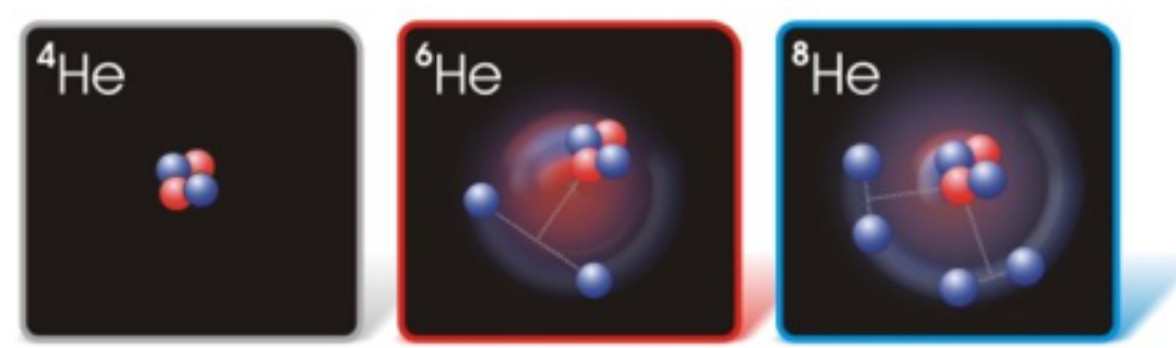
Towards the measurement of the nuclear charge radius of 226Ra

Andreas Knecht, Paul Scherrer Institute

for the muX collaboration

Nuclear Charge Radii

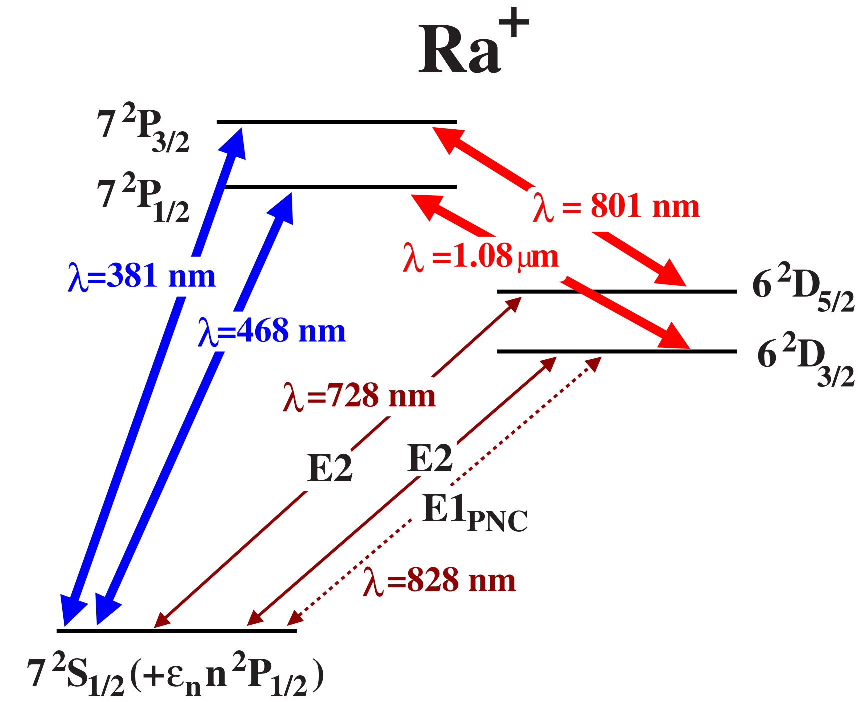
- Charge radius fundamental parameter of a nucleus
- Despite all our knowledge there are still surprises (proton radius)
- Low-Z nuclei can be understood ab-initio
- Nuclear models for high-Z nuclei

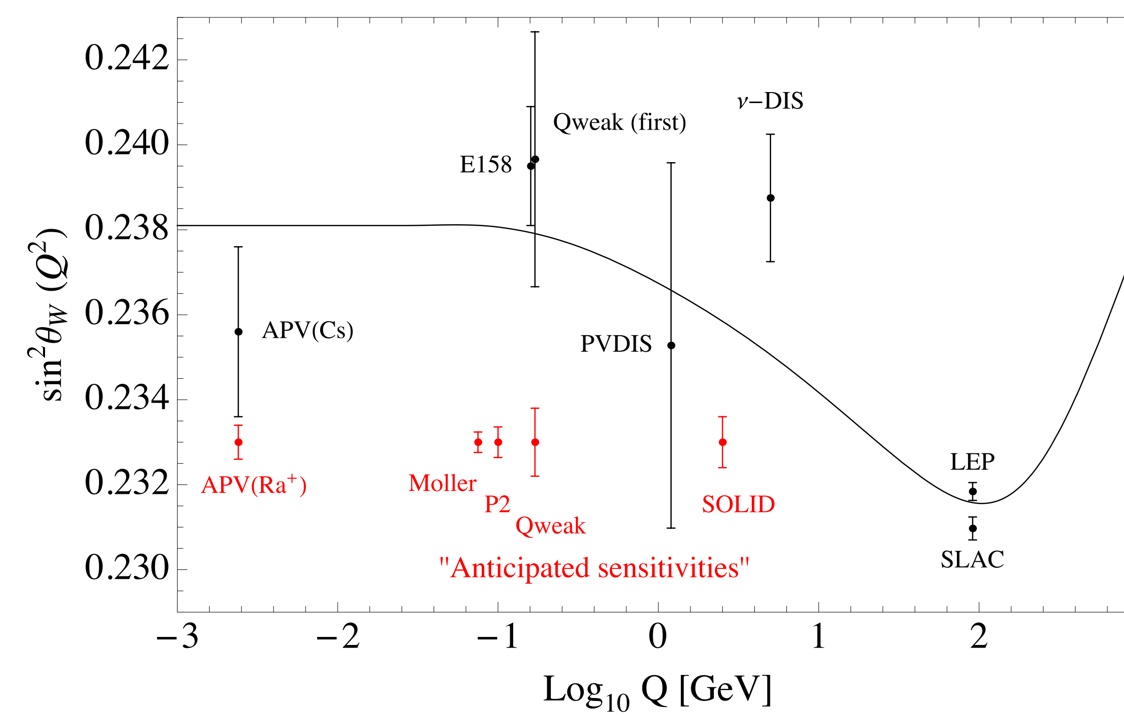


Pohl et al., Nature **466**, 213 (2010)
Mueller et al., PRL **99**, 252501 (2007)

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)
Lee, arXiv:1511.03783 (2015)

Charge Radii from Laser Spectroscopy

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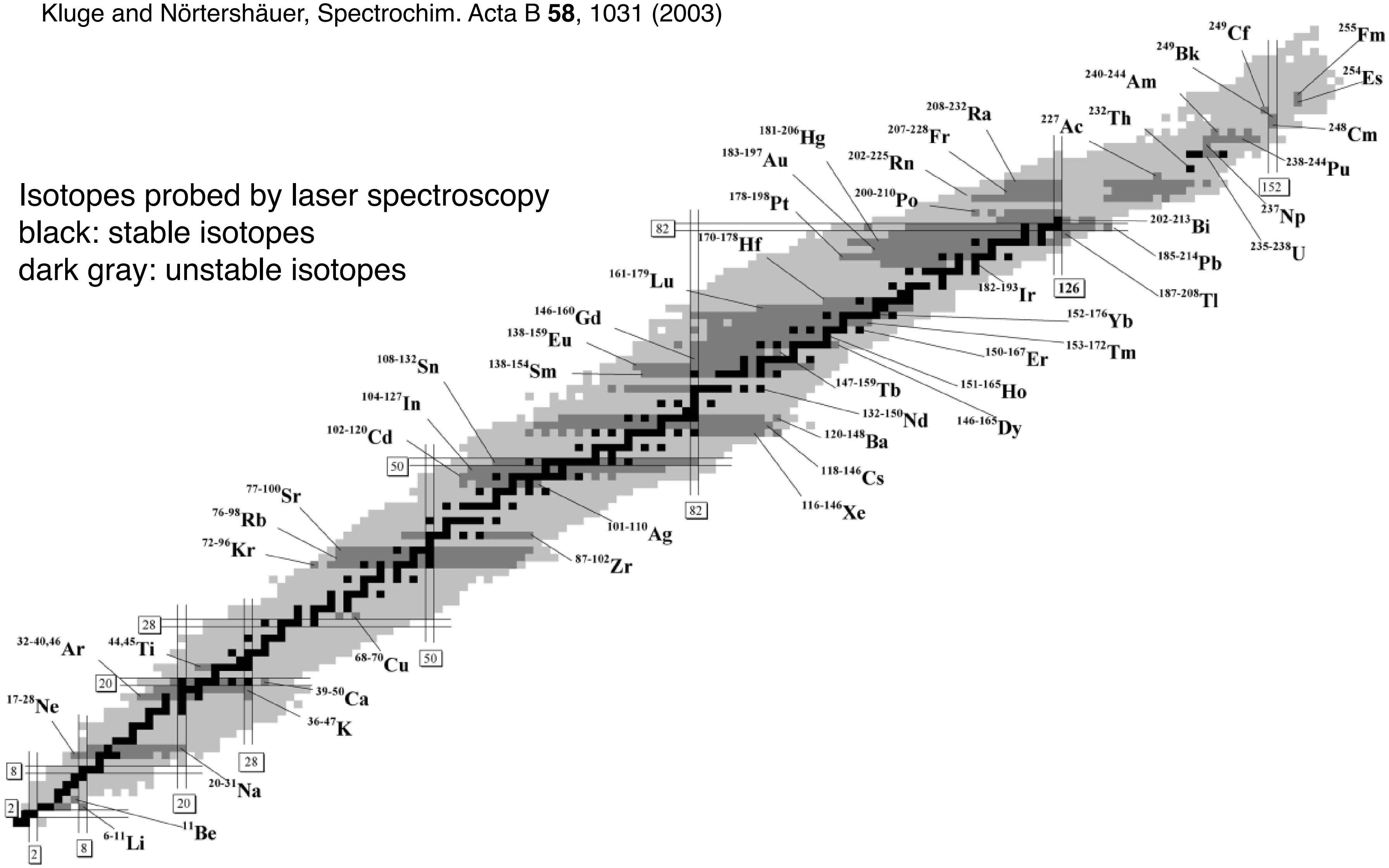
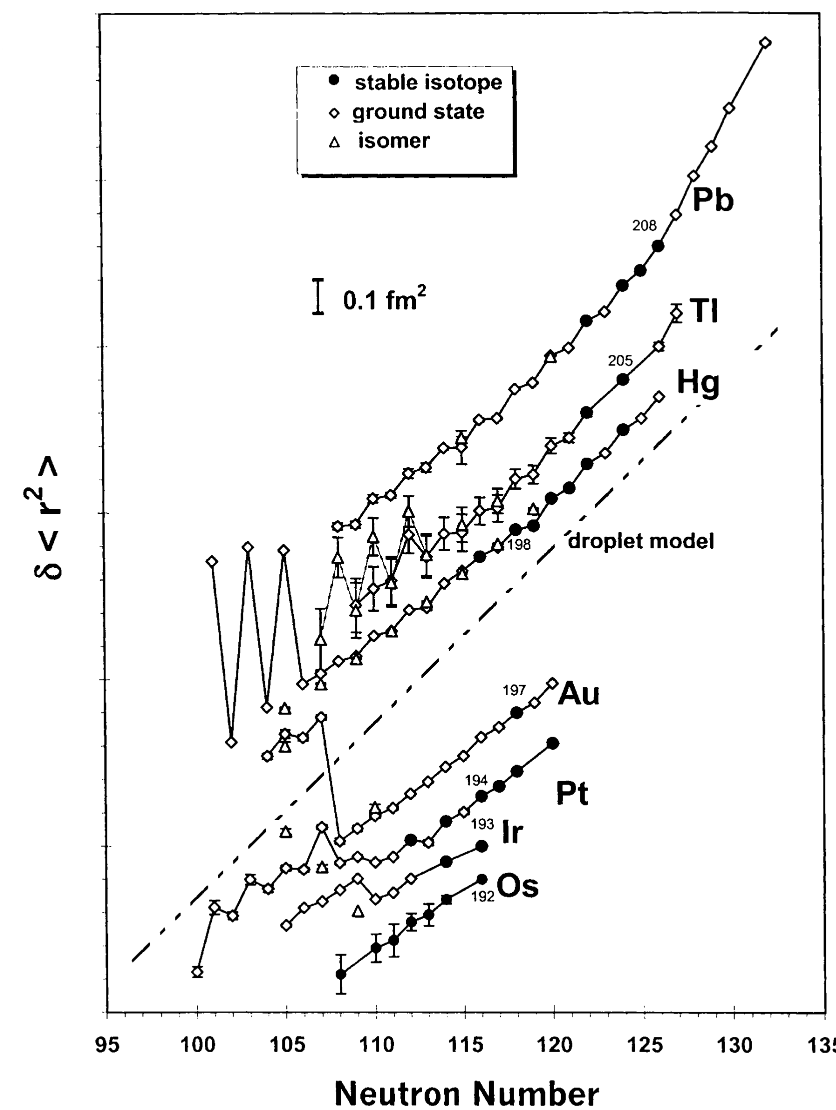
Kluge and Nörtershäuer, Spectrochim. Acta B **58**, 1031 (2003)



