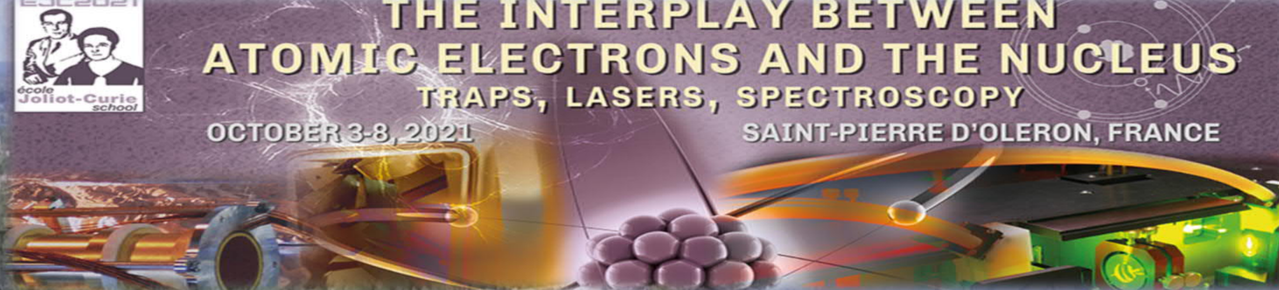
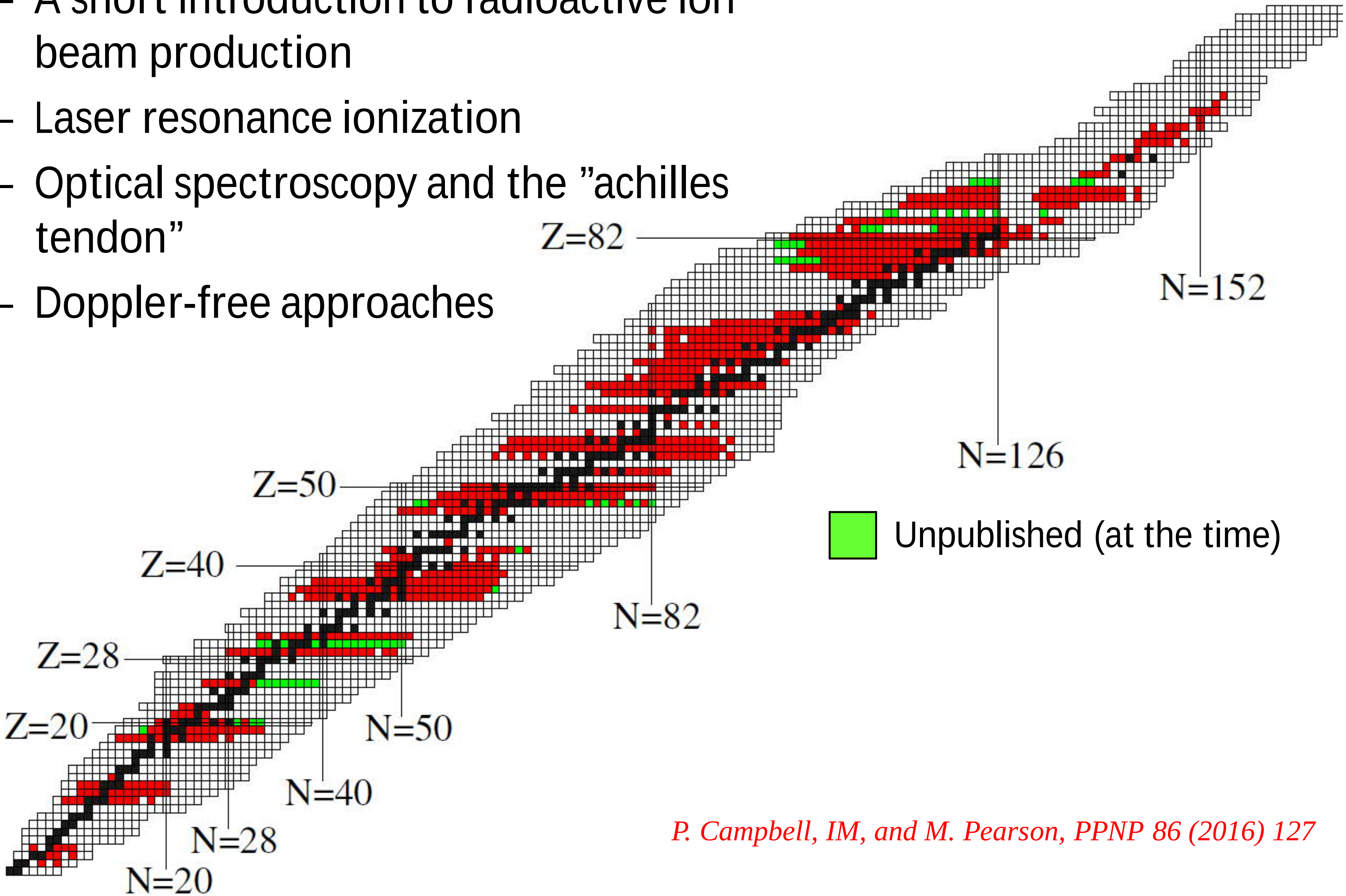


Laser spectroscopy for nuclear structure physics

Iain Moore (iain.d.moore@jyu.fi)
Department of Physics,
University of Jyväskylä, Finland

Lecture 2:

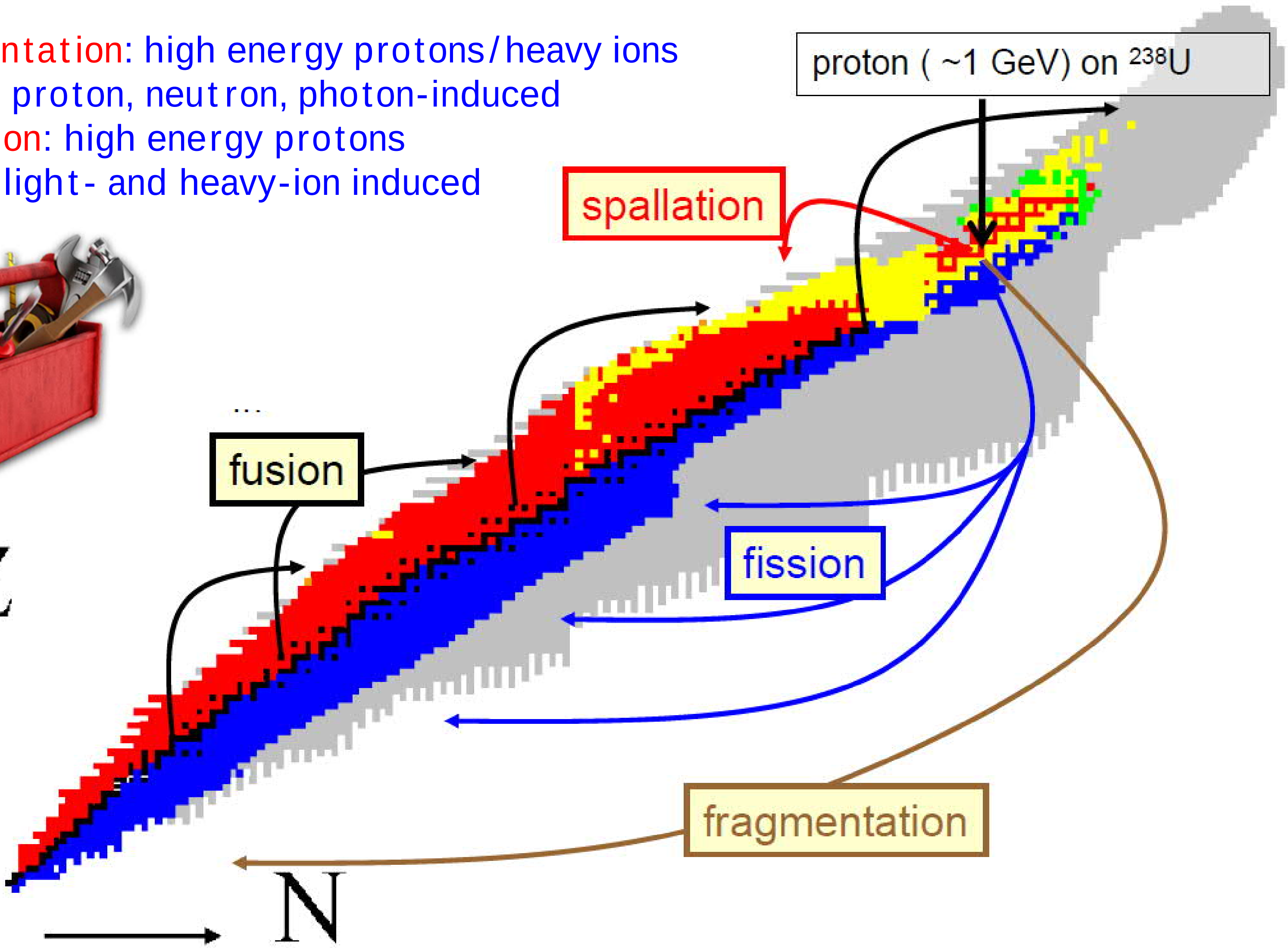
– A short introduction to radioactive ion beam production
– Laser resonance ionization
– Optical spectroscopy and the ”achilles tendon”
– Doppler-free approaches



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

A radioactive ion beam toolbox

- Fragmentation: high energy protons/heavy ions
- Fission: proton, neutron, photon-induced
- Spallation: high energy protons
- Fusion: light- and heavy-ion induced



The Isotope Separation On-Line method

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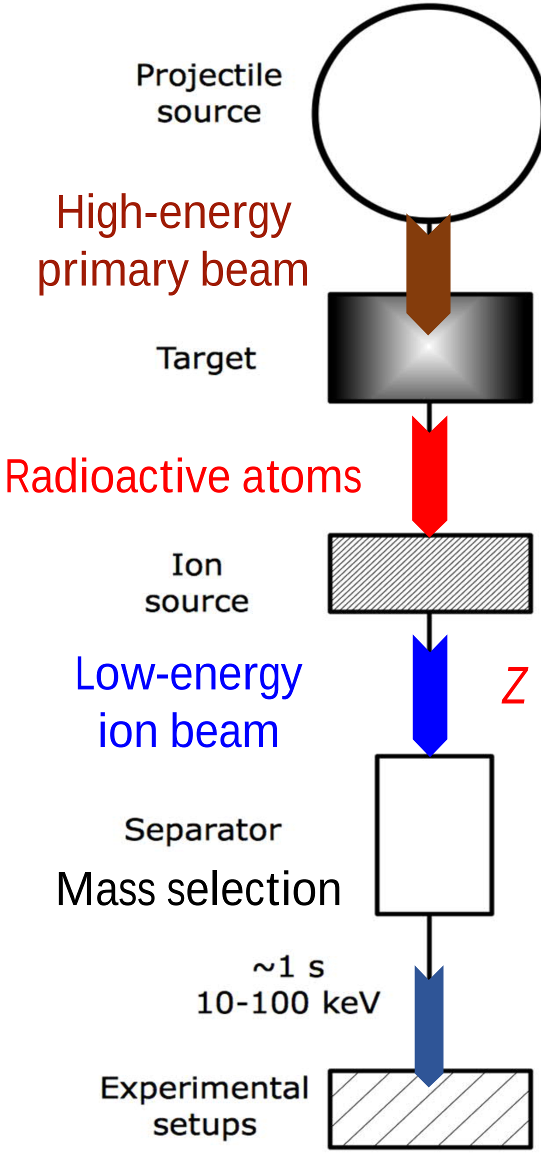
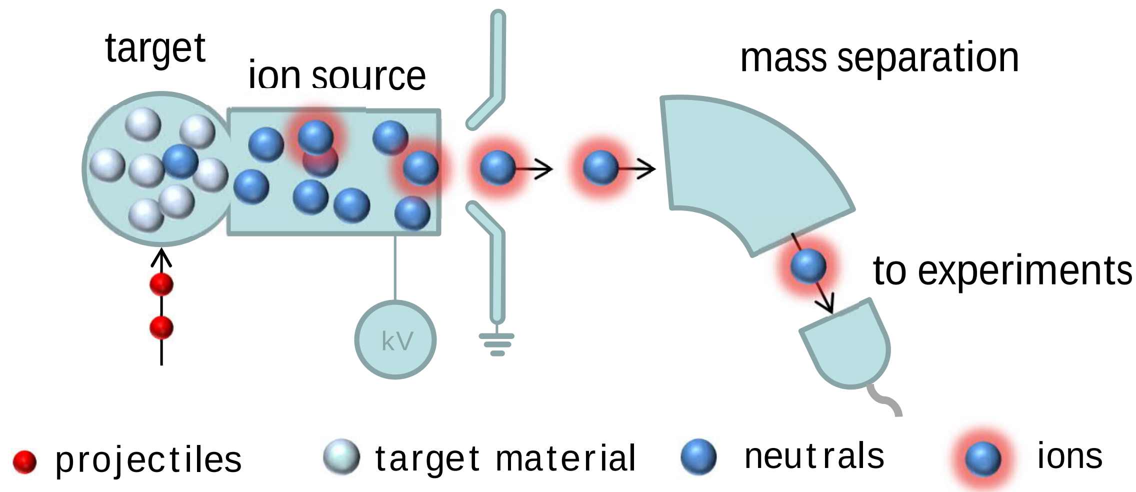
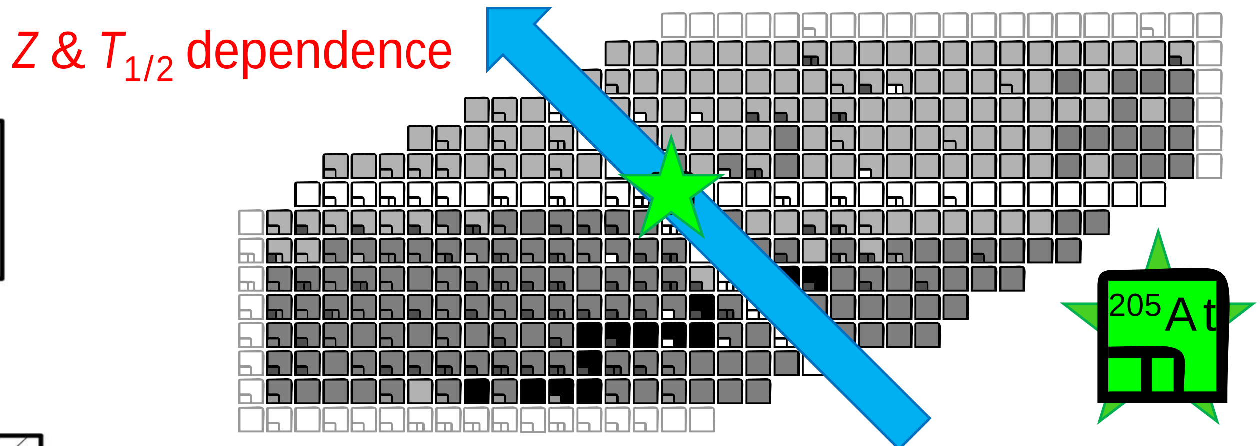


