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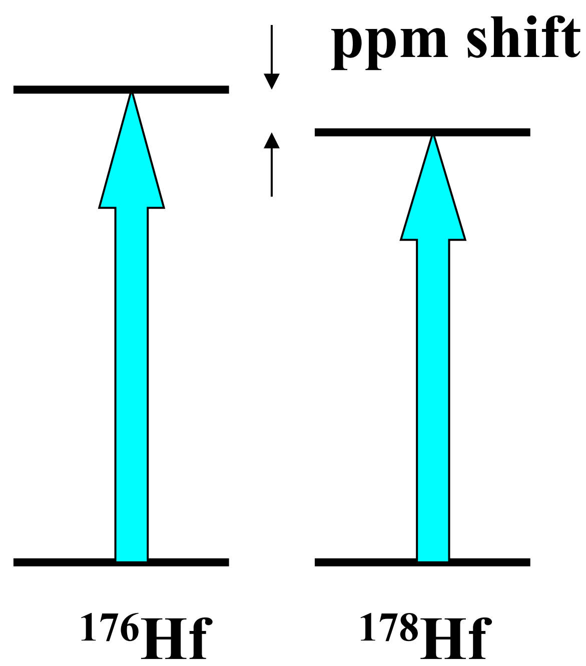
Ground state properties and moments via laser spectroscopy

Jon Billowes

RILIS lasers at ISOLDE

Isotope shift of an atomic transition



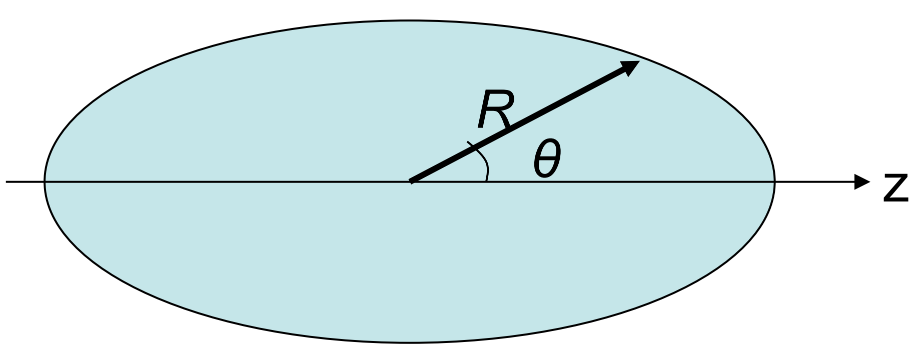
Two components: mass shift (nuclear recoil) and *volume shift*

Analysis of *volume shift* yields the change in nuclear mean square charge radius, **δ<r²>** → Nuclear size, deformation

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

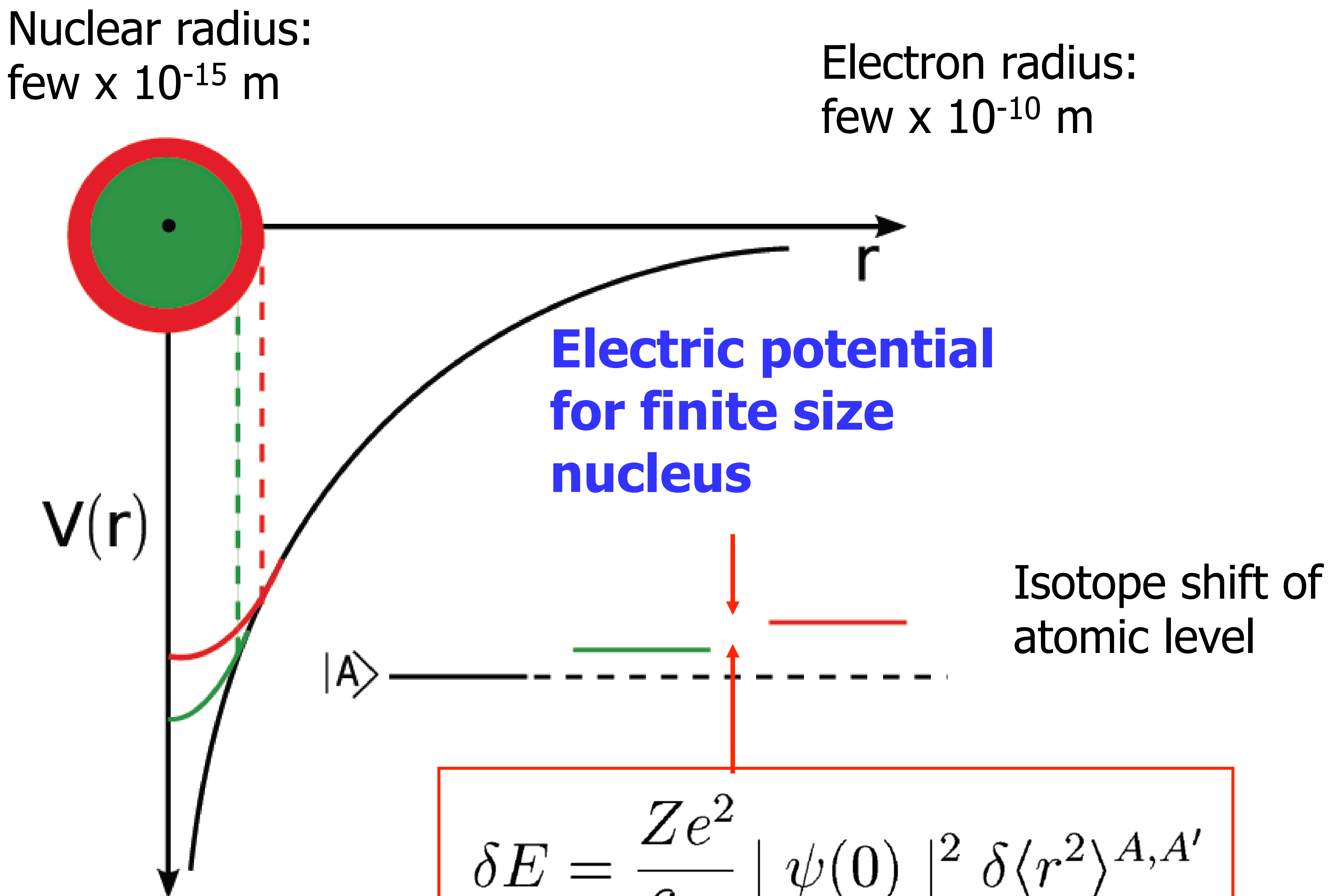
volume

dynamic deformation



$R = R_0\,(1 + \beta_2\, Y_{2,0}\,(\theta,\varphi))$

The volume shift component

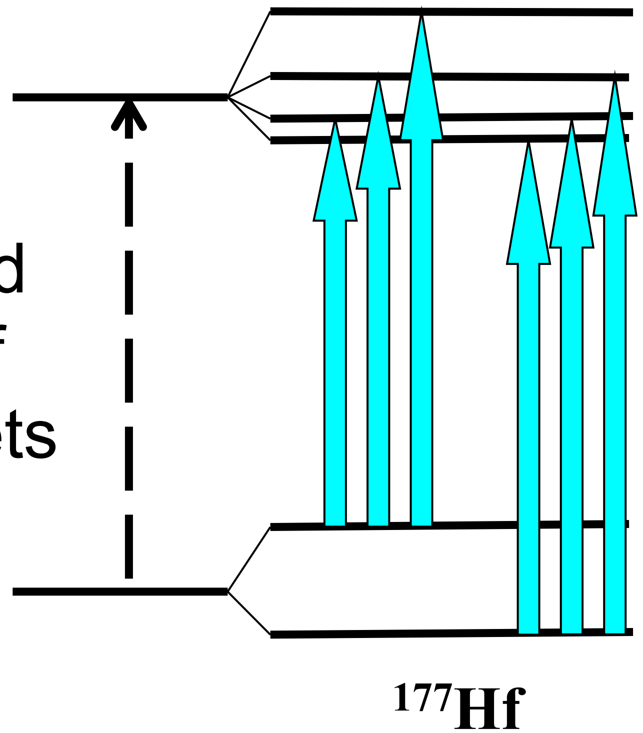


$$\delta E = \frac{Ze^2}{6\epsilon_0} \mid \psi(0) \mid^2 \delta\langle r^2\rangle^{A,A'}$$

electron density at the nucleus

Hyperfine structure of an atomic transition

Isotope shift found using centroids of hyperfine multiplets



Analysis yields A and B hyperfine factors of both atomic states

$$A = \frac{\mu_I B_e(0)}{I J} \quad B = eQ_s \left\langle \frac{\partial^2 V_e}{\partial z^2} \right\rangle$$

↓

Nuclear spin I

Magnetic moment μ

Quadrupole moment Q_s

Without a definite spin, none of the other nuclear parameters can be deduced

Isotope shift ⟶ $\langle \beta_2^2 \rangle$ Dynamic deformation

Q_s ⟶ $\langle \beta_2^2 \rangle$ Static deformation

$\langle \beta_2^2 \rangle \approx \langle \beta_2 \rangle^2$ in well-deformed nuclei

Isotope shift = (normal + specific) mass shift + volume shift

$$\delta\langle r^2\rangle^{A'A}$$

Approximate magnitudes for ΔA = 2

Element	Transition	Normal	Specific	Volume	Doppler Broadening
$_{11}$Na	3s – 3p	550 MHz	200 MHz	-10 MHz	1400 MHz
$_{70}$Yb	6s – 6p	20 MHz	‹ 20 MHz	-1500 MHz	500 MHz

(isomers: no mass shift to worry about)

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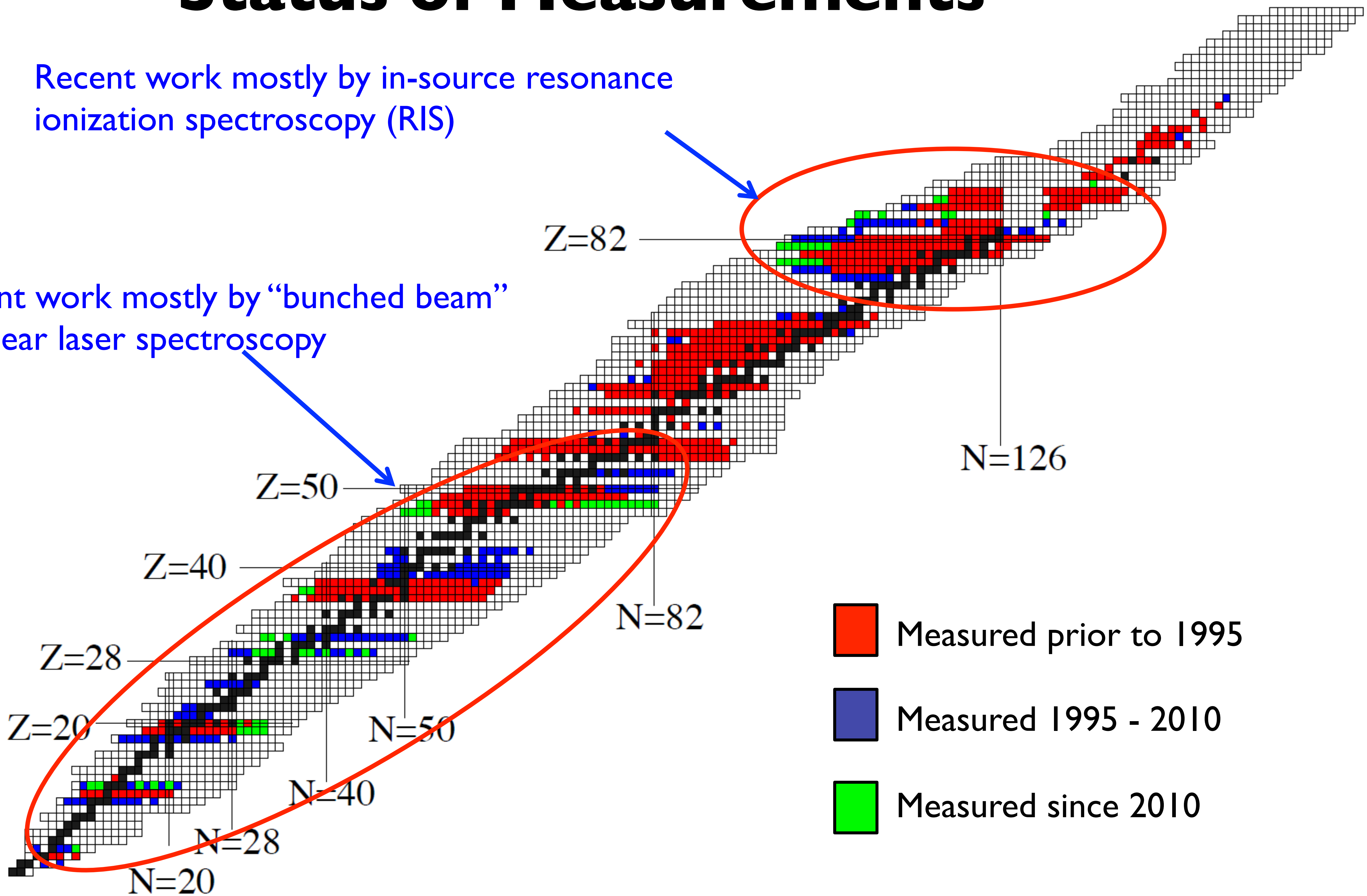
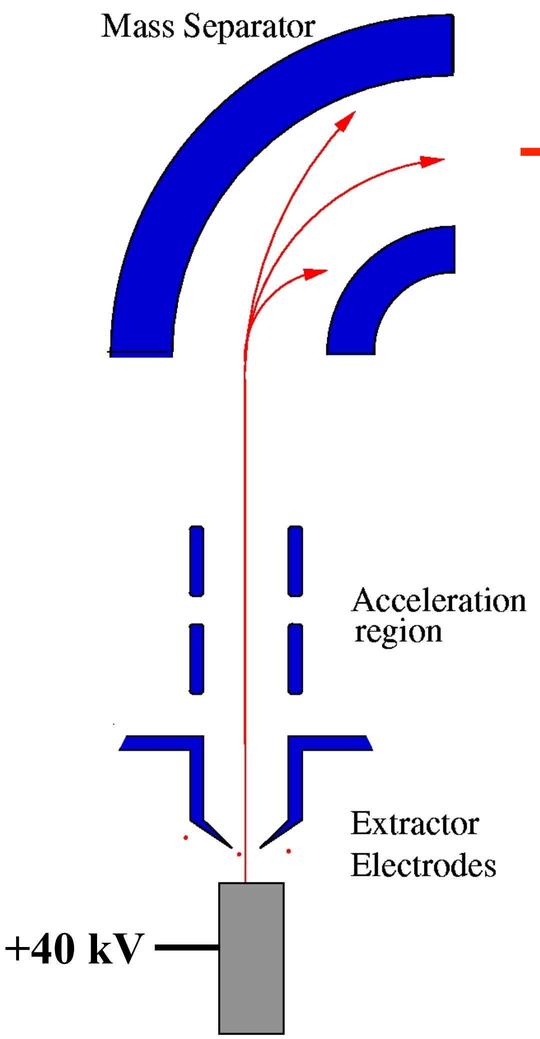
Laser spectroscopy – Status of Measurements



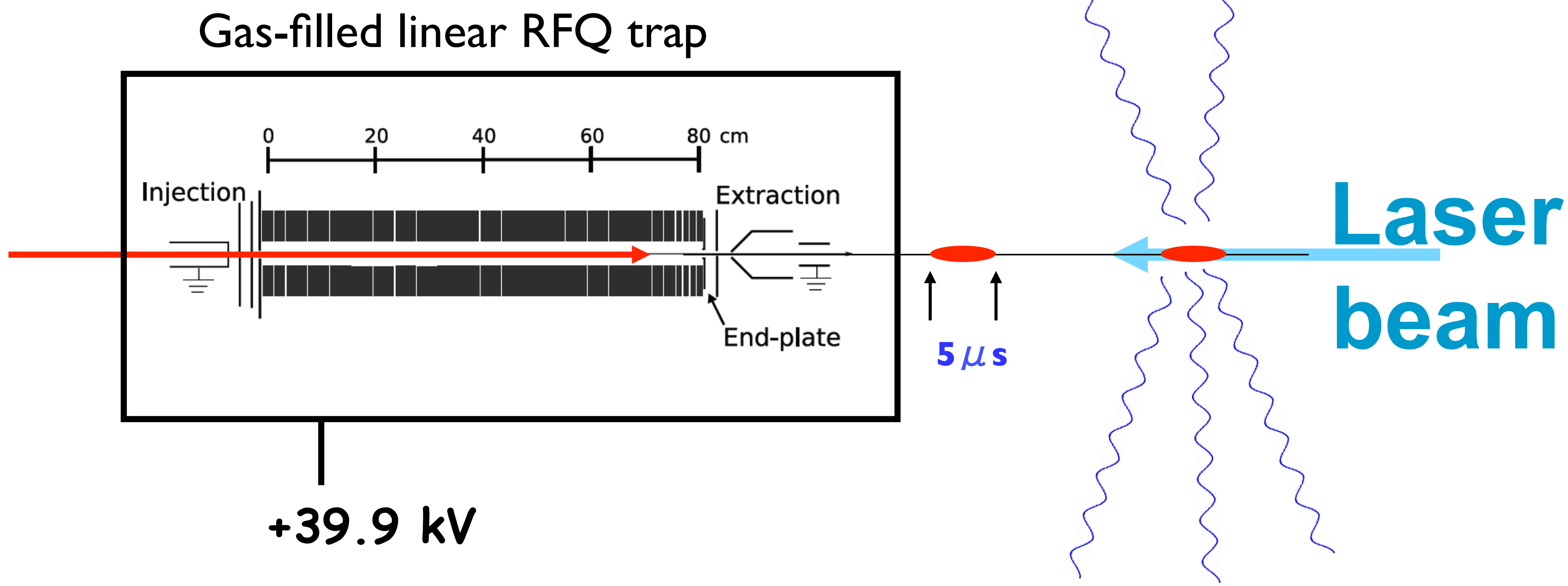
Updated plot provided by Bradley Cheal from 2010 review (B. Cheal & K.T. Flanagan J. Phys. G 37 (2010) 113101)

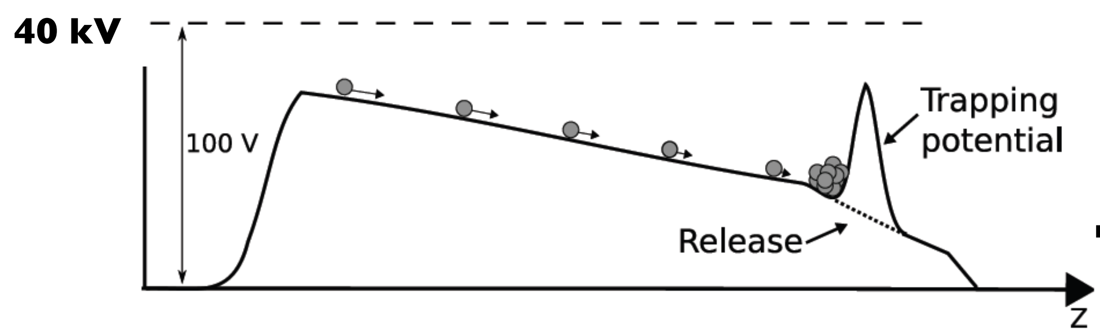
Bunched-beam collinear laser spectroscopy

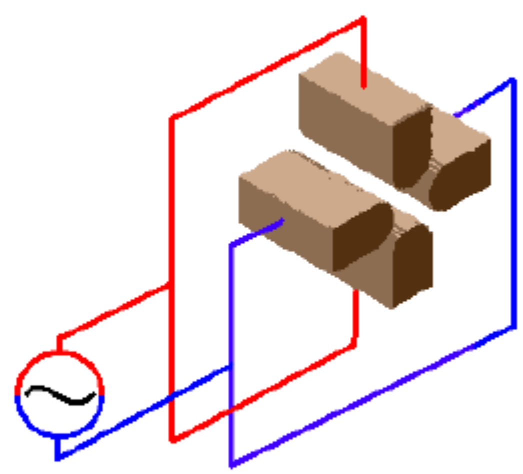
(Doppler-free, greatly reduced background)



