Исследование запаздывающего деления и сосуществования форм в ядрах таллия, астата и золота (ISOLDE, CERN)

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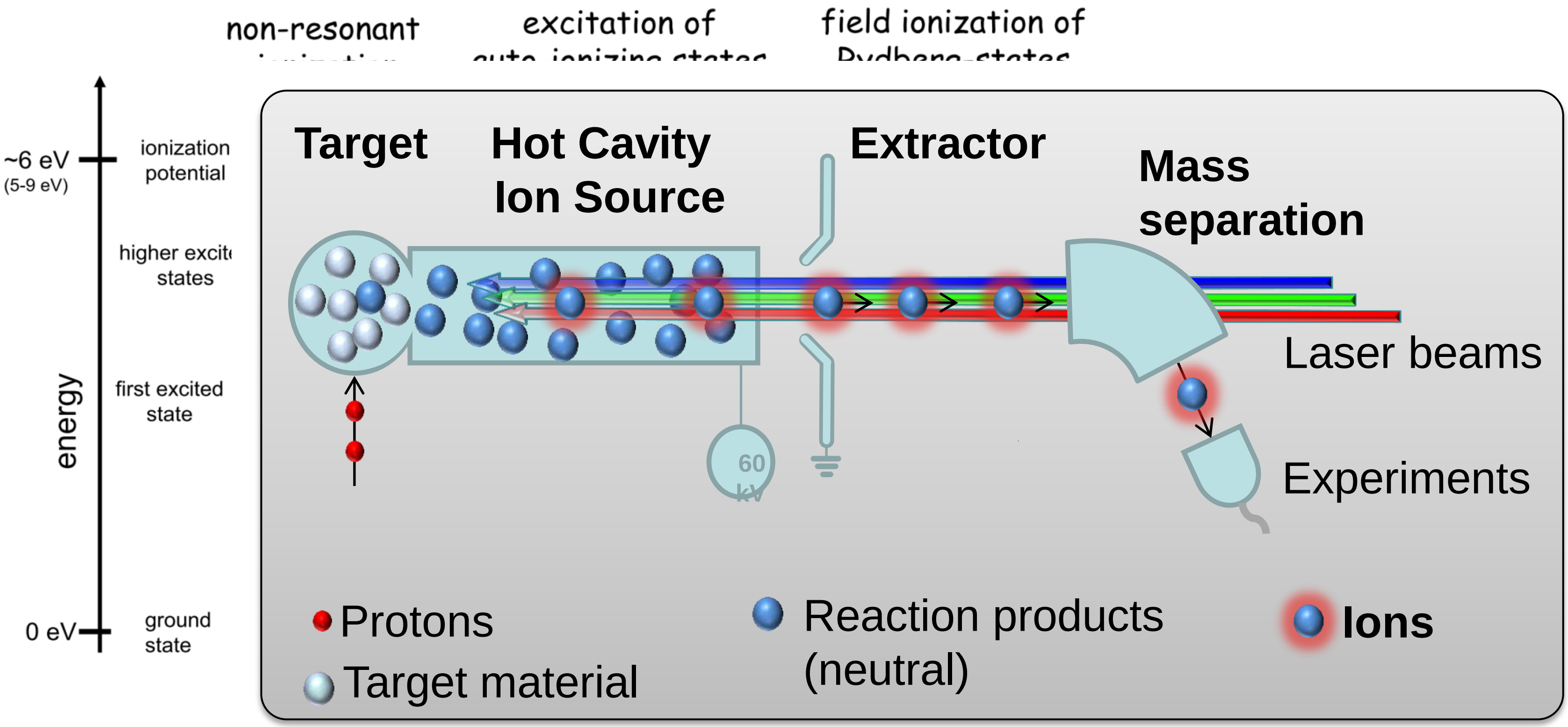
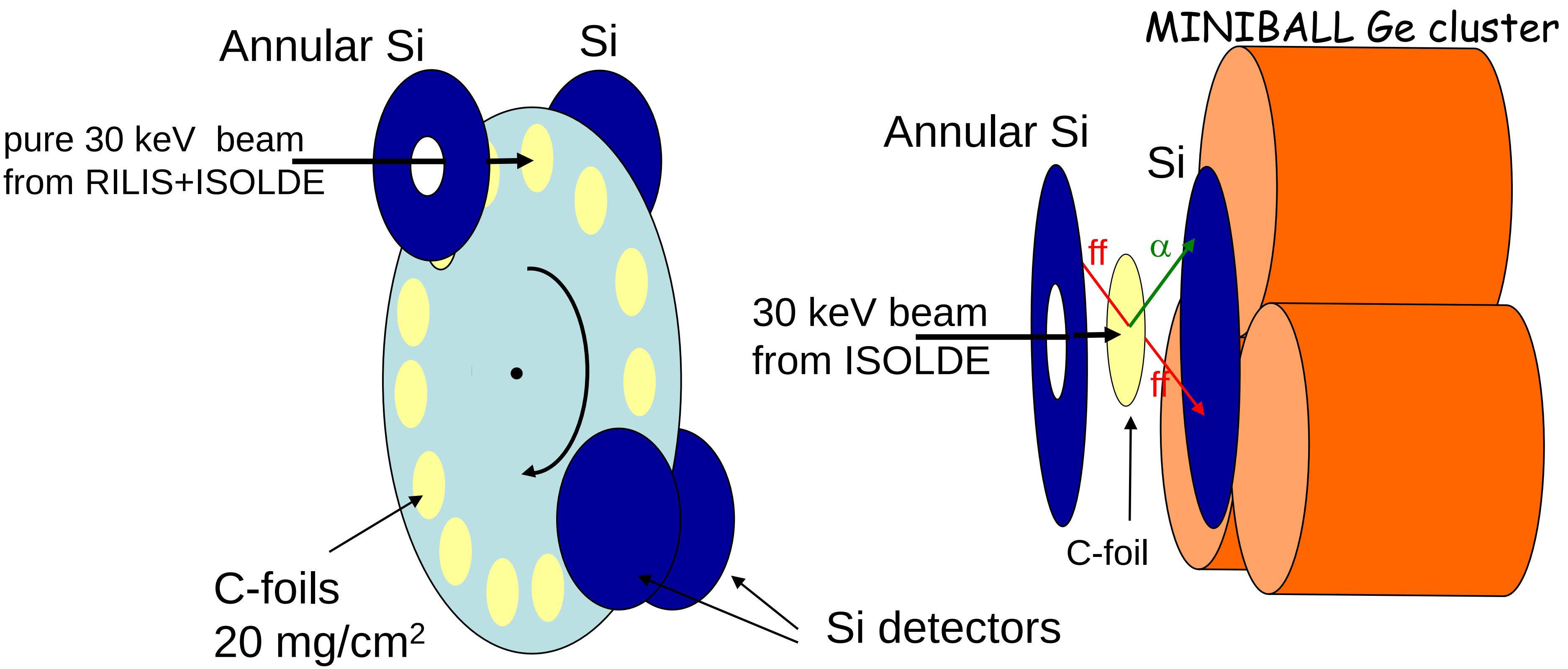
Laser Ion Source at ISOLDE



- **Scanning the laser frequency of the first/second step of the selective ionisation scheme for a particular isotope (or an isomer)**
- **Isotope shift (IS), hyperfine structure (HFS) measurements**
- **Measuring FC current, α/γ or ToF spectra while scanning the frequency**

Windmill System at ISOLDE

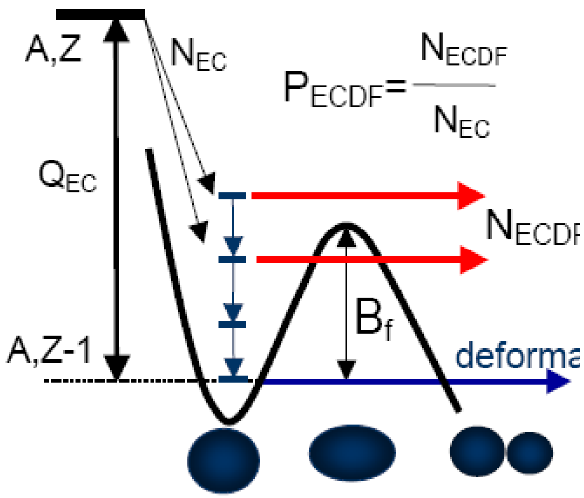
A. Andreyev et al., PRL 105, 252502 (2010)



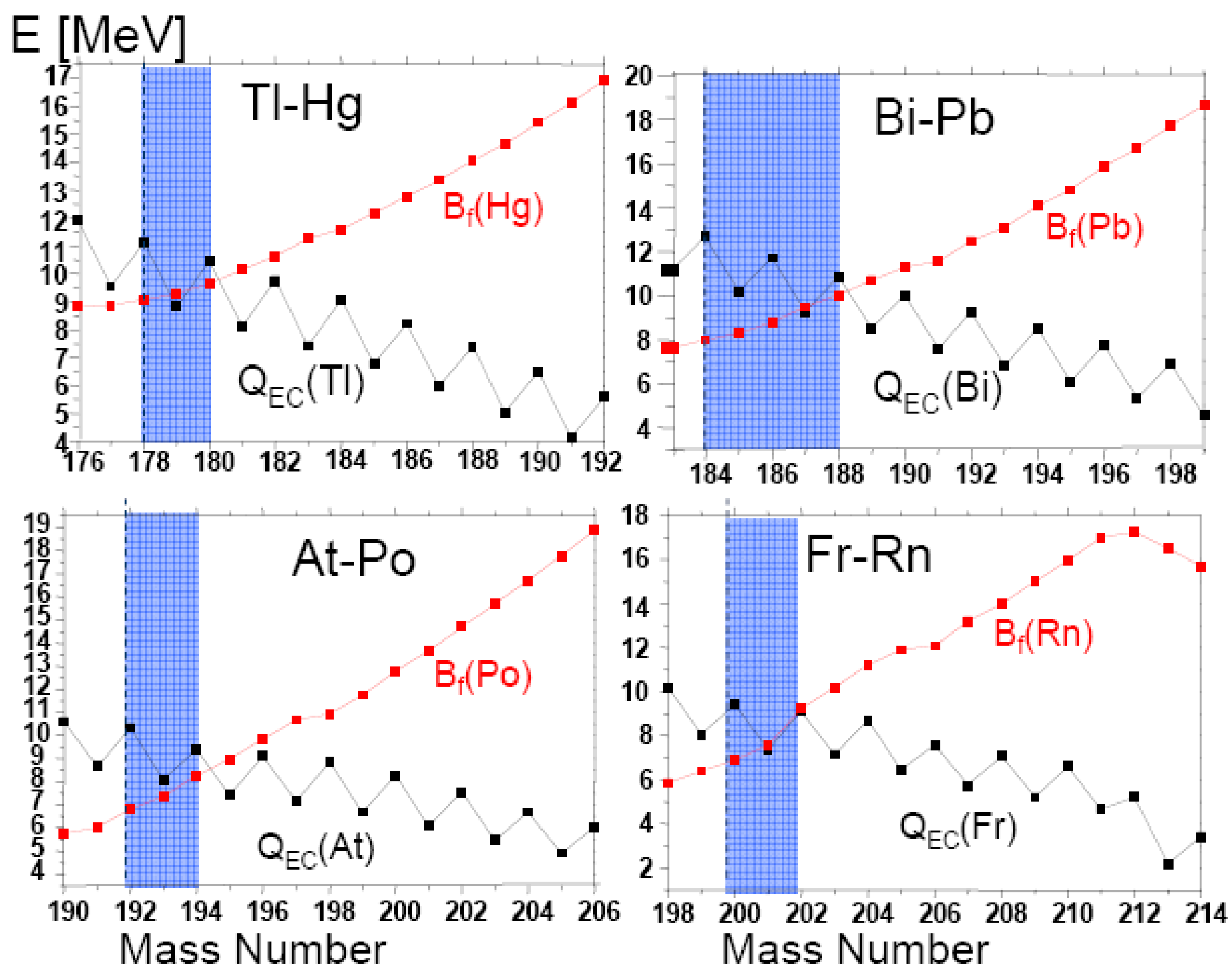
Setup: Si detectors from both sides of the C-foil

- Large geometrical efficiency (up to 80%)
- 2 fold fission fragment coincidences
- ff-γ, γ-α, γ-γ, etc coincidences

