EMIS 2012 – Matsue, Japan 2nd – 7th December 2012

New developments of the in-source spectroscopy method at RILIS/ISOLDE

On behalf of York-KU Leuven-Gatchina-Mainz-Manchester-Bratislava-Liverpool-ISOLDE collaboration

The University of York
Petersburg Nuclear Physics Institute
University of Liverpool
RILIS
IKS
Manchester 1824
Universitas Comeniana Bratislavensis MCMXIX
ISOLTRAP
LARISSA

Bruce Marsh - CERN EN-STI-LP

Outline of Talk

- Introduction to laser spectroscopy of atoms
  - Observables: Isotope Shifts and Hyperfine Structure
  - Laser spectroscopy of exotic isotopes at ISOL Facilities

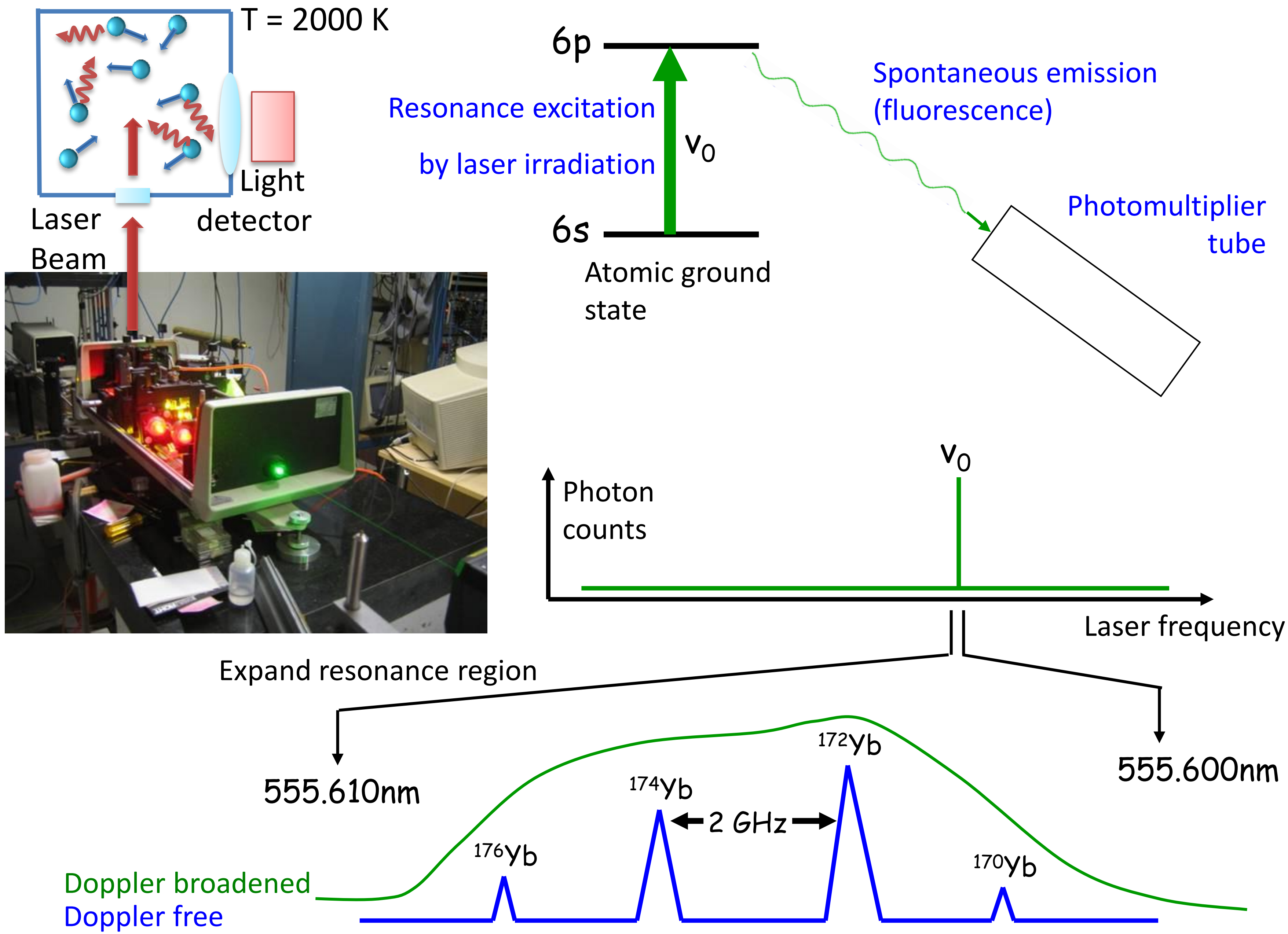
- In-Source Resonance Ionization Spectroscopy (RIS)
  - Isotopes of interest
  - Technical requirements and considerations
  - ISOLDE RILIS In-source RIS setup
  - New developments:
    - Lasers, ion source, detectors, data acquisition

- Recent measurements (2011, 2012)
  - Emphasis on measurements that relied on the latest technical developments

- Outlook

Laser spectroscopy of atoms

Laser-fluorescence of an Yb atomic vapour



The origin of the isotope shift

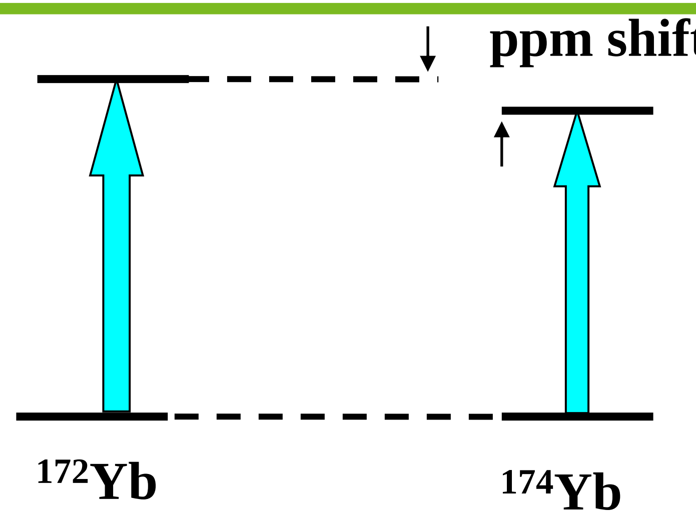
Isotope shifts have two components:

- *Mass Shift*

  change in reduced mass of electron

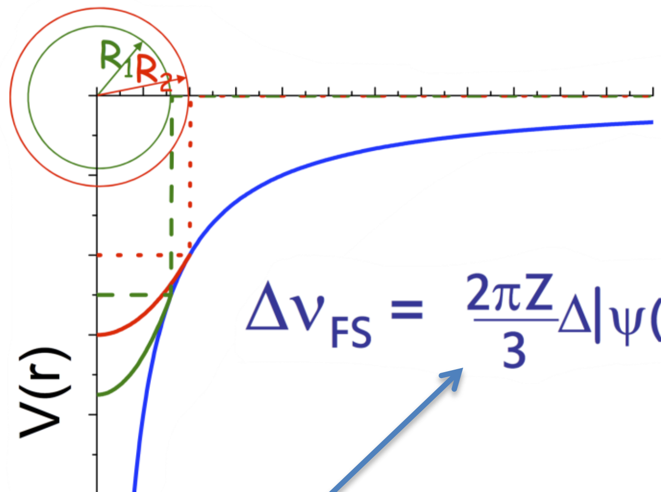
- *Volume or Field Shift*

  change in size of the nucleus



The *Field Shift* is directly proportional to the change in nuclear mean square charge radius, **$\delta\langle r^2\rangle$** .

Analysis of the shift provides information on the nuclear size and shape – even for short-lived (radioactive nuclei):



$$\Delta\nu_{FS} = \frac{2\pi Z}{3}\Delta|\psi(0)|^2\delta\langle r^2\rangle$$

Probability density of the electron at the nucleus

(electronic part)

Difference in the mean square nuclear charge radius

(nuclear part)

$$\delta\langle r^2\rangle = \delta\langle r^2\rangle_{\rm sph} + \langle r^2\rangle_{\rm sph}\frac{5}{4\pi}\delta\langle\beta_2^2\rangle$$

volume deformation

Practical considerations for measuring the Isotope Shift

$$\delta\nu_{IS} = \delta\nu_{MS} + \delta\nu_{FS}$$

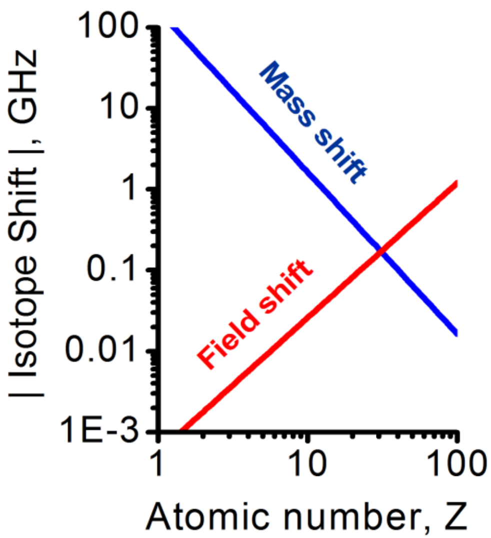
$$\delta\nu_{FS} = \frac{2\pi Z}{3}\Delta|\psi(0)|^2\delta\langle r^2\rangle$$

EXPERIMENT

THEORY

It is easier to extract charge radii information if the mass shift is small → heavier elements

Calculations of the **atomic factor** (electron density at the nucleus) are important and are easier for ground state transitions. Transitions involving s electrons have larger field shifts – higher measurement precision.