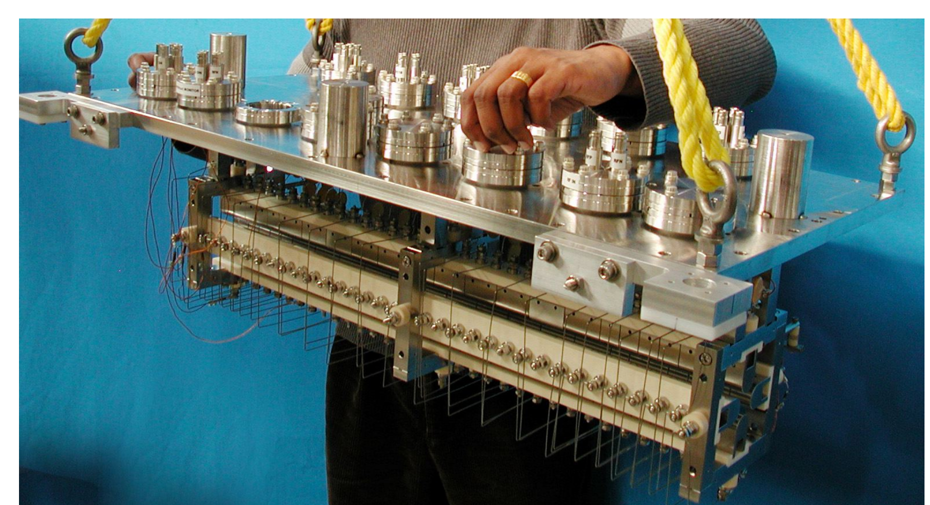
Radioactive beam ion source



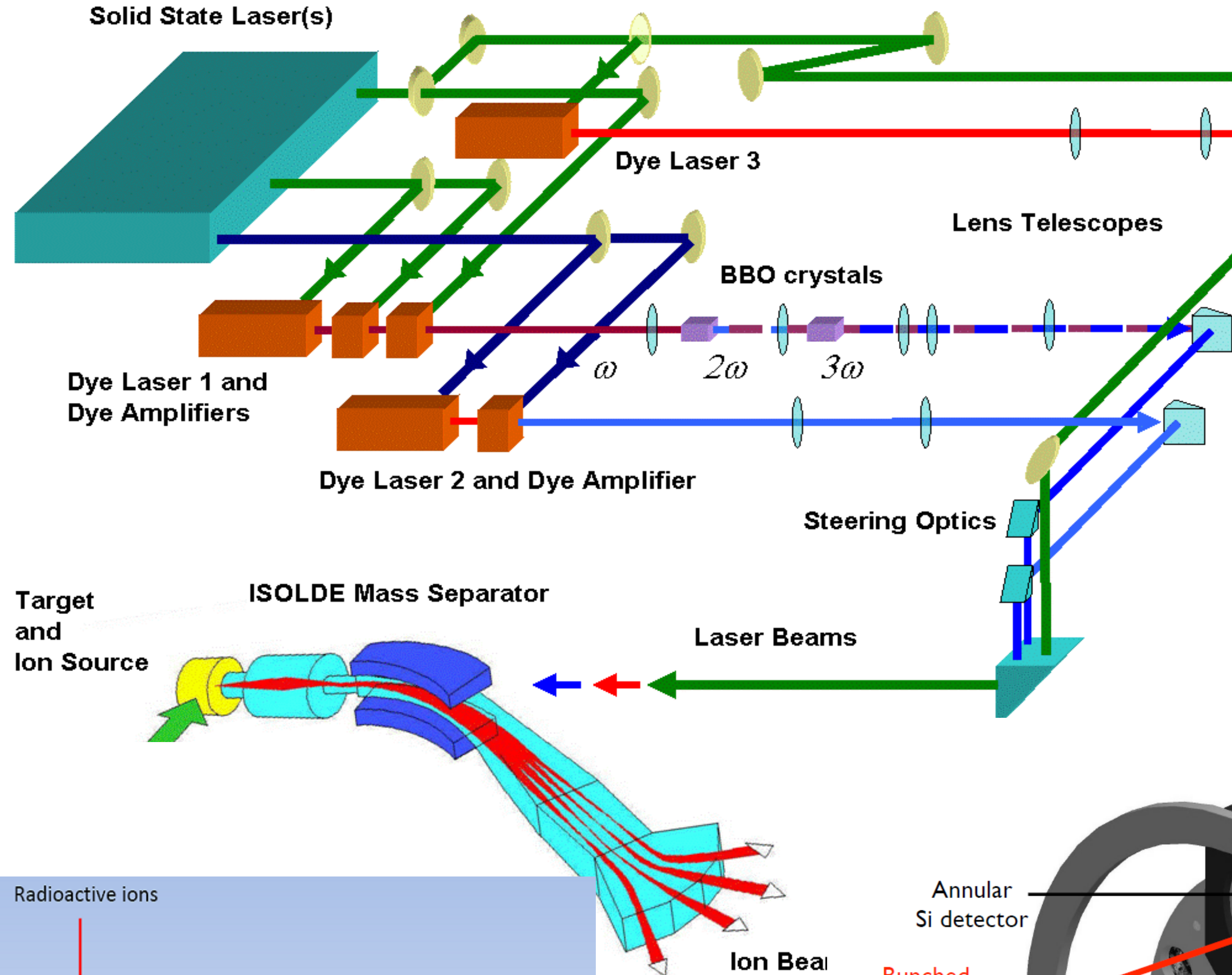




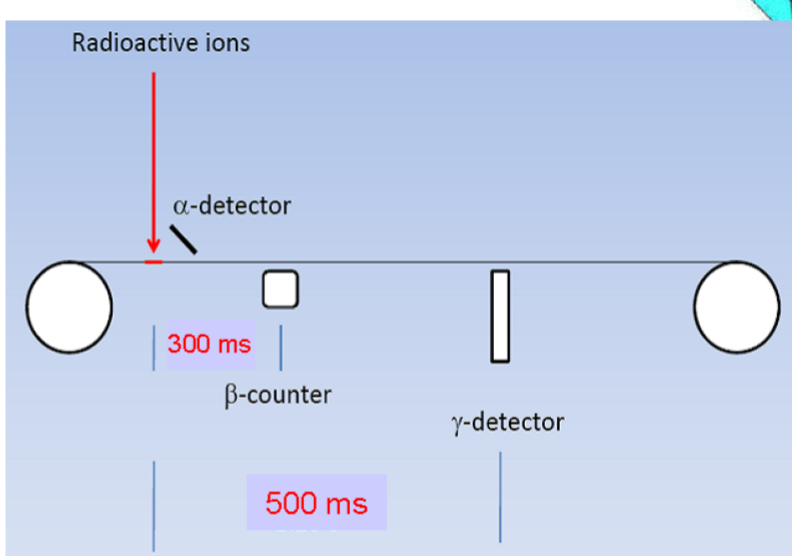
TRIUMF ion beam cooler/ buncher



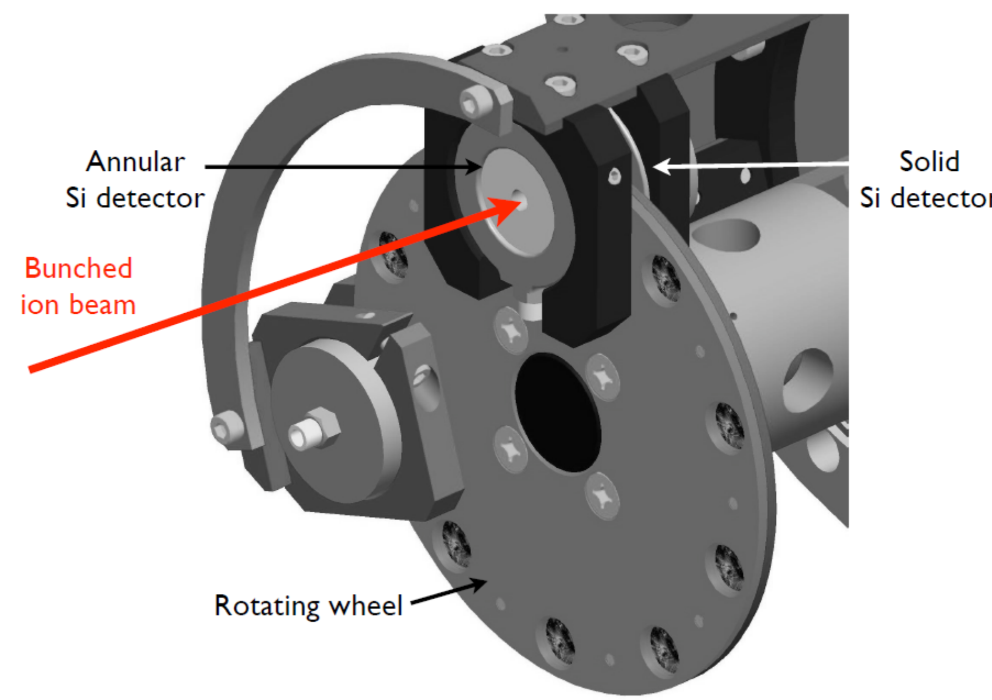
Resonance Ionization Spectroscopy with RILIS Pulsed laser system



- High sensitivity
- Doppler broadened (resolution usually too low to measure quadrupole interaction or make spin assignments)

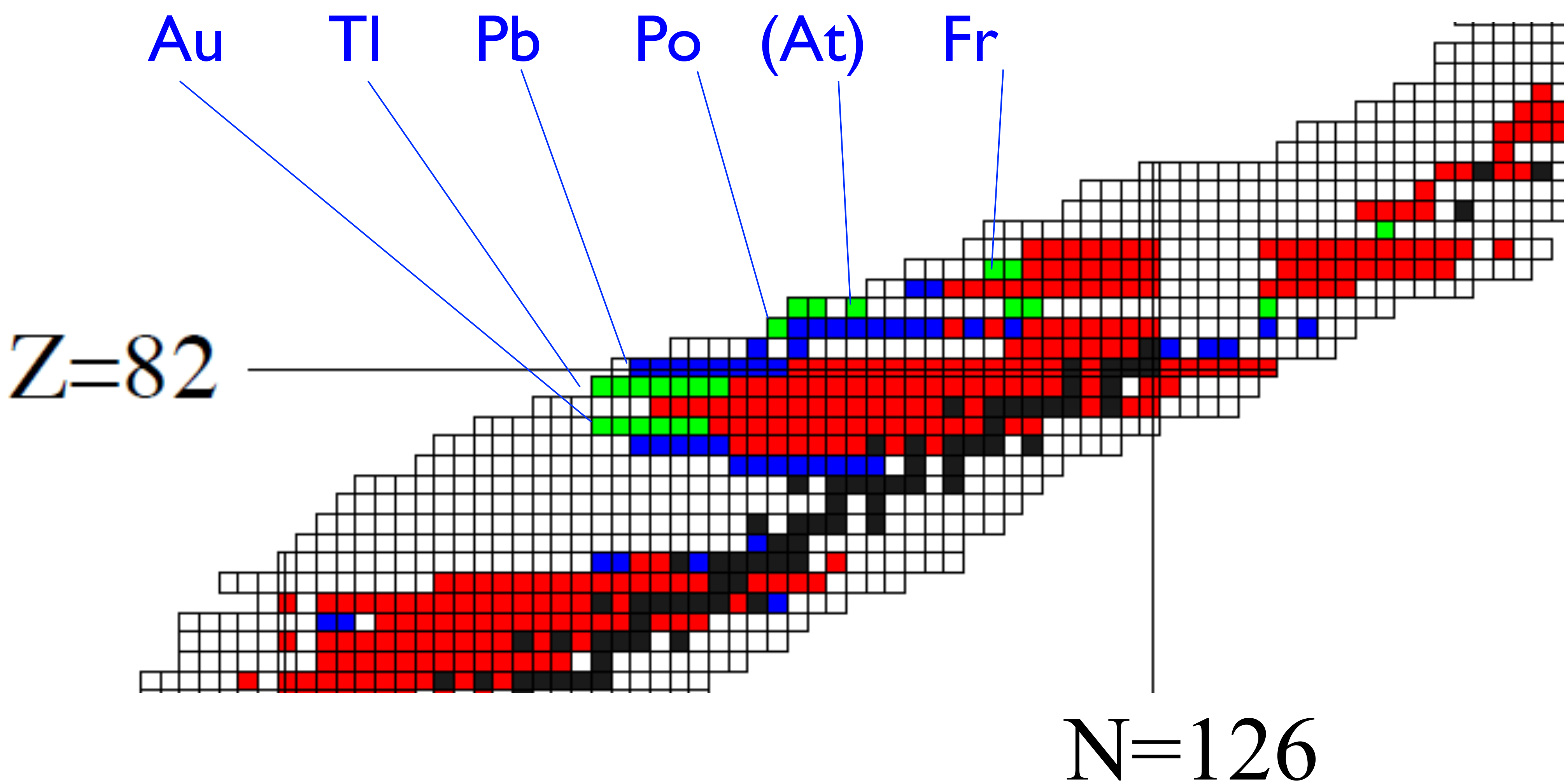


IRIS (Gatchina) tape station



"windmill" detection system (ISOLDE)

Charge radii systematics near Z = 82

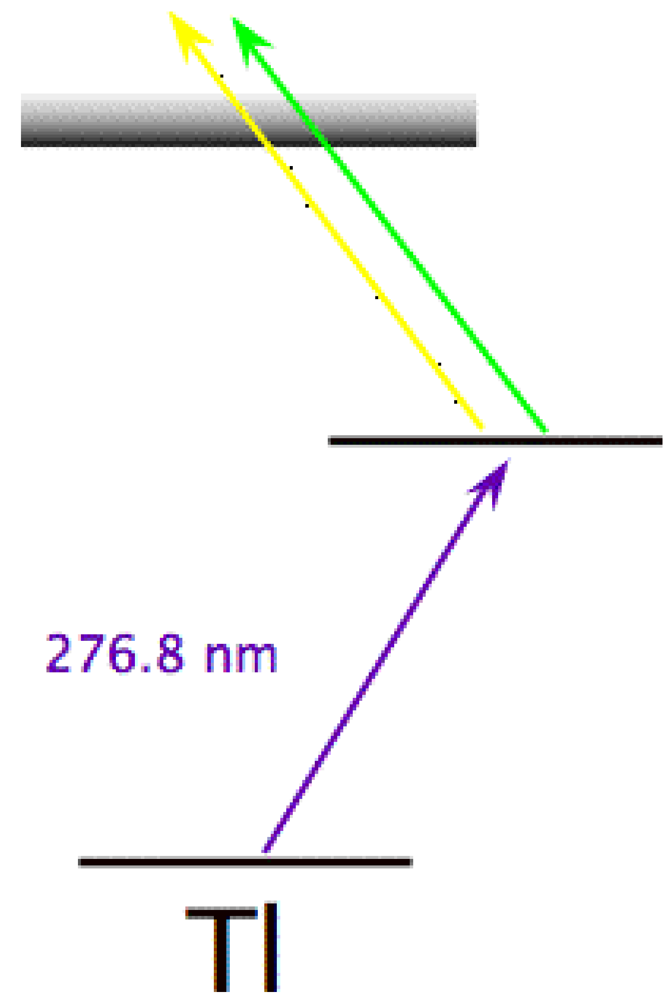


(Astatine RIS schemes developed by ISOLDE (RILIS) and TRIUMF (TRILIS) in preparation for in-source spectroscopy measurements at ISOLDE in September 2012)

Neutron-deficient Tl isotopes and isomers:

Collaboration between ISOLDE and the IRIS facility, PNPI, Gatchina

Measured isotope shifts and magnetic moments on 276.8 nm transition (unable to measure small quadrupole interaction)

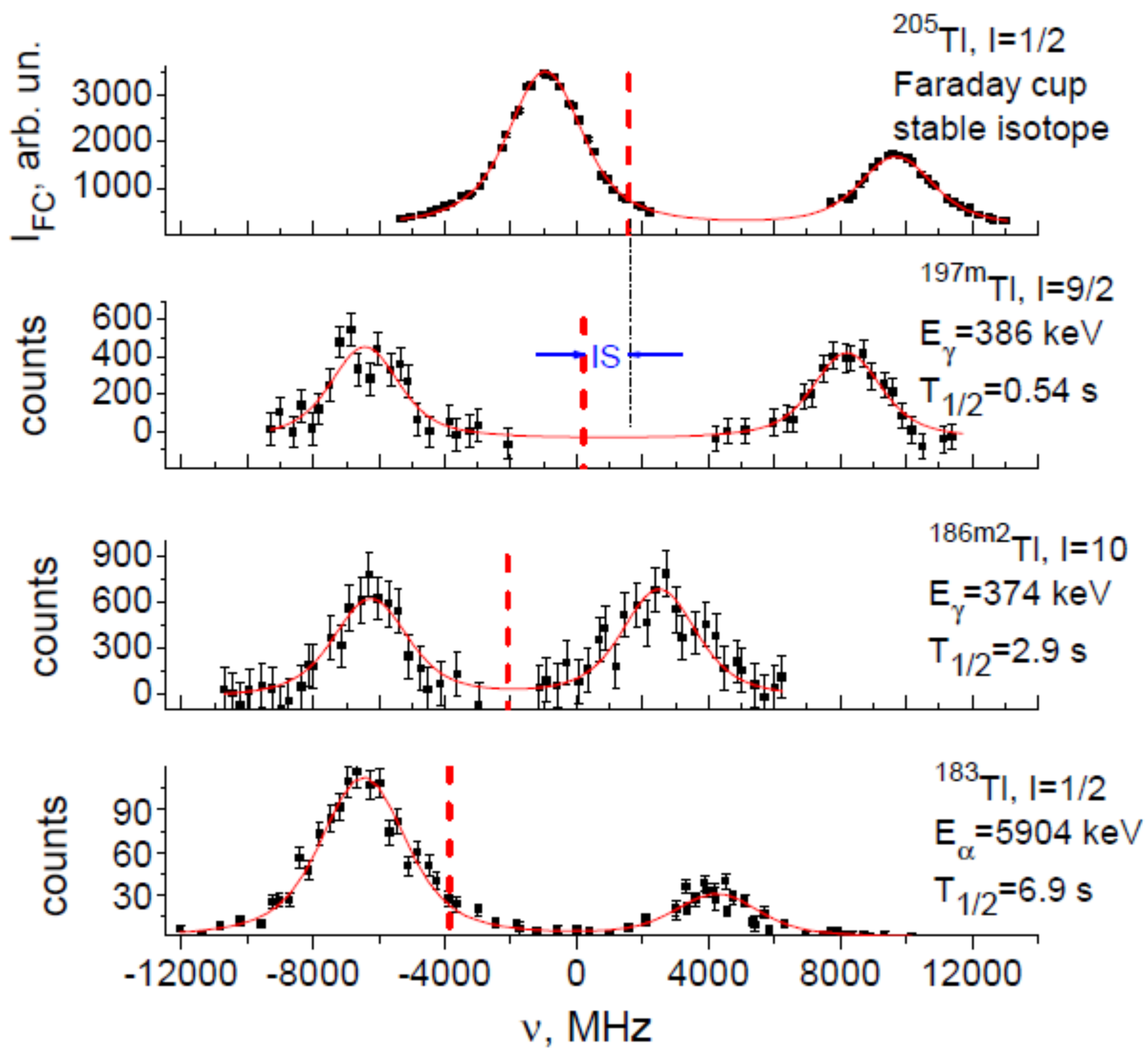


IRIS measurements:
A = 183 – 195, 197, 203, 205, 207

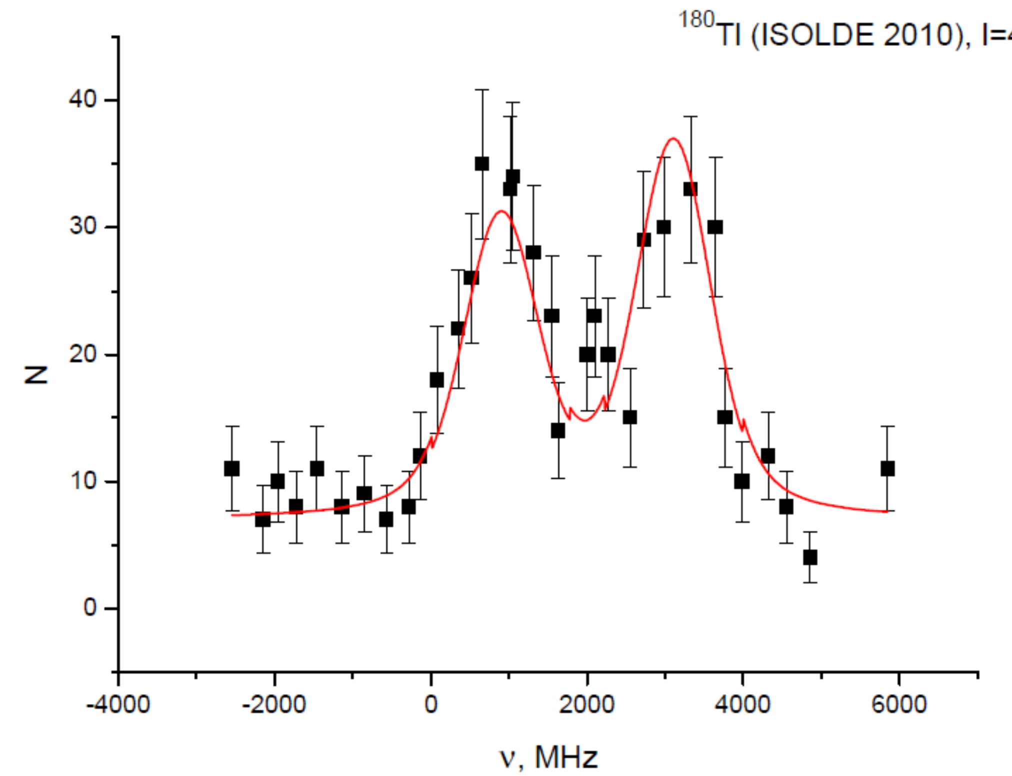
King plot calibration of 277nm atomic factors

ISOLDE measurements:
A = 179 - 184

Thallium spectra



IRIS Spectra

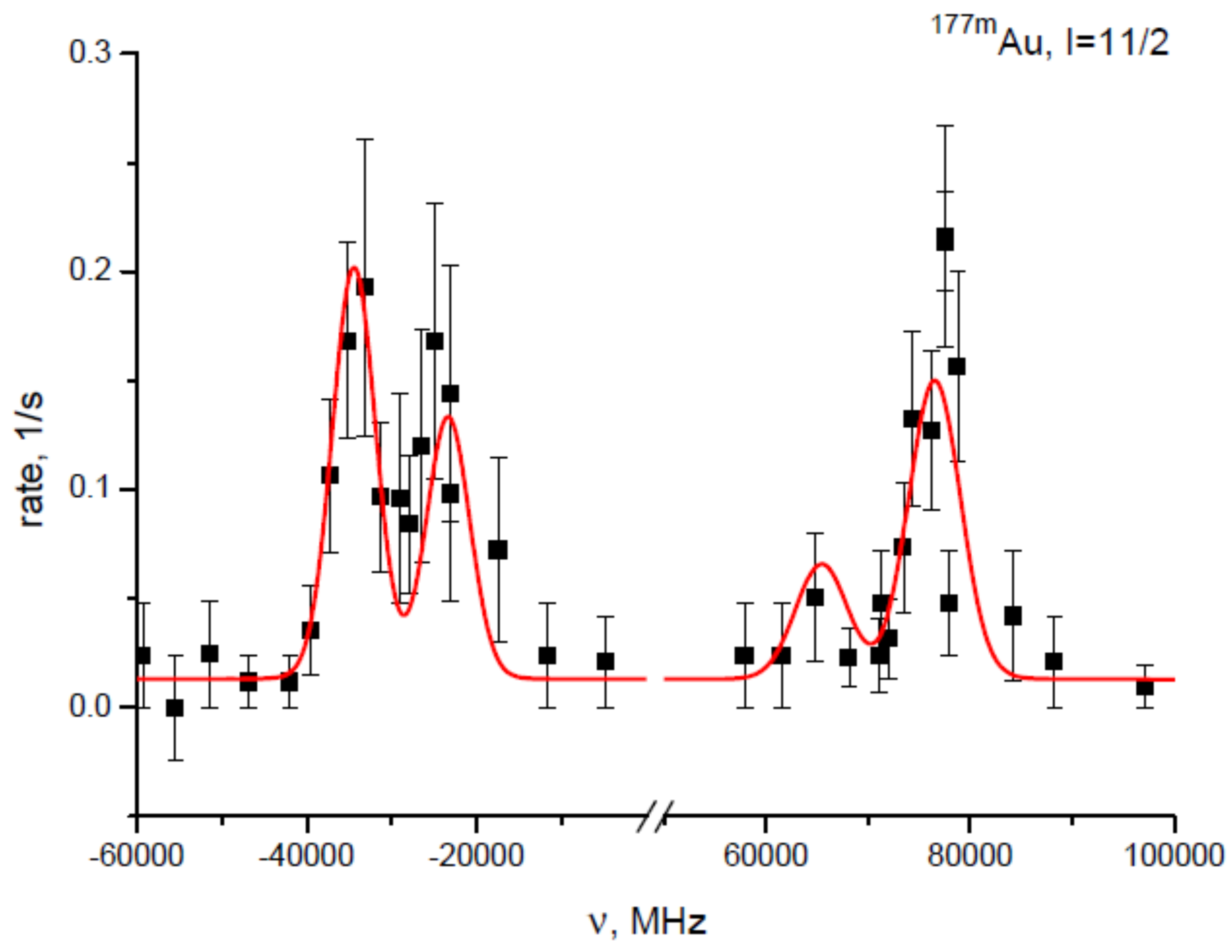


ISOLDE Spectrum

Data Courtesy Andreyev & Barzakh

Earlier IRIS work on Tl: Barzakh et al, Phys. Rev. C 86 (2012) 014311

Au isotopes: (ISOLDE/RILIS and PNPI)
Measurements made at ISOLDE



6s $^2S_{1/2}$ - 6p $^2P_{1/2}$ (268 nm)

