Perspectives for laser spectroscopy at the next generation of European RIB facilities

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The University of Manchester

Outline of talk

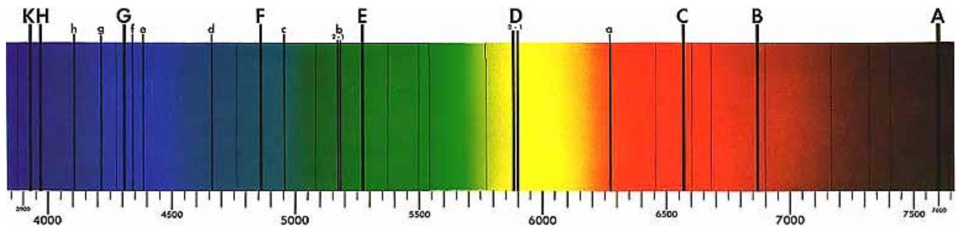
- Introduction to laser spectroscopy
- Status of Measurements
- Different techniques on offer at facilities across Europe
- Some future challenges for laser spectroscopy at the next generation of European facilities

Laser Spectroscopy for nuclear physics

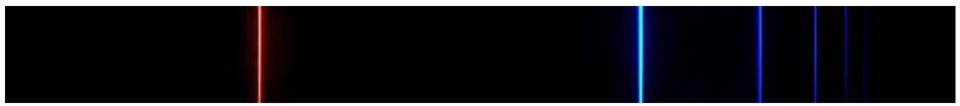
- A Prelude to Atomic Spectroscopy

17th Century: Newton demonstrates that the Sun's white light can be dispersed into a "spectrum" of colours

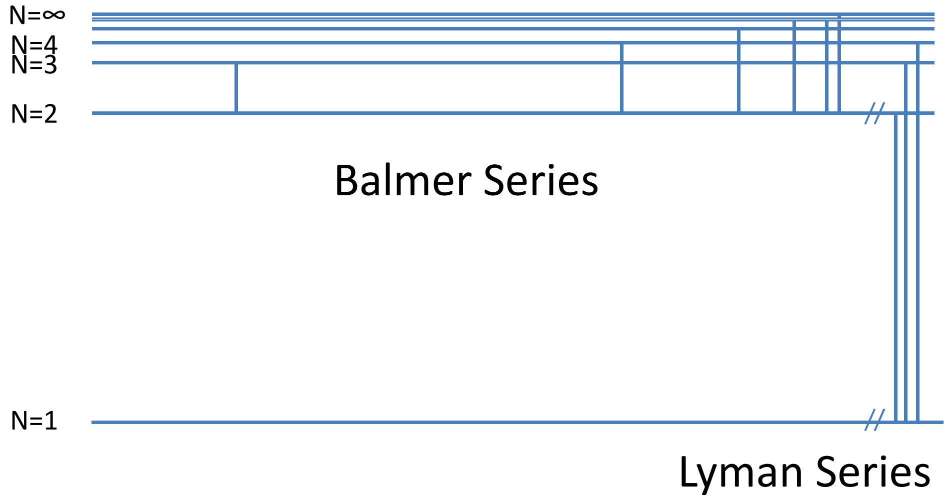
19th Century (1814) J. Fraunhofer measures dark lines in the Sun's spectrum.



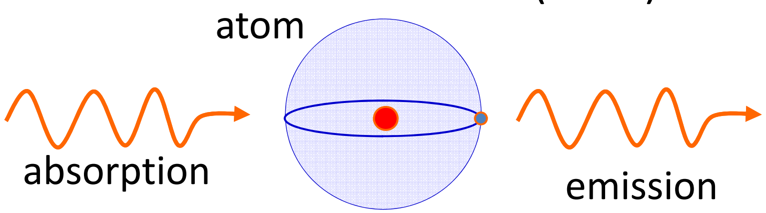
1859: Kirchhoff & Bunsen explain the dark lines in the solar spectrum in terms of absorption by elements in the Sun's surface.



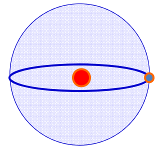
1885: J. Balmer describes the series of lines atomic hydrogen.



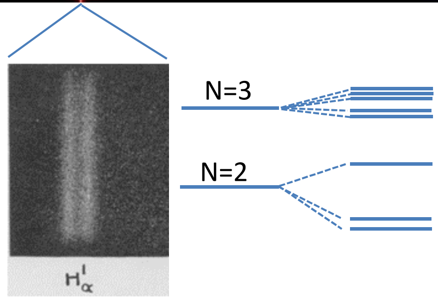
This discrete structure required quantum mechanics and Neils Bohr (1913)

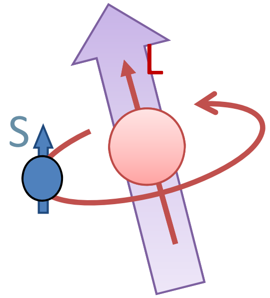


Higher Resolution

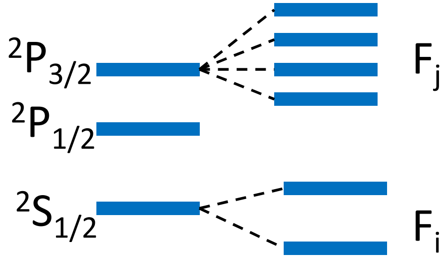


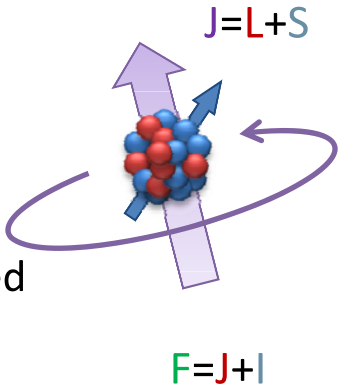
• By increasing the resolution by a factor of ~5000 a fine structure splitting of the hydrogen is observed: key evidence for the spin of the electron.



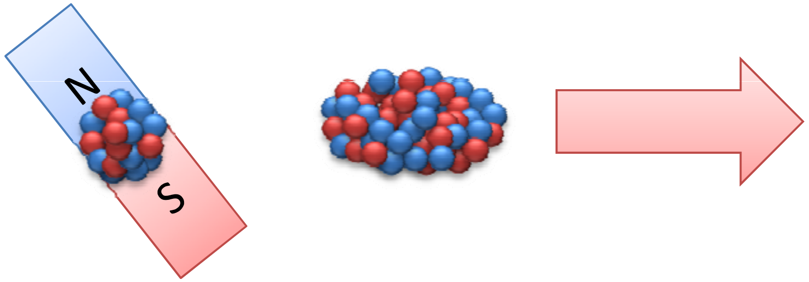


•A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.



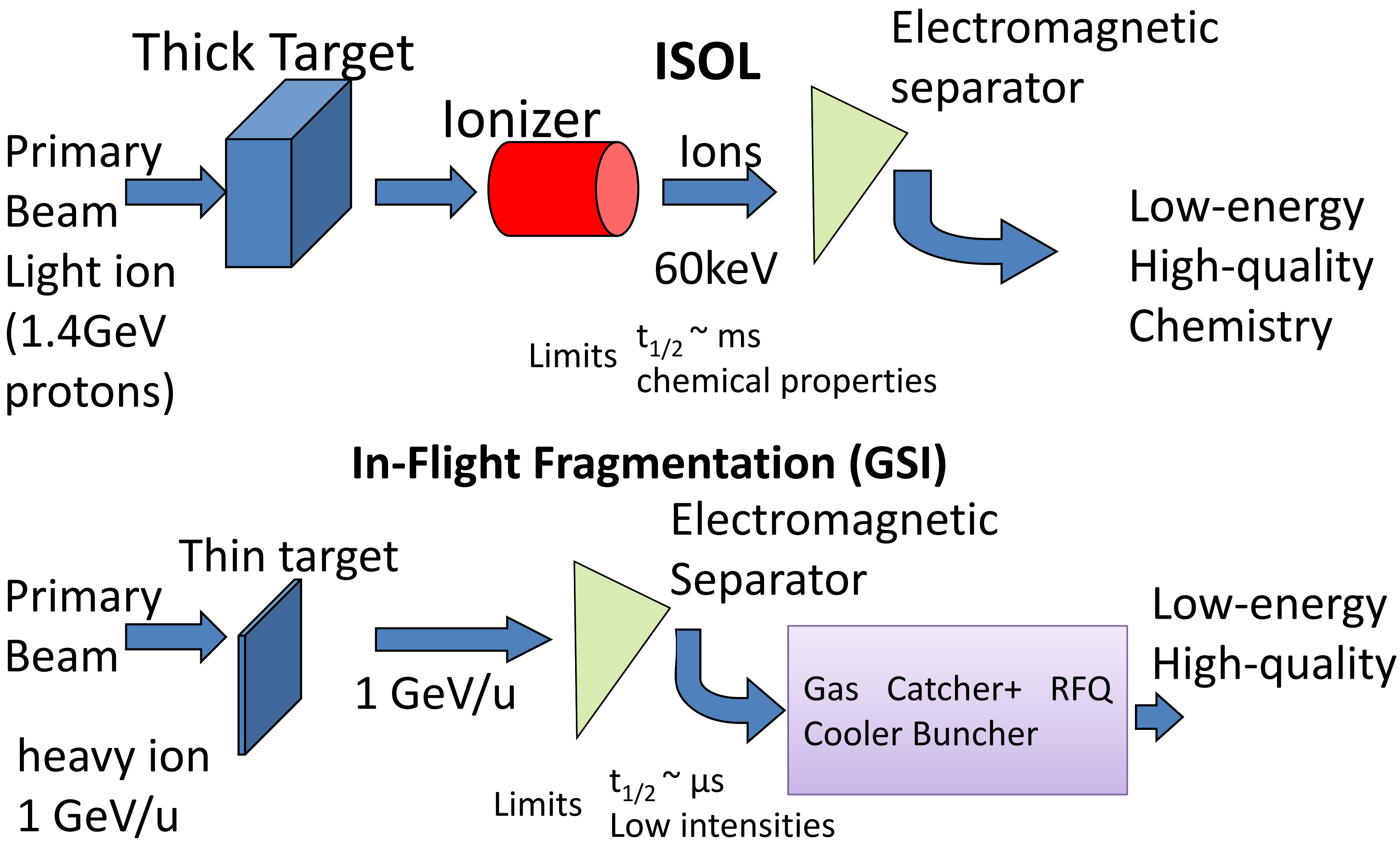


•The splitting of the hyperfine structure results from the presence of a permanent magnetic field associated with the nucleus and/or a non-symmetric electric field associated with a deformed nuclear charge distribution.

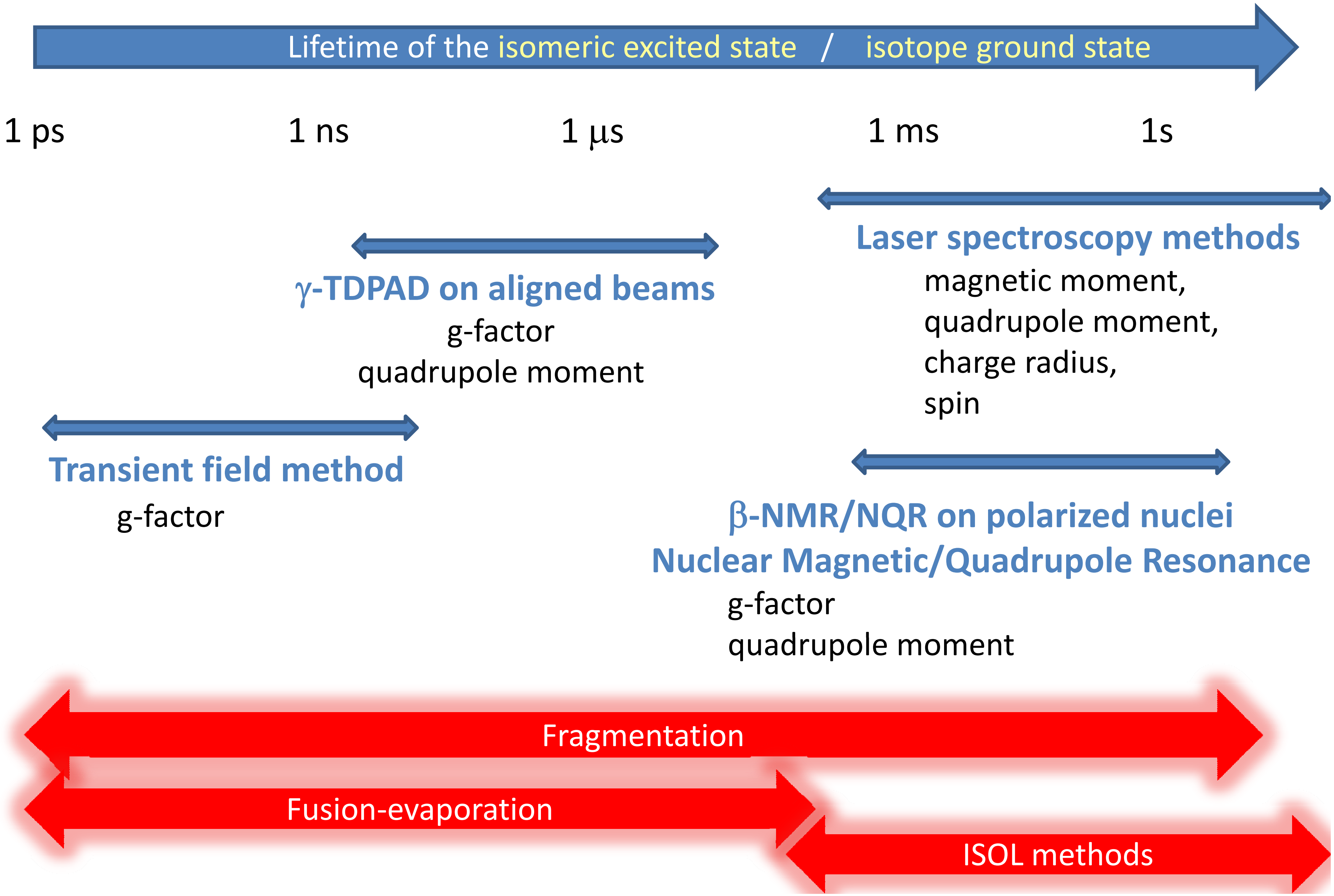


If we can measure the splitting of the atomic transitions with sufficient resolution it is possible to deduce the nuclear observables (magnetic and electric moments, spin and size) without any model (nuclear) dependence.

