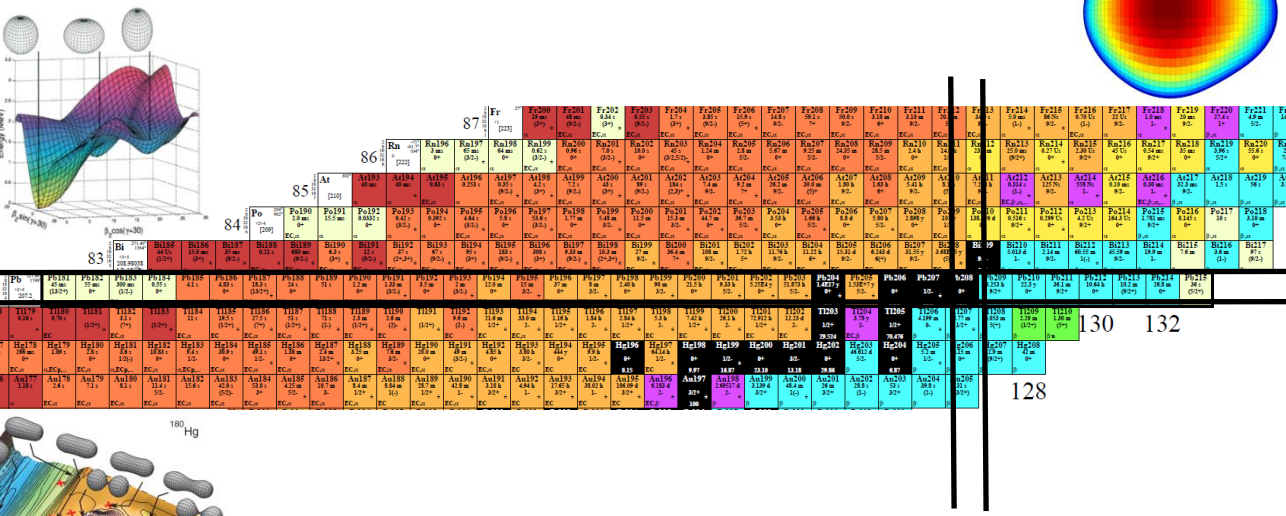
Windmill Collaboration Status Report on Studies in the Lead Region Addenda IS456/IS534

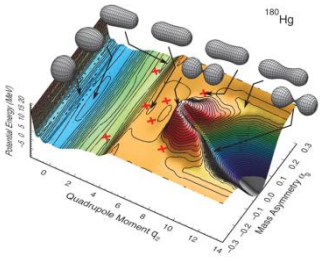
Andrei Andreyev

University of York, UK and JAEA, Tokai, Japan

on behalf of the Windmill Collaboration

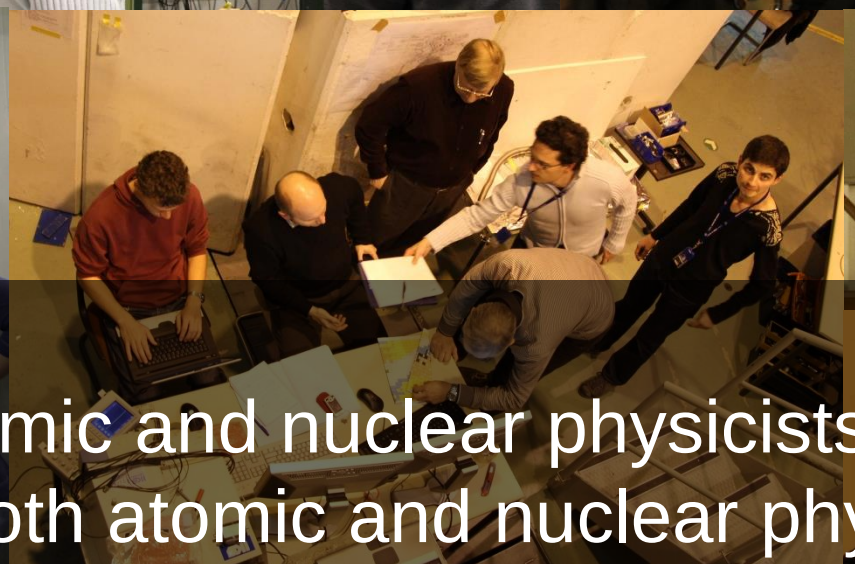
- **HFS measurements in long chains of Au, Tl, Pb, Po, At (~70 isotopes)**
- **Shape coexistence (E0's, new states…)**
- **Beta-delayed fission (Tl, At, Fr)**
- **Atomic spectroscopy (IP, configuration…)**





INTC, 12th February 2014

Windmill Collaboration ‘2014



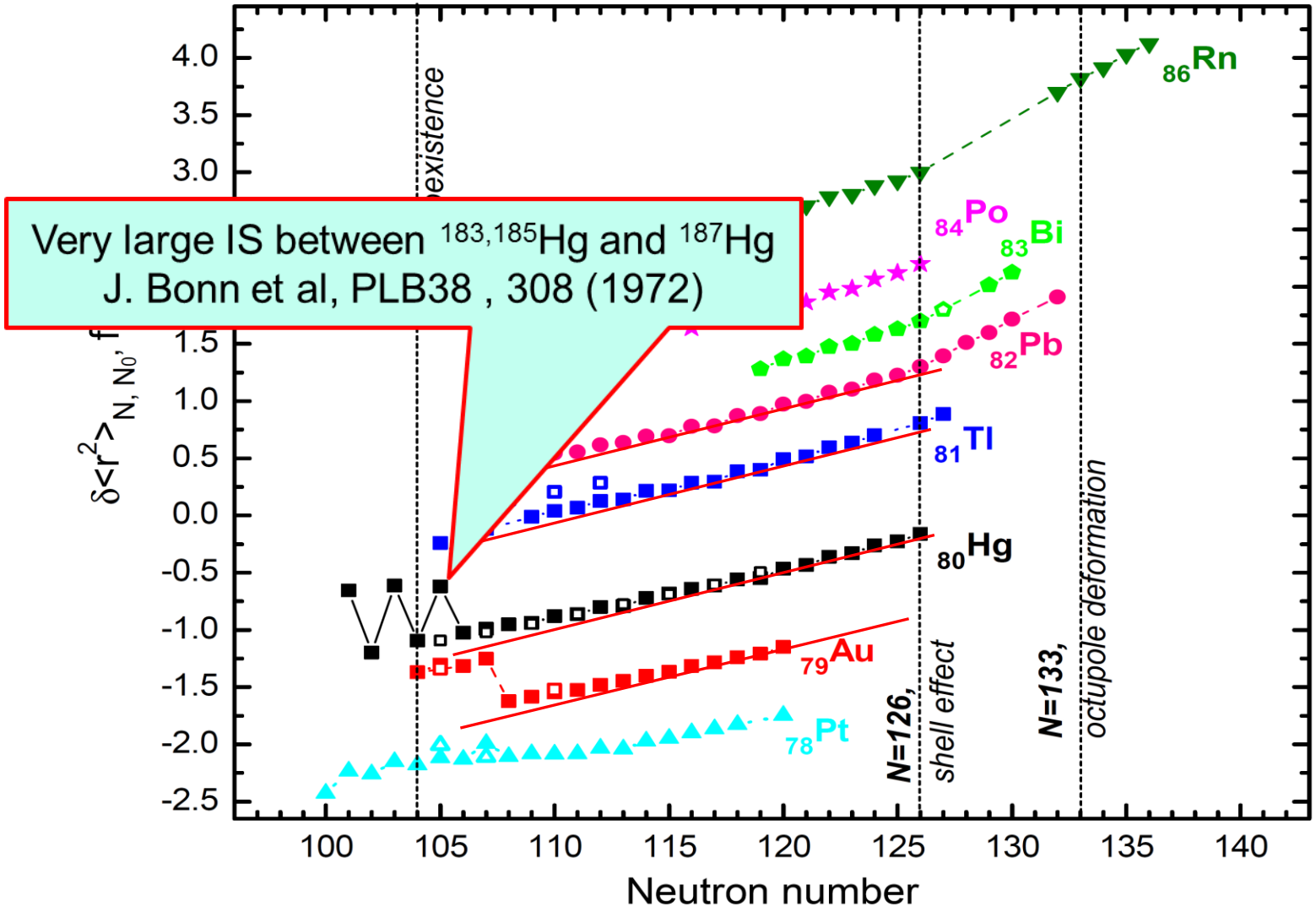
- Highly collaborative
- 15 institutions, >40 atomic and nuclear physicists
- Many PhD students, both atomic and nuclear physics

Windmill Collaboration ‘2014

Comenius University, Bratislava, Slovakia
GANIL, Caen, France
Helmholtz Institut Jena, Germany
ILL, Grenoble, France
Institut für Physik, Johannes Gutenberg-Universität Mainz, Germany
IPN Orsay, France
JAEA, Tokai, Japan
KU Leuven, IKS, Belgium
PNPI, Gatchina, Russian Federation — A. Barzakh
RILIS and ISOLDE, CERN, Switzerland — E. Rapisarda, B. Marsh
SCK-CEN, Mol, Belgium
The University of Manchester, United Kingdom — T.E. Cocolios
The University of York, United Kingdom
University of Liverpool, United Kingdom
University of the West of Scotland, United Kingdom

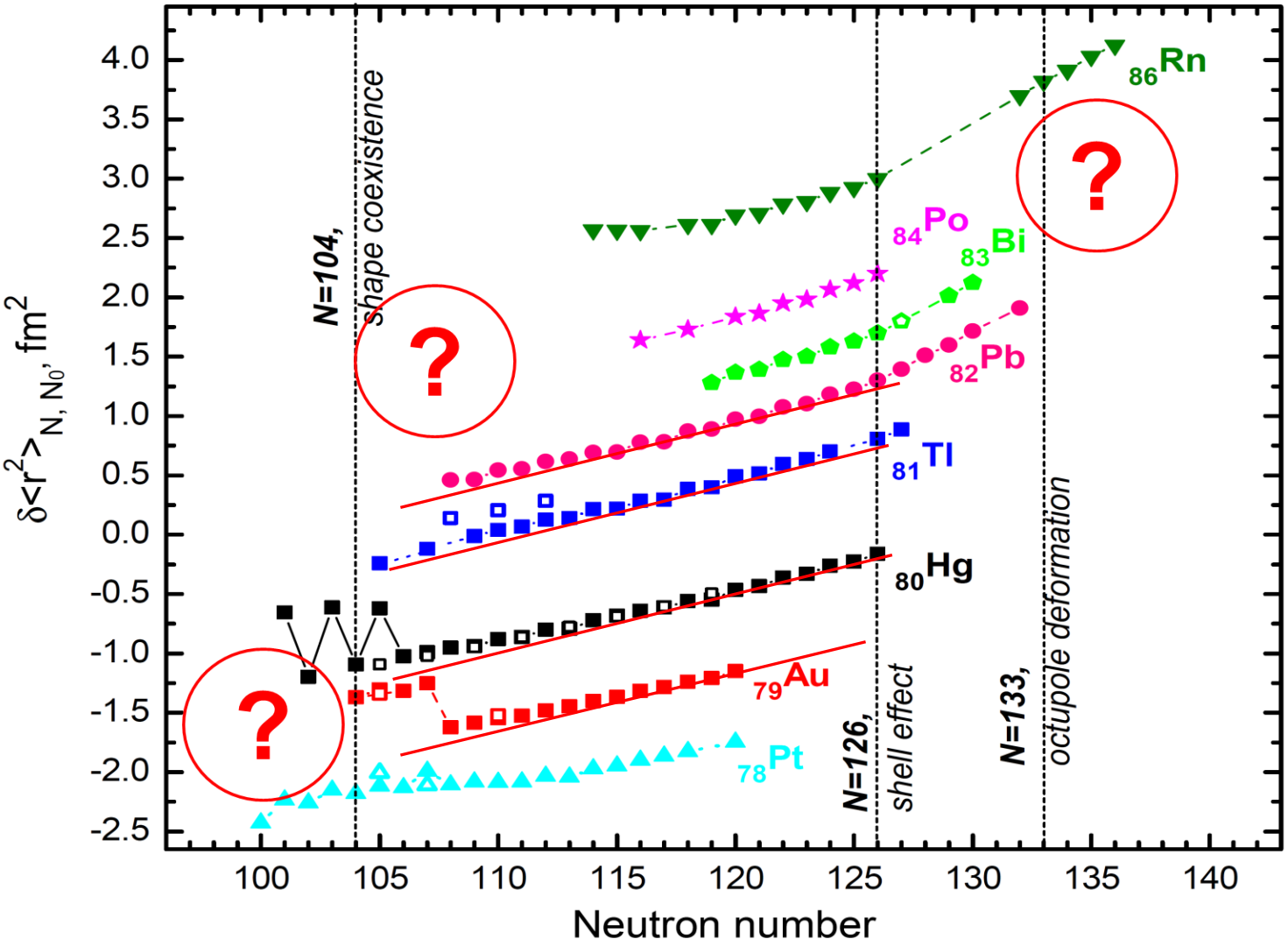
Extra thanks to the MR-TOF@ISOLTRAP team
and the GSI Target Laboratory

Pre-2003: Charge Radii in the Lead Region



- Shape coexistence around N~104
- Sphericity around N=126, kink in radii, high-spin isomers
- Octupole effects around N~132, inverse odd-even radii staggering

Pre-2003: Charge Radii in the Lead Region



- Shape coexistence around N~104
- Sphericity around N=126, kink in radii, high-spin isomers
- Octupole effects around N~132, inverse odd-even radii staggering

2002- Birth of the "Windmill Collaboration"
Proof-of-principles: isomer separation in ^{185}Pb

Eur. Phys. J. A 14, 63–75 (2002)
DOI 10.1140/epja/iepja1387

THE EUROPEAN PHYSICAL JOURNAL A
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Springer-Verlag 2002

Nuclear spins, magnetic moments and α-decay spectroscopy of long-lived isomeric states in ^{185}Pb

A.N. Andreyev[1,a], K. Van de Vel[2], A. Barzakh[3], A. De Smet[2], H. De Witte[2], D.V. Fedorov[3], V.N. Fedoseyev[4,b], S. Franchoo[5,6], M. Górska[2,c], M. Huyse[2,5], Z. Janas[7], U. Köster[5], W. Kurcewicz[7], J. Kurpeta[7], V.I. Mishin[4], K. Partes[5], A. Plochocki[7], P. Van Duppen[2], and L. Weissman[5,d]

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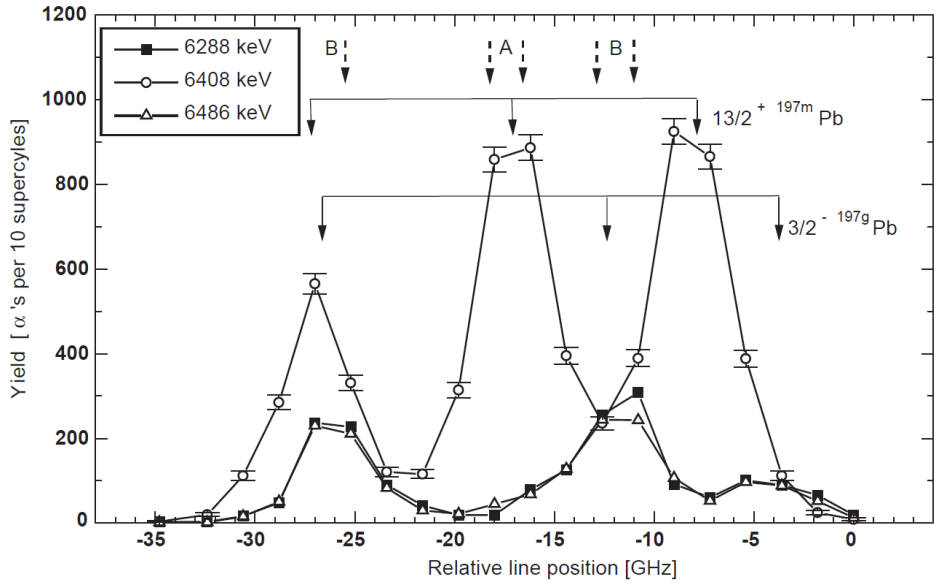
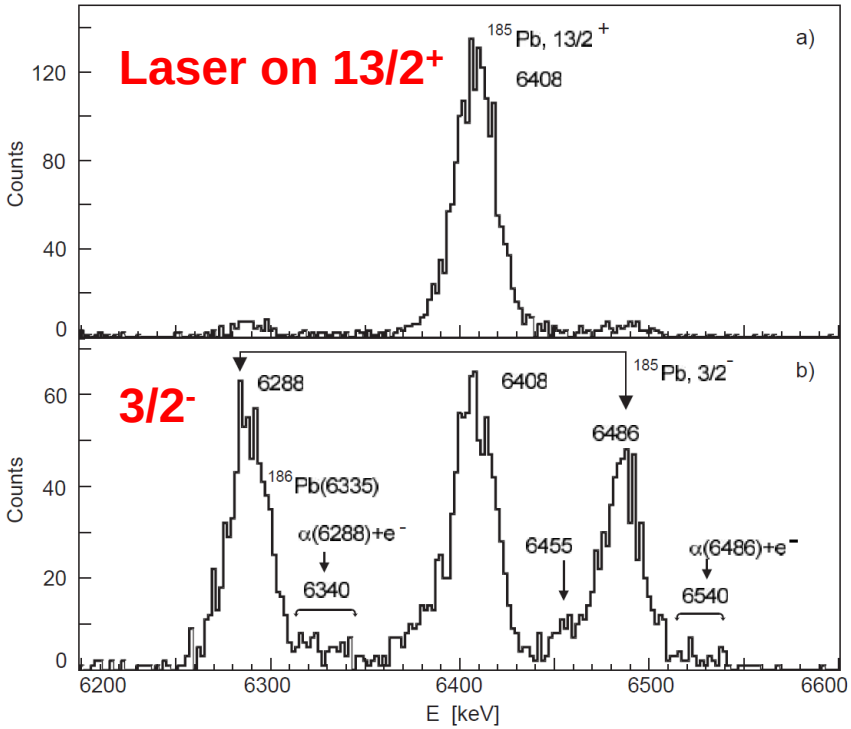
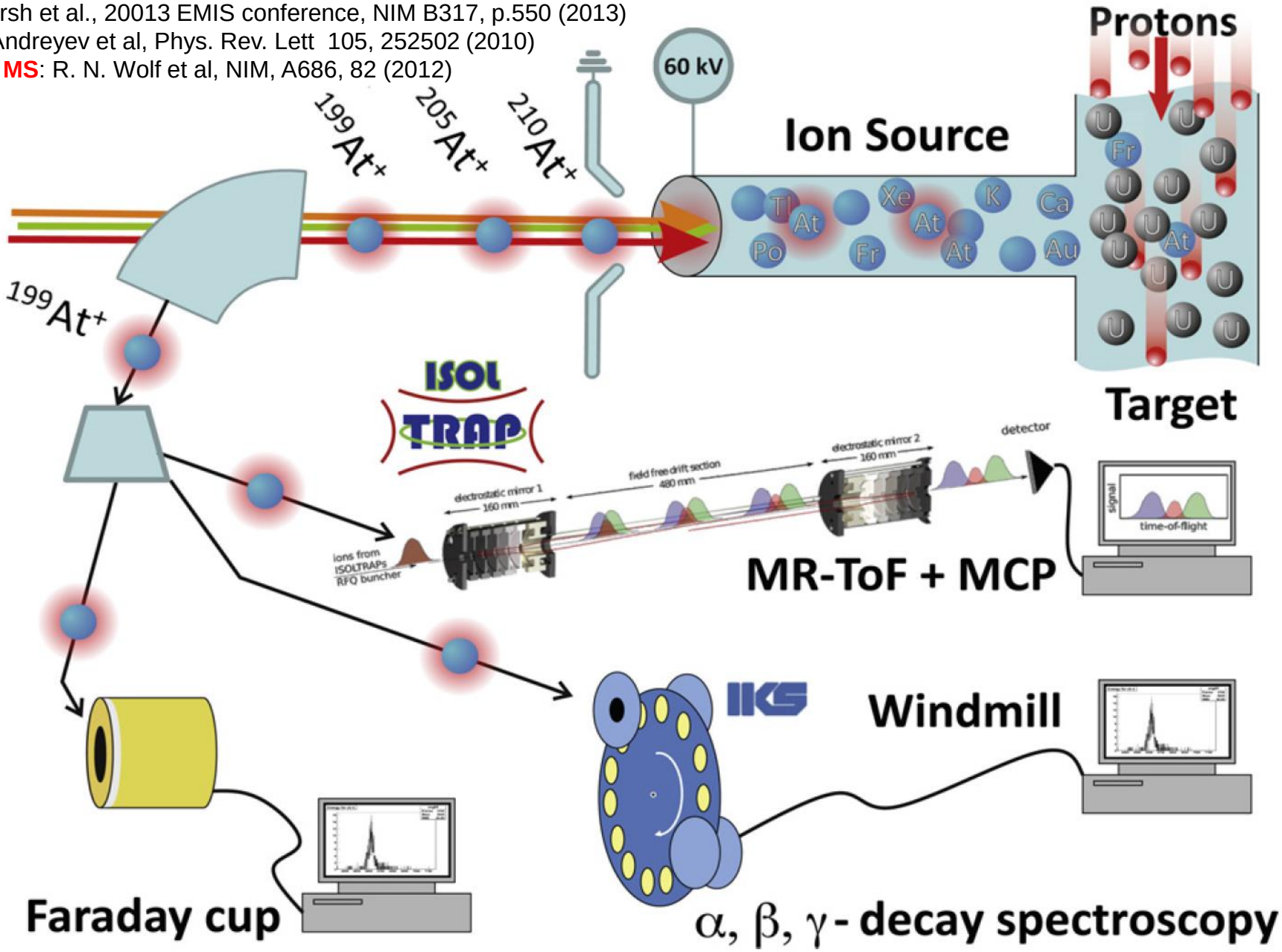
[4] Institute of Spectroscopy, Russian Academy of Sciences, 142190, Troitsk, Russia
[5] ISOLDE CERN, CH-1211 Genève 23, Switzerland
[6] University of Mainz, D-55099, Mainz, Germany
[7] Institute of Experimental Physics, University of Warsaw, Hoza 69, PL-00681, Warsaw, P
IS387 Collaboration and ISOLDE Collaboration



