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Laser spectroscopy at the IGISOL facility

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Outline

- Nuclear fingerprints on the atomic spectra
- All shapes and sizes – deformation around N~60
- Silver – complementarity with laser- and mass measurements
- Proton-rich studies between ^{40}Ca and ^{56}Ni
- Nuclear structure studies below ^{100}Sn
- Summary

Nuclear fingerprint on atomic spectra

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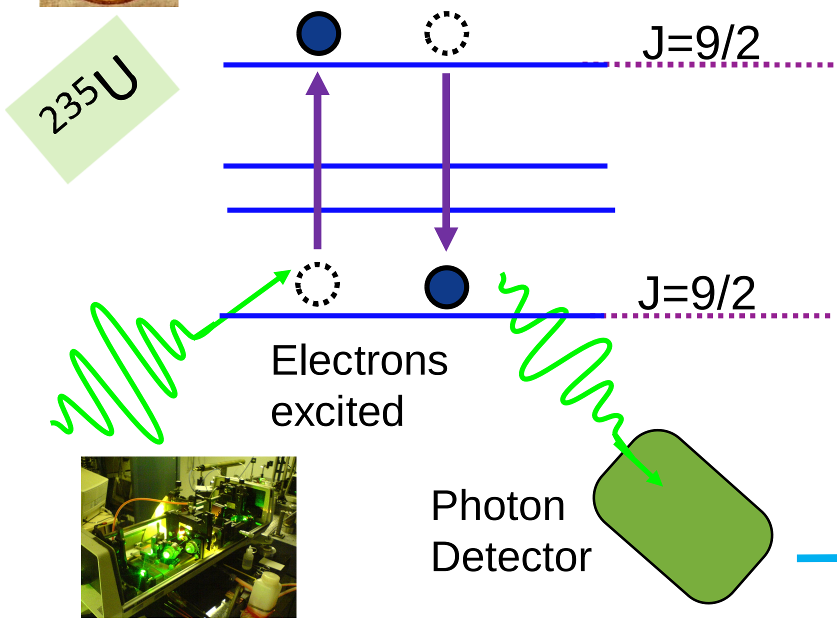
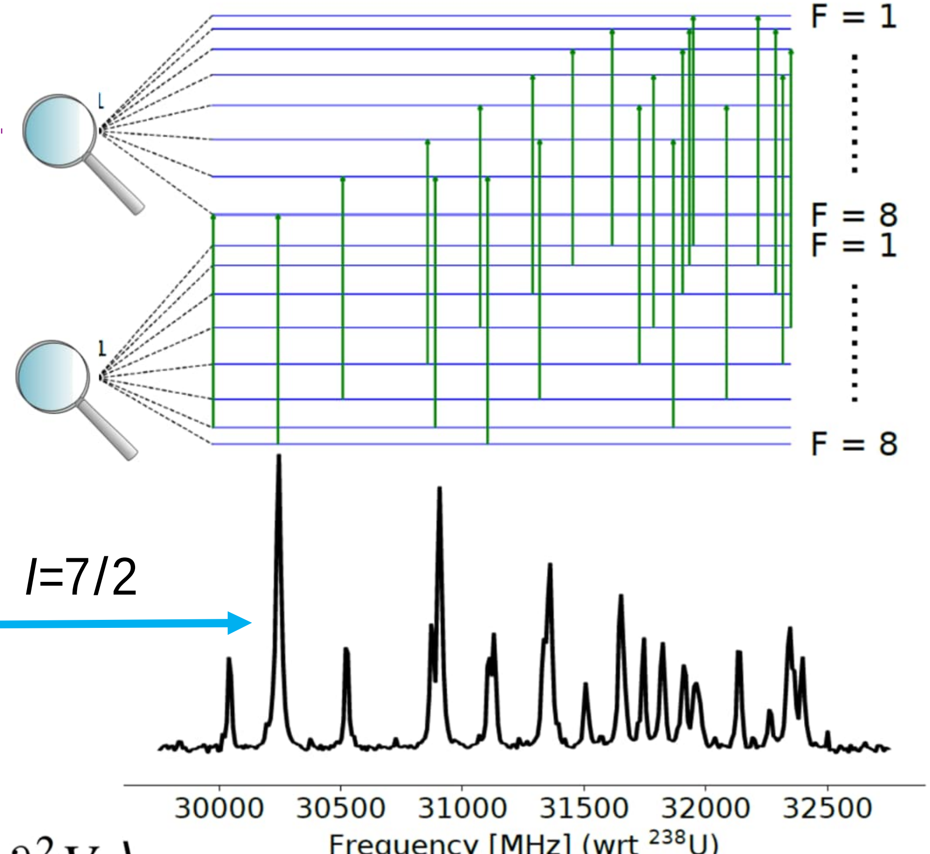
Fine structure

Electronic *hyperfine* structure





Hyperfine structure

$$A = \frac{\mu_I B_e(0)}{I J}$$

Magnetic dipole interaction

$$B = e Q_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

Electric quadrupole interaction

$$I$$

Nuclear spin

Ground states & isomers

Isotope shifts of electronic transitions

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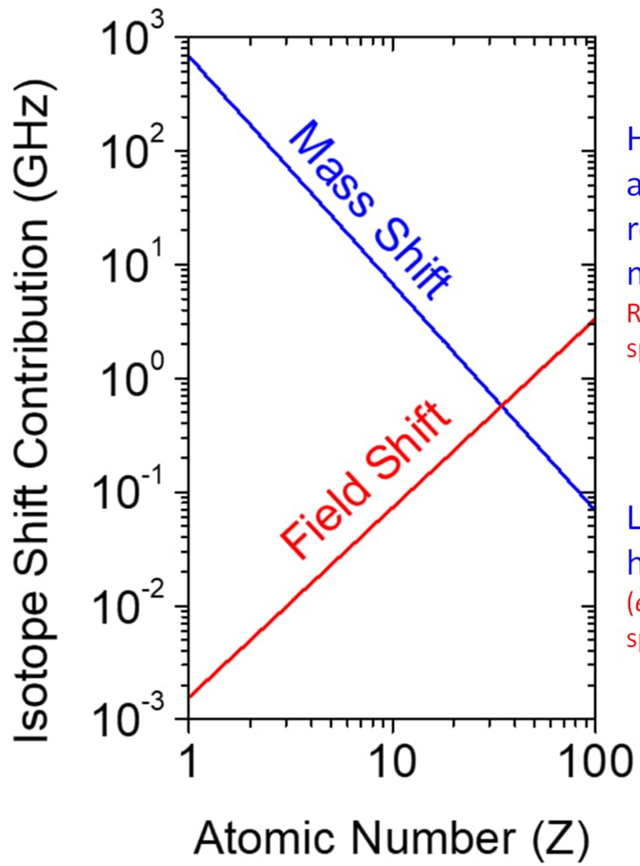
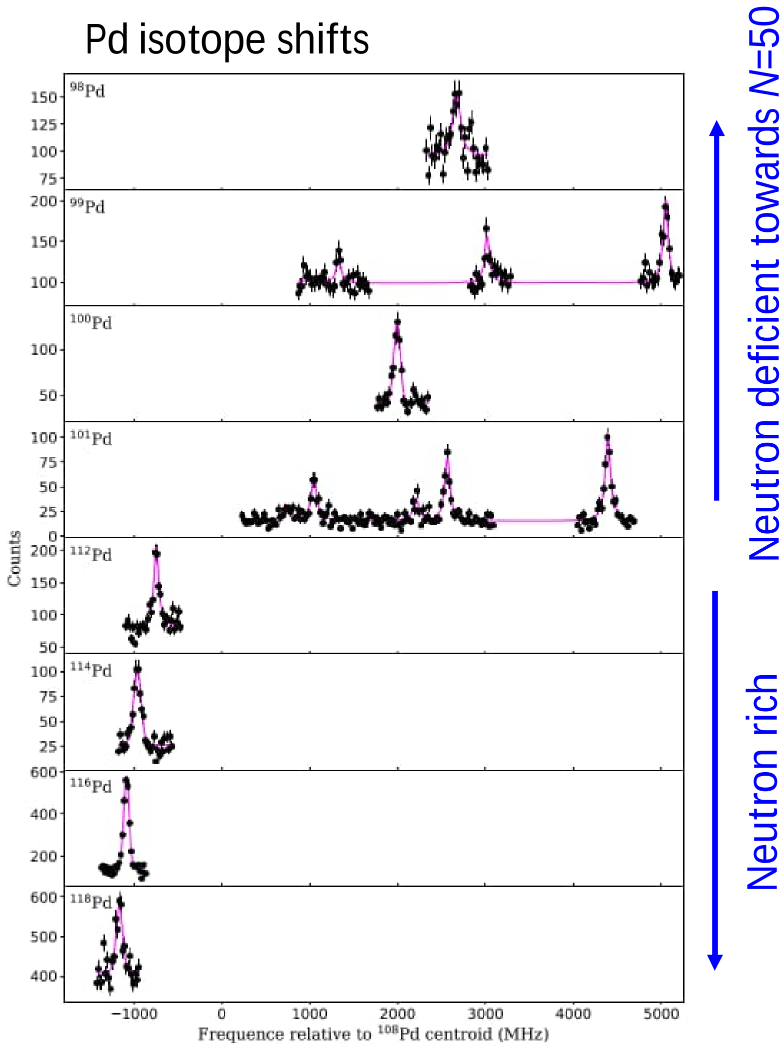
Nuclear mass   Nuclear size

$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \delta\langle r^2\rangle^{A,A'}$$



Higher *Z* can afford lower resolution methods (*e.g.*, Resonance ionization spectroscopy)

Lower *Z* requires high resolution (*e.g.*, Collinear laser spectroscopy)



S. Geldhof et al., Phys. Rev. Lett. 128 (2022) 152501

What can the nuclear charge radii tell us?