(No quadrupole interaction)

Preliminary data down to Au-177 but further experiments scheduled (October 2012)

Data Courtesy Andreyev & Barzakh

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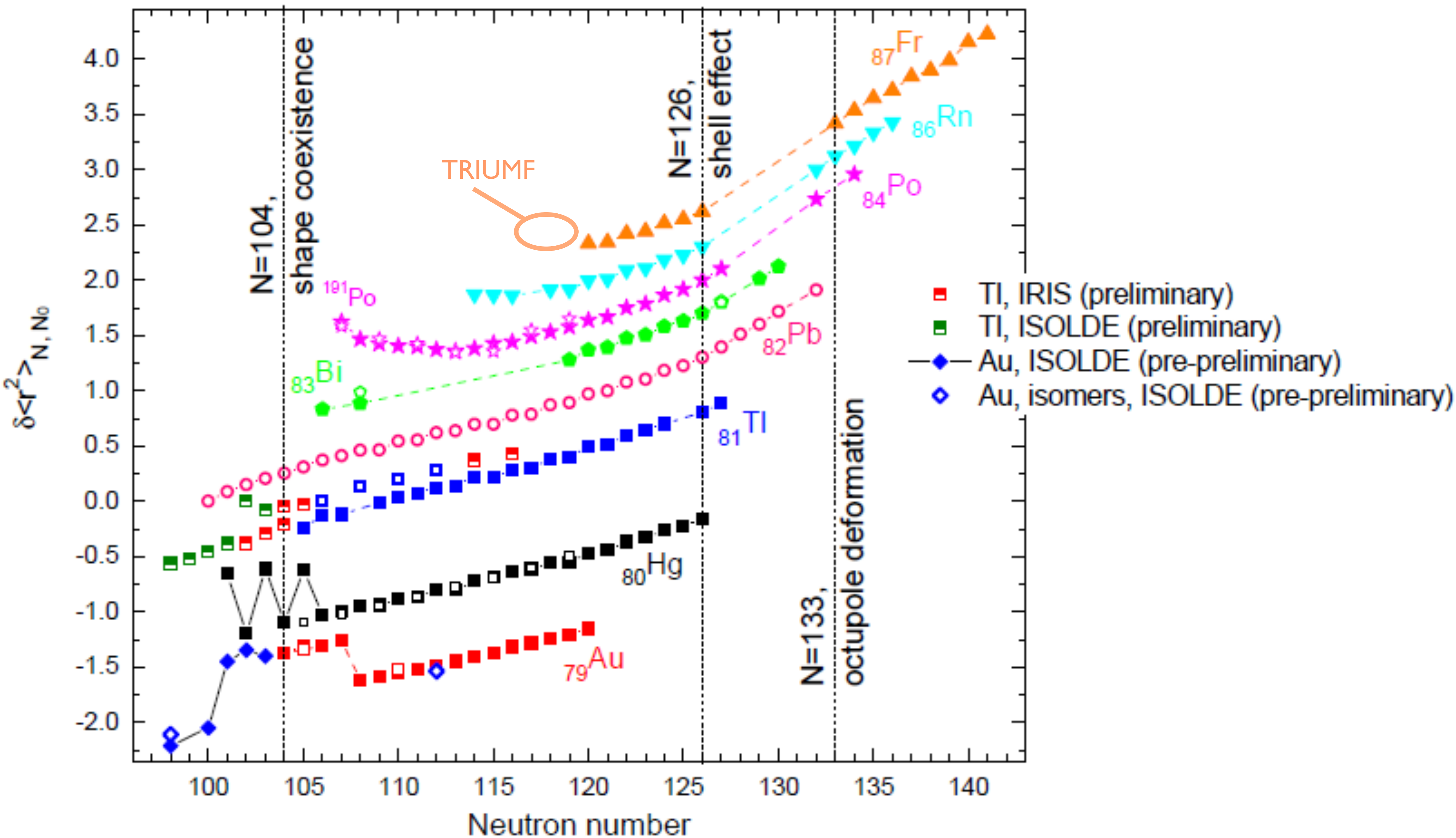
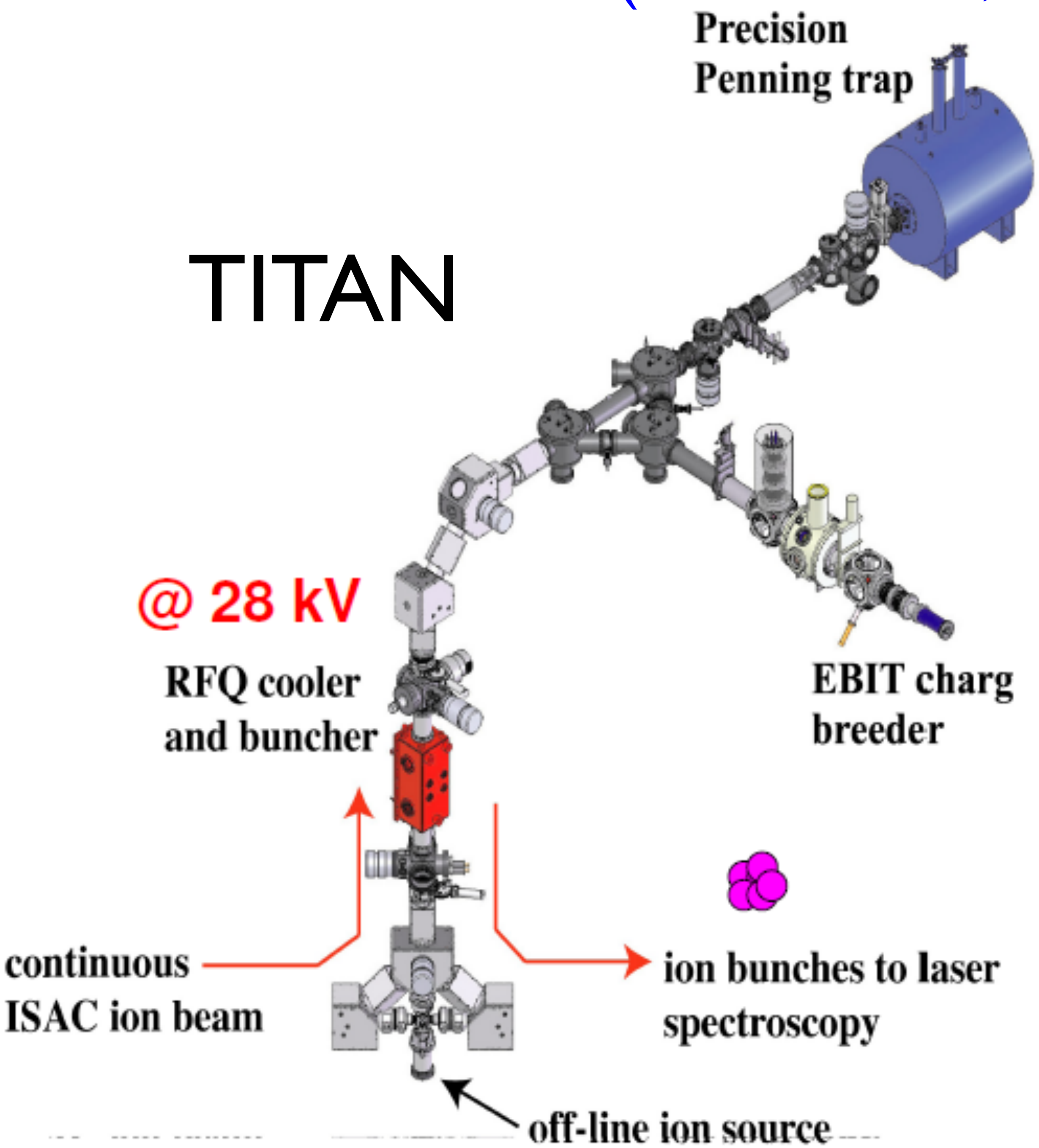


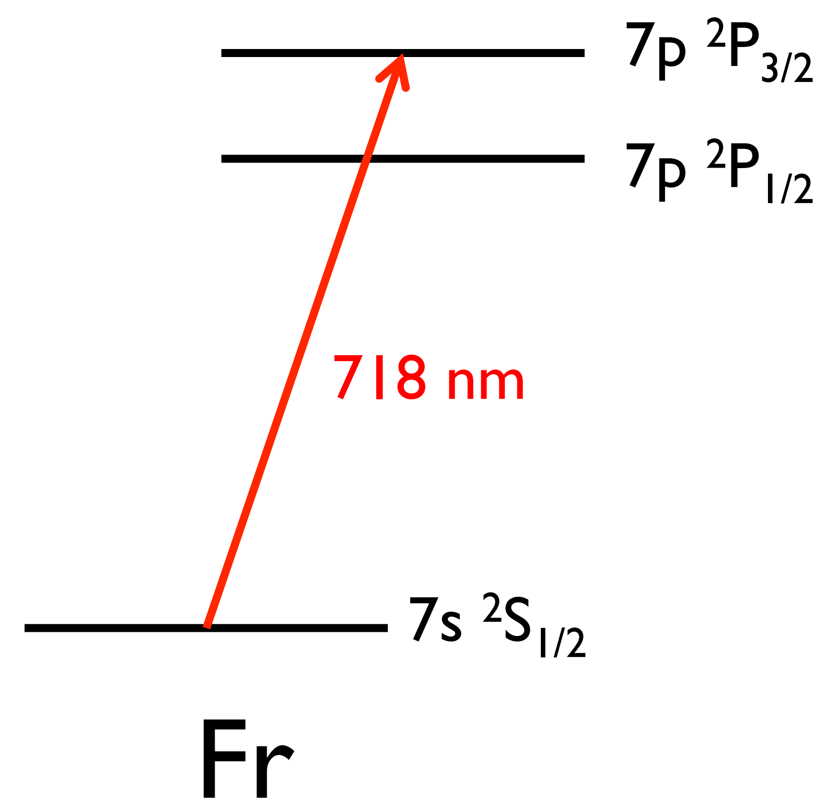
Courtesy Andreyev & Barzakh

Collinear laser spectroscopy of francium

A = 205, 206, 206m

(Annika Voss, PhD Thesis 2012)





Isotope shifts, μ, Q_s and spins measured.

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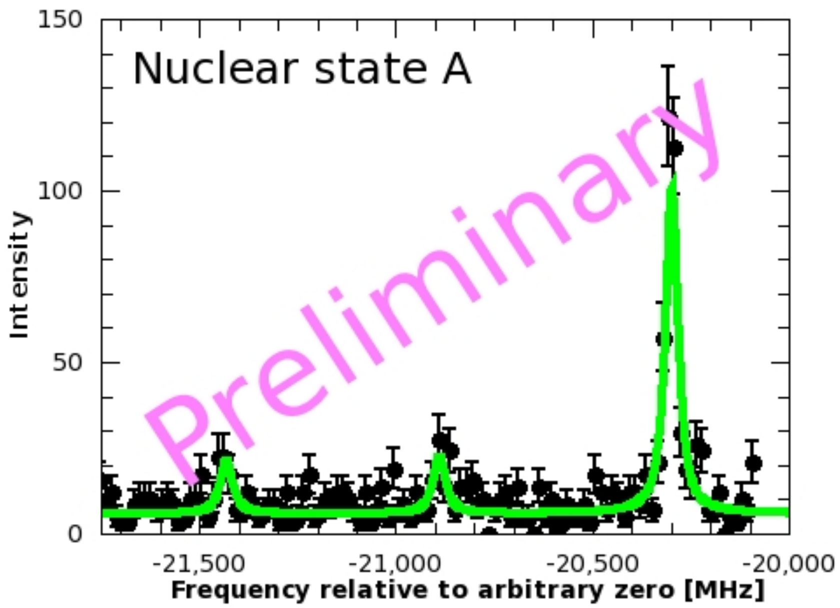
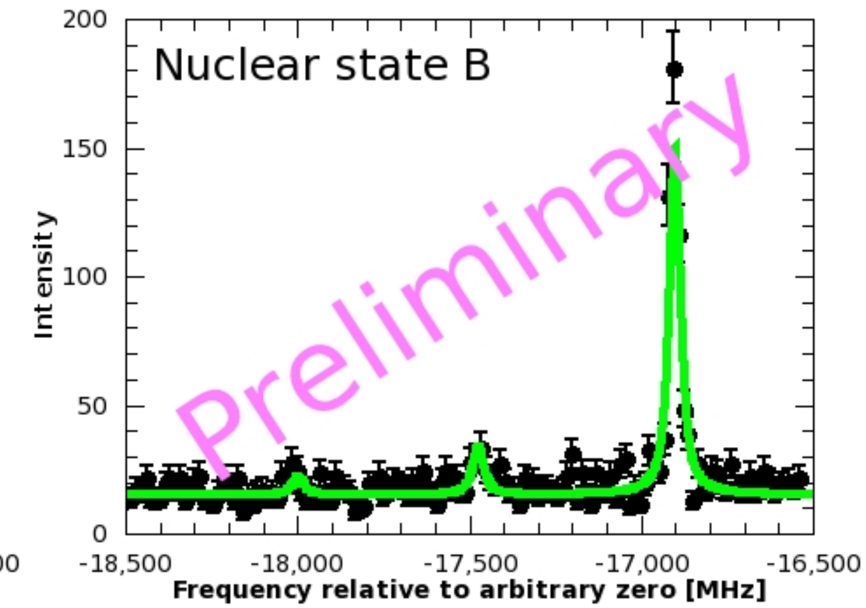
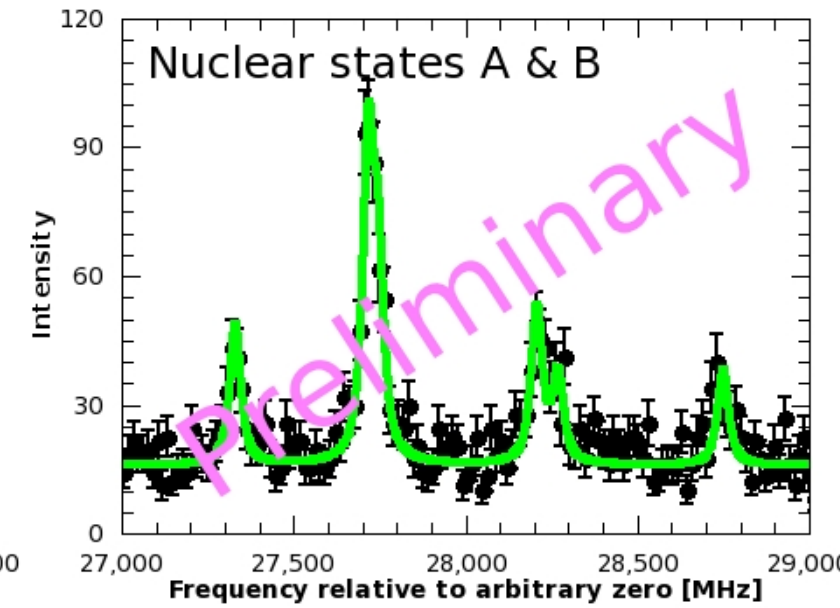
$^{206,206m}Fr$

