Proposal for BVR 47

Measurement of the charge radius of radium

A. Antognini[1,2], N. Berger[3], D. vom Bruch[3], R. Dressler[1], R. Eichler[1], P. Indelicato[4], K. Jungmann[5], K. Kirch[1,2], A. Knecht[1], A. Papa[1], R. Pohl[6], M. Pospelov[7,8], E. Rapisarda[1], N. Severijns[9], F. Wauters[3], and L. Willmann[5]

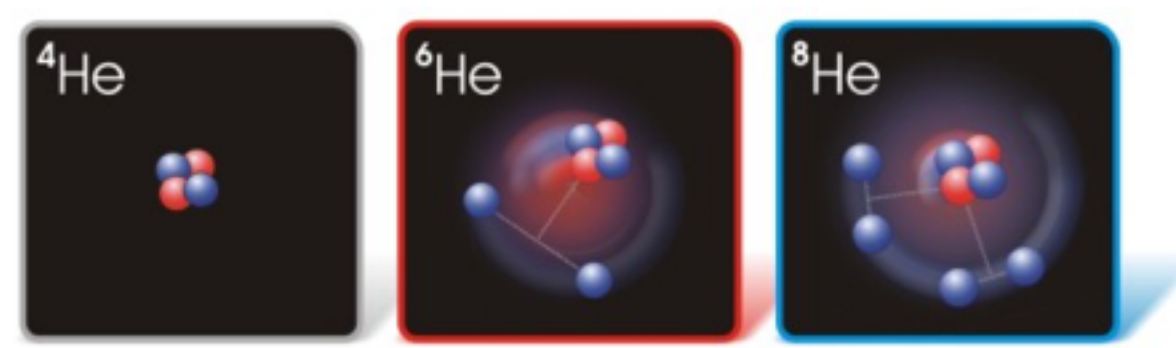
[1]Paul Scherrer Institut, Villigen, Switzerland
[2]ETH Zürich, Switzerland
[3]University of Mainz, Germany
[4]LKB Paris, France
[5]University of Groningen, The Netherlands
[6]Max Planck Institute of Quantum Optics, Germany
[7]University of Victoria, Canada
[8]Perimeter Institute, Waterloo, Canada
[9]KU Leuven, Belgium

Overview

- Interest in nuclear charge radii
- Muonic atom spectroscopy
- Proposal:
  - Beam line
  - Target
  - Detector
- Conclusions & Outlook

Nuclear Charge Radii

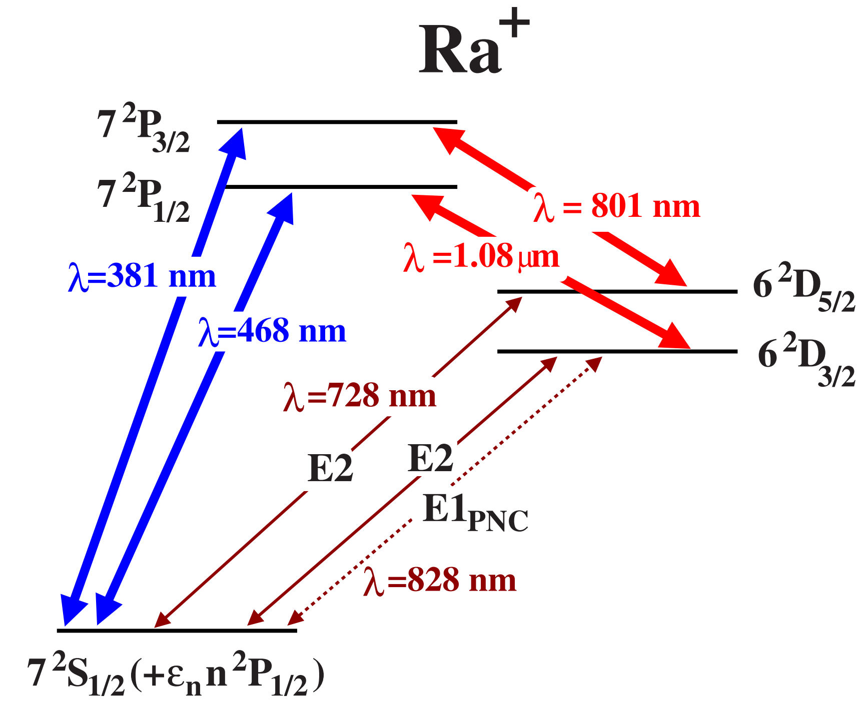
- Charge radius fundamental parameter of a nucleus
- Despite all our knowledge there are still surprises (proton radius)
- Low-Z nuclei can be understood ab-initio
- Nuclear models for high-Z nuclei

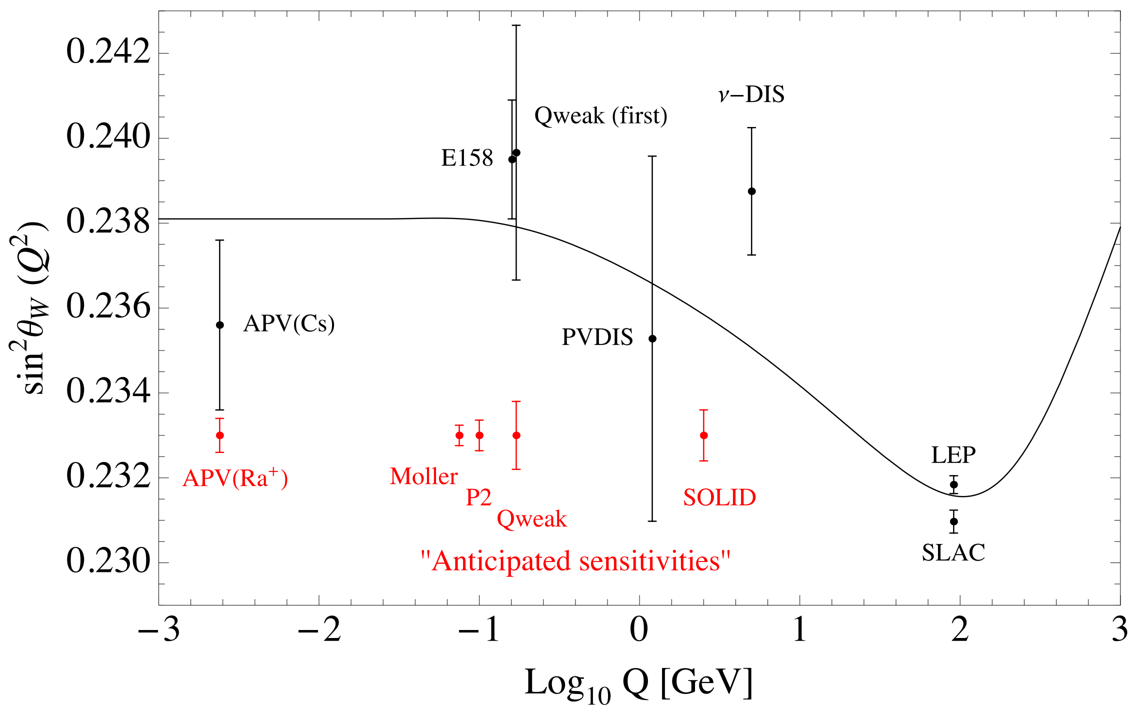


Pohl et al., Nature **466**, 213 (2010)
Mueller et al., PRL **99**, 252501 (2007)

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





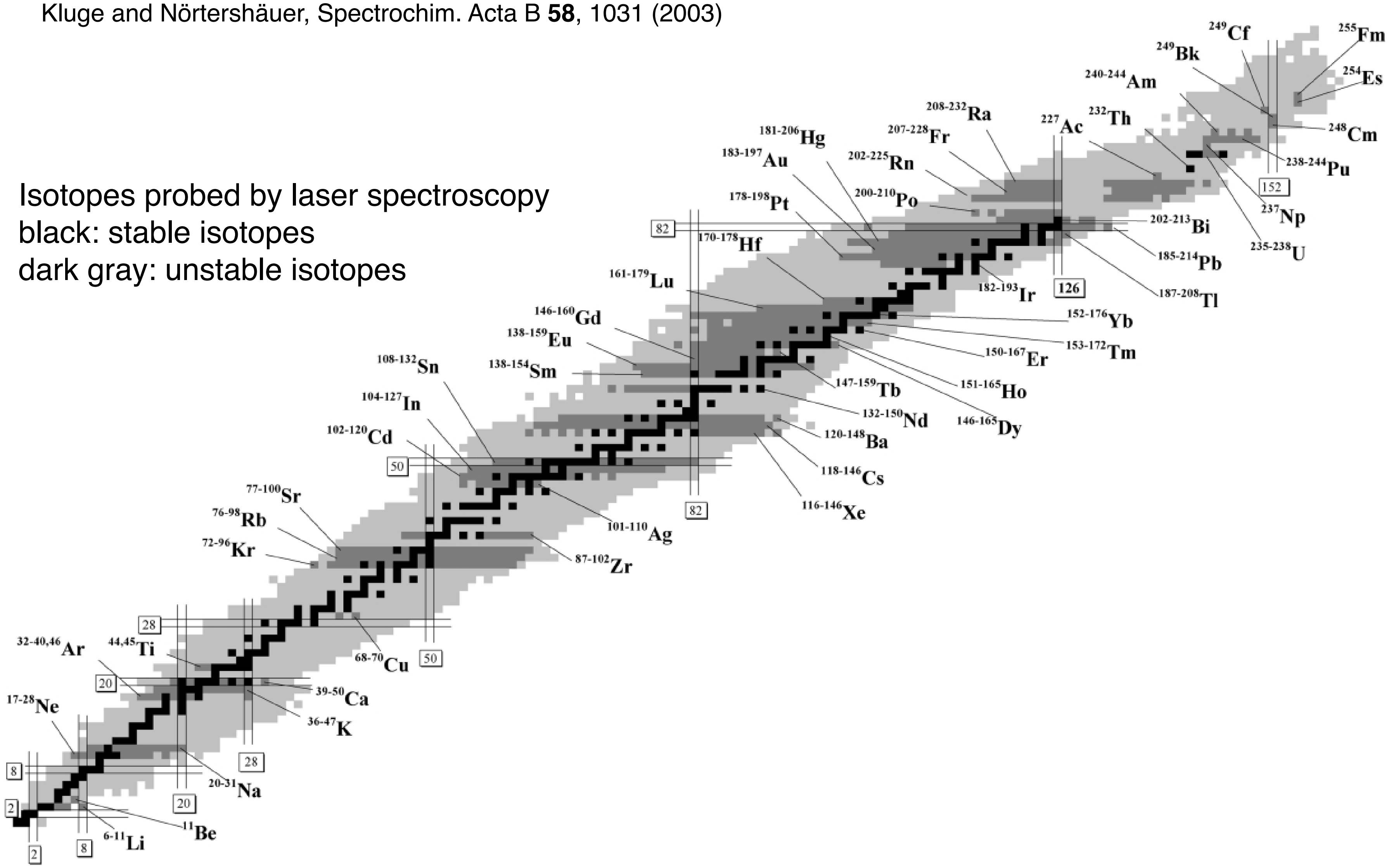
Wansbeek et al., PRA **78**, 050501 (2008)
Wood et al., Science **275**, 1759 (1997)
Lee, arXiv:1511.03783 (2015)