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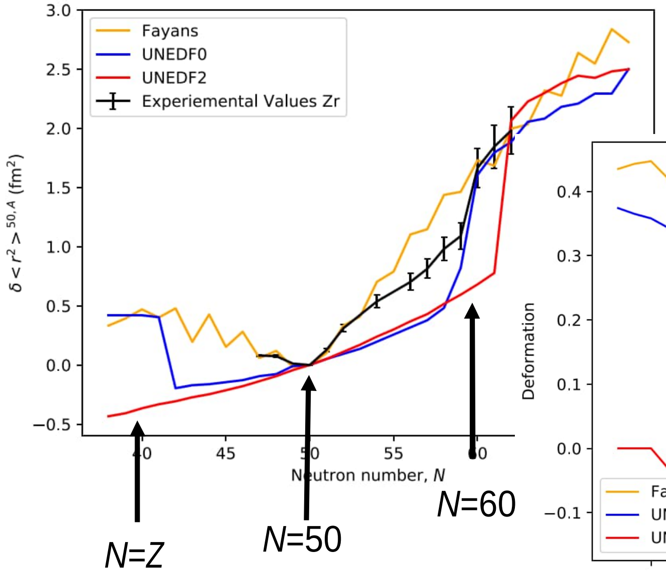
From a simple droplet model approach:

$$\langle r^2 \rangle = \langle r^2 \rangle_{sph} \left(1 + \frac{5}{4\pi}\left(\langle \beta_2^2 \rangle + \cdots\right)\right)$$

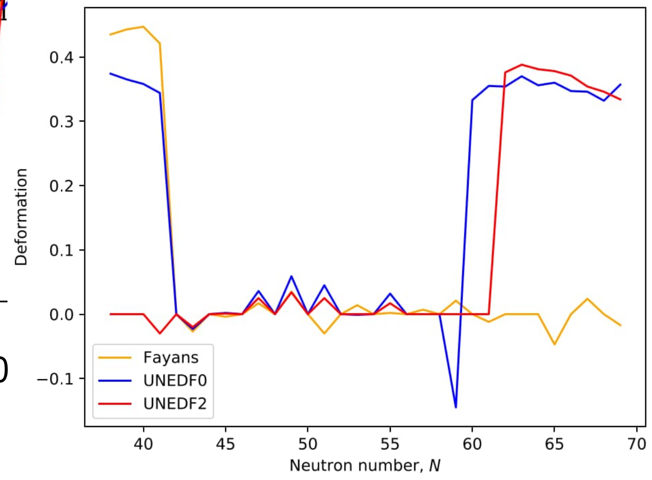
Size
(liquid droplet model)

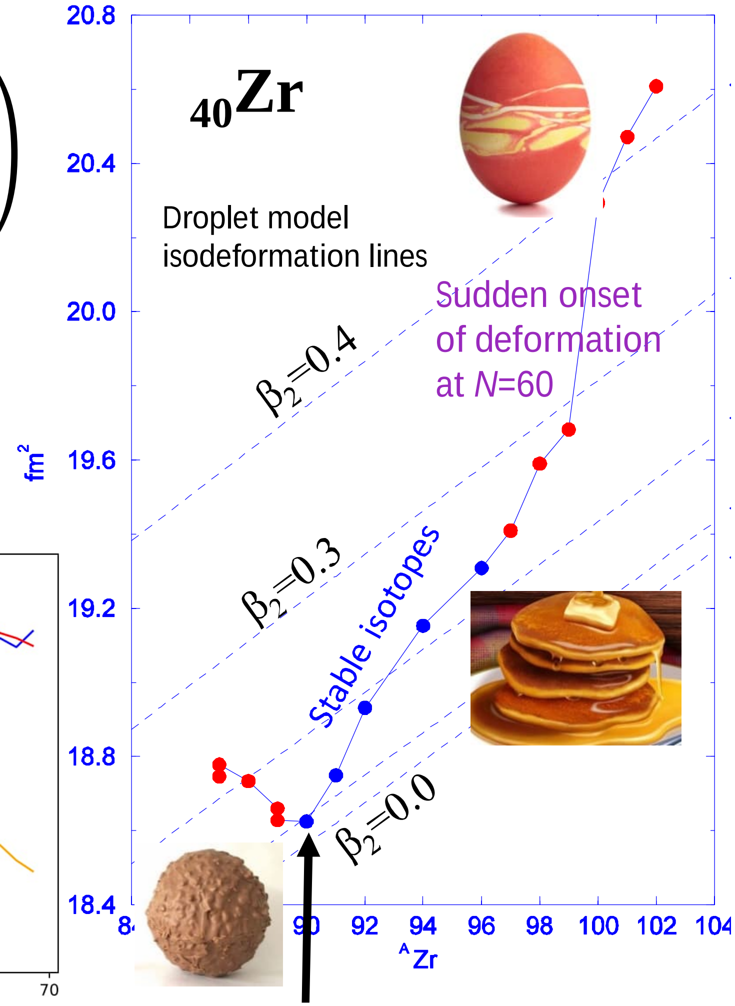
Shape (Quadrupole term)

Charge radii and density functional theory



Courtesy of M. Kortelainen





Note: the sign of the deformation cannot be obtained!

How common is quadrupole deformation?

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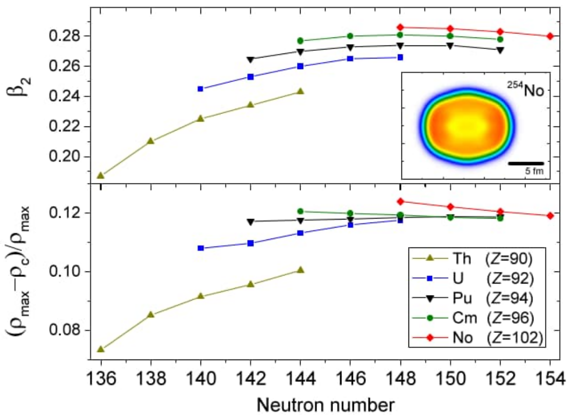
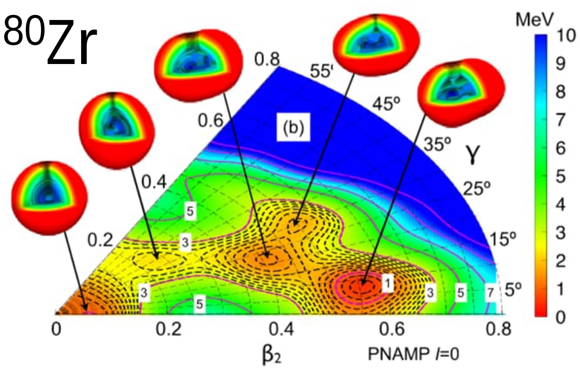
One might even ask how ”uncommon” spherical nuclei are?

