Studying muonic atoms with Miniball at PSI

01st December 2015

On behalf of the muX collaboration

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Paul Scherrer Institute

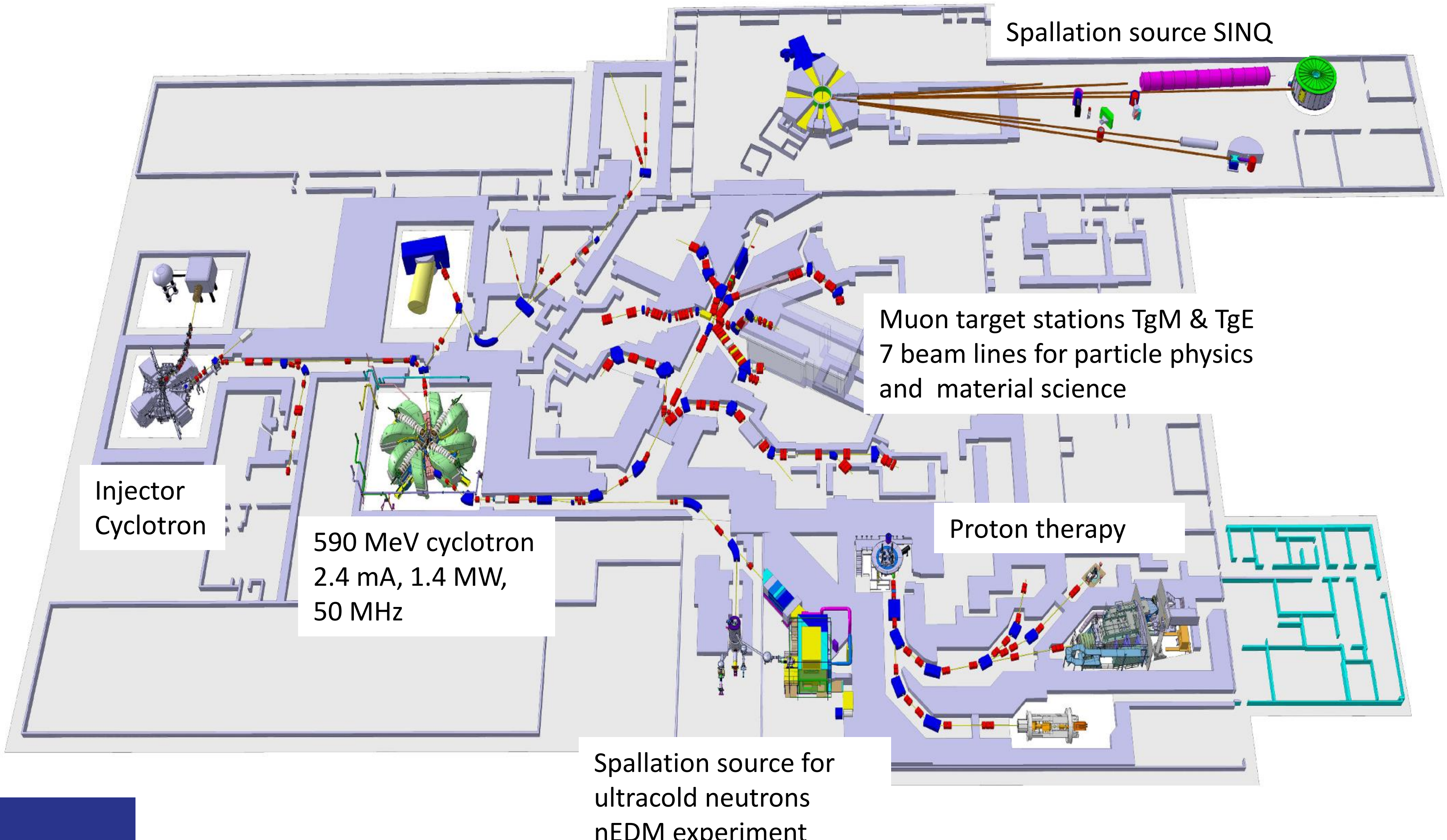
SwissFEL
X-rays free electron laser

Swiss Light Source – SLS

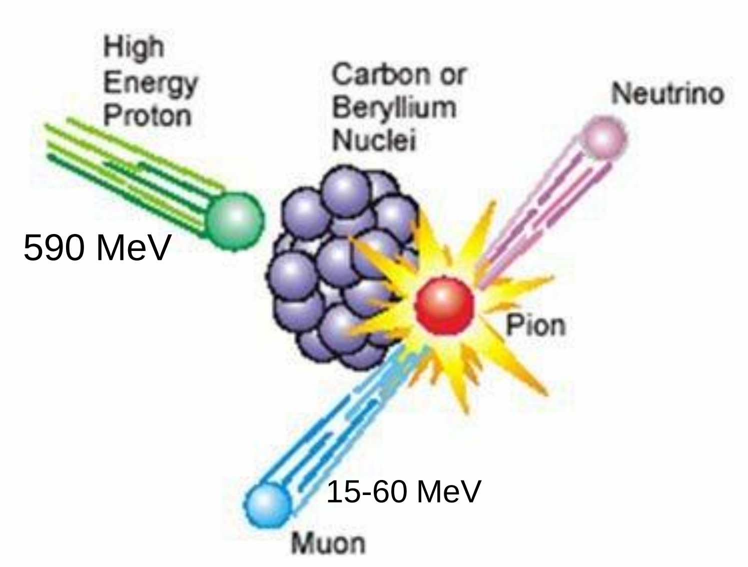
- *SINQ spallation source*
- *Ultra-cold neutron spallation source*
- *Swiss Muon Source*

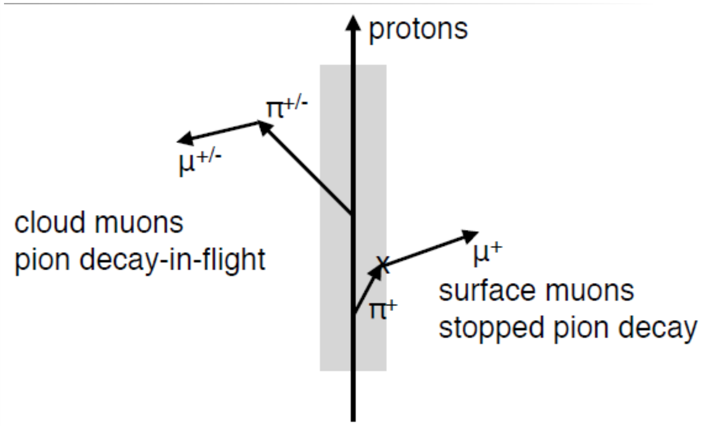
powered by a 590 MeV cyclotron which
delivers 1.3 MW proton beam (HIPA)