Rare isotope production for laser spectroscopy



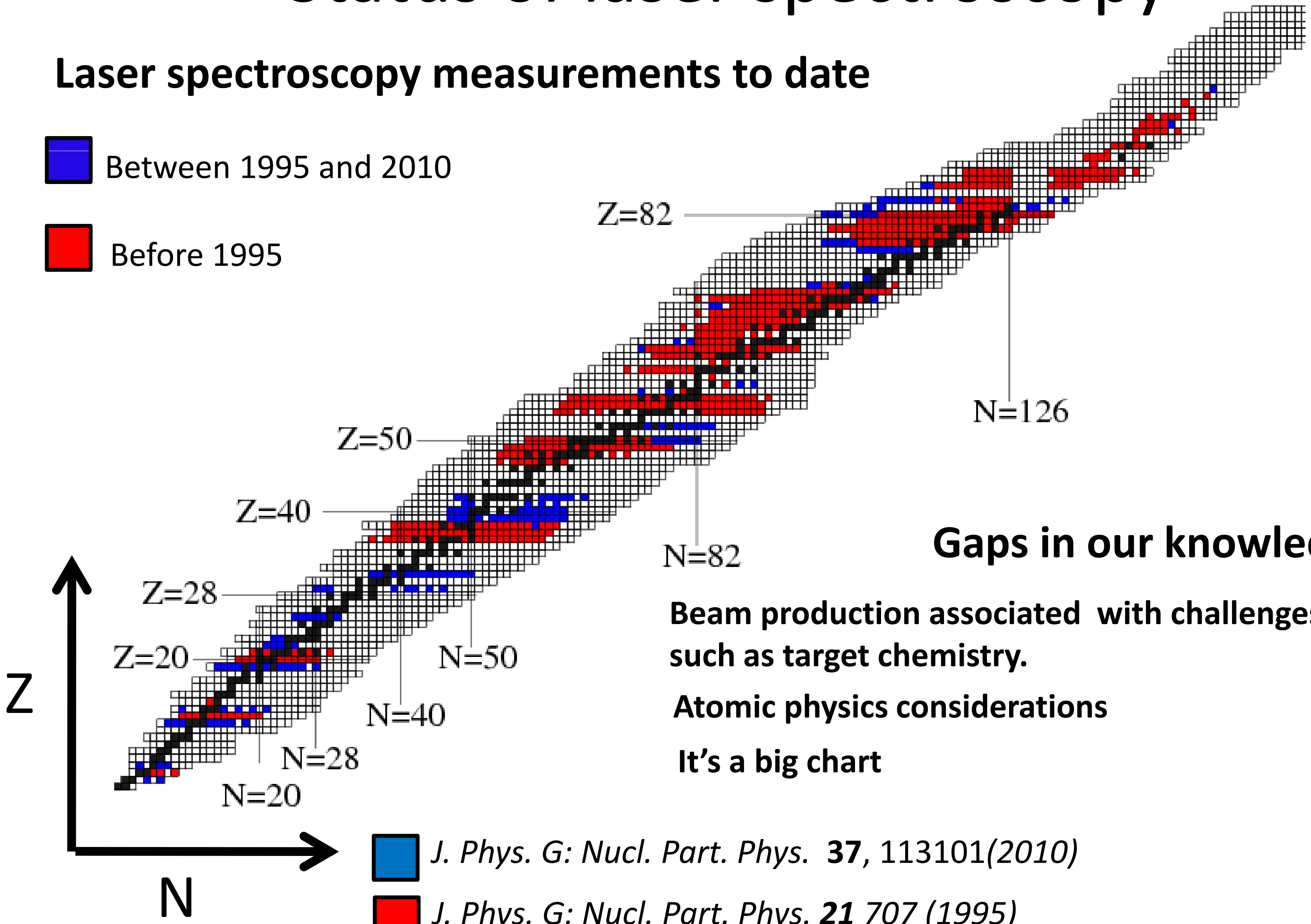
Methods to measure moments, radii, spin



Status of laser spectroscopy

Laser spectroscopy measurements to date

- Between 1995 and 2010
- Before 1995



Gaps in our knowledge

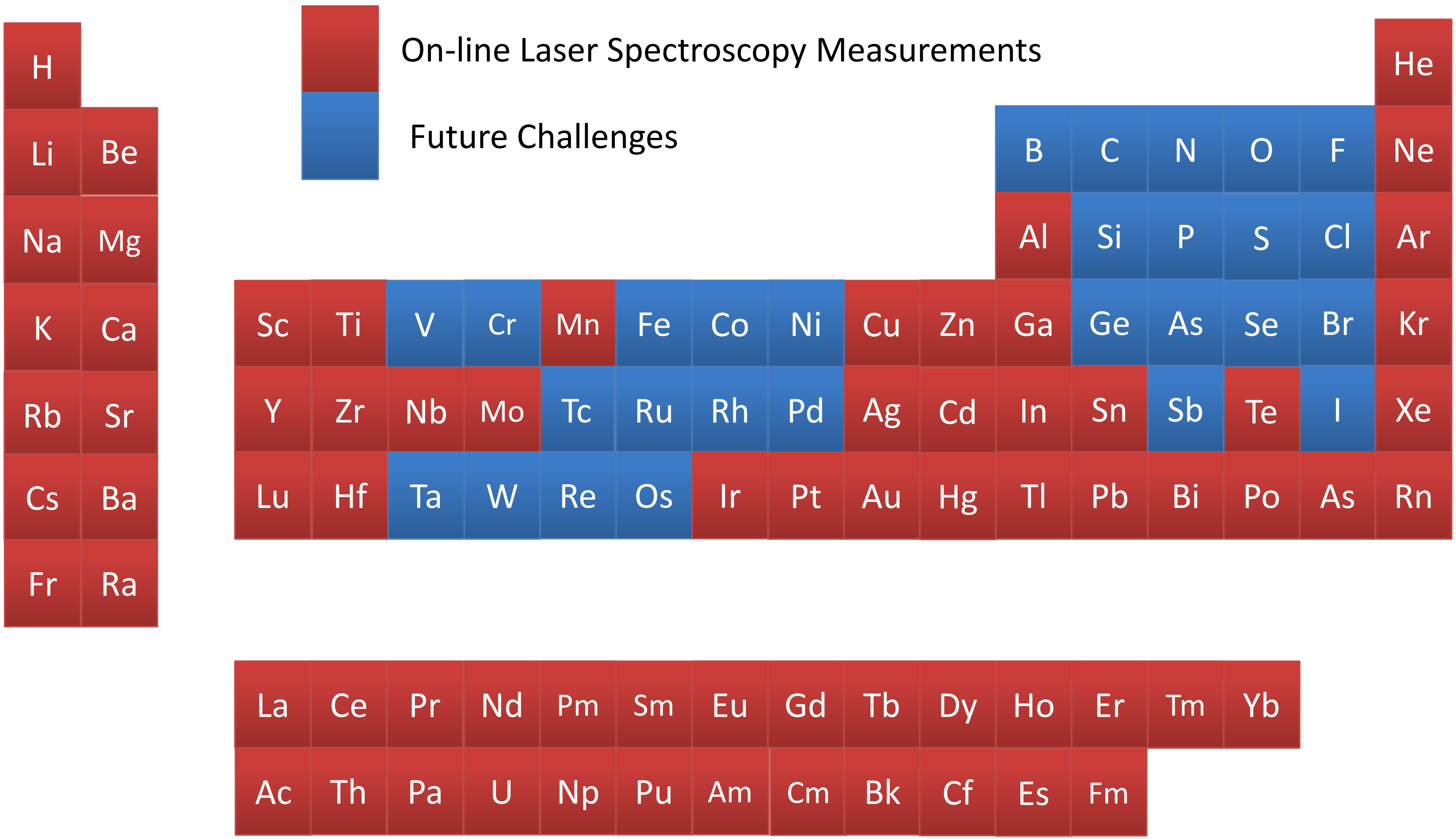
Beam production associated with challenges such as target chemistry.

Atomic physics considerations

It's a big chart

- *J. Phys. G: Nucl. Part. Phys.* **37**, 113101*(2010)*
- *J. Phys. G: Nucl. Part. Phys.* ***21*** *707 (1995)*

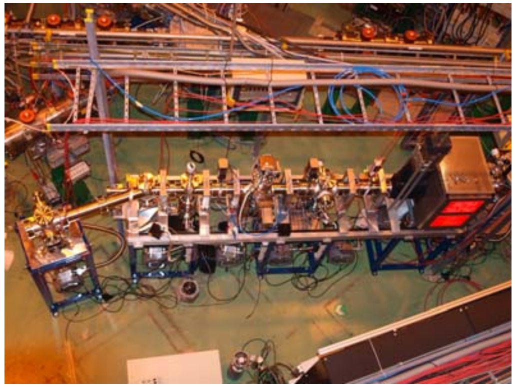
Ion resonance ionization cases



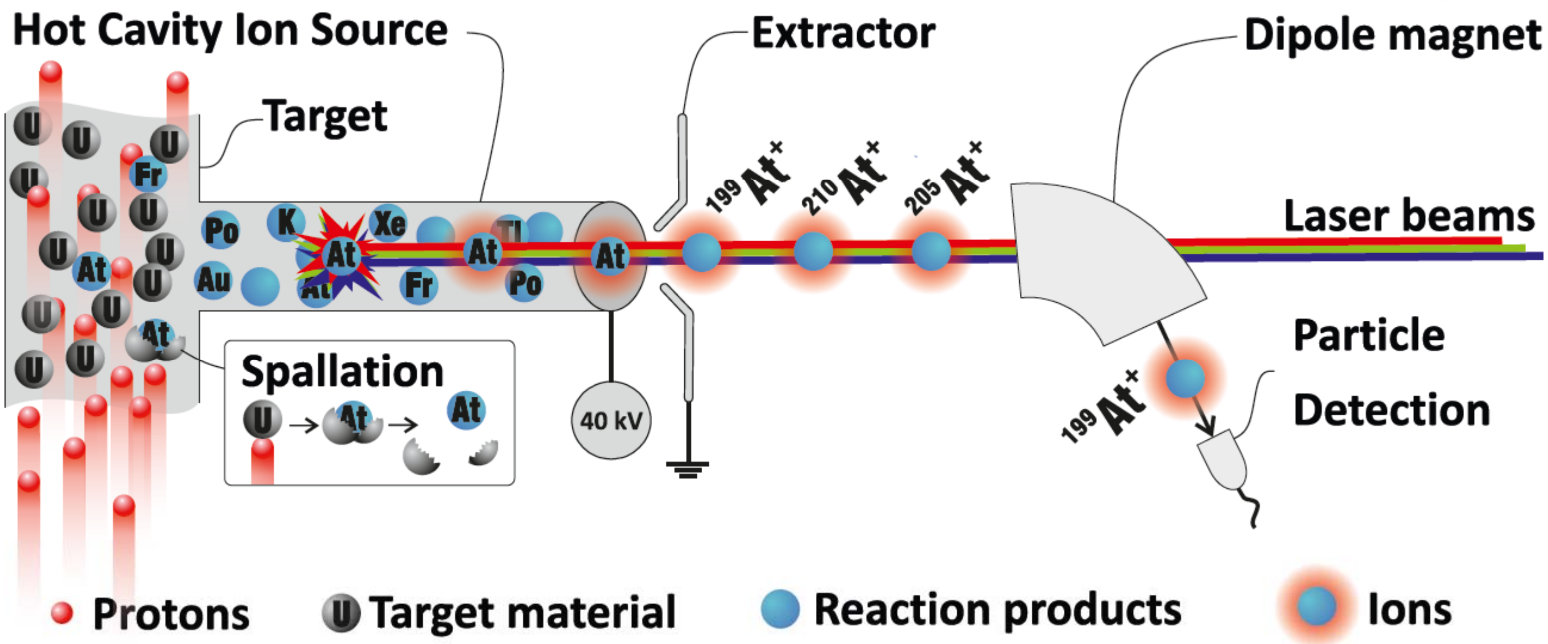
European Laser Spectroscopy Options

- In-source: RILIS, ALTO
  - Sub 1 atom/s sensitivity
  - Wide range of elements studied (~30 currently accessible)
  - 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
  - High resolution (typically limited by natural linewidth)
  - Highly adaptable



In-source laser spectroscopy



- Need to satisfy the Flux and Fluence conditions in order to saturate transitions and maximise efficiency.
- Short duration pulsed lasers (10-20ns) with ~1-10mJ per pulse. EASY
- CW Laser> 500W (and tight focus) just to saturate the first step. DIFFICULT