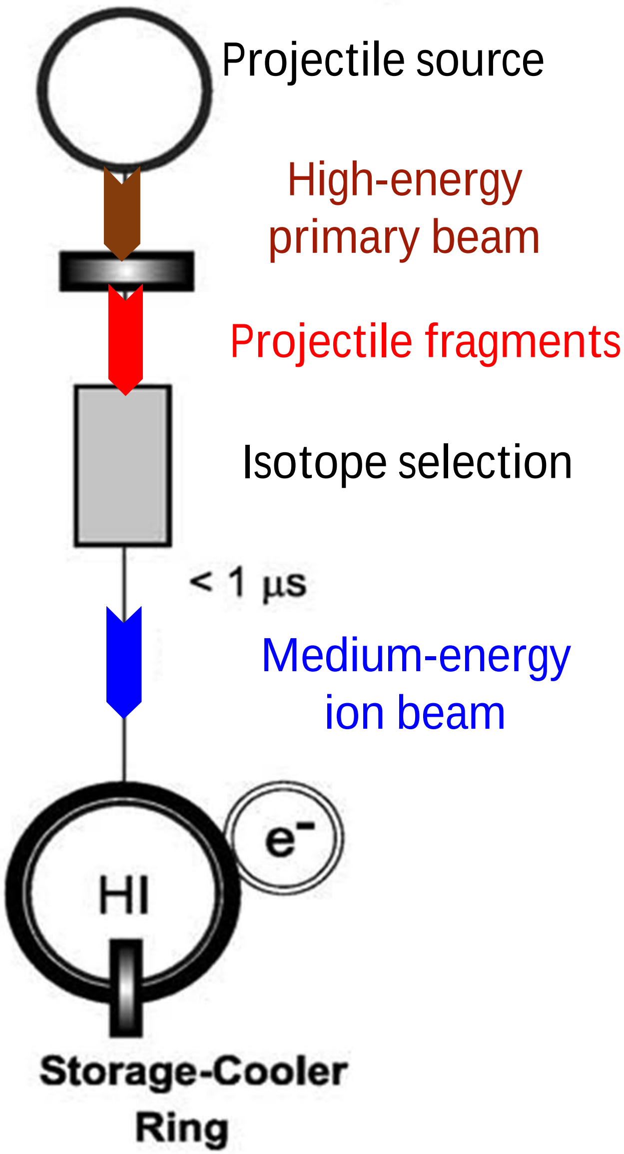
First developed in 1951, Niels Bohr Institute



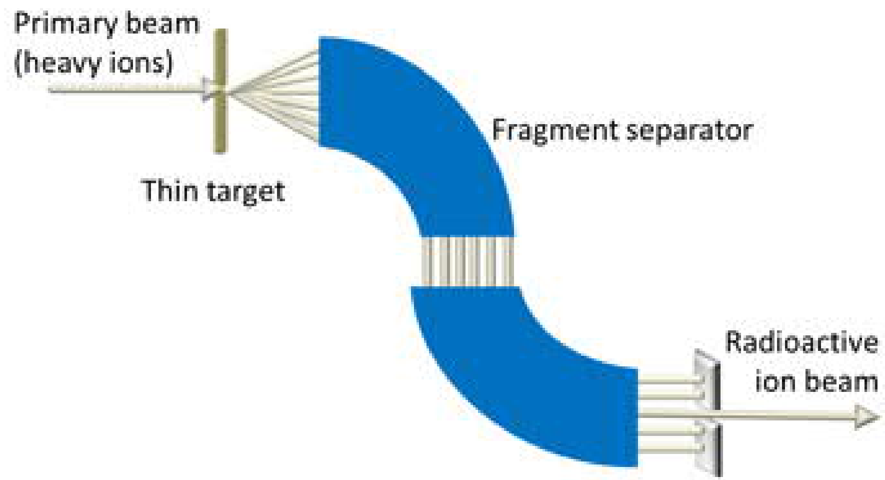


eg, ISOLDE, TRIUMF, GANIL... + ^{205}Pb, Bi, Po, Rn, Fr...

The in-flight method



First in-flight separator, Oak Ridge (1958)



- Very fast separation, access to μs half-lives and beams of ALL elements
- Often poor beam quality
- Precision experiments at low-energy not directly accessible

eg, GANIL, GSI, NSCL/MSU, RIBF RIKEN…

The (IG)ISOL / gas catcher (hybrid) method

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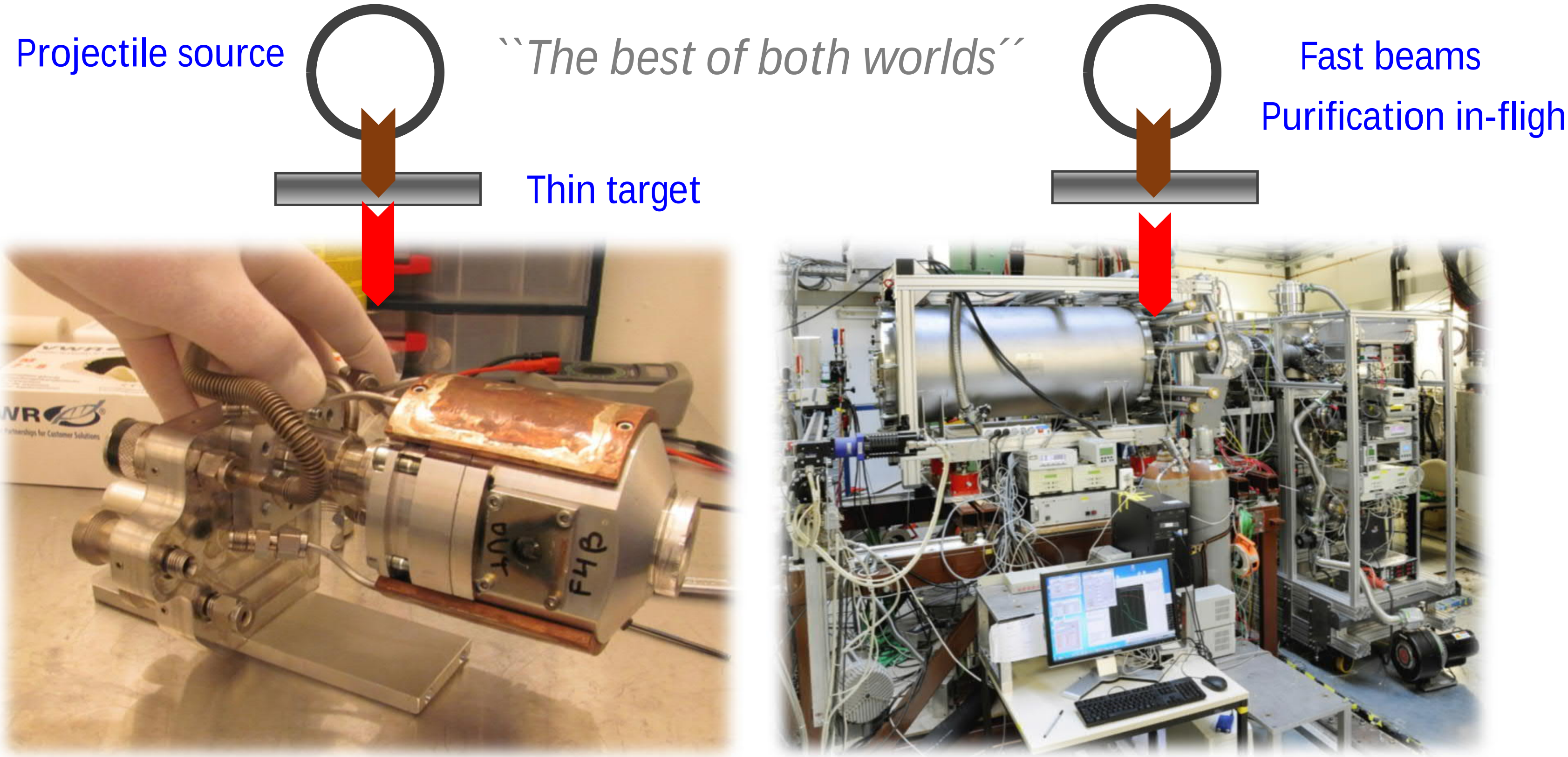

- Extraction of ions in gas flow (ion guide), or electrical fields (gas catcher)
- For the IGISOL method the (stopping) efficiency is relatively low, poor selectivity
- Universal method of radioactive ion beam production

Universality – an advantage and a drawback

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Your favorite exotic nucleus

Gas catcher, Argonne National Lab

=

+

Selectivity – why do we care?

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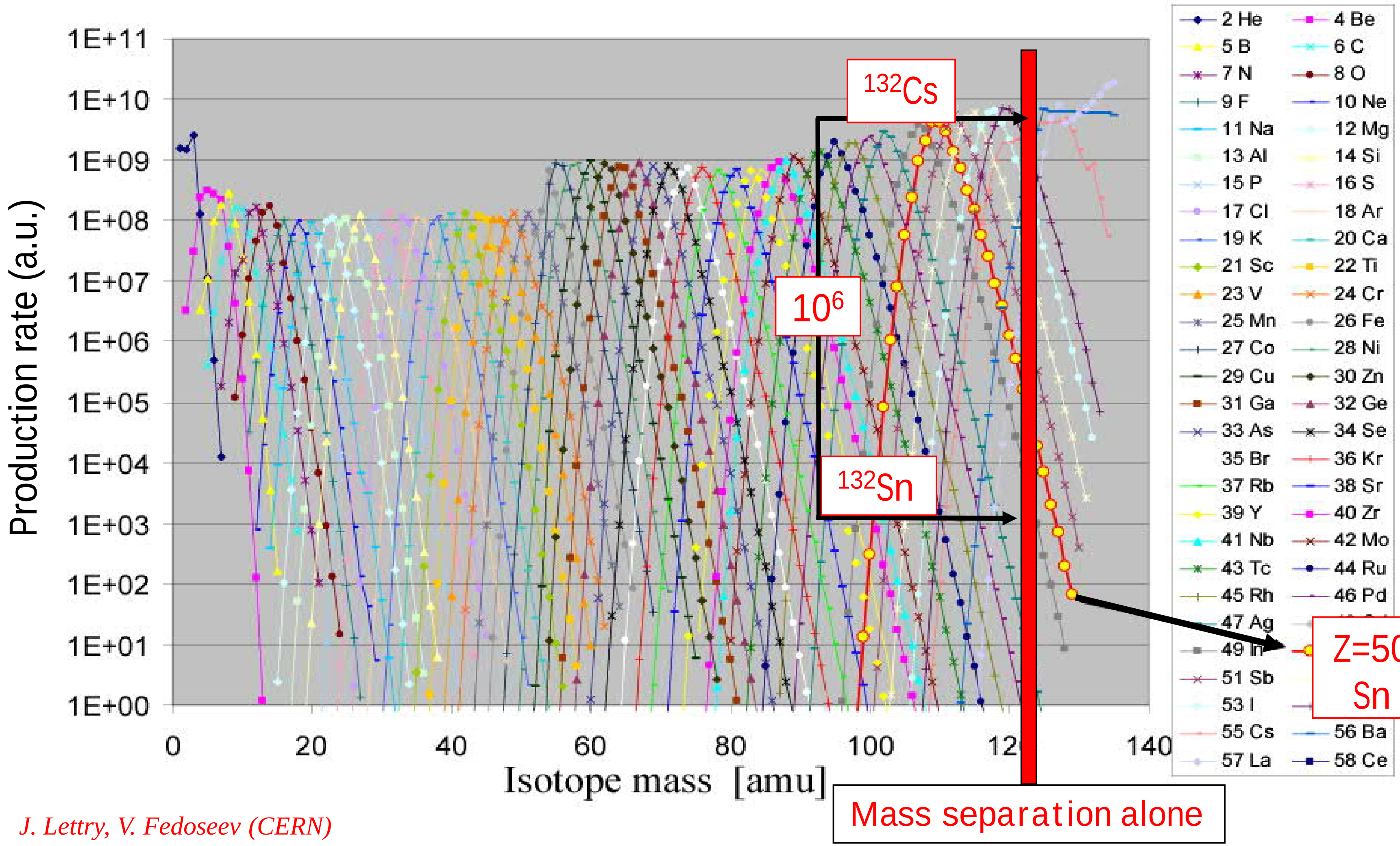
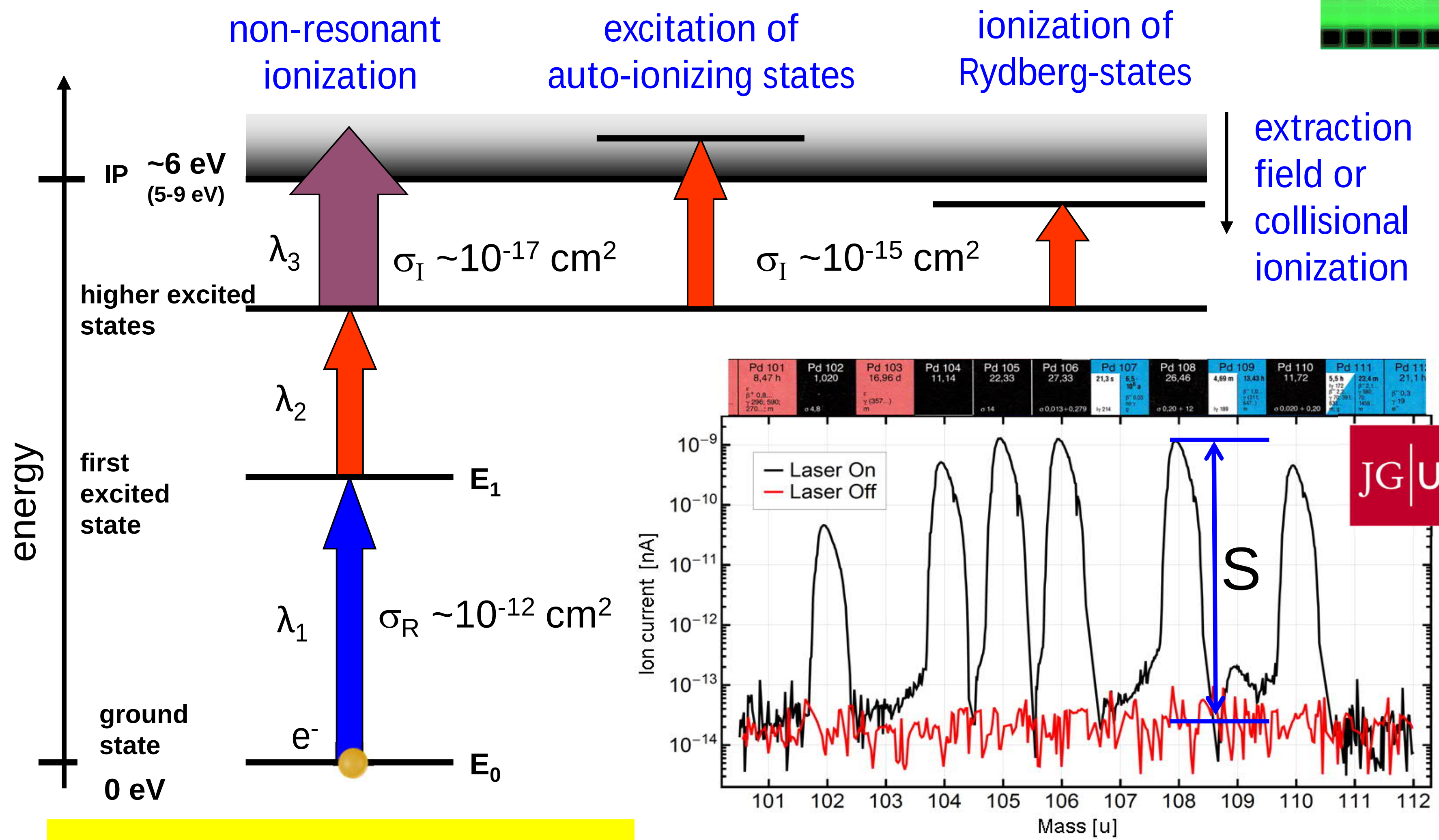
Isotope production for a 1 GeV p beam on a La target