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



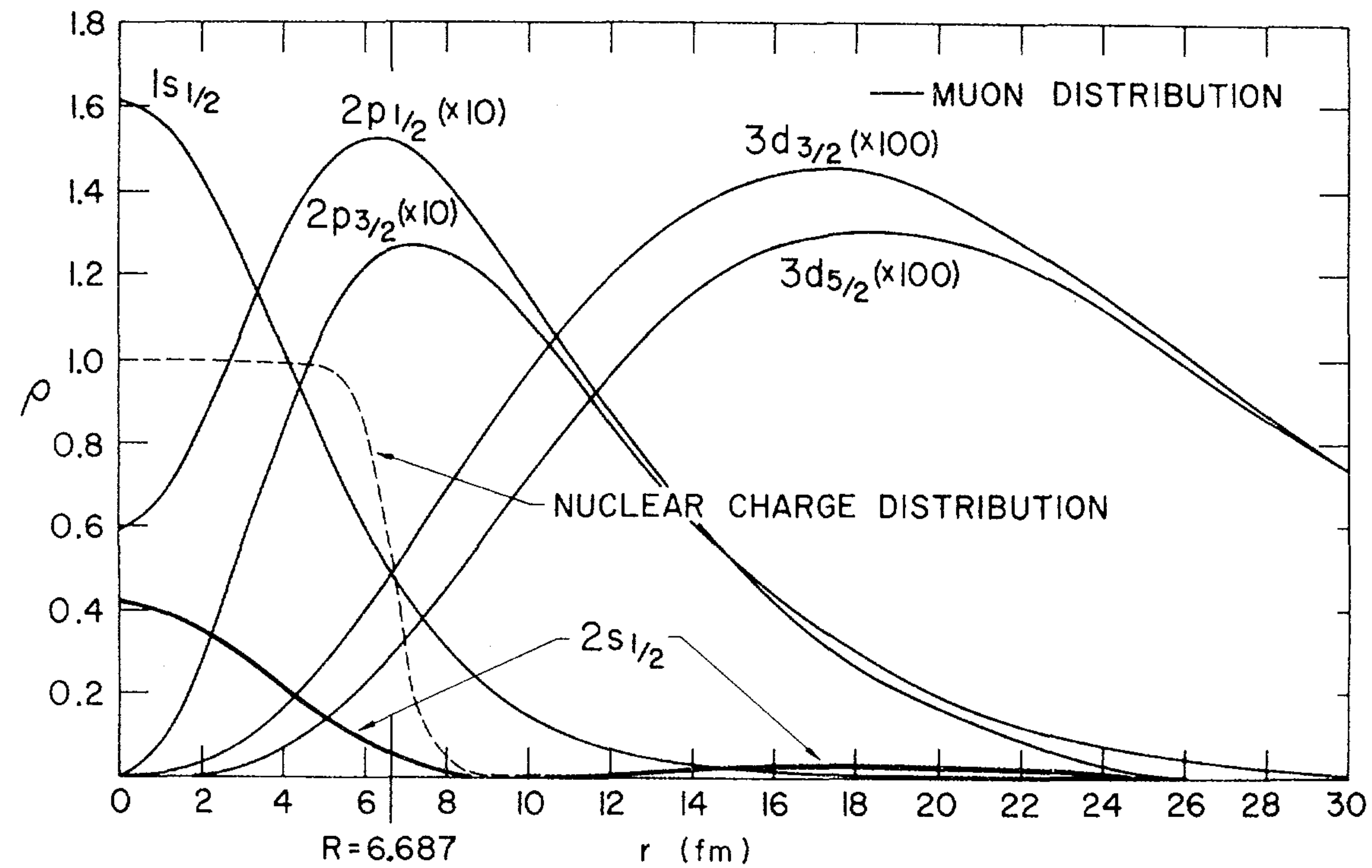
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

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

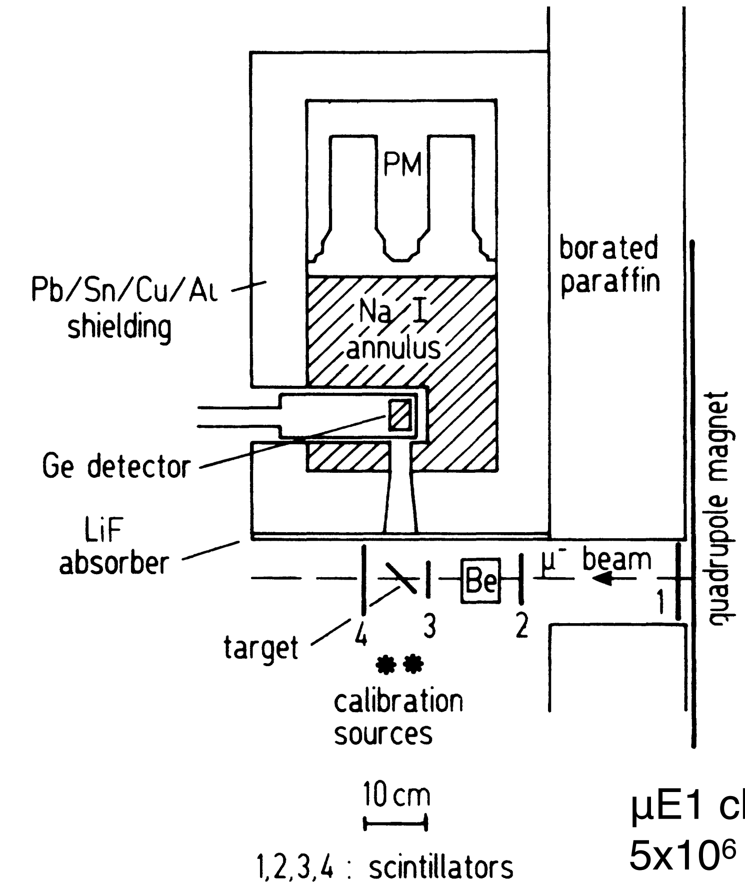
- Impressive precision in the extracted charge radius can be achieved

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

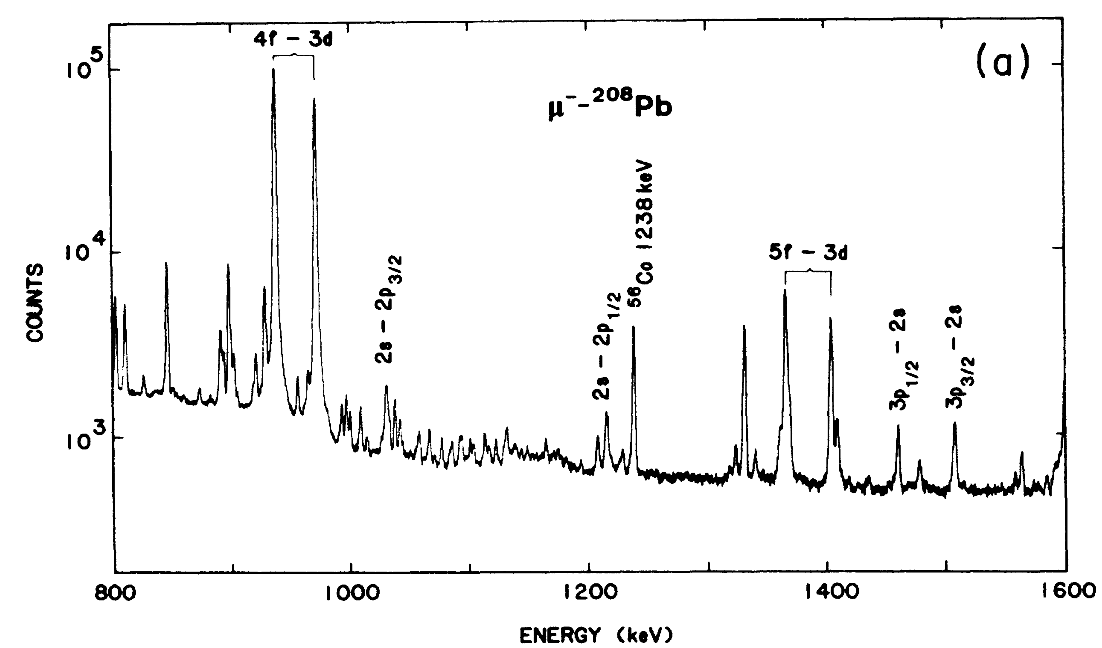
TABLE V. Experimental muonic transition energies (keV) in ^{208}Pb (recoil corrected).

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)

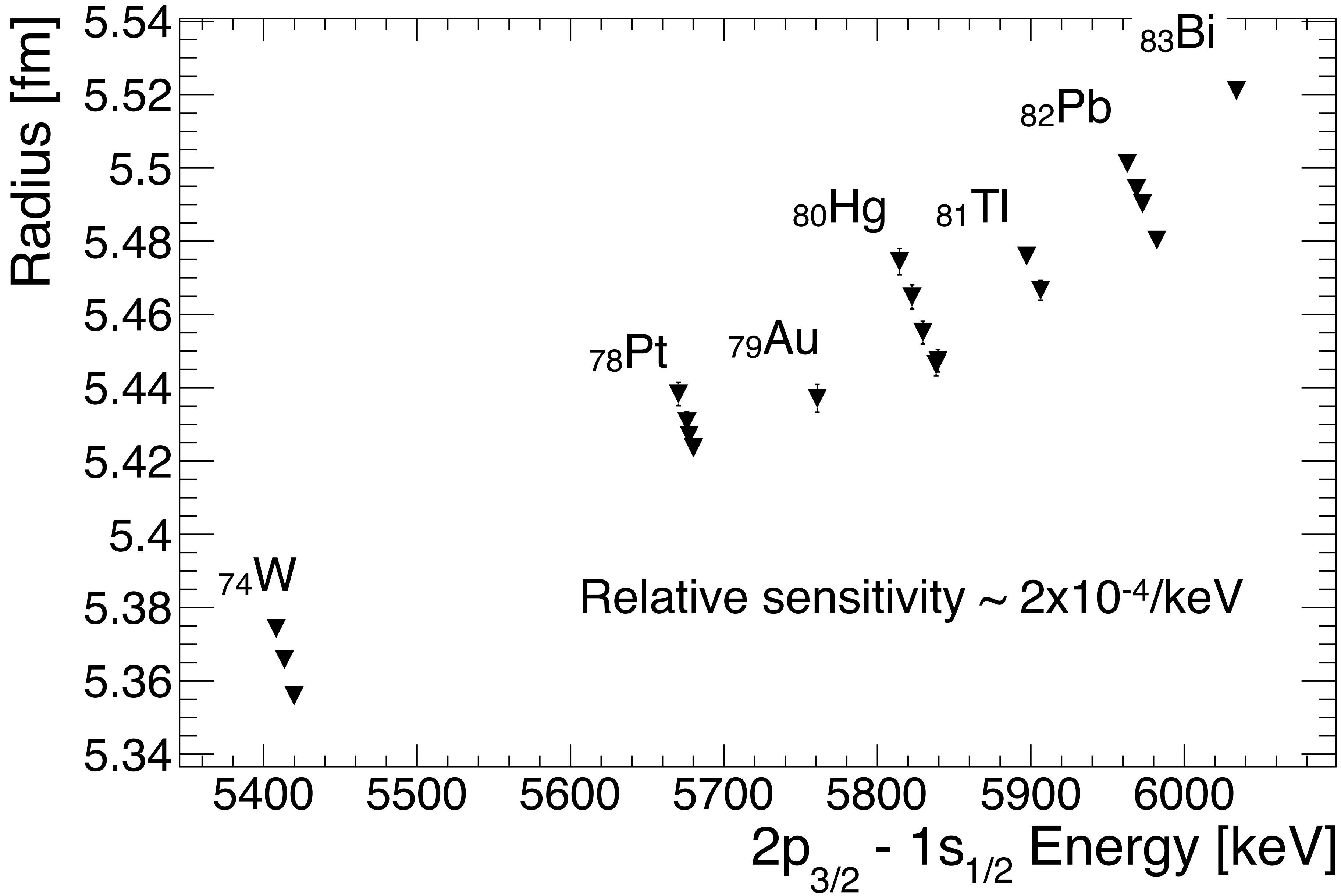
Bergem et al., PRC **37**, 2821 (1988)



μE1 channel at PSI
5×10^6 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%

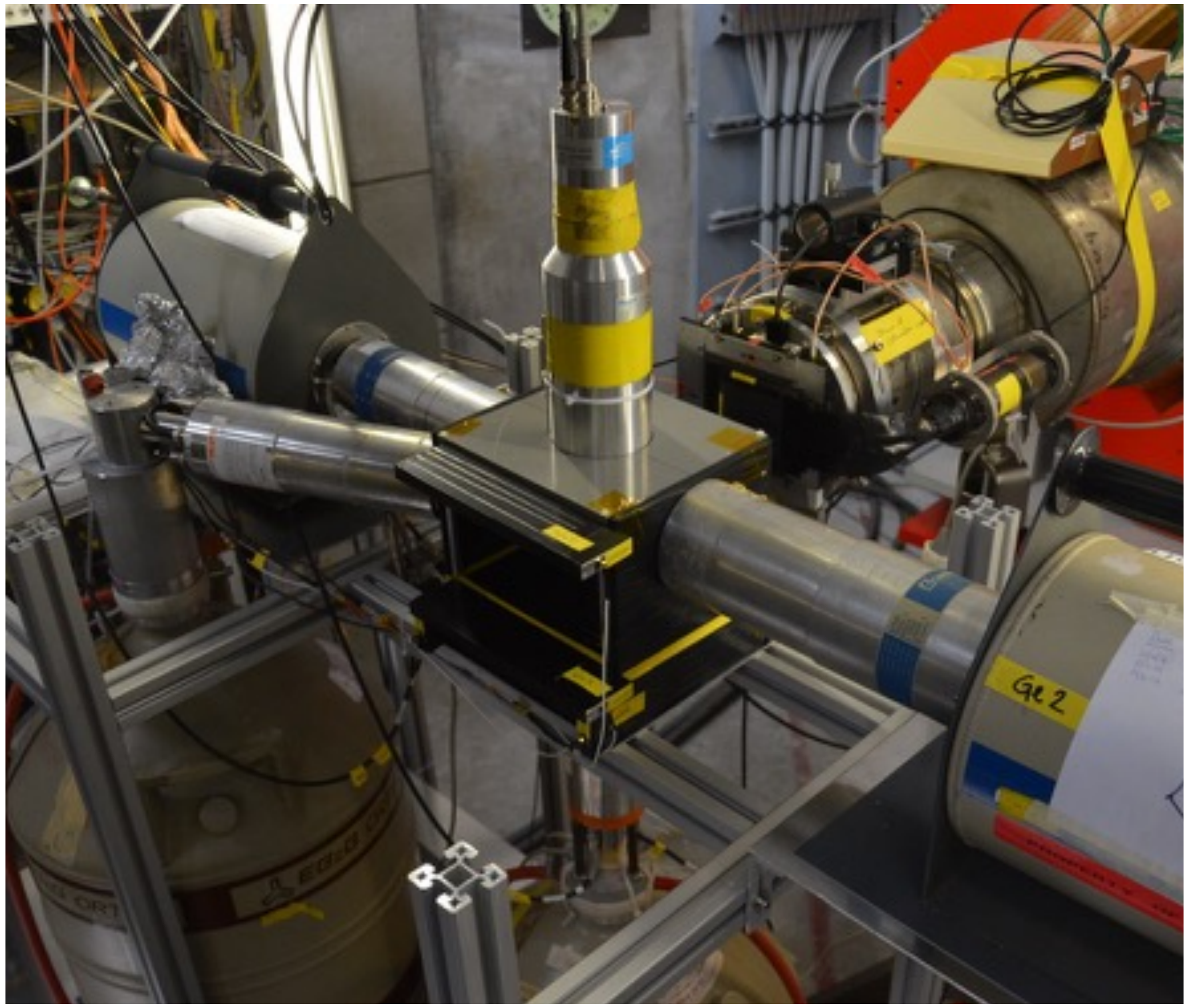
TABLE II. Theoretical nuclear polarization corrections in ^{208}Pb.