G. D. Alkhazov et al., NIM B69 (1992) 517
U. Koester et al., Nucl. Phys. A 701 (2002) 441c
V.N. Fedoseev *et al.*, NIM B266 (2008) 4378

~100mW at 10kHz for resonant steps
~1-5W at 10kHz for quasi resonant steps
~10-20W at 10kHz for non-resonant steps

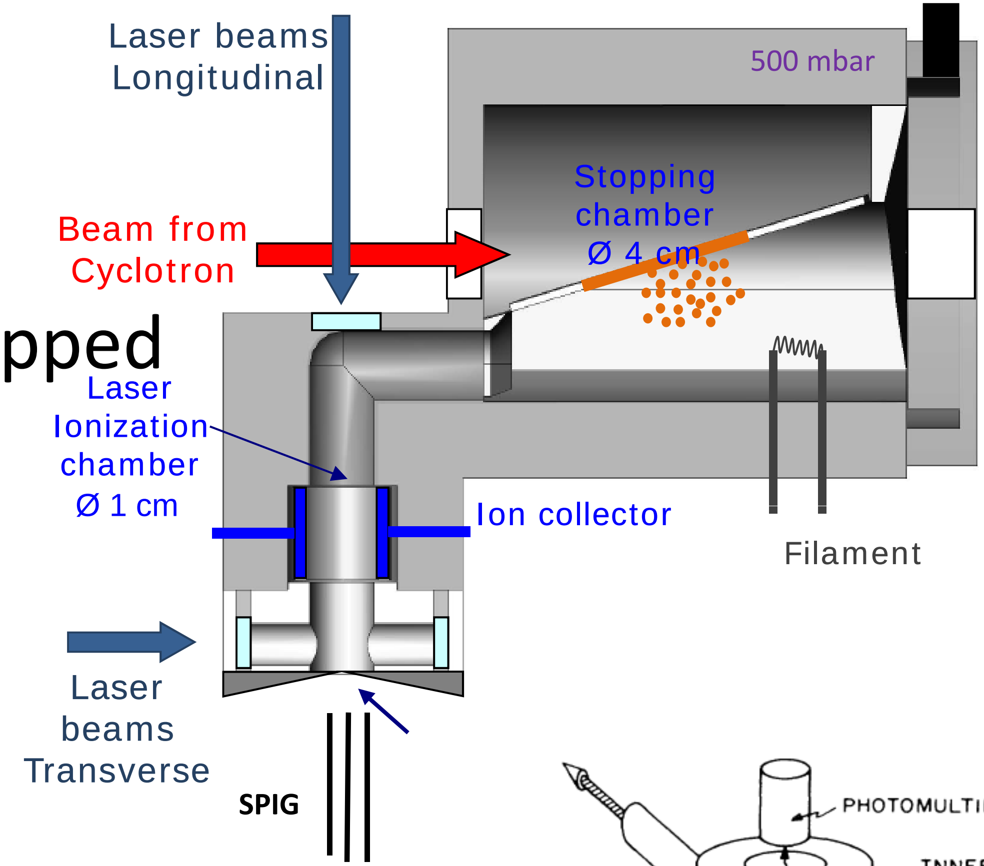
Talk by Bruce Marsh

Sebastian Rothe

Gas cell laser spectroscopy

- JYFL, Leuven
  - ^{57,58,59}Cu, ^{97,99,101}Ag

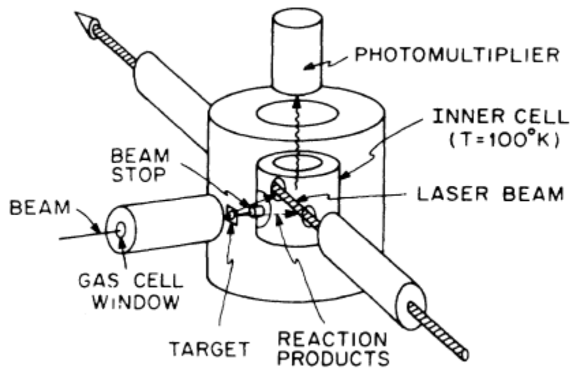
    T. E. Cocolios et al., PRL 103, 102501 (2009)
    T. E. Cocolios et al., PRC 81, 014314 (2010)
    Iain Darby Phys. Lett. B (in preparation)



- Future S3 work on stopped beams
  - N=Z line: ^{94}Ag, ^{101,103}Sn,
  - SHE region >Ac

R. Ferrer Garcia, Talk in the next session

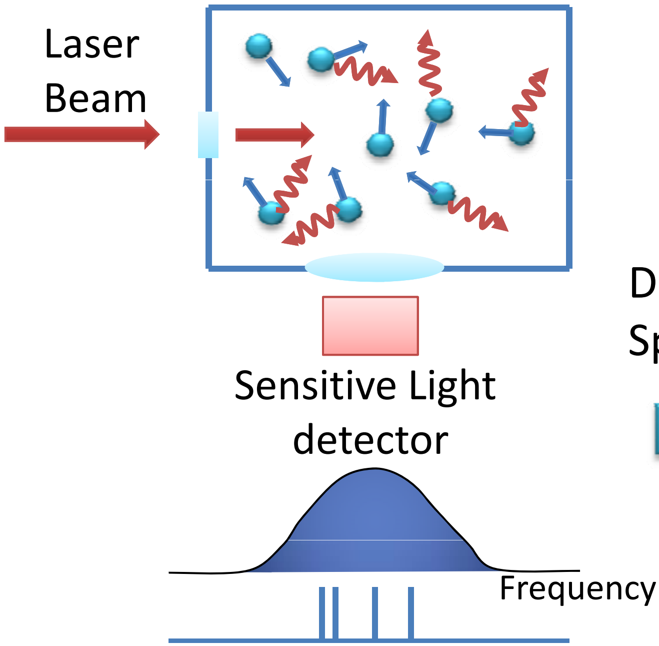
- Cryogenic gas cell and fluorescence detection
  - 900/s yields, Γ~300MHz
  - Possible route to probe μs half-lives



G. D. Sprouse et al., PRL **63** 1463 (1989)

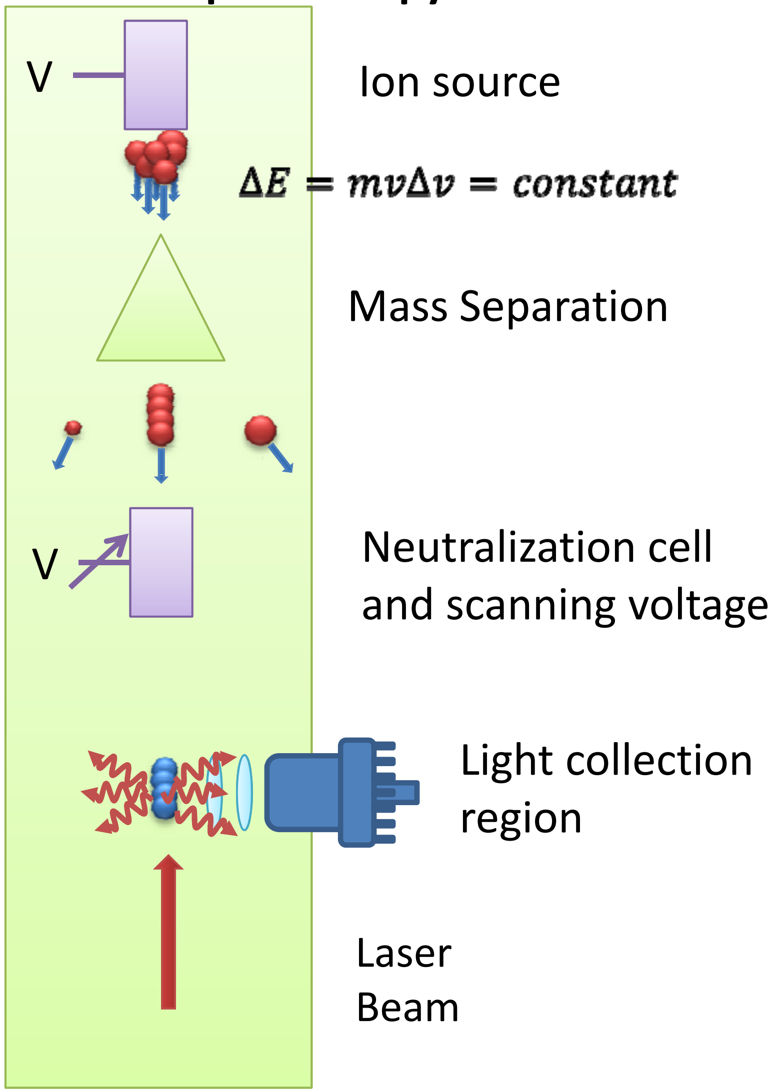
Laser Spectroscopy

Closed box of atoms at temperature for a vapour to form (100K for Yb)



Doppler Free Spectroscopy

Collinear Laser Spectroscopy

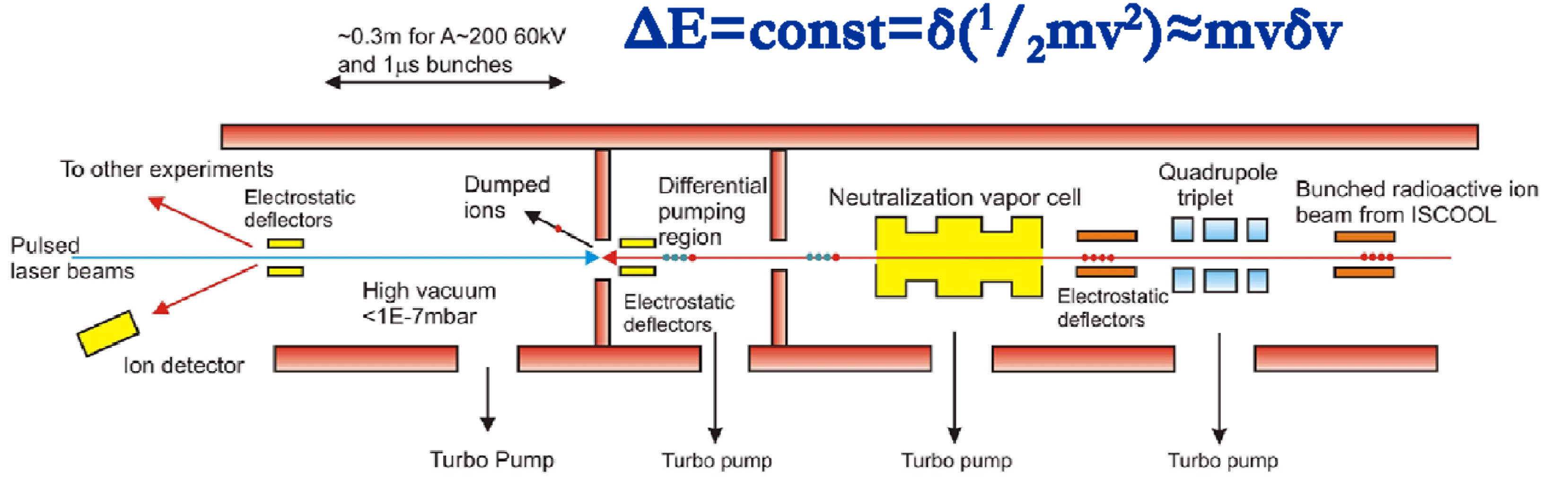


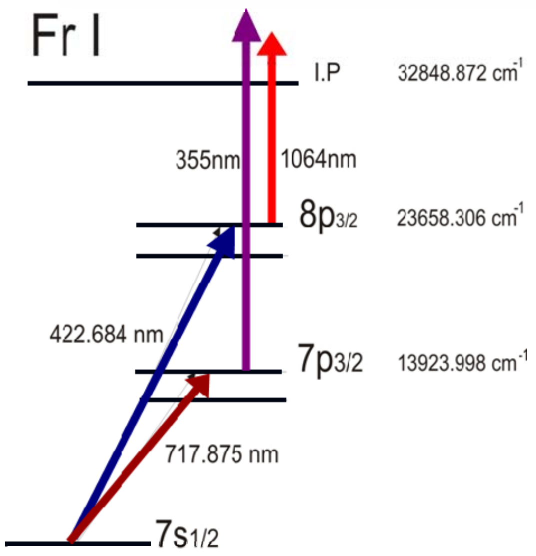
The thermal motion of the atoms broadens the transition, masking the hyperfine structure: Doppler Broadening 300-400 MHz

