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Laser spectroscopy at the IGISOL: recent physics highlights and future plans

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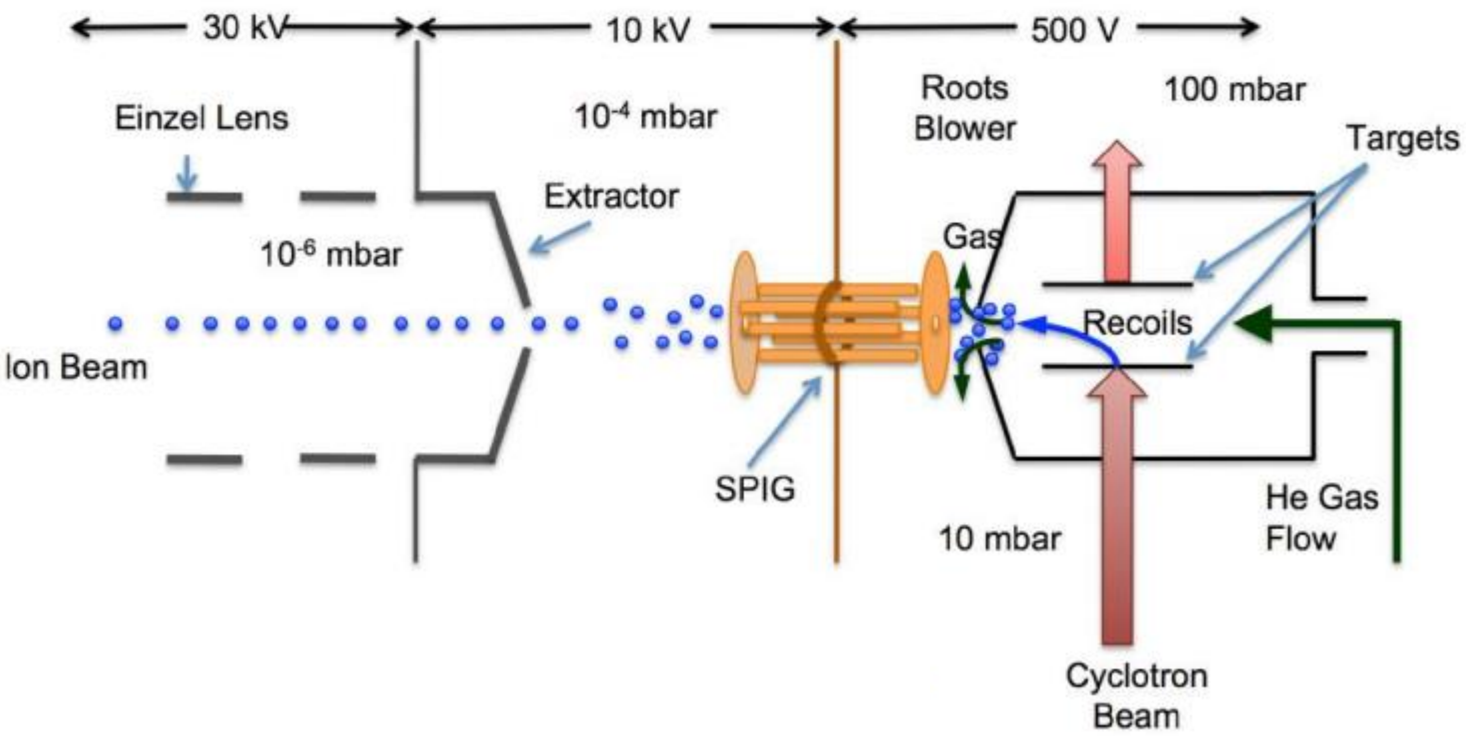
Outline

- Laser spectroscopy at the IGISOL
  - The IGISOL concept
  - Principles of laser spectroscopy
- Recent measurements
  - Shape coexistence near *N*=60: ^{98m}Y and ^{100m}Nb
  - High-resolution laser spectroscopy of silver
  - In-source spectroscopy of silver
- Upcoming developments
  - Future plans in the *Z*~45 region
  - Improving sensitivity: resonance ionization of refractory species and actinides

Laser spectroscopy at the IGISOL

The IGISOL concept

- Cyclotron beam hits thin target
- Recoils stopped in He buffer gas
- Supersonic jet guides into an ion guide
- Fast and chemically insensitive
  => universal

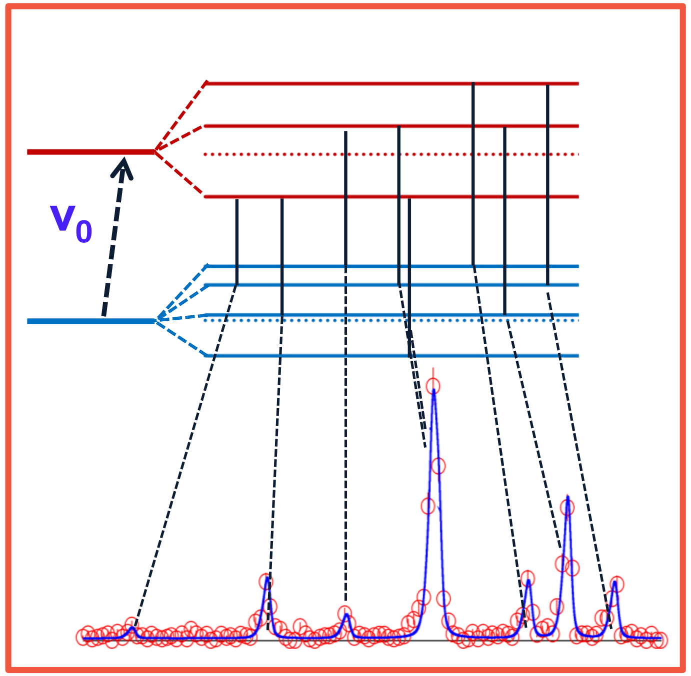


Laser spectroscopy

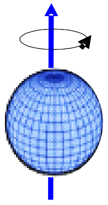
- Hyperfine interaction: nuclear and atomic properties

$$h\nu \sim \nu_0 + A\frac{C}{2} + B\frac{1}{4}\frac{(3/2)C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)}$$

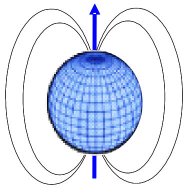
$\delta\langle r^2\rangle$ $\quad$ $\boxed{A = \frac{\mu_I B_J}{IJ}}$ $\quad$ $\boxed{B = eQV_{zz}}$



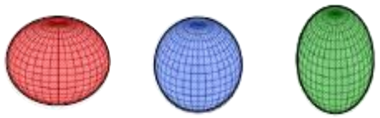
- Model-independent extraction of:



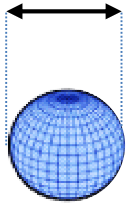
Spin I



Magnetic moment μ



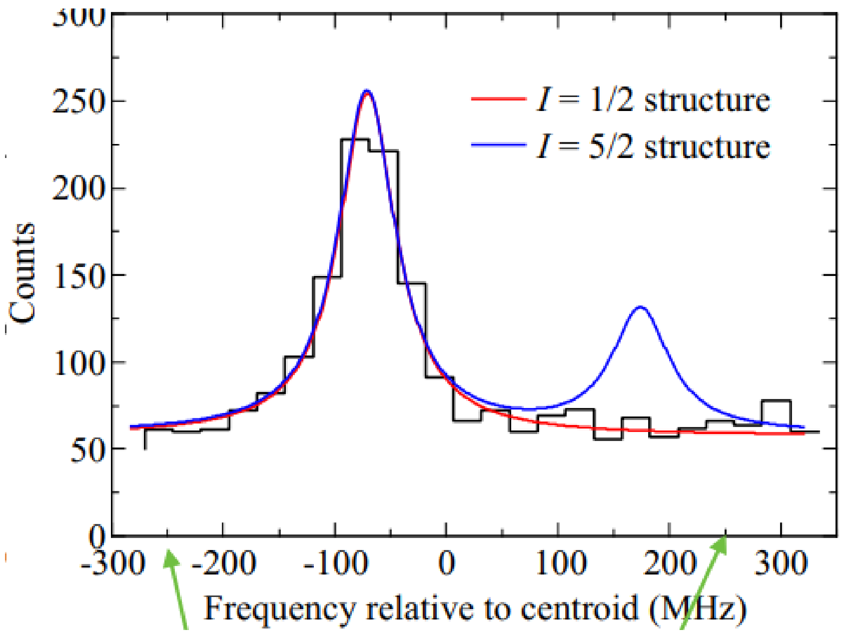
Quadrupole moment Q_s



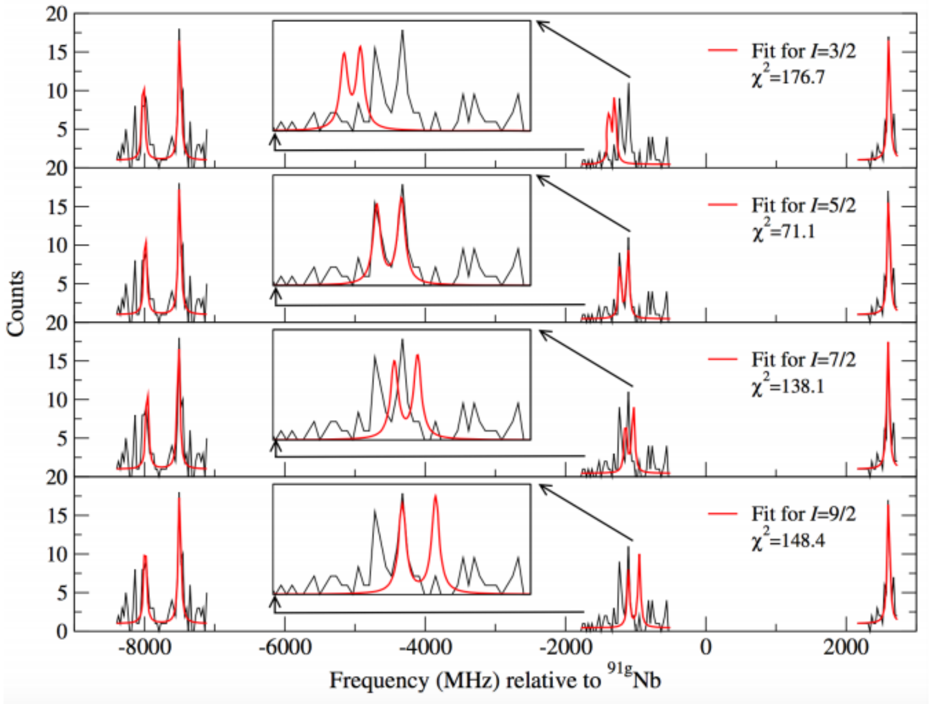
Charge radii $\delta\langle r^2\rangle$

Measuring spins

- Some cases quite easy



- Other cases a bit more tricky



- In general: higher nuclear spins are harder to tell apart
- Higher atomic spins make the assignment easier, but measurement harder