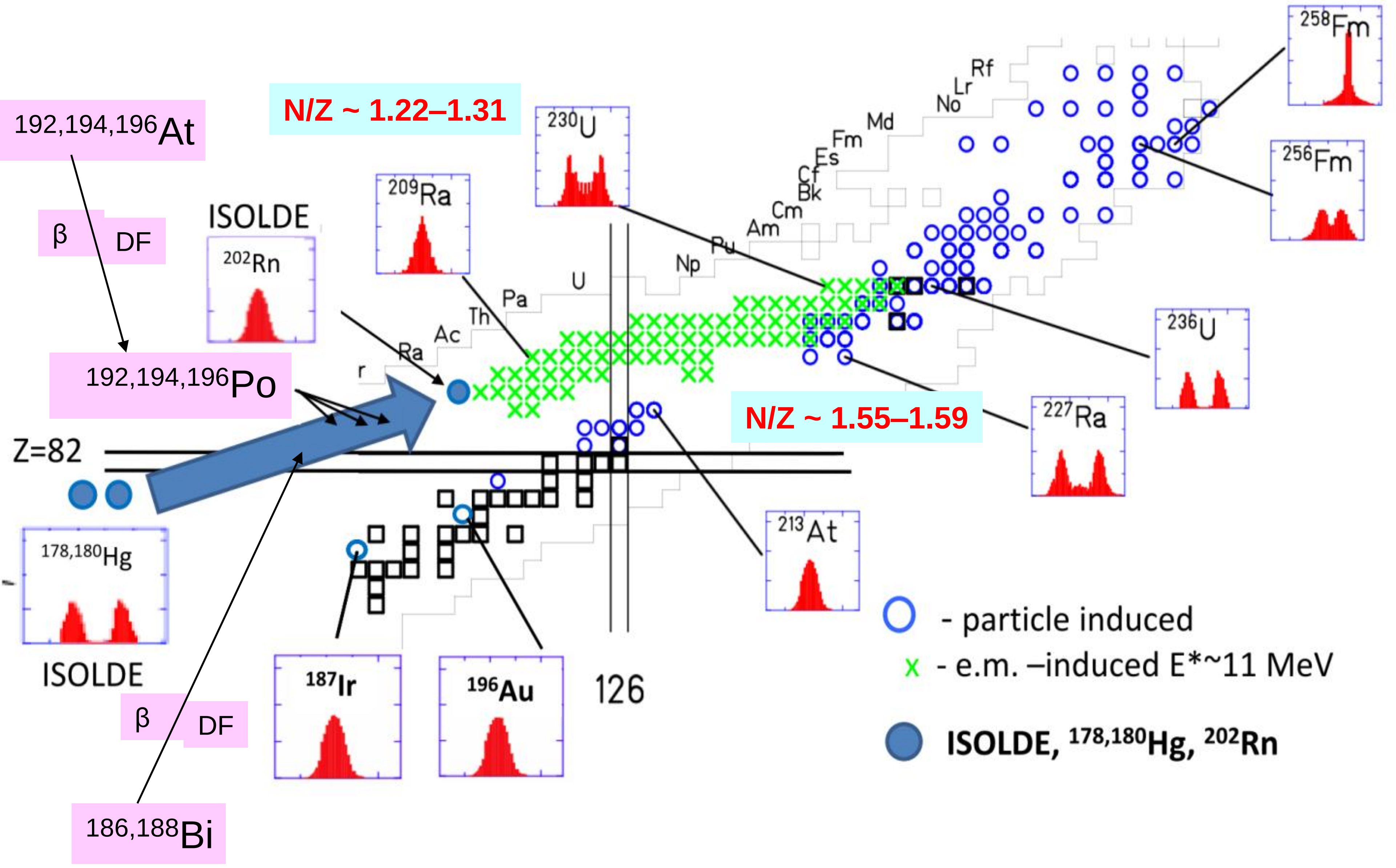
Beta-Delayed Fission



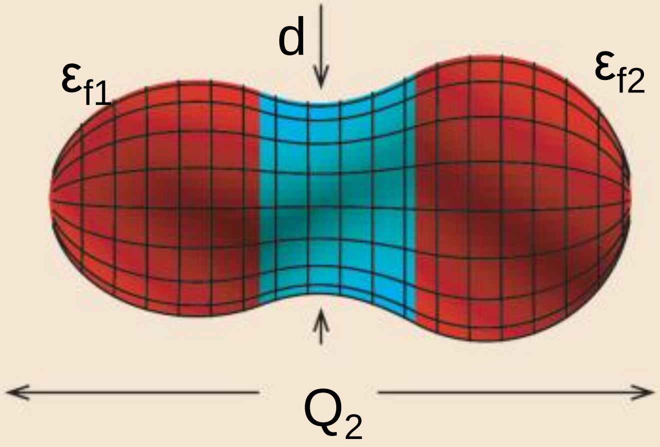
$Q_{EC}(A, Z) \gtrsim B_f(A, Z\text{-}1)$



Beta-Delayed Fission

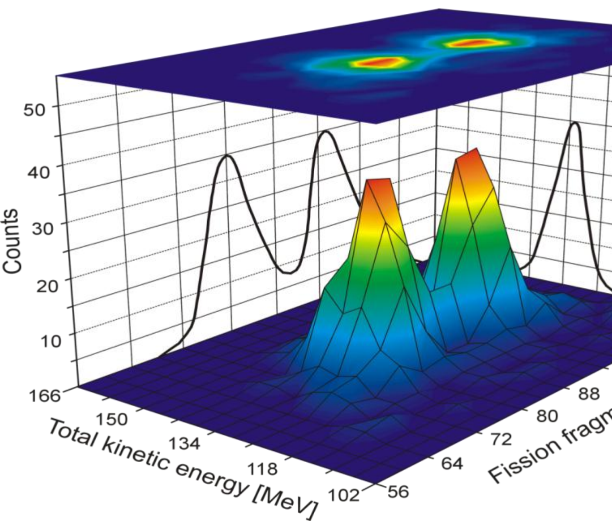


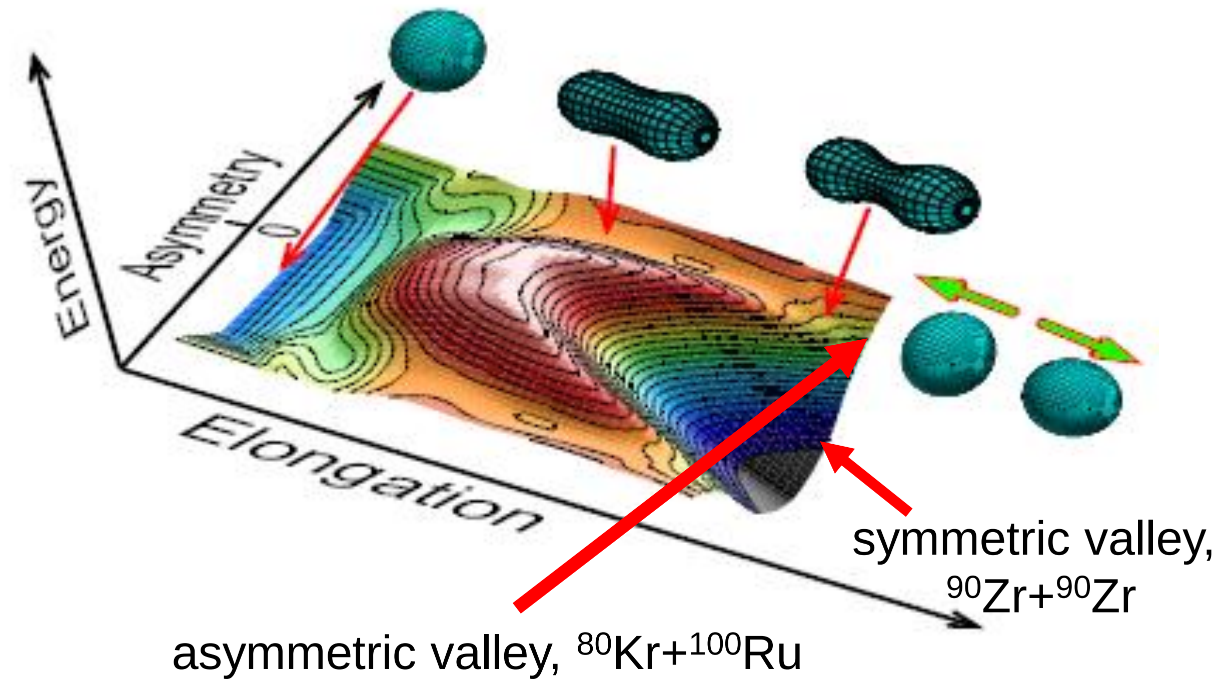
Five Essential Fission Shape Coordinates



Q_2 ~ Elongation (fission direction)
α_g ~ Mass asymmetry (M1-M2)/(M1+M2)
ε_{f1} ~ Left fragment deformation
ε_{f2} ~ Right fragment deformation
d ~ Neck

P. Möller's calculations (2D projection of the total 5D picture):



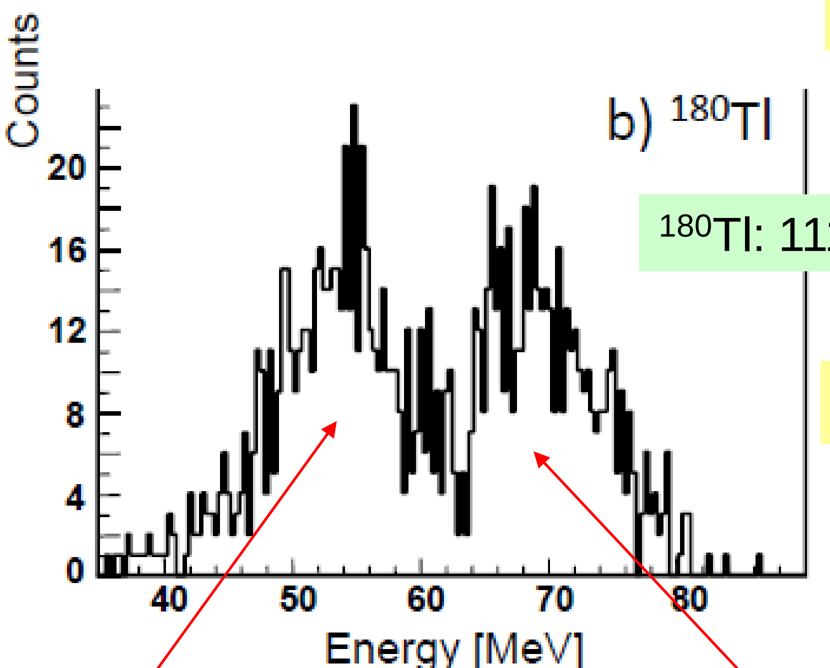


Fragment mass distribution in βDF of Tl isotopes

. ions/μC/s, 8 fission events

experiment

$P_{\beta DF}$ (^{178}Tl)=0.15(6)%



^{180}Tl: 1111 fission events

$P_{\beta DF}$ (^{180}Tl)=3.2(2)×10^{-3}%

corresponds to A=80(1)

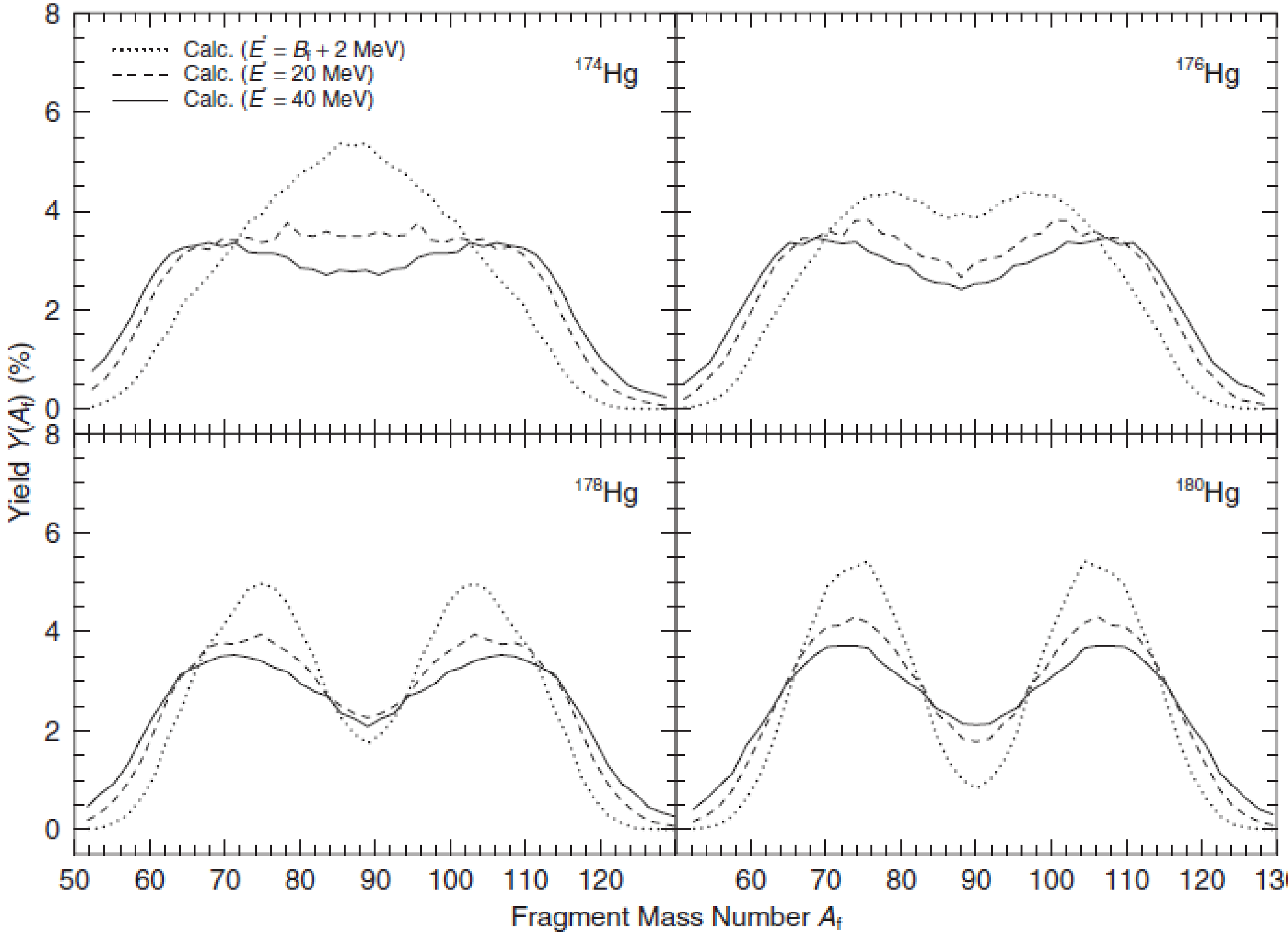
FWHM ≈ 9 amu

A=100(1)

Fragment mass distribution in βDF of Tl isotopes

calculations

Model: BSM(M)
Brownian shape motion on five-dimensional (5D) potential energy surfaces in Metropolis random-walk approximation



Calculated yields for four Hg isotopes at three excitation energies. For the lighter isotopes the yields become more symmetric with decreasing energy, an unusual behavior.

