Optical spectroscopy for nuclear and atomic science at JYFL, Finland

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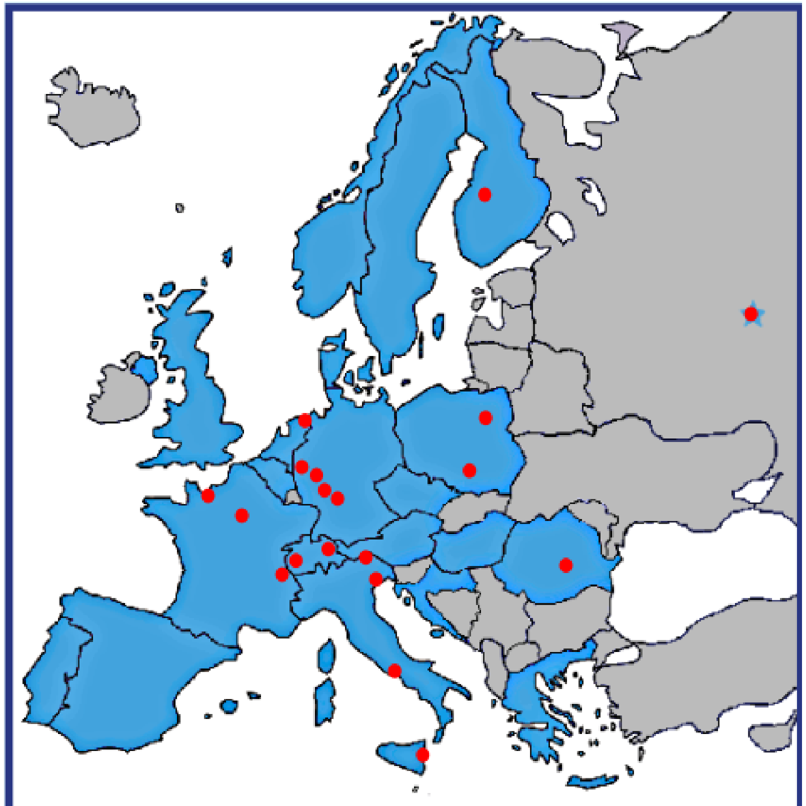
Outline

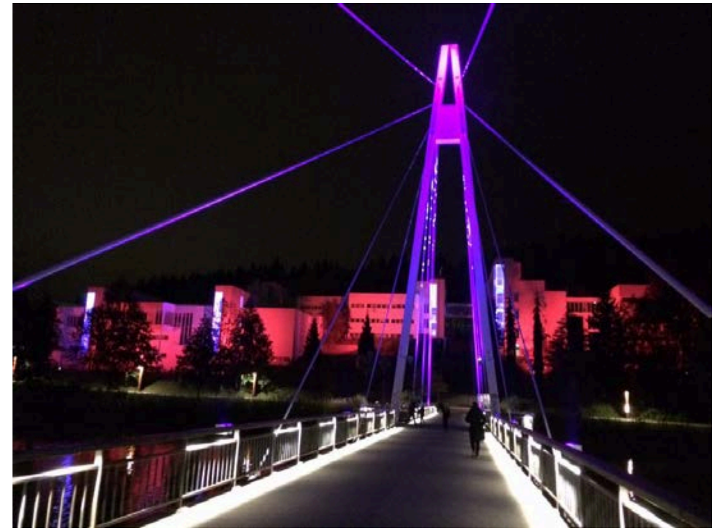
- Introduction to the JYFL Accelerator Lab
- Optical spectroscopy
- Spectroscopy of heavy elements
  - techniques
  - results (Ac, Pu)
- ^{229}Th and the nuclear clock transition
- Summary

European research infrastructures



● From North to South:
JYFL (Jyväskylä, Finland), **JINR** (Dubna,Russia),
KVI-CART (Groningen, The Netherlands), **HIL** (Warsaw, Poland),
GANIL (Caen, France), **COSY** (Jülich, Germany), **ELSA** (Bonn, Germany),
MAMI (Mainz, Germany), **GSI** (Darmstadt, Germany), **ALTO** (Orsay, France),
CCB (IFJ, PAN Kraków, Poland), **ILL** (Grenoble,France),
CERN (Genève, Switzerland), **PSI** (Villingen, Switzerland),
ECT* (Trento, Italy), **LNL-INFN** (Legnaro, Italy), **IFIN-HH** (Bucharest, Romania),
LNF-INFN (Frascati, Italy), **LNS-INFN** (Catania, Italy)

http://www.nupecc.org/



- University laboratory
- Academy of Finland Centre of Excellence
- Horizon 2020 Access facility
- National status as Centre of Expertise
- Only national infrastructure on the roadmap (2017-2020) in ”Natural Sciences and Technology”
- Accredited test laboratory for ESA
- About 80 staff (Professors, Researchers, students)
- Average about 5 PhD’s / year (in-house)
- Total budget (salaries, rent, etc) ~5 M€

Accelerator facilities at JYFL

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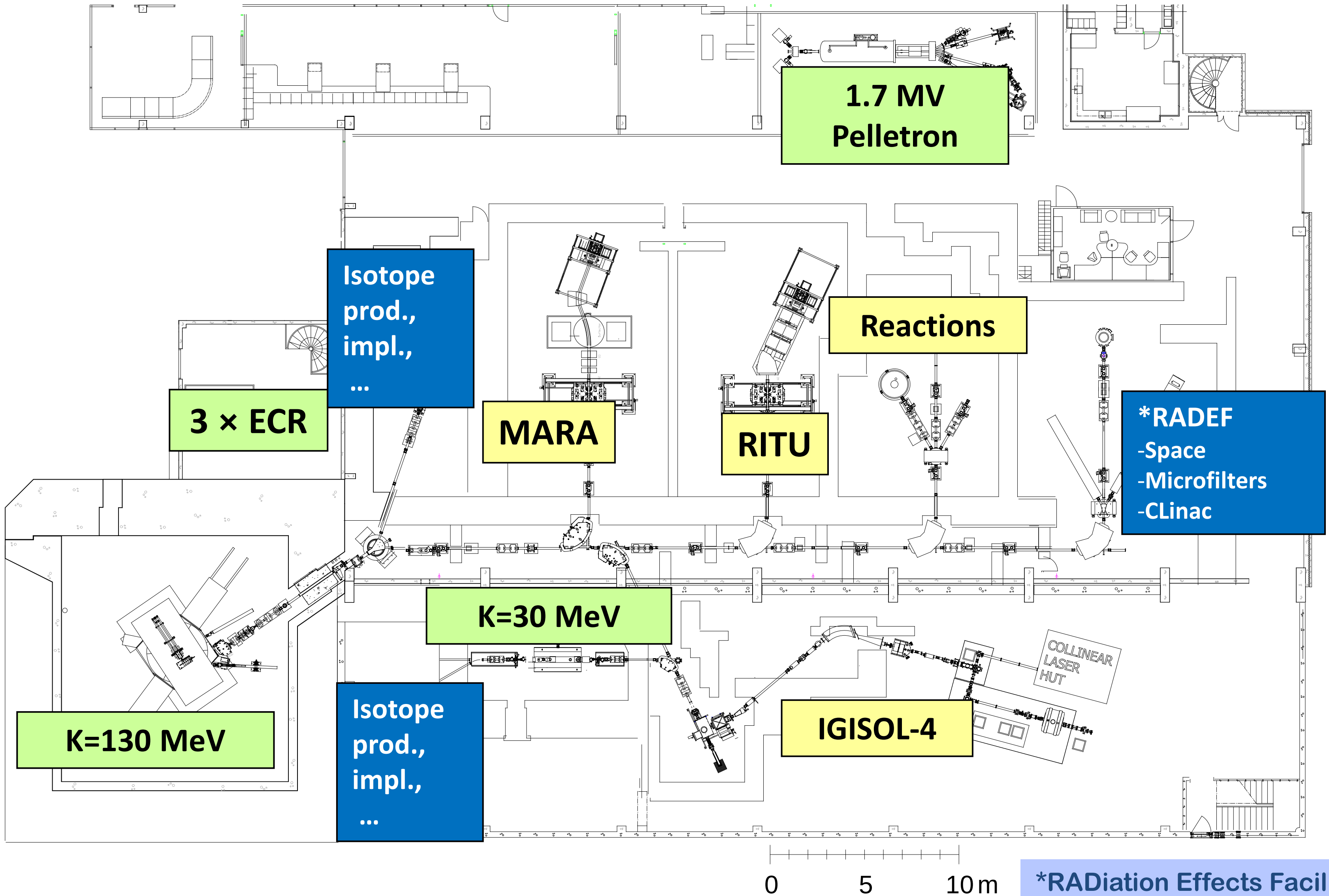
K130 – accelerates p to Xe
E = Q^2/A 130 MeV
Ion sources:
6.4 GHz ECRIS, 14 GHz ECRIS
Multicusp (H^-, D^-)
2016-2017 – 18 GHz ECRIS

Electron linac
Electrons: 6,9,12,16 or 20 MeV
Brehmstrahlung X-rays 6 or 15 MeV

MCC30/15
H^- 18-30 MeV
d^- 9-15 MeV
Beam current 200/62 μA
New RF ion source
Users: IGISOL
Radioisotope prod.

Pelletron
H, He, Cl, Cu, Br, I, + other heavy ion beams;
0.2 – 20 MeV; 4 beam lines available

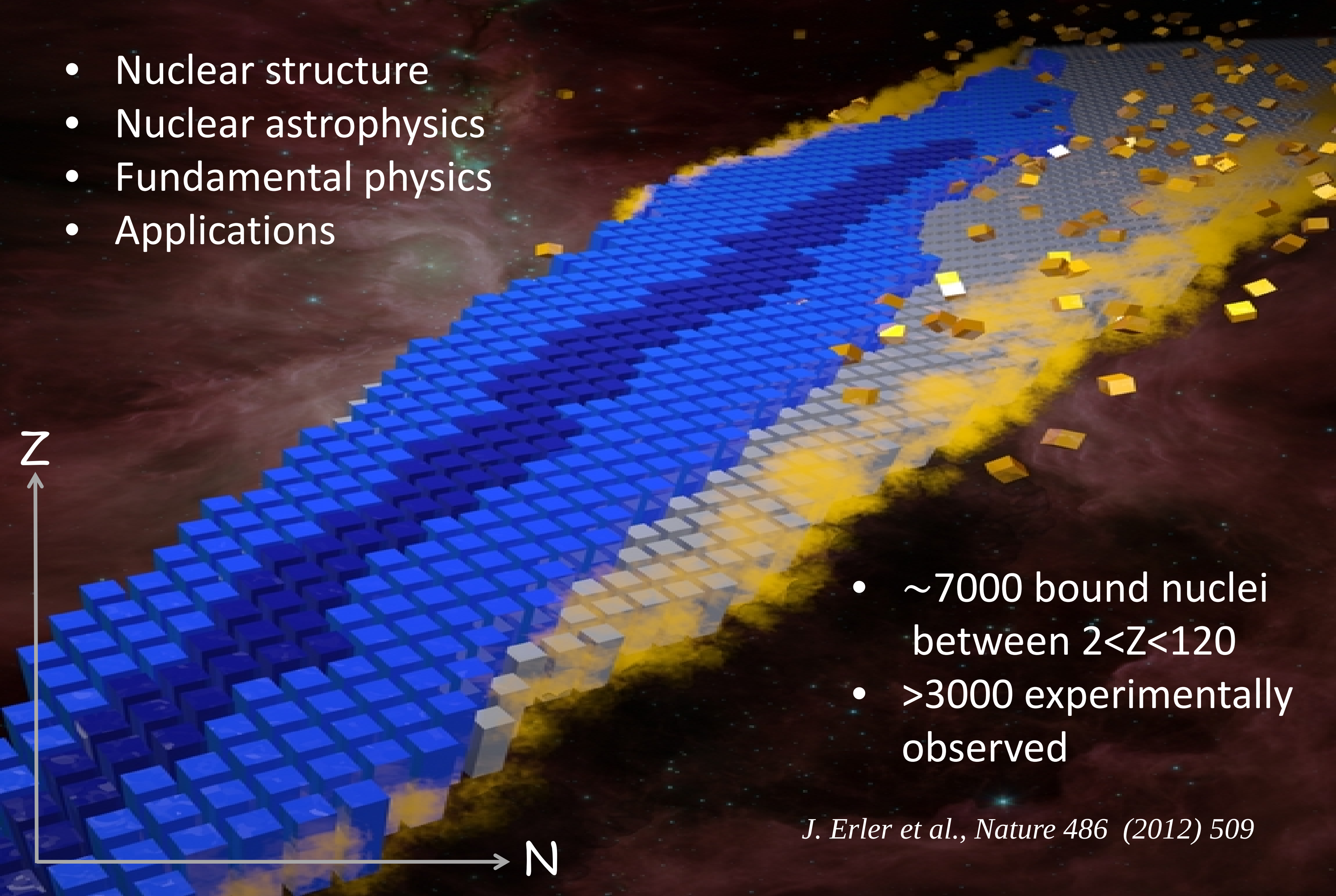
Accelerator Laboratory today



*RADiation Effects Facility

The nuclear physicists playground

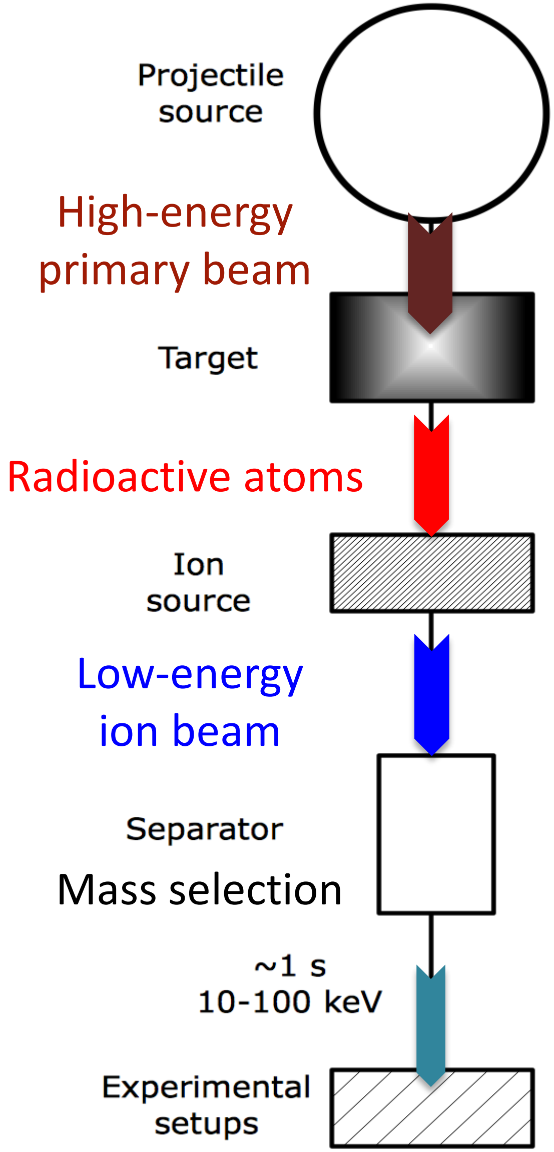
- Nuclear structure
- Nuclear astrophysics
- Fundamental physics
- Applications