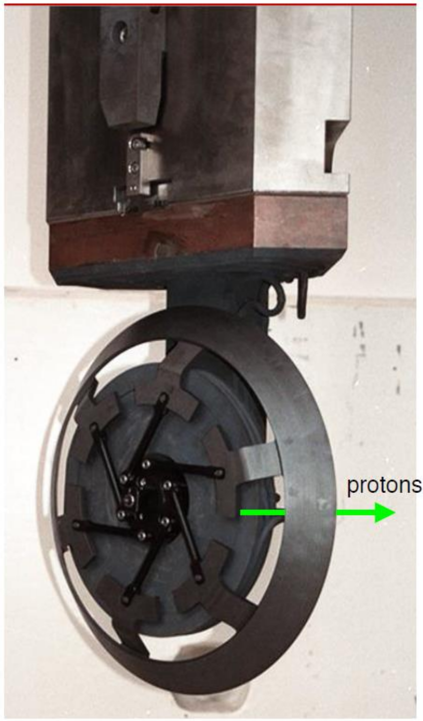
Overview HIPA facility



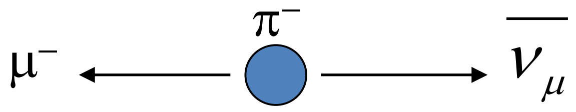
Muon Production



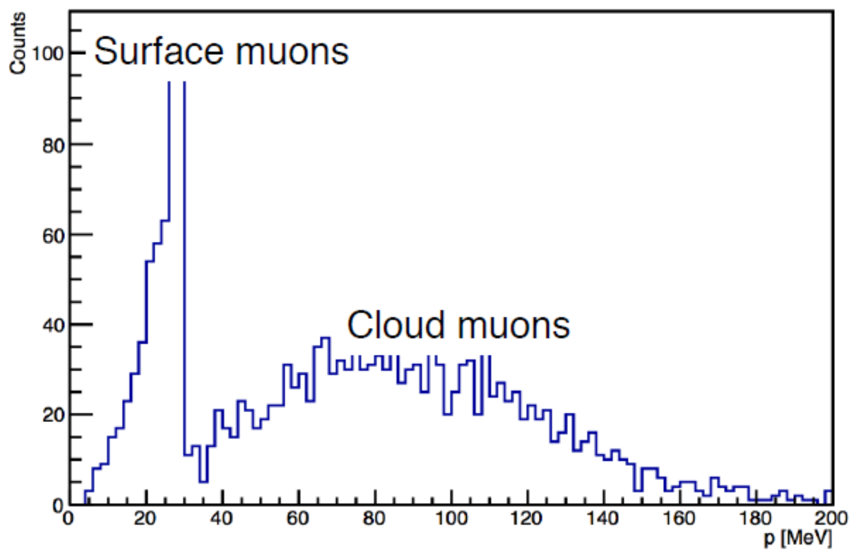




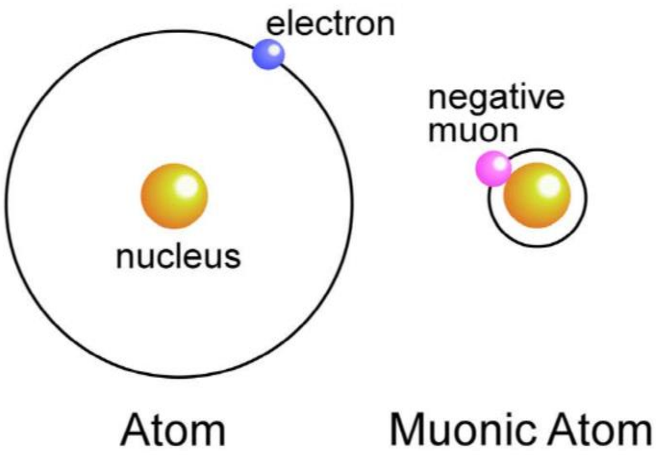
Graphite targets: rotating with 1 Hz

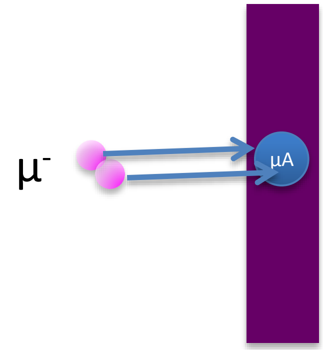


- Negative muons only available as clouds muons
- almost 100% polarized
- Low energy muons beam line ~ 5keV (Moderated in a cyclotron trap)



Muonic Atoms





$$r \sim \frac{1}{m_\mu} \cdot \frac{1}{Z}$$

$$E \sim m_\mu \cdot Z^2$$

Atomic energies: keV-MeV ≥ Nuclear energies

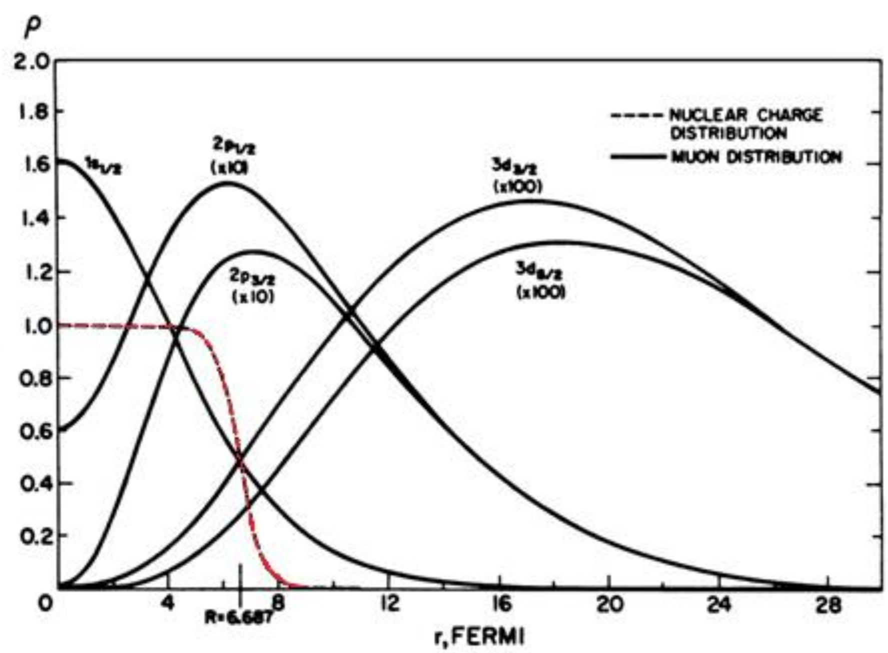
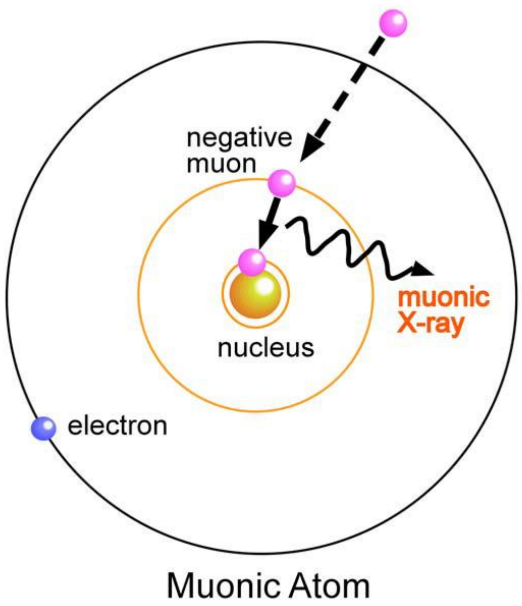


Fig. 15.8 The probability densities of finding a muon in the state indicated, at a distance r from the nuclear centre (full lines), are compared with the nuclear charge distribution in the case of lead. In the $S_{1/2}$ state, the probability of finding a muon within the nucleus is close to 50% (Devons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

