Laser spectroscopy of actinides at the IGISOL facility, JYFL

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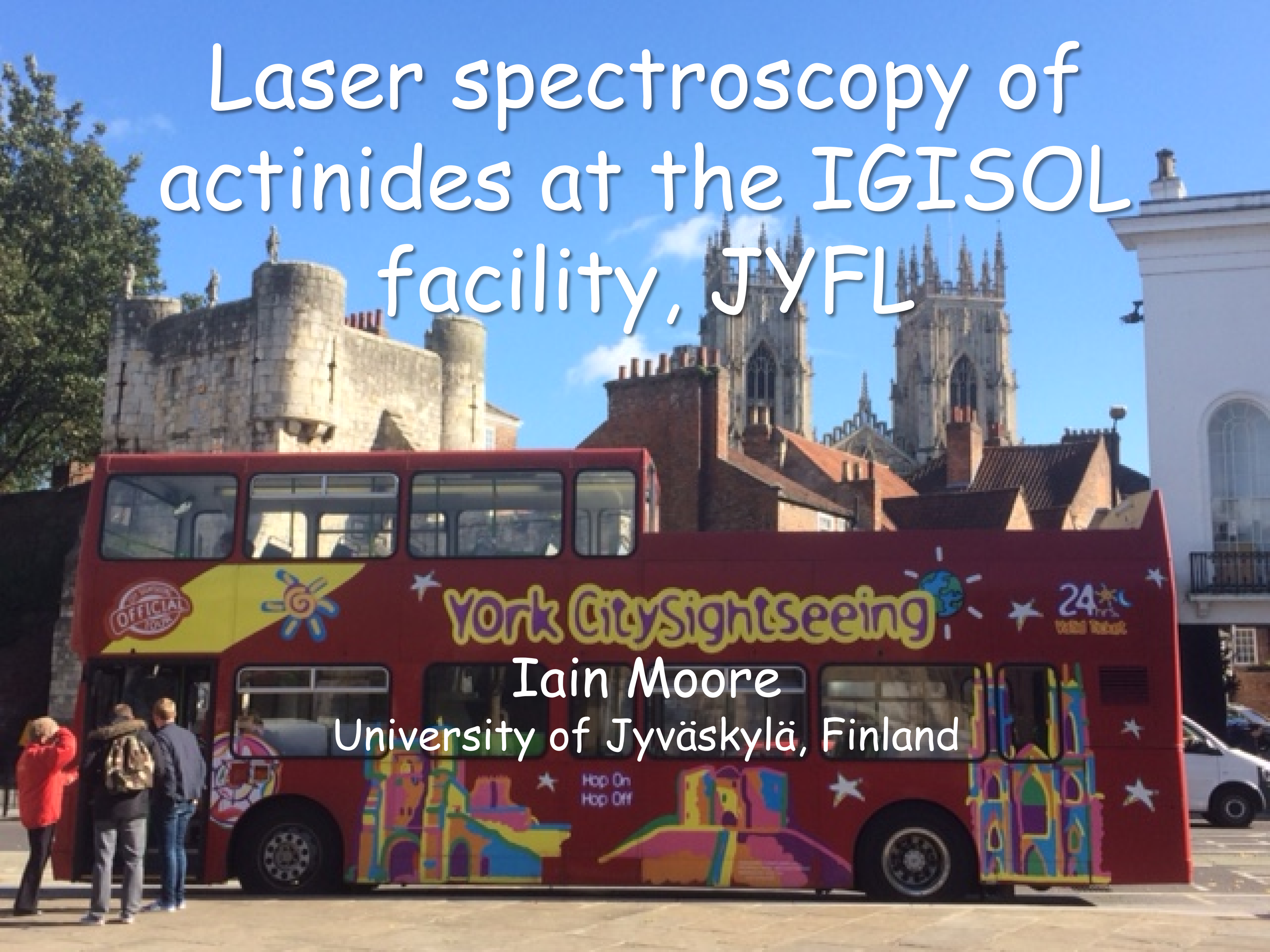
University of Jyväskylä, Finland

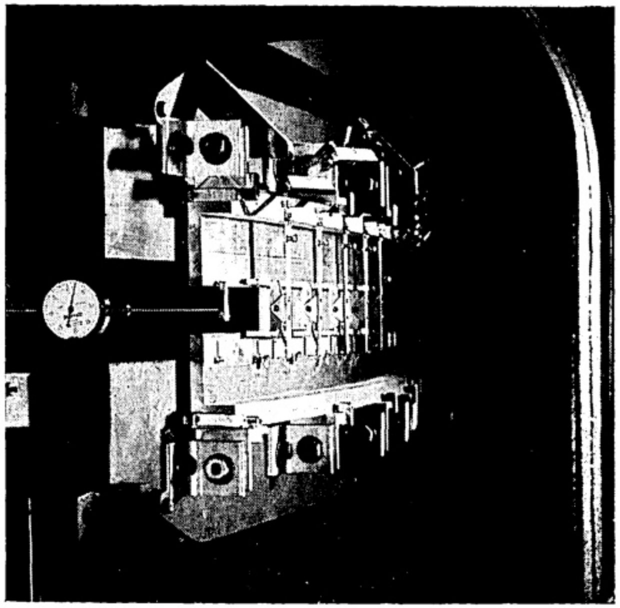


Outline

- Motivation for heavy element studies
- Laser ionization and spectroscopy of plutonium
- Comparison of RIS vs. collinear spec
- Laser ionization of thorium – towards the nuclear clock
- Outlook

History: towards heavy & rare isotopes

In the 1950s, physicists and chemists expected it would be possible to deduce many properties of an element from a detailed knowledge of electronic configurations. Transuranium elements (Np to Fm) could be bred in small amounts in reactors, or from nuclear fallout.

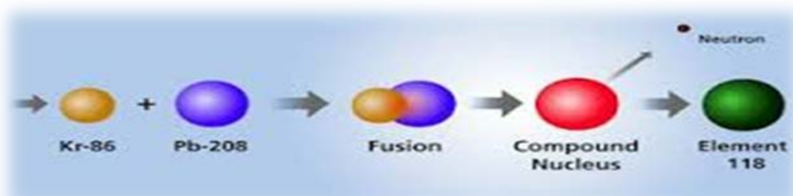


30 m Argonne Paschen-Runge spectrometer

Tomkins & Fred, Spectr. Chem. Acta 6 (1954) 139

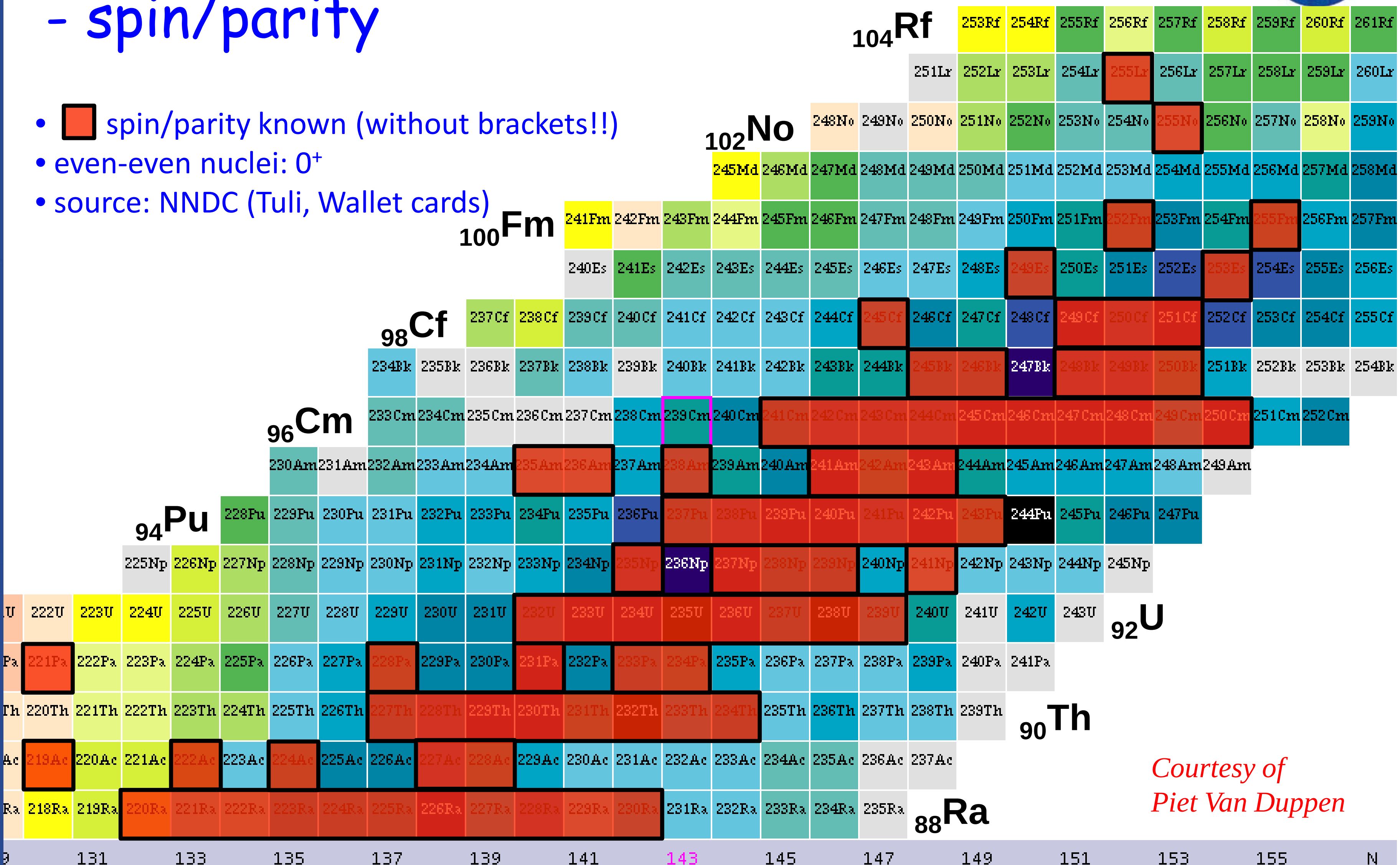
Huge spectrographs built: tens of thousands of atomic emission lines observed for each actinide. Sample sizes 0.1 mg. Quite good info available up to Es (Z=99)