P. Möller, J. Randrup, A. Sierk, Phys. Rev. C **85**, 024306 (2012)

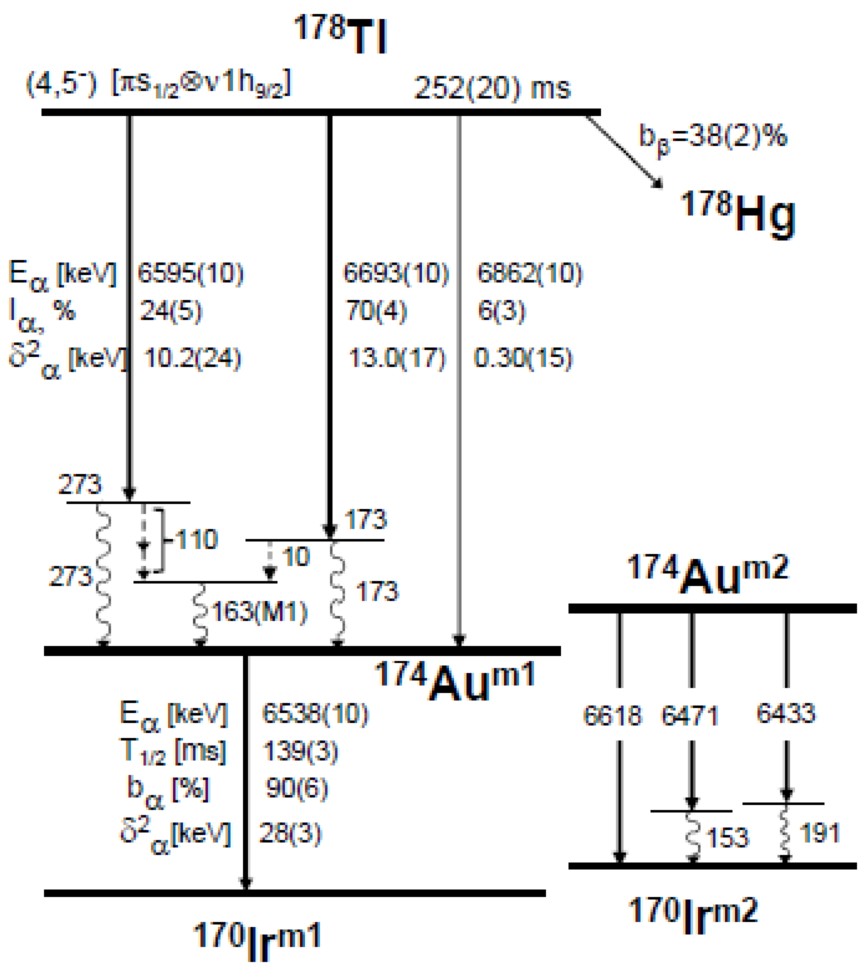
Fission barriers for Hg isotopes

	B_f, exp (model), MeV	B_f, theor MeV
^{180}Hg	7.5(1.5)	9.8
^{178}Hg	~ 7	9.3

$P_{\beta DF}$ (^{180}Tl)$_{theor}$= 2×10^{-6}% to be compared with the experimental value 3.2(2)×10^{-3}%

M. Veselsky *et al*. Phys. Rev. C **86**, 024308 (2012)

Nuclear spectroscopic information for ^{178}Tl



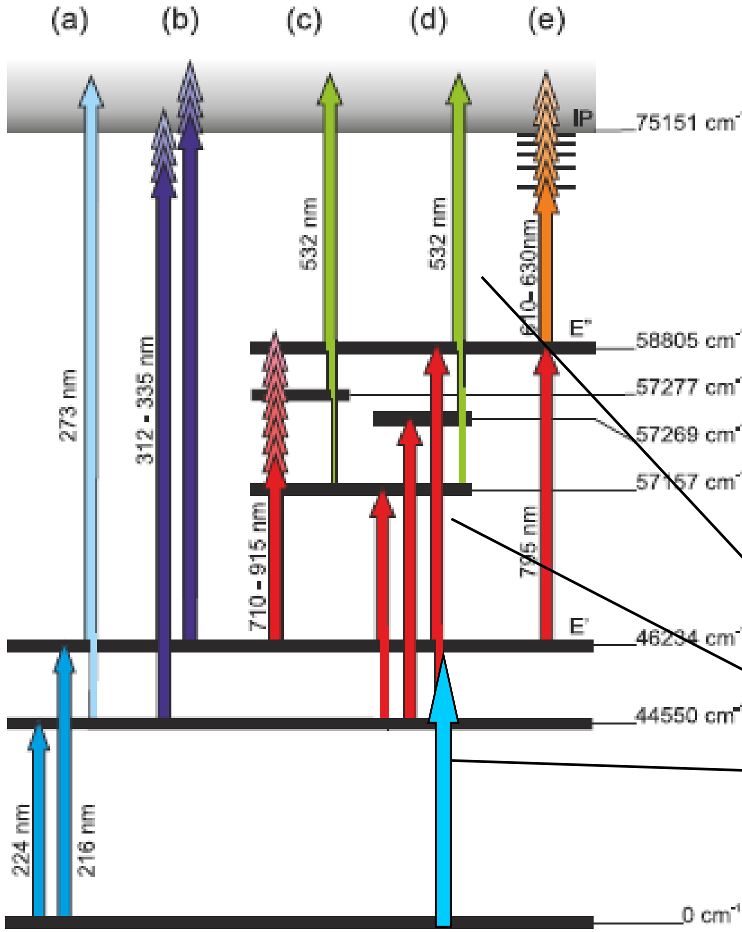
Development and use of laser-ionized At beams at ISOLDE

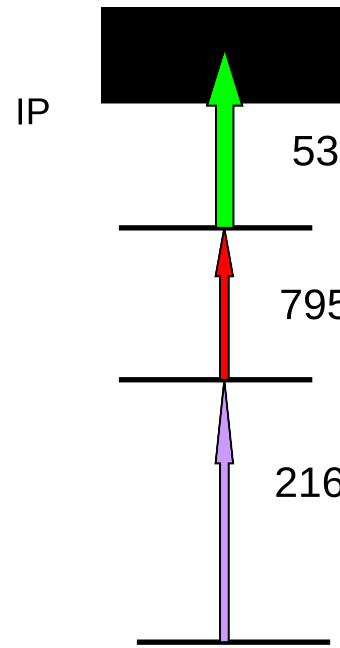
• Determination of optical lines and efficient photoionization scheme. First measurement of the ionization potential of the element At

• Beta delayed fission of $^{194,196}At$

• Charge radii measurement for At isotopes

Photoionization scheme for the radioactive element At



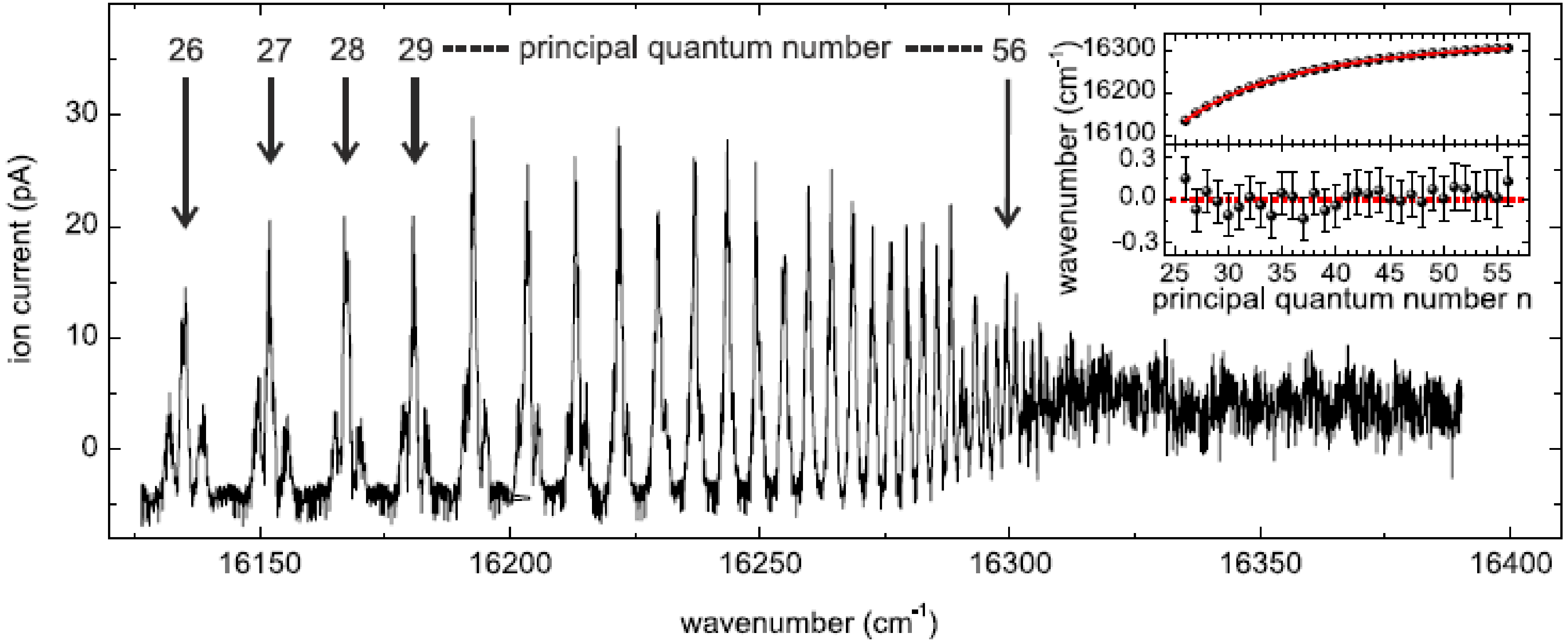


Optimal photoionization scheme.

Narrow band lasers for 1st and 2nd transitions

(a) Verification of the two transitions from the ground state at λ_1 = 216 nm and 224 nm. (b) Ionization threshold: Scan of the ionizing laser wavelength λ_2. (c) Development of a three-color scheme: Scan of λ_2 in the infra-red region for second excited states starting with λ_1 = 216 nm first step. (d) Verification of the levels found by exciting via the λ_1 = 224 nm first step. (e) Rydberg series: A wavelength scan of the ionizing laser (λ_3) in the visible range using the {216, 795, λ_3} excitation path.