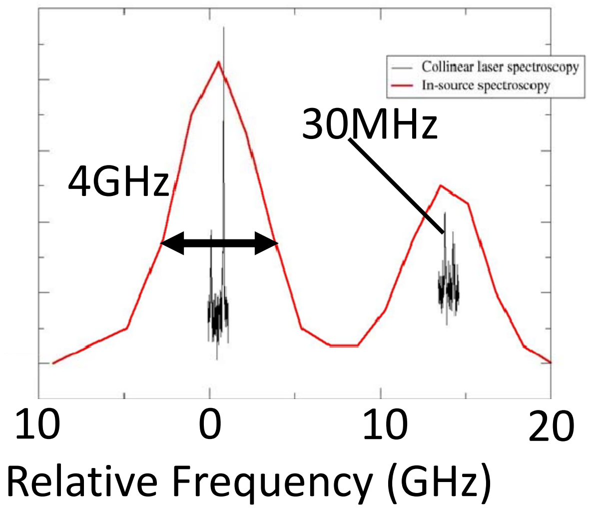
Deyan Yordanov, next talk

Collinear Resonant Ionization Spectroscopy (CRIS) @ ISOLDE

$\Delta E = const = \delta({}^{1}/{}_{2}mv^{2}) \approx mv\delta v$



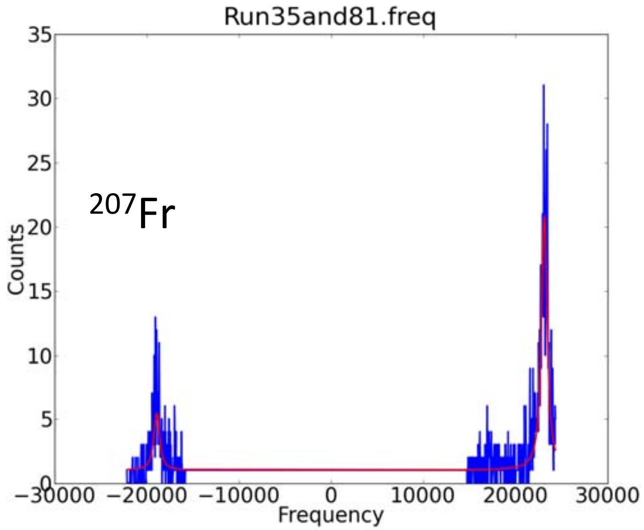


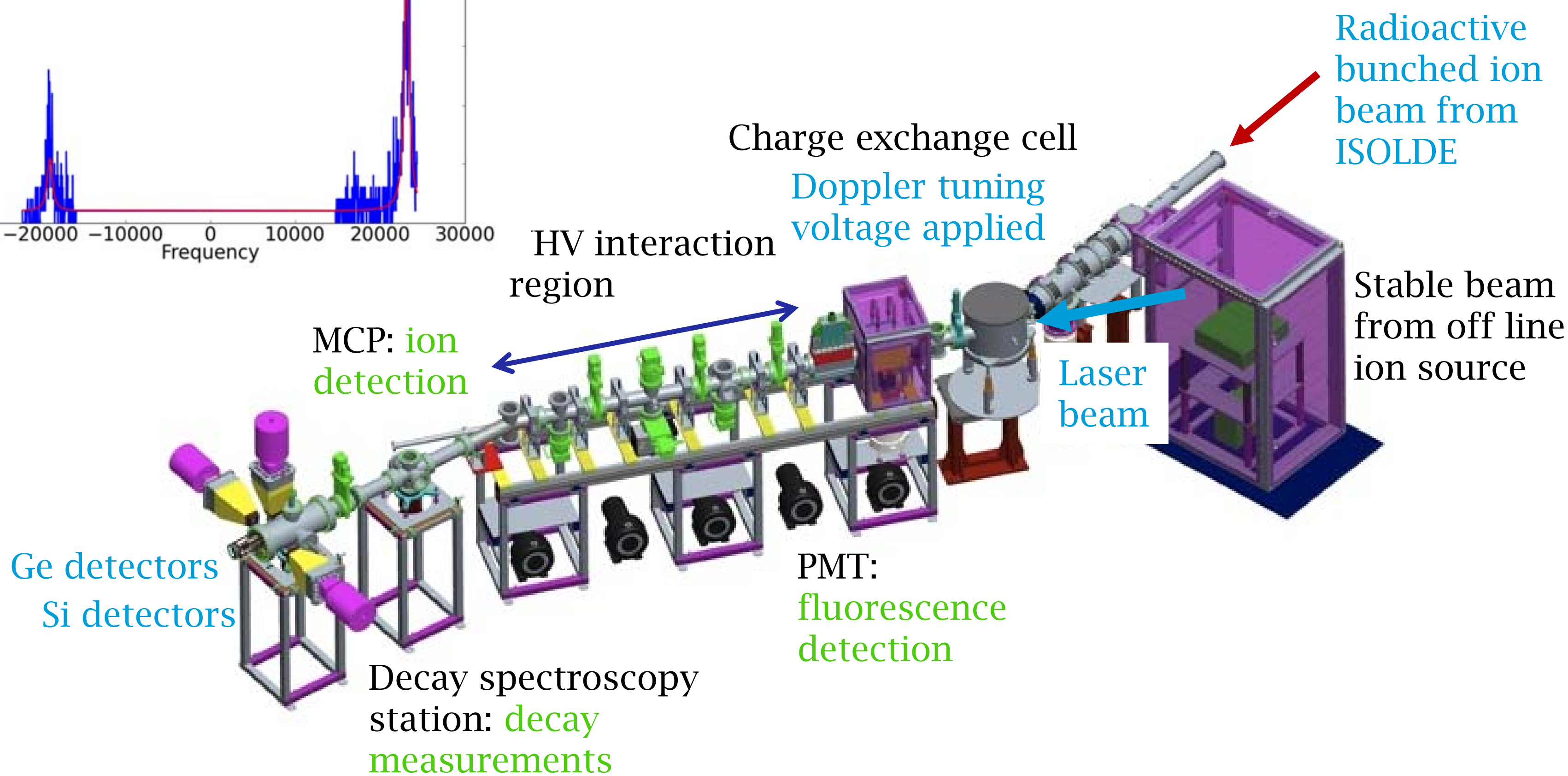


Combining high resolution nature of collinear beams method with high sensitivity of in-source spectroscopy. Allowing extraction of B factors and quadrupole moments.

Yu. A. Kudriavtsev and V. S. Letokhov, *Appl. Phys.* **B29** 219 (1982)

Layout of the CRIS beam line



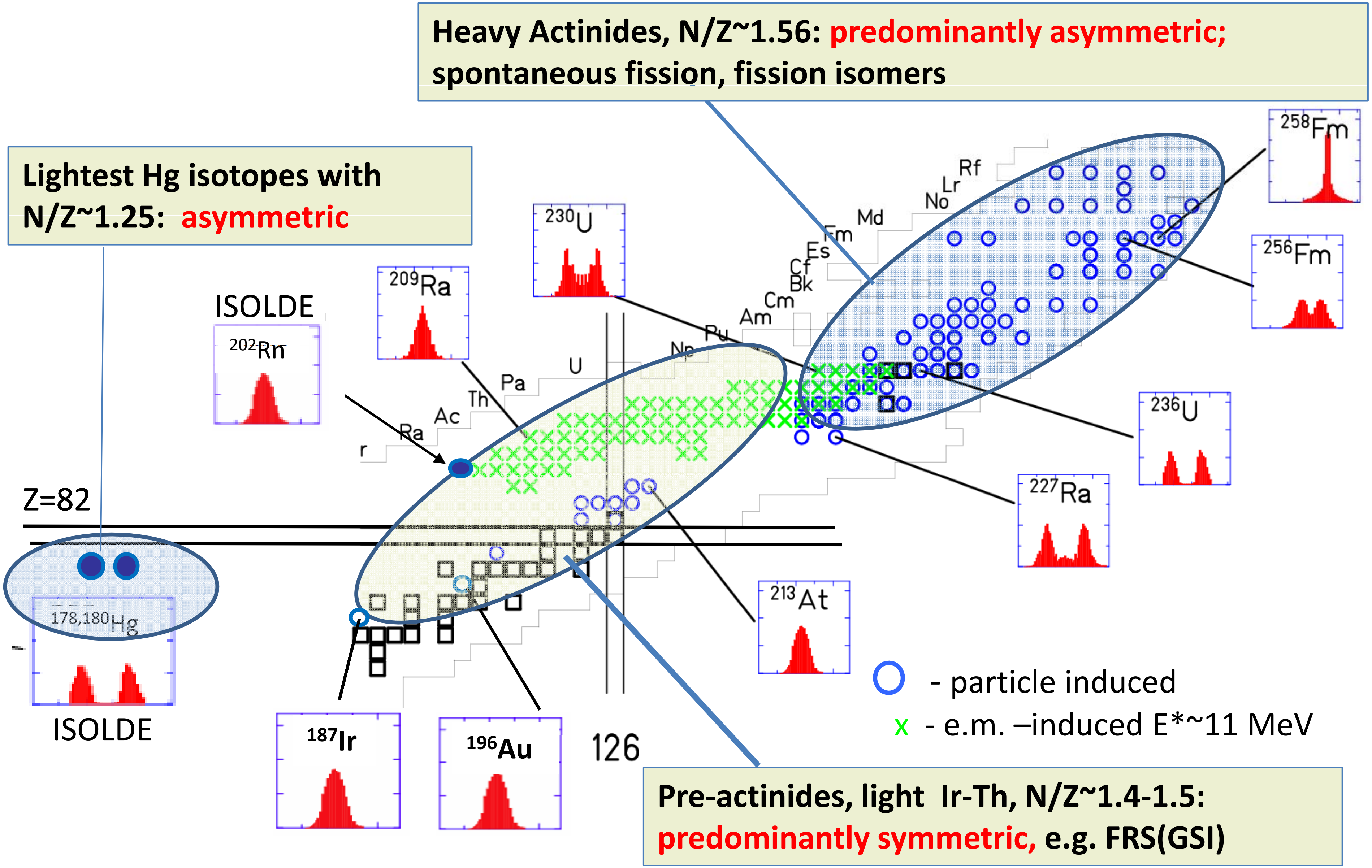


- Collinear geometry gives a reduction in the thermal Doppler broadening by a factor of 10^3, improving resolution

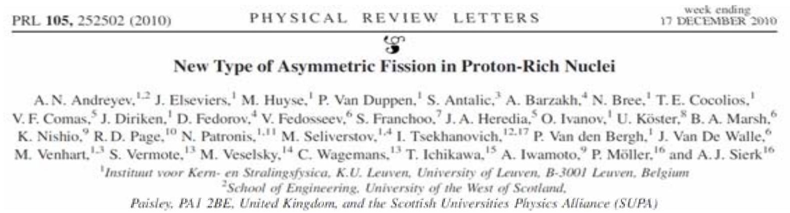
$$\Delta E = \delta(\tfrac{1}{2} mv^2)$$
$$= mv\delta v$$
$$\approx \text{constant}$$

New Region of Asymmetric Fission $^{178,180}Hg$

A. Andreyev et al., PRL105,252502(2010)



β-delayed fission of ^{202}Fr

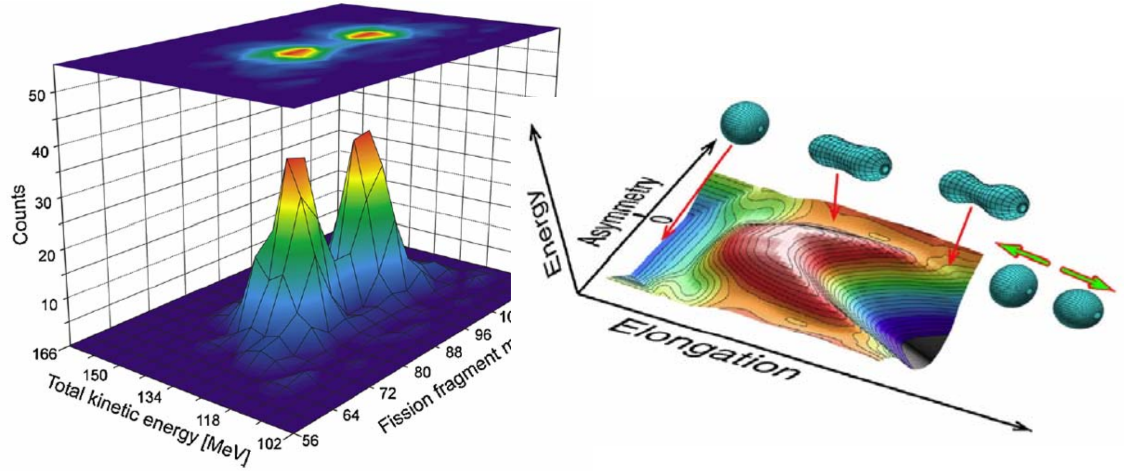


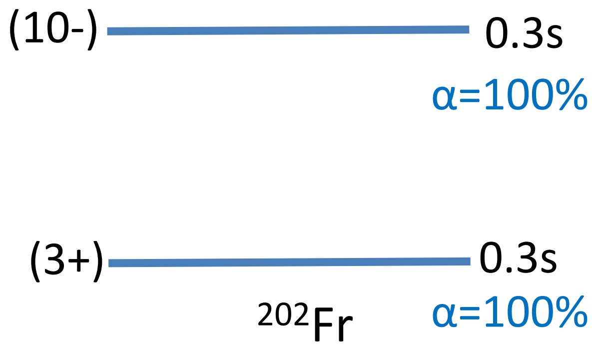
PRL **105**, 252502 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

New Type of Asymmetric Fission in Proton-Rich Nuclei

A. N. Andreyev,[1,2] J. Elseviers,[1] M. Huyse,[1] P. Van Duppen,[1] S. Antalic,[3] A. Barzakh,[4] N. Bree,[1] T. E. Cocolios,[1] V. F. Comas,[5] J. Diriken,[1] D. Fedorov,[4] V. Fedosseev,[6] S. Franchoo,[7] J. A. Heredia,[5] O. Ivanov,[1] U. Köster,[8] B. A. Marsh,[6] K. Nishio,[9] R. D. Page,[10] N. Patronis,[1,11] M. Seliverstov,[1,4] I. Tsekhanovich,[12,17] P. Van den Bergh,[1] J. Van De Walle,[6] M. Venhart,[1,3] S. Vermote,[13] M. Veselsky,[14] C. Wagemans,[13] T. Ichikawa,[15] A. Iwamoto,[9] P. Möller,[16] and A. J. Sierk[16]

