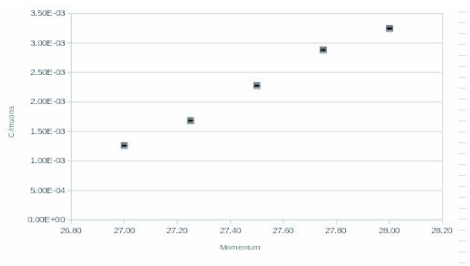
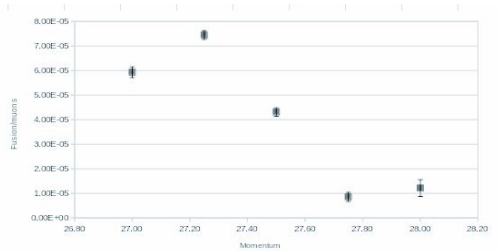
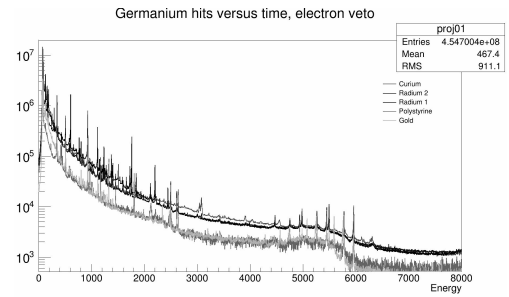
PAUL SCHERRER INSTITUT

DFG Deutsche Forschungsgemeinschaft

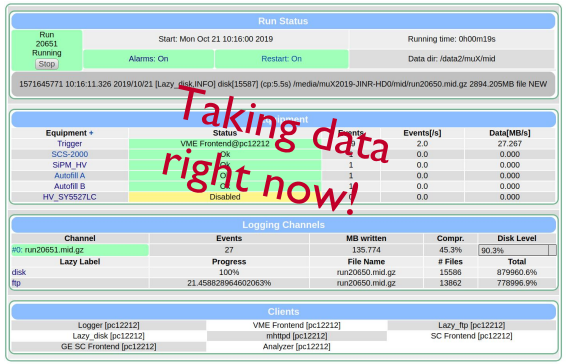




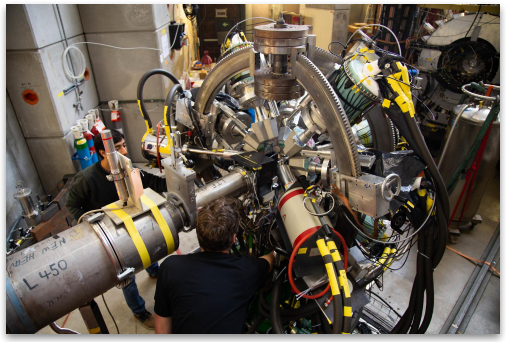


The muX project

Measuring muonic X-rays at PSI with a germanium detector array



Frederik Wauters on behalf of the muX collaboration
Johannes Gutenberg University Mainz



JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

Muonic atoms

Particle physics with muons

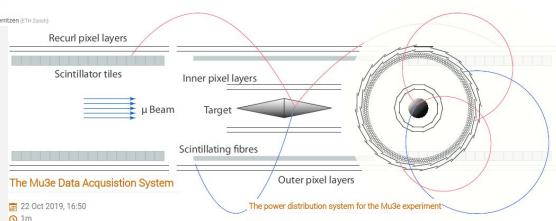
The Muon g-2 experiment at Fermilab: Overview and status update
23 Oct 2019, 15:00
30m
WHGA/001 - Auditorium (PSI)
Speaker
Peter Winter (Argonne National La...)

Study on Aging of Photomultiplier Tubes for MEG II Liquid Xenon Calorimeter
22 Oct 2019, 16:53
1m
WHGA/001 - Auditorium (PSI)
Speaker
Kazuki Toyoda (The University of Tok...)

Positron Reconstruction Algorithms for MEG II Pixelated Timing Counter
22 Oct 2019, 17:15
1m
WHGA/001 - Auditorium (PSI)
Speaker
Masashi Usami (The Univ. of Tokyo, I...)

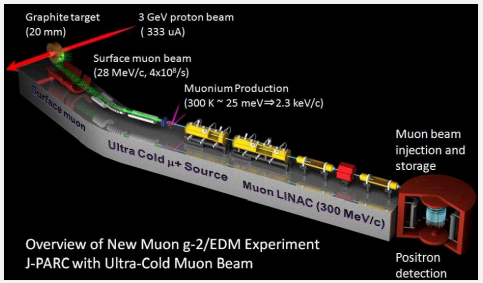
Calibration of VUV-sensitive MPPCs of MEG II Liquid Xenon Gamma-ray Detector
22 Oct 2019, 17:38
1m
WHGA/001 - Auditorium (PSI)
Speaker
Satoru Kobayashi (The University of Tok...)

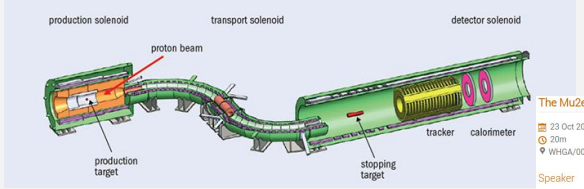
Mu3e fibre telescope
22 Oct 2019, 18:06
1m
WHGA/001 - Auditorium (PSI)
Speaker
Lukas Gerritzen (ETH Zurich)



The Mu3e Data Acqusistion System
22 Oct 2019, 16:50
1m
WHGA/001 - Auditorium (PSI)
Speaker
Niklaus Berger (Mainz University, Insti...)

The power distribution system for the Mu3e experiment
22 Oct 2019, 16:58
1m
WHGA/001 - Auditorium (PSI)
Speaker
Frederik Wauters (Universes Gutenberg...)





The Mu2e experiment
23 Oct 2019, 10:00
20m
WHGA/001 - Auditorium (PSI)
Speaker
Dr Stefano Di Falco (INFN Pisa)

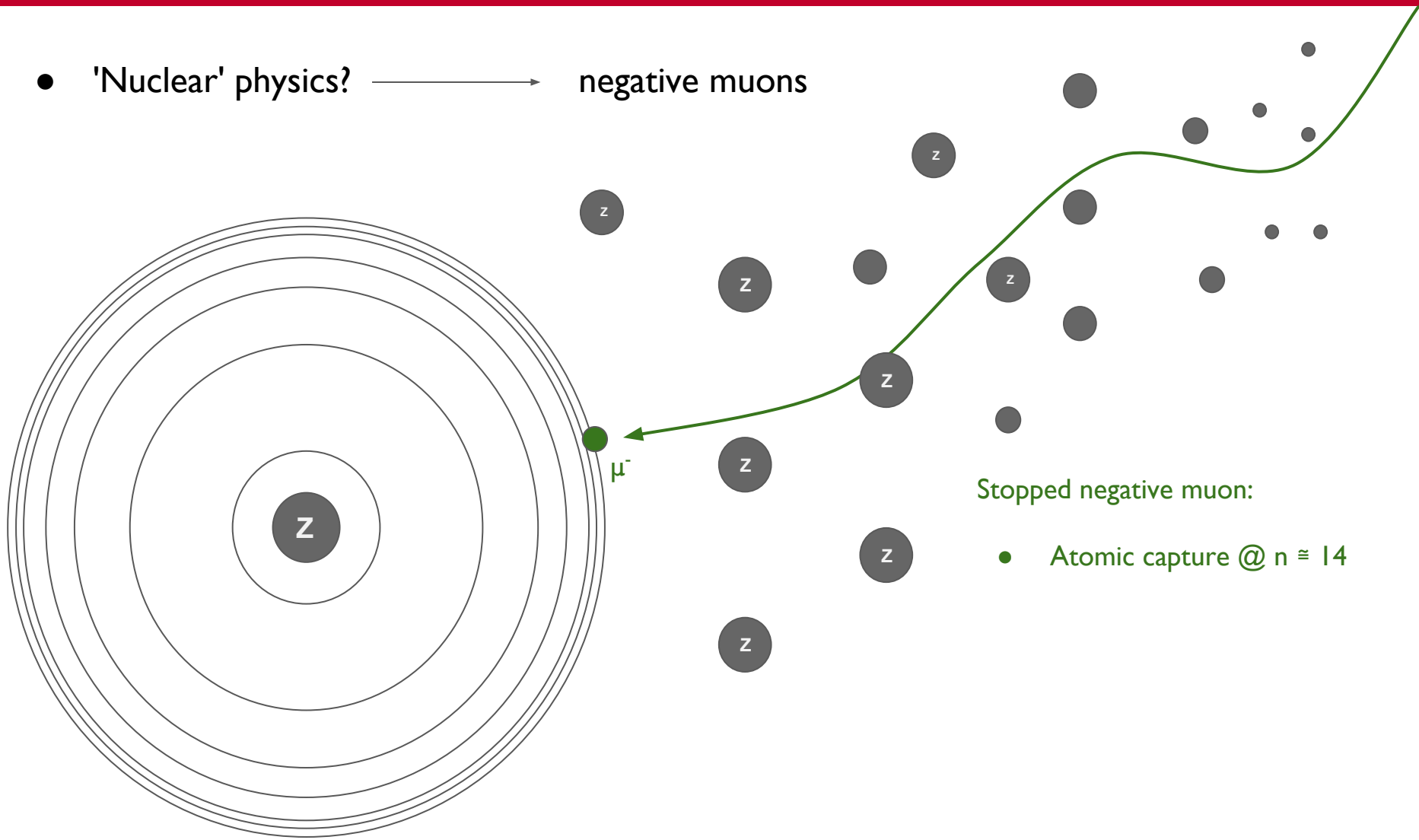
. . .

n ≅ 14

< 1 ns (<< μ lifetime)

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons



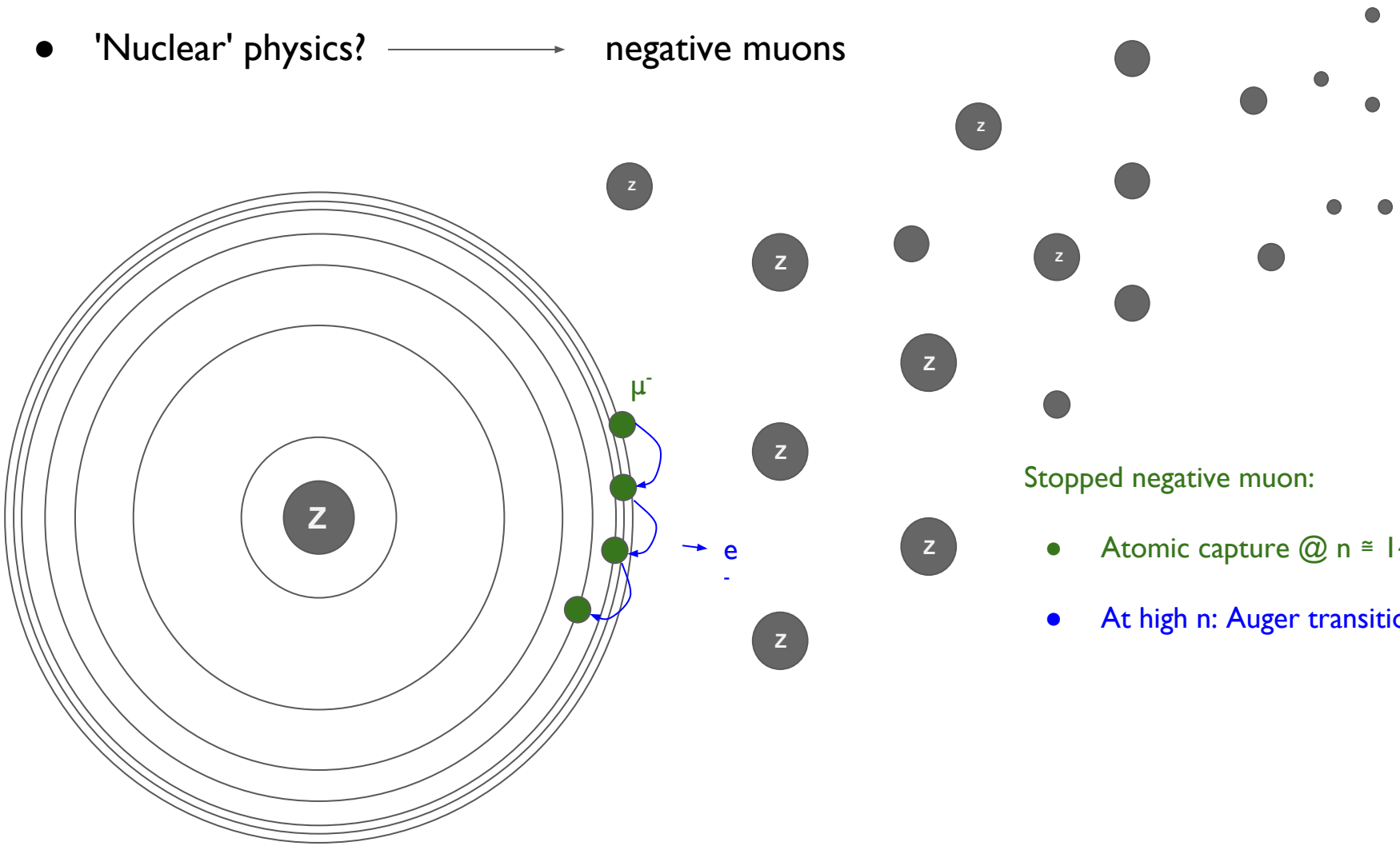
Stopped negative muon:

- Atomic capture @ n ≅ 14

< 1 ns (<< μ lifetime)

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons



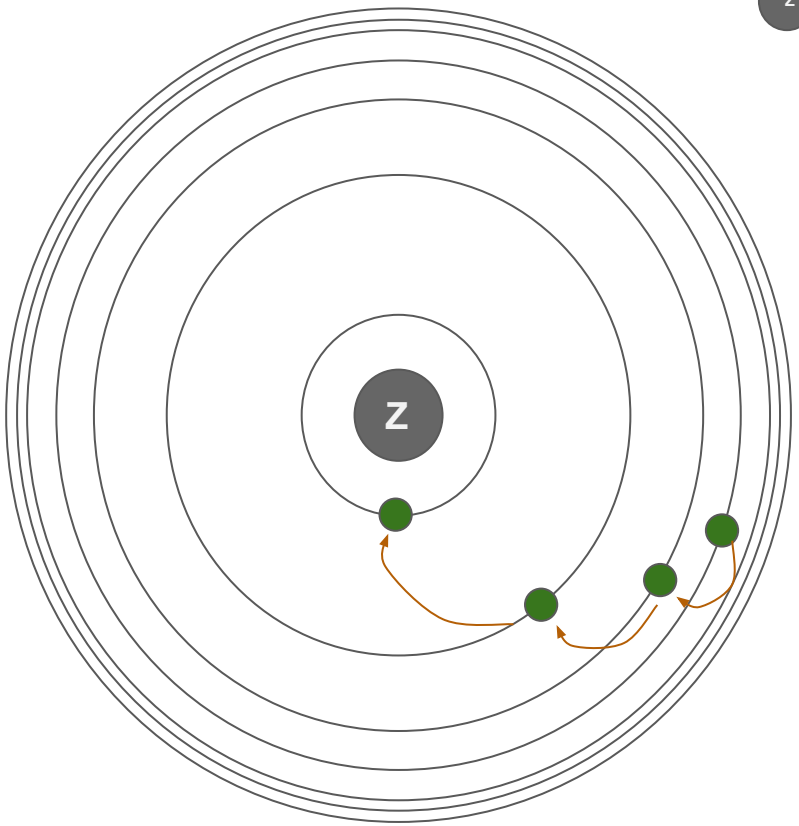
Stopped negative muon:

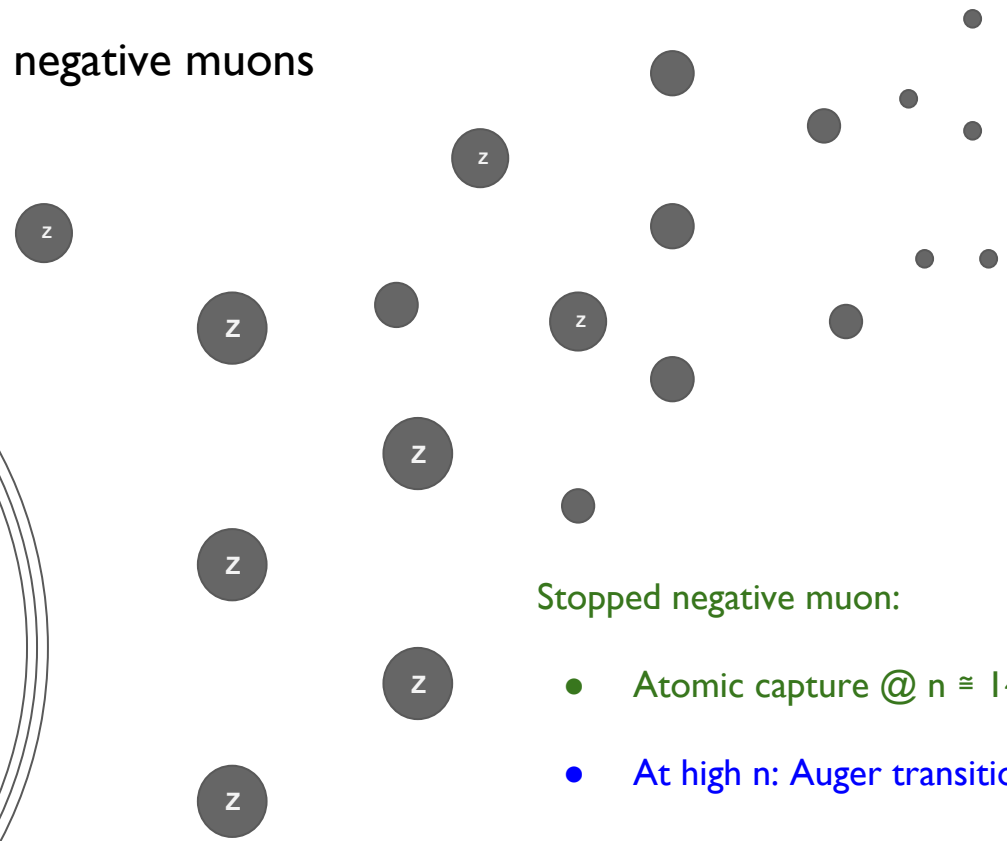
- Atomic capture @ n ≅ 14
- At high n: Auger transitions

< 1 ns (<< μ lifetime)

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons





Stopped negative muon:

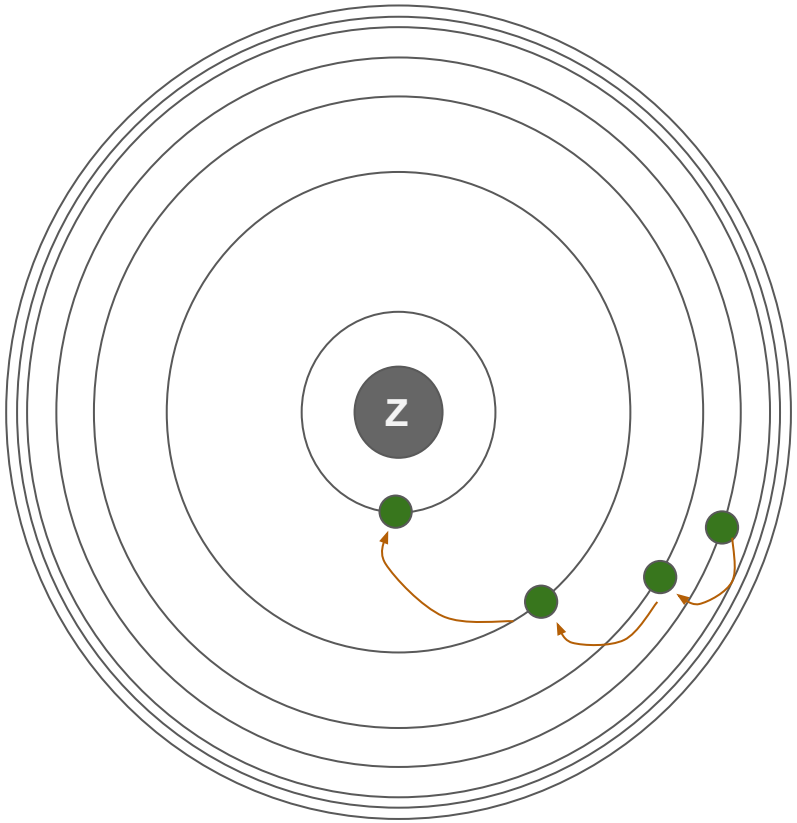
- Atomic capture @ n ≅ 14
- At high n: Auger transitions
- At lower n radiative transitions dominate:

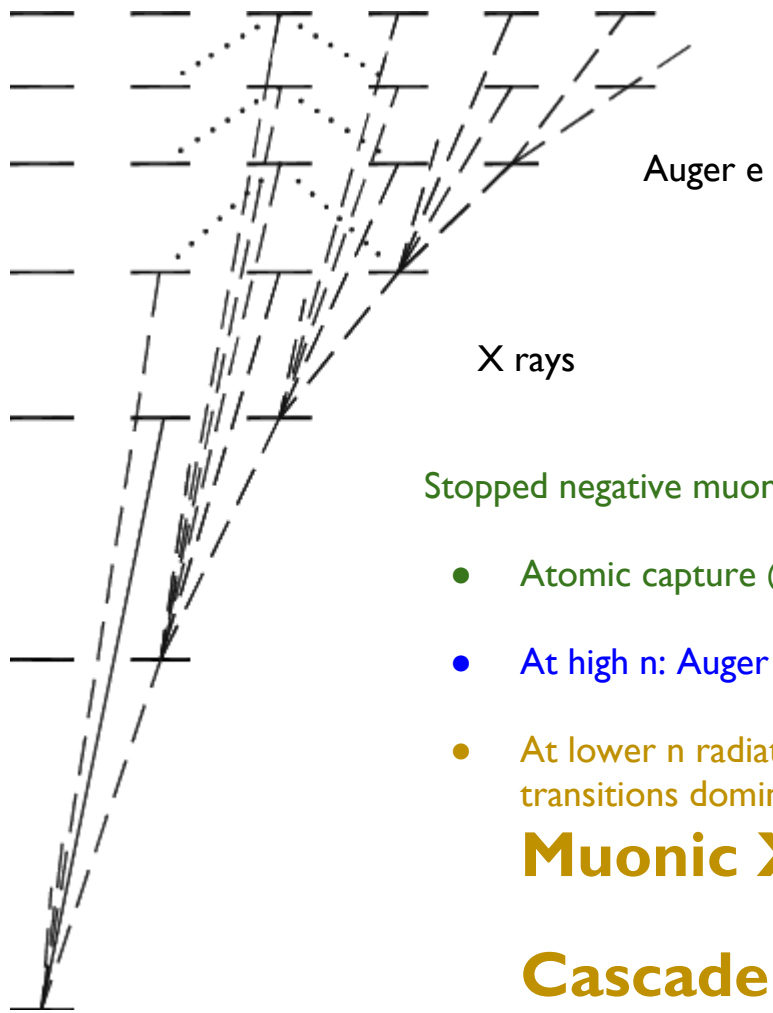
Muonic X-rays

< 1 ns (<< μ lifetime)

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons





Stopped negative muon:

- Atomic capture @ n ≅ 14
- At high n: Auger transitions
- At lower n radiative transitions dominate:

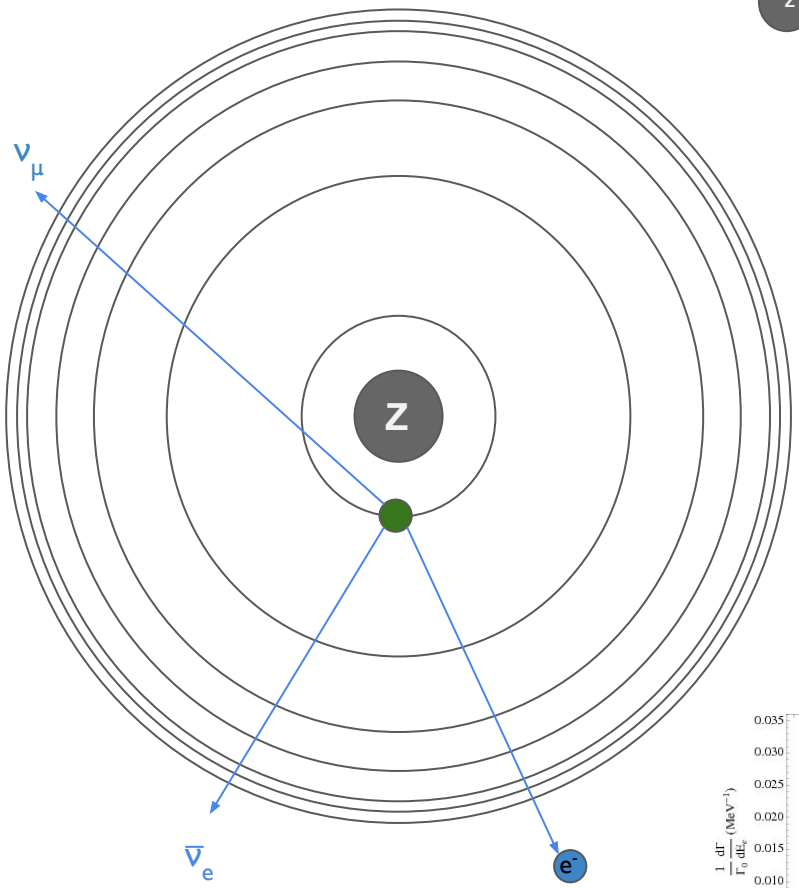
Muonic X-rays

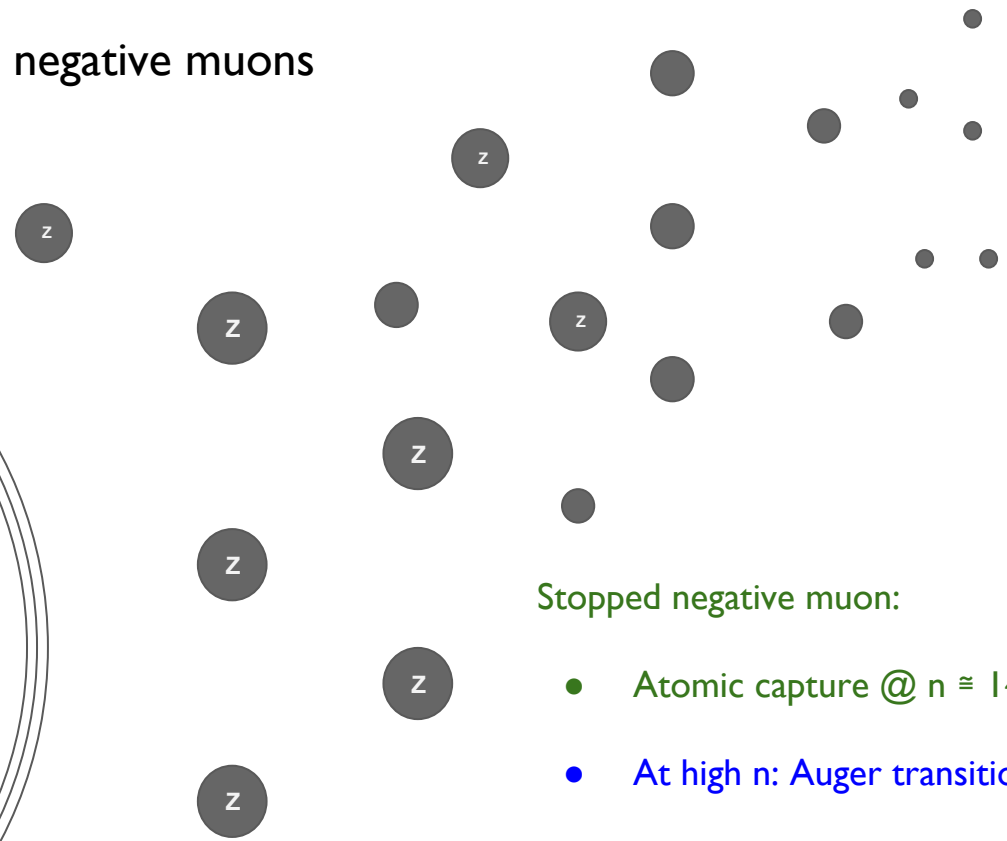
Cascade

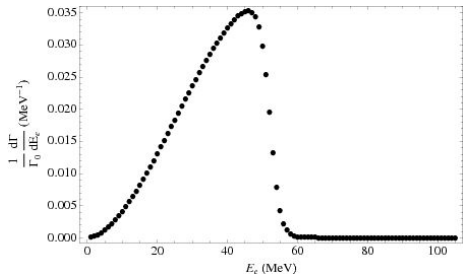
< 1 ns (<< μ lifetime)

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons





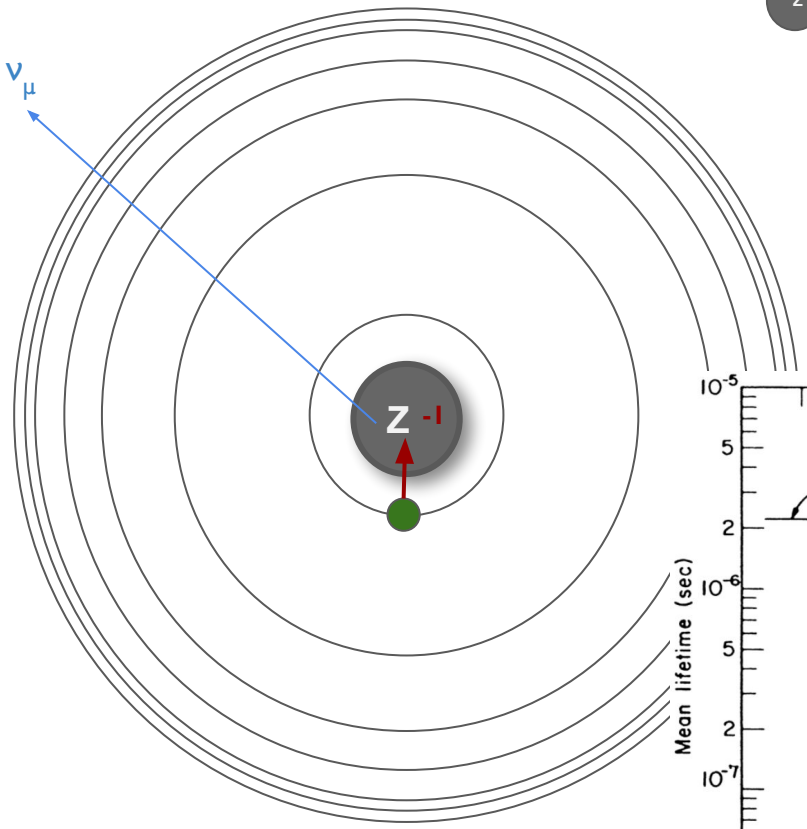


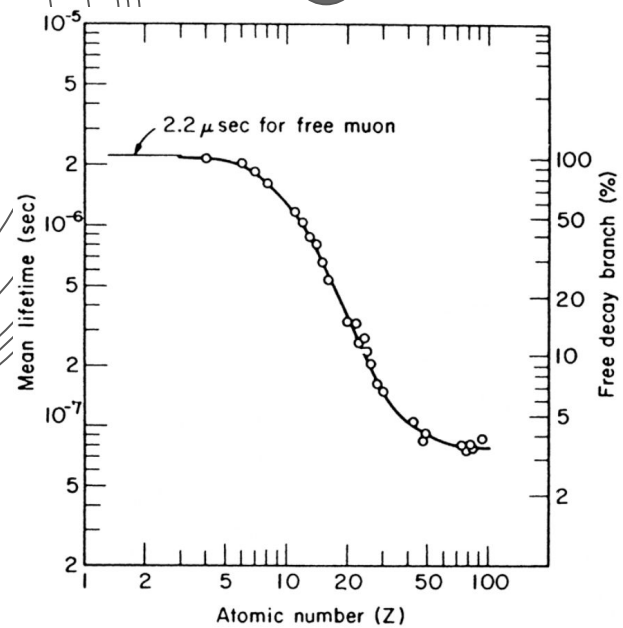
Stopped negative muon:

- Atomic capture @ n ≅ 14
- At high n: Auger transitions
- At lower n radiative transitions dominate: **Muonic X-rays**
- **Decay in orbit**

Muonic atoms

- 'Nuclear' physics? ⟶ negative muons





Stopped negative muon:

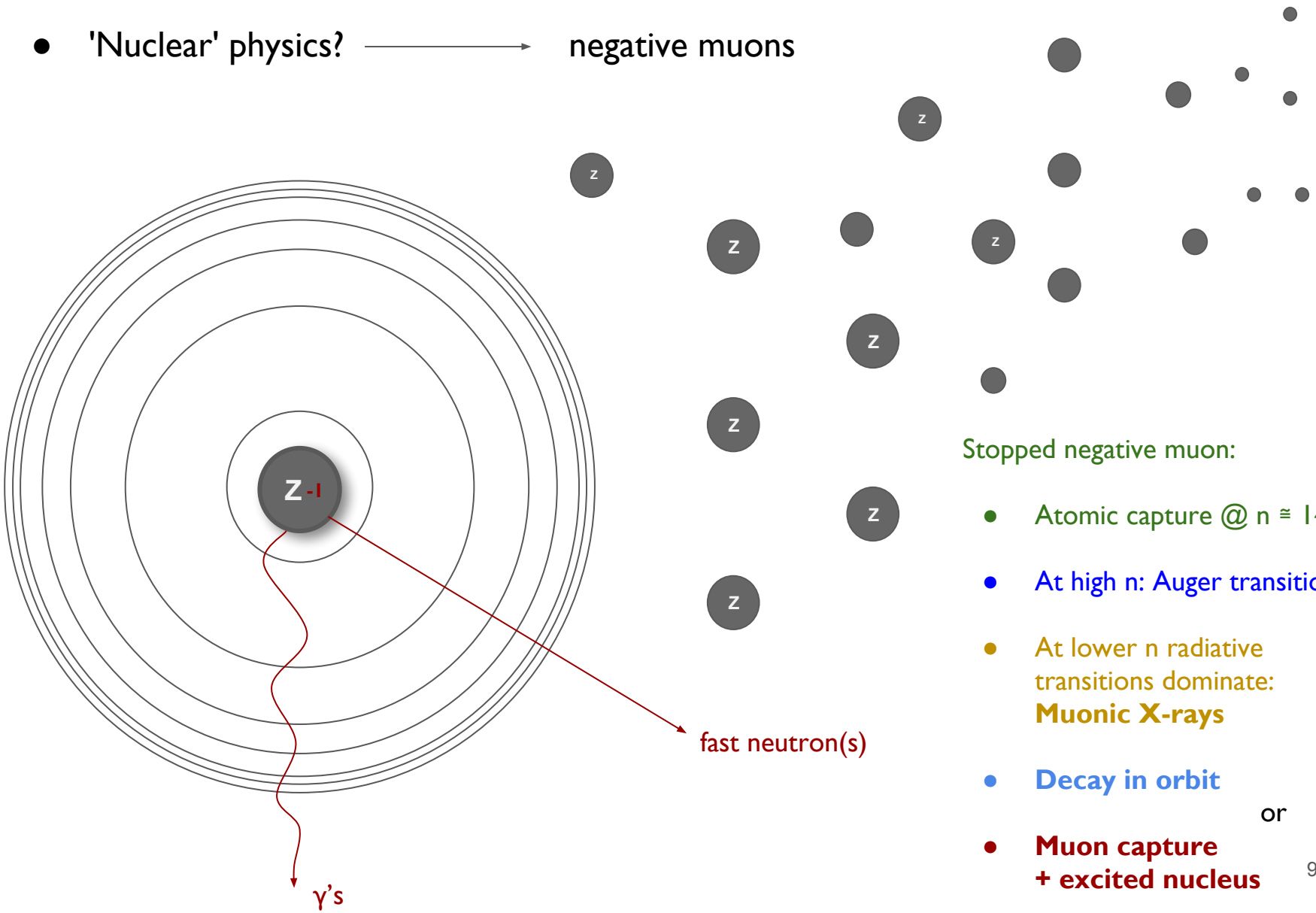
- Atomic capture @ n ≅ 14
- At high n: Auger transitions
- At lower n radiative transitions dominate: **Muonic X-rays**
- **Decay in orbit**

or

- **Muon capture + excited nucleus**

Muonic atoms

- 'Nuclear' physics? → negative muons



Stopped negative muon:

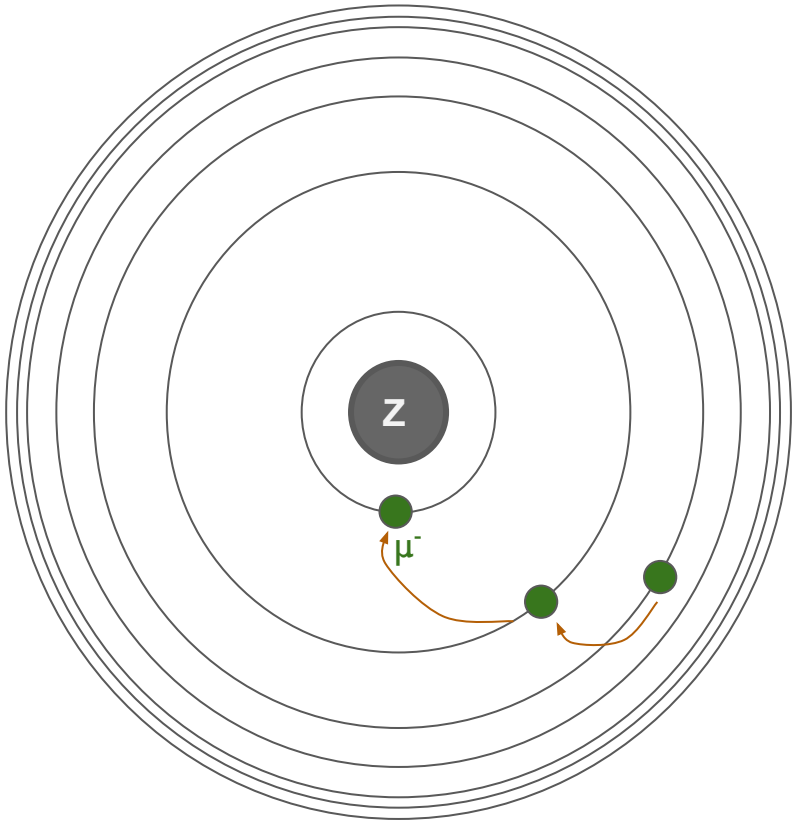
- Atomic capture @ n ≅ 14
- At high n: Auger transitions
- At lower n radiative transitions dominate: **Muonic X-rays**
- **Decay in orbit**

or

- **Muon capture + excited nucleus**

Muonic atoms

- Why (nuclear) physics with muonic atoms?



Very much like the H atom, but:

Bohr energies: $$E_n = \frac{mc^2}{2}\frac{\alpha^2 Z^2}{n^2}$$

Bohr radii: $$r_n = \frac{n^2}{mc^2}\frac{\hbar c}{\alpha Z}$$

Energies 200 higher:
→ 100 keV , few MeV range

Radii 200 times smaller:
→ significant overlap with the nucleus

Muonic atoms

- Why (nuclear) physics with muonic atoms?

The muon spends quite some time inside the nucleus:

Laboratory for (short range) muon-nucle(ar)(on) interactions

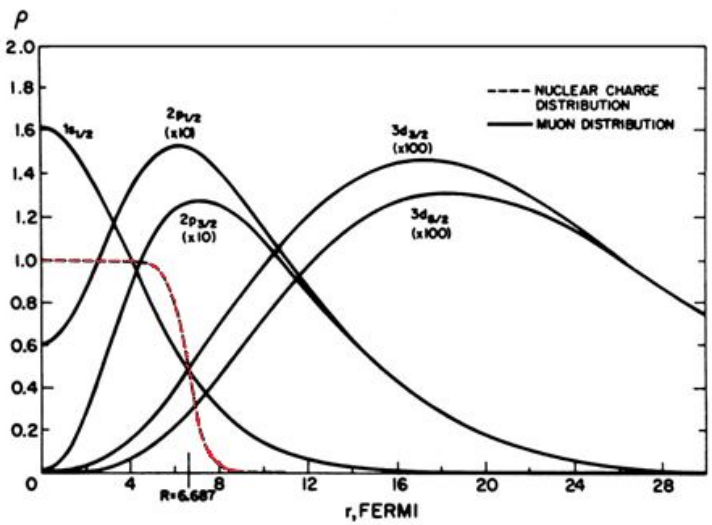


Fig. 15.8 The probability densities of finding a muon in the state indicated, at a distance r from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons and Duerdoth 1969).

Very much like the H atom, but:

Bohr energies: $$E_n = \frac{mc^2}{2}\frac{\alpha^2 Z^2}{n^2}$$

Bohr radii: $$r_n = \frac{n^2}{mc^2}\frac{\hbar c}{\alpha Z}$$

Energies 200 higher:
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Radii 200 times smaller:
→ significant overlap with the nucleus

The proton radius puzzle

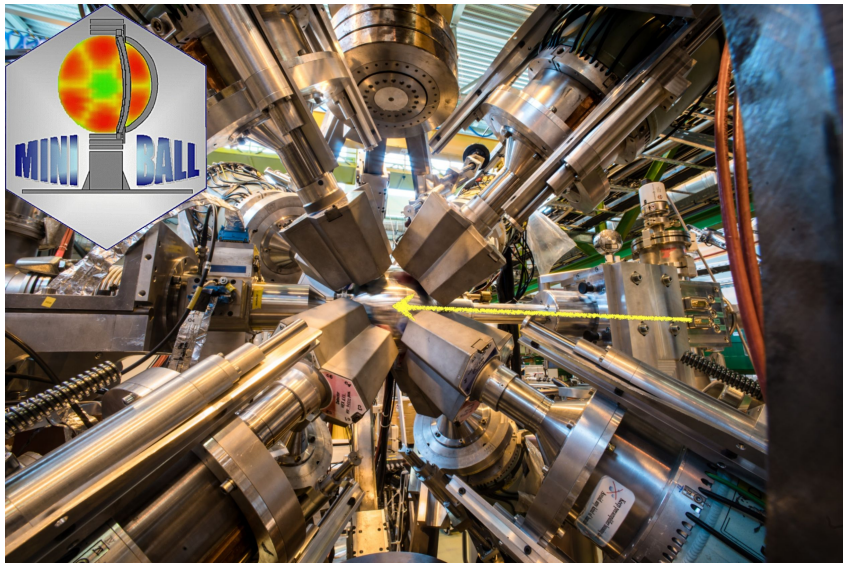
22 Oct 2019, 11:00
40m
WHGA/001 - Auditorium (PSI)

Speaker

Aldo Antognini (ETH)

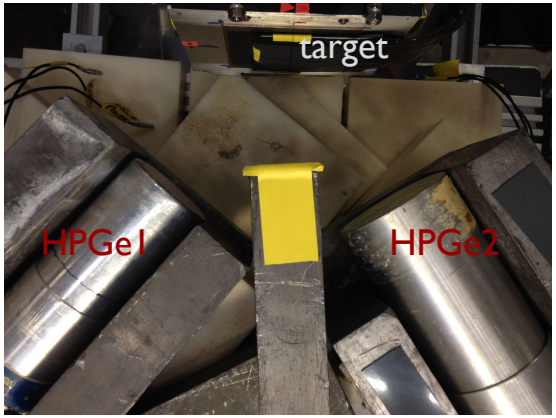
MuX

- What is muX?
  - A renewed effort for precision muonic X ray measurements at the Paul Scherrer Institute with germanium detectors
  - Particle physics / neutral currents main motivation
    - **Measuring 2P1S in ^{226}Ra to determine charge radius of radioactive atom Support electric APV measurement**
    - **Detecting 2S1S transitions motivated by APV**
  - Measuring muonic X-rays in μg of materials
  - Nuclear physics as it comes along:
    - Quadrupole moment of $^{185/187}$Re
    - γ's after muon capture, motivated by double β-decay searches
  - 2019: Miniball high-purity germanium array @ PSI (thank you LHC/CERN shutdown!)



Experimental setup

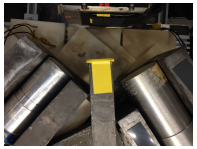
2015



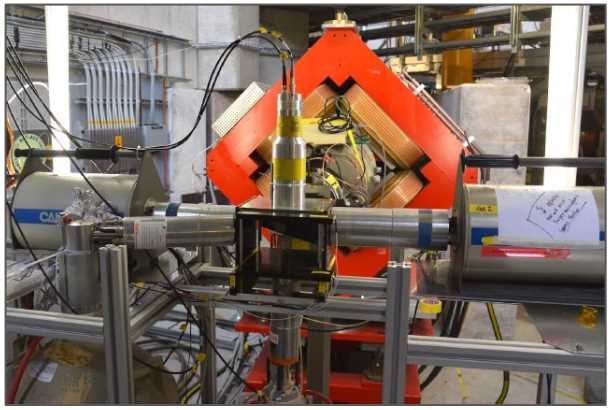
- Operate high-purity germanium detectors (HPGe) at a muon beam line

Experimental setup

2015



2016

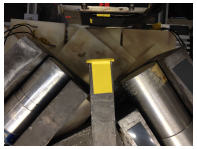


γ's @ 100 keV - few MeV

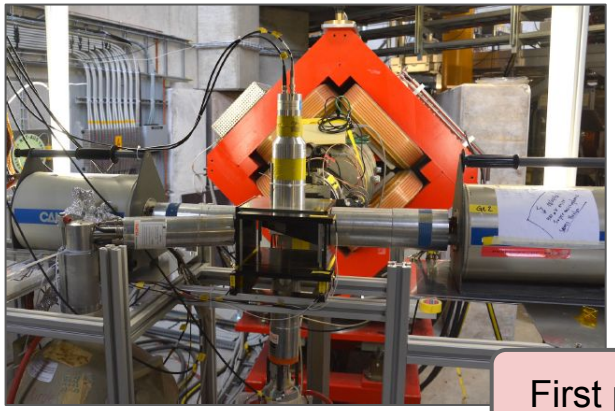
- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with D_2/H_2 gas cell
- Measure muonic X-ray spectrum of Re

Experimental setup

2015



2016



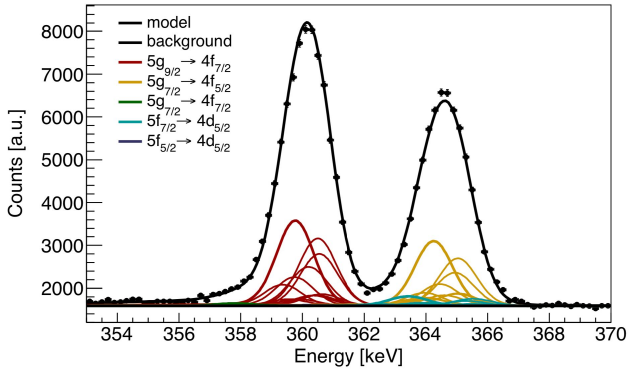
γ's @ 100 keV - few MeV

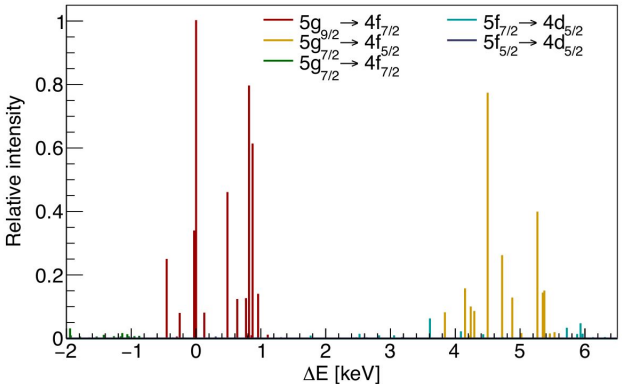
- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with D_2/H_2 gas cell
- Measure muonic X-ray spectrum of Re

First physics results!