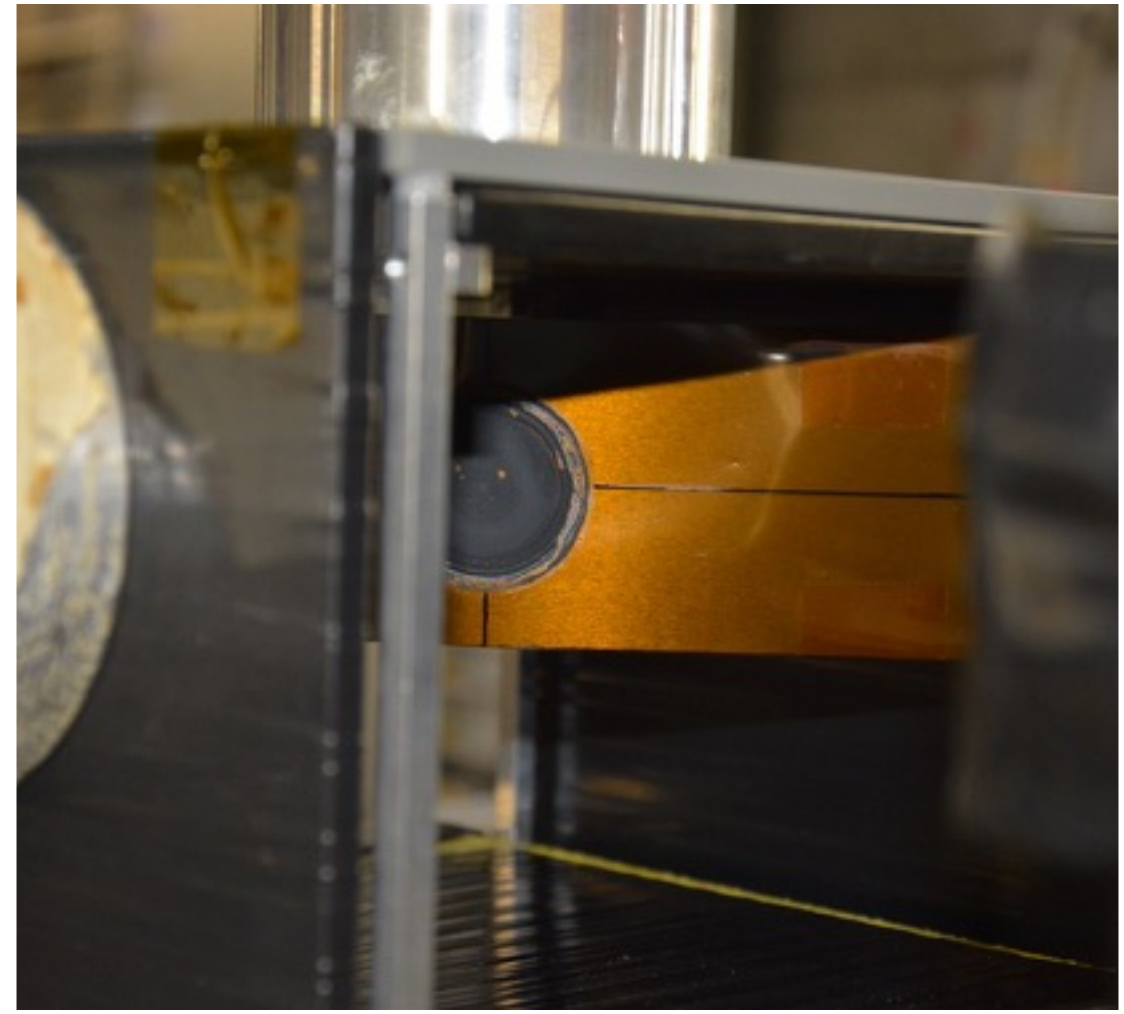
Energy (MeV)	I^{π}	$B(E\lambda)\uparrow$ ($e^2b^{2\lambda}$)	$1s_{1/2}$ (eV)	$2s_{1/2}$ (eV)	$2p_{1/2}$ (eV)	$2p_{3/2}$ (eV)	$3p_{1/2}$ (eV)	$3p_{3/2}$ (eV)	$3d_{3/2}$ (eV)	$3d_{5/2}$ (eV)
2.615	3^-	0.612	135	12	90	84	26	26	111	−63
4.085	2^+	0.318	198	20	182	180	76	84	6	4
4.324	4^+	0.155	14	1	8	7	2	2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

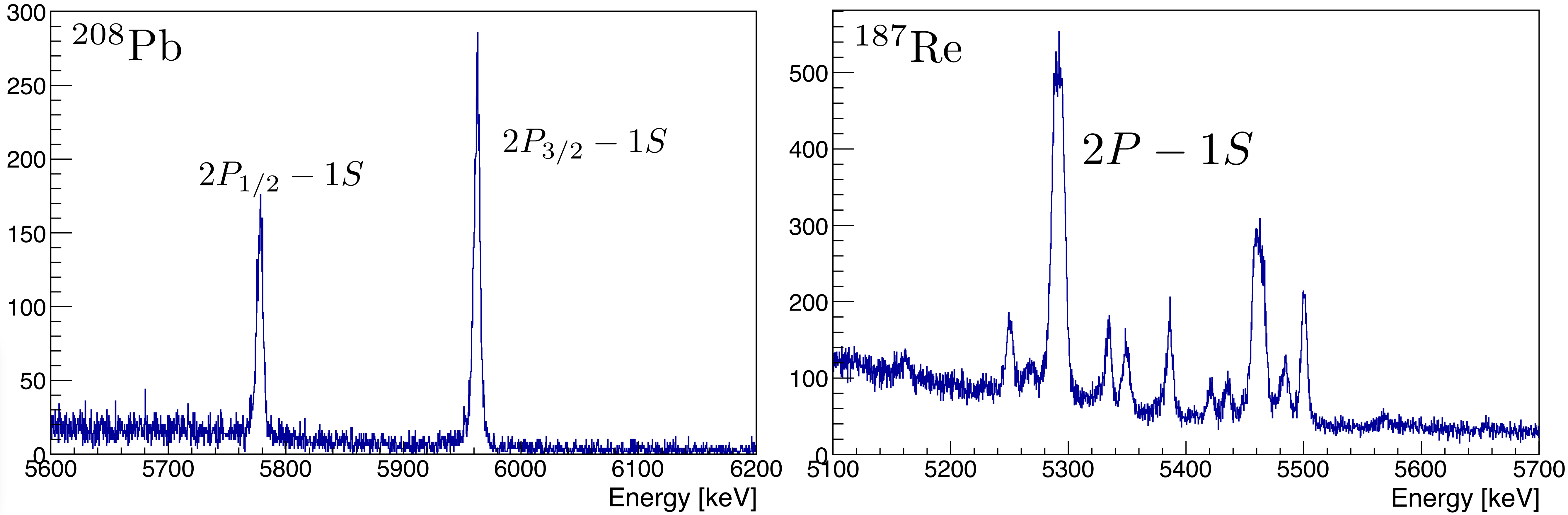
Our first steps





- Preliminary beam time in Nov. 2015
- Just finished 2 weeks of beam time on Monday
- Measured with 500 mg of ^{185}Re, ^{187}Re and 1000 mg of ^{208}Pb for calibration

Our first steps



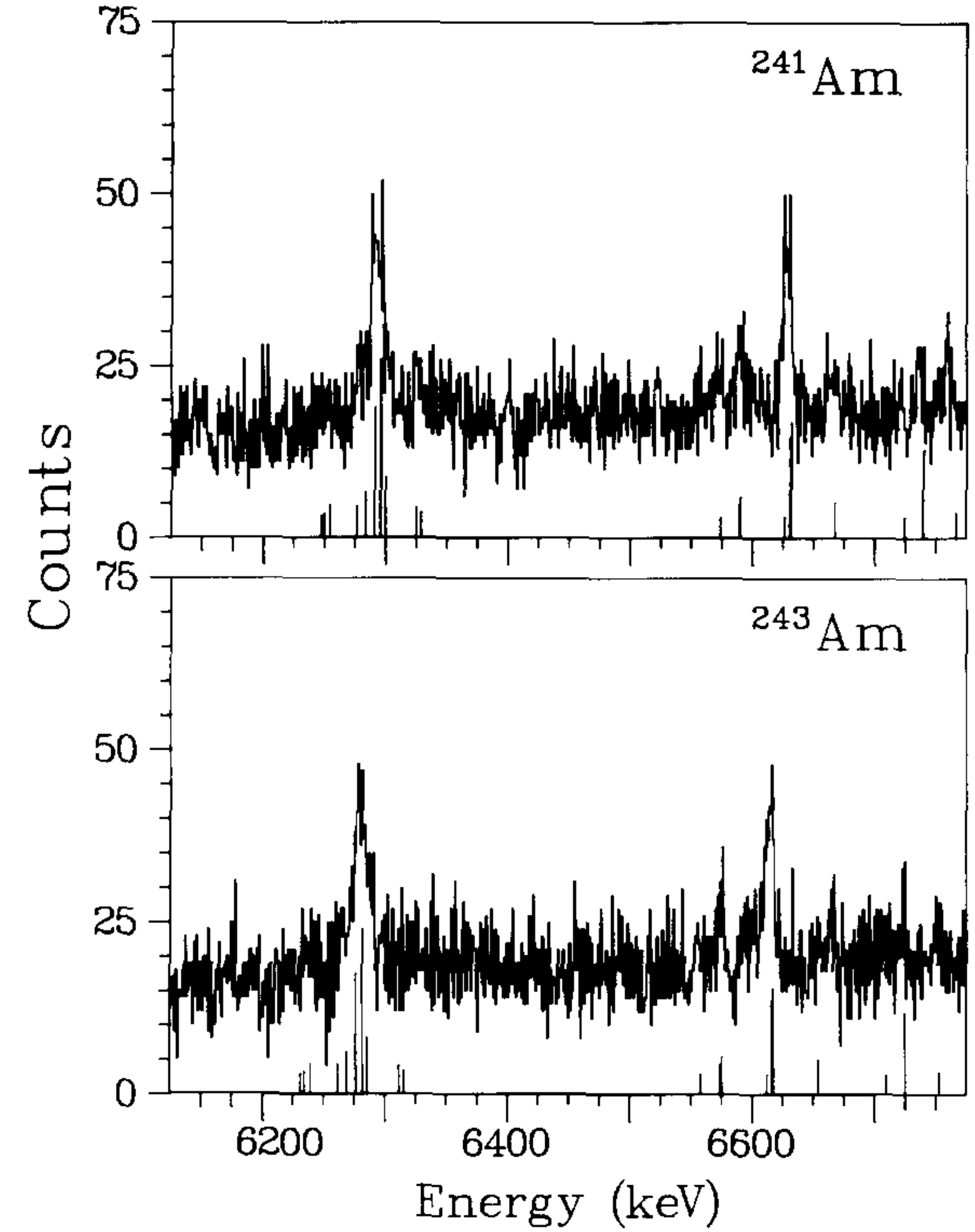
- Rhenium is the last stable element without absolute charge radius
- Complicated spectrum due to hyperfine structure and low-energy nuclear excitations

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)



Radioactive Isotopes in Experimental Hall

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Isotope	Half-life	Max. Activity	Max. Mass	Density
^{226}Ra	1600 y	200 kBq	5 µg	~ 1 µg/cm^2
^{248}Cm	350'000 y	5 kBq	32 µg	~ 7 µg/cm^2
^{209}Po	102 y	200 kBq	0.3 µg	~ 0.1 µg/cm^2

- Interesting radioactive isotopes that can be used as targets and without measured absolute charge radius
- Maximum activity based on current regulations and without major modifications to experimental area infrastructure (100 x approval limit)

Methods for low-mass targets

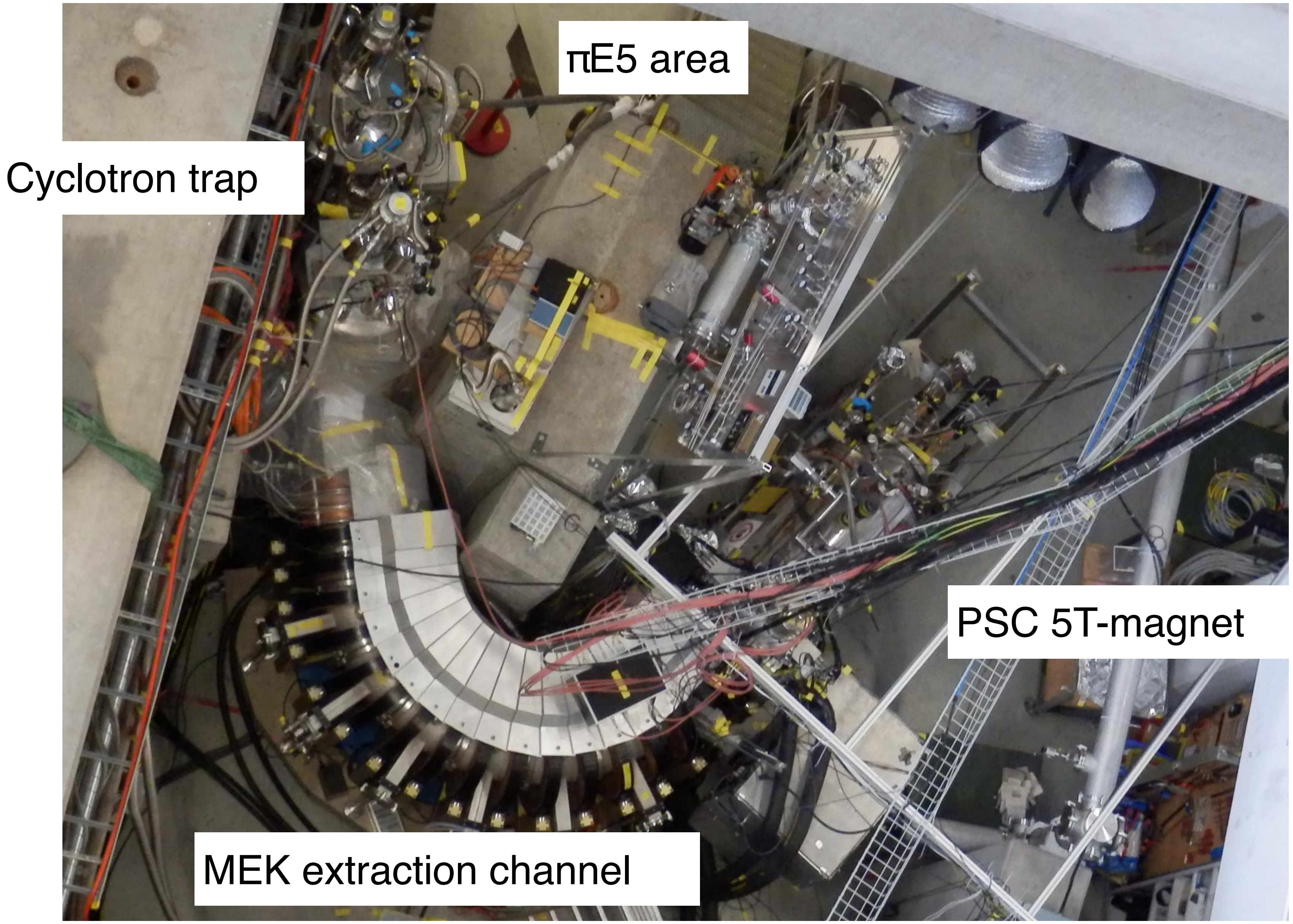
- Low-energy negative muon beam to stop directly in low-mass target

