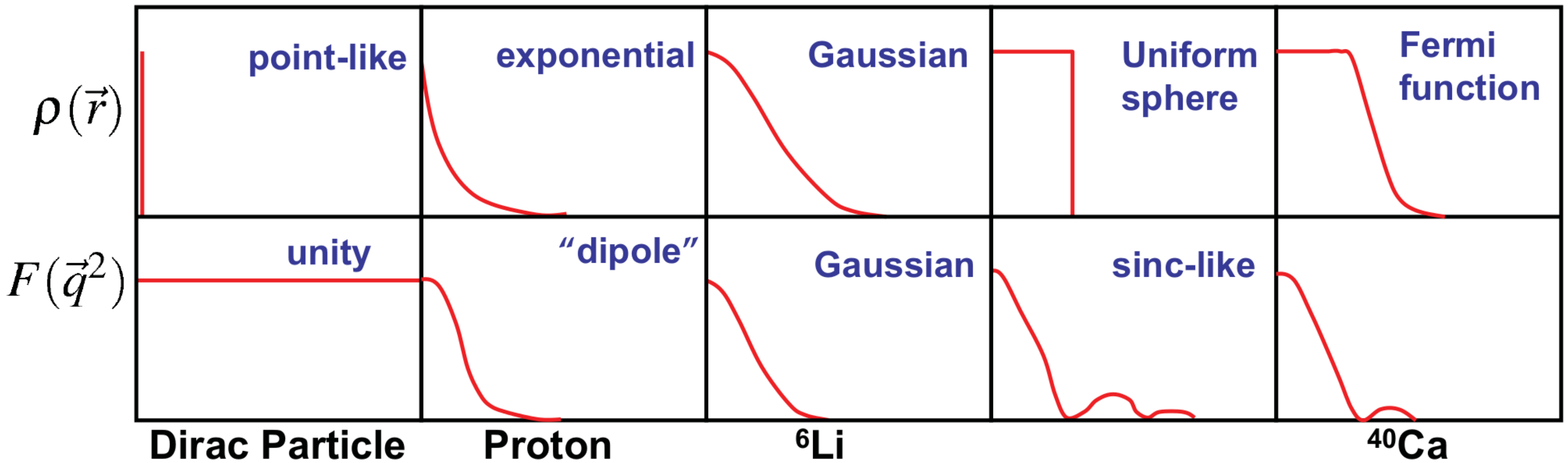
Form factor

- There is nothing mysterious about form factors – similar to diffraction of plane waves in optics.



- The finite size of the scattering centre introduces a phase difference between plane waves "scattered from different points in space". If wavelength is long compared to size all waves in phase and $F(\vec{q}^2) = 1$

For example:

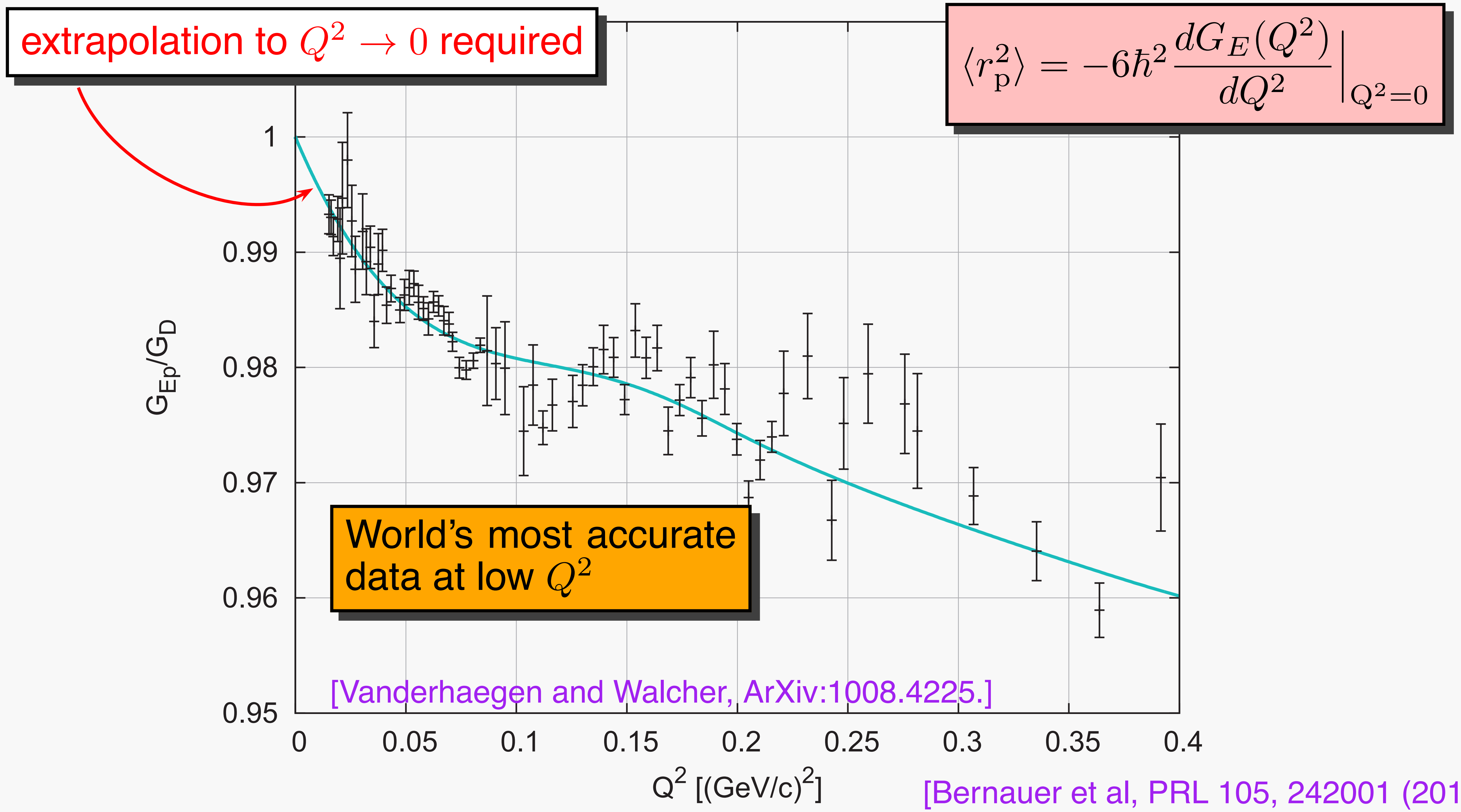


- NOTE that for a point charge the form factor is unity.

- For small $|\vec{q}|^2$ we can expand the form factor as

$$
\begin{aligned}
F(q^2) &= \int e^{i\vec{q}\vec{x}} \rho(\vec{x})\, d^3x \\
&\approx \int \left(1 + i\vec{q}\vec{x} - \frac{(\vec{q}\vec{x})^2}{2} + \ldots\right) \rho(\vec{x})\, d^3x \\
&= 1 - \frac{1}{6}|\vec{q}|^2 \langle r^2 \rangle + \frac{1}{24}|\vec{q}|^4 \langle r^4 \rangle + \ldots
\end{aligned}
\quad \rightarrow \quad \langle r^2 \rangle = 6 \frac{\mathrm{d}F(q^2)}{\mathrm{d}q^2}\Big|_{q^2=0}
$$

2010 Mainz data: most accurate



[Bernauer et al, PRL 105, 242001 (2010)]

$$r_p = (0.879 \pm 0.005_{\text{stat}} \pm 0.004_{\text{sys.}} \pm 0.005_{\text{model}})\ \text{fm}$$