Muonic atoms: unique laboratory for precision measurements

- ✓ Precision tool to measure NUCLEAR CHARGE RADII and Deformation properties of nuclei
- ✓ Successfully used since more than 40 years to study STABLE isotopes (and few radioactive)
- ✓ Proton radius

  Nature 466, 213 (2010),
  Science 339, 417 (2013)



1. Measurement of the nuclear charge radius of muonic Ra

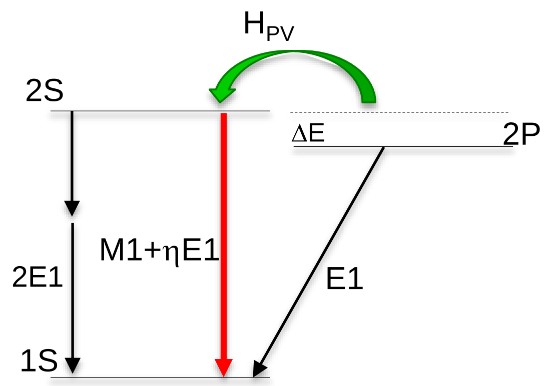
Expression of Interest (June 2015)

PARITY VIOLATION IN ATOMIC SYSTEMS

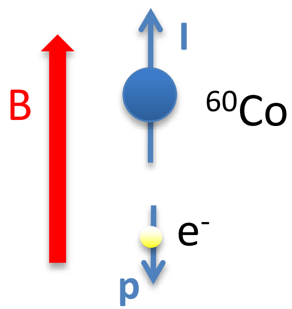
- ✓ Large ATOMIC PARITY VIOLATION enhancement four-orders of magnitude
- ✓ Proposed in the 80's
  J. H. Missimer and L. M. Simons, **Phys. Rept 118 (1985) 179.**
- ✓ Due to experimental limitations, early attempts were unsuccessful

2. Measurement of Atomic Parity Violation effects in muonic atoms

Parity Violation in atoms



Measurement of the asymmetry … as in Wu's experiment



l=0 to l=0 Electric Dipole transition are forbidden by parity selection rules (QED)

Weak interaction violates parity:

○ Atomic states acquire tiny admixture of opposite-parity states

$$\eta = \frac{\langle 2P|H_{PV}|2S\rangle}{\Delta E}$$

○ A non-zero transition amplitude can be measured

○ Experimental observable: Asymmetry of 2S→1S

$$A \sim \eta \frac{E1(2P\to 1S)}{M1(2S\to 1S)}$$

○ ~ m² → the effect in muonic atoms is enhanced 4-order of magnitude

- **2S→1S** in muonic atoms has never been observed
- **SURPRISES from muons**
  - Proton radius
  - Muon magnetic moment g-2
  - B-decays at LHCb shows O(3σ) deviations especially in channels involving muons.
- **Test parity violation in muonic systems**

MUON-ELECTRON UNIVERSALITY ?

Populating the 2S state

Experimental challenges

A. Standard muonic cascade:

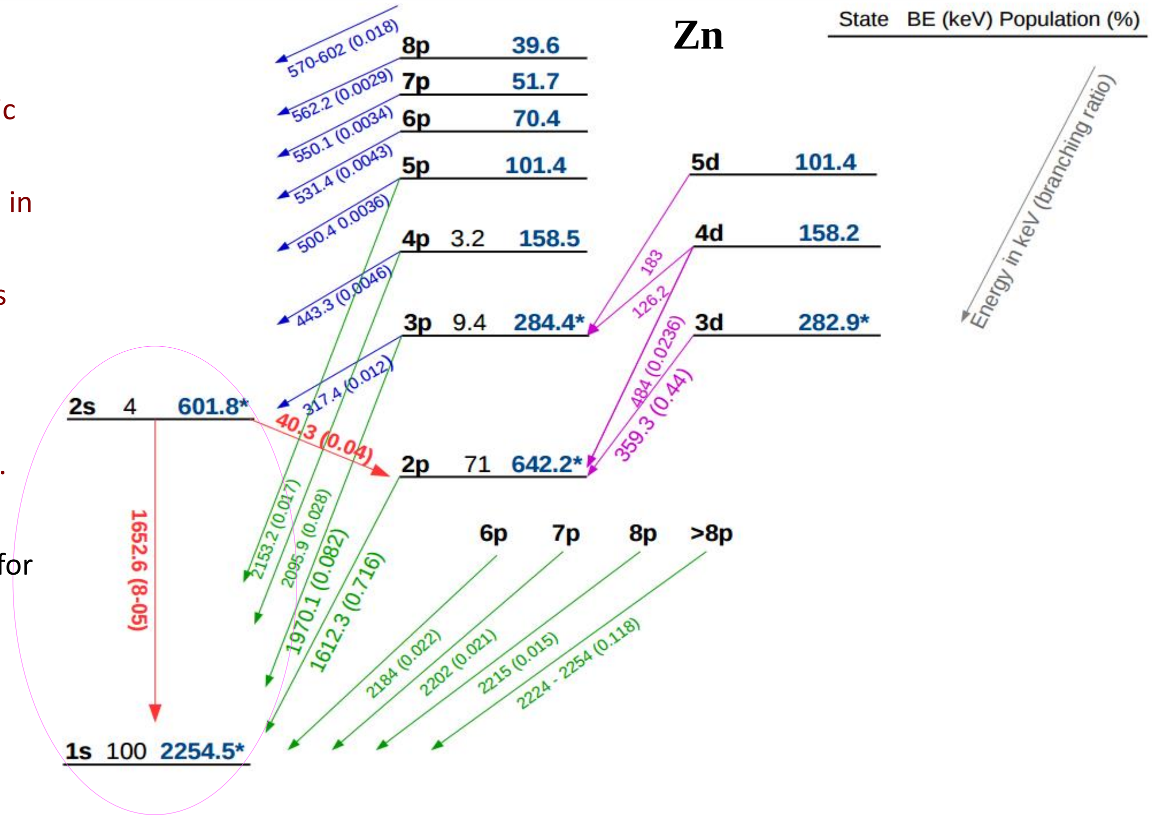
(i) 2S population: few percent of muonic cascade

(ii) 2P→1S very intense transition, close in energy to 2S→1S

(iii) High background of nP-1S transitions (n>2)
(S/N ~ 1/20 for single coax HPGe)

(iv) Suppress background with X ray coincidences with modern Ge arrays.