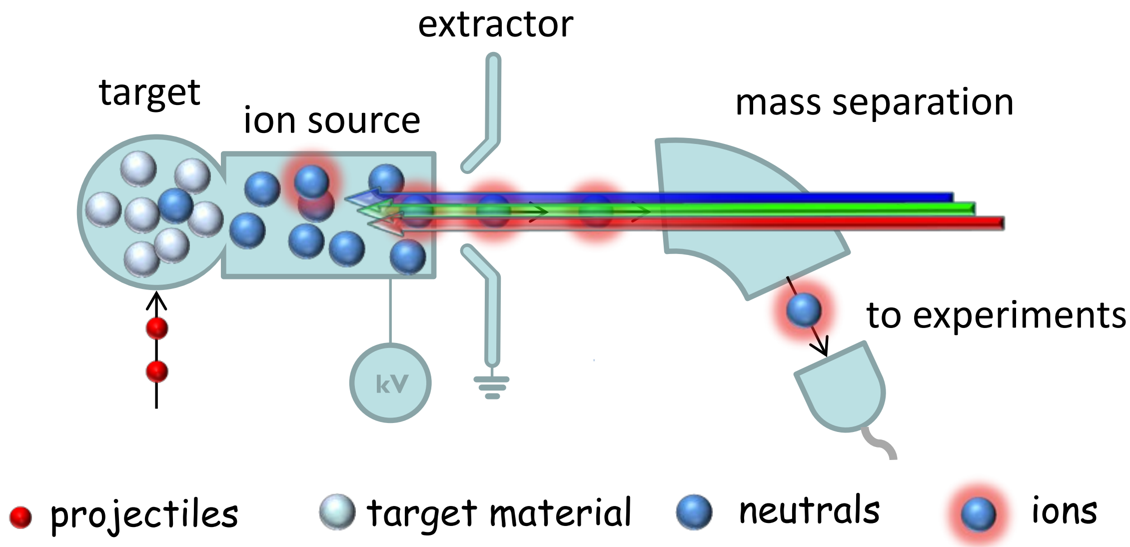


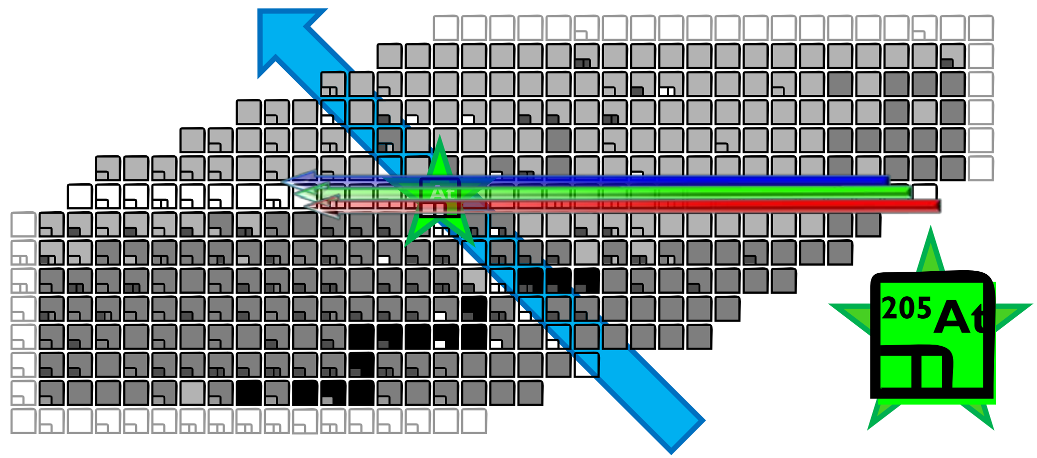
- ~7000 bound nuclei between 2<Z<120
- >3000 experimentally observed

J. Erler et al., Nature 486 (2012) 509

The Isotope Separation On-Line method







+ ^{205}Pb, Bi, Po, Rn, Fr etc

The (IG)ISOL method of RIB production

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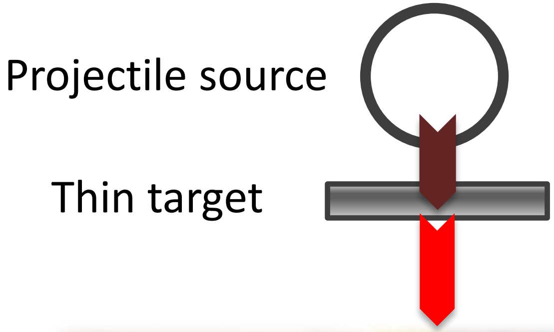
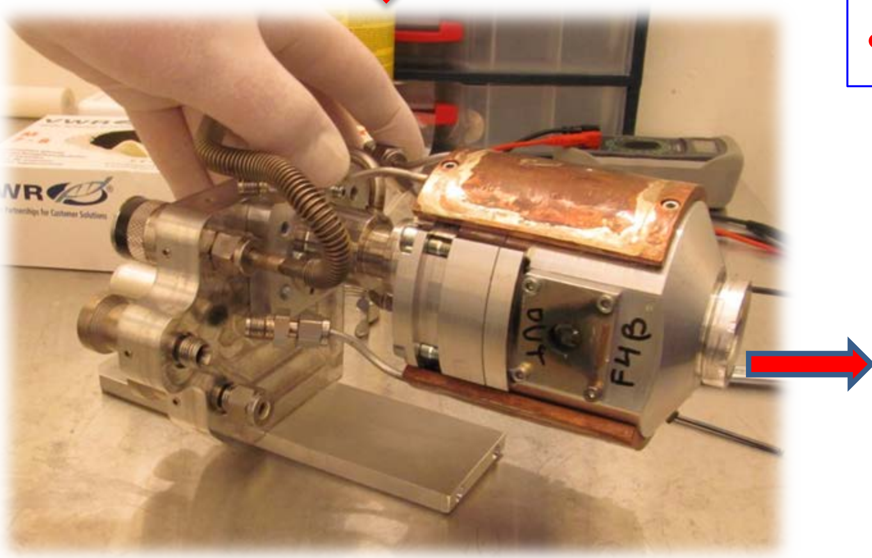




=

+

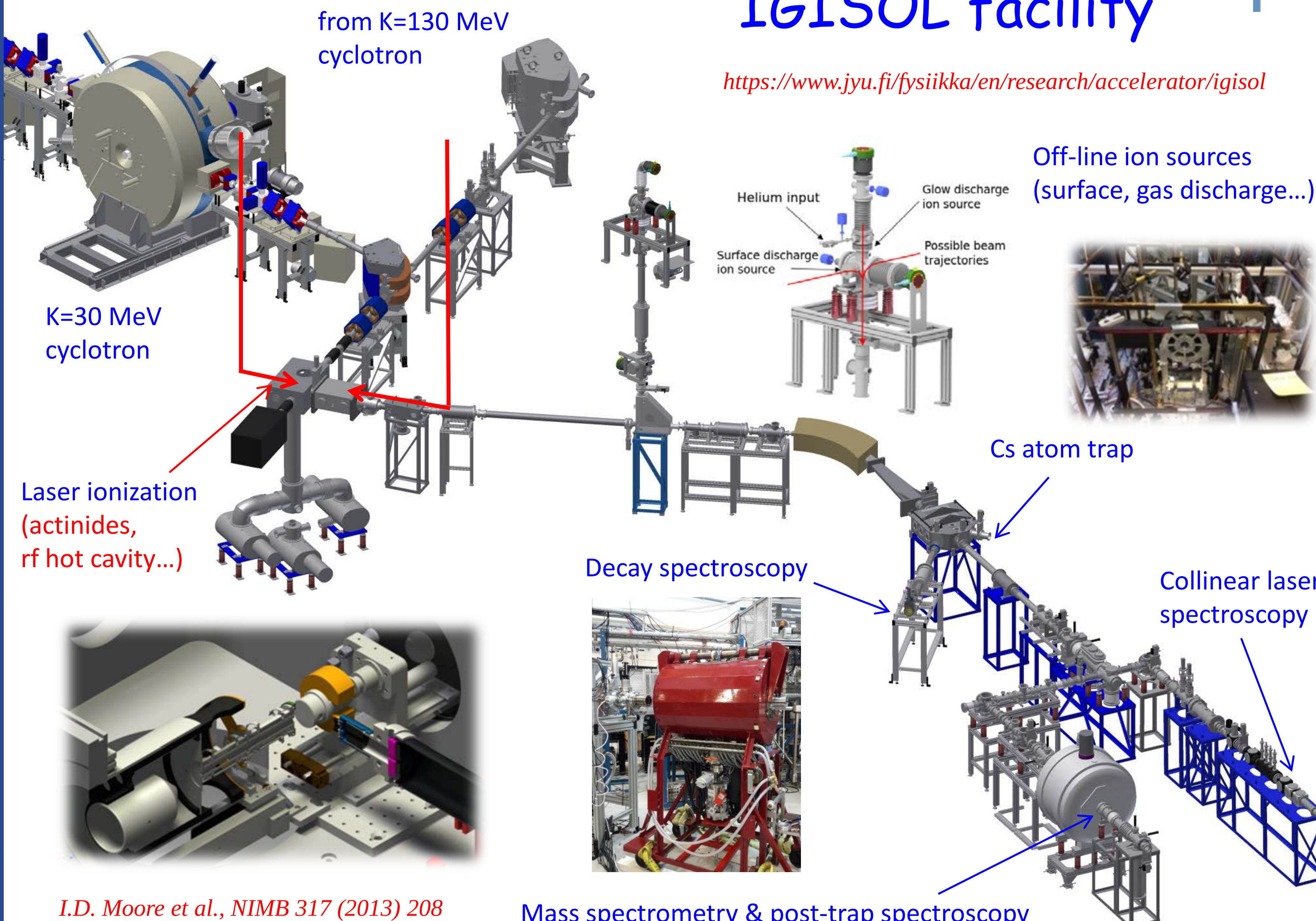
- An ISOL system for ALL elements
- Fast extraction (~ms)
- Relatively low efficiency
  - ~1-2% light-ion reactions
  - ~0.1% fission
- Poor selectivity

- Ion survival → ion guide method (non-selective)
- Neutralization → laser re-ionization (*Z* selectivity)

I.D. Moore et al., Hyp. Int. 223 (2014) 17

IGISOL facility

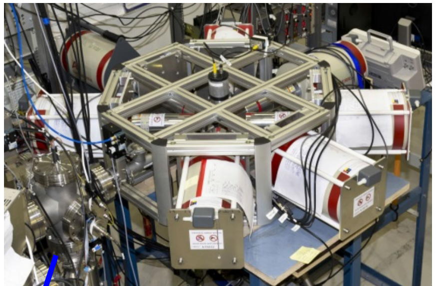
https://www.jyu.fi/fysiikka/en/research/accelerator/igisol

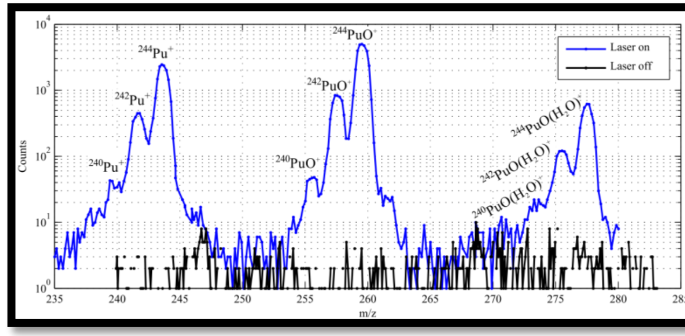


I.D. Moore et al., NIMB 317 (2013) 208

Experimental area

JYFLTRAP Penning trap
(mass measurements)





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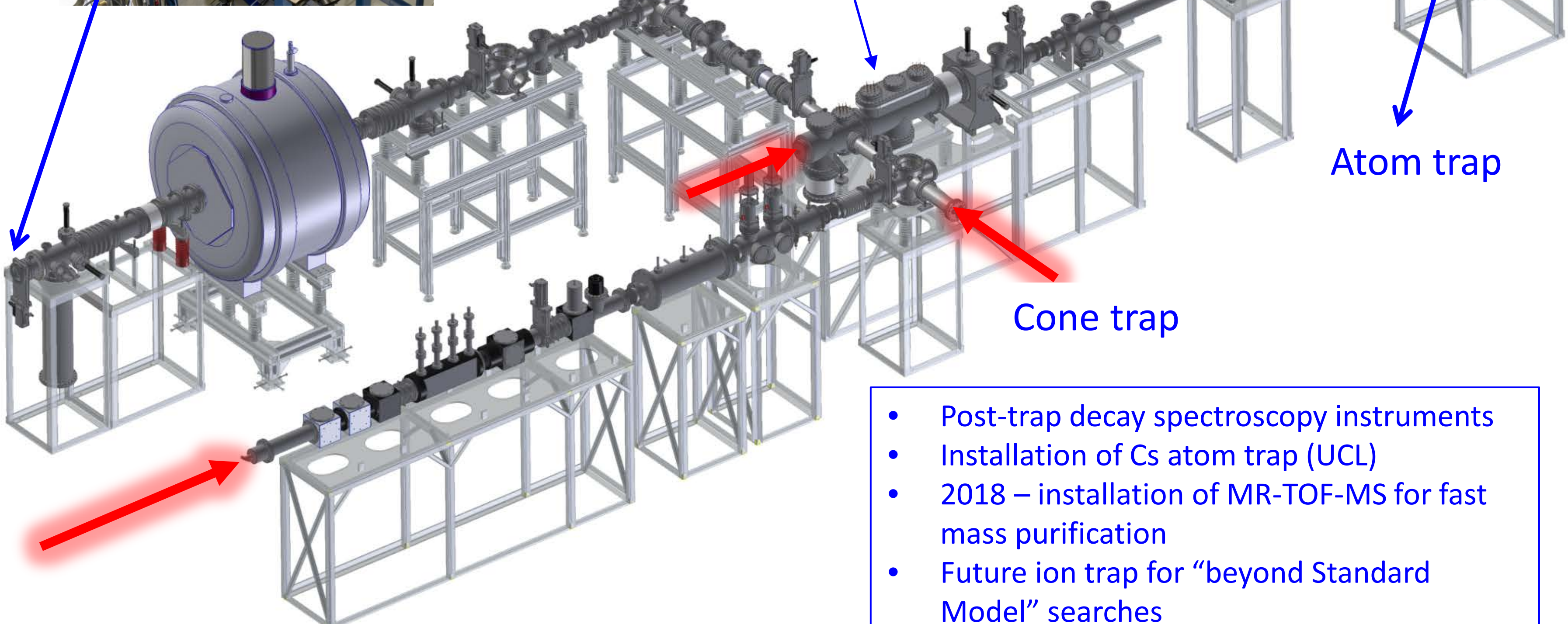


RF cooler-buncher
(+optical manipulation)