- Uranium is heaviest ISOL target
- Need fusion reactions in HI collisions
- Low production cross sections
- Lack of stable isotopes – lack of optical transitions



Ground state nuclear structure - spin/parity

- spin/parity known (without brackets!!)
- even-even nuclei: 0^+
- source: NNDC (Tuli, Wallet cards)

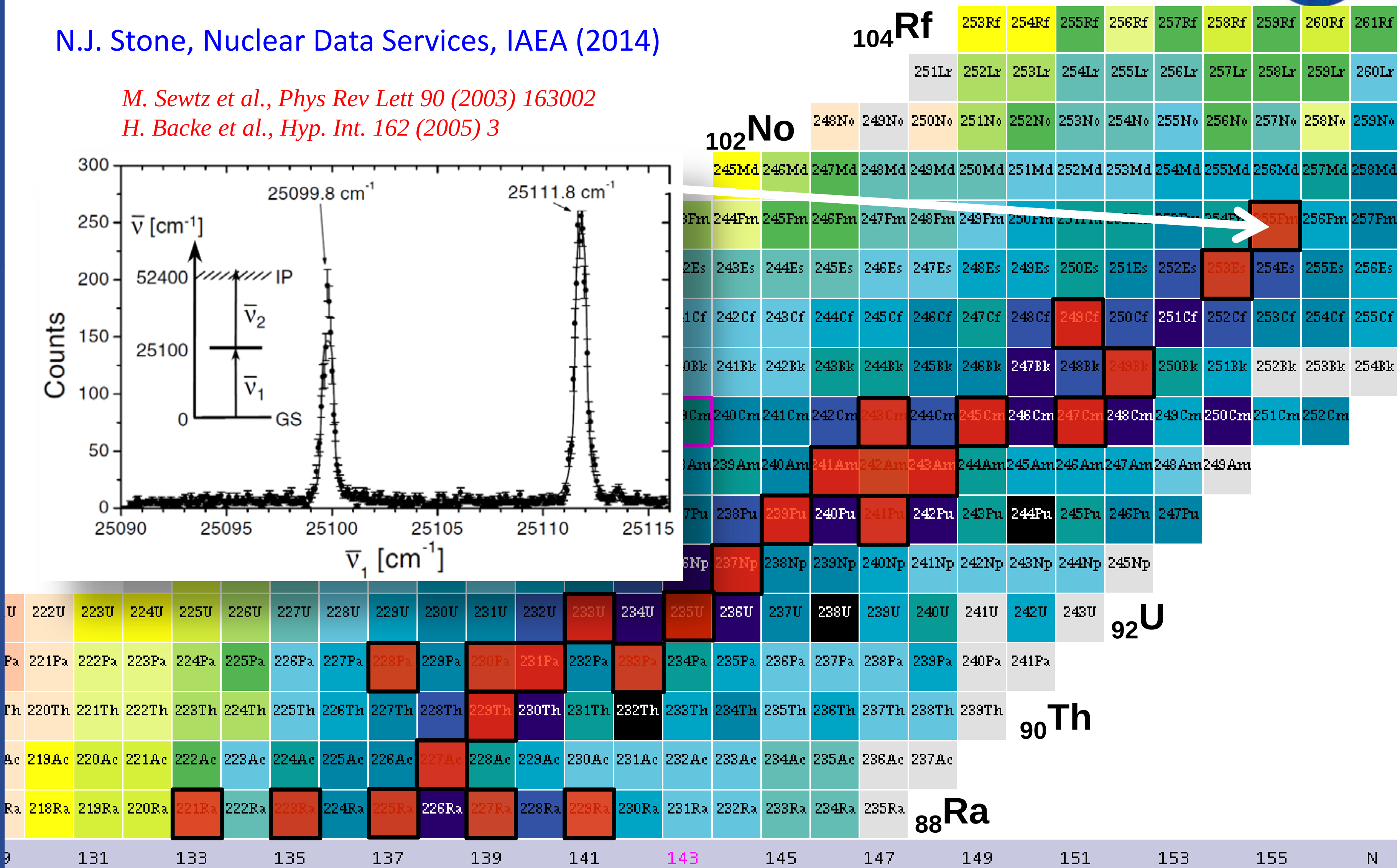


Courtesy of Piet Van Duppen

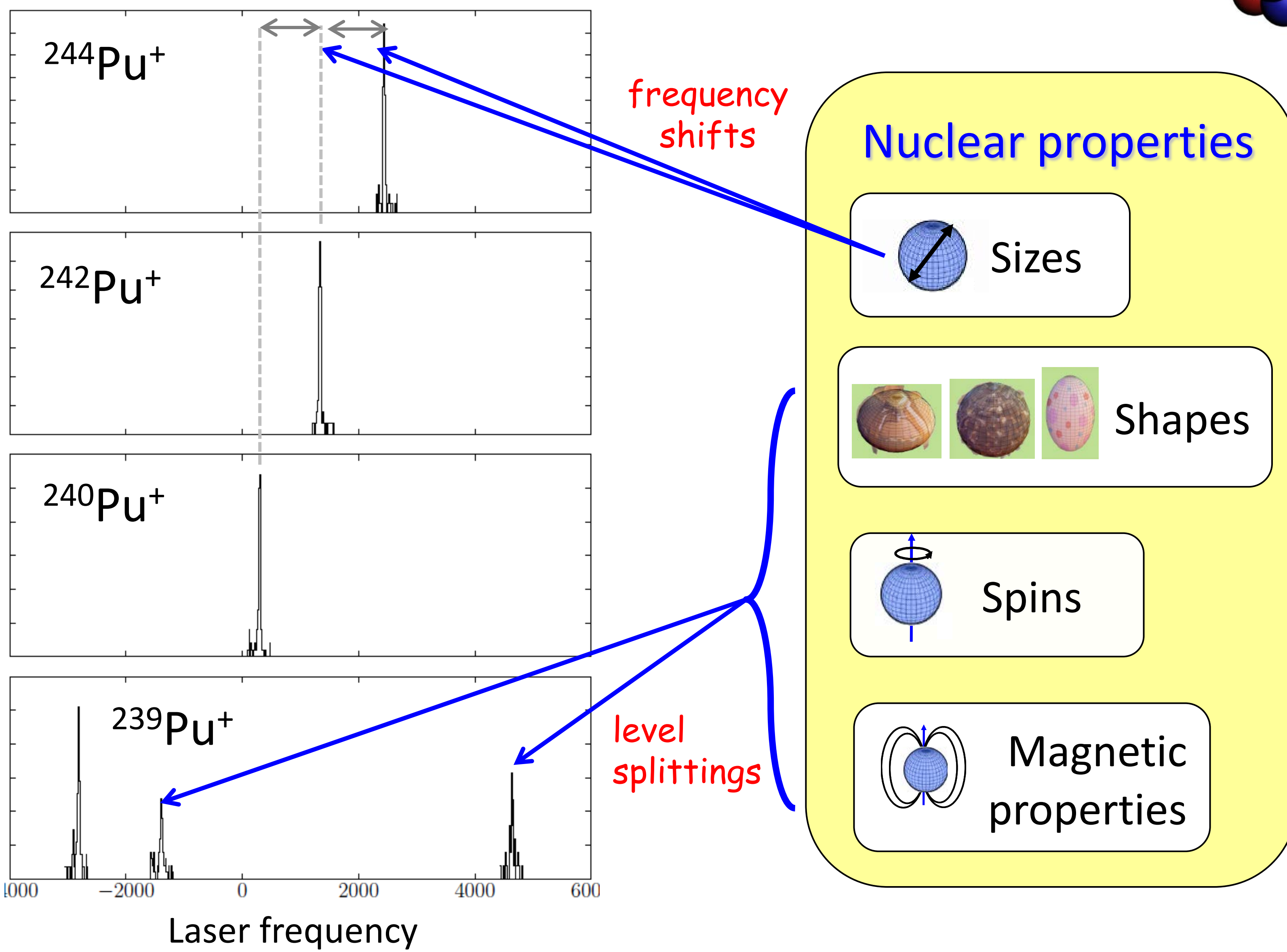
…and for the magnetic moments?