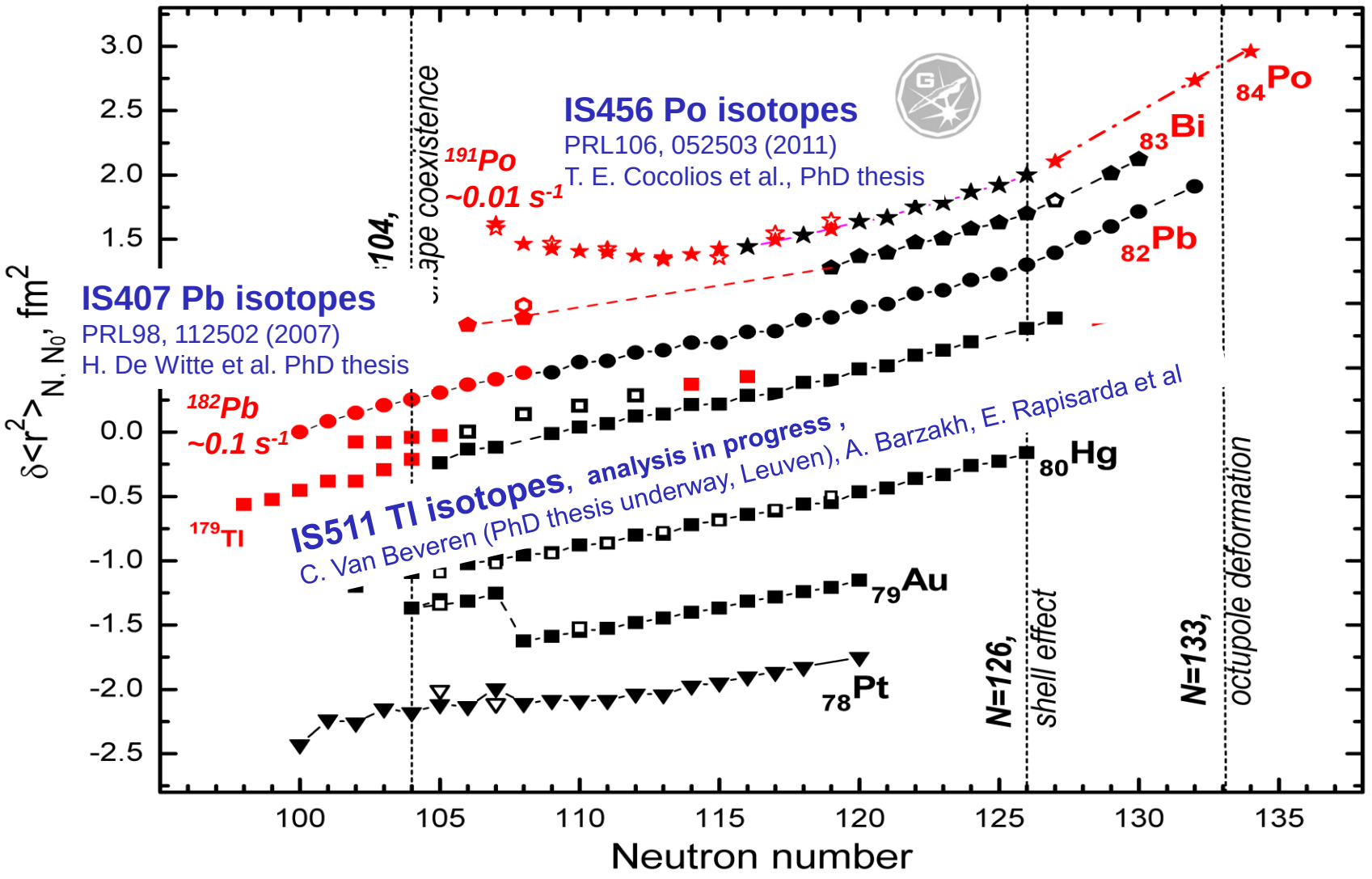


Measurement Tools '2014: WM, FC, MR-TOF MS

B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)
WM: A.Andreyev et al, Phys. Rev. Lett 105, 252502 (2010)
MR-ToF MS: R. N. Wolf et al, NIM, A686, 82 (2012)



~2006-2011: HFS for Tl, Pb and Po



- 3 PhD theses: Pb - H. De Witte (KU Leuven); Bi: B.A. Marsh (Manchester); Po: T.E. Cocolios (KU Leuven)
- 2 PRL's, 1 PLB, + 5 papers

IS466 (2008): Beta-delayed fission of ^{178,180}Tl
(first ever fission studies at ISOLDE?)

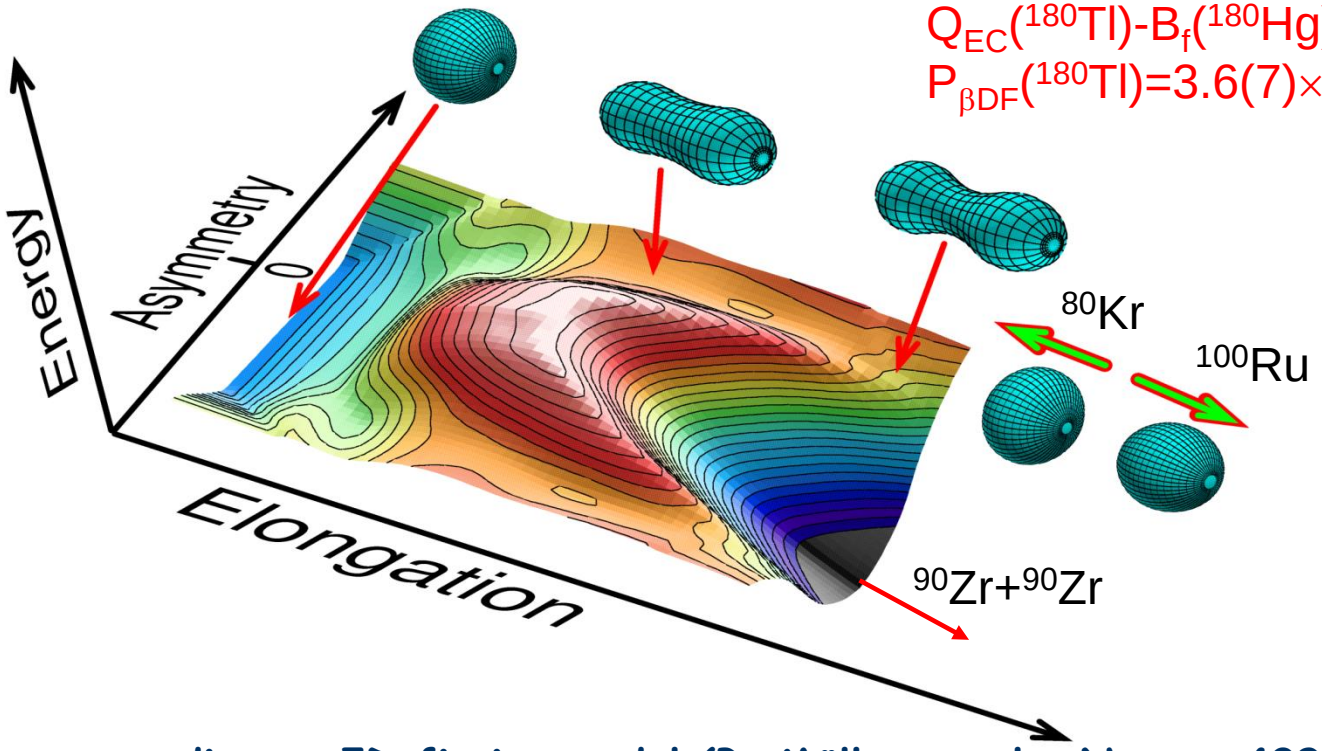
PRL **105,** 252502 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

New Type of Asymmetric Fission in Proton-Rich Nuclei via βDF of ^{180}Tl

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)*

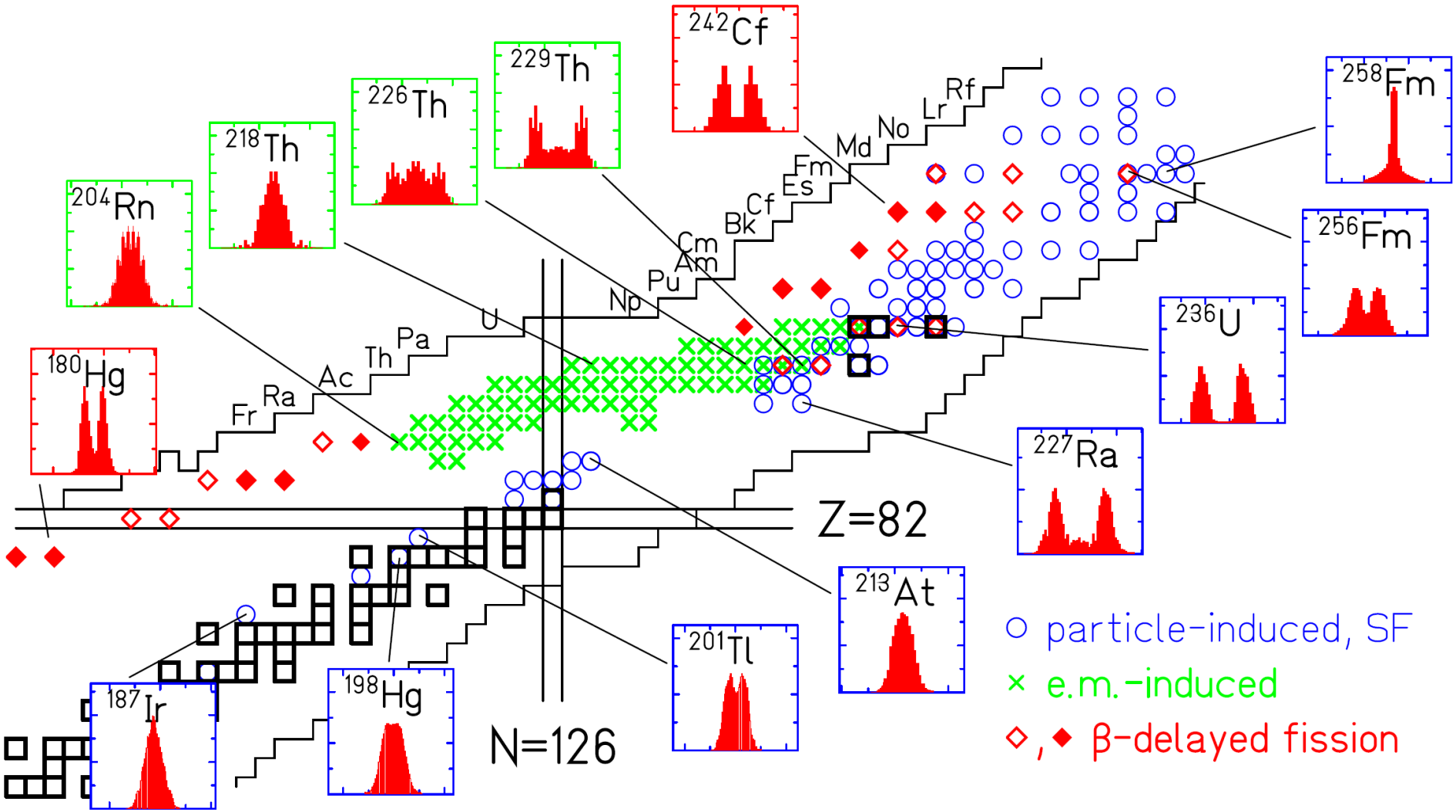
$Q_{EC}(^{180}Tl)=E^*_{max}=10.44$ MeV
$Q_{EC}(^{180}Tl)-B_f(^{180}Hg)=0.63$ MeV
$P_{\beta DF}(^{180}Tl)=3.6(7)\times10^{-5}$



Calculations according to 5D fission model (P. Möller et al., Nature 409, 785 (2001))

IS466/534: Mapping 'Terra Incognita' in Low-Energy Fission
Beta-delayed fission of ^{178,180}Tl, ^{194,196}At, ^{200,202}Fr

A.N. Andreyev, M. Huyse, P. Van Duppen, "Beta-delayed Fission", Reviews of Modern Physics, 85, 1541 (2013)

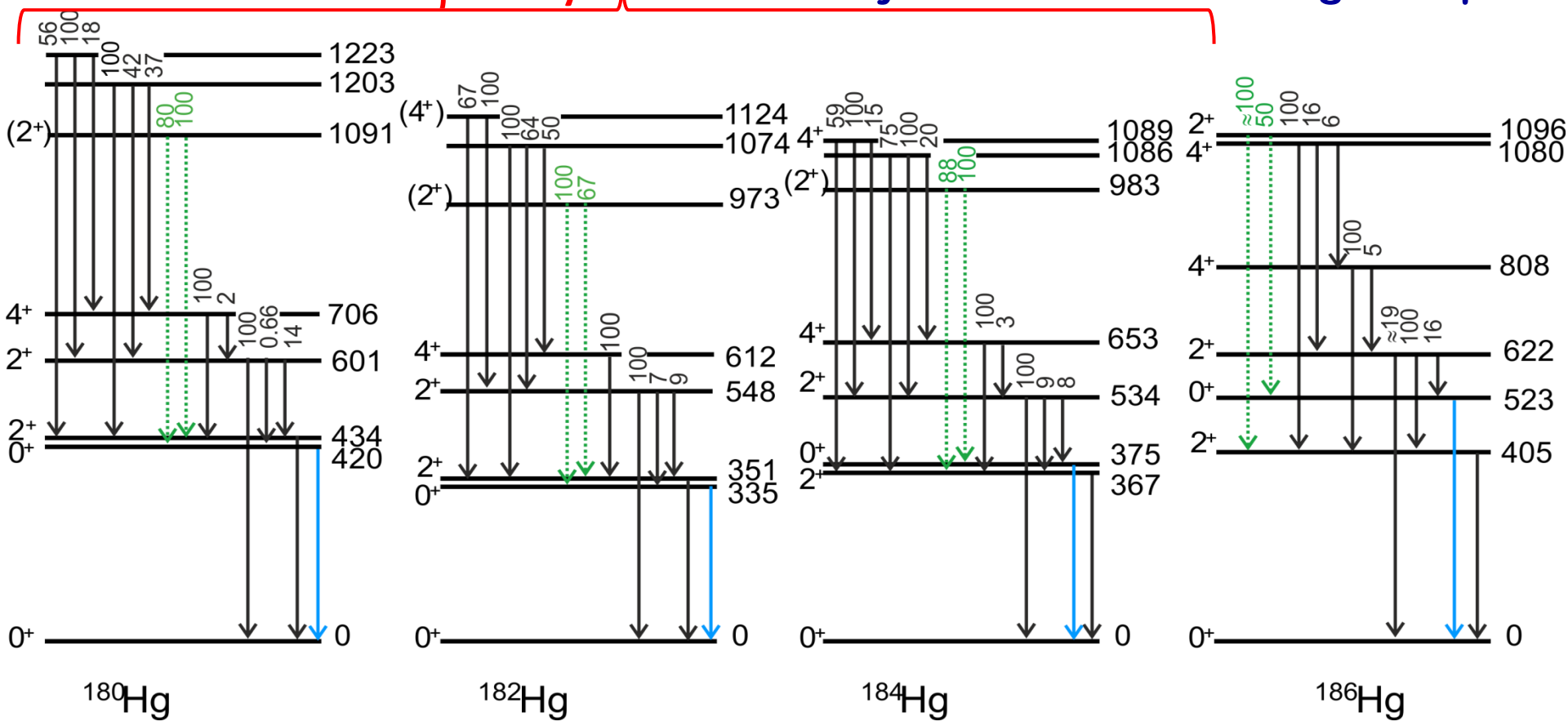


- 1 PhD thesis completed (UWS, 2014), Rev. Mod. Phys., PRL, 3 PRC's
- PRL+2 PRC's in preparation, 2 PhD theses underway, L. Ghys (KU Leuven), V. Truesdale (York)

IS466/IS511/IS534: Shape coexistence and unusually large E0's in Hg isotopes via Tl β decay (courtesy E. Rapisarda)

ISOLDE β-decays

Systematics of even Hg isotopes



α_{CE} ($2^+_2 \rightarrow 2^+_1$) = 3.5(4)

α_{CE} ($2^+_2 \rightarrow 2^+_1$) = 4.7(13)

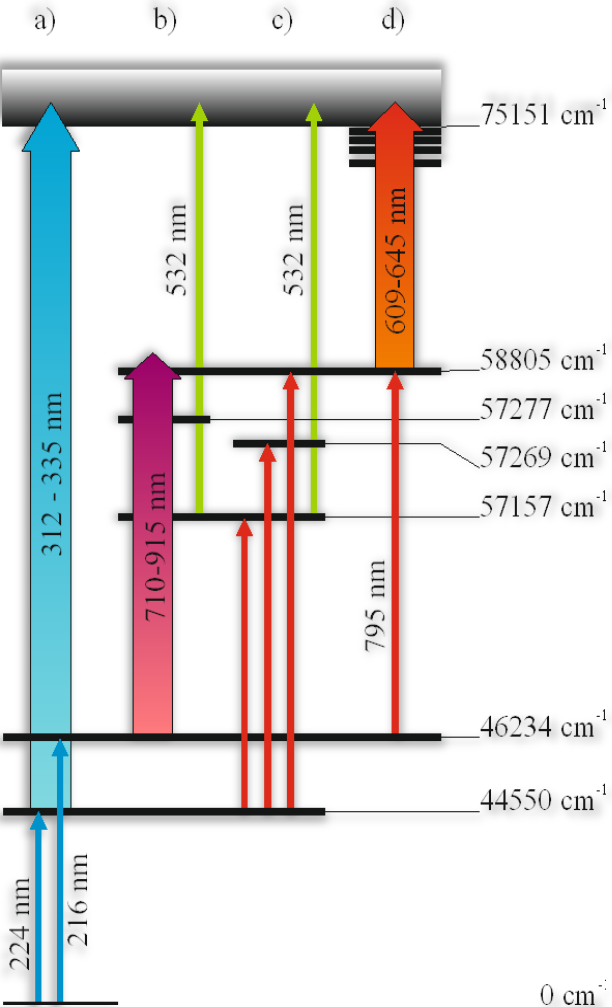
$\rho^2(E0)=89(9)\times10^{-3}$

α_{CE} ($2^+_2 \rightarrow 2^+_1$) = 23(5)

$\rho^2(E0)=54(8)\times10^{-3}$

- Decay properties of low-lying states well characterized by β-decay – **link to Coulex studies**
- More information are expected from the laser spectroscopy of $^{179\text{-}184}$Tl → analysis on going
- more information are expected from the α-decay of $^{182\text{-}184}$Tl → analysis on going

From 2010 on: I086/IS534 Astatine's HFS and βDF



2010: Letter of Intent I086

Development of astatine ion beams with RILIS

Spokespersons: A. Andreyev and V. Fedosseev

- Measurements of HFS, μ, Q for At's
- Shape coexistence in daughter Bi, Po and Rn
- β-delayed fission ^{194,196}At
- Octupole region (N~132-136)
- Atomic spectroscopy (spins of excited states)

nature COMMUNICATIONS

Sebastian Rothe, PhD thesis (2012)

Atomic calculations by two theory groups from GSI

ARTICLE

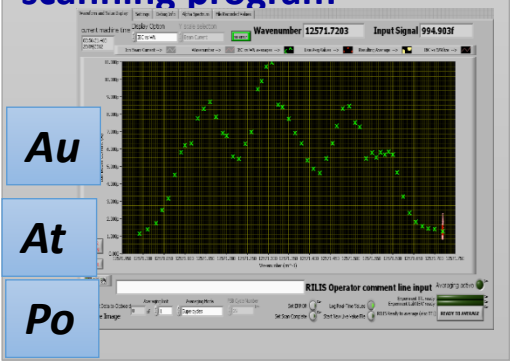
Received 21 Aug 2012 | Accepted 27 Mar 2013 | Published 14 May 2013 DOI: 10.1038/ncomms2819 OPEN

Measurement of the first ionization potential of astatine by laser ionization spectroscopy

S. Rothe[1,2], A.N. Andreyev[3,4,5,6], S. Antalic[7], A. Borschevsky[8,9], L. Capponi[4,5], T.E. Cocolios[1], H. De Witte[10], E. Eliav[11], D.V. Fedorov[12], V.N. Fedosseev[1], D.A. Fink[1,13], S. Fritzsche[14,15,†], L. Ghys[10,16], M. Huyse[10], N. Imai[1,17], U. Kaldor[11], Yuri Kudryavtsev[10], U. Köster[18], J.F.W. Lane[4,5], J. Lassen[19], V. Liberati[4,5], K.M. Lynch[1,20], B.A. Marsh[1], K. Nishio[6], D. Pauwels[16], V. Pershina[14], L. Popescu[16], T.J. Procter[20], D. Radulov[10], S. Raeder[2,19], M.M. Rajabali[10], E. Rapisarda[10], R.E. Rossel[2], K. Sandhu[4,5], M.D. Seliverstov[1,4,5,12,10], A.M. Sjödin[1], P. Van den Bergh[10], P. Van Duppen[10], M. Venhart[21], Y. Wakabayashi[6] & K.D.A. Wendt[2]