J. Lettry, V. Fedoseev (CERN)

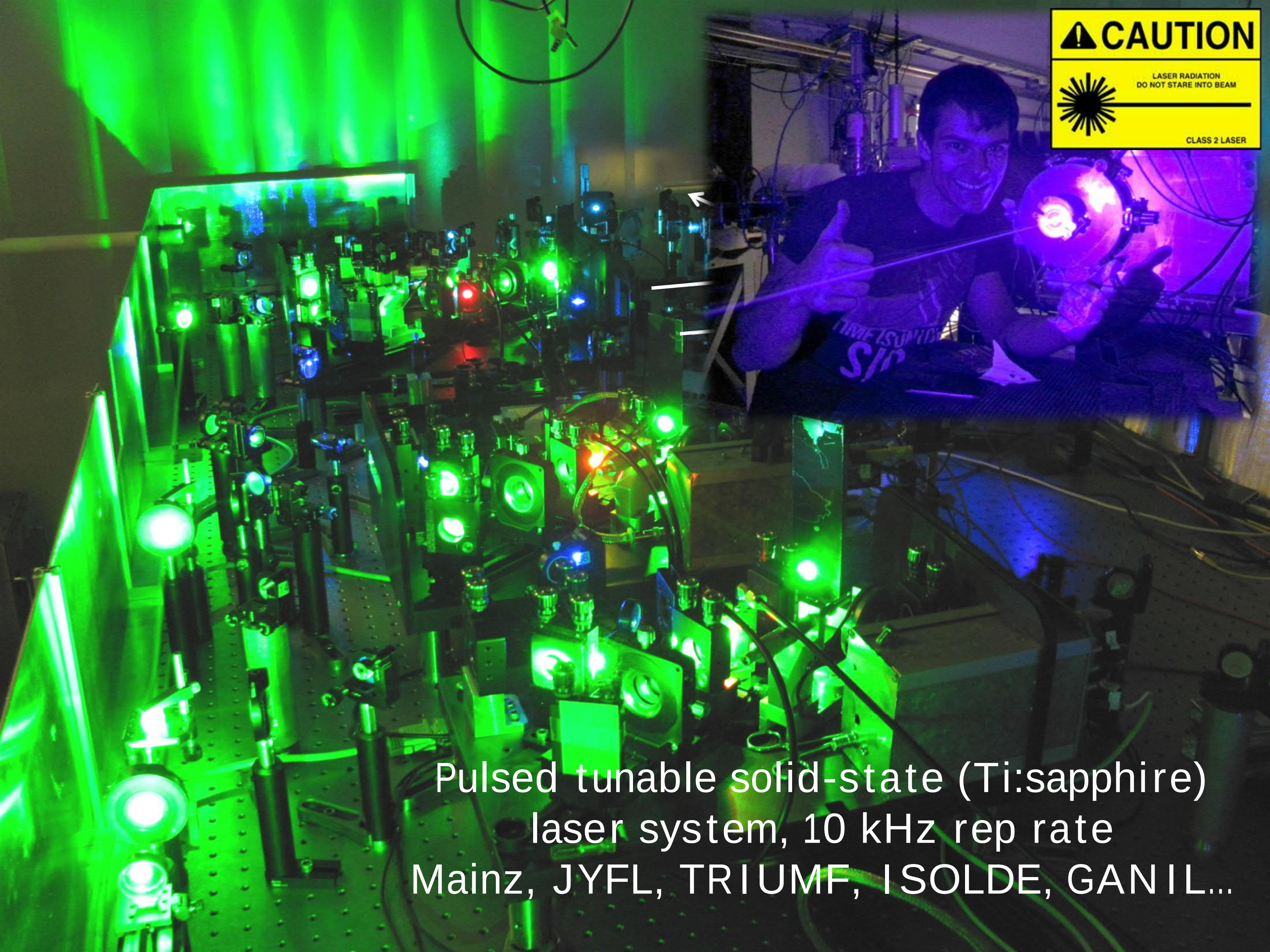
Element selectivity – the atomic fingerprint



SELECTIVITY & EFFICIENCY

Mass scan over all stable Pd isotopes

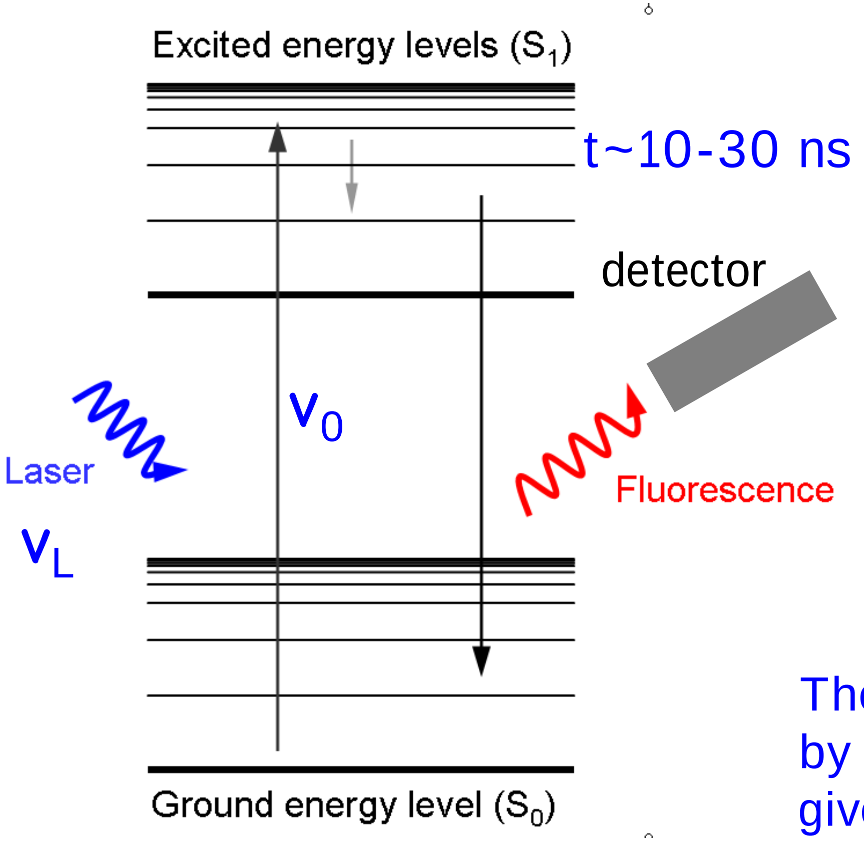
V.N. Fedosseev, Y. Kudryavtsev, V.I. Mishin, Phys. Scr. 85 (2012) 058104

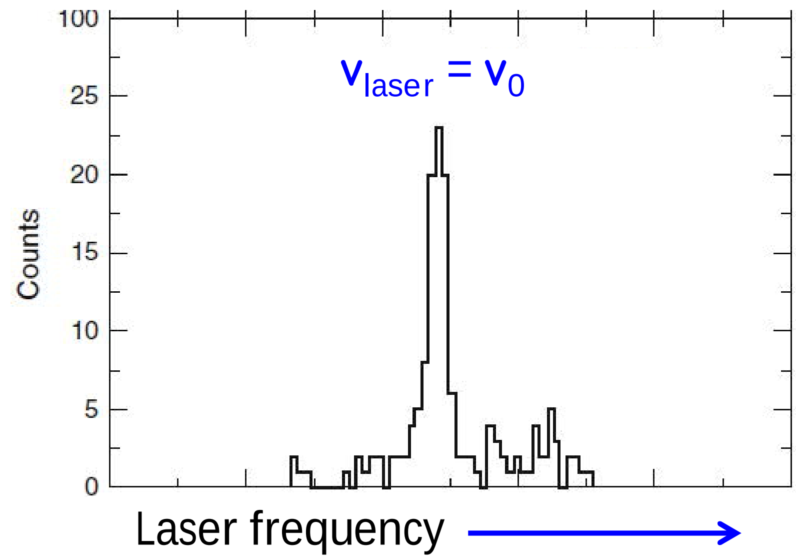


Pulsed tunable solid-state (Ti:sapphire)
laser system, 10 kHz rep rate
Mainz, JYFL, TRIUMF, ISOLDE, GANIL...


Brief pause, let’s take a moment to enjoy the company
of this exotic (locally bred) animal….

What is optical (laser) spectroscopy?





When $\nu_L = \nu_0$,
resonant absorption.

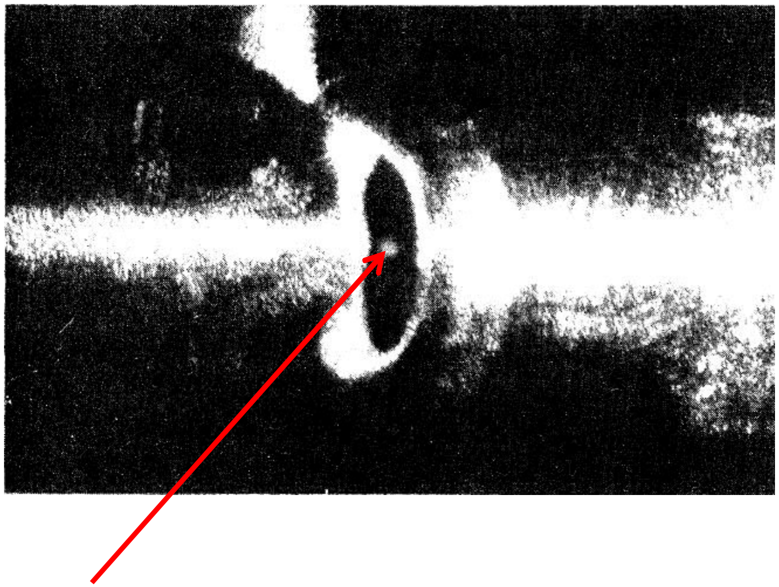
$\sigma \approx \lambda^2 / 2\pi$

The absorption cross section of a photon by an atom and subsequent relaxation is given by a Lorentzian function:

$$\sigma = \frac{\lambda^2}{2\pi}\left\{\frac{1}{1+[4\pi\tau(\nu-\nu_0)]^2}\right\}$$

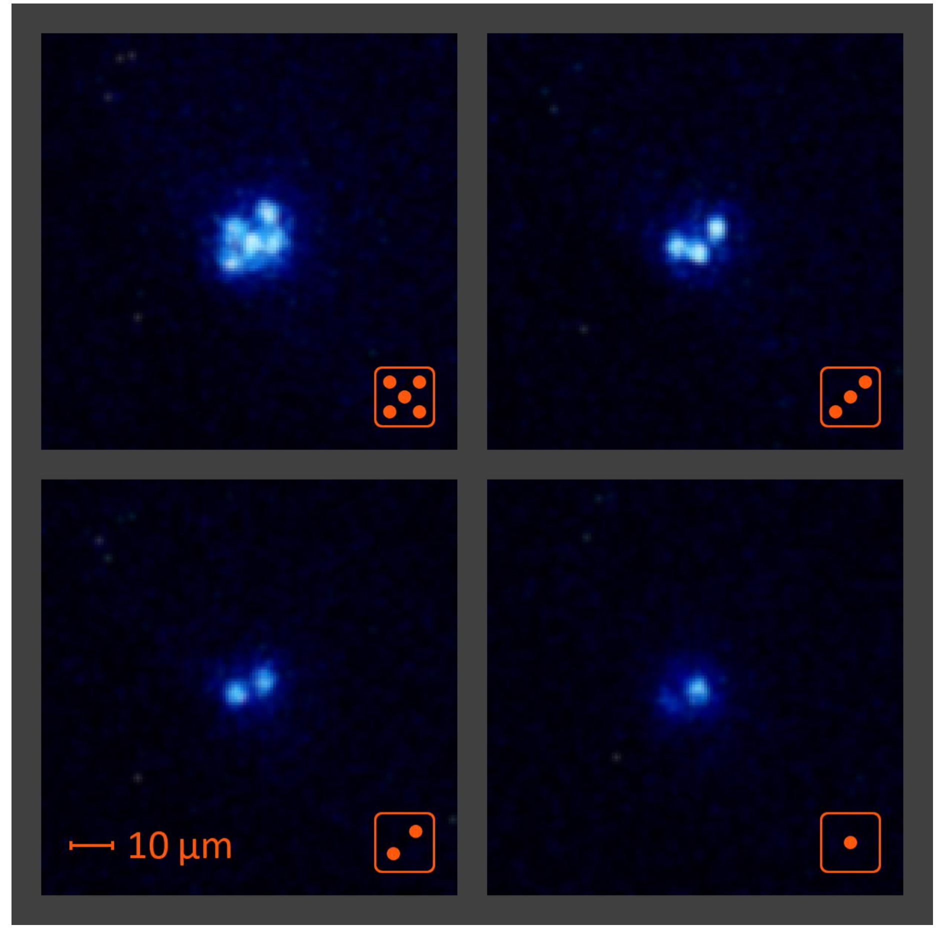
I.D. Moore, EJC 2021

Detection of single trapped barium ions



A trapped Ba^+ ion cloud with estimated number <50 ions in the cloud

W. Neuhauser et al, PRL 41 (1978) 233

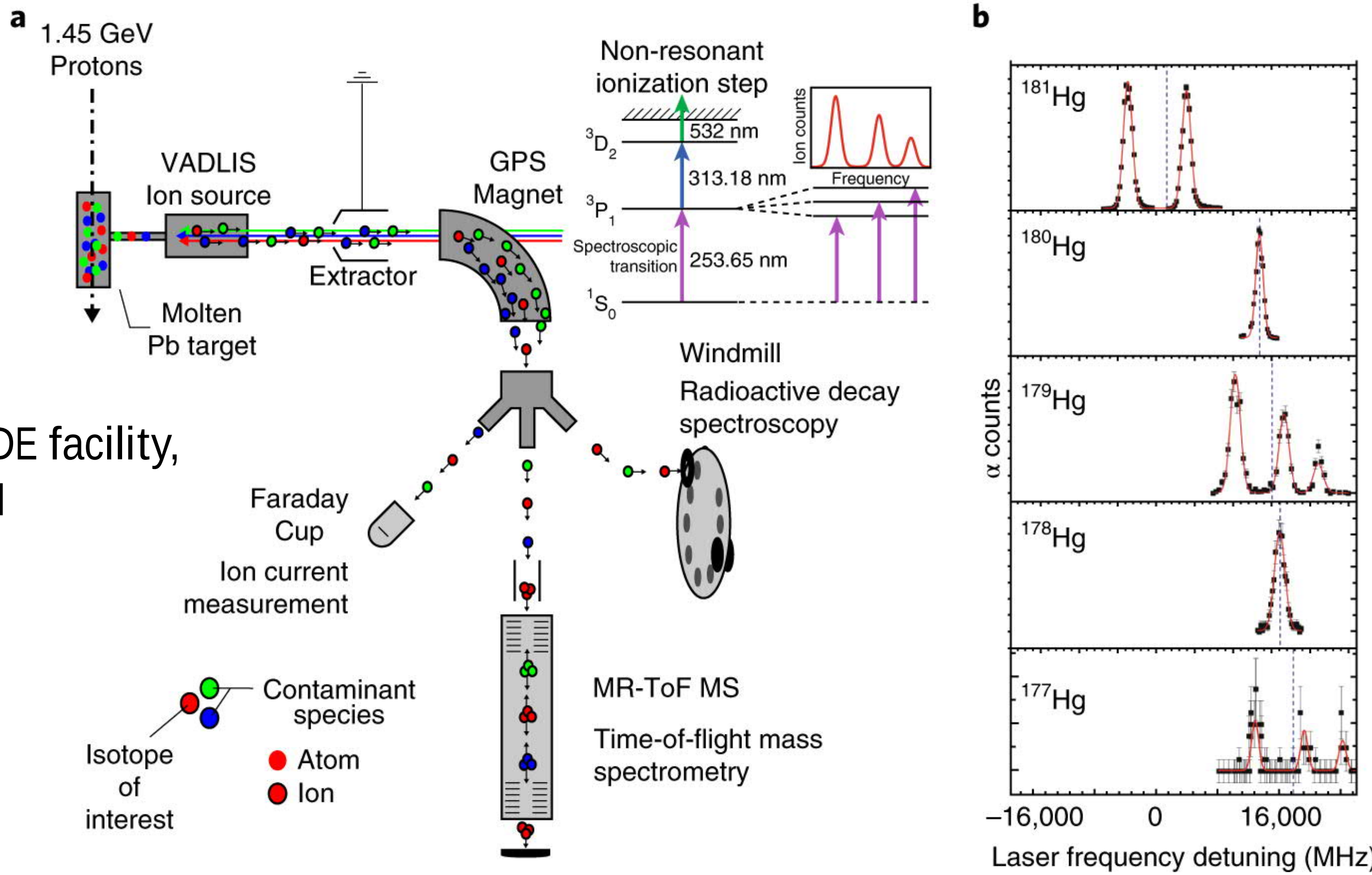


Individual trapped laser-cooled Ba^+ ions (Courtesy of the TRIµP group, former KVI)

Ruben will discuss barium as an example of a precision measurement

Resonance ionization spectroscopy (RIS)

In a variant to laser ionization for RIB production, we can tune the laser frequency of a chosen transition = Resonance Ionization Spectroscopy (RIS). The lasers are sent into the ion source and the wavelength of an atomic excitation step is scanned.