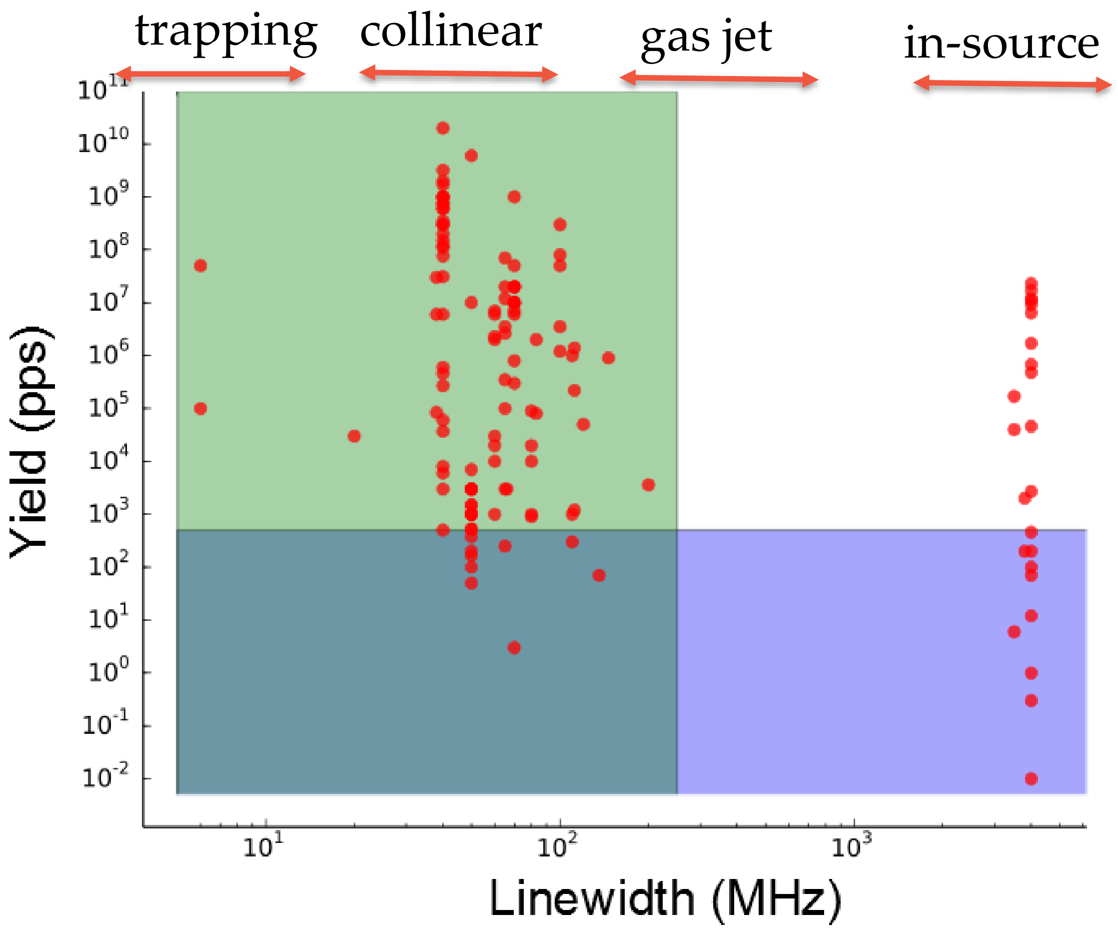
Experimental lay of the land

Precision vs. sensitivity tradeoff

- Collinear laser spectroscopy
  - Less efficient, high precision
- In-source laser spectroscopy
  - High efficiency, low resolution

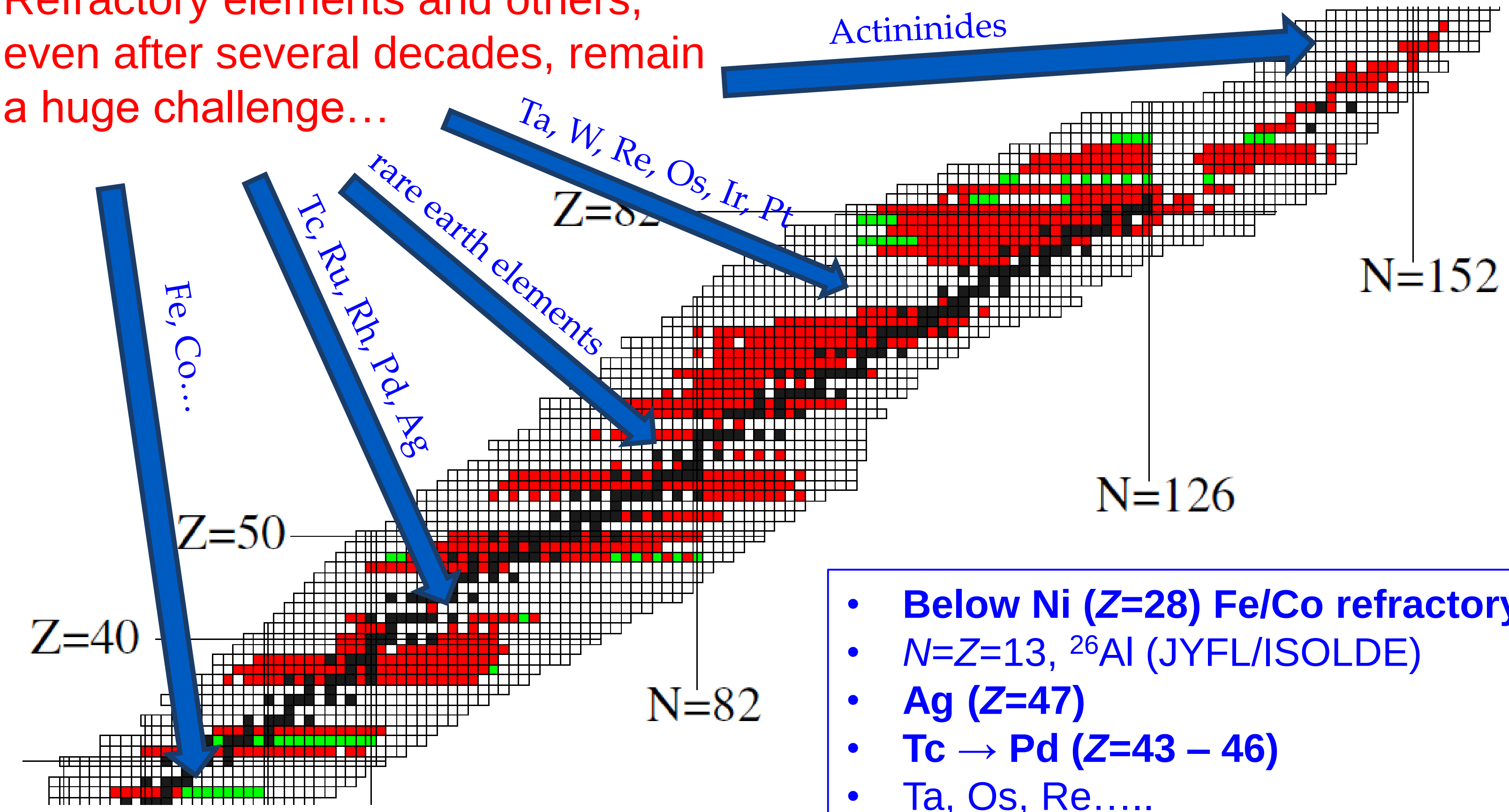
But, picture is changing!

- In gas-jet, PI-LIST: high-res in-source
- CRIS, MIRACLS: high-efficiency collinear



Blind spots in the optical landscape

Refractory elements and others, even after several decades, remain a huge challenge…



- **Below Ni (*Z*=28) Fe/Co refractory**
- *N*=*Z*=13, ^{26}Al (JYFL/ISOLDE)
- **Ag (*Z*=47)**
- **Tc → Pd (*Z*=43 – 46)**
- Ta, Os, Re…..
- **Actinides (Pu, Th, U….)**

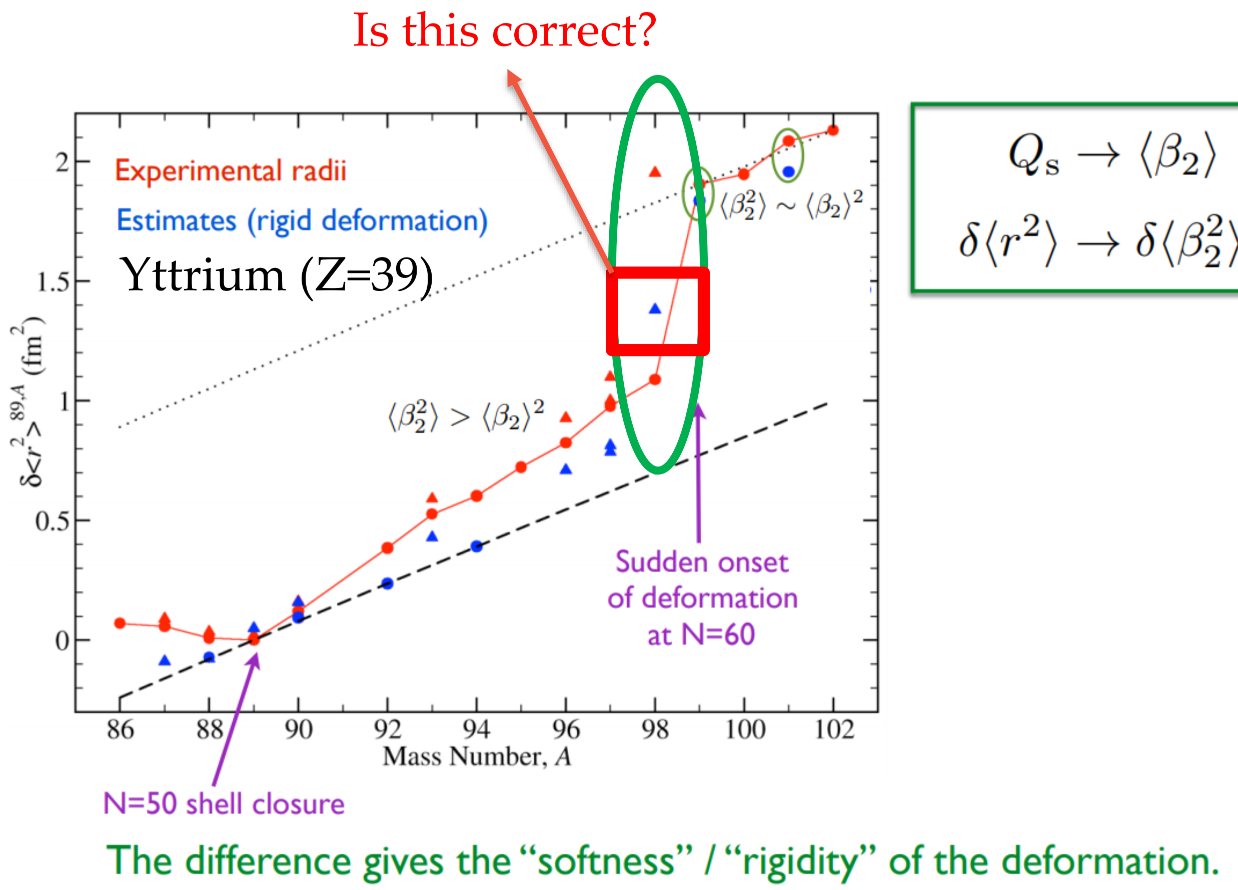
- IGISOL offers access to these blind spots
- Challenging region: low production rates, complex atomic structures
- Many methods required; flexibility is key!