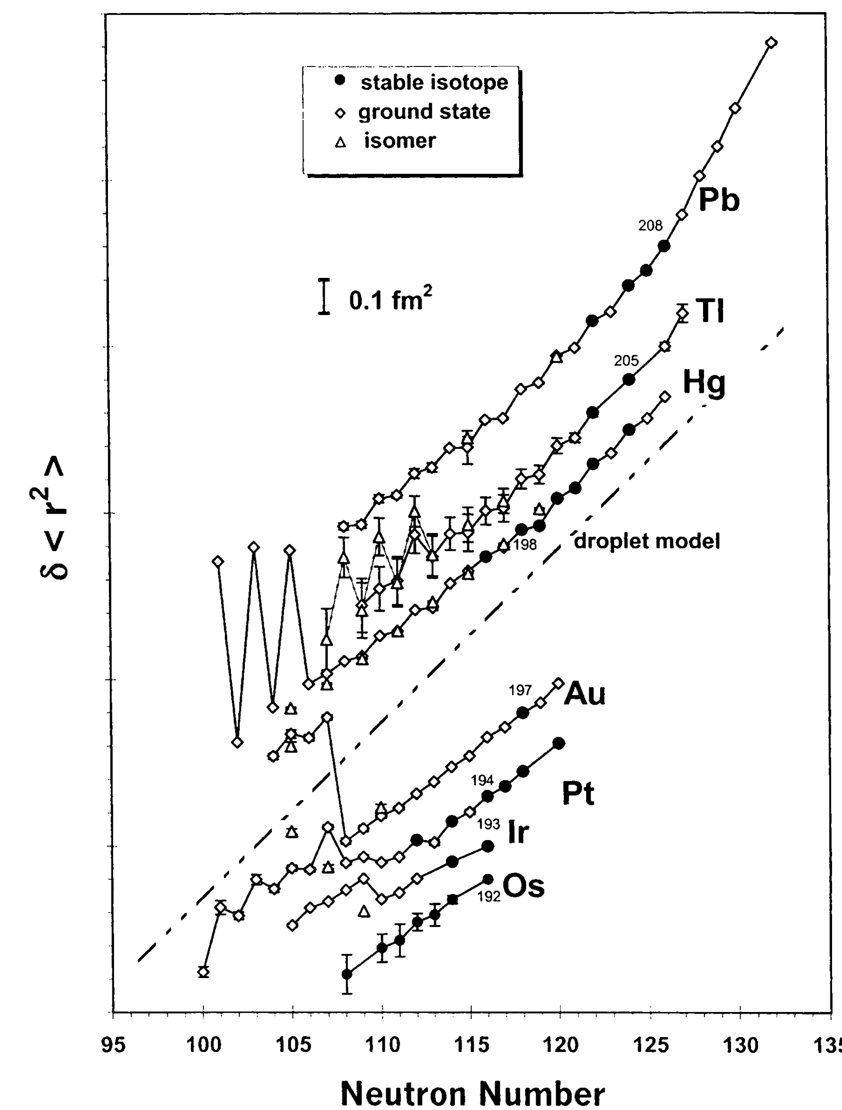
Charge Radii from Laser Spectroscopy

PAUL SCHERRER INSTITUT

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

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





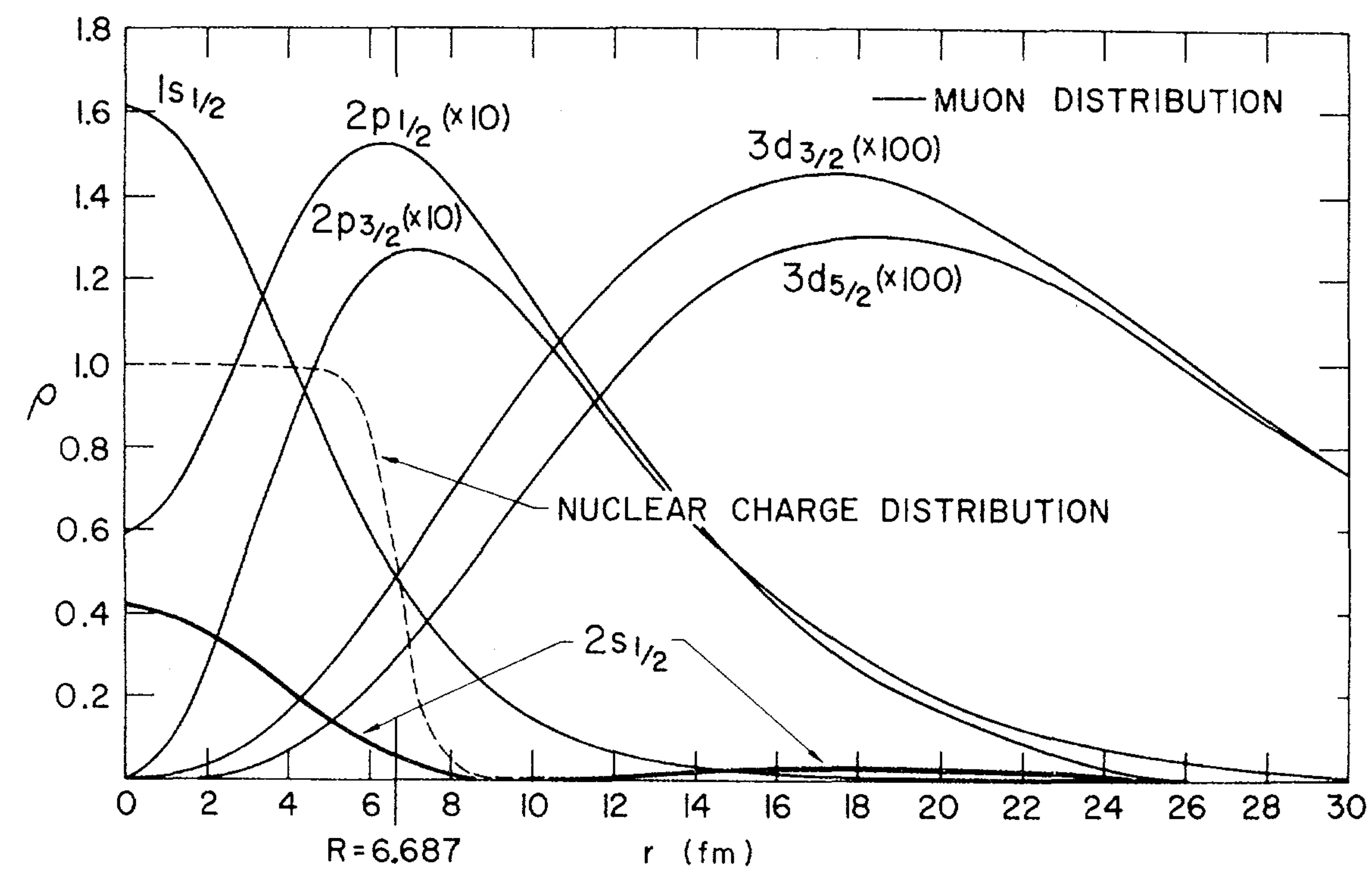
- Wealth of information on nuclear properties from laser spectroscopy
- Need electron scattering or muonic atom spectroscopy for absolute radii

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:

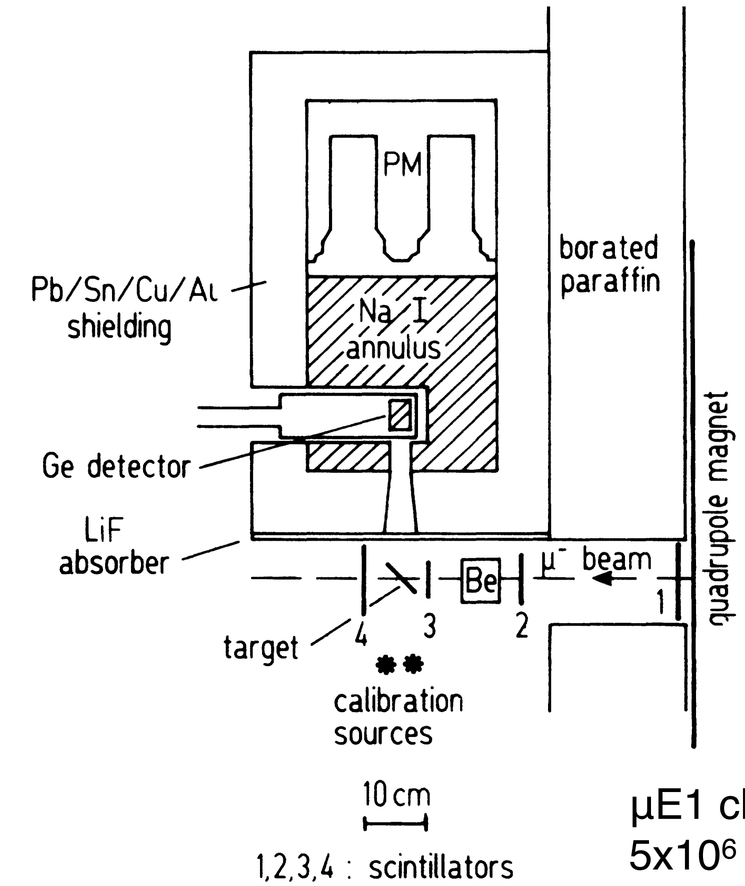
E_{1s} (Z=82) ~ 19 MeV (point nucleus)
→ 10.6 MeV (finite size)

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

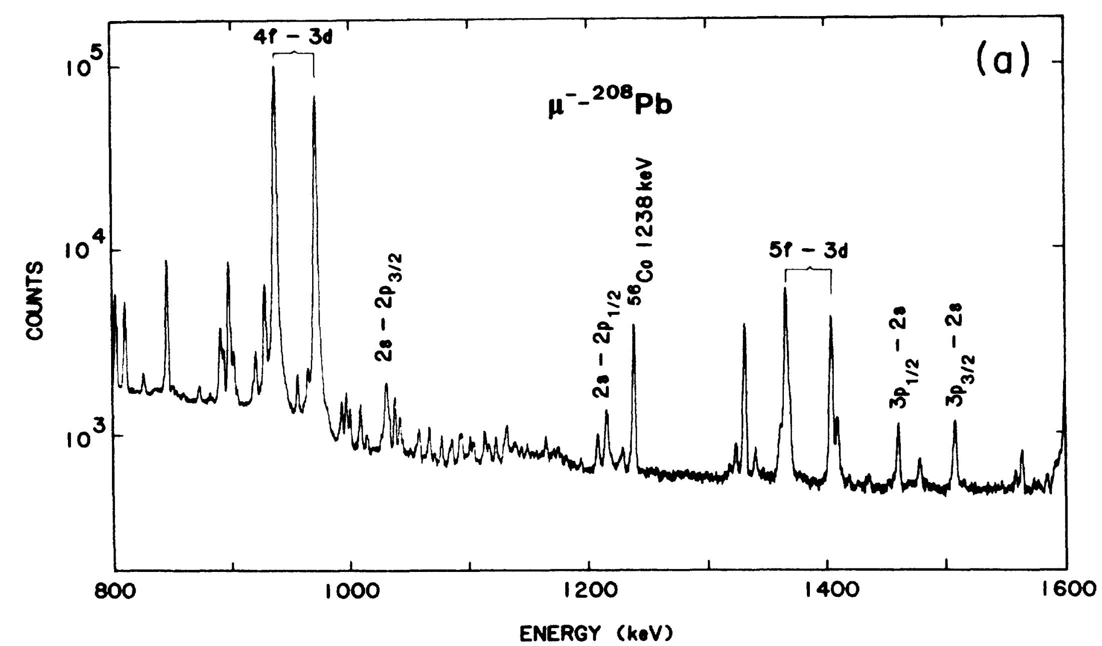
Bergem et al., PRC **37**, 2821 (1988)



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).

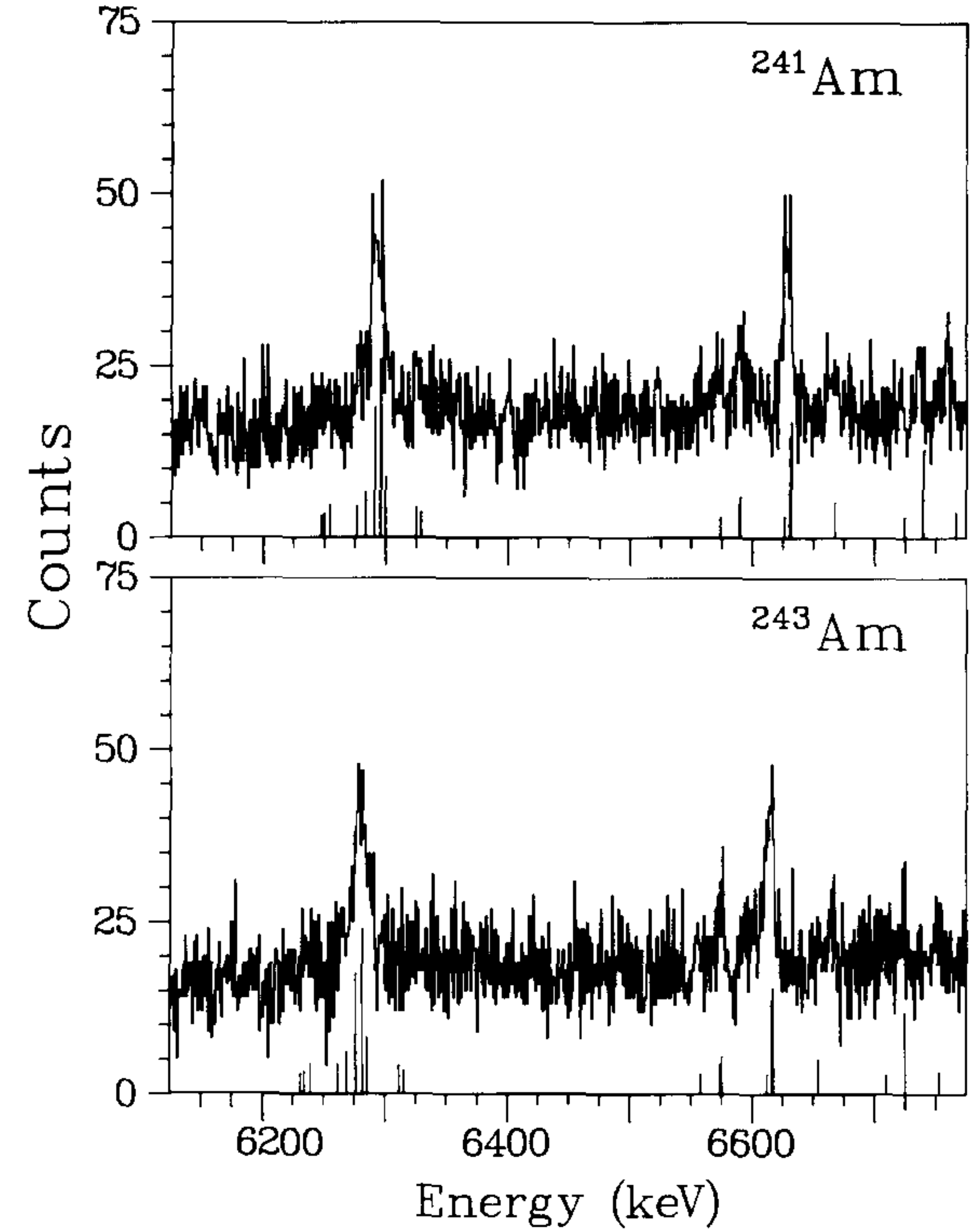
Transition	Kessler (Ref. 9)	Hoehn (Ref. 27)	This experiment
$2p_{3/2}$-$1s_{1/2}$	5 962.770(420)		5 962.854(90)
$2p_{1/2}$-$1s_{1/2}$	5 777.910(400)		5 778.058(100)
$3d_{3/2}$-$2p_{1/2}$	2 642.110(60)	2642.292(23)	2 642.332(30)
$3d_{5/2}$-$2p_{3/2}$	2 500.330(60)	2500.580(28)	2 500.590(30)
$3d_{3/2}$-$2p_{3/2}$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

- 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)