The **medium Z nuclei** are good candidates for the observation of the 2S→1S

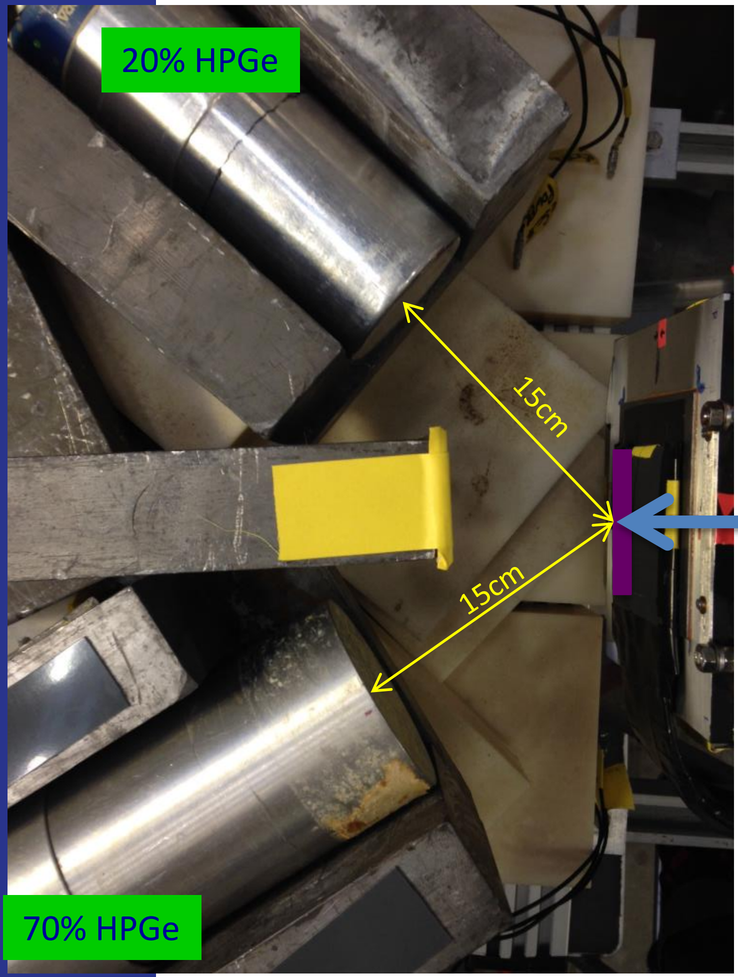


B. Atomic radiative capture from continuum

(i) Emission of one photon $E_{\gamma} = E^{\mu}{}_{KE} + B.E.$

(ii) 2S population ~ 10^{-6}

Hunting the 2S→1S transition



μ^-

Test Beam at PSI on 27-28 Nov. 2015

(i) 10^5 μ^-/s

(ii) 30h of data

(iii) Detection efficiency ~0.7% and ~ 0.2%

With Miniball detectors in close geometry

(i) Detailed level scheme of the muonic cascade

(ii) Branching ratios and feedings

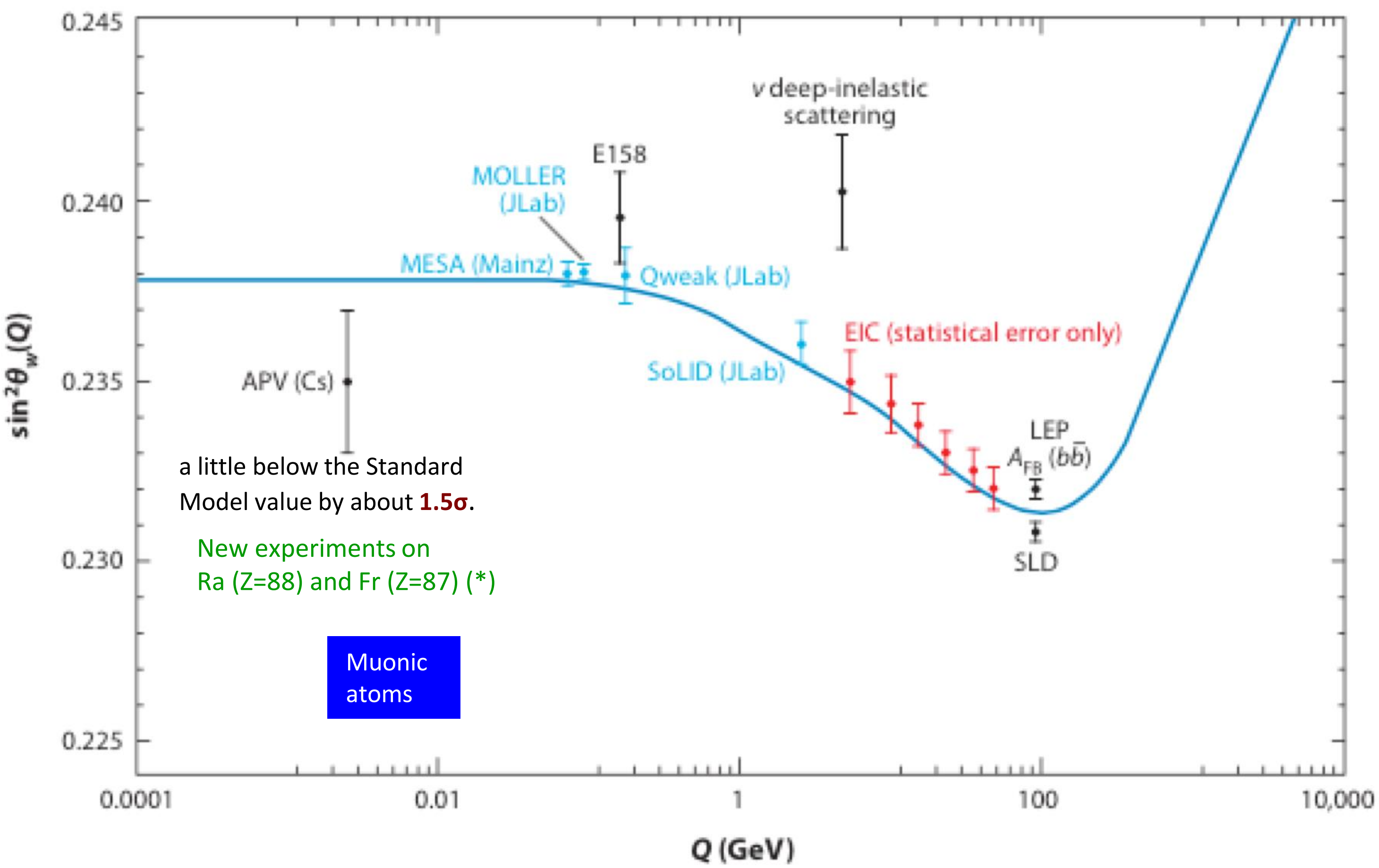
(iii) Detection of the 2S→1S

EXPRESSION OF INTEREST
observation of the 2S→1S transition in Zn (Z=30)

It paves the way to Atomic Parity Violation in muonic atoms

Atomic Parity Violation and the running of $\sin^2\theta_W$

Atomic parity violation effects allow the extraction of the weak mixing angle, the Weinberg angle θ_W at low Q that can be used to test the Standard Model running of the $\sin^2\theta_W$



(*) no stable isotopes exist in Nature. Fundamental nuclear parameters, like the nuclear charge radius, are not known.