Recent measurements

- Shape coexistence near A=100
- Laser spectroscopy of $^{96-104,\,113-121}Ag$

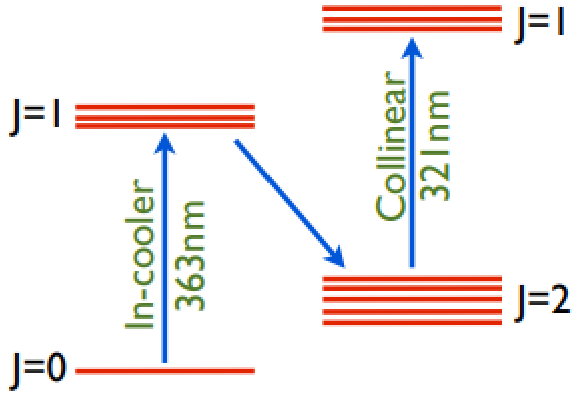
Shape coexistence in the A=100 region

- Status in 2007:
  - (weak) oblate to (strong) prolate
  - ^{98}Y is at the center point of this transition
  - ^{98m}Y is somewhat soft (?)

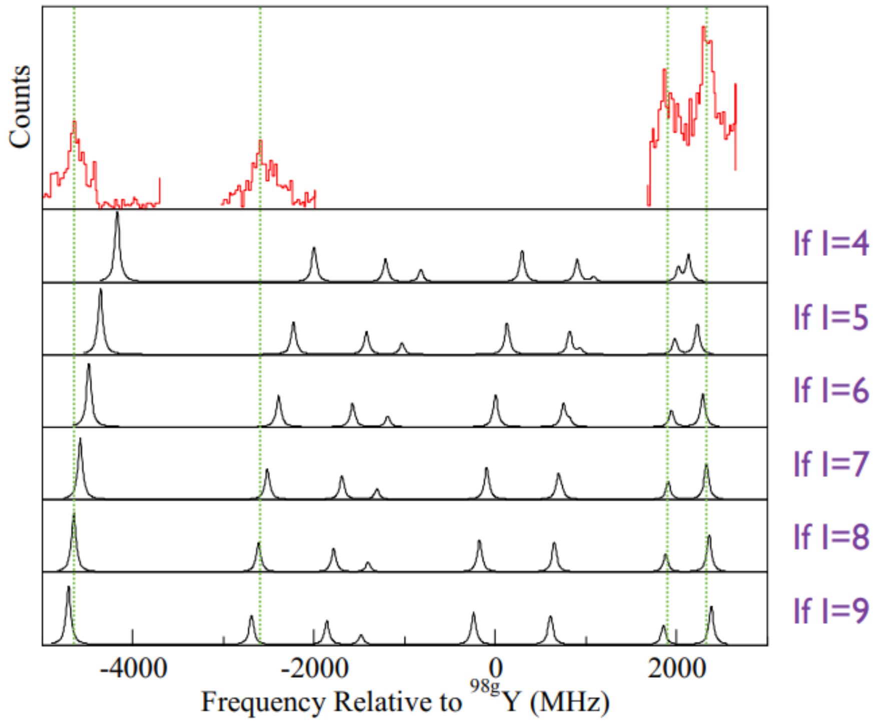


$$Q_s \rightarrow \langle\beta_2\rangle$$
$$\delta\langle r^2\rangle \rightarrow \delta\langle\beta_2^2\rangle$$

Laser spectroscopy of yttrium



- Status in 2019:
  - / (weak) oblate to (strong) prolate
  - / ^{98}Y is at the center point of this transition
  - / ^{98m}Y is somewhat soft (?)
  - / New data with J=2 to J=1 line
    - → Spin is 7 or 8 (analysis will tell)
    - → Q moment can be unambiguously determined

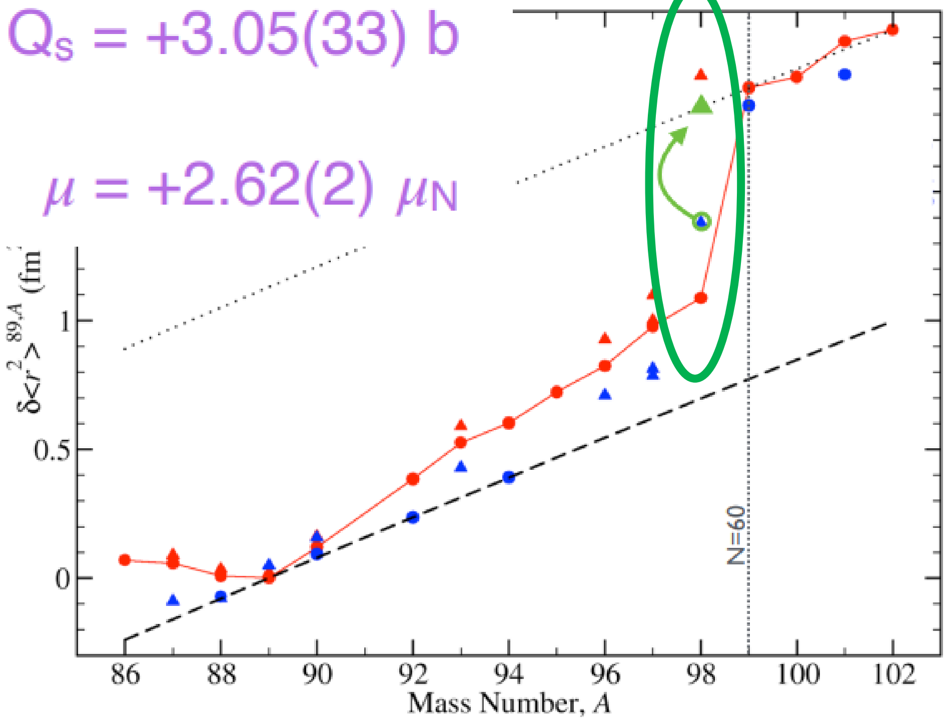


Laser spectroscopy of yttrium

Preliminary!

Q_s = +3.05(33) b

μ = +2.62(2) μ_N



- Status in 2019:
  - ~~^{98m}Y is somewhat soft~~
  - New data with J=2 to J=1 line
    - → Spin is 7 or 8 (analysis will tell)
    - → Q moment can be unambiguously determined

^{98m}Y is rigid, prolate deformed

Clear shape coexistence

PHYSICAL REVIEW C **96**, 044333 (2017)

Shape coexistence in the odd-odd nucleus ^{98}Y: The role of the $g_{9/2}$ neutron extruder

W. Urban,[1] M. Czerwiński,[1] J. Kurpeta,[1] T. Rząca-Urban,[1] J. Wiśniewski,[1] T. Materna,[2] Ł. W. Iskra,[3] A. G. Smith,[4] I. Ahmad,[5] A. Blanc,[6] H. Faust,[6] U. Köster,[6] M. Jentschel,[6] P. Mutti,[6] T. Soldner,[6] G. S. Simpson,[7] J. A. Pinston,[7] G. de France,[8] C. A. Ur,[9] V.-V. Elomaa,[10] T. Eronen,[10] J. Hakala,[10] A. Jokinen,[10] A. Kankainen,[10] I. D. Moore,[10] J. Rissanen,[10] A. Saastamoinen,[10] J. Szerypo,[10] C. Weber,[10] and J. Äystö[10]

isomer to determine its configuration. The spin of the isomer was increased from the previous $I = (4,5)$ to $I^{\pi} = (6,7)^{+}$. The