N.J. Stone, Nuclear Data Services, IAEA (2014)

M. Sewtz et al., Phys Rev Lett 90 (2003) 163002
H. Backe et al., Hyp. Int. 162 (2005) 3



Laser spectroscopy: a window to the nucleus



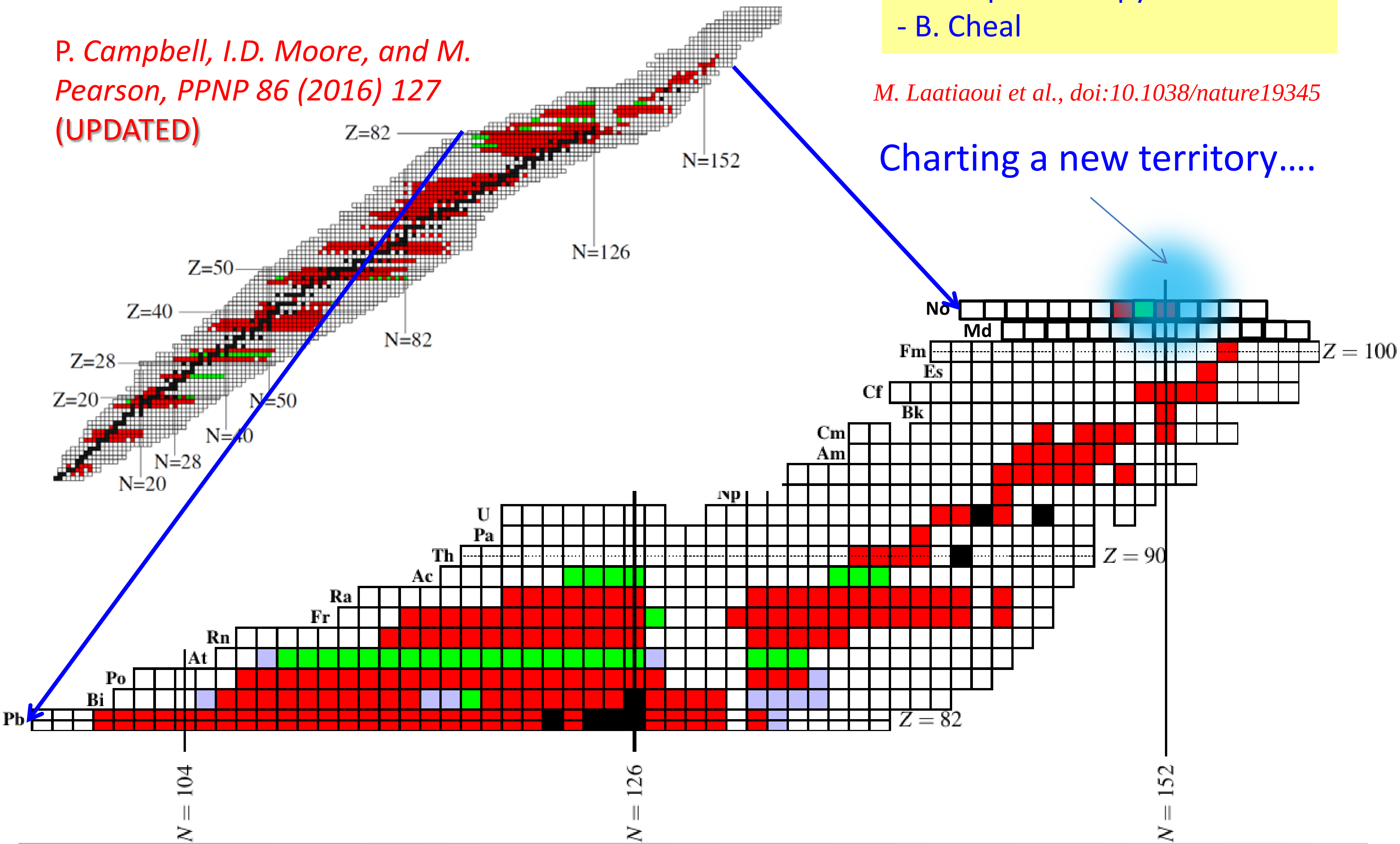
An overview of optical measurements for heavy nuclei

P. Campbell, I.D. Moore, and M. Pearson, PPNP 86 (2016) 127 (UPDATED)

Laser spectroscopy of nobelium - B. Cheal

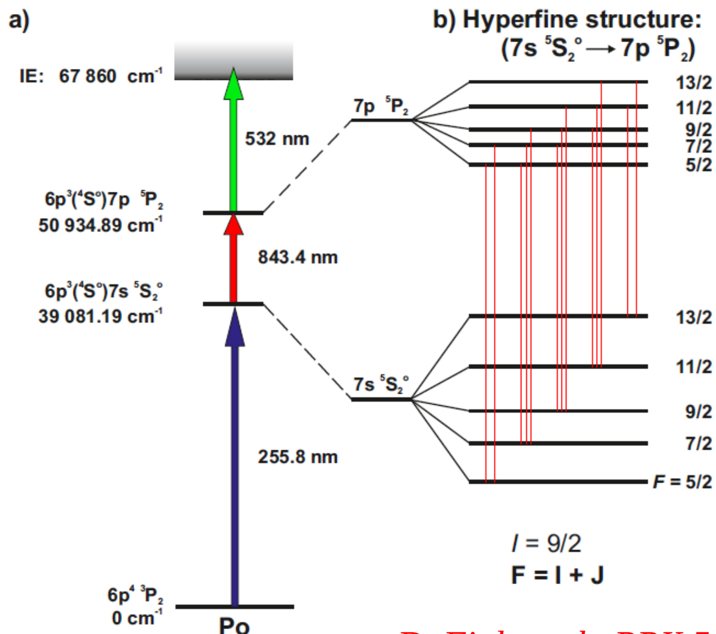
M. Laatiaoui et al., doi:10.1038/nature19345

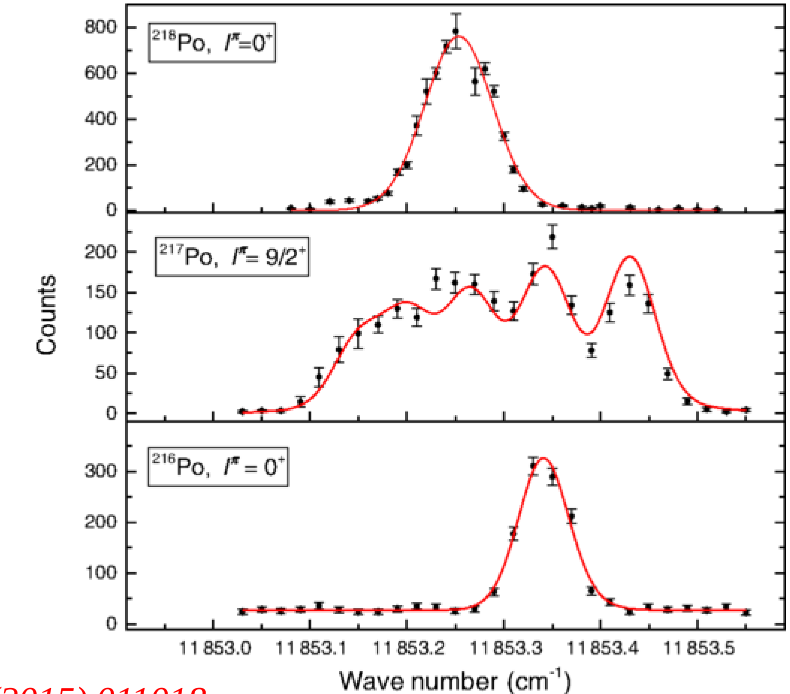
Charting a new territory….



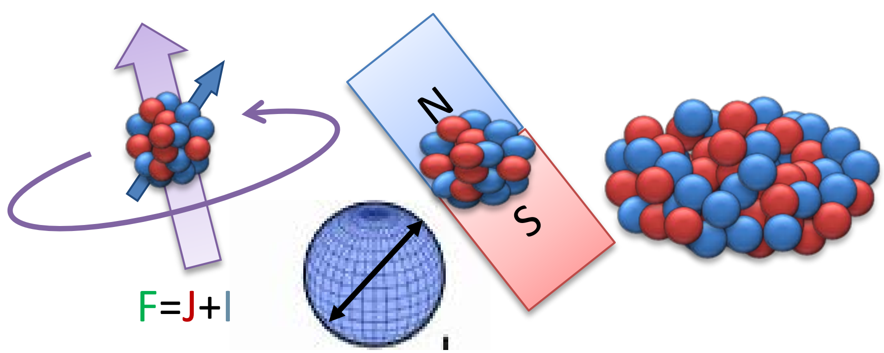
Resonance ionization spectroscopy (RIS)

Po (Z=84)