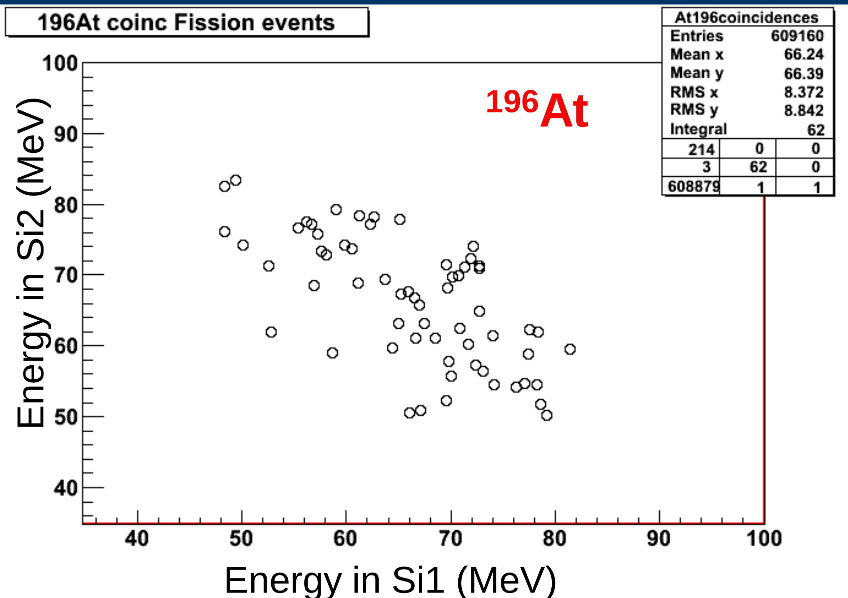
Precise determination of the Ionization Potential for the radioactive element At



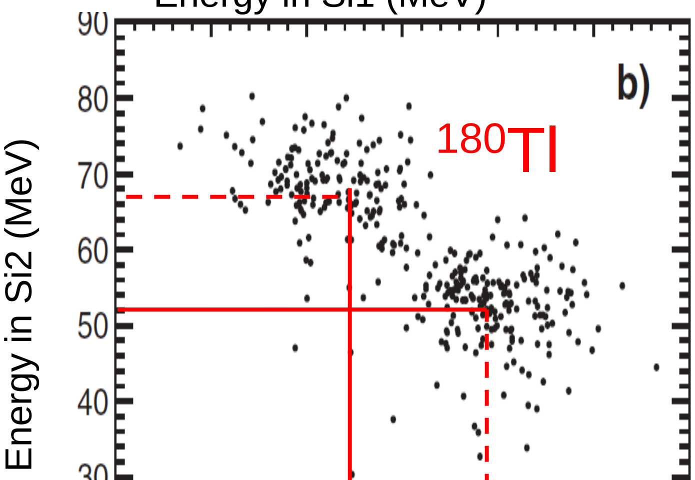
$$\nu_n = IP - E_2 - \frac{R_M}{(n-\delta)^2}$$

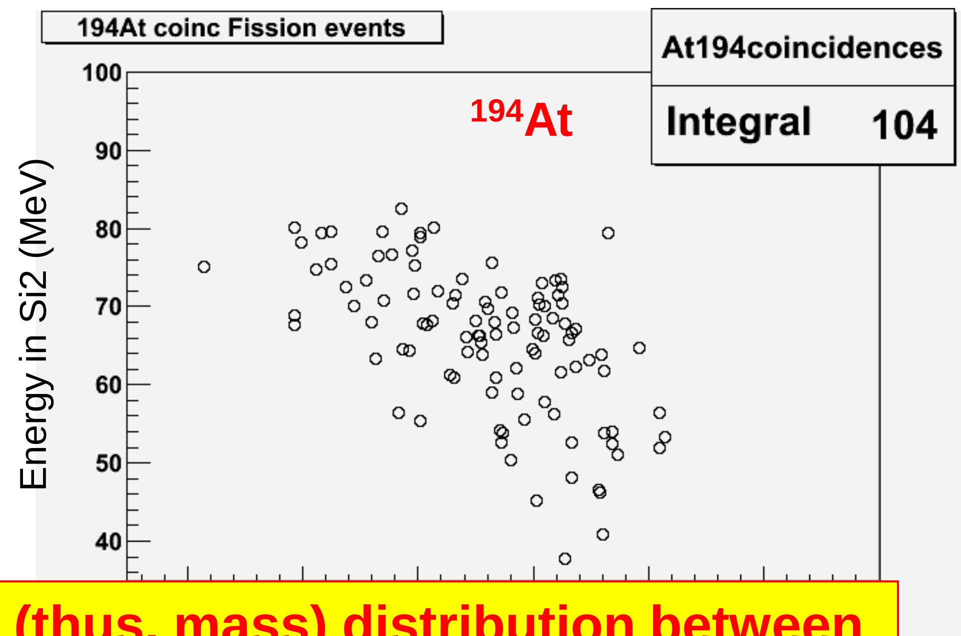
IP (At)=9.317510(84) eV

IS534, 9-14 May 2012: Mass Distributions Measurements for βDF of ^{194,196}At



Two isomers (~40 and 250 ms) were reported in ^{194}At. Therefore, to obtain true mass distribution and $P_{\beta DF}$ isomer selectivity is needed



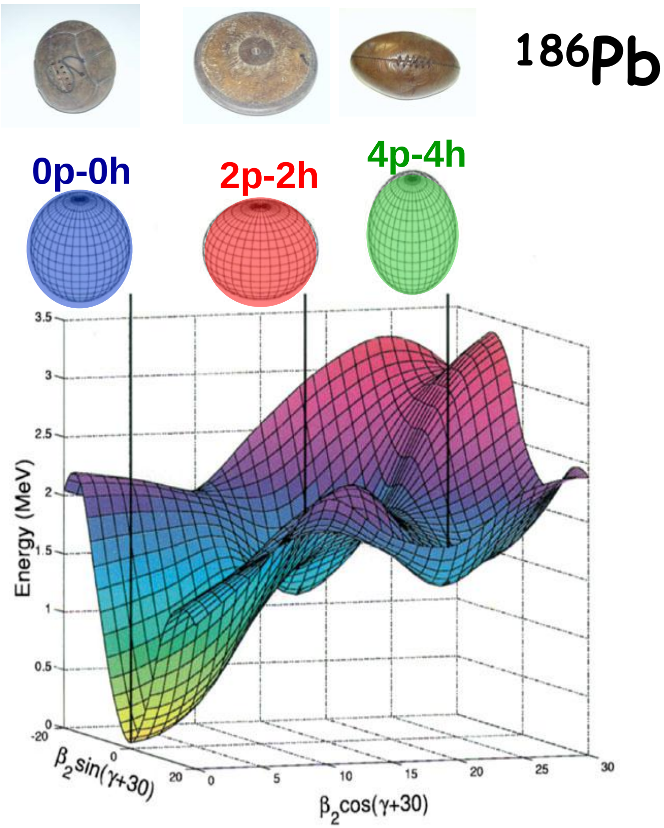


Clear difference in energy (thus, mass) distribution between fission of ^{180}Hg and ^{194,196}Po

30

Energy in Si1 (MeV)

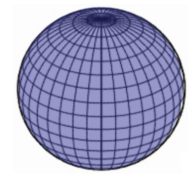
Shape Coexistence in the Pb region



Potential Energy Surface for ^{186}Pb

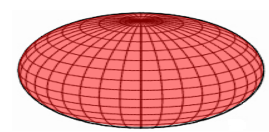
A.Andreyev et al. Nature, 405, 430 (2000)

- Pb (Z=82) g.s.: π(0p-0h) – spherical

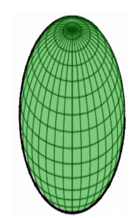


Proton pair excitations across Z=82 shell gap (neutrons are spectators):

- 1 pair excitation: π(2p-2h) -oblate



- 2 pair excitation: π(4p-4h) -prolate



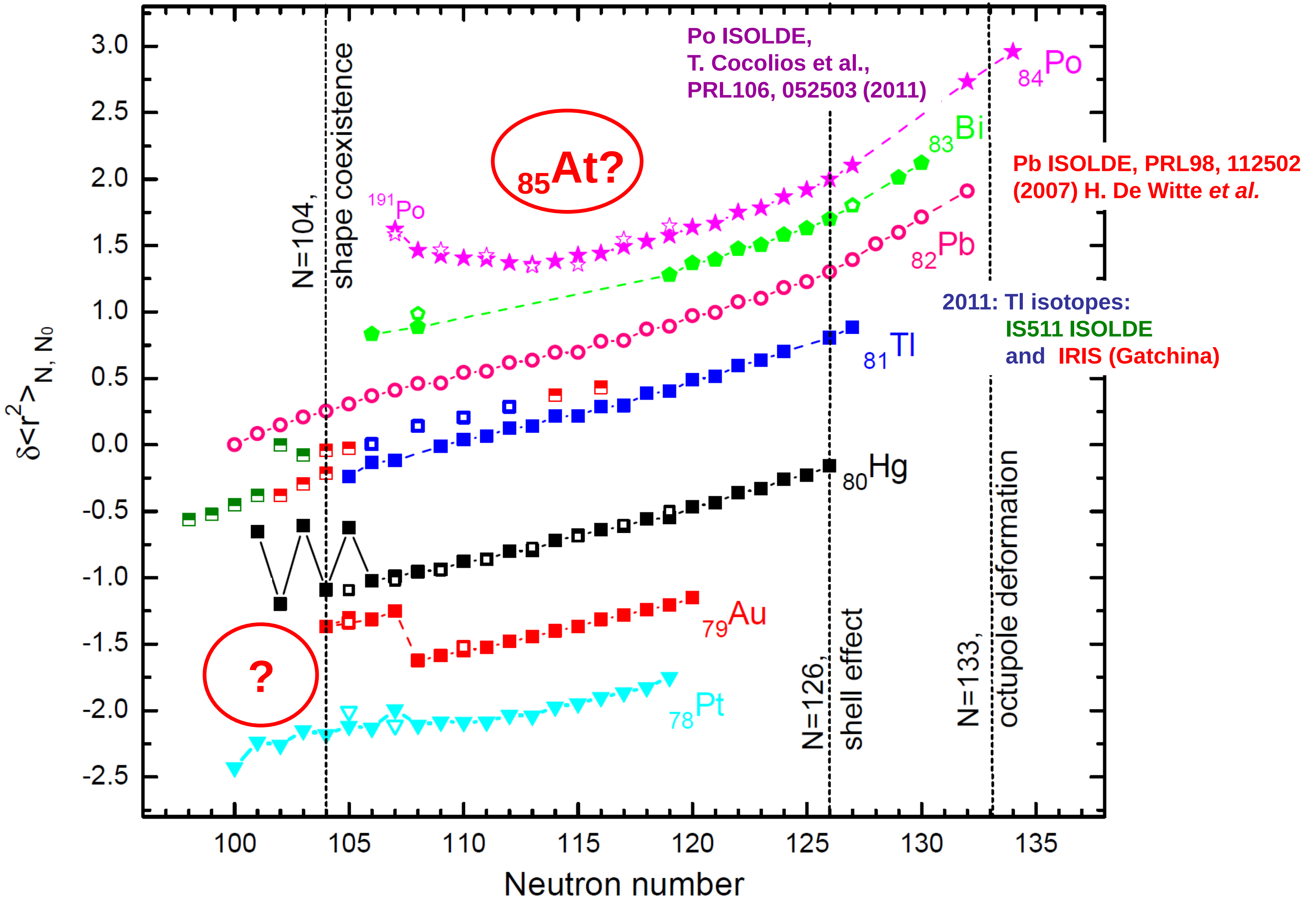
K. Heyde et al., Phys. Rep. 102 (1983) 291

J.L. Wood et al., Phys. Rep. 215 (1992) 101

A. Andreyev et al., Nature 405 (2000) 430

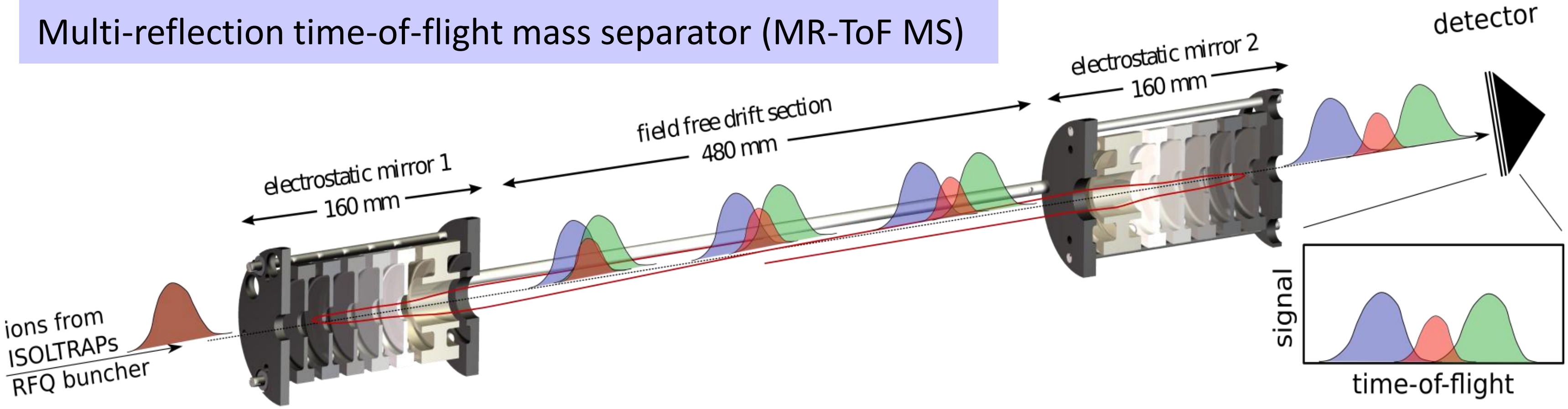
K. Heyde and J. Wood, Review of Modern Physics, 2012