ISOLDE facility, CERN

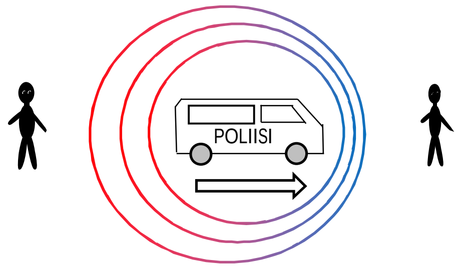
Nuclear spin

	Nuclear spin
^{181}Hg	½$^-$
^{180}Hg	0^+
^{179}Hg	$(7/2^-)$
^{178}Hg	0^+
^{177}Hg	$(7/2^-)$

B. Marsh et al., Nature Phys. 14 (2018) 1163

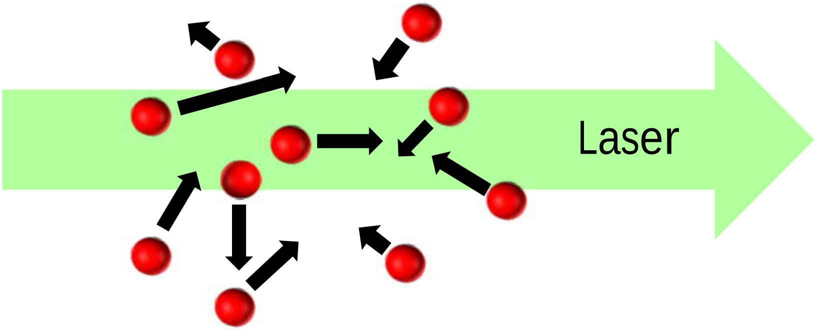
The ``achilles heel´´ of optical spectroscopy

The observed transition linewidth can be broadened by Doppler effects



Doppler shift

$$f' = f_0 \left(1 \pm \frac{v}{c}\right)$$



Doppler broadening

Thermal motion is a Maxwell-Boltzmann probability distribution. Causes a spread of frequencies observed by atoms

$$P(f)df \propto \exp\left(-\frac{mc^2 (f - f_0)^2}{2k_b T f_0^2}\right)df$$

$$\Delta_{FWHM} = f_0 \sqrt{\frac{8k_b T \ln 2}{mc^2}}$$

Doppler broadening

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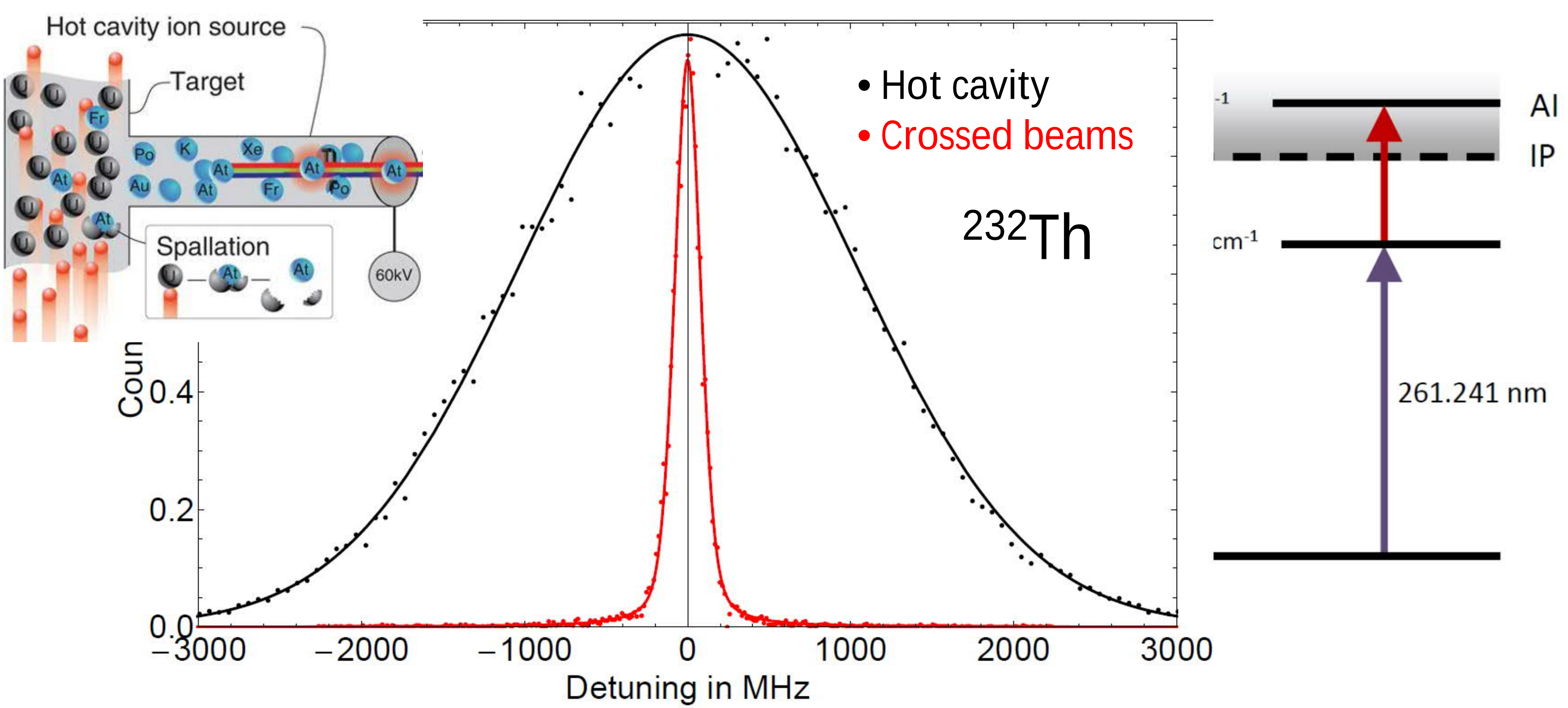
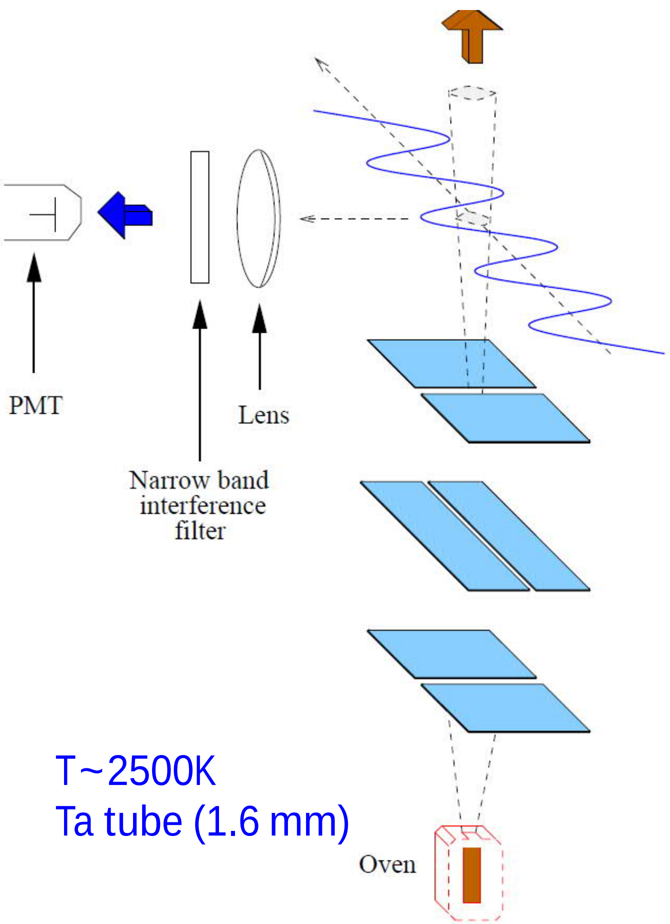


Natural linewidth 35 MHz; spectral linewidth 2.4 GHz (in oven), 170 MHz (crossed beams configuration)

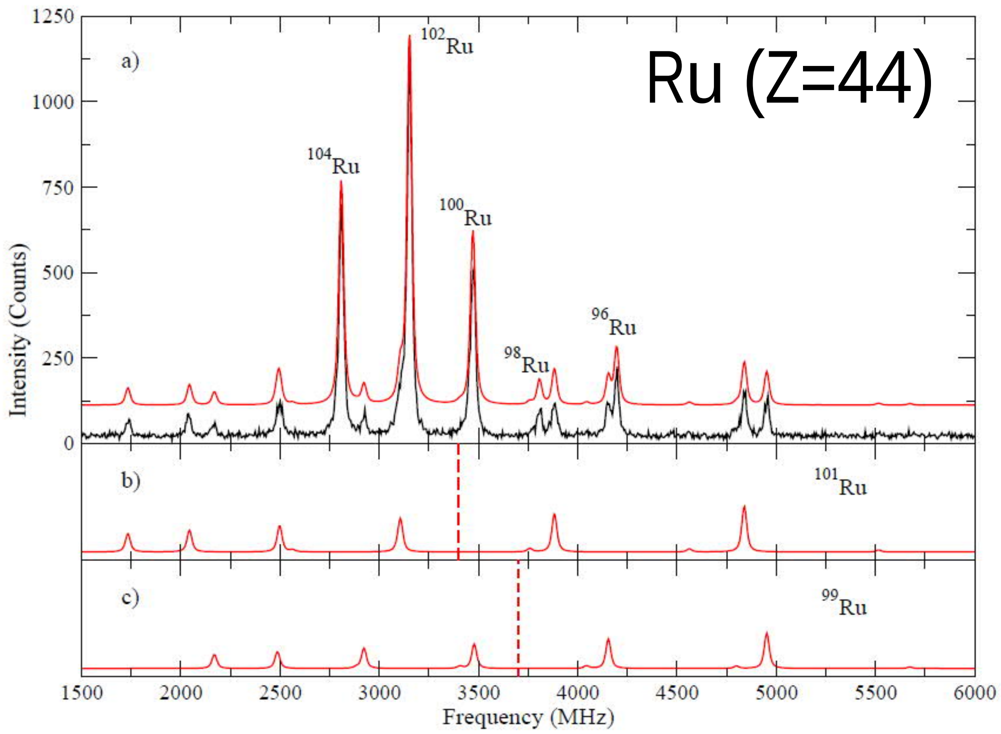
The Doppler broadening is often comparable or greater than HFS or IS!

Crossed atomic beam laser spectroscopy

Incident laser beam interacts perpendicularly with a collimated beam of atoms. Resonant photons are detected orthogonally.



T~2500K
Ta tube (1.6 mm)



- 5 even-even isotopes
- 2 odd-A isotopes (15 HF components each)

D.H. Forest et al., J. Phys. G 41 (2014) 025106

Power broadening

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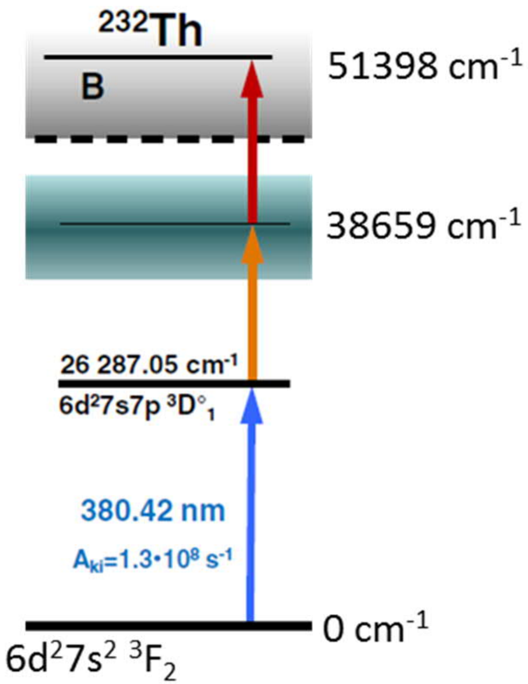
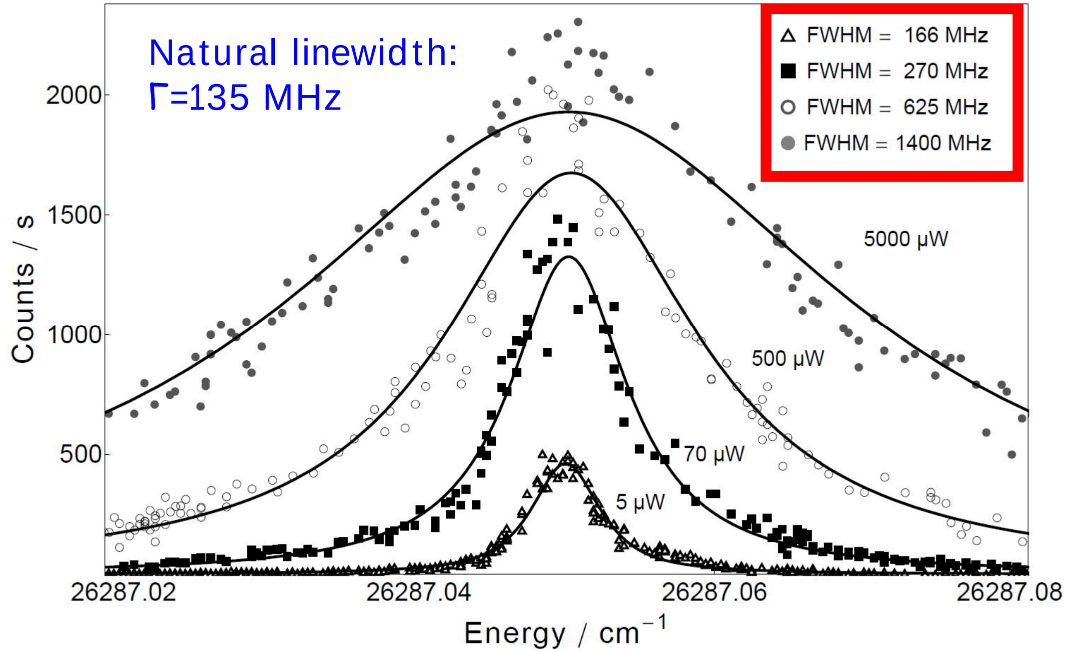
Another source is due to the laser intensity – power broadening.





