Fundamental properties of heavy nuclei studied with laser spectroscopy

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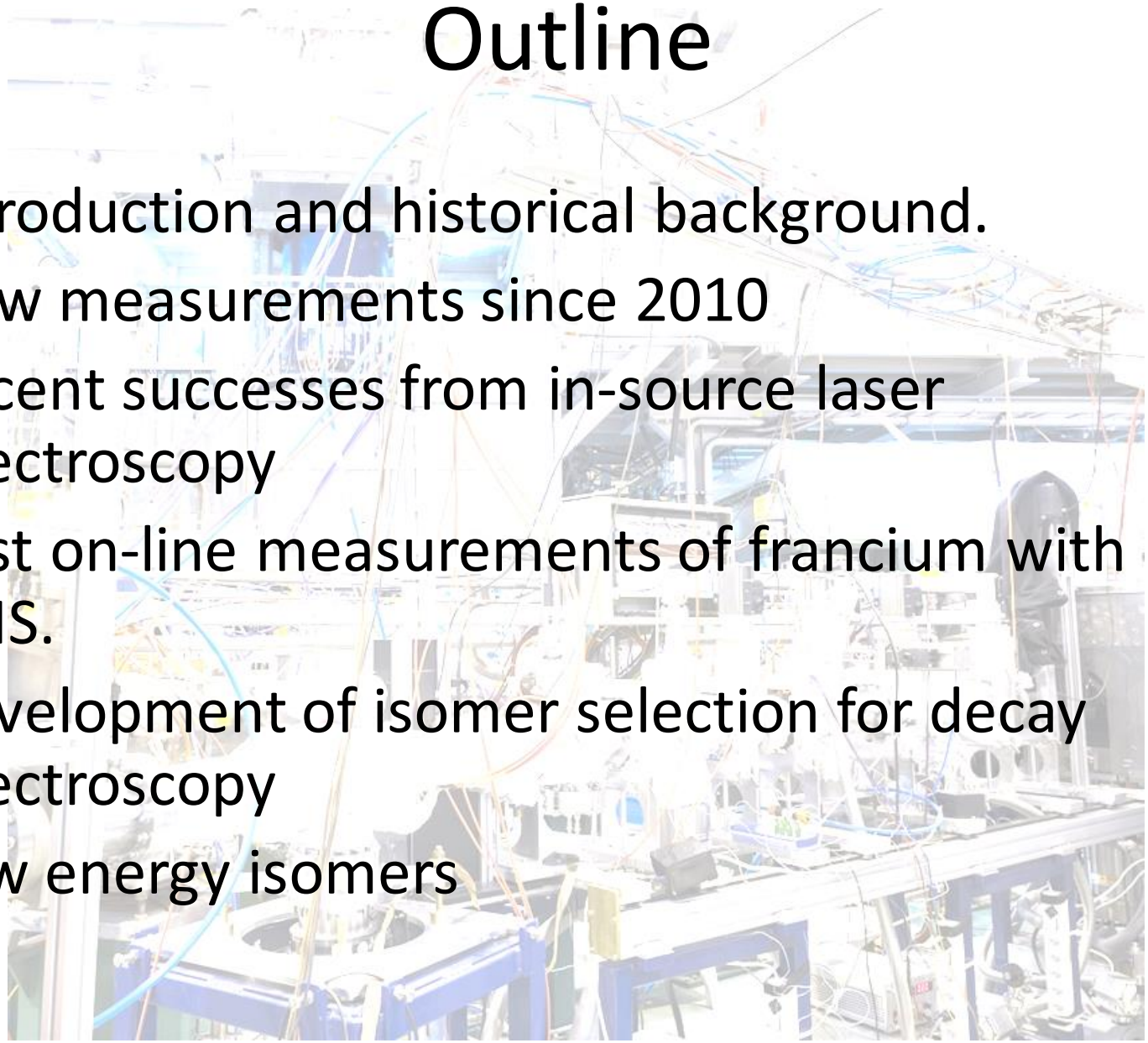
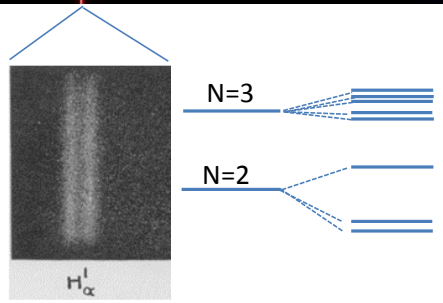
Outline

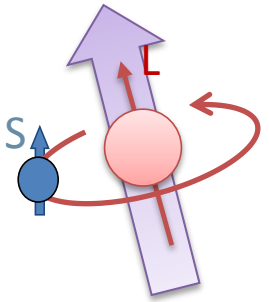
- Introduction and historical background.
- New measurements since 2010
- Recent successes from in-source laser spectroscopy
- First on-line measurements of francium with CRIS.
- Development of isomer selection for decay spectroscopy
- Low energy isomers



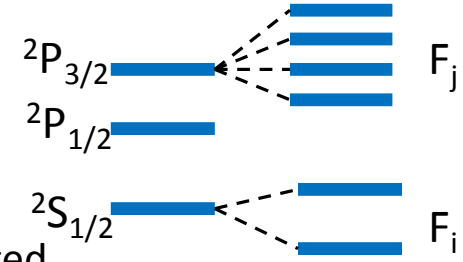
Atomic spectroscopy for nuclear physics

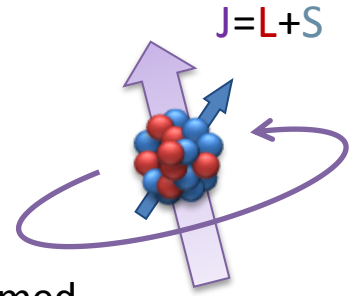
• By increasing the resolution by a factor of ~5000 a fine structure splitting of the hydrogen is observed: key evidence for the spin of the electron.





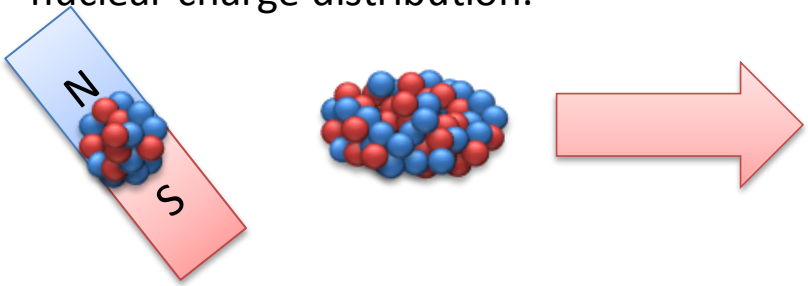
•A further factor of 1000 zoom into the structure reveals finer splitting due to the coupling of the nucleus with the electronic orbital: the hyperfine structure.





•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.

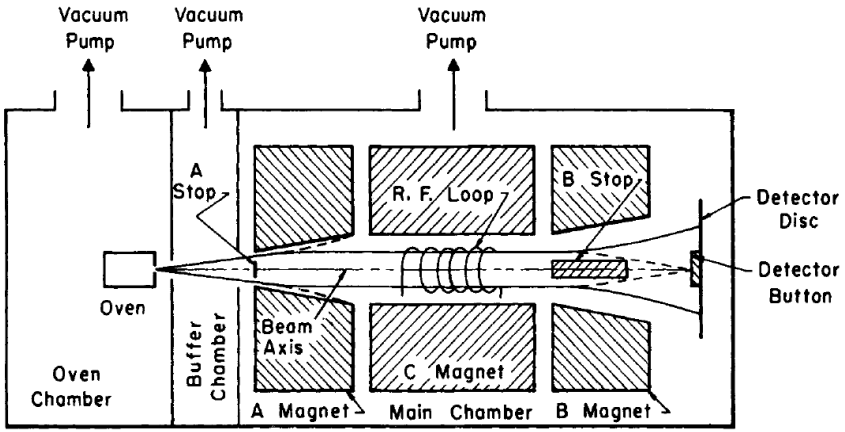
F=J+I



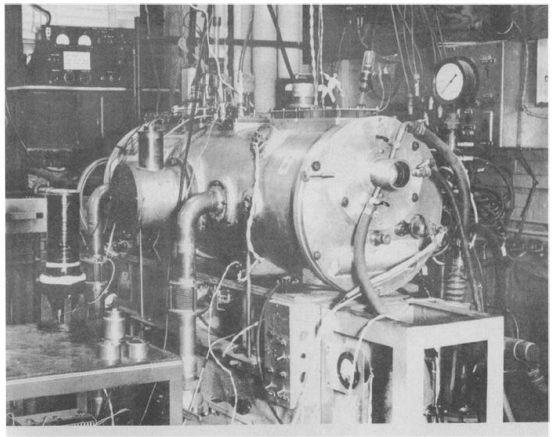
If we can measure the splitting of the atomic transitions with sufficient resolution it is possible to deduce the nuclear observables (magnetic and electric moments, spin and size) without any model (nuclear) dependence.

Progress in atomic spectroscopy of unstable nuclei

- 1952: 13 Unstable isotopes measured
- 5 techniques: ABMR, rf nuclear resonance, paramagnetic resonance, microwave molecular rotation and optical spectroscopy. Samples "As low as 10^{14} atoms"
- 1957: 63 Unstable Isotopes measured with samples as low as 10^{10} atoms and half-lives down to 30 mins (ABMR) leading the way
- 1956 Group Lead by DR Hamilton at Princeton ^{198,199}Au (group includes a postdoc with a familiar name at ISOLDE: HH Stroke)

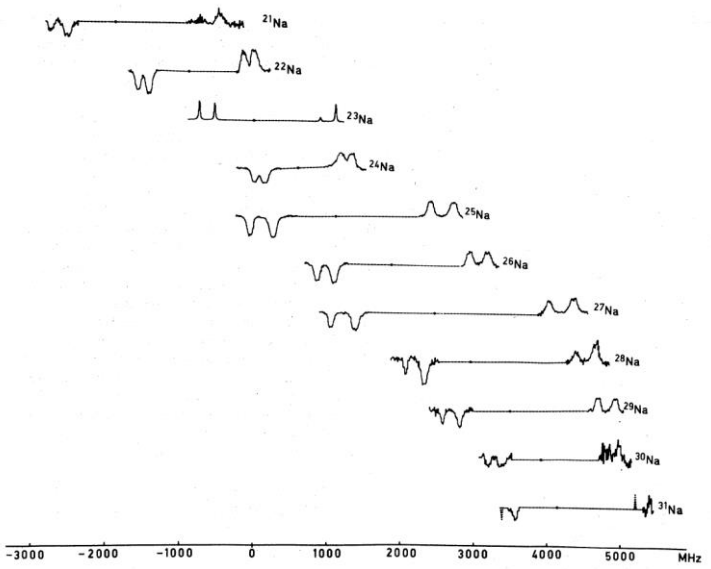


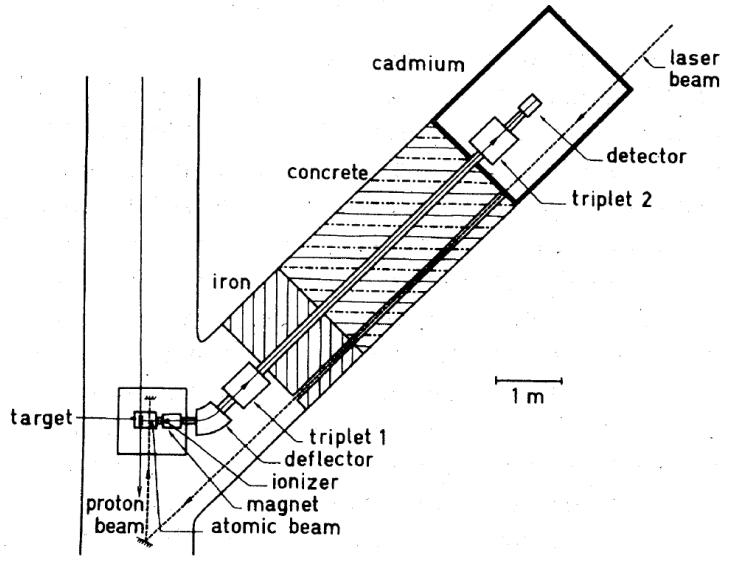
ATOMIC BEAM APPARATUS



The paradigm shift in atomic spectroscopy of unstable isotopes

- 1987: 400 radioactive isotopes have been measured by optical techniques
- On-line facilities developed in the 1960s (first demonstrated 1951)
- Between 1972 and 1978 there was a paradigm shift with the development of tunable narrow-bandwidth (<1MHz) lasers.
- 1978 ^{31}Na measured with 3 counts/proton pulse and t1/2 17ms (5 orders of magnitude shorter half-life!)