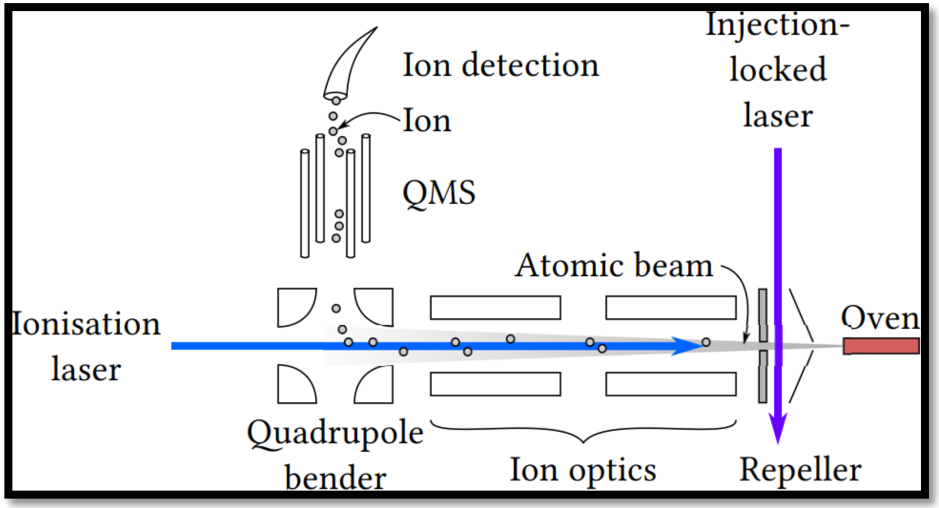


D. Fink et al., PRX 5 (2015) 011018

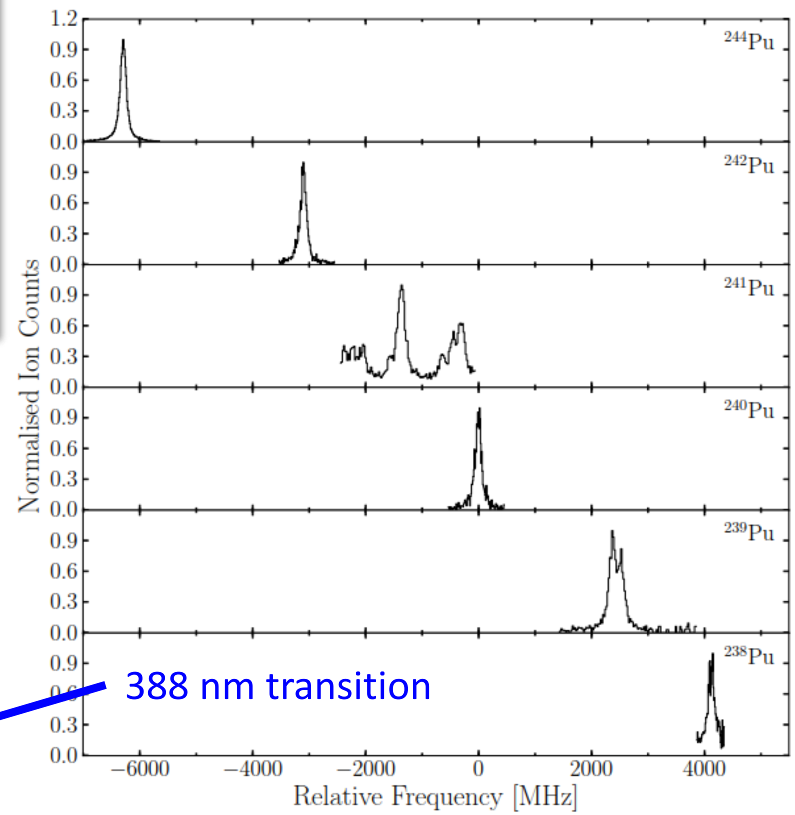


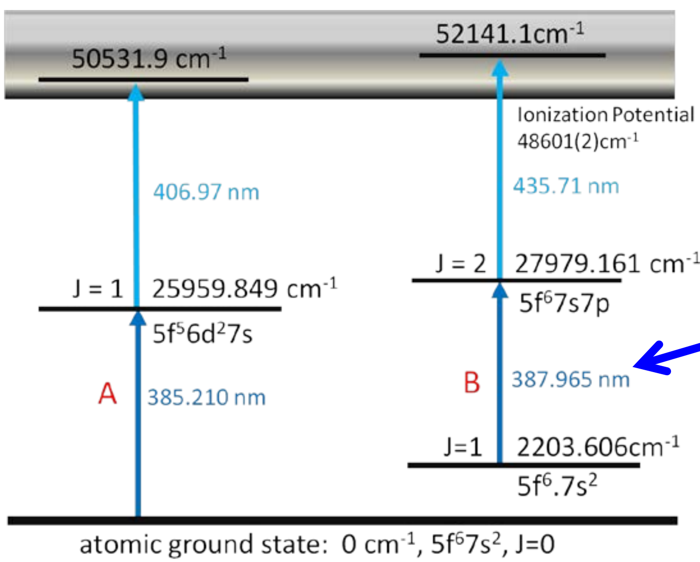
- ☺ Selective process
- ☺ Short lifetimes, low yields (<1 ion/s)
- ☺ High detection efficiency
- ☹ Poor resolution (line broadening)

High-resolution RIS of Pu at Mainz



Atomic HF spectra: 238-242,244Pu





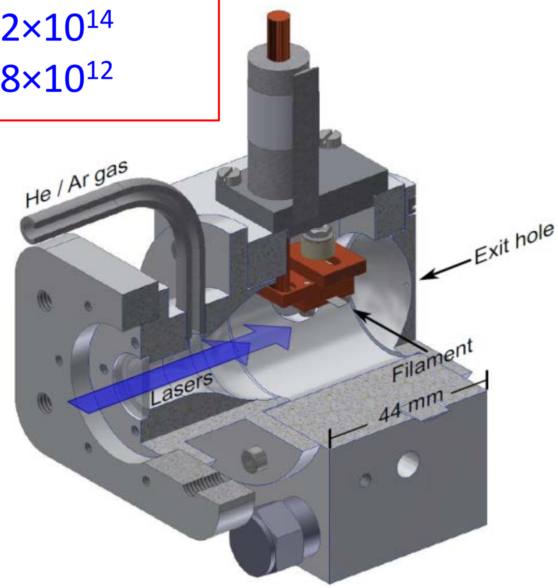
388 nm transition

Transition ``B´´: $5f^67s^2\ ^7F_1 \rightarrow 5f^67s7p$

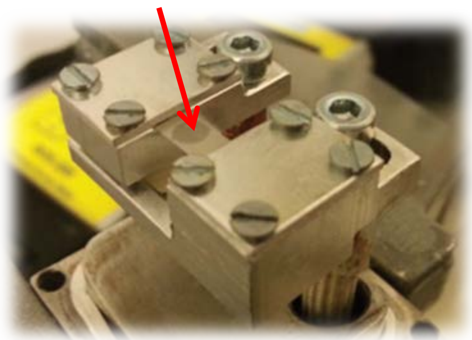
V. Sonnenschein, PhD thesis, University of Jyväskylä (2015)

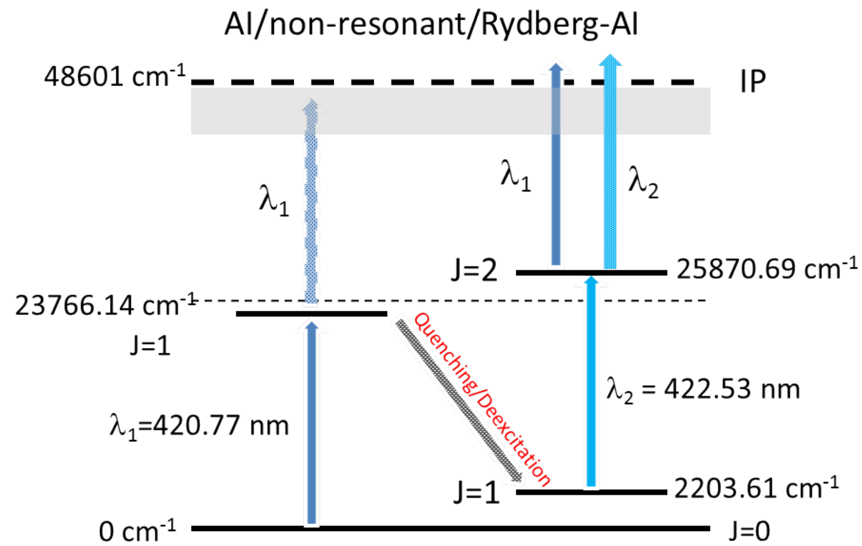
In-gas laser ionization of Pu at JYFL

^{244}Pu ~10^{16} atoms
^{239}Pu ~2×10^{14}
^{238}Pu ~8×10^{12}



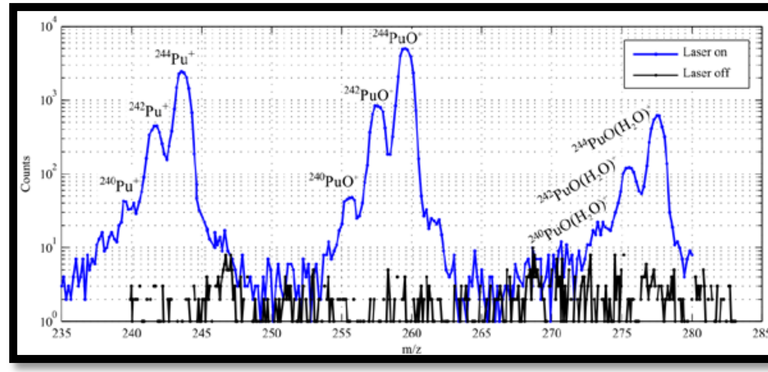
$^{238-242,244}$Pu on tantalum substrate
(~1µm Ti on top): T~1000-1200°C