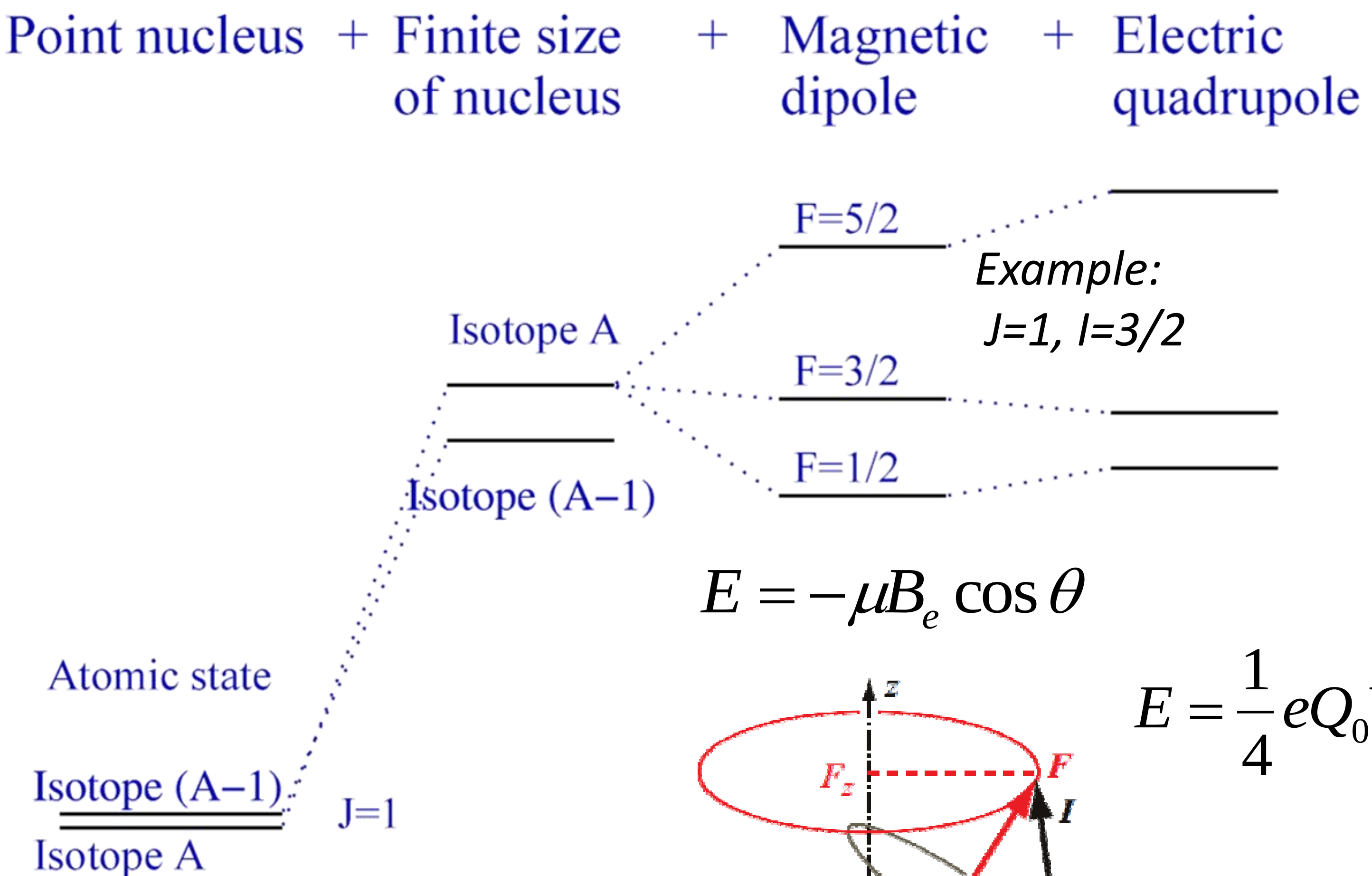


Element	Transition	Mass Shift (MHz)		Field shift (MHz)	Doppler broadening
		Normal	Specific		
$_{2}$He	2s – 3p	35000	8000	-1.4	3300
$_{11}$Na	3s – 3p	550	200	-10	1400
$_{70}$Yb	6s – 6p	20	<20	-1500	500

Heavy elements: useful results can be obtained from Doppler-broadened spectra

Light and medium mass elements: Doppler-free methods of laser spectroscopy are required

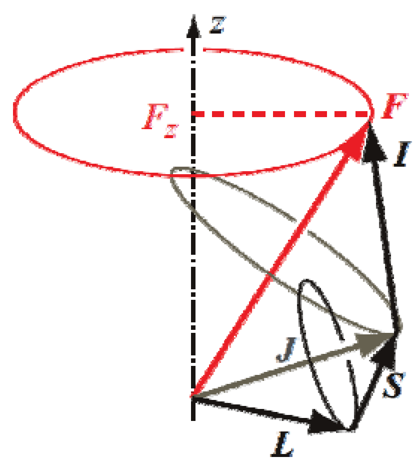
Hyperfine structure



+ higher multipoles
(too small to consider in laser measurements)

$$E = -\mu B_e \cos\theta$$

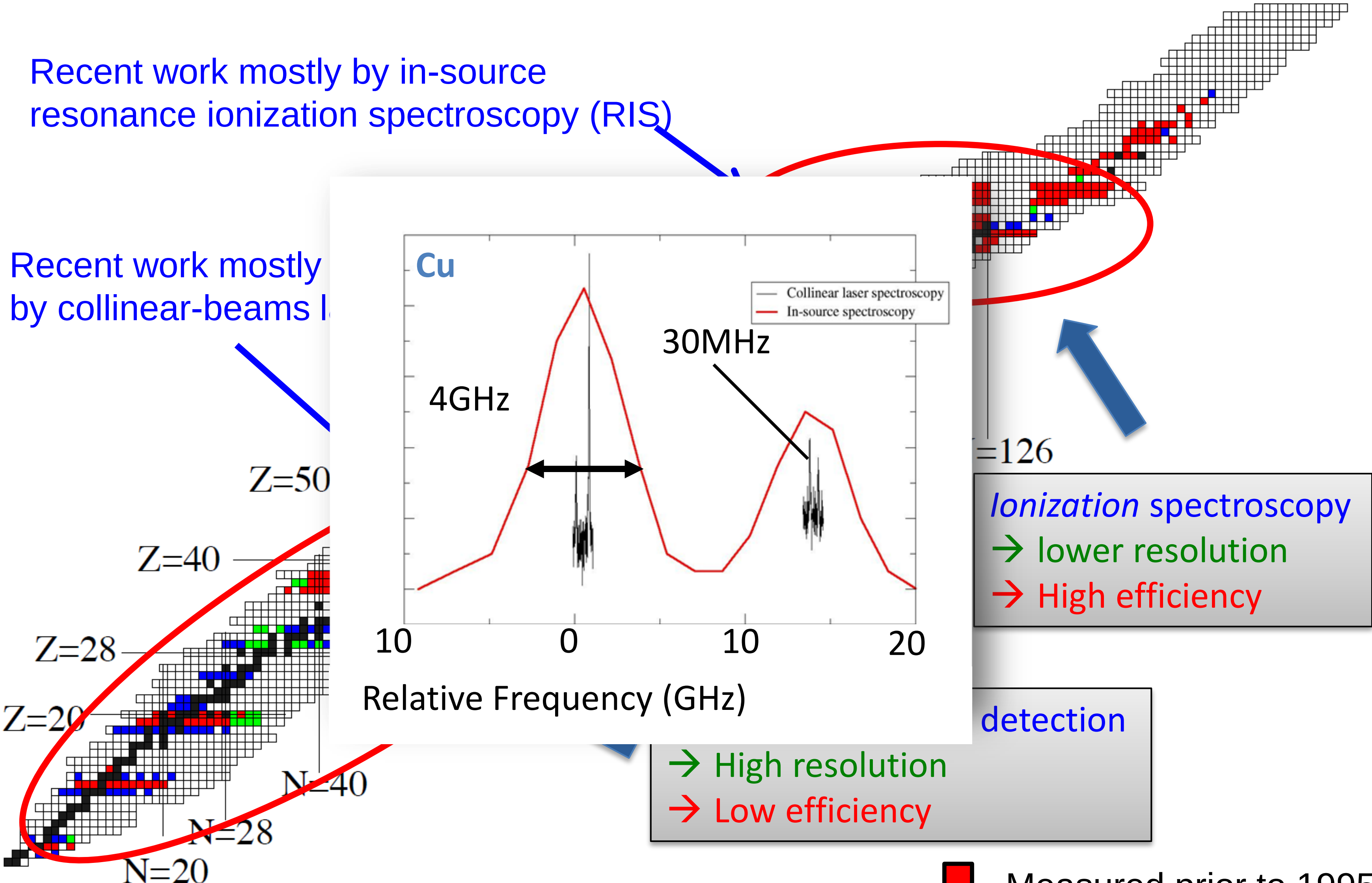
$$E = \frac{1}{4} e Q_0 V_{JJ} P_2(\cos\theta)$$



Laser spectroscopy of radioisotopes - status

Recent work mostly by in-source resonance ionization spectroscopy (RIS)

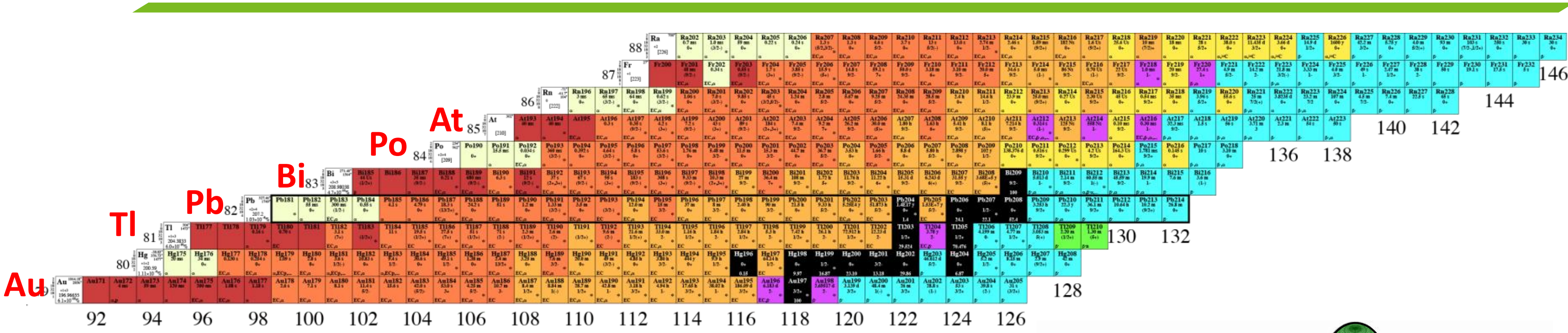
Recent work mostly by collinear-beams l



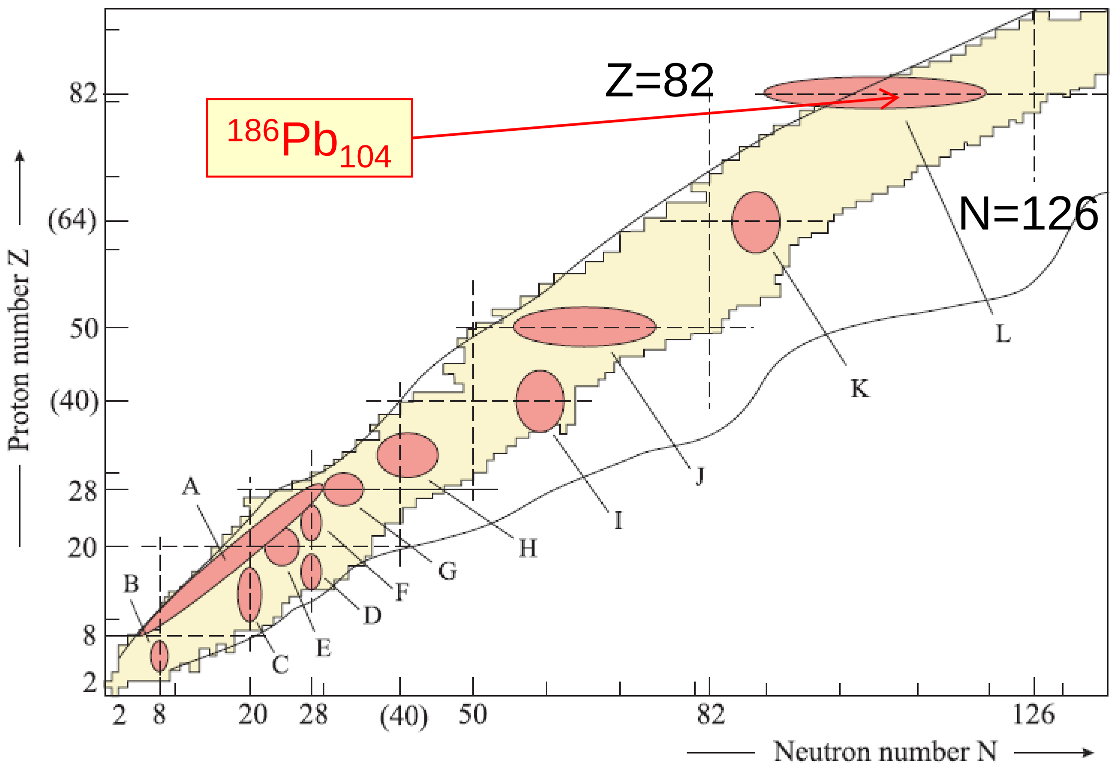
Measured prior to 1995
Measured 1995 - 2010
Measured since 2010