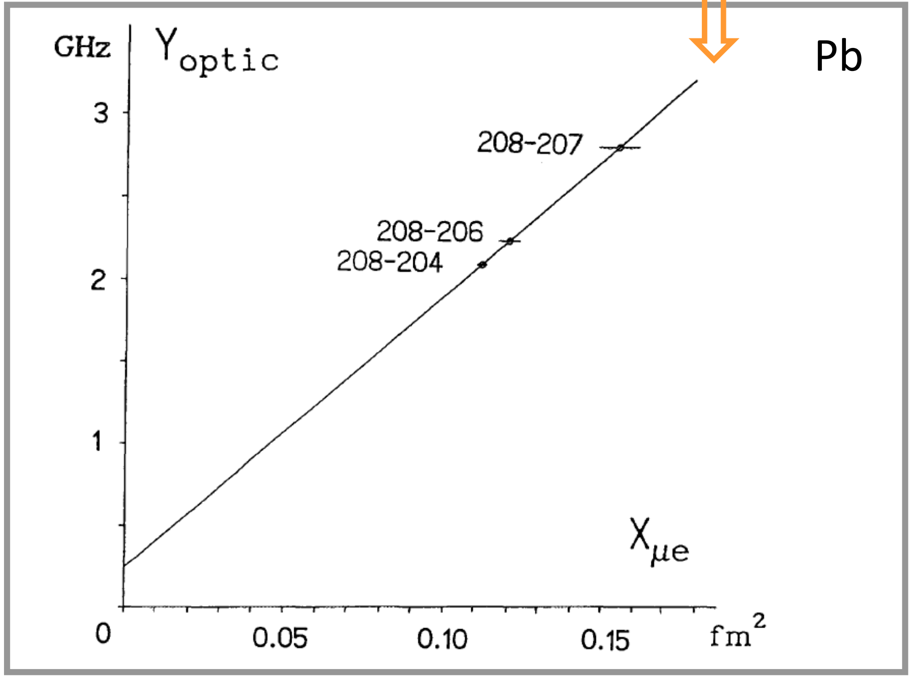
Methods for nuclear charge radii

- APV in Ra: extraction of the Weinberg angle with 0.1% precision (compare to 0.35% in Cs) require knowledge of the charge radius of Ra with 0.2% uncertainty (0.01fm)

1. Elastic electron scattering gives the radial dependence of the nuclear charge distribution
2. Optical Spectroscopy measures difference of mean-square radii $\delta\langle r^2\rangle^{A,A'}$
3. Muonic atoms sensitive to nuclear charge distribution

Nuclear Ground State Charge Radii from Electromagnetic interactions

G. Fricke et al. Atomic Data Nuclear Data Table 60 (1995) 214

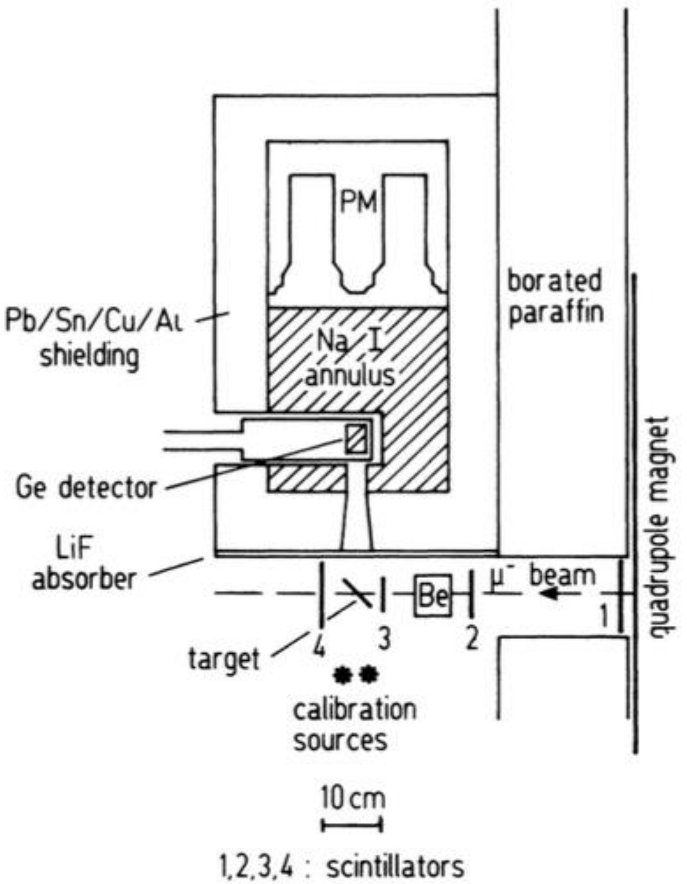


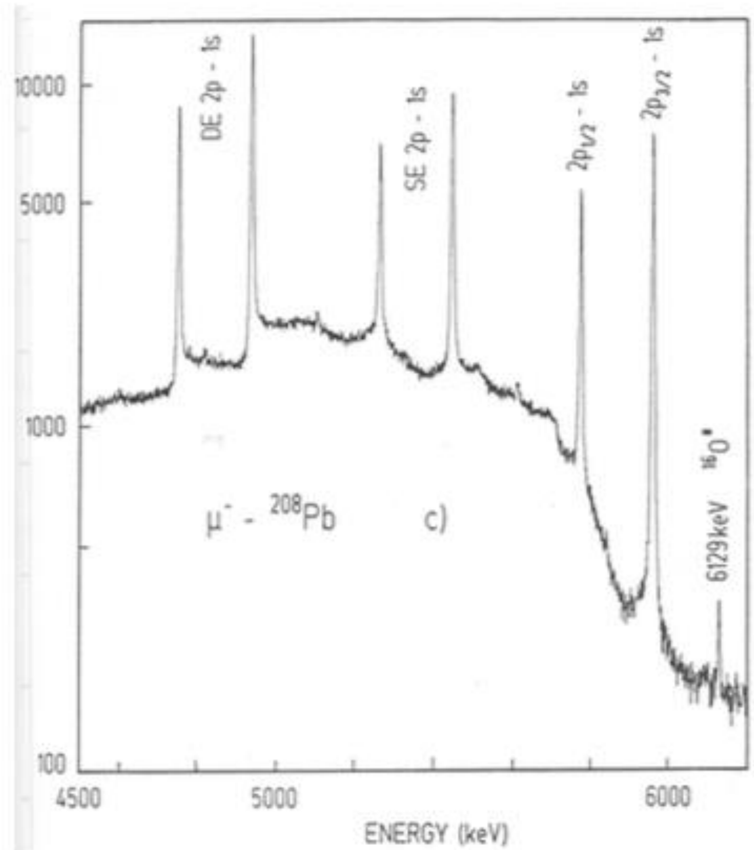
- Elastic electron scattering and muonic atoms provide absolute values to calibrate the laser-spectroscopy data

- Above Z=83 → laser spectroscopy: relative difference in mean-square radii along isotopic chain

Radius of Pb

P. Bergem, Phys. Rev C37 (1988)
P. Bergem, Muonic X-Ray energies and nuclear polarization in 208Pb, Ph.D. thesis, Unicersité de Fribourg (1987).





- Precise measurement of the energy levels (mainly 2P→1S)
- Extraction of the **n** and **c** parameters using a two-parameters Fermi distribution $\rho(r) = \rho_0/\{1 + exp[\mathbf{n}((r - \mathbf{c})/\mathbf{c}]\}$

FINITE SIZE EFFECT $\propto |\Psi(r=0)|^2 \propto m^3$ 10^7

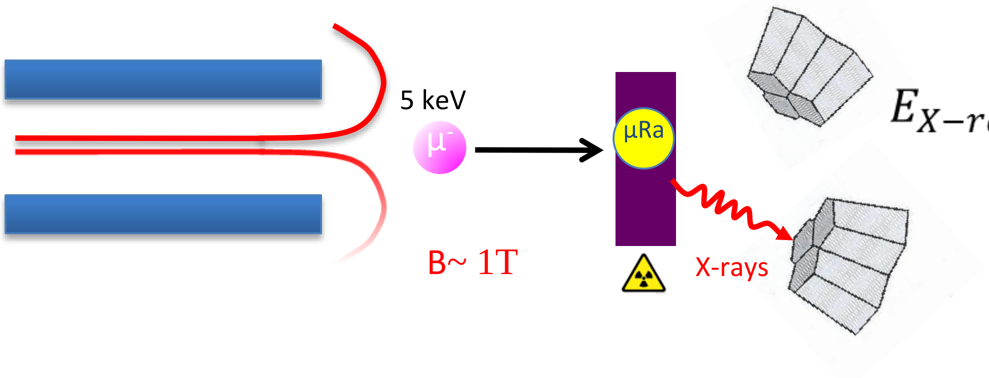
Radii are are measured with precision as few parts per 10^{-4} !