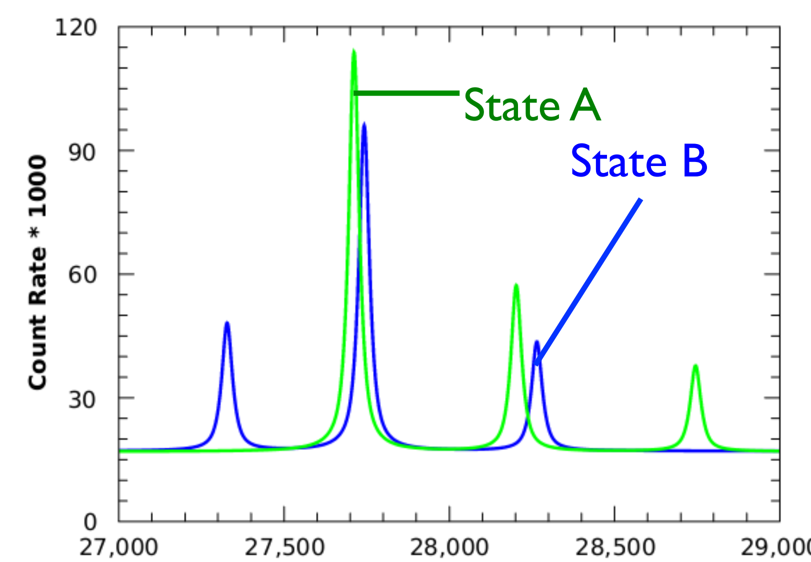
Low frequency multiplets

High frequency multiplets

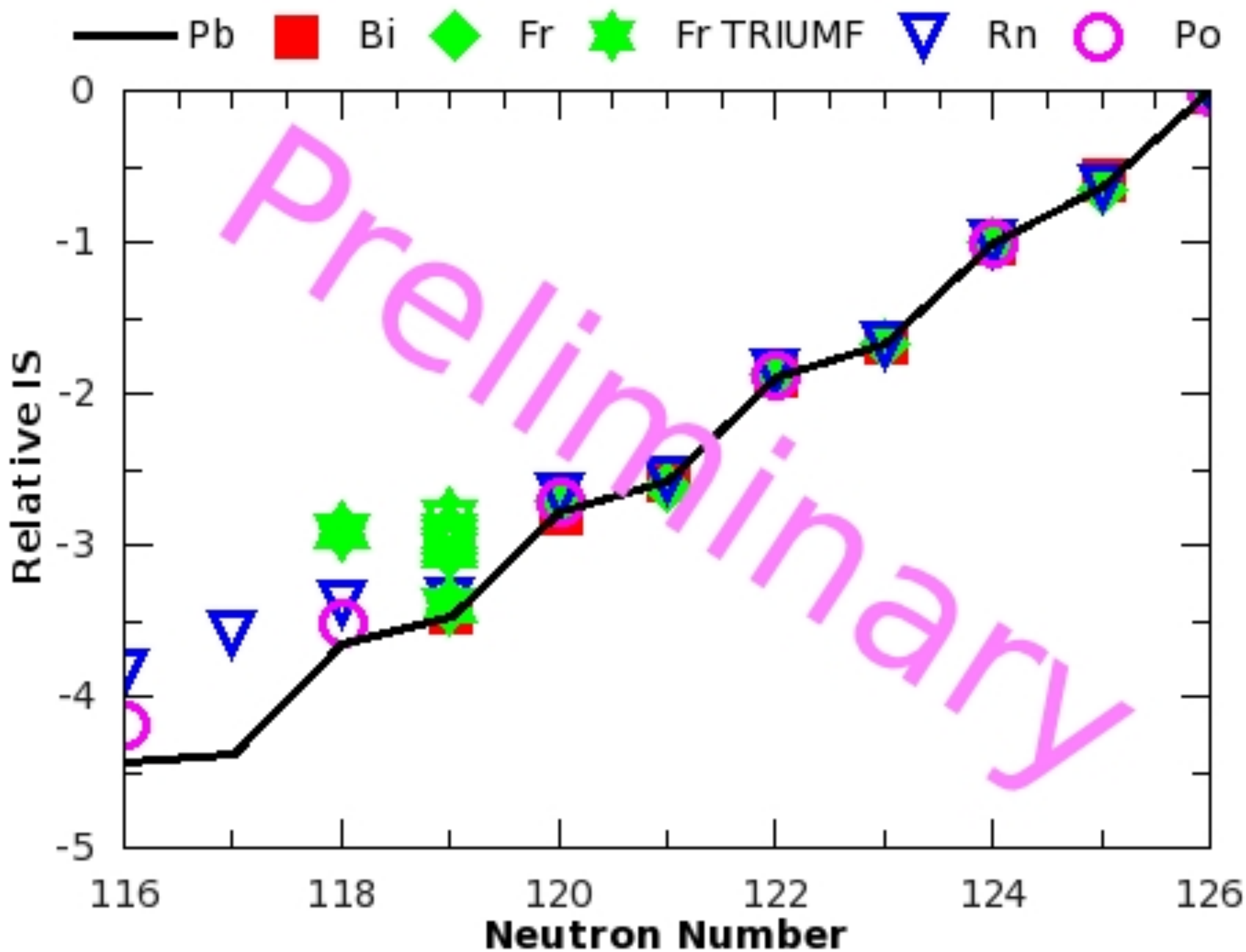




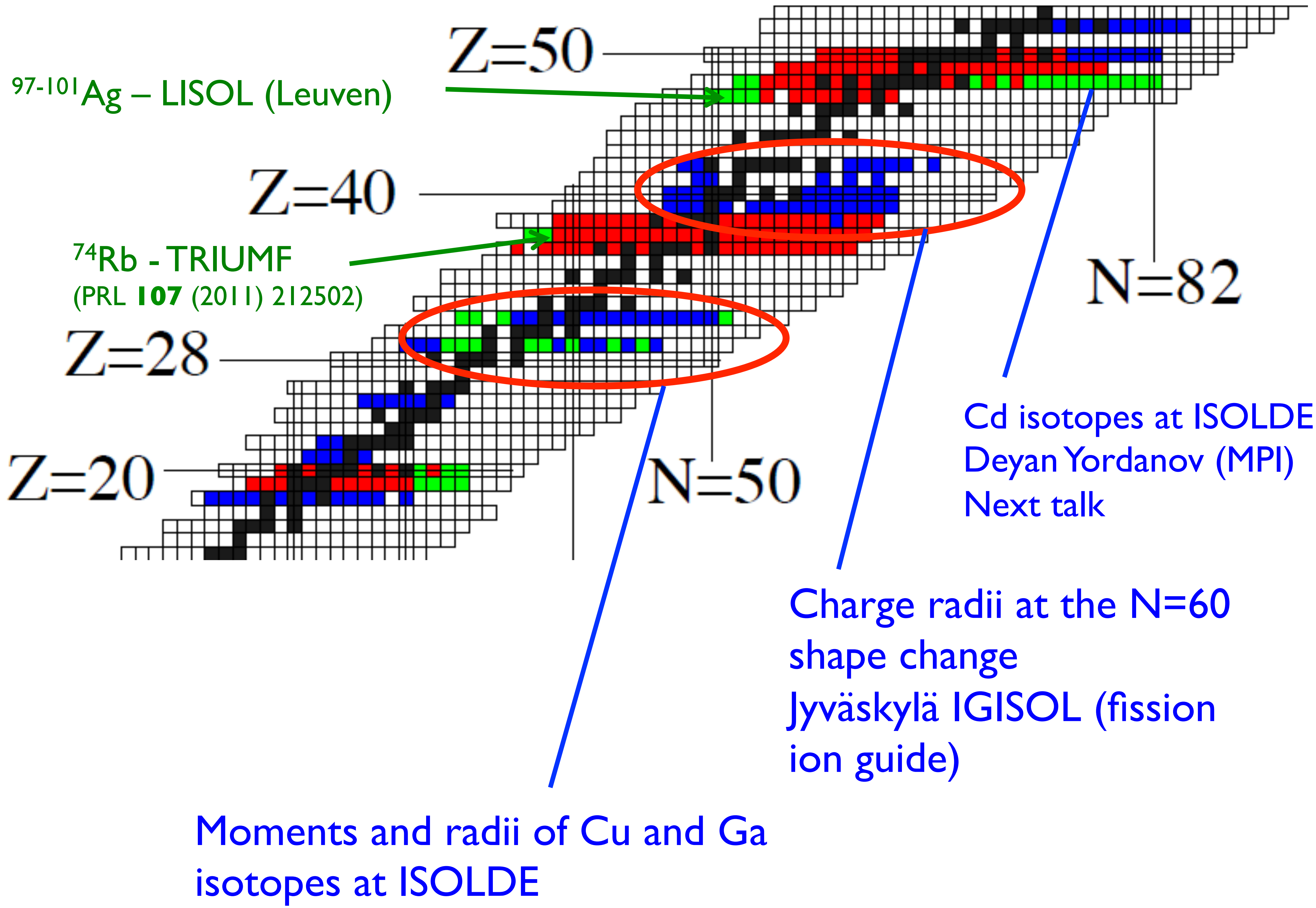




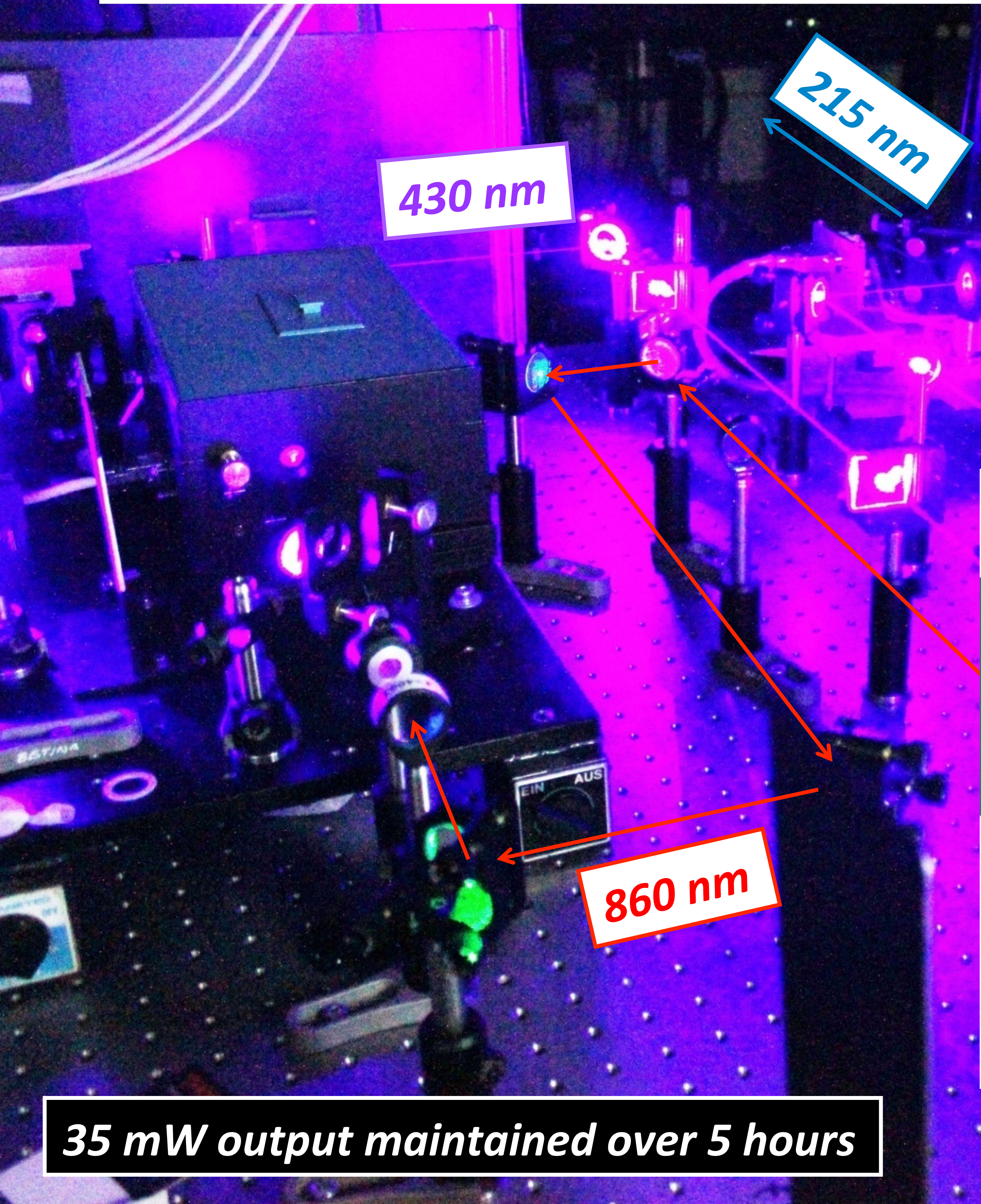
Annika Voss, PhD Thesis 2012

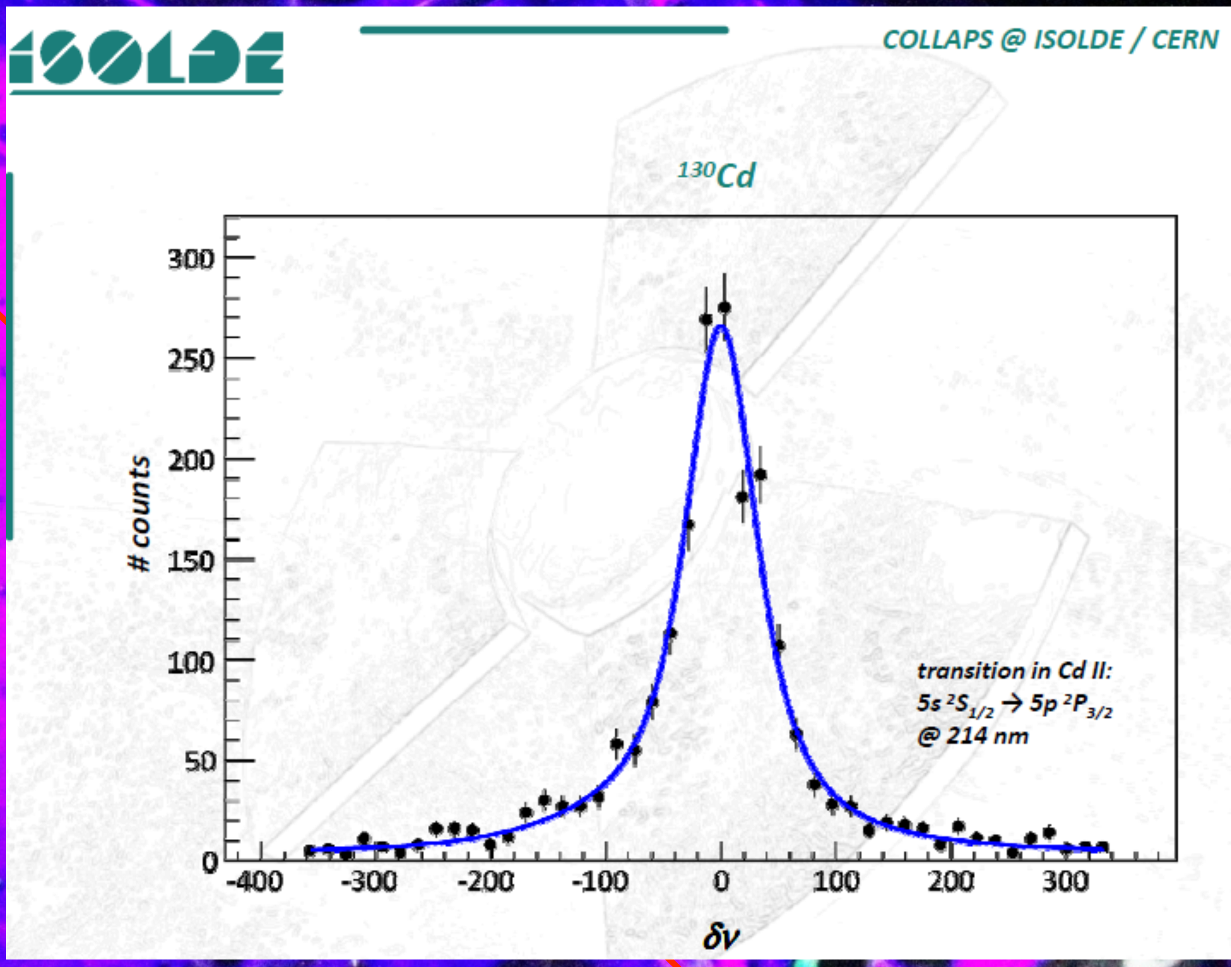


Annika Voss, PhD Thesis 2012


Z=50
Z=40
Z=28
Z=20
N=82
N=50
97-101Ag – LISOL (Leuven)
74Rb - TRIUMF
(PRL 107 (2011) 212502)
Cd isotopes at ISOLDE
Deyan Yordanov (MPI)
Next talk
Charge radii at the N=60
shape change
Jyväskylä IGISOL (fission
ion guide)
Moments and radii of Cu and Ga
isotopes at ISOLDE

Cd isotopes – Deyan Yordanov





35 mW output maintained over 5 hours

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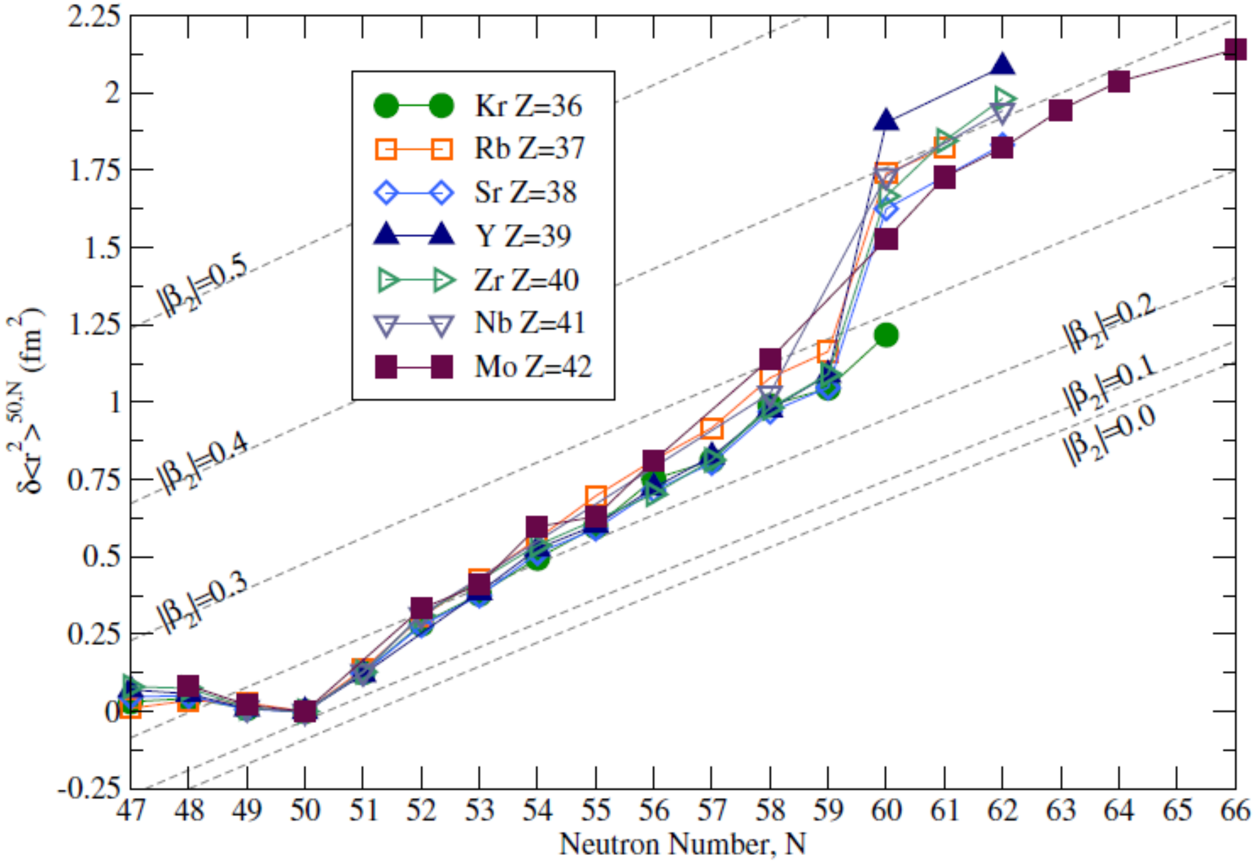
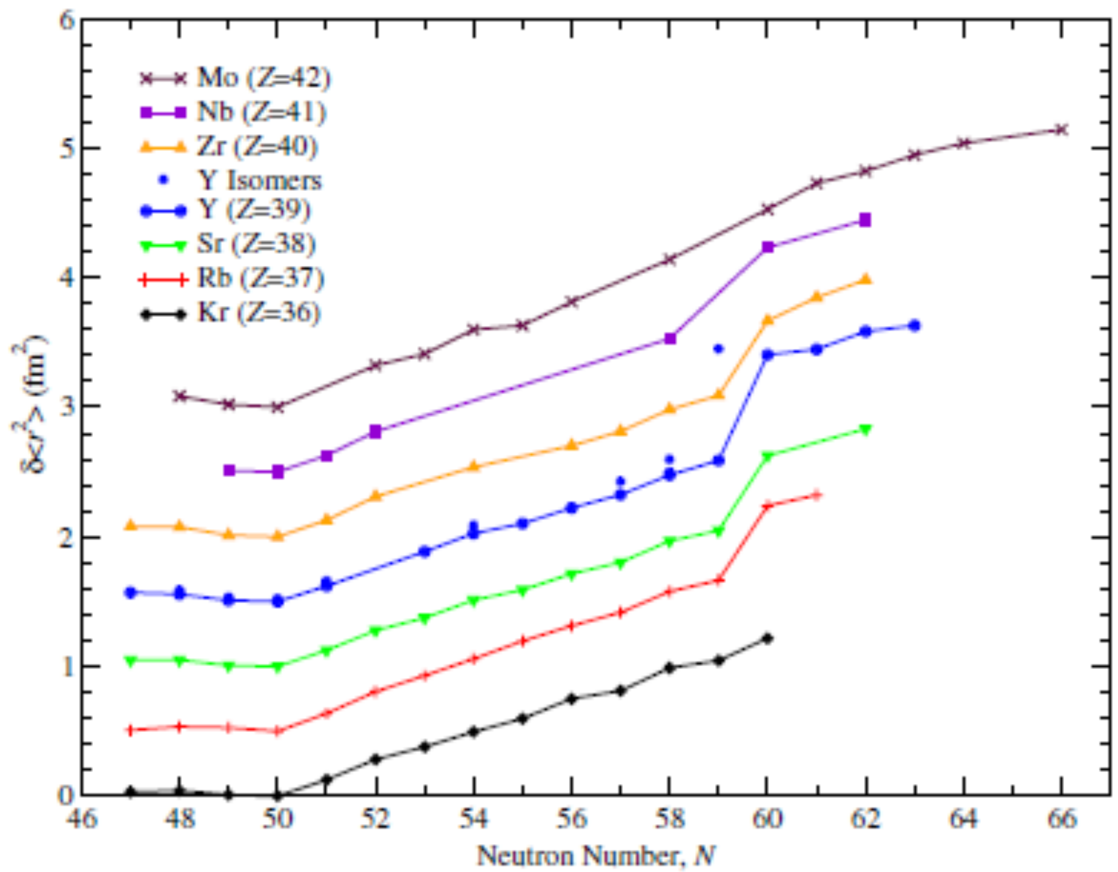
Charge radii for Kr, Rb, Sr, Y, Zr, Nb and Mo in region of N=60 shape change (Jyväskylä IGISOL)



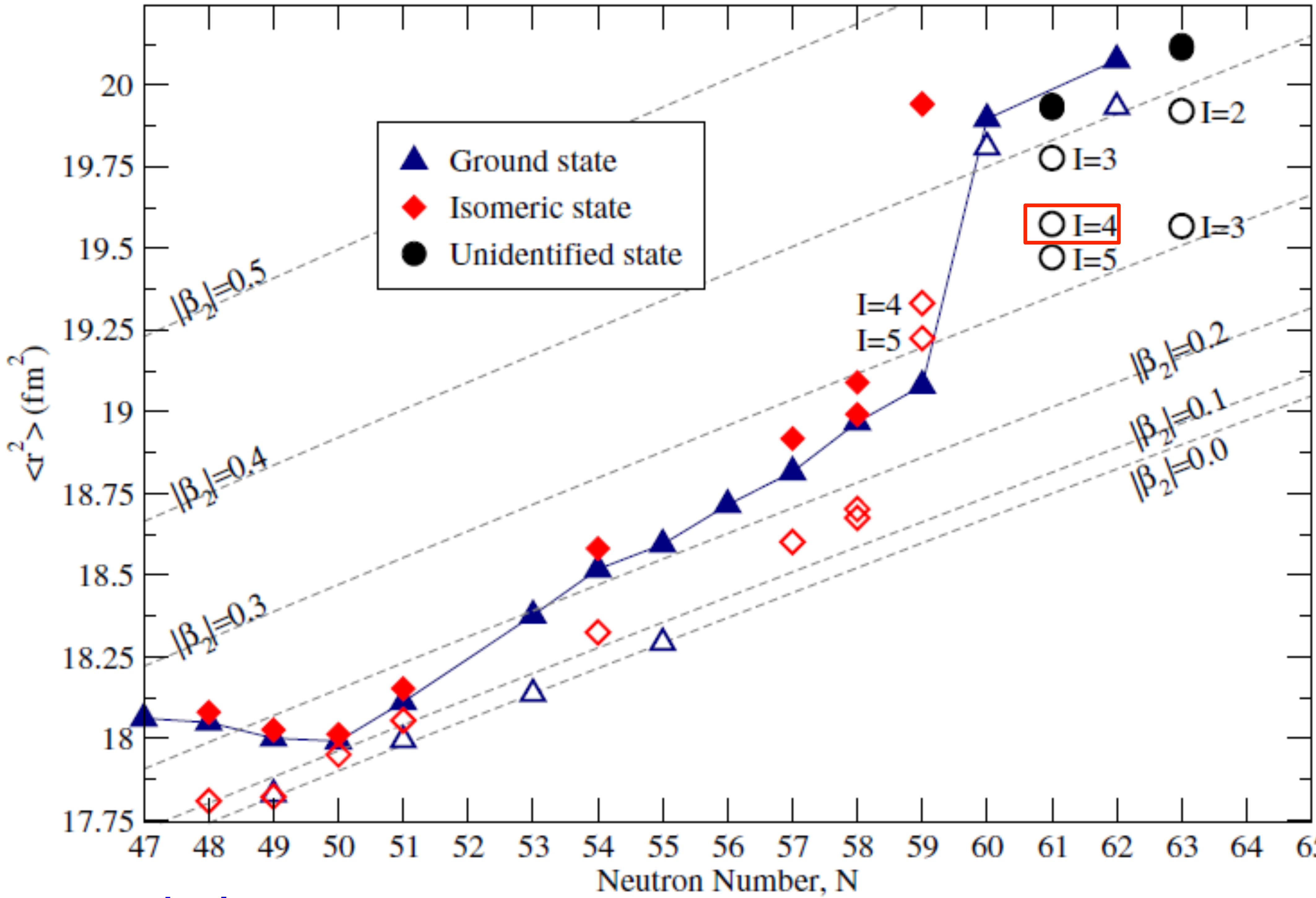
Overlapped



Arbitrarily offset

Review by B. Cheal & K.T. Flanagan, J. Phys. G. 37 (2010) 105103

Droplet model analysis for yttrium isotopes



Open symbols:

static deformation model: $$\delta\langle r^2\rangle = \delta\langle r^2\rangle_{\mathrm{sph}} + \langle r^2\rangle_{\mathrm{sph}}\frac{5}{4\pi}\delta\langle\beta_2^2\rangle$$ (crossed out, replaced by $\langle\beta_2\rangle^2$)

K. Baczynska et al. J. Phys. G 37 (2010) 105013

Motivation for Ga and Cu measurements

Tensor force **attractive** between l+½ and l-½
Otsuka et al. Phys. Rev. Lett. **95** (2005) 232502)

- When does $p_{3/2}$ and $f_{5/2}$ ordering invert?