  → Beam developed for Lamb shift experiment

- Standard negative muon beam stopped in D_2/H_2 mixture and exploiting transfer reactions to stop in low-mass target

  → Method pioneered by Strasser, Nagamine et al., based on the wealth of information that was gathered measuring muon catalyzed fusion

Lamb Shift Beam Line



- Negative pions at 100 MeV/c captured in cyclotron trap
- Decay muons slowed down in passages through thin foil and extracted by applied HV

Lamb Shift Gas Target

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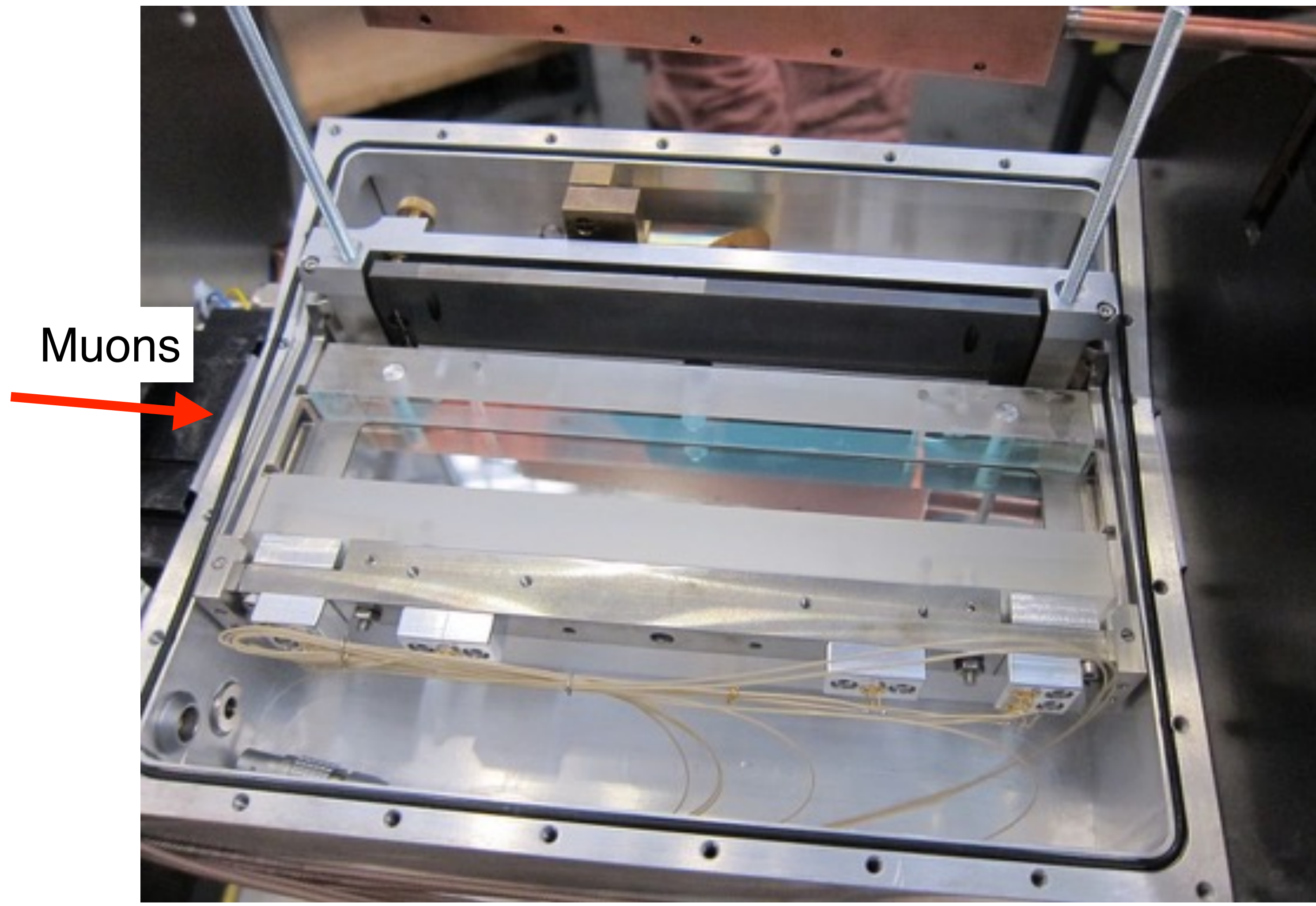
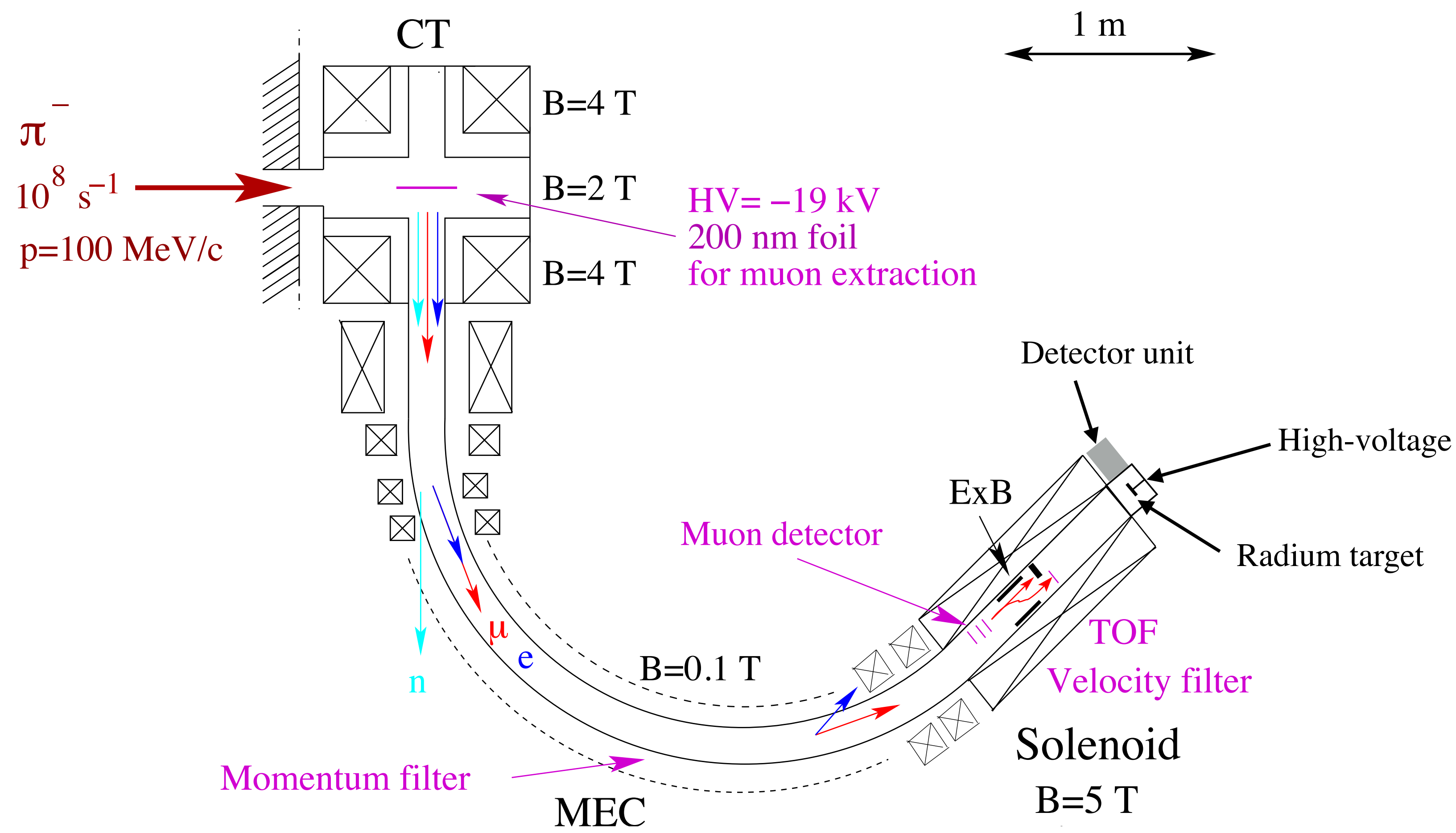
- Gas target located inside 5T-magnet
- *O*(1 mbar) of H_2, D_2, ^3He, ^4He
- Densities of ~ 2 µg/cm², ~80% stopping efficiency
- Ideal beam to stop in low mass radioactive targets



Setup for Proposed Measurements

- Radioactive targets and germanium detector in fringe field of 5T-magnet

- Target and detector at ~ 1 T



Target Chamber

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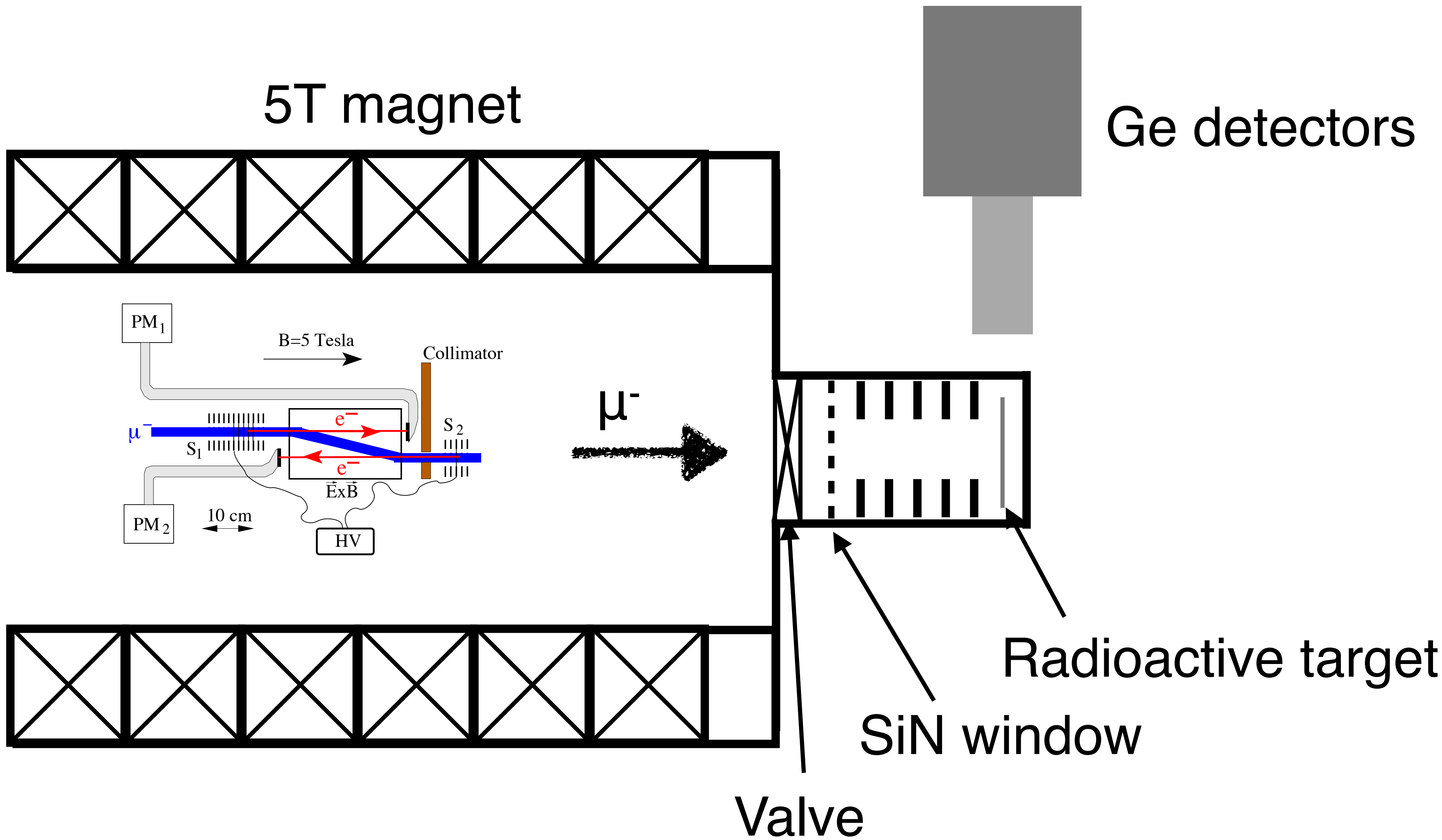

- Target chamber separated by thin SiN window
- High voltage applied to window and target to adapt muon energy
- Large germanium detectors close to radioactive target

Transfer reactions in H_2/D_2 gas

- Suggested to us by P. Kammel
- Based on the experience by Strasser et al. and Kraiman et al.
- Low-mass target coated on thin foil suspended in gas
- Material budget not enough to coat many foils (5 µg Ra = 5 nm on 2 cm^2)
  → Need cryogenic high-pressure target to have high-enough stopping power: 35 K, 8 bar
  → z_{rms} ~ 5 mm

Kraiman et al., PRL **63**, 1942 (1989)

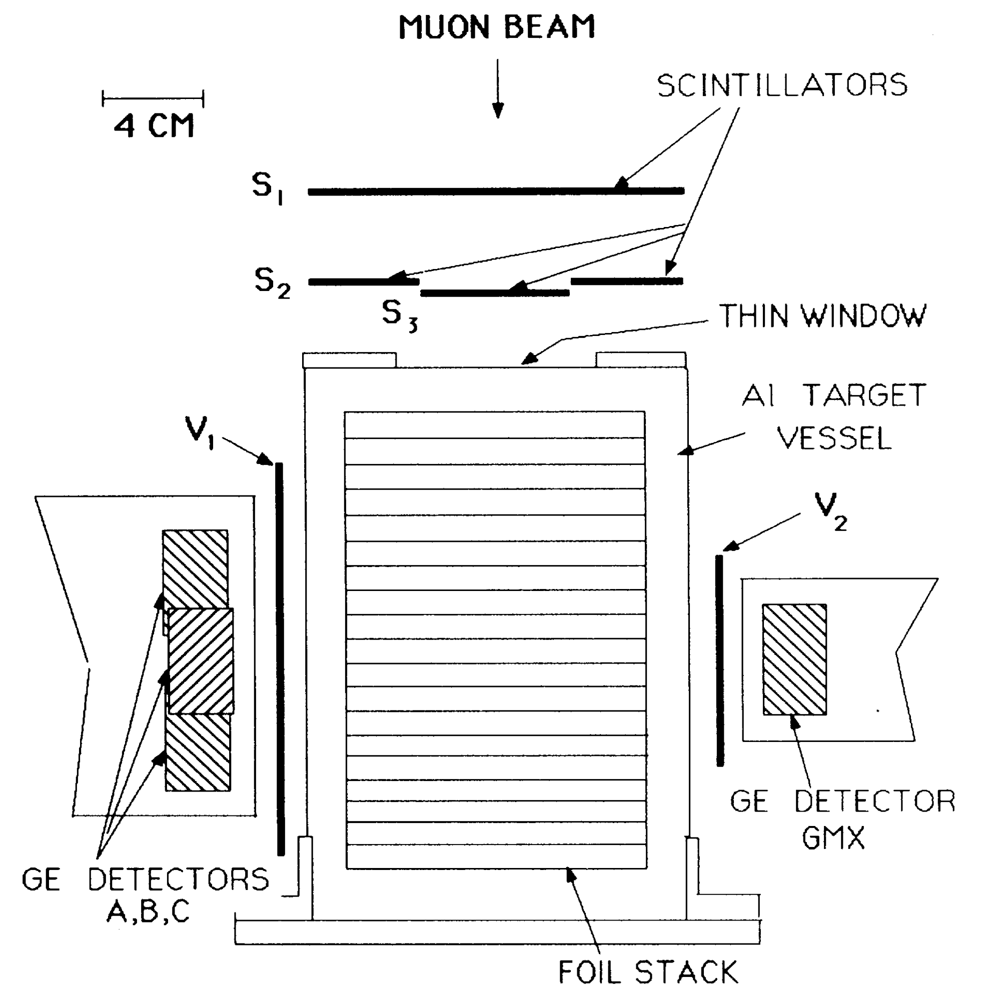

FIG. 1. Experimental setup for the diffusion experiment. Plastic scintillators S_1,S_2,S_3 are beam telescope counters. Scintillators V_1,V_2 veto charged particles. The foils are 10 cm in diameter.