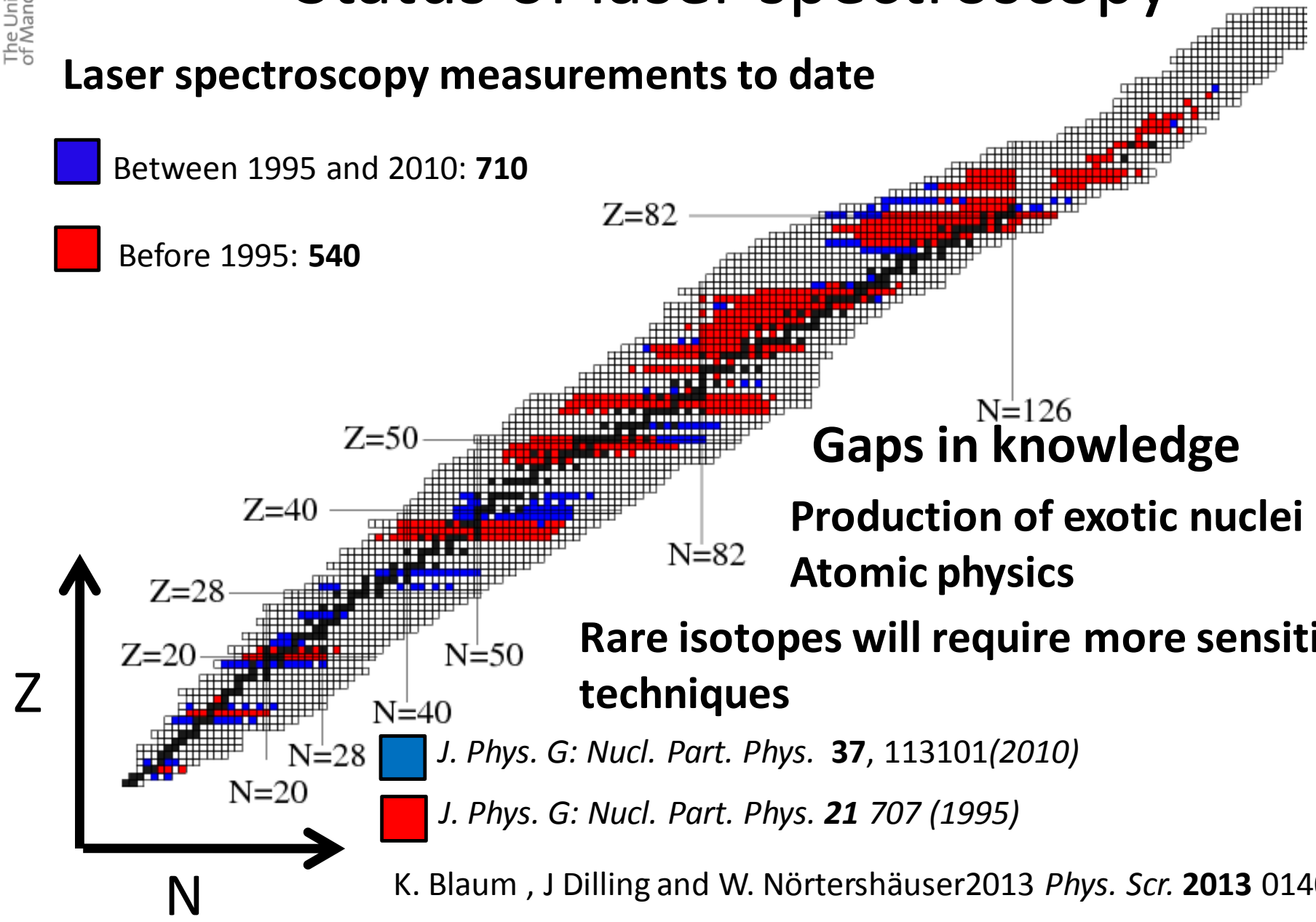
G Huber et al. Phys. Rev. C 18, 2342–2354 (1978)

Status of laser spectroscopy

Laser spectroscopy measurements to date

Between 1995 and 2010: **710**

Before 1995: **540**



Gaps in knowledge

Production of exotic nuclei

Atomic physics

Rare isotopes will require more sensitive techniques

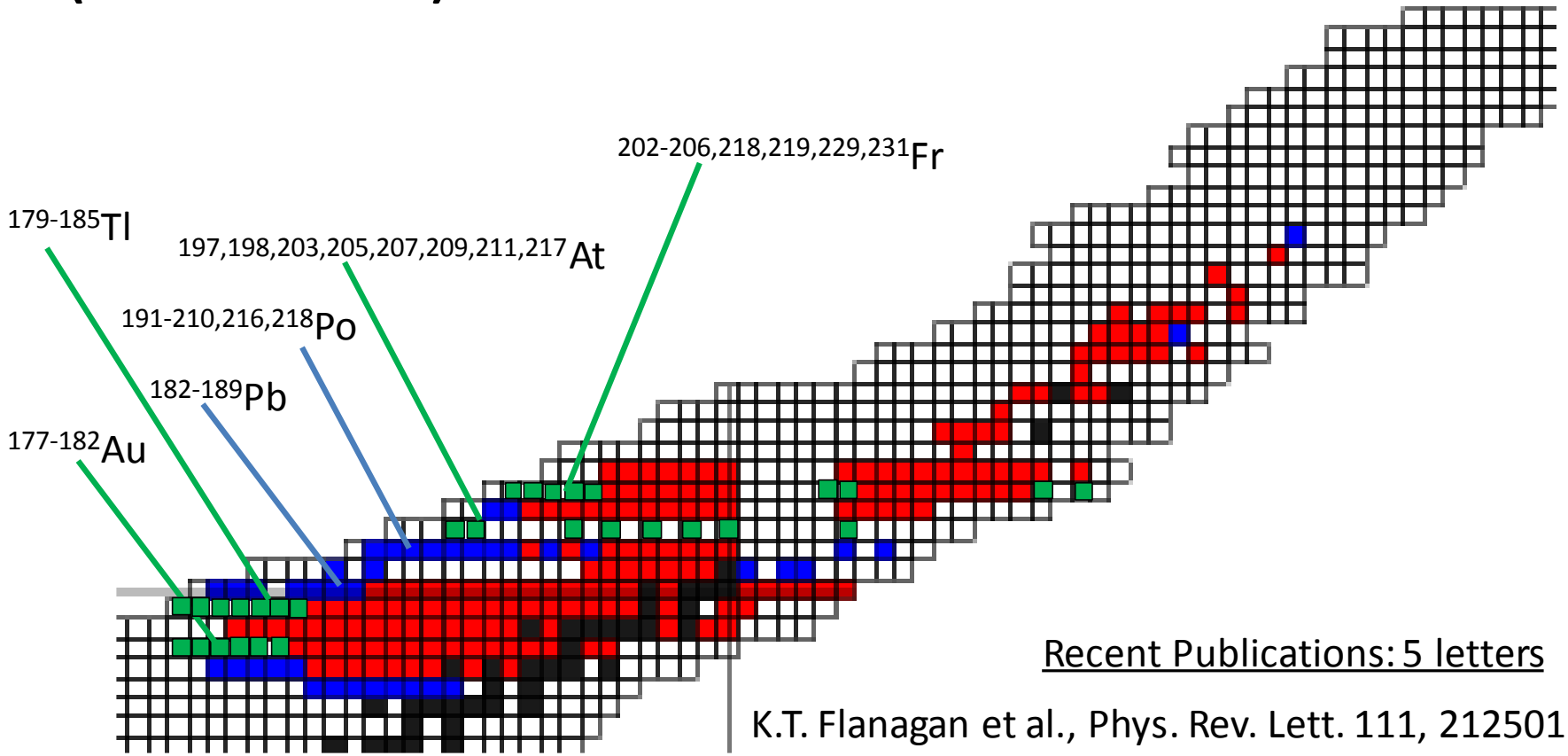
J. Phys. G: Nucl. Part. Phys. **37**, 113101*(2010)*

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

K. Blaum , J Dilling and W. Nörtershäuser2013 *Phys. Scr.* **2013** 014017

New optical measurements since 2010

(not exhaustive)



Recent Publications: 5 letters

K.T. Flanagan et al., Phys. Rev. Lett. 111, 212501 (2013)

A. Voss et al., Phys. Rev. Lett. 111, 122501 (2013)

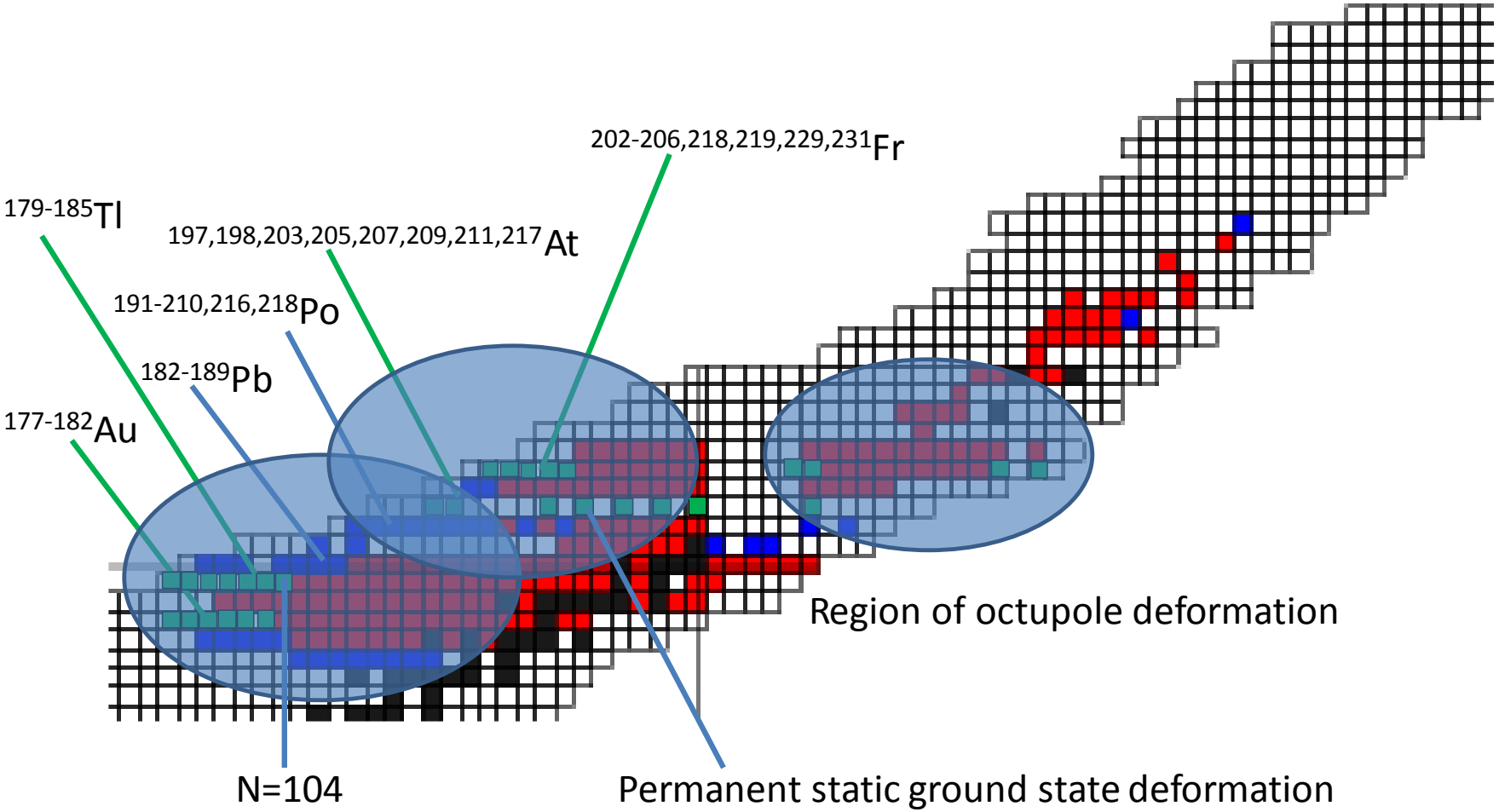
A. E. Barzakh et al.,Phys. Rev. C 88, 024315 (2013)

MD Seliverstov et al., Phys. Lett. B 719, 362 (2013)

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

H. De Witte et al., Phys. Rev. Lett. 98, 112502 (2007)

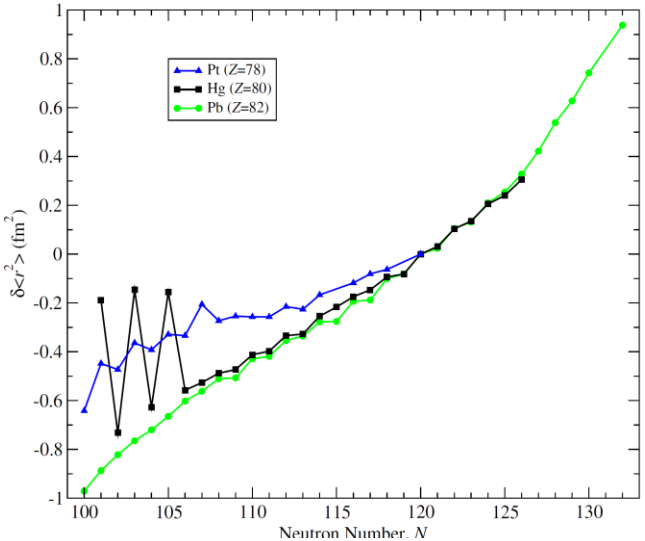
Nuclear physics considerations

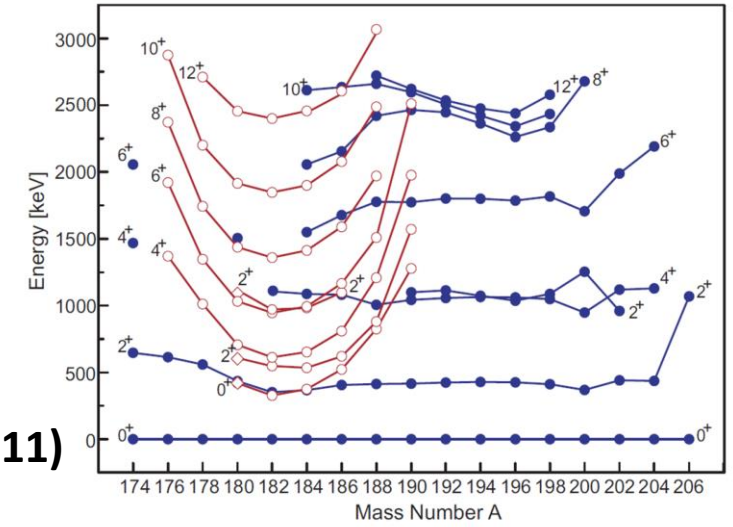


Shape Coexistence
Intruder States

First evidence of shape coexistence in the lead region

- Large odd-even staggering observed in Hg between 183,185Hg and 187Hg (J. Bonn et al, PLB38 , 308 (1972))
- Mechanism driving this huge odd-even staggering was elucidated by in-beam spectroscopy and decay scheme spectroscopy, these measurements revealed excited 0+ states with rotational bands built upon them.
- These deformed states showed a systematic c intrusion with decreasing N reaching a minimum at the mid-shell N=104