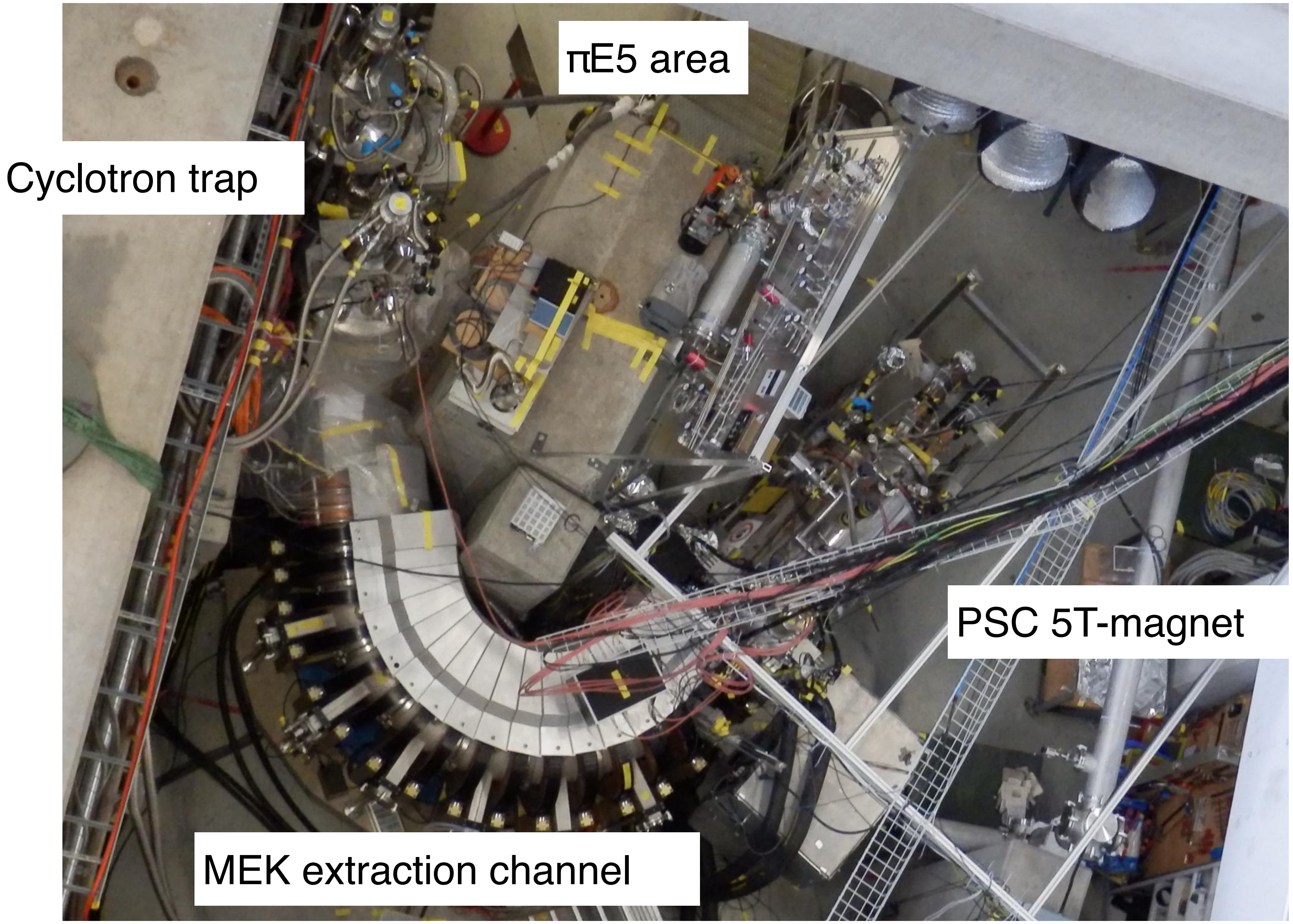


Radioactive Isotopes in Experimental Hall

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
$^{185,187}Re$	-	-	-	-

- Isotopes without measured charge radius that will be addressed in this proposal
- Maximum activity based on current regulations and without major modifications to experimental area infrastructure (100 x approval limit)

Lamb Shift Beam Line

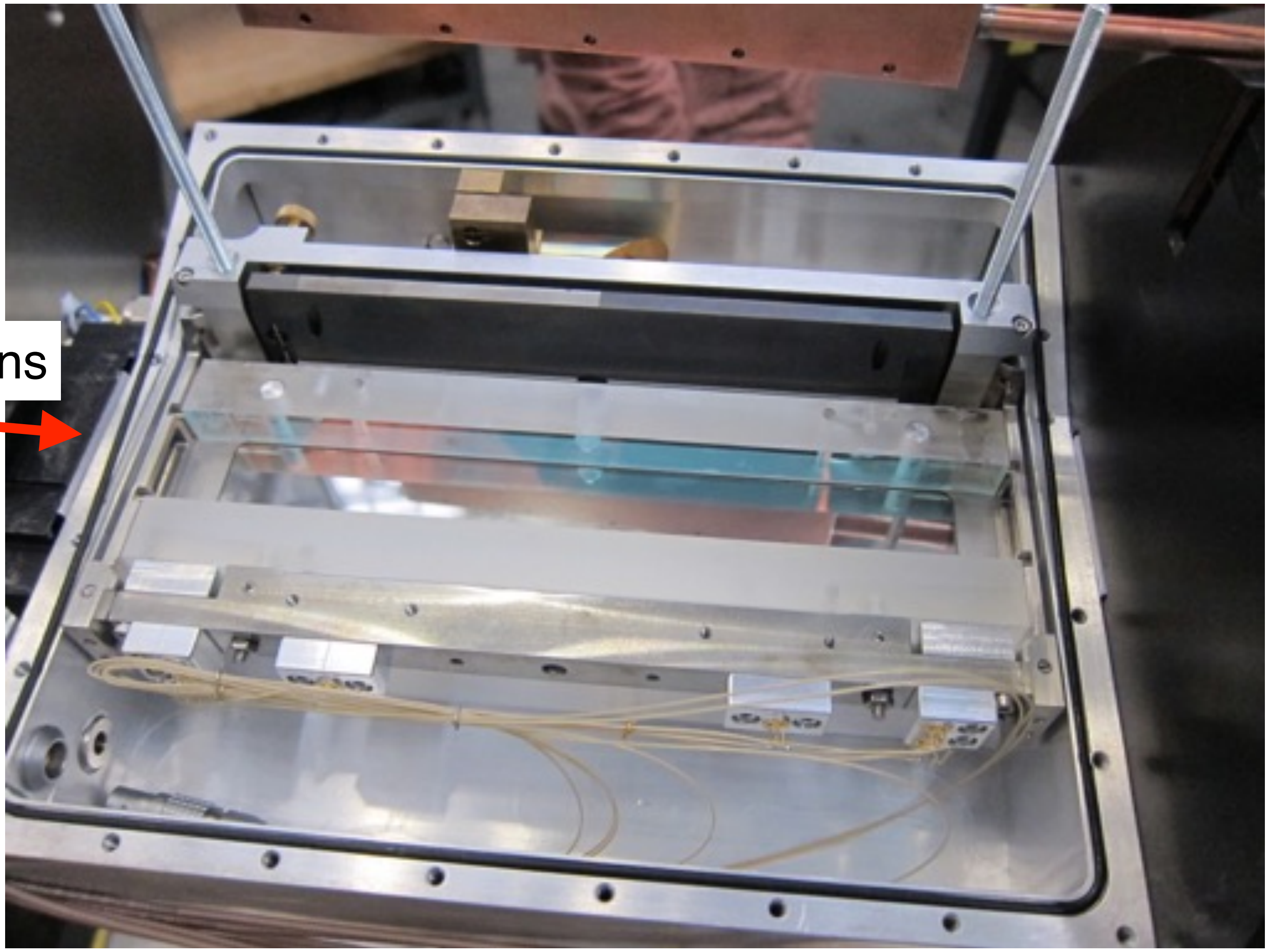


- Negative pions at 100 MeV/c captured in cyclotron trap
- Decay muons slowed down in passages through thin foil and extracted by applied HV

Lamb Shift Gas Target

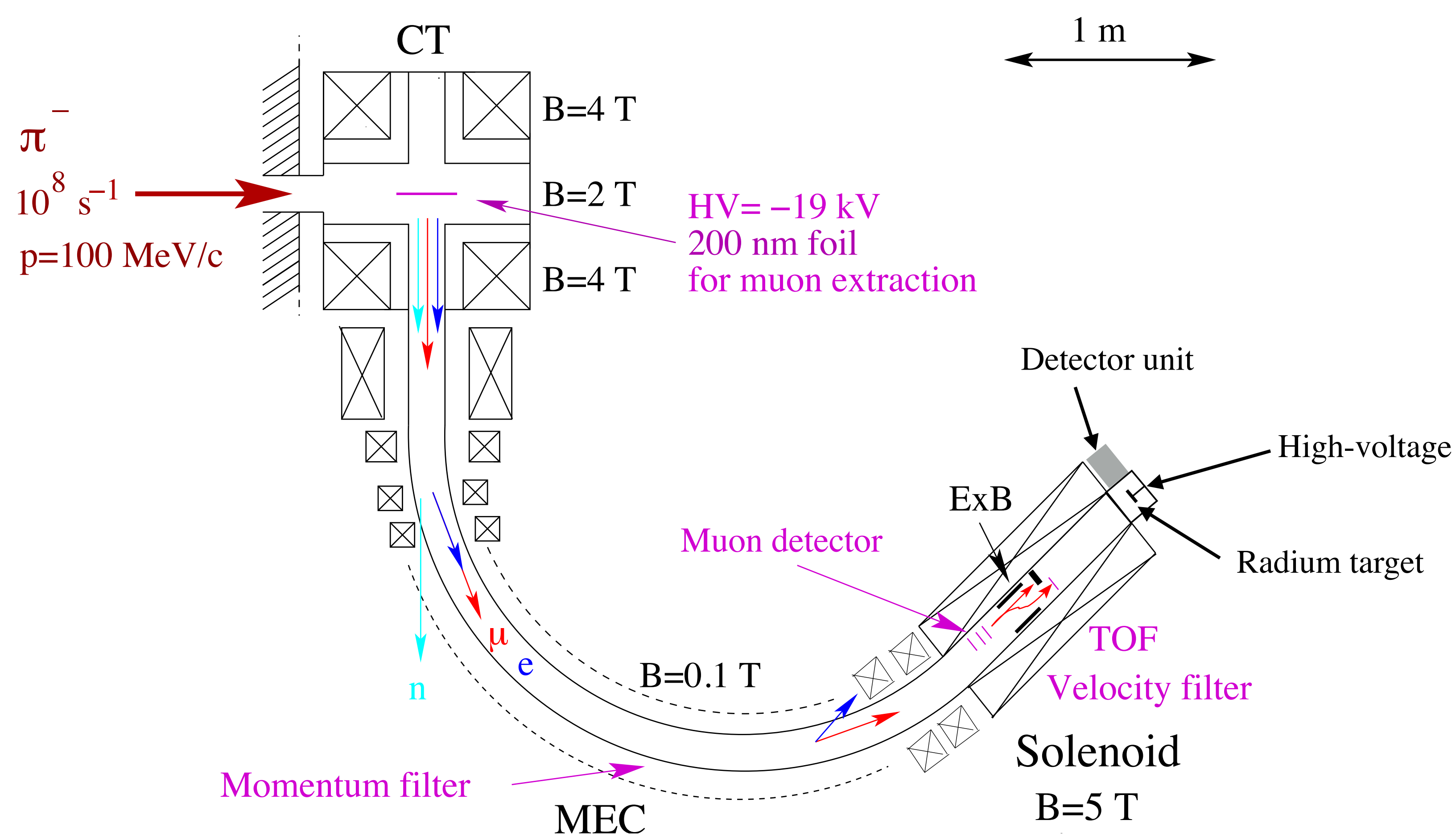
- Gas target located inside 5T-magnet
- $\mathcal{O}$(1 mbar) of H_2, D_2, ^{3}He, ^{4}He
- Densities of ~ 2 µg/cm^2, ~80% stopping efficiency
- Ideal beam to stop in low mass radioactive targets

Muons

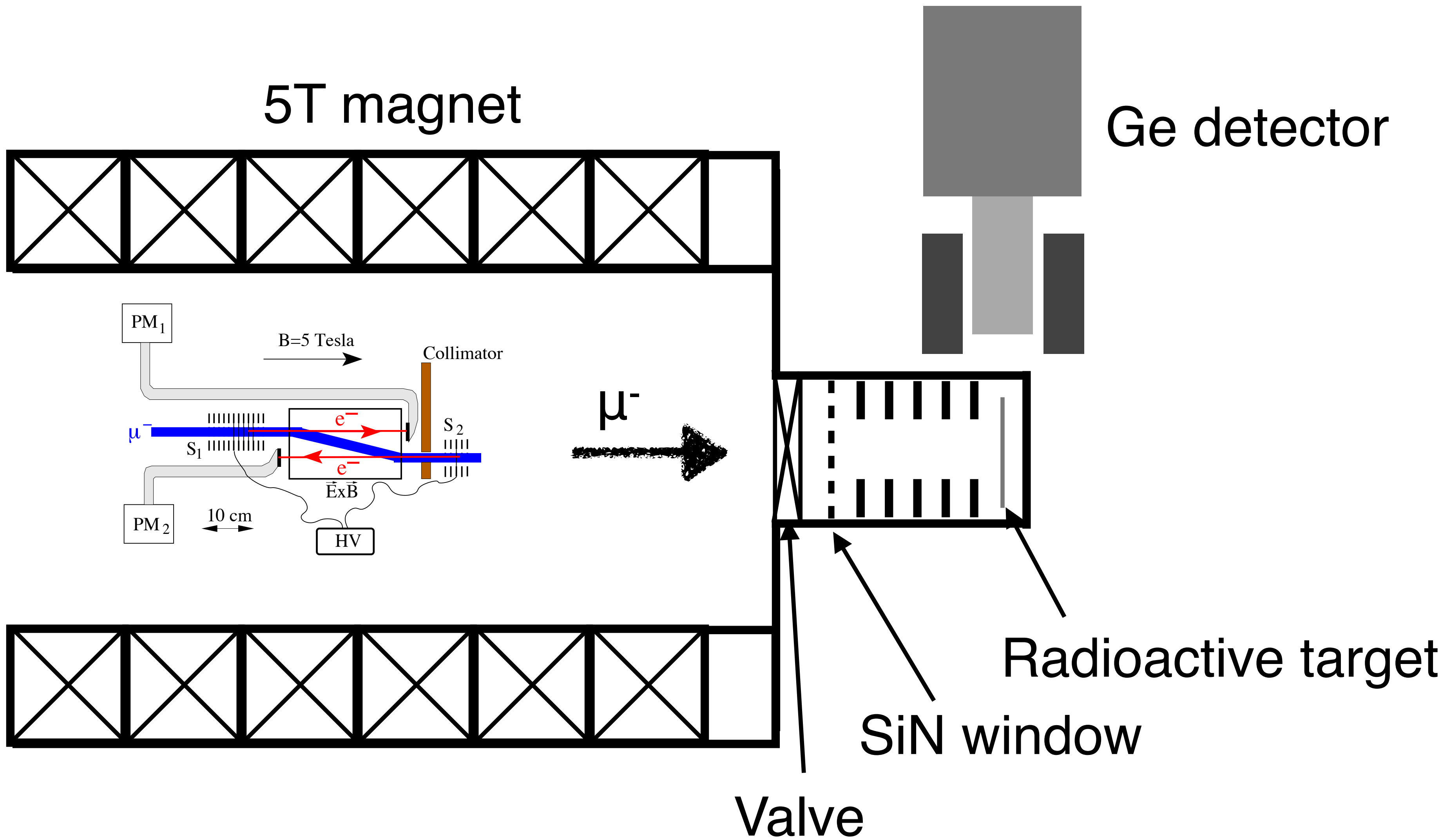


Setup for Proposed Measurements

- Radioactive targets and germanium detector in fringe field of 5T-magnet
- Target and detector at ~ 1 T
- Expansion of beam by factor 2