- How good are the new shell model interactions?
(for example, jj44b of Alex Brown, using ^{56}Ni core)

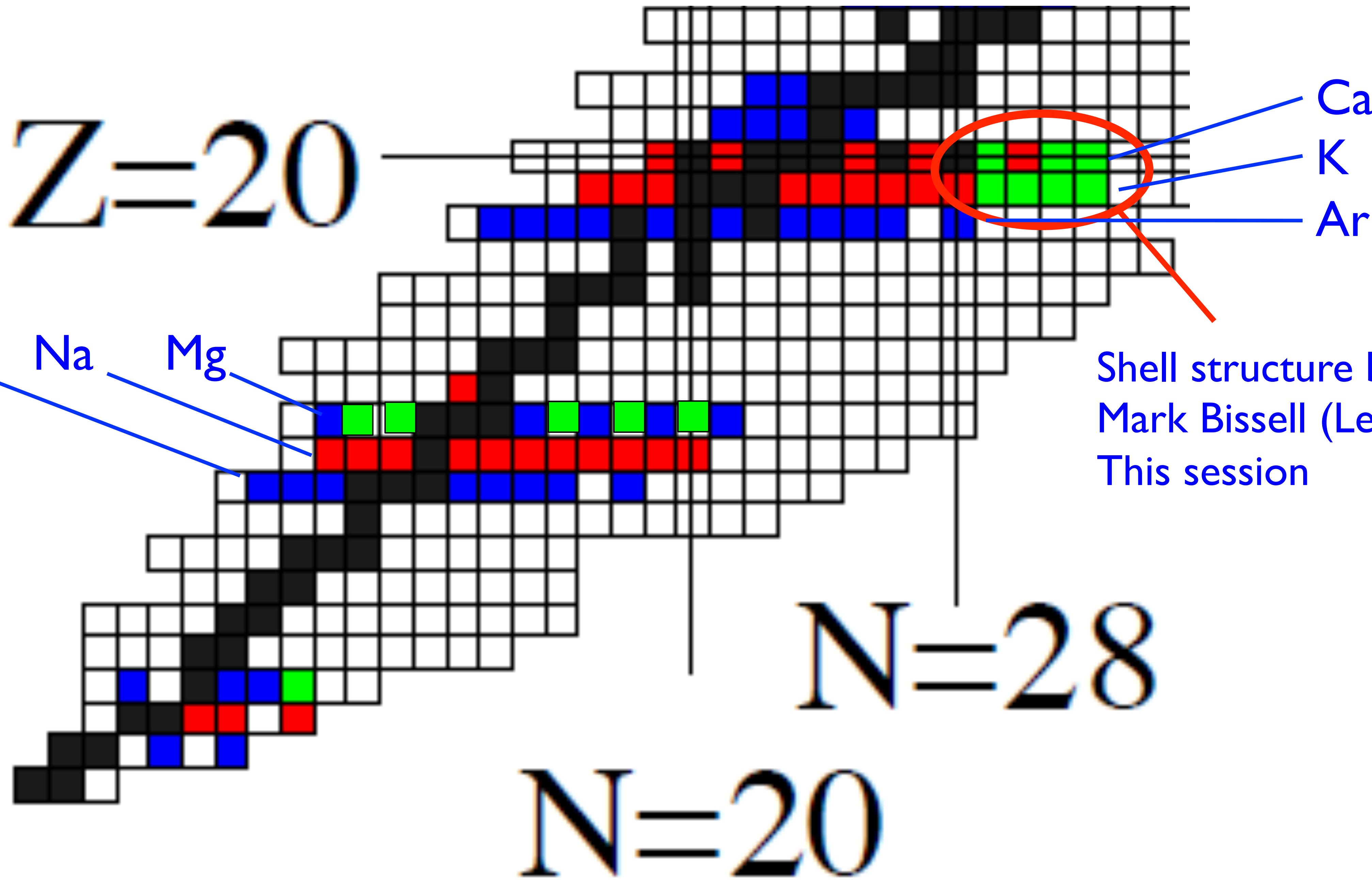
Cu: K.T. Flanagan et al., Phys. Rev. Lett. 103 (2009) 142501
Ga: B. Cheal et al., Phys. Rev. Lett. 104 (2010) 252502

Gallium odd-A spins and moments

		Spin	Magnetic moment		Quadrupole moment	
A	N	I	μ	μ (jj44b)	Q_s	Q_s (jj44b)
63	32	3/2	+1.471(4)	+1.605	+0.210(13)	+0.215
67	36	3/2	+1.848(5)	+2.079	+0.20(2)	+0.117
69	38	3/2	+2.018(4)	+2.284	+0.17(1)	-0.112
71	40	3/2	[+2.256227(2)]	+2.203	+0.106(3)	-0.244
73	42	1/2	+0.209(2)	-0.176	0	0
75	44	3/2	+1.836(4)	+2.441	-0.29(2)	-0.256
77	46	3/2	+2.020(3)	+2.463	-0.21(1)	-0.147
79	48	3/2	+1.047(3)	+2.543	+0.16(1)	-0.057
81	50	5/2	+1.747(5)	+1.477	-0.048(8)	-0.035

B. Cheal et al. Phys. Rev. Lett. 104 (2010) 252502

Charge radii of light nuclei



Shell structure beyond N=28
Mark Bissell (Leuven)
This session

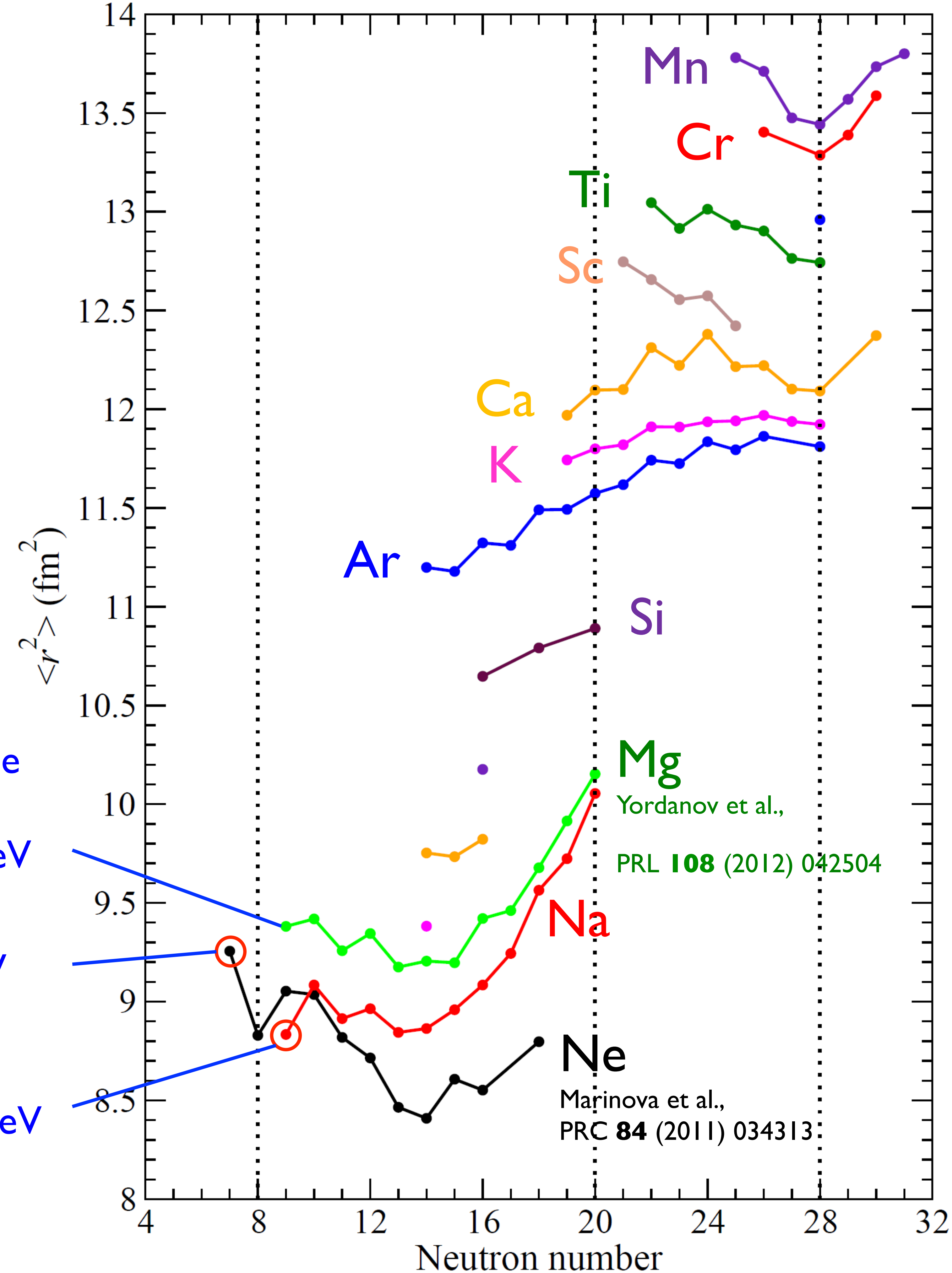
Proton haloes?

○ = Isotope at proton drip line

S_p = 3.2 MeV

S_p = 1.51 MeV S_{2p} = 0.93 MeV

S_p = 2.19 MeV



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Proton haloes?

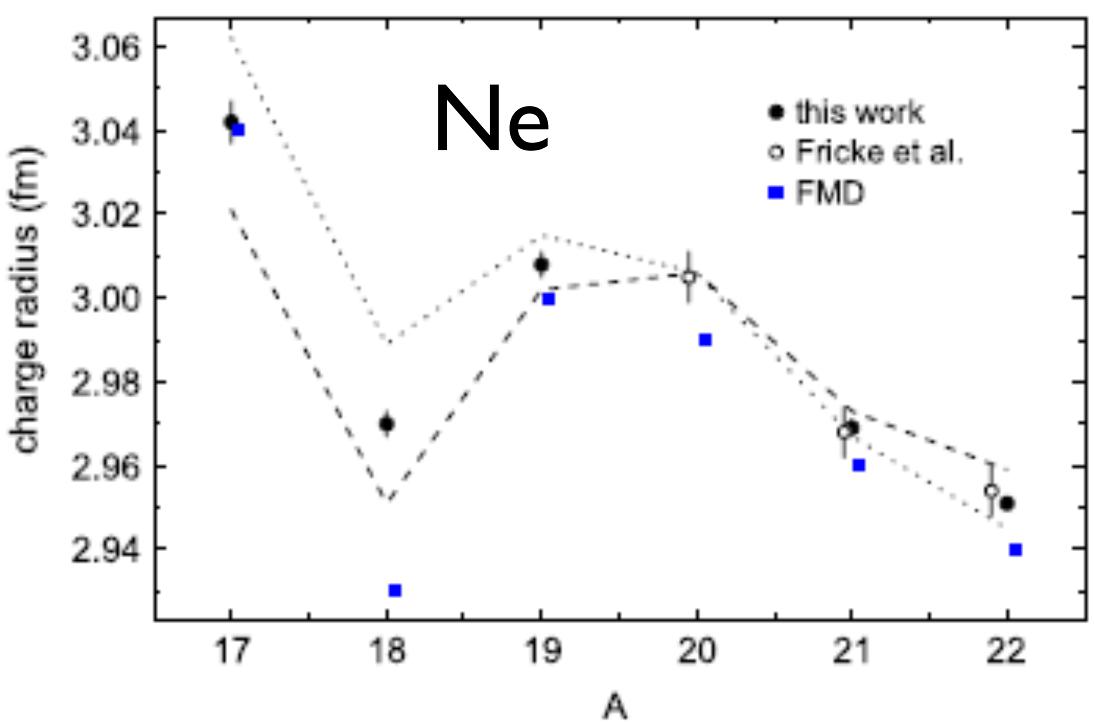
Best candidates: ^{8}B, ^{17}F, ^{17}Ne (Coulomb barrier in heavier nuclei will inhibit proton tunnelling beyond the nuclear potential)

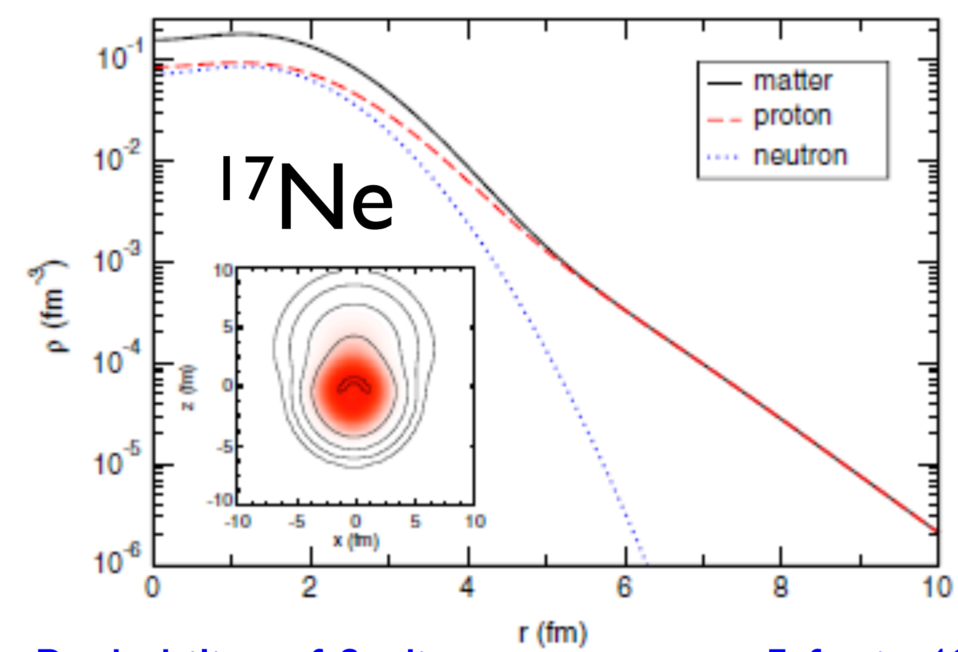
PRL 101, 252502 (2008) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2008

Masses and Charge Radii of $^{17-22}$Ne and the Two-Proton-Halo Candidate ^{17}Ne

W. Geithner,[1] T. Neff,[2] G. Audi,[3] K. Blaum,[1,2,*] P. Delahaye,[4] H. Feldmeier,[2] S. George,[1,2] C. Guénaut,[3] F. Herfurth,[2] A. Herlert,[4,5] S. Kappertz,[1] M. Keim,[1] A. Kellerbauer,[4,*] H.-J. Kluge,[2,6] M. Kowalska,[4] P. Lievens,[7] D. Lunney,[3] K. Marinova,[8] R. Neugart,[1] L. Schweikhard,[5] S. Wilbert,[1] and C. Yazidjian[2]

"Fermionic molecular dynamics calculations reproduced absolute charge radii and evolution with neutron number"



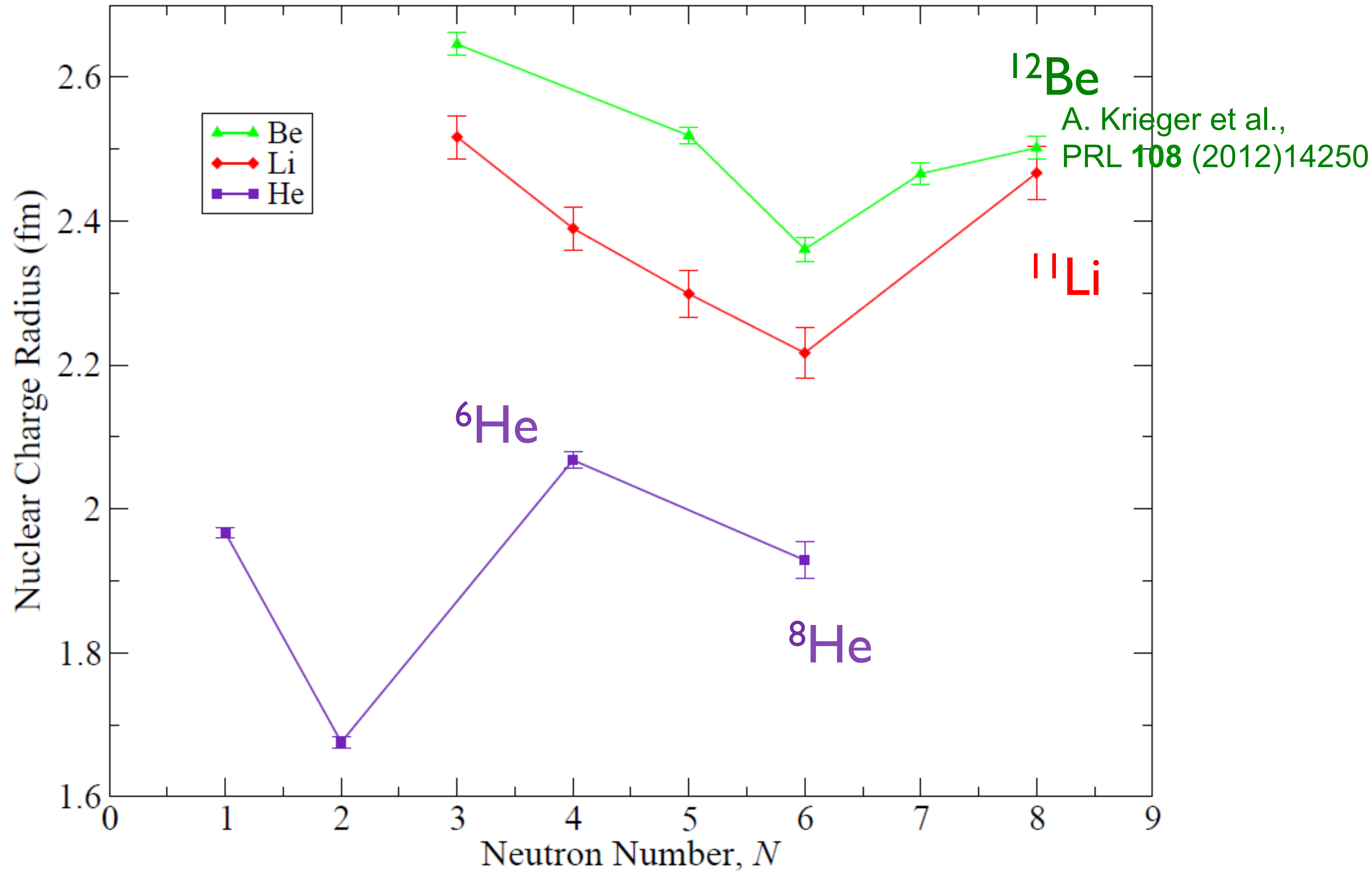


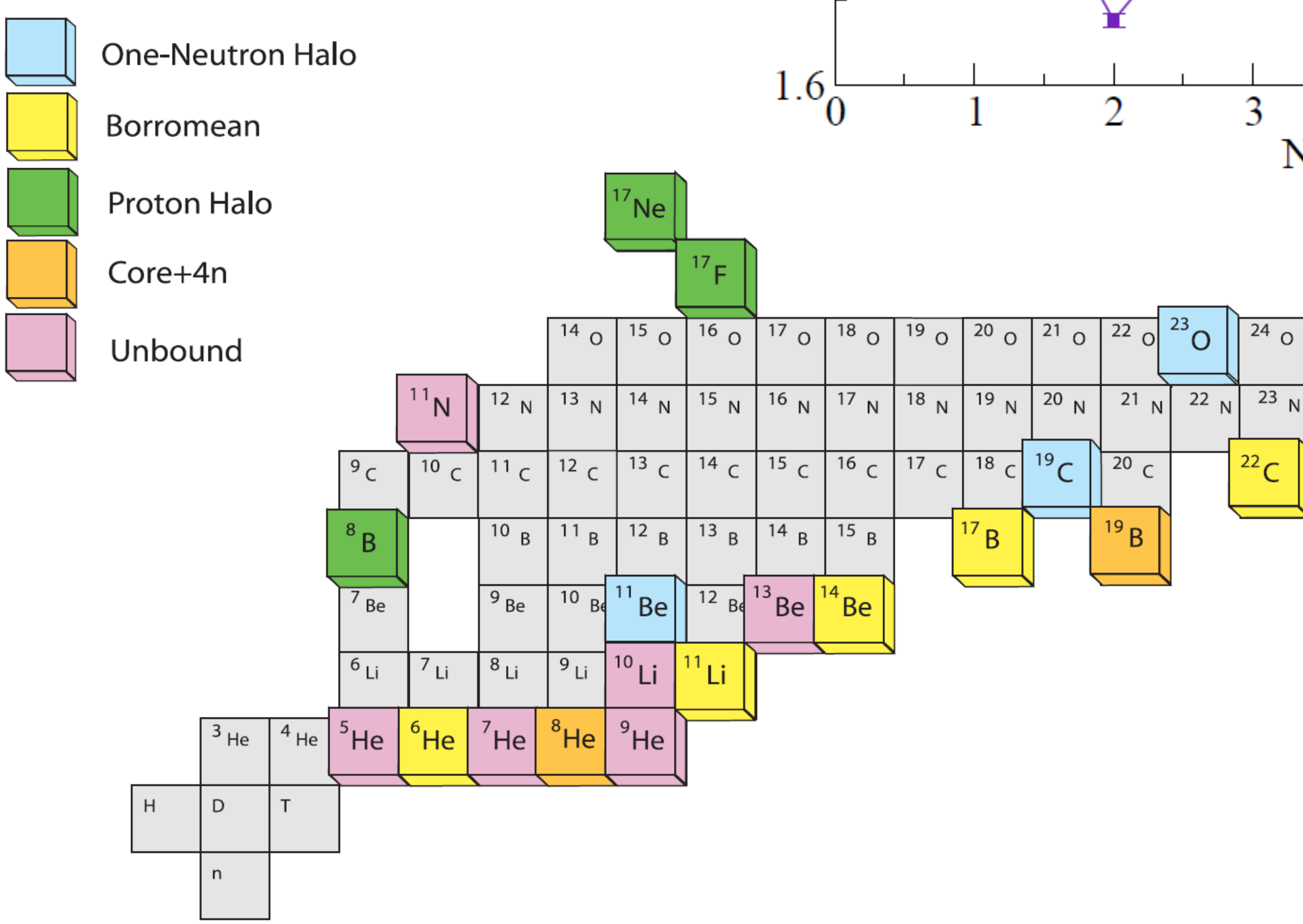
Probability of finding proton at r>5 fm is 40%

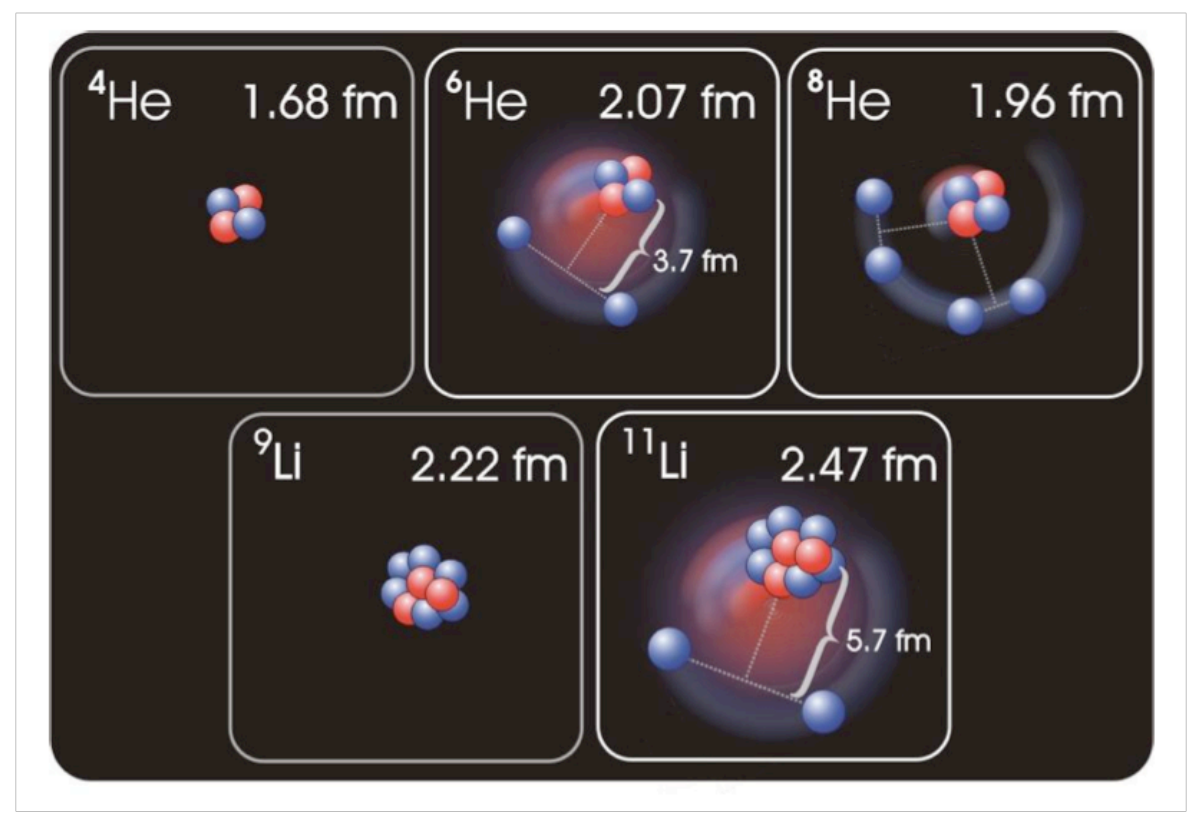
Conclusion:

s^2 proton admixture in ^{17}Ne ground state is about 40% - development of a proton halo component, but not a well-developed halo.