[1]Instituut voor Kern- en Stralingsfysica, K.U. Leuven, University of Leuven, B-3001 Leuven, Belgium
[2]School of Engineering, University of the West of Scotland, Paisley, PA1 2BE, United Kingdom, and the Scottish Universities Physics Alliance (SUPA)

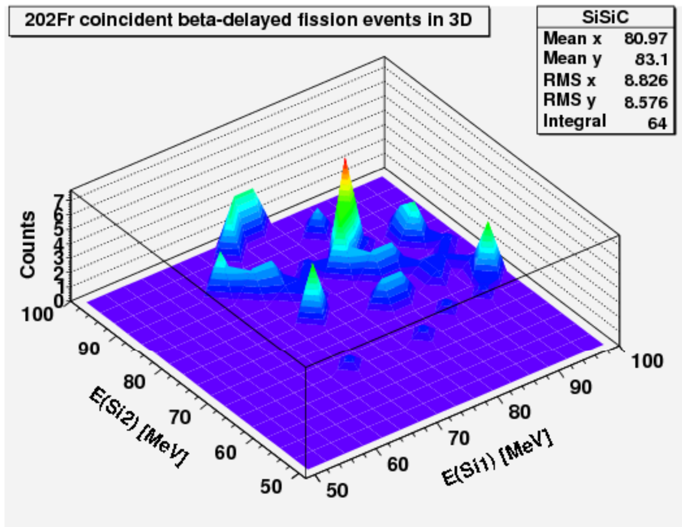




200-300/s ^{202}Fr with 1-2f/hr
Unknown if just one state or both leads to fission.
Possible candidate for shape coexistence

Surprising asymmetric fission mass split of ^{180}Hg (A_H~100,A_L~80)v

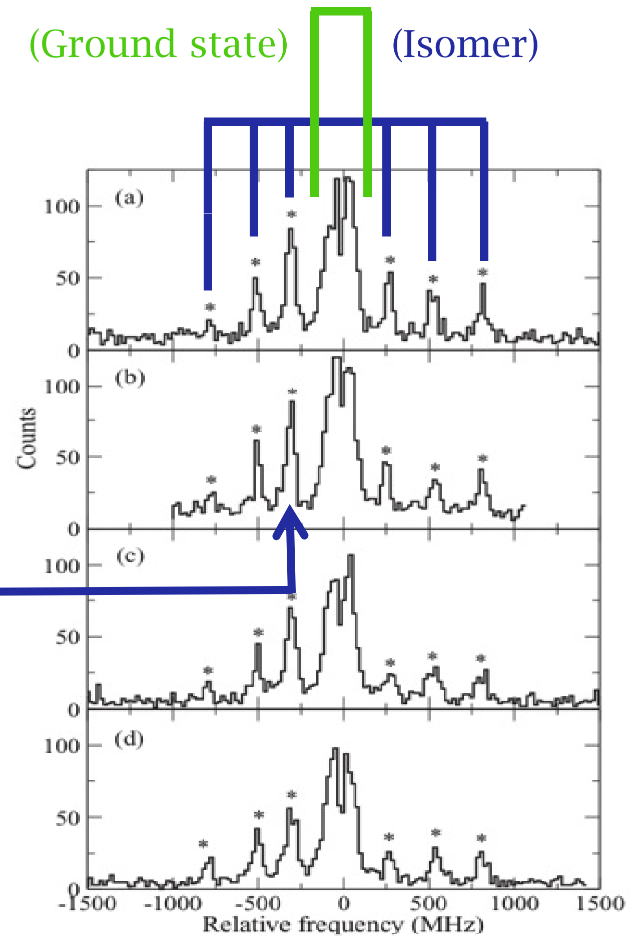
CRIS offers the ability to produce a clean beam of ^{202}Fr while simultaneously measuring the spin and deformation of the states.



Spectroscopy on isomeric beams

- Using CRIS as a purification technique
- Differences in the nuclear structure between the ground and isomeric states leads to different HFS
- Sitting the laser on resonance with a characteristic HF transition only ionizes this state
  - e.g. on this frequency only the isomer would be ionized
- Decay spectroscopy can be performed on pure isomeric beams with a suppression of the ground state by a factor of 10^4

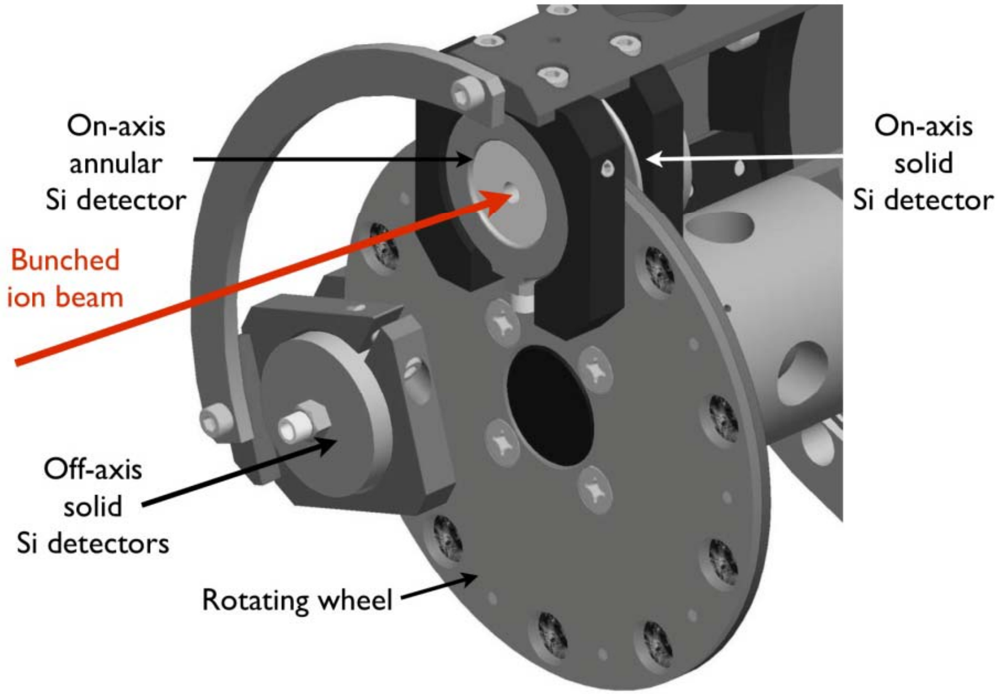
Hyperfine spectrum of ^{80g,m}Ga

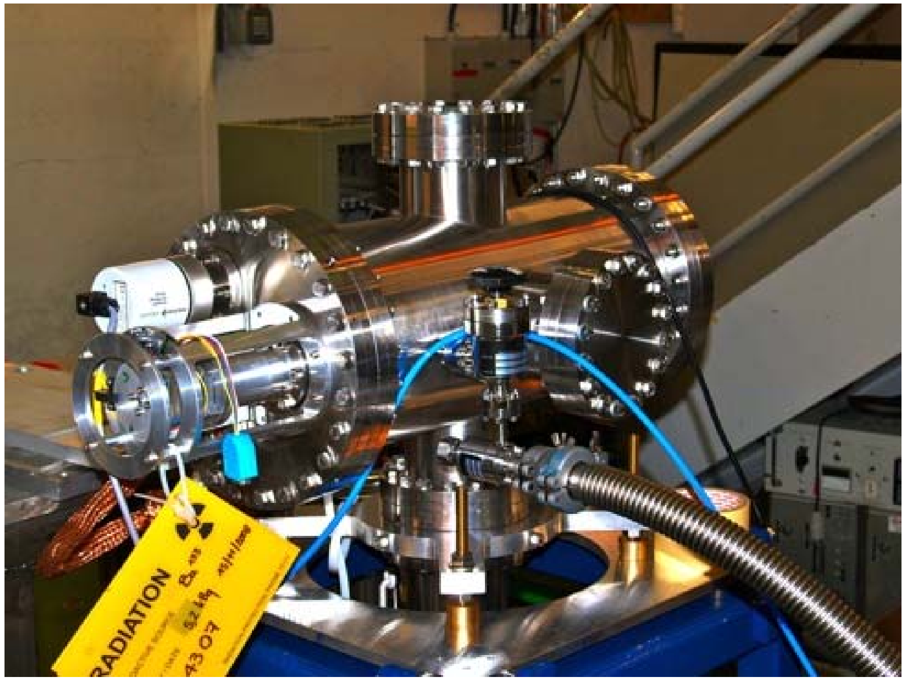


B. Cheal *et al.* Phys Rev C **82** 051302(R) (2010)

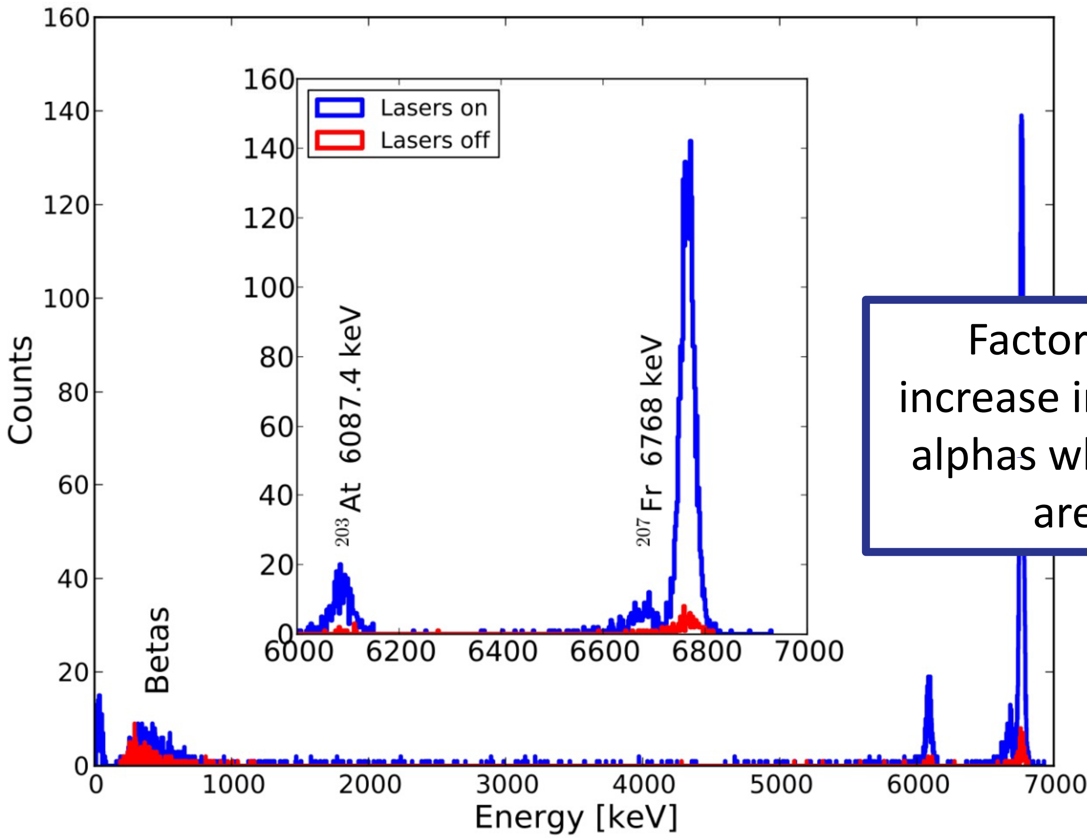
The decay spectroscopy station

- Rotating wheel implantation system
- Steel wheel rotates and a new ion bunch is implanted into the fresh carbon foil