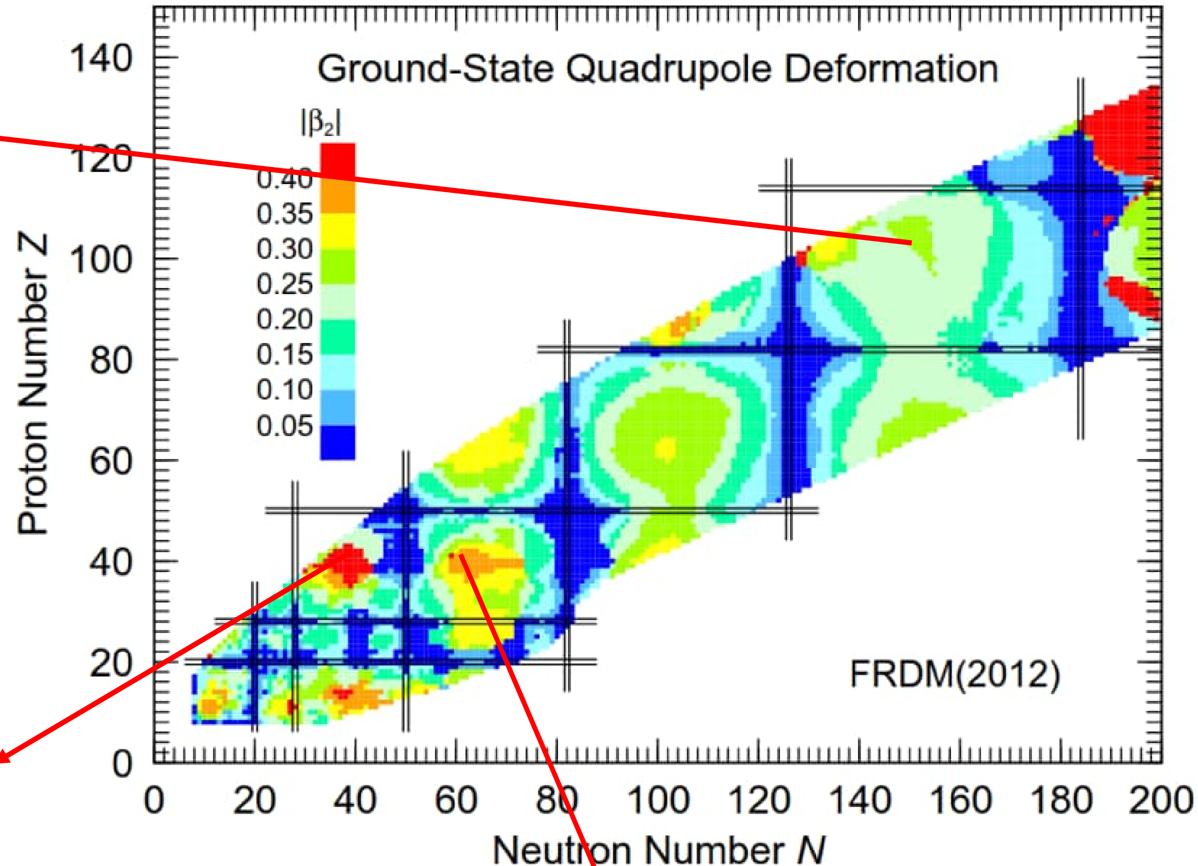


S. Raeder et al., PRL 120 (2018) 232503

^{80}Zr



Rodriguez and Egido, PLB 705 (2011) 255



Region around ^{100}Zr

Status of the ``optical´´ nuclear landscape

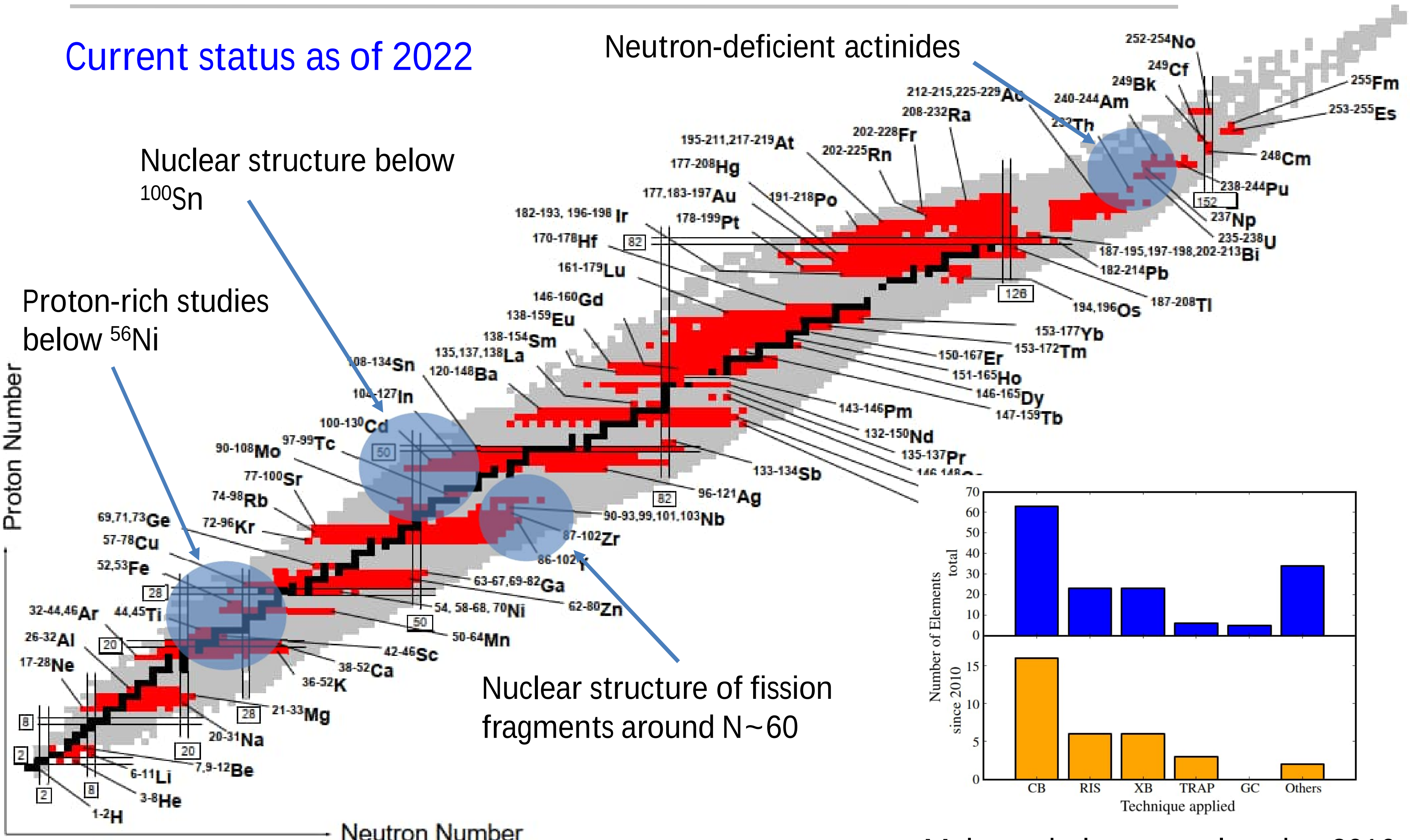
Current status as of 2022

Neutron-deficient actinides

Nuclear structure below ^{100}Sn

Proton-rich studies below ^{56}Ni

Nuclear structure of fission fragments around N~60



Major techniques employed to 2016

IGISOL-4 facility layout

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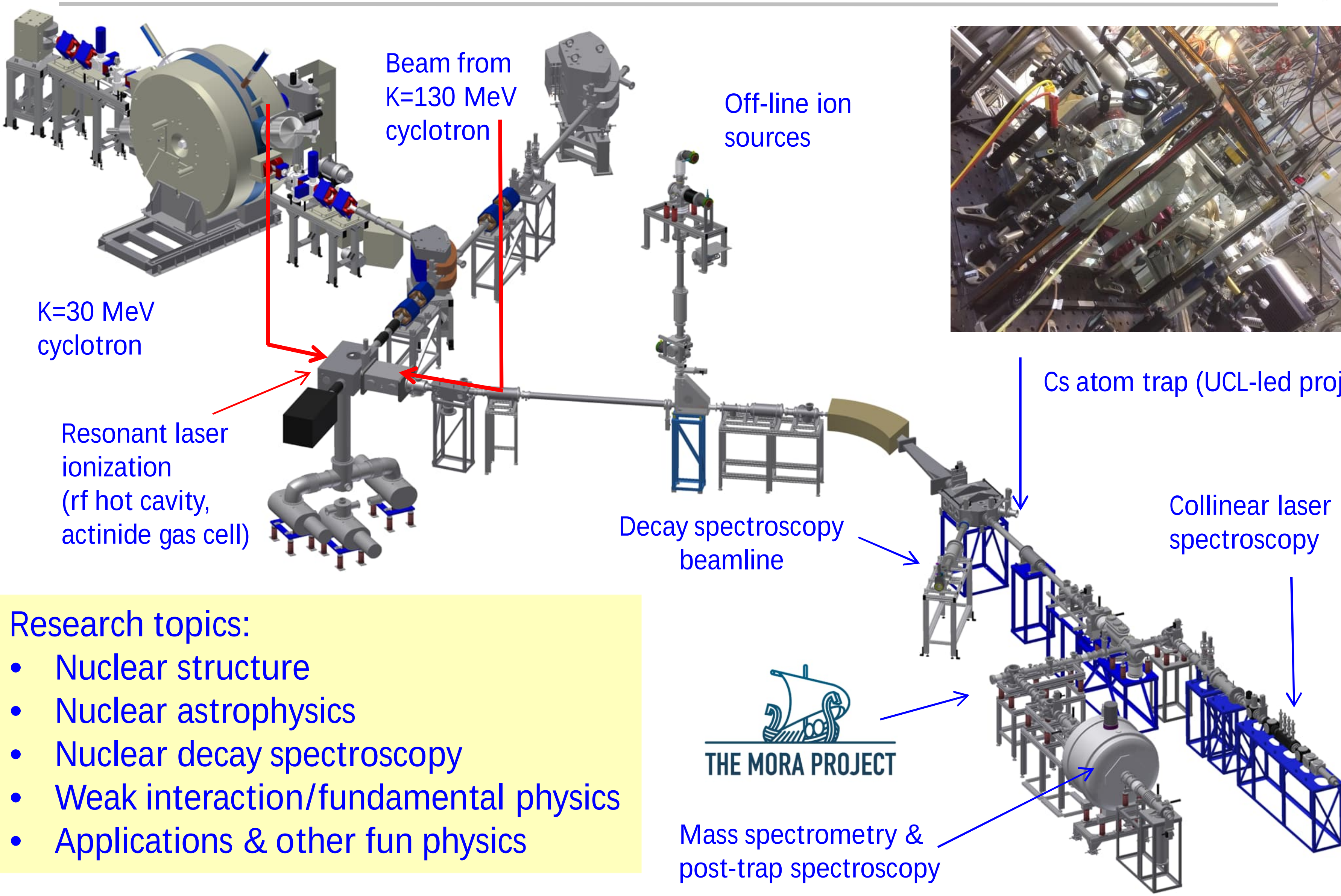

Research topics:

- Nuclear structure
- Nuclear astrophysics
- Nuclear decay spectroscopy
- Weak interaction/fundamental physics
- Applications & other fun physics

Collinear beams laser spectroscopy

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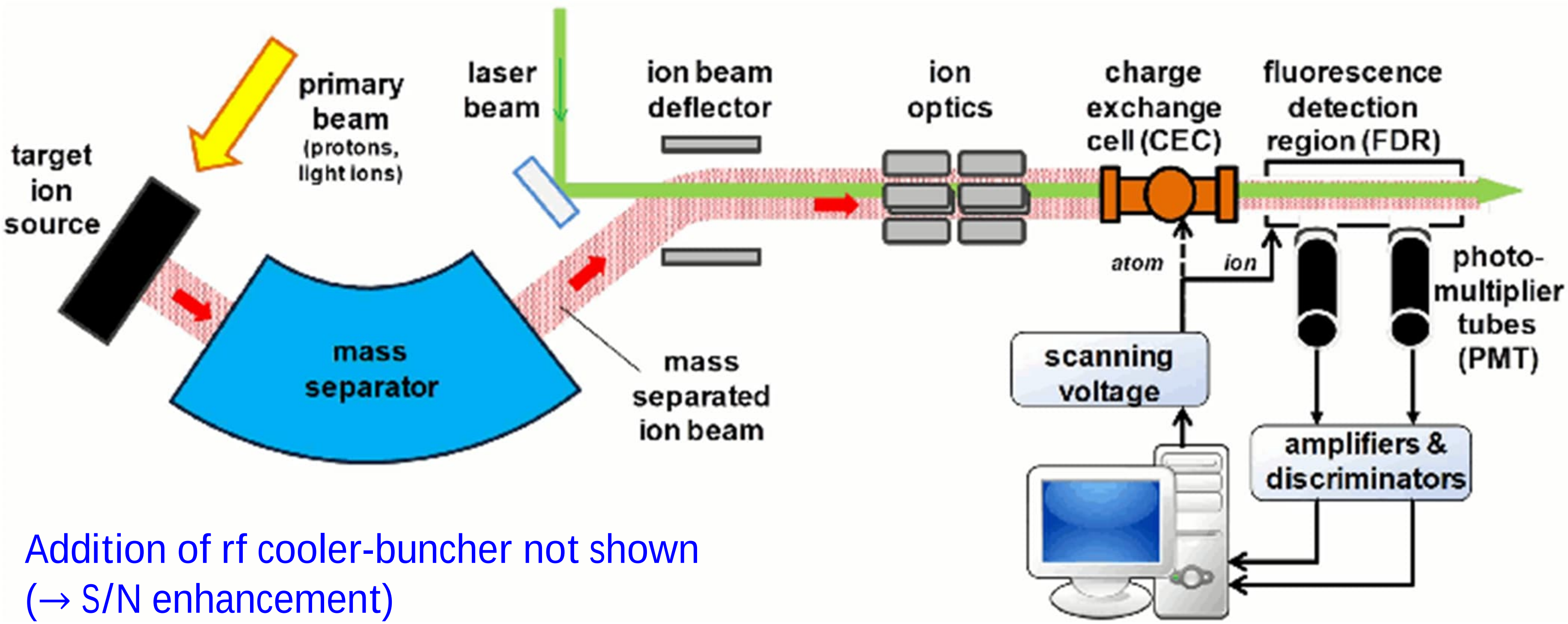
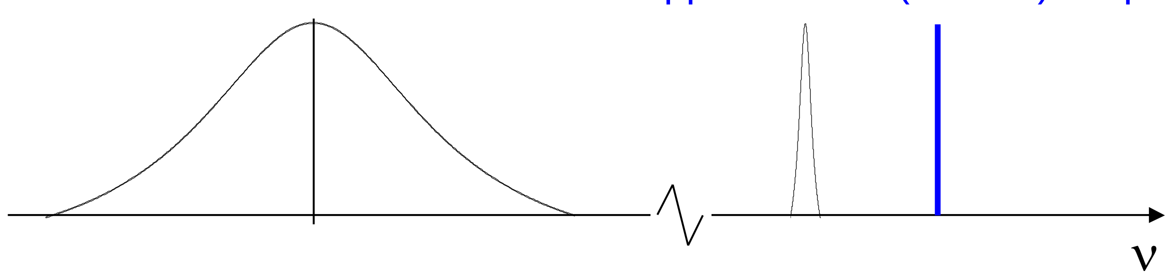
General schematic of the collinear fast-beams technique