Cluster structure of light nuclei







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Coming very soon...

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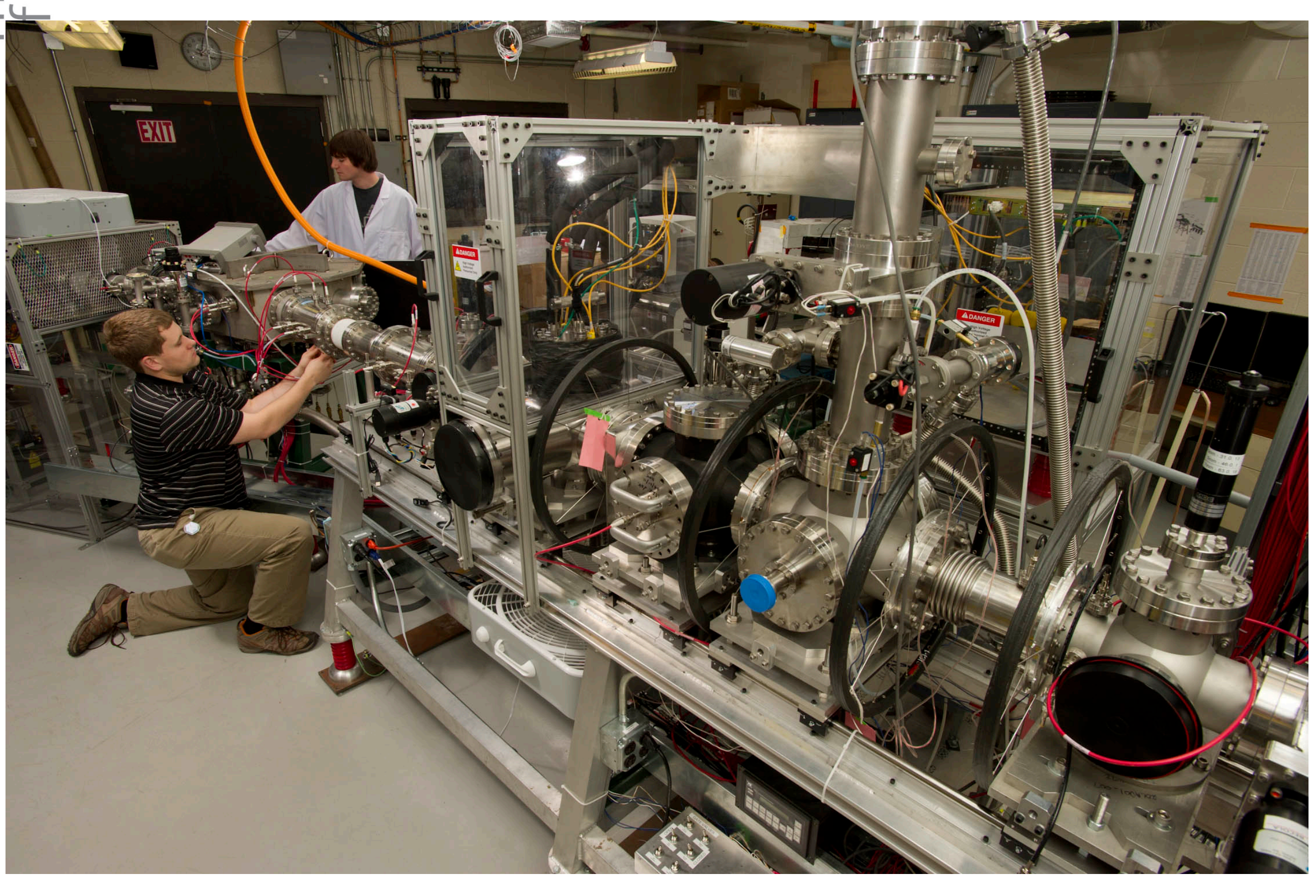
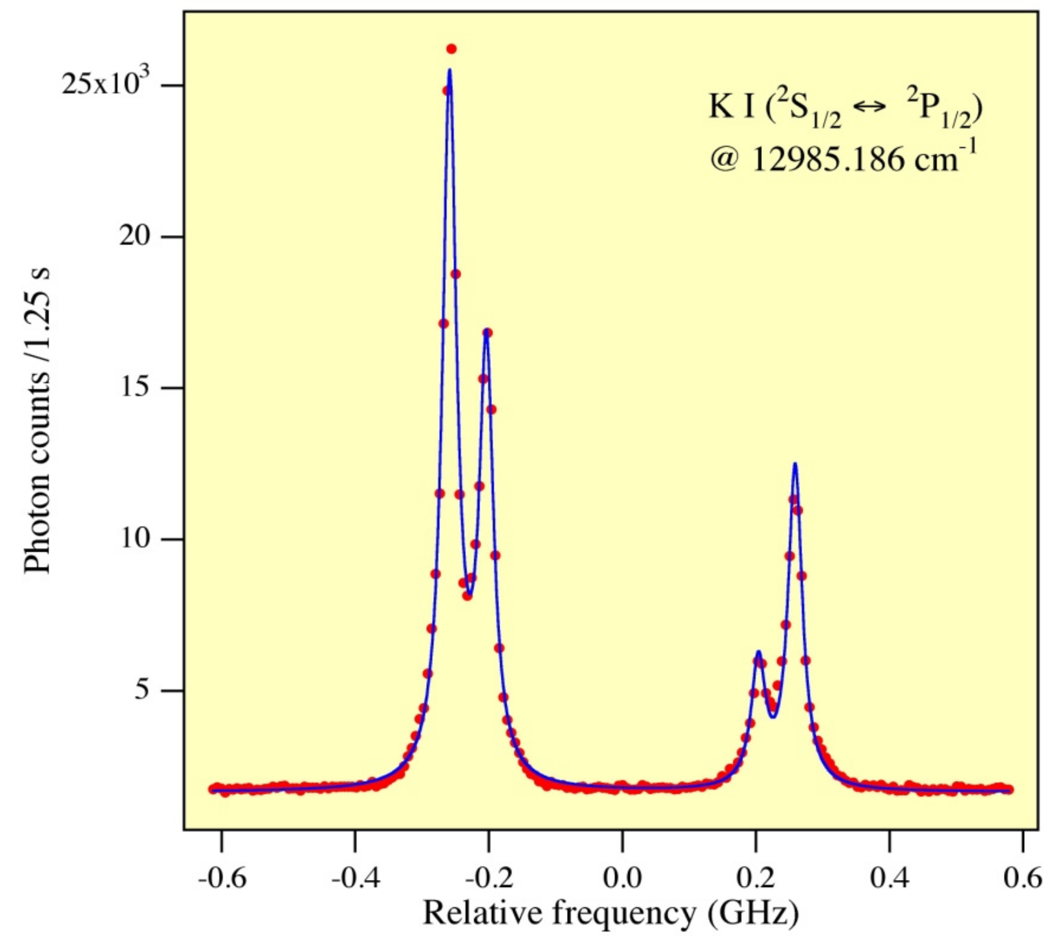
BEam COoling and LAser spectroscopy (BECOLA) facility at NSCL



Left: Photograph of the collinear laser beam line of BECOLA.
Below: spectrum of ^{39}K obtained using BECOLA.



- Commissioning of CLS beam line with stable beams completed
- Cryogenic cooler/buncher under construction and will be completed in 2012
- On-line measurements will commence in 2013 with a NSCL-PAC approved experiment (commissioning run on n-deficient K isotopes)

Poster 34 (A. Klose)
Poster 45 (K. Minamisono)

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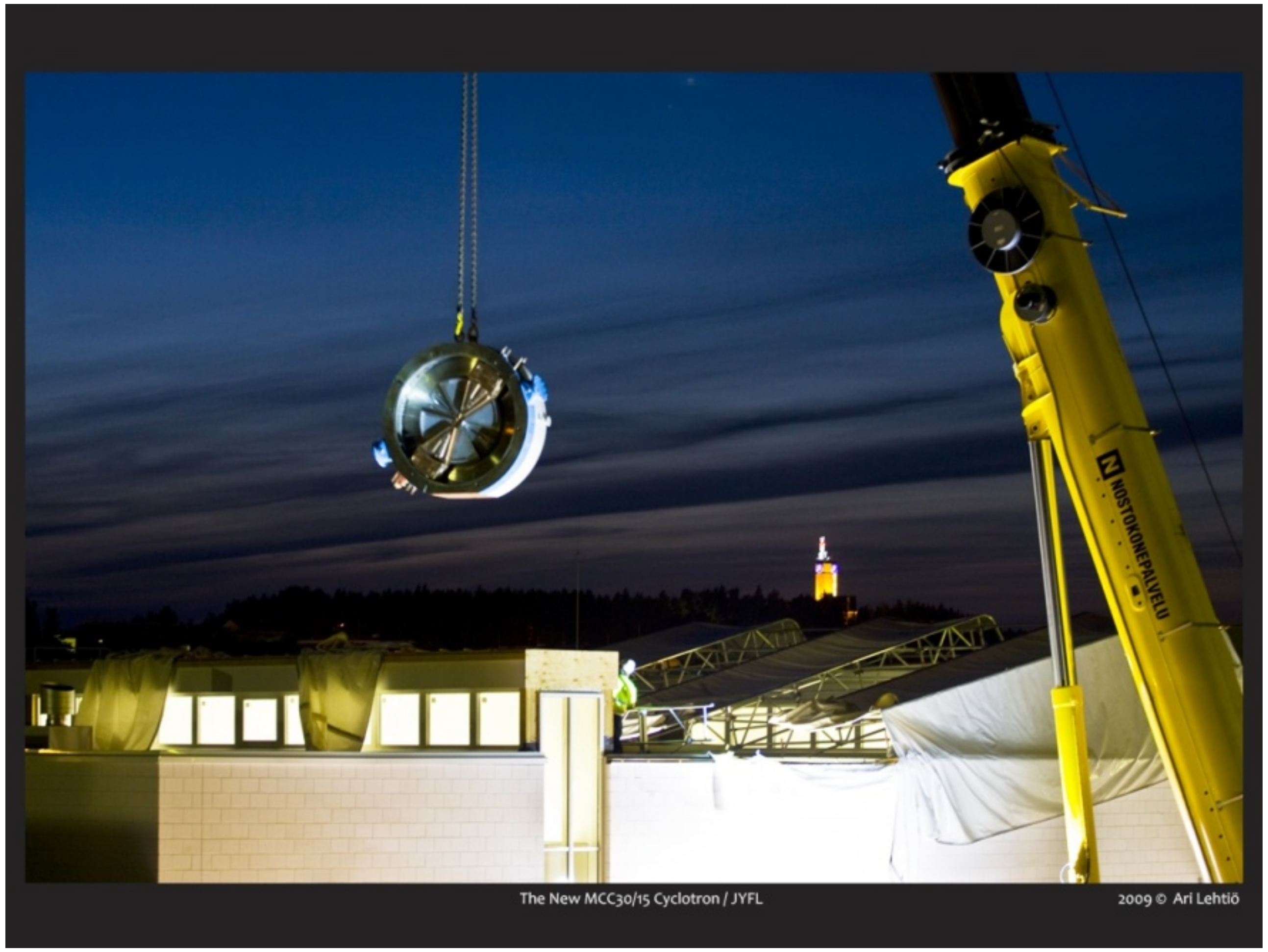
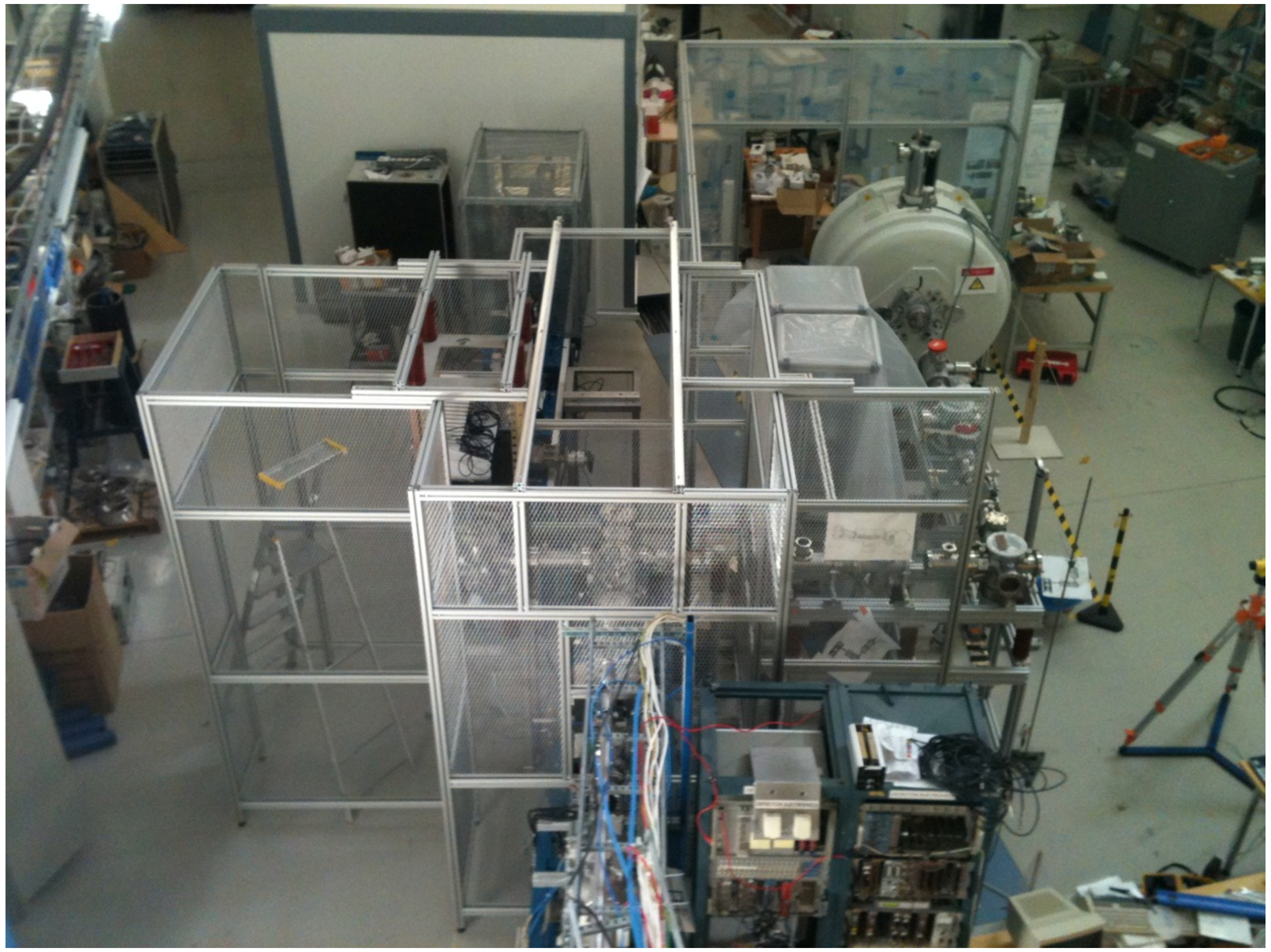
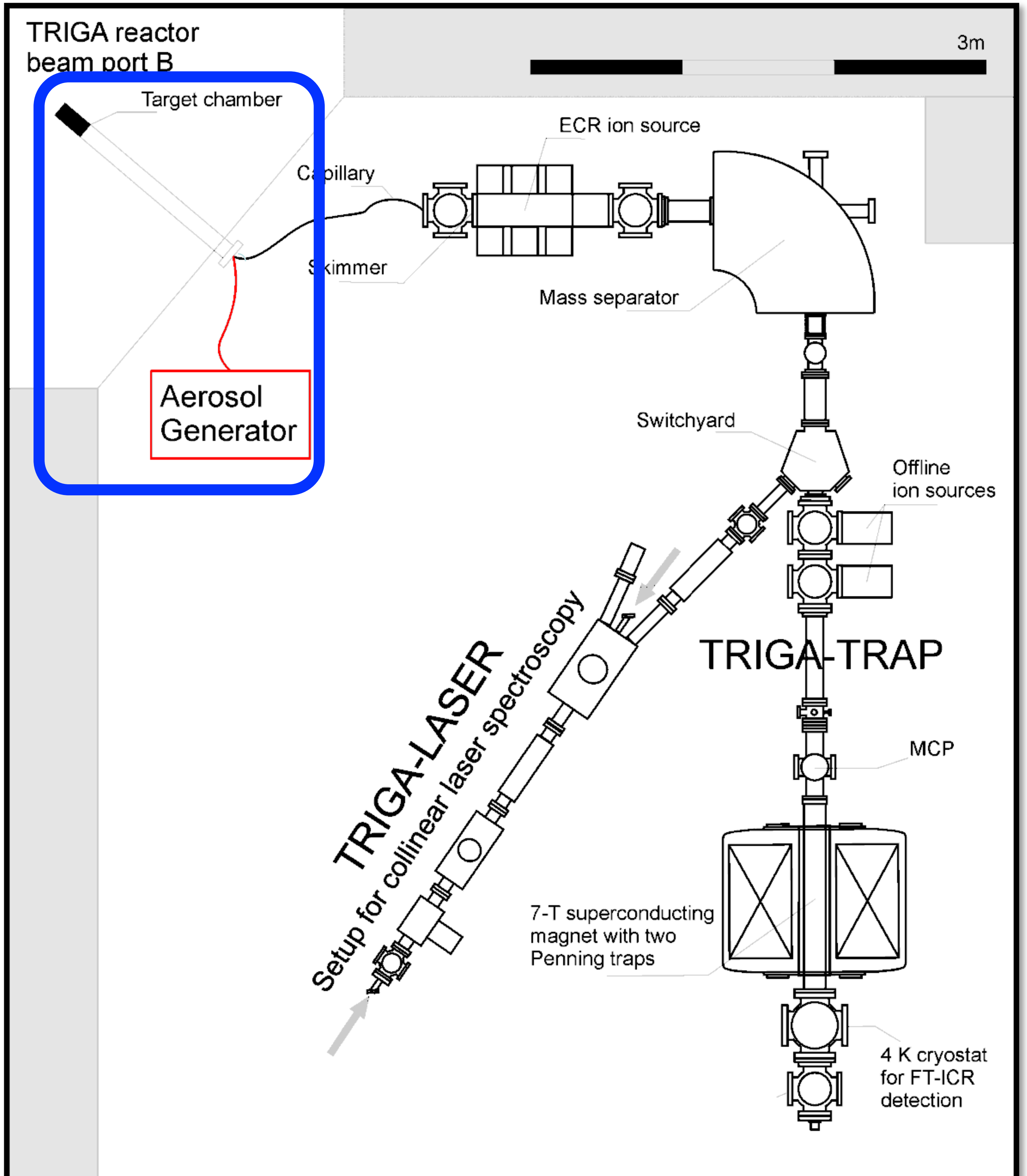
IGISOL IV almost ready at Jyväskylä