Pre-2012: Charge Radii in Au-Po isotopes

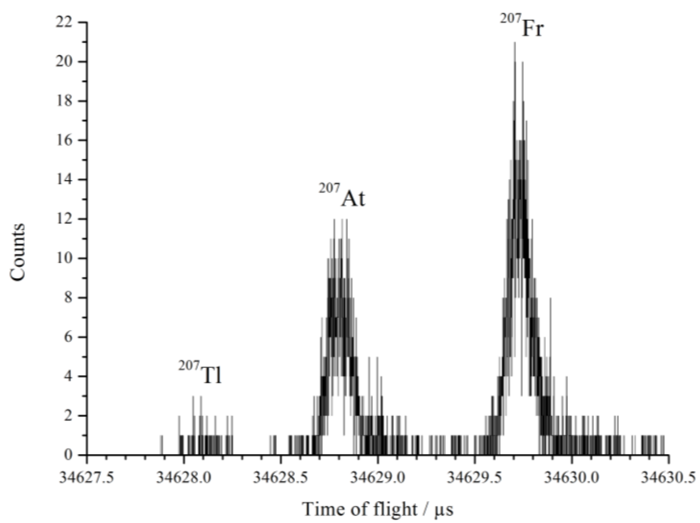


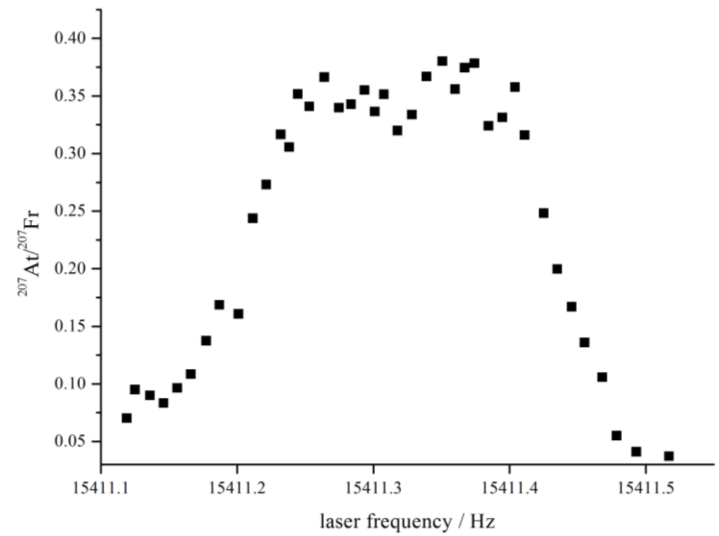
In-Source Spectroscopy with MR-ToF MS

Multi-reflection time-of-flight mass separator (MR-ToF MS)



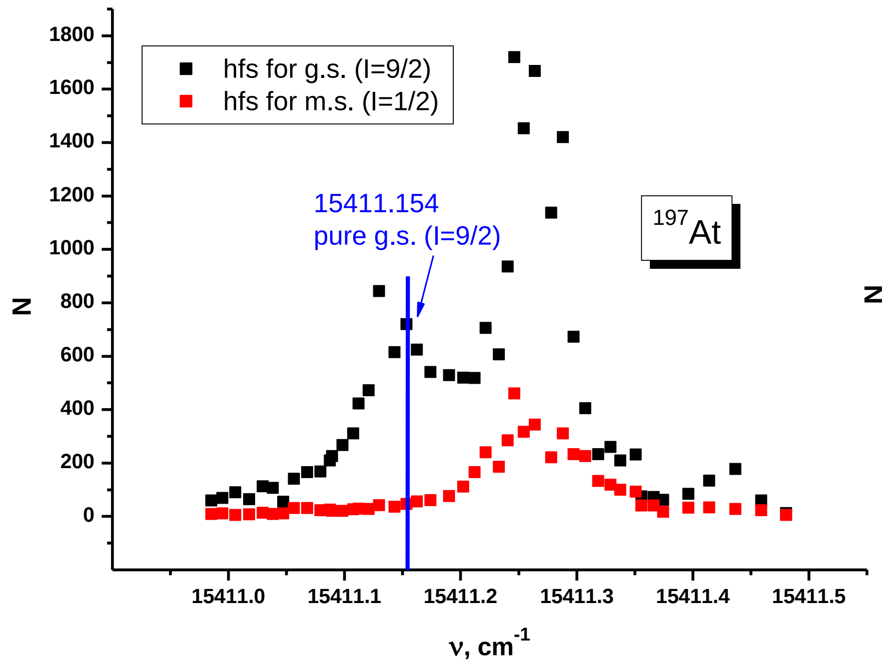
~1000 revolutions, ~35 ms, m/Δm ~ 10^5

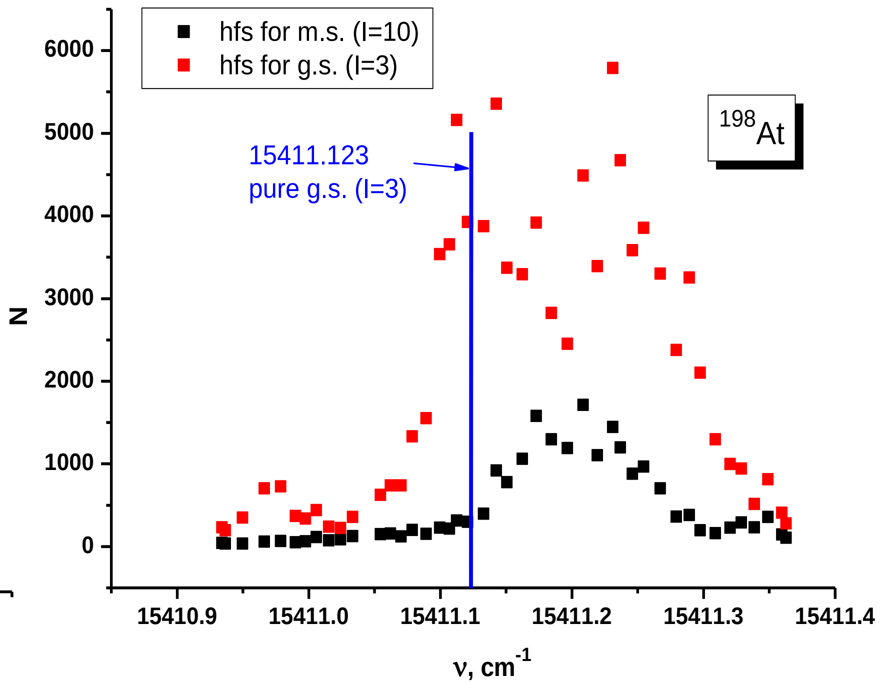




R. N. Wolf *et al.*, Nucl. Instr. and Meth. A 686, 82-90 (2012), S. Kreim *et al.,* INTC-P-299, IS 518 (2011)

Isomer selectivity for $^{197,198}At$

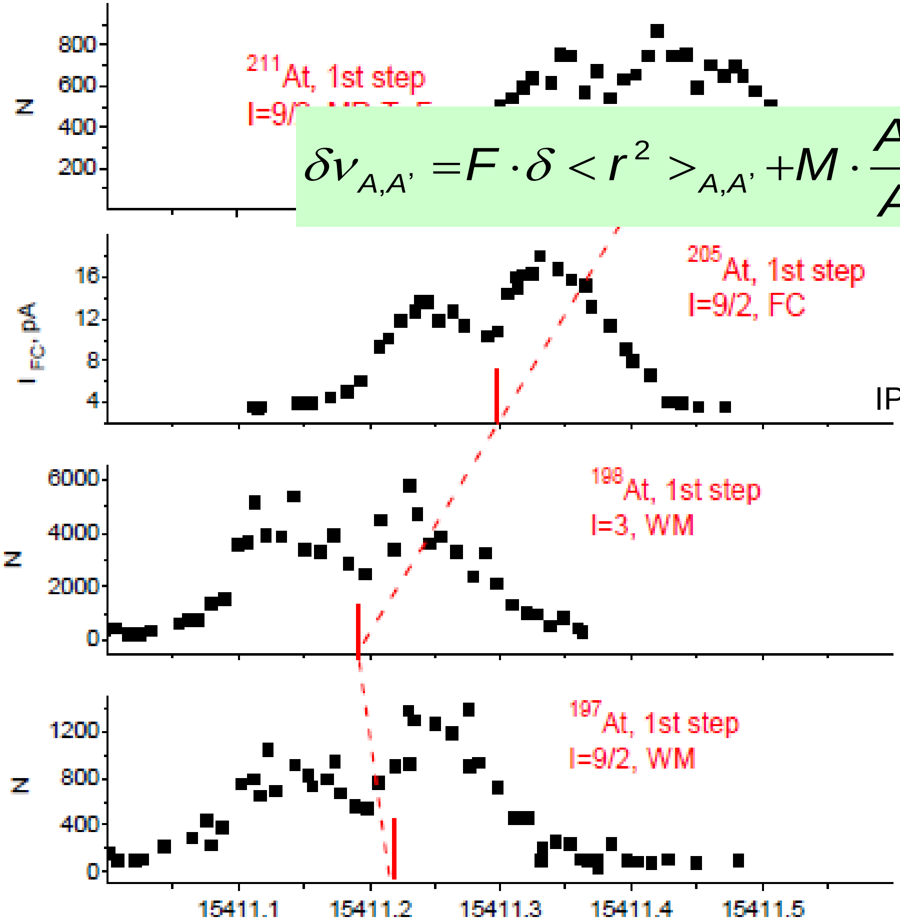


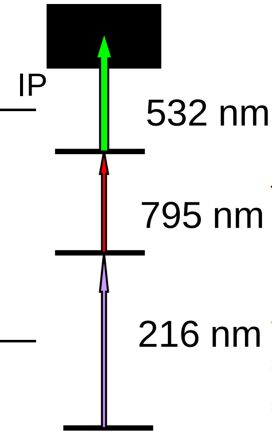


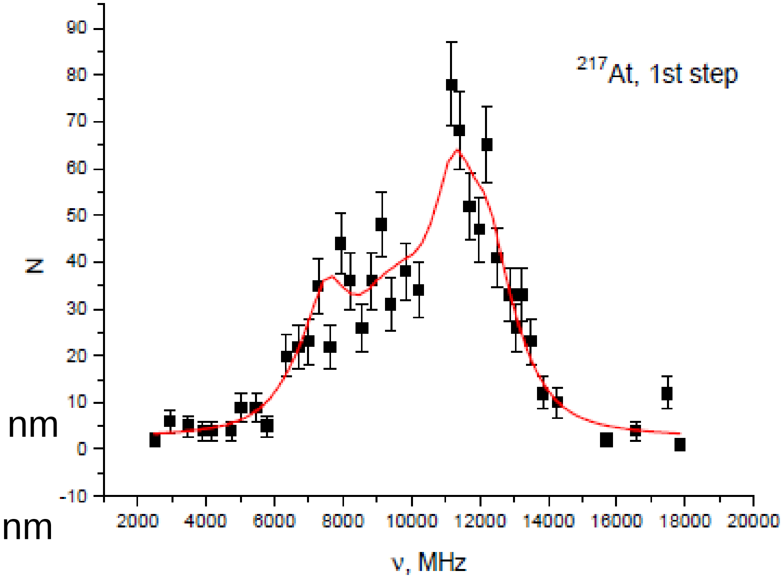
Isomer selectivity enable us to measure masses of $^{197g,198g}At$ and receive nuclear spectroscopic information for pure g.s.

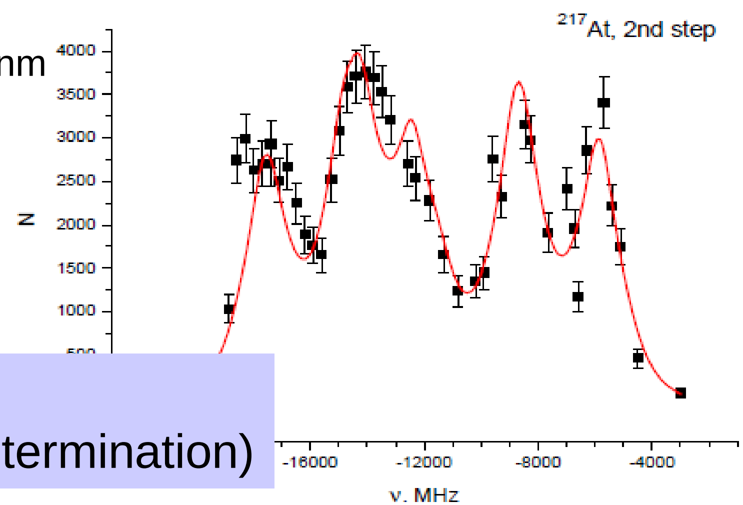
Astatine HFS spectra

$$\delta\nu_{A,A'} = F \cdot \delta < r^2 >_{A,A'} + M \cdot \frac{A - A'}{A \cdot A'}$$