- Quadrupole moment of $^{185/187}$Re from 5g →4f transitions
  nuclear ground-state hyperfine splitting

  i. Fit E(7-6) and two intensities
  ii. Line shape from neighboring γ transitions
  iii. Convolute with finite width transition
  iv. Calculate all other energies and intensities in terms of Q





PHYSICAL REVIEW A **99**, 042501 (2019)

Higher-order corrections to the dynamic hyperfine structure of muonic atoms

Niklas Michel* and Natalia S. Oreshkina†
Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany

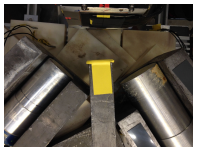
PHYSICAL REVIEW A **96**, 032510 (2017)

Theoretical prediction of the fine and hyperfine structure of heavy muonic atoms

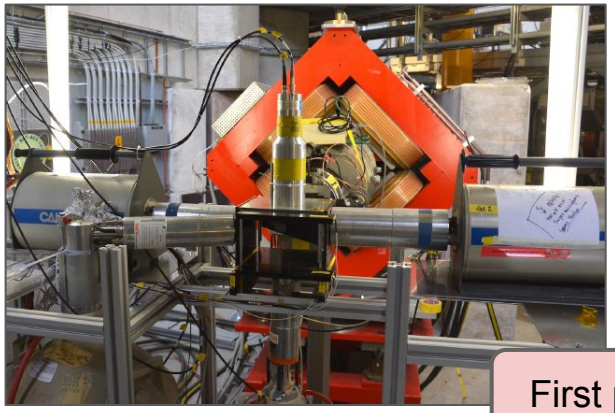
Niklas Michel,* Natalia S. Oreshkina,† and Christoph H. Keitel
Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
(Received 19 August 2017; published 28 September 2017)

Experimental setup

2015



2016



γ's @ 100 keV - few MeV

- Operate high-purity germanium detectors (HPGe) at a muon beam line
- First tests with D_2/H_2 gas cell
- Measure muonic X-ray spectrum of Re

First physics results!

- Quadrupole moment of $^{185/187}$Re from 5g →4f transitions

	Q (Barn)
^{185}Re ^{187}Re Our result	2.07(2)(5) 1.94(2)(5)
^{185}Re ^{187}Re Konijn et al. (neglecting $5f_{5/2}\rightarrow 4d_{5/2}$ & $5g_{7/2}\rightarrow 4f_{7/2}$ transitions)	2.21(4) 2.09(4)

Analysis of the hyperfine splitting of the 5 → 4 transitions in muonic Re-185 and Re-187

22 Oct 2019, 17:13
1m
WHGA/001 - Auditorium (PSI)

Speaker

Stergiani Marina Vogiatzi (PSI - Paul Scherrer In...)

Master thesis Stella Vogiatzi

Theoretical prediction of the fine and hyperfine structure of h... atoms

Niklas Michel,* Natalia S. Oreshkina,† and Christoph H. Keitel
Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany
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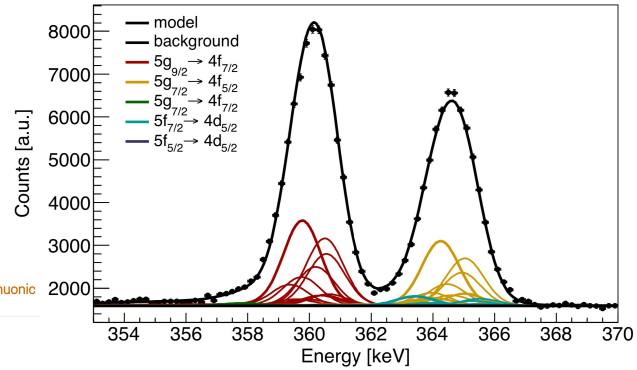
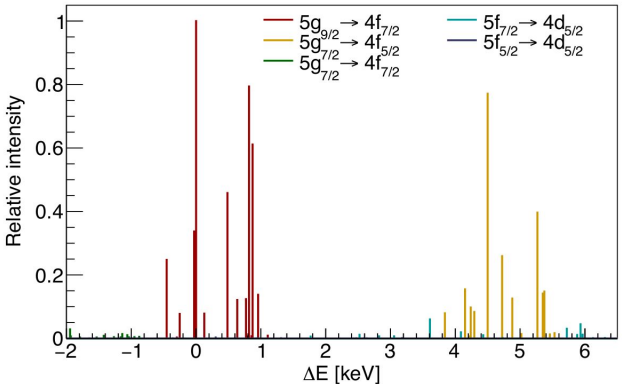
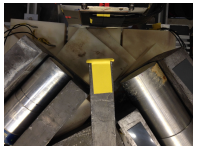


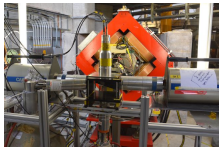


Experimental setup

2015

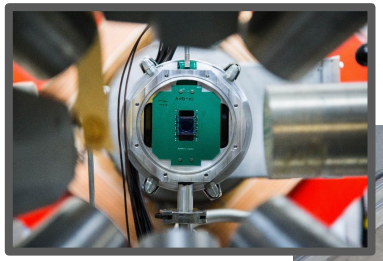


2016



- Develop *triggerless* DAQ and analysis
- 11 HPGe detectors from various collaborators & French/UK Ge Pool
- Muon counters, Electron counters, BGO shield
- Physics:
  - Stop muons in μg of material
  - Measure 2s1s transition in Zn and Kr

Got serious no longer a side project

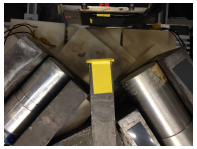


2017 - 2018

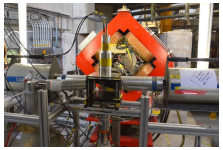
10-100 kHz μ^- @ 20-40 MeV/c

Experimental setup

2015



2016



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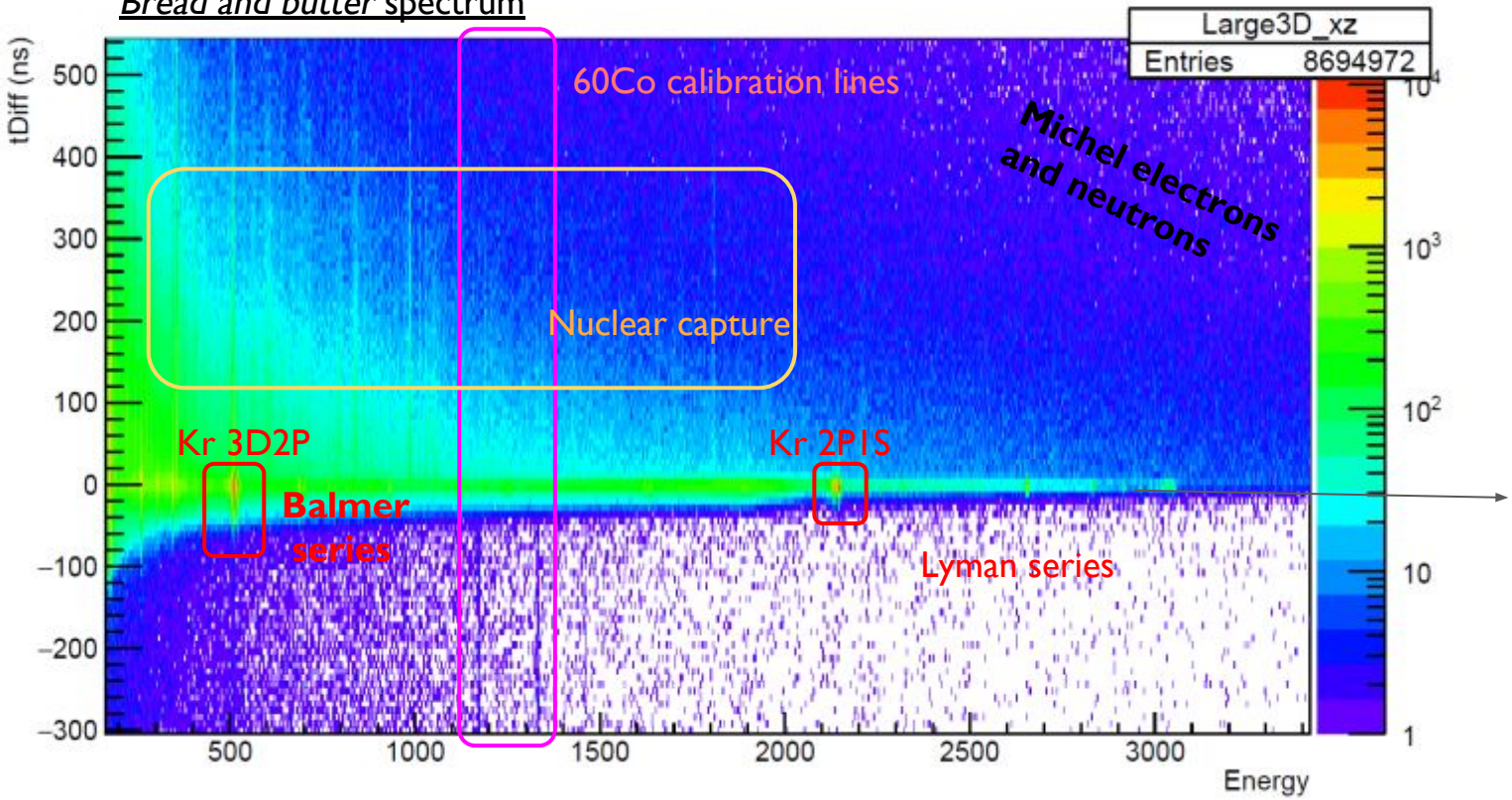
  - Stop muons in μg of material
  - Measure 2s1s transition in Zn and Kr

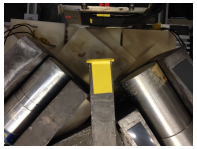
<u>*Bread and butter* spectrum</u>



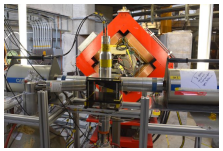
10 ns time resolution on HPGe detectors!

Experimental setup

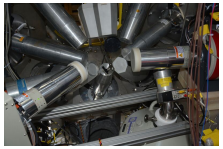
2015



2016



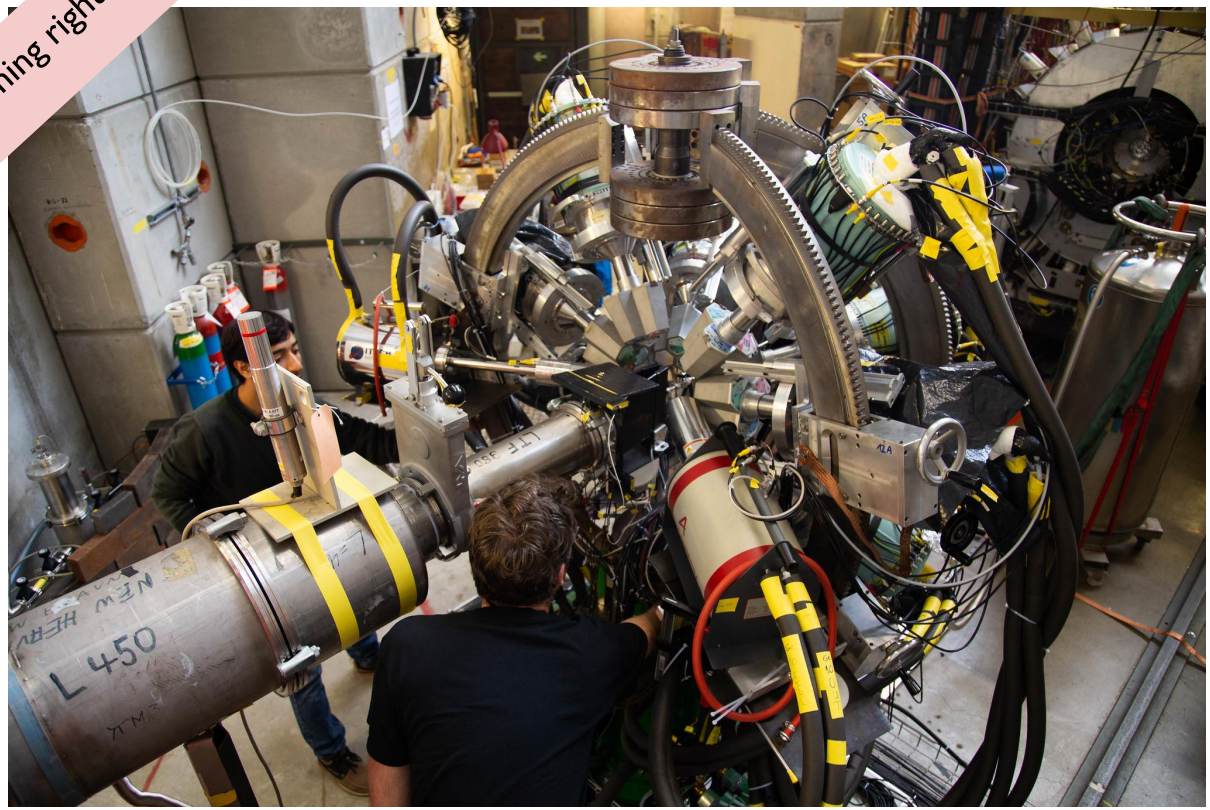
2017-18



- Move the MiniBall HPGe array from ISOLDE/CERN to PSI
- Measurements with radioactive targets
- Extended 7 week program
  - Ra and Cm measurements (A. Knecht & Co)
  - γ's after muon capture (Dubna)
  - Elemental analysis
  - 2s1s measurements in Zn (F. Wauters & Co)

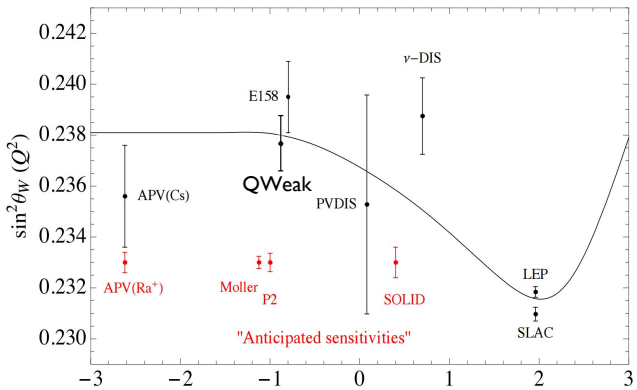
Running right now

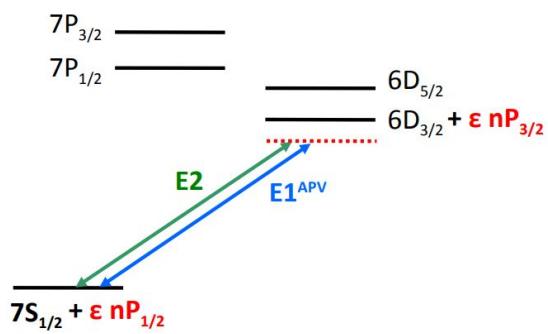
2019



muX physics results & plans

- Measuring 2P1S in 226Ra → Input for a APV experiment on a single trapped Ra ion.