Recent technical improvements of the in-source spectroscopy method (2012 onwards)

New live spectra plotting and RILIS DAQ and scanning program



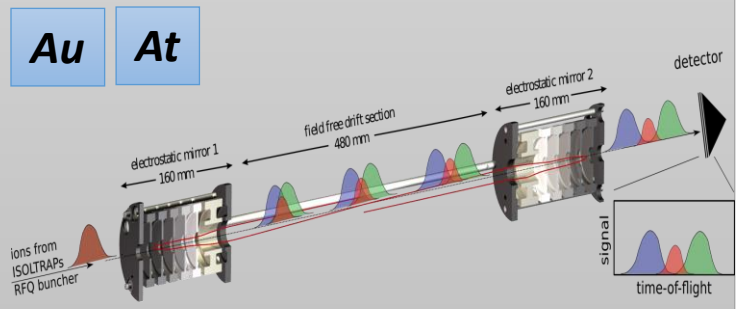
General RILIS

Active beam position stabilization

Dual TiSa and dye laser operation
- 2 spectroscopic transitions in one experiment

Higher laser power for non-resonant ionization

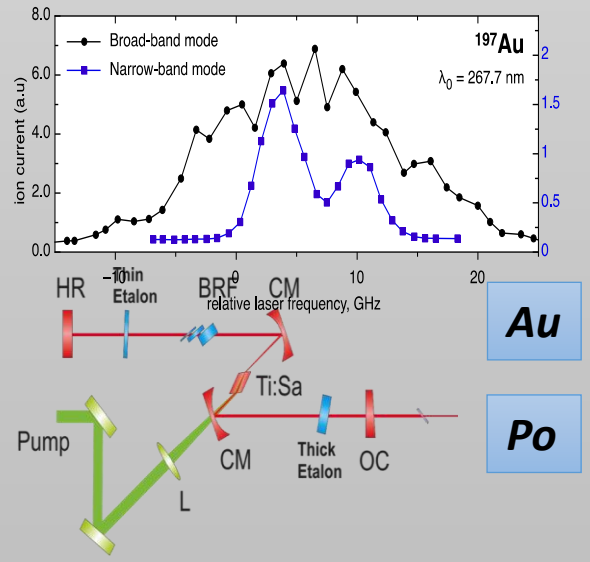
ISOLTRAP MR-ToF MS ion detection



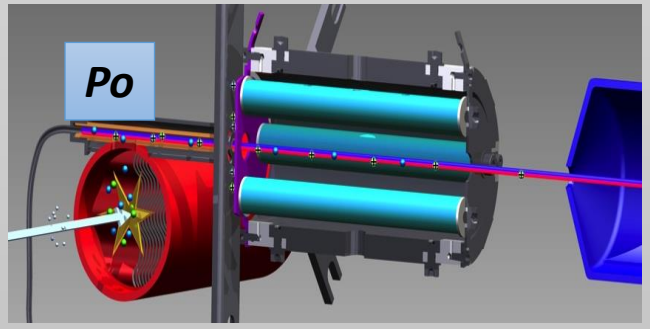
Not limited by decay mod or long half-lives

Mass resolution in the range of $M/\Delta M = 10^5$

Dual etalon, narrow-band Ti:Sa



LIST for francium isobar suppression



CURRENT quality factors:

Selectivity improvement = 10^4-10^5

Efficiency loss = 20x

Reference cell for RILIS

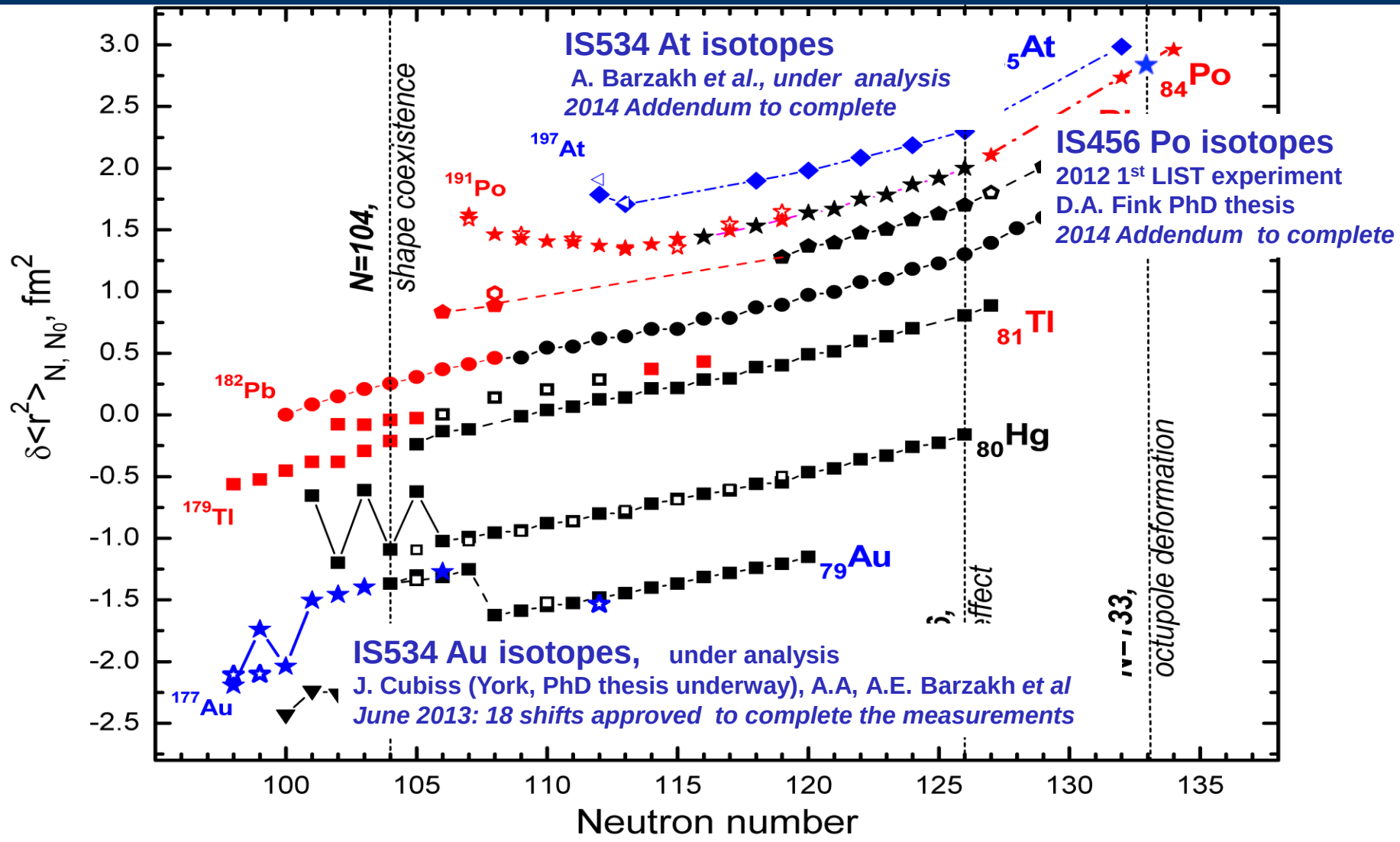
Available in 2014

Reference measurements of stable isotopes

slide courtesy Bruce Marsh

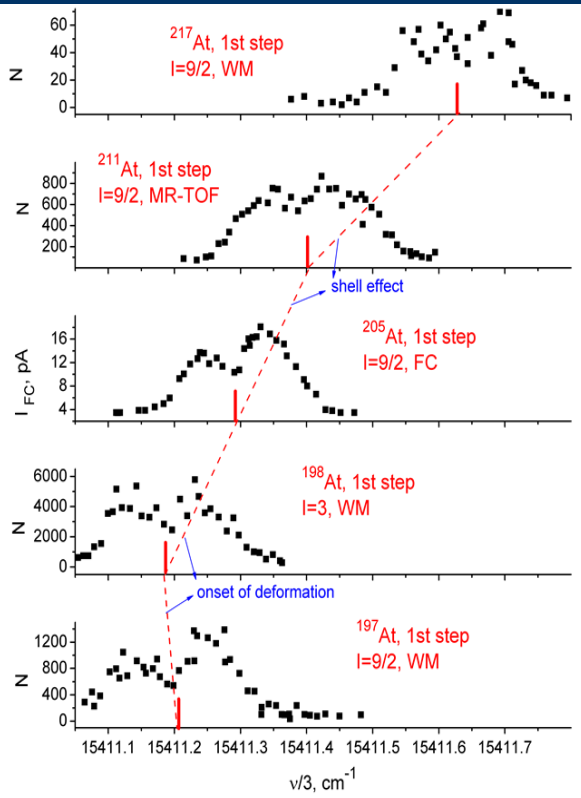
B. A. Marsh et al., 20013 EMIS conference, NIM B317, p.550 (2013)

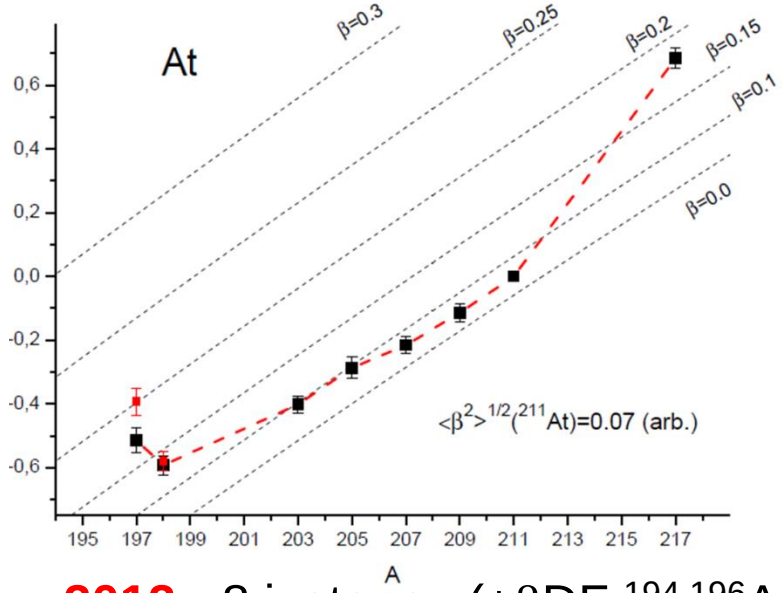
2011-2012 IS534: HFS in Au and At chains

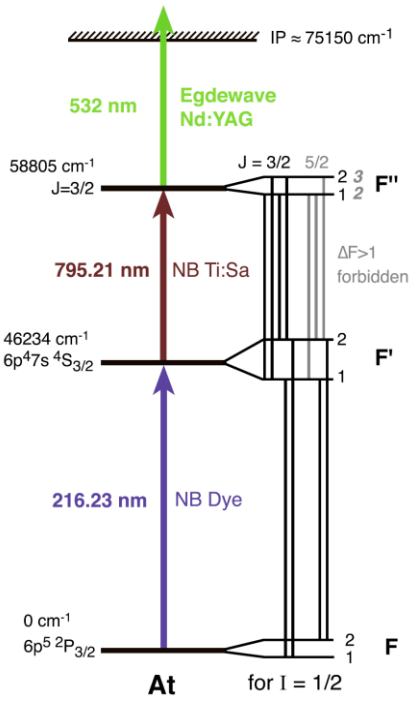


- "Back to sphericity" in the lightest Au isotopes: $^{177\text{-}182,185,191}$Au – IS534
- First measurement for At isotopes: ^{197,198,203,205,207,209,211,217}At – IS534
- First experiment with the LIST: ^{217}Po –IS456

2014: IS534 Addendum to complete HFS studies for $^{193-196,199,201,202,204,206,218,219}$At isotopes (+βDF of ^{194}At)







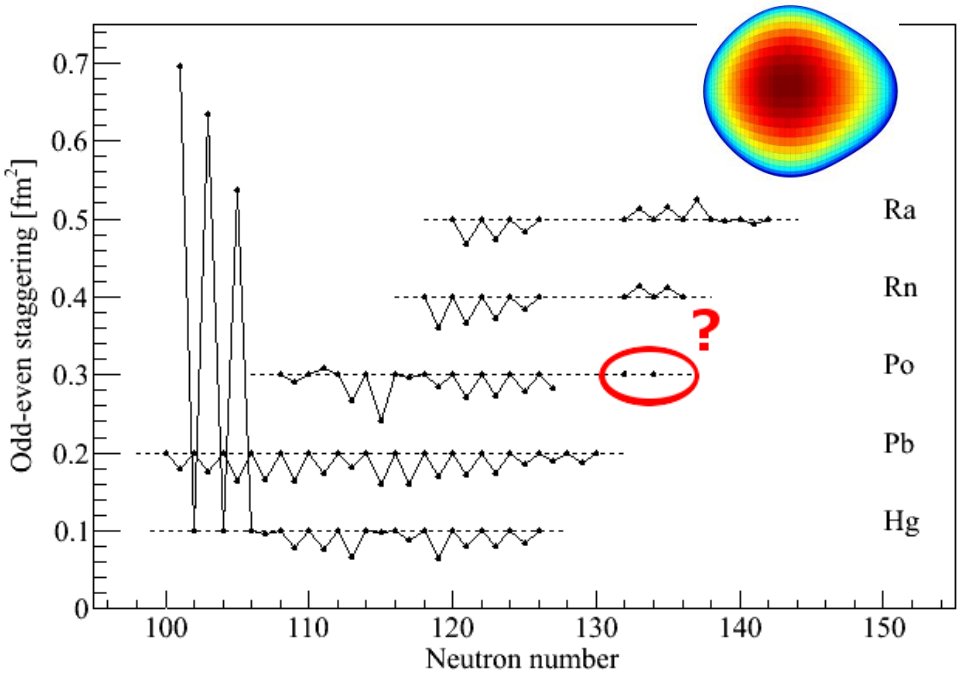
- **2012:** 8 isotopes (+βDF ^{194,196}At)
- WM, FC and MR-ToF MS used
- Both 1st and 2nd step scanning – needed for the King's plot

- **2013-2014**- analysis underway, good understanding of further needs, e.g. better precision needed (in several cases only 1 scan was available)
- **New Addendum:** 2nd step; broader HFS; better precision; (use King's plot '2012)
- IS/HFS for $^{193-196,199,201,202,204,206,218,219}$At: 17 shifts, narrowband HFS scans
- βDF of isomerically-pure beams of ^{194m1,m2}At: 3 shifts, narrowband
- ***In total, 16.5 shifts requested (+3.5 remaining from 2012)***

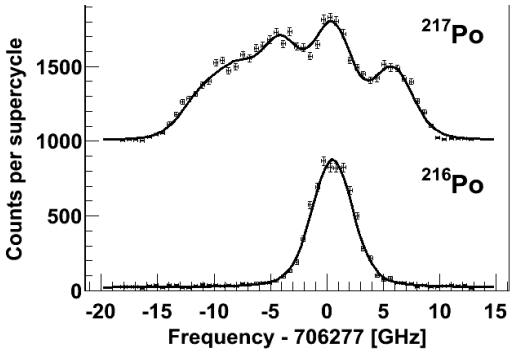
IS456 Addendum: ^{211,212,219,220}Po, goals and shift request

(T.E. Cocolios, S. Raeder et al.)

- Odd-even staggering reversal in charge radii associated with octupole deformation (N~136)
- High-spin isomers and the role of the $\nu i_{11/2}$ orbital for the kink at N=126 (^{211m,212m}Po)
- Further LIST characterization
- **13.5 shifts requested (+4.5 from 2012)**

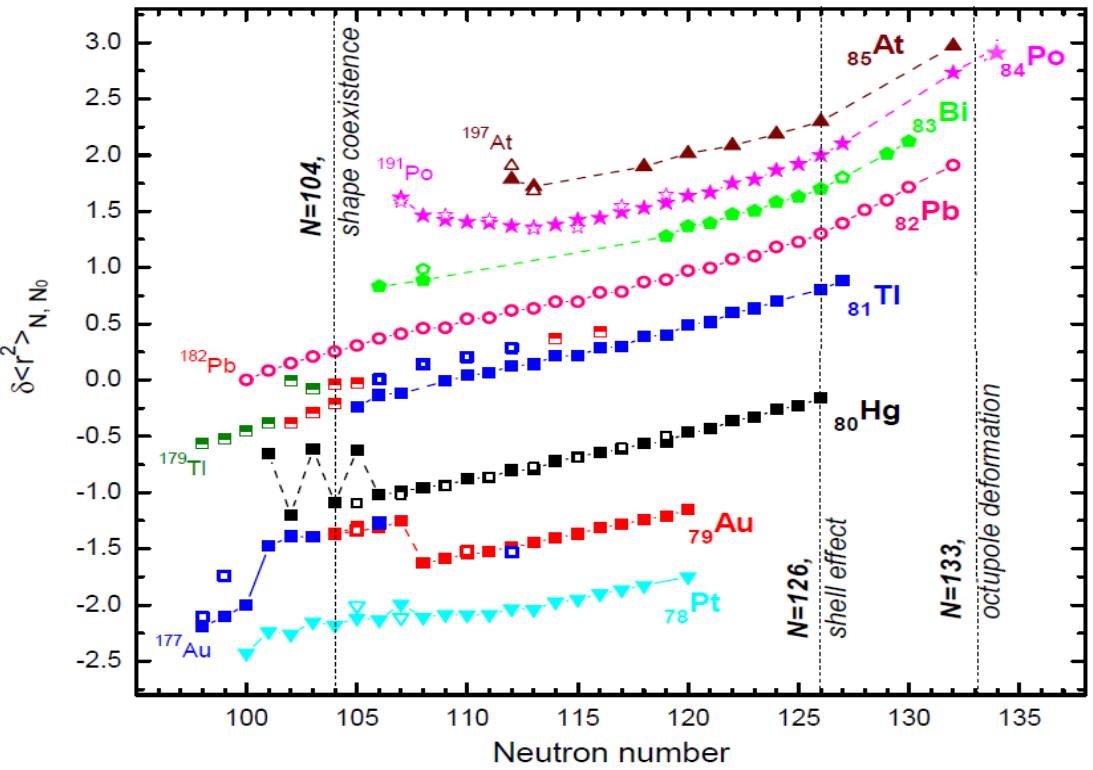


'2012: HFS of ^{217}Po with LIST



Isotope	$T_{1/2}$ [s]	Yield ions/uC	After LIST	Shifts	Isotope	$T_{1/2}$ [s]	Yield ions/uC	After LIST
^{211m}Po	25.2	$5x10^5$	$5x10^4$	1+1	^{211}Fr	186	$1.5x10^8$	*$2.2x10^6$*
^{212m}Po	45.1	$4x10^5$	$4x10^4$	1+1	^{212}Fr	1200	$1.6x10^8$	*$2.3x10^6$*
^{219}Po	~600		30	1+6	^{219}Fr	0.021	$9x10^3$	<100
^{220}Po	?		~10#	1+4+2	^{220}Fr	27.4	$3.8x10^7$	*$4x10^4$#*

Summary: Windmill Collaboration '2014
Charge Radii, Shape Coexistence, Beta-Delayed Fission




nature COMMUNICATIONS

ARTICLE

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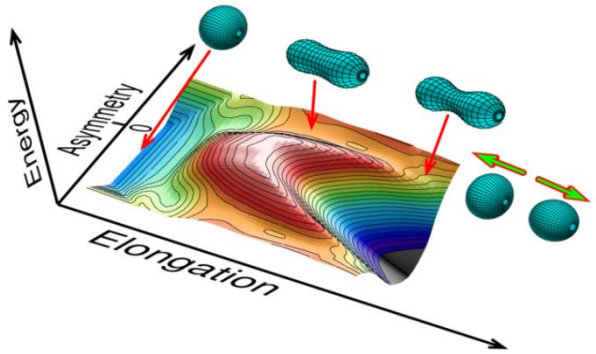
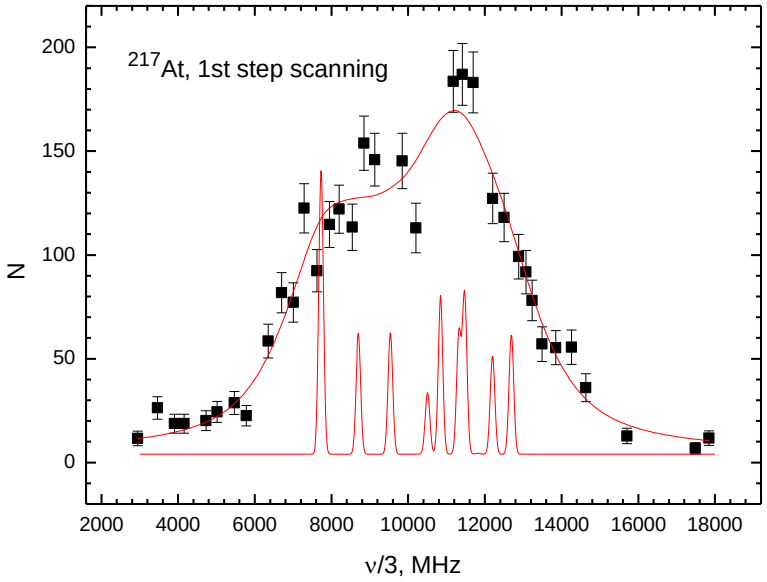
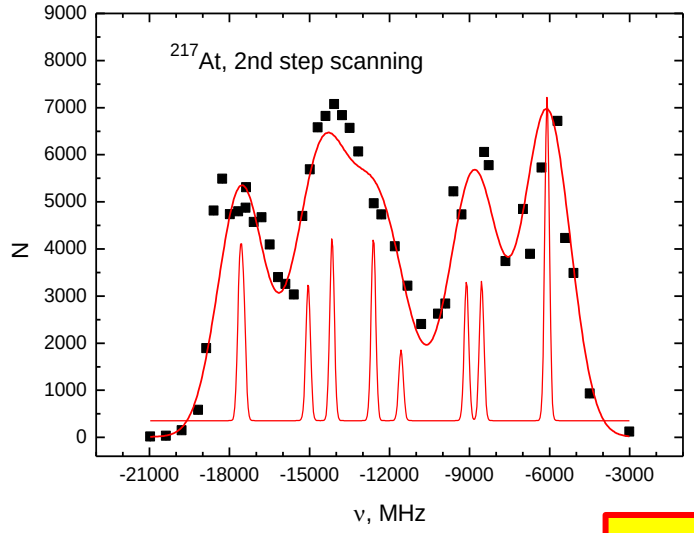