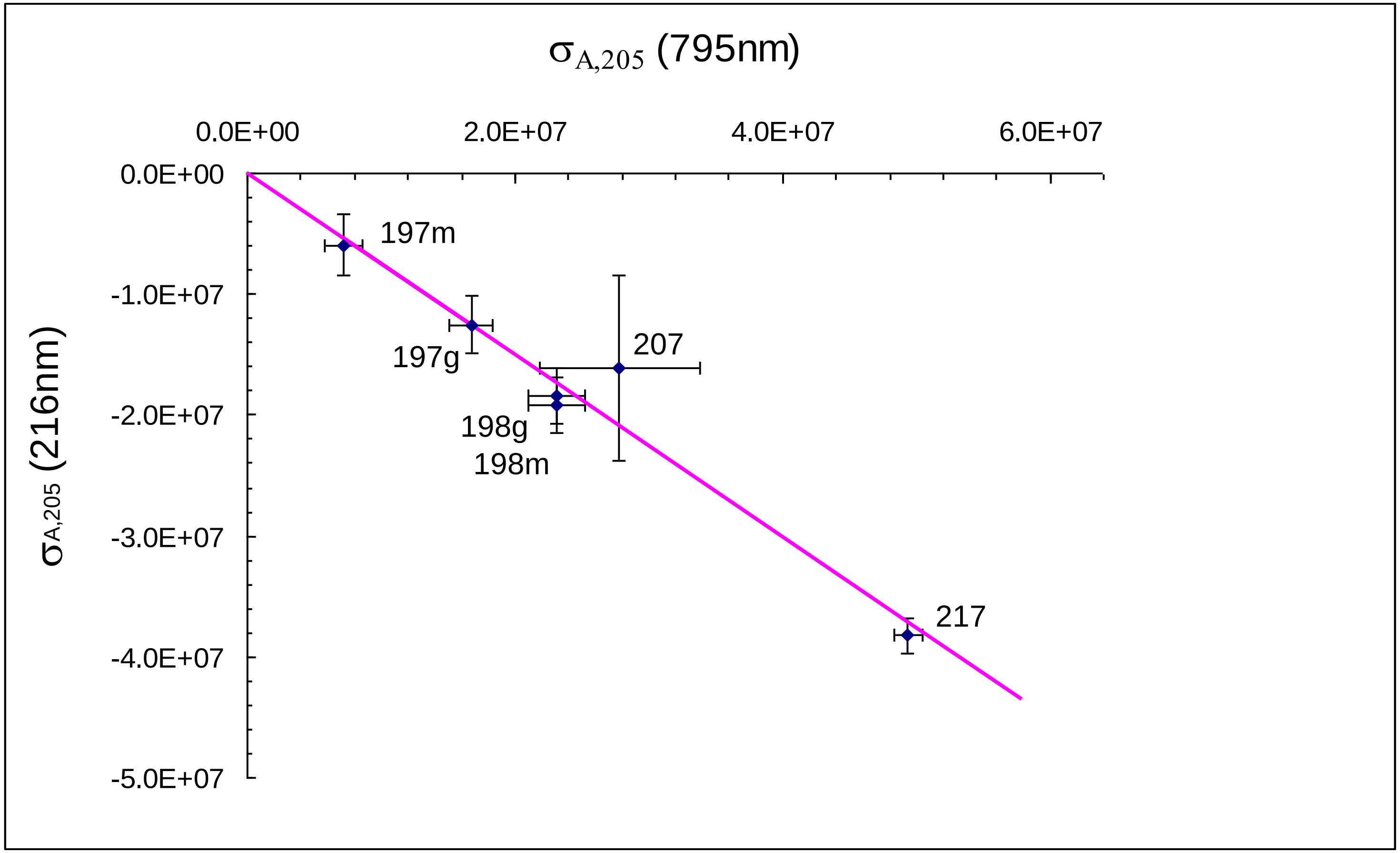




1st step is better for $\Delta<r^2>$ extraction

2nd step is better for hfs resolution (Q and μ determination)

King plot for 216 nm and 795 nm lines in At



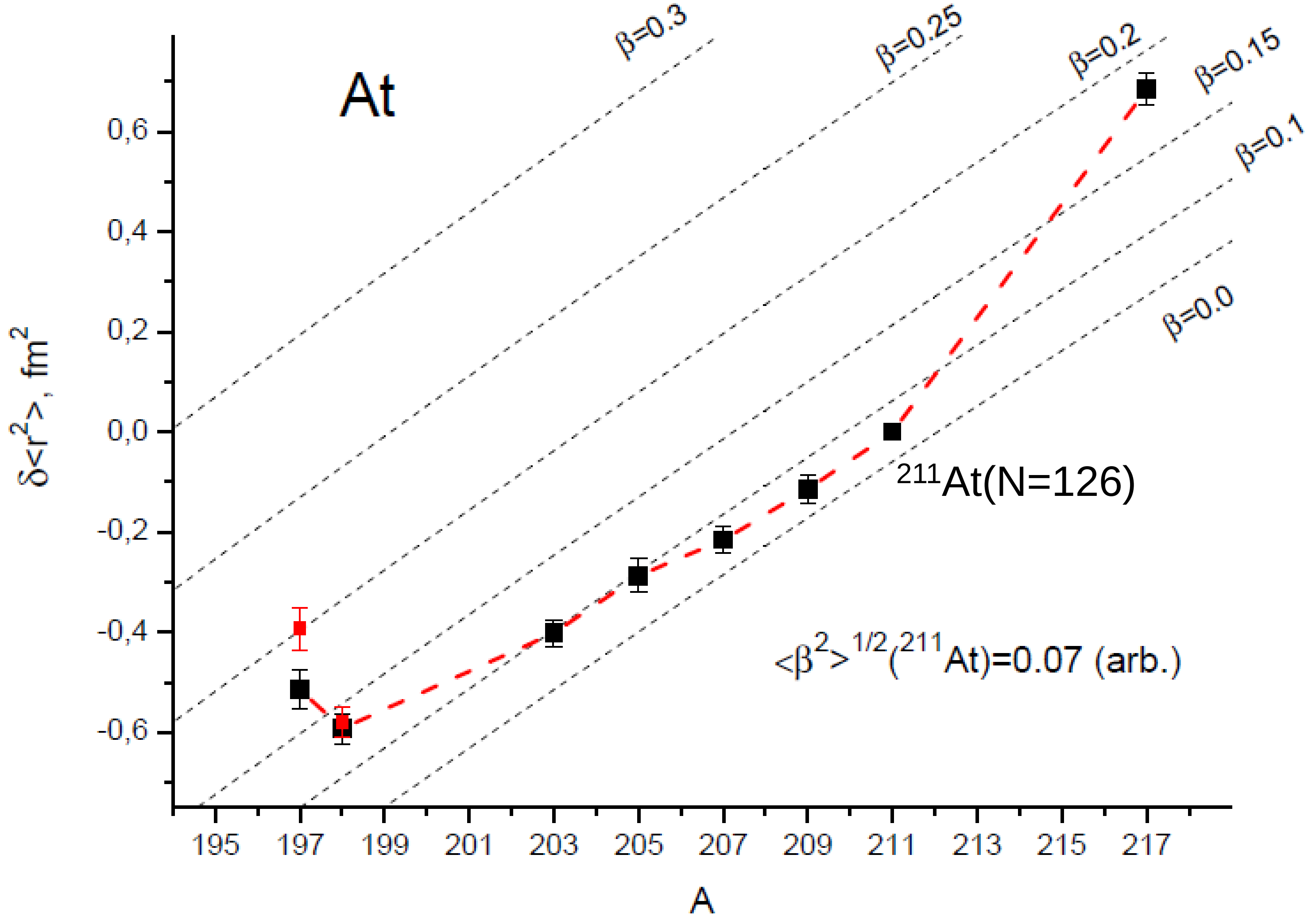
Isotope shift $\delta\ \nu_{A,A'}$:

$$\delta\nu_{A,A'} = F \cdot \delta < r^2 >_{A,A'} + M \cdot \frac{A - A'}{A \cdot A'}$$

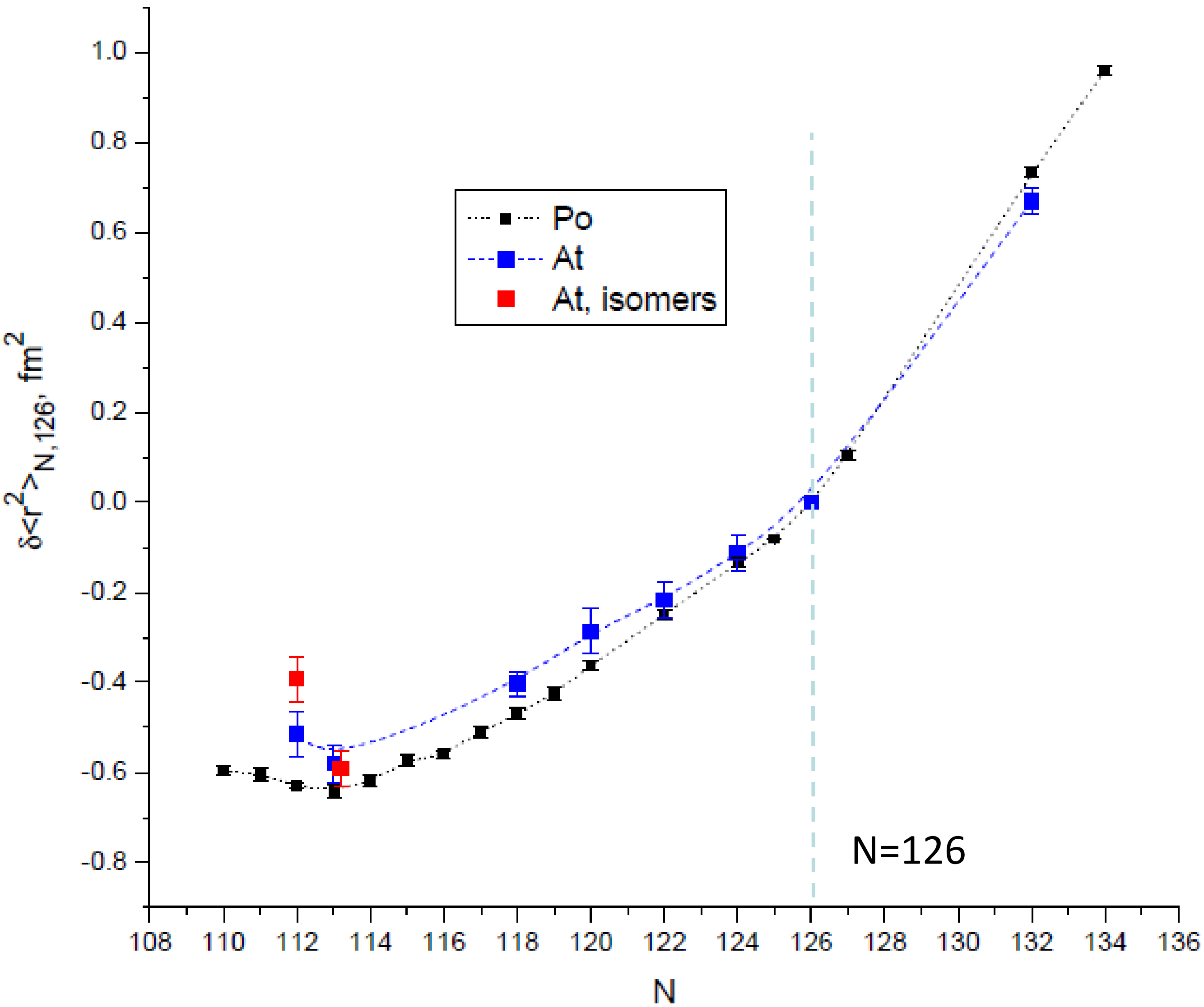
$$\Delta\sigma_{A,A'} = \Delta\nu_{A,A'} \cdot \frac{A \cdot A'}{(A - A')}$$

Δσ for different transitions should lie on the straight line with a slope $F_{\lambda 1}/F_{\lambda 2}$

IS534 October 2012: Charge radii of At isotopes



$_{85}$At vs $_{84}$Po charge radii

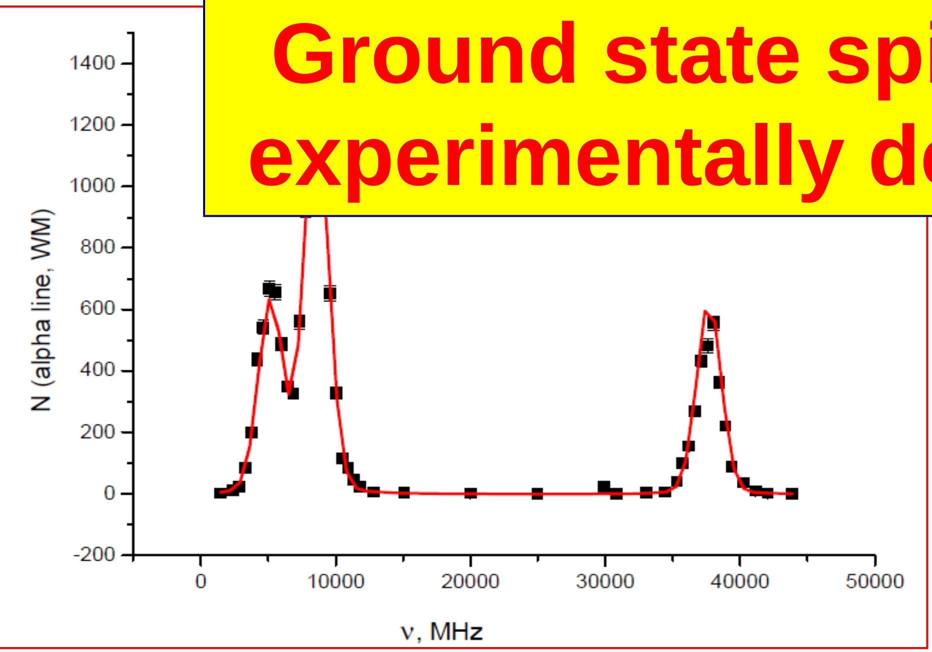


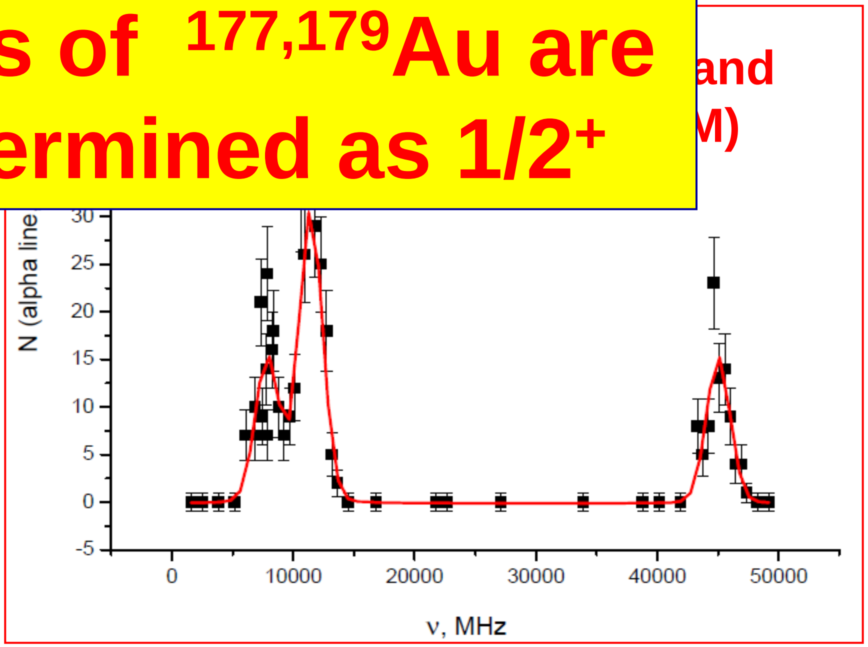
October 2012: IS534 experiment at ISOLDE – Au isotopes