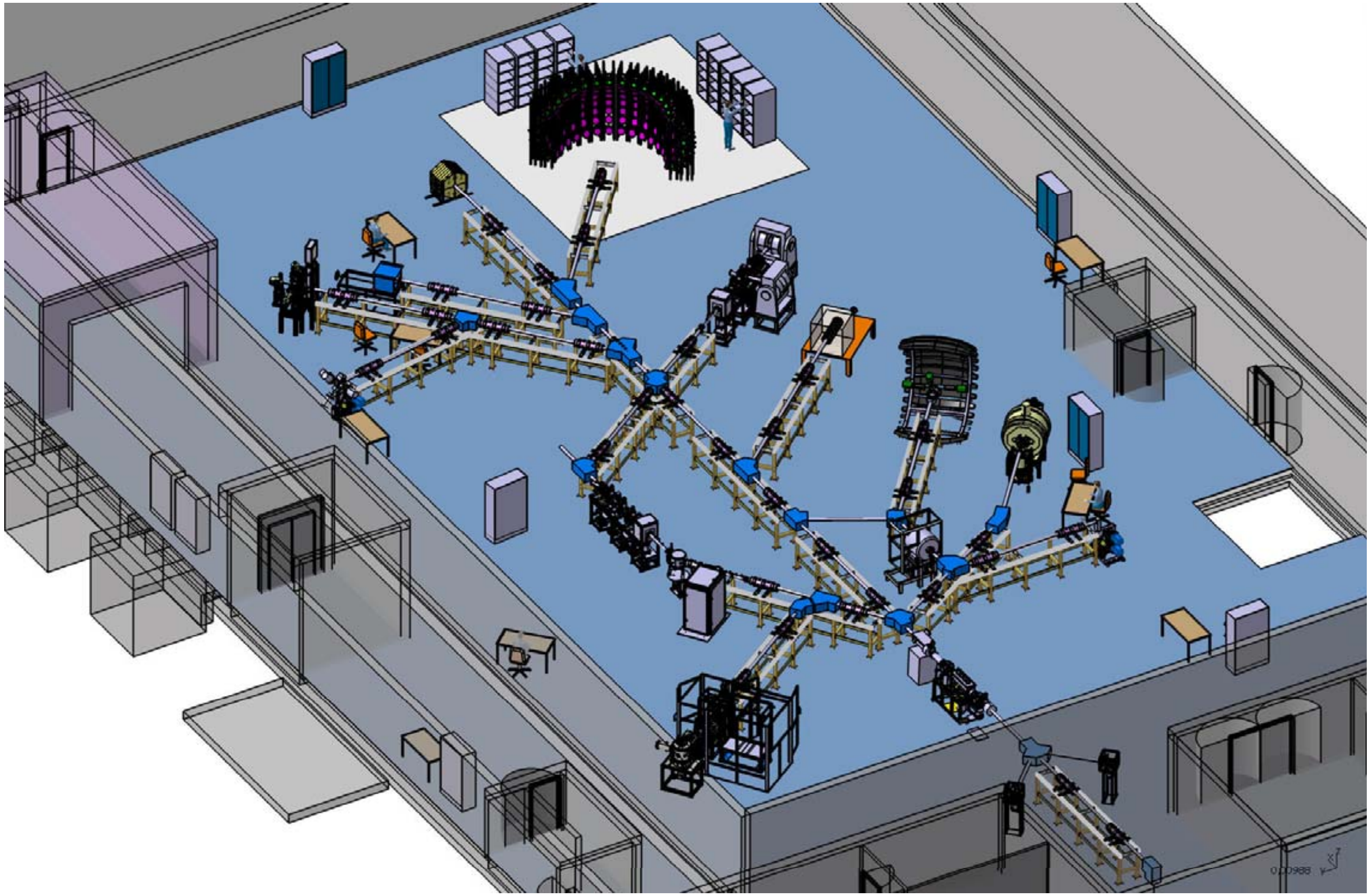
Laser assisted decay spectroscopy of ^{207}Fr



Factor of ~70 increase in detected alphas when lasers are on

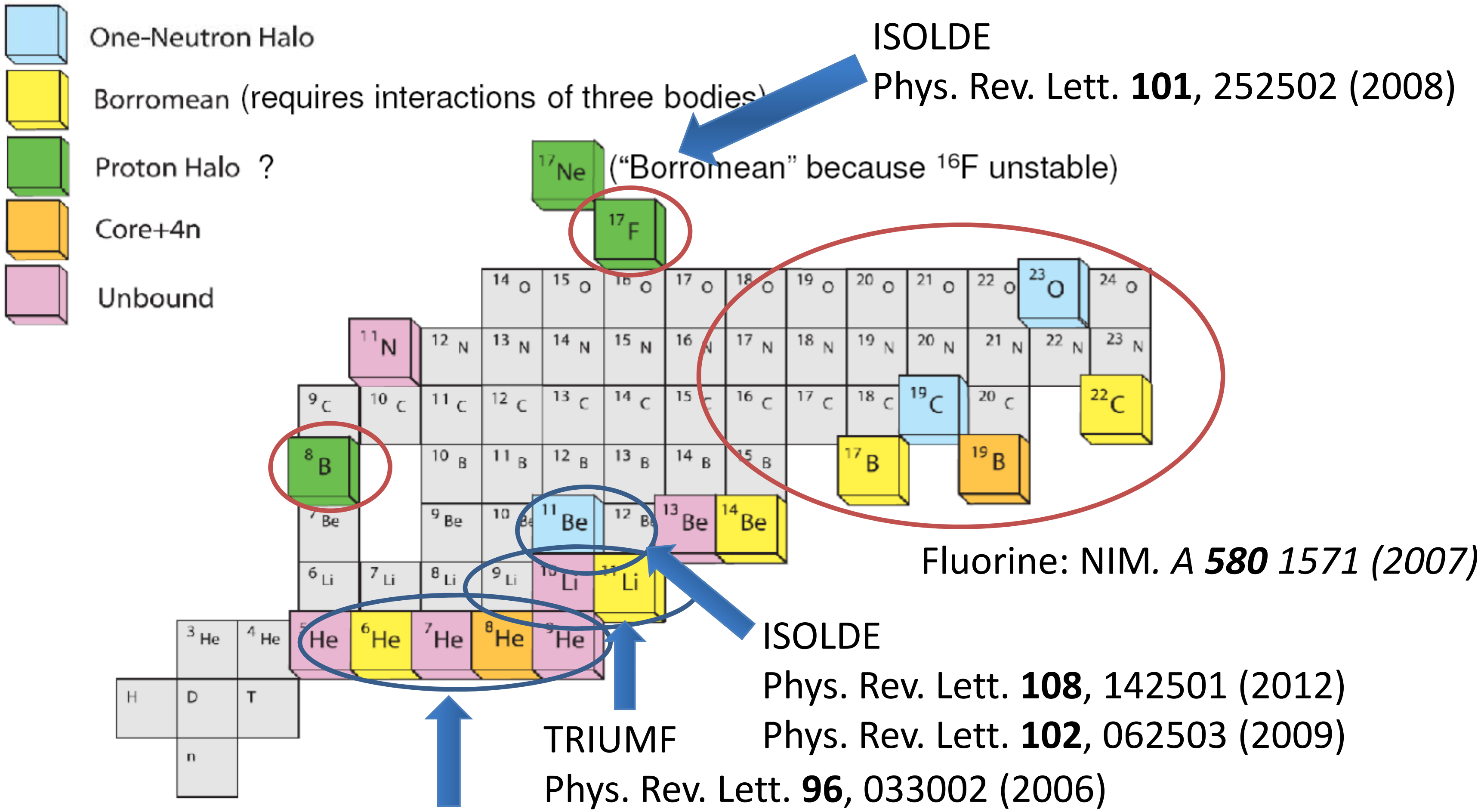
- 15 mins data collection time
- Data in red is due to collisional re-ionization in the interaction region at a pressure of 2e-8 mbar. Have already improved on this pressure by an order of magnitude in 2012

DESIR: New layout for laser assisted decay spectroscopy



Charge Radii of Halo Nuclei

I. Tanihata, J. Phys. G 22 (1996) 157



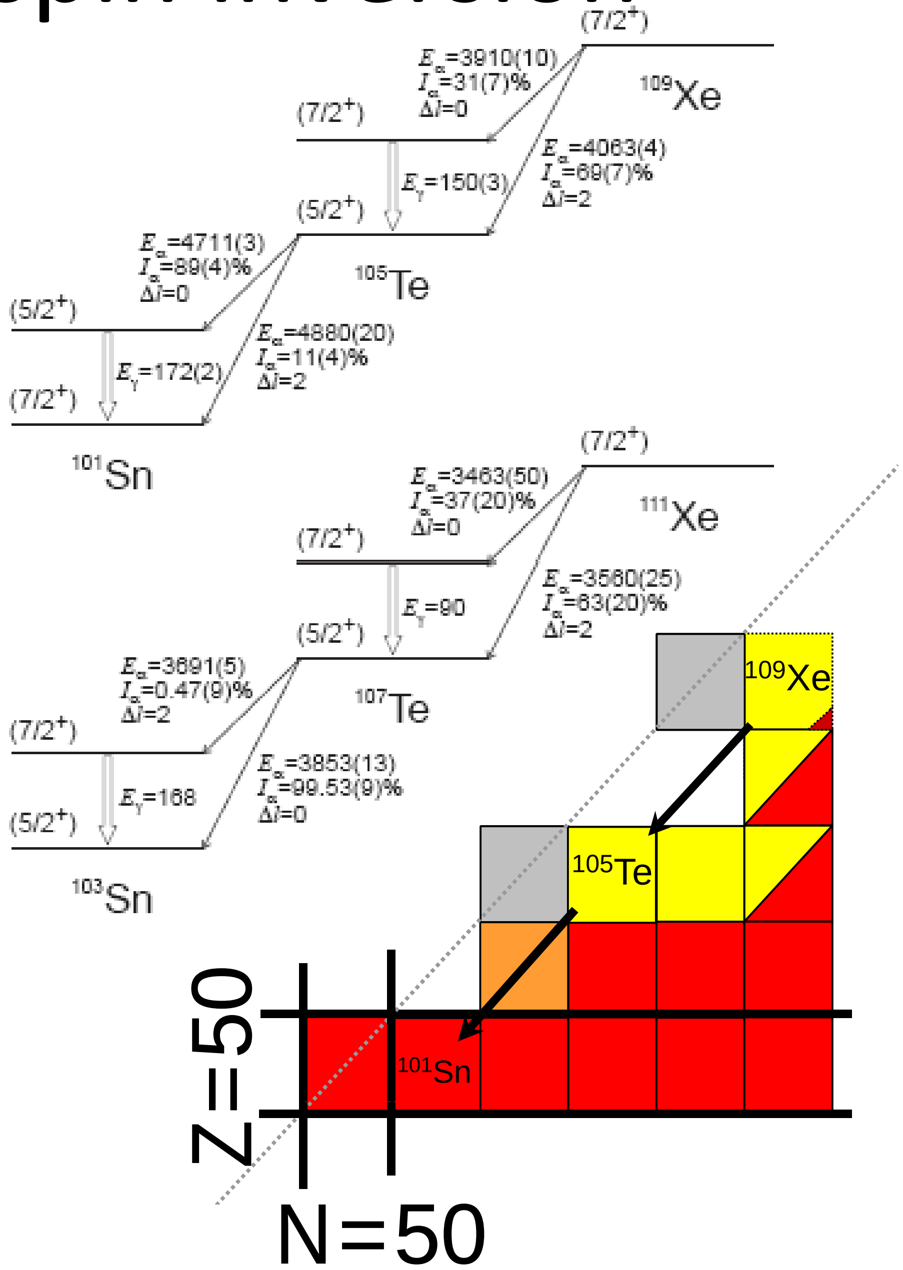
Argonne and GANIL

Phys. Rev. Lett. **99**, 252501 (2007)

Phys. Rev. Lett. **93**, 142501 (2004)

^{101}Sn: Ground state spin inversion

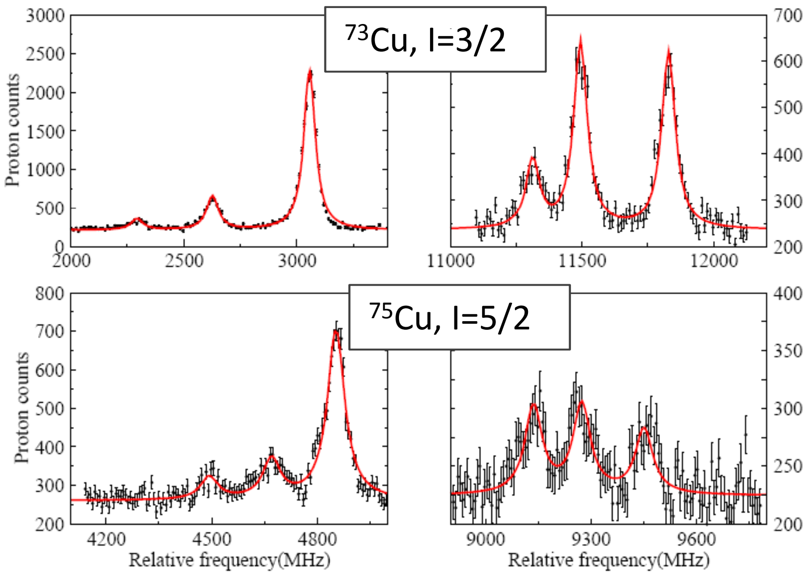
- Model independent measurement of spin from laser spectroscopy would be desirable
- Moment measurements in these isotopes would provide a better understanding the evolution of structure and further test contributions from the two-body tensor force.
- Case for SPIRAL2, S^3 and the laser gas cell method.



Darby et al., Phys. Rev. Lett. 105, 162502 (2010)

Ground-state spins of ^{71,73,75}Cu

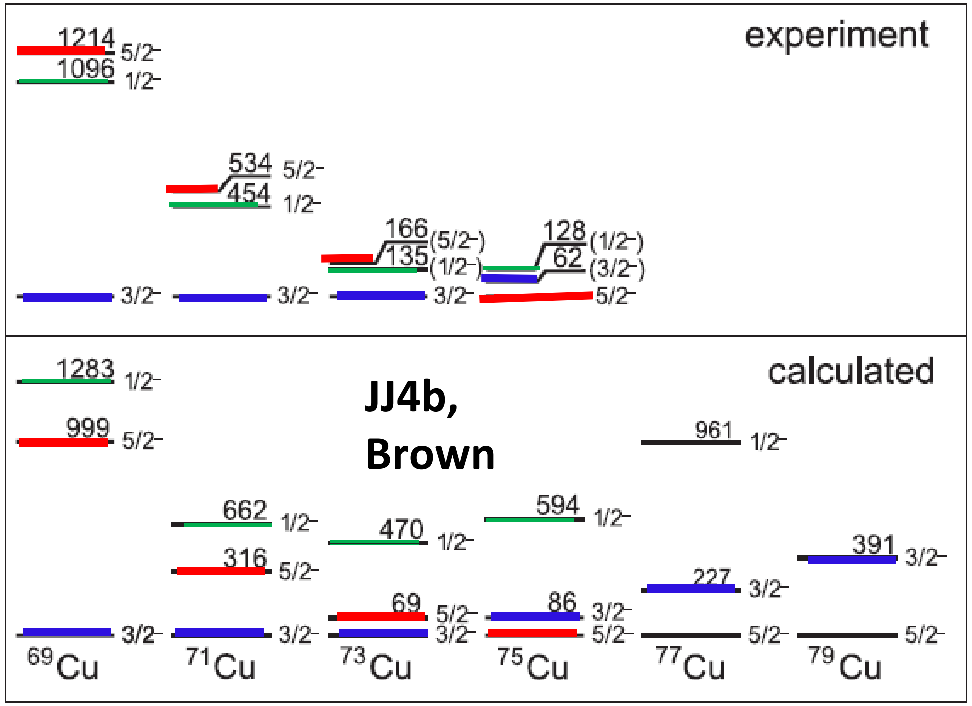
K.T. Flanagan et al., PRL 103, 142501 (2009)



➔ g.s. spins measured with laser spectroscopy
➔ spins assigned to isomeric levels in ^{75}Cu (based on measured lifetimes)

→Theory reproduces lowering of 5/2$^-$ correctly
→ theory overestimates the 1/2- energy from ^{69}Cu to ^{75}Cu !