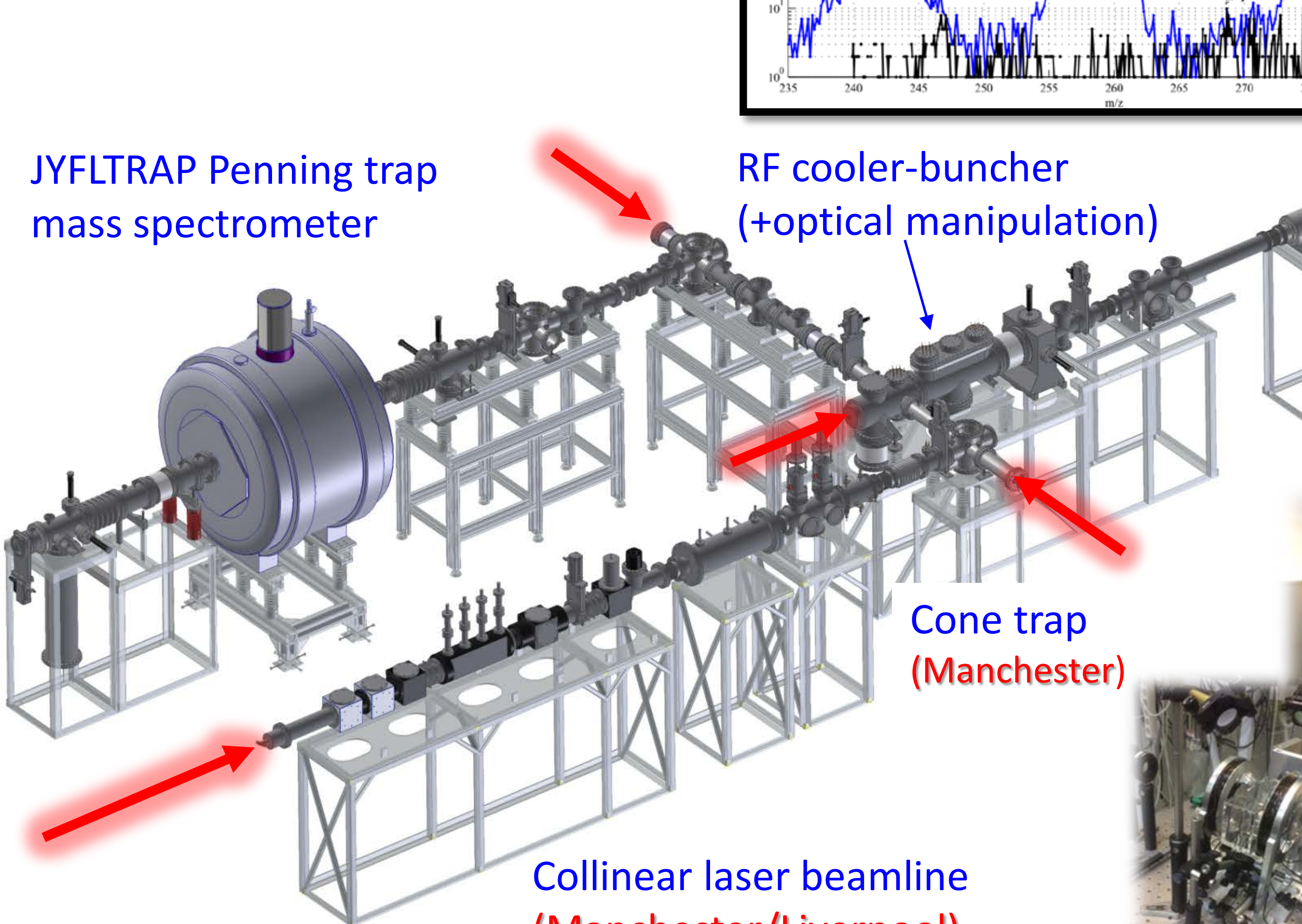


I. Pohjalainen, I.M. et al., NIMB 376 (2016) 233

Layout of IGISOL-4 experimental area



150
AHEAD OF ITS TIME FOR 150 YEARS



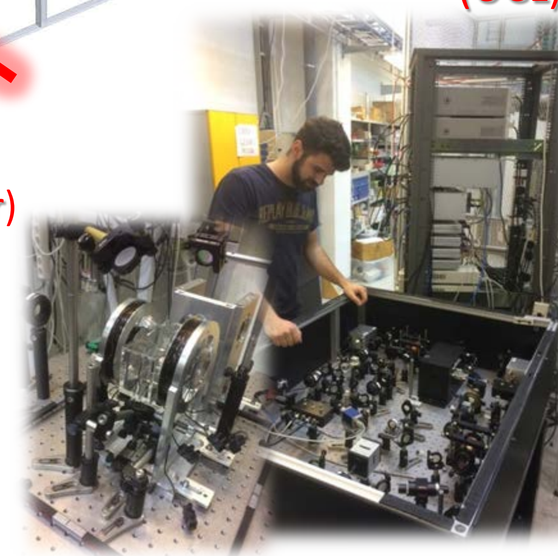
JYFLTRAP Penning trap mass spectrometer

RF cooler-buncher (+optical manipulation)

Atom trap/BEC (UCL)

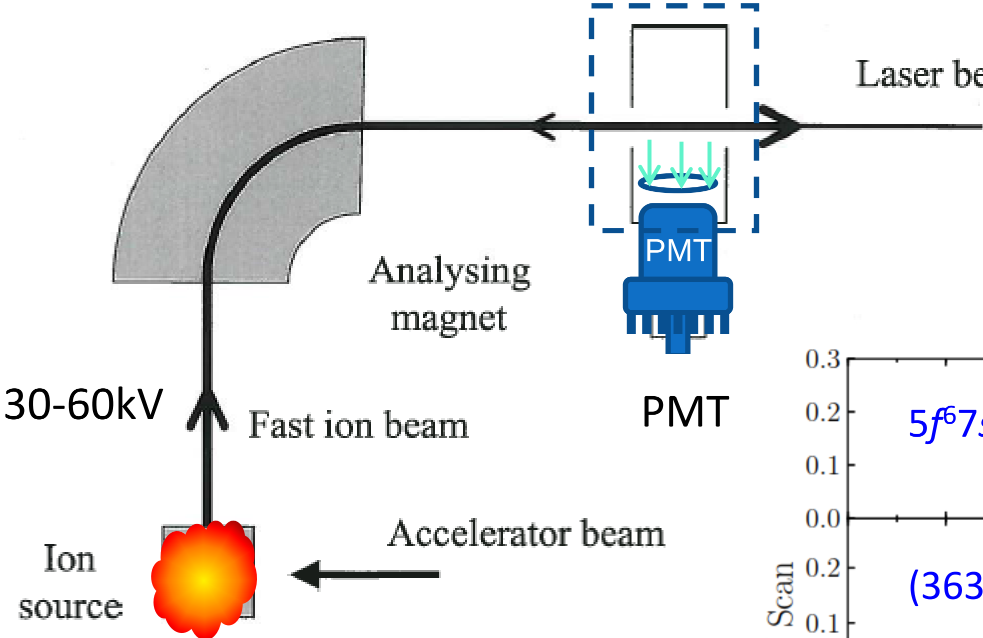
Cone trap (Manchester)

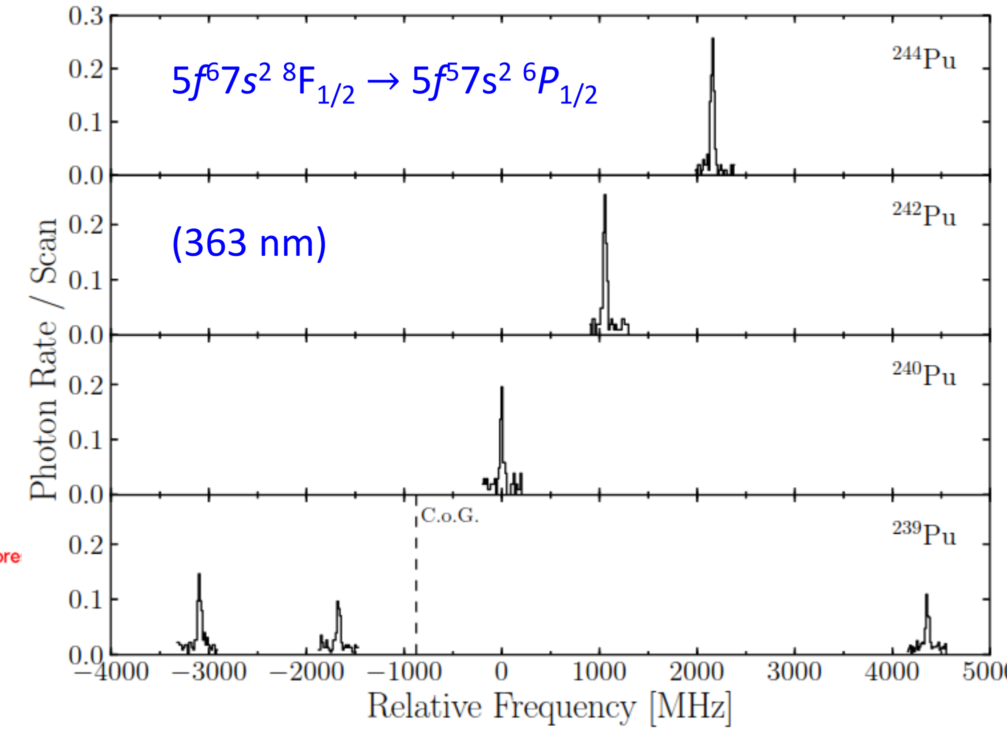
Collinear laser beamline (Manchester/Liverpool)