Atom trap

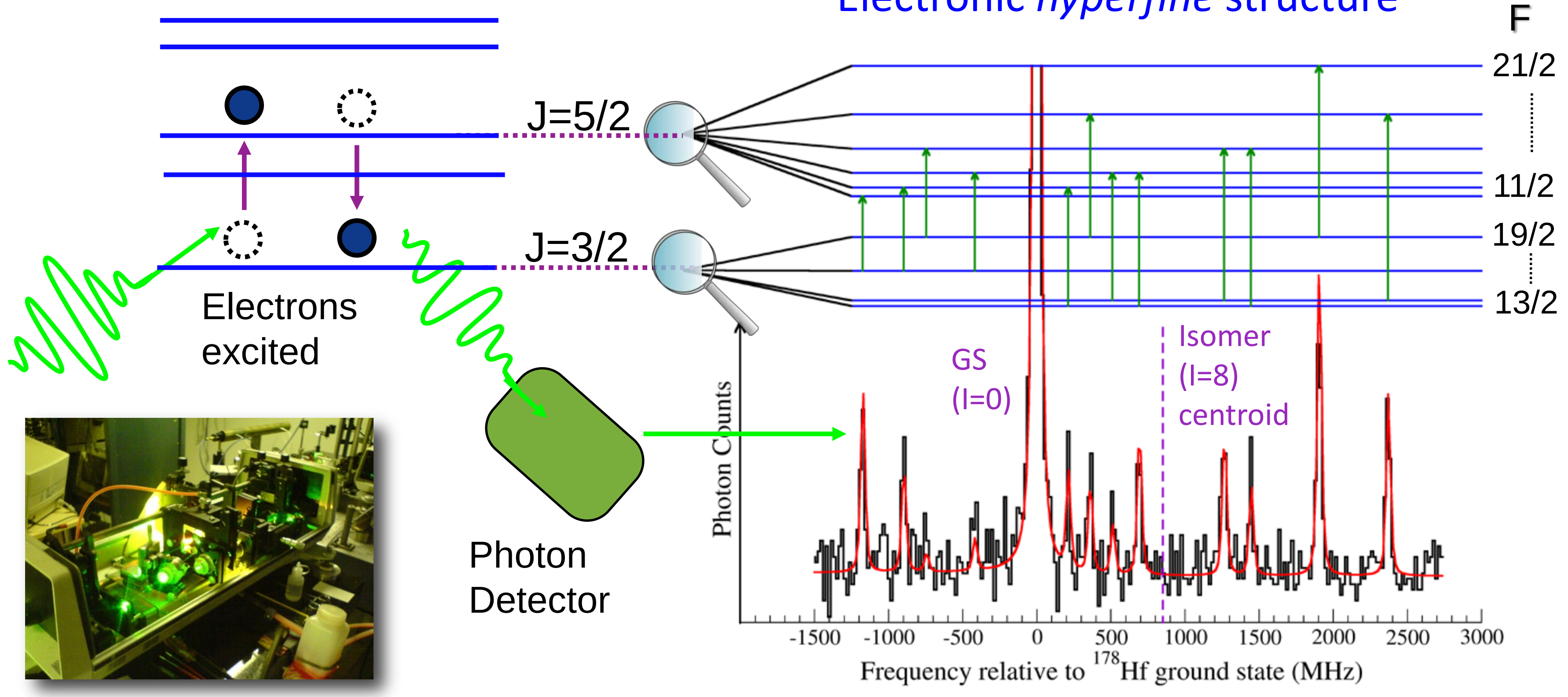
Cone trap

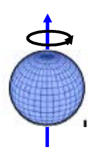
- Post-trap decay spectroscopy instruments
- Installation of Cs atom trap (UCL)
- 2018 – installation of MR-TOF-MS for fast mass purification
- Future ion trap for "beyond Standard Model" searches

Collinear laser beamline (Manchester/Liverpool)

What is optical (laser) spectroscopy?

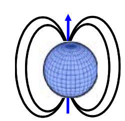
Electronic *hyperfine* structure





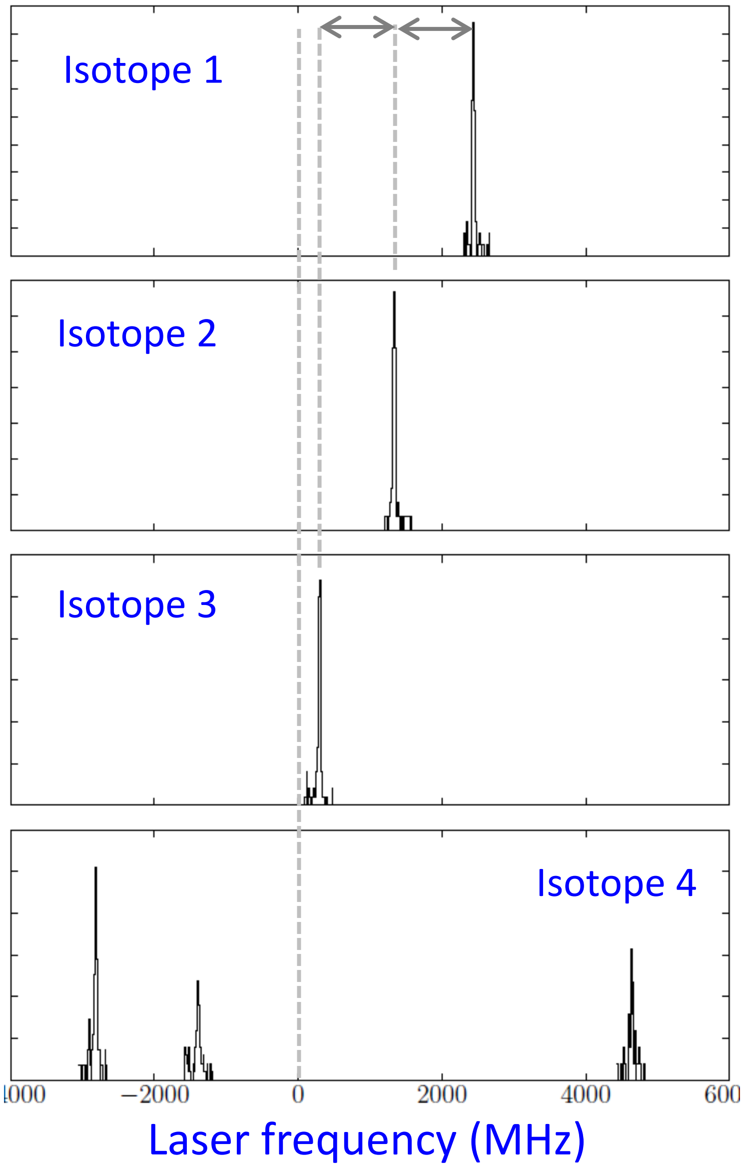
Nuclear spin, I

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



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

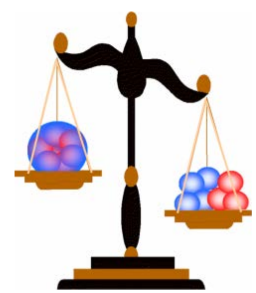
Isotopic shifts of electronic transitions

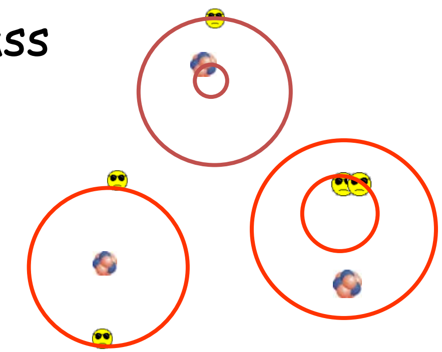


= Frequency difference in an electronic transition between two isotopes

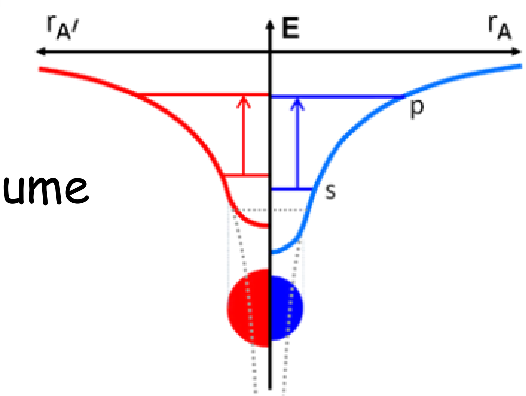
$$\delta\nu^{AA'} = \nu^{A'} - \nu^{A}$$

Finite nuclear mass effect





Nuclear volume effect

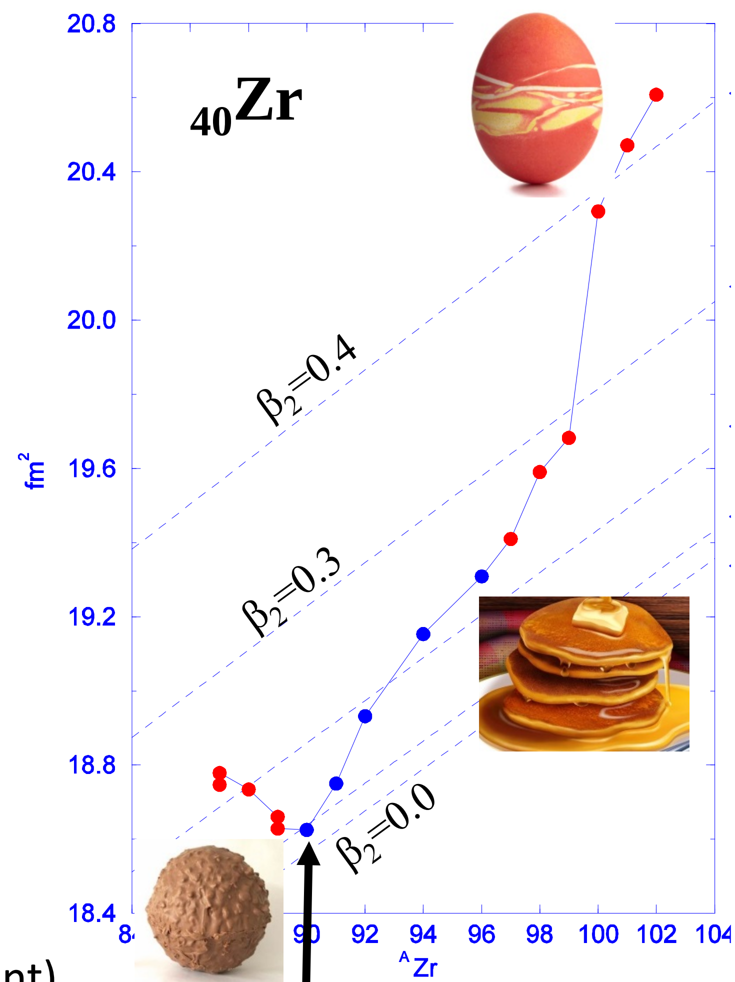


The nuclear mean-square charge radius

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

Depends on optical transition, i, **only**

Depends on isotopes only



N=50 shell closure

What can it tell us?

- e.g., extreme sensitivity to the nuclear shape

$$\langle r^2\rangle = \langle r^2\rangle_{sph}\left(1+\frac{5}{4\pi}\left(\langle\beta_2^2\rangle+\ldots\right)\right)+3\sigma^2$$

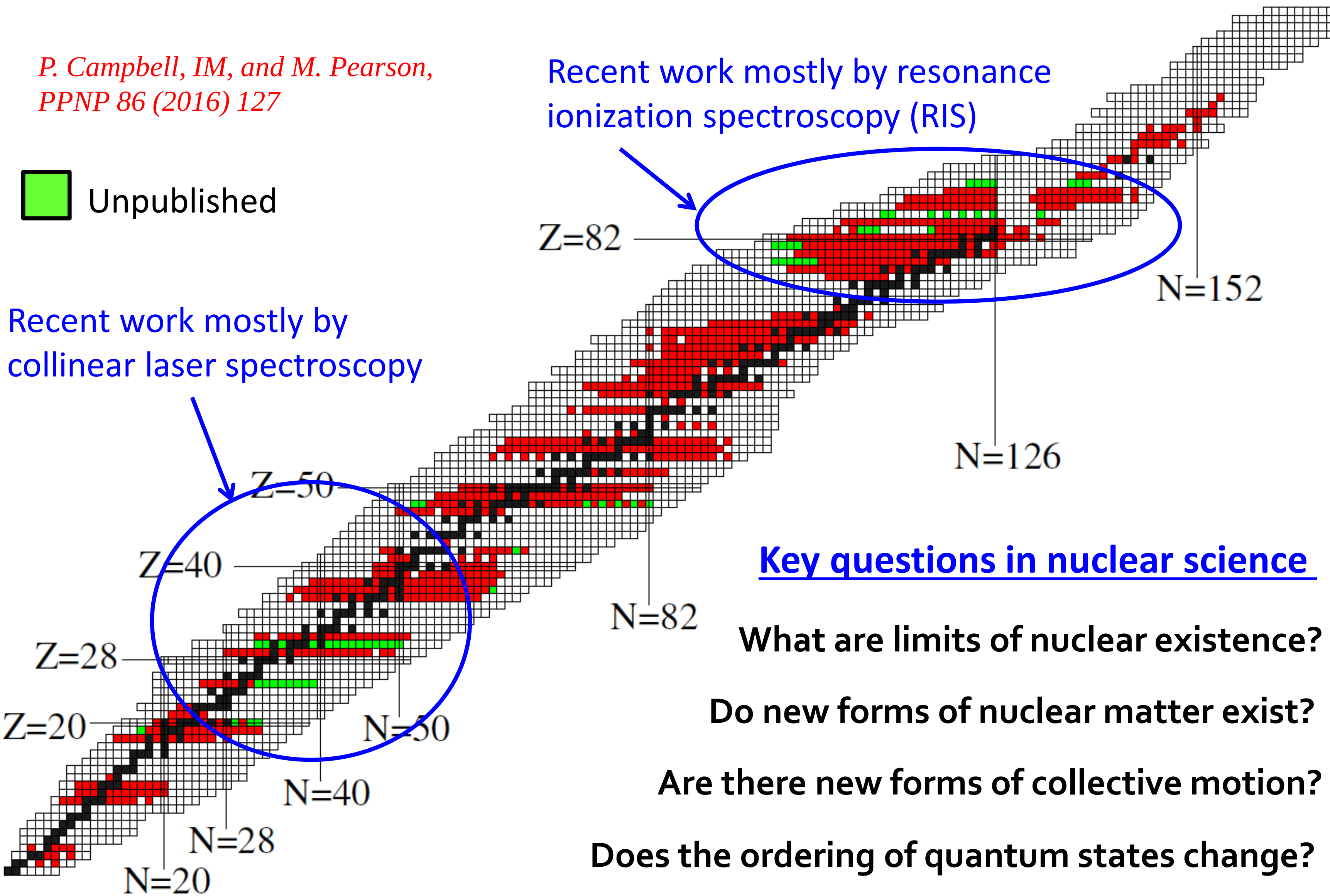
Size (droplet model)

Shape (Quadrupole term)

Diffuseness (assumed constant)

Exploration of the nuclear chart with lasers

P. Campbell, IM, and M. Pearson, PPNP 86 (2016) 127



Key questions in nuclear science

What are limits of nuclear existence?

Do new forms of nuclear matter exist?

Are there new forms of collective motion?

Does the ordering of quantum states change?