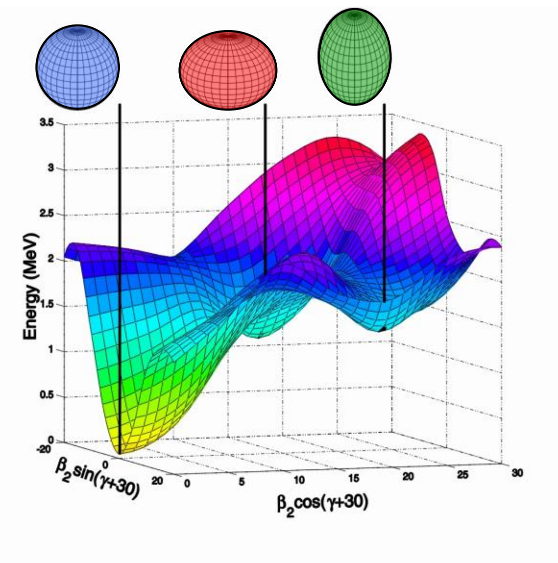
Updated plot provided by Bradley Cheal from 2010 review
(B. Cheal & K.T. Flanagan J. Phys. G 37 (2010) 113101)

Regions of interest



- Shape coexistence at and around closed proton and/or neutron shells (and subshells):



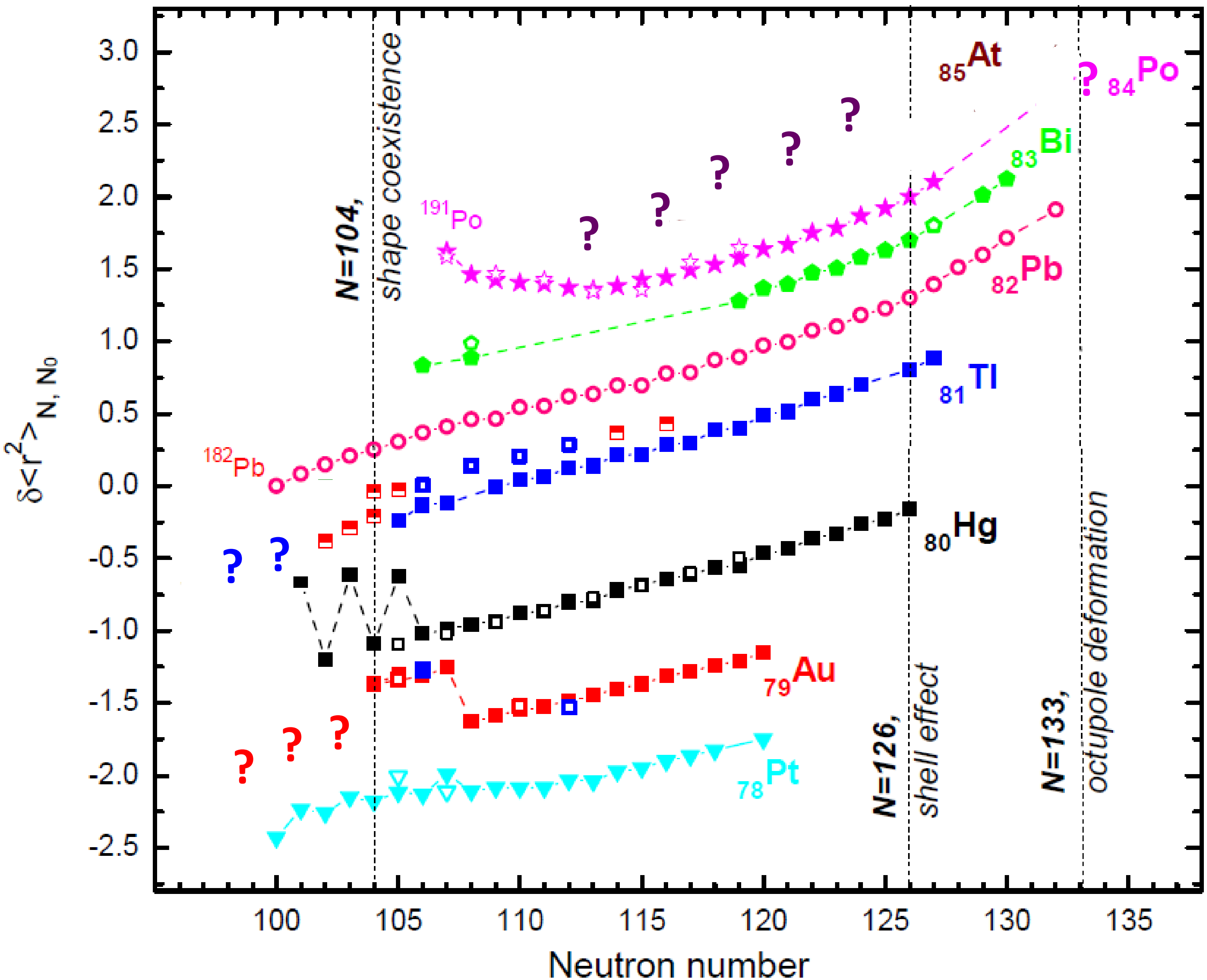


Potential Energy Surface for ^{186}Pb

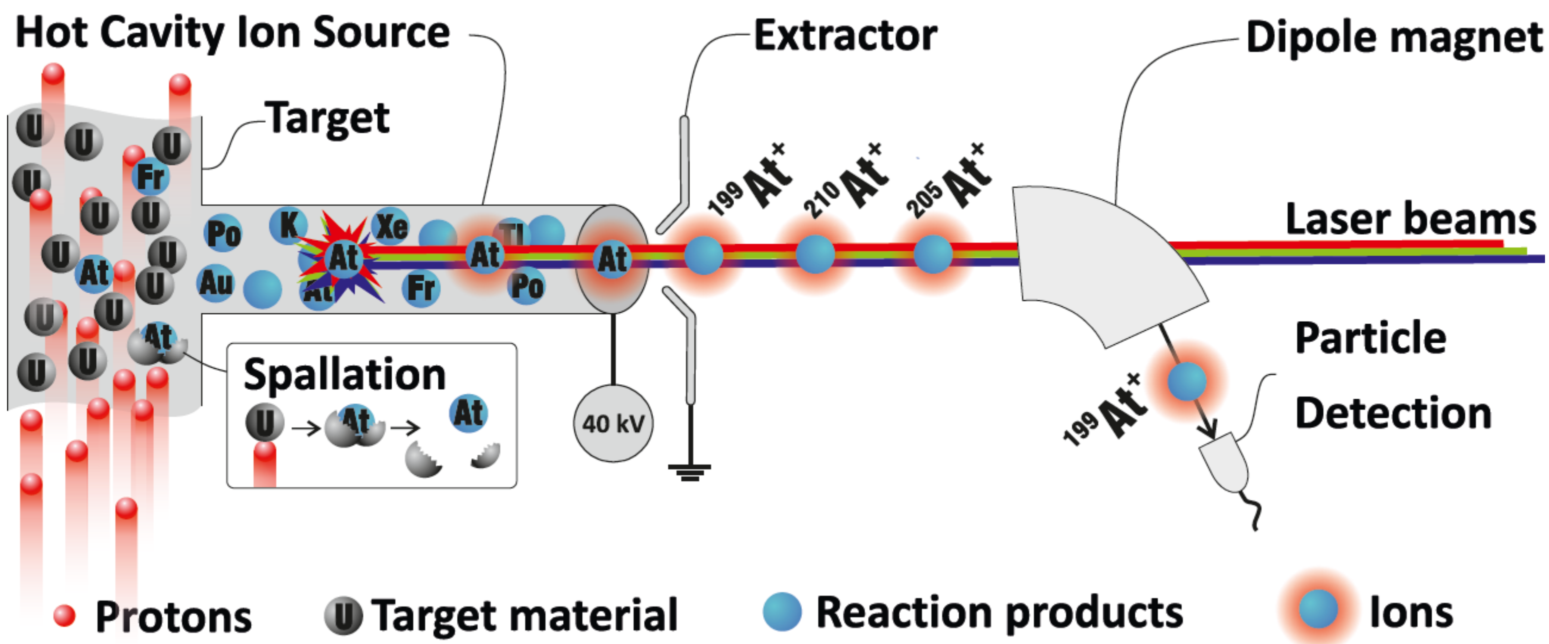
A. Andreyev et al., Nature 405 (2000) 430

"Shape coexistence in atomic nuclei" K. Heyde and J.L. Wood, Rev. Mod. Phys. (2011)

Regions of interest



In-source laser spectroscopy



- Efficient ionization schemes with a suitable spectroscopic transition is needed
- Flux/Fluence conditions → Short pulse lasers (5-50ns) with ~0.1-10mJ/pulse
- Duty cycle consideration: High repetition rate (>10kHz).
- Laser line-width for spectroscopic transition should be less than the Doppler broadened transition line-width (~1-2GHz for A > 150)

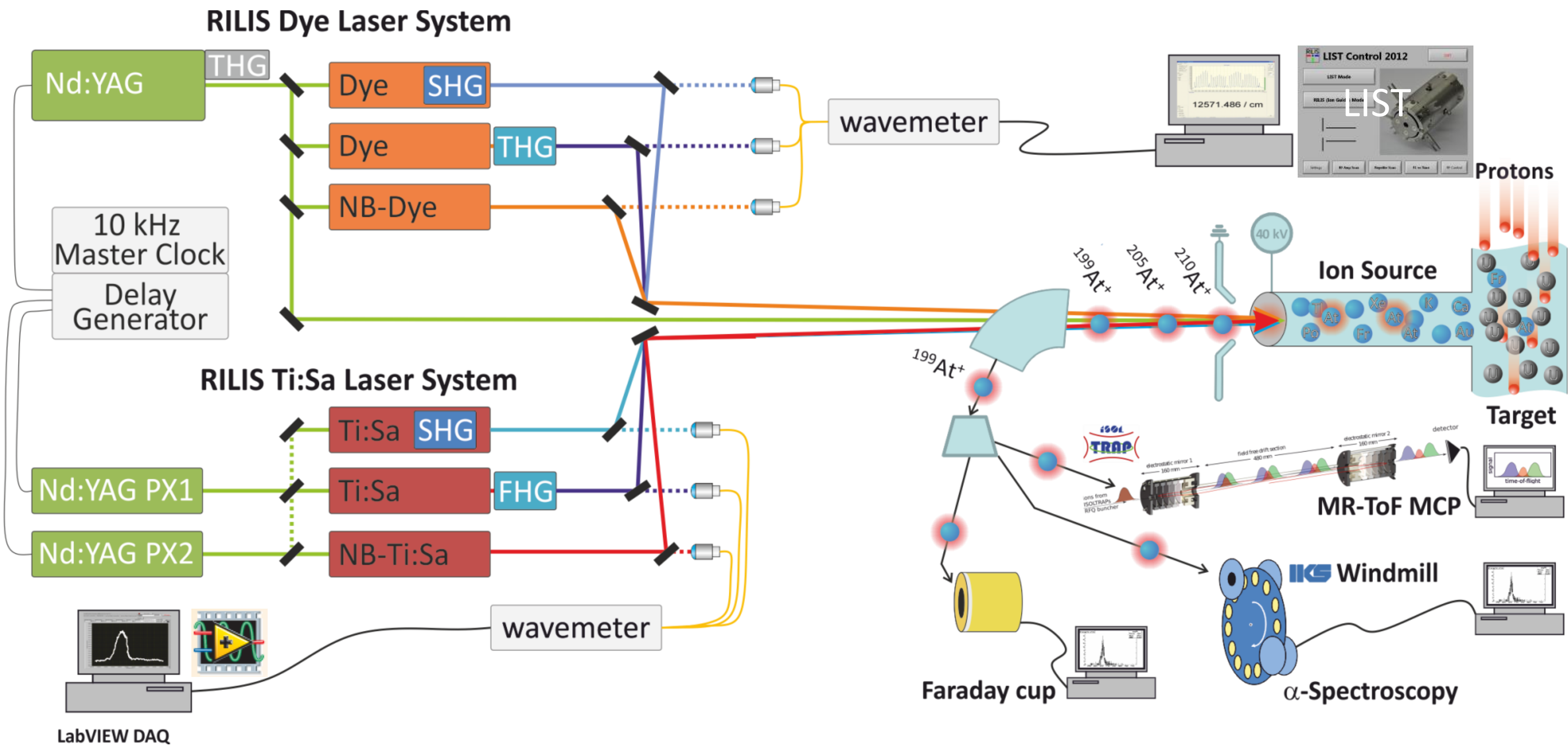
- Hugely varying production rates 0.1/s → 100pA!
  - Requires multiple measurement approaches
- Isobar suppression
  - Either at the ion source or at the detection setup