V. Sonnenschein, I.D. Moore et al., EPJA 48 (2012) 52

- For RIB production: optimum efficiency
- For spectroscopy we trade efficiency for spectroscopic resolution

$$\Gamma_{power} = \Gamma_{nat}\sqrt{1 + {}^{I}/{}_{I_{sat}}}$$

Pressure broadening (in-gas cell RIS)

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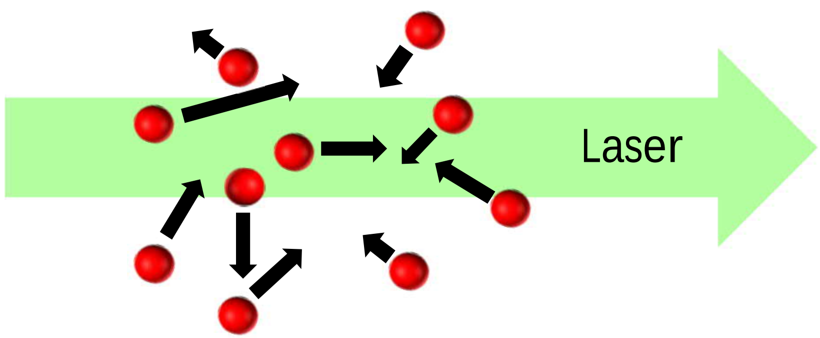
In a similar drawback to the ISOL (hot cavity) approach, the spectral resolution of an atomic resonance suffers within the gas cell – pressure broadening and shifts due to collisions with buffer gas atoms.

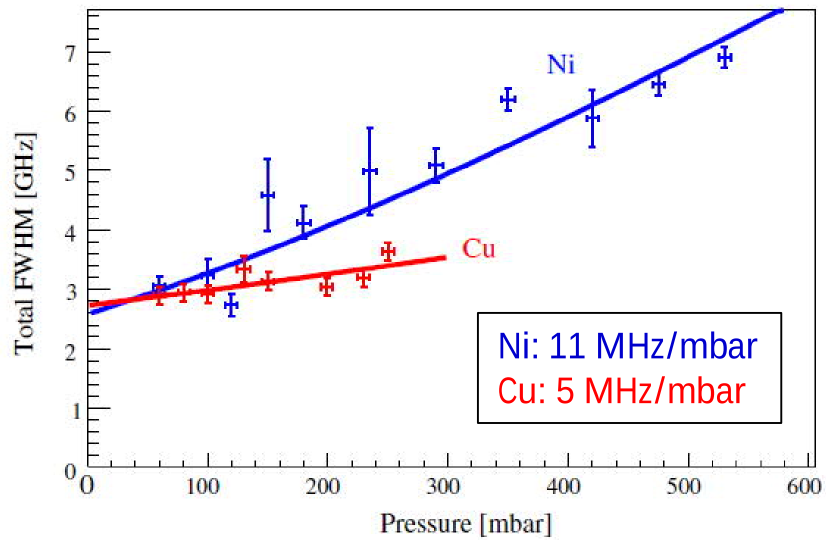


Doppler + Collisional

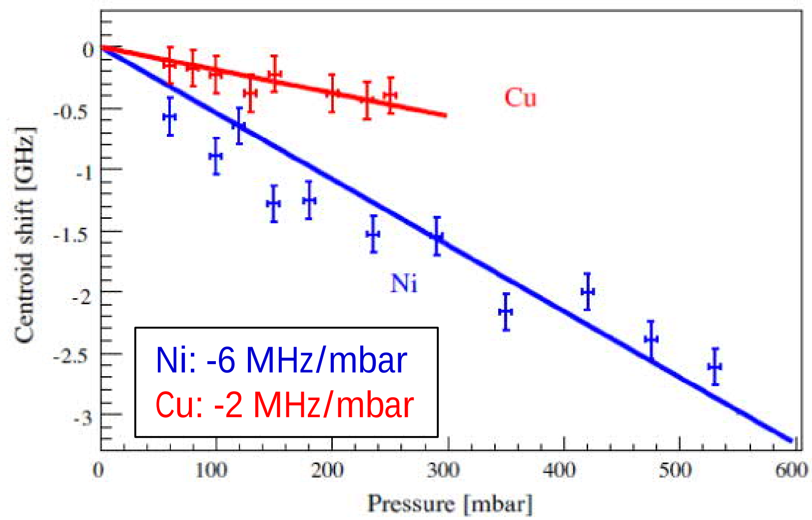
- Element dependent
- Shifts can be +/-

T. Sonoda et al., NIMB 267 (2009) 2918

Pressure broadening



Pressure shift



In-gas cell RIS of stable tin isotopes

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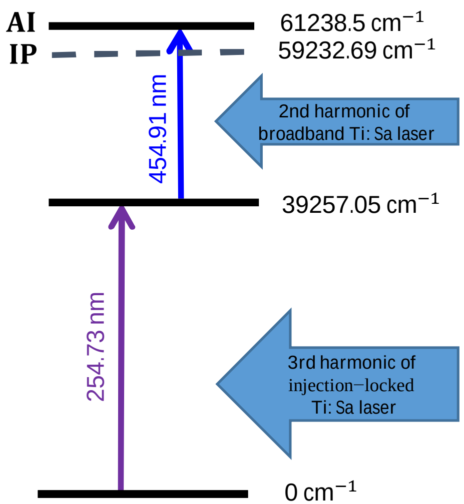

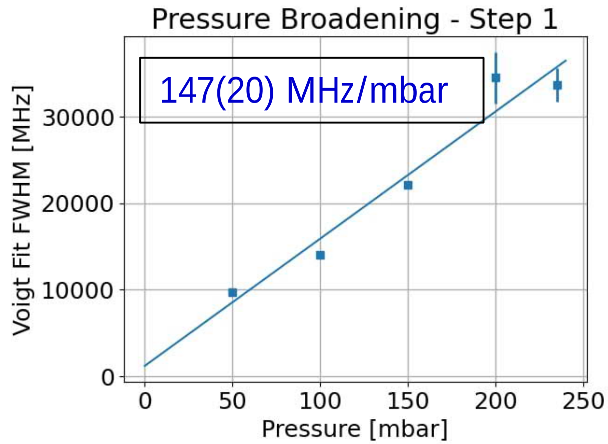

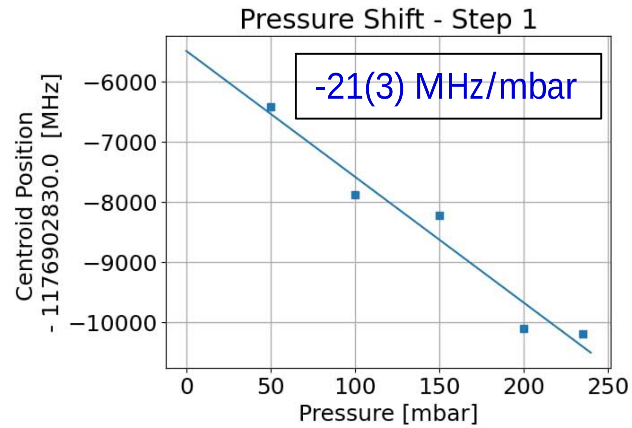

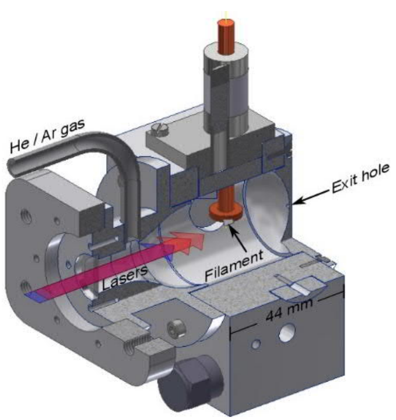

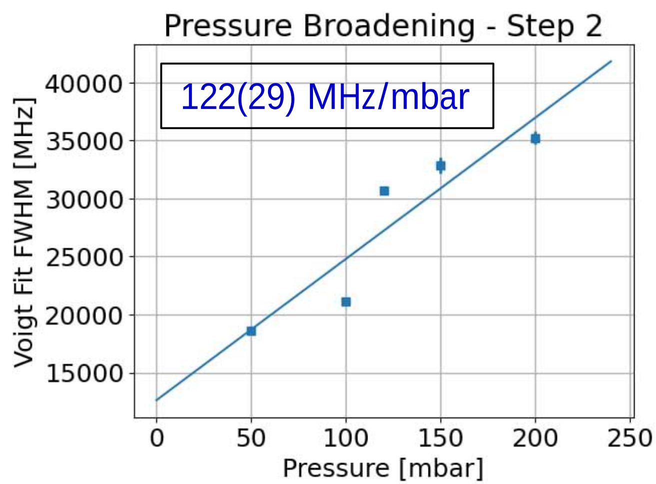

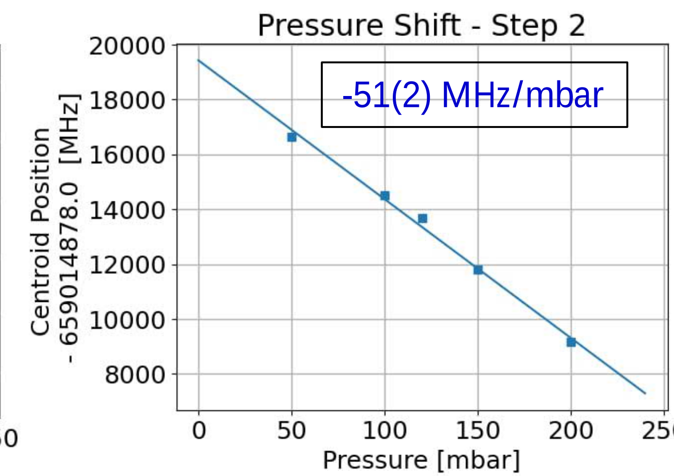

For more details, please visit the poster of J. Romero!

Gas jets: a cold environment for spectroscopy

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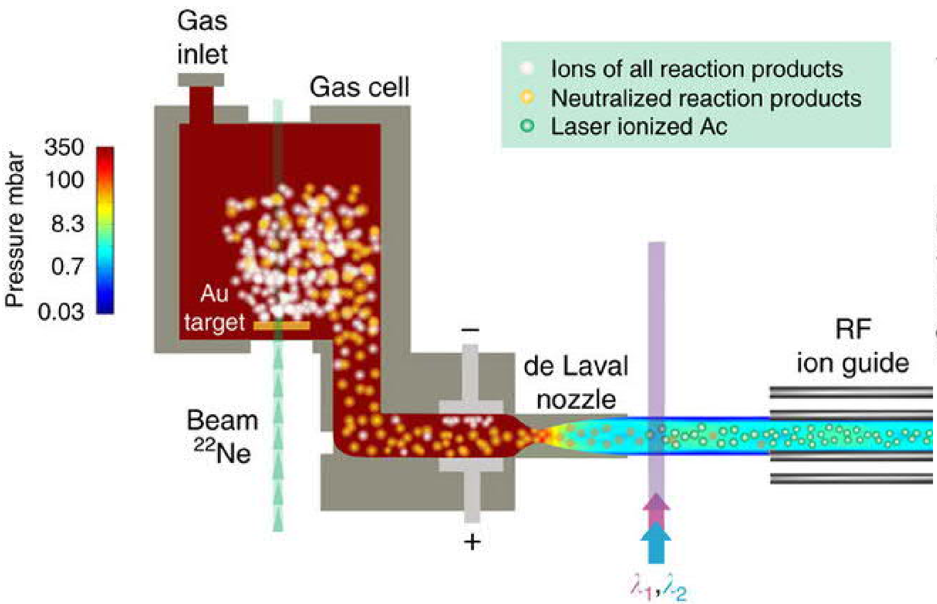
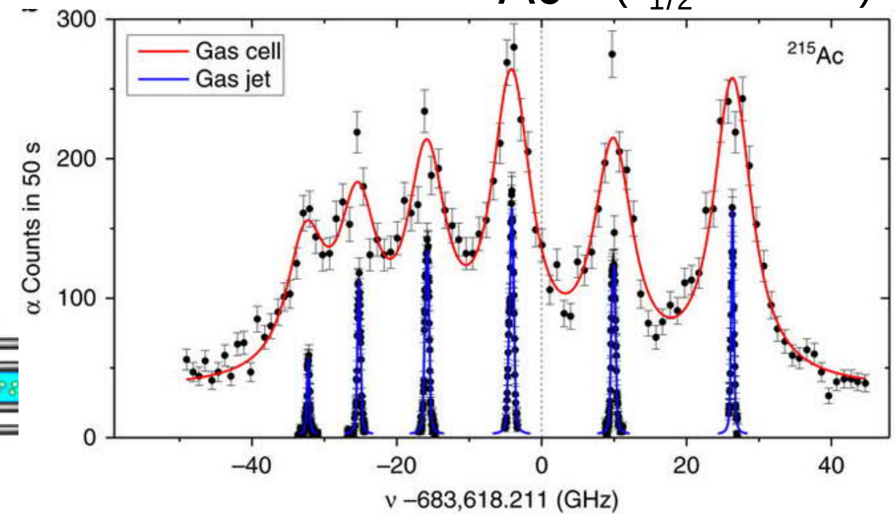
Current efforts are invested into exploiting the gas-jet enviroment, in combination with state-of-the-art (injection-seeded) laser systems



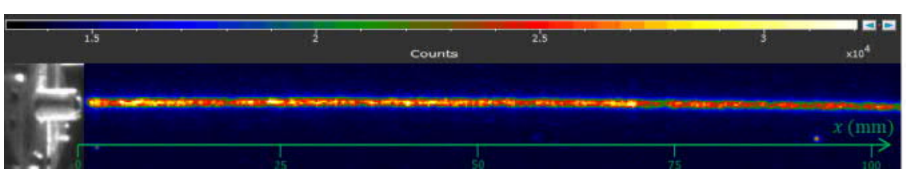
^{215}Ac ($\tau_{1/2}$=170 ms)



- in gas cell - in gas jet

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

Gas jet exploration:



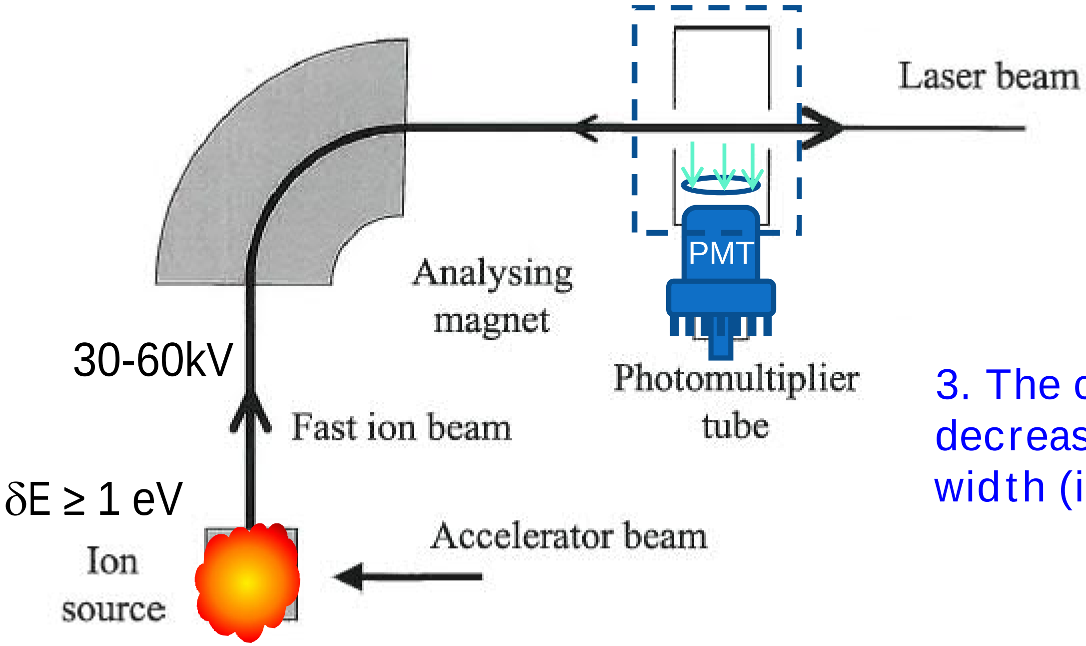
A. Zadvornaya et al., PRX 8 (2018) 041008