Spectroscopy of the heaviest nuclei

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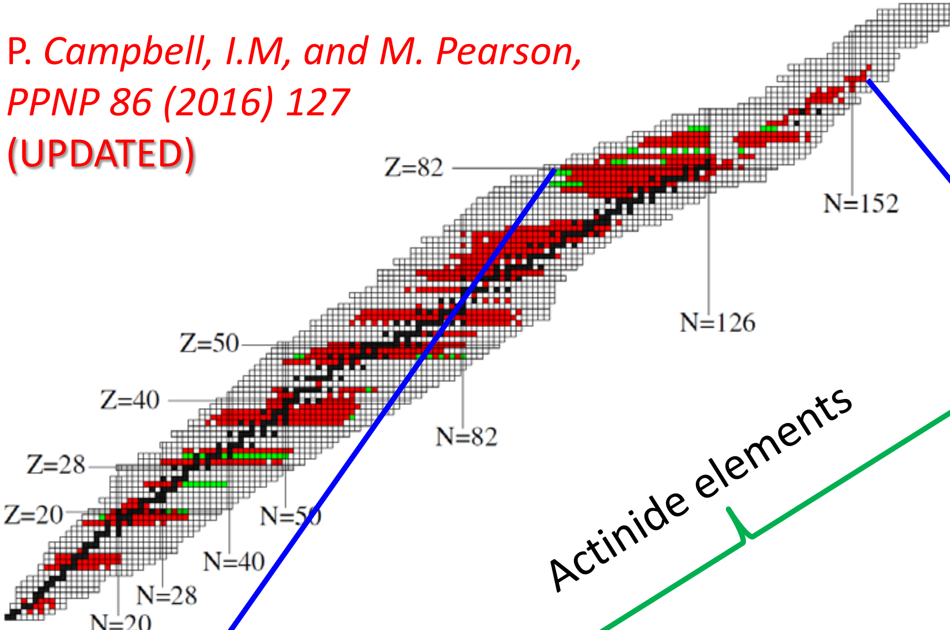
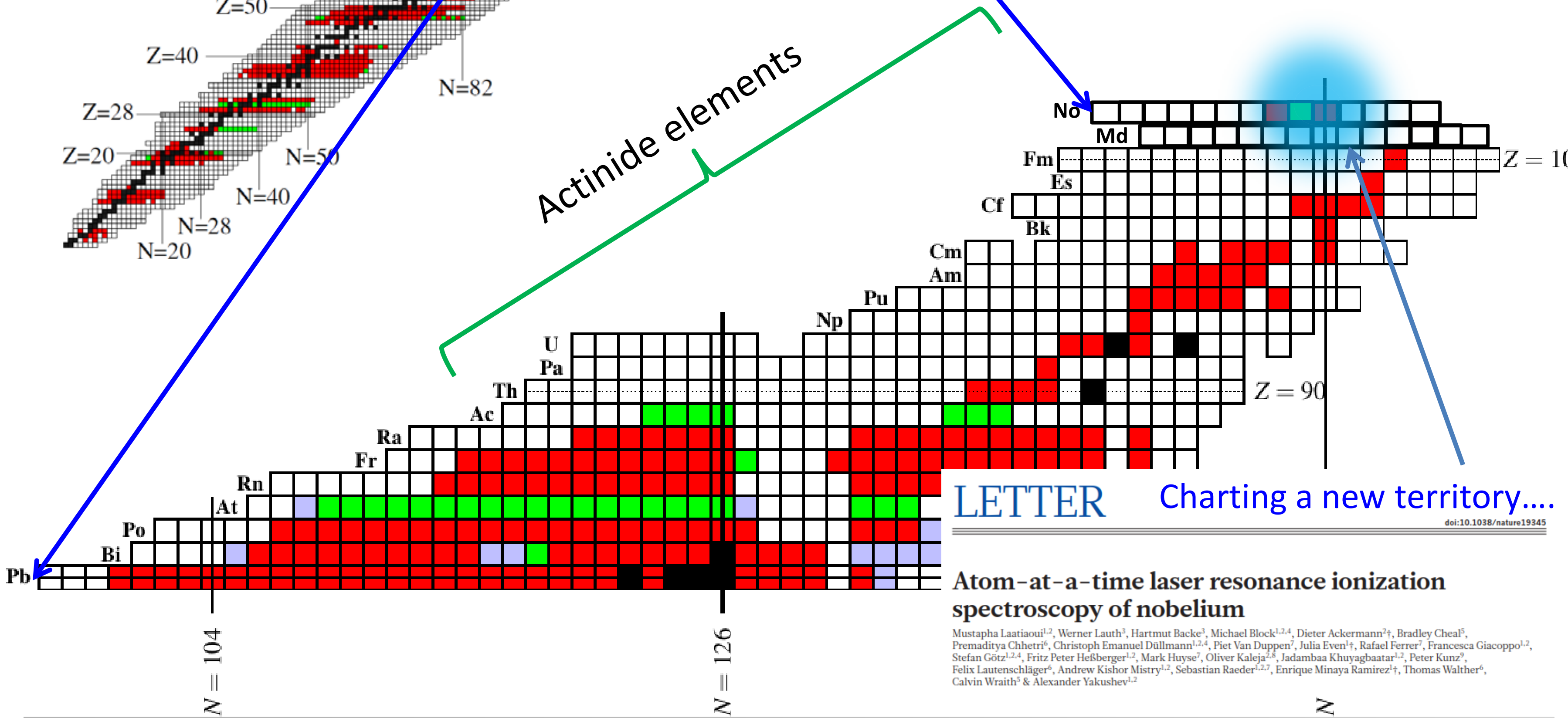
P. Campbell, I.M, and M. Pearson, PPNP 86 (2016) 127
(UPDATED)



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



Resonance ionization spectroscopy (RIS)

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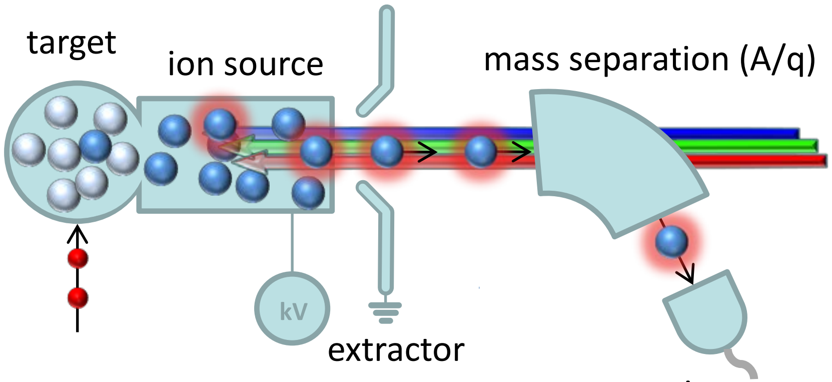
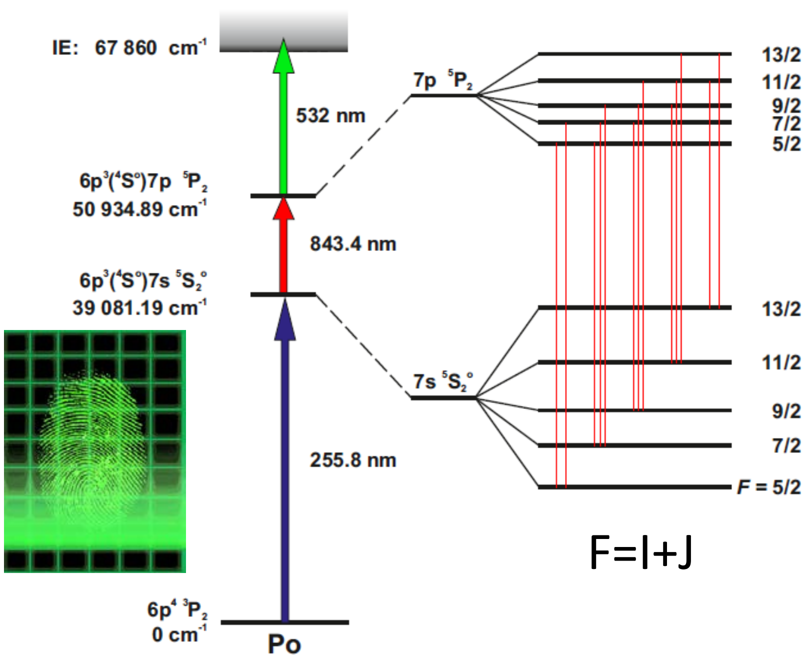
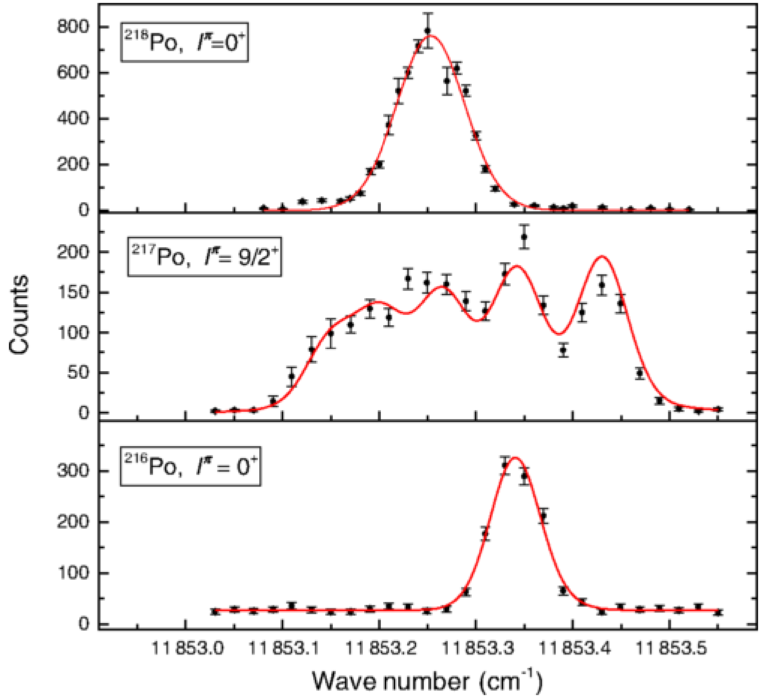


Po (*Z*=84)



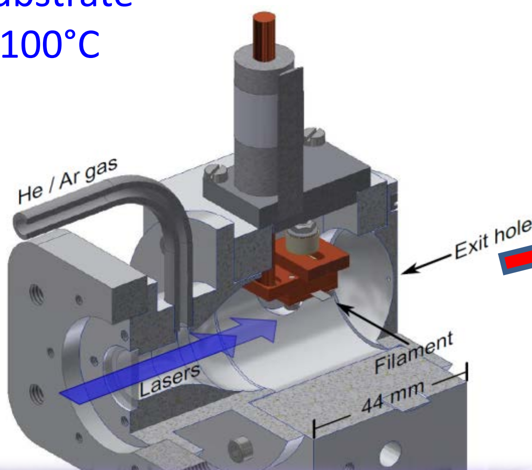


D. Fink et al., PRX 5 (2015) 011018

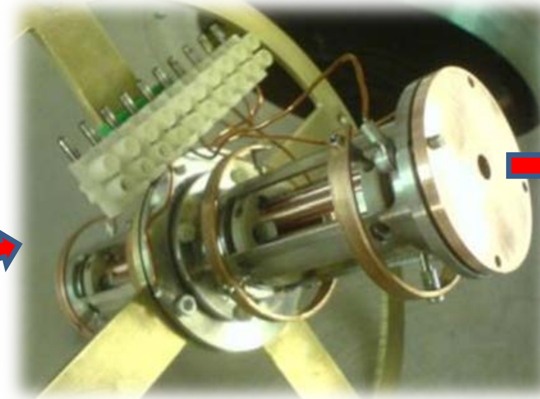
- ☺ Selective process
- ☺ Short lifetimes, low yields (<1 ion/s)
- ☺ High detection efficiency
- ☹ Poor resolution (line broadening)

In-gas laser ionization of Pu at JYFL

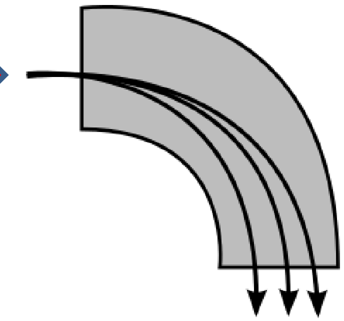
$^{238-242,244}Pu$ (10^{16} – 10^{12} atoms) on Ta substrate
T~1100°C



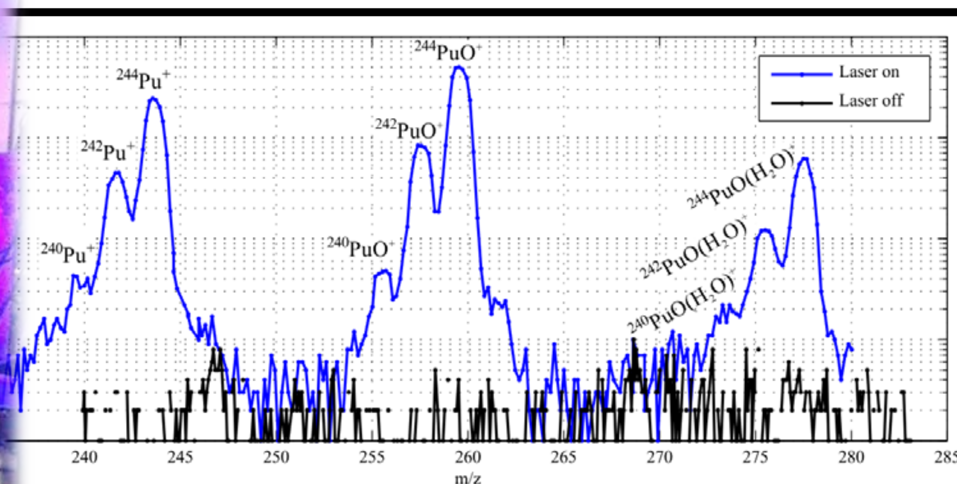
RF guidance



Mass separator



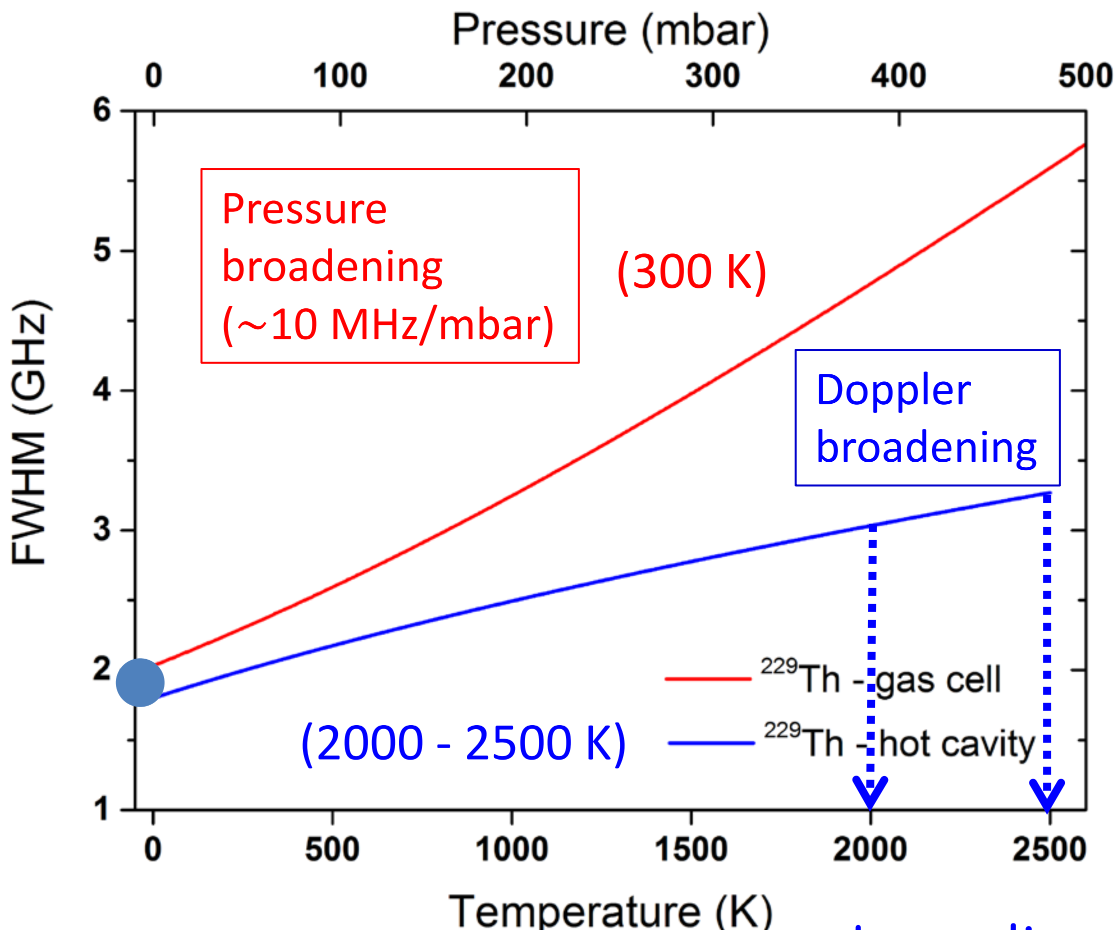
to experiments

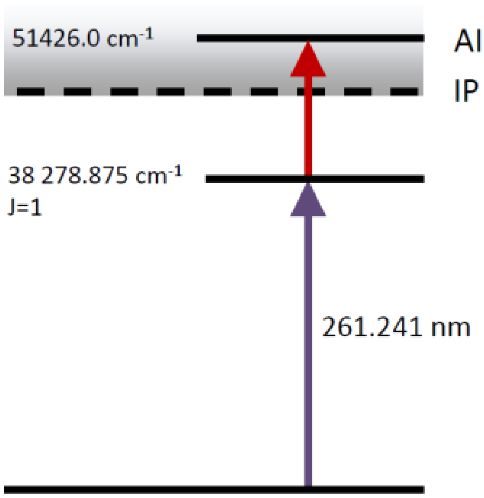


m/q

Atomic transition broadening

Simulation of an atomic transition in ^{229}Th.