G. D. Alkhazov et al.
NIM B69 (1992) 517

V.N. Fedoseev *et al.*
NIM B266 (2008) 4378

U. Koester et al.
Nucl. Phys. A 701 (2002) 441

In-Source RIS at ISOLDE/CERN



Many new developments:

NB-TiSa Poster: Sebastian Rothe

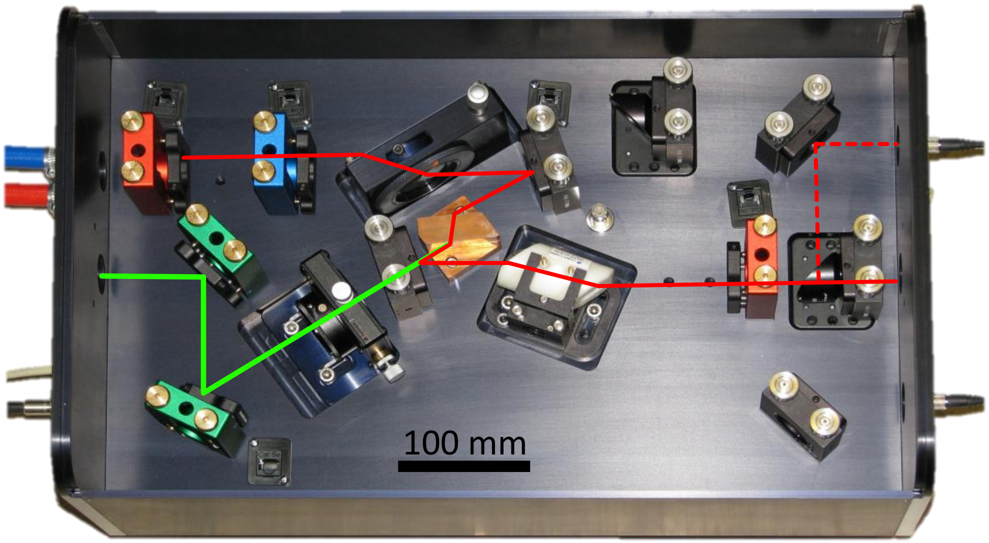
LIST Talk: Daniel Fink

Sub pA Faraday cup sensitivity

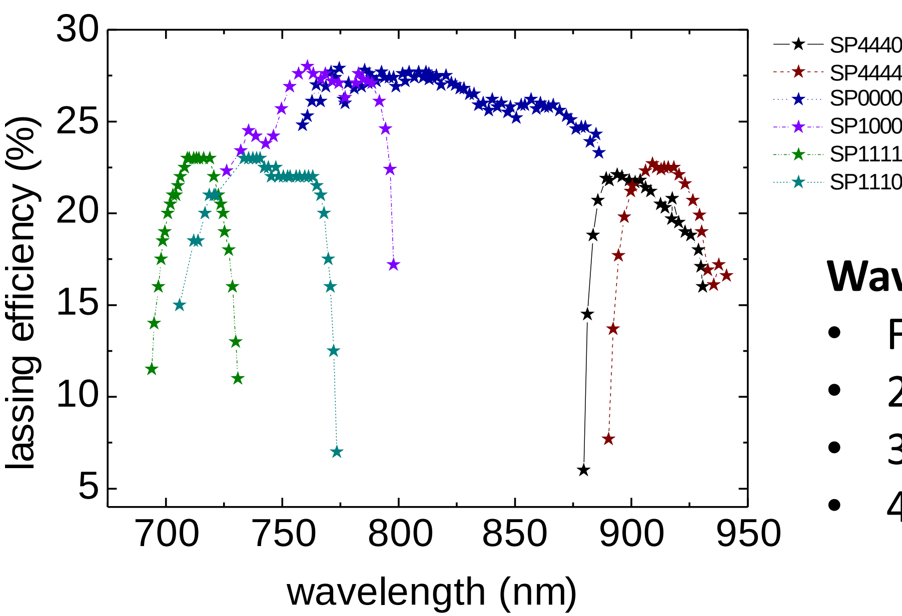
MR-TOF / ISOLTRAP Talk
Susanne Kreim

RILIS DAQ, control and communication
Poster: Ralf Rossel

The RILIS Ti:Sa lasers



Pump laser: Nd:YAG (532 nm),
Photonics Industries Ltd. DM60
Repetition rate: 10 kHz
Pulse length: 180 ns
Power: 60 W



Ti:Sa lasers:
Line width: 5 GHz
Pulse length: 30-50 ns

Wavelength tuning range (6 mirror sets):

- Fundamental (ω) **690** - **940** nm (5 W)
- 2nd harmonic (2ω) **345** - **470** nm (1 W)
- 3rd harmonic (3ω) **230** - **310** nm (150 mW)
- 4th harmonic (4ω) **205** - **235** nm (50 mW)

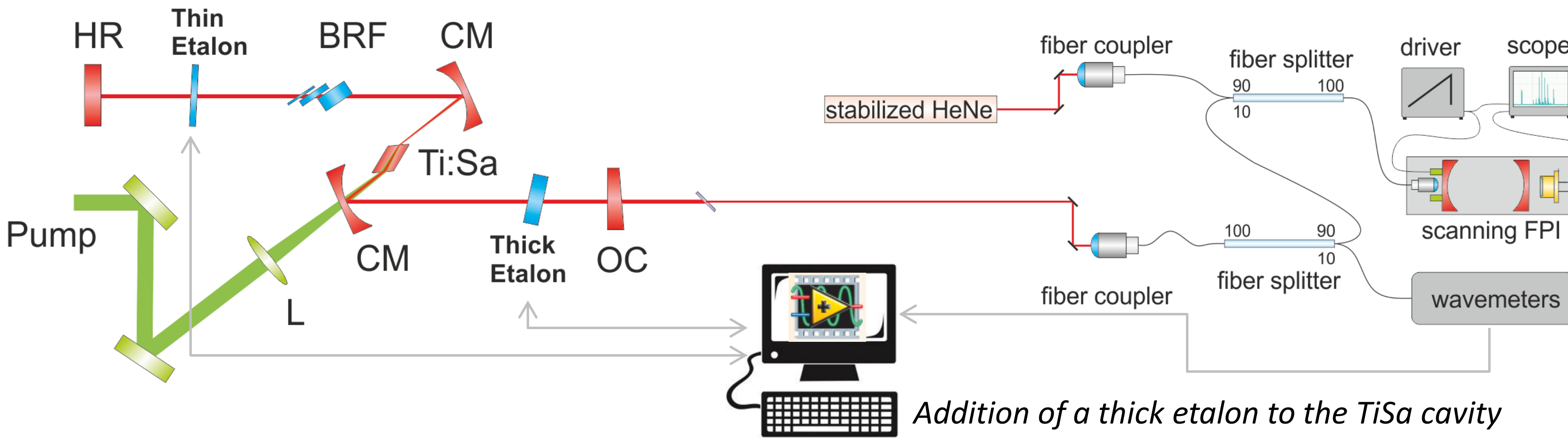
“A complementary laser system for ISOLDE RILIS”

S Rothe et al: Journal of Physics: Conference Series 312 (2011) 052020

ISOLDE

The Dual Etalon Narrow Linewidth TiSa

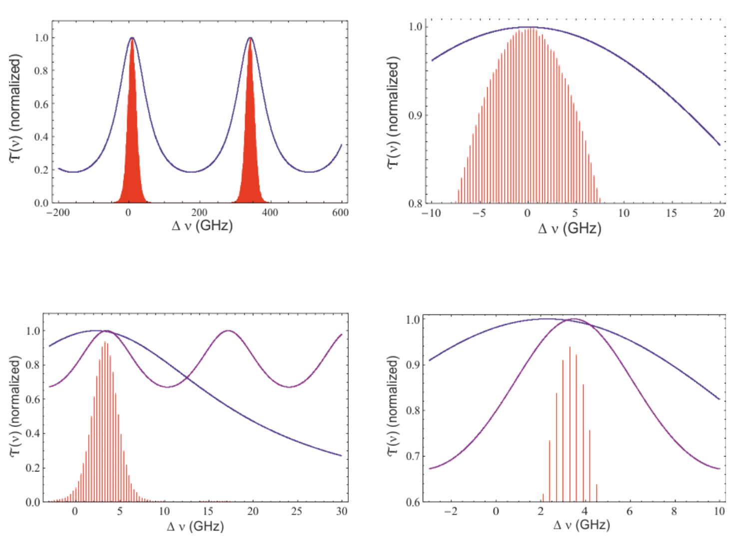
Poster: Sebastian Rothe (CERN Fellow EN/STI/LP)