Charge Radius of Radium - setup

Experimental approach as the one used for stable isotopes

2. Measurement of the nuclear charge radius of muonic Ra

✧ Long-living isotopes in Ra: ^{226}Ra ($T_{1/2}$=1600 y), ^{225}Ra ($T_{1/2}$=14.8 d), ^{224}Ra ($T_{1/2}$=3.66 d), ^{223}Ra ($T_{1/2}$=11.43 d)



$$E_{X-ray} = QED + k \cdot r^2$$

Challenges:

✧Tiny amount of Ra (μg)

✧ Stop muons in target (low energy muon beams) → ✧ Use special beam line (used for proton radius)

✧Low muon rates ~ 10^2

✧Measure X-rays from cascade → ✧ Large Coverage Germanium array to operate in 1T magnetic field (from the solenoid part of the beam line)

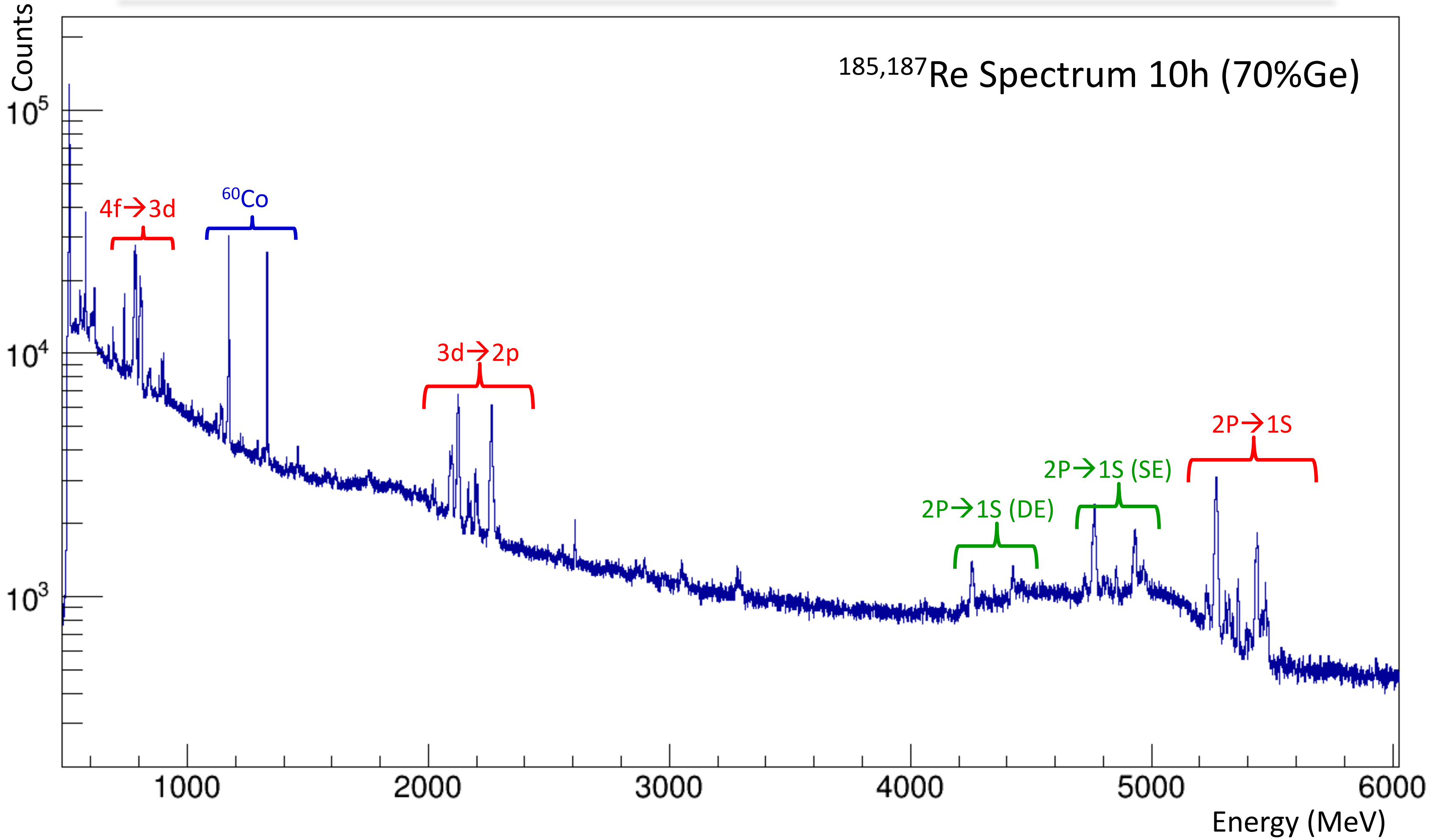
It can be extended to other short-lived nuclei

Or it can be done by stopping muons in thin films of hydrogen

P. Strasser, et al. Nucl. Phys. B, Proc. Suppl. **149 (2005) 390-392.**

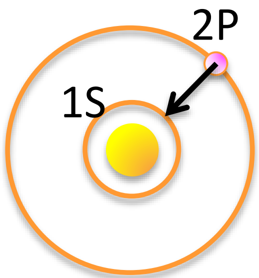
Muonic X-rays from Rhenium

Experimental challenges



- Hyperfine splitting due to Rhenium large deformation
- With 10^4 μ^-/s 10h (70% coax. Ge detector , $\varepsilon(1.33) = 0.7\%$)
- With 10^2 μ^-/s ??