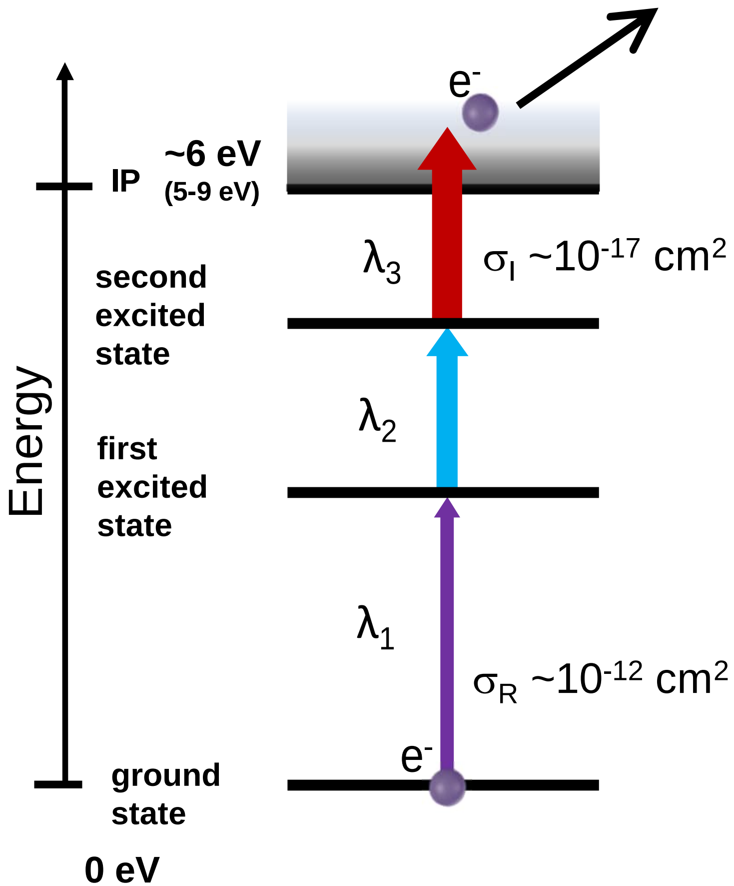


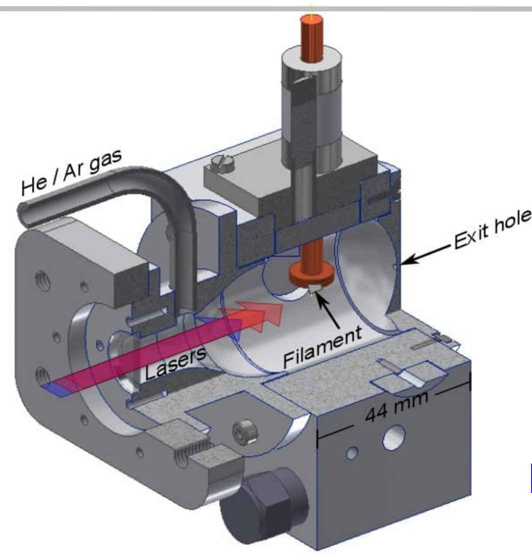
Addition of rf cooler-buncher not shown
(→ S/N enhancement)

Doppler-shifted (relative) frequency



Resonance ionization spectroscopy

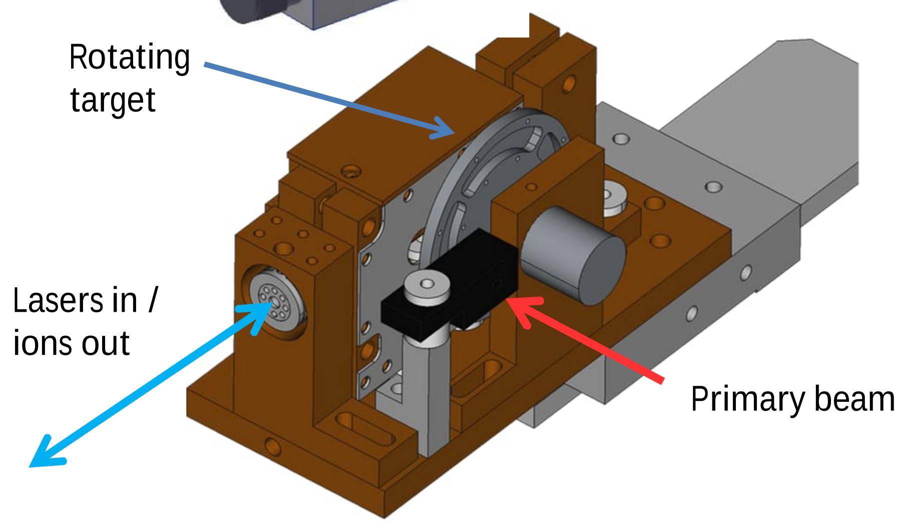




In gas-cell RIS:

- dual-chamber
- actinide (filaments)
- MARA-LEB (S^3-LEB)

RF-heated hot cavity



A selective and efficient spectroscopic method. Combine with mass separator (+ Penning trap!). Shorter lifetimes achieveable. Lower resolution wrt collinear method.

Charge radii and the region around N~60

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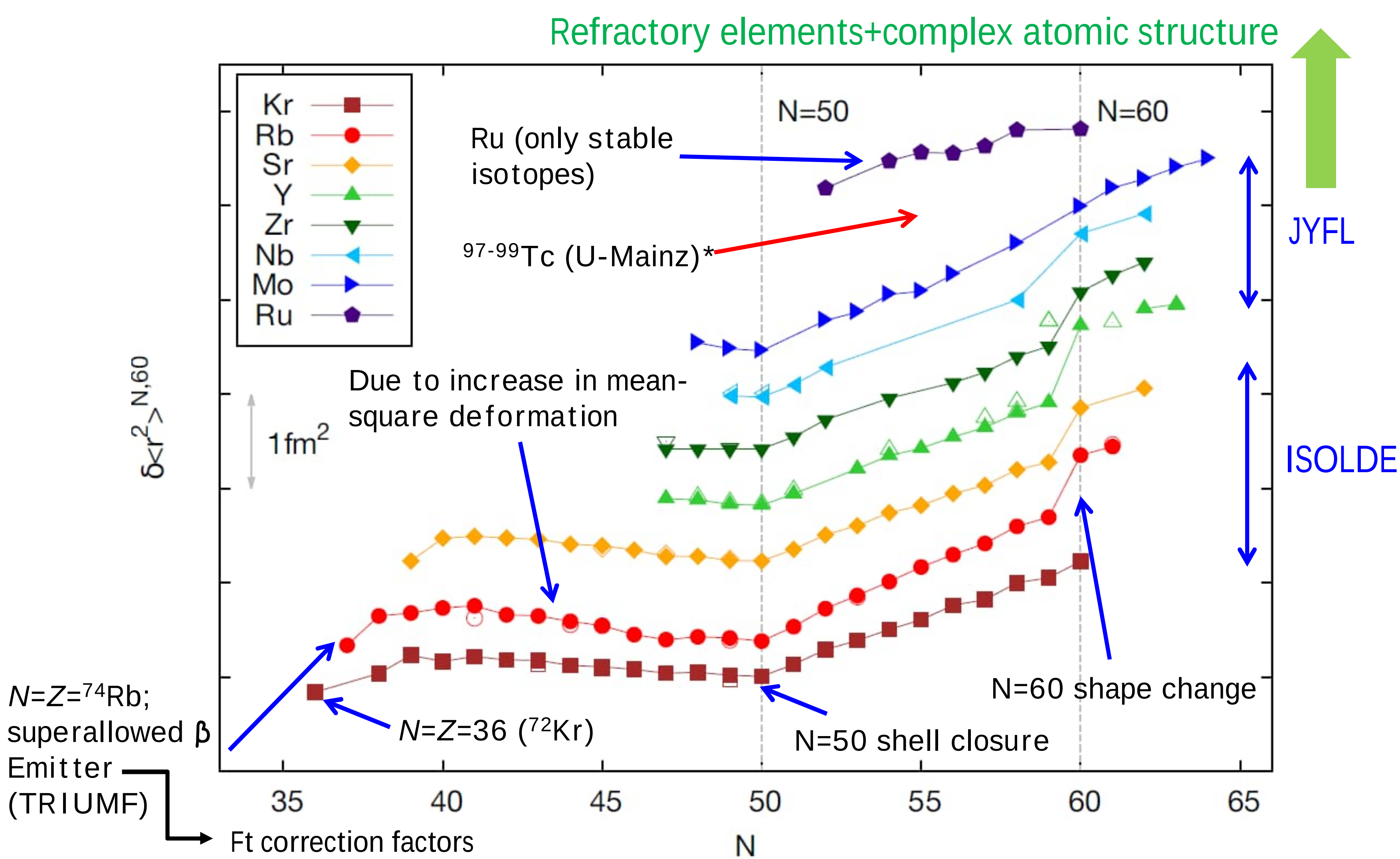
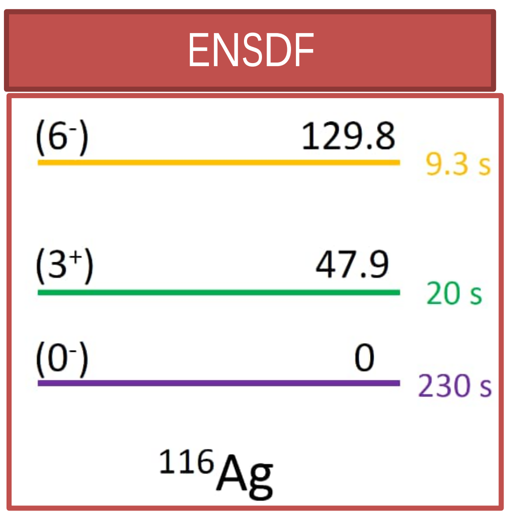