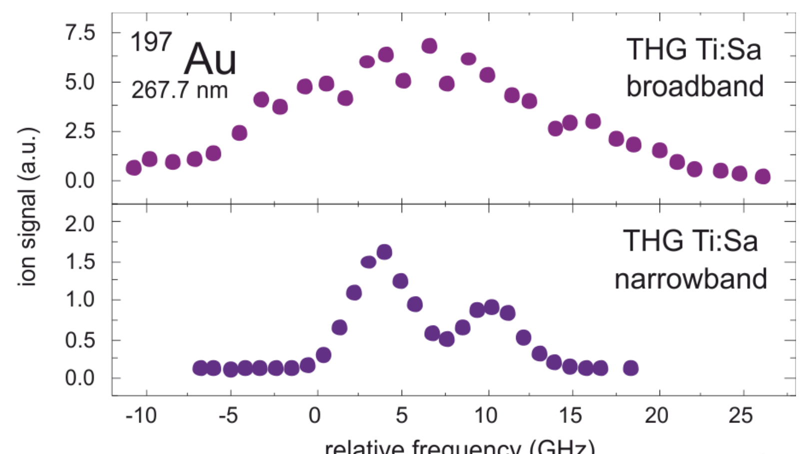


Addition of a thick etalon to the TiSa cavity

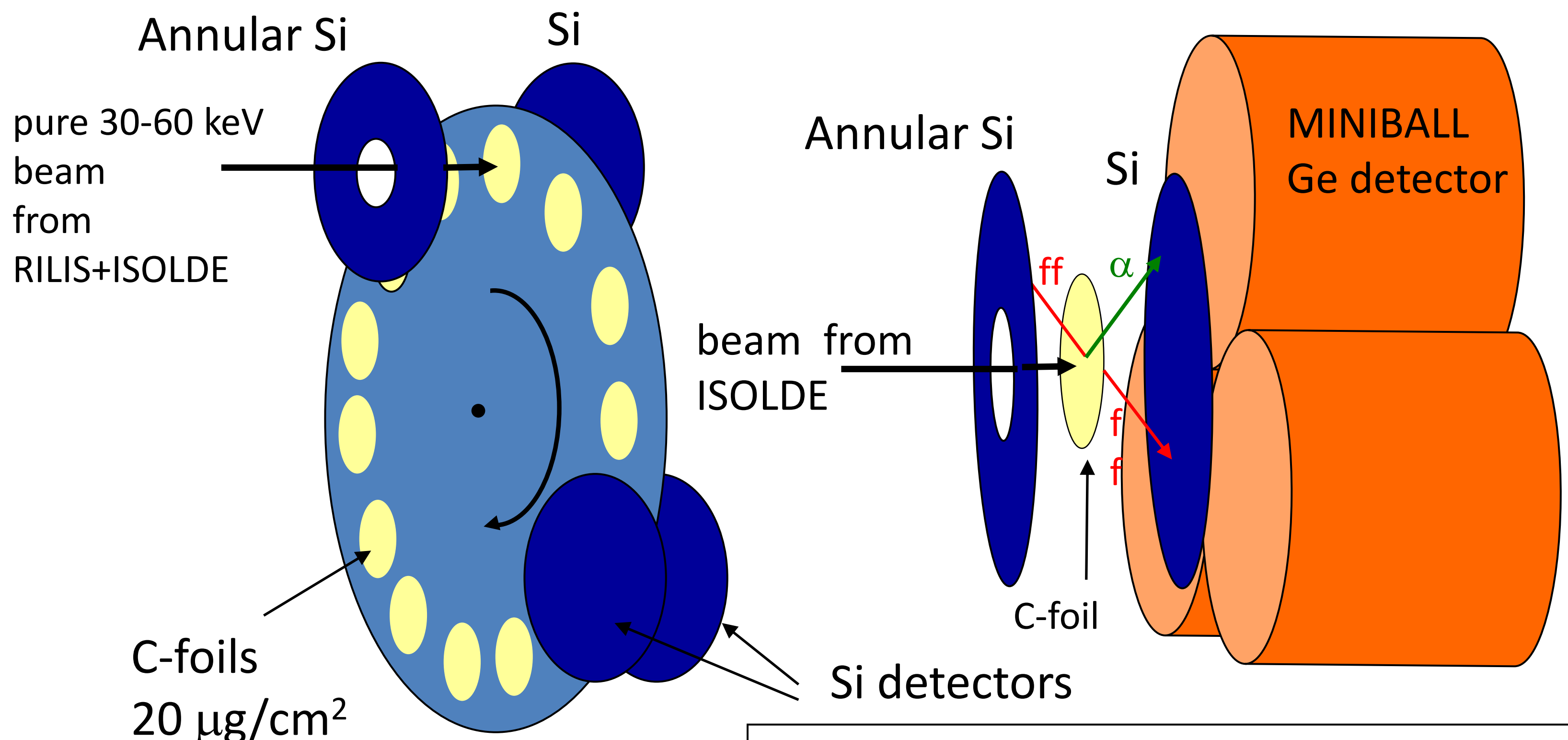
Reduction of linewidth from >5 GHz → <1GHz

Remote dual etalon control, automatic optimization routine and feedback based frequency stabilization





Windmill for α- and γ- decay spectroscopy



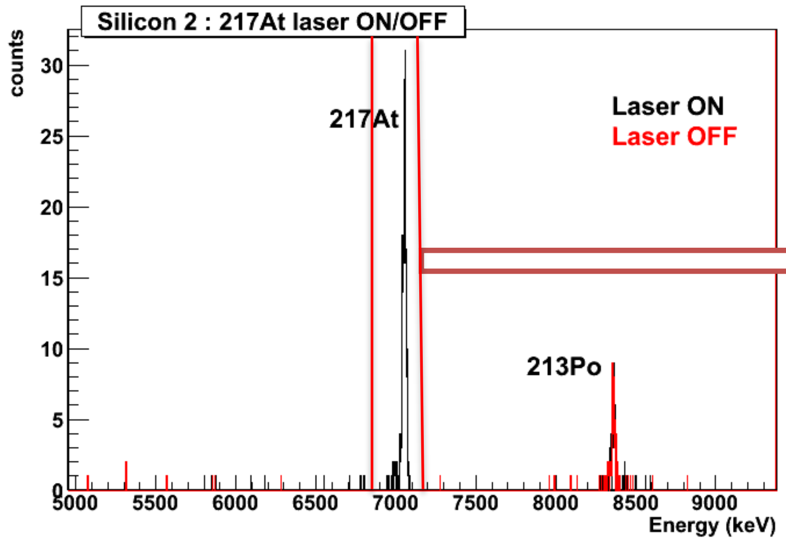
Dual output amplifier → DAQ + LabView DSM to plot live laser spectra

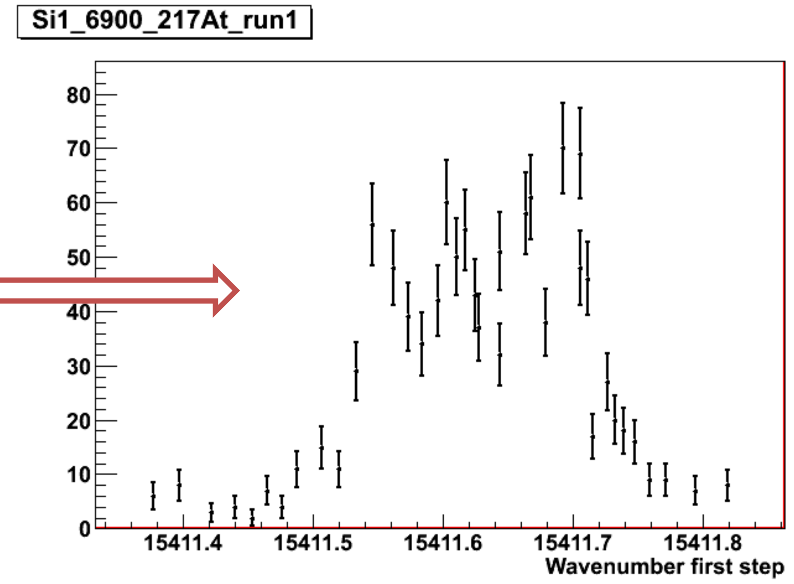
Setup: Si detectors from both sides of the C-foil

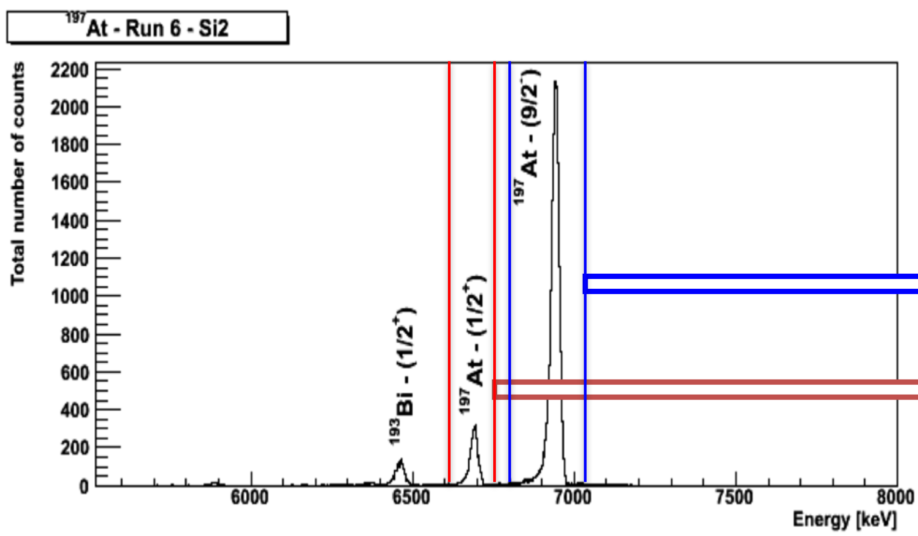
- Simple setup & DAQ: 4 PIPS (1 of them – annular)
- Large geometrical efficiency (up to 80%)
- 2 fold fission fragment coincidences
- ff-gamma coincidences
- Digital electronics

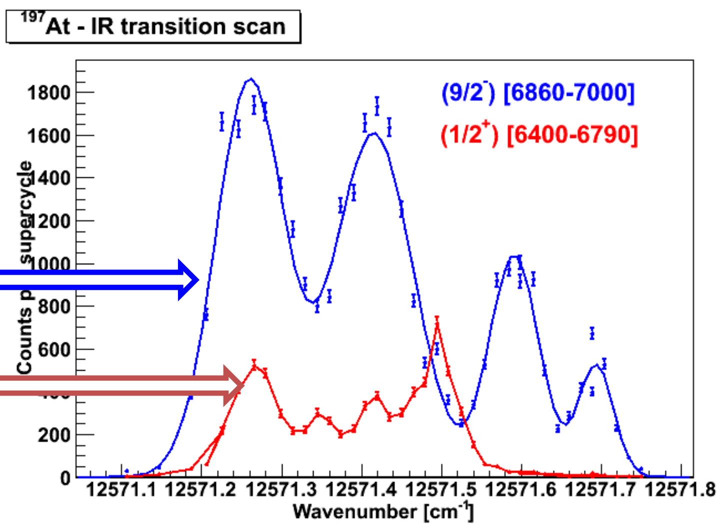
A.N. Andreyev et al,, Phys. Rev. Lett. 105, 252502,(2010)