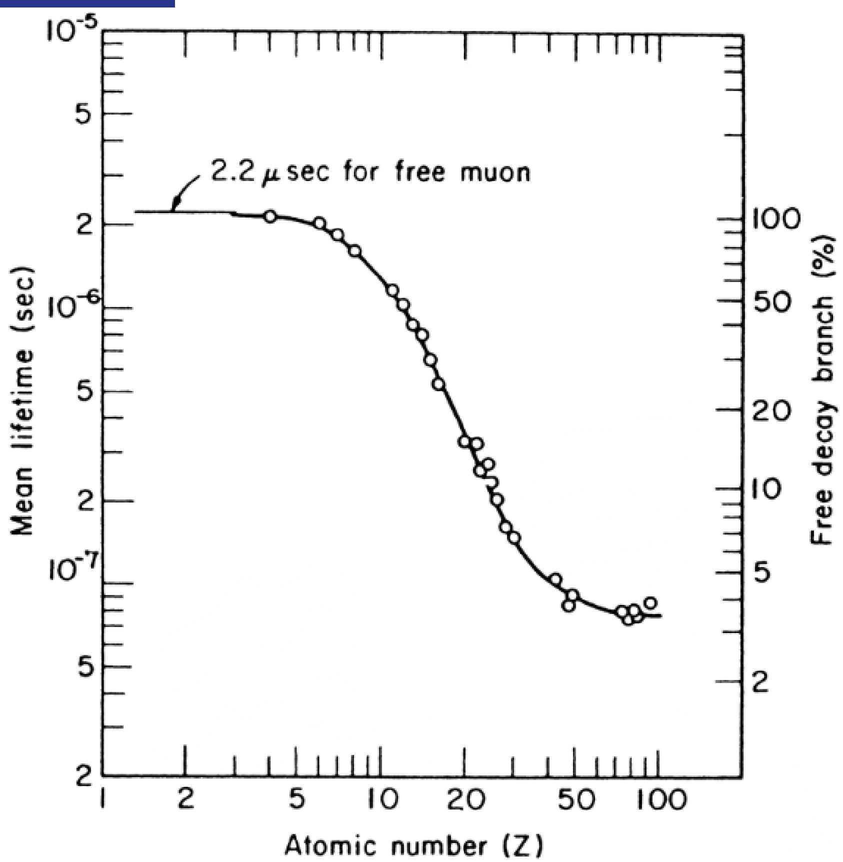
Muon capture and neutrons



Once in the 1S state the muon can

- decay (lifetime = 2.2 us) $\mu^- \rightarrow e + \bar{\nu}_e + \nu_\mu$

- be captured by the nucleus $p + \mu^- \rightarrow n + \nu_\mu$



MUON CAPTURE

- Populate **highly excited states** in nuclei (in the range 10-20 MeV)
- Majority of the atoms populate excited states reaching beyond the **neutron separation** energy

1 to 2 neutron emitted per muon capture

DAMAGE DUE TO NEUTRON DOSE?

Neutron Damage

neutron flux of ~3×10^{9} n/cm^{2} over a period of 5 days

GRETINA Coll.

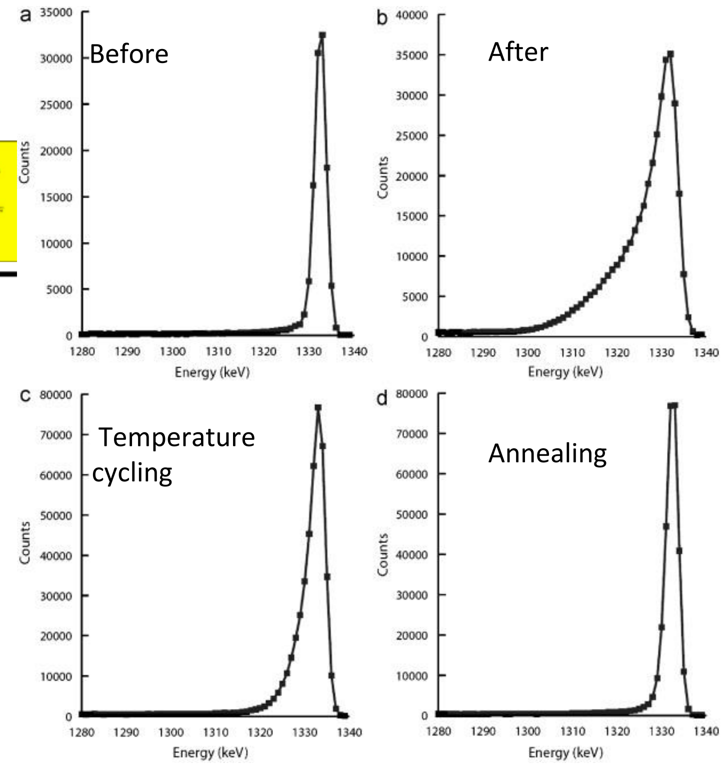
Nuclear Instruments and Methods in Physics Research A 606 (2009) 533–544

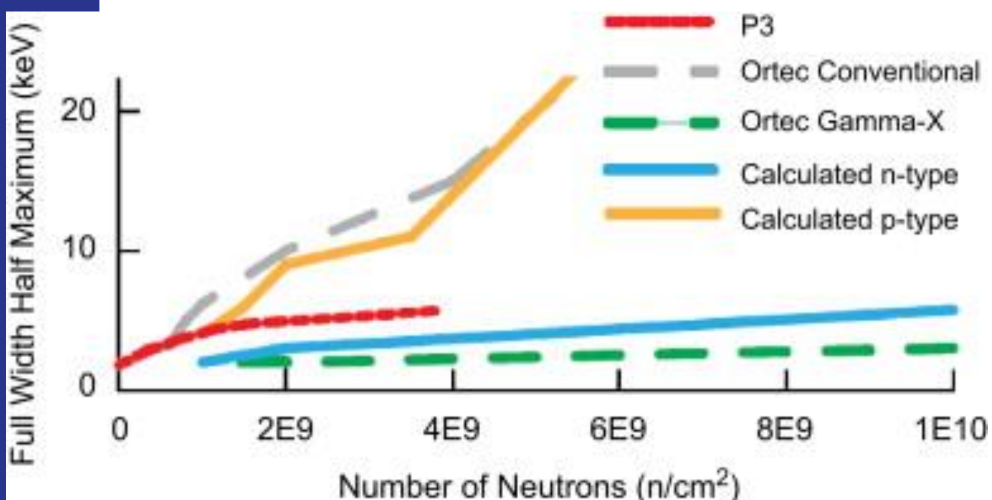
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Neutron damage tests of a highly segmented germanium crystal





"It demonstrates that this type highly segment Ge detector can be successfully annealed, recovering the energy and position resolution"

Perspective

- Measure the 2S-1S transition, 2015-2017
  - Characterizing the muonic cascade: population of the 2S state
  - First measurement of 2S-1S
  - Observe it in several promising elements
- Measure of Ra radius, 2016-2017
  - Test of Miniball clusters (KULeuven, Koeln) in magnetic field
  - Measurement of X-rays (target to be developed)
- Workshop on PV in muonic atoms and Measurement of Nuclear Charge Radii, 2016
  Theoretical motivation, experimental feasibility
- Design a PV setup, 2016-2017