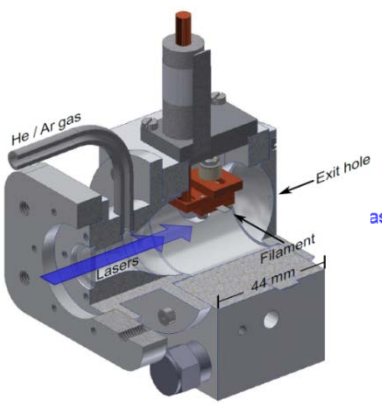


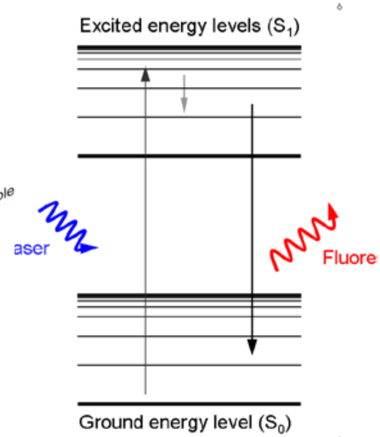
Collinear spectroscopy of Pu^+ at IGISOL

AHEAD OF ITS TIME FOR 150 YEARS







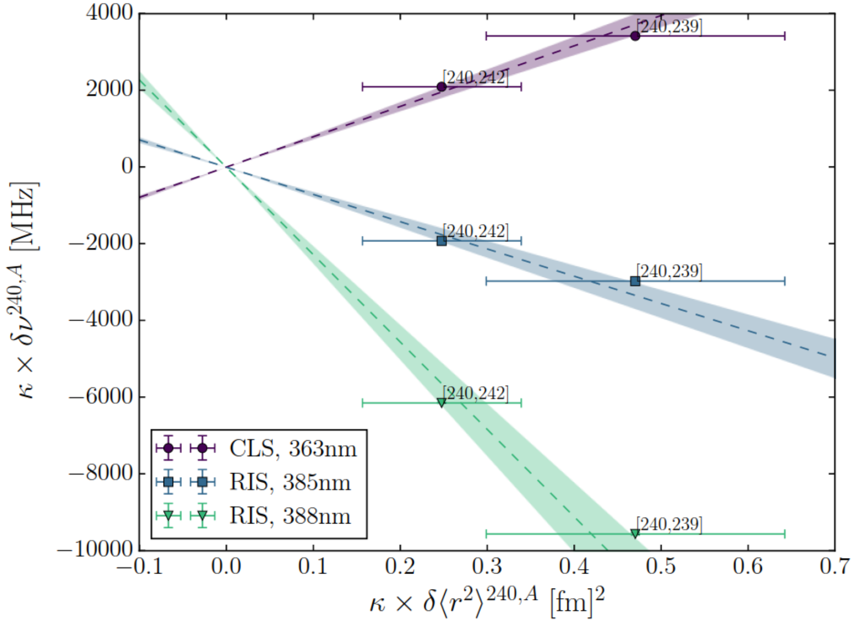


Extraction of nuclear information

AHEAD OF ITS TIME FOR 150 YEARS

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

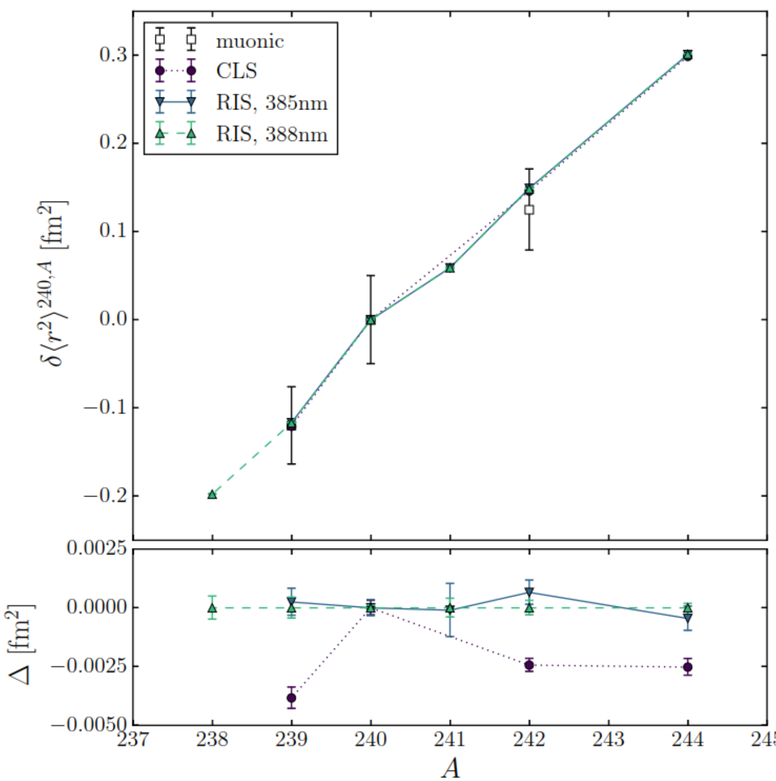
King plots of isotope shifts vs. δ<r²>



<u>Calibration of atomic factors:</u>

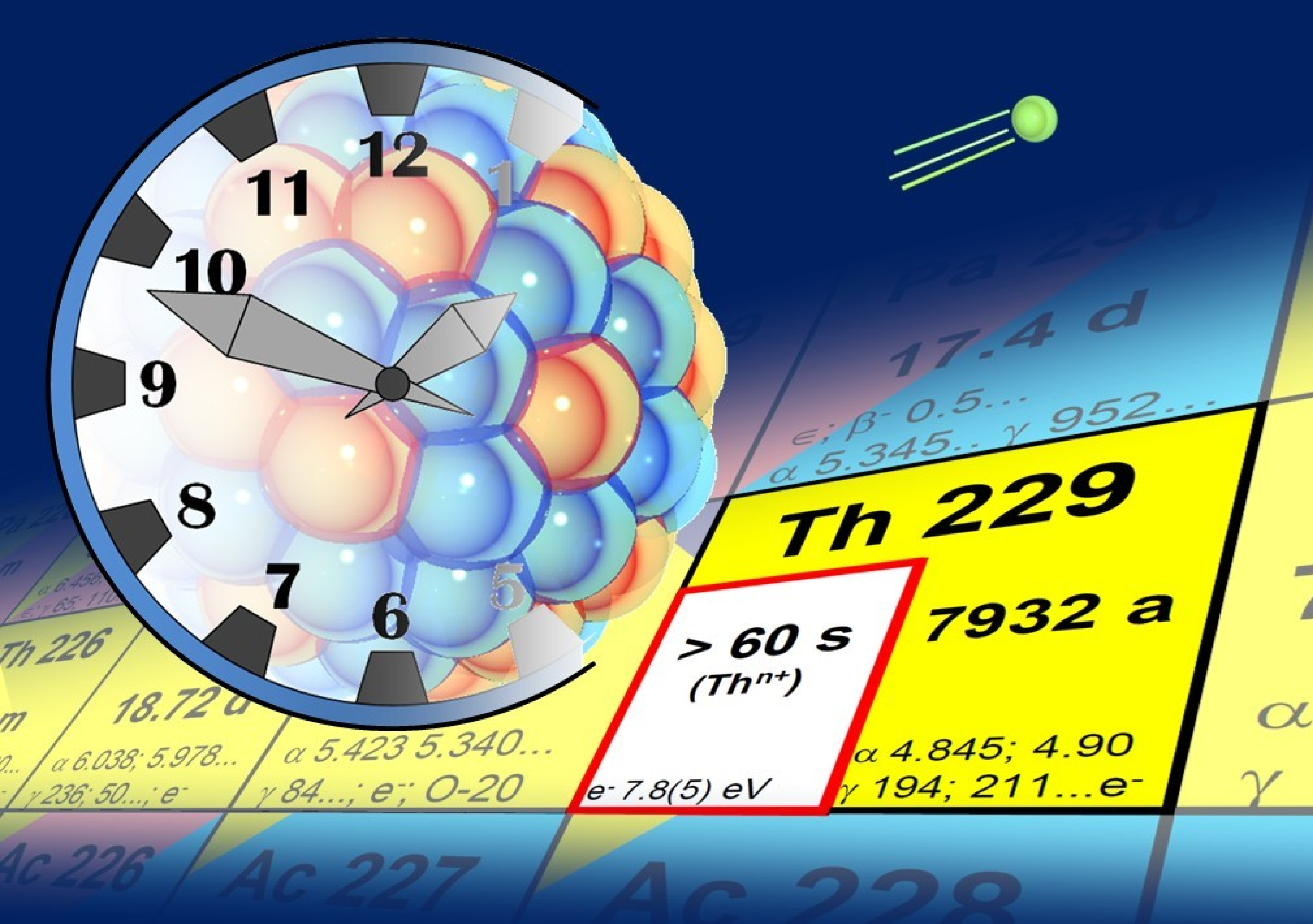
- F_{385nm} = -7.1(7) GHz/fm^2
- F_{388nm} = -22.8(23) GHz/fm^2
- F_{363nm} = +7.9(6) GHz/fm^2

δ<r²> from optical and X-rays from muonic atoms



Discrepancy seen between techniques – under discussion (complete error budget)