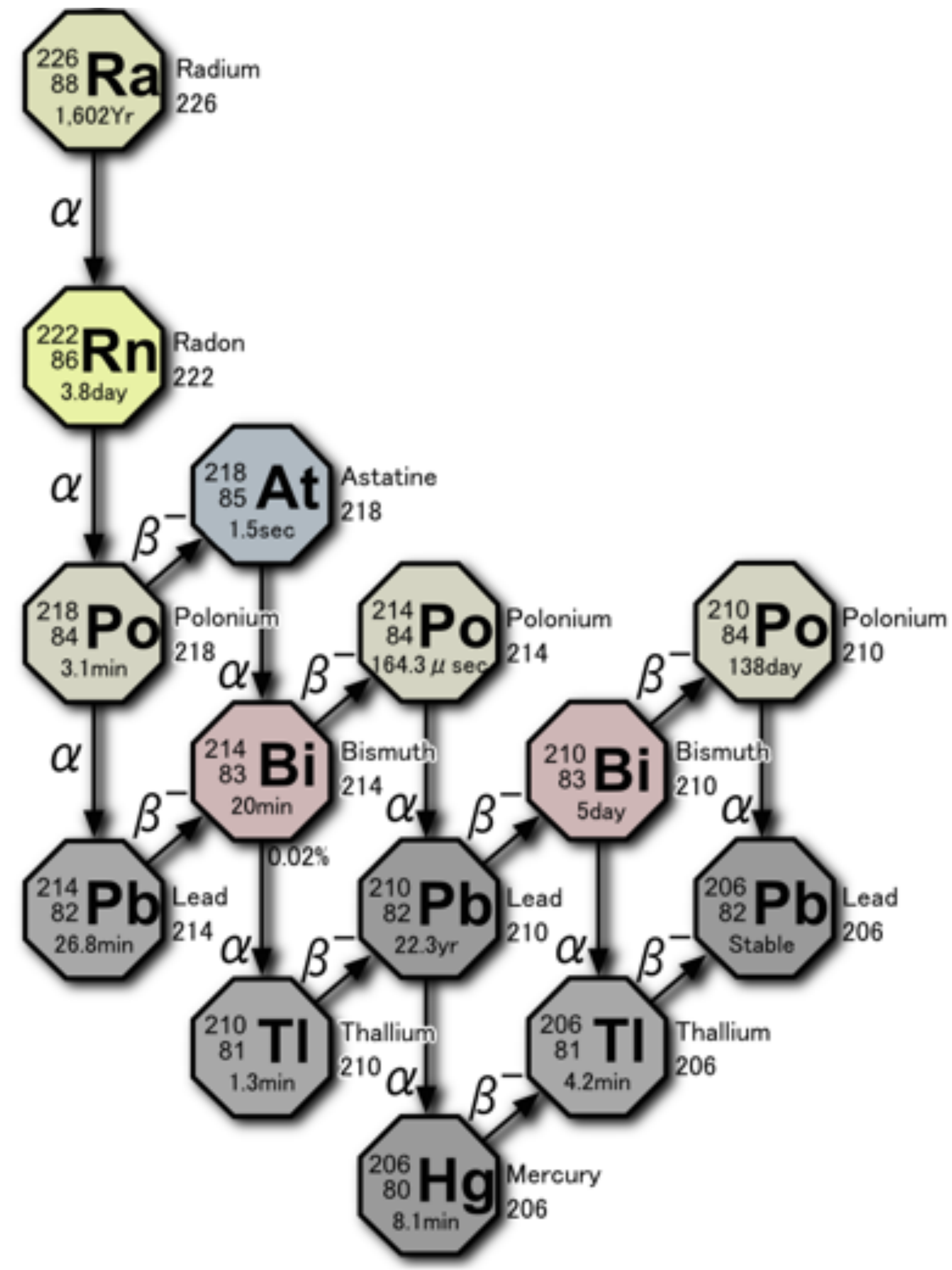
Target Chamber



- Target chamber separated by thin SiN window
- High voltage applied to window and target to adapt muon energy
- Well shielded, large germanium detector close to radioactive target

^{226}Ra

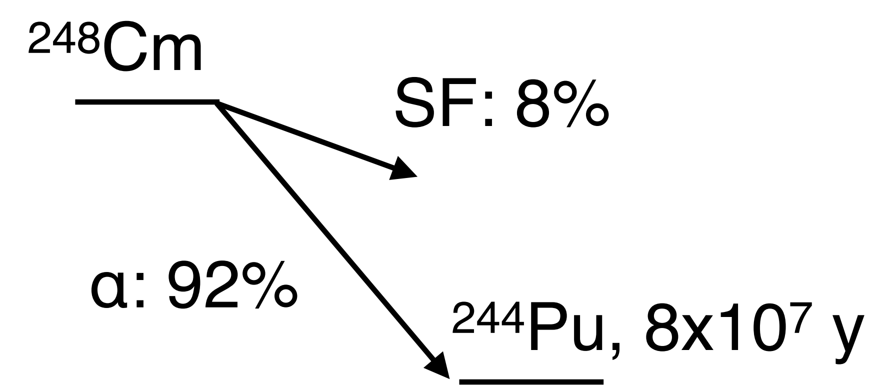
- Large decay chain with many daughter isotopes
- Strongest gamma emitter ^{214}Bi with E_γ up to 2.5 MeV
- From 200 kBq ^{226}Ra
  → 500 kBq γs with $E_\gamma > 100$ keV
- Retention of ^{222}Rn in target?

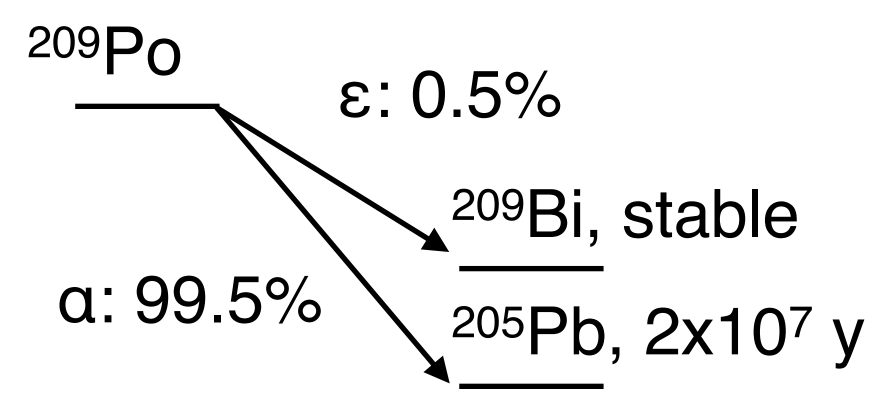


^{248}Cm & ^{209}Po

- Radioactivity from curium and polonium much easier to handle

- Only relatively small amount of gammas





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

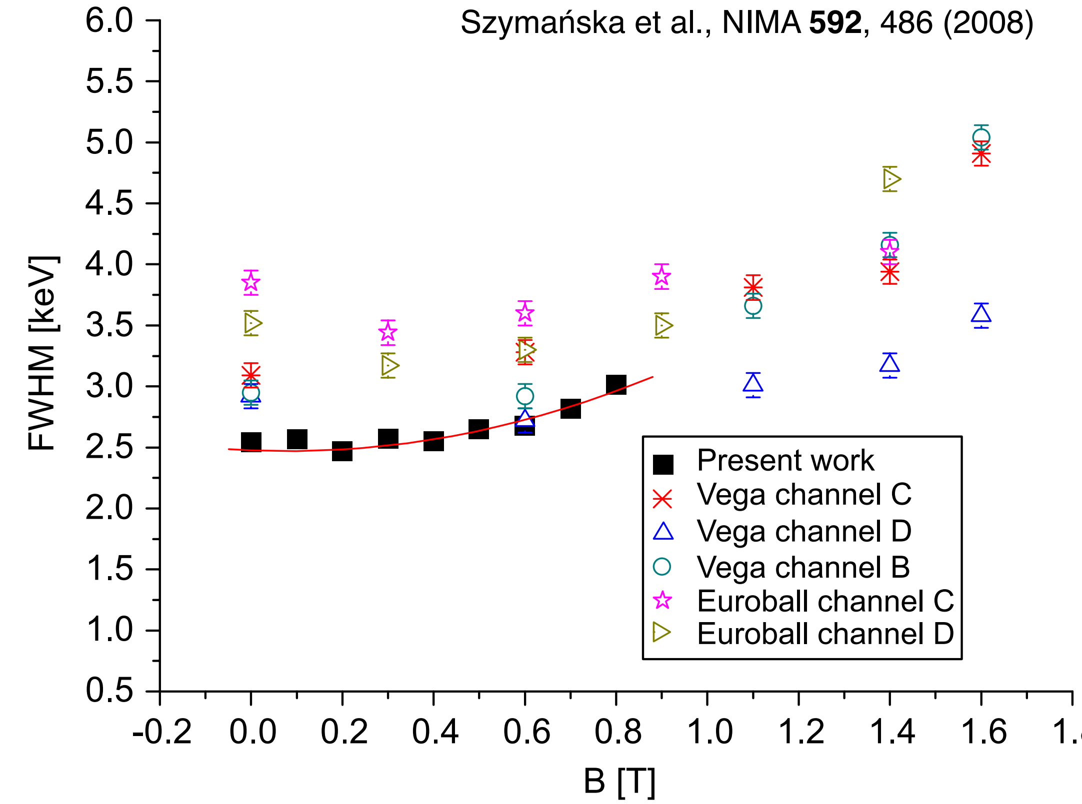
- ^{226}Ra available from University of Bern
- ^{248}Cm available from PSI/nTOF
- ^{209}Po will probably need to be bought (other options under investigation)

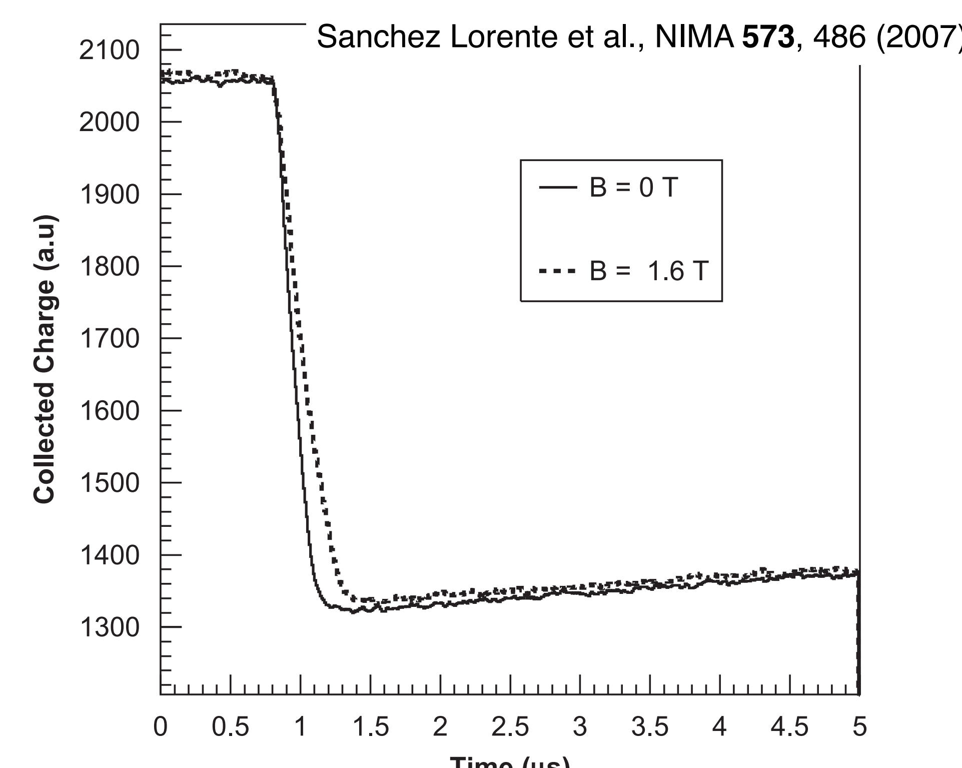
HPGe Detection System

- Large coaxial germanium detectors have been operated and tested in high magnetic fields