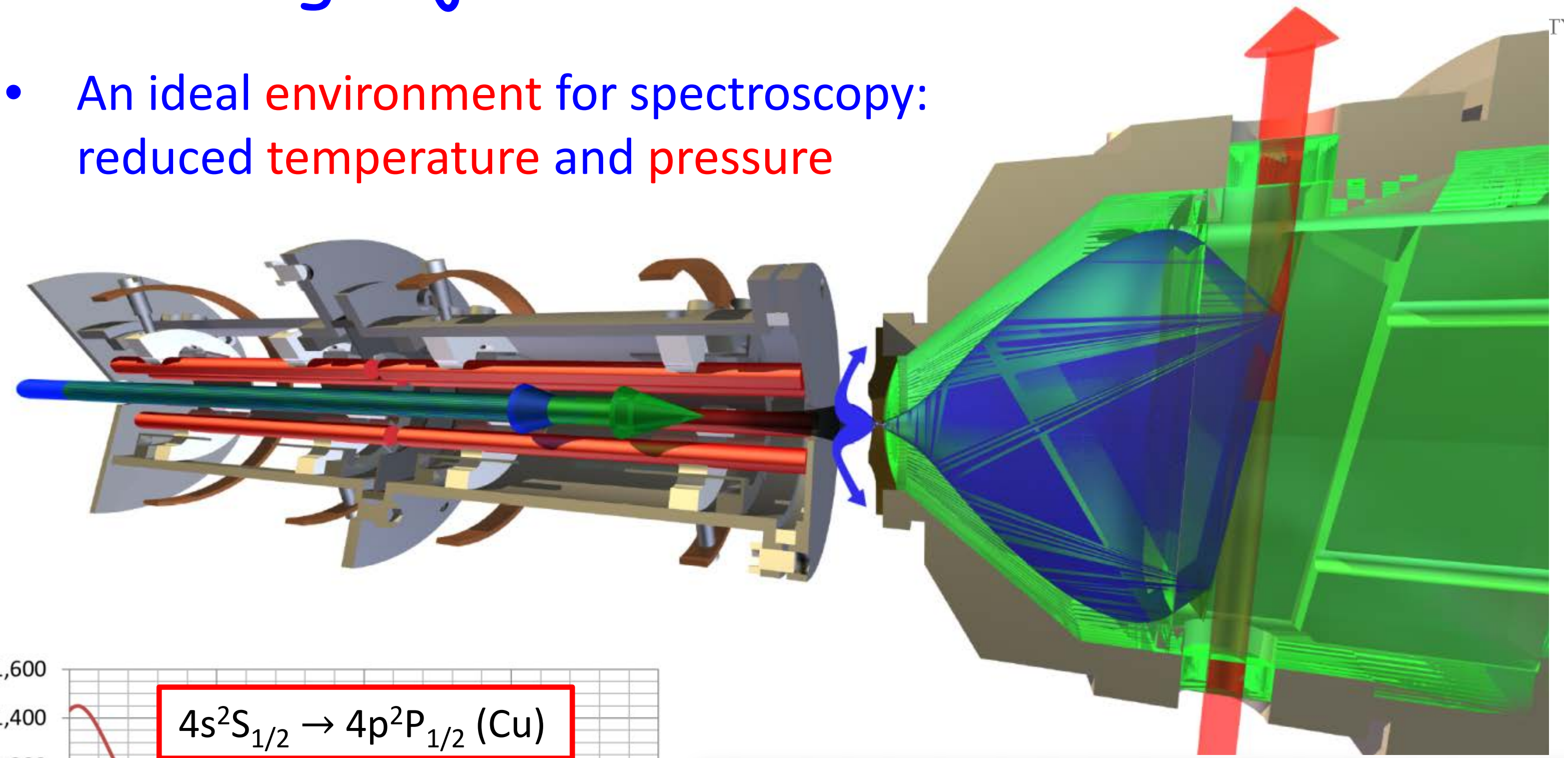


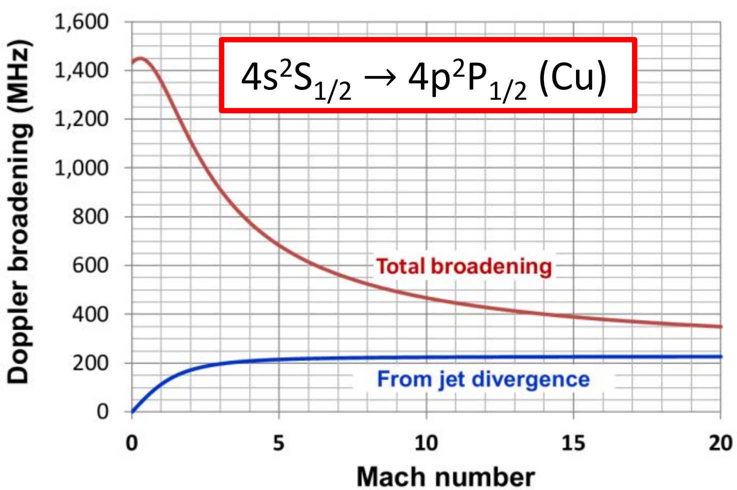


Laser linewidth-limited ~2GHz

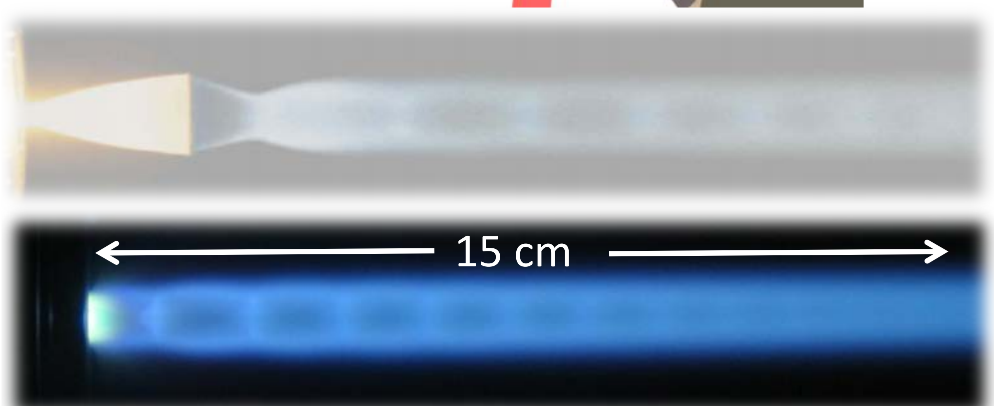
Towards gas jet laser ionization

- An ideal environment for spectroscopy: reduced temperature and pressure



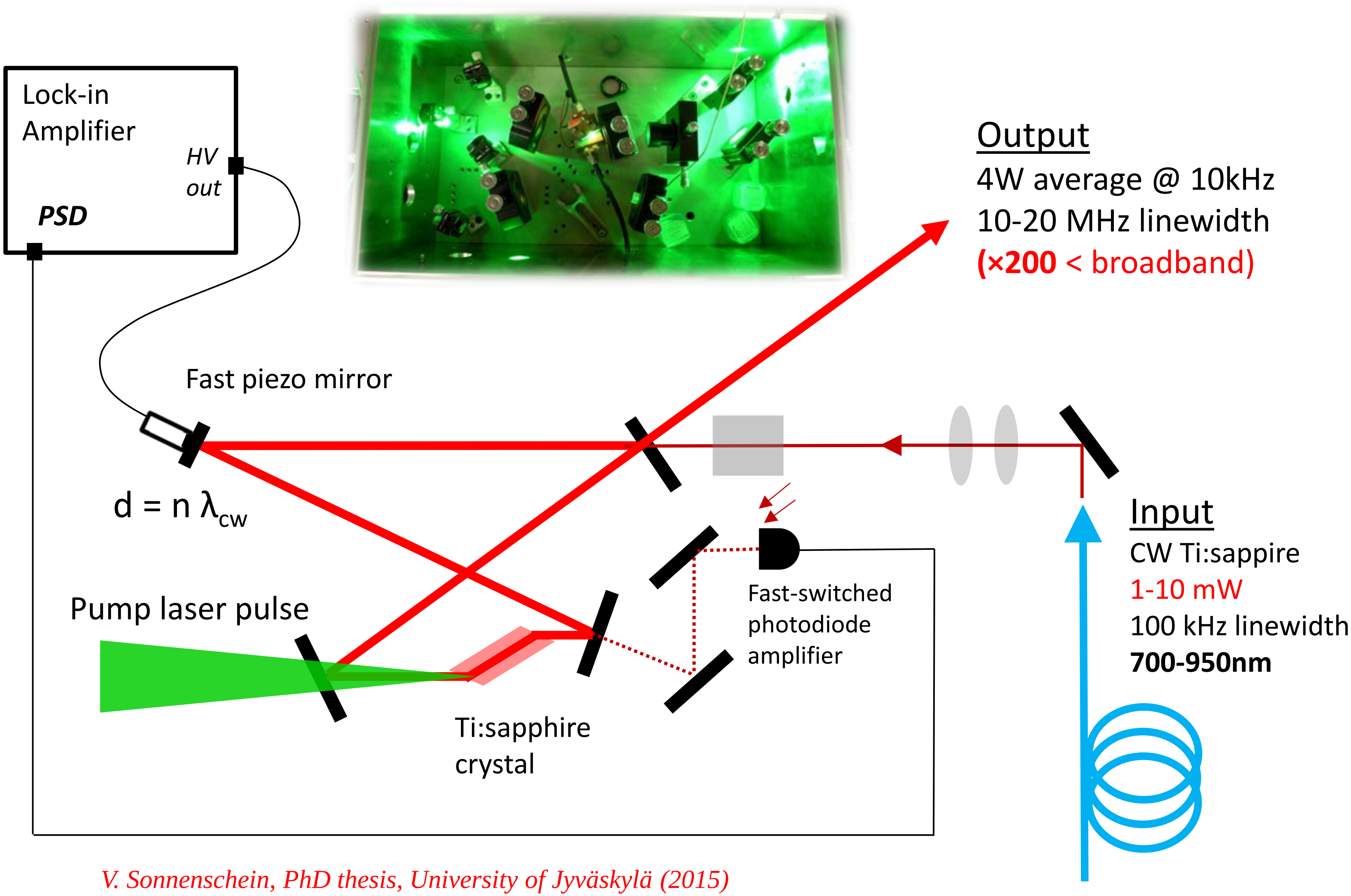


Yu. Kudryavtsev et al., NIMB 297 (2013) 7



M. Reponen, I.D. Moore, et al., NIMA 635 (2011) 24

Development of a new solid-state laser



V. Sonnenschein, PhD thesis, University of Jyväskylä (2015)
V. Sonnenschein et al., Laser Physics 27 (2017) 085701

Dec. 2014 – Louvain-la-Neuve, Belgium

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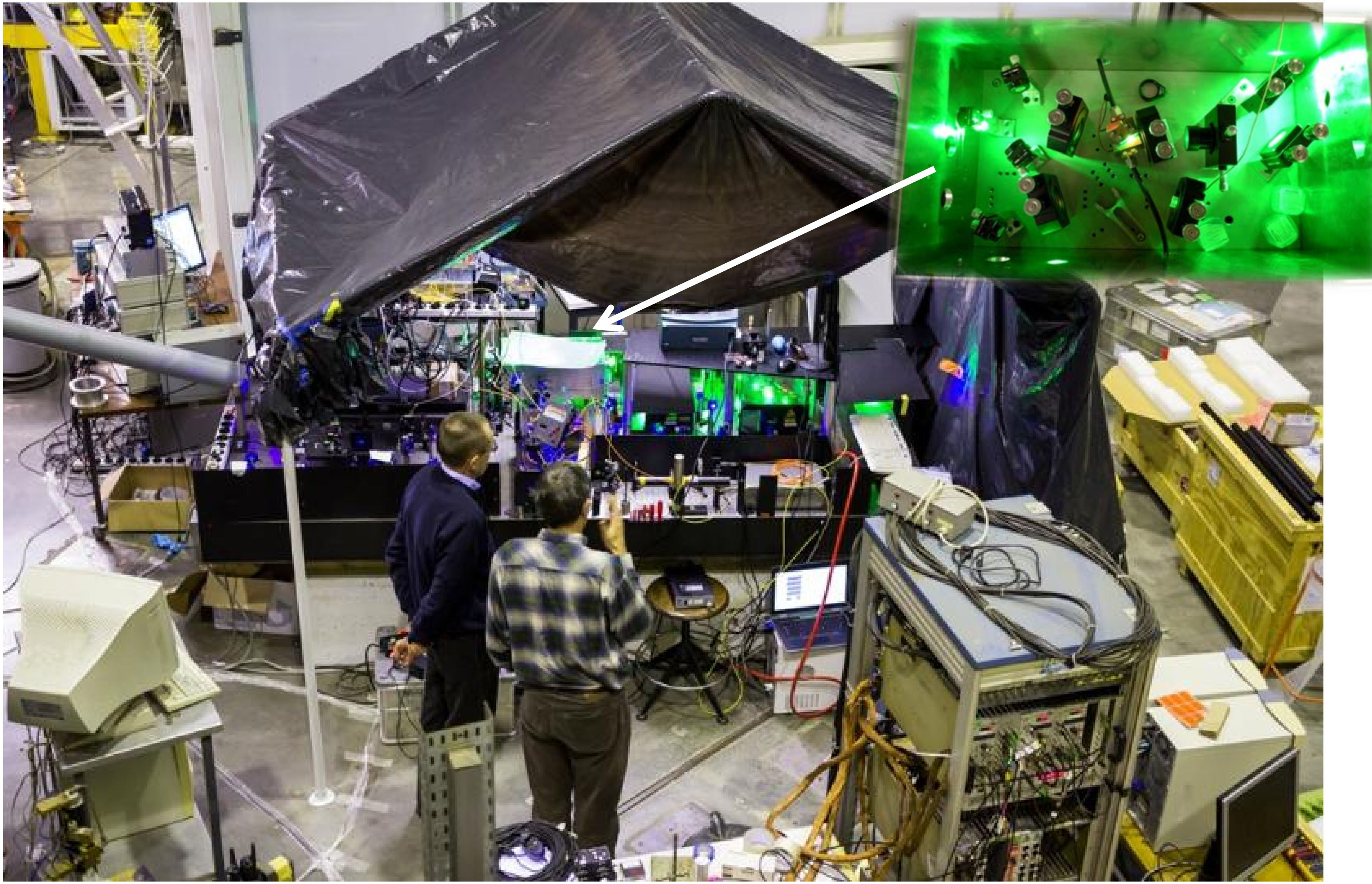