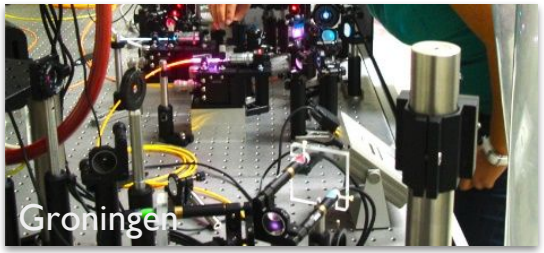




Hyperfine Interact (2011) 199:9–19
DOI 10.1007/s10751-011-0296-6

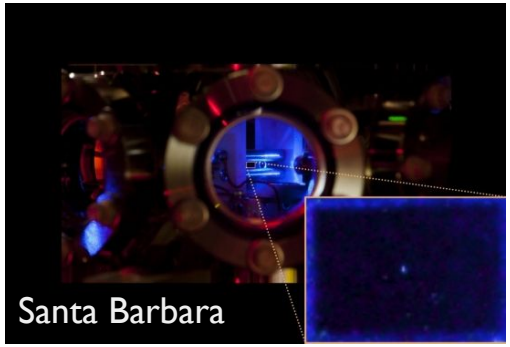
Atomic parity violation in a single trapped radium ion

O. O. Versolato · L. W. Wansbeek · G. S. Giri · J. E. van den Berg · D. J. van der Hoek · K. Jungmann · W. L. Kruithof · C. J. G. Onderwater · B. K. Sahoo · B. Santra · P. D. Shidling · R. G. E. Timmermans · L. Willmann · H. W. Wilschut



Laser Cooling of Radium Ions

M. Fan, C. A. Holliman, A. L. Wang, and A. M. Jayich
Phys. Rev. Lett. **122**, 223001 – Published 7 June 2019



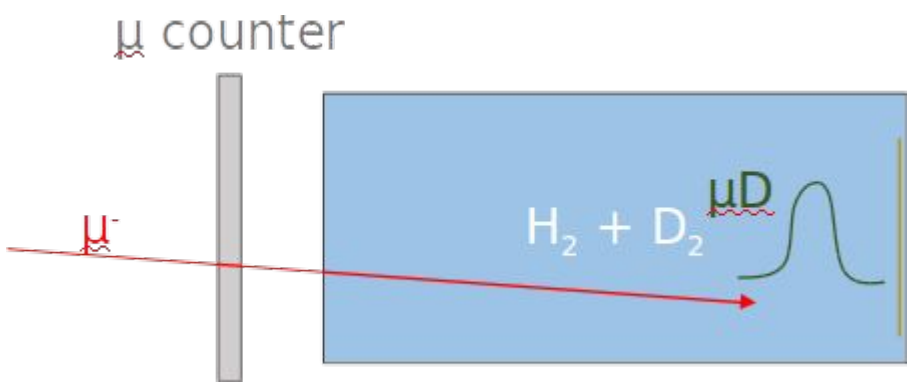
$$E1_{PNC} = K_r\ Z^3\ Q_W$$

- Determine E(2P1S) < 10 keV to determine charge radius < 0.2% needed to calculate K_r

- All Ra isotopes are radioactive! → **< 5 µg of 226Ra**

muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material
    1. Stop in 100 Bar of H_2 + 0.25% - 1% of D_2
    2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy



muX physics results & plans

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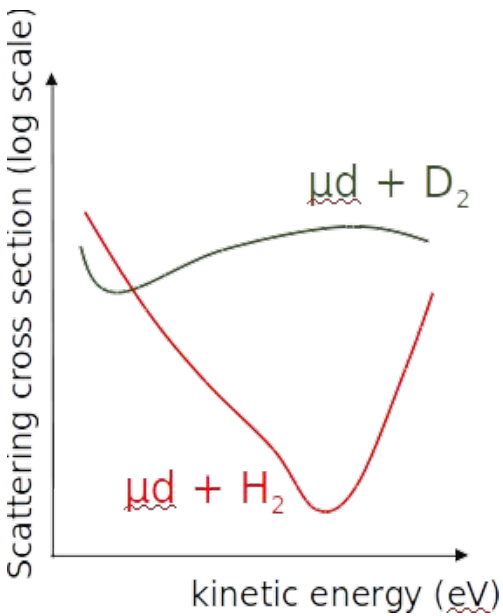
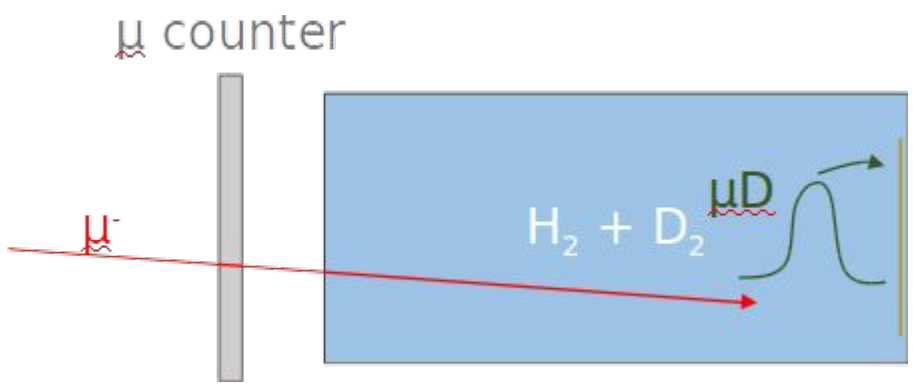
    3. μD moves freely through H2 gas at ca. 5 eV





PHYSICAL REVIEW A **73**, 034501 (2006)

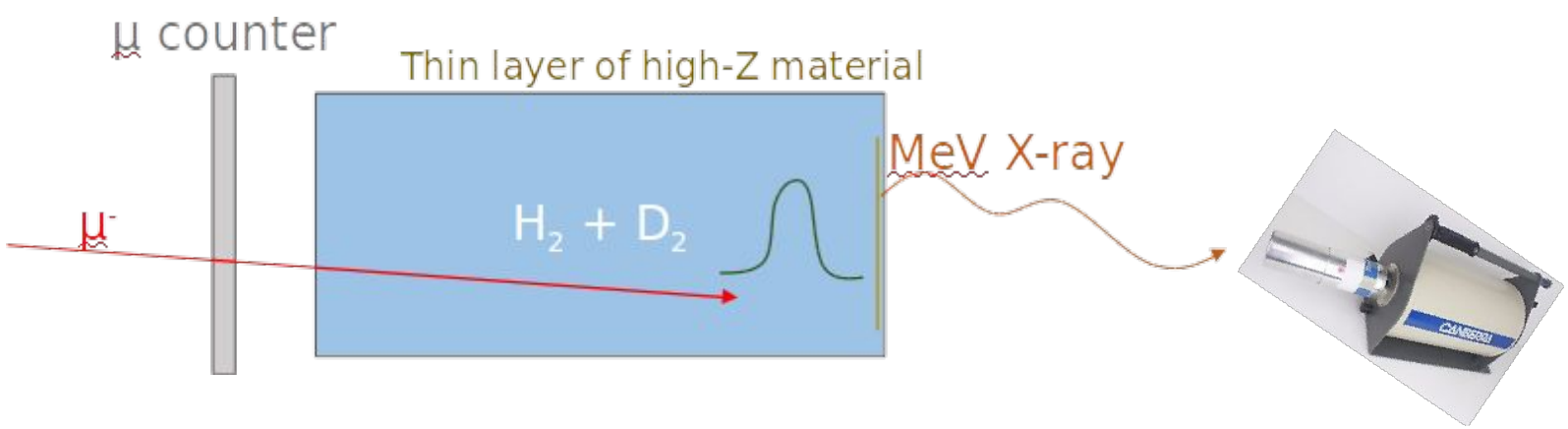
Ramsauer-Townsend effect in muonic atom scattering

F. Mulhauser,[1,*] A. Adamczak,[2,†] G. A. Beer,[3] V. M. Bystritsky,[4] M. Filipowicz,[5] M. C. Fujiwara,[6] T. M. Huber,[7] O. Huot,[1] R. Jacot-Guillarmod,[1,‡] P. Kammel,[8,*] S. K. Kim,[9] P. E. Knowles,[1] A. R. Kunselman,[10] G. M. Marshall,[6] A. Olin,[6] C. Petitjean,[11] T. A. Porcelli,[6] L. A. Schaller,[1] V. A. Stolupin,[4] J. Woźniak,[12] and J. Zmeskal[13]
(TRIUMF Muonic Hydrogen Collaboration)

muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material

    1. Stop in 100 Bar of H_2 + 0.25% - 1% of D_2
    2. Transfer from μH to μD in ~100 ns + 45 eV of kinetic energy
    3. μD moves freely through H2 gas at ca. 5 eV
    4. Upon hitting the chamber walls: μD → μZ transfer



PHYSICAL REVIEW A **73**, 034501 (2006)

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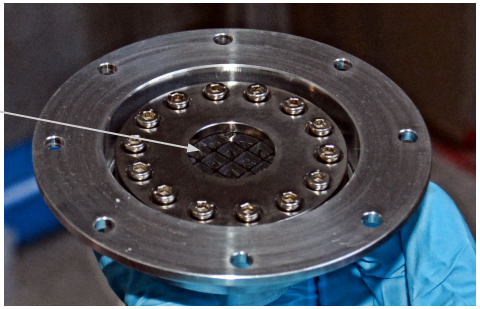
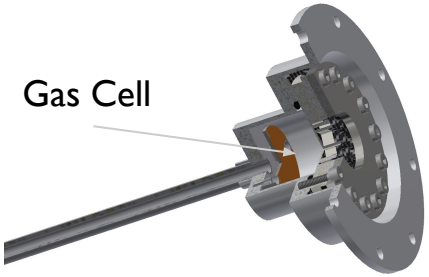
muX physics results & plans

- Measuring 2P1S in 5 μg of radium
  - Stop 30 MeV/c muons in a small amount of material
  - Demonstrated in 2017, few % efficiency

CFO window

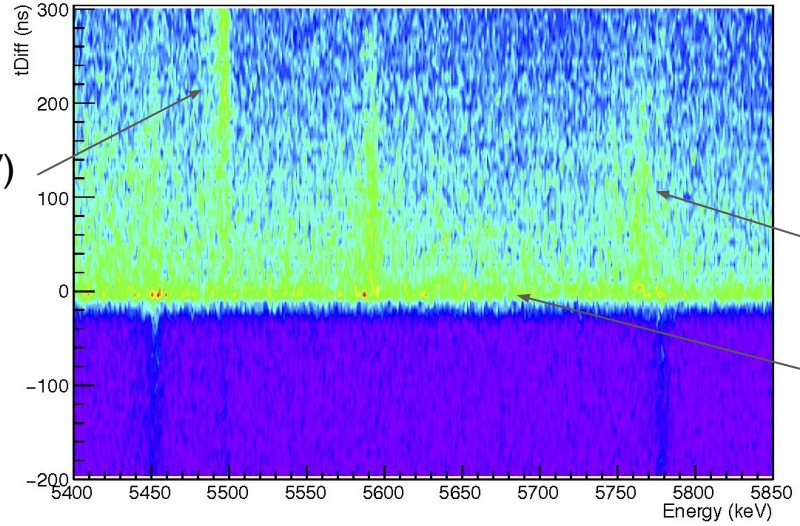


Gas Cell



Small gas cell for 100 Bar of H_2 with a Cu disk + 3-50nm of Au

μD + H → 3He + γ (5.5 MeV)

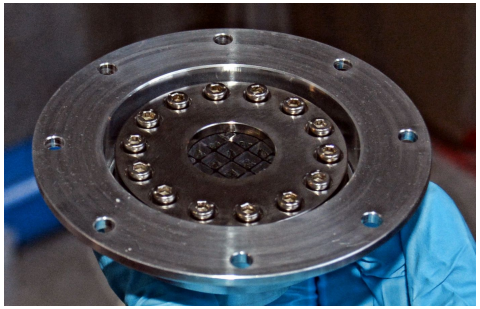


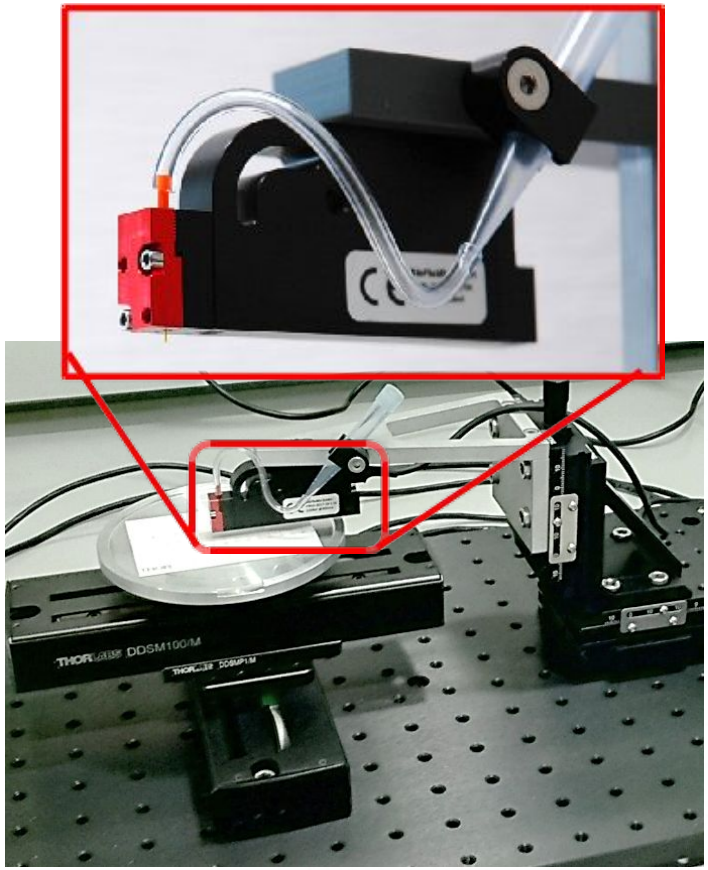
Delayed (after transfer) Au X-rays

Prompt events

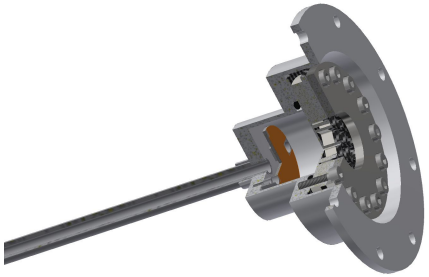
muX physics results & plans

- Measuring 2P1S in 5 µg of radium
  - Stop 30 MeV/c muons in a small amount of material
  - Demonstrated in 2017, few % efficiency
  - Measured 248/246Cm & 226Ra 2 weeks ago!

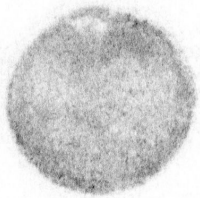




Drop on Demand target production at Institut für Kernchemie (Mainz)



Radiography of target:



	Method	Activity (kBq)
^{248}Cm/^{246}Cm	Plating / Printing(1)	2.5 / 8.4
^{248}Cm/^{246}Cm	Plating / Printing(2)	2.4 / 8.1
^{248}Cm/^{246}Cm	Printing(1)	2.1 / 7.3
^{248}Cm/^{246}Cm	Printing(2)	2.2 / 7.4
^{226}Ra	Plating / Printing	49.5
^{226}Ra	Plating	91.6
^{226}Ra	Plating / Printing	160.1

muX physics results & plans

- Measuring 2P1S in 5 µg of radium
  - Stop 30 MeV/c muons in a small amount of material
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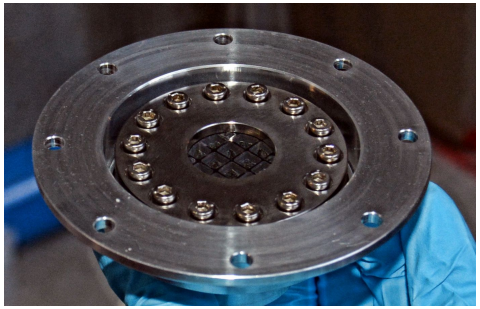
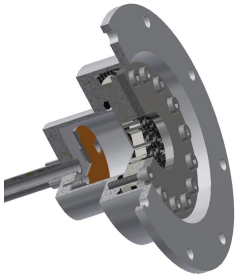
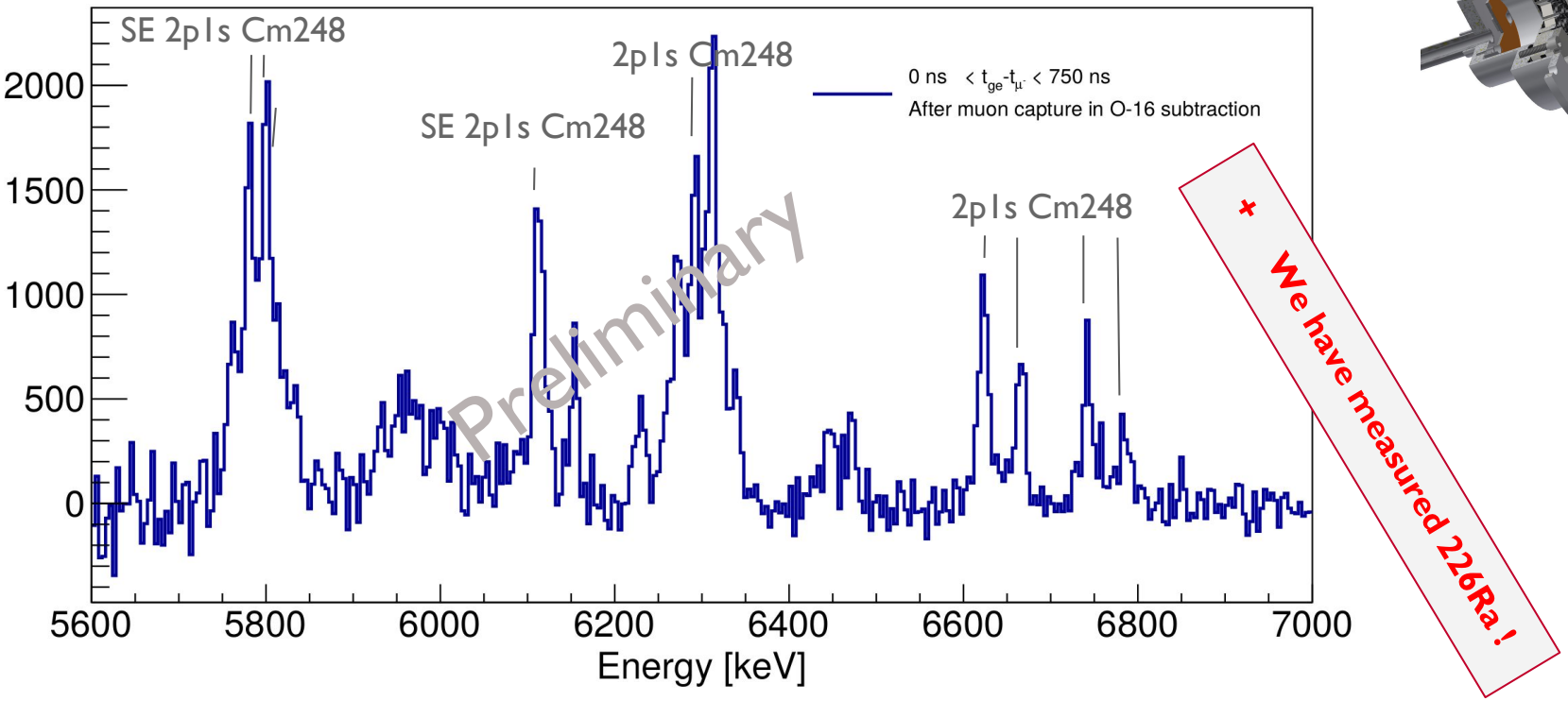