Examples of Windmill spectra for At

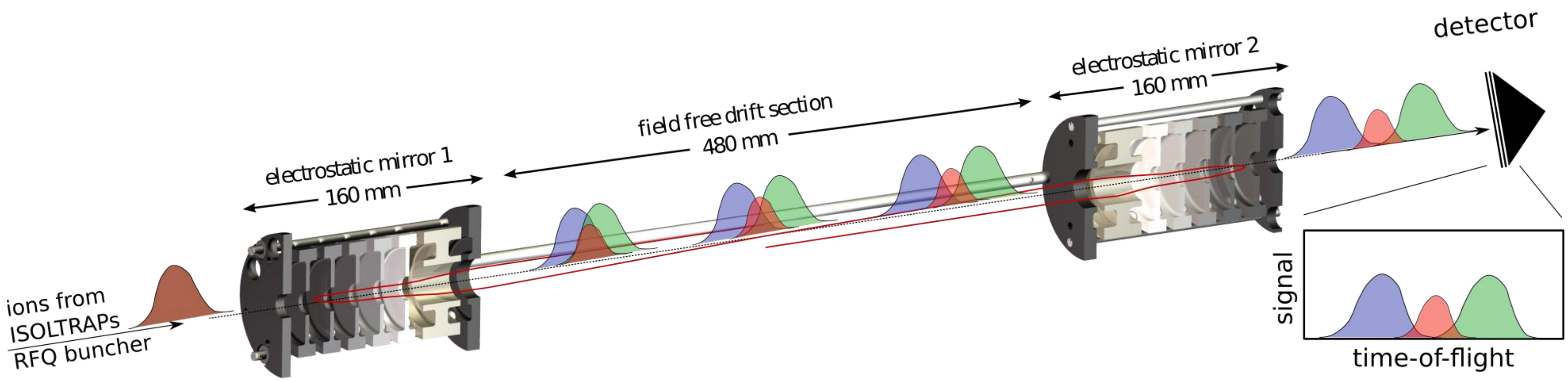


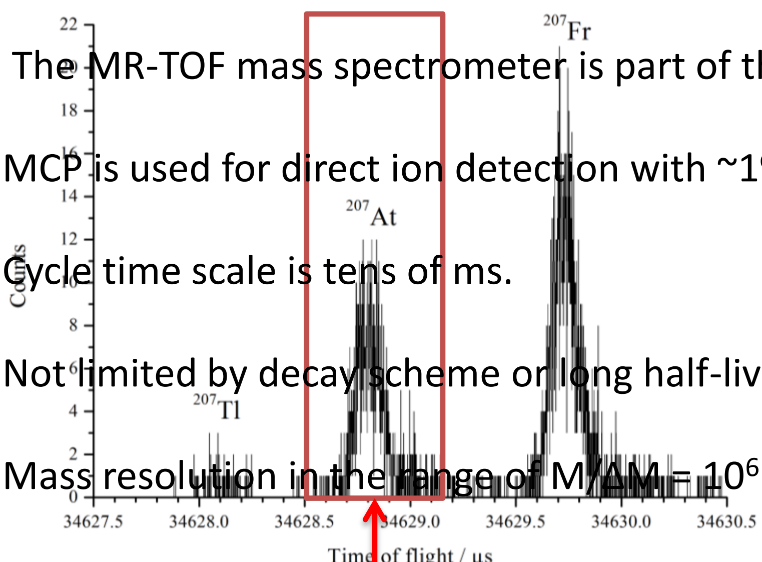


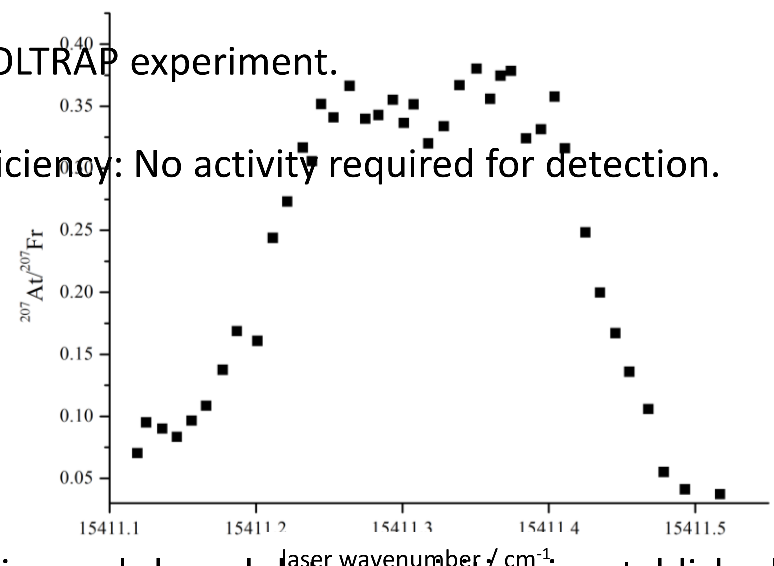




The ISOLTRAP Multi Reflection Time Of Flight Separator MR-TOF







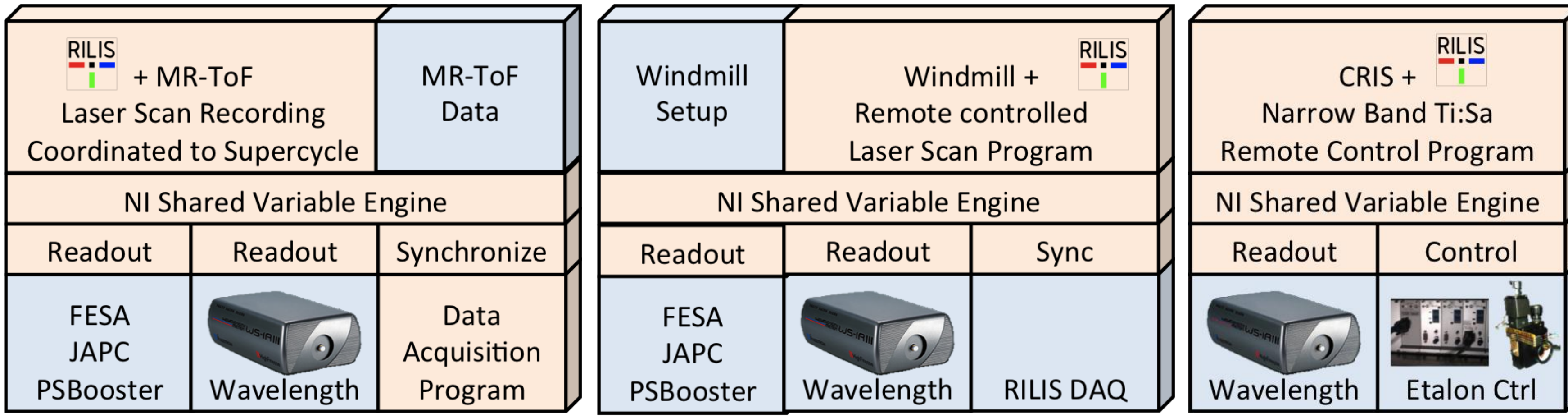
- The MR-TOF mass spectrometer is part of the ISOLTRAP experiment.
- MCP is used for direct ion detection with ~1% efficiency: No activity required for detection.
- Cycle time scale is tens of ms.
- Not limited by decay scheme or long half-lives.
- Mass resolution in the range of $M/\Delta M = 10^6$
- Direct communication with RILIS for cycle triggering and shared data acquisition is established.

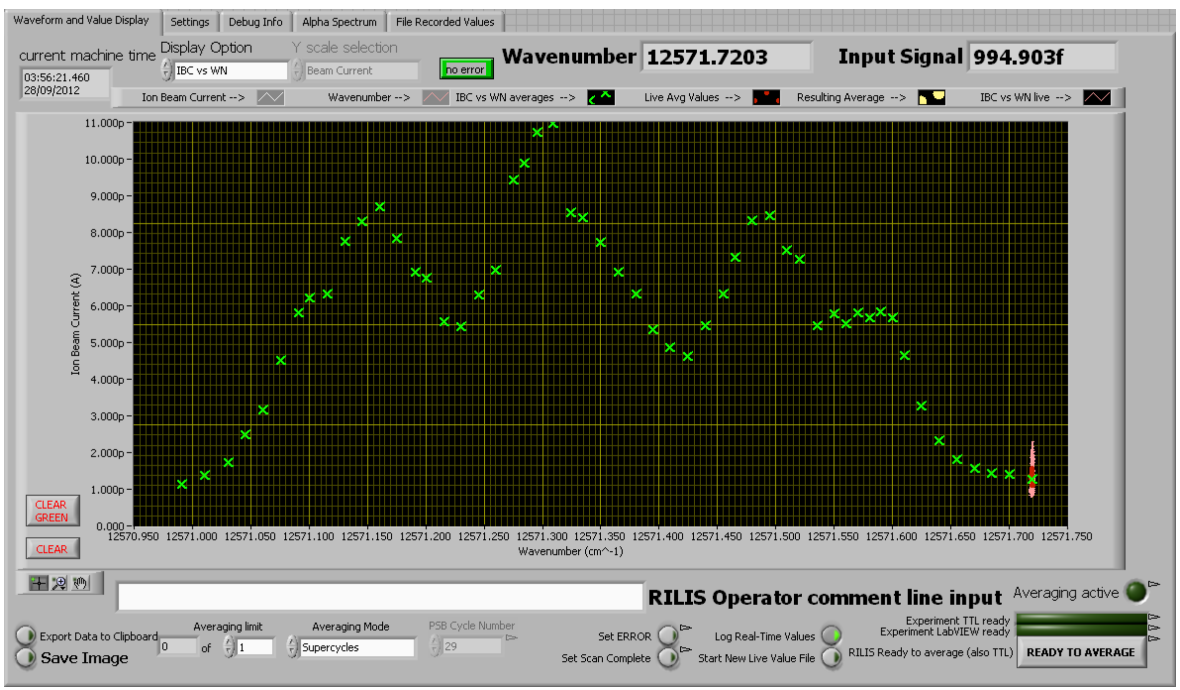
Apply a gate and measure at different laser frequencies

R. N. Wolf *et al.*, Nucl. Instr. and Meth. A 686, 82-90 (2012),
S. Kreim *et al.*, INTC-P-299, IS 518 (2011), A. Andreyev *et al.*, INTC-P-319 (2012)

RILIS Spectroscopy DAQ, synchronization and remote control

Poster: Ralf Rossel (University of Mainz)





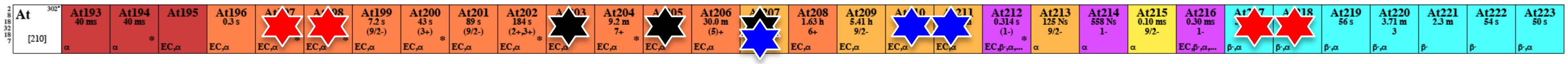
NI shared variables

Remote laser control

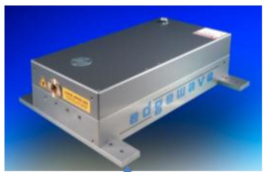
Send/receive ready signals for measurement SYNC

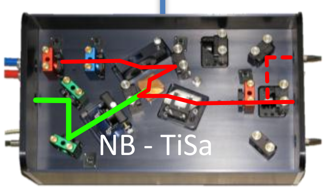
Live recording of laser scans
Wavelength vs. Faraday cup
Windmill
MR-TOF