A. Voss et al., to be submitted to PRA (2016)



Christoph Düllman, JGU Mainz

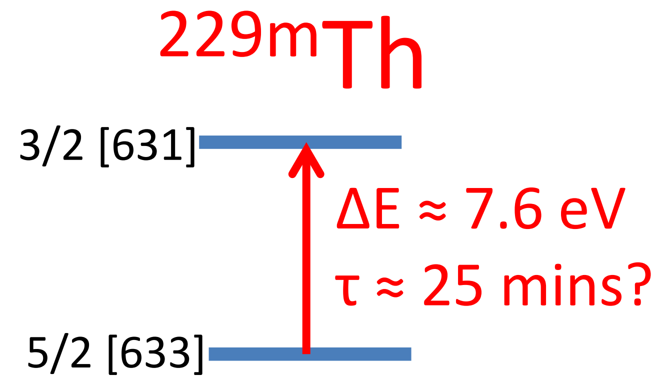
^{229}Th and the low-lying isomeric state

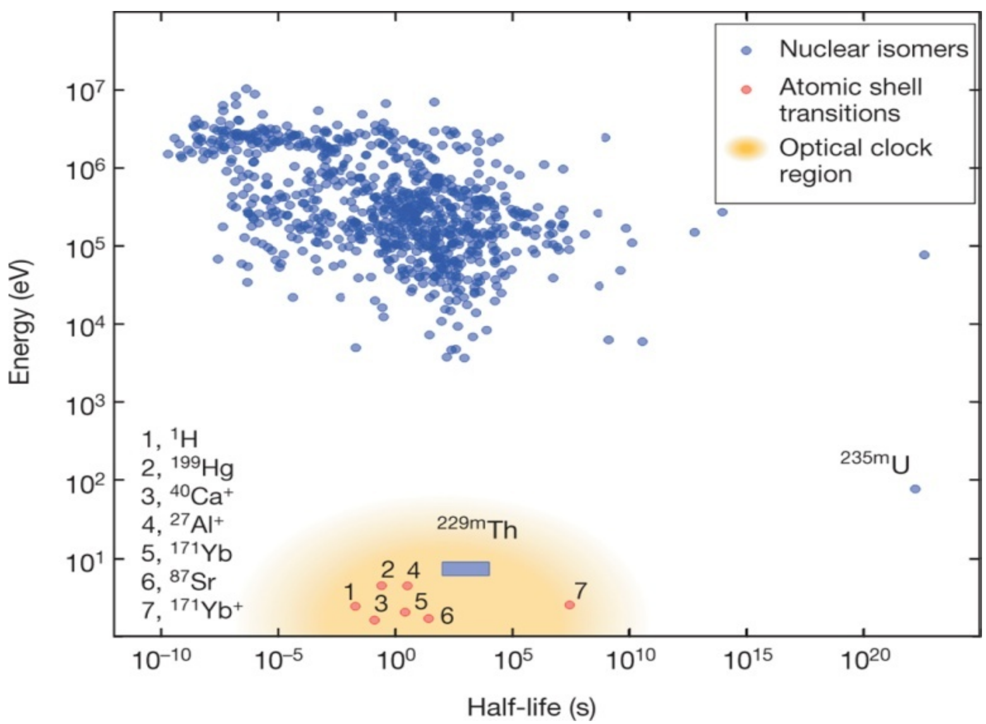

ARTICLE

doi:10.1038/nature17669

Direct detection of the ^{229}Th nuclear clock transition

Lars von der Wense[1], Benedict Seiferle[1], Mustapha Laatiaoui[2,3], Jürgen B. Neumayr[1], Hans-Jörg Maier[1], Hans-Friedrich Wirth[1], Christoph Mokry[3,4], Jörg Runke[2,4], Klaus Eberhardt[3,4], Christoph E. Düllmann[2,3,4], Norbert G. Trautmann[4] & Peter G. Thirolf[1]





ΔE ≈ 6.3 – 18.3 eV

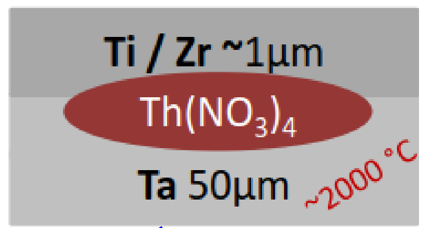
<u>Impact</u>

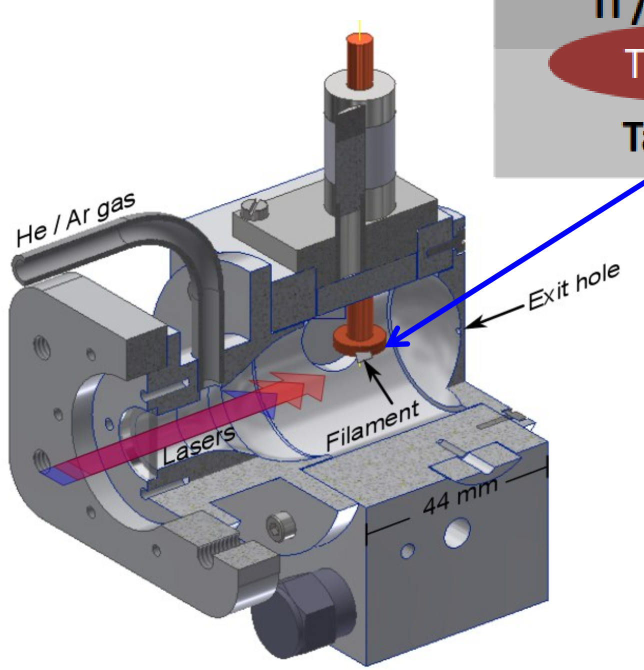
- Nuclear clock
- Gamma ray laser
- Qubit
- Test of fundamental constants
- NEET

Laser ionization of thorium at JYFL

OBJECTIVES:

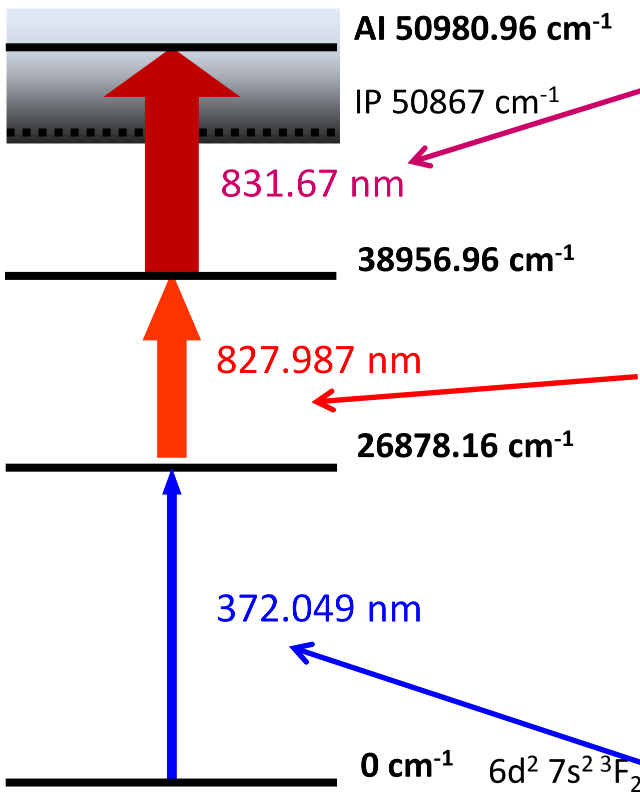
a) Identify and characterize the ^{229}Th isomer transition
b) Implement key components to operate a nuclear clock