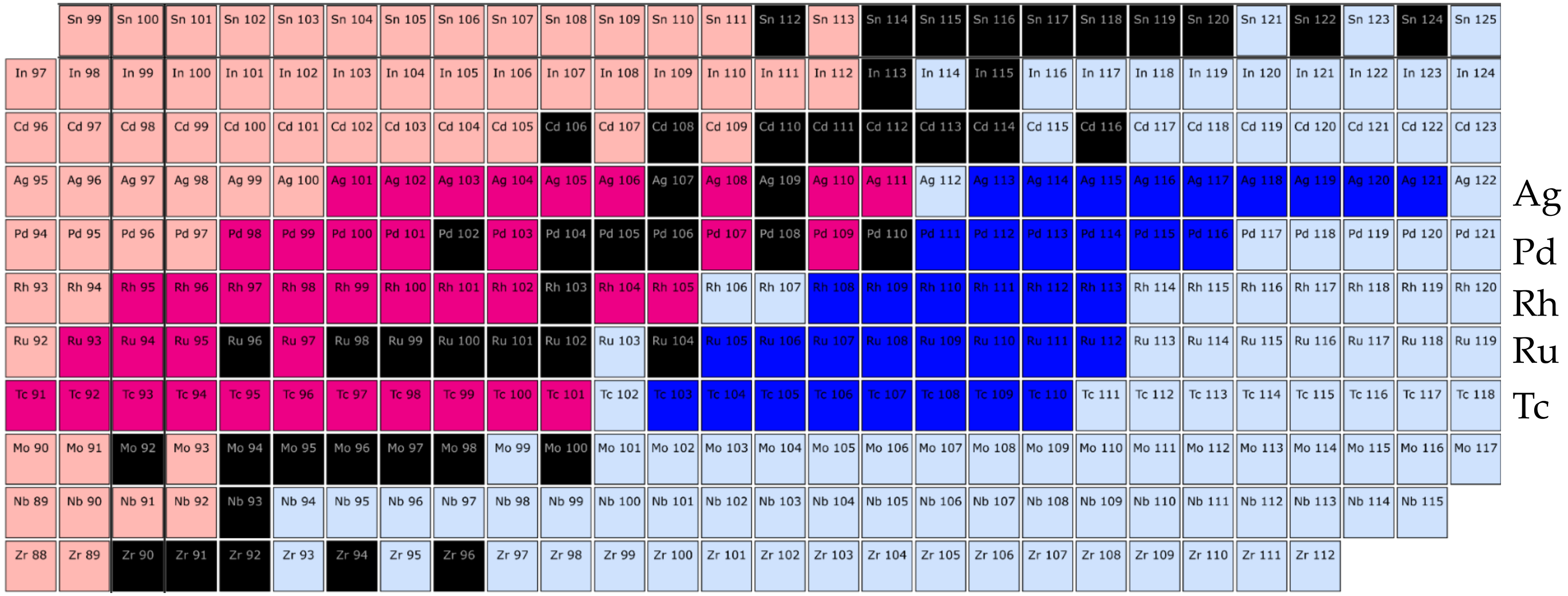
C. S. Devlin, in preperation

Recent measurements

- Laser spectroscopy of silver

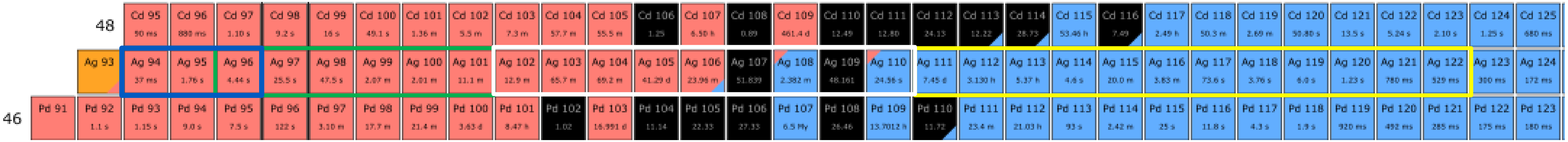
Nuclear structure between Z=40 and Z=50

- IGISOL produces these beams!
- But: developments required
  - CEC, optical pumping, frequency mixing, or a combination of these
- Silver: ongoing
- Palladium: planned July
- Rhodium: likely possible
- Technetium: under investigation



Laser spectroscopy of silver

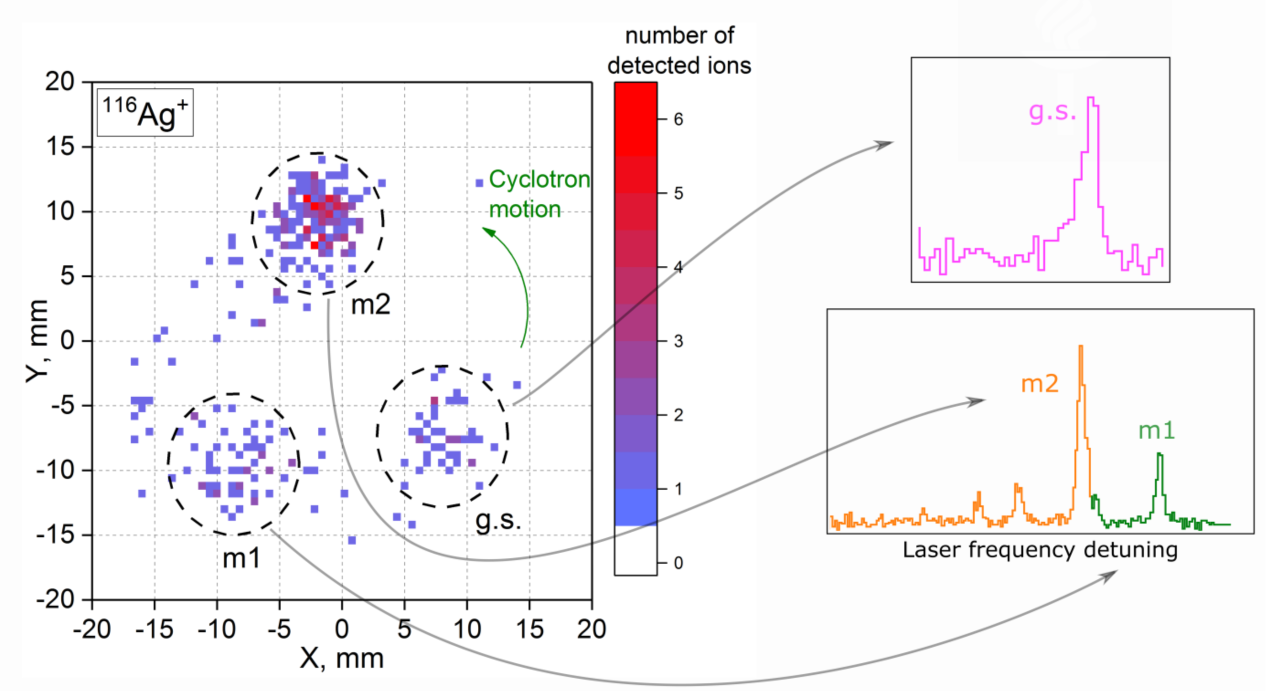
- Cyclotron can produce a variety of beams, so many target-beam combinations possible

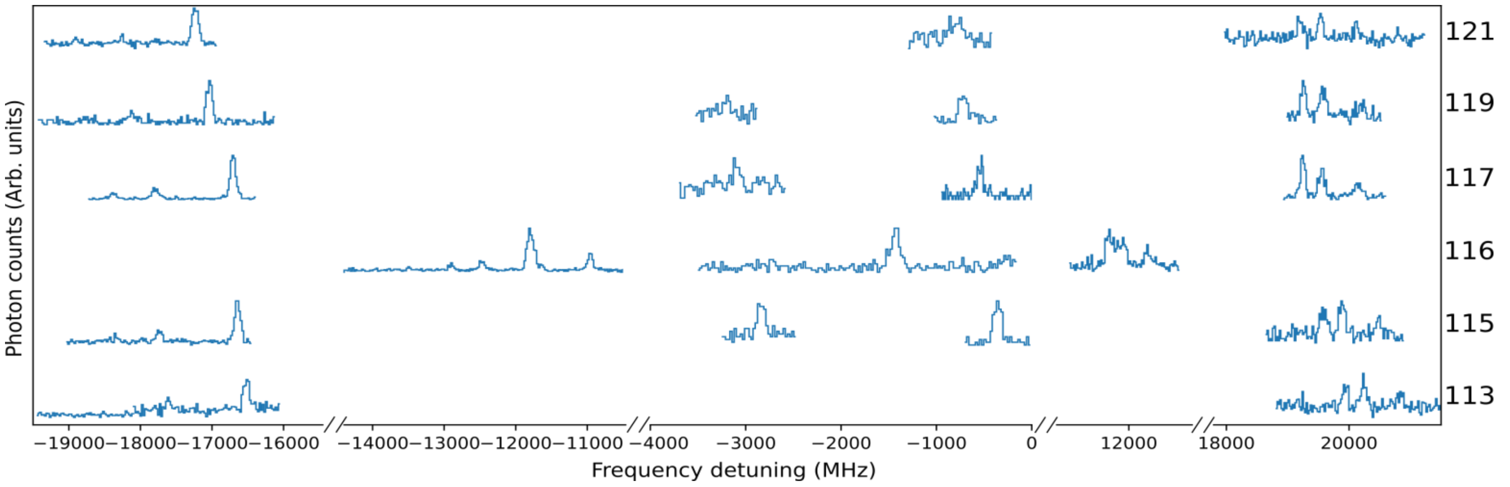


- Collinear laser spectroscopy:
  - ^{nat}Pd(p, xn)Ag ~ $^{100-110}$Ag
  - **p,d-induced fission ~ $^{111-122}$Ag**
- In-source laser spectroscopy
  - **^{nat}Mo, ^{92}Mo(^{14}N,2pxn)Ag ~ $^{98-103}$Ag – we actually did ^{96}Ag!**
  - ^{58}Ni(^{40}Ca,pxn)Ag ~ $^{94-96?}$Ag (few per second?)

Collinear laser spectroscopy of silver

- First online use of CEC at IGISOL
- Isotopes in the range A=113-121
- odd-A: 7/2$^+$ and 1/2$^-$ states
  - Spin assignments firm
- Even-A: more complex, three states in 116,118 observed
  - Firm spin assignments will be hard (analysis ongoing)



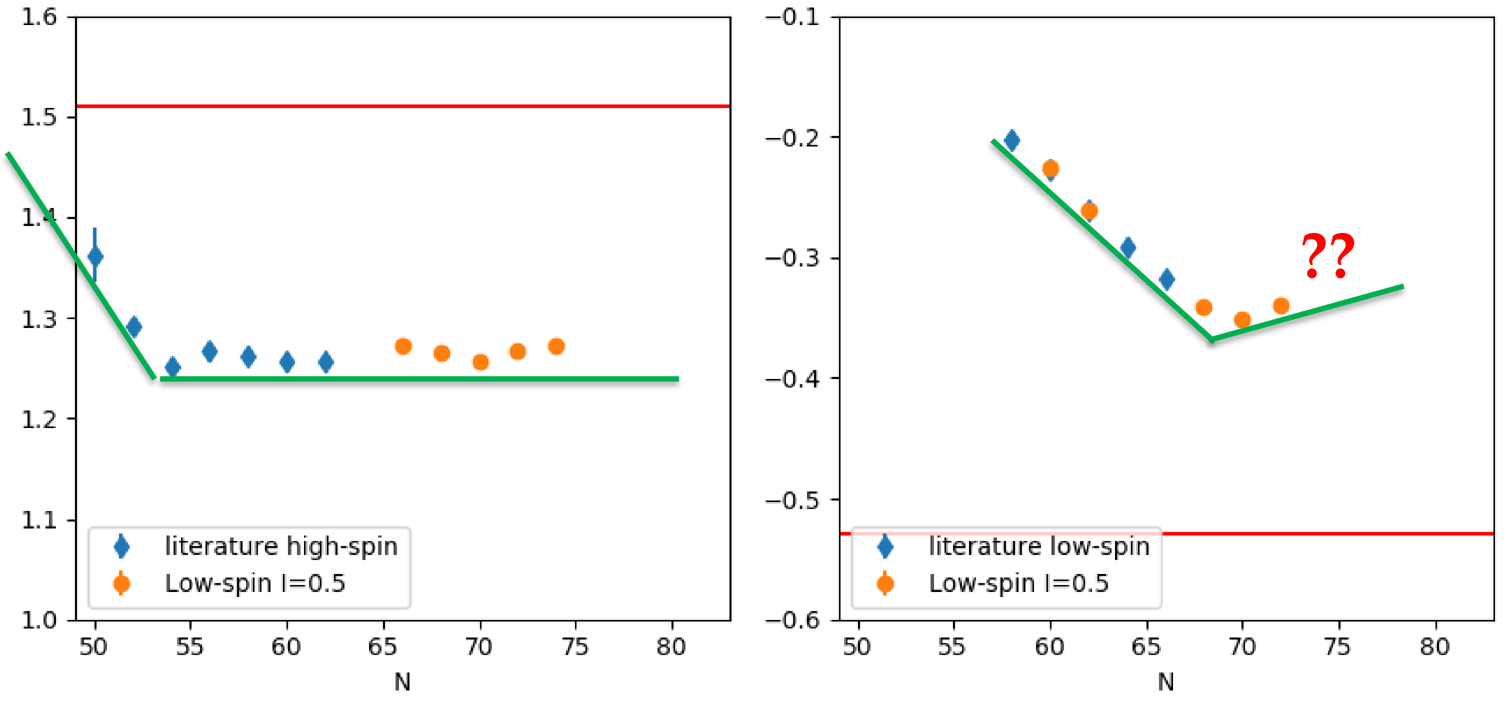


Moments of odd-A isotopes

more data on n-rich isotopes required!
(currently only have partial scan for 121)