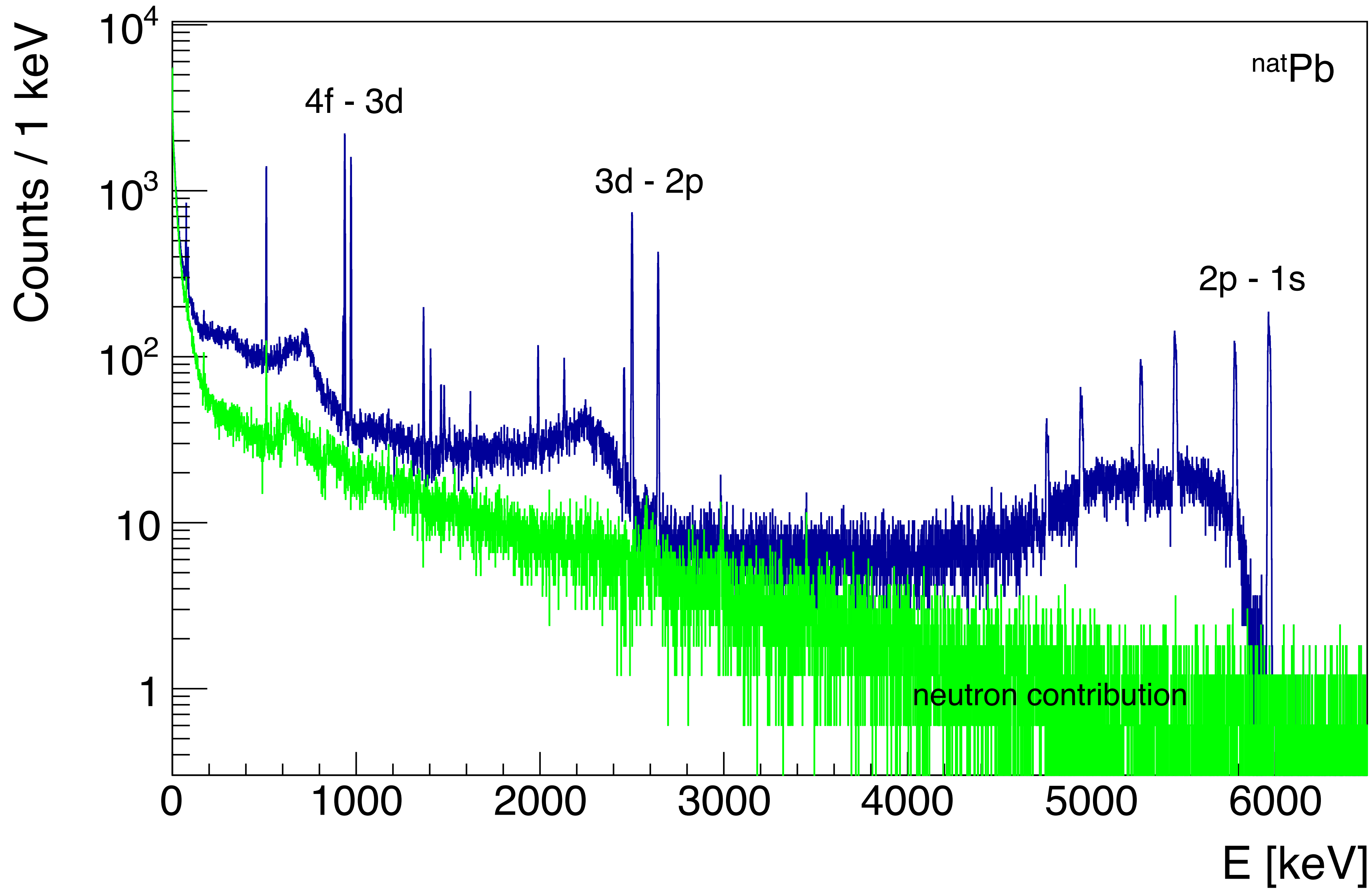
  → decreased rise-time, loss of resolution

- Pulse shape analysis allows to recover part of the decreased performance





Expected Energy Spectrum



- Simulated muonic lead energy spectrum with 10^7 muons on target
- 60% germanium detector at 10 cm distance
- With ~ 100 stopped μ^-/s → 1 day of data taking

Required Statistics

- Precision on extracted charge radius to first order linear in uncertainty of measured transition energies
- Taking ^{208}Pb measurements as benchmark
  → need ~1 keV at 6 MeV & ~0.3 keV at 1 - 2.5 MeV for 0.2% precision on charge radius
- Achievable with little statistics due to intrinsic high-resolution of germanium detectors

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)

Backgrounds

- Accidental gammas from radioactive target
- Neutrons from muon capture

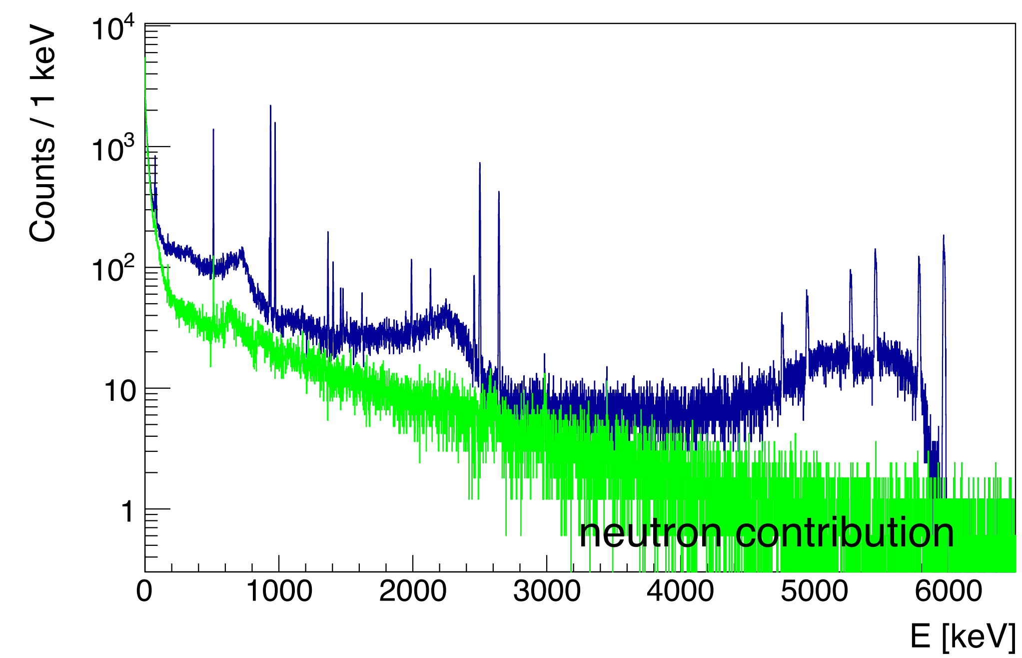
$$\mu^- \rightarrow e^- + \nu_{\bar{e}} + \nu_\mu$$
$$\mu^- + p \rightarrow n + \nu_\mu$$

→ 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

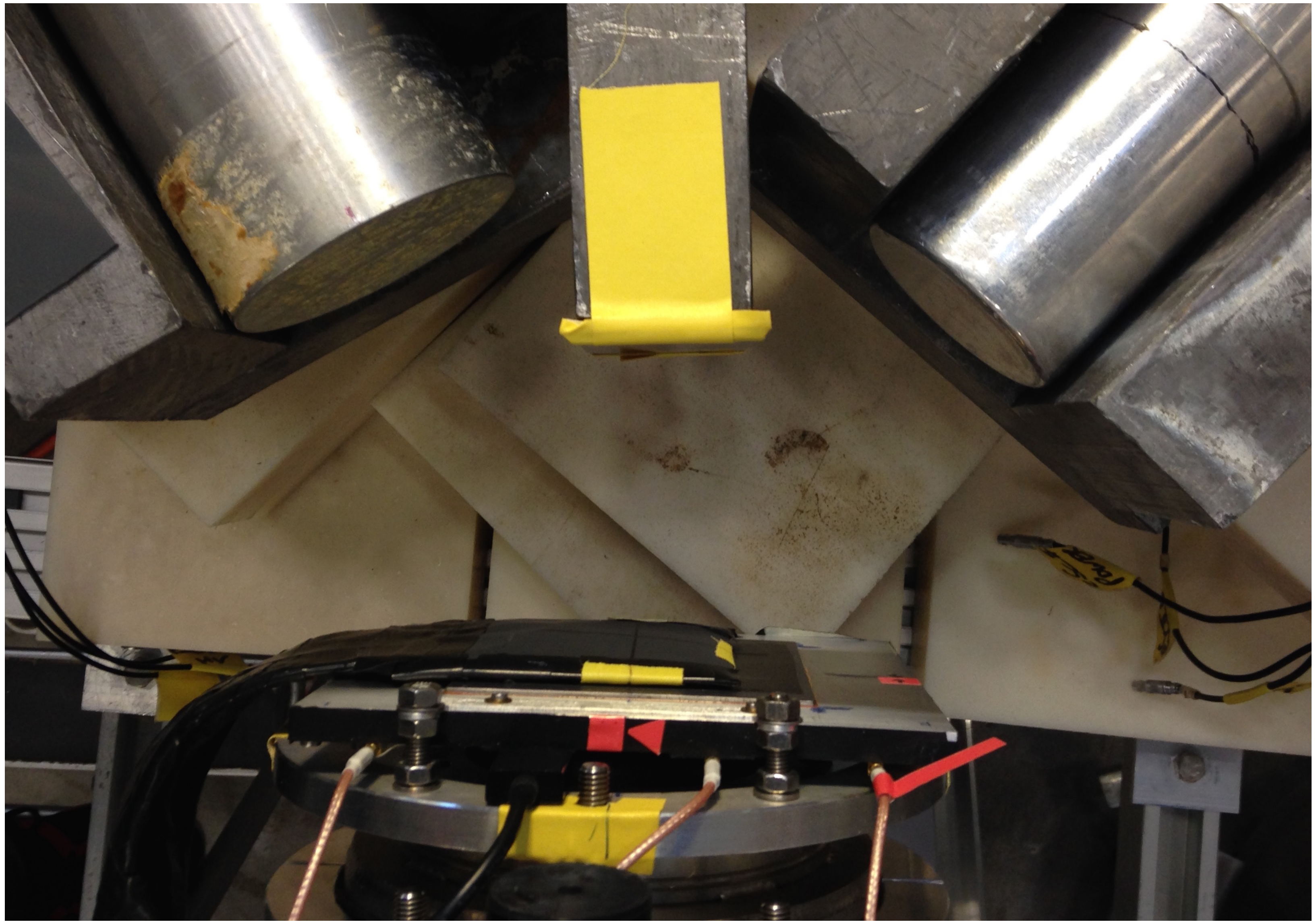


Rate Estimates

Parameter	Value	Comment
Muon rate R_μ	100 Hz	Rate of 500 μ^-/s with 20% trigger & stop efficiency
Gamma rate R_μ	500 kHz	Gamma rate from radium target with E_γ >100 keV
Solid angle f_Ω	3%	60% germanium detector at 10 cm distance
Detection efficiency ϵ	50%	For $E_\gamma \sim 1$ MeV
Timing resolution Δt	10 ns	Lower limit; depends on muon time-of-flight
Trace length t_{trace}	10 μs	Digitized trace length
Detector rate R_{det}	7.5 kHz	$R_{det} = R_\gamma f_\Omega \epsilon$; free-running
Accidental rate R_{acc}	0.008 Hz	$R_{acc} = R_\mu (R_\gamma \Delta t) f_\Omega \epsilon$
Signal rate R_{sig}	$\mathcal{O}$(1 Hz)	$R_{sig} = R_\mu f_\Omega \epsilon$; needs energy dependent ϵ; neglecting multiple gammas from muonic cascade
Prob. for additional γ	7.5%	$p_{add} = R_\gamma t_{trace} f_\Omega \epsilon$; additional γ during digitized trace length

- Good signal to accidental background ratio
- Free-running detector rate and pile-up during long digitized traces critical
- Trigger DAQ on muon entrance signal