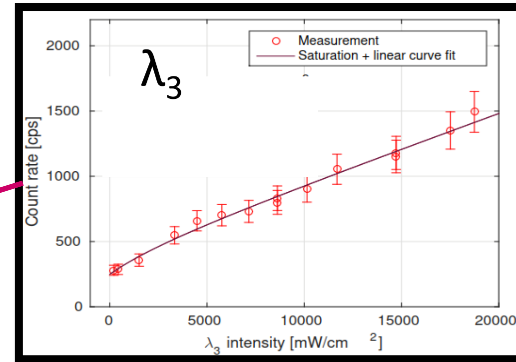


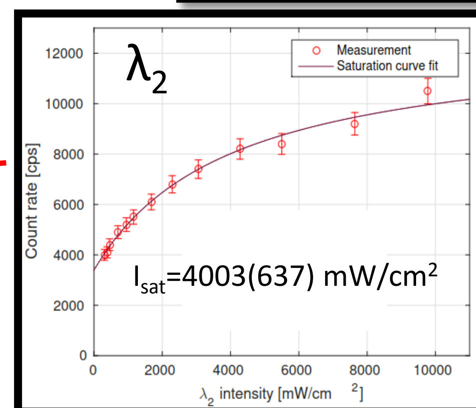


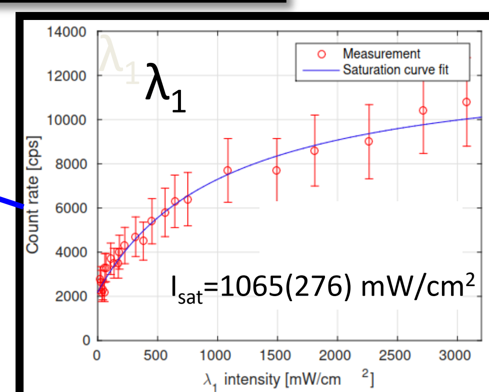
^{232}Th ~10^{15} atoms

Characterizing the ionization scheme





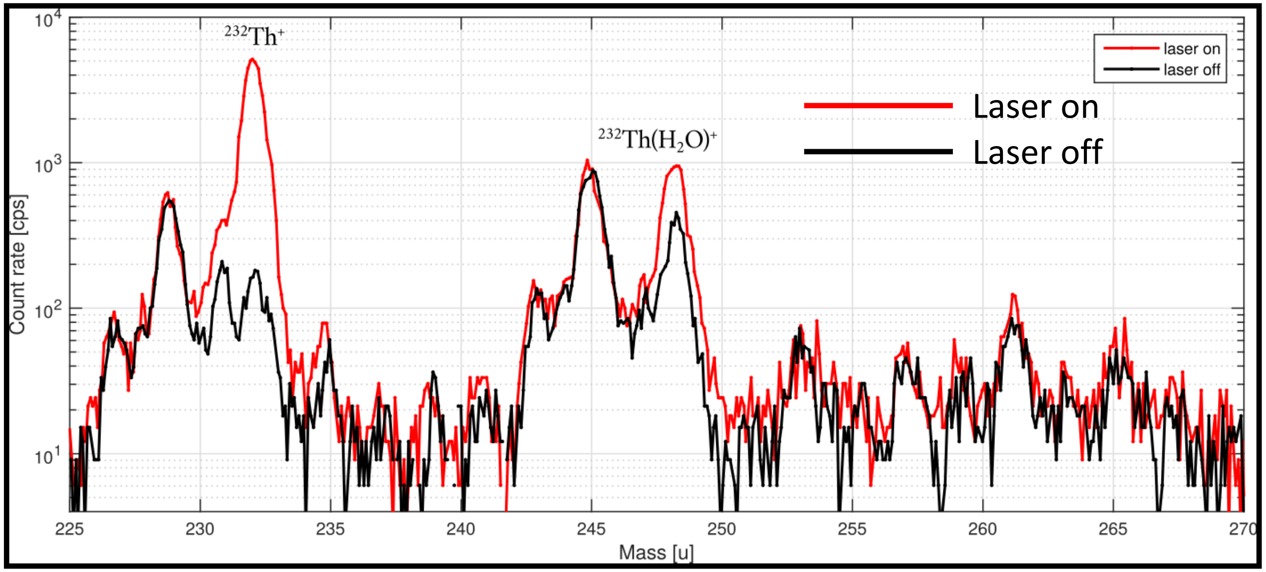




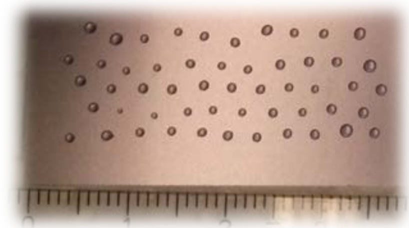
Y. Liu and D. Stracener, NIMB 376 (2016) 233

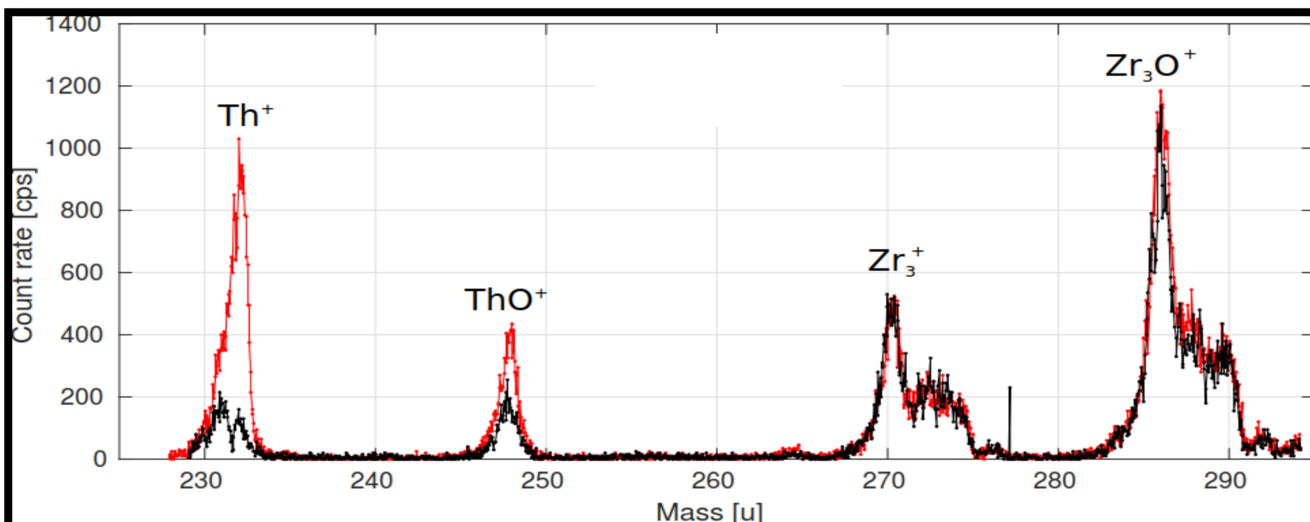
I. Pohjalainen et al., manuscript under preparation

Mass separator scans (Th with Ti/Zr coatings)

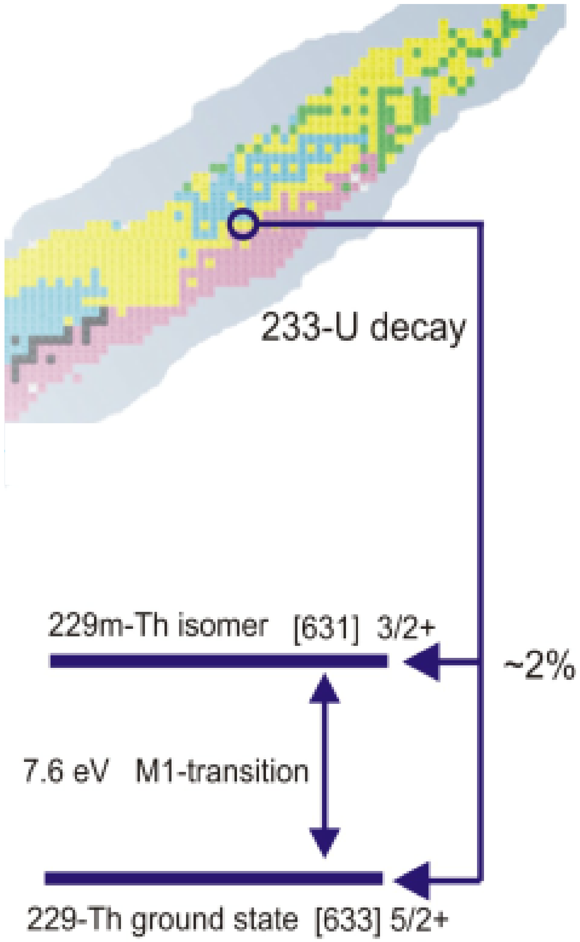


^{232}Th on tantalum substrate (~1µm Ti on top): T~1800-2000°C

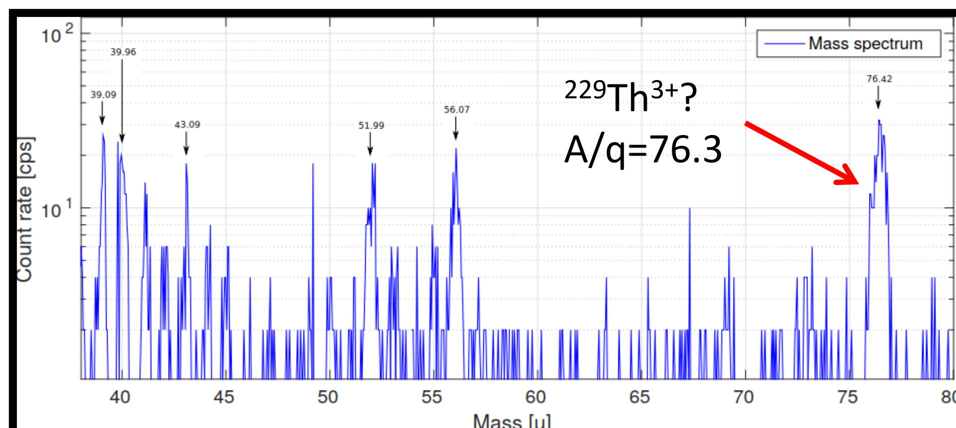




Populating the isomer via ^{233}U α decay



- 200 kBq $^{233}UF_4$ evaporated onto 20 mm ϕ steel
- ~10000 ^{229}Th α-recoil ions/s leaving source
- α-recoil ions stopped in ultra-pure He gas
- charge exchange forms $^{229}Th^{3+}$



Summary + Outlook

- New programme of high-resolution laser spectroscopy on actinide elements (ng of material)
- HR-RIS and collinear laser spectroscopy on Pu isotopes: comparison of techniques; extraction of HF factors and changes in mean-square charge radii; heaviest element using CLS to date
- Preparations towards ^{239}Pu ”target” – α-recoil source with 100% branching ratio into ^{235m}U isomeric state
- Awaiting ^{229}Th samples from Vienna – ground state hyperfine template
- ^{233}U source from Munich – production of ^{229m}Th isomer
- On-line production – ^{232}Th(p,p3n)^{229g,m}Th at 50 MeV

Thanks to all collaborators on these projects & for your attention ☺