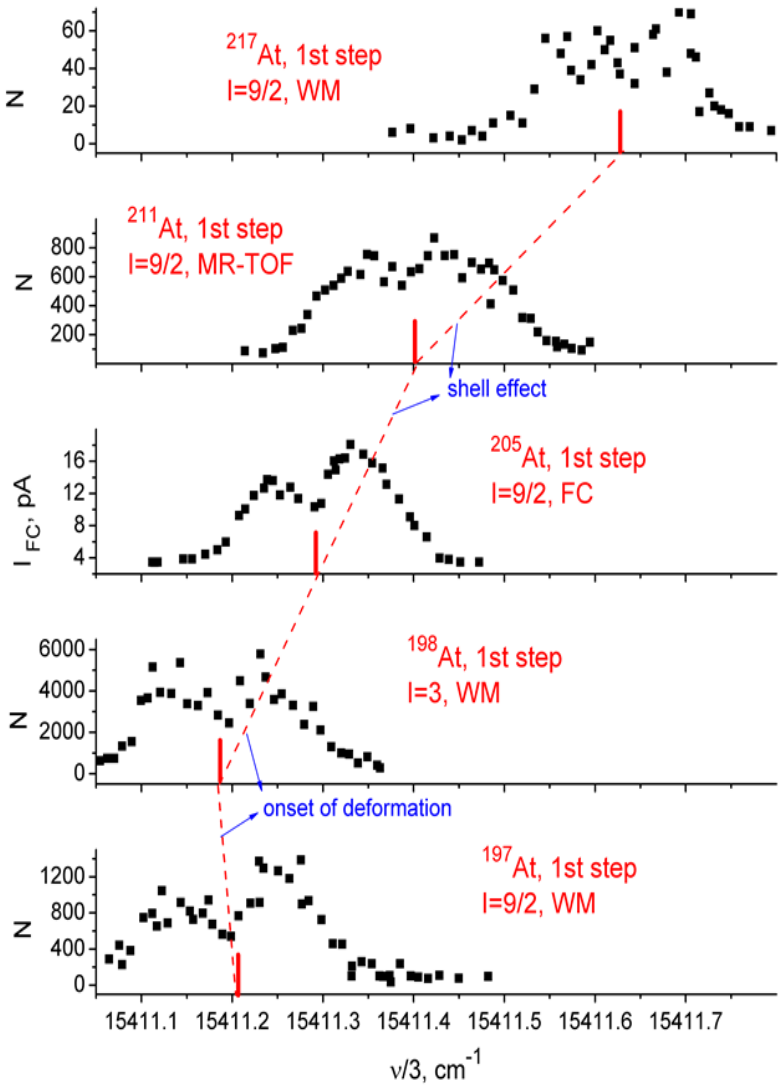
- **HFS measured for ~70 isotopes in the long chains of Au, Tl, Pb, Po and At**
- **Shape coexistence**
- **Beta-delayed fission**
- **Large amount of "by-product" nuclear spectroscopic information (e.g. E0's)**
- **1 RMP, 1 Nat. Comm., 3 PRL's, 1 PLB, + >10 articles**
- **6 PhD and 6 MSc theses completed, 6 PhD projects in progress: Gatchina (1), Leuven (2), Manchester(1), York(2)**
- **Longer-term plans: Bi's -HFS and βDF; Hg's – HFS; heaviest Fr's - βDF**

Thank you!

1st Step scanning vs 2nd step for ^{197}At

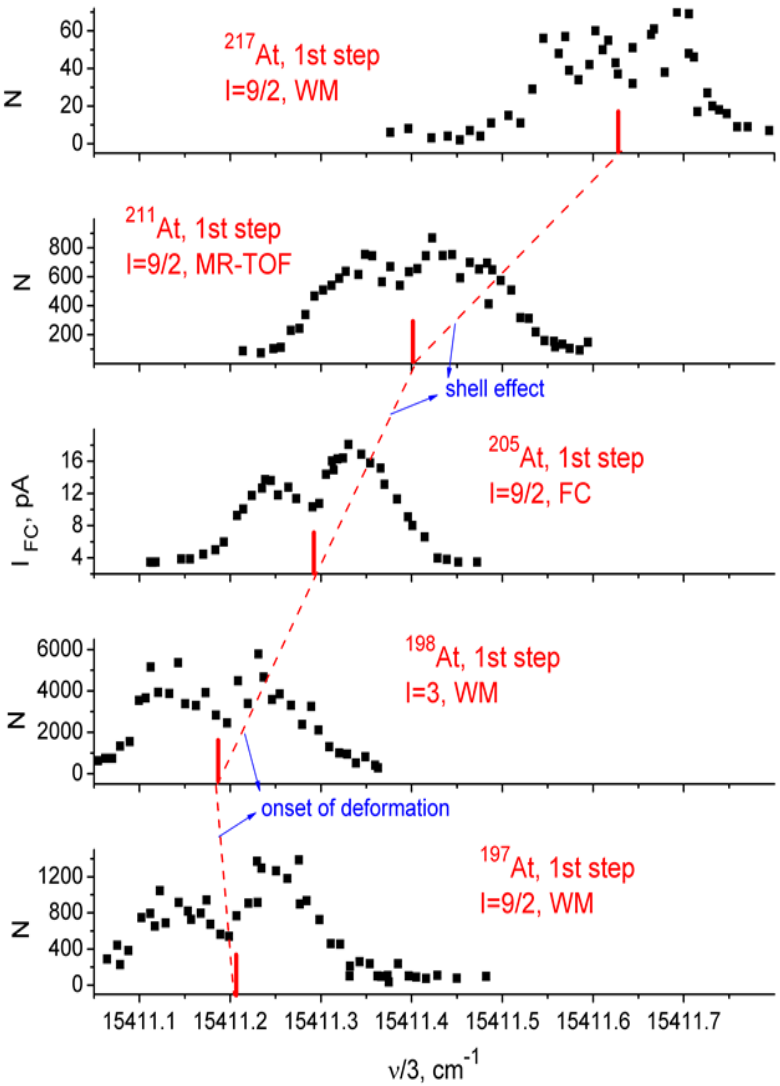


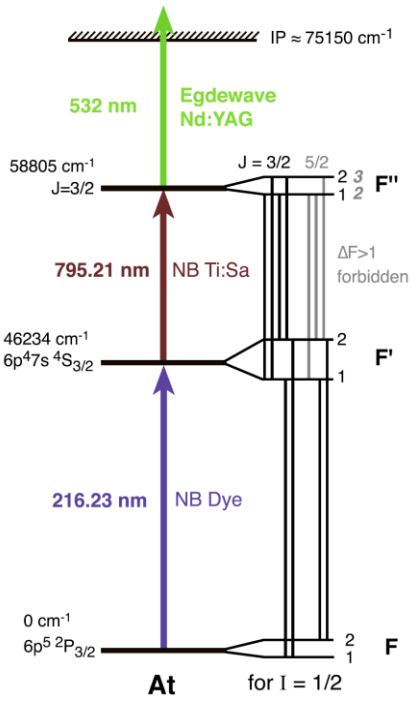


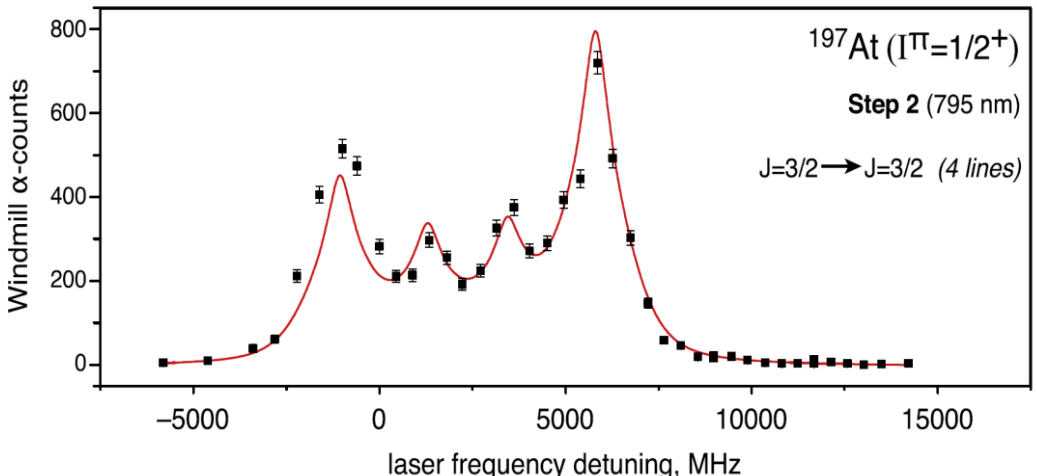


Target temperature!!!

1st Step scanning vs 2nd step for ^{197}At







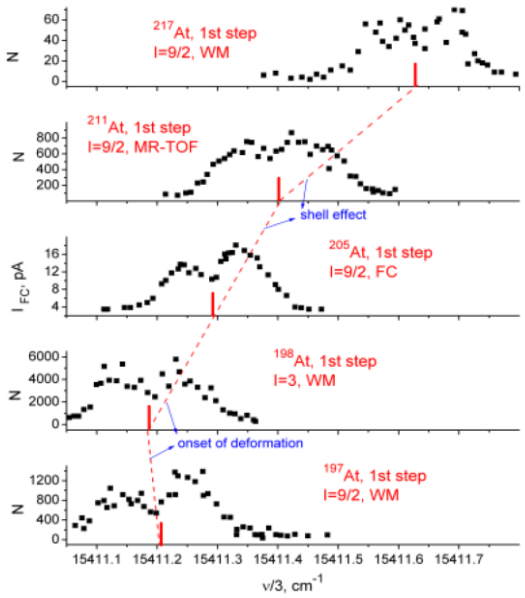


Fig.1. HFS spectra for ^{197,198,205,211,217}At measured in October 2012 at HRS, by using WM, MR-TOF MS and FC. Vertical bars — centres of gravity of the corresponding HFS spectra.

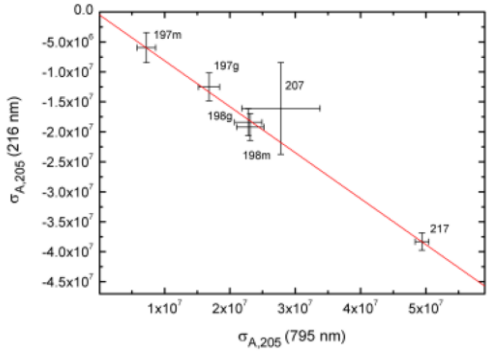


Fig.2. (Preliminary) King plot for 216 nm and 795 nm transitions in astatine.

The $\Delta\sigma$ value for a specific transition (e.g. 216 nm or 795 nm) is defined as:

$$\Delta\sigma_{A,A'} = \Delta\nu_{A,A'} \cdot \frac{A \cdot A'}{(A - A')}, \text{where}$$

$\Delta\nu$ is the isotope shift between two isotopes with masses A and A'.

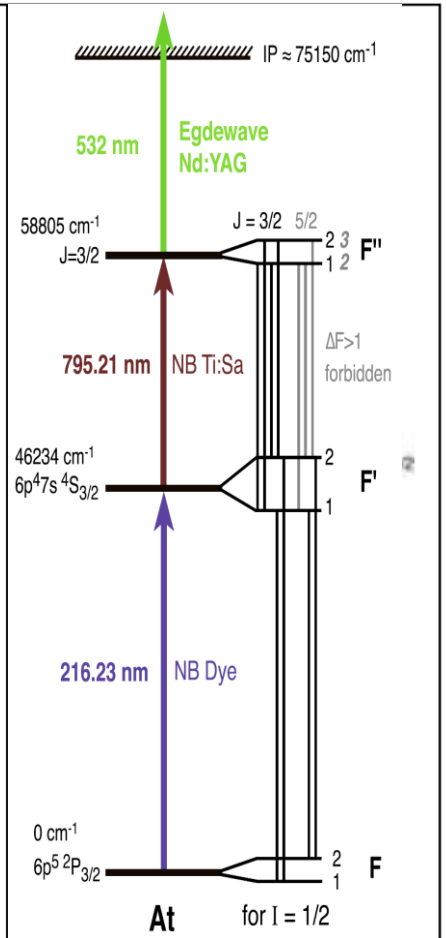
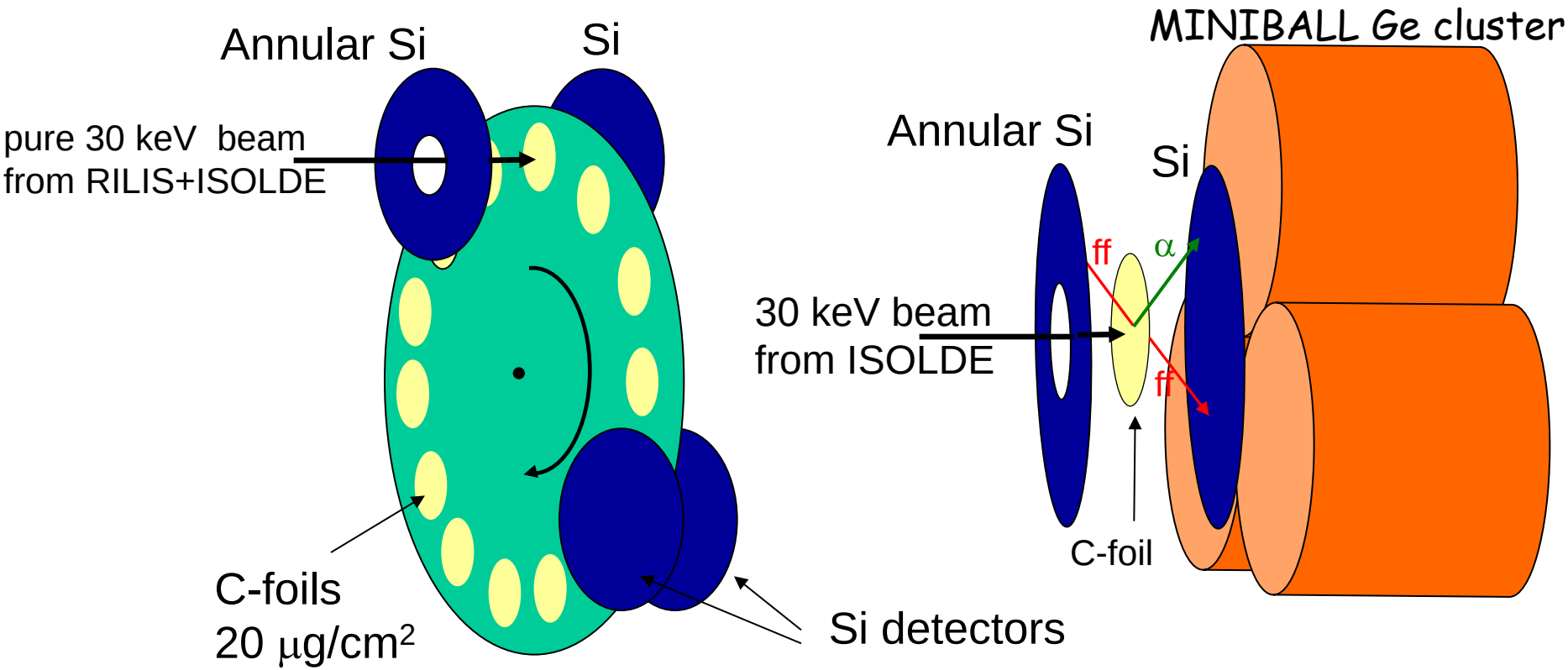


Fig. 3 Ionization scheme for astatine.

Windmill System (WM) at ISOLDE

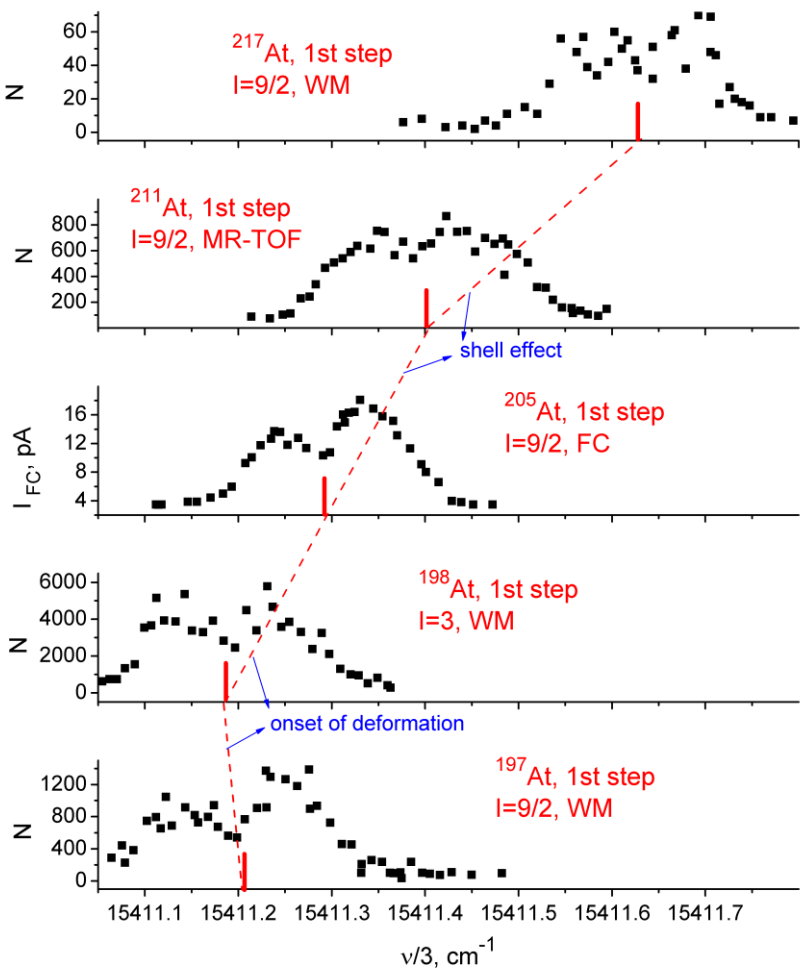
A. Andreyev et al., PRL 105, 252502 (2010)

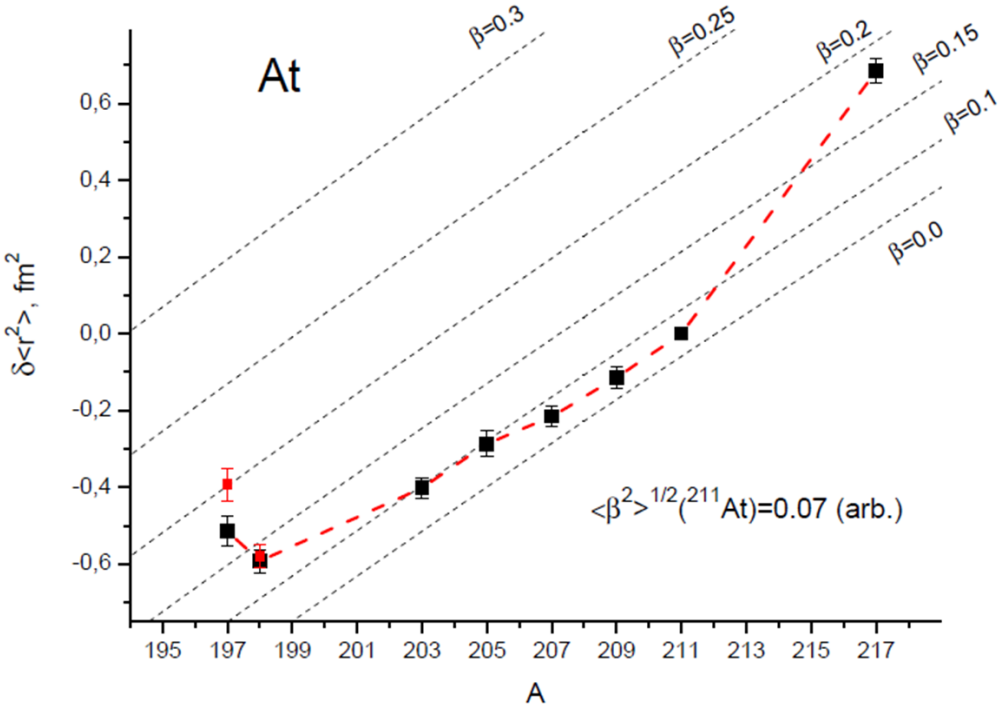


Setup: Si detectors from both sides of the C-foil

- 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

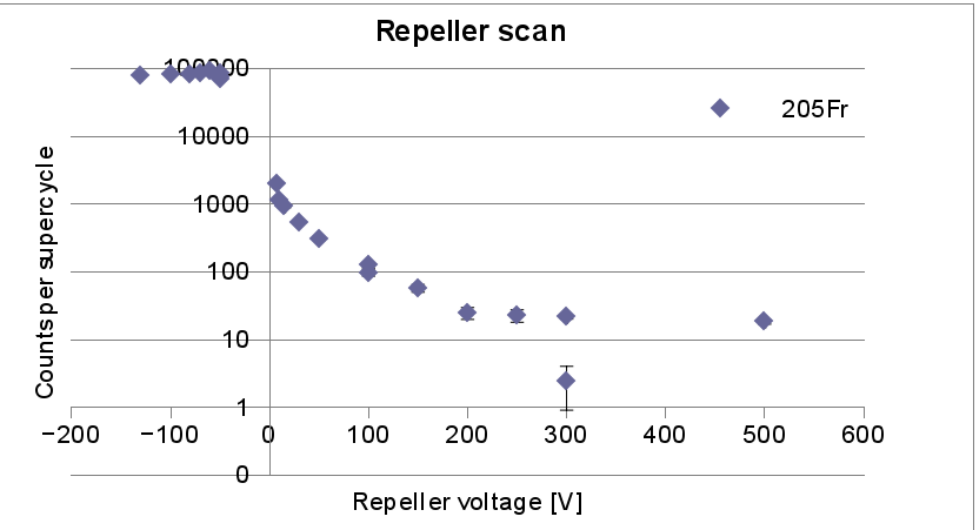
2012: IS534 HFS spectra for At isotopes (+ βDF of ^{194,196}At)