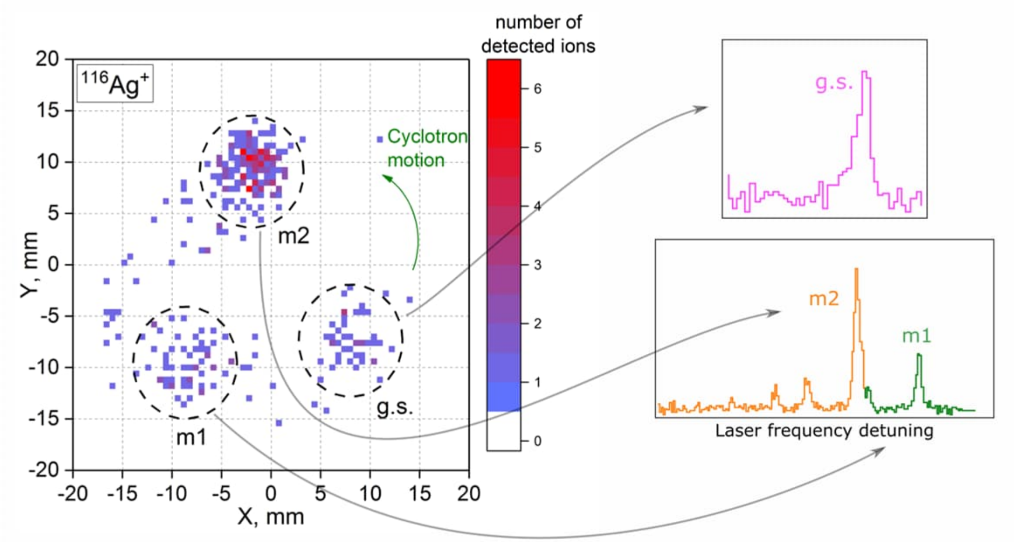
E. Mane et al., PRL (2011) 212502

*T. Kron et al., Phys. Rev. C 102 (2020) 034307

Silver isotopes: masses and optical spectroscopy

- Neutron-rich isotopes of elements of Pd, Ag, In etc are rich in isomerism
- Collinear laser spectroscopy performed on n-rich Ag isotopes in mass range A = 113 – 121
- JYFLTRAP Penning trap has probed Ag isotopes from A = 113 to 125
- Excitation energies of ^{119m,120m,122m,123m,124m}Ag measured for the first time
- eg, ^{116}Ag, 3 states in literature
  - mass and laser spectroscopy done together (back-to-back beam times)
  - masses, excitation energies, electromagnetic moments, charge radii and spins!
- DFT calculations (Dobaczewski *et al*) exploring spin-orbit strength and time-odd mean fields





de Groote and Nesterenko, to be submitted (2022)

Rich in isomerism

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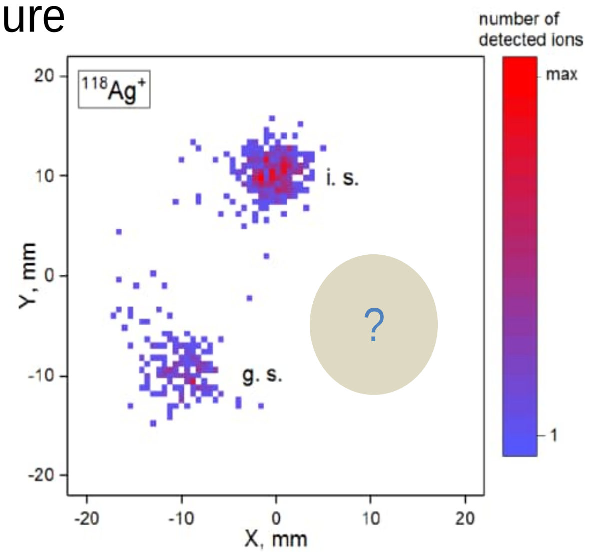
- On the other hand:
  ^{118,120}Ag, 2 states in literature

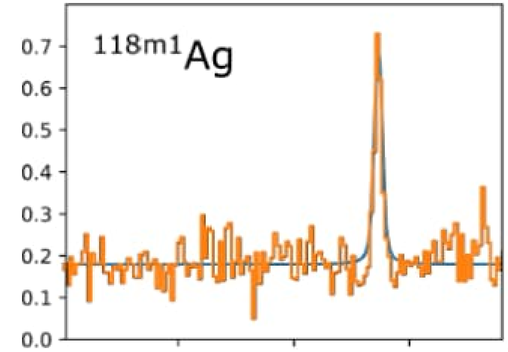
ENSDF

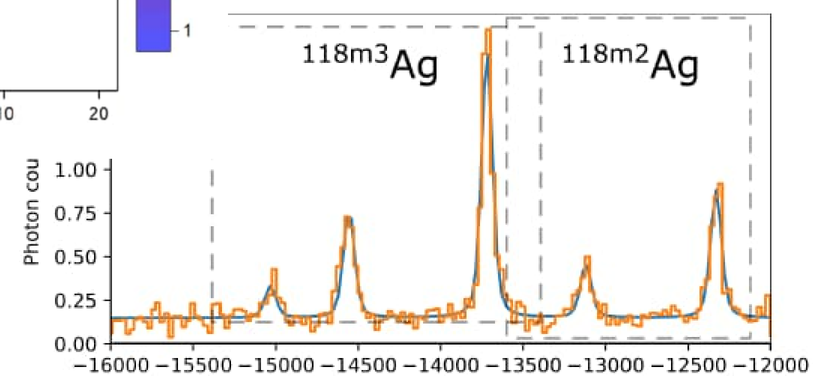
4(+) 128 — 2.0 s

1(-) 0 keV — 3.76 s

^{118}Ag







- 3 states in ^{118,120}Ag found with laser
- Only two seen with PI-ICR
  - too short lived?
  - too close-lying in energy?
- Requires future measurements
  - RAPTOR

Trap-assisted β-decay spectroscopy of isomeric states in neutron-rich Ag (M. Stryjczyk)

Proton-rich nuclei in the f7/2 shell

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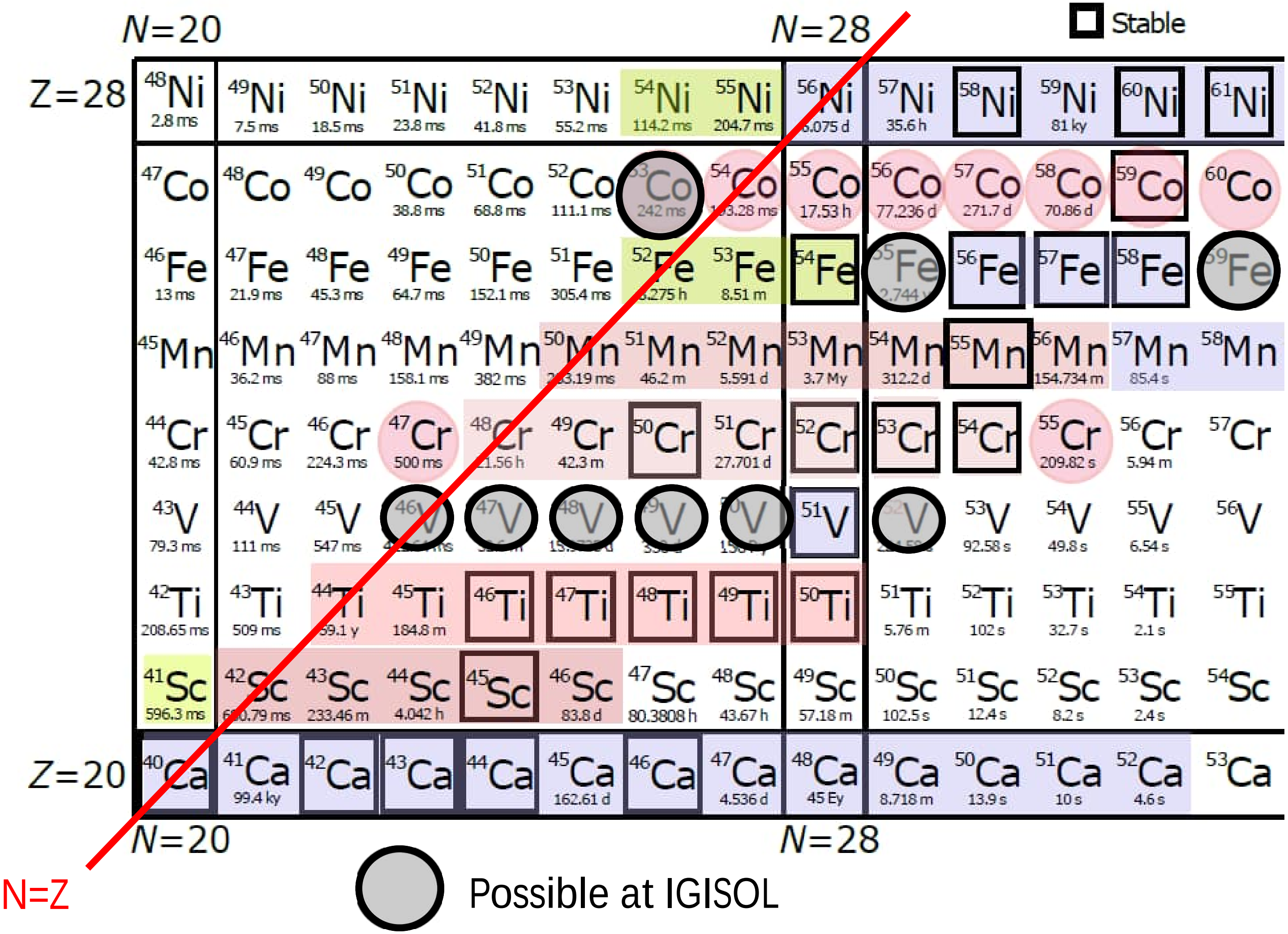
Proposed at IGISOL | Measured at IGISOL | Measured at NSCL | Measured at ISOLDE