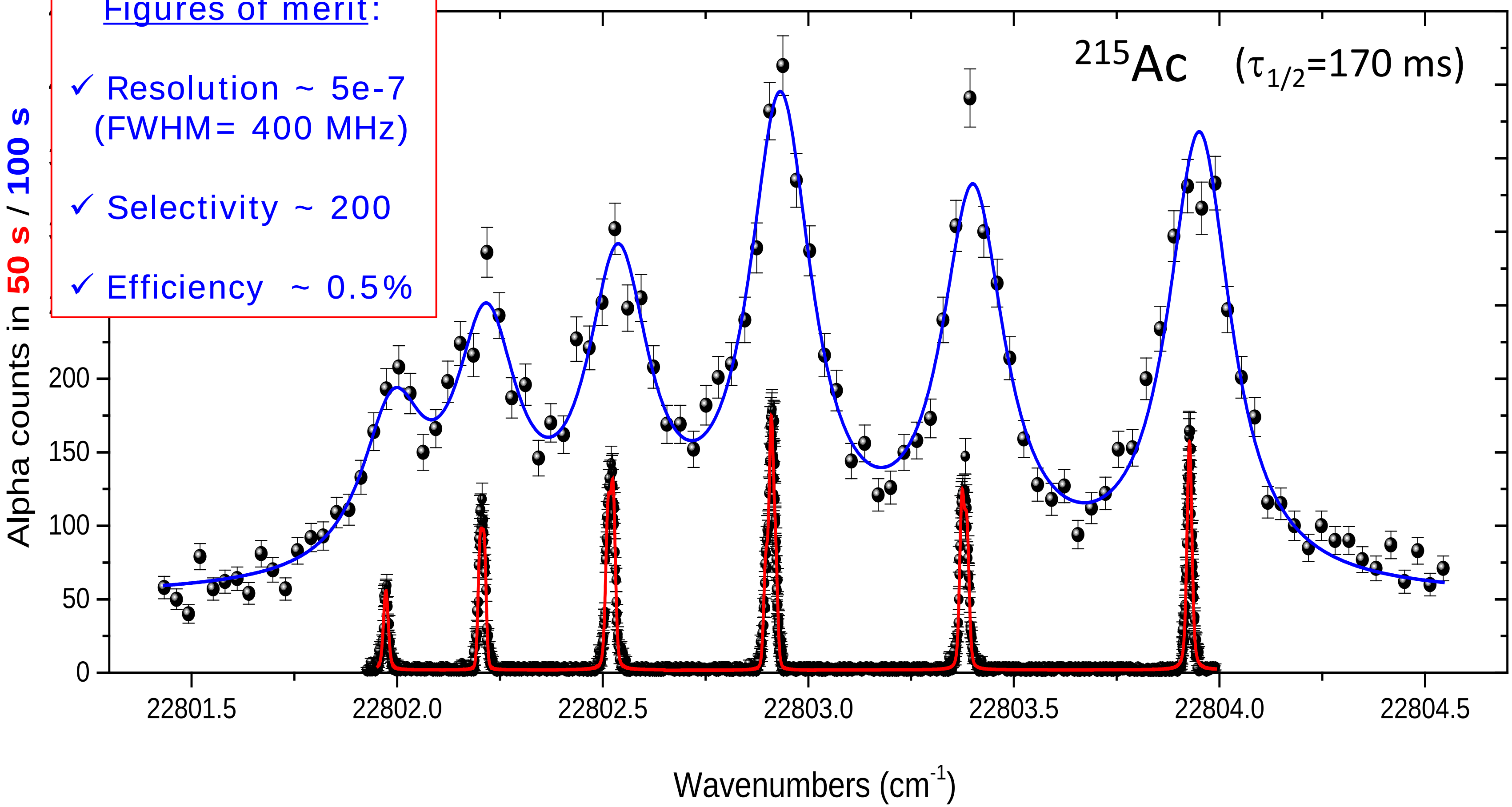


A pioneering experiment - Gas jet spectroscopy of $^{214,215}Ac$

Figures of merit:

- ✓ Resolution ~ 5e-7 (FWHM= 400 MHz)
- ✓ Selectivity ~ 200
- ✓ Efficiency ~ 0.5%



- in gas cell **- in gas jet**

R. Ferrer et al., Nature Communications 8 (2017) 14520

Projected reach of in-gas-jet spectroscopy

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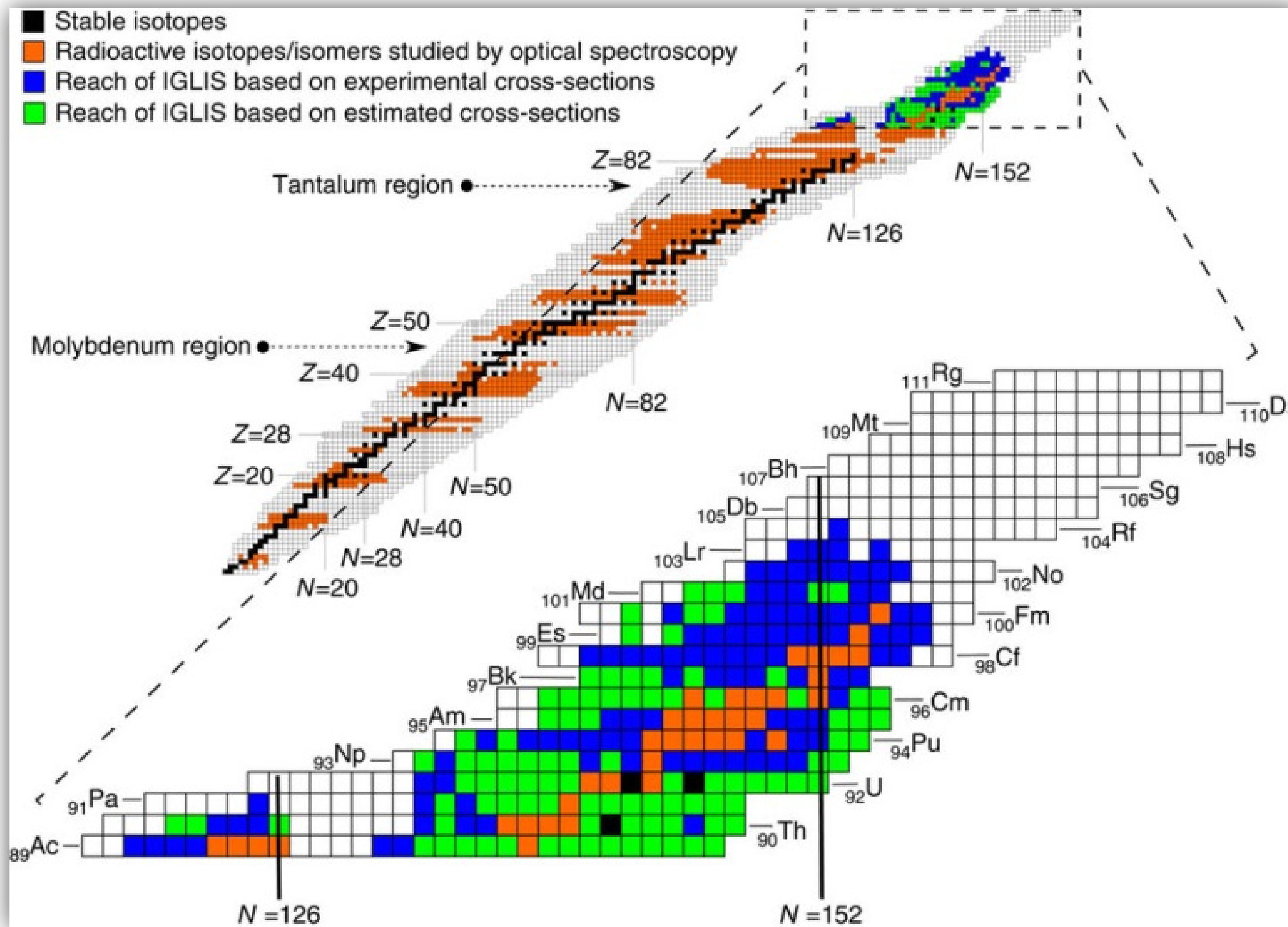
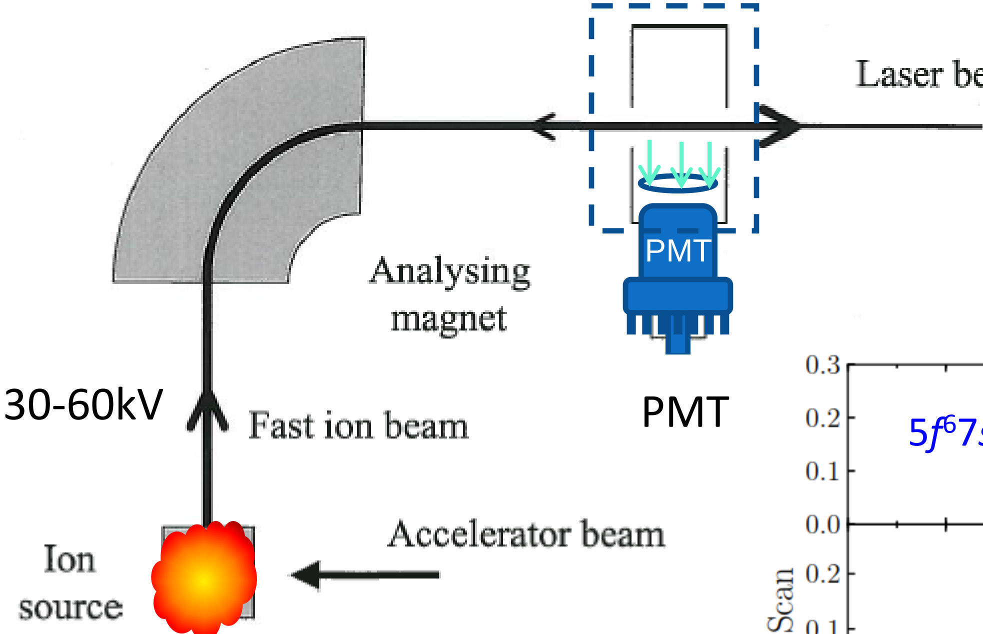
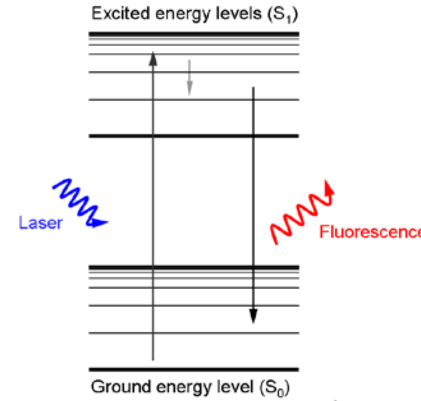
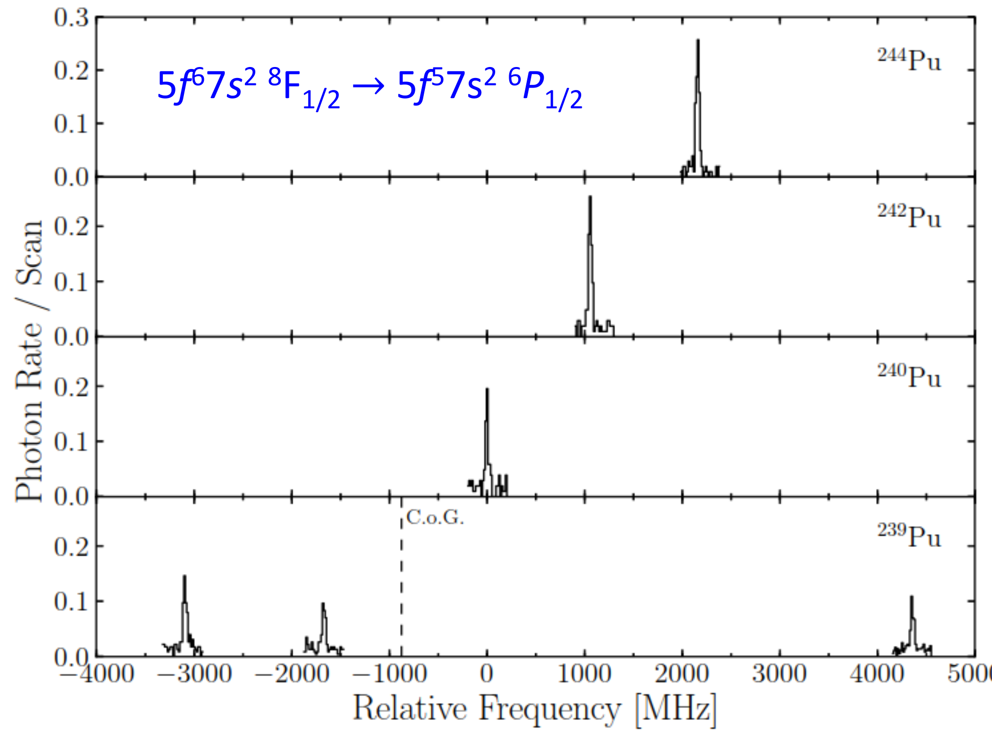


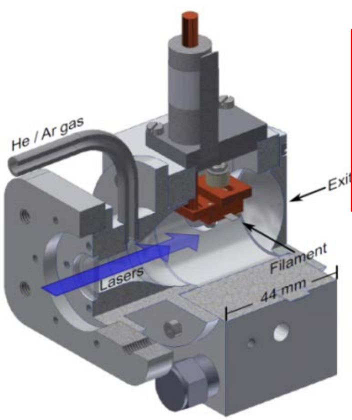
0.1 pps, $T_{1/2}$ >100ms, ε=10% (@10 pμA)