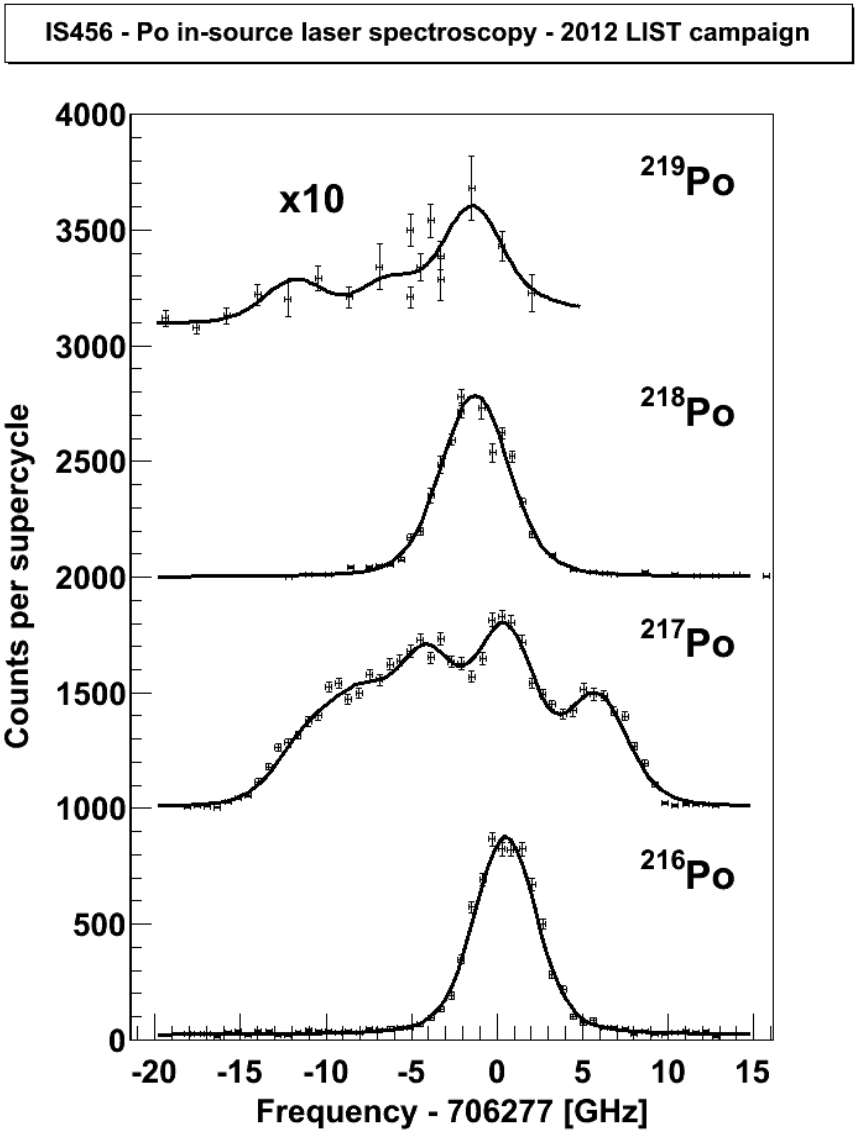


'2012 IS456 Results for $^{216-219}$Po with LIST and Addendum (courtesy T.E.Cocolios)

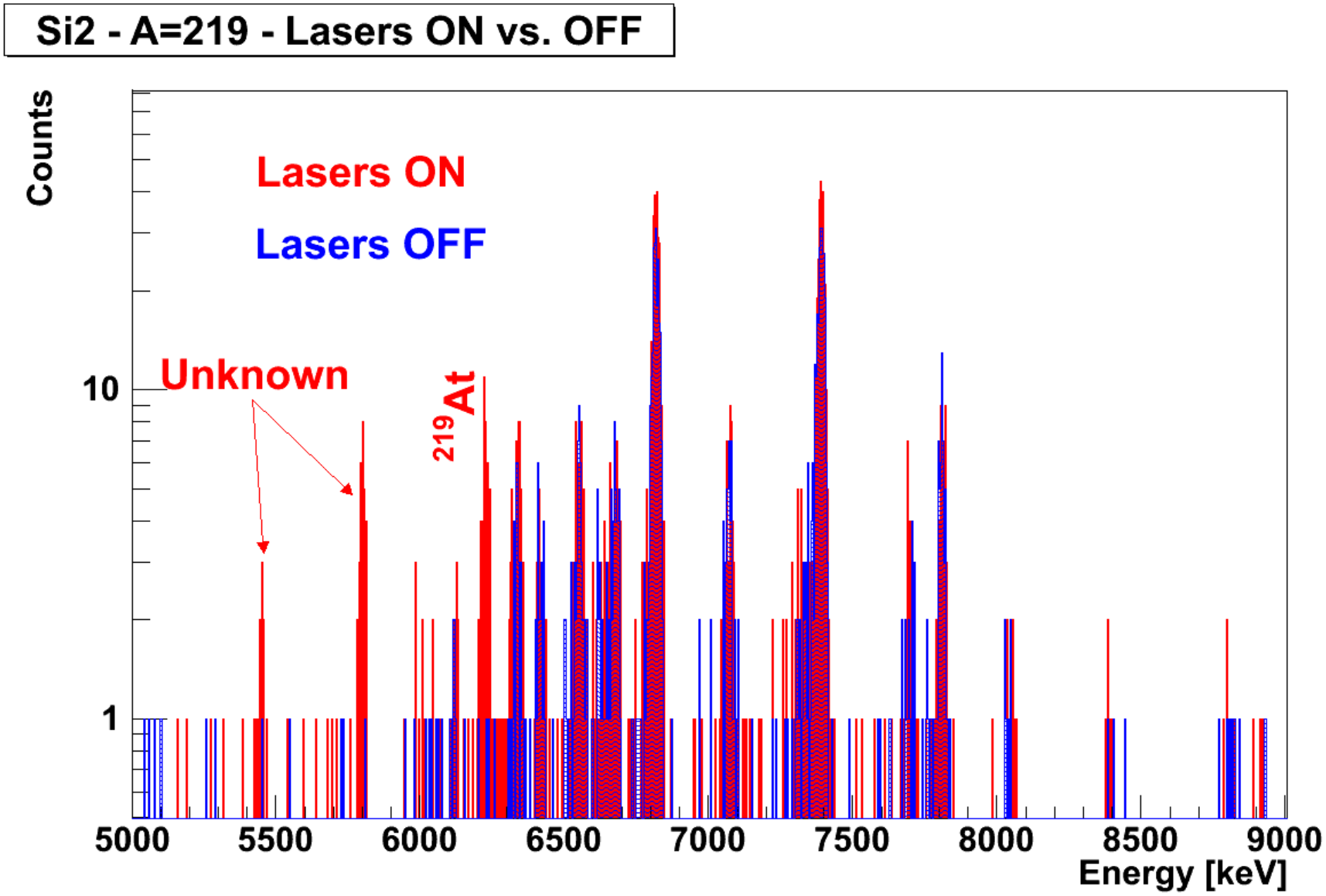
- 2006-2009 campaigns – mostly neutron-deficient, need data for ^{211,212,219,220}Po, but dominant Francium contamination
- **2012 campaign with LIST**
- **Fr suppression by >1000**
- **Po reduction by <10**
- **First laser spectroscopy of $^{216-219}$Po possible**



D.A.Fink et al, NIMB 317 (2013) 417-421



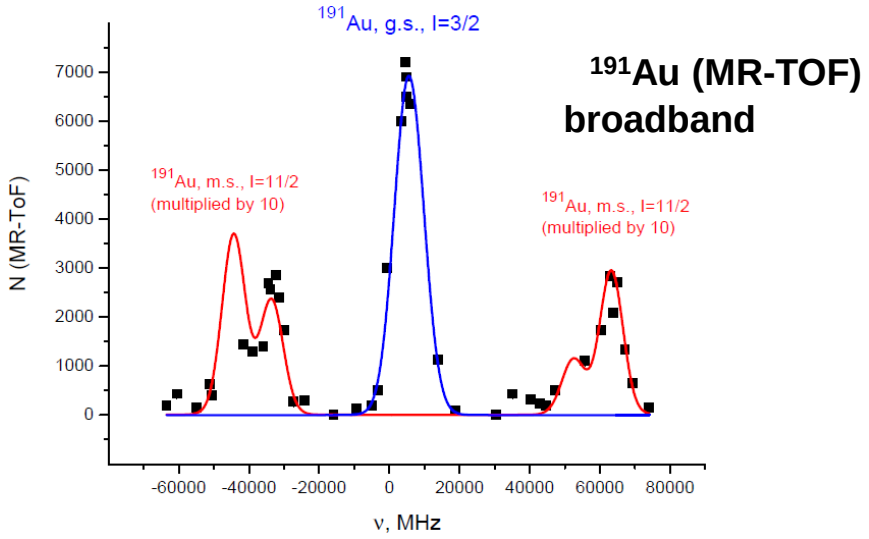
2012' IS456: First decay spectroscopy of ^{219}Po



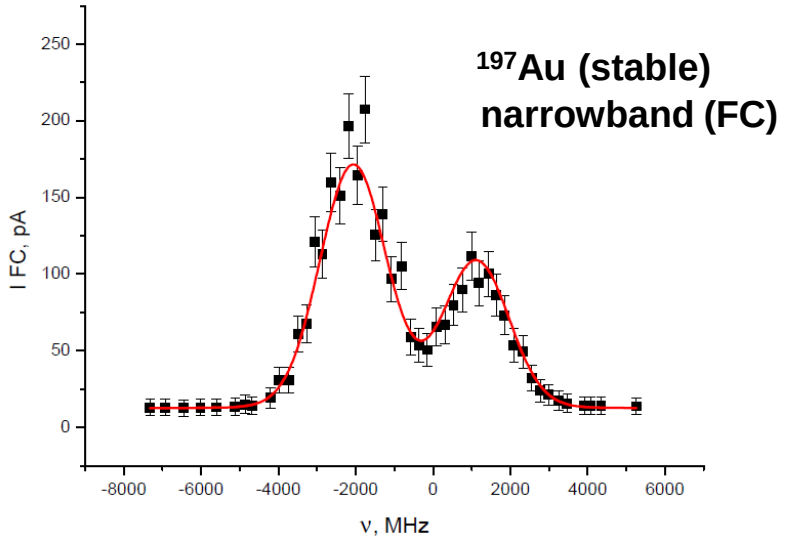
Goals of the IS456 Add: high-spin isomers, deformation and $\nu i_{11/2}$

- For N>126, kink is seen in charge radii.
- Recent work by Goddard & Stevenson claims it relates to occupancy of $\nu i_{11/2}$.
- Long-lived, high-spin (18^+) isomer in ^{212}Po arises from a neutron occupying this orbital.
- Direct study of its properties (spin, magnetic dipole moment, quadrupole moment, charge radii) to determine the importance of this orbital for the isotopes with N>126.

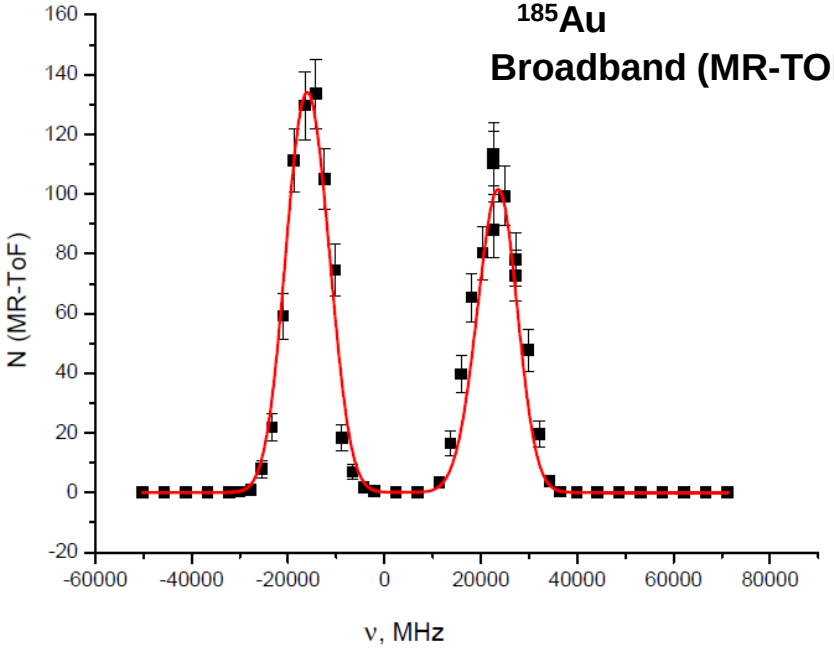
Hyperfine Splitting Scans for ^{178,185,191,197}Au



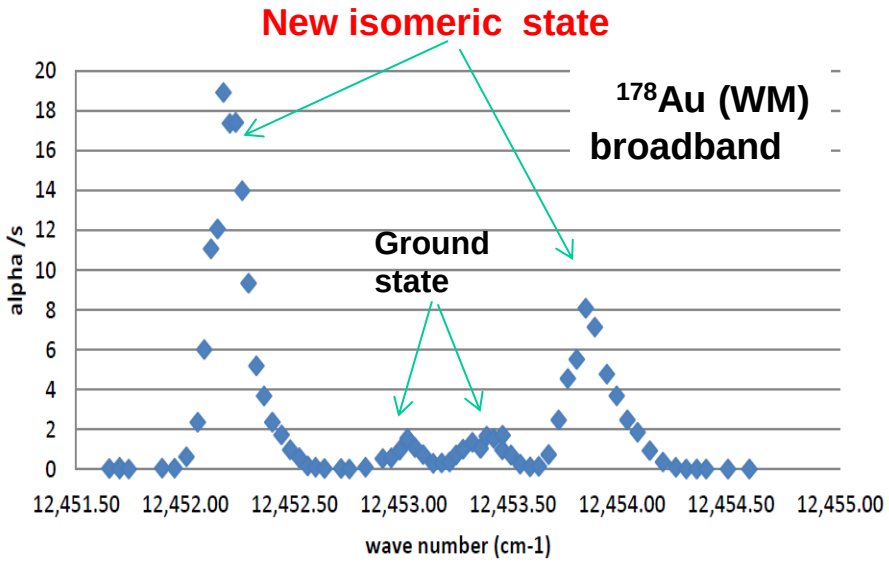
^{191}Au (MR-TOF)
broadband



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

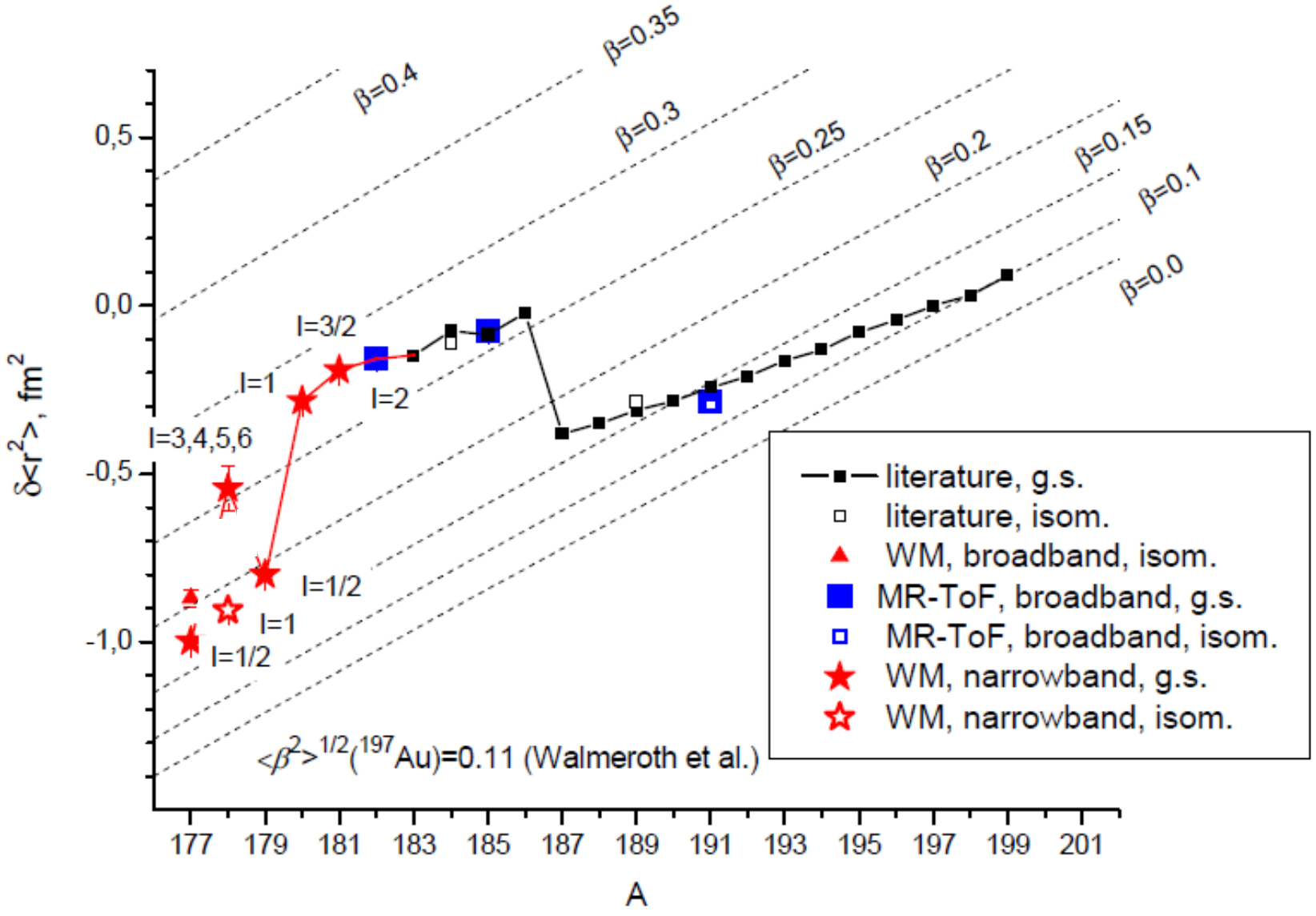


^{185}Au
Broadband (MR-TOF)