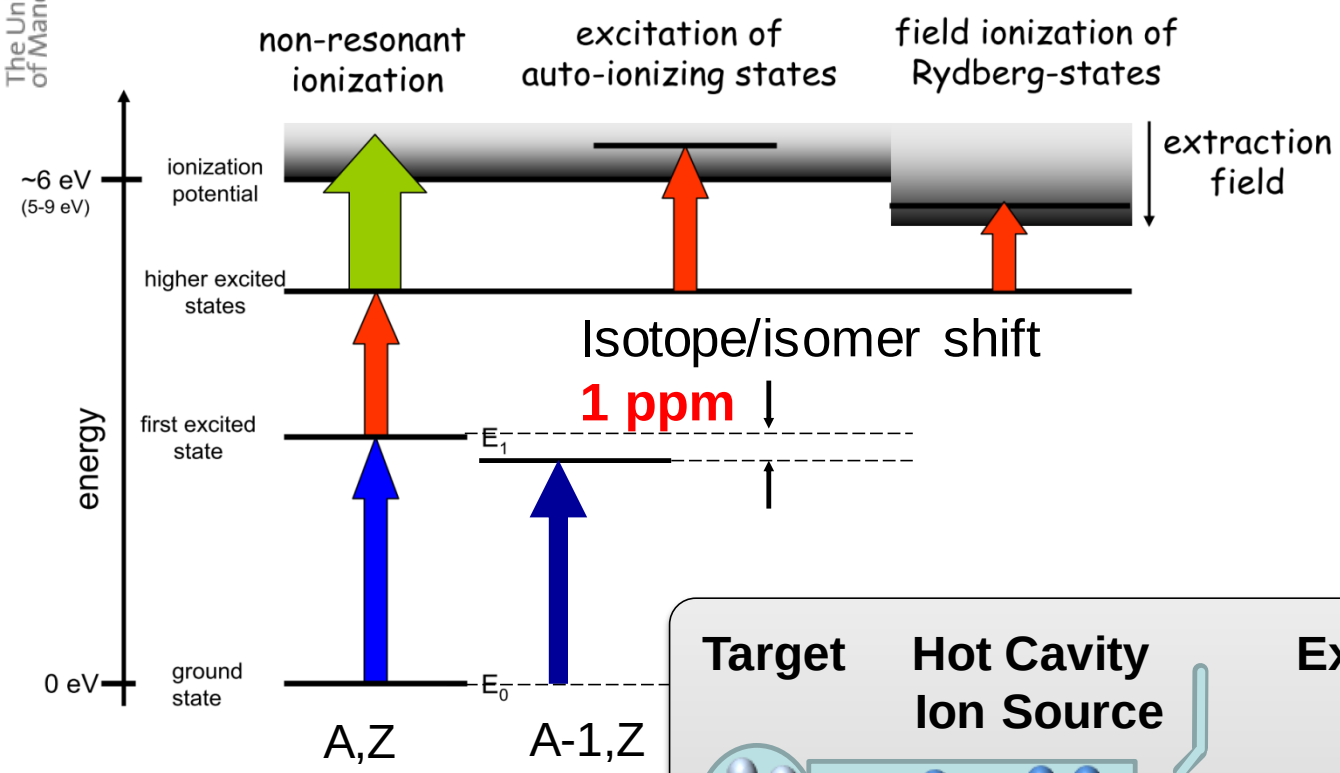




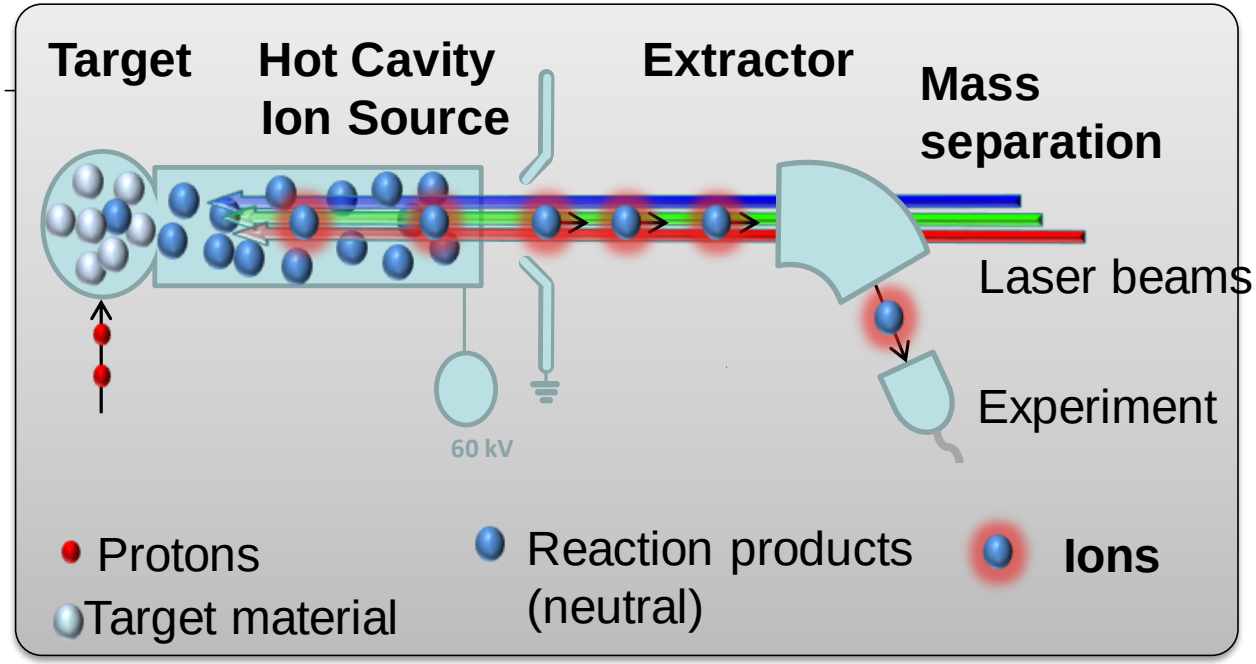
J. Elseviers et al. PRC 84 (2011) 034307

K. Heyde and J. L. Wood Rev. Mod. Phys. 83, 1467 (2011)

In-source laser spectroscopy



Scanning the laser frequency of the first/second step - selective ionisation of a particular isotope (or an isomer)

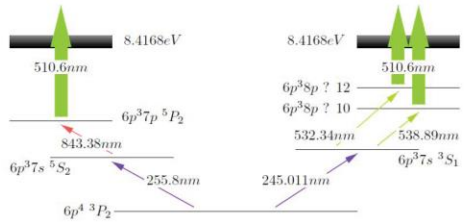


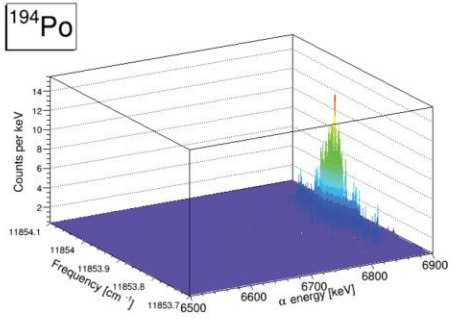
Measuring a/g or ToF spectra while scanning the frequency

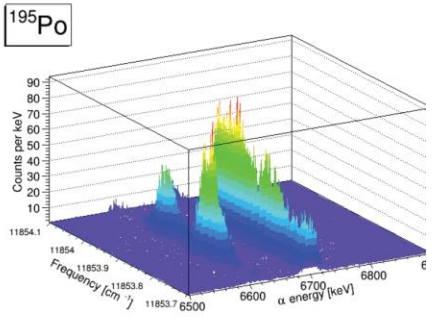
Courtesy A. Andreyev and A. Barakh, IS534 collaboration

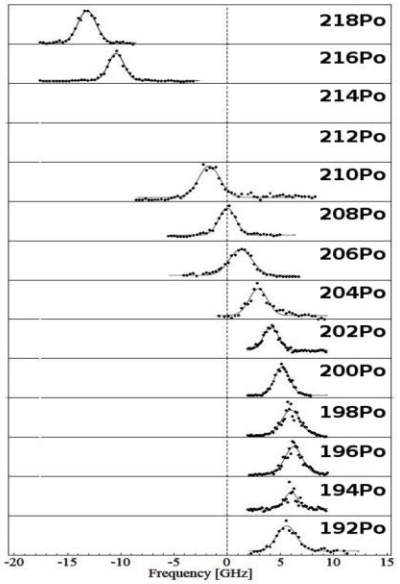
In-source laser spectroscopy of Po

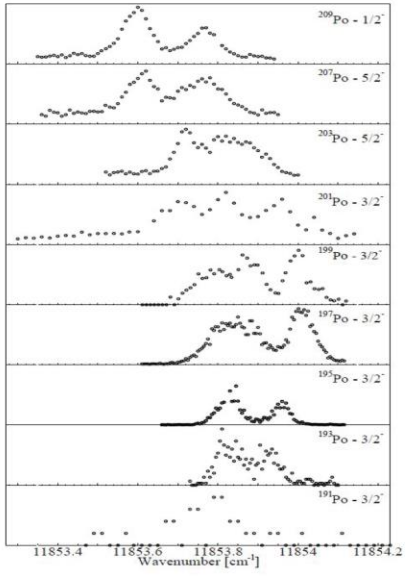
T.E. Cocolios, B.A. Marsh et al., NIMB 266 (2008) 4403.

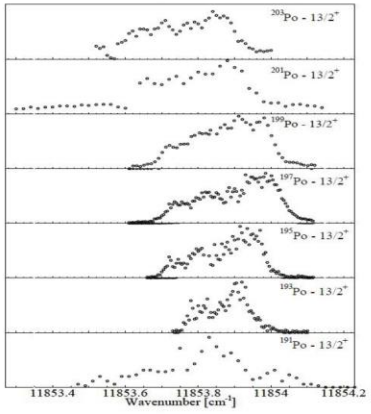












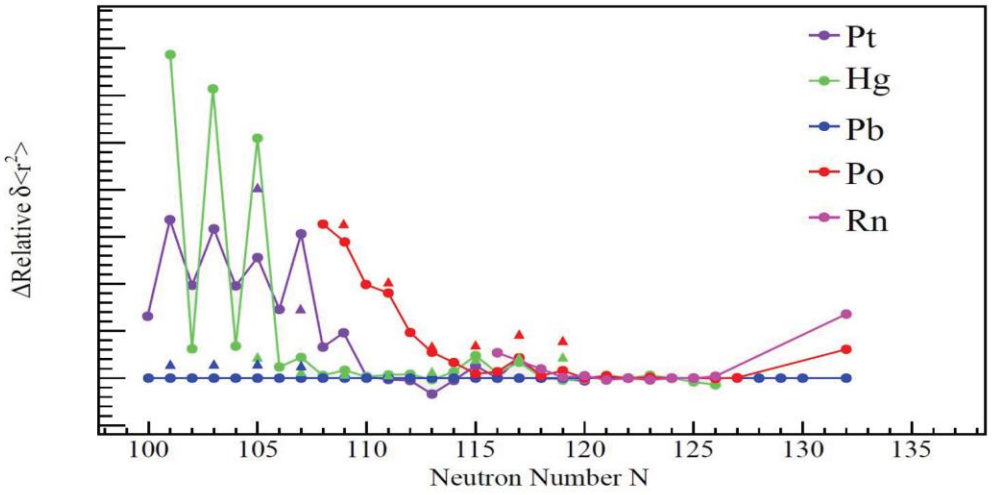
T.E. Cocolios et al., PRL 106 (2011) 052503.

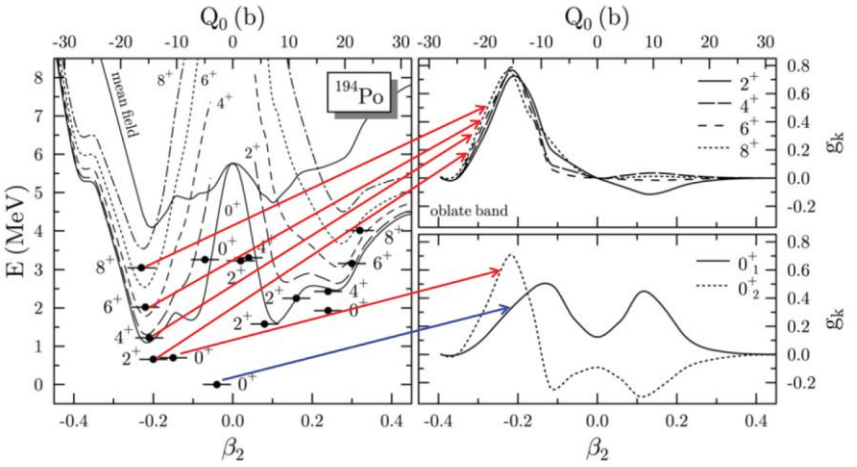
M.D. Seliverstov et al., PLB 719 (2013) 362.

Courtesy T.E. Cocolios

Depature from a spherical description

- While Pb follows a spherical description, Po departs early from FRDM and spherical mean field predictions.
- BMF calculations reproduce the trend in Po and point towards an ill-defined shape which remains spherical on average.
- However since $\delta\langle r^2\rangle$ is only sensitive to rms deformation it is difficult to draw conclusions directly and measurement of the quadrupole moments is required.





T. Duguet et al., PLB 559, 201 (2003)
M. Bender et al., PRC 78 054312 (2008)

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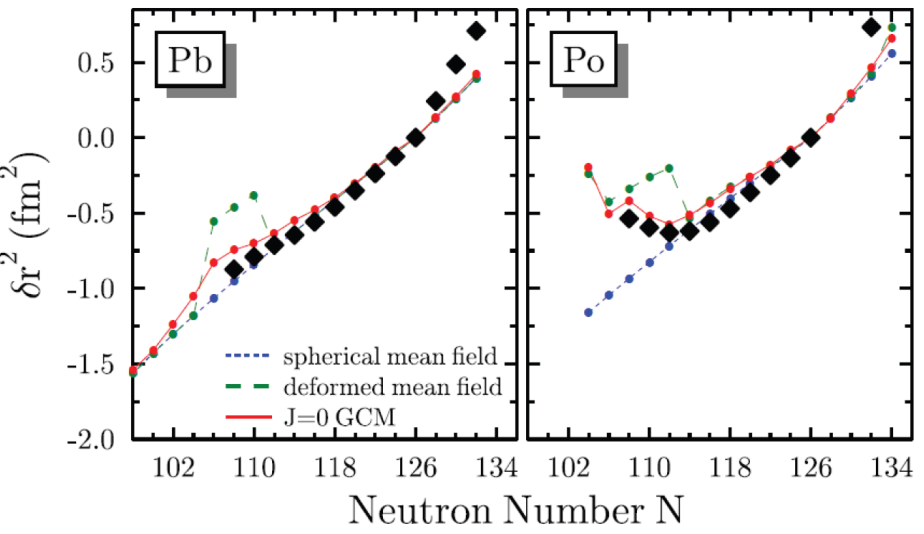

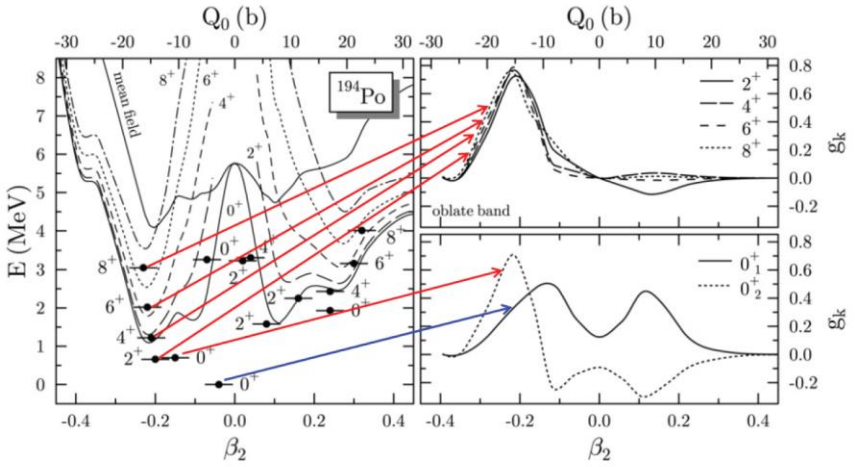

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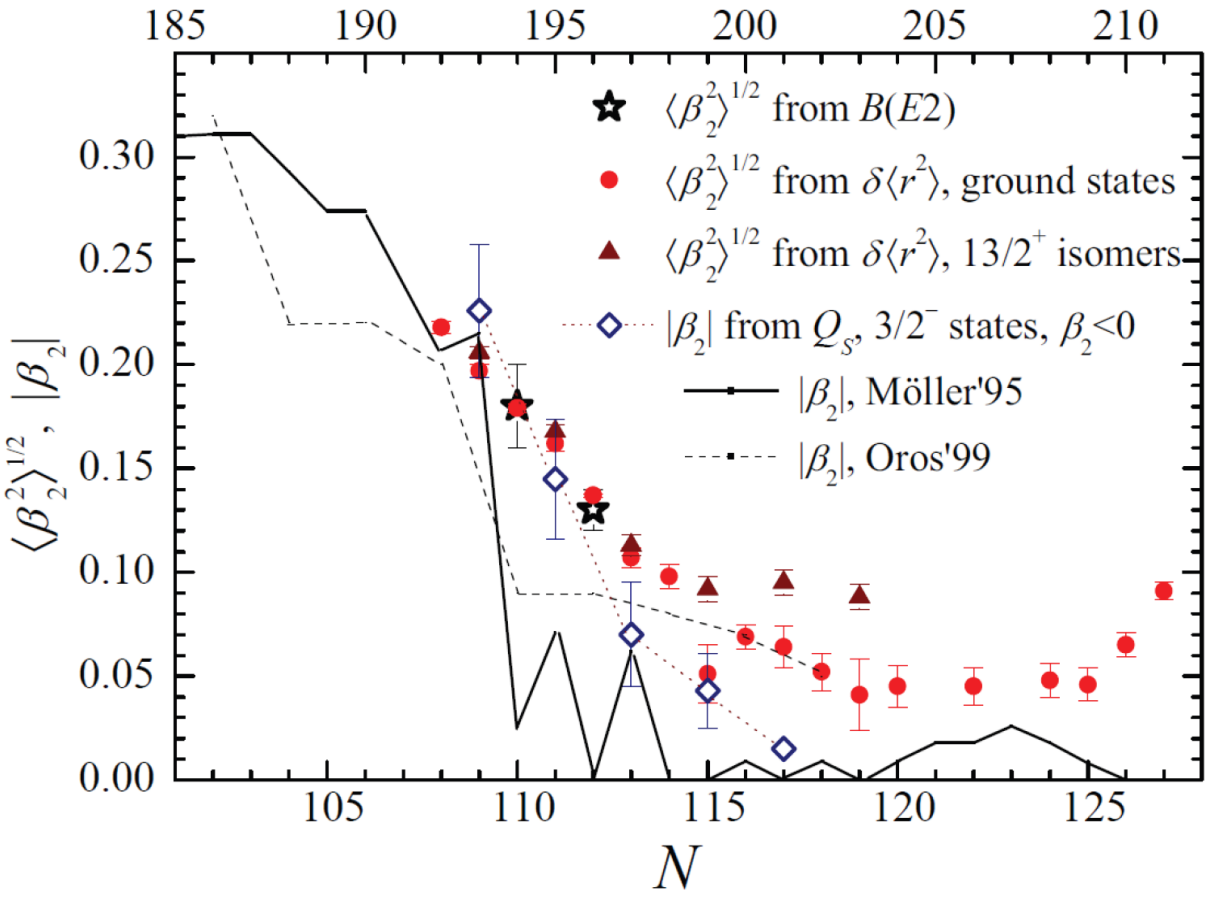
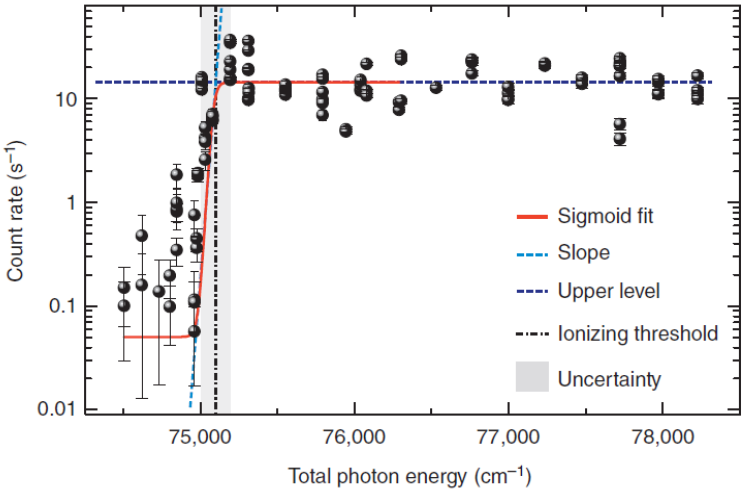


- When the deformation parameters extracted from $\delta\langle r^2\rangle$, quadrupole moments and B(E2) are plotted they match closely.
- This indicates that the deformation is static and well defined.

Courtesy T.E. Cocolios

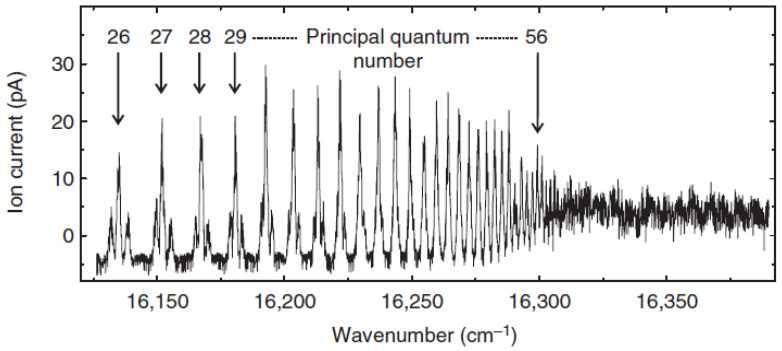
MD Seliverstov et al., in preparation.

First determination of the ionization potential for the radioactive element At



3 successful **on-line** development runs
ISOLDE (Nov. 2010, May 2011)
TRIUMF, Canada (Dec. 2010)

- Many new atomic levels found
- Transition strengths measured

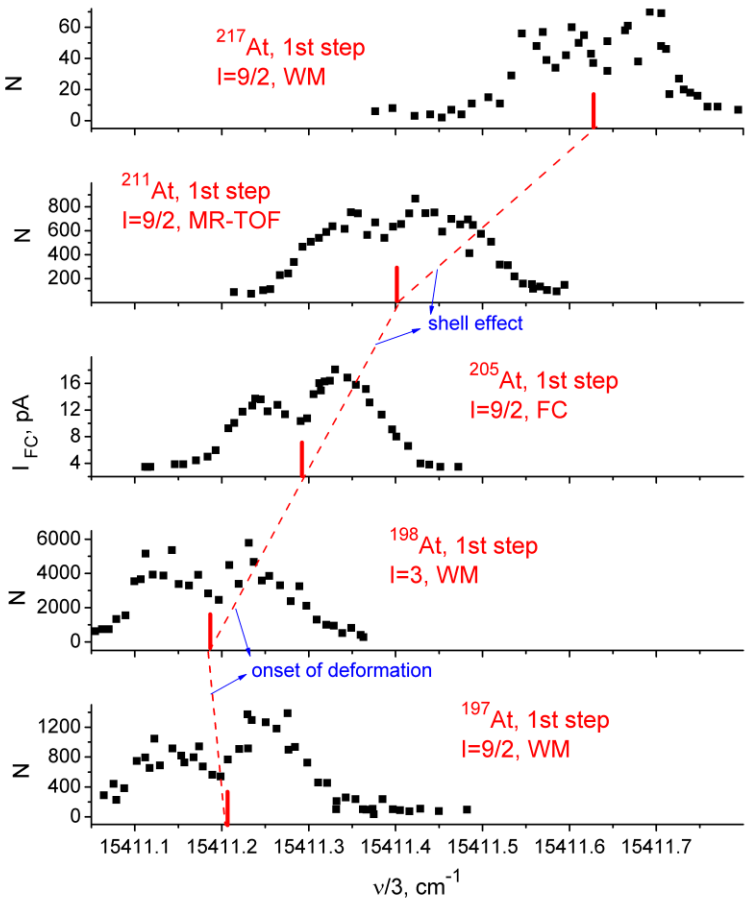


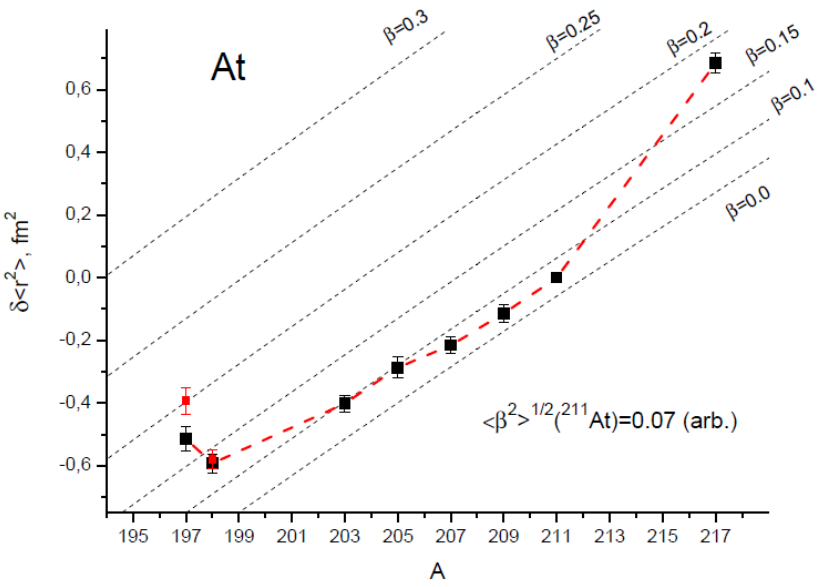
- **Ionization potential measured** (scan of ionizing laser: converging Rydberg levels allow precise determination of the IP)

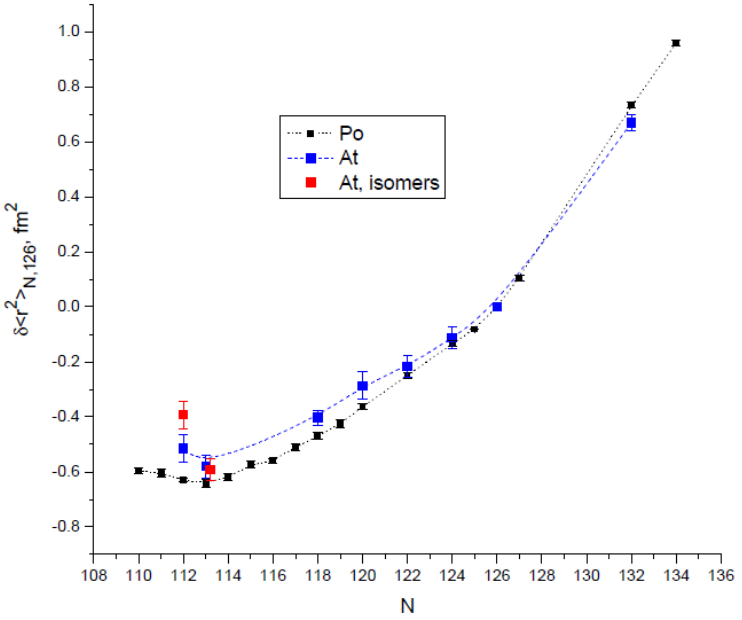
"First determination of the Ionization Potential for element Astatine" S Rothe et al., Nature communications 4, 1835 (2013)

HFS spectra for At isotopes

May and September 2012



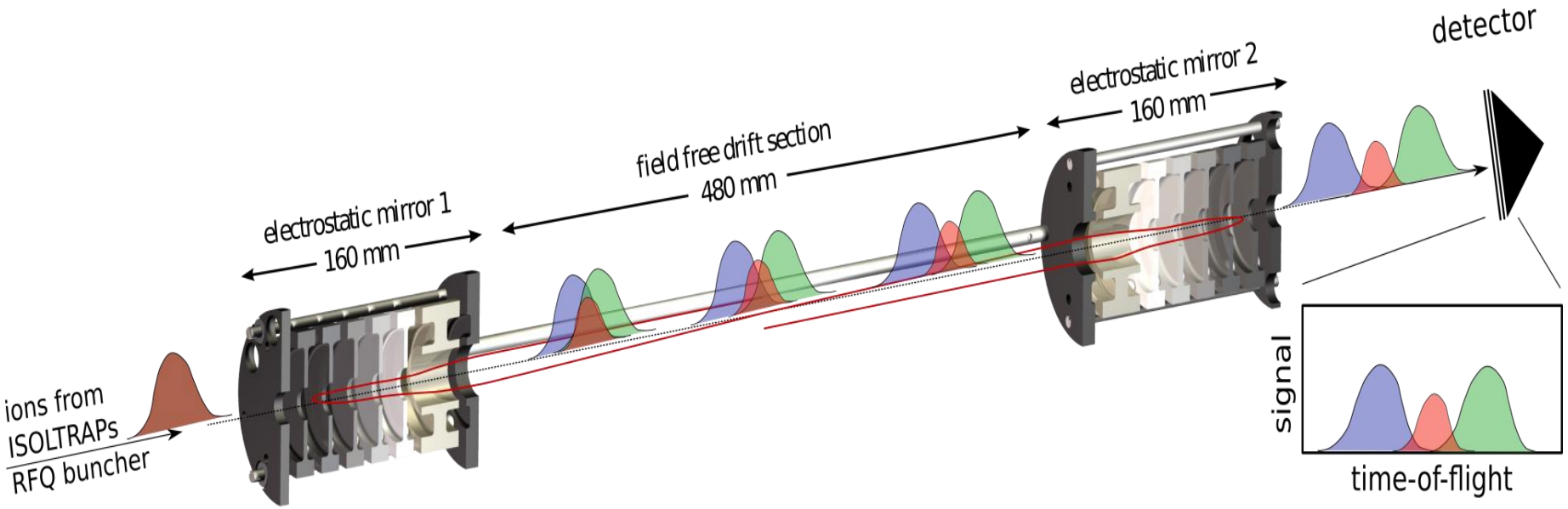




Courtesy A. Andreyev and
A. Barakh, IS534
collaboration

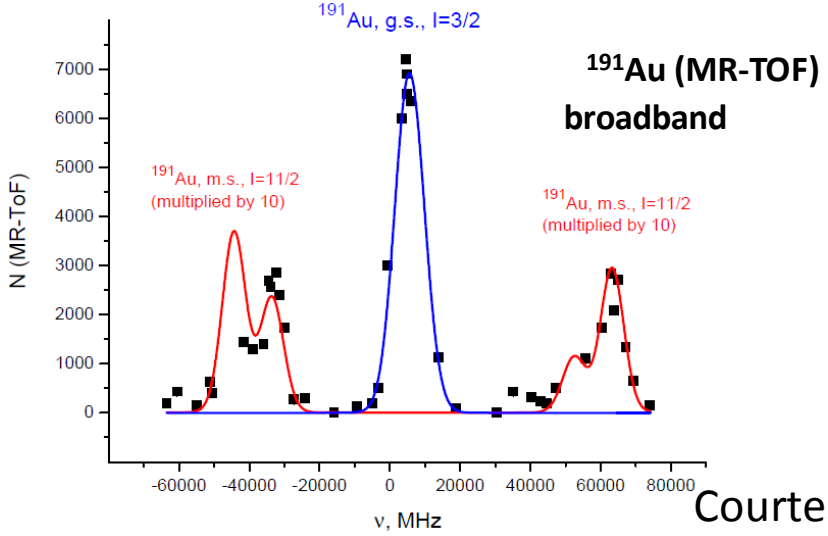
Multi-reflection time-of-flight (MR-ToF) spectrometer for HFS studies

- The WM technique requires **waiting for the decay** of the isotope (usually, α-decay, to provide selectivity between isotopes/isomers). Not practical for long-lived or stable isotopes (or for β-decaying)
- Alternative – to **use 'counting' ions** (instead of waiting for decay)

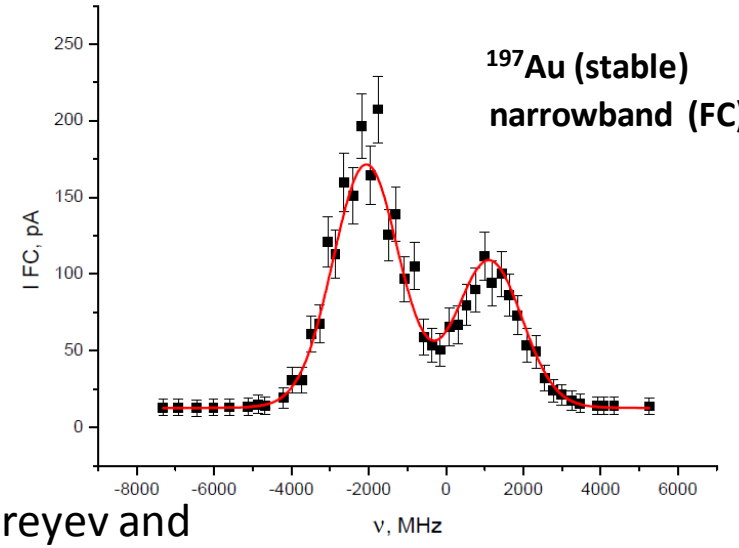


Courtesy A. Andreyev and A. Barakh, IS534 collaboration

Hyperfine splitting scans for ^{178,185,191,197}Au

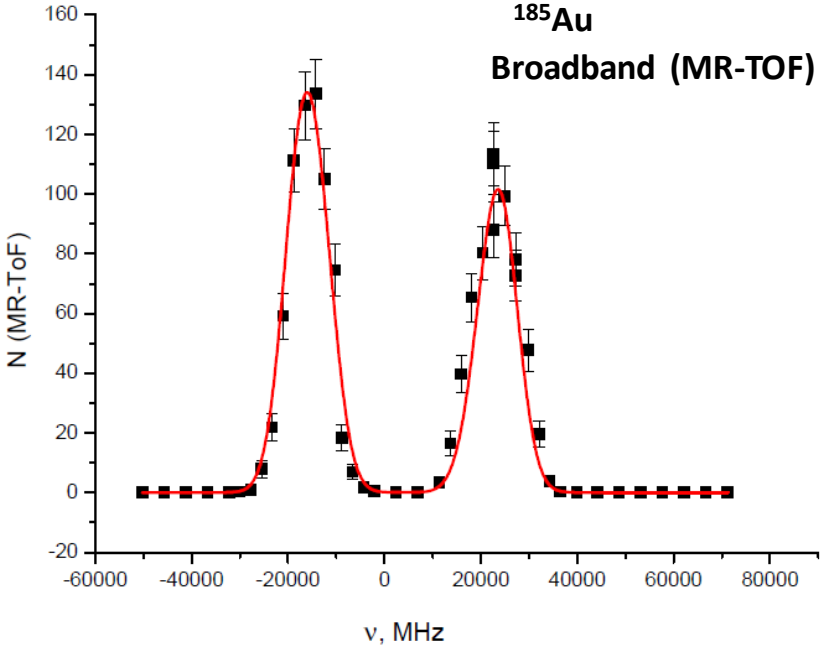


^{191}Au (MR-TOF)
broadband

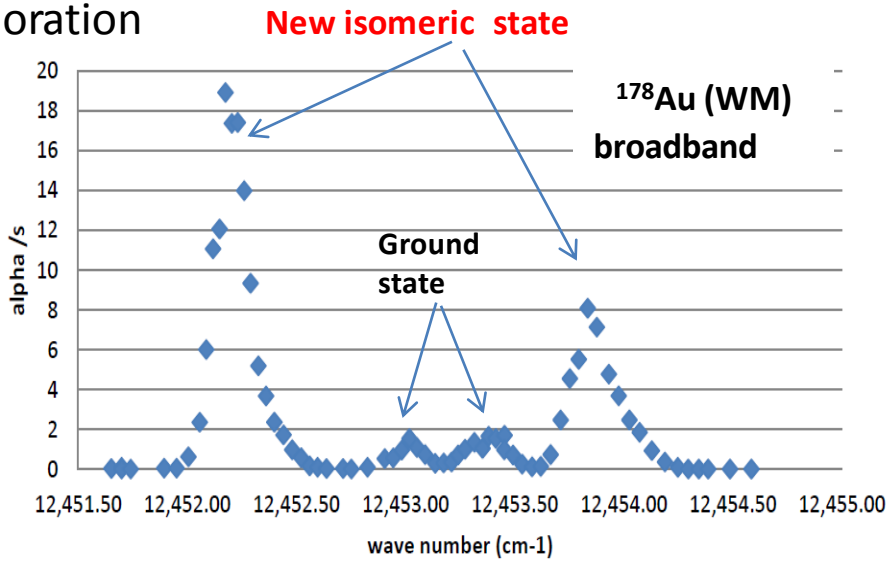


^{197}Au (stable)
narrowband (FC)

Courtesy A. Andreyev and A. Barakh, IS534 collaboration

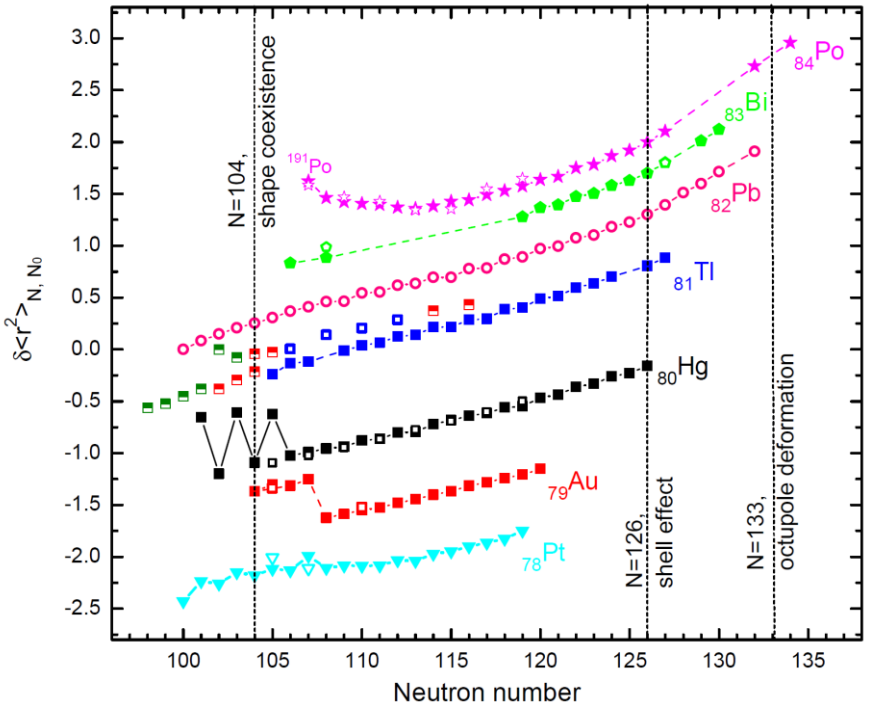


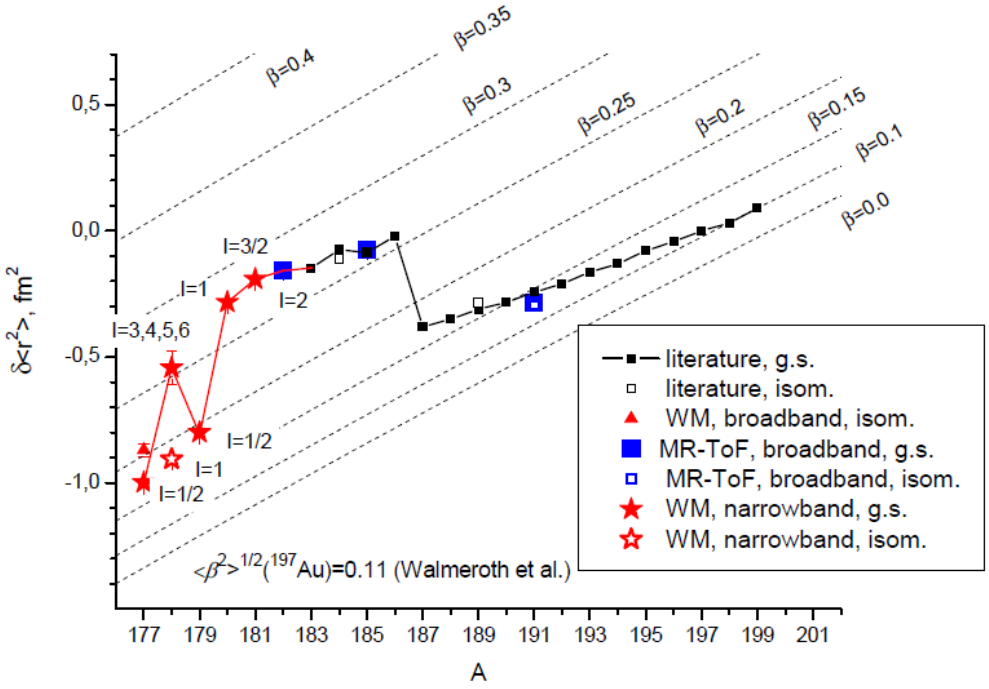
^{185}Au
Broadband (MR-TOF)



^{178}Au (WM)
broadband

How does the deformed character evolve towards the proton drip-line in gold



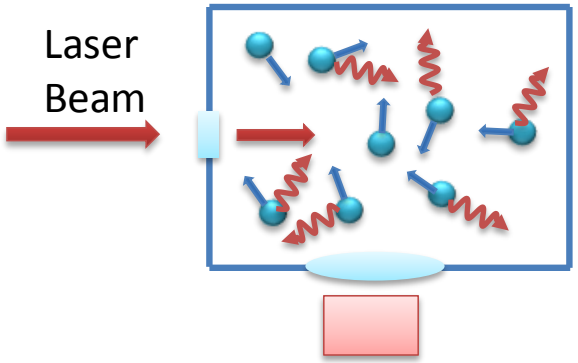


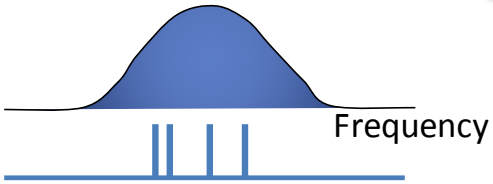
- **Deformation jump toward less deformed shapes in the light Au isotopes**
- **Shape staggering in ^{178}Au (large deformation difference between 2 states)**

Courtesy A. Andreyev and
A. Barakh, IS534
collaboration

Towards higher resolution laser Spectroscopy

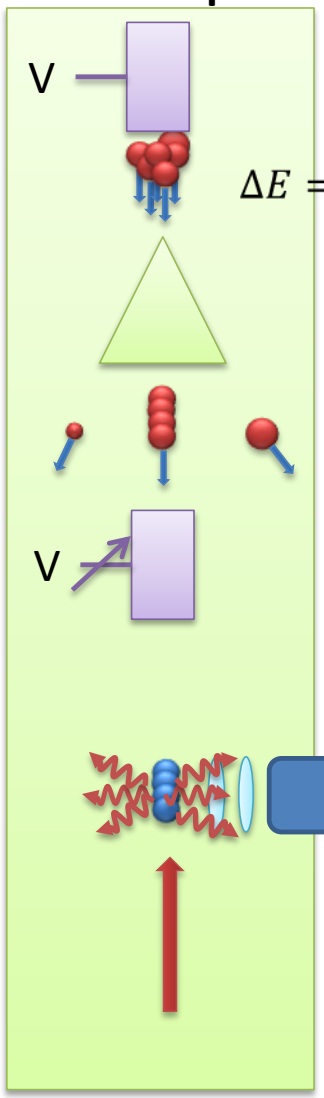
Closed box of atoms at temperature for a vapour to form (1000-2000C)





Doppler Free Spectroscopy

Collinear Laser Spectroscopy



Ion source

$\Delta E = mv\Delta v = constant$

Mass Separation

Neutralization cell and scanning voltage

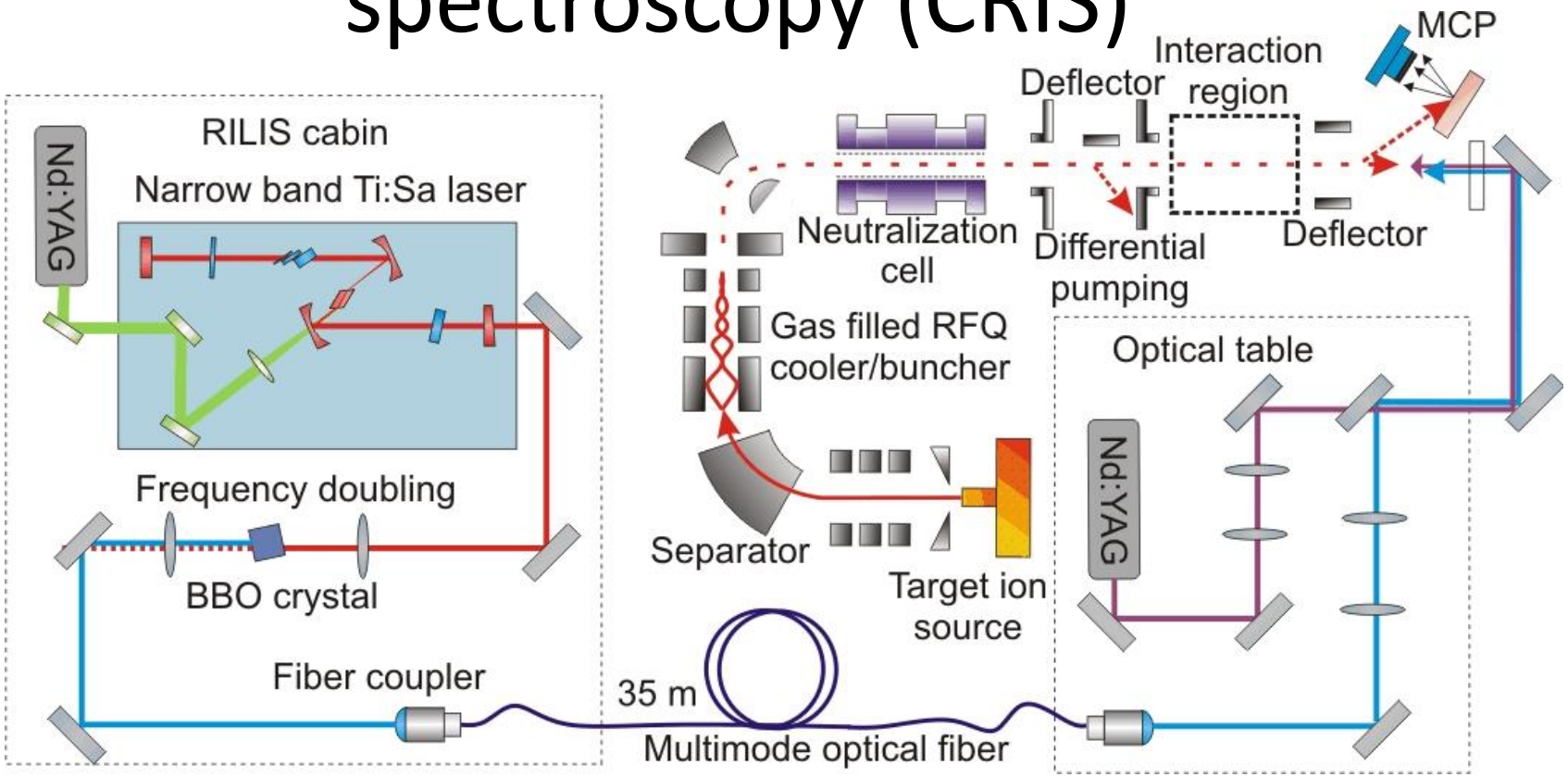
Light collection region

Laser Beam

The thermal motion of the atoms broadens the transition, masking the hyperfine structure: Doppler Broadening

$\Delta v_D = {}^{v_0 \Delta v}/_{c}$ ~ 1-5 GHz

Collinear resonance ionization spectroscopy (CRIS)

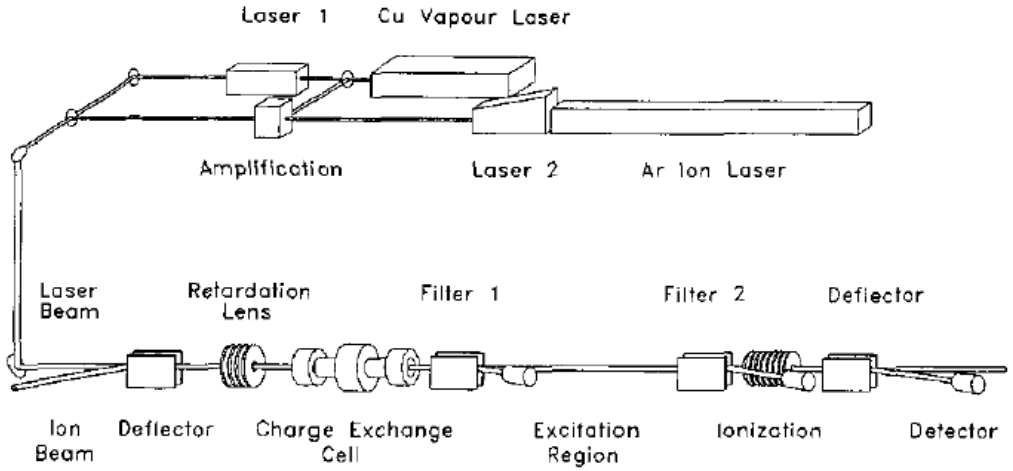


$$\Delta E = \text{const} = \delta(^1/_2 mv^2) \approx mv\delta v$$

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

Previous CRIS of Yb at ISOLDE

The technique was able to reject the intense isobaric beams and successfully measured ^{157,159}Yb among other isotopes.



Background 1:10^8

Linewidth 50 MHz

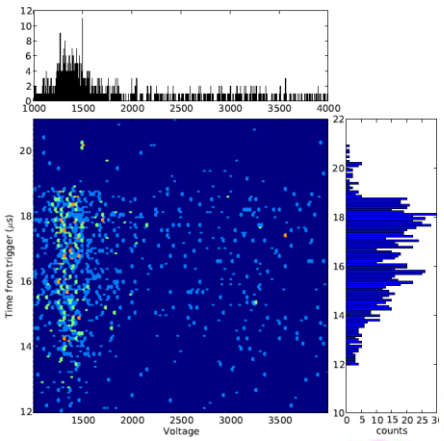
Detection efficiency 1:10^5

- Low charge exchange efficiency into meta stable states.
- Below saturation on second step.
- DC beam and duty cycle losses due to pulsed lasers.
- 1984 proposal pointed out the need for a laser ion source producing a bunched ion beam to reduce duty cycle losses.

V.S. Letokhov et al, Zinal D7, 1984

Ch. Schulz *et al.*, J. Phys. B, **24** (1991) 4831

Layout of the CRIS beam line



Radioactive bunched ion beam from ISOLDE

Charge exchange cell

Doppler tuning voltage applied

UHV interaction region

MCP: ion detection

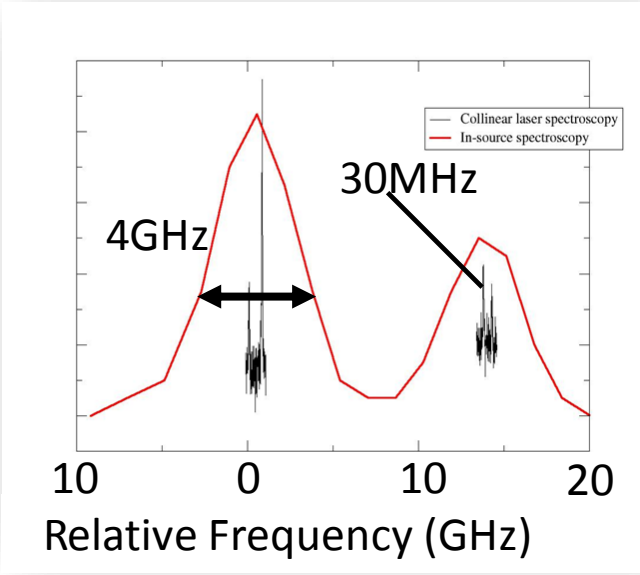
Laser beam

Stable beam from off line ion source

Ge detectors

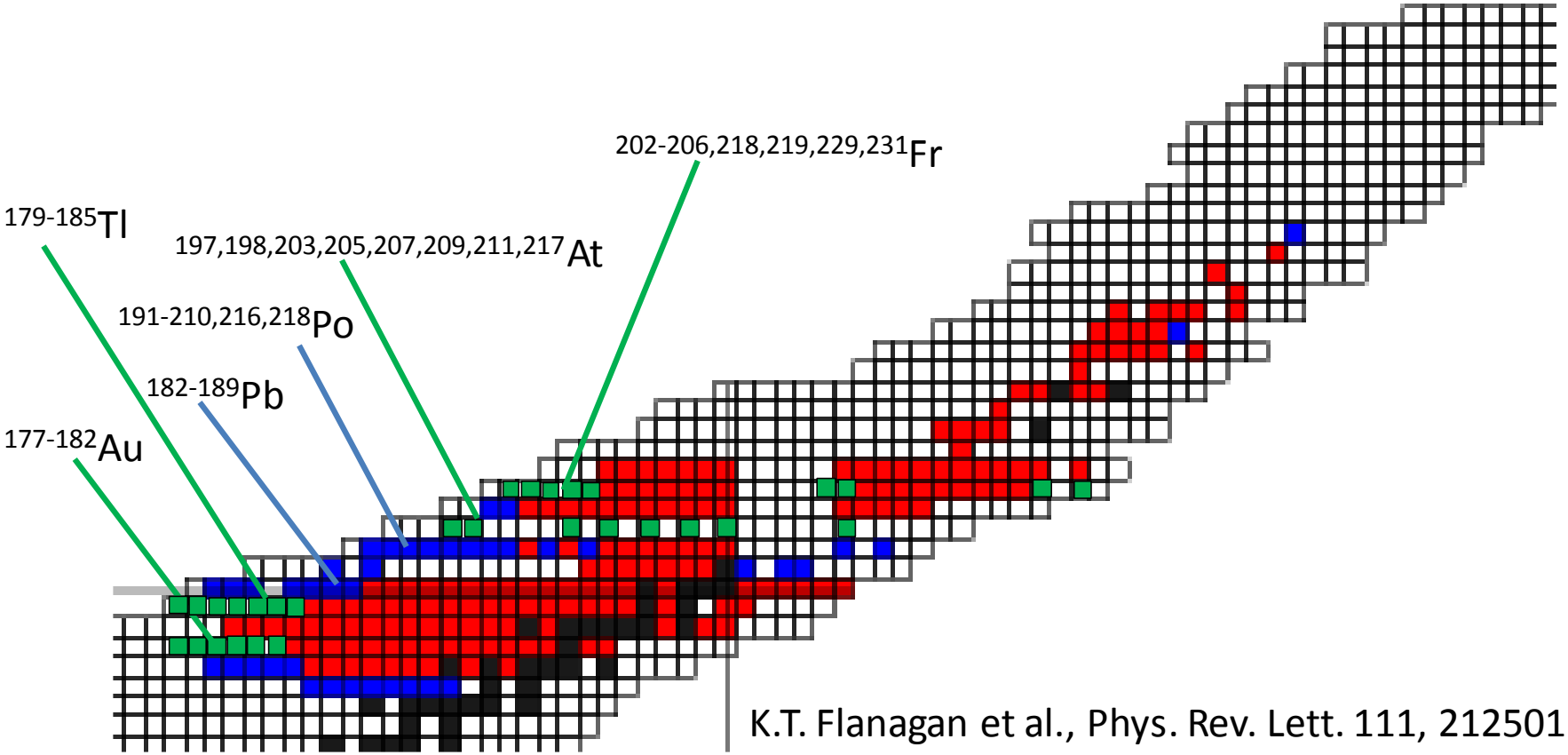
Si detectors

Decay spectroscopy station: decay measurements



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

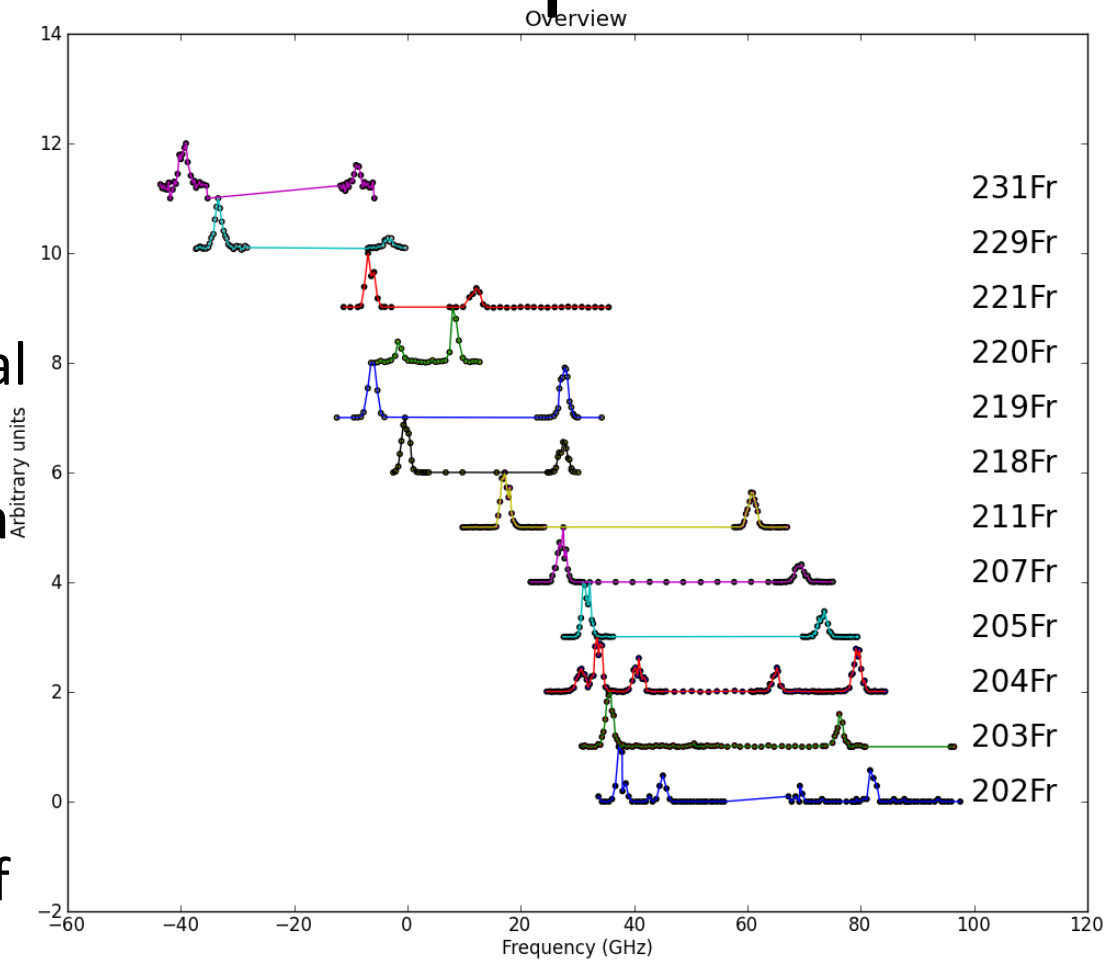
First CRIS campaign



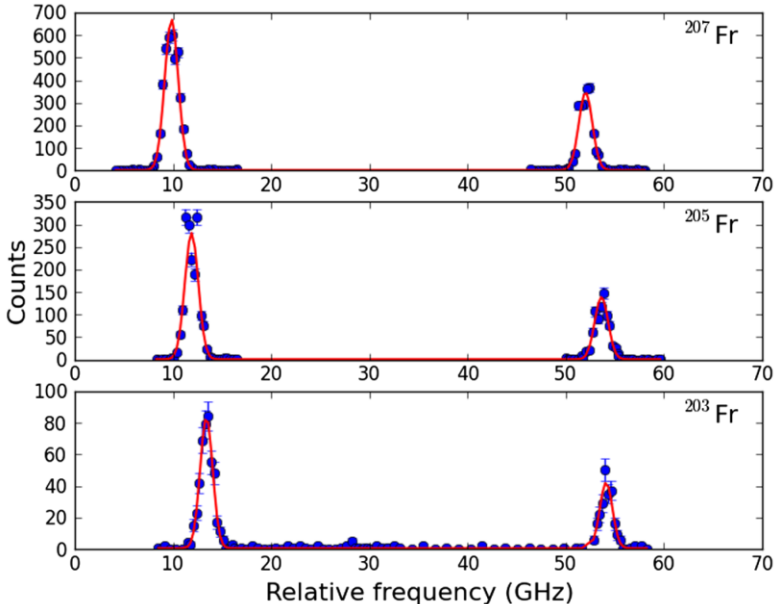
K.T. Flanagan et al., Phys. Rev. Lett. 111, 212501 (2013)
A. Voss et al., Phys. Rev. Lett. 111, 122501 (2013)
A. E. Barzakh et al.,Phys. Rev. C 88, 024315 (2013)
MD Seliverstov et al., Phys. Lett. B 719, 362 (2013)
T.E. Cocolios et al., Phys. Rev. Lett. 106, 052503 (2011)
H. De Witte et al., Phys. Rev. Lett. 98, 112502 (2007)

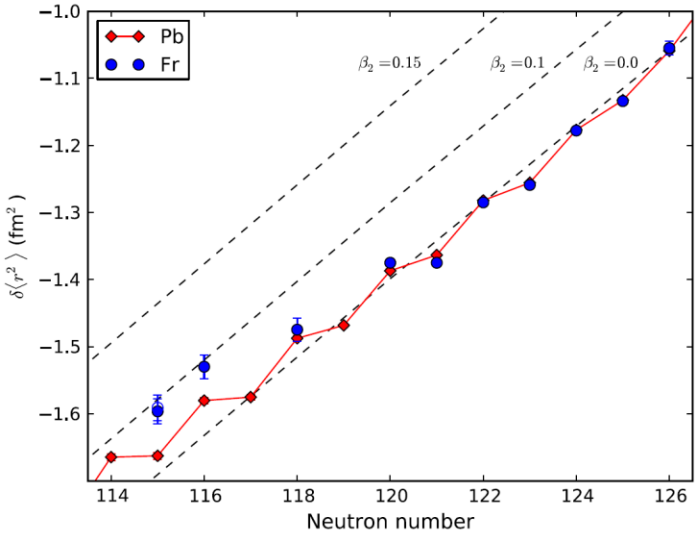
Summary of first CRIS experiment

- 9 new isotopes were measured (+4 isomeric states).
- Spectrum of ^{202}Fr used to estimate the experimental efficiency of 1%
- Factor of 1000 increase in detection efficiency compared to previous spectroscopy of francium
- New data studied cases with a production yield of ~100 atoms/s almost 10^6 less than previous method required (^{207}Fr 4×10^8ppp).



Interpretation of neutron deficient Francium

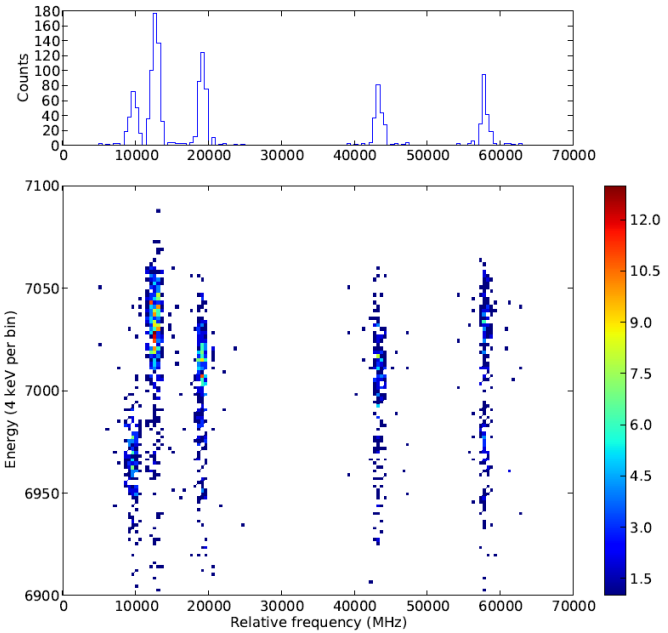


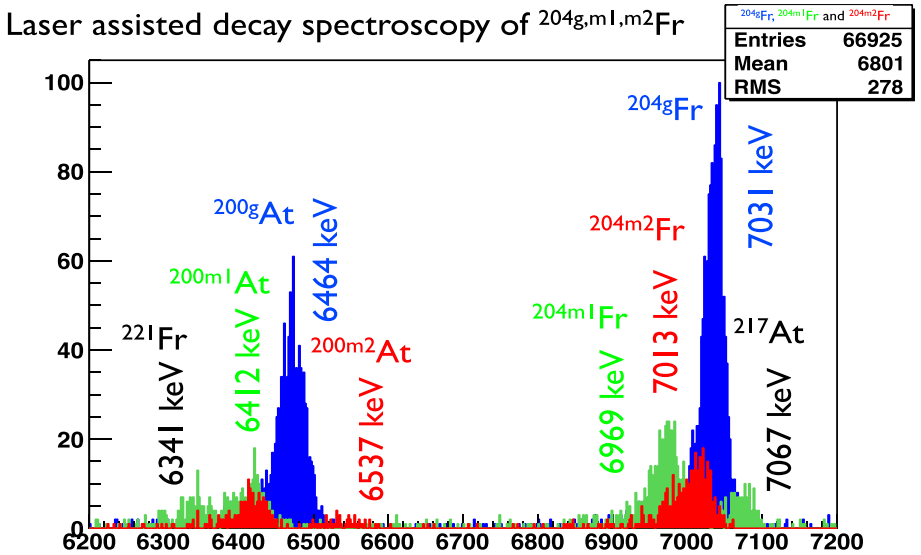


- The band structure built onto the ground state of 203;205Fr suggests that while these isotopes have an increased collectivity, they remain spherical.
- The magnetic moments of 203;205Fr closely match the steadily decreasing trend from N=126, suggesting that the ground state is still dominated by a spherical $h_{9/2}$ configuration.
- ^{205}Fr Q_0 -64.4(7) efm^2, which corresponds to a β_2=- 0.0204(2) while the RMS deformation (using FRDM) $|\beta_2|$=0.06, neither of which are considered deformed.
- Will return to measure the quadrupole moments of ^{202,203}Fr and extend the measurements to ^{201}Fr

K.T. Flanagan et al., Phys. Rev. Lett. 111, 212501 (2013)
A. Voss et al., Phys. Rev. Lett. 111, 122501 (2013)

Laser assisted decay spectroscopy of ^{204}Fr





- The HFS of ^{204}Fr was scanned across
- Decay measurement was taken every frequency step
  - Collection time of 1 minute
- Gating on the energy of the ^{204}Fr alphas yielded clean HFS for each isomer

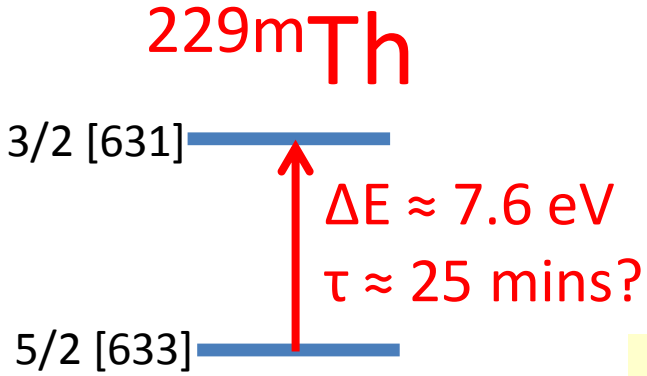
Unambiguous determination of the low energy isomer in ^{229}Th

Nuclear clock

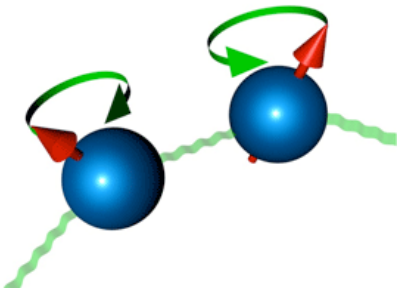
Peik and Tamm, Europhys. Lett. 61 (2003) 181
Campbell et al., PRL 108 (2012) 120802

Gamma ray laser

Tkalya, PRL 106 (2011) 162501



Qubit: quantum computing



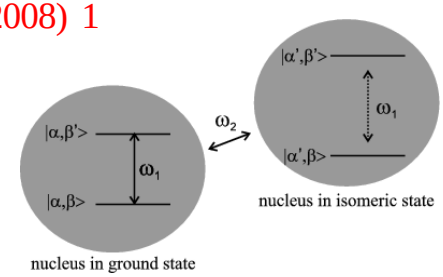
P&T, Europhys. Lett. 61 (2003) 181

Evolution of fundamental constants

Litvinova *et al.*, PRC 79 (2009) 064303
Flambaum & Wiringa, PRC 79 (2009) 034302

Nuclear Excitation by Electron Transition

Izosimov, J. Nucl. Sci. Tech. Supp. 6 (2008) 1

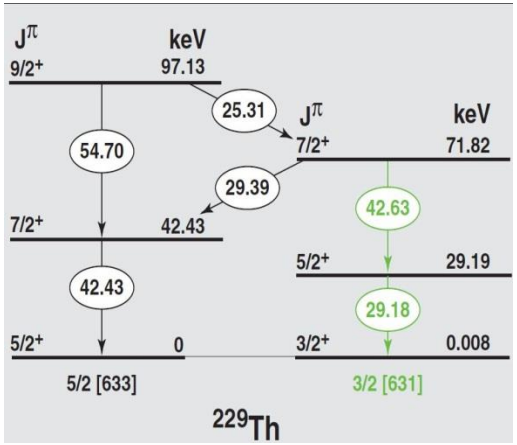


Courtesy I.D Moore on behalf of the JYFL-Mainz collaboration

Towards the detection of the isomer

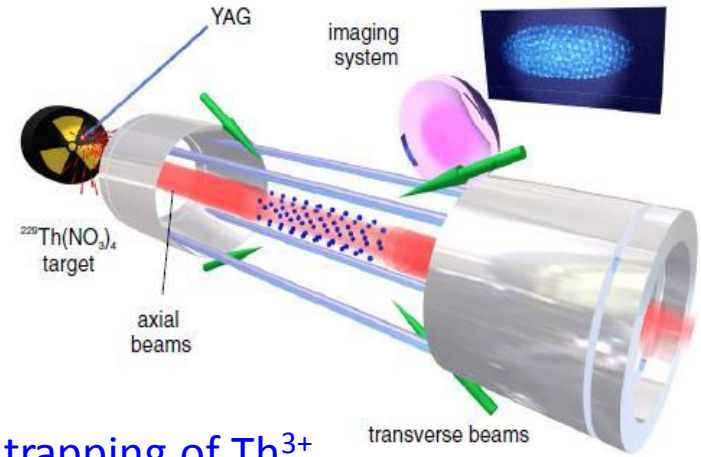
Despite 3 decades of study, over 70 publications (several PRL), theoretical and experimental efforts, the major breakthrough is still pending:

- Direct observation of the transition
- Definitive evidence of the existence of the isomer



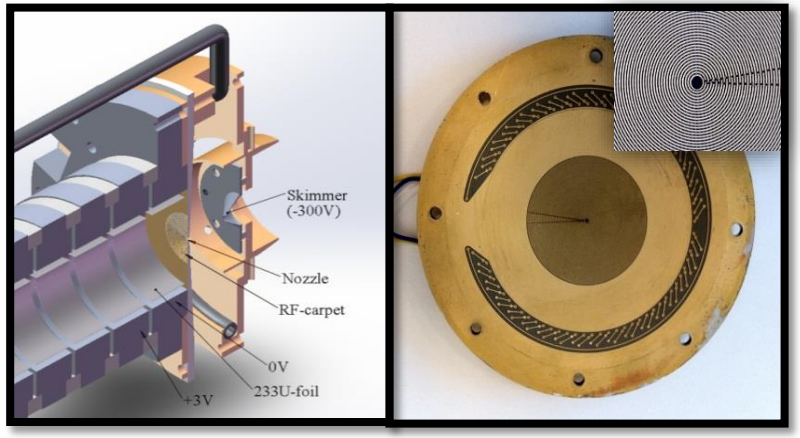
B.R. Beck et al., PRL 98 (2007) 142501

Detect via the Hyperfine Structure



Ion trapping of Th^{3+}

C.J. Campbell et al., PRL 106 (2011) 223001
C.J. Campell et al., PRL 108 (2012) 120802



Collinear or gas cell/gas jet spectroscopy

V. Sonnenschein, I.D. Moore et al., Eur. Phys. J A 48 (2012) 52

Courtesy I.D Moore on behalf of the JYFL-Mainz collaboration

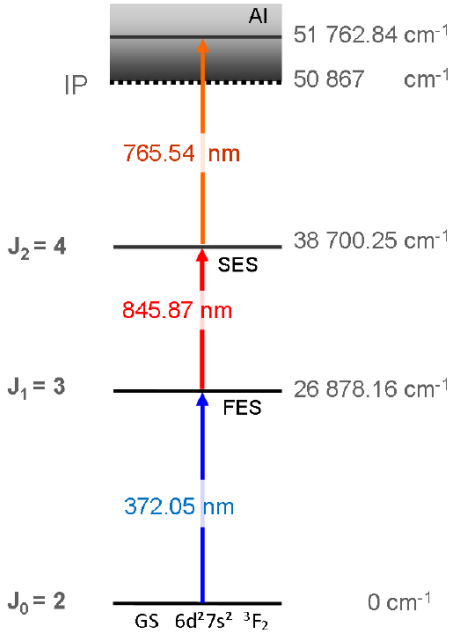
Identification of the isomeric state

Collinear fluorescence spectroscopy

- detection efficiency = 1/5000

+ *A* and *B* factors for ion known

→ Enhance ion current by efficient laser ionization



S. Raeder *et al.*, J. Phys. B 44 (2011) 165005

High resolution-RIS

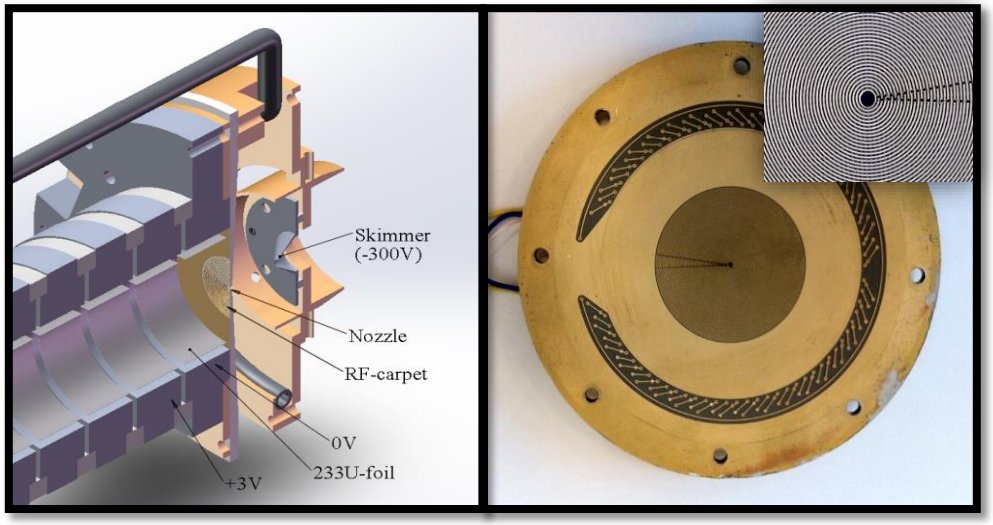
+ ion detection efficiency ≈ 100%

- Doppler reduction required

- *A* and *B* factors for ground state unknown

→ Find suitable high resolution scheme.

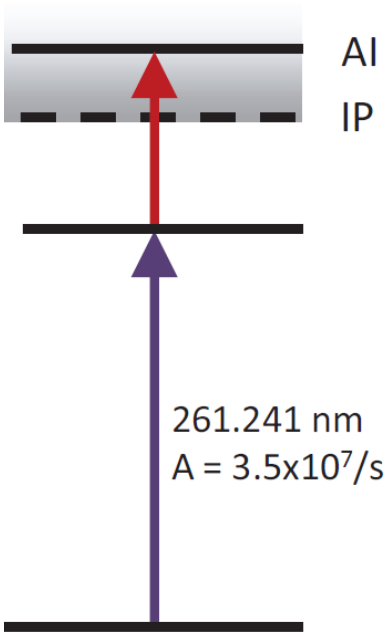
Determine ground state HFS

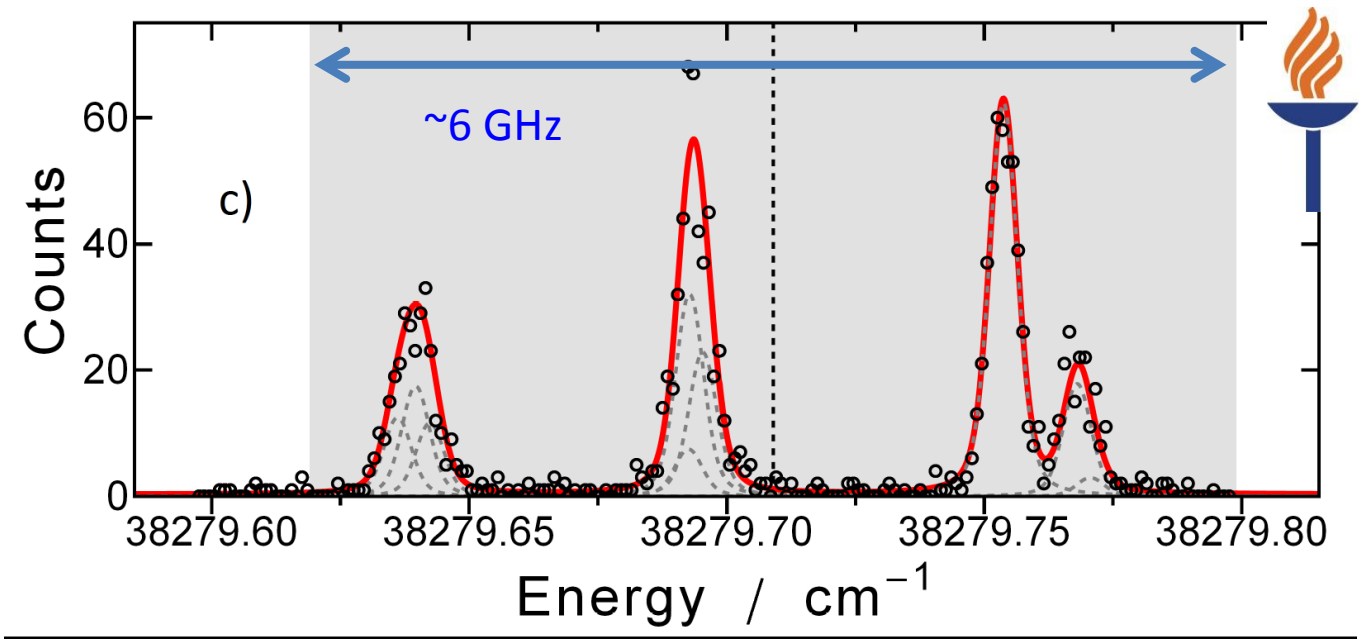


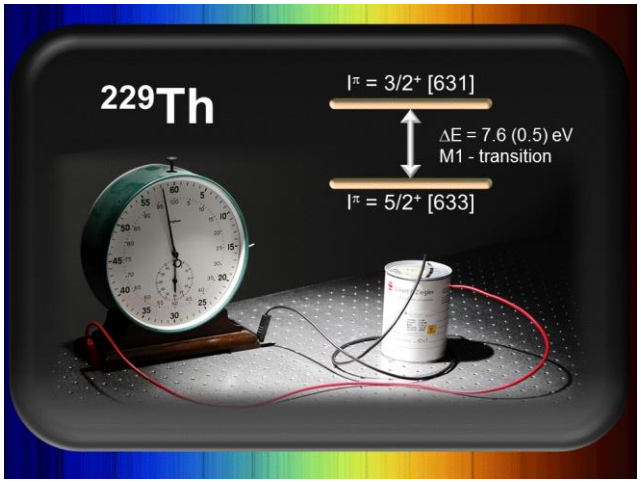
V. Sonnenschein, I.D. Moore *et al.*, Eur. Phys. J. A 48 (2012) 52

Courtesy I.D Moore on behalf of the JYFL-Mainz collaboration

High-resolution Resonance Ionization Spectroscopy







V. Sonnenschein, S. Raeder, I.D. Moore et al., J. Phys. B 45 (2012) 165005

September 27-29, 2012, EMMI Workshop
The ^{229m}Th Nuclear Isomer Clock
GSI, Darmstadt.

http://www.gsi.de/emmi/workshops

Courtesy I.D Moore on behalf of the JYFL-Mainz collaboration

Summary

The CRIS Collaboration

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