Collinear laser spectroscopy of Pu⁺ at IGISOL









^{244}Pu ~10^{16} atoms

^{239}Pu ~2×10^{14}

^{238}Pu ~8×10^{12}

Extraction of nuclear information

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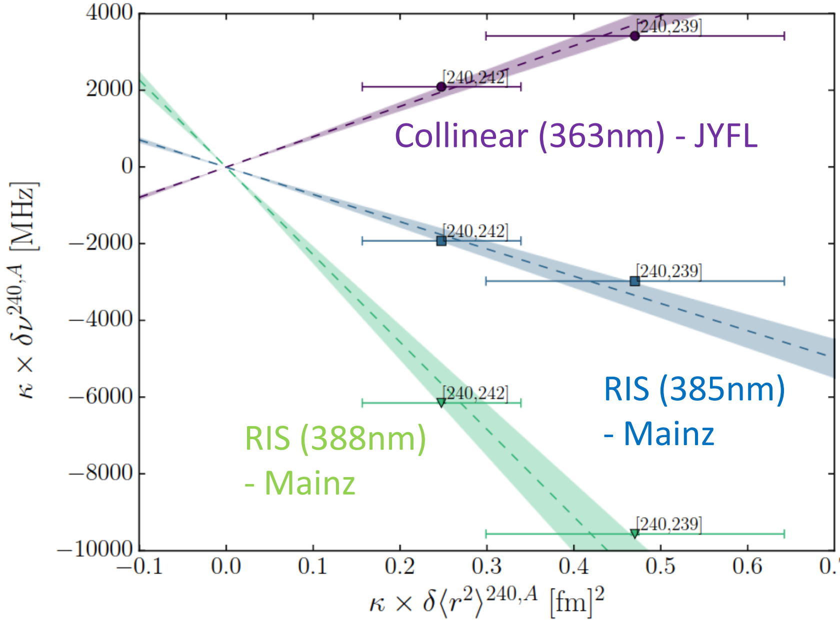
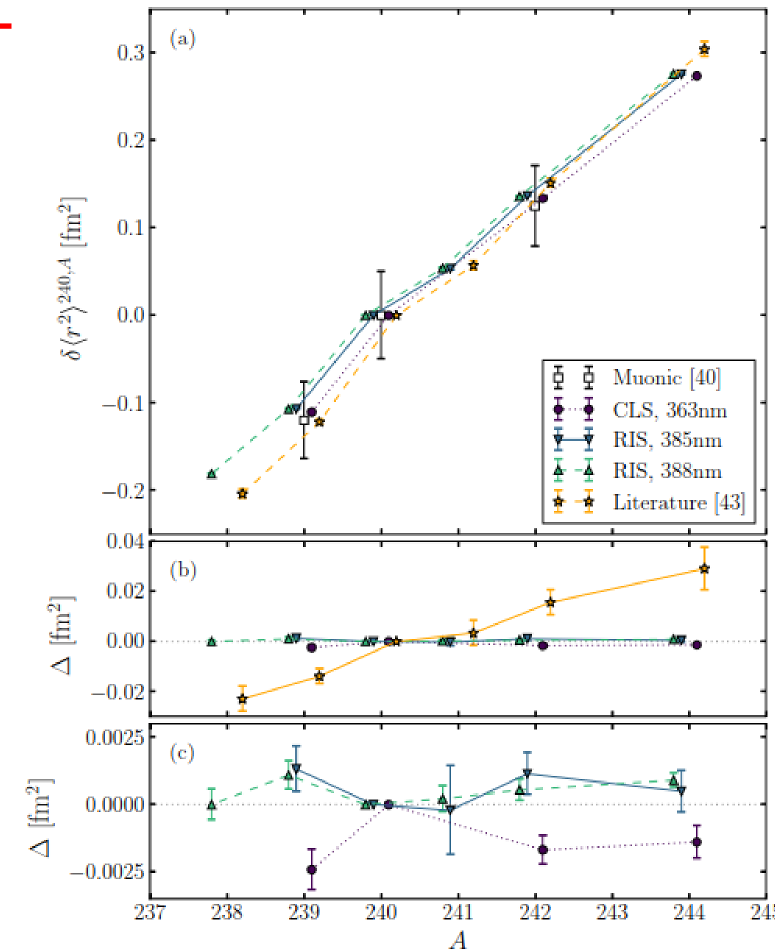
$$\delta\nu_i^{A,A'} = M_i \frac{A'-A}{AA'} + F_i \delta\langle r^2\rangle^{A,A'}$$

King plots of isotope shifts vs. δ<r²>



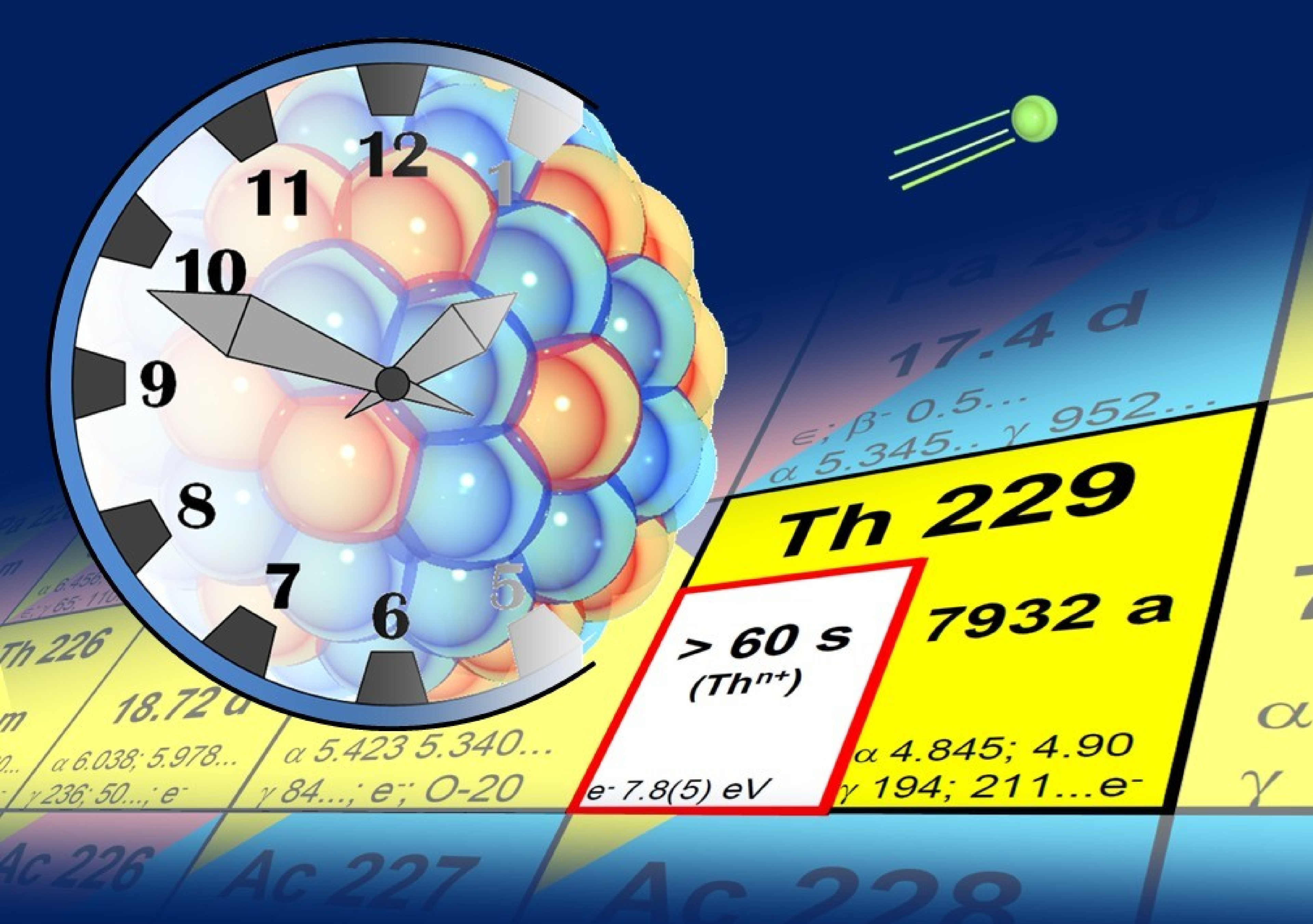
δ<r²>: optical vs. X-rays, muonic atoms



Calibration of atomic factors:

- F_{385nm} = -7.1(7) GHz/fm²
- F_{388nm} = -22.8(23) GHz/fm²
- F_{363nm} = +7.9(6) GHz/fm²

A. Voss et al., PRA 95 (2017) 032506



Christoph Düllman, JGU Mainz

A measurement of time

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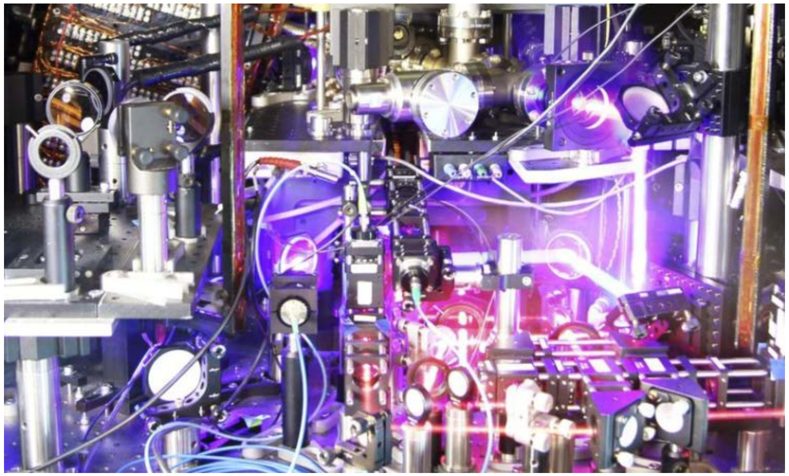
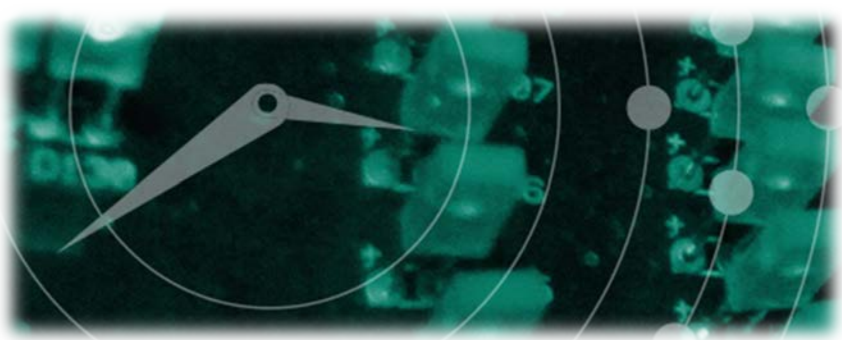


Best atomic clock:

- Strontium lattice clock at NIST
- *Frequency uncertainty 2.1×10^{-18}
- Precision limited by external influences

T.L. Nichelson et al., Nature Commun. 7896 (2015)

nuClock



The nuclear clock:

- Better performance (resistant to external influences)
- higher ”ticking rates”
- lose 1 second in 100 billion years!

www.nuclock.eu

What is special about ^{229}Th ?

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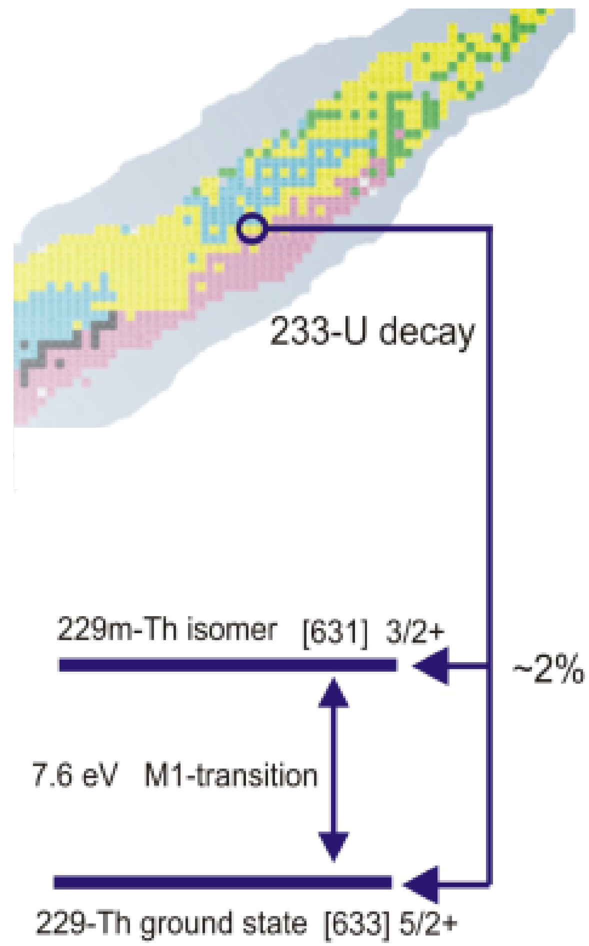
- Total number of known isotopes: 3339
- Total number of known levels: 175441
- Total number of known γ-ray transitions: 268089

Only one transition may be considered as a nuclear-based frequency standard – ^{229m}Th

$\Delta E = 7.6 \pm 0.5$ eV*
$T \sim 10^4$ s
$\Delta E/E \sim 10^{-20}$



*B.R. Beck et al., Phys. Rev. Lett. 98 (2007) 142501

Direct detection of the isomeric state

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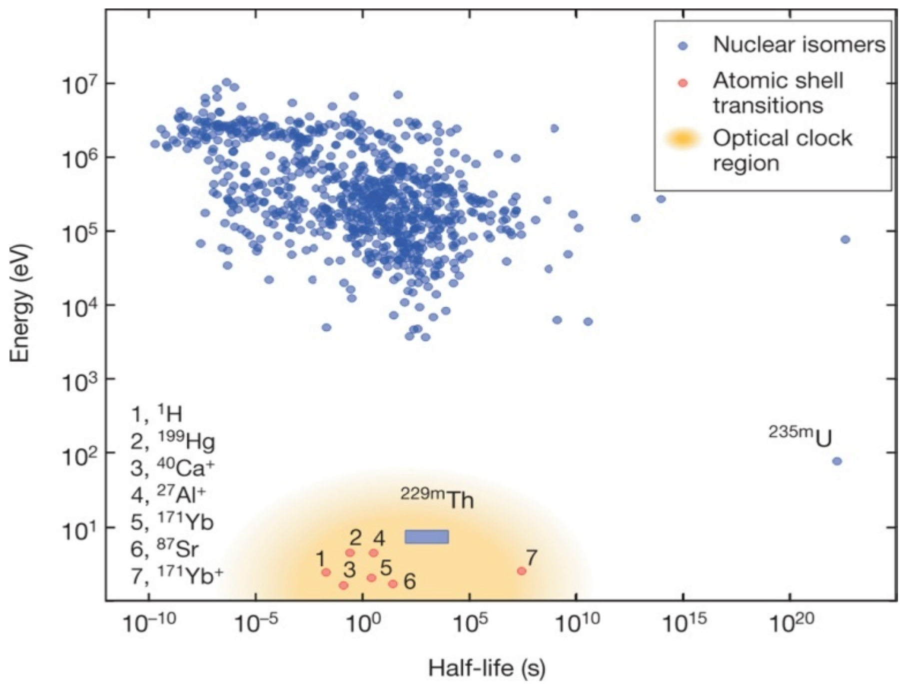
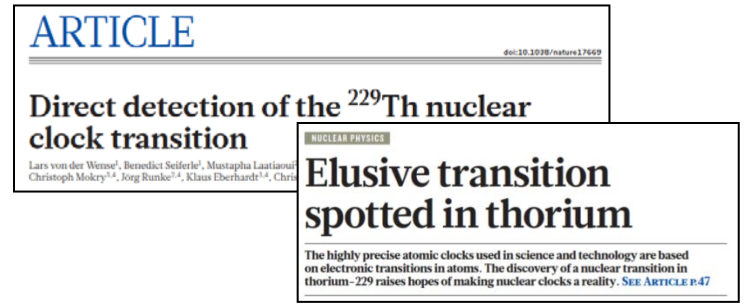



ARTICLE

doi:10.1038/nature17669

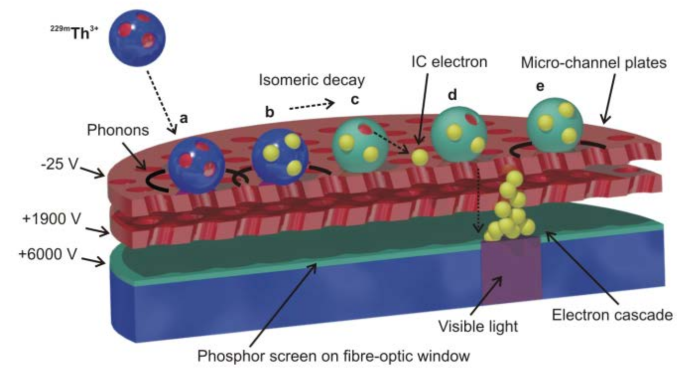
Direct detection of the ^{229}Th nuclear clock transition

Lars von der Wense[1], Benedict Seiferle[1], Mustapha Laatiaoui... Christoph Mokry[3,4], Jörg Runke[2,4], Klaus Eberhardt[3,4], Chris...