I. Stefanescu Phys. Rev. Lett 100 (2008)



Model space: ^{56}Ni core + $f_{5/2}\ p_{3/2}\ p_{1/2}\ g_{9/2}$

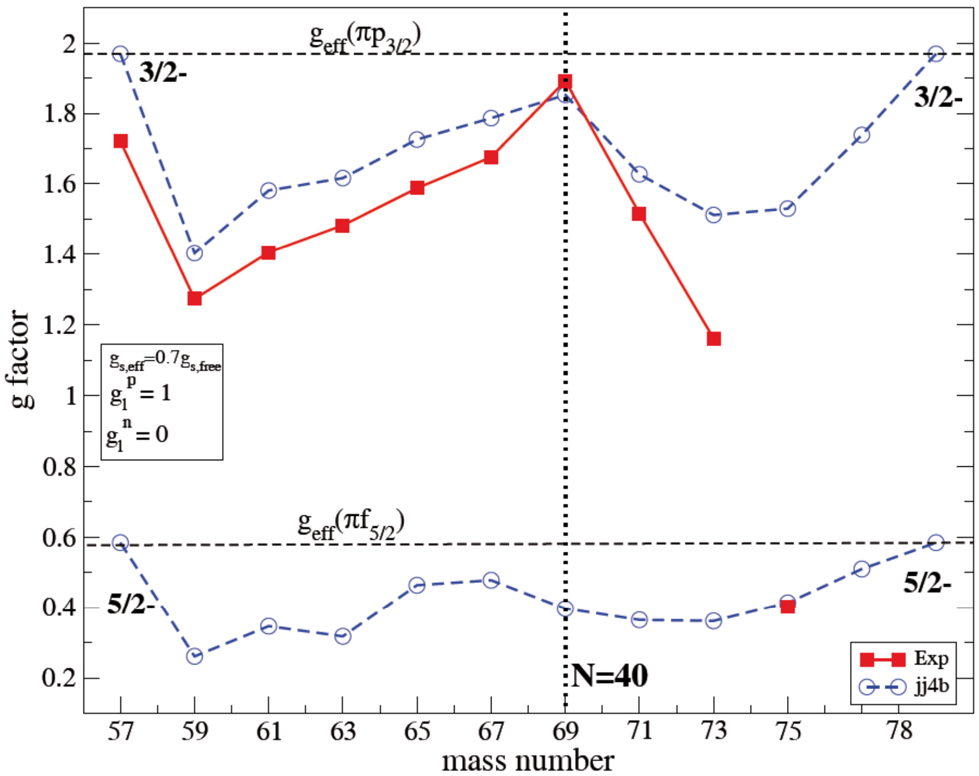
Effective interaction: Lisetsky and Brown based on A. F. Lisetskiy et al., Phys. Rev. C 70, 044314 (2004)

J. Daugas, Phys. Rev. C.

Magnetic moments of odd-Cu isotopes from N=28 to N=46

T. Cocolios et al., PRL 103, 102501 (2009)

K.T. Flanagan et al., PRL 103, 142501 (2009)



Calculations:

Model space (**^{56}Ni core**) + $f_{5/2}$ $p_{3/2}$ $p_{1/2}$ $\mathbf{g_{9/2}}$

Effective Interactions:

(**JUN45, Honma et al., PRC80, 064323, 2009)**

* **jj44b, Brown, private communication**

Conclusions:

(1) ^{69}Cu magnetic moment very close to the reduced single particle value

(2) used $g_s = 0.7\ g_s^{free}$ (^{56}Ni core, no f7/2)

(3) Towards N=28: both π and ν $f_{7/2}$ core excitations needed to reproduce core softness (GXPF1 gives perfect agreement)!

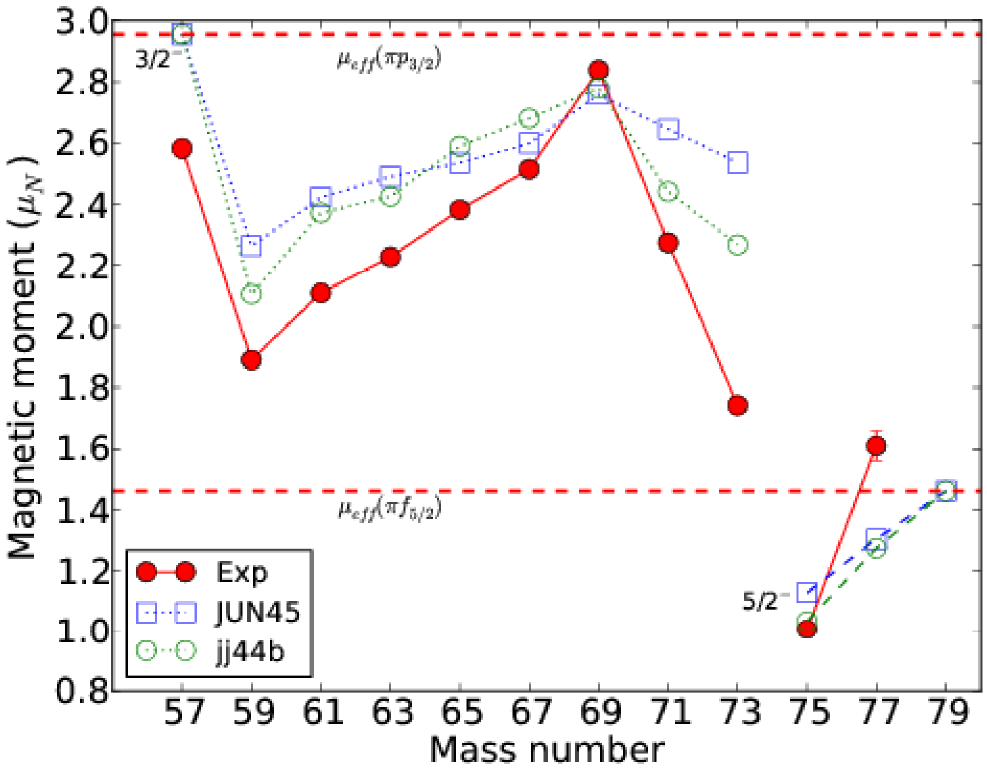
(4) Beyond N=40:

* ^{75}Cu, 5/2 g-factor well reproduced (because nearly pure $\pi f_{5/2}$ wave function)

* ^{71,73}Cu, 3/2 values largely overestimated → need more mixing with $(\pi f_{5/2} \otimes 2^+)_{3/2}$

Magnetic moments of ^{77}Cu

U Köster et al Phys. Rev. C 84, 034320 (2011)



Calculations:

Model space (^{56}**Ni core**) + $f_{5/2}$ $p_{3/2}$ $p_{1/2}$ $\mathbf{g_{9/2}}$
Effective Interactions:
(**JUN45, Honma et al., PRC80, 064323, 2009)**
* **jj44b, Brown, private communication**

The repulsive nature of the residual interaction between *πf7/2* and *νg9/2* orbital may be much stronger than previously predicted, which would favour particle-hole excitations across *Z = 28.*
Recent calculations by Sieja and Nowacki agree with this conclusion.
Phys. Rev. C 81, 061303 (2010).

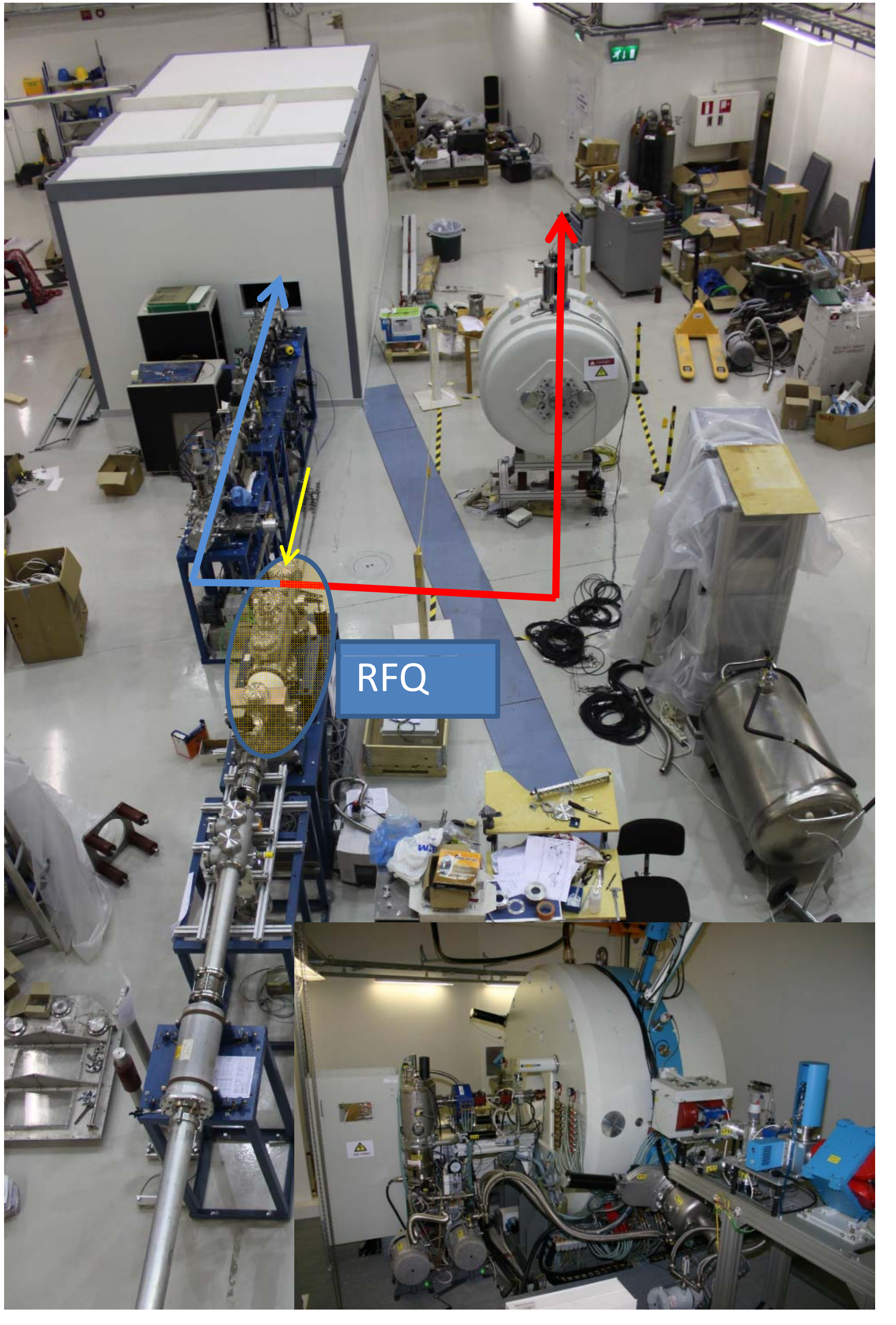
New proposal at CRIS, ISOLDE will study these isotopes with the eventual aim to extend laser spectroscopy measurements to ^{79}Cu

IGISOL4

The IGISOL , collinear laser spectroscopy and JYFLTRAP have been moved into a new hall at JYFL