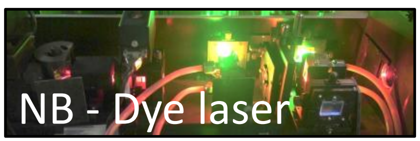
Astatine Isotopes

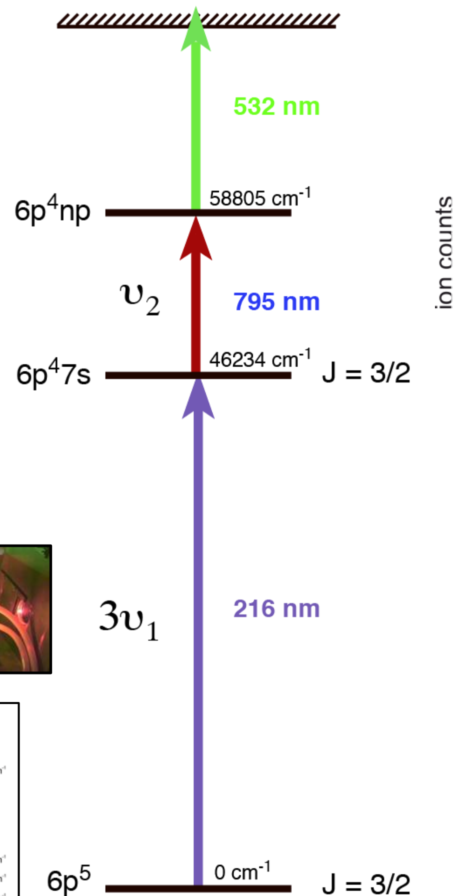


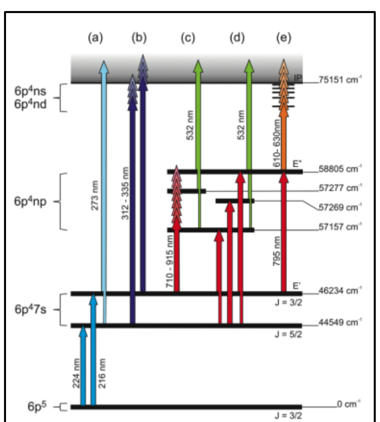
Windmill   Faraday Cup   MR-TOF



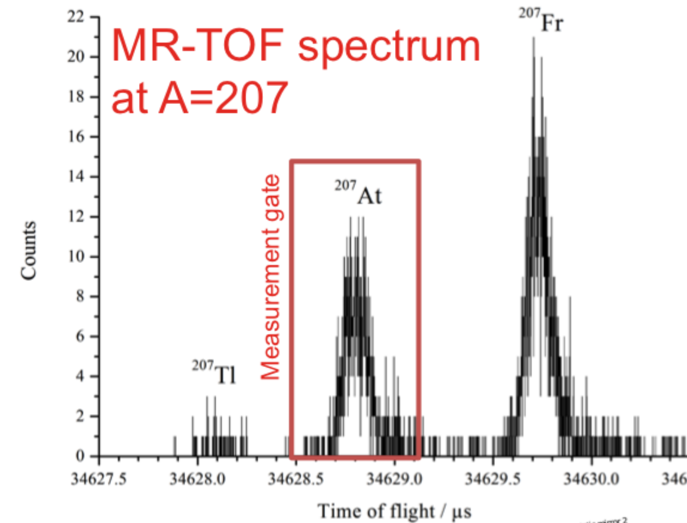


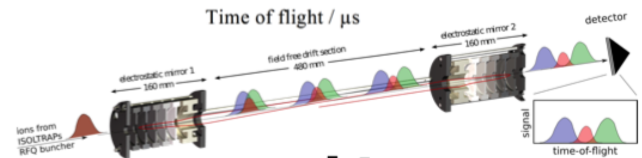


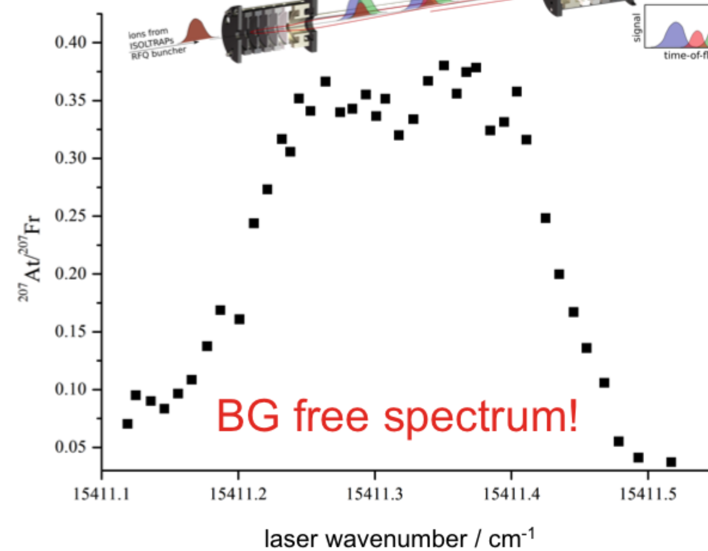


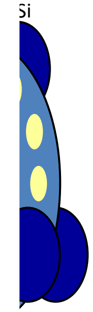


Extensive Ioniztion scheme development was required

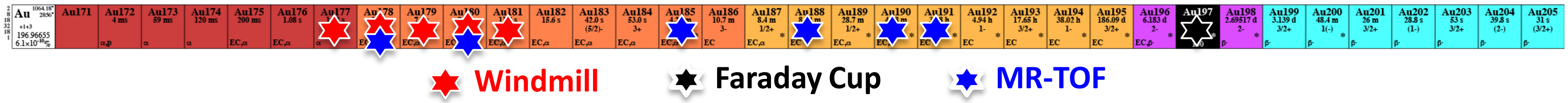


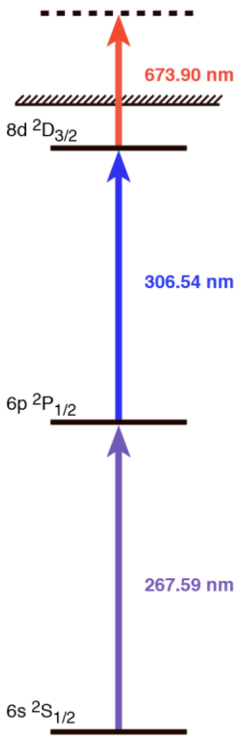


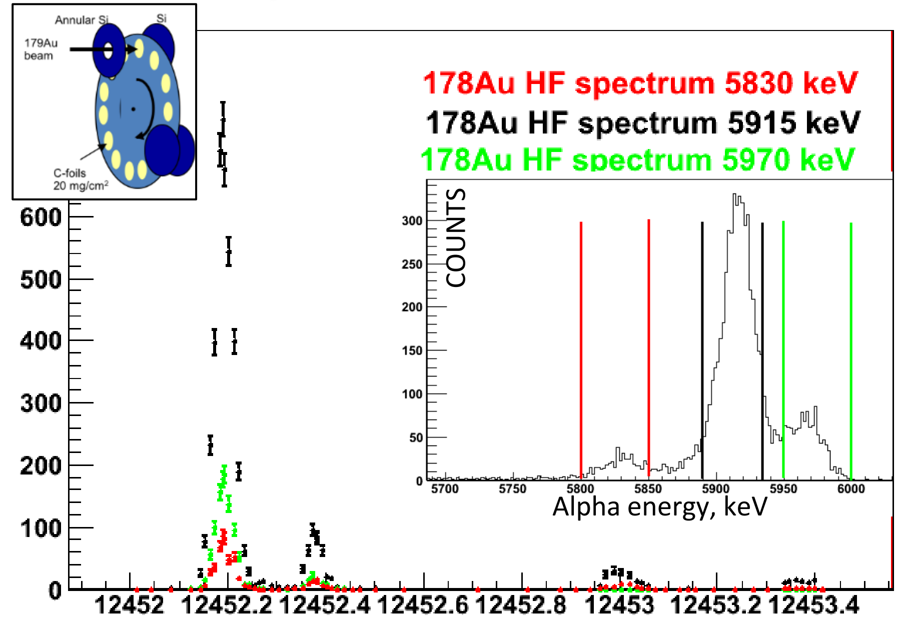


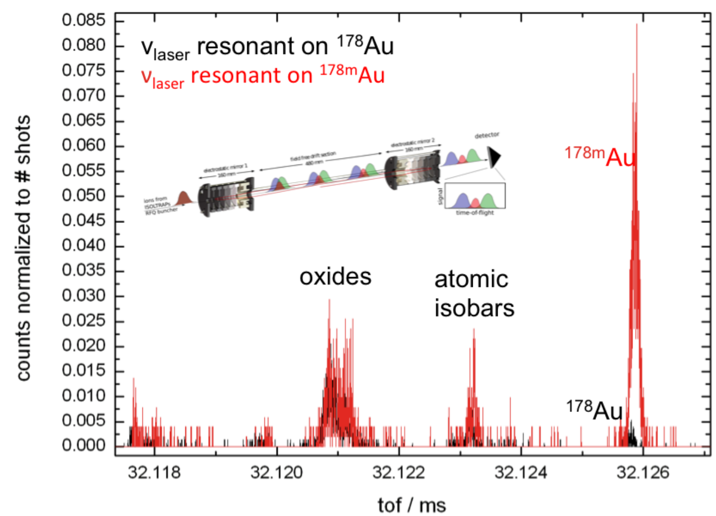


Gold Isotopes









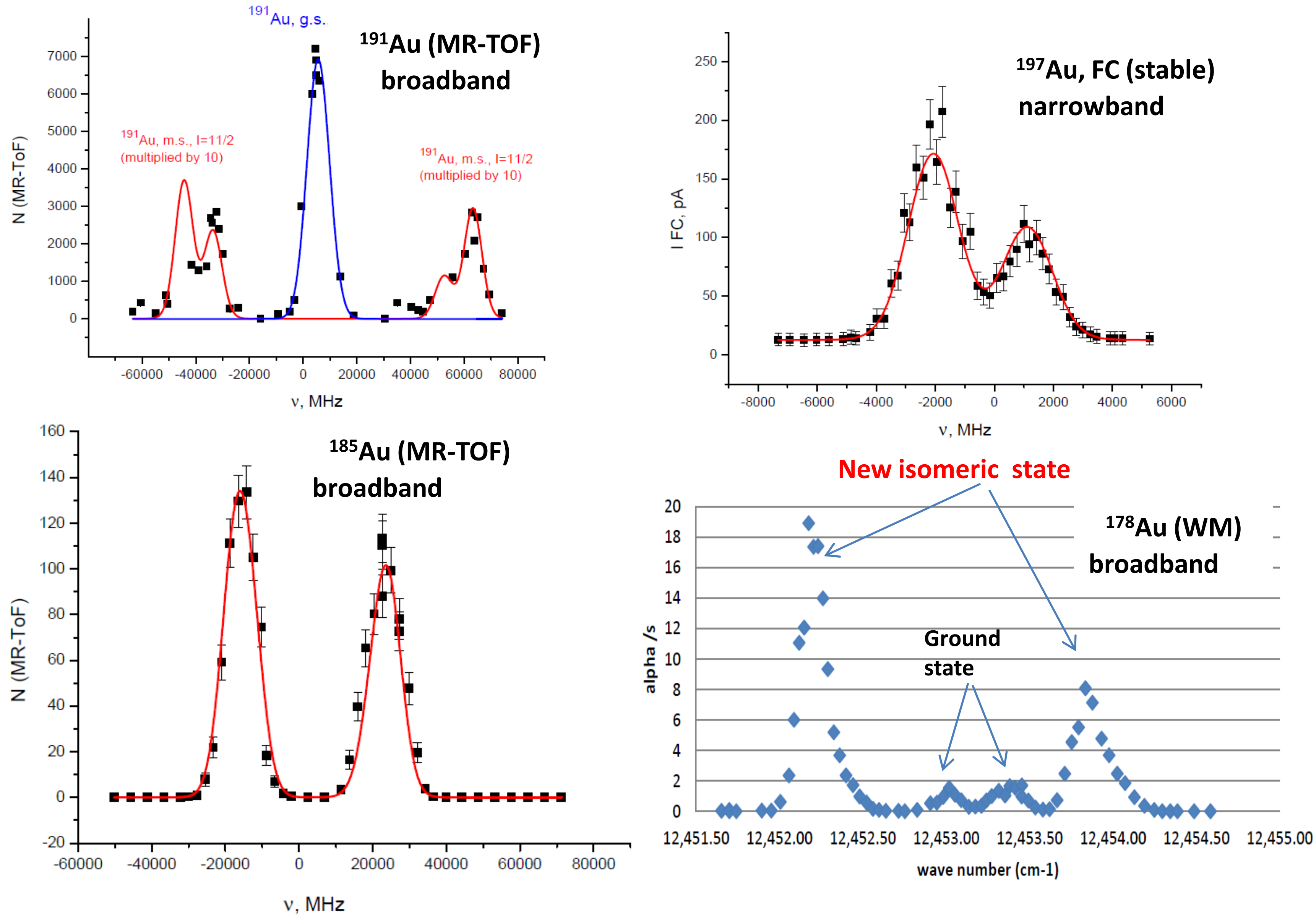
→ 1st transition is difficult with dye laser (UV pump beam required)

→ NB-TiSa was therefore advantageous: scanning stability with 3rd harmonic was demonstrated