Only stable isotopes known for V, Cr and Co (until 2021)

$^{48-55}$Cr measured at IGISOL (2021)

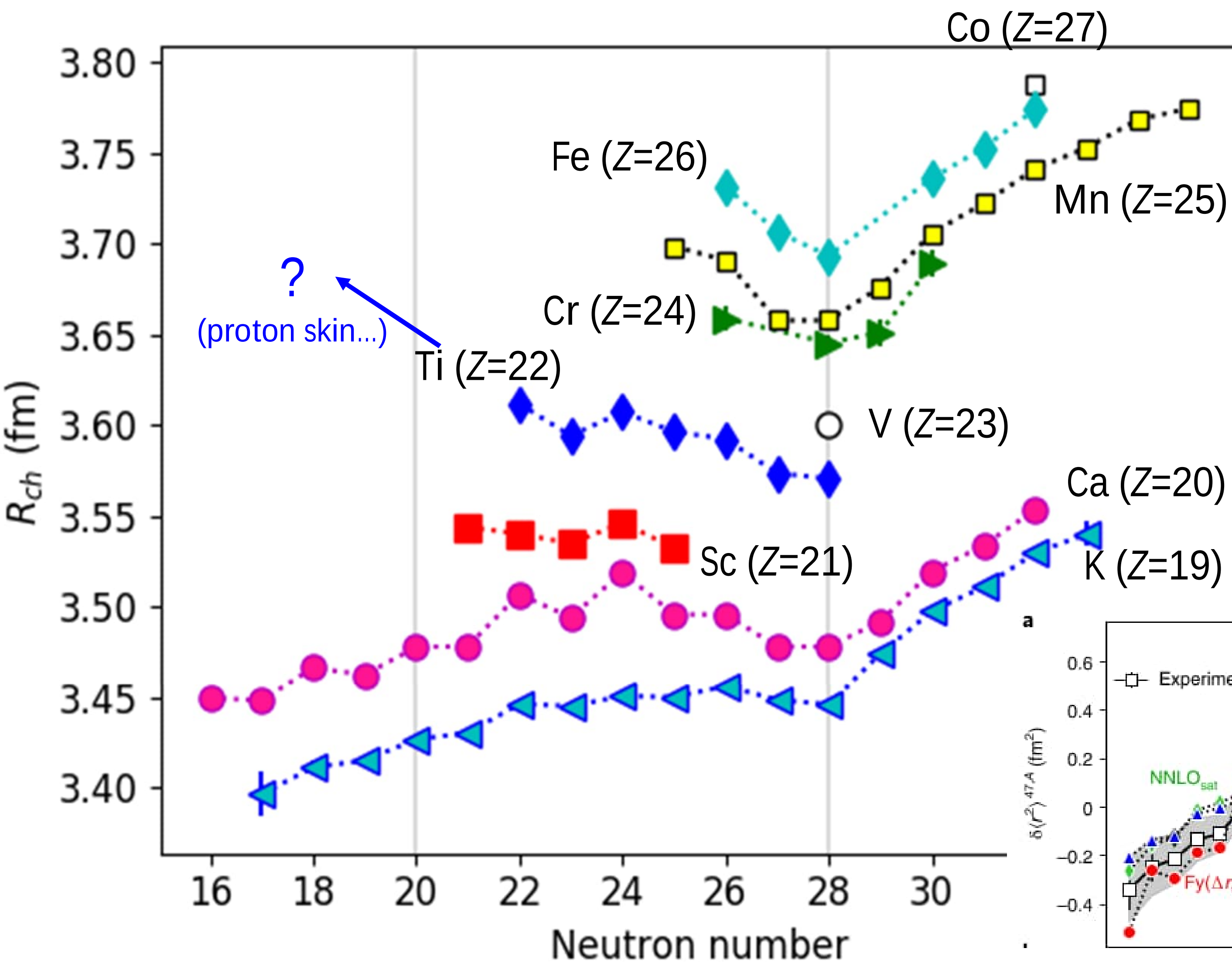
Offline test performed on V, Fe and Co

Proposal accepted for $^{54-60}$Co (to partly run in June/July)

Proposal accepted for $^{52-59}$Fe (March 2022 PAC)

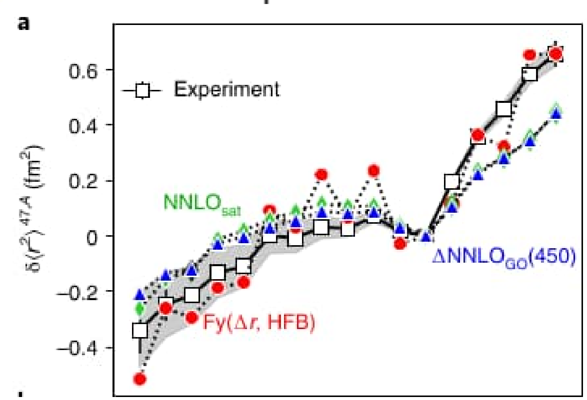
Courtesy of A. Koszorus

Why is this region interesting?



Laser spectroscopy of Co will pave the way for an investigation of the proton-emitting isomer in ^{53}Co!!

Exploring magicity and challenging theory from nuclear sizes



A. Koszorus et al., Nature Phys. 17 (2021) 439

Kinky shell closures…

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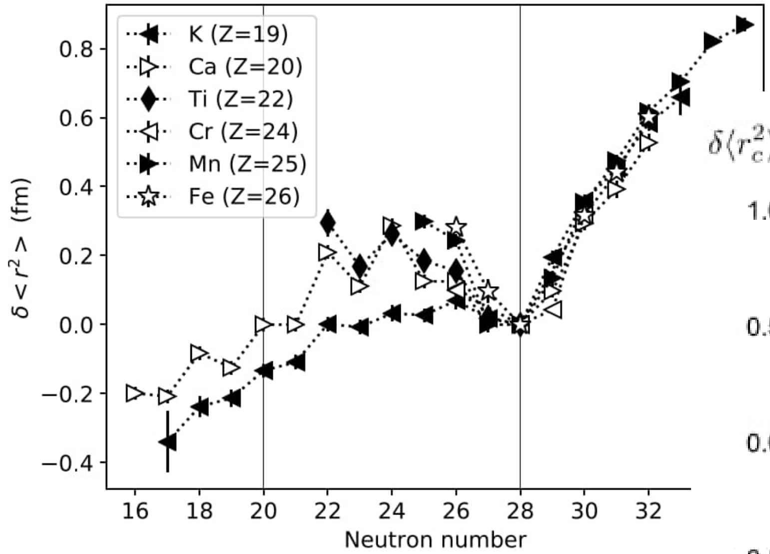
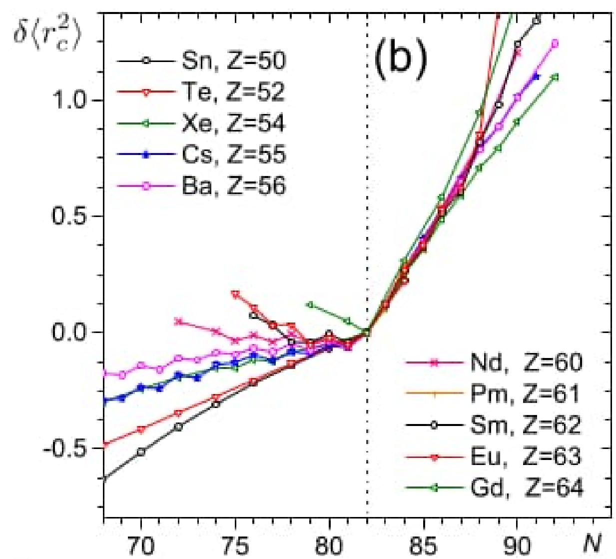
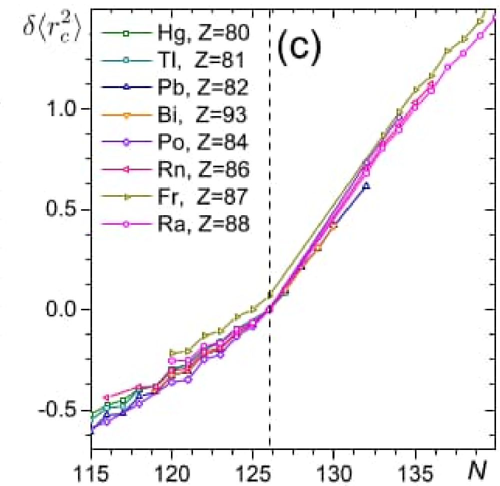
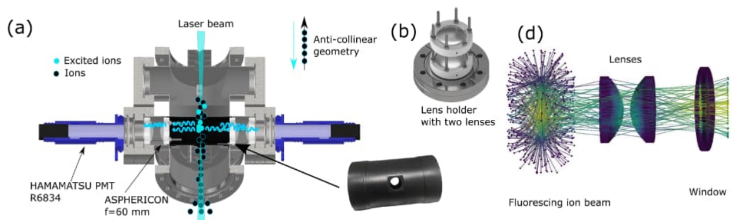
- Charge radii display many microscopic phenomena – one of these are so-called ``kinks´´ seen at the shell closures
- Finer effects can also be probed via laser spectroscopy, eg an odd-even staggering between isotopes









Challenges for our $f_{7/2}$ region of interest:

- Requires deep-UV spectroscopy of refractory systems
- New light collection system installed 2021