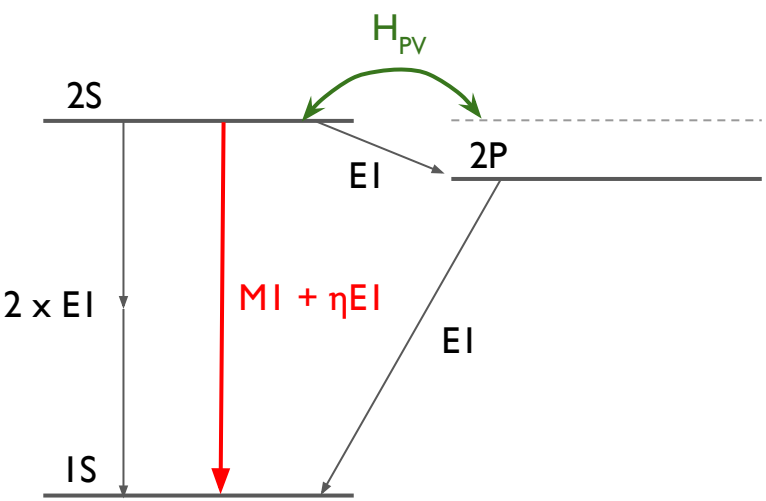


Cm 2P1S multiplet (complicated due to dynamic hyperfine splitting)



muX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure APV with muons directly?
  - Motivation:
    - i. Is the muon special
    - ii. Neutral currents at low Q^2 have not yet been measured
  - Goal of muX:
    - i. Observe 2S1S transition
    - ii. Achieve good S/B for a 10^{-4} B.R. transition



Not a new idea:

PHYSICS REPORTS (Review Section of Physics Letters) 118, No. 4 (1985) 179–238. North-Holland, Amsterdam

THE NEUTRAL WEAK CURRENT IN MUONIC ATOMS

John MISSIMER*
*Institut für Physik, Johannes-Gutenberg Universität, 6500 Mainz, Federal Republic of Germany and Swiss Institute for Nuclear Research,** 5234 Villigen, Switzerland*

Leopold M. SIMONS
Kernforschungszentrum Karlsruhe, Institut für Kernphysik und Universität Karlsruhe, Institut für Experimentelle Kernphysik Karlsruhe, Federal Republic of Germany

Received August 1984

Is the muon special?

Extending theories on muon-specific interactions
Carl E. Carlson and Michael Freid
Phys. Rev. D **92**, 095024 – Published 23 November 2015

Constraints on muon-specific dark forces
Savely G. Karshenboim, David McKeen, and Maxim Pospelov
Phys. Rev. D **90**, 073004 – Published 13 October 2014; Erratum Phys. Rev. D **90**, 079905 (2014)

Testing Parity with Atomic Radiative Capture of μ^-
David McKeen and Maxim Pospelov
Phys. Rev. Lett. **108**, 263401 – Published 29 June 2012

muX physics results & plans

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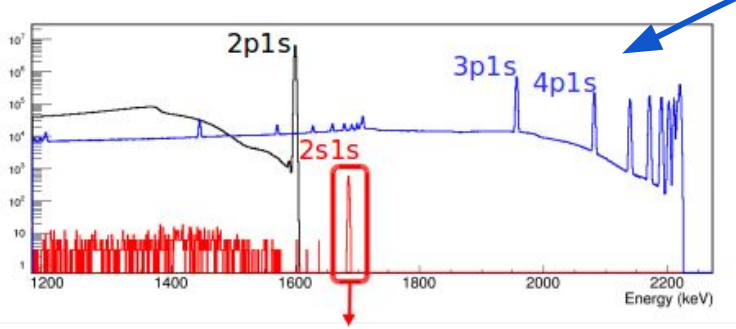
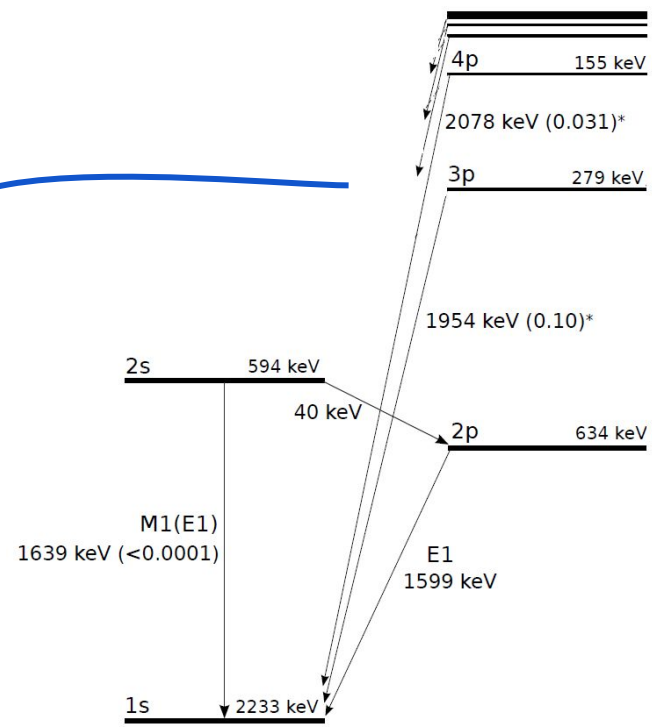


MC estimate of signal to background: 0.05

Level scheme Zn:

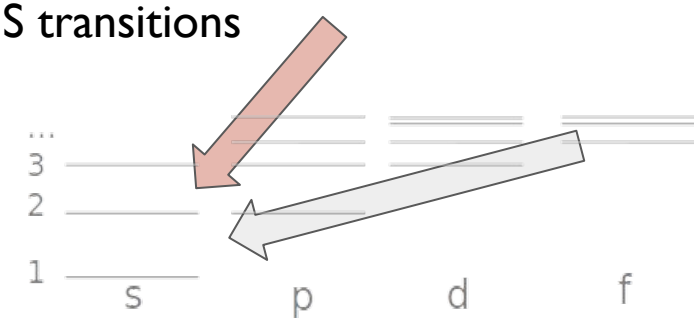


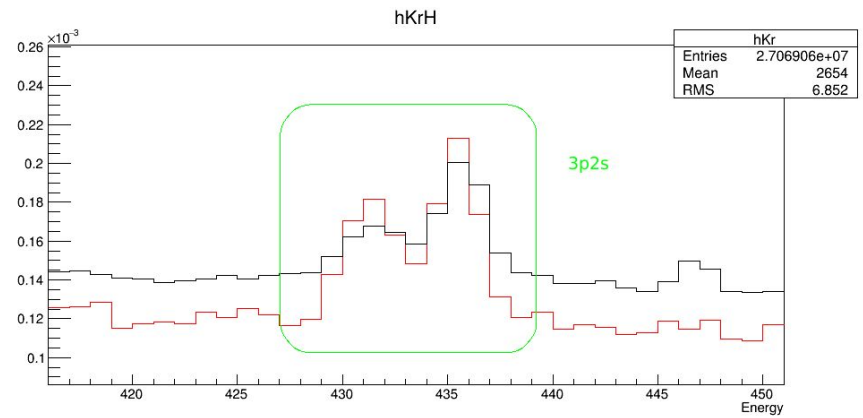
Our current project focuses on:

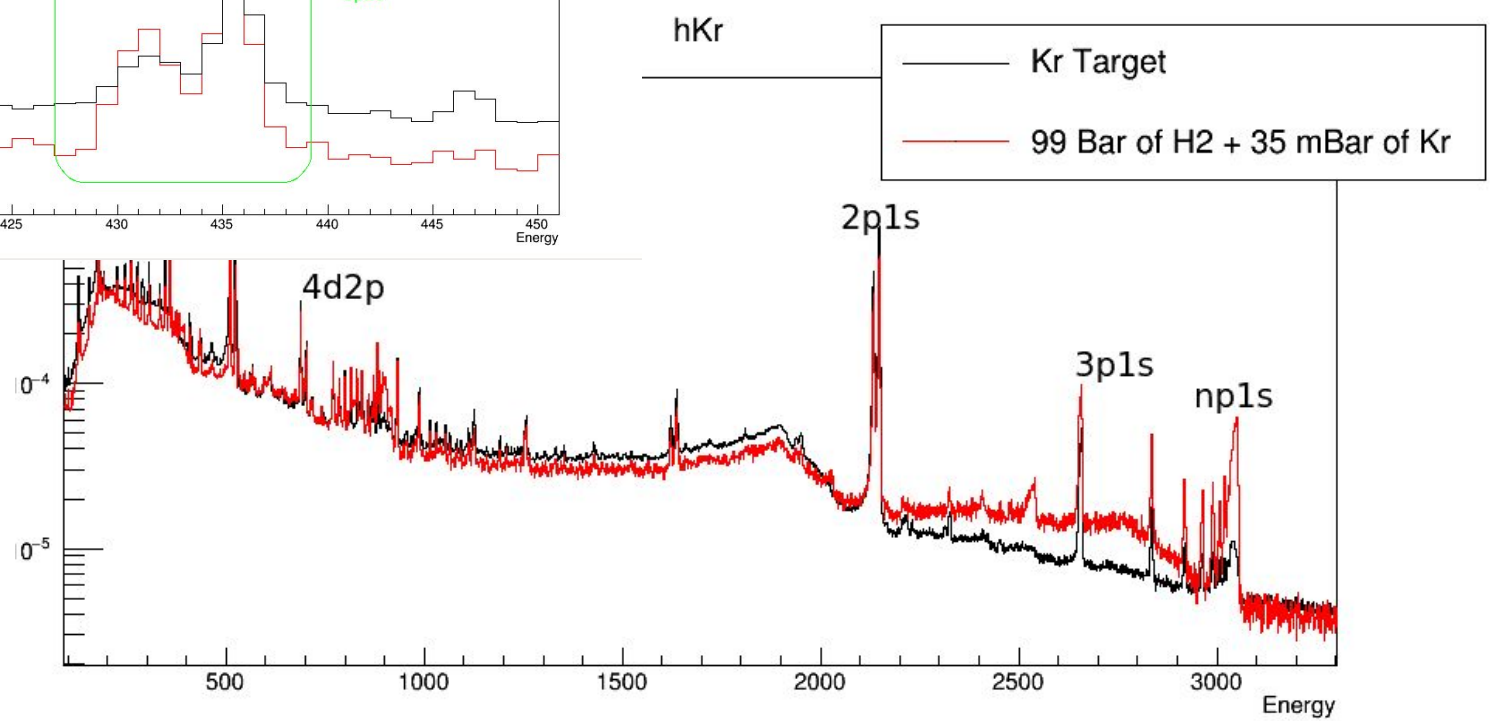
1. Detecting the 2S1S transition 2017/2018
2. Establishing a signal to BG of O(1) 2019
3. Determine reach of APV experiment 2020+

muX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  - Increase the 2S population with μH → μKr transfer

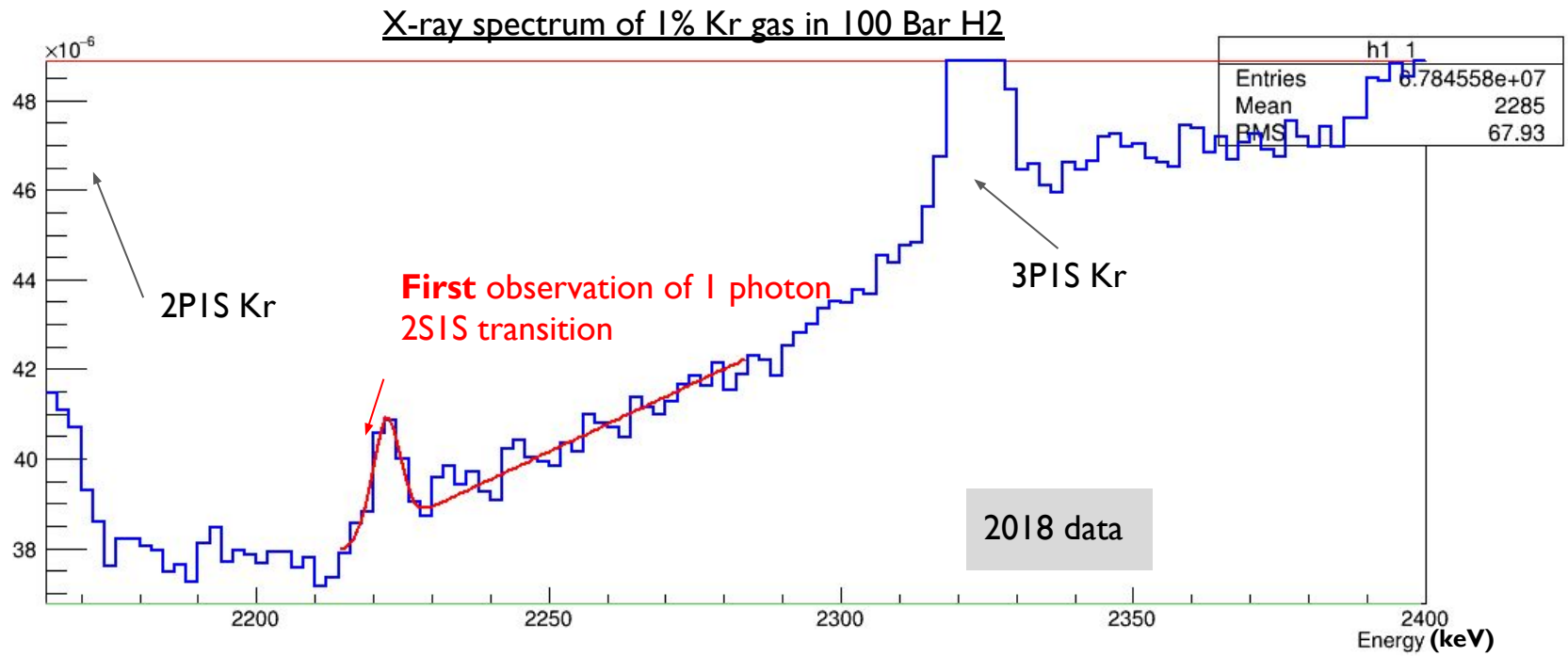






muX physics results & plans

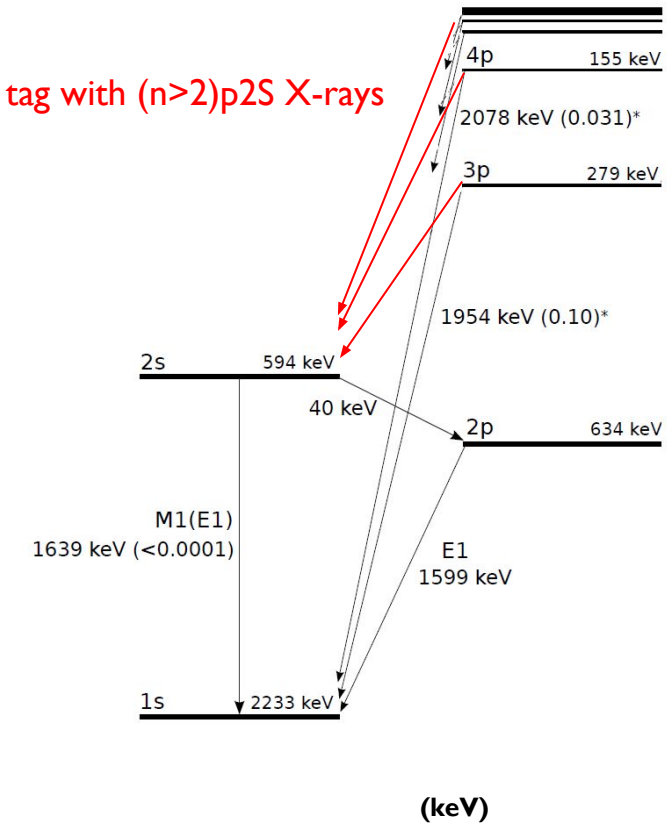
- Measuring 2P1S in 5 µg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  - Increase the 2S population with µH → µKr transfer
    - i. 3-4 fold increase of 2S population
    - ii. BR ≈ 6 • 10^{-4} for 2S1S
    - iii. Still Compton BG dominated



muX physics results & plans

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
  - Increase the 2S population with μH → μKr transfer
  - Select 2S population by tagging on (n>2)P2S transitions
    - i. Loose efficiency
    - ii. Potential to achieve S/B of O(1)