Posters of Steven Nothhelfer & Jekabs Romans –gas jet spectroscopy for heavy elements & S3


Brief pause, enjoy scenary and spot the local camouflage

Collinear beams laser spectroscopy

In a collinear geometry, light, whether co- or counter-propagating with the ion beam, interacts with accelerated ionic ensembles.



$$\delta\nu_D = \nu_0 \frac{v}{c}$$ Doppler broadening (frequency space)

1. Accelerate all ions to energy E

$$E = eV = ½mv^2$$

2. The energy spread δE (from source) remains constant

$$\delta E = \delta\left(\frac{mv^2}{2}\right) = mv\delta v = const.$$

3. The corresponding velocity spread is decreased and we obtain the Doppler width (in frequency):

$$\delta\nu_D = \nu_0 \frac{\delta E}{\sqrt{2eVmc^2}}$$

S.L. Kaufmann, Opt. Comm. ***17*** *(1976) 309*

W.H. Wing et al., PRL ***36*** *(1976) 1488*

The effect of the velocity compression

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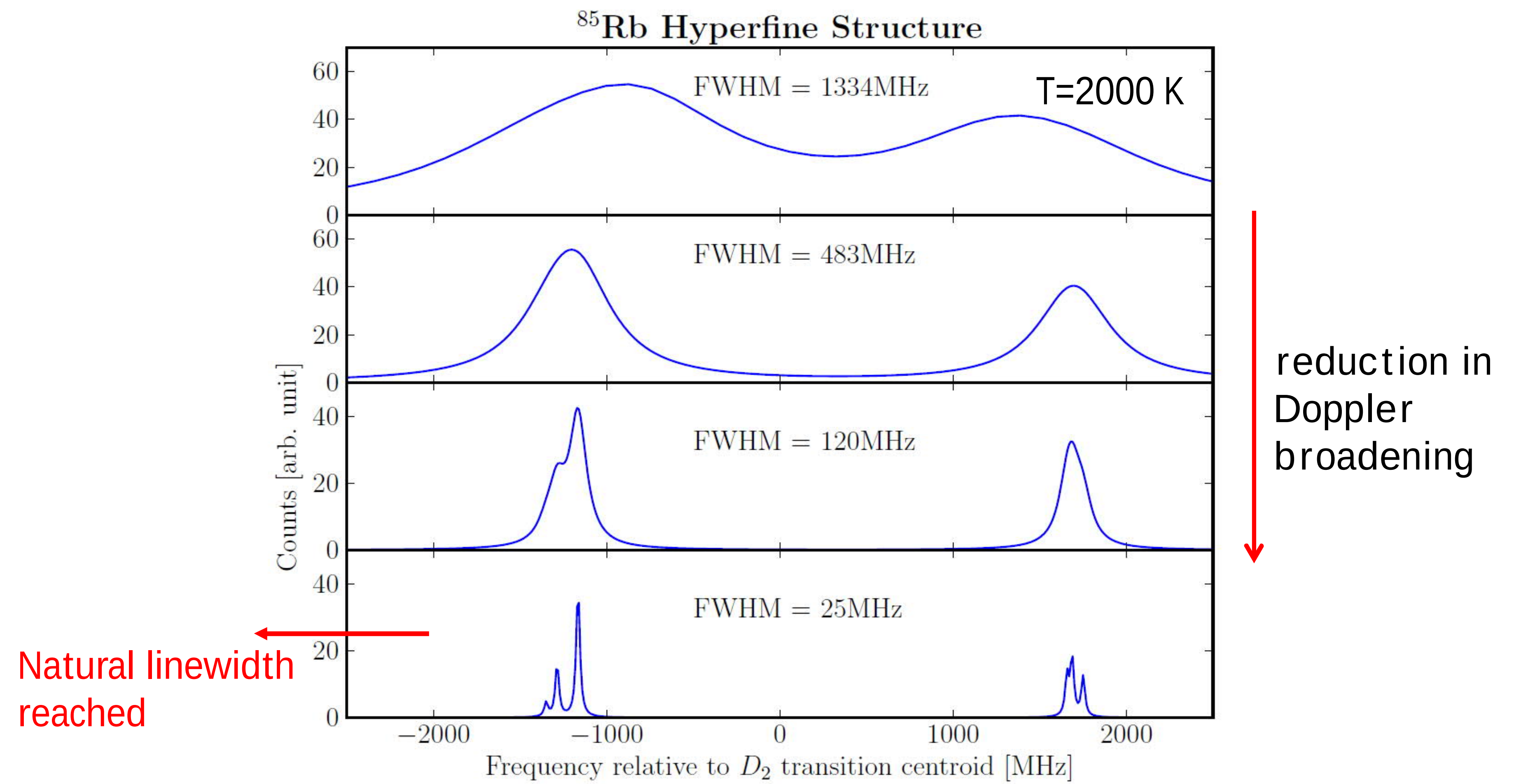
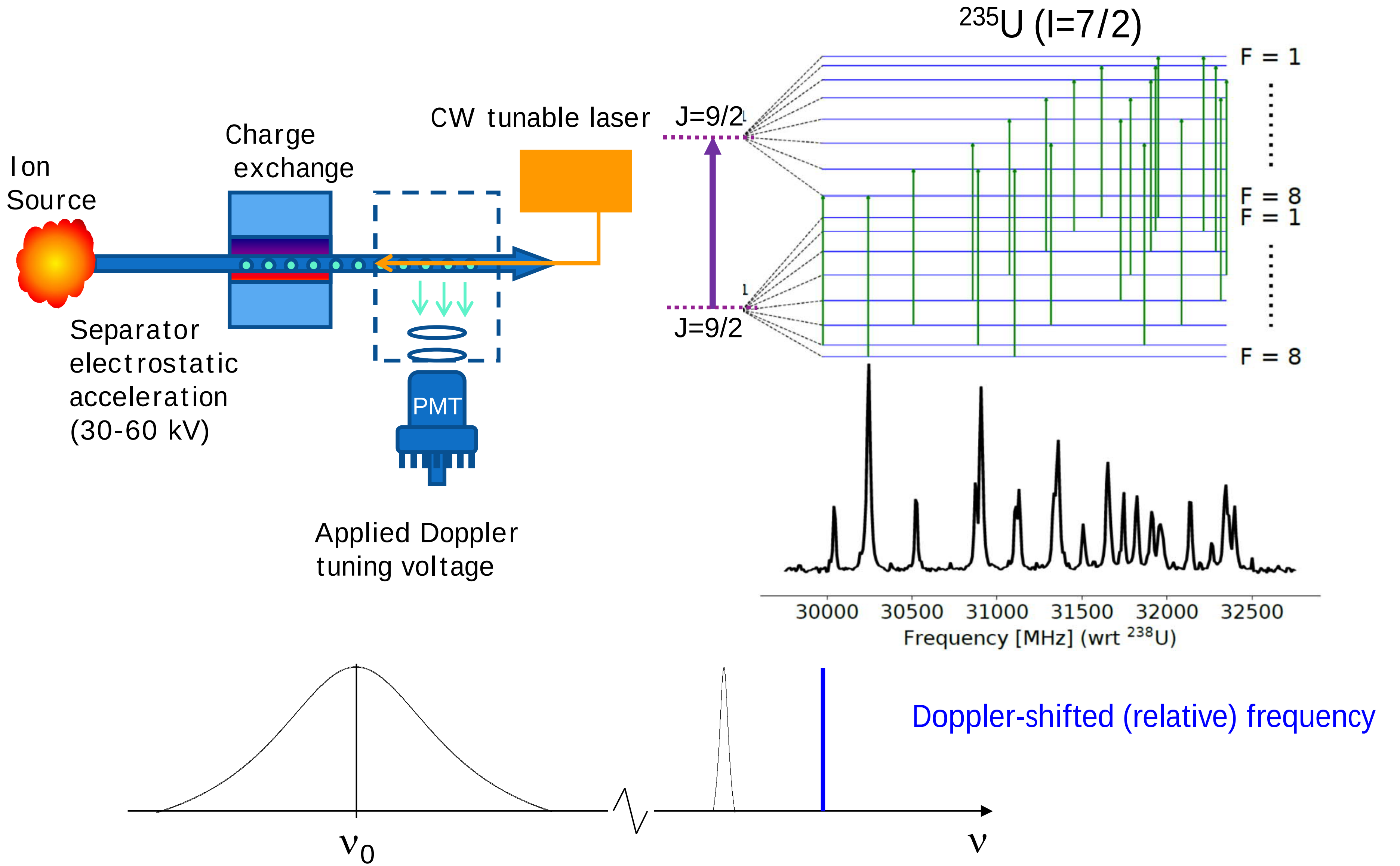


Typical ion source energy spreads are ~1 eV. Acceleration of medium-mass nuclei to 30 keV produces a 3 order of magnitude velocity compression

Doppler tuning the ion/atom beam



I.D. Moore, EJC 2021

Count rates for low flux ion beams

The collinear beams technique has high sensitivity. All ions/atoms pass through the laser beam and contribute to the fluorescent signal.

However……

Signal (laser on resonance) =
1 photon detected per 1,000 ions in beam

Background (laser light scatter) = 200 photons / sec
(per mW of laser light)

Low-flux beams (1,000 ions / sec): background must be suppressed to see signal.

Photon-ion coincidence technique

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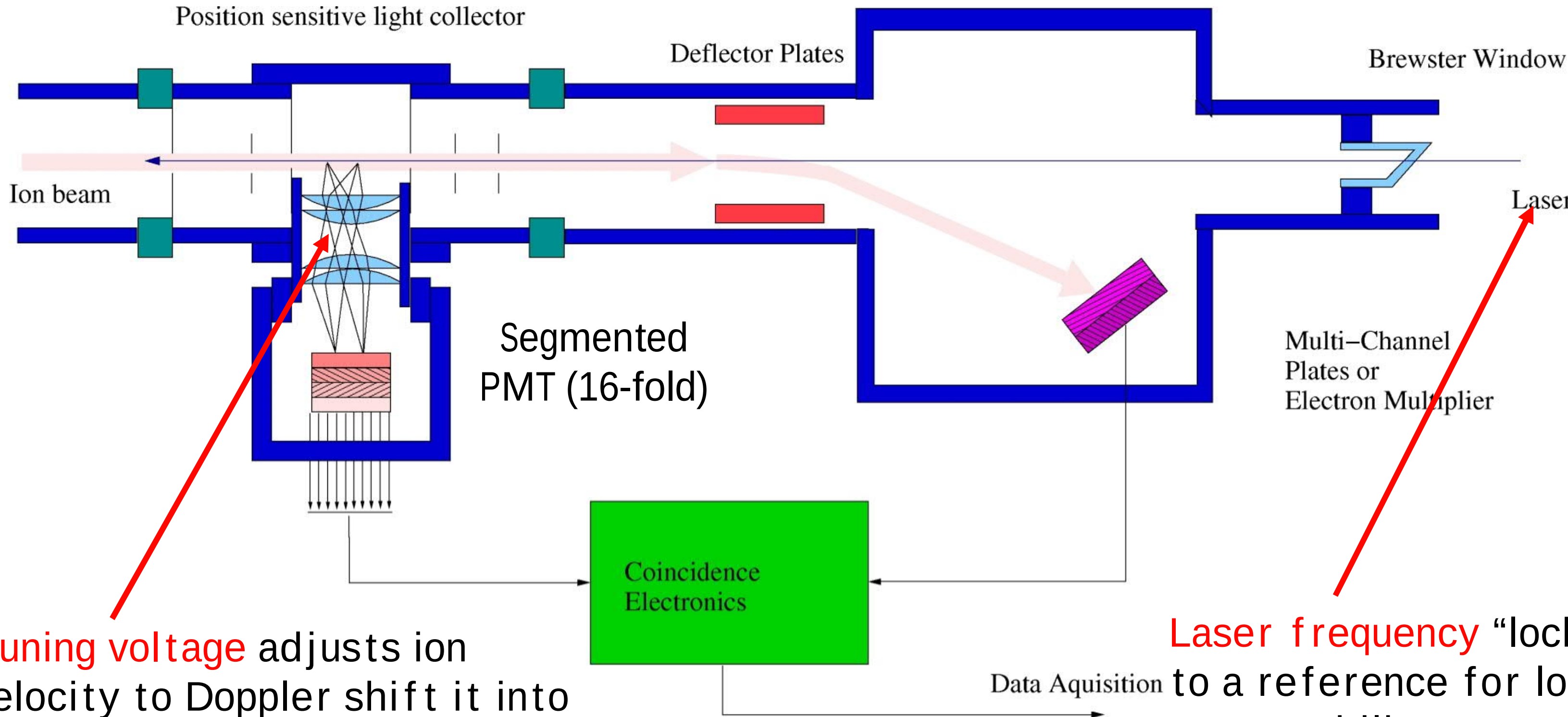
The laser-ion interaction region



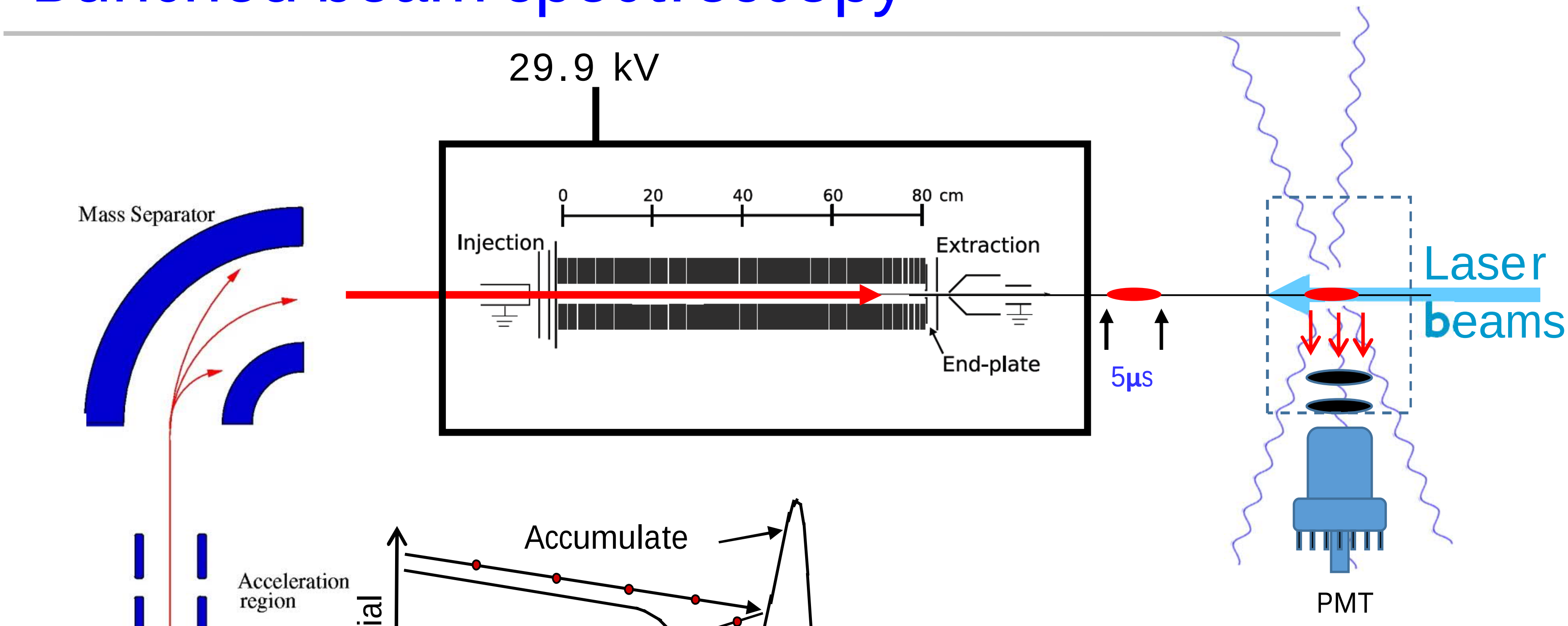
Tuning voltage adjusts ion velocity to Doppler shift it into resonance with locked laser

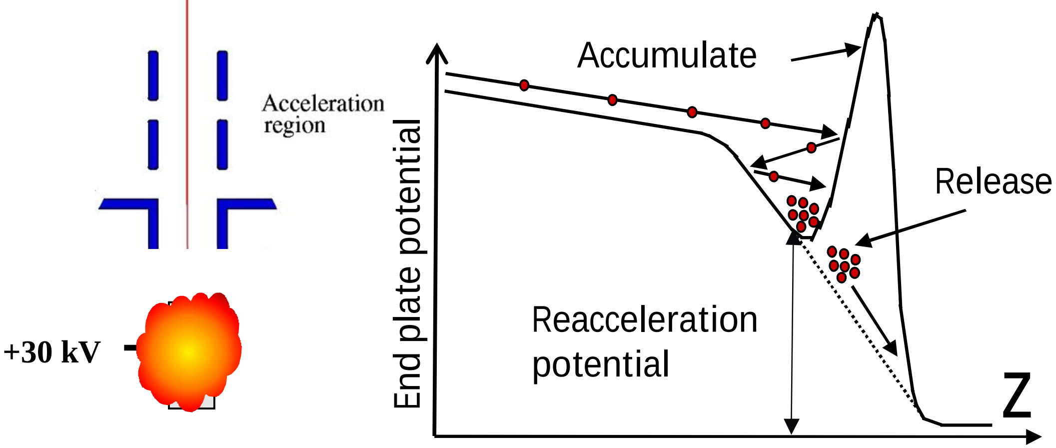
Laser frequency "locked" to a reference for long-term stability

Accept photons in delayed coincidence with the corresponding ion (or atom). Position sensitivity along the detection region can enhance the time resolution (to ~20 ns).