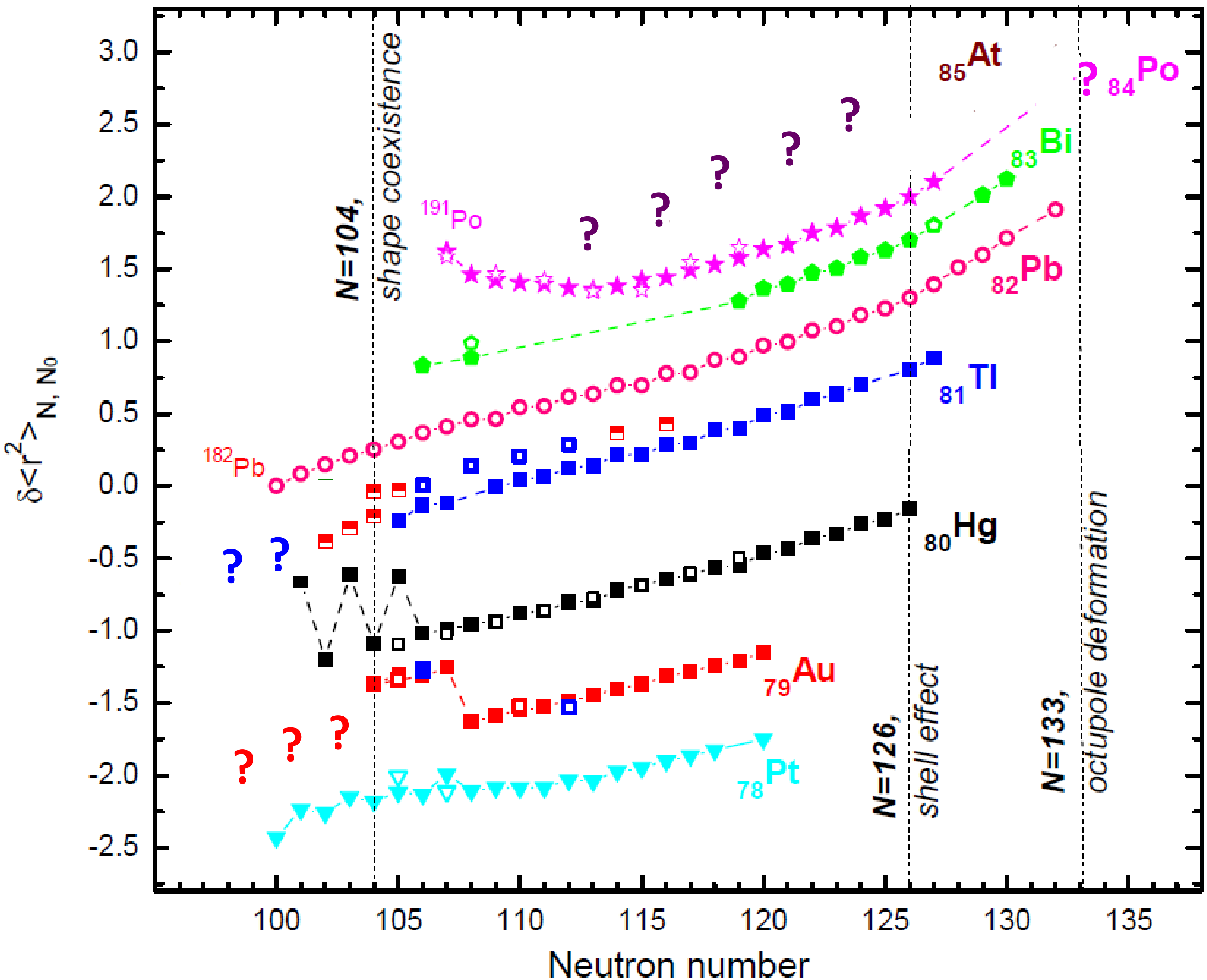
→ MR-TOF, windmill and FC were used

Beam time was extremely limited !

Gold Isotopes – Examples of laser scans



Overview of results for charge radii measurements



Outlook, future developments

General RILIS

- Extension of RILIS cabin
- Dedicated, high beam quality laser for non resonant ionization
- Fully motorized TiSa – automatic tuning/optimization
- Further optimization of LIST
- Other means of surface ion suppression

- Investigate RILIS for refractory metals at ISOLDE — KEK-JAPAN *Visiting associate* *Nobuaki Imai*
- Improved RILIS schemes for the Dual RILIS system — LA³NET *Marie Curie Fellow* *Tom Goodacre*

In-source spectroscopy

- Installation of a reference cell at RILIS
- Pulsed amplification of CW seeded Dye laser or TiSa

Acknowledgements

University of York - KU Leuven - Gatchina - Mainz – Manchester - Bratislava-Liverpool - ISOLDE collaboration

IS511

Shape coexistence in the lightest Tl isotopes studied by laser spectroscopy
http://greybook.cern.ch/programmes/experiments/IS511.html

IS534

Beta-delayed fission, laser spectroscopy and shape-coexistence studies with radioactive At beams
http://greybook.cern.ch/programmes/experiments/IS534.html

IS456

Study of polonium isotopes ground state properties by simultaneous atomic- and nuclear-spectroscopy
http://greybook.cern.ch/programmes/experiments/IS456.html

A. Andreyev[1,16], S. Antalic[2], A. Barzakh[3], R. Chapman[1], T. E. Cocolios[15], X. Derkx[1], H. De Witte[5], J. Elseviers[5], D. Fedorov[3], K. Flanagan[4], L. Ghys[5,6], M. Huyse[5], N. Imai[14], Z. Kalaninova[2], U. Köster[7], J.Lane[1], V. Liberati[1], P. Molkanov[3], K. Nishio[8], D. Pauwels[6], L. Popescu[6], R.D. Page[9], D. Radulov[5], E. Rapisarda[5], K. Sandhu[1], M. Seliverstov[1,4], J. F. Smith[1], K. Spohr[1], I. Tsekhanovich[10], V. Truesdale[1], P. Van den Bergh[5], C. Van Beveren[5], P. Van Duppen[5], M. Veselský[11], S. Fritzsche[12], K. Wendt[13], S. Raeder[13]
ISOLTRAP: S. Kreim, V. Manea, F. Wionholtz, R. Wolf, M. Rosenbusch, C. Borgmann
RILIS@CERN[4]: V. Fedosseev, D. Fink, N. Imai, B. Marsh, R. Rossel, S. Rothe, M. Sjodin

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[7]ILL, Grenoble, France
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[11]Slovak Academy of Science, Bratislava, Slovakia
[12]GSI, Darmstadt, Germany
[13]Mainz University, Germany
[14] KEK, Japan
[15] Manchester
[16] York

LA NET

1st Topical Workshop on Laser Based Particle Sources

20-22 February 2013 at CERN, Geneva, Switzerland

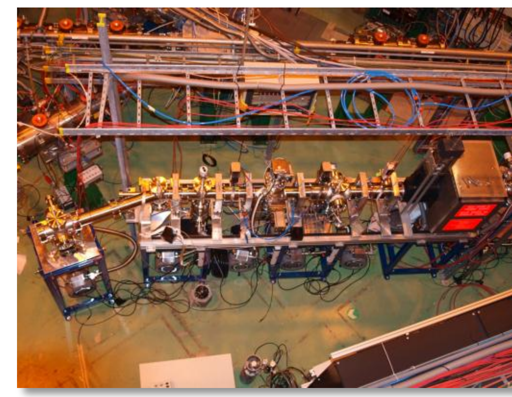
https://indico.cern.ch/conferenceDisplay.py?confId=212365

ISOLDE

Some Worldwide Laser Spectroscopy Options

In-source: RILIS, PNPI, TRILIS

- Sub 1 atom/s sensitivity
- Wide range of ionization schemes known
- Hot Cavity and associated Doppler broadening
- Target chemistry and release time dependence

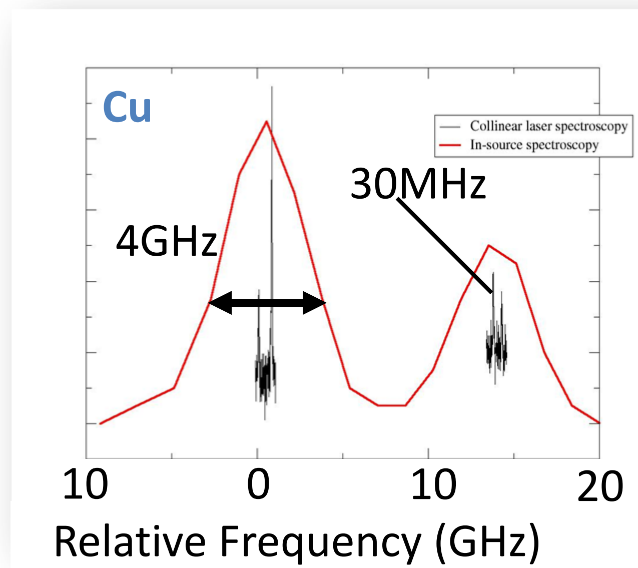


In-gas cell laser spectroscopy: LISOL, IGISOL

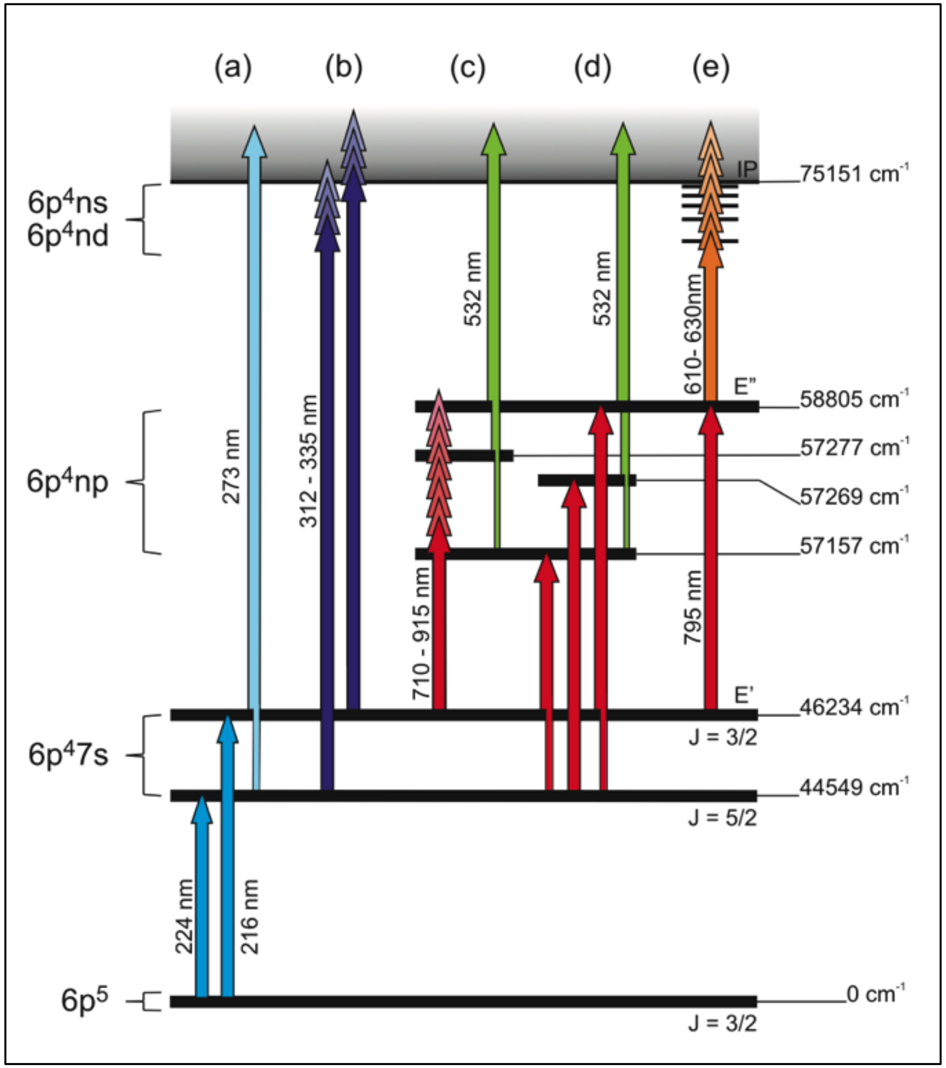
- Relatively insensitive to chemistry
- Access to short half-lives
- Pressure broadening and shifts

Collinear: COLLAPS, IGISOL, CRIS, TRIUMF

- High resolution
  (typically limited by natural linewidth)
- Highly adaptable



Sensitivity / resolution trade off!



(a)
(b)
(c)
(d)
(e)
6p4ns
6p4nd
6p4np
6p47s
6p5
IP
75151 cm-1
E"
58805 cm-1
57277 cm-1
57269 cm-1
57157 cm-1
E'
46234 cm-1
J = 3/2
44549 cm-1
J = 5/2
0 cm-1
J = 3/2
273 nm
312 - 335 nm
532 nm
532 nm
610- 630nm
710 - 915 nm
795 nm
224 nm
216 nm