A. Koszorus et al., to be submitted to Spectrochimica Acta (2022)

Penning trap-assisted in-source RIS

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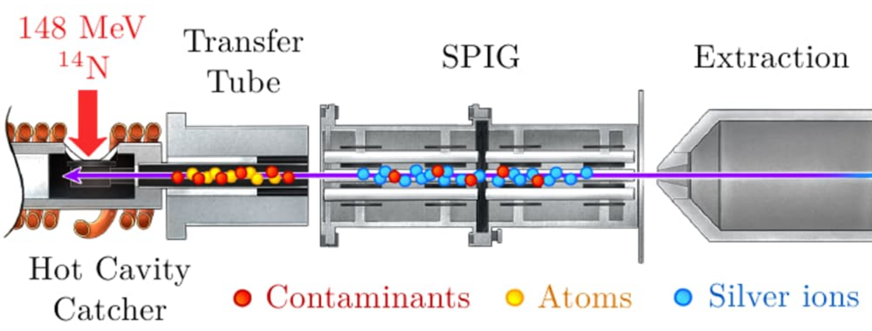
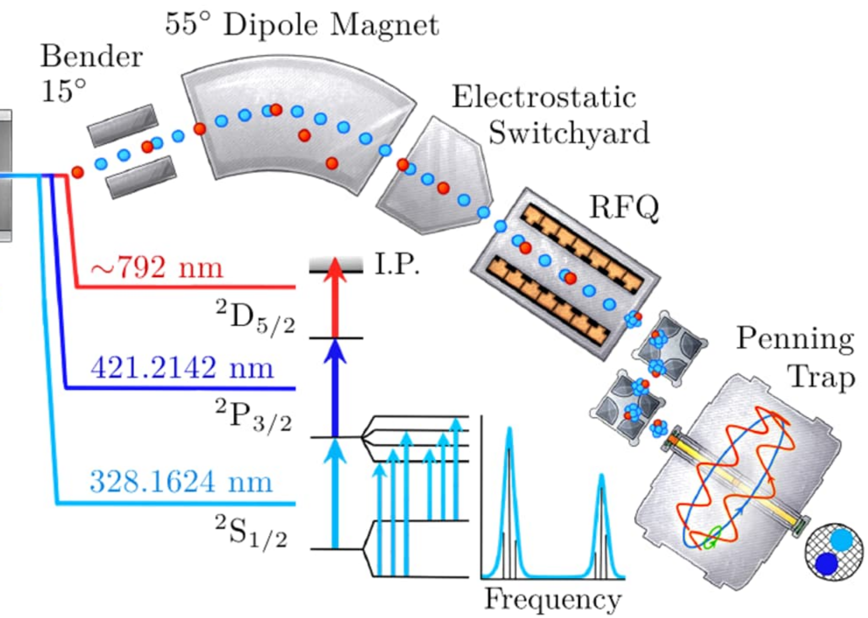
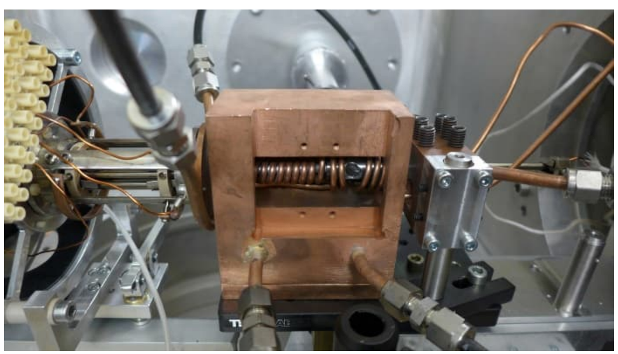
~15 years of developments





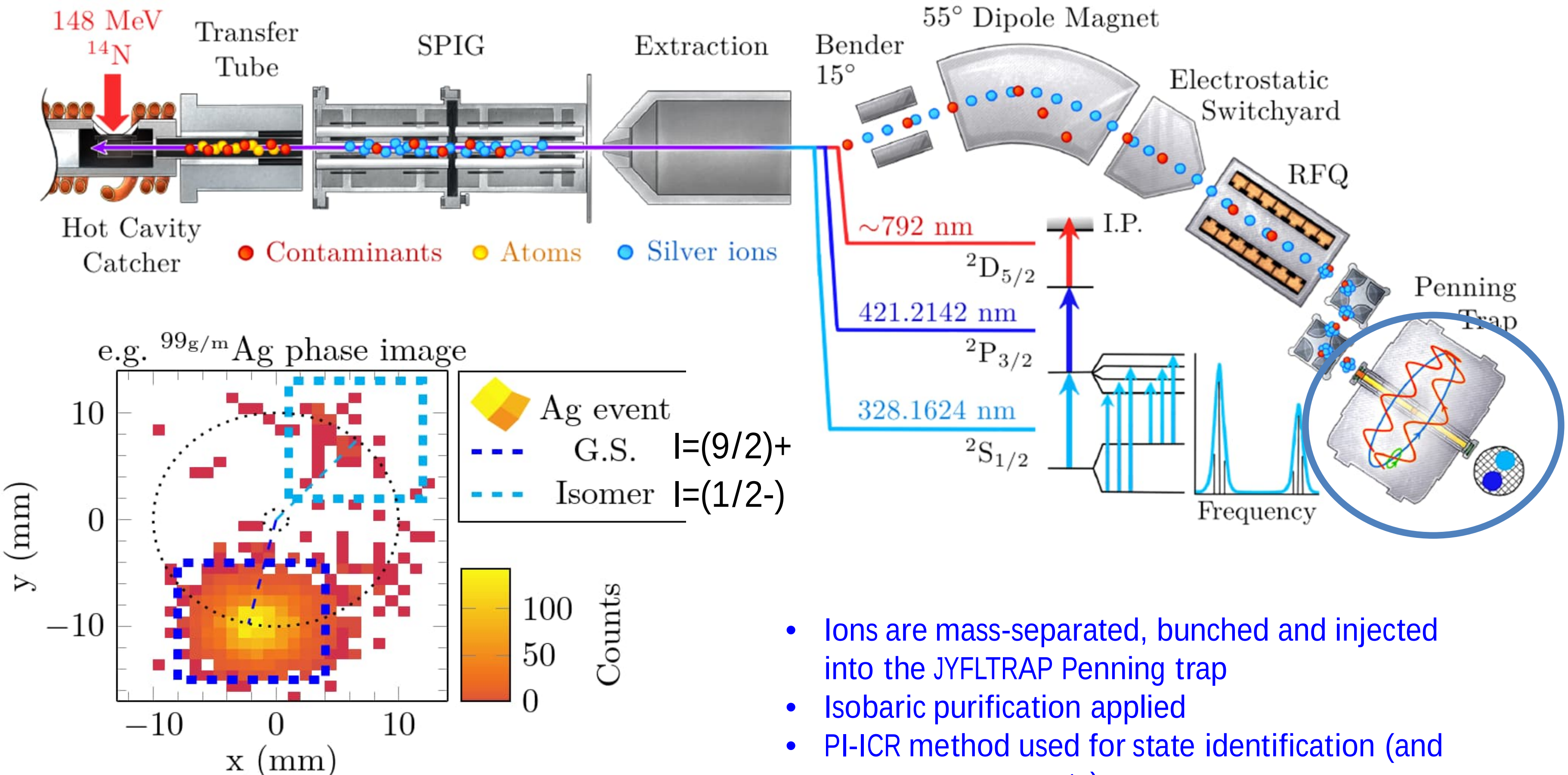
^{nat,92}Mo(^{14}N,2p*x*n)$^{104\text{-}96}$Ag



M. Reponen et al., Rev. Sci. Instrum 86 (2015) 123501

- GSI work (Kirchner) – Ag has excellent extraction from graphite
- In collaboration with ECR team, a new inductively-heated cavity source
- Tested online, confirming ~1% total efficiency for Ag
- Three-step resonance laser ionization and spectroscopy

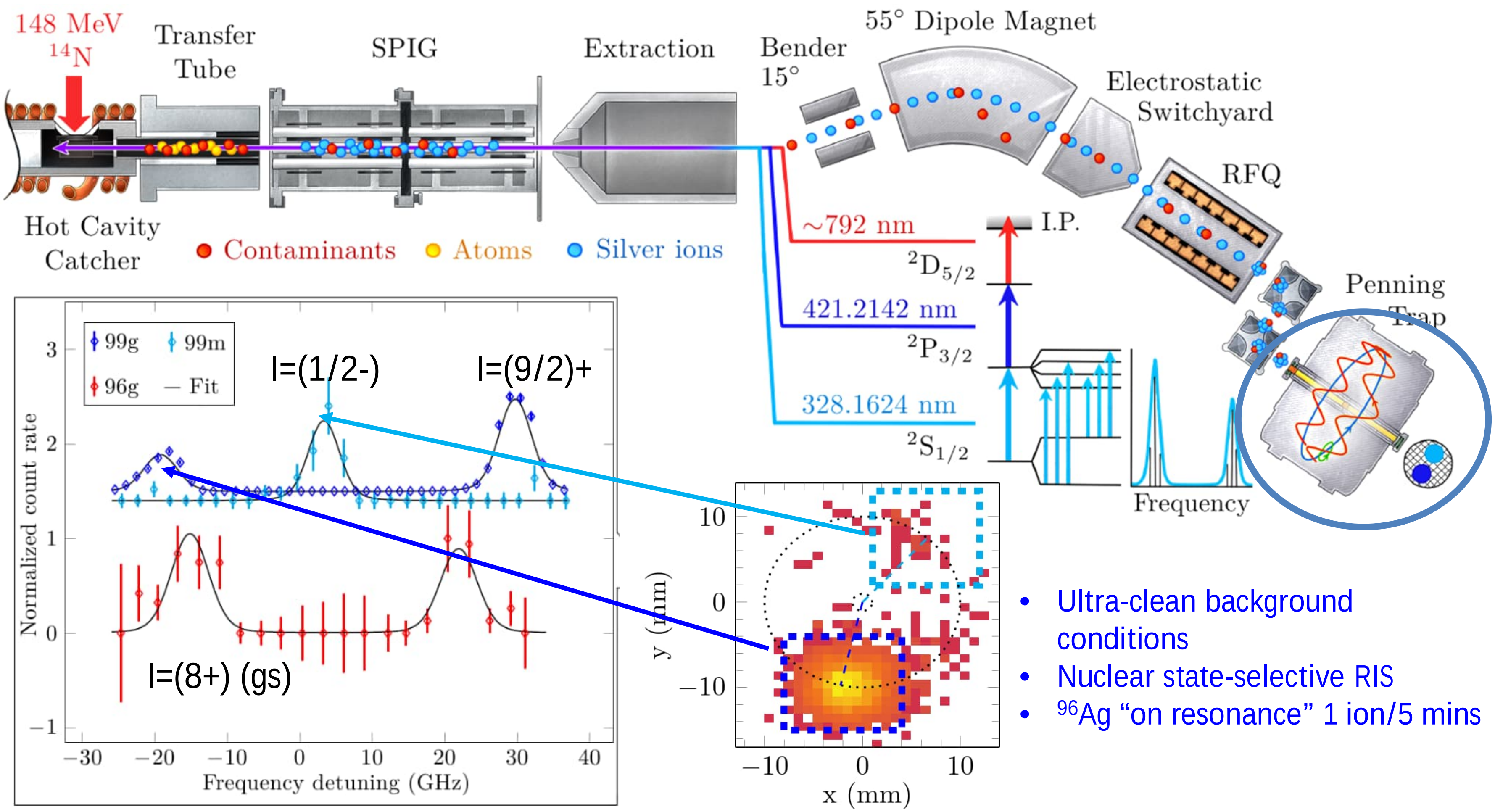
Penning trap-assisted in-source RIS



Trap-assisted spectroscopy + laser selectivity

- Ions are mass-separated, bunched and injected into the JYFLTRAP Penning trap
- Isobaric purification applied
- PI-ICR method used for state identification (and mass measurements)
- Information on isomeric yield ratios