G-factors

- ~ constant g-factor for I=7/2 (9/2) states + shell effect towards N=50
- G-factors of spin ½ not constant…
  - Mixing? But $p_{1/2}$ moments are insensitive to first order config mixing…*
  - Similar trend observed for indium (Z=49) I = ½ states

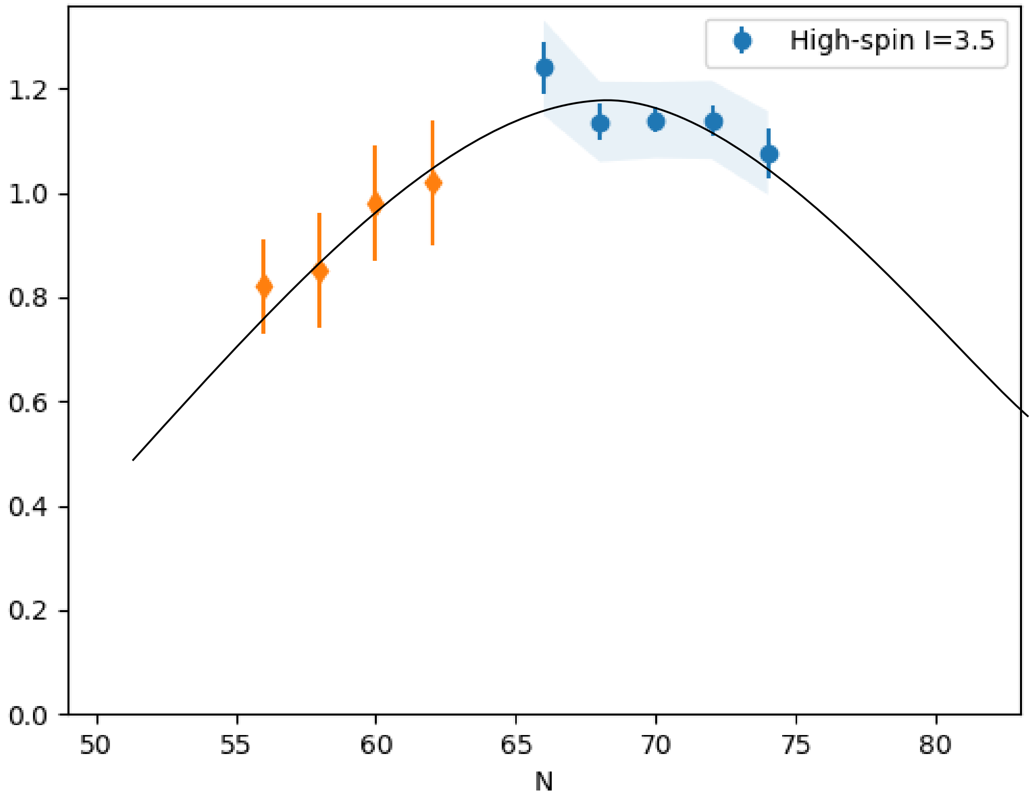


* A. Arima et al., Progress of Theoretical Physics 12, 623–641 (1954).

Moments of odd-A isotopes

Q moments

- Maximum reached near N=70
- Shaded area is systematic error
  - Measurement on ^{107m,109m}Ag would reduce all errors by factor 3 (also literature)
- More n-rich data would be interesting!



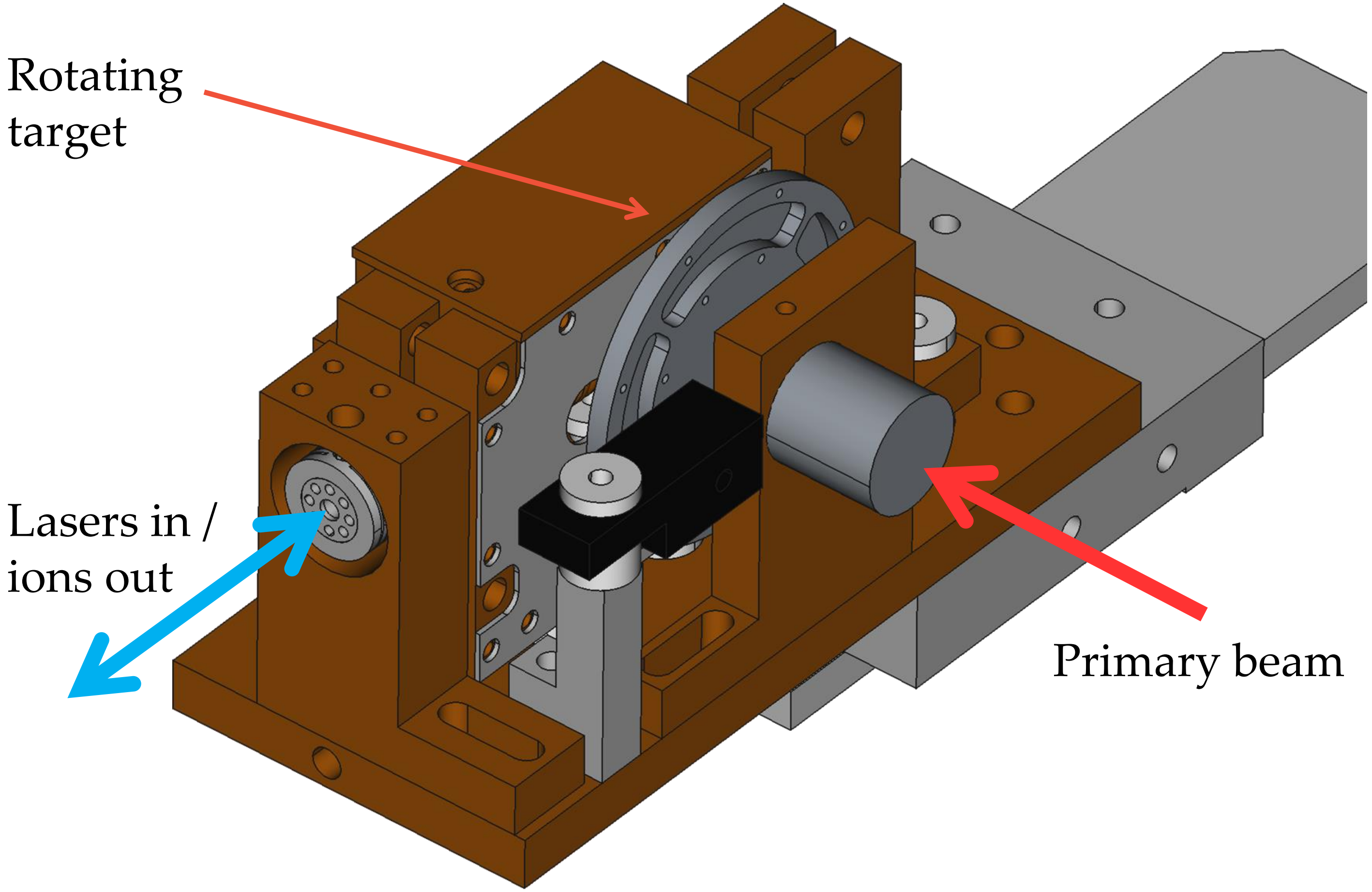
Recent measurements

- Laser spectroscopy of $^{96\text{-}104}Ag$

In-source laser spectroscopy of $^{96\text{-}104}Ag$

An inductively-heated hot cavity graphite catcher

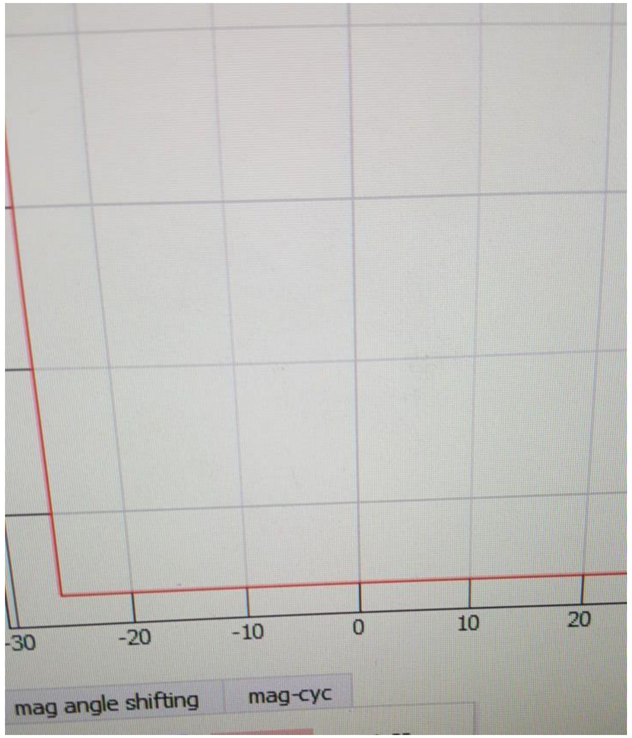
- Laser-ionization
  - **High efficiency**
- Broadband conditions
- Injecting beam into penning traps
  - Ultra-clean (bkg rate <<1/hr)



Based on an upgraded design of M. Reponen et al., Rev. Sci. Instrum. 86 (2015) 123501.