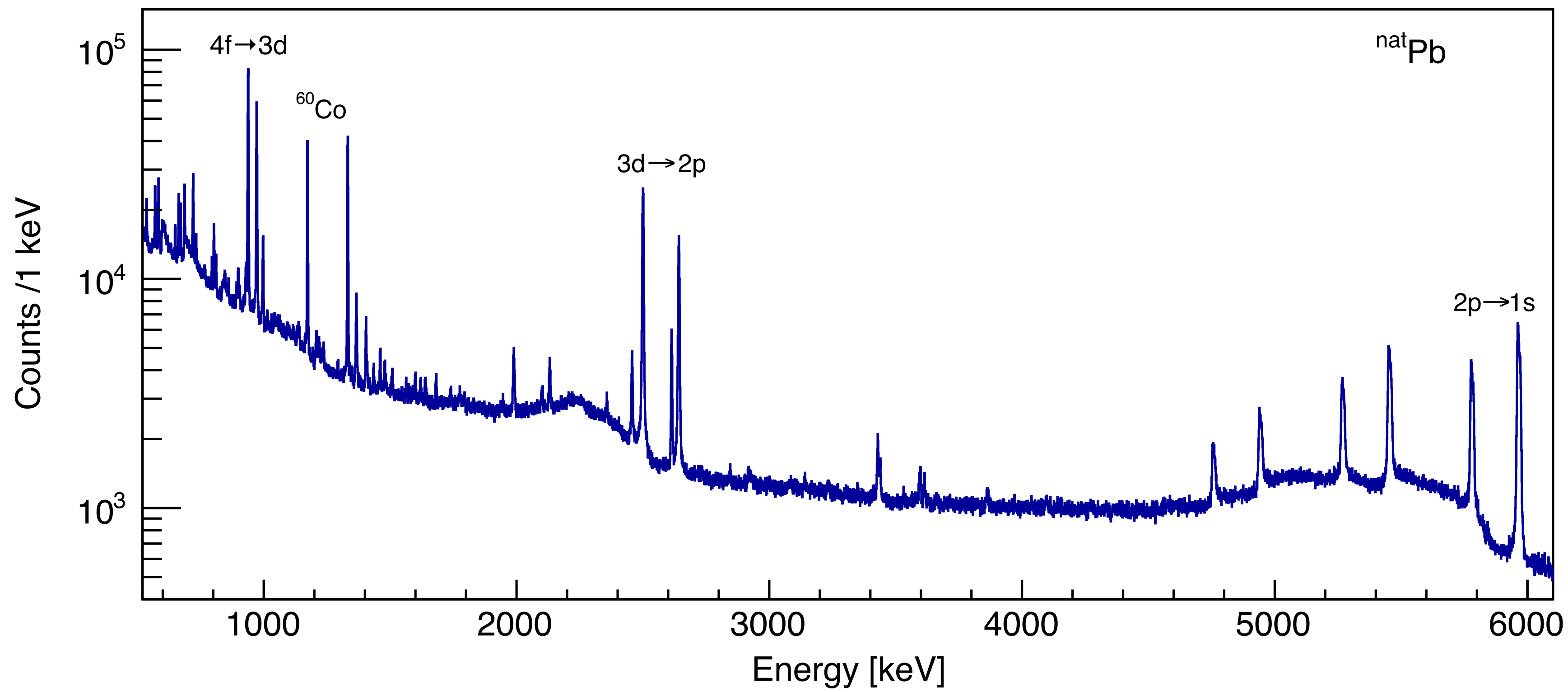
Preliminary Measurements

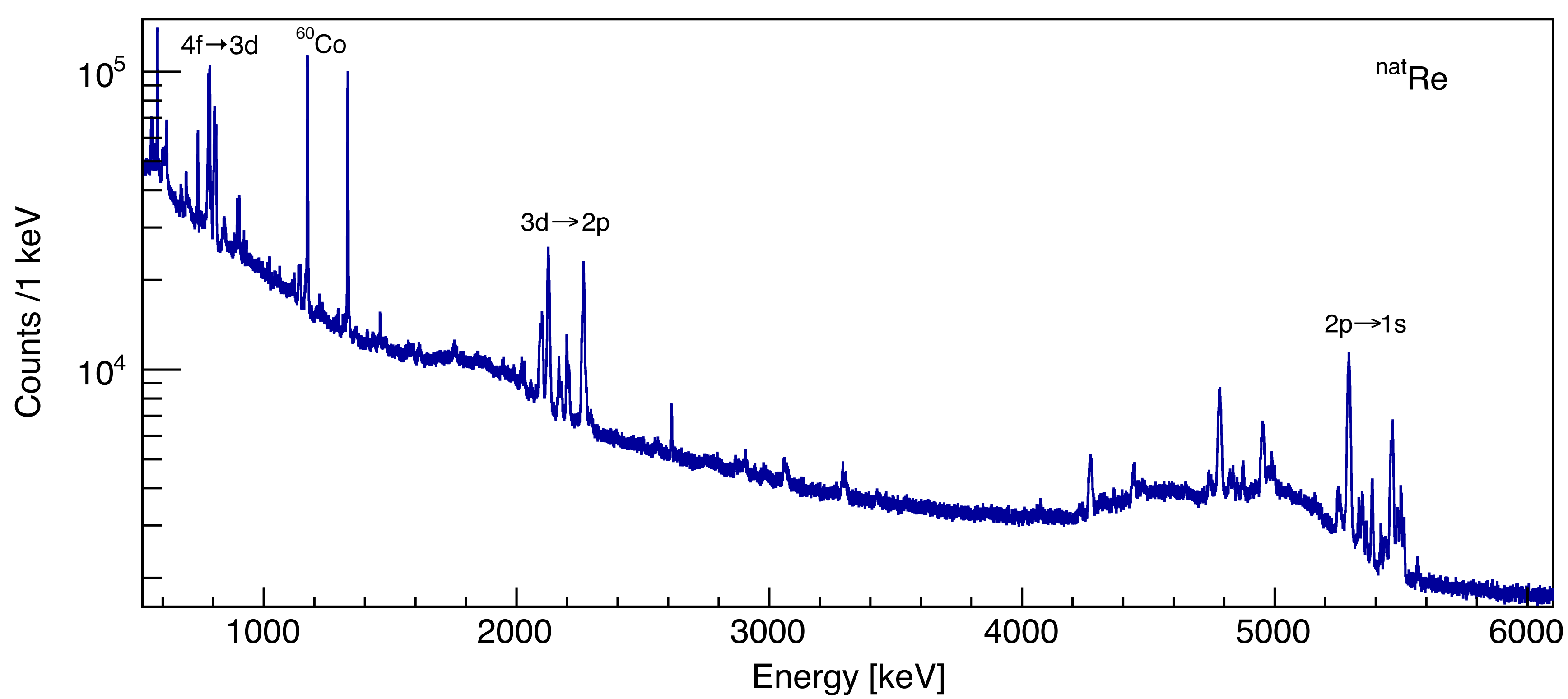


- Preliminary test during 3 days in November 2015
- 20 kHz μ^- at 30 MeV/c in πE1 area
- 75% and 20% germanium detectors

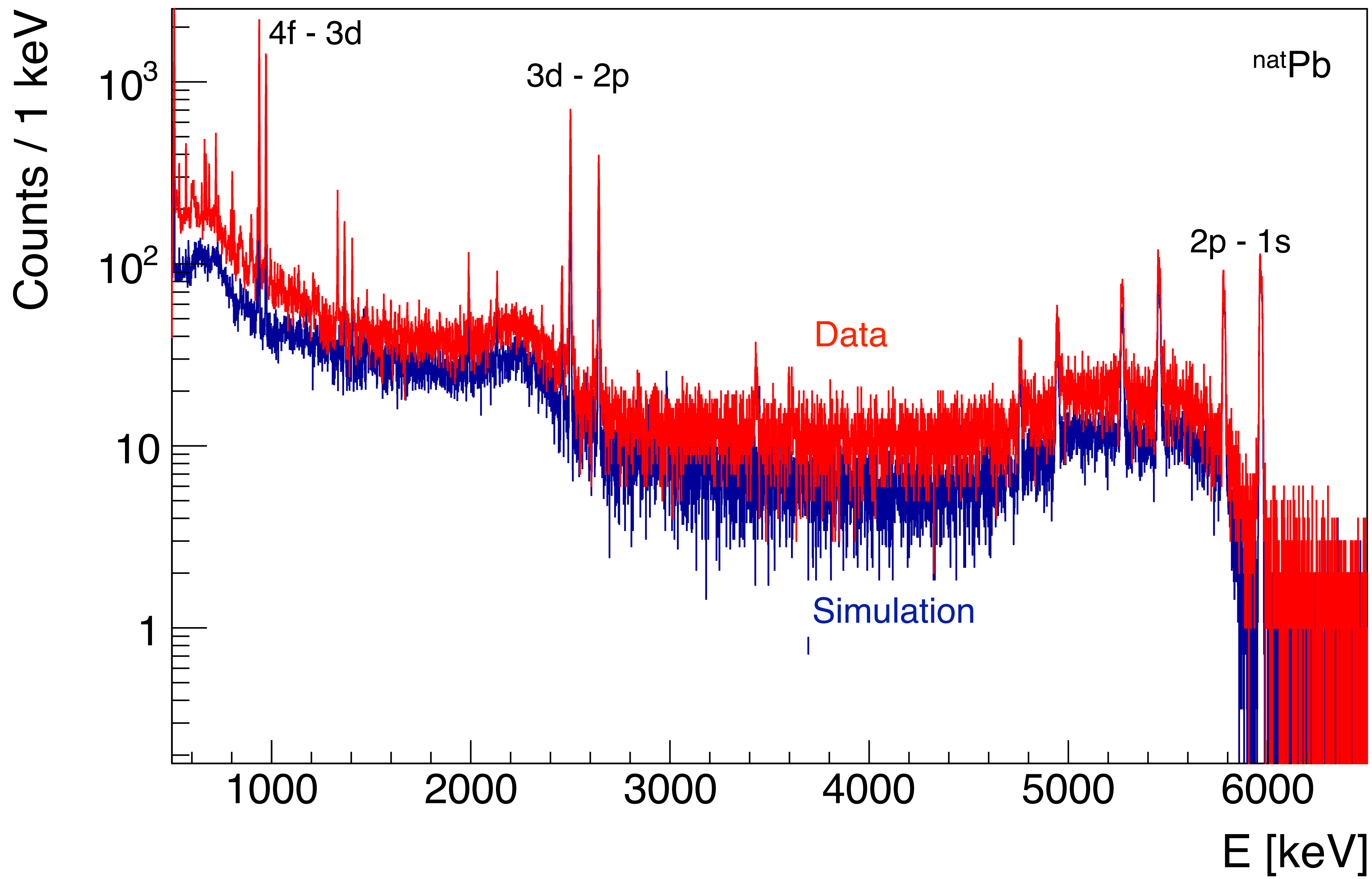
Preliminary Energy Spectra

- Natural lead, tungsten and rhenium measured
- Free-running spectra without any background reducing cuts
- Additional lines in rhenium due to low-lying nuclear levels





Validating the Simulations



- Preliminary data allows to tune our simulations
- Work in progress but decent agreement so far

Beam Request

- 2016: 2 weeks beam time in πE1
  - Measurement of rhenium ($^{185,187}Re$) charge radius
  - Test of detecting muonic x-rays in the presence of high gamma background
  - Development of calibration strategies
  - Development of DAQ, pulse-shape analysis
- Depending on outcome of 2016 beam time
  2017/2018: 8 weeks at Lamb shift beam line in πE5
  - 4 weeks: setup and commissioning of beam line (part without beam)
  - 4 weeks: measurements with stable and radioactive low-mass targets

Conclusions & Outlook

- Interest in charge radii from atomic parity violation experiment and nuclear physics

- Lamb shift beam line offers the possibility to measure charge radii of low-mass, radioactive targets
- Proven technology, only limited development necessary

- Techniques learned during the measurements proposed here as a step to
  - Measurement of atomic parity violation in muonic atoms
  - Measurement of even lower mass targets through transfer in solid hydrogen
  - Measurements of other nuclei of interest to nuclear physics community

Strasser et al., Hyperf. Int. **193**, 121 (2009)

Announcement

Workshop on Muonic Atom Spectroscopy

21 October 2016 *Paul Scherrer Institut*
Europe/Zurich timezone

Overview
Timetable
Contribution List
Author index
My conference

Support

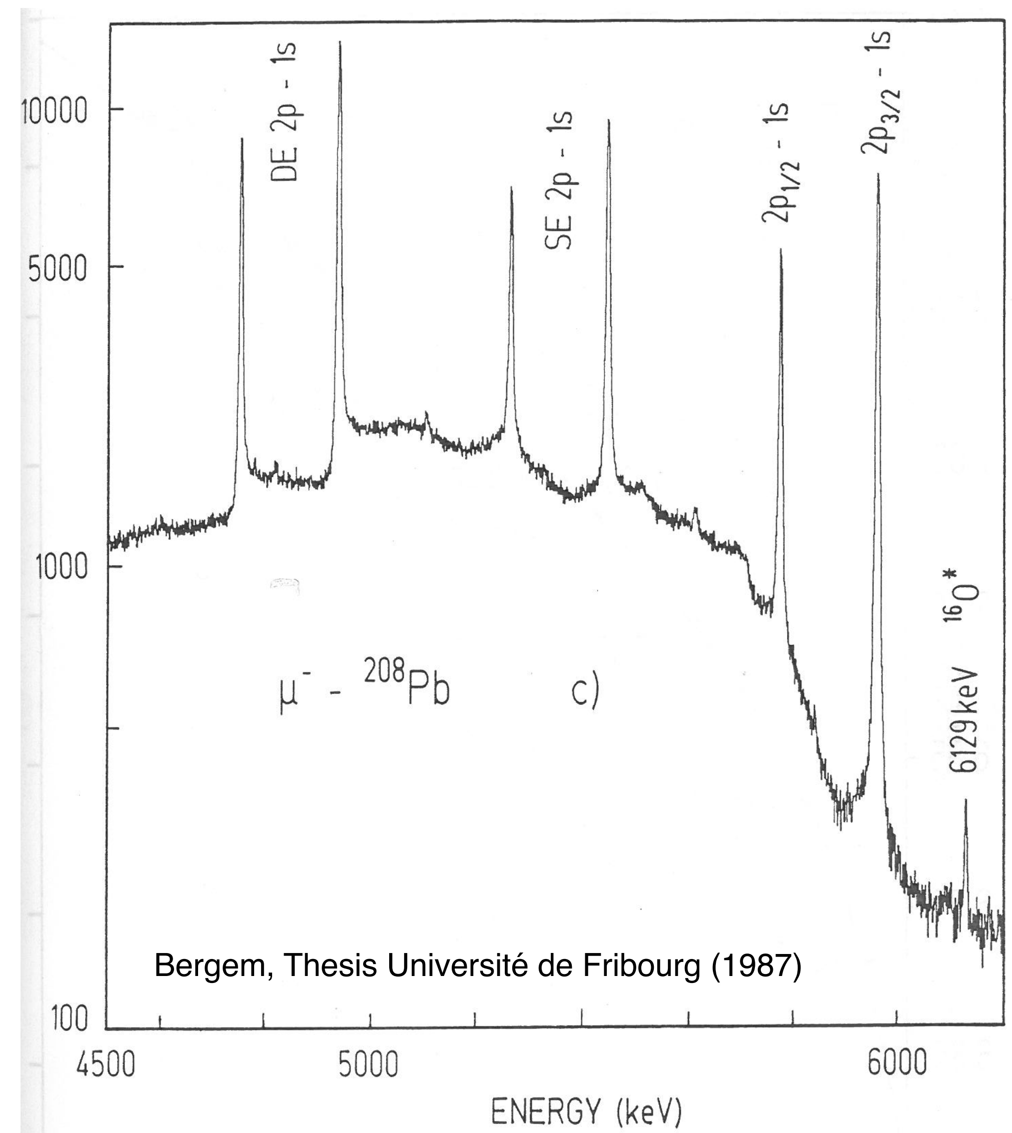
This workshop aims to bring together the physics community interested in performing high resolution muonic X-rays spectroscopy. While muon beam intensities and quality have been improved in recent years at PSI, still muonic x-rays have never been studied with highly efficient multi-Ge-detector arrays covering large solid angles. Such advancements open the way to the measurements of nuclear charge radii in radioactive elements and of atomic parity violation effects in muonic atoms. From the fruitful exchange between theoreticians and experimenters, the workshop aims to strengthen the physics case of these measurements and to discuss future plans and ideas.