Collaboration

A. Antognini, K. Kirch, A. Knecht, E. Rapisarda, *Paul Scherrer Institut, Villigen and ETH Zürich, Switzerland*
N. Berger, D. vom Bruch, F. Wauters, *University of Mainz, Germany*
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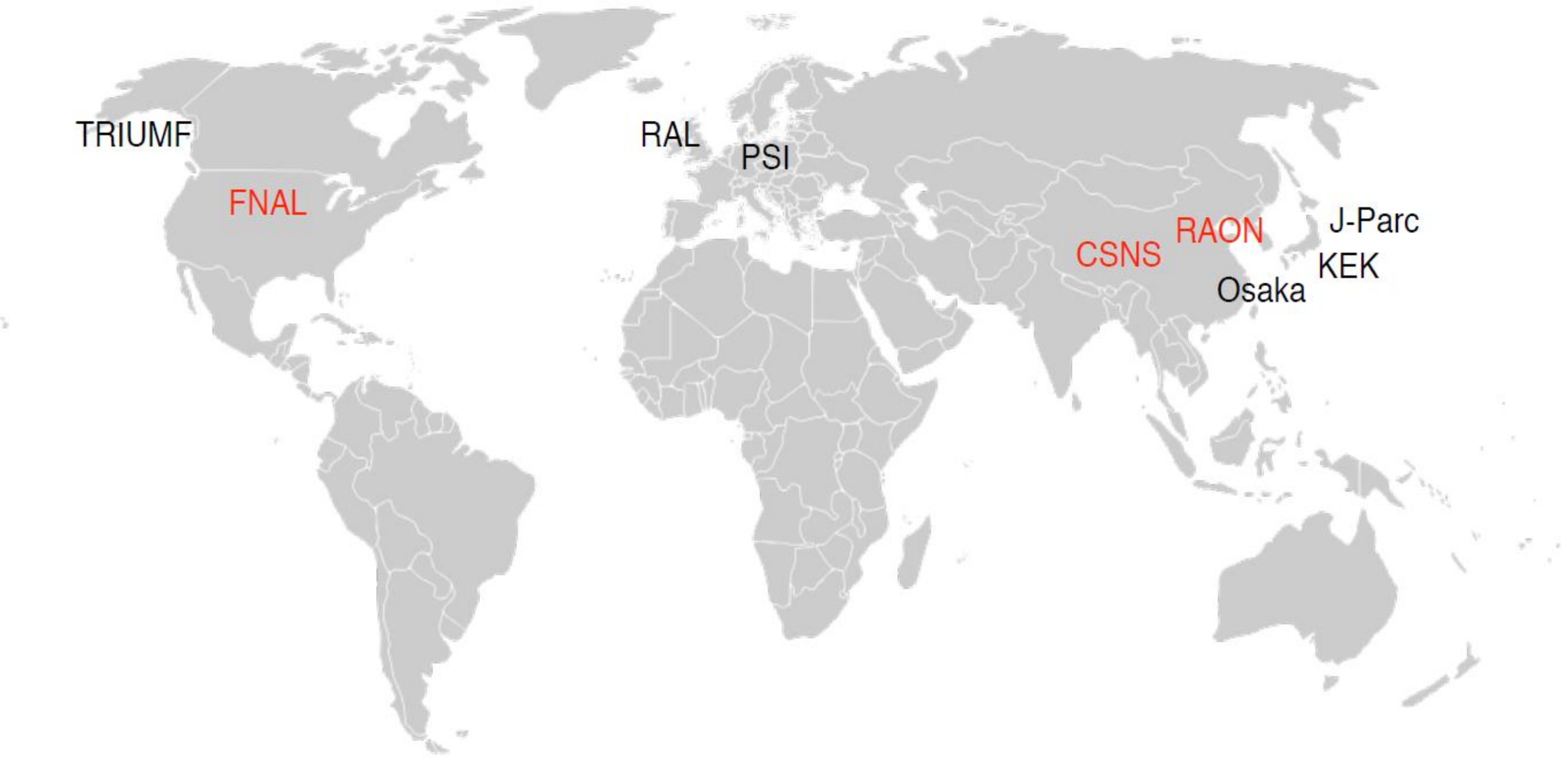
N. Severijns, *KU Leuven, Belgium*

Muon Facilities in the world



Existing

Future

Expression of Interest

1. Measurement of Atomic Parity Violation effects in muonic atoms

2. Measurement of the nuclear charge radius of radioactive muonic Ra

PRL **108**, 263401 (2012) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2012

Testing Parity with Atomic Radiative Capture of μ^-

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(Received 22 March 2012; published 29 June 2012)

ELSEVIER

Nuclear Physics A

Volume 475, Issue 4, 28 December 1987, Pages 615-629

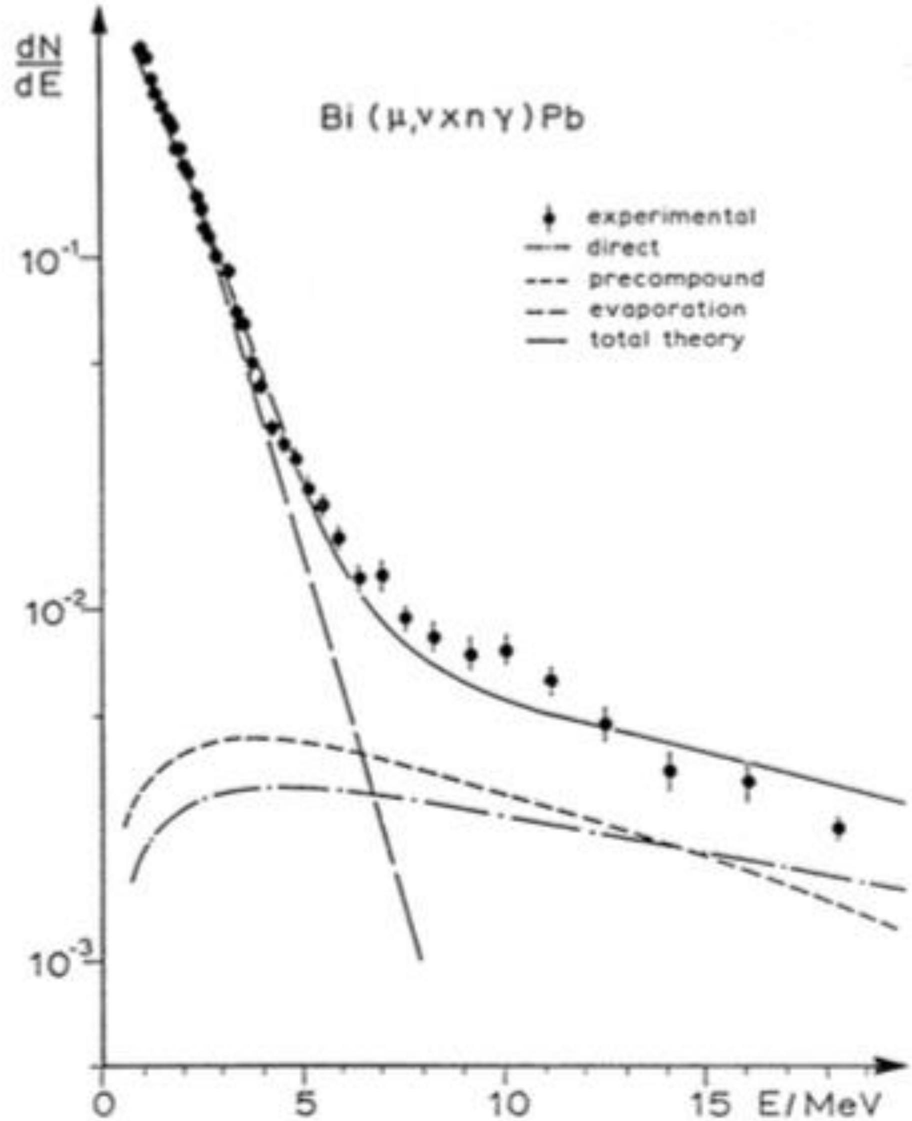
Polarization transfer from polarized nuclear spin to μ^- spin in muonic atom

Yoshitaka Kuno [1], Kanetada Nagamine

Toshimitsu Yamazaki

MUON REPOLARIZATION

V.S. Evseev, in: V.W. Hughes, C.S. Wu (Eds.), Muon Physics III Academic Press, New York, 1975, p. 235.


dN/dE
Bi (μ,ν x n γ) Pb
experimental
direct
precompound
evaporation
total theory
10⁻¹
10⁻²
10⁻³
0
5
10
15
E/MeV