Level scheme Zn:



muX physics results & plans

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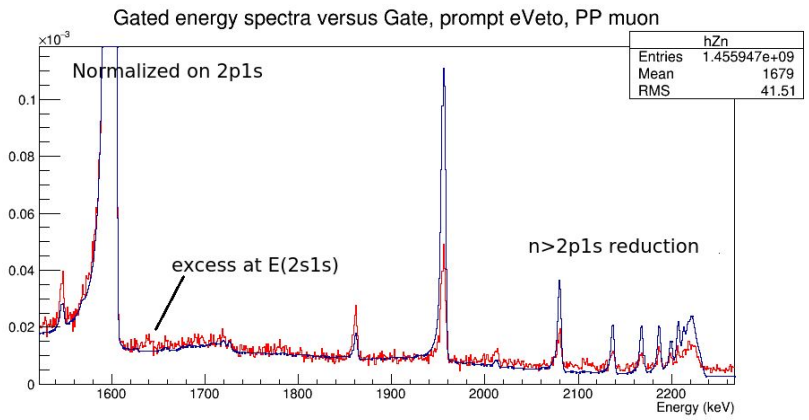
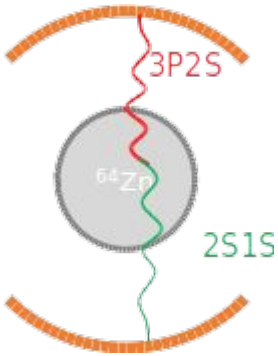
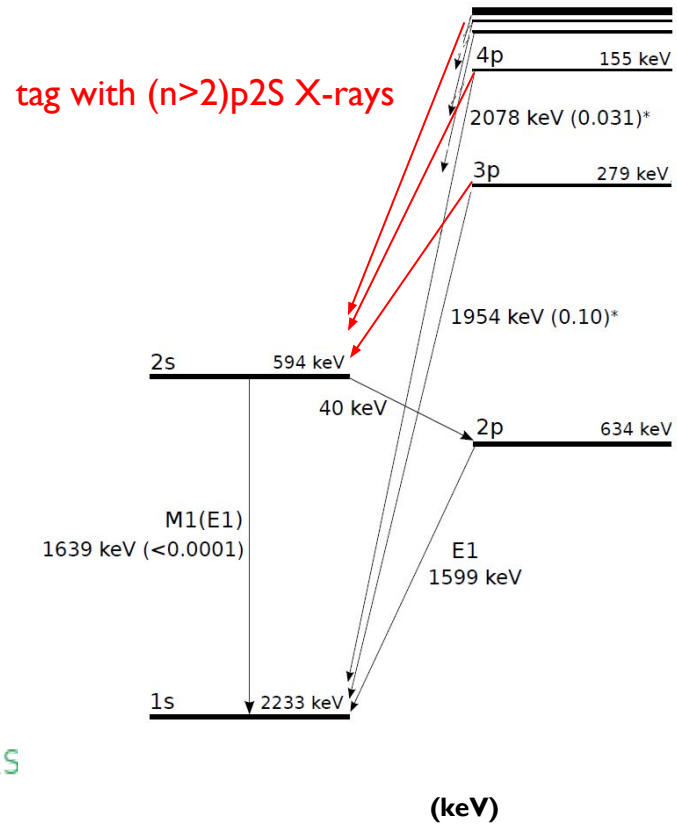
  - Select 2S population by tagging on (n>2)P2S transitions
    - i. Loose efficiency
    - ii. Potential to achieve S/B of O(1)

First attempt in 2017





Level scheme Zn:



2019:

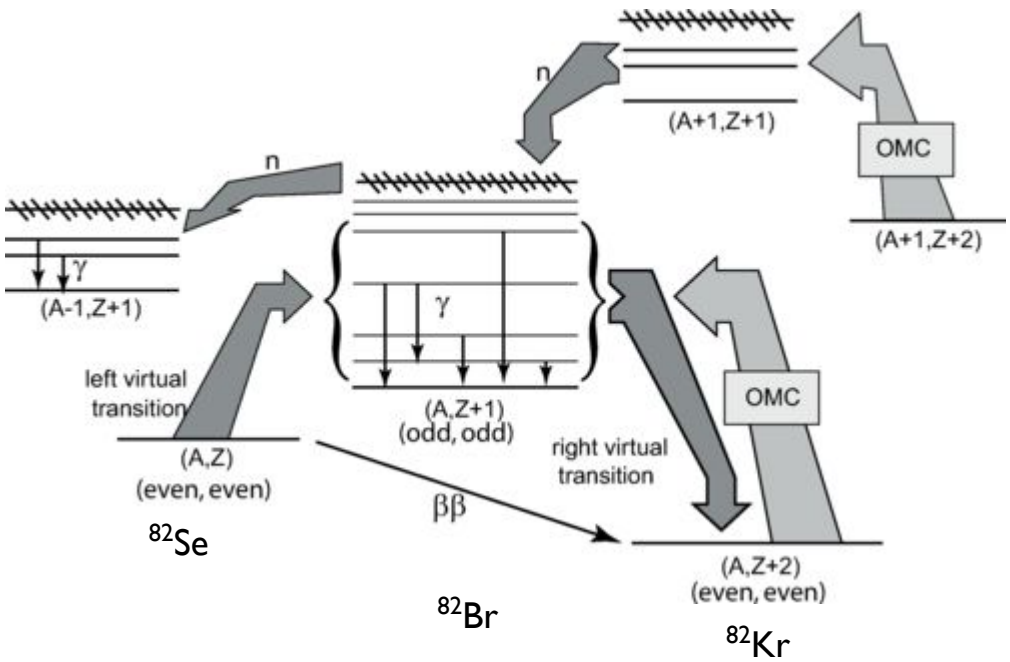
- 1 week of beam time in November
- Optimized detector geometry
- >100 counts with conservative analysis cuts

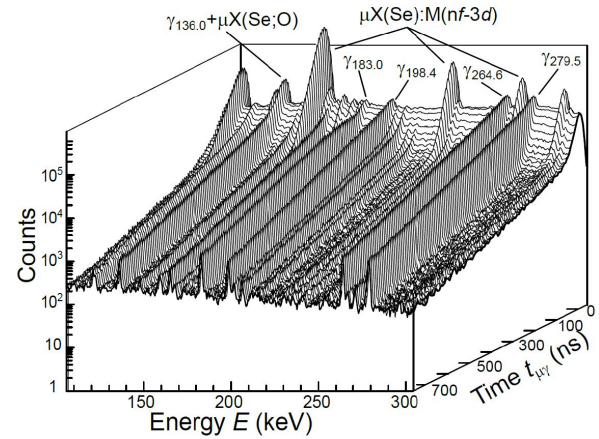
muX physics results & plans

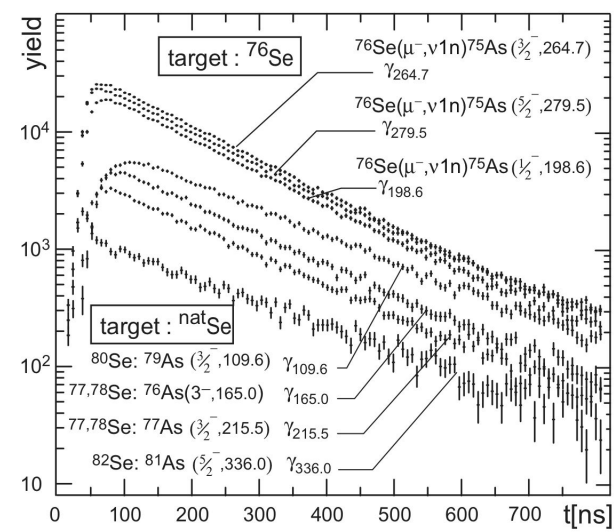
Ordinary muon capture studies for the matrix elements in $\beta\beta$ decay

D. Zinatulina, V. Brudanin, V. Egorov, C. Petitjean, M. Shirchenko, J. Suhonen, and I. Yutlandov
Phys. Rev. C **99**, 024327 – Published 28 February 2019

- Measuring 2P1S in 5 μg of radium
- Measure 2S1S for Z≈30 nuclei → measure 2S1S transitions
- Nuclear γ transitions after muon capture, of interest for matrix element calculations for double β-decay







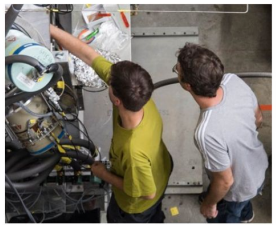
- ^{82}Kr (^{82}Se of SuperNemo)
- ^{130}Xe (^{130}Te of Cuore)

muX status

The collaboration:

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

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



Muonic Atom Spectroscopy: Preparations Regarding a Measurement of the Charge Radius of Radium

22 Oct 2019, 17:36
1m
WHGA/001 - Auditorium (PSI)

Speaker

Alexander Albert Skawran

Analysis of the hyperfine splitting of the $5 \rightarrow 4$ transitions in muonic Re-185 and Re-187

22 Oct 2019, 17:13
1m
WHGA/001 - Auditorium (PSI)

Speaker

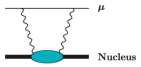
Stergiani Marina Vogiatzi (PSI - Paul Scherrer In...)

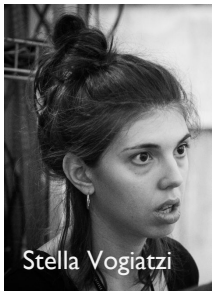
SNF and DFG grant
3 PhD students

Outlook:

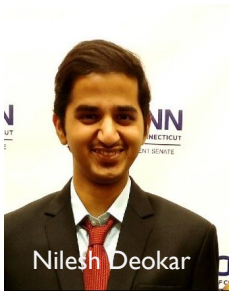
- Finish analysis of 2017 → 2019 data
- Determine reach 2S1S APV experiment
- Get $\langle r^2 \rangle$ from 2P1S transition energies