Transfer reactions in H_2/D_2 gas

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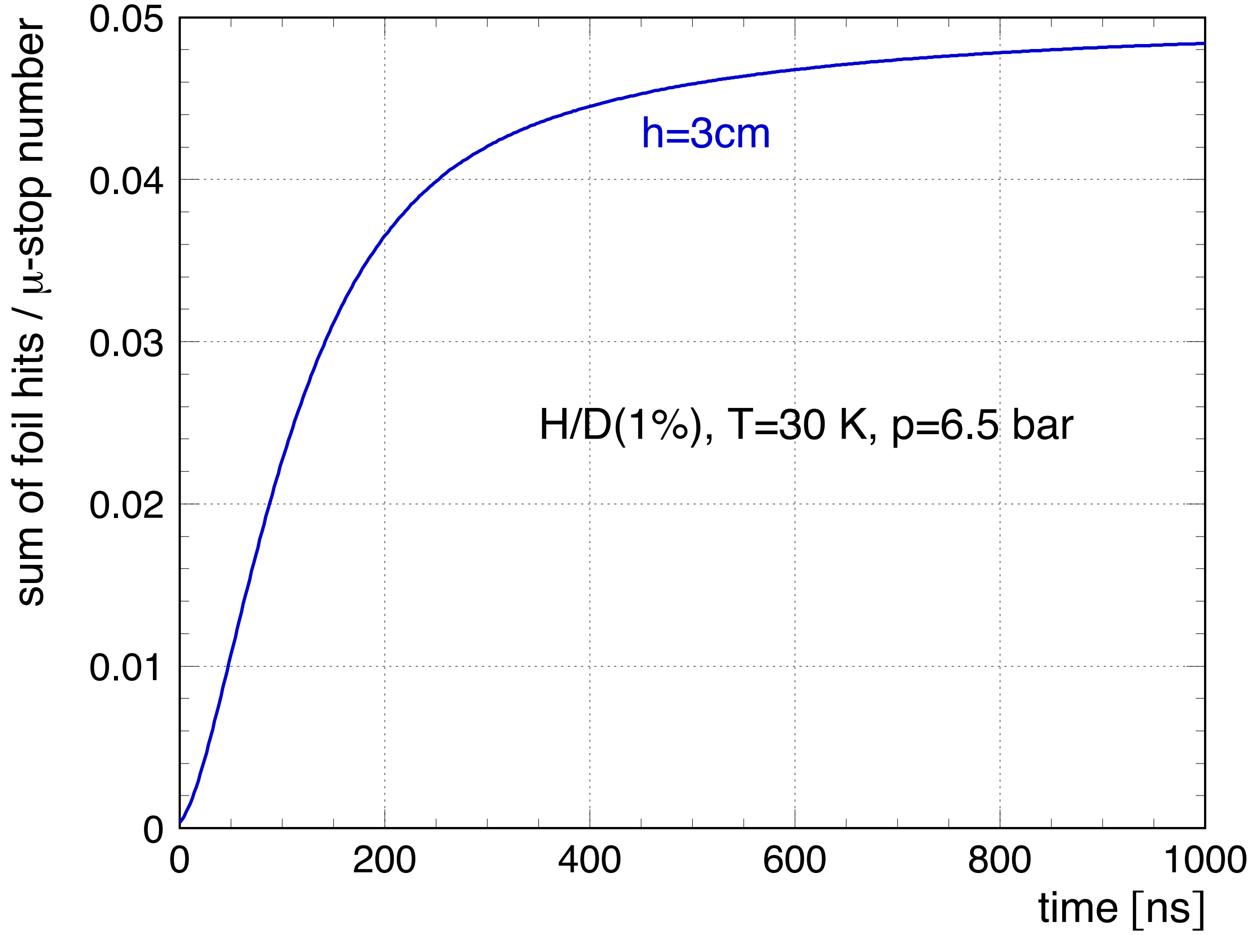
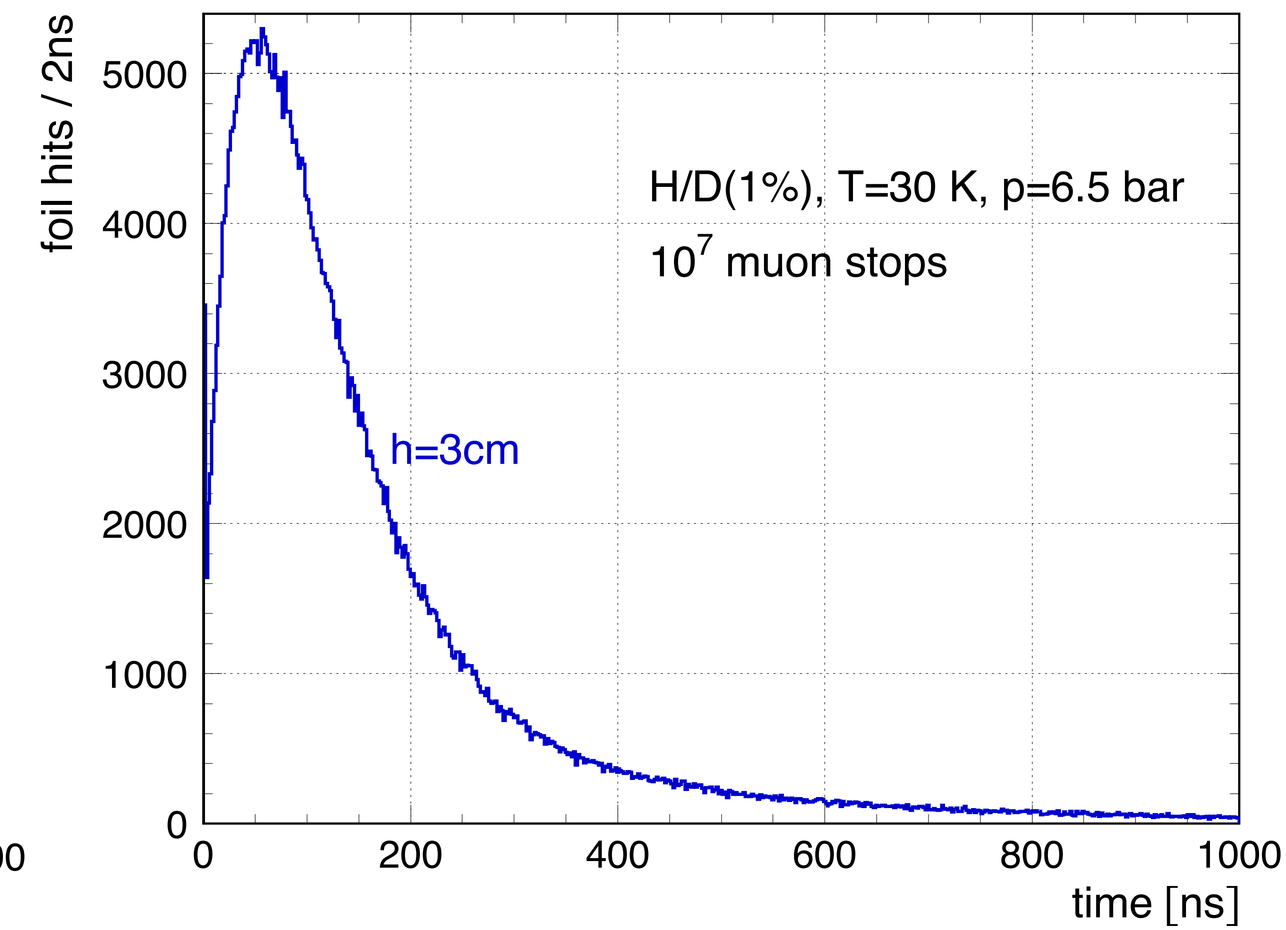
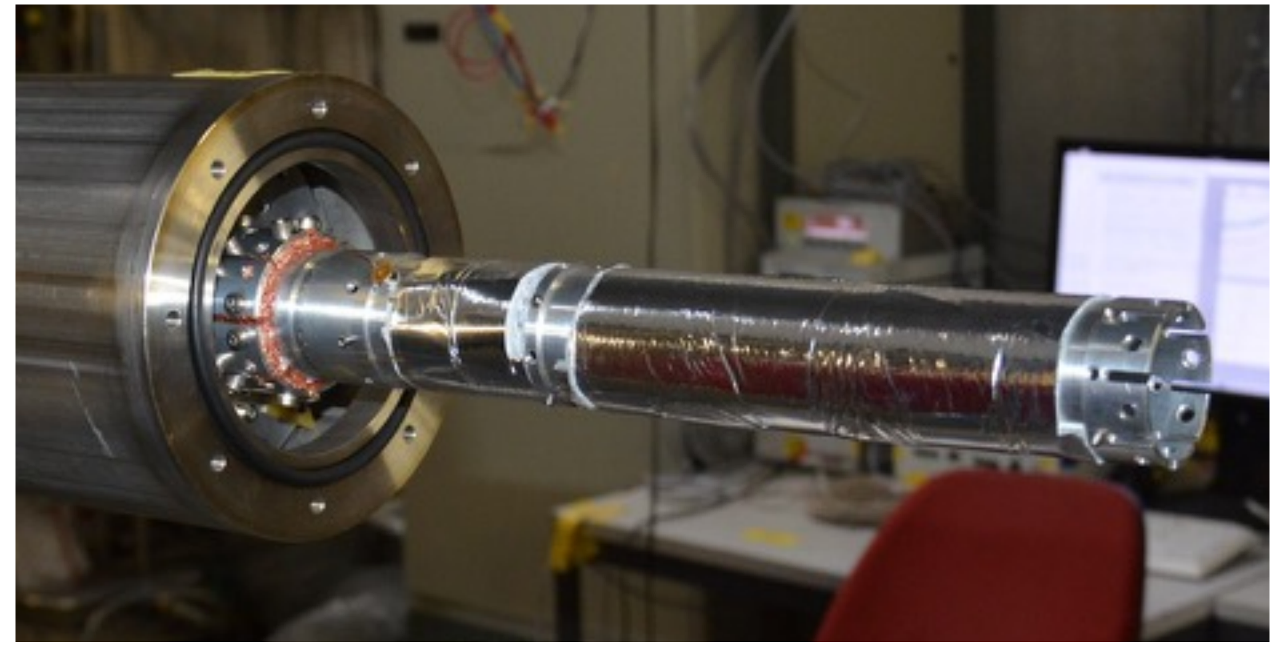




- Minimum in scattering cross-section for μD in H_2 (Ramsauer-Townsend effect) for μD energies after transfer → μD travel far!
- Muon transfer from μD to high-Z material upon hitting target
- Geometry of simulation: Two foils of 1 cm^2 separated by 3 cm, muons stopped uniformly in between foils
- Simulations by A. Adamczak

Our first steps



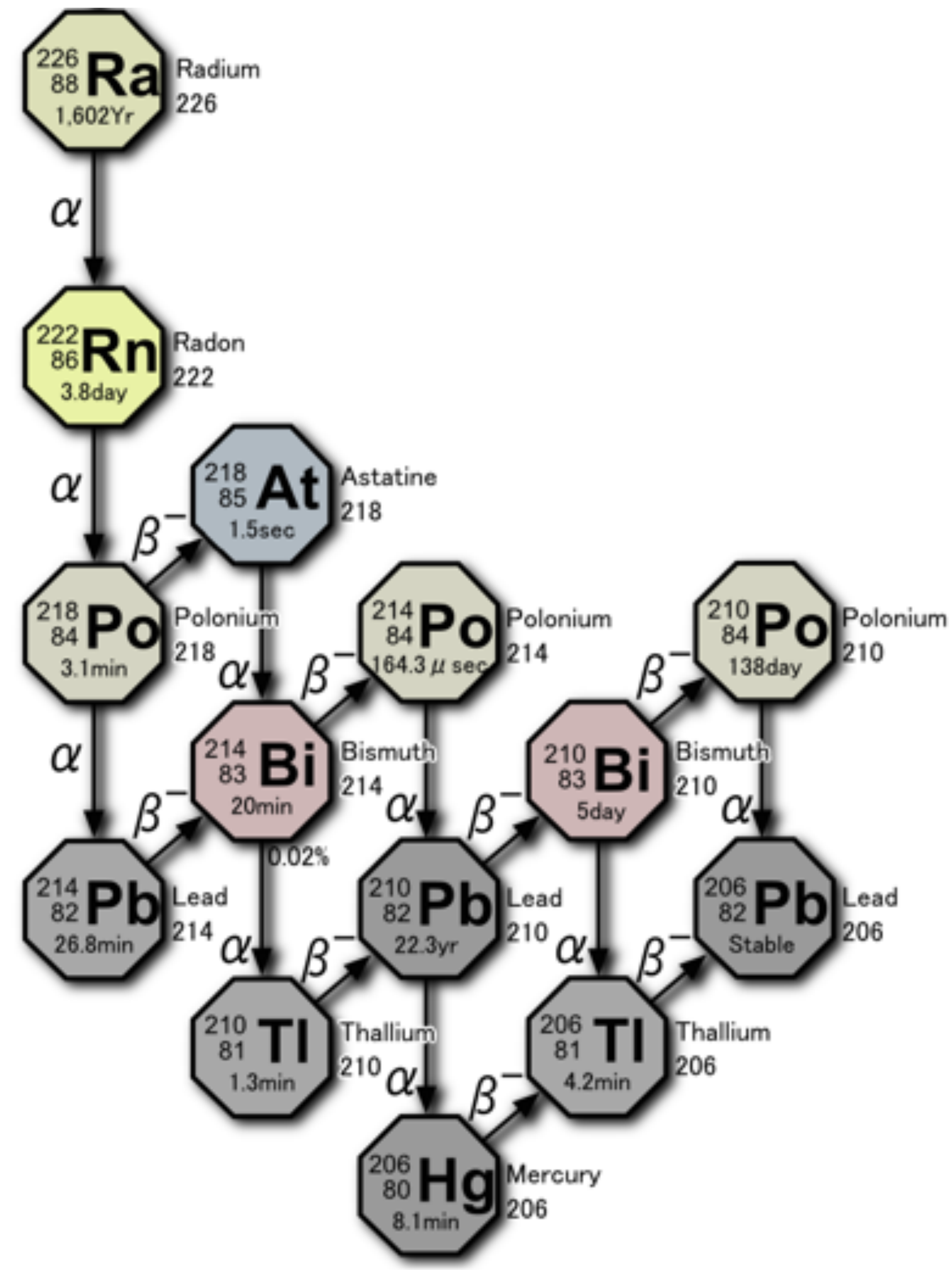
- Constructed gas cell cooled by 4 K pulse-tube refrigerator (typically used for different experiment)
- Small gas cell with copper back wall coated with ~50 nm of gold