JYFL

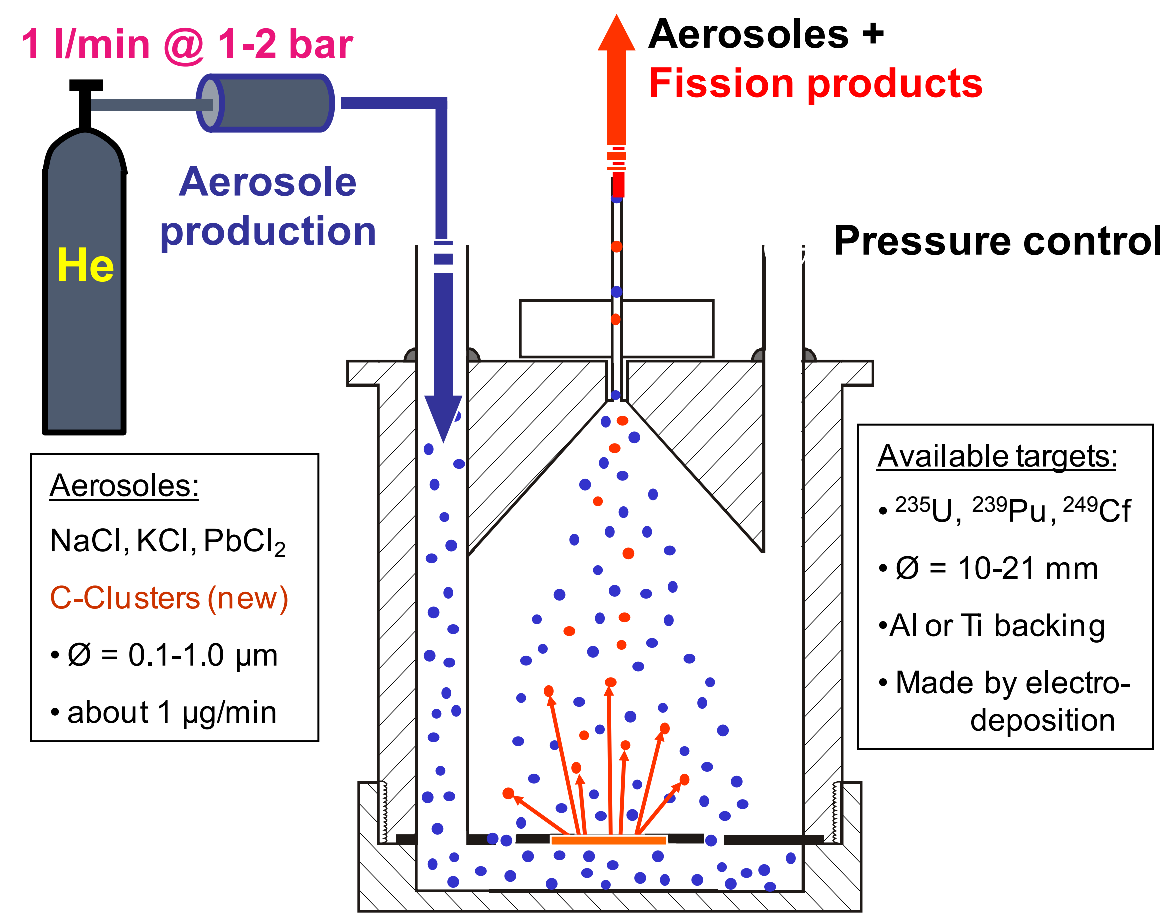




TRIGA-Spec (Mainz)



Ion creation



M. Eibach, NIM A 613 (2010) 226–231

Poster 22 (N. Frömmgen)

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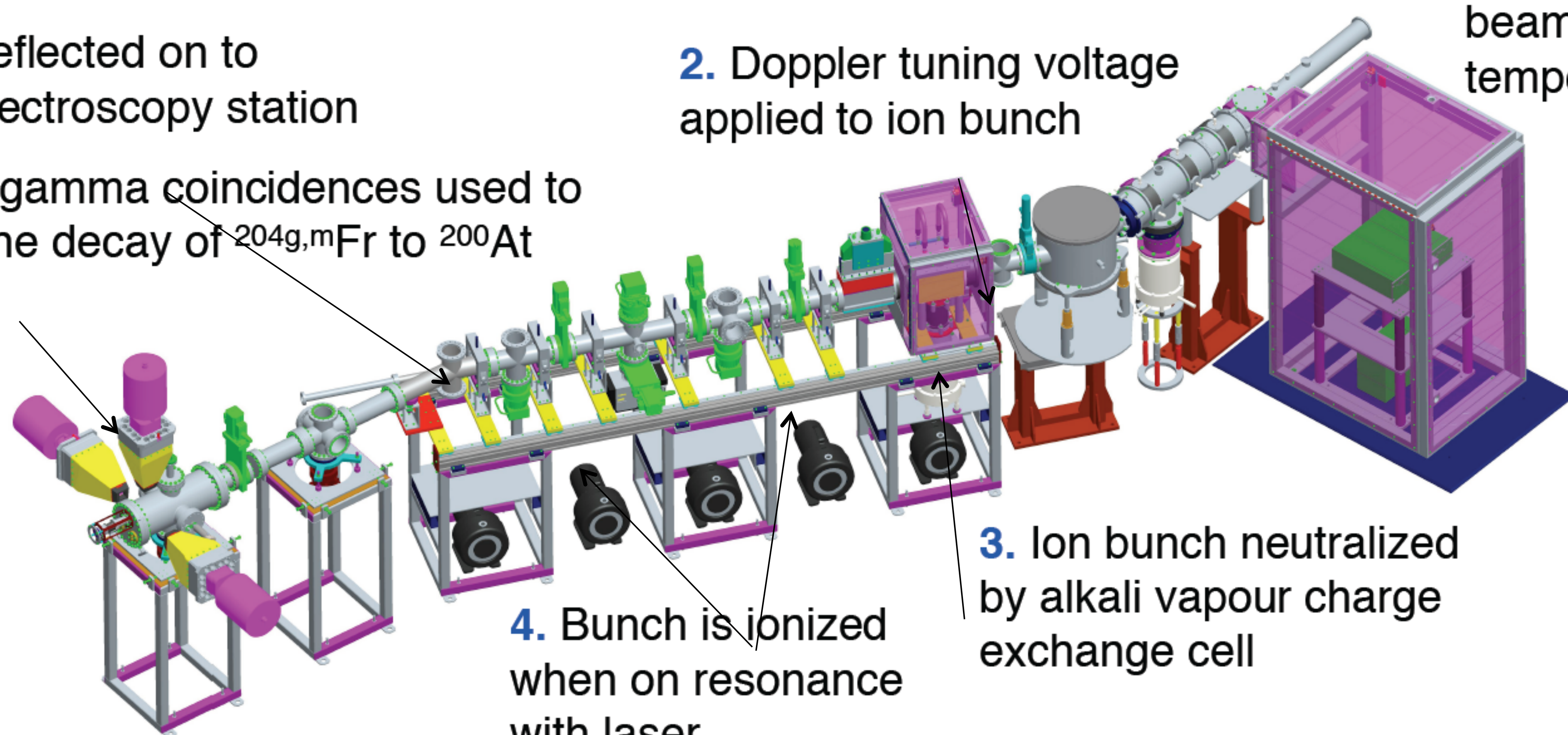
Collinear Resonance Ionisation Spectroscopy CRIS@ISOLDE



ISOLDE

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KATHOLIEKE UNIVERSITEIT LEUVEN

Poster 60 (M.M. Rajabali)

From K. Lynch, ARIS-2011 poster

Summary

- Recent measurements have concentrated on the most exotic nuclei accessible.

- These data provide stringent tests of nuclear models (shell model interactions, shell structure, FDM in light nuclei).

- The field has been re-invigorated through use of ion beam coolers and in-source RIS techniques.

- Many new facilities and experiments in the pipeline

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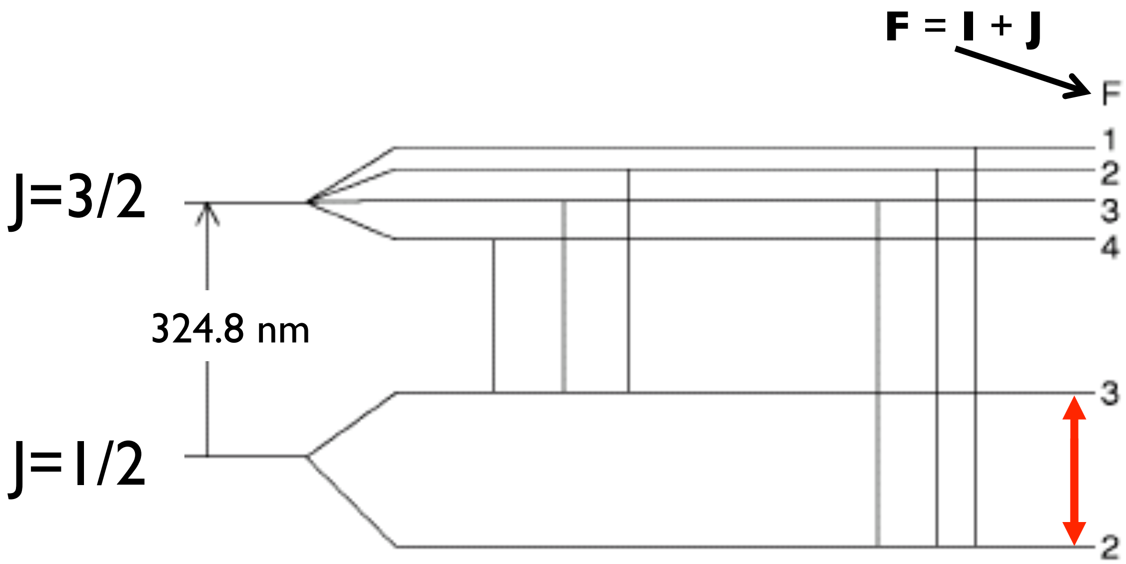
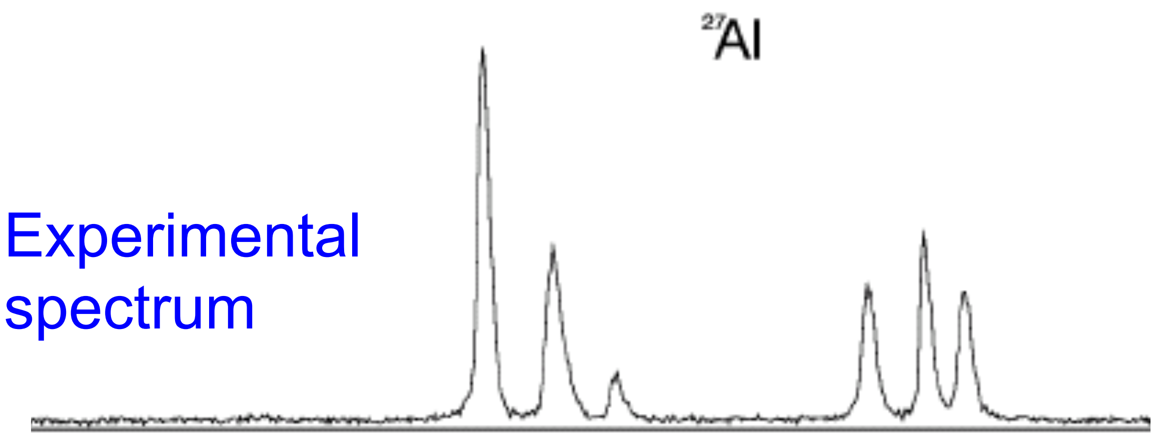
Determining the nuclear spin, I



Intervals depend on A_{upper} , B_{upper}, and I, J, F

Interval depends on A_{lower} , and I, J, F

Experimental spectrum



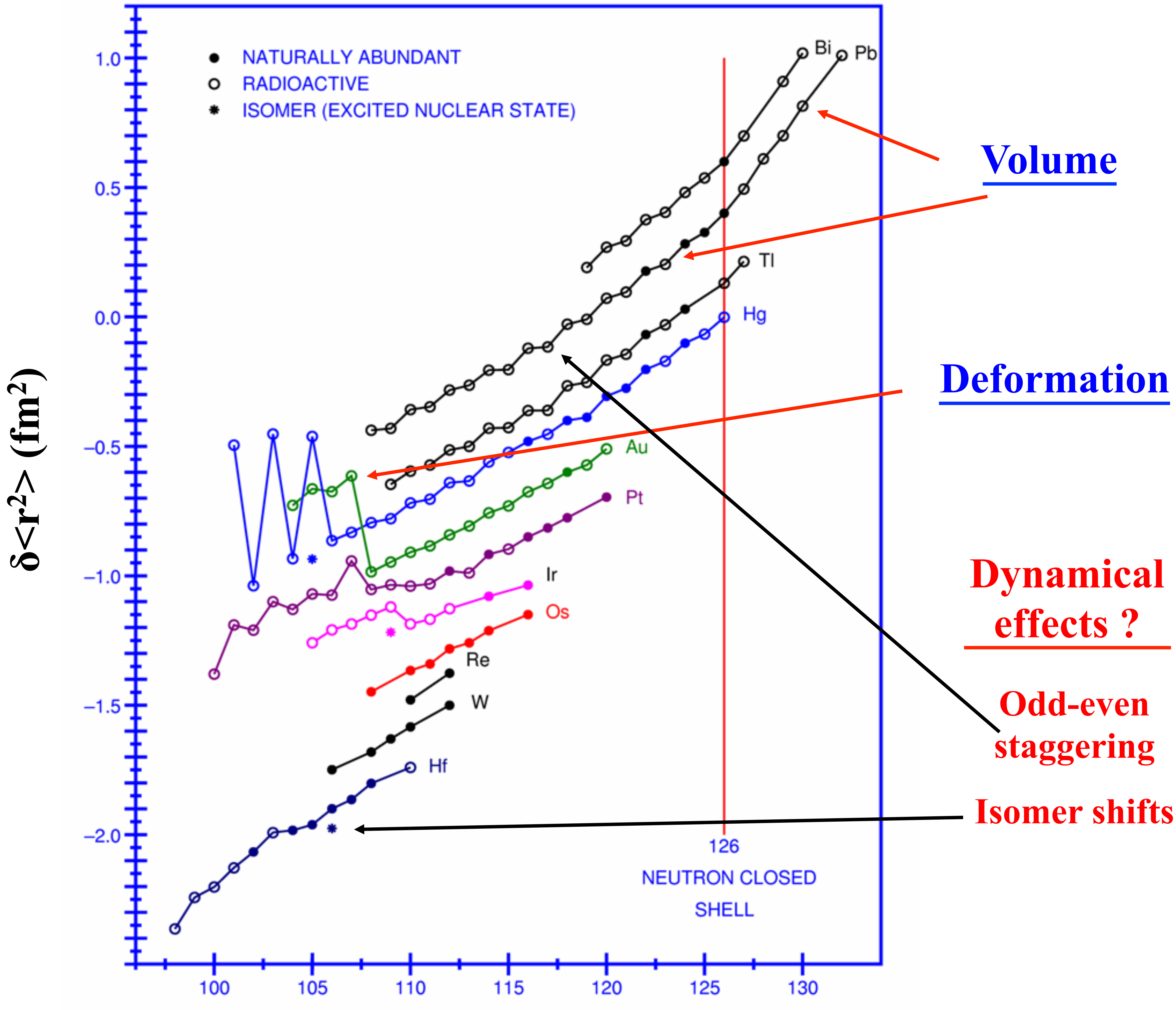
Ratio A_{upper}/A_{lower} is independent of nuclear moment (ie same for all isotopes)

If the wrong value of I is used to fit the hyperfine structure then:

- May be impossible to fit structure (position or number of peaks)
- Deduced ratio A_{upper}/A_{lower} is wrong
- Deduced relative peak intensities are wrong (Racah coefficients)

Without a definite spin, none of the other nuclear parameters can be deduced

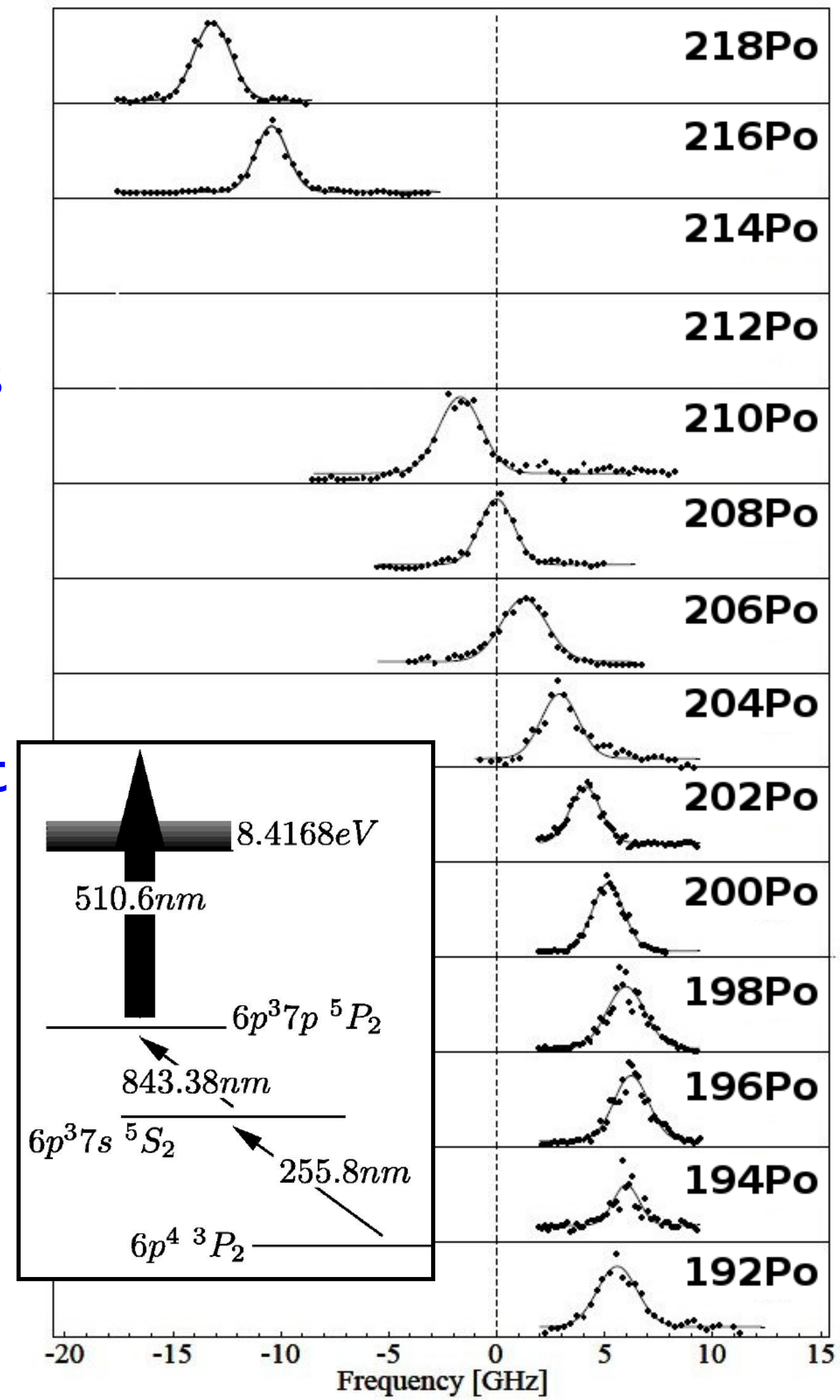
Mean square charge radii



Neutron-deficient Po isotopes

(Cocolios et al, Phys. Rev. Lett. 106 (2011) 052503)

- ISOLDE in-source RIS. Measurements made on the 843nm transition.
- Even-A results published.
- Odd-A hyperfine structures were not fully resolved and further experiments are scheduled (September 2012) using RILIS in narrow band mode and the LIST (laser ion source and trap) method

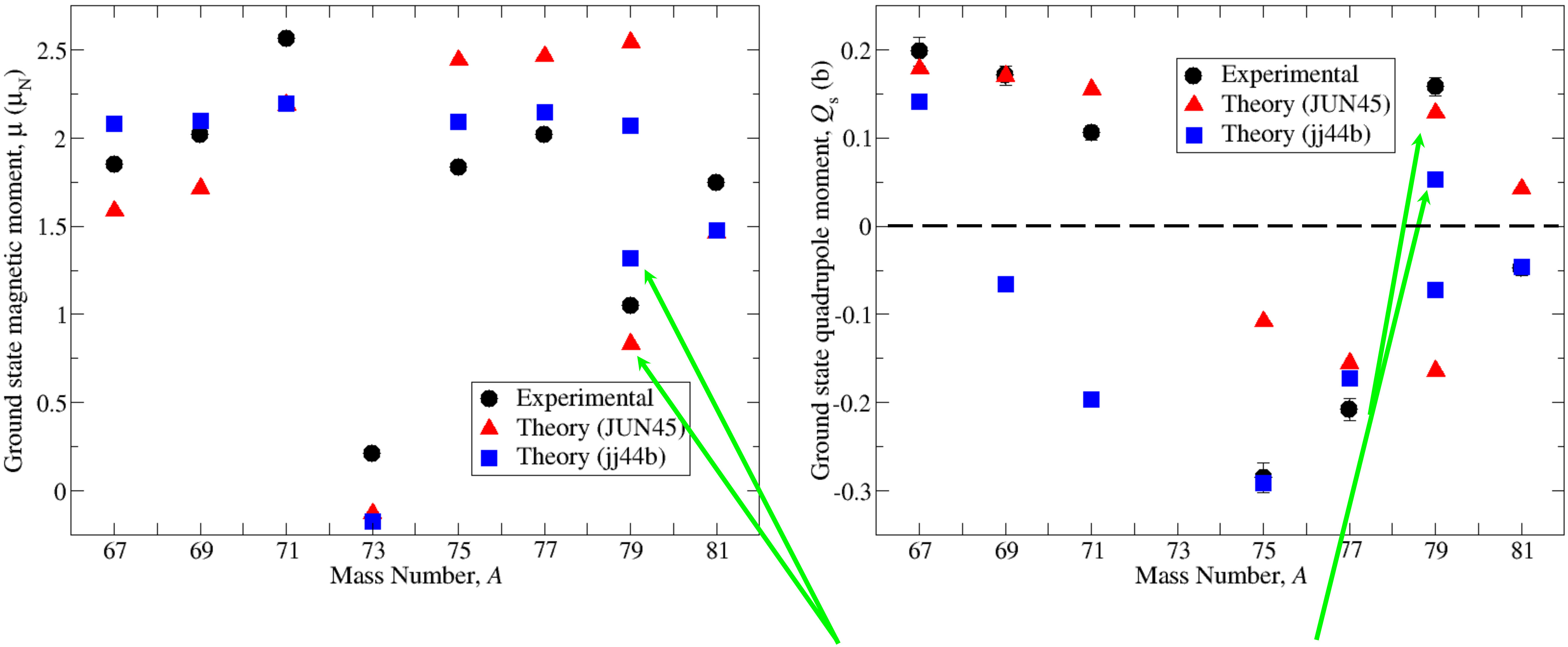


Ga shell model calculations (^{56}Ni core)

JUN45 (Honma et al) jj44b (Alex Brown)