Exciting moments… (pun intended)

- ^{96}Ag



Exciting moments… (pun intended)

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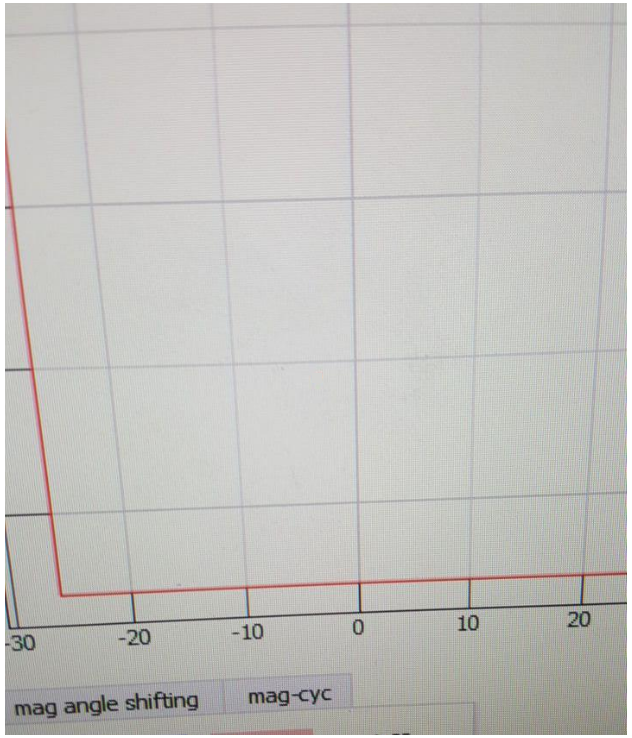
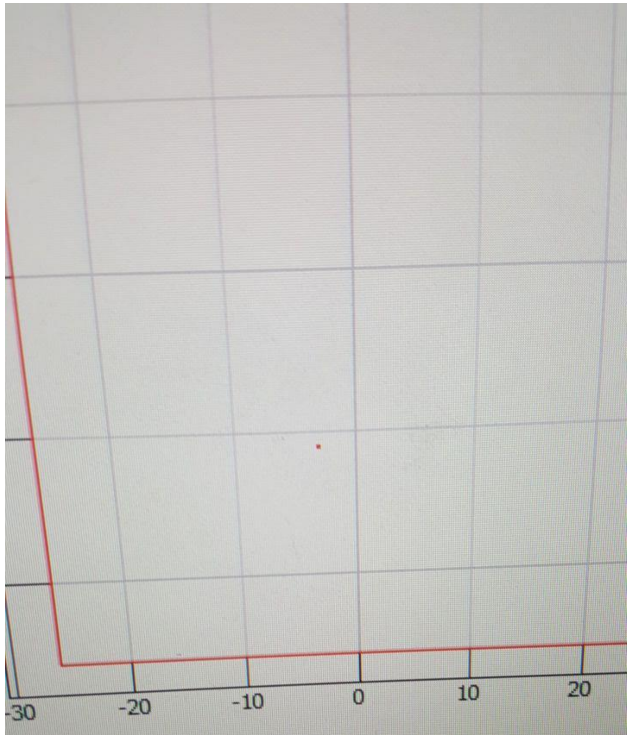
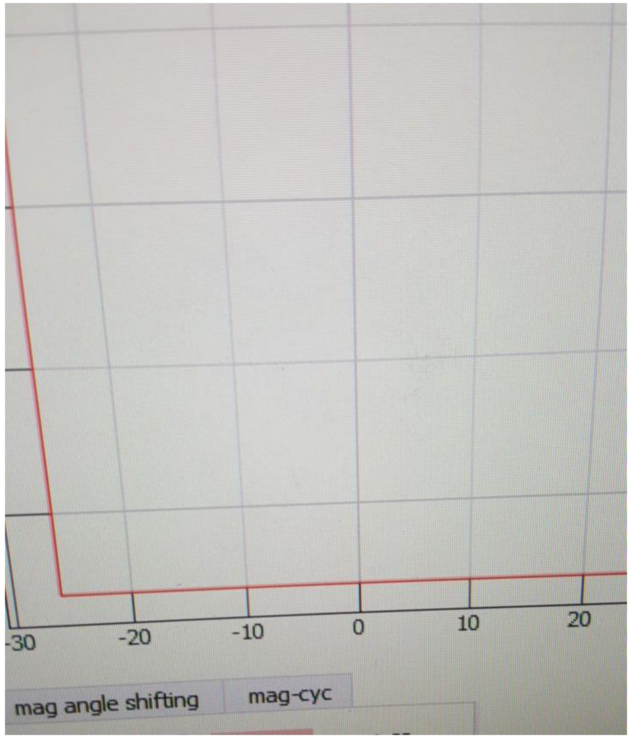
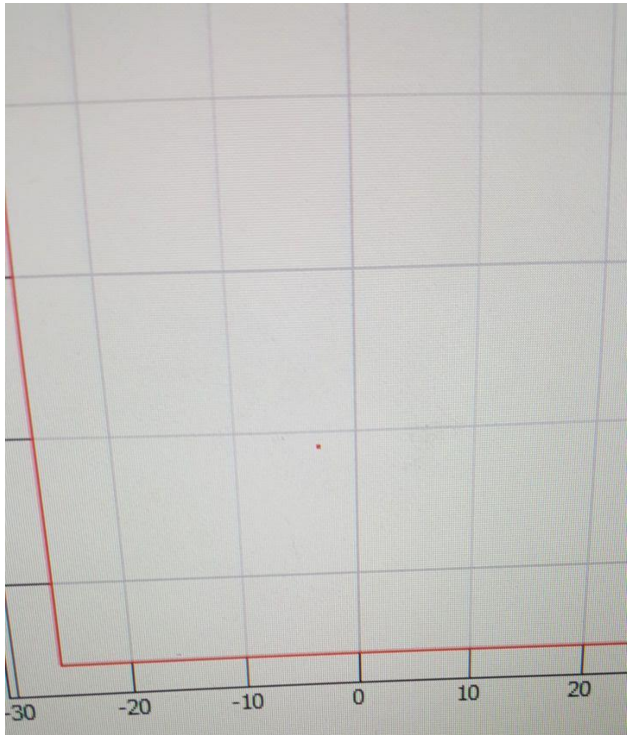


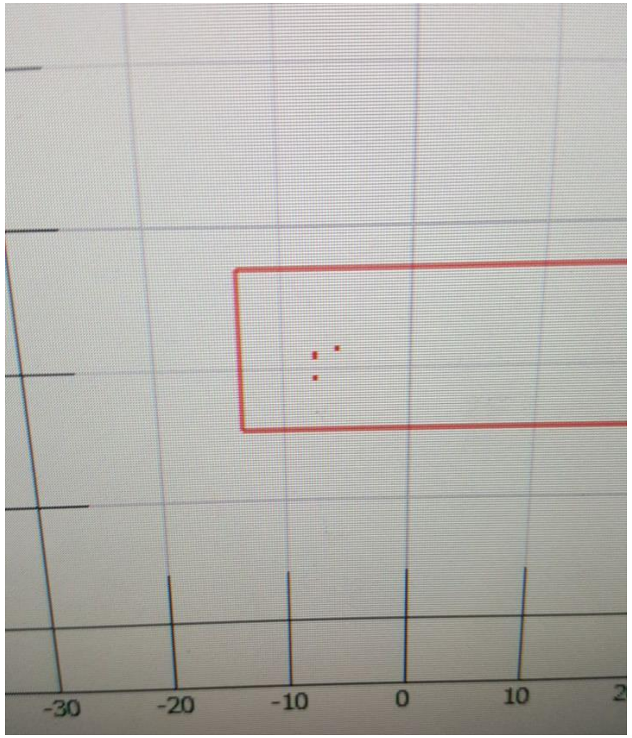


Exciting moments… (pun intended)