Dates:	21 October 2016 (09:00-17:10)
Timezone:	Europe/Zurich
Location:	*Paul Scherrer Institut* CH-5232 Villigen Room: Auditorium / WHGA001
Additional info:	Organizing committee : K. Kirch, A.Knecht, B.Lauss, E. Rapisarda, A.Govaerts Van Loon

Backup

Calibration

- Calibration and non-linearity corrections of vital importance
- Calibrations need to be done online
- Will use various calibration sources
  - Intrinsic activity from radioactive target
  - Small part of radioactive target with ^{208}Pb
  - Conventional calibration gamma sources
  - ^{16}N from $^{16}O(n,p)$ reaction in cooling water around TgE



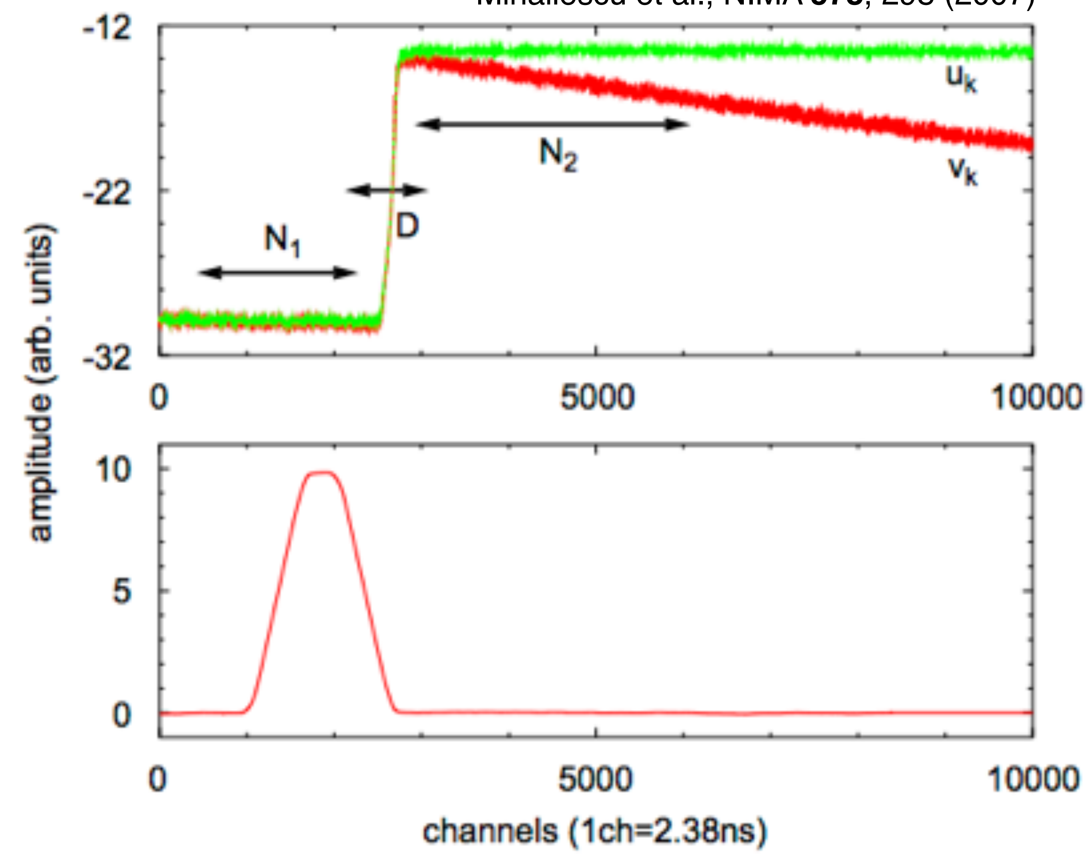
Bergem, Thesis Université de Fribourg (1987)

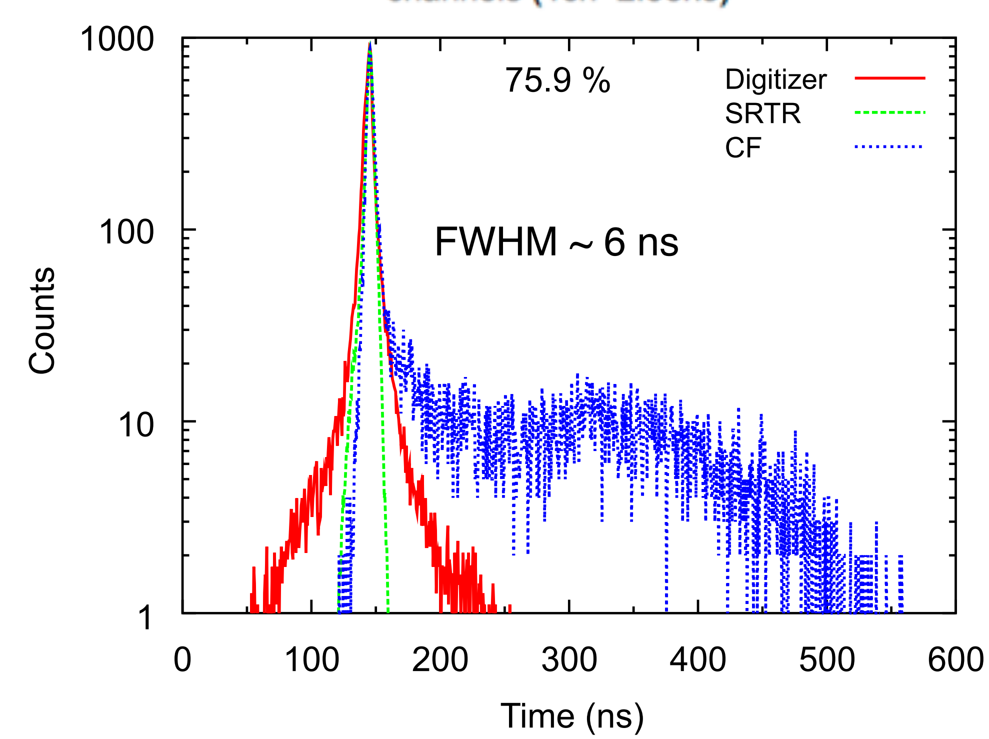
Time Resolution of Large HPGe

PAUL SCHERRER INSTITUT

- 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

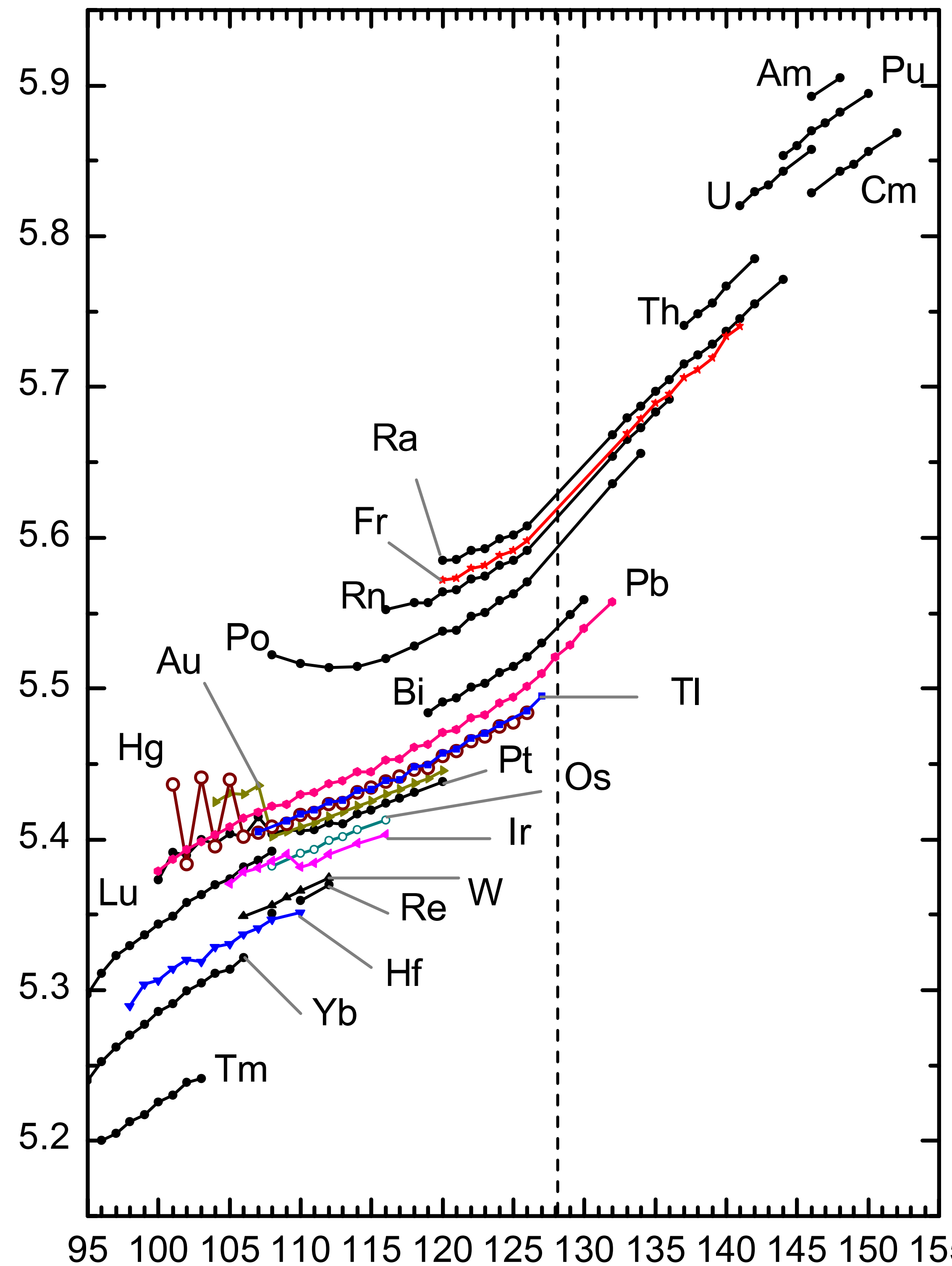
Mihailescu et al., NIMA **578**, 298 (2007)





Charge Radii for Unmeasured Isotopes

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



- 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

Extraction of Charge Radius

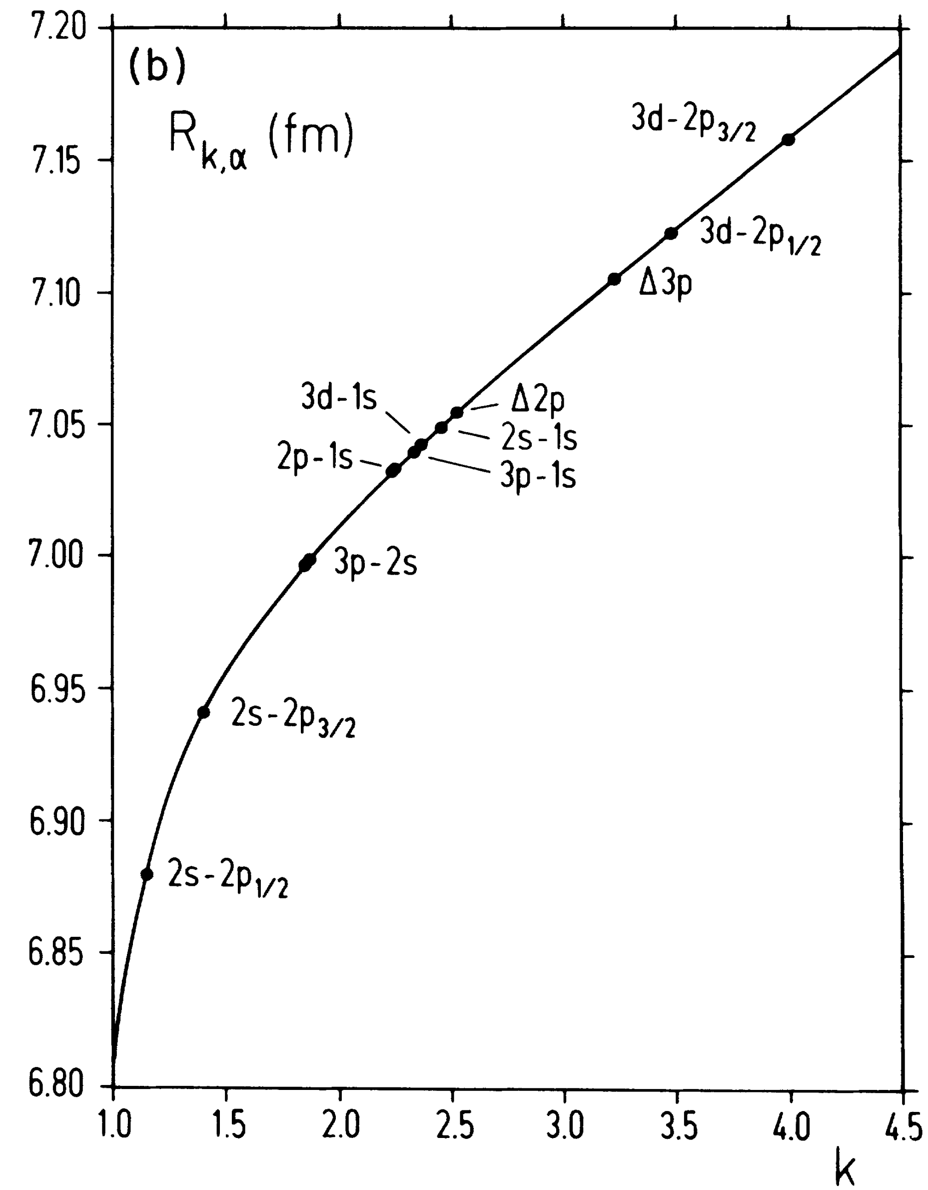
Bergem et al., PRC **37**, 2821 (2008)
Barrett, Phys. Lett. **33B**, 388 (1970)

- Analysis of muonic atom spectra through extraction of Barret moments

$$\langle r^k e^{-\alpha r}\rangle = (4\pi/Ze)\int \rho(r) r^k e^{-\alpha r} r^2 dr.$$

- Appears in papers as “black box” computer codes by Rinker and Tanaka

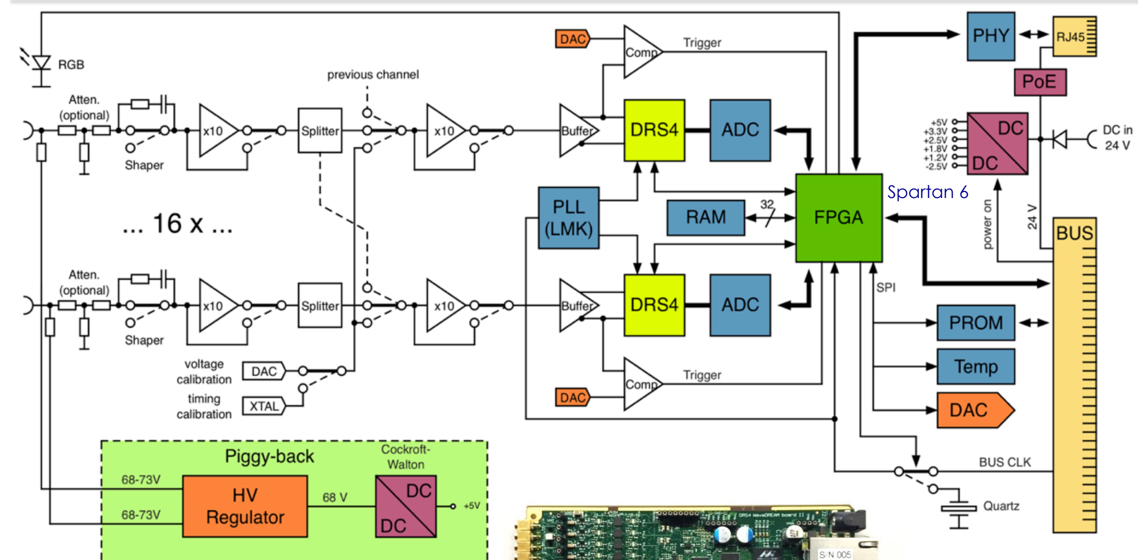
- Work needed to bring charge radius determination to more up-to-date style similarly as done for proton radius