Our first steps

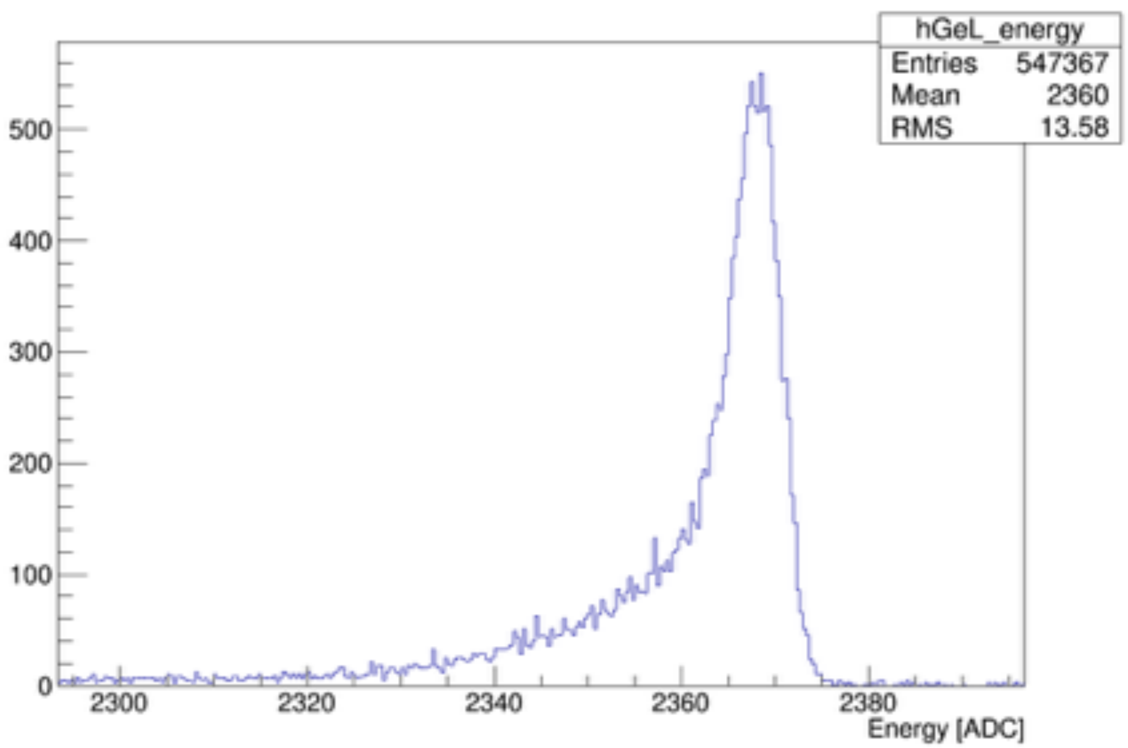
- Unfortunately did not observe any transfer x-rays due to several problems
- Cooled down and warmed up cryostat 4 times within one week to do changes:
  - First cell had lead sputtered onto mylar, suspected that penetration was too deep
  - Realized that gas lines were too cold and got frequently blocked by freezing out hydrogen/deuterium
  - Two cold leaks on our gas cell
- Might have the possibility to do a room temperature test still this year

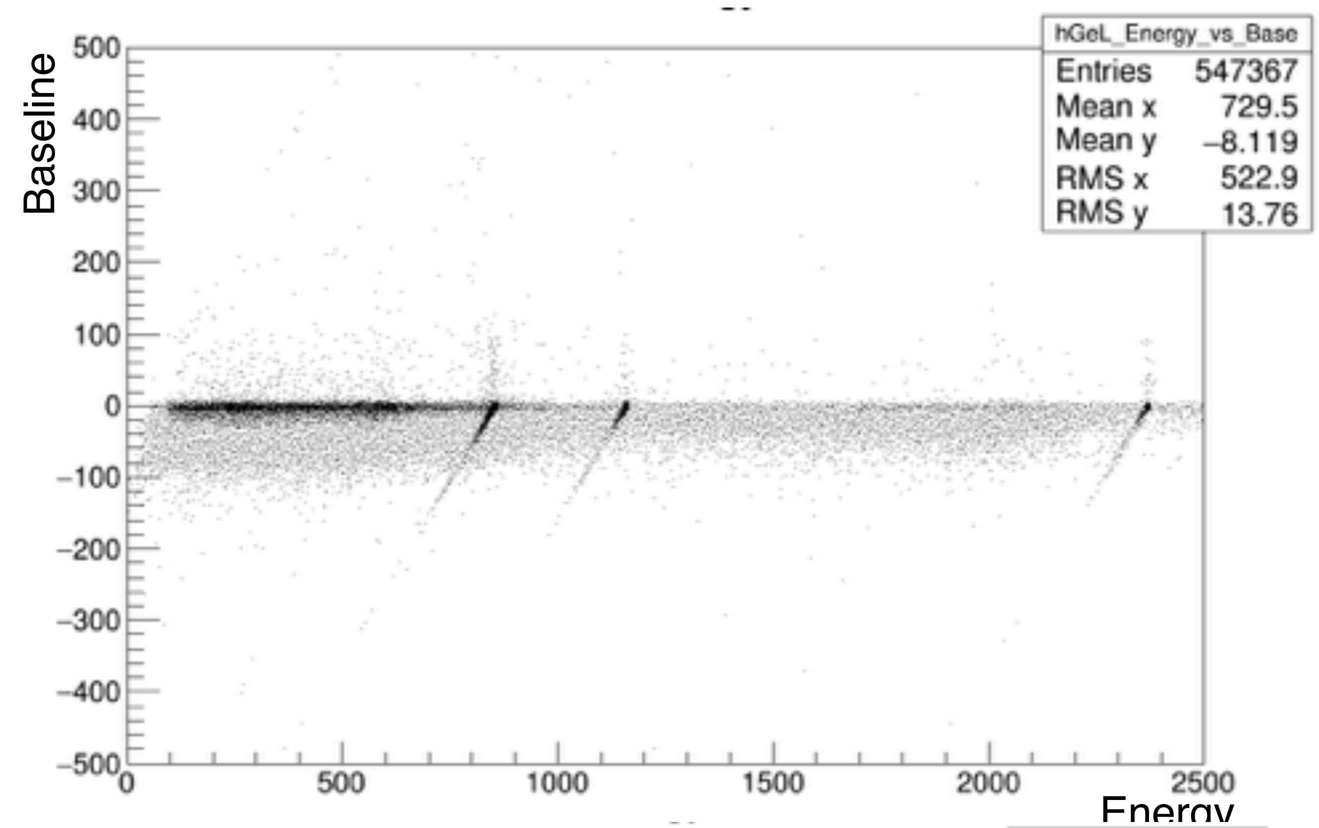
^{226}Ra

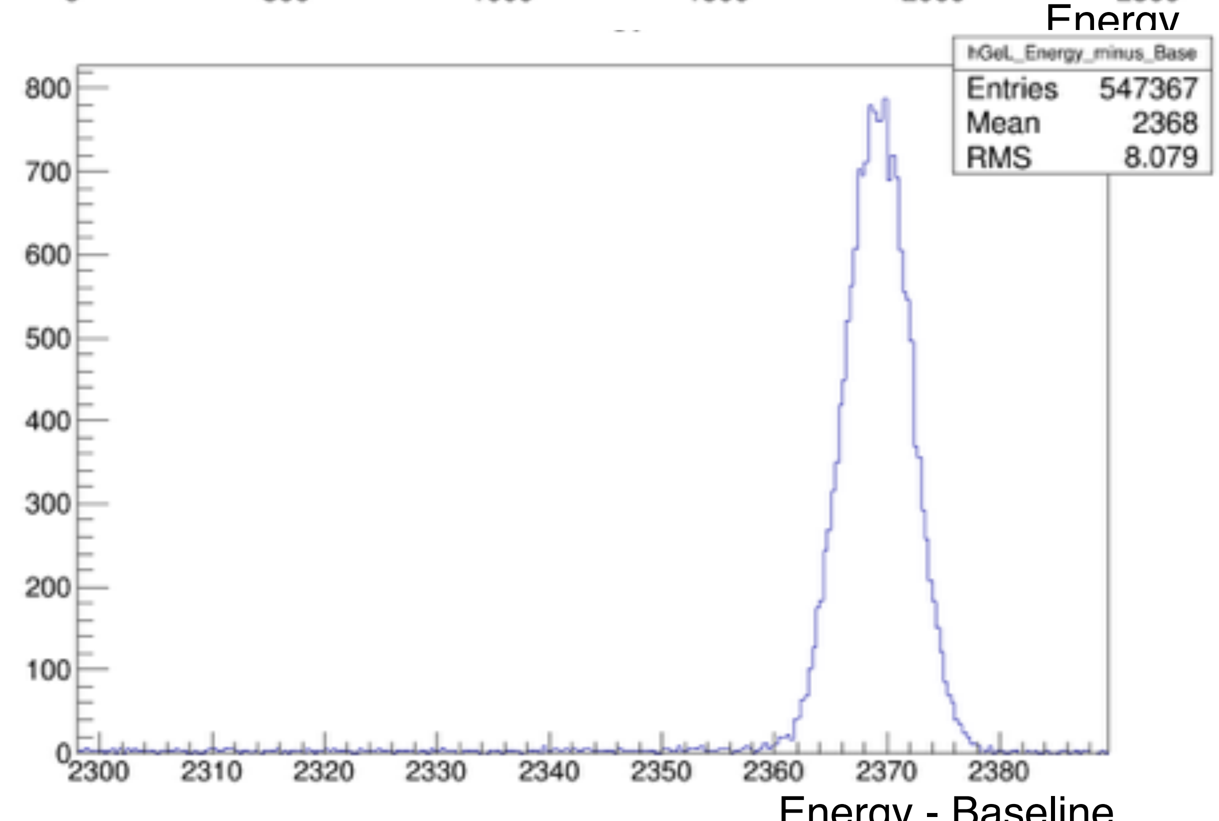
- Large decay chain with many daughter isotopes
- Strongest gamma emitter ^{214}Bi with E_γ up to 2.5 MeV
- From 200 kBq ^{226}Ra
  → 500 kHz γs with $E_\gamma > 100$ keV
- Retention of ^{222}Rn in target?