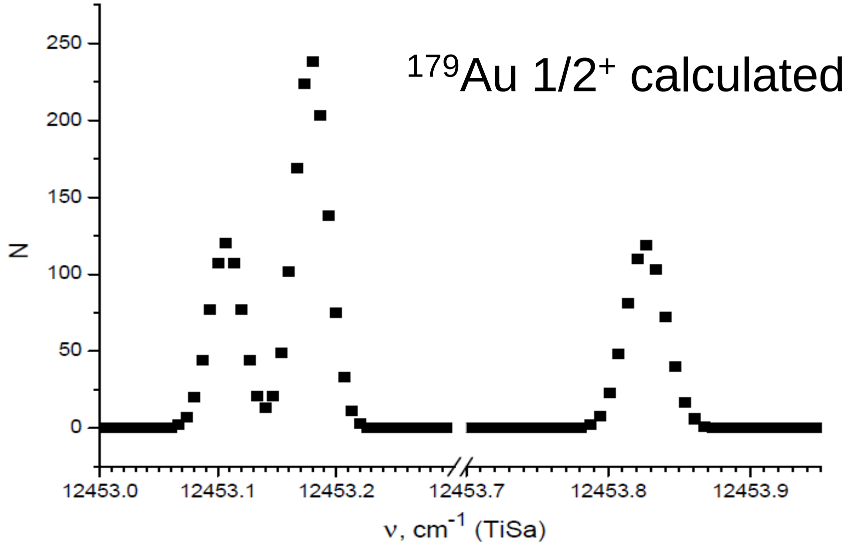
- **Are the light Au isotopes deformed?**
- **What are the spins of ground and isomeric states?**

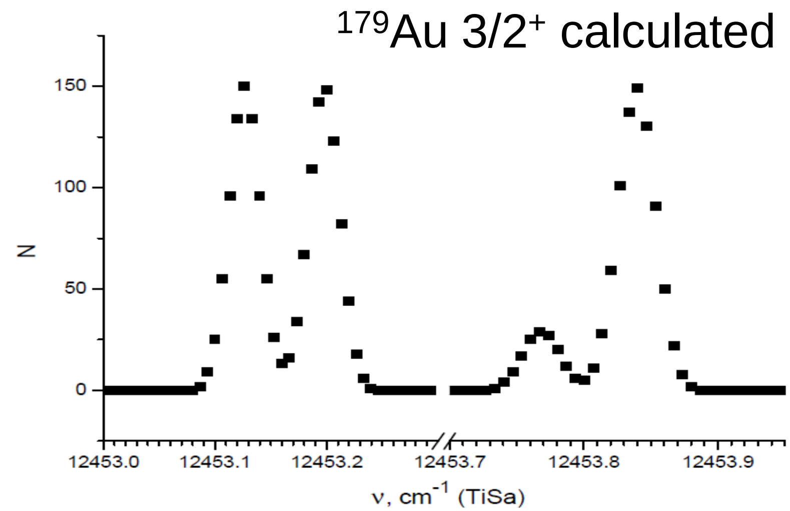
IS534: Hyperfine Structure Scans for ^{177,179}Au

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

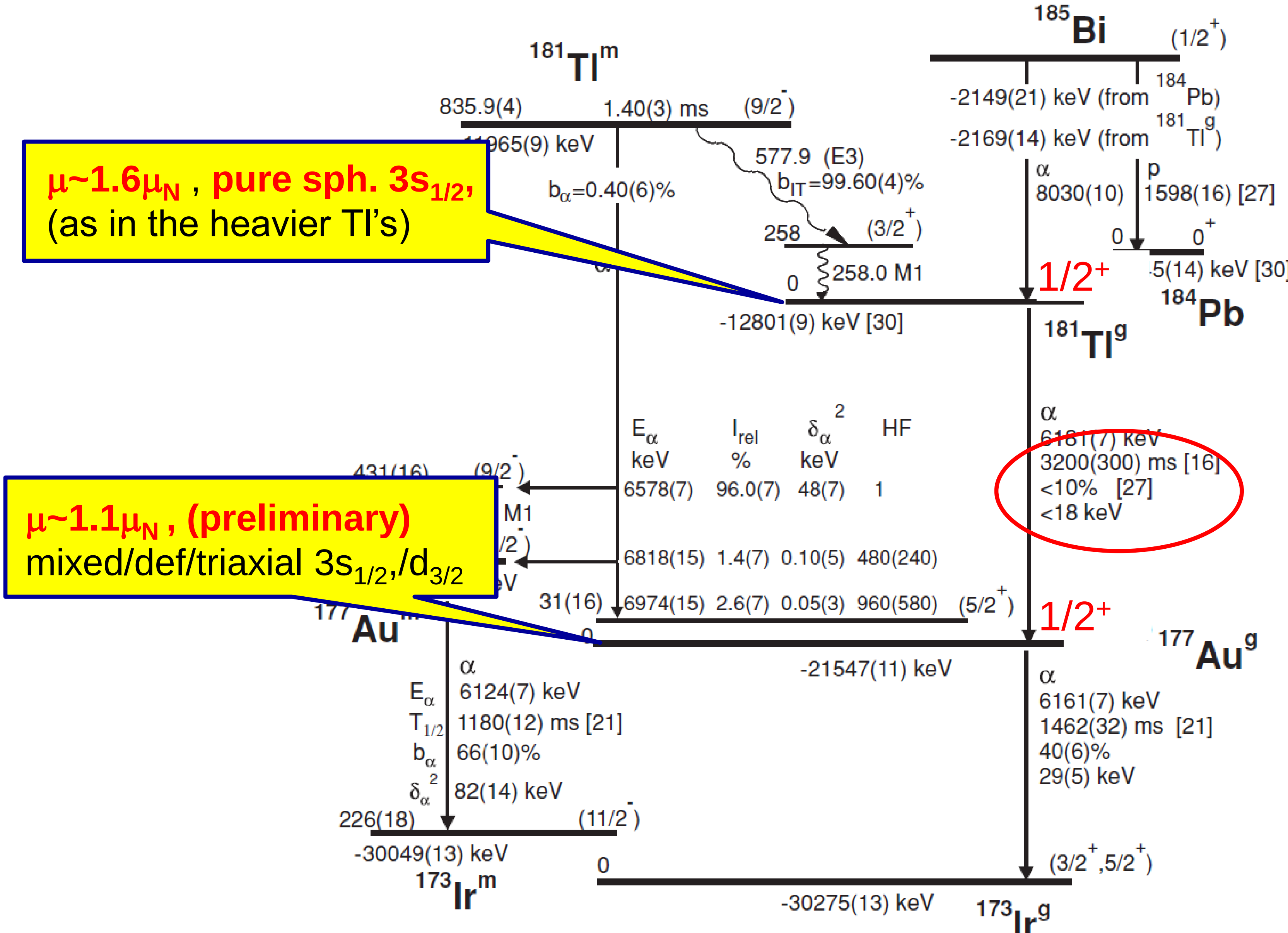






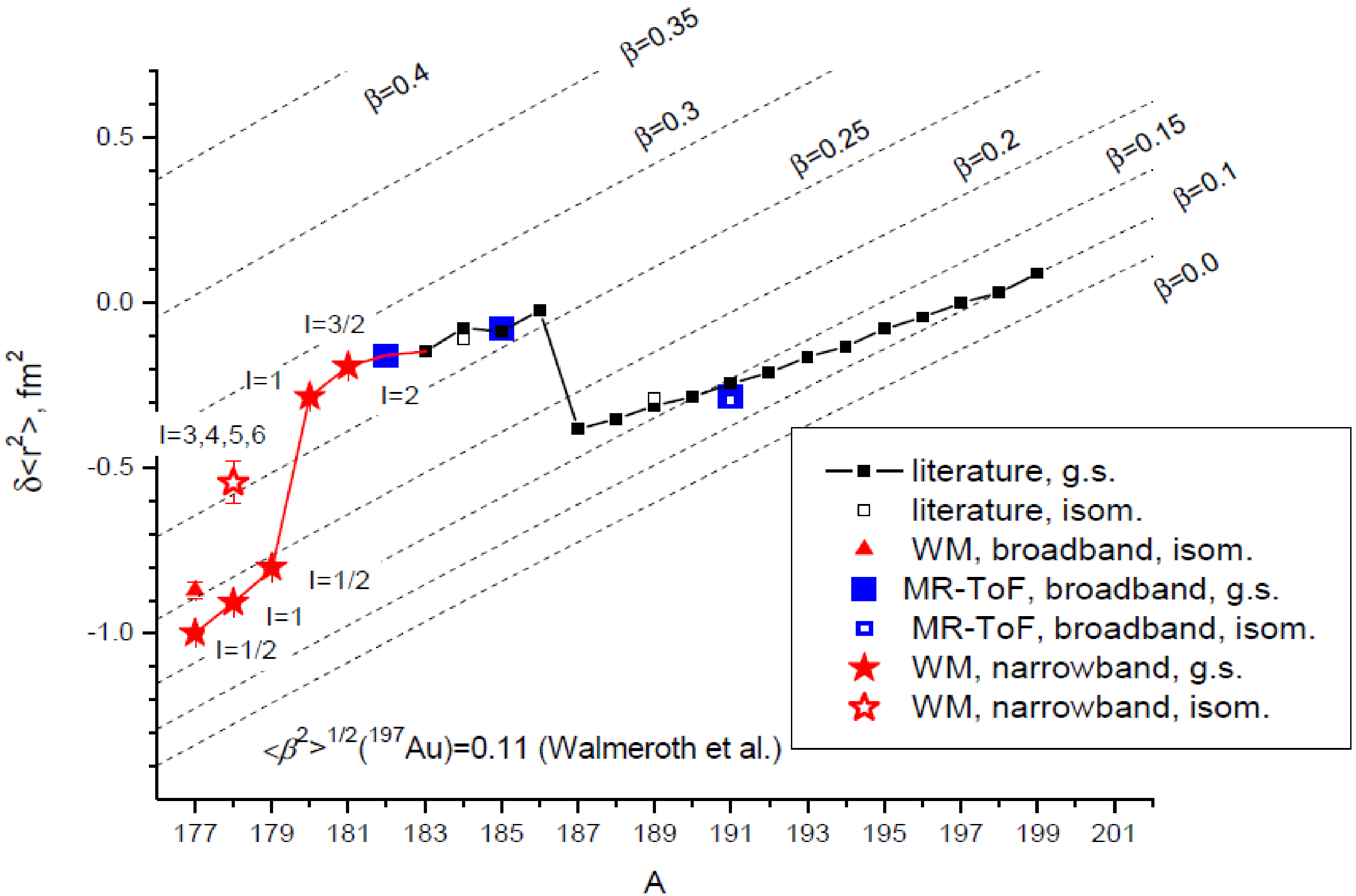


Why is 1/2⁺→1/2⁺ ^{181}Tl→^{177}Au α decay hindered?