DAQ

- Digitize scintillator (entrance, veto) and germanium signals
- WaveDREAM digitizer boards developed in-house for MEGII
- Optimized for SiPM
- 100 MHz ADC option
- Dedicated crate system
- Alternative:
  - Struck SIS3316 16 channel, 250 MHz digitizer
  - Firmware for online pulse processing

WaveDREAM Board (WDB)



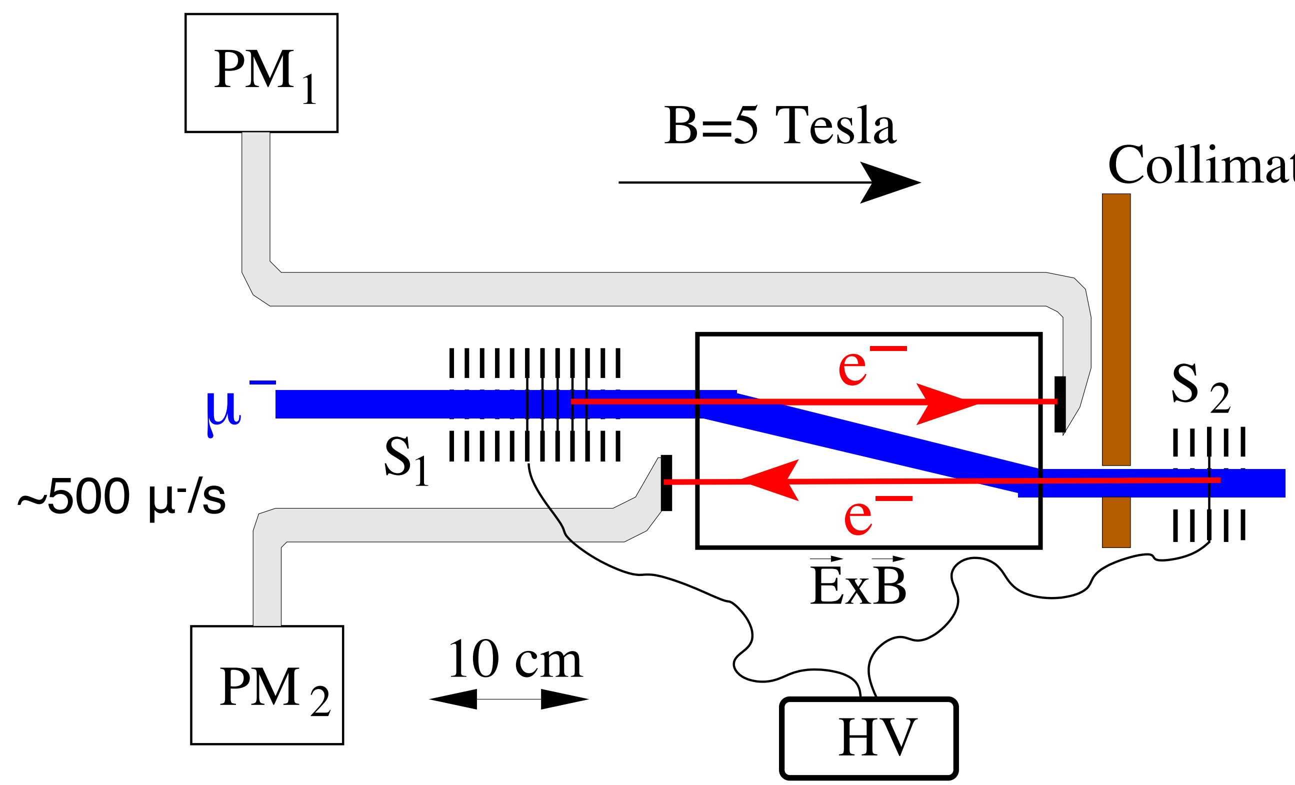
Drs4 based READout Module

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

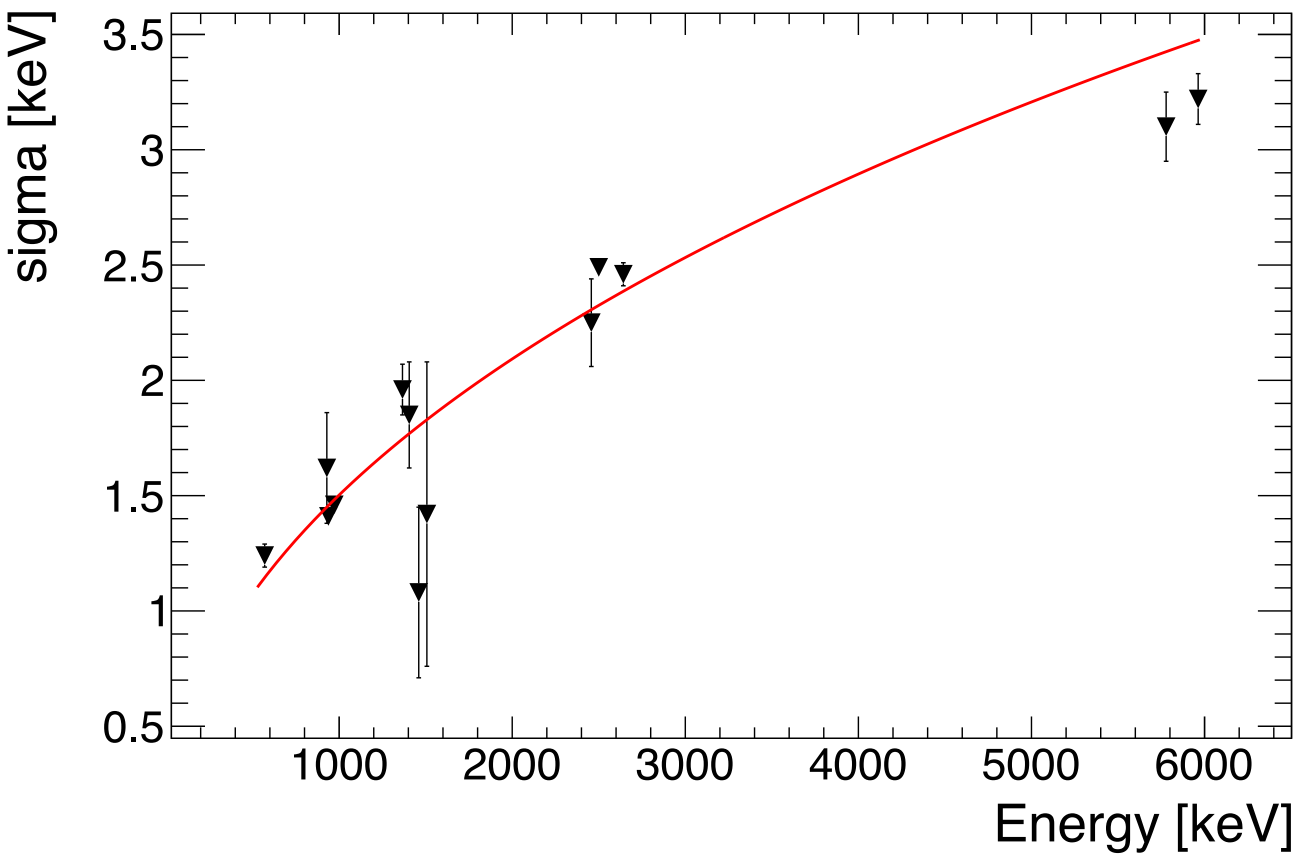
Lamb Shift Entrance Detector

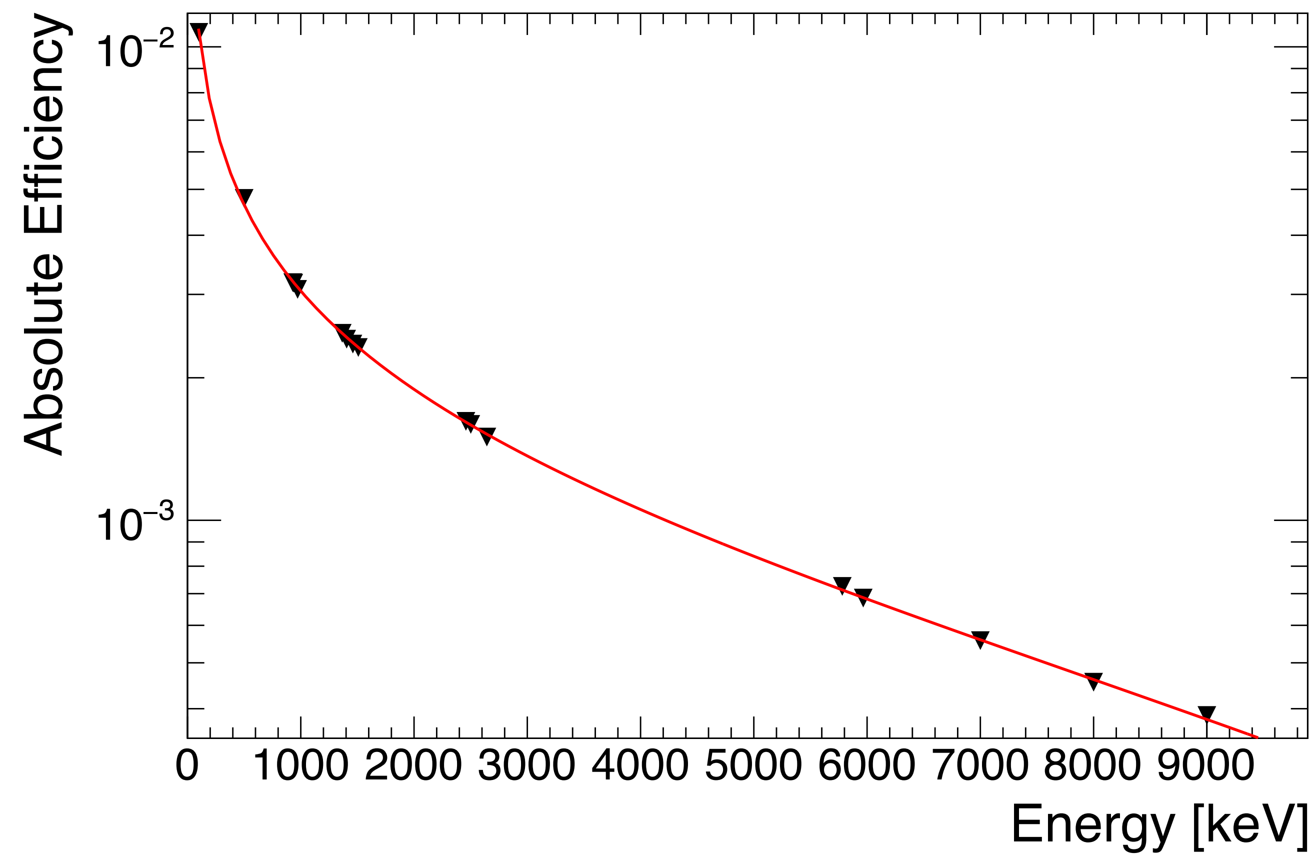
- Stack of thin carbon foils of 4 µg/cm²
- Some frictional cooling
- Ejection of secondary electrons from foils detected by scintillators

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



Energy Resolution & Efficiency





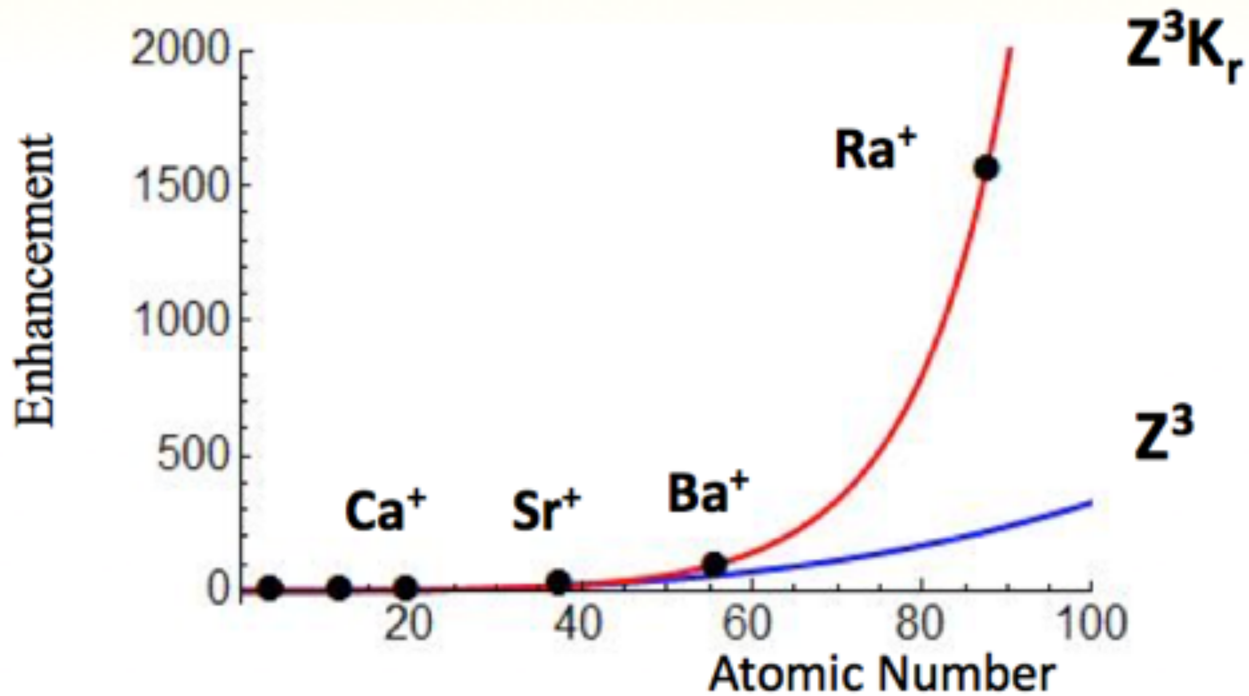
- Energy resolution and efficiency of the 75% germanium detector during the preliminary measurements

Atomic Parity Violation

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^+

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

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).)