Spectra with strong source

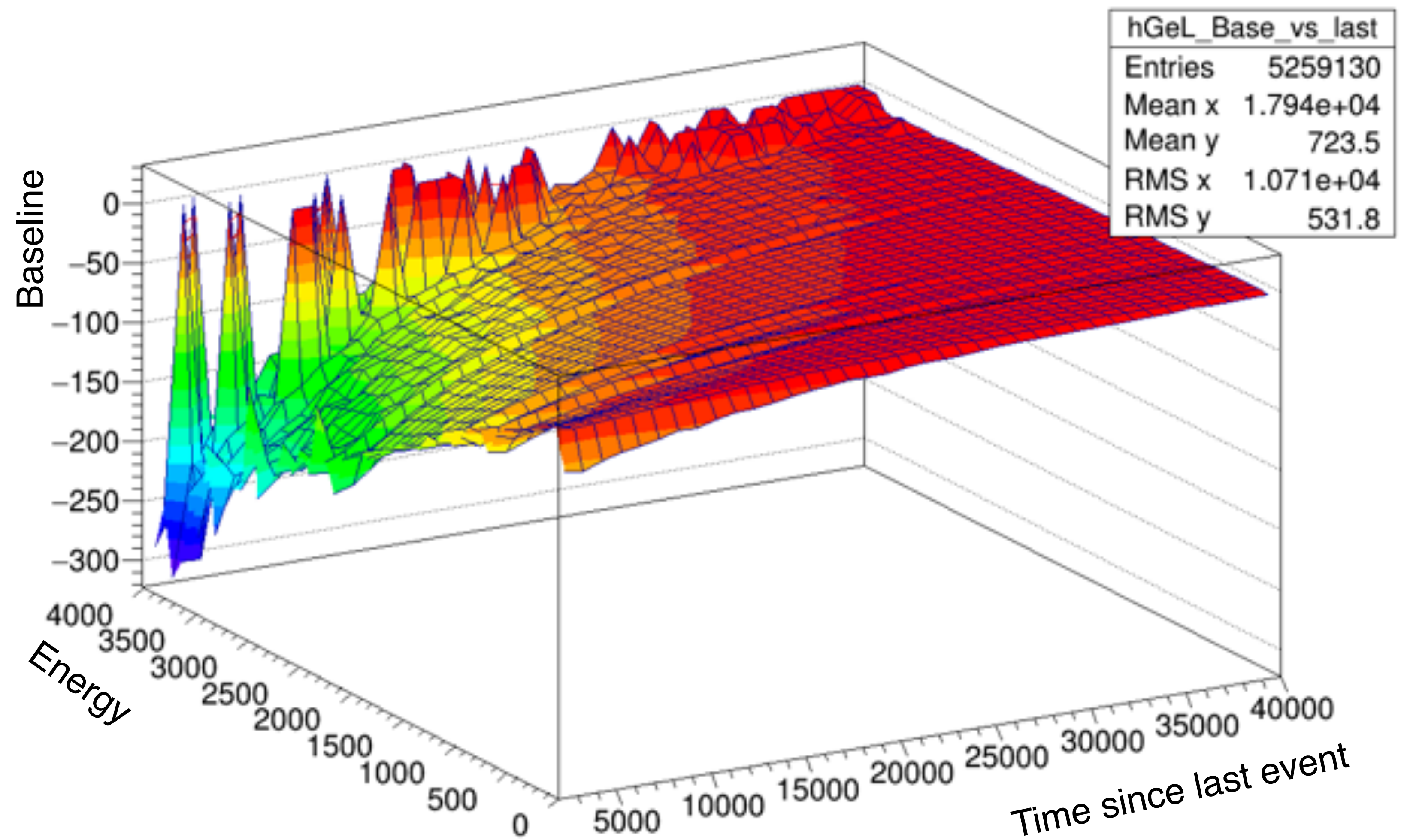






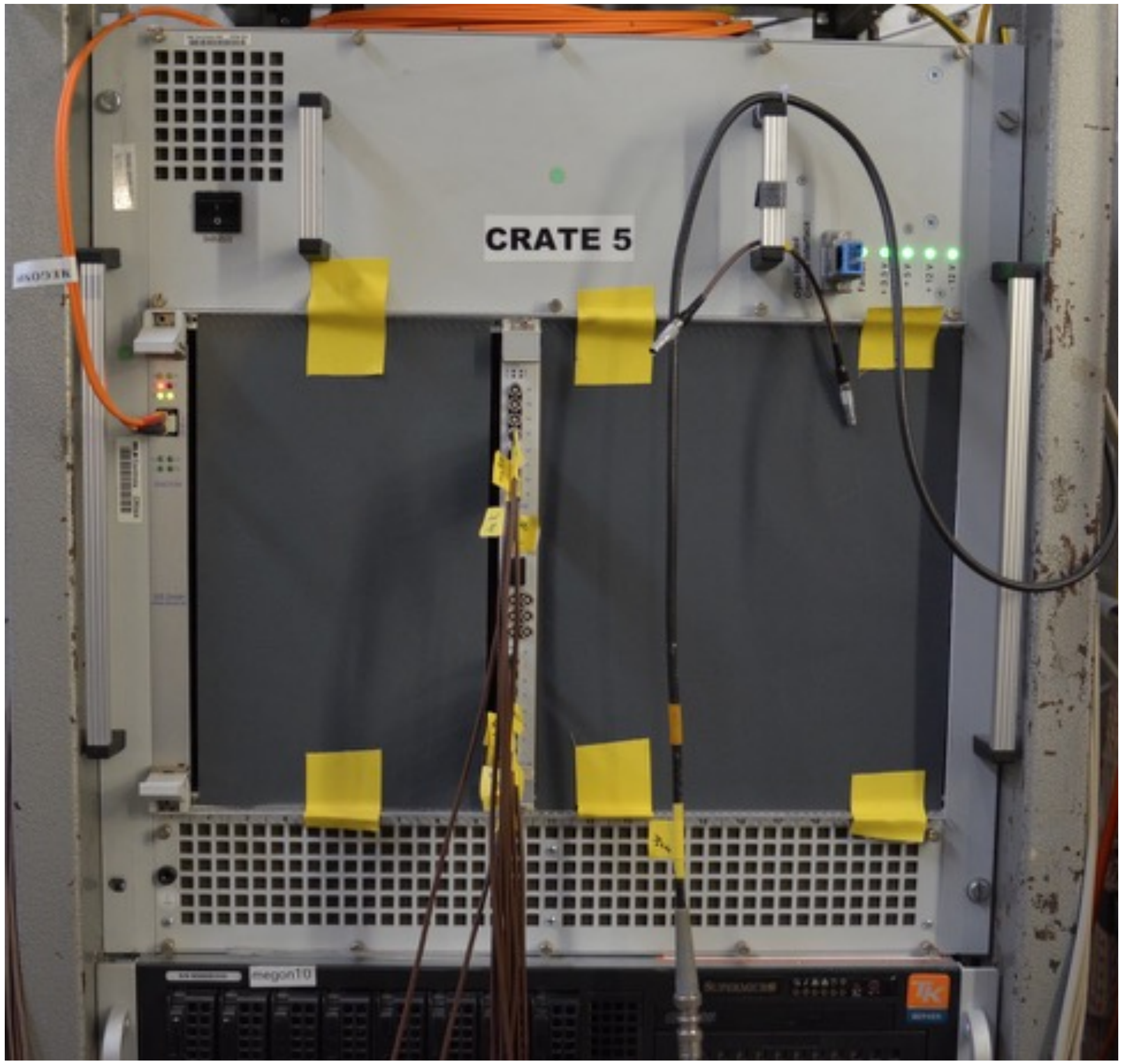
- Took muonic spectra in the presence of 500 kHz gammas
  → 6 kHz on large germanium detector
- Loose 10% of muonic x-rays due to pileup
- Low-energy tails on peaks
- Trivial correction, but √2 increased resolution

Spectra with strong source



- Looking at absolute baseline correction based on amplitude and time of last event
  → no hit on resolution!

Tested new DAQ module



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

- Struck SIS3316 digitizer: 16 channel, 14 bit, 250 MHz
- Firmware for online pulse processing
- Worked very nicely! All detectors (scintillators, germanium) recorded with same module
- Able to record all events in all detectors with muons and 500 kHz gammas present (no traces)

Conclusions & Outlook

- Interest in charge radii from atomic parity violation experiment and nuclear physics
- Radium as a first measurement and possibility to develop the method for several low-mass targets
- Germanium spectroscopy of muonic x-rays well under control
- Focus lies now on measuring with low-mass targets

muX Collaboration

A. Antognini[1,2], N. Berger[3], D. vom Bruch[3], R. Dressler[1], A. Eggenberger[2], R. Eichler[1], P. Indelicato[4], K. Jungmann[5], K. Kirch[1,2], A. Knecht[1], A. Papa[1], R. Pohl[3], M. Pospelov[7,8], E. Rapisarda[1], N. Ritjoho[1,2], N. Severijns[9],A. Skawran[1,2], F. Wauters[3], L. Willmann[5]

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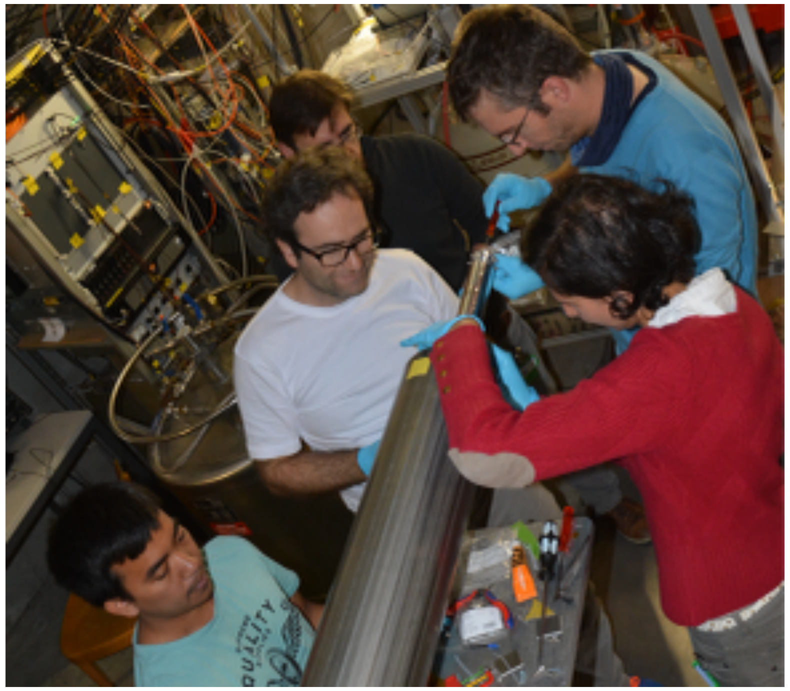
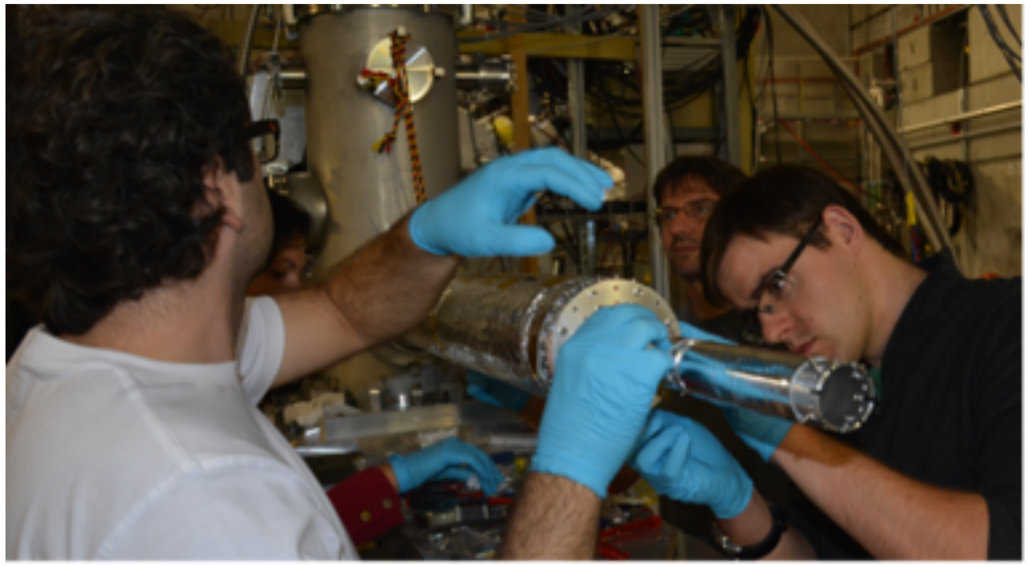
[8] Perimeter Institute, Canada
[9] KU Leuven, Belgium



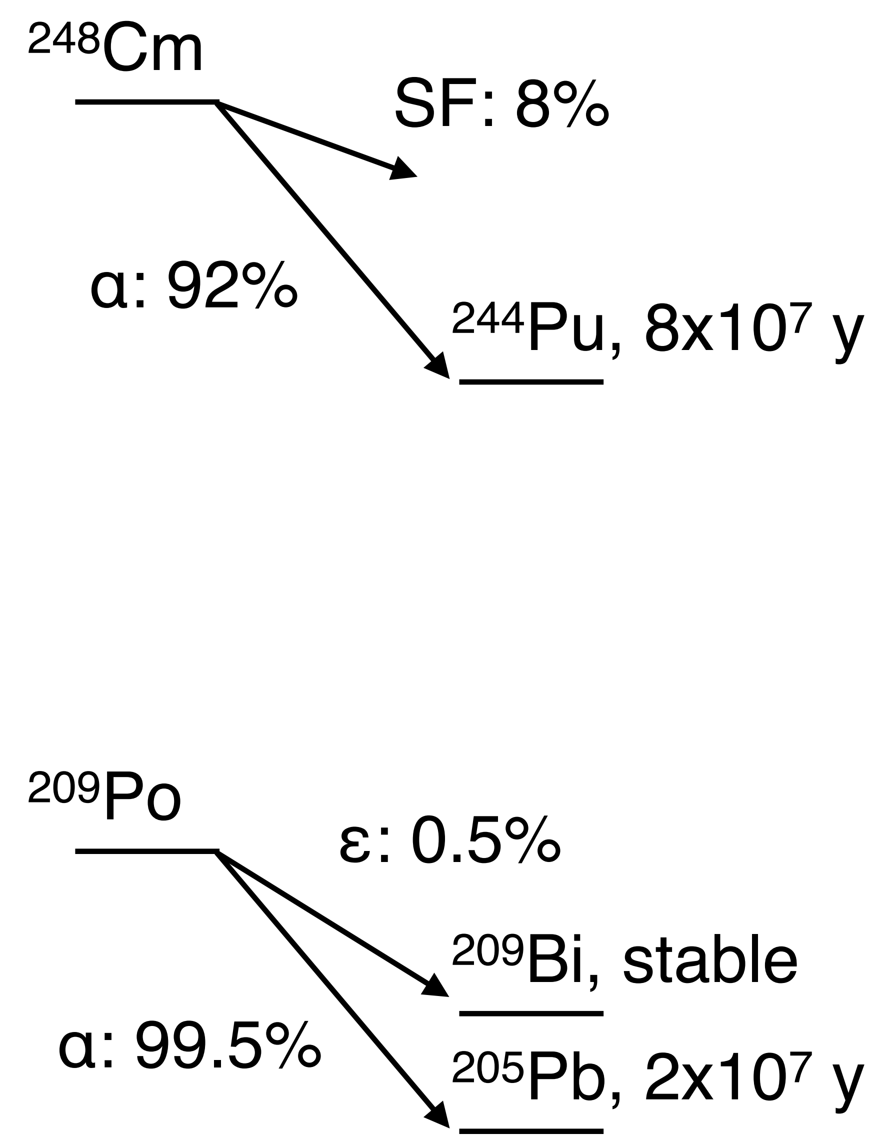


Backup

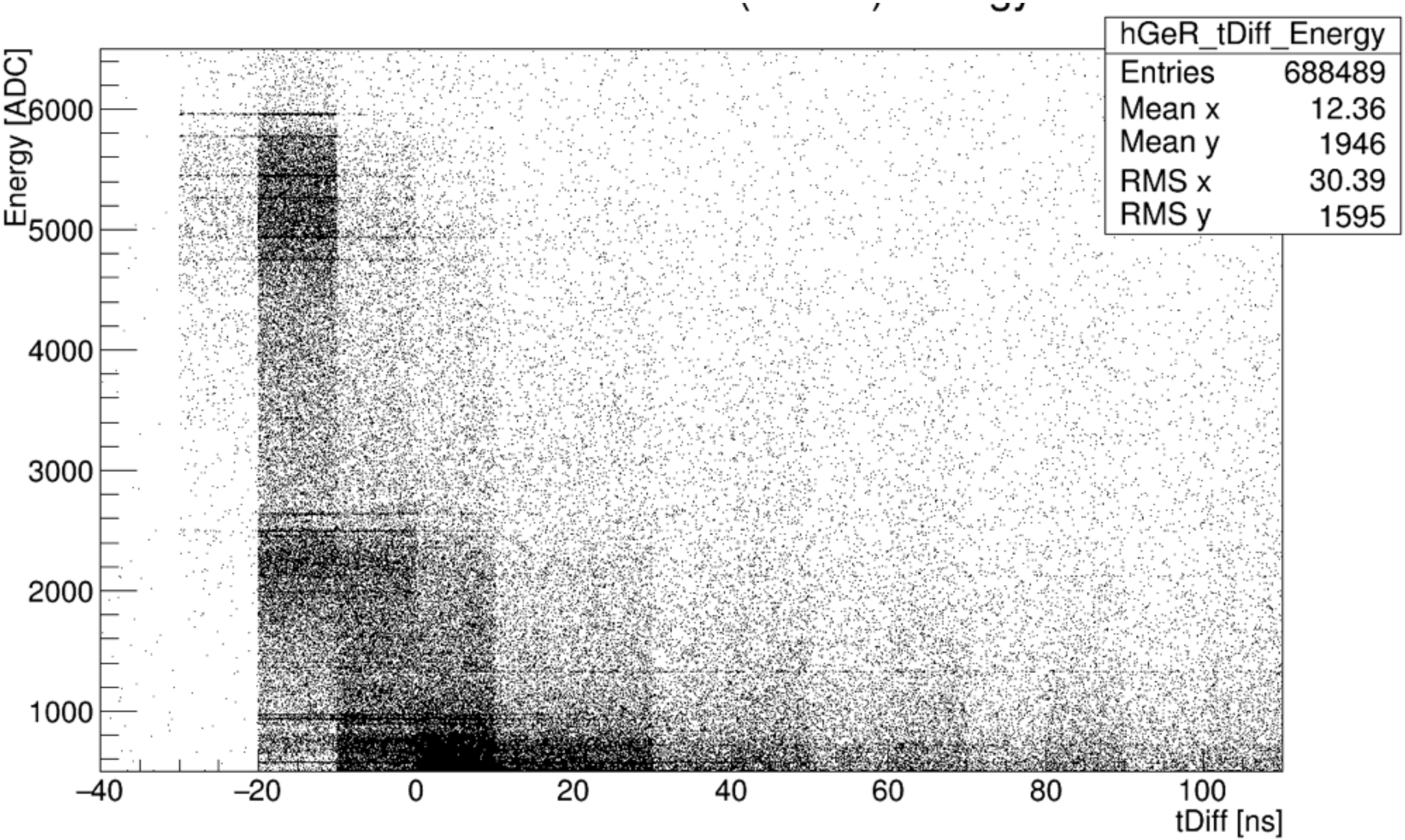
^{248}Cm & ^{209}Po

- Radioactivity from curium and polonium much easier to handle

- Only relatively small amount of gammas



Timing



hGeR_tDiff_Energy
Entries 688489
Mean x 12.36
Mean y 1946
RMS x 30.39
RMS y 1595
Energy [ADC]
1000
2000
3000
4000
5000
6000
−40
−20
0
20
40
60
80
100
tDiff [ns]