D.A. Eastham et al., Opt. Commun. ***82 (1-2)*** *(1991) 23*

Bunched beam spectroscopy





- Helium-filled radio-frequency trap
- Ion beam accumulated 10 - 100s of ms
- Released as a few μs bunch

Accept photons in a time window during which the bunched beam passes. Temporal background compression of $\sim 10^4$ routinely achieved.

*P. Campbell et al., PRL **89** (2002) 082501*

Photon-ion coincidence vs. bunched beams

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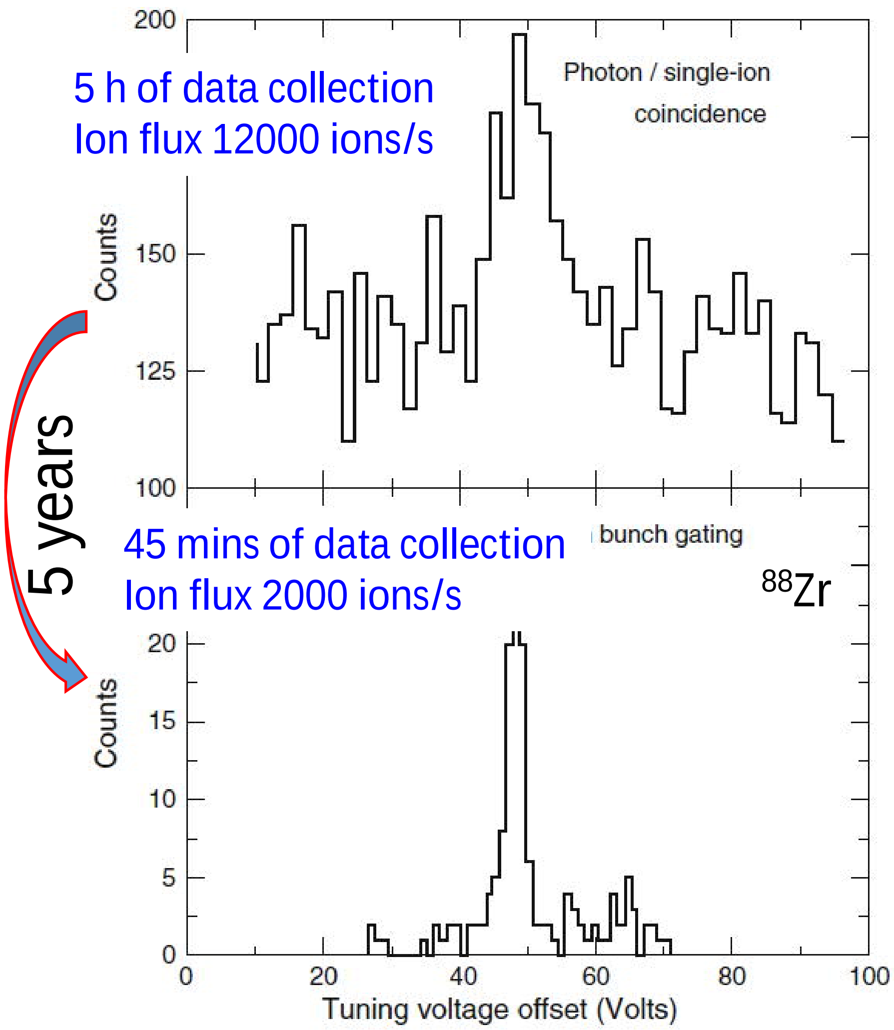
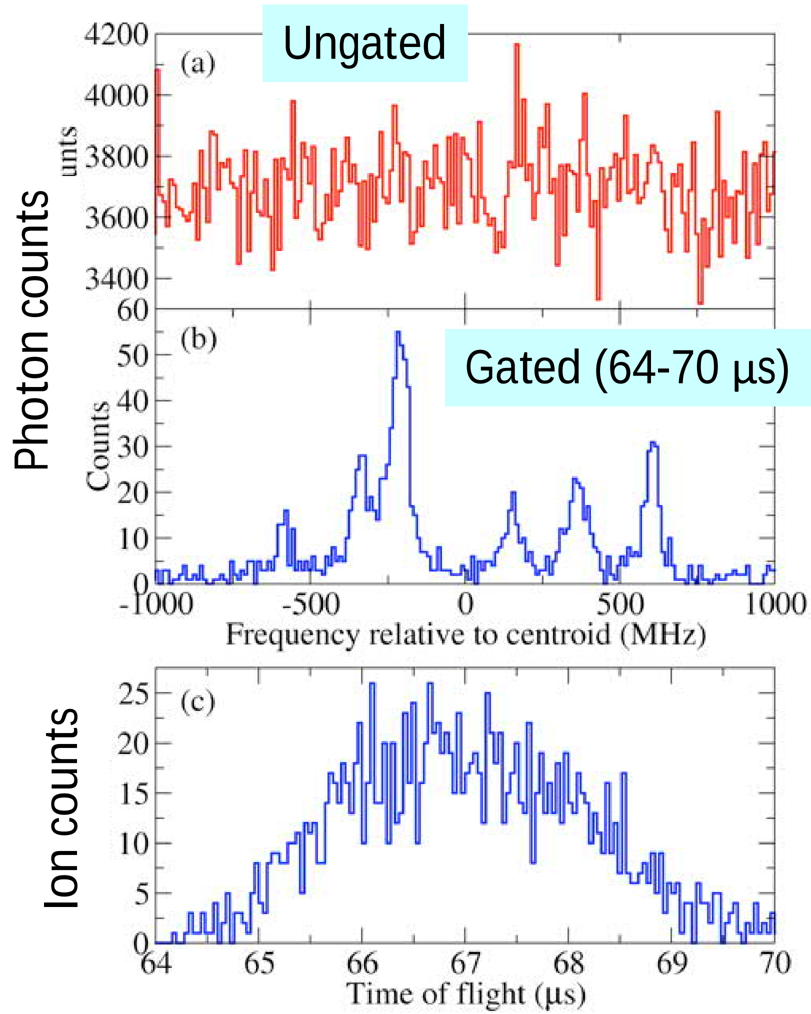


B. Cheal and D.H. Forest, Hyp. Int. ***223*** *(2014) 63*



E. Mané et al., PRC ***84*** *(2011) 024303*

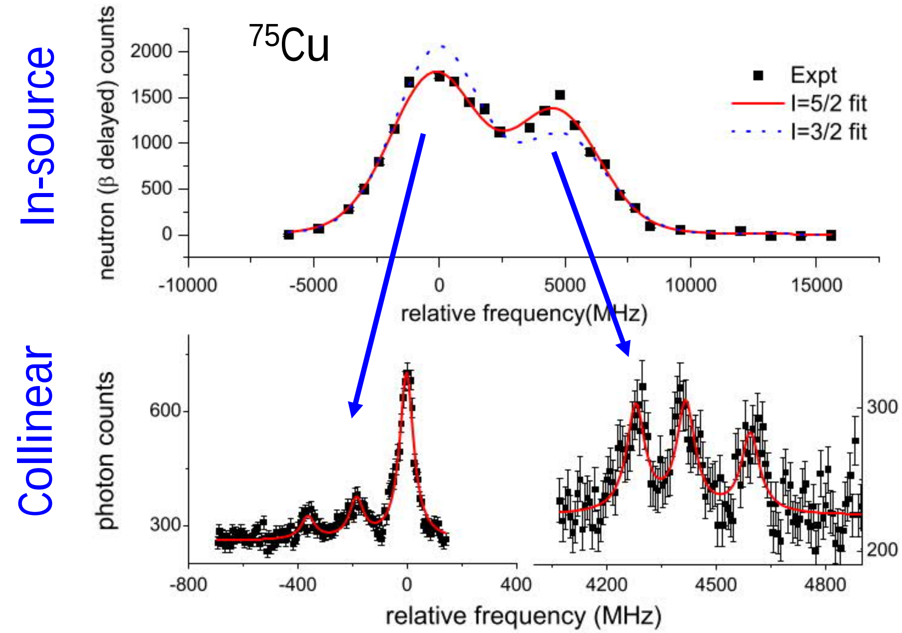
Complementarity in the techniques

IN-SOURCE (RIS)

- Selective process
- Short lifetimes, low yields (<1 ion/s)
- High detection efficiency
- Poor resolution (100-1000× < CLS)

COLLINEAR

- High resolution
- Scanning voltage, not frequency
- Detect photons
- Beams of some 10^3 ions/s



- In-source laser spectroscopy at ISOLDE used for a low-resolution probe of ^{75}Cu HFS
- High-resolution collinear laser spectroscopy resolved both atomic ground and excited state HFS

K.T. Flanagan et al., Phys. Rev. Lett. 103 (2009) 142501

Certainly not the end of the story….

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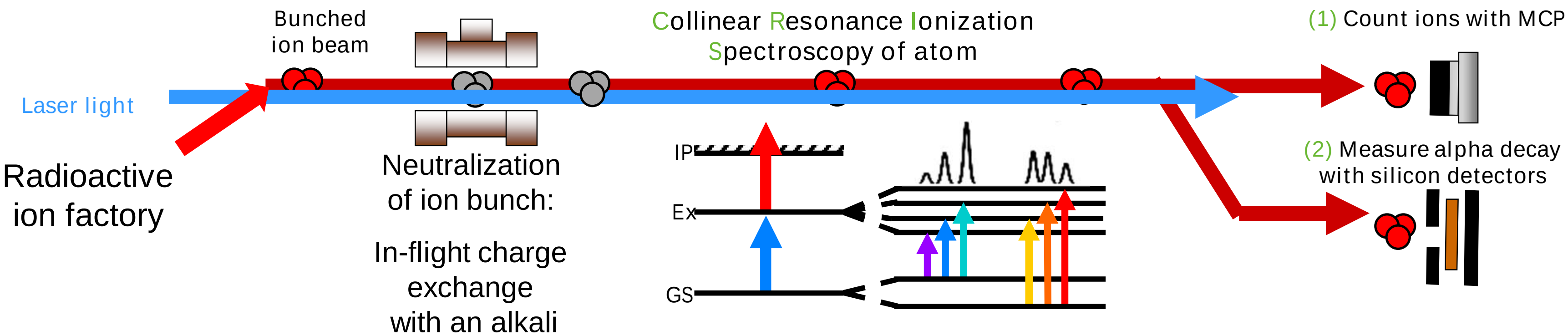
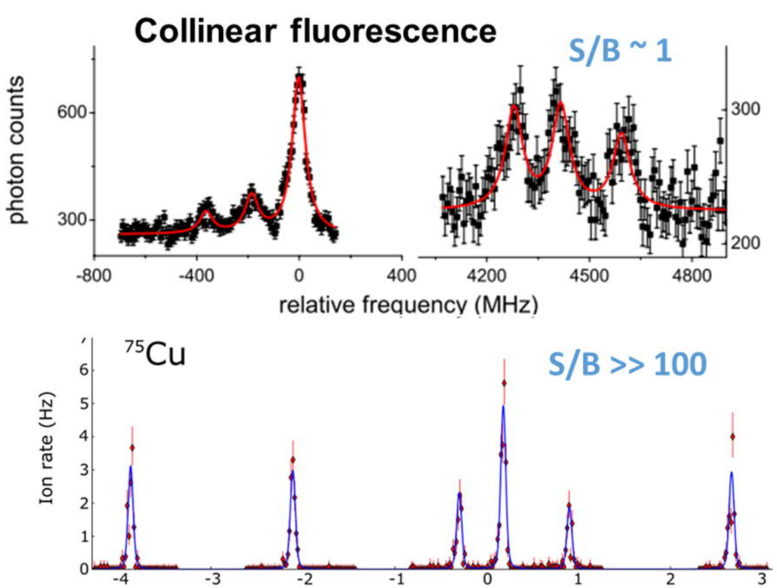
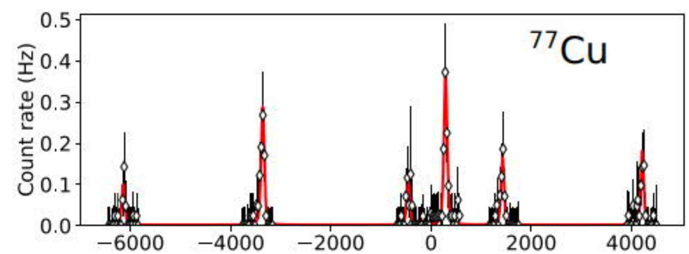
Collinear resonance ionization spectroscopy





CRIS: improving the experimental sensitivity by ×300…



R.P. de Groote et al., Phys. Rev. C 96 (2017) 041302(R)

Poster of Sonja Kujänpää – recent results from CRIS & RAPTOR development

We have work to do so welcome new faces!