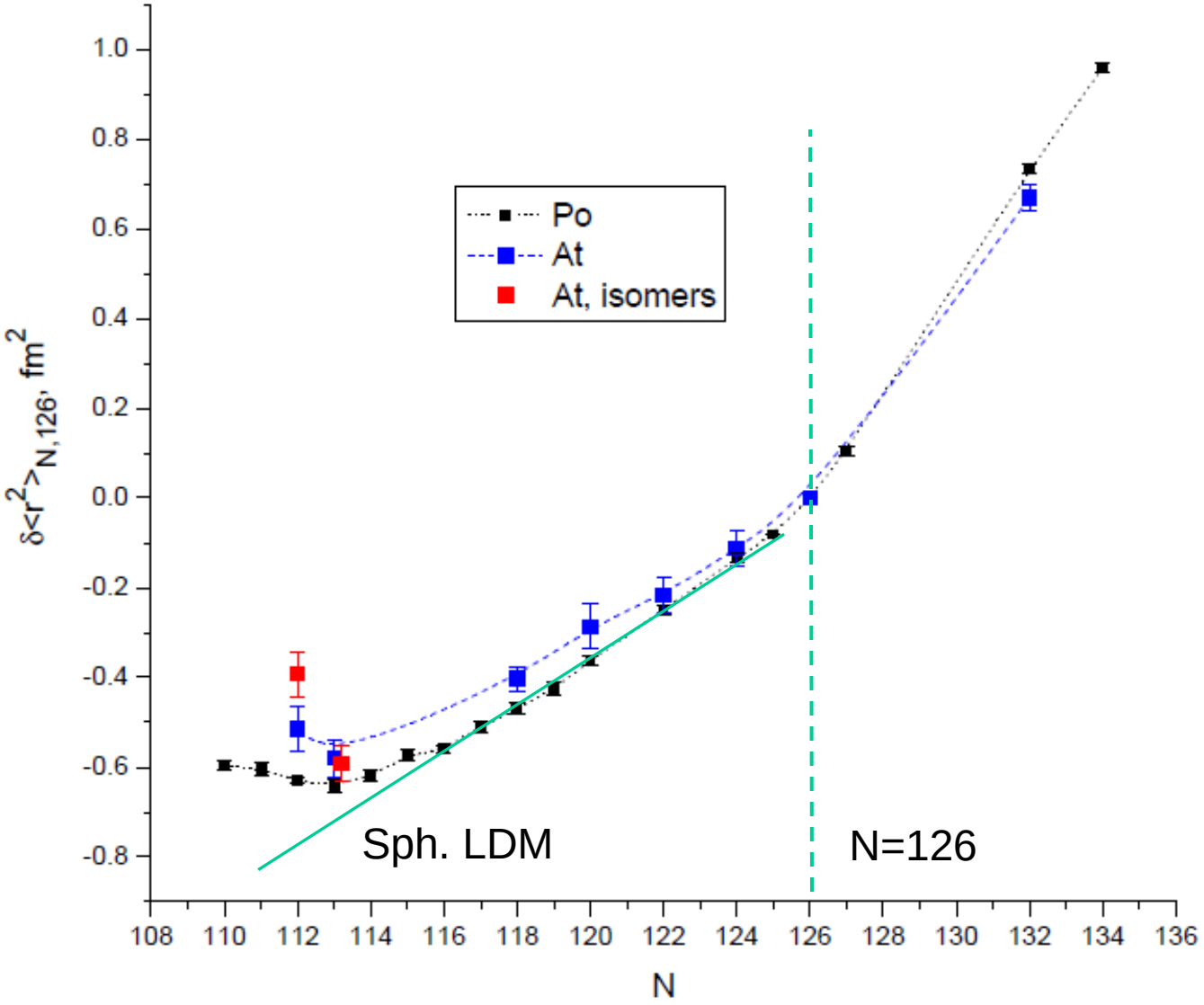
^{178}Au (WM)
broadband

IS534: Charge Radii of Au isotopes, ISOLDE 2012



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

At vs Po charge radii



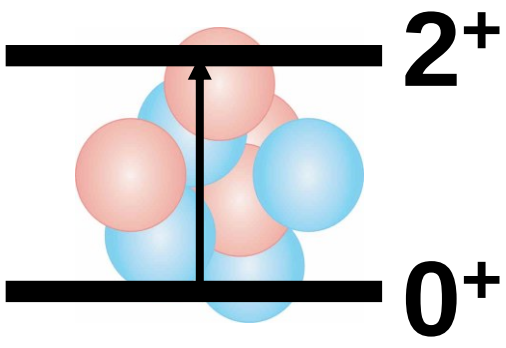
Result II: to be more quantitative → ρ^2(E0)

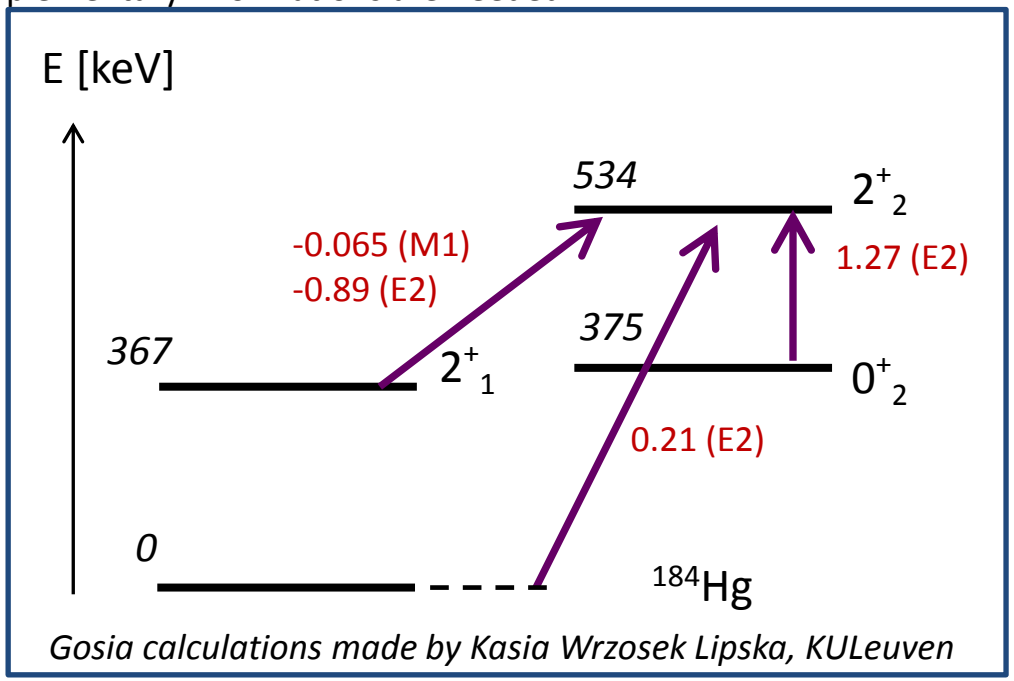
We can get the strength of the E0 transition but complementary informations are needed …

ICC → $N_e(E0) + N_e(\overset{?}{M1}) + N_e(\overset{?}{E2})$

From Coulomb excitation of ^{182,184}Hg

(Nick Bree, PhD in KULeuven)





$(2^+_2 \rightarrow 2^+_1)$	
^{184}Hg	^{182}Hg
$\rho^2(E0)\cdot10^3$ 54±8	$\rho^2(E0)\cdot10^3$ 89±9

unusually large $\rho^2(E0)$ (values in this mass region are ~ 10)

$$\rho^2(E0) \times 10^3 = \alpha_I^2 \cdot \alpha_{II}^2 \cdot \frac{Z^2}{R^4} \cdot \Delta\langle r^2\rangle^2$$

Using the two states mixing model, by knowing the mixing amplitudes $\alpha_I^2 \cdot \alpha_{II}^2$, we can:

- ✓ extract the difference in mean-square radii $\Delta\langle r^2\rangle^2$
- ✓ compare it to the isomeric shifts measurements

WORK in PROGRESS

Five Physics Cases for LoI I086

- **Studies of the beta-delayed fission (βDF)** in At isotopes

- **HFS, IS and charge radii measurements within the long chain of At isotopes**, from the very neutron-deficient side, across the N=126 neutron closure, up to the most neutron-rich isotopes

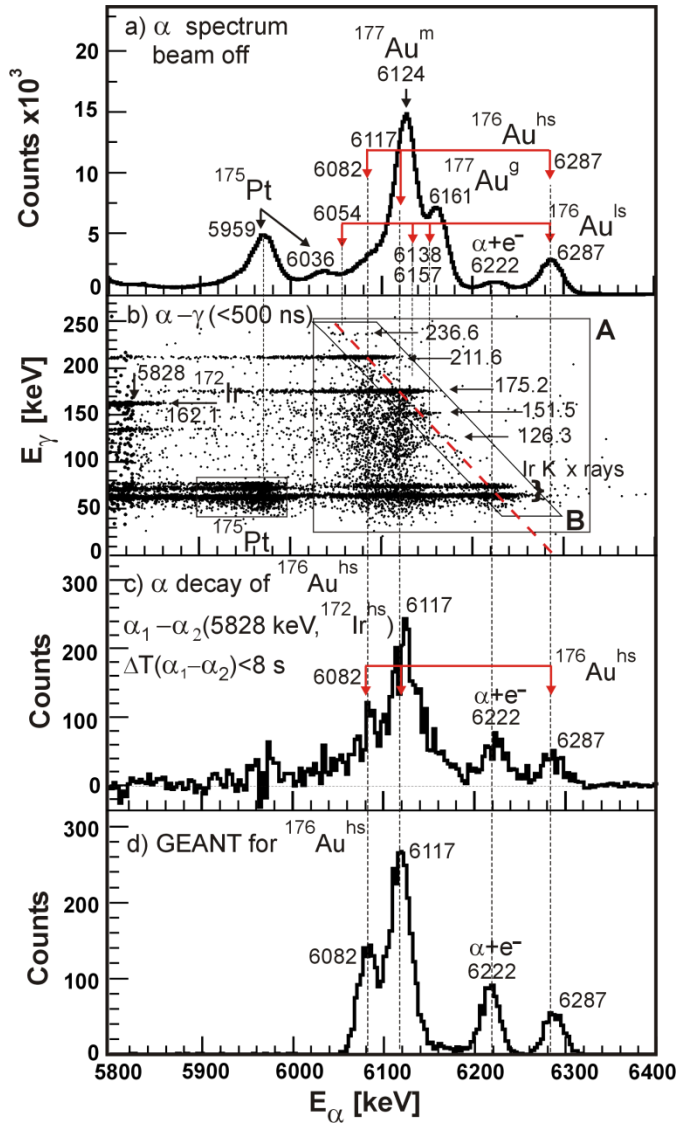
- **Shape coexistence in the lightest Po isotopes** (β^+/EC -decay products of At), in particular the search for coexisting oblate, prolate and spherical 0^+ band-heads and corresponding excitations in the odd-A Po isotopes

- **Search for octupole collectivity in the neutron-rich Rn isotopes** (beta-decay products of At) (

- **Few-nucleon transfer reactions of At isotopes** to study single-particle around N=126 and multi-particle multi-hole structures in the neutron-deficient and neutron-rich isotopes. This would need beam energies from HIE ISOLDE.

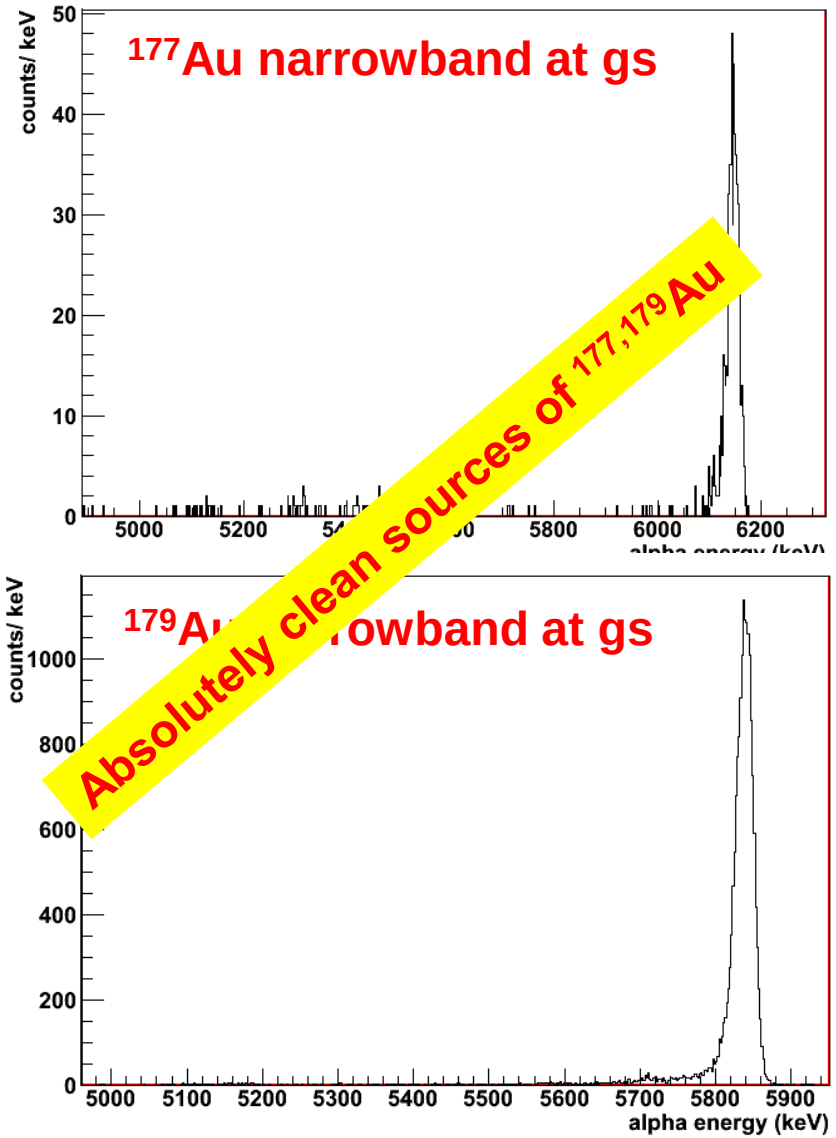
9-12 October 2012: Laser spectroscopy of Au isotopes with RILIS+ISOLDE