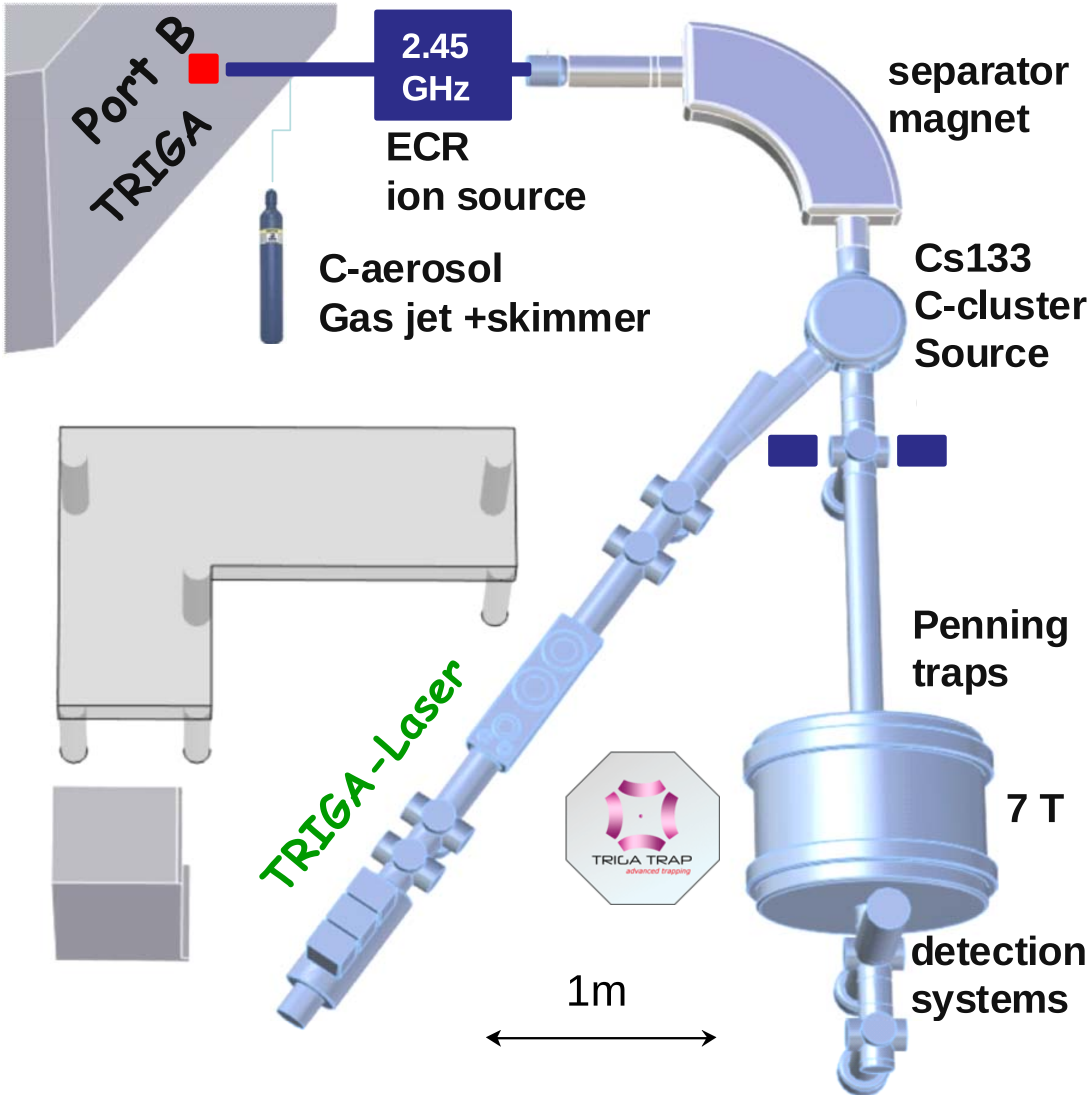
- MCC30 & K130 cyclotrons
- x10 more protons (30 MeV)
- Extended beam times
- First radioactive beams in 2012
  - RFQ cooler+buncher (existing)
  - Penning trap line
  - Collinear laser spectroscopy line (Birmingham+Manchester)
  - Optical pumping

A. Kankainen Talk this afternoon



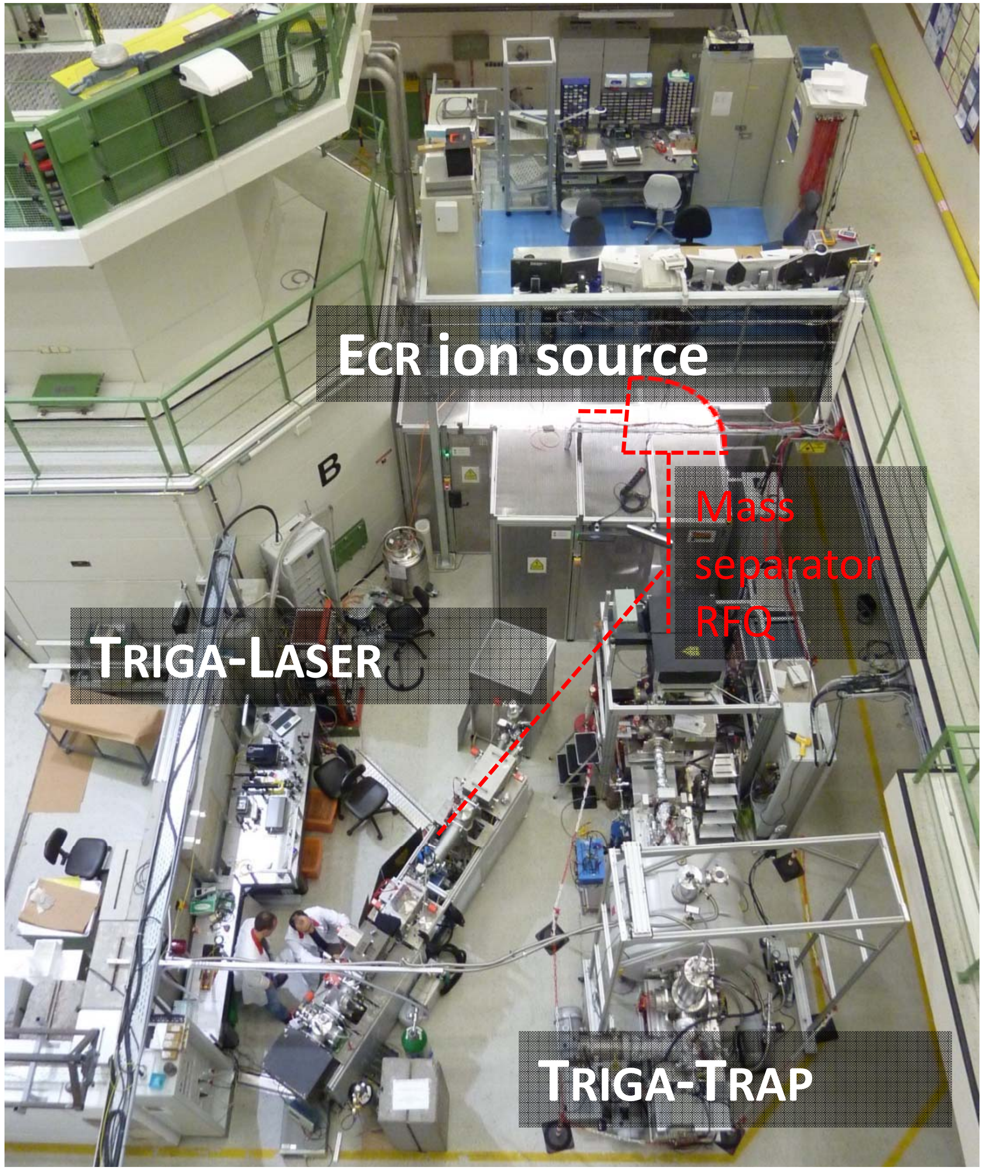
TRIGA-SPEC: TRIGA-LASER + TRIGA-TRAP

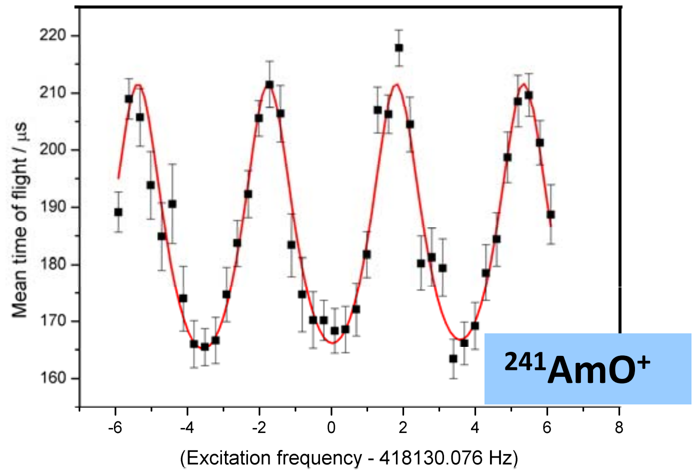
steady 100 kW,
pulsed 250 MW,
neutron flux 1.8x10^{11} / cm^{2}s

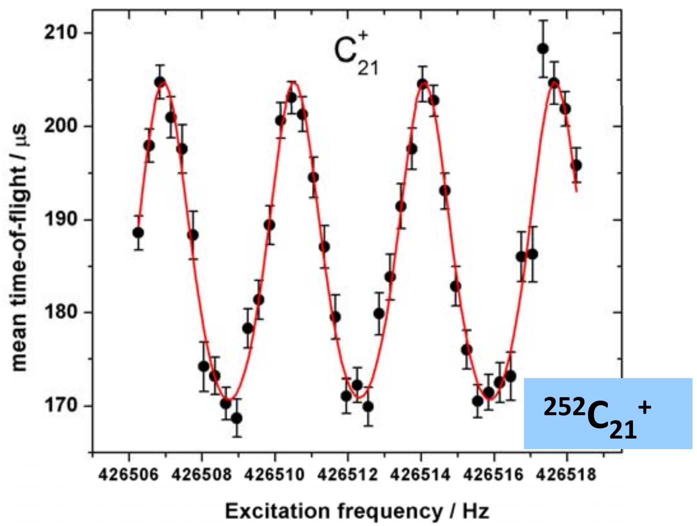


J. Ketelaer et al., Nucl. Instr. Meth. A 594 (2008) 162–177

TRIGA-SPEC: Status and first results





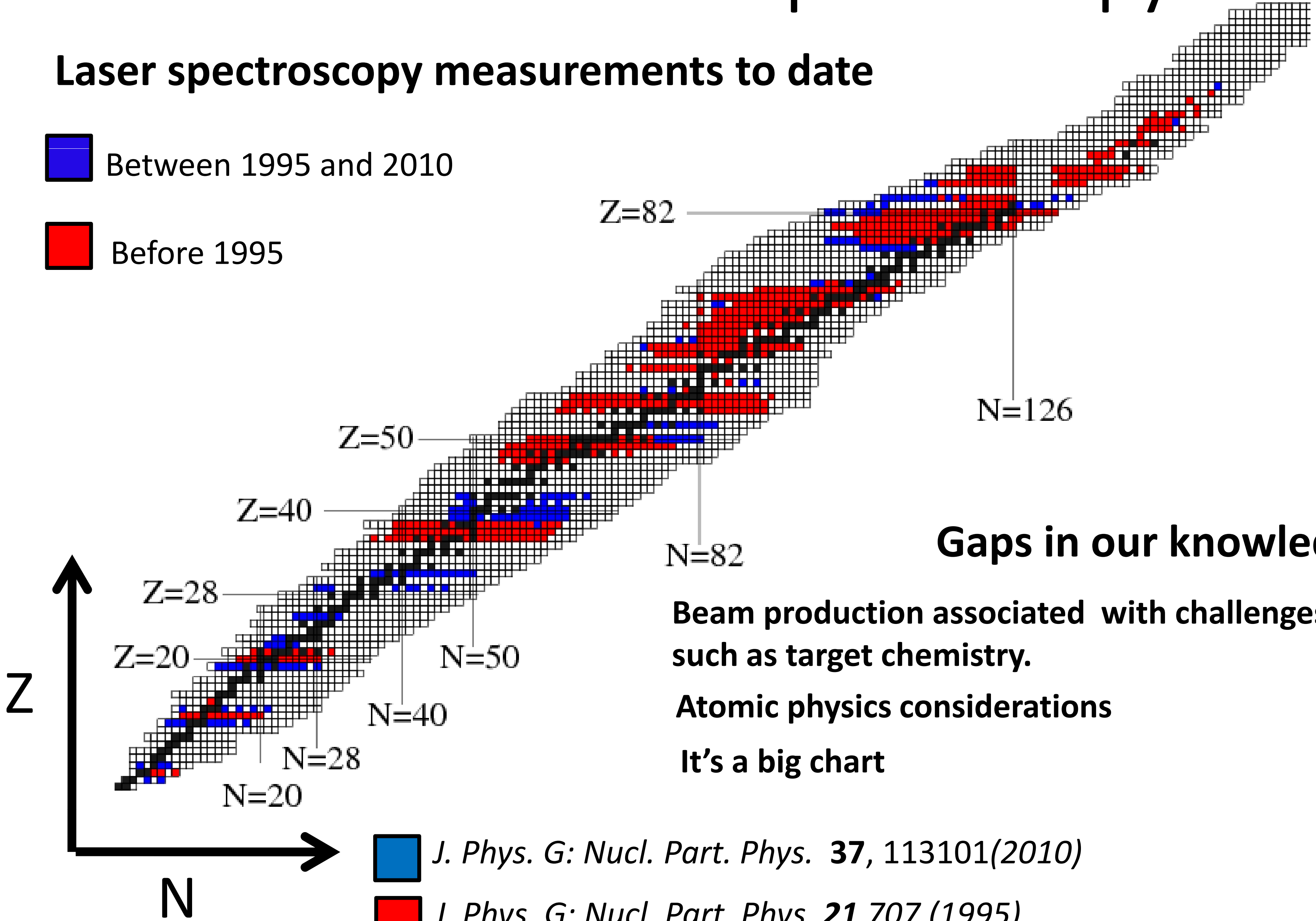


Status of laser spectroscopy

Laser spectroscopy measurements to date

Between 1995 and 2010

Before 1995



Gaps in our knowledge

Beam production associated with challenges such as target chemistry.

Atomic physics considerations

It's a big chart

J. Phys. G: Nucl. Part. Phys. **37**, 113101*(2010)*

J. Phys. G: Nucl. Part. Phys. ***21*** *707 (1995)*

Thank you for your attention