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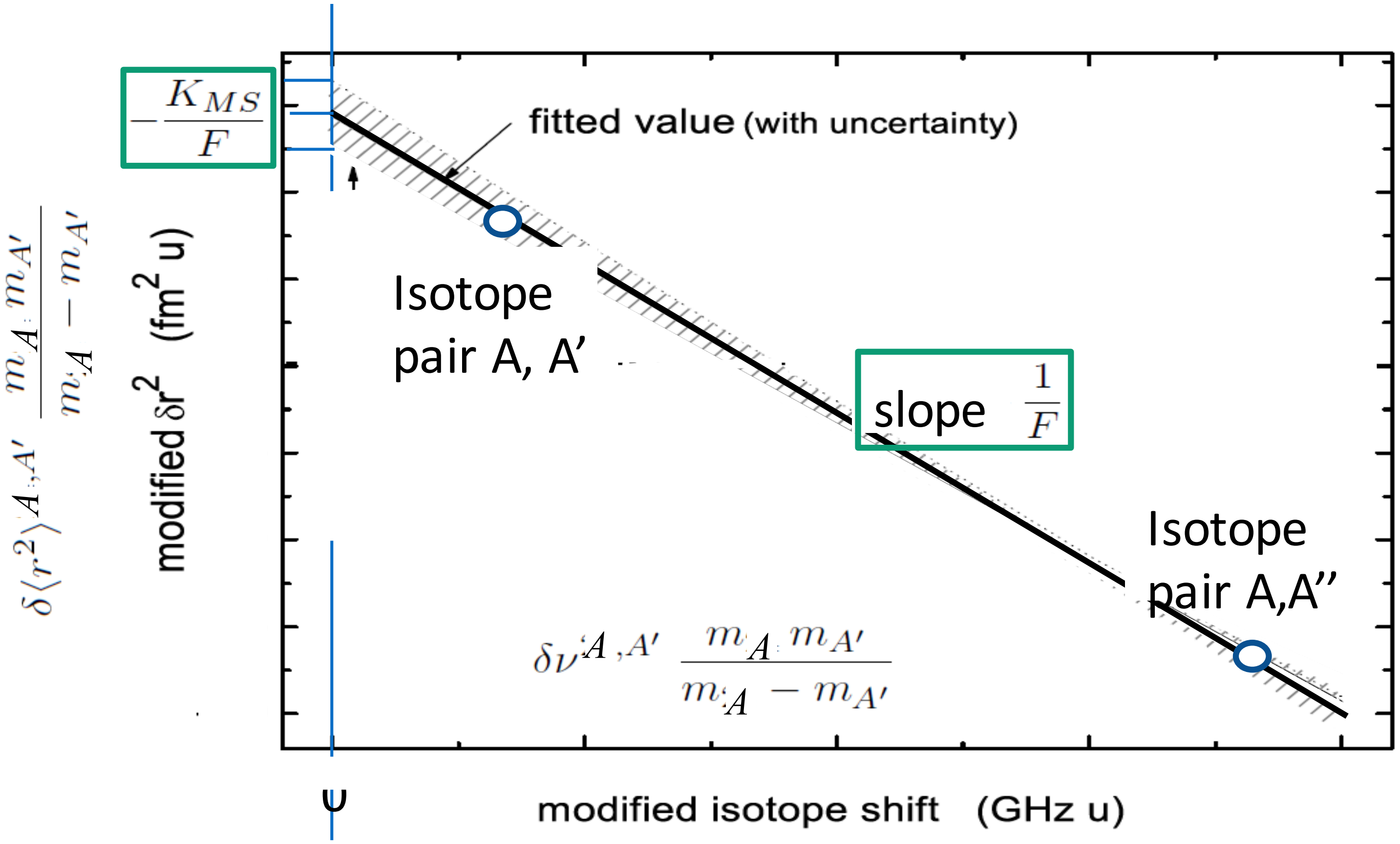
M. Kowalska, Workshop on Muonic Atom Spectroscopy (2016)

=> 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

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

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

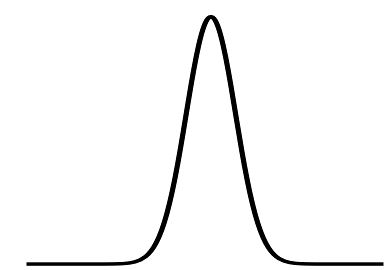


But if there are fewer stable isotopes …
See Na, Mn, Cu, Ga …

Instrumental line-shape analysis

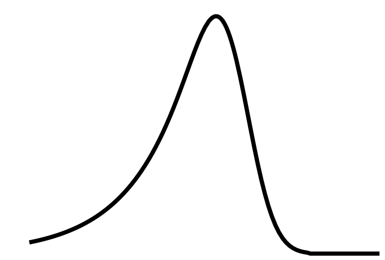
- **Gaussian** shape due to statistical fluctuations and electronic noise:

$$G(E) = \frac{1}{\sqrt{2\pi}\boldsymbol{\sigma}} \exp\left(-\frac{(E-m)^2}{2\sigma^2}\right)$$



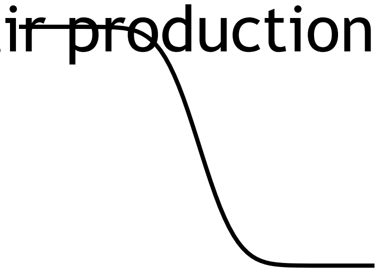
- **Hypermet** shape due to incomplete charge collection:

$$T(E) = \frac{1}{2\,\boldsymbol{b}} \exp\left(\frac{E-m}{b} + \frac{\sigma^2}{2b^2}\right) \operatorname{erfc}\left(\frac{E-m}{\sqrt{2}\sigma} + \frac{\sigma}{\sqrt{2}b}\right)$$



- **Step-like shelf** shape due to accumulation of Compton scattering and pair production effects:

$$S(E) = \frac{\boldsymbol{A}}{2} \operatorname{erfc}\left(\frac{E-m}{\sqrt{2}\sigma}\right)$$



Total PDF in RooFit: $P(E) = N_{signal}\,(f_G\,G(E) + f_T\,T(E) + S(E)) + B$