SHIP: $^{40}Ca^{+141}Pr \rightarrow ^{176}Au+5n$

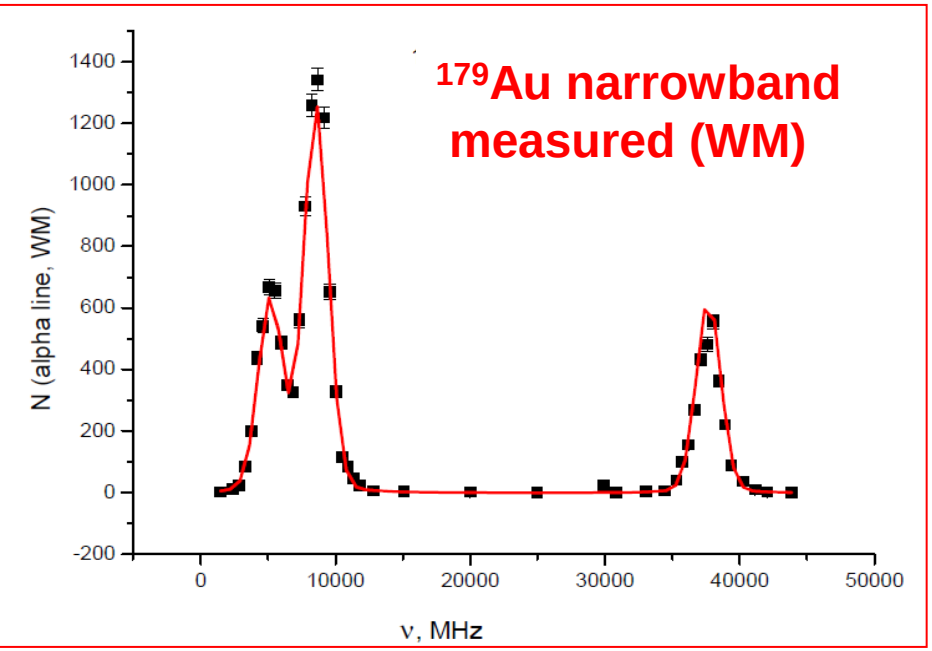


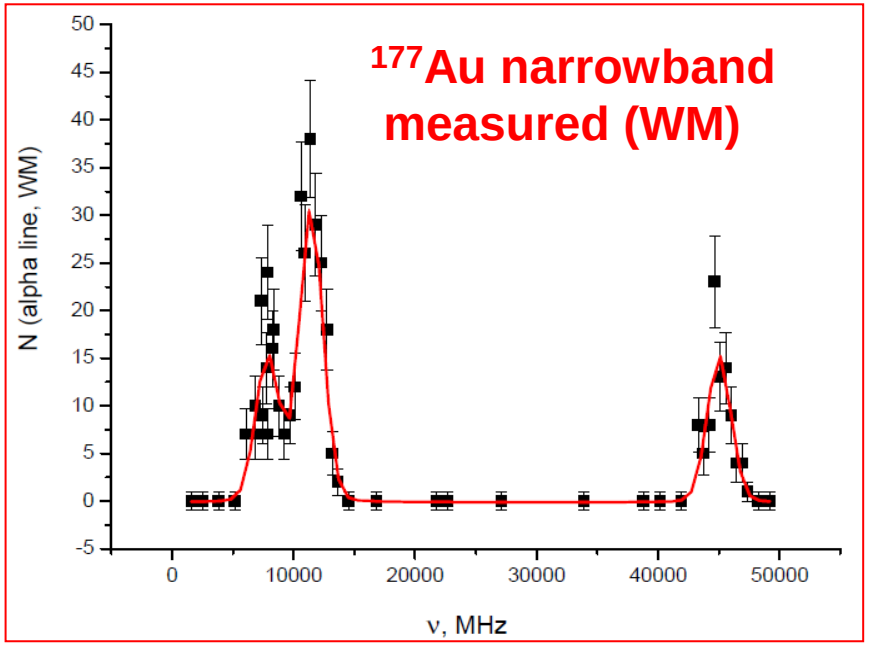
A. Andreyev et al, draft ready

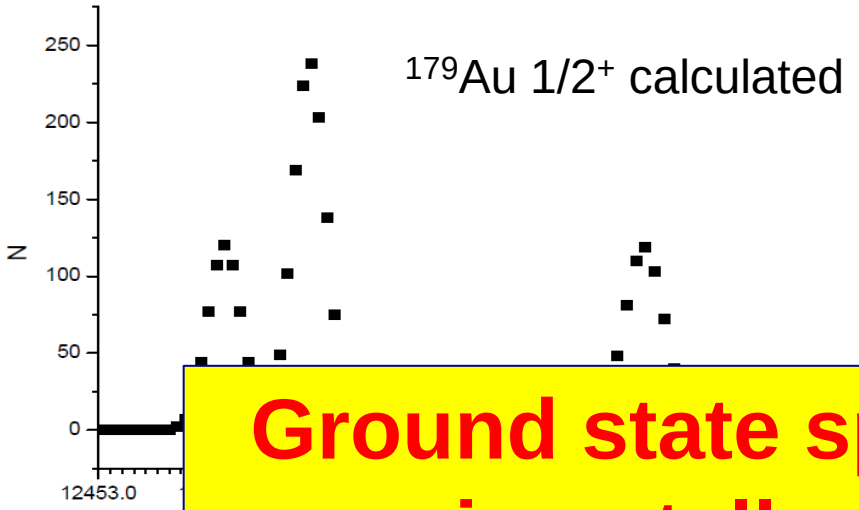
$^{177,179}Au$, RILIS+ISOLDE

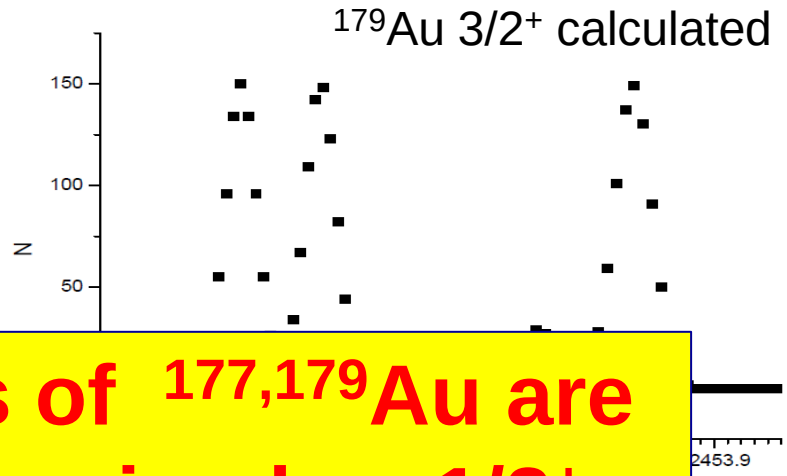


IS534: Hyperfine Splitting Scans (HFS) for ^{177,179}Au





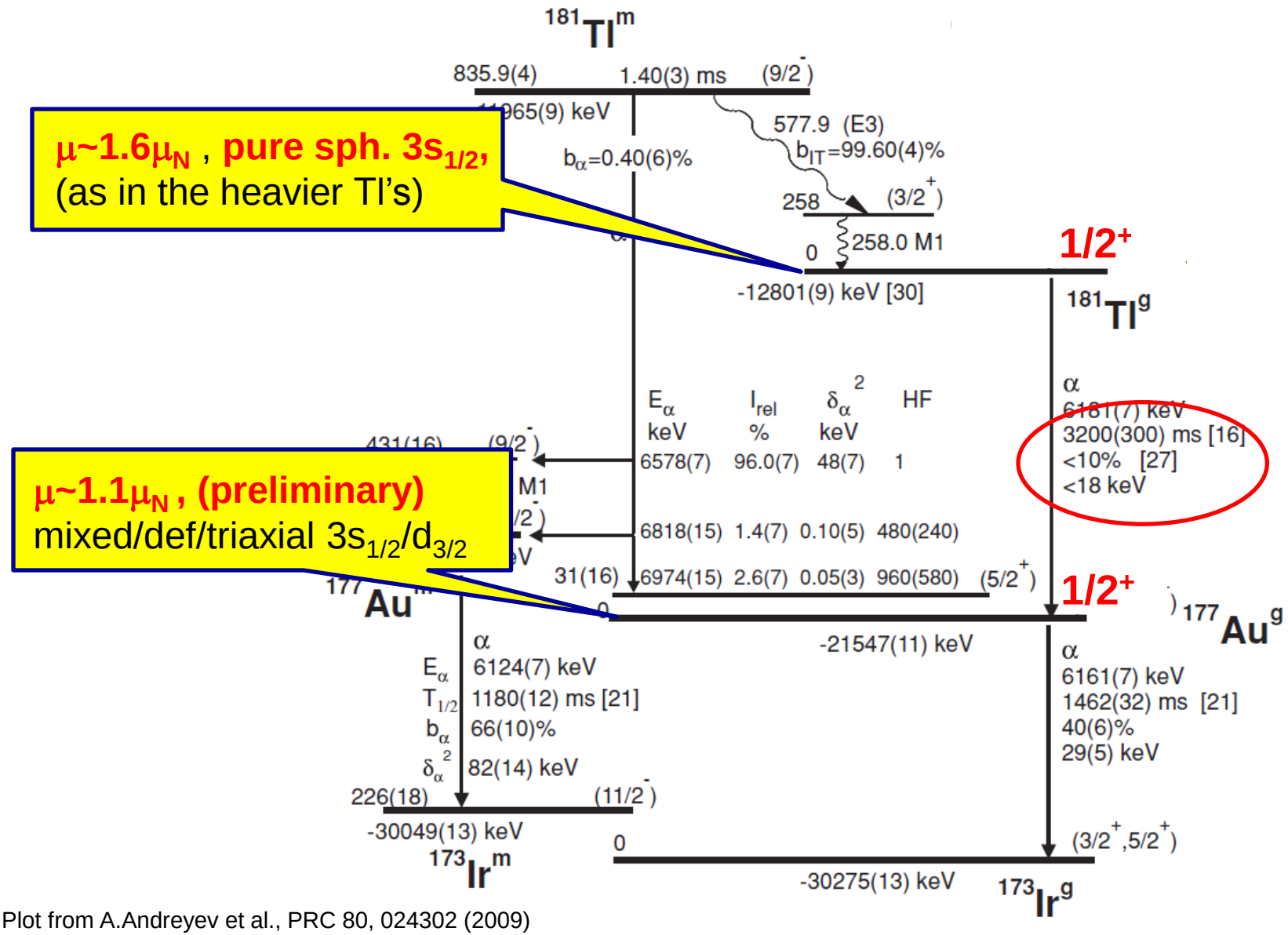




Ground state spins of ^{177,179}Au are experimentally determined as 1/2$^+$

Calculations co

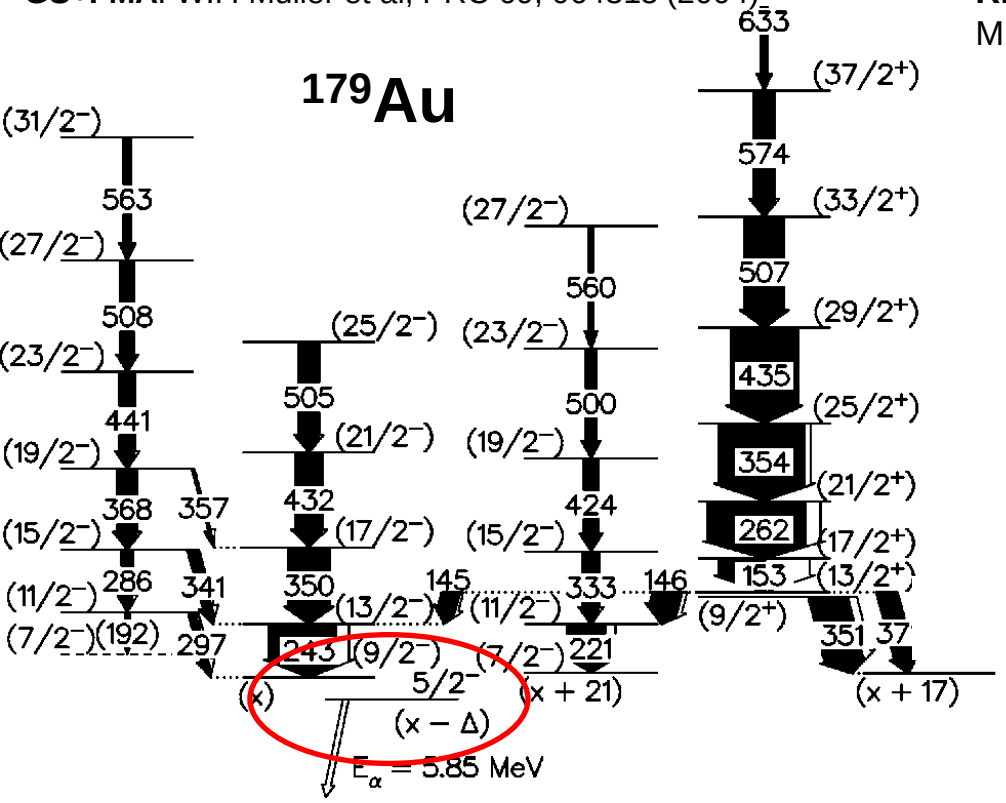
Why is $1/2^+ \rightarrow 1/2^+$ $^{181}Tl \rightarrow ^{177}Au$ α decay hindered?



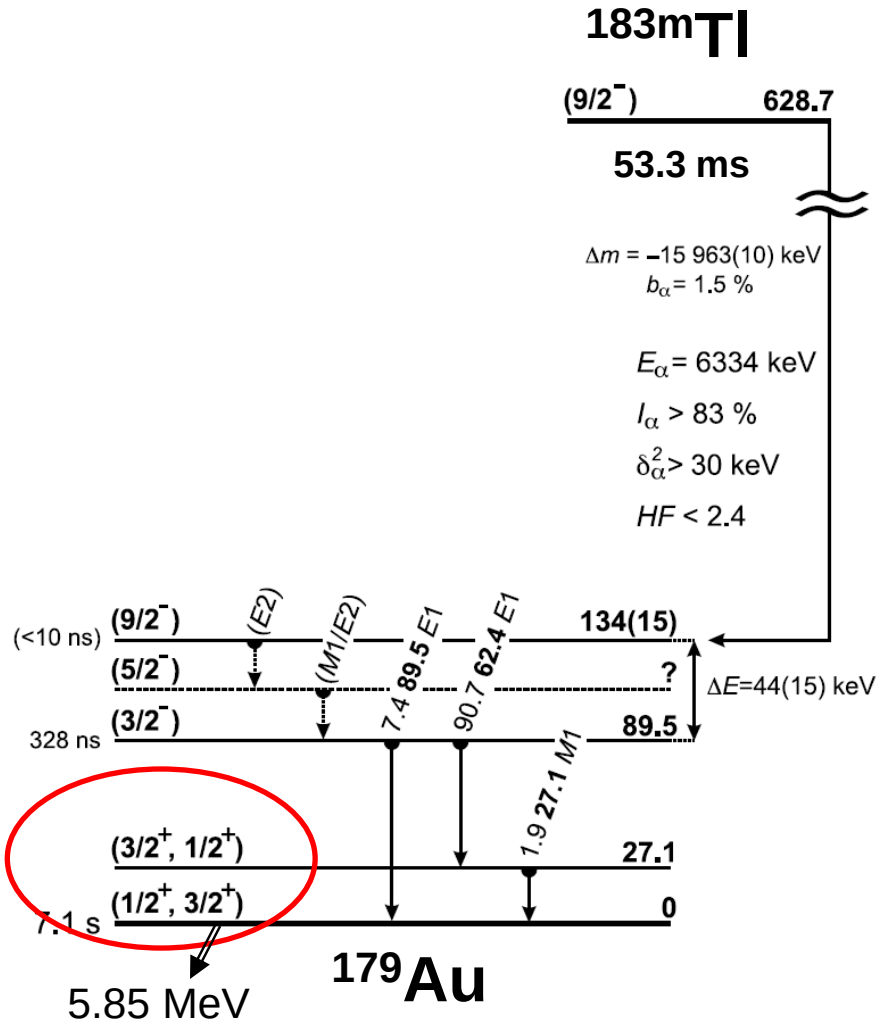
Plot from A.Andreyev et al., PRC 80, 024302 (2009)

What is the ground state spin of ^{179}Au: 1/2$^+$,3/2$^+$or 5/2$^-$?

GS+FMA: W.F. Muller et al, PRC 69, 064315 (2004)



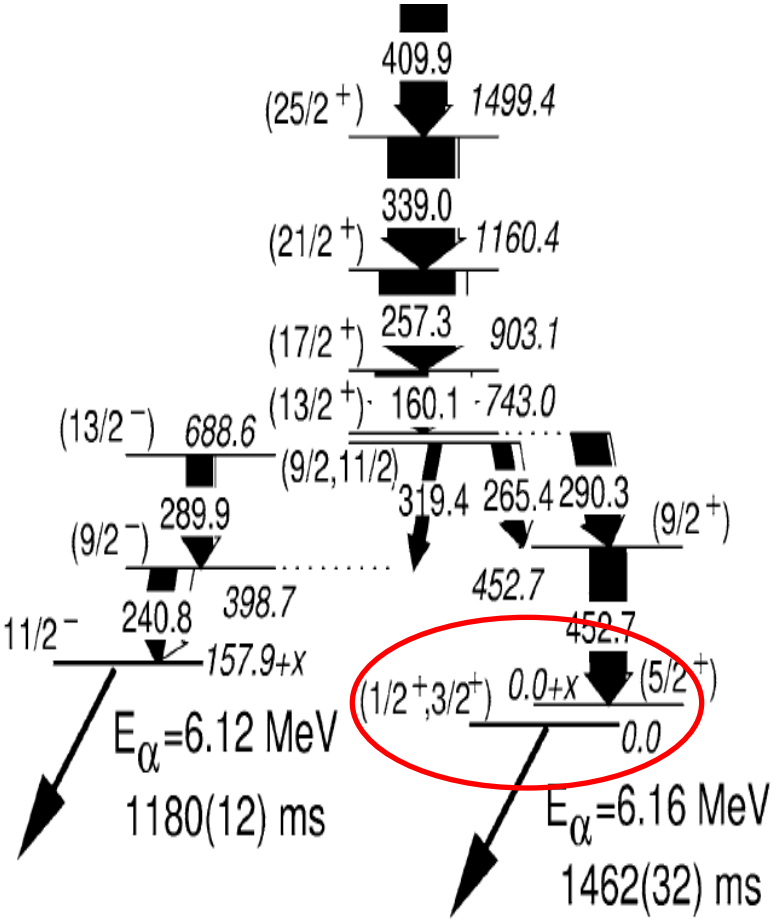
RITU: A. Andreyev et al., R35 experiment (+ISOLDE data)
M. Venhart et al, PLB 695, 82 (2011)



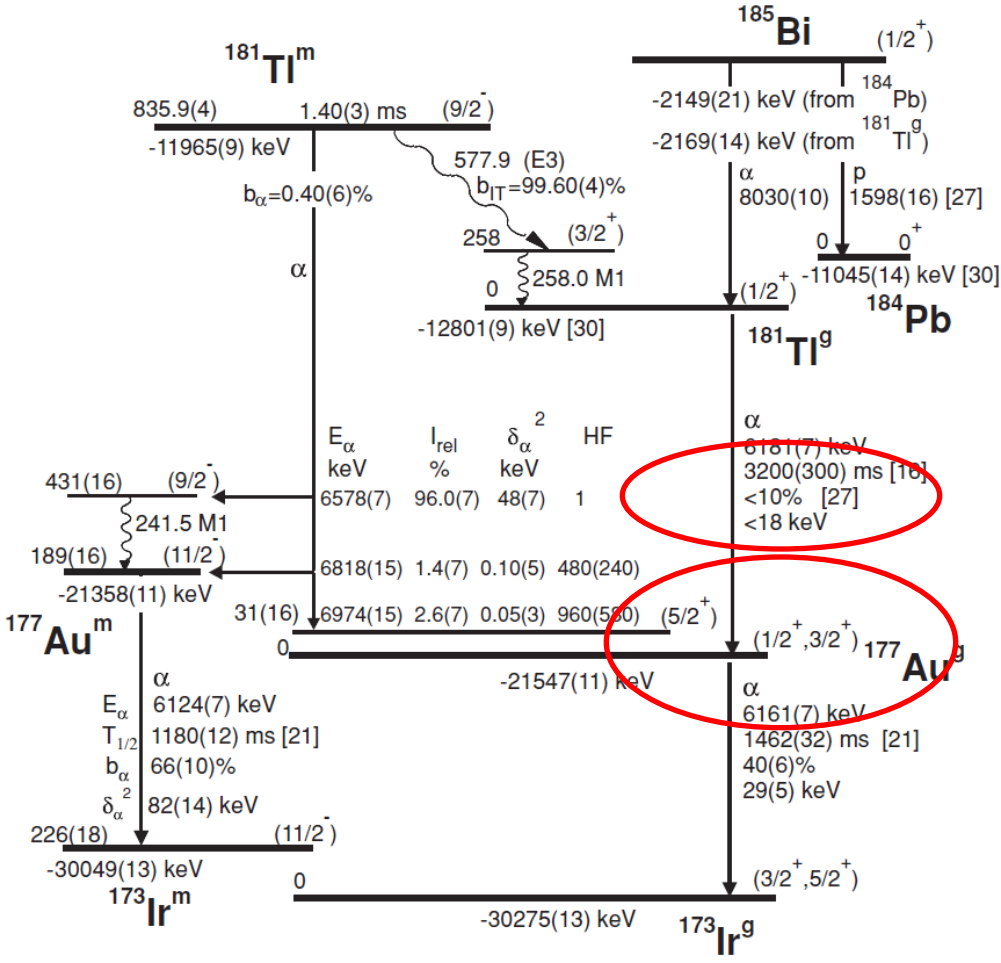
Extensive ISOLDE data for g.s. of ^{183}Tl are available, analysis underway

What is the ground state spin of ^{177}Au: 1/2$^+$ or 3/2$^+$?

GS+FMA (ANL):
F.G. Kondev et al., PLB 512, 268 (2001)

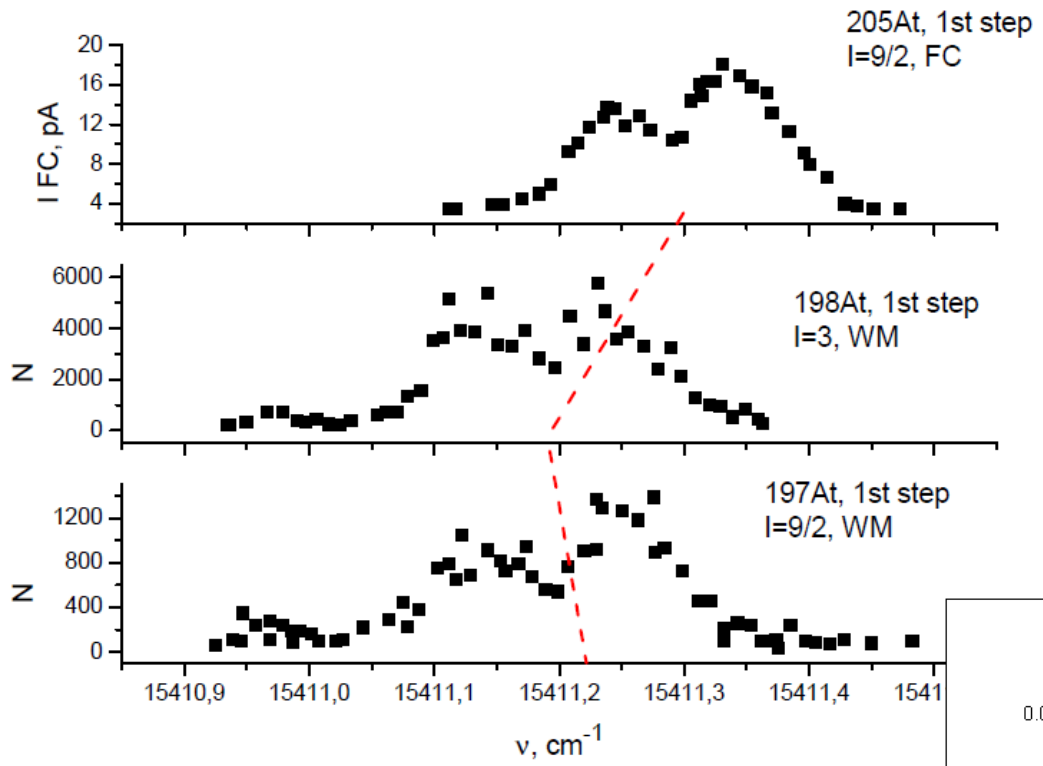


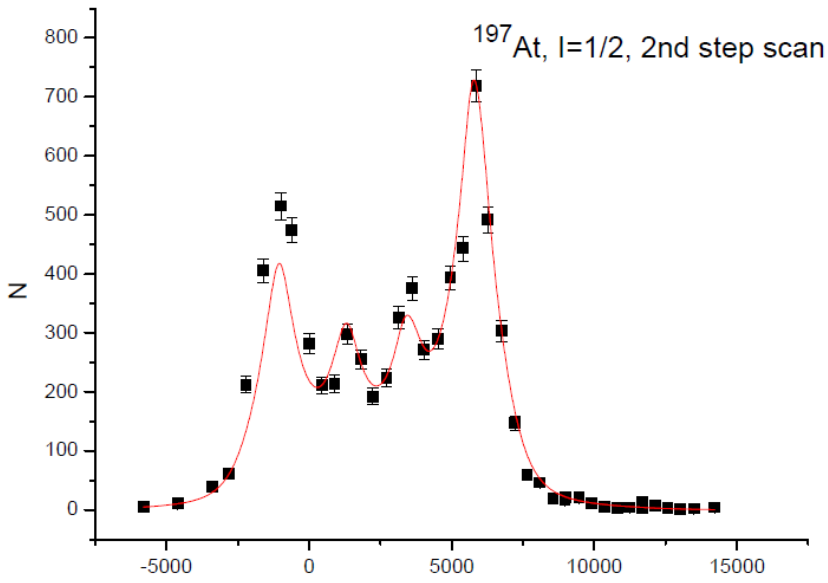
SHIP(GSI): A.Andreyev et al., PRC 80, 024302 (2009)

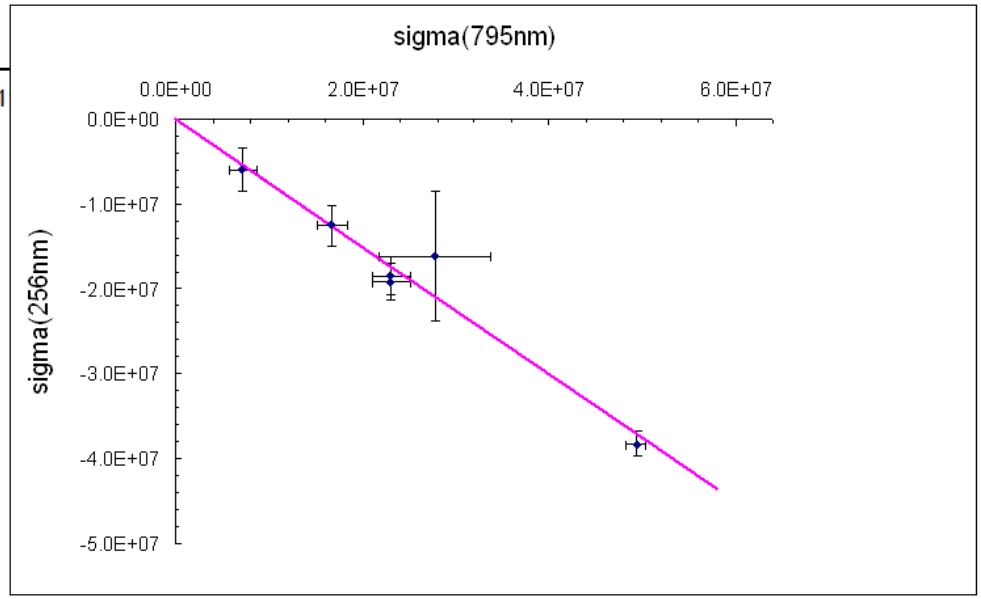


Why is α decay of 1/2$^+$ gs of ^{181}Tl hindered, HF>3?
Extensive ISOLDE data for g.s. of ^{181}Tl are available, analysis underway

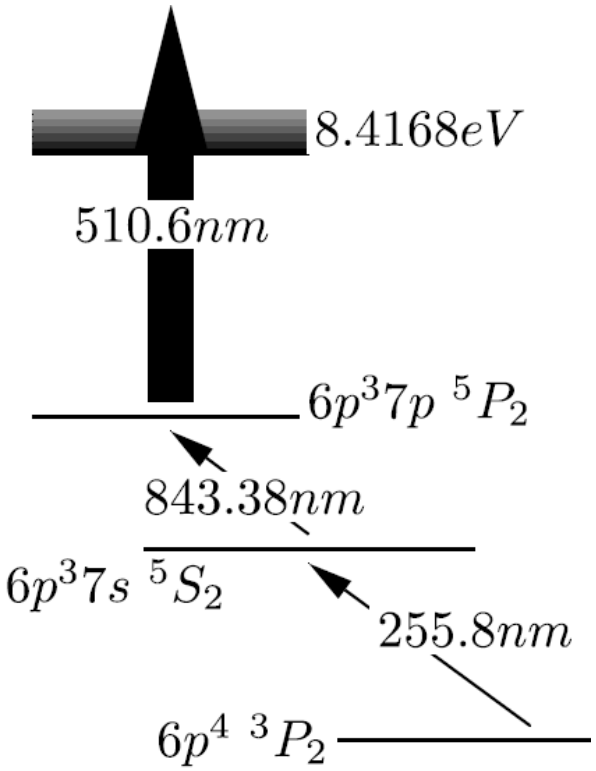
HFS spectra for ^{197,198,217}At







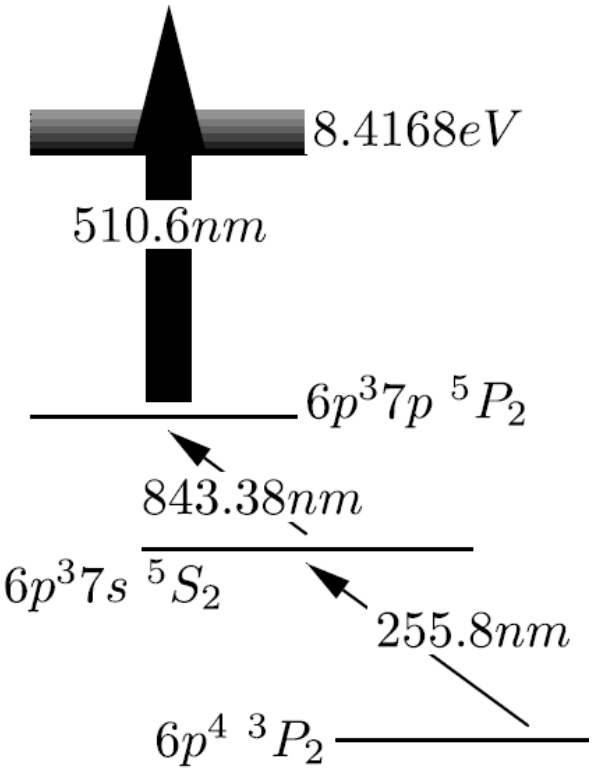
Laser Spectroscopy of Po isotopes at ISOLDE