Penning trap-assisted in-source RIS



- Ultra-clean background conditions
- Nuclear state-selective RIS
- ^{96}Ag "on resonance" 1 ion/5 mins

Evolution of charge radii near ^{100}Sn

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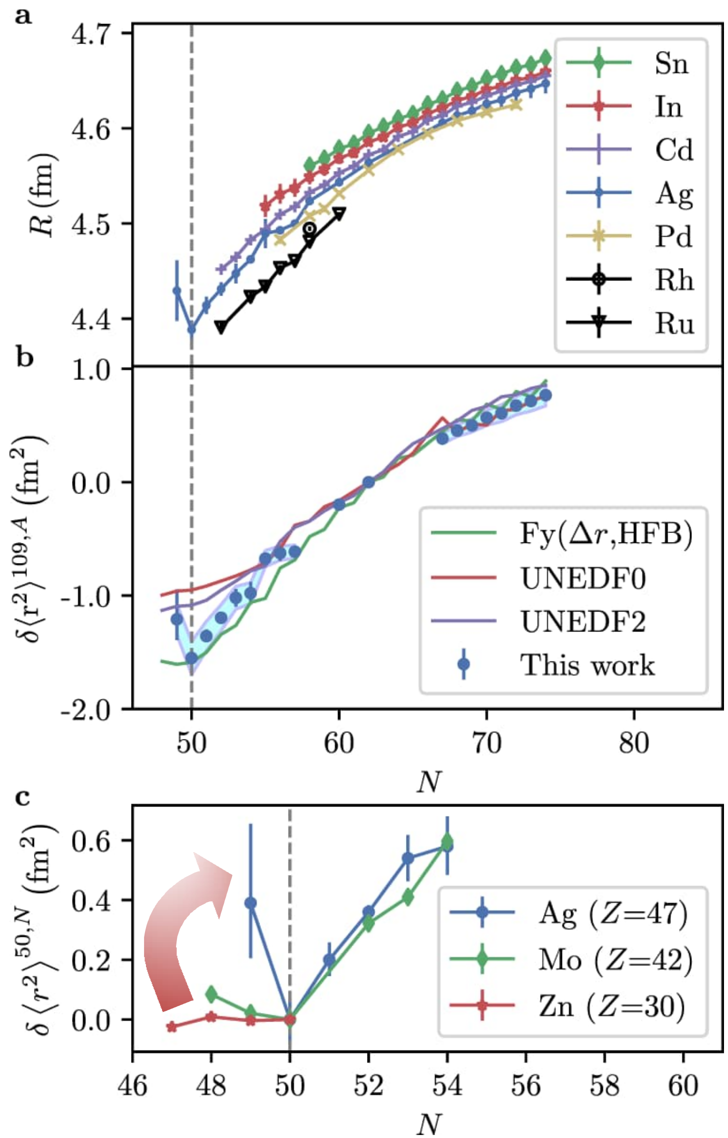

Article | Open Access | Published: 28 July 2021

Evidence of a sudden increase in the nuclear size of proton-rich silver-96

M. Reponen, R. P. de Groote, [...]I. D. Moore

Nature Communications **12**, Article number: 4596 (2021) | Cite this article

- New measurements cross N=50 shell closure in the region of ^{100}Sn
- UNEDF functionals predict a rather smooth behaviour; Fayans EDF better reproduces local variations
- None of the models reproduces the pronounced increase in crossing N=50
- Fayans functional also applied to recent Pd charge radii data; exploration of the strength of pairing correlations

PHYSICAL REVIEW LETTERS **128,** 152501 (2022)

Impact of Nuclear Deformation and Pairing on the Charge Radii of Palladium Isotopes

S. Geldhof,[1,2,*] M. Kortelainen,[1,†] O. Beliuskina,[1] P. Campbell,[3] L. Caceres,[4] L. Cañete,[1] B. Cheal,[5] K. Chrysalidis,[6] C. S. Devlin,[5] R. P. de Groote,[1] A. de Roubin,[1] T. Eronen,[1] Z. Ge,[1] W. Gins,[1] A. Koszorus,[5] S. Kujanpää,[1] D. Nesterenko,[1] A. Ortiz-Cortes,[1,4] I. Pohjalainen,[1,7] I. D. Moore,[1] A. Raggio,[1] M. Reponen,[1] J. Romero,[1,5] and F. Sommer[8]

Future hot cavity measurement campaigns

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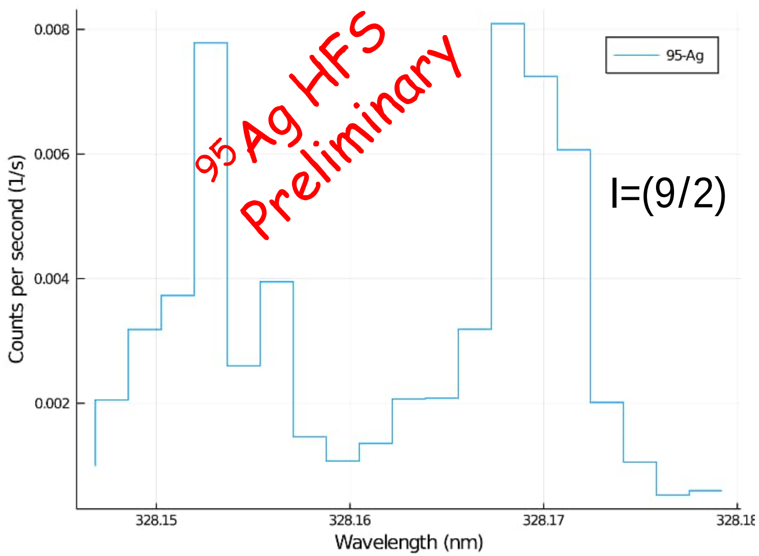
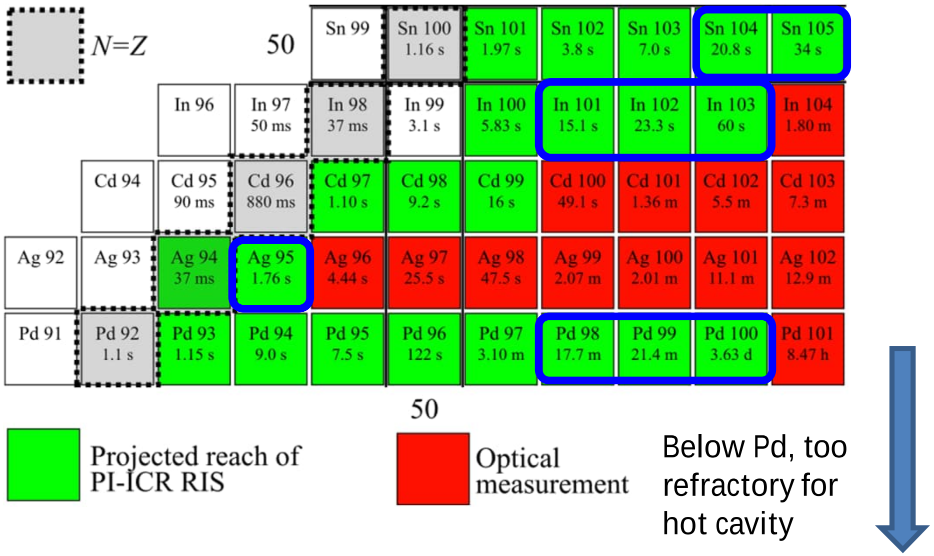
May 2021: ^{58,60}Ni(^{40}Ca,pxn)$^{103-95}$Ag





Projections:

- Ca beam intensity 40-50 pnA (average)
- Charge radius of ^{95}Ag extracted
- Magnetic dipole moments for ^{95,96}Ag
- Mass measurements of ^{95,96,96m}Ag
- Tentative signs for (7^+) isomer in ^{94}Ag (0.001/s)
- April 2022 – 200 pnA Ca beam demonstrated!

- LISE++ simulations and Gemini++ cross sections
- Assume 0.5% efficiency after mass separation, 10% transmission RFQ and trap
- Laser ionization efficiency ~10%
- ^{40}Ca or ^{58}Ni primary beam, 50 pnA
- Similar statistics as for ^{96}Ag (0.005 ions/s) in <12h

Proposal accepted for mass measurements of ^{94}Ag (14 days)
Two day test beam time for Pd in 2 weeks

Summary

- We have a wide programme of optical spectroscopy, both collinear and ``in-source´´ motivated primarily by nuclear structure physics
- Programme to explore neutron-deficient actinide isotopes – exploration of octupole-deformed region (not discussed)
- RAPTOR under commissioning – low-energy CRIS platform
- Cs atom trap – magnetic octupole moments; BEC
- MARA-LEB will focus on in-gas jet RIS towards the N=Z line – complementary to S3-LEB at GANIL
- The lab tour later this morning will give you an opportunity to explore the facility and the laser systems available.

- + Jorge Romero (dual-doctoral student MARA/MARA-LEB)
- + Andrea Raggio (Marie Curie PhD, actinides)
- + Wirunchana Rattanasakuldilok (PhD student atom trap)
- + Arthur Jaries (PhD FAIR cooler + trap)
- + Juoni Ruotsalainen (PhD trap)
- + Nikas Stylianos (postdoc – astrophysics)
- + Marek Stryjczyk (postdoc – decay spectroscopy)
- + Maxime Mougeot (postdoc from summer 2022)

ACADEMY OF FINLAND

MARIE CURIE ACTIONS

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European Research Council

Thanks to this excellent team!