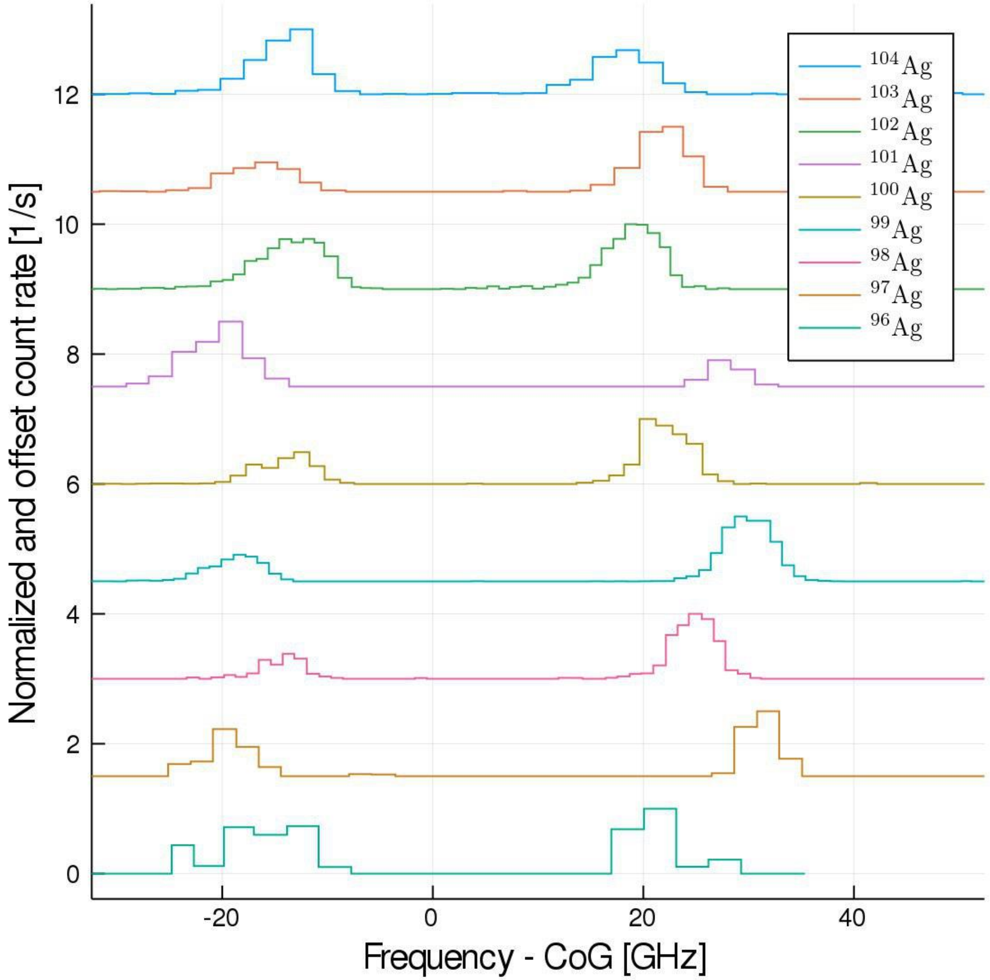
- ^{96}Ag

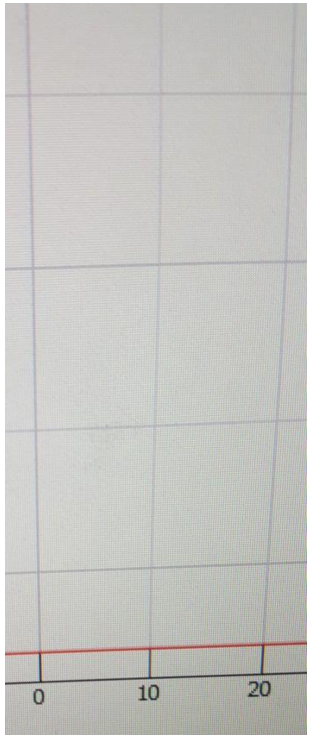


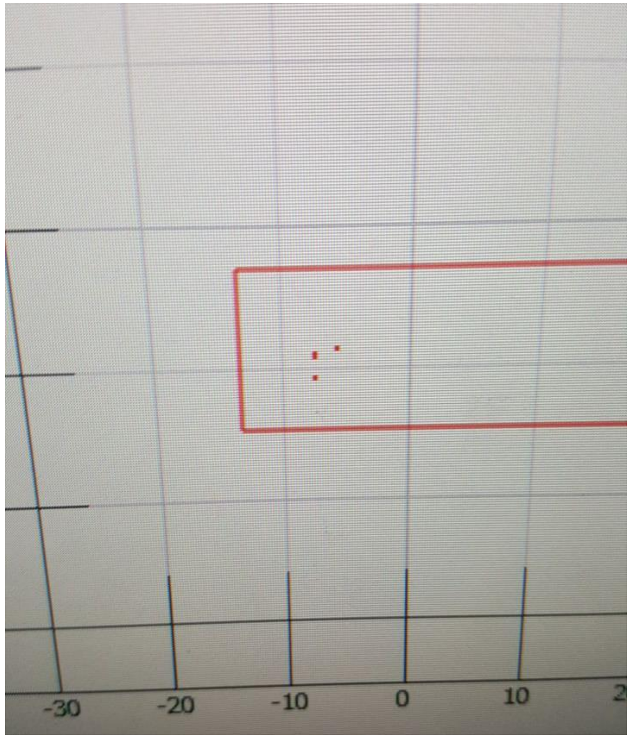




Exciting moments… (pun intended)

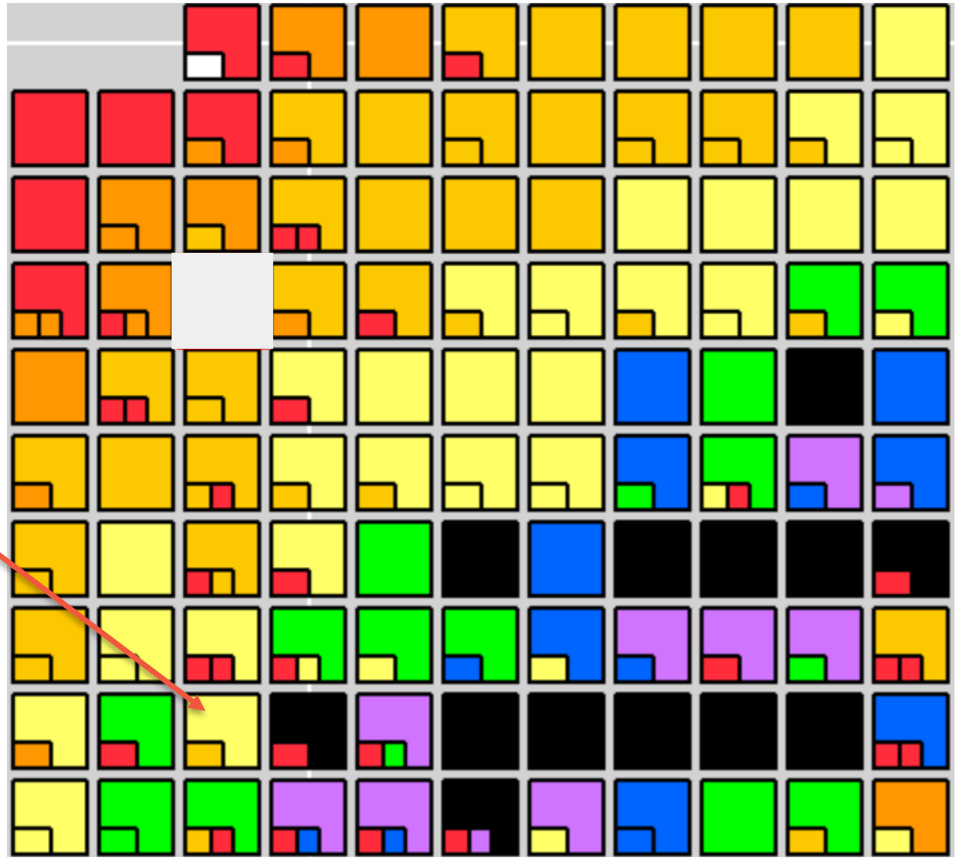






Exciting moments… (pun intended)

- ^{96}Ag
  - Production approx. 5 / 100 s
  - Z=47, N = 49
  - Previous laser spec: heaviest across N=50 was for molybdenum (Z=42…)!!



Upcoming developments and future plans

New opportunities

Some elements we can access, so far totally unexplored:

Light-ion fusion evaporation

p-induced fission

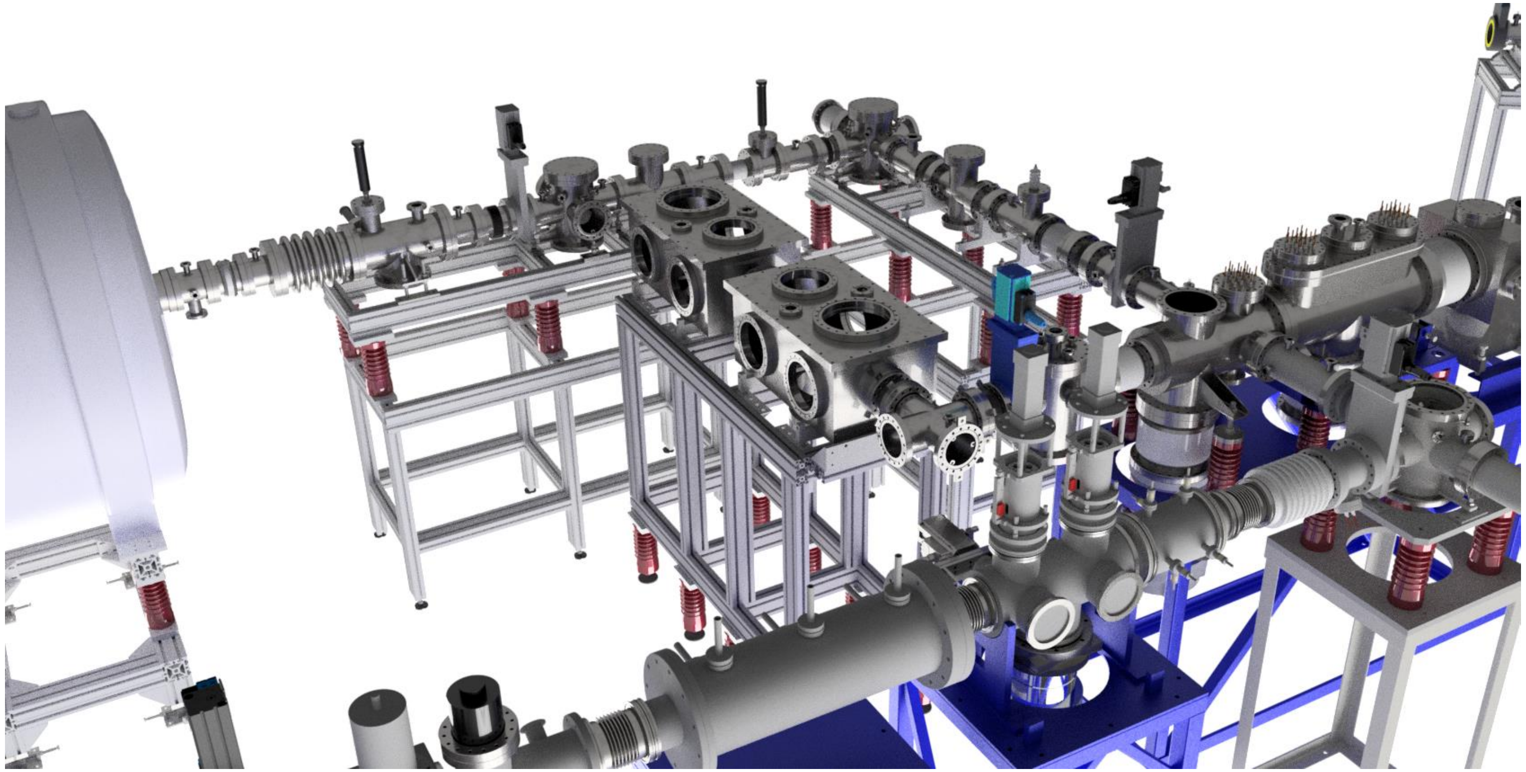
Experiment end of July

		Sn 99	Sn 100	Sn 101	Sn 102	Sn 103	Sn 104	Sn 105	Sn 106	Sn 107	Sn 108	Sn 109	Sn 110	Sn 111	Sn 112	Sn 113	Sn 114	Sn 115	Sn 116	Sn 117	Sn 118	Sn 119	Sn 120	Sn 121	Sn 122	Sn 123	Sn 124	Sn 125	Sn 126
	In 97	In 98	In 99	In 100	In 101	In 102	In 103	In 104	In 105	In 106	In 107	In 108	In 109	In 110	In 111	In 112	In 113	In 114	In 115	In 116	In 117	In 118	In 119	In 120	In 121	In 122	In 123	In 124	In 125
Cd 95	Cd 96	Cd 97	Cd 98	Cd 99	Cd 100	Cd 101	Cd 102	Cd 103	Cd 104	Cd 105	Cd 106	Cd 107	Cd 108	Cd 109	Cd 110	Cd 111	Cd 112	Cd 113	Cd 114	Cd 115	Cd 116	Cd 117	Cd 118	Cd 119	Cd 120	Cd 121	Cd 122	Cd 123	Cd 124
Ag 94	Ag 95	Ag 96	Ag 97	Ag 98	Ag 99	Ag 100	Ag 101	Ag 102	Ag 103	Ag 104	Ag 105	Ag 106	Ag 107	Ag 108	Ag 109	Ag 110	Ag 111	Ag 112	Ag 113	Ag 114	Ag 115	Ag 116	Ag 117	Ag 118	Ag 119	Ag 120	Ag 121	Ag 122	Ag 123
Pd 93	Pd 94	Pd 95	Pd 96	Pd 97	Pd 98	Pd 99	Pd 100	Pd 101	Pd 102	Pd 103	Pd 104	Pd 105	Pd 106	Pd 107	Pd 108	Pd 109	Pd 110	Pd 111	Pd 112	Pd 113	Pd 114	Pd 115	Pd 116	Pd 117	Pd 118	Pd 119	Pd 120	Pd 121	Pd 122
Rh 92	Rh 93	Rh 94	Rh 95	Rh 96	Rh 97	Rh 98	Rh 99	Rh 100	Rh 101	Rh 102	Rh 103	Rh 104	Rh 105	Rh 106	Rh 107	Rh 108	Rh 109	Rh 110	Rh 111	Rh 112	Rh 113	Rh 114	Rh 115	Rh 116	Rh 117	Rh 118	Rh 119	Rh 120	Rh 121
Ru 91	Ru 92	Ru 93	Ru 94	Ru 95	Ru 96	Ru 97	Ru 98	Ru 99	Ru 100	Ru 101	Ru 102	Ru 103	Ru 104	Ru 105	Ru 106	Ru 107	Ru 108	Ru 109	Ru 110	Ru 111	Ru 112	Ru 113	Ru 114	Ru 115	Ru 116	Ru 117	Ru 118	Ru 119	Ru 120
Tc 90	Tc 91	Tc 92	Tc 93	Tc 94	Tc 95	Tc 96	Tc 97	Tc 98	Tc 99	Tc 100	Tc 101	Tc 102	Tc 103	Tc 104	Tc 105	Tc 106	Tc 107	Tc 108	Tc 109	Tc 110	Tc 111	Tc 112	Tc 113	Tc 114	Tc 115	Tc 116	Tc 117	Tc 118	Tc 119
Mo 89	Mo 90	Mo 91	Mo 92	Mo 93	Mo 94	Mo 95	Mo 96	Mo 97	Mo 98	Mo 99	Mo 100	Mo 101	Mo 102	Mo 103	Mo 104	Mo 105	Mo 106	Mo 107	Mo 108	Mo 109	Mo 110	Mo 111	Mo 112	Mo 113	Mo 114	Mo 115	Mo 116	Mo 117	
Nb 88	Nb 89	Nb 90	Nb 91	Nb 92	Nb 93	Nb 94	Nb 95	Nb 96	Nb 97	Nb 98	Nb 99	Nb 100	Nb 101	Nb 102	Nb 103	Nb 104	Nb 105	Nb 106	Nb 107	Nb 108	Nb 109	Nb 110	Nb 111	Nb 112	Nb 113	Nb 114	Nb 115		
Zr 87	Zr 88	Zr 89	Zr 90	Zr 91	Zr 92	Zr 93	Zr 94	Zr 95	Zr 96	Zr 97	Zr 98	Zr 99	Zr 100	Zr 101	Zr 102	Zr 103	Zr 104	Zr 105	Zr 106	Zr 107	Zr 108	Zr 109	Zr 110	Zr 111	Zr 112				

Ag
Pd
Rh
Ru
Tc

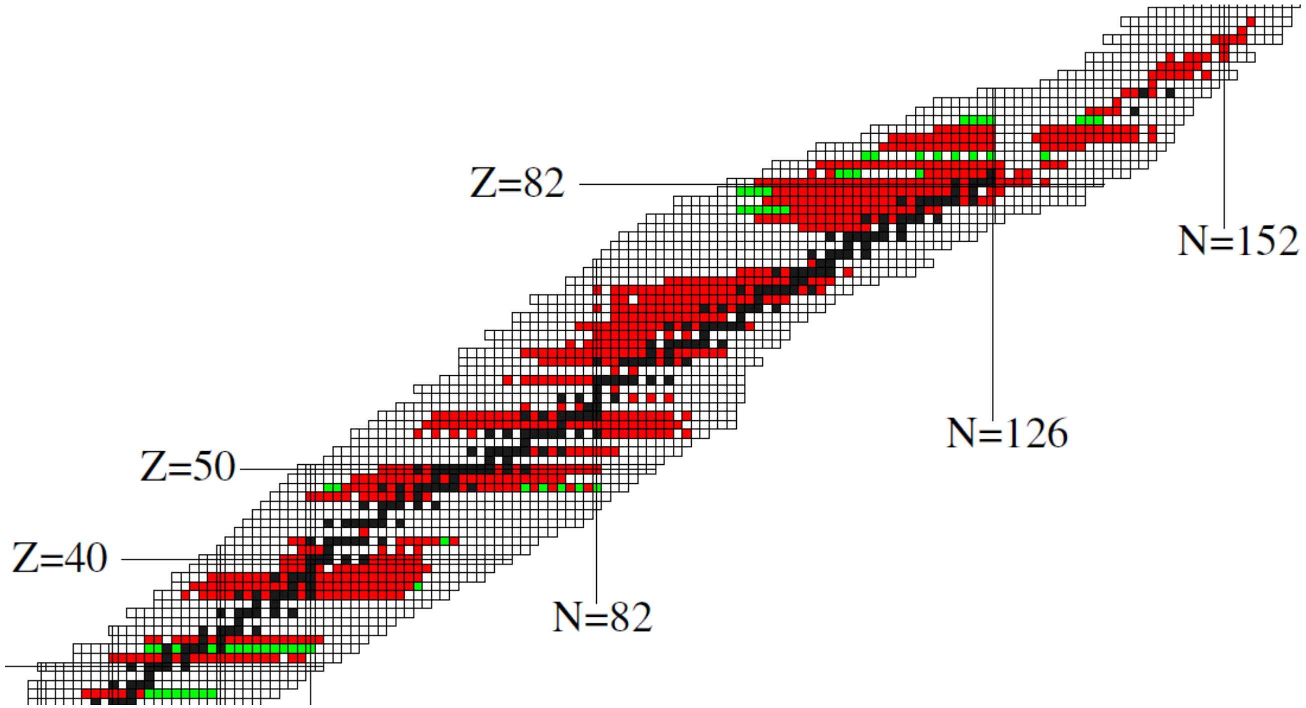
RIS And Purification Traps for Optimized spectRoscopy (RAPTOR)

- Low-energy, medium resolution RIS
- Goal: refractory isotopes, actinides
  - Large HFS, complex atomic structures
- Long-term goal: injection into penning traps



In conclusion

- IGISOL 4 has a broad physics programme planned
  - Refractory isotopes Z~45, Actinides (Z>92), Fe, Co, …
- Versatile tool of optical methods
  - Collinear laser spectroscopy (CEC, in-cooler optical pumping)
  - Hot-cavity ion sources
- More developments are always needed!
  - Cone trap, MR-TOF for in-vacuum optical pumping
  - Laser spectroscopy in cooler-buncher?
  - RAPTOR



Thanks!

I. D. Moore

M. Reponen

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S. Geldhof

B. Cheal

C. Devlin

P. Campbell

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MANCHESTER 1824
The University of Manchester

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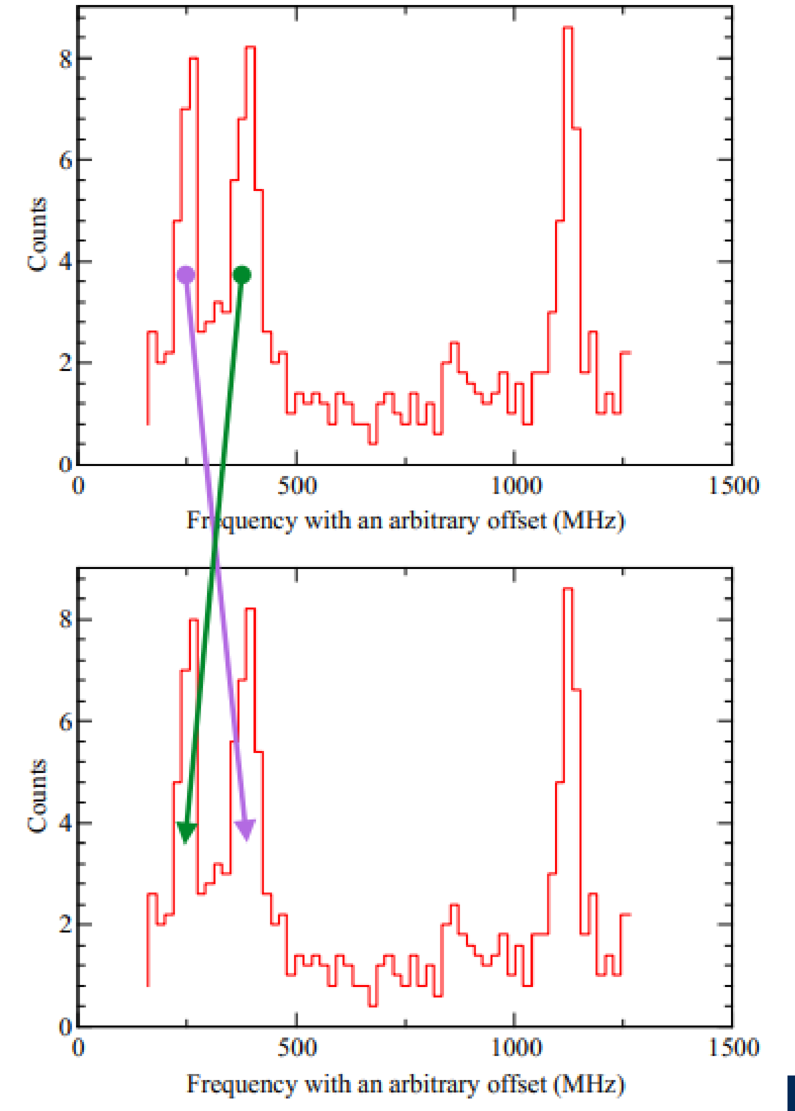
$$Q_0 \approx \frac{5Z\langle r^2\rangle_{\mathrm{sph}}}{\sqrt{5\pi}}\langle\beta_2\rangle\left(1+0.36\langle\beta_2\rangle\right)$$

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

Laser spectroscopy of yttrium

- Status in 2007:
  - (weak) oblate to (strong) prolate
  - ^{98}Y is at the center point of this transition
  - ^{98m}Y is somewhat soft
  - BUT: limited by J=0 to J=1 transition
    - → No sensitivity to spin
    - → No way to tell how these two peaks should be interpreted



Odd-A isotopes: isomers everywhere

- ^{116}Ag:
  - Three states in literature
  - Laser- and mass spectroscopy done together!

- ^{118}Ag:
  - Three states found with lasers, two with PI-ICR
    - → Third state short-lived? Low-lying?