Magnetic dipole

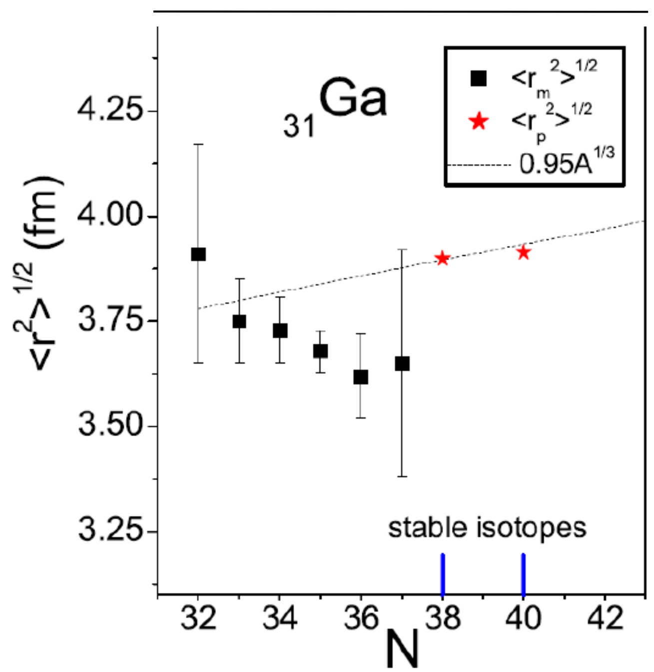
Electric quadrupole



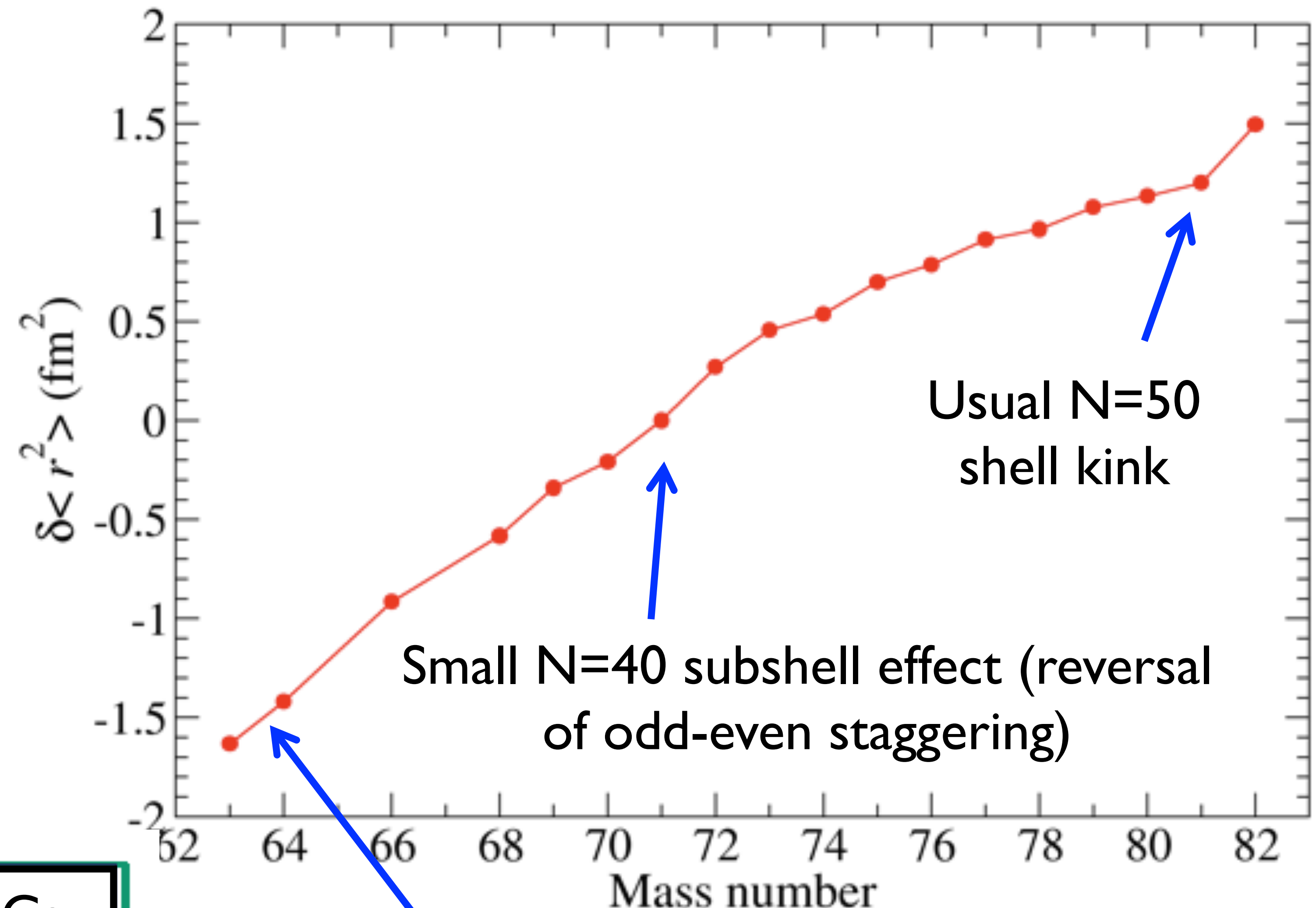
Predictions for **second** 3/2 states

It is these which match actual gs properties ($f^3_{5/2}$ dominated)

Gallium isotopes - charge radii



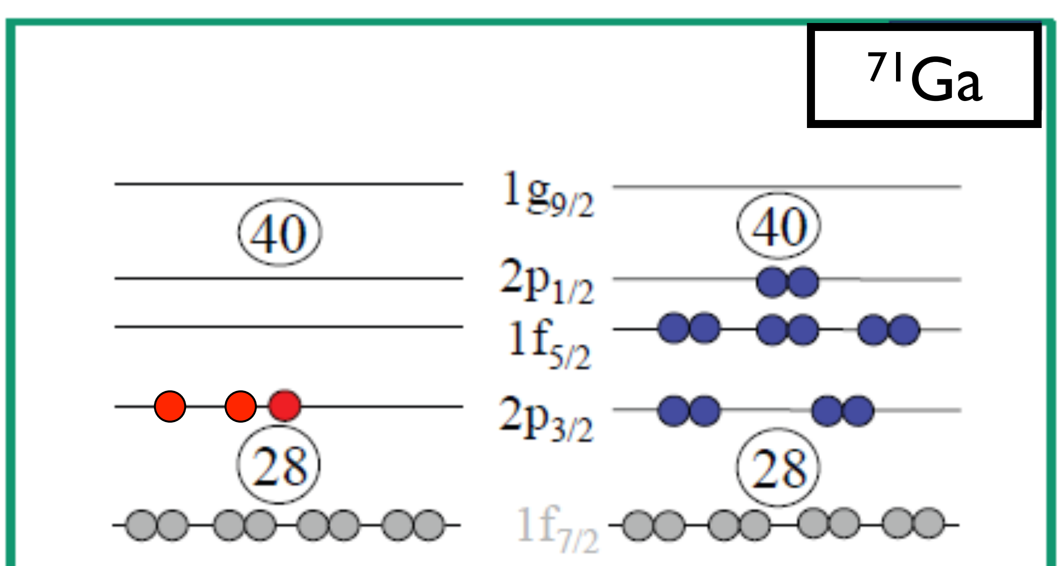
Matter radii of light isotopes – proton skin?
Lépine-Szily et al. Eur.. Phys. A**25** (2005) 227



Usual N=50 shell kink

Small N=40 subshell effect (reversal of odd-even staggering)

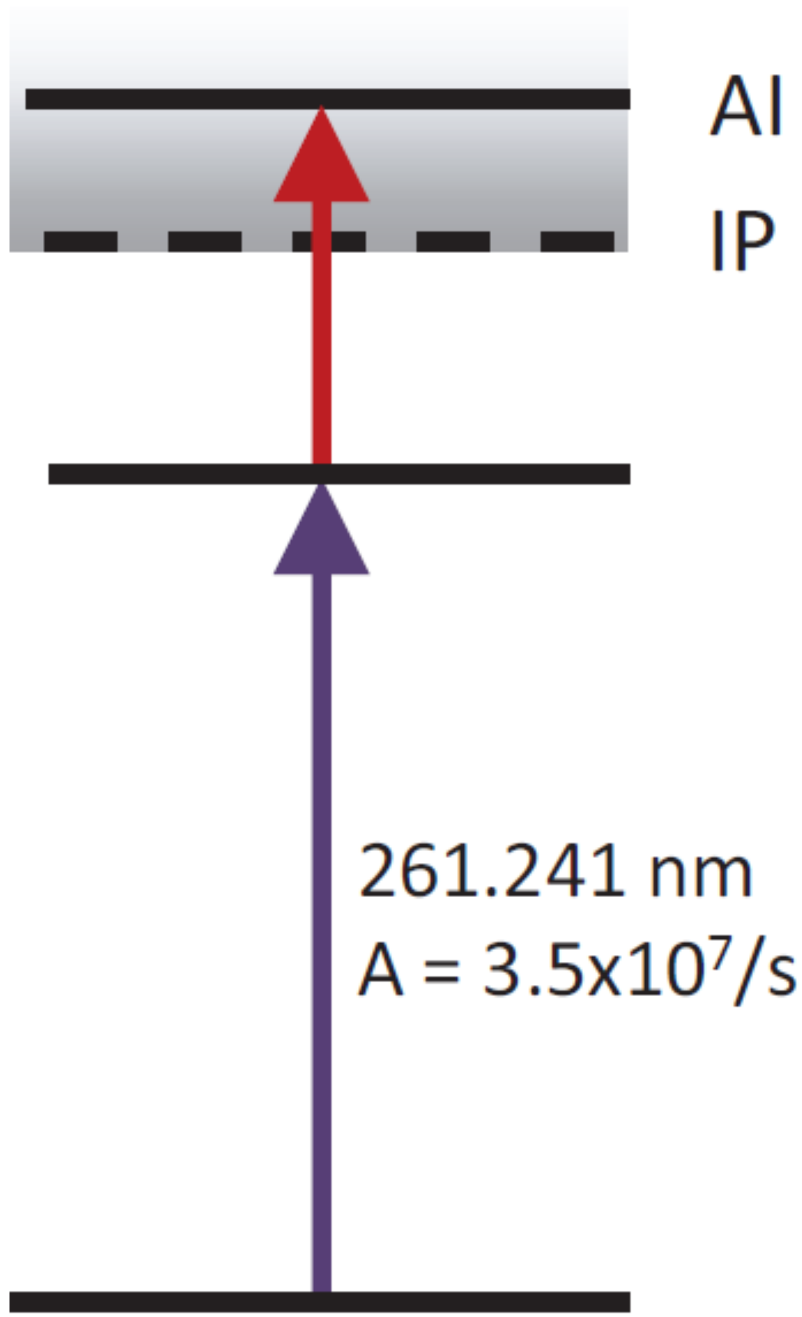
No anomalous effects in the proton charge radii for light isotopes

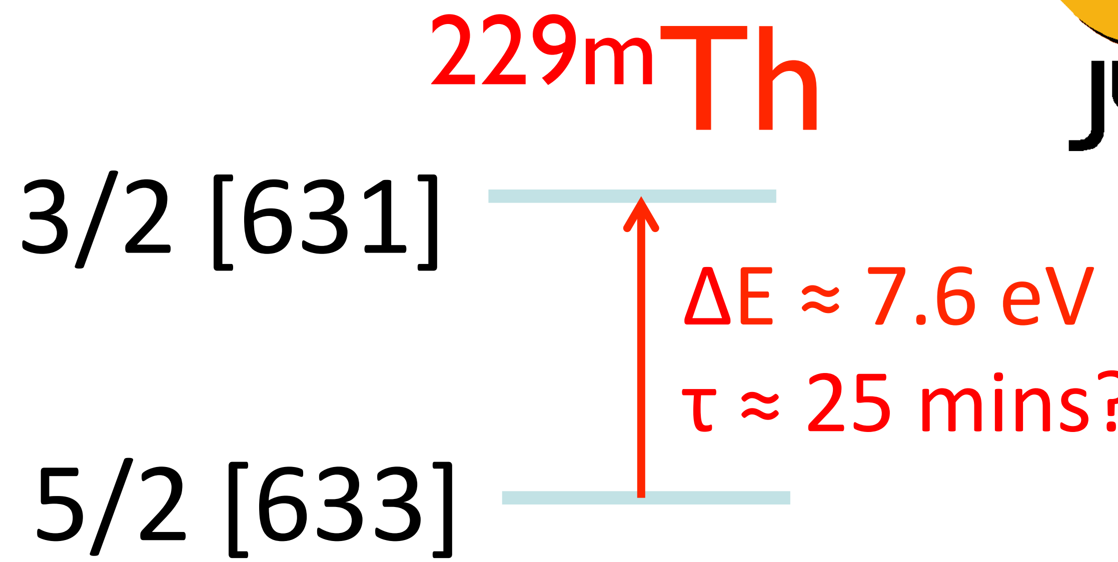


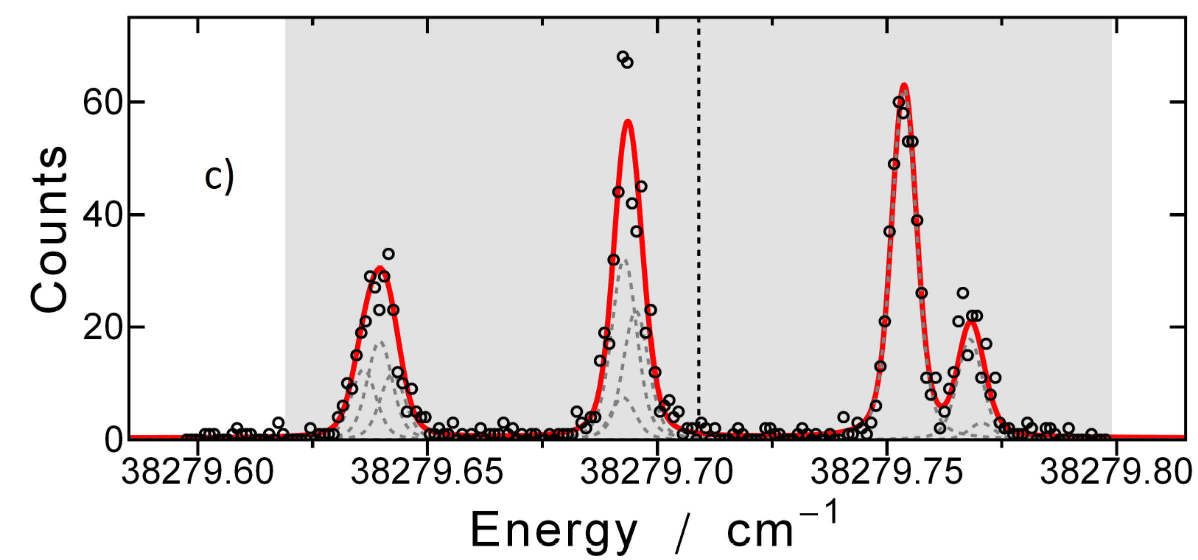
MANCHESTER 1824

The University of Manchester

Hyperfine structure of atomic ^{229}Th



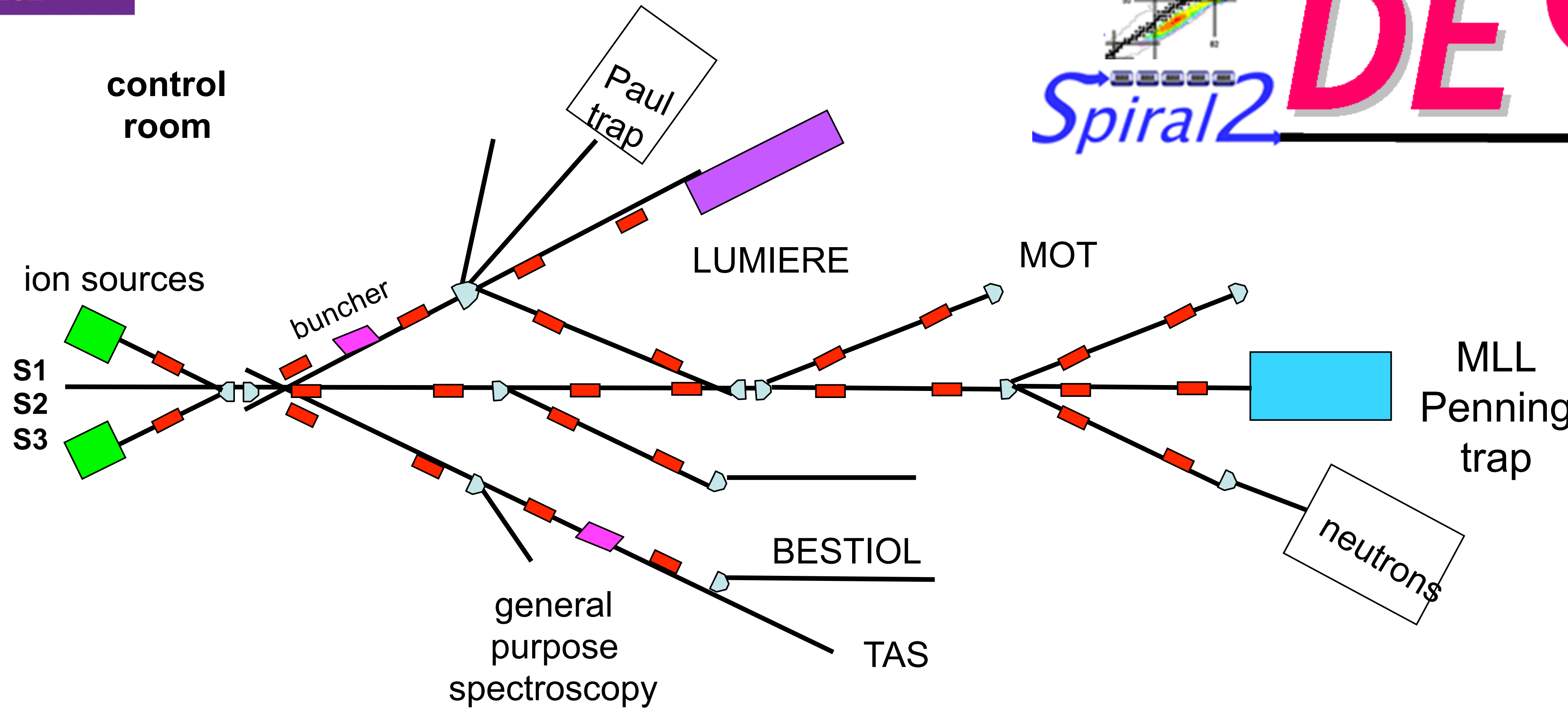


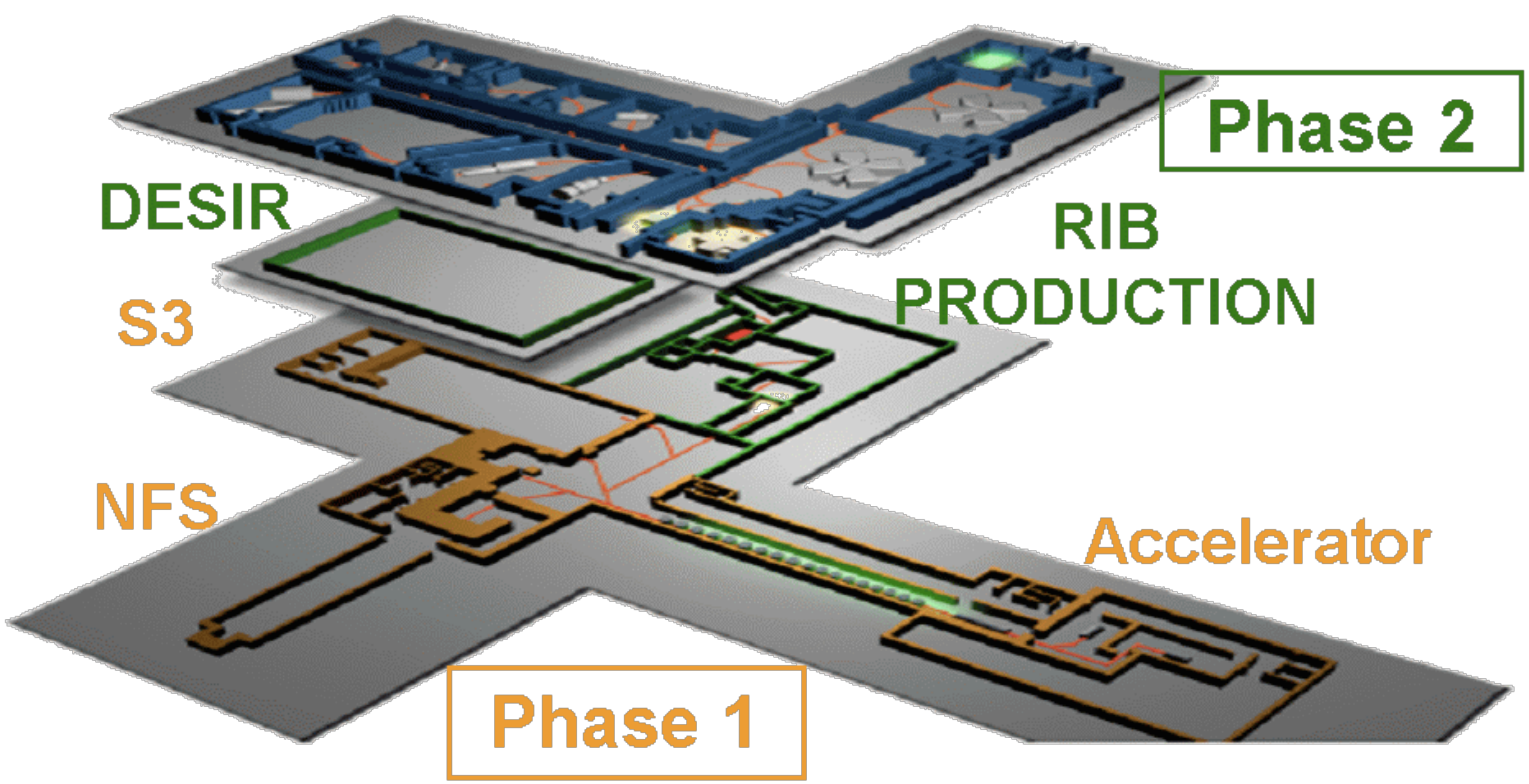


JYFL

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

LARISSA


control room
Paul trap
LUMIERE
MOT
ion sources
buncher
S1
S2
S3
MLL Penning trap
neutrons
BESTIOL
general purpose spectroscopy
TAS


Phase 2
DESIR
RIB PRODUCTION
S3
NFS
Accelerator
Phase 1

GANIL: HELIOS
Heavy Element Laser Ionization Spectroscopy

- Production of the heavy elements: heavy-ion fusion evaporation reactions
- Separation of the primary and secondary beam: e.g. S3-GANIL
- Thermalization in the gas cell
- Repelling unwanted ions
- Formation of a cooled atomic beam through e.g. a 'de Laval' nozzle (gas jet)
- Resonant laser ionization: high-repetition rate laser system (>10 kHz)
- Ion capture and transport in the RF Ion Guide followed by mass separation
- Detection of the ions: radioactivity / ion counting