NUCLEAR PHYSICS

Elusive transition spotted in thorium

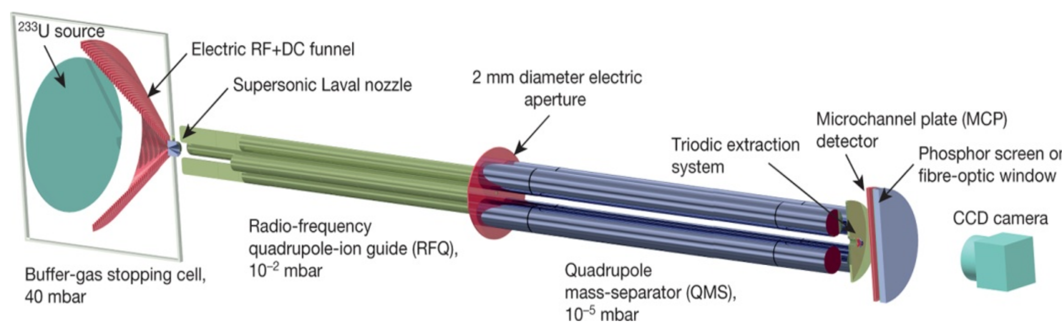
The highly precise atomic clocks used in science and technology are based on electronic transitions in atoms. The discovery of a nuclear transition in thorium-229 raises hopes of making nuclear clocks a reality. SEE ARTICLE P.47



ΔE ≈ 6.3 – 18.3 eV

T = 7(1)μs (neutral atom*)

T >60s ($^{229m}Th^{2+}$)



*L. von der Wense et al., Nature 533 (2016) 47; *B. Seiferle et al., Phys. Rev. Lett. 118 (2017) 042501*

Towards spectroscopy of ^{229m}Th at JYFL

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nuclock

<u>OBJECTIVES:</u>

- Spectroscopy on singly-charged ^{229g,m}Th produced on-line
- Spectroscopy on $2^{+}/3^{+}$ charged states (off-line)

Spectroscopy on atomic ground state performed (2012)

V. Sonnenschein, S. Raeder, IM et al., J. Phys. B 45 (2012) 165005

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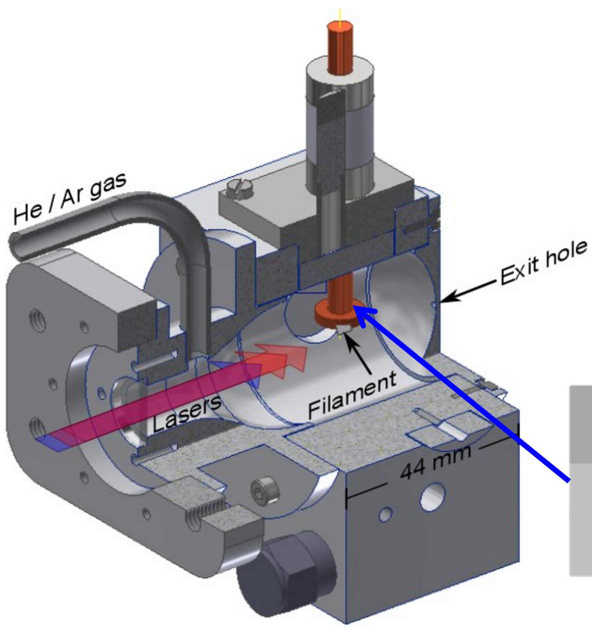
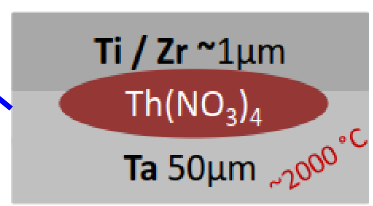
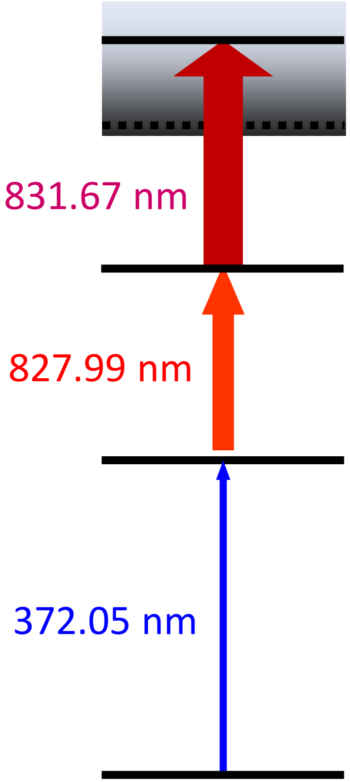


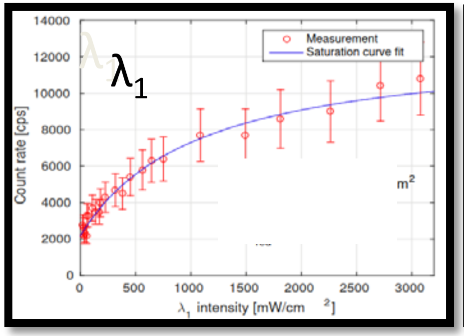


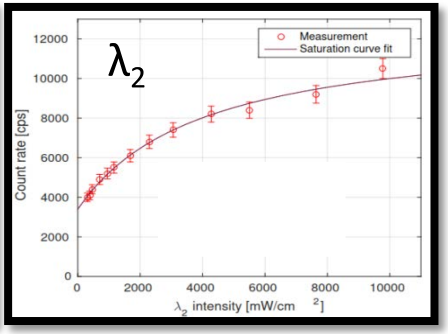
^{232}Th $\sim 10^{15}$ atoms

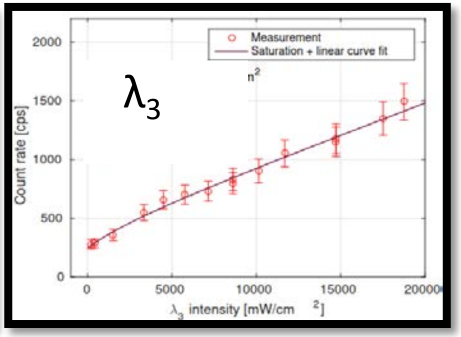
Laser ionization of ^{232}Th

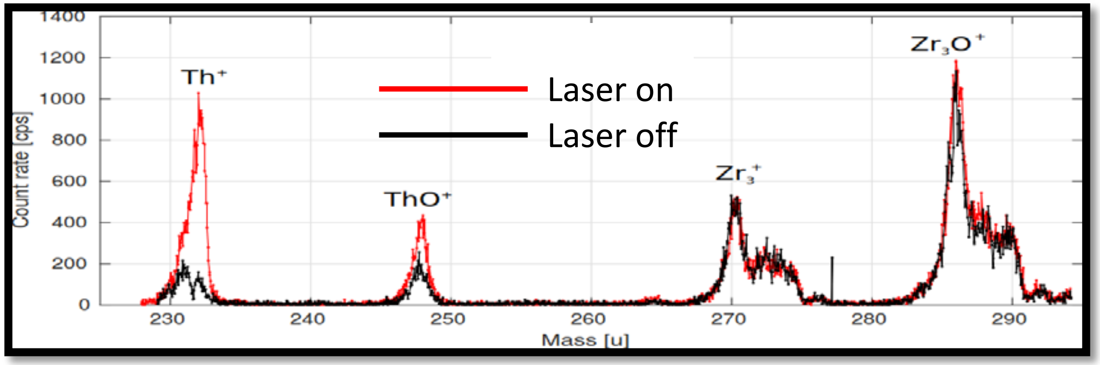


Y. Liu and D. Stracener, NIMB 376 (2016) 233







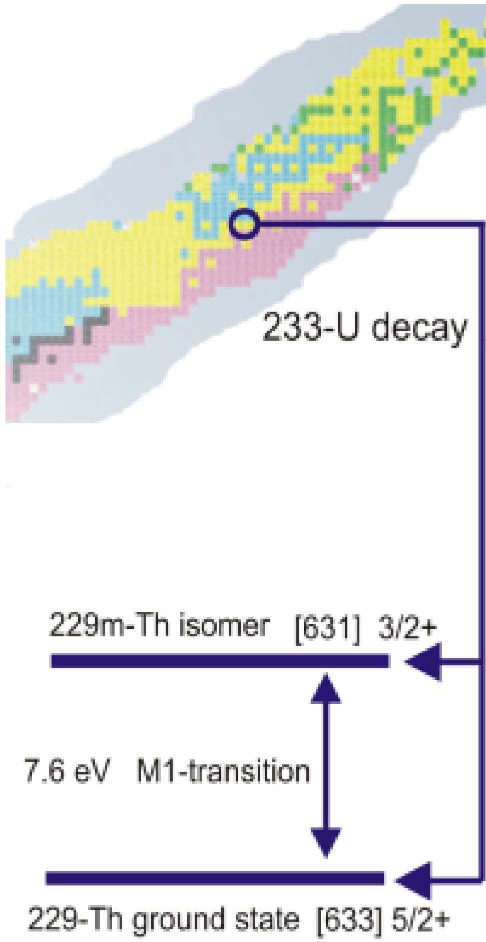


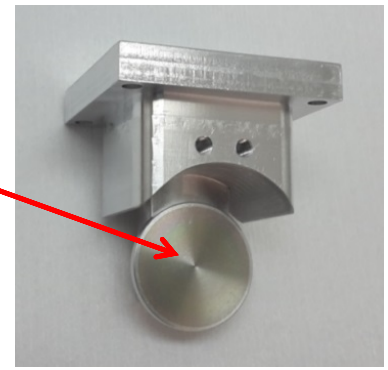
- Faraday cup yields of $^{232}Th^{+}$ available
- Currently waiting for new electrodeposited ^{229}Th samples from Vienna

I. Pohjalainen et al., manuscript under preparation

Populating the isomeric state

- 200 kBq $^{233}UF_4$ evaporated onto 20 mm ϕ steel
- ~10000 ^{229}Th α-recoil ions/s leaving source
- Stopped and extracted from ultra-pure He gas

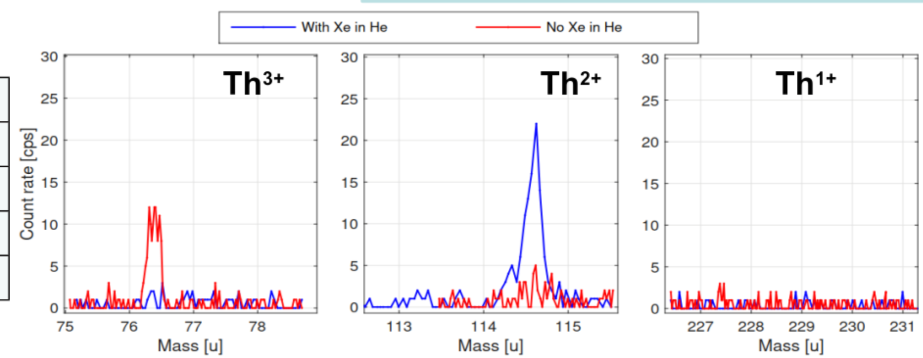




$$Xe + {}^{229}Th^{3+} \rightarrow Xe^{1+} + {}^{229}Th^{2+}$$

Charge state manipulation by adding Xe/Kr to the helium gas

Th IPs (eV)	
1+	6.31 eV
2+	11.5 eV
3+	18.3 eV
4+	28.8 eV



$^{232}Th(p,p3n)^{229(m)}Th$

A new gas cell for ^{229m}Th from ^{233}U

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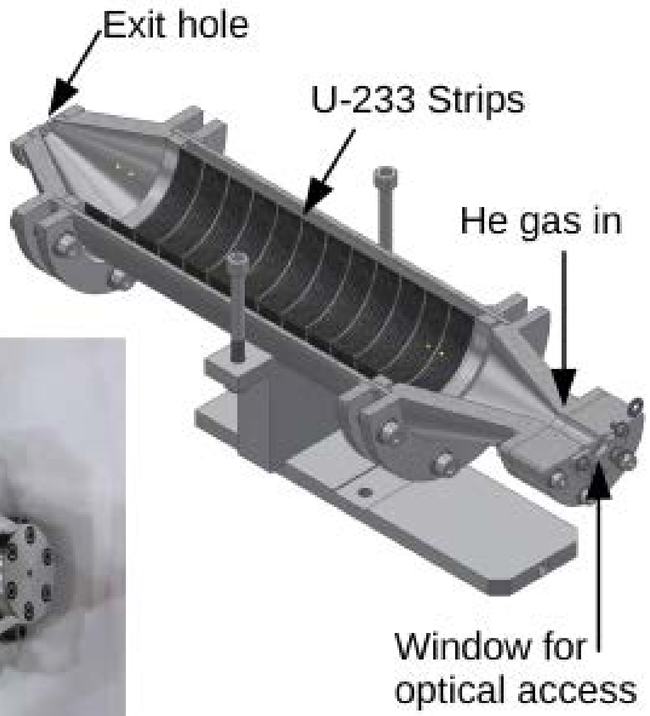
A new U-233 strip gas cell built at IGISOL housing the JYFL source strips

- Smooth gas flow
- Exit hole d=2.5 mm
  ⇨ Fast extraction
- First tests on going



Summary and outlook

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- Laser spectroscopy (in its many variants) is a sensitive probe for nuclear structure across the nuclear landscape
- The actinide region and above is one current challenge
- Plutonium is the heaviest element studied with collinear laser spectroscopy to date
- Nobelium is the heaviest element studied (using RIS) – previously no atomic levels were known!
- Thorium and its unique isomer has many potential impacts, if it can be accessed with a laser

  - currently waiting ^{229}Th samples from Vienna
  - characterizing ^{233}U sources using nuclear spectroscopy
  - planned on-line production later in 2017

IGISOL team

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+ collaborators

https://www.jyu.fi/fysiikka/en/research/accelerator/igisol

Thank you