Radioactive Target

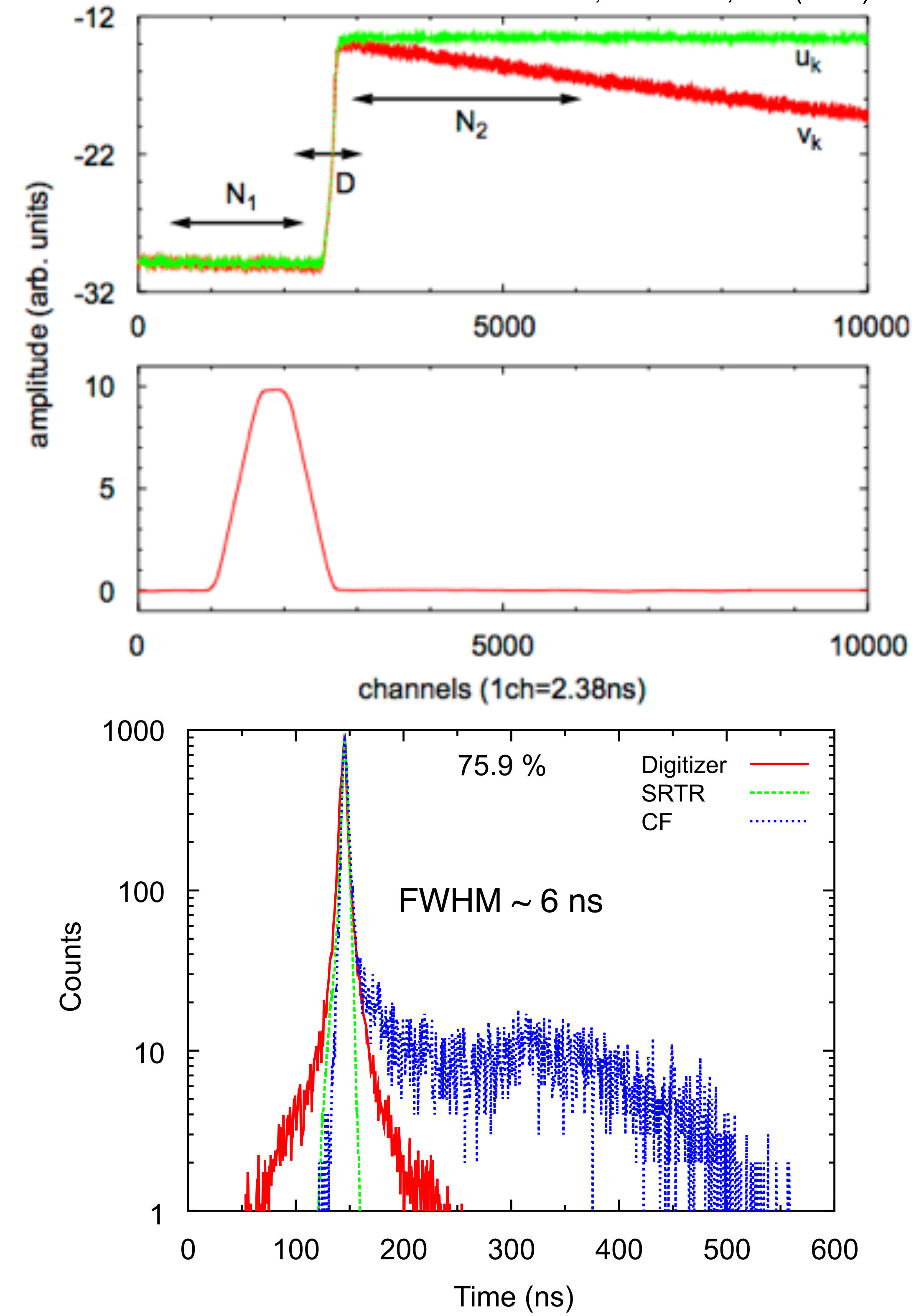
- Radioactive targets produced by electroplating on glassy carbon substrate
- Standard practice in radiochemistry
- Rugard Dressler and Robert Eichler from radiochemistry group joined the collaboration

- ^{226}Ra available from University of Bern
- ^{248}Cm available from PSI/nTOF
- ^{209}Po will probably need to be bought (other options under investigation)

Time Resolution of Large HPGe

- Digital pulse processing on recorded preamplifier waveforms
- Similar energy resolution as analog system
- Excellent timing resolution of ~ 6 ns achieved
- Timing precision of muon entrance detector currently unknown - depends on muon time-of-flight

Mihailescu et al., NIMA **578**, 298 (2007)



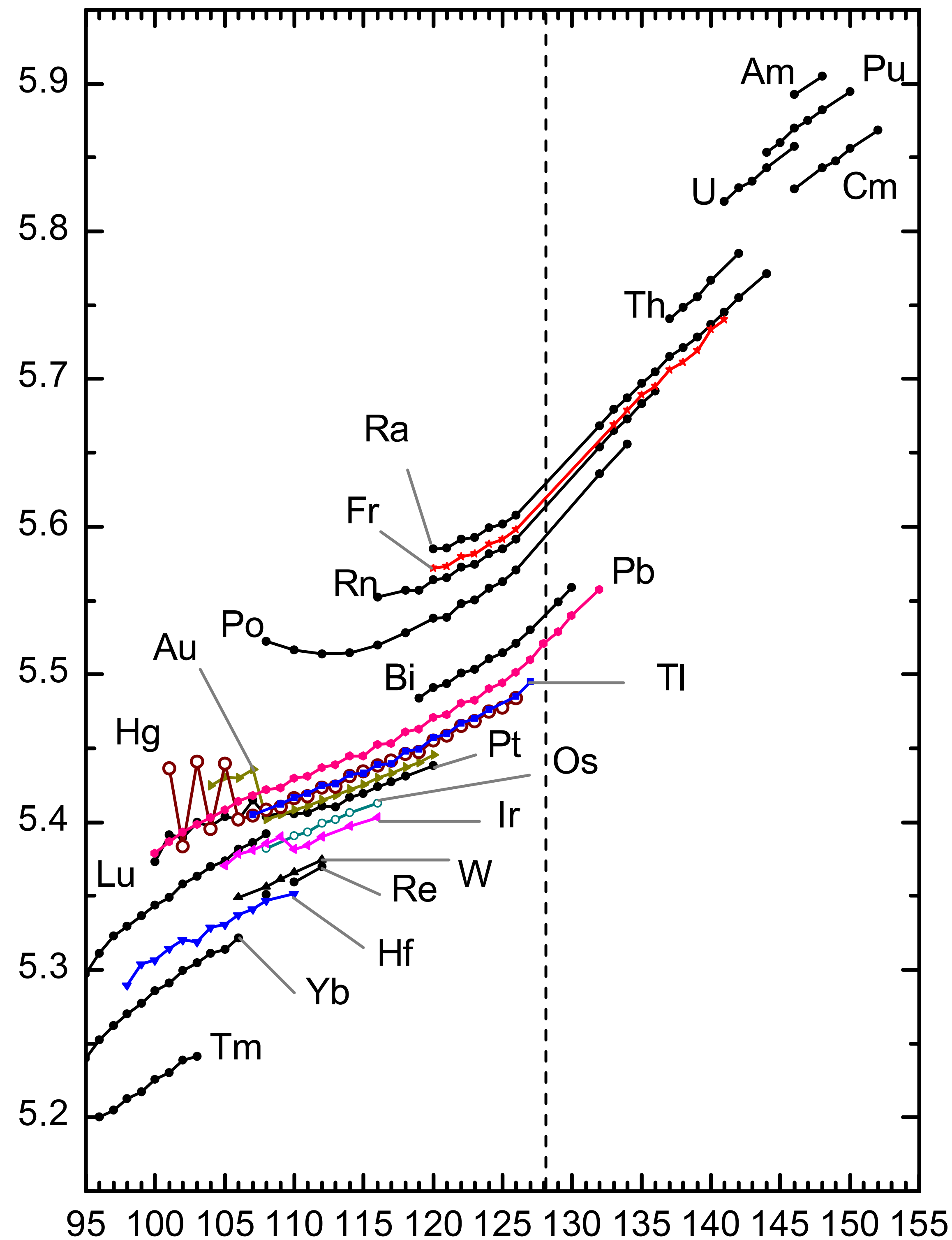
Charge Radii for Unmeasured Isotopes

- Where no absolute charge radii are known, interpolations based on simple formula is used

$$R_0 = \left(r + \frac{r_1}{A_0^{2/3}} + \frac{r_2}{A_0^{4/3}} \right) \times A_0^{1/3}$$

→ can maybe be trusted at the % level

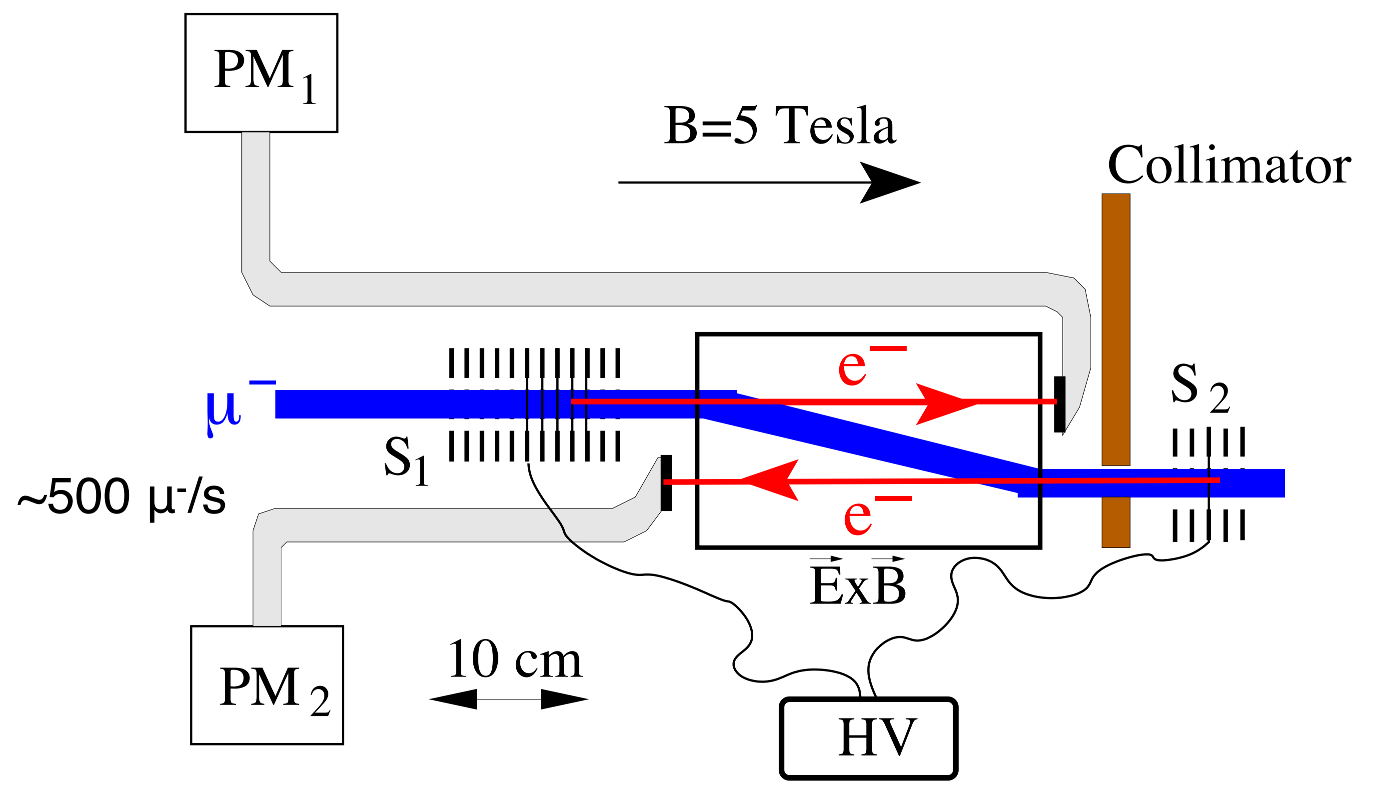
Angeli and Marinova, Aom. Data Nucl. Data **99**, 69 (2013)



Lamb Shift Entrance Detector

- Stack of thin carbon foils of 4 µg/cm²
- Some frictional cooling
- Ejection of secondary electrons from foils detected by scintillators

- Currently ~30% detection efficiency in coincidence
- Plans for improvements



Backgrounds

- Accidental gammas from radioactive target
- Neutrons from muon capture

$$\mu^- \rightarrow e^- + \nu_{\bar{e}} + \nu_\mu$$
$$\mu^- + p \rightarrow n + \nu_\mu$$

→ good timing resolution will help to reduce both

Total lifetime ~ 80 ns in high-Z elements

- Plastic scintillator as veto against charged particles

- Dominant factor: Compton background from incomplete charge deposition
→ large germanium detector, Compton suppressor most probably not necessary