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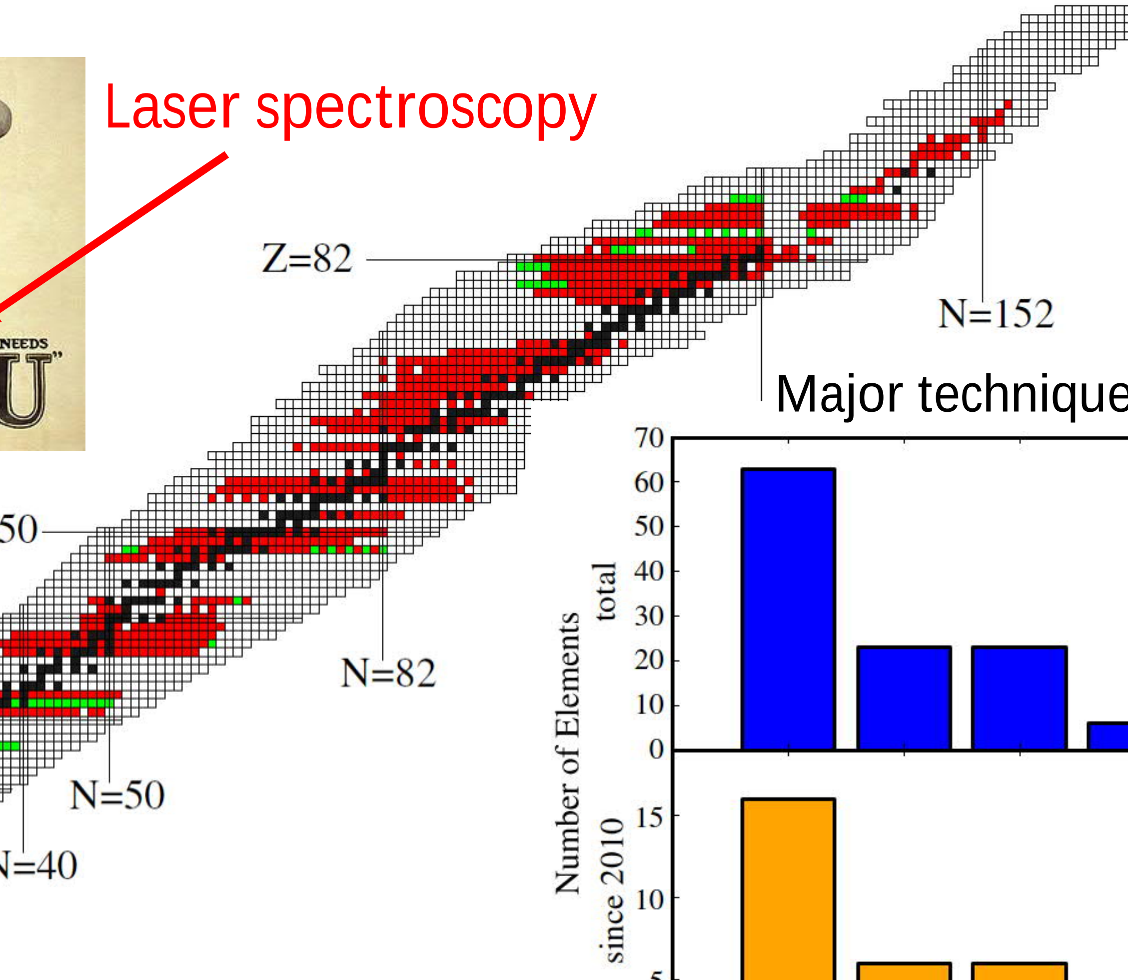
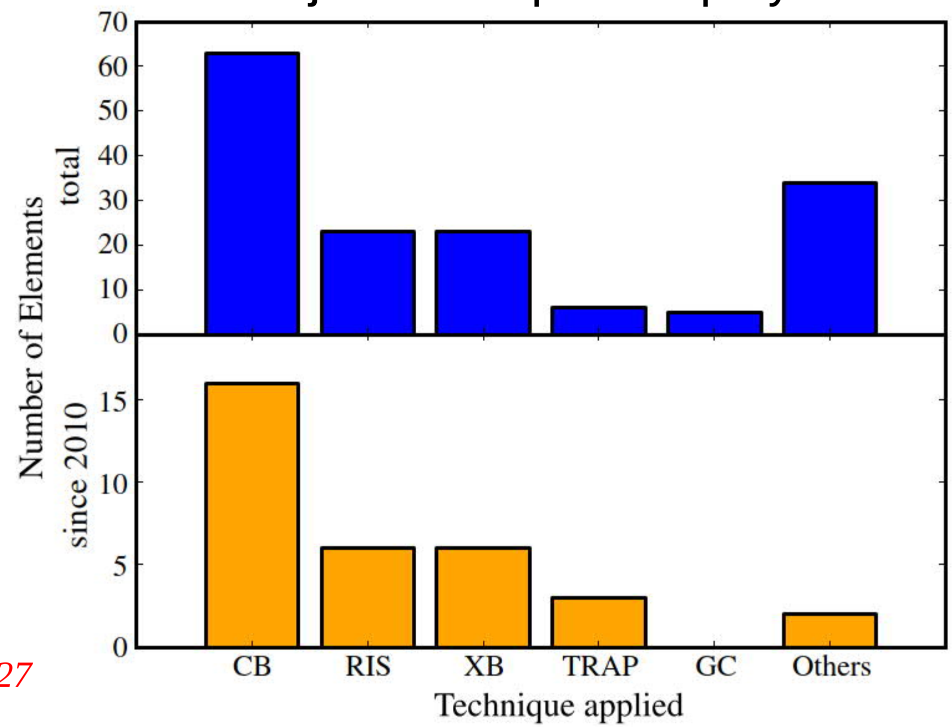
Laser spectroscopy



Major techniques employed



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

Summary

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- Laser spectroscopy of radioactive nuclei features (or is planned) at almost all online radioactive ion beam facilities
- Our spectroscopy can be performed at both ISOL (traditional) as well as fragmentation facilities (via gas catcher developments)
- Element selectivity is critically important in RIB production and laser ion sources are widely used/planned (ISOL)
- Lower-resolution in-source methods are complementary to high-resolution techniques and are often used ”together”
- New techniques both in ion and optical manipulation as well as laser developments help to keep the field thriving
- Many techniques not discussed (ion/atom traps, MIRACLS...), other variants in the detection techniques of the collinear method

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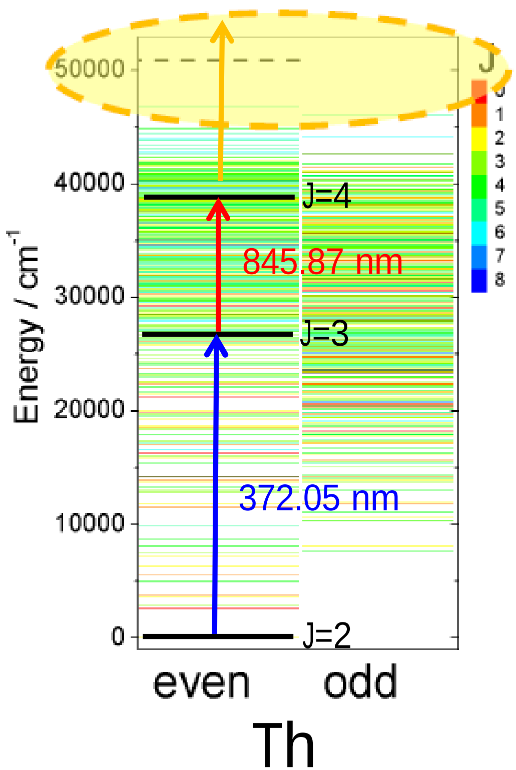
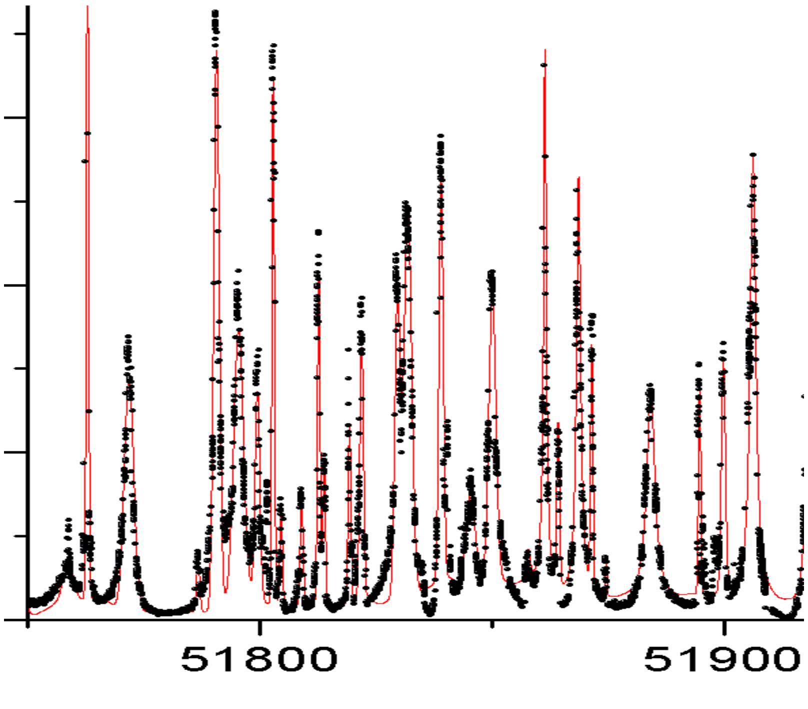
How do we develop the ionization scheme

Literature Search

On-line atomic spectral line databases, published spectroscopy work.

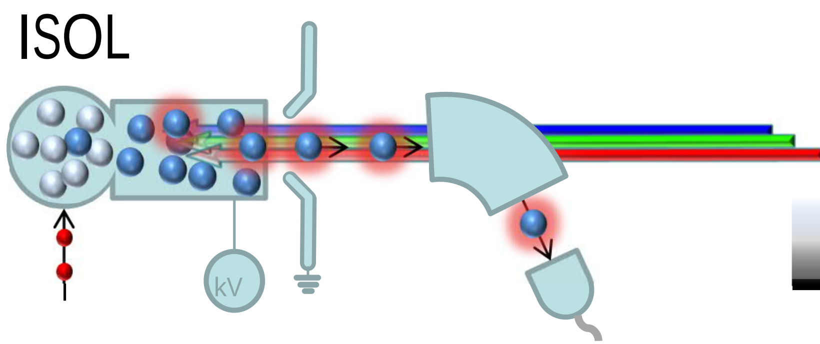
- R.L. Kurucz' CD-ROM 23 Atomic Line Database: http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html
- NIST atomic spectral line database: http://www.nist.gov/pml/data/asd.cfm
- Blaise and Wyart (actinides): http://web2.lac.u-psud.fr/lac/Database/Contents.html

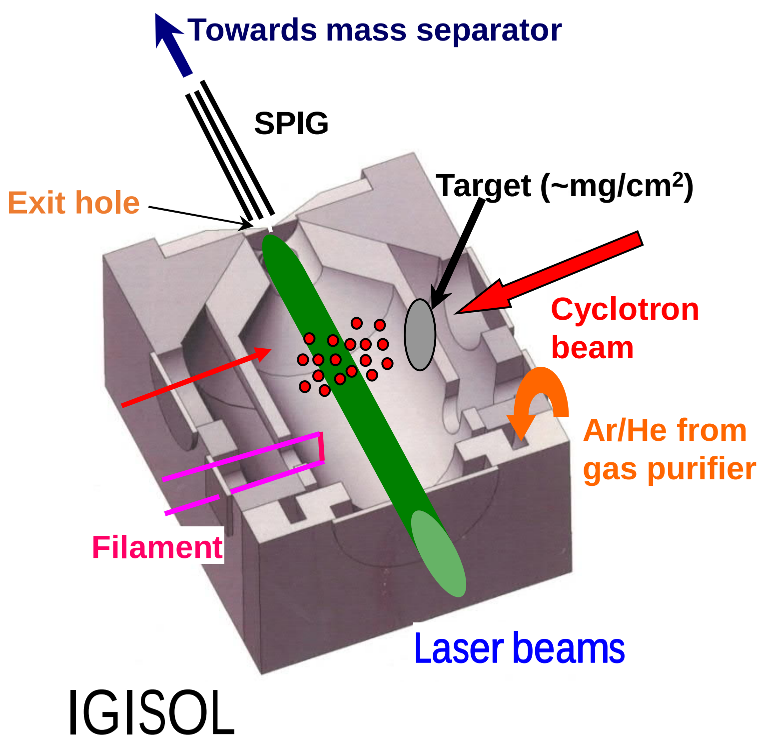


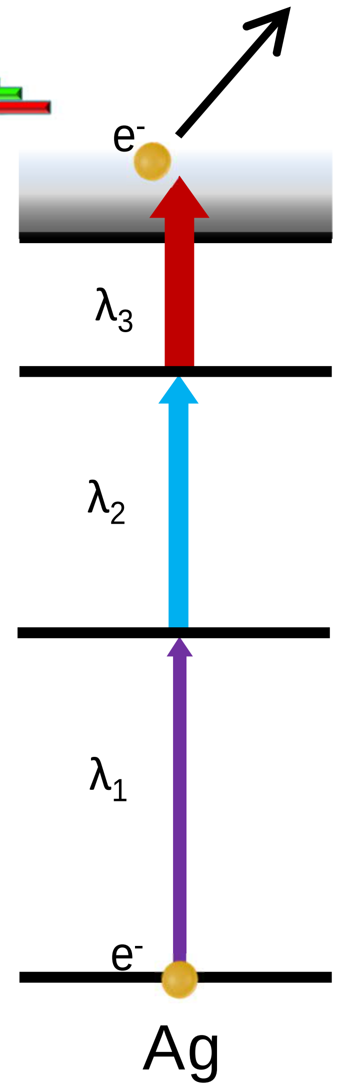


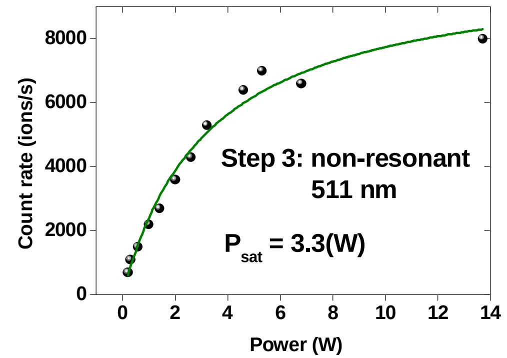
V. Sonnenschein, I.D. Moore et al., EPJ A 48 (2012) 52

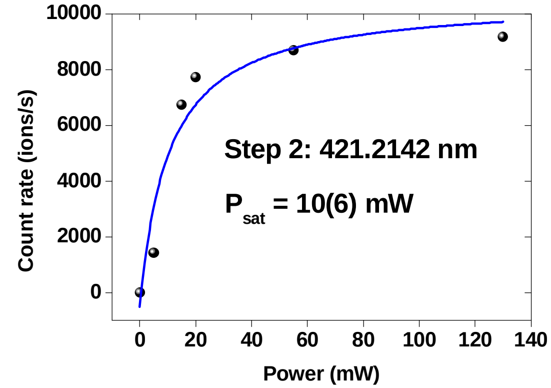
From the optical table to the ion source

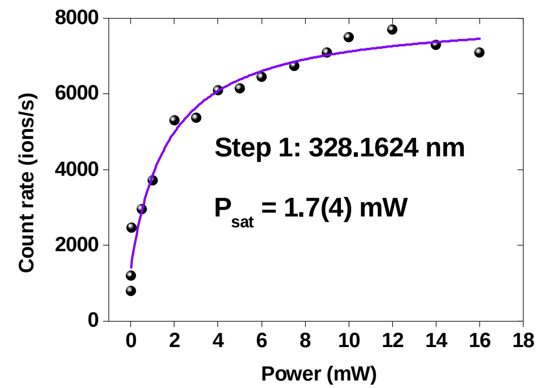












How do we quantify the optical selectivity?

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The excitation probability of an atom in a laser beam whose frequency is tuned near resonance:

$$P \propto \frac{1}{\delta^2 + \frac{\Gamma^2}{4}}$$

$\delta = \omega_L - \omega_0$,
Γ is the interaction linewidth

When the laser is in resonance with a selected isotope and but far from other "contaminating" elements or isotopes (Δ), the selectivity S

$$S \sim 4 \times \frac{\Delta^2}{\Gamma^2}$$

<u>Pd isotopes</u>
Γ ~3 MHz, Δ ~100 MHz (neighbouring isotopes):
S ~4000

Δ ~10^{15} Hz (palladium to silver):
S ~10^{17} !!!

Multi-step excitation: $S = S_1 \cdot S_2 \ldots \cdot S_n$.