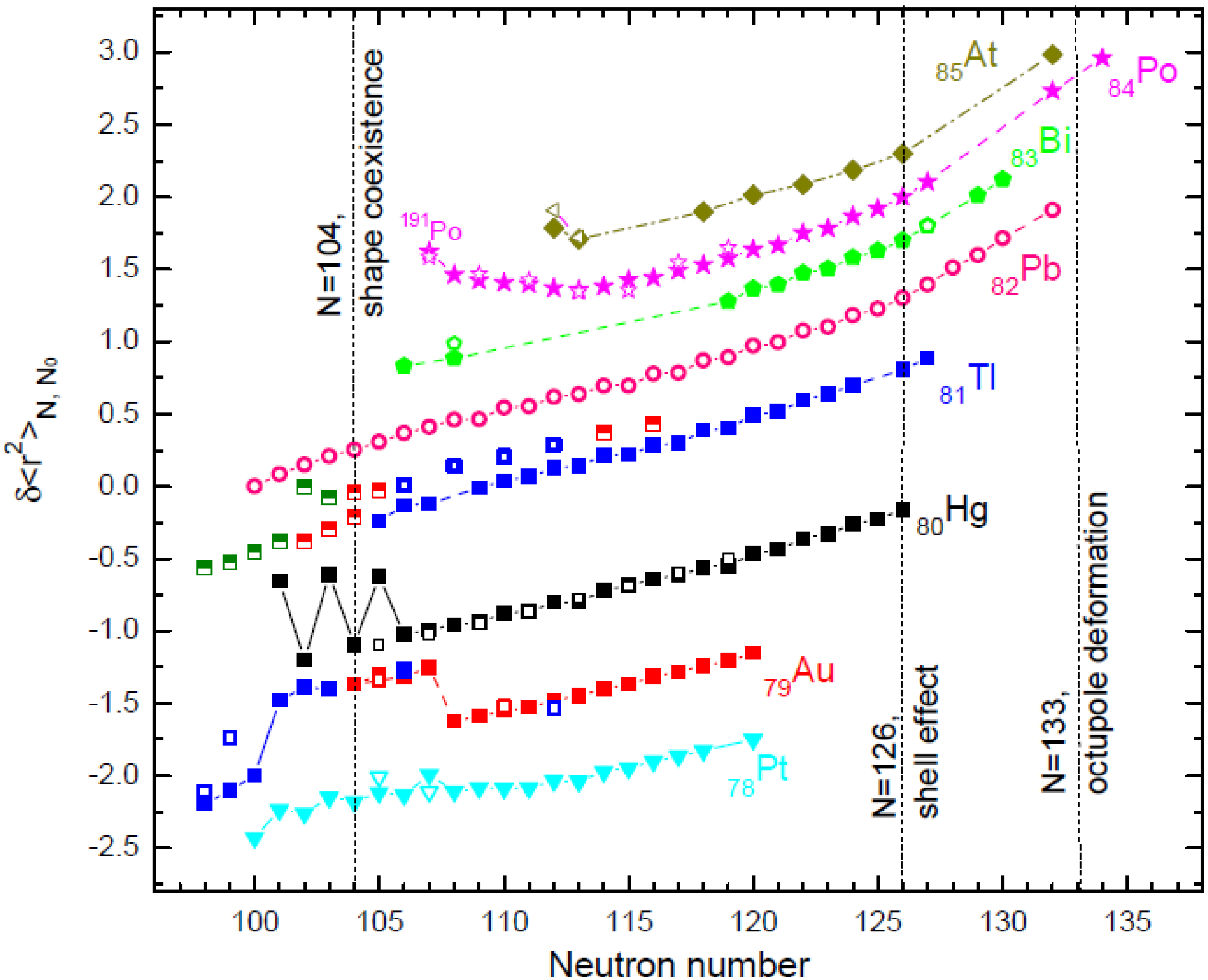
Plot from A.Andreyev et al., PRC 80, 024302 (2009)

IS534: Charge Radii of Au isotopes, ISOLDE 2012



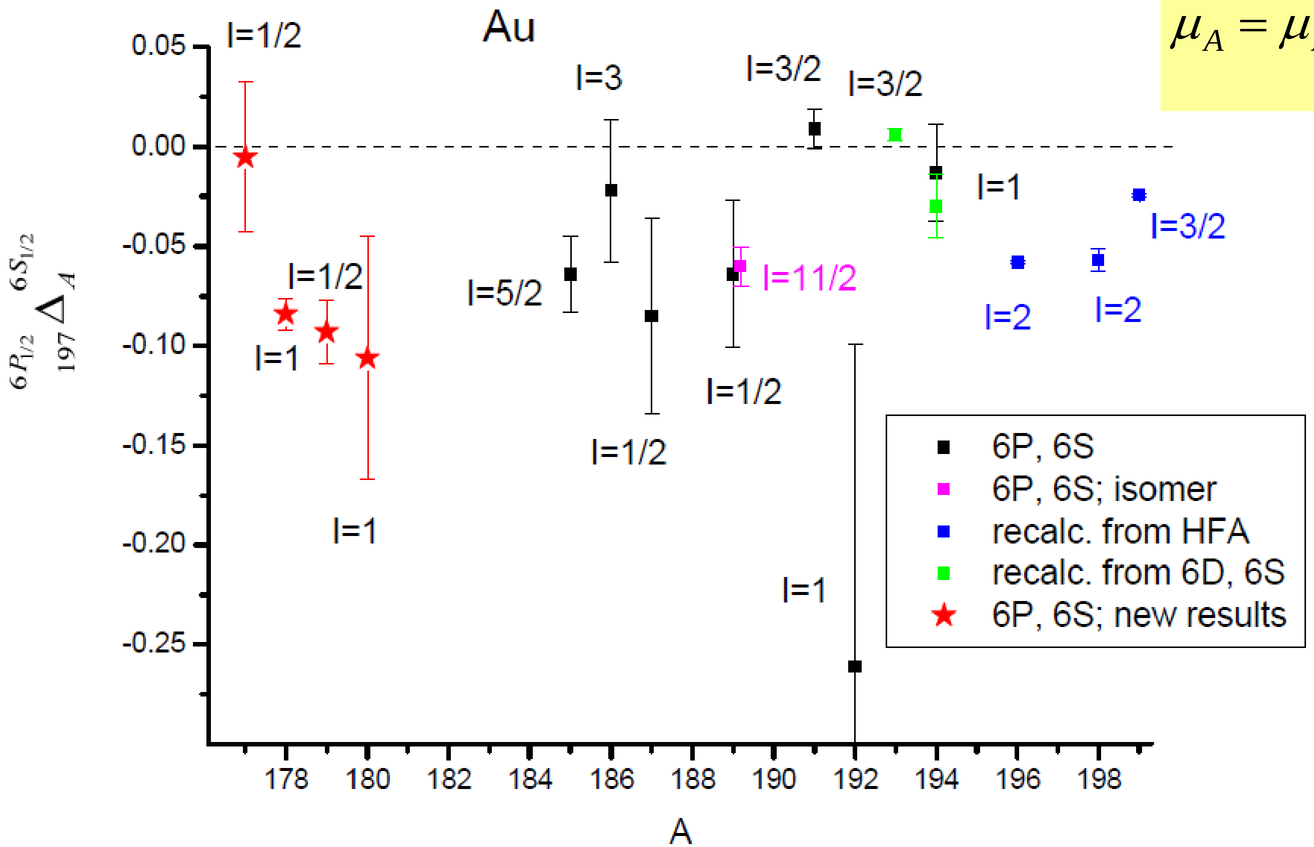
- **Deformation jump toward less deformed shapes in the light Au isotopes**
- **Shape staggering in ^{178}Au (large deformation difference between 2 states)**

Summary: Charge Radii in Pb region



- IS/charge radii for 10 At nuclei were measured
- "Back to sphericity" in the lightest Au isotopes
- Magnetic/quadrupole moments will be deduced
- Large amount of by-product nuclear spectroscopic information on At and Au and their daughter products

Hyperfine structure anomaly for Au isotopes



$$\mu_A = \mu_{A_0} \cdot \frac{I_A}{I_{A_0}} \cdot \frac{a_A(nl)}{a_{A_0}(nl)} \cdot (1 + {}^{A_0}\Delta^{A}_{nl})$$

$$\rho^{A}_{n_1 l_1, n_2 l_2} = \frac{a^{A}_{n_1 l_1}}{a^{A}_{n_2 l_2}},$$

$$^{n_1 l_1}_{A_1}\Delta^{n_2 l_2}_{A_2} = \frac{\rho^{A_1}_{n_1 l_1, n_2 l_2}}{\rho^{A_2}_{n_1 l_1, n_2 l_2}} - 1 = {}^{A_1}\Delta^{A_2}(n_1 l_1) - {}^{A_1}\Delta^{A_2}(n_2 l_2)$$

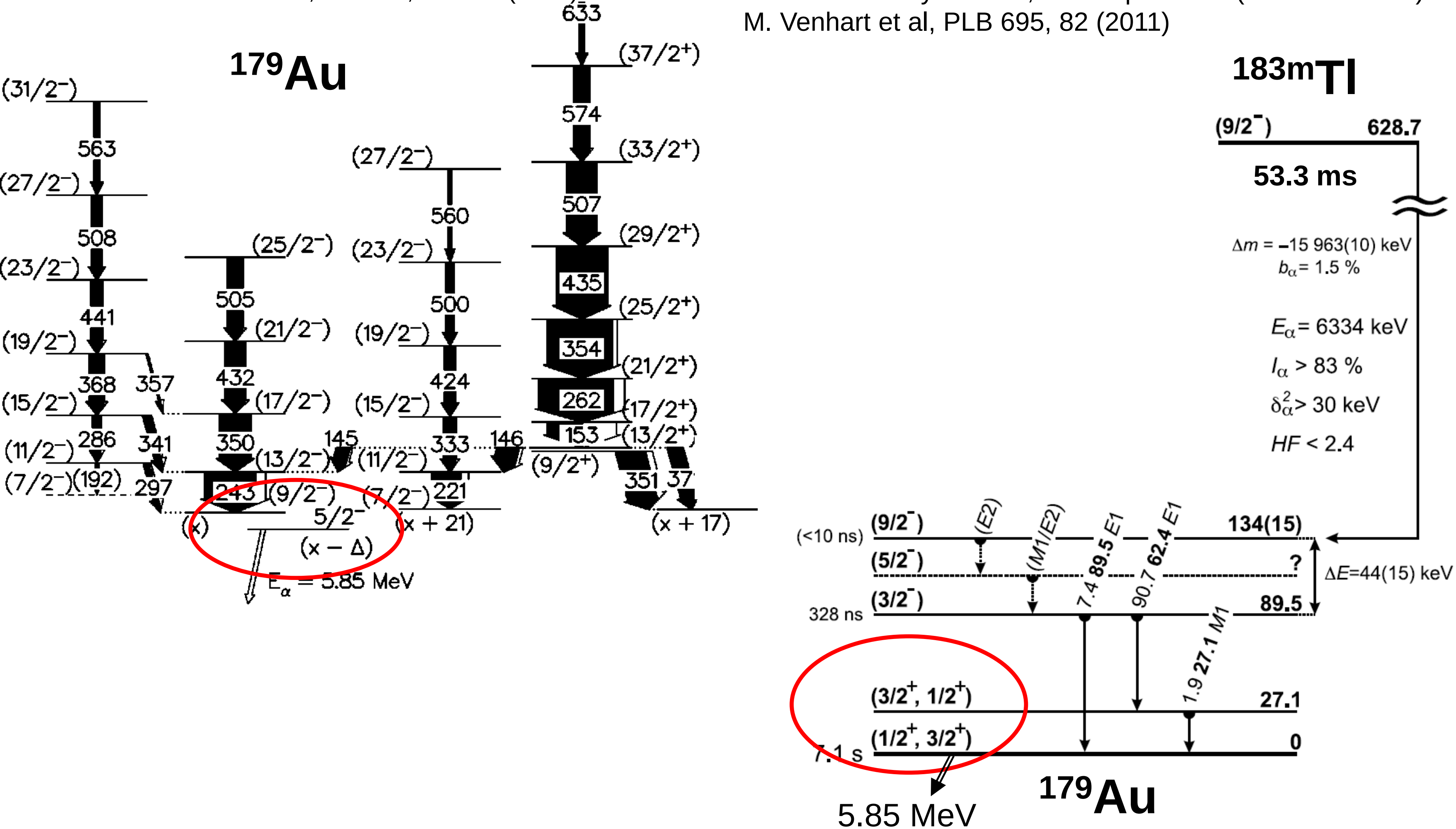
Заключение

1. Измерено асимметричное массовое распределение осколков запаздывающего деления ^{178}Tl и определена вероятность такого распада. Получены значения барьеров деления для ^{178,180}Hg.
2. Для исследования ядер At найдена эффективная схема фотоионизации, обнаружено около 20 ранее не известных атомных переходов, впервые определен потенциал ионизации At.
3. Обнаружено запаздывающее деление ^{196,194}At. Предварительный анализ свидетельствует о его симметричном характере.
4. Измерены изотопические сдвиги и сверхтонкое расщепление для 10 изотопов (изомеров) At на двух переходах, 216 nm и 795 nm, что позволит получить новые данные о μ, Q, $\delta\langle r^2\rangle$ и деформации этих изотопов (изомеров). Впервые для детектирования фотоионов использована установка MR-ToF.
5. Измерены изотопические сдвиги и сверхтонкое расщепление (μ, $\delta\langle r^2\rangle$) для 9 изотопов (изомеров) Au на переходе 267.6 nm. Впервые обнаружен «обратный скачок деформации» — возвращение к сферичности ядер с $N<101$. Обнаружены два изомера с существенно разной деформацией в ядре ^{178}Au.
6. Получены новые данные об аномалии сверхтонкой структуры для изотопов Au, что позволит, в частности, уточнить значения ранее измеренных магнитных моментов.

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)