Theoretical predictions for nuclear polarization will limit final precision



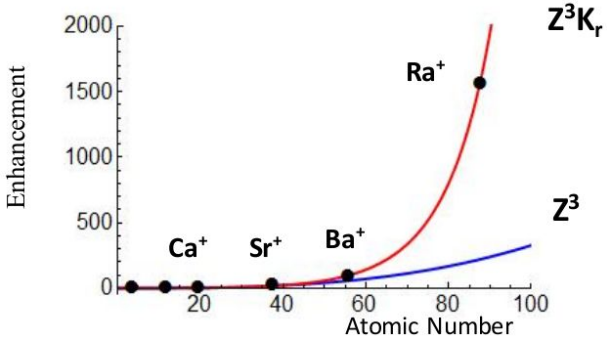

Stella Vogiatzi

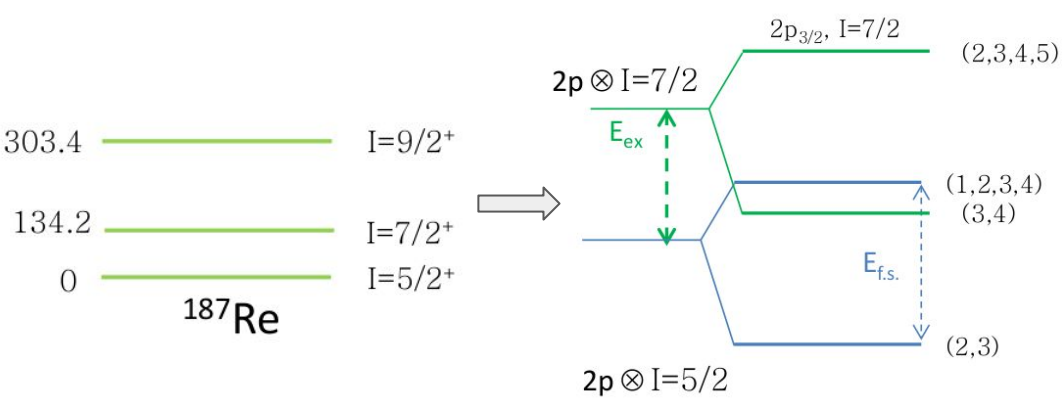

Alexander Skawran

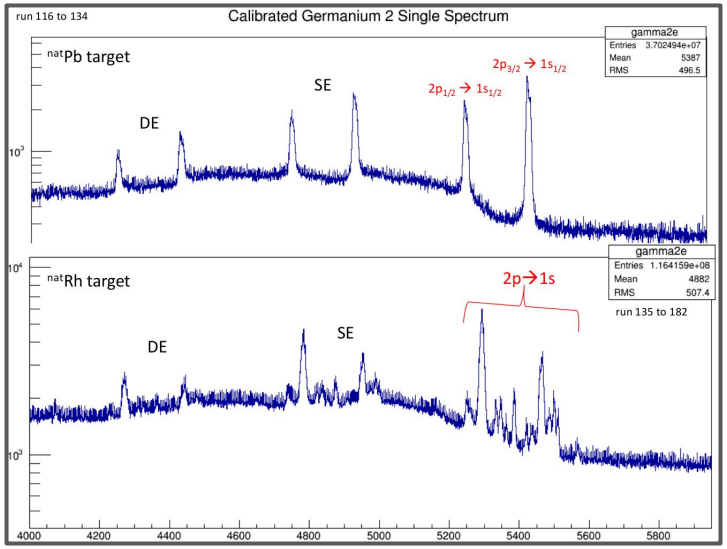

Nilesh Deokar

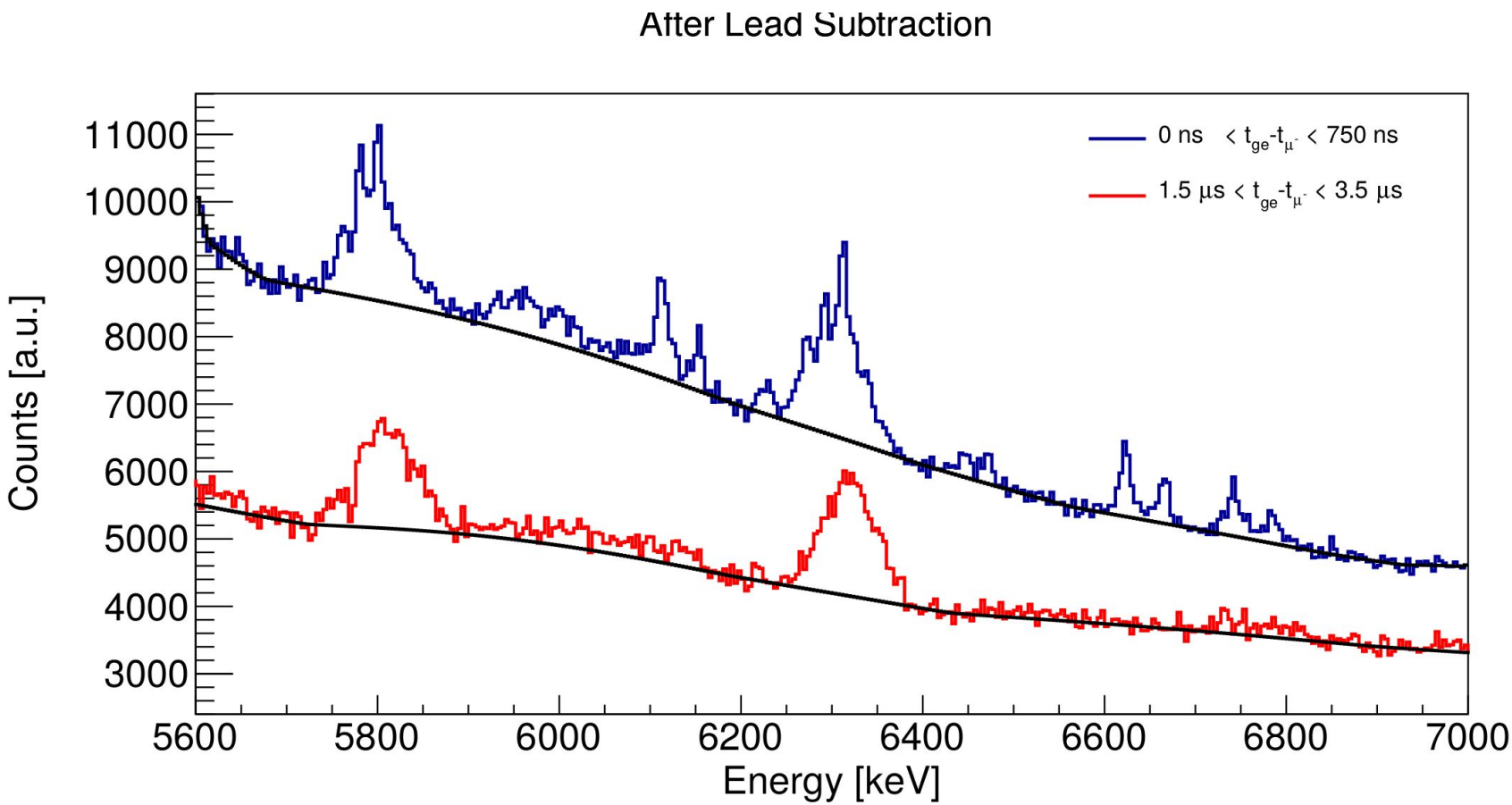
+ Jonas Nuber, Narongrit Ritjoho, Julian Krauth, Ahmed Ouf, Madalina Ravar, David Werner, ...

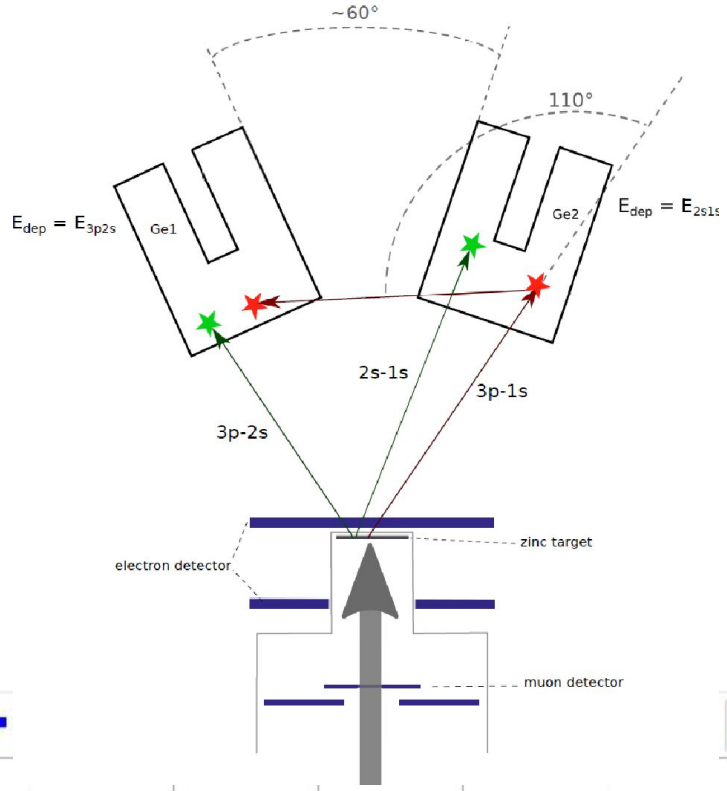
EXTRA

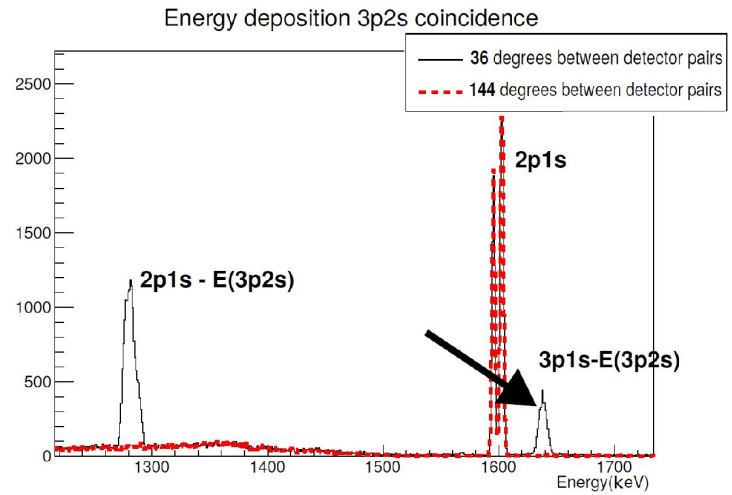

Enhancement
Atomic Number
2000
1500
1000
500
0
20
40
60
80
100
Ca+
Sr+
Ba+
Ra+
Z3Kr
Z3

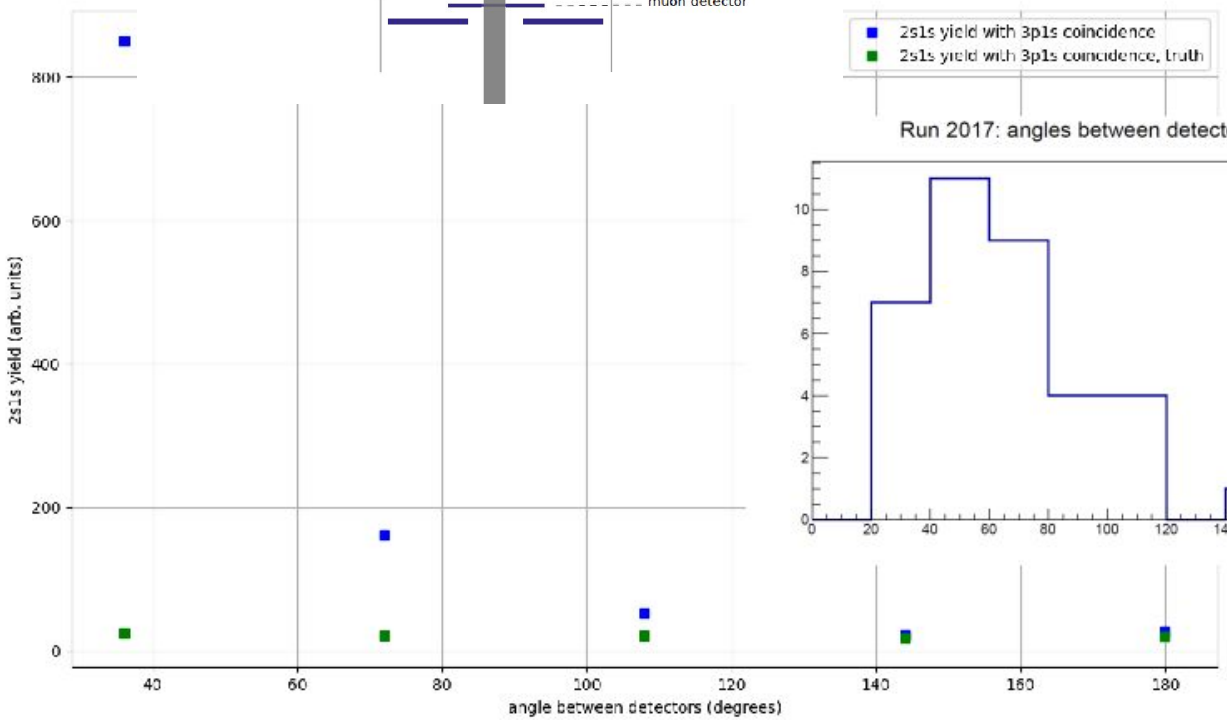

303.4
I=9/2+
134.2
I=7/2+
0
I=5/2+
187Re
2p ⊗ I=7/2
2p ⊗ I=5/2
Eex
Ef.s.
2p3/2, I=7/2
(2,3,4,5)
(1,2,3,4)
(3,4)
(2,3)

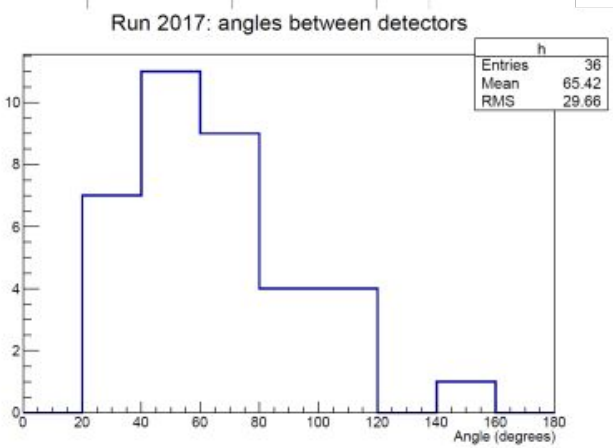

run 116 to 134
Calibrated Germanium 2 Single Spectrum
natPb target
DE
SE
2p1/2 → 1s1/2
2p3/2 → 1s1/2
gamma2e
Entries 3.702494e+07
Mean 5387
RMS 496.5
natRh target
DE
SE
2p→1s
run 135 to 182
gamma2e
Entries 1.164159e+08
Mean 4882
RMS 507.4
4000
4200
4400
4600
4800
5000
5200
5400
5600
5800

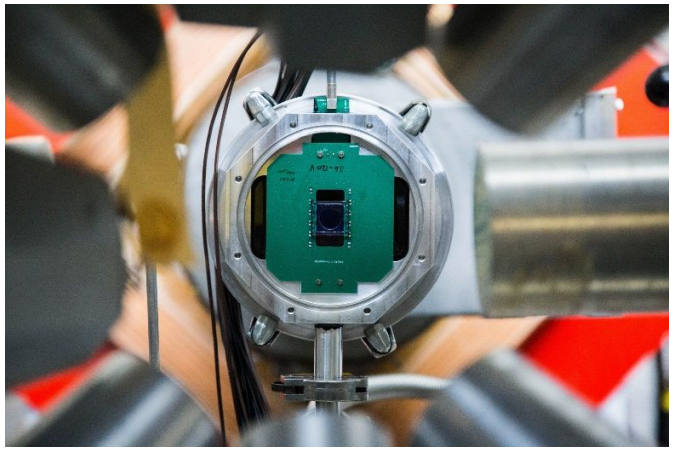

After Lead Subtraction
0 ns < t_{ge}-t_{μ^-} < 750 ns
1.5 μs < t_{ge}-t_{μ^-} < 3.5 μs
Counts [a.u.]
11000
10000
9000
8000
7000
6000
5000
4000
3000
5600
5800
6000
6200
6400
6600
6800
7000
Energy [keV]


~60°
110°
$E_{dep} = E_{3p2s}$
Ge1
Ge2
$E_{dep} = E_{2s1s}$
2s-1s
3p-1s
3p-2s
zinc target
electron detector
muon detector


Energy deposition 3p2s coincidence
36 degrees between detector pairs
144 degrees between detector pairs
2p1s
2p1s - E(3p2s)
3p1s-E(3p2s)
Energy(keV)


2s1s yield with 3p1s coincidence
2s1s yield with 3p1s coincidence, truth
2s1s yield (arb. units)
angle between detectors (degrees)

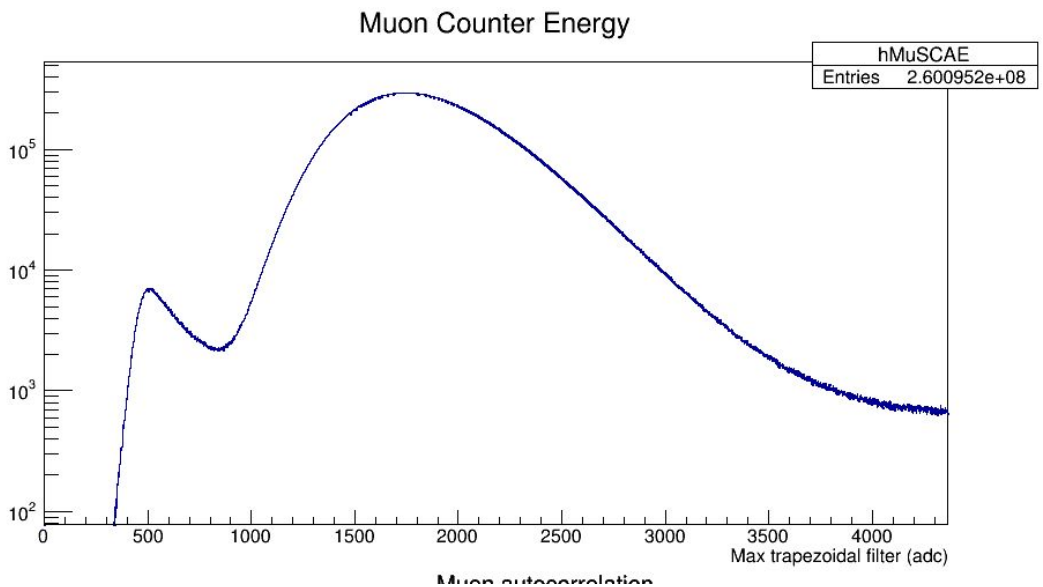

Run 2017: angles between detectors
h
Entries 36
Mean 65.42
RMS 29.66
Angle (degrees)



20 x 20 x 0.20 mm beam counter

80 x 80 x 4 mm veto counter with 18 mm hole

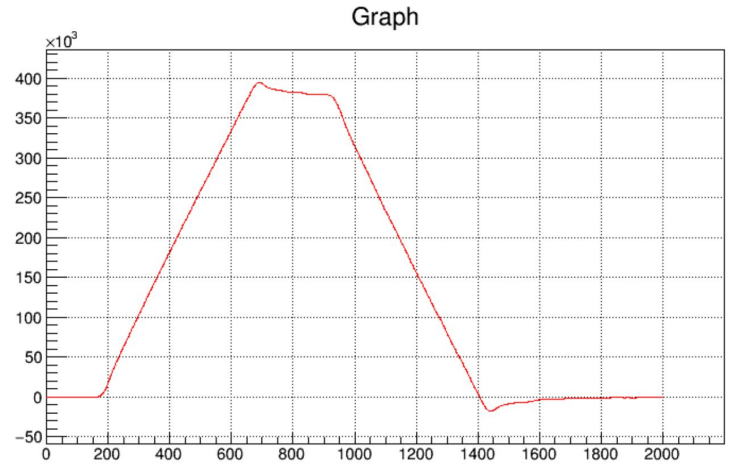
SiPM readout



- SIS3316 digitizer modules

- 250 MHz
- Save every single channel trigger (coincidences & events in software)
- Save raw waveforms

Trapezoidal filter



Save raw waveforms