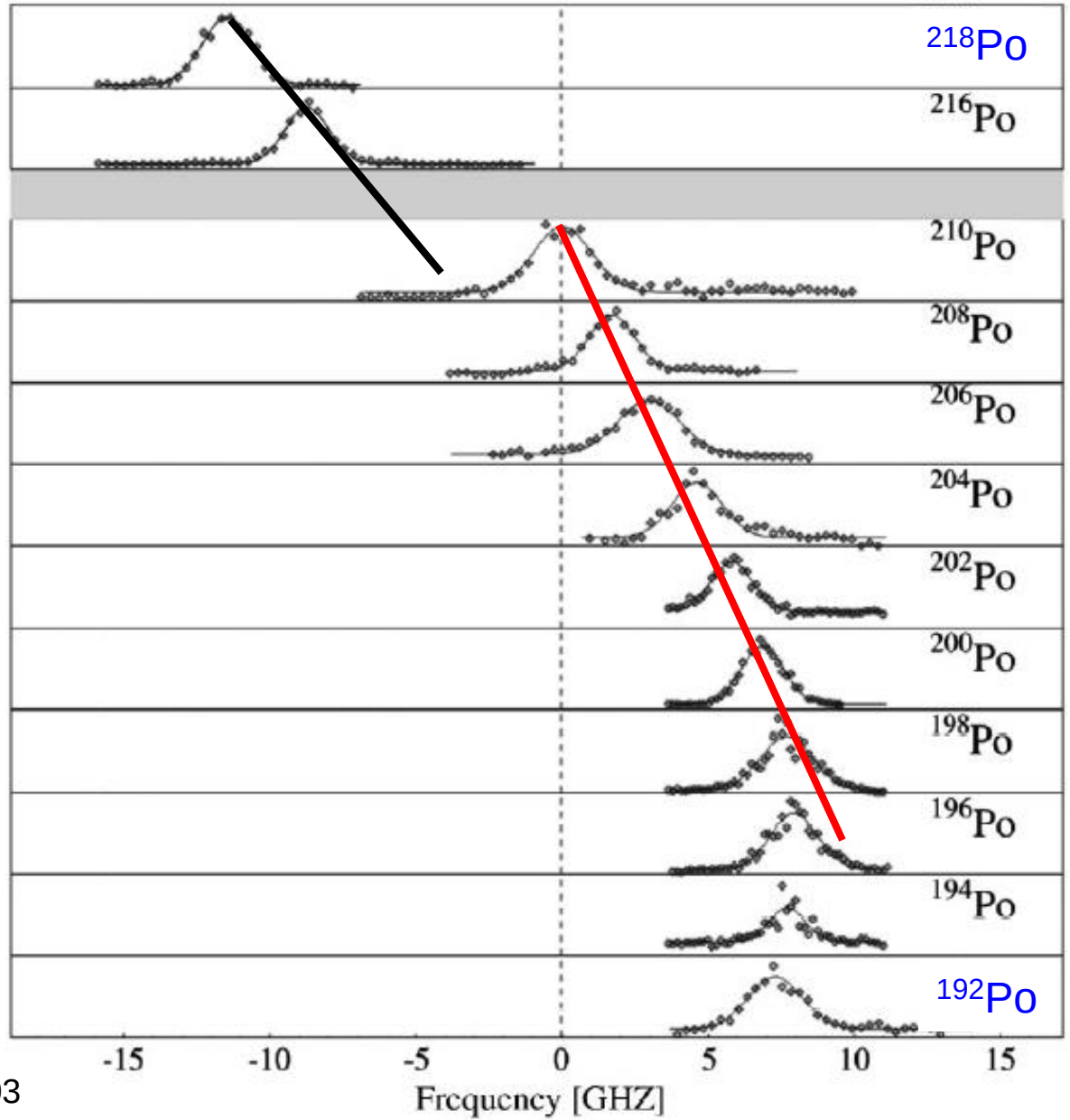


- In-source laser spectroscopy :
  - production rate as a function of laser frequency
  - deduction of charge radii using atomic physics input
- A=218 to 192
- T1/2 = 3 yr to 33 ms
- Intensity form 0.3 ion/s to over 10^7 ion/s

Th. Cocolios et al., PRL106 (2011) 052503

Shape Coexistence in Po isotopes





Th. Cocolios et al., PRL106 (2011) 052503

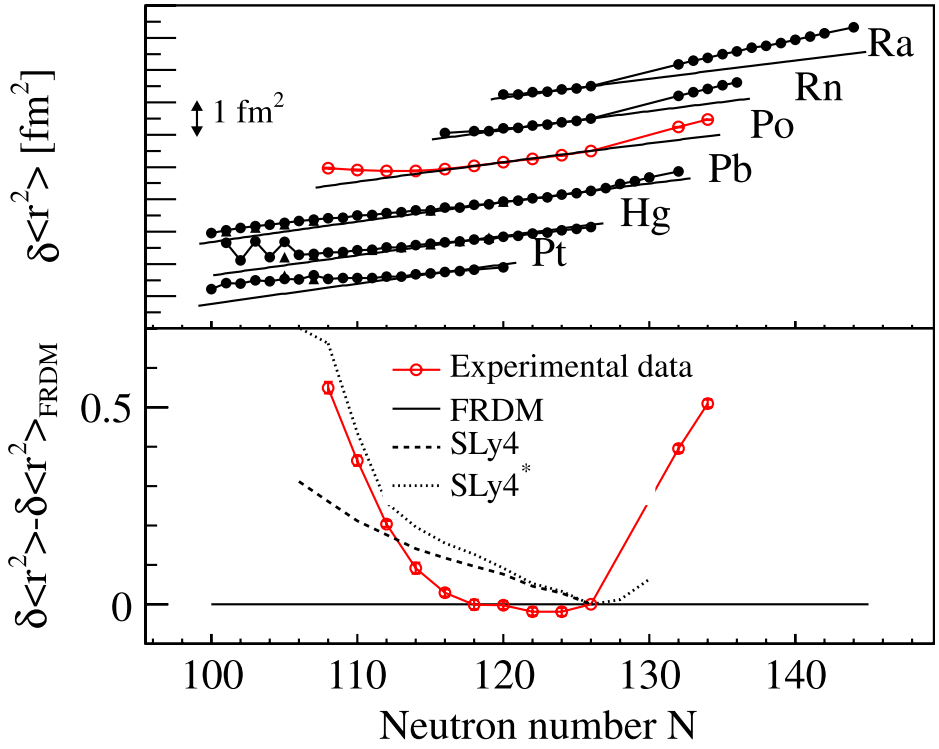
Shape Coexistence in Po isotopes

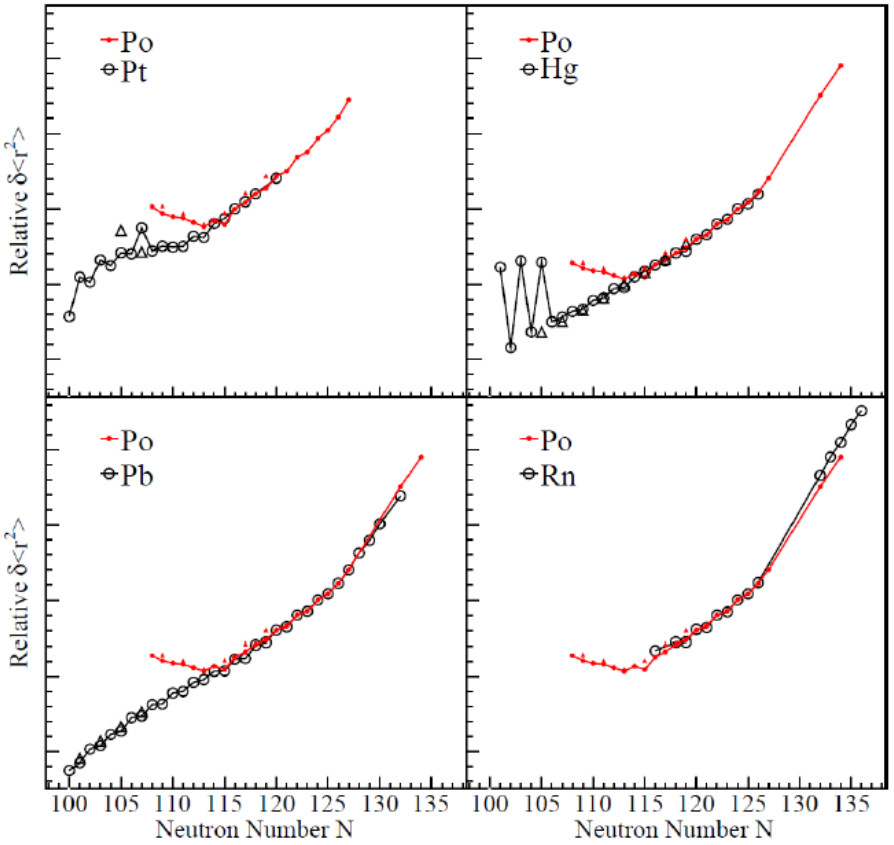
PRL **106,** 052503 (2011) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2011

Early Onset of Ground State Deformation in Neutron Deficient Polonium Isotopes

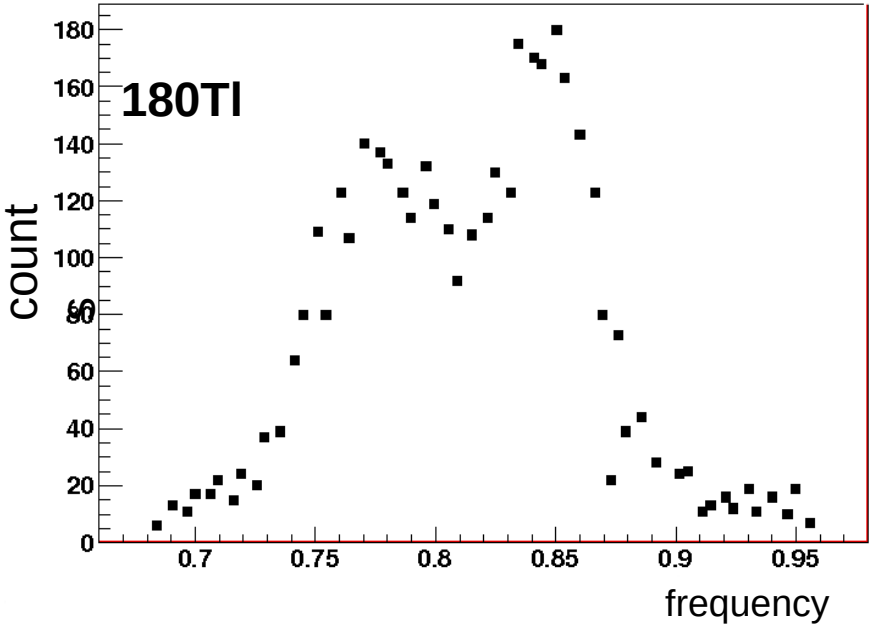
T. E. Cocolios,[1,2] W. Dexters,[1] M. D. Seliverstov,[1,3,4] A. N. Andreyev,[1,5] S. Antalic,[6] A. E. Barzakh,[3] B. Bastin,[1,*] J. Büscher,[1] I. G. Darby,[1] D. V. Fedorov,[3] V. N. Fedosseyev,[7] K. T. Flanagan,[8,9] S. Franchoo,[10] S. Fritzsche,[11,12] G. Huber,[4] M. Huyse,[1] M. Keupers,[1] U. Köster,[13] Yu. Kudryavtsev,[1] E. Mané,[8,†] B. A. Marsh,[7] P. L. Molkanov,[3] R. D. Page,[14] A. M. Sjoedin,[7,15] I. Stefan,[10] J. Van de Walle,[1,2,‡] P. Van Duppen,[1] M. Venhart,[1,16] S. G. Zemlyanoy,[17] M. Bender,[18] and P.-H. Heenen[19]

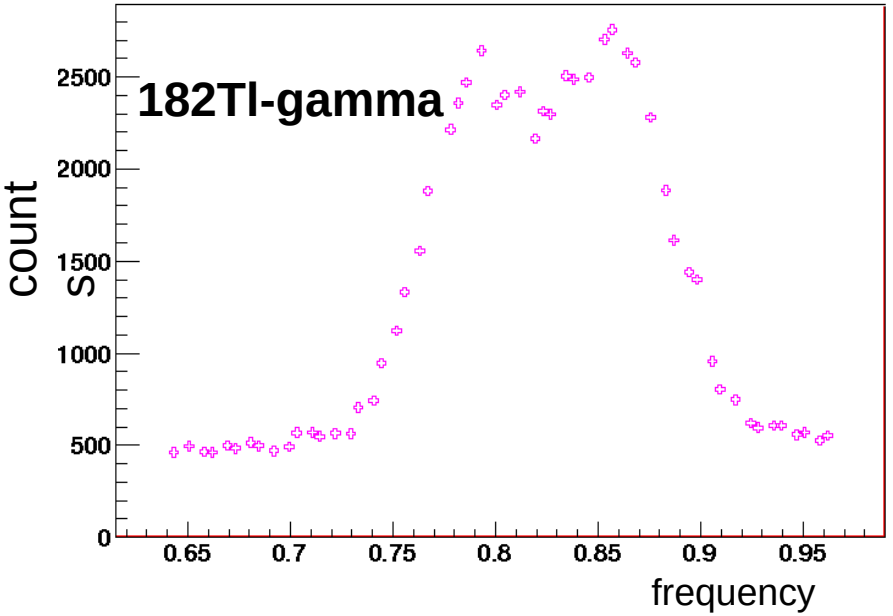
[1]*Instituut voor Kern- en Stralingsfysica,*
[2]*ISOLDE, CERN, CH-121*

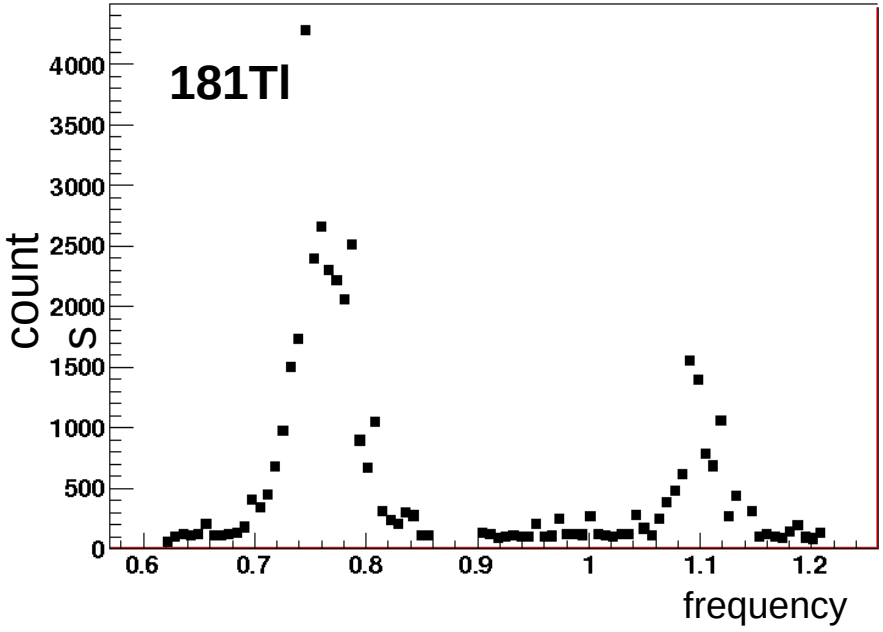


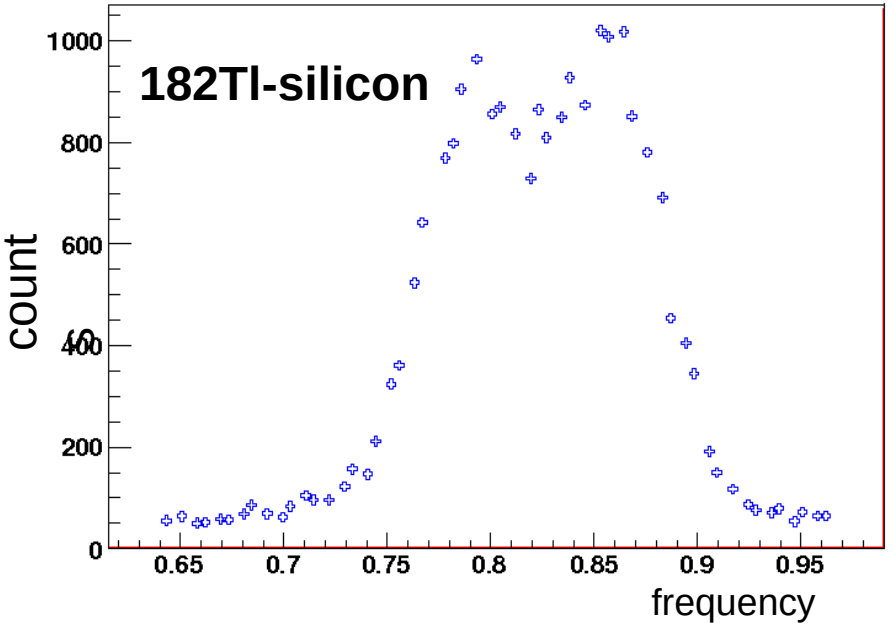


July 2011: Shape Coexistence in Tl isotopes









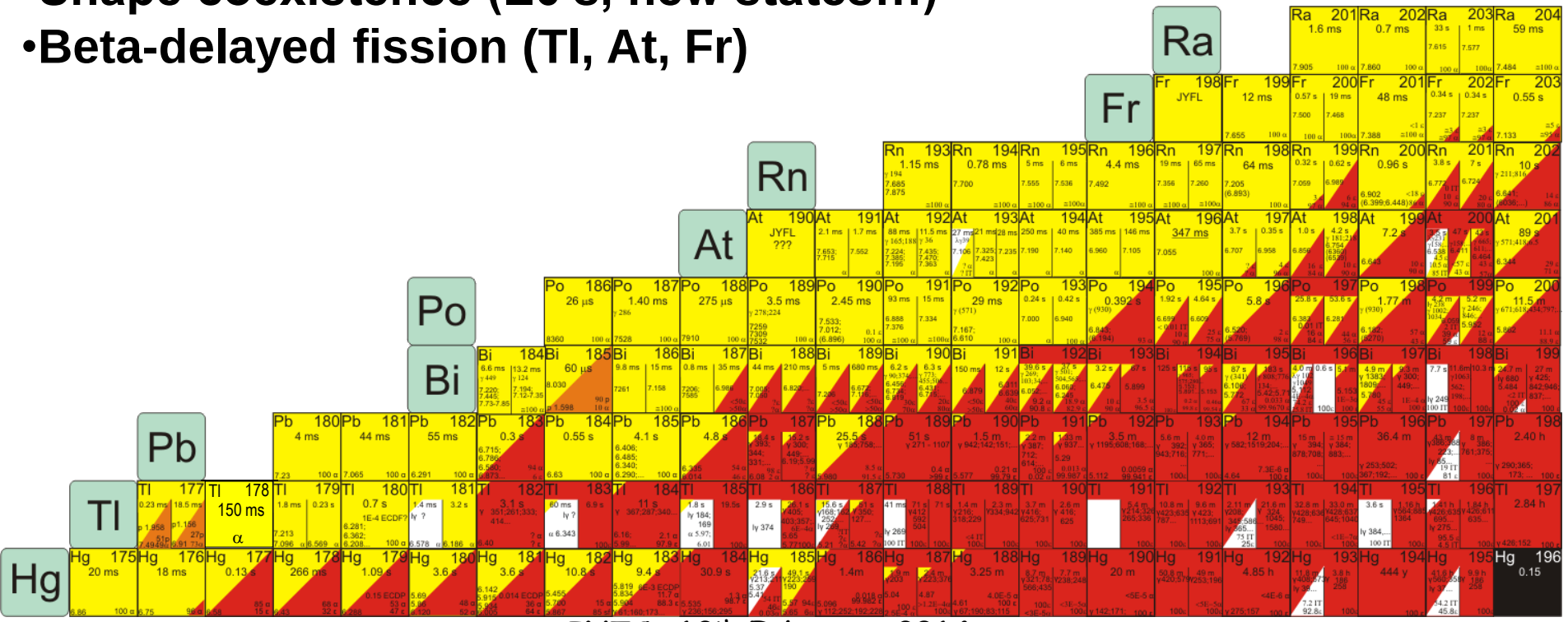
Windmill Collaboration Status Report on Studies in the Lead Region Addenda IS456/IS534

Andrei Andreyev

University of York, UK and JAEA, Tokai, Japan

on behalf of the Windmill Collaboration

- **Charge radii in the long chains of Au, Tl, Pb, Po, At (~70 isotopes)**
- **Shape coexistence (E0's, new states…)**
- **Beta-delayed fission (Tl, At, Fr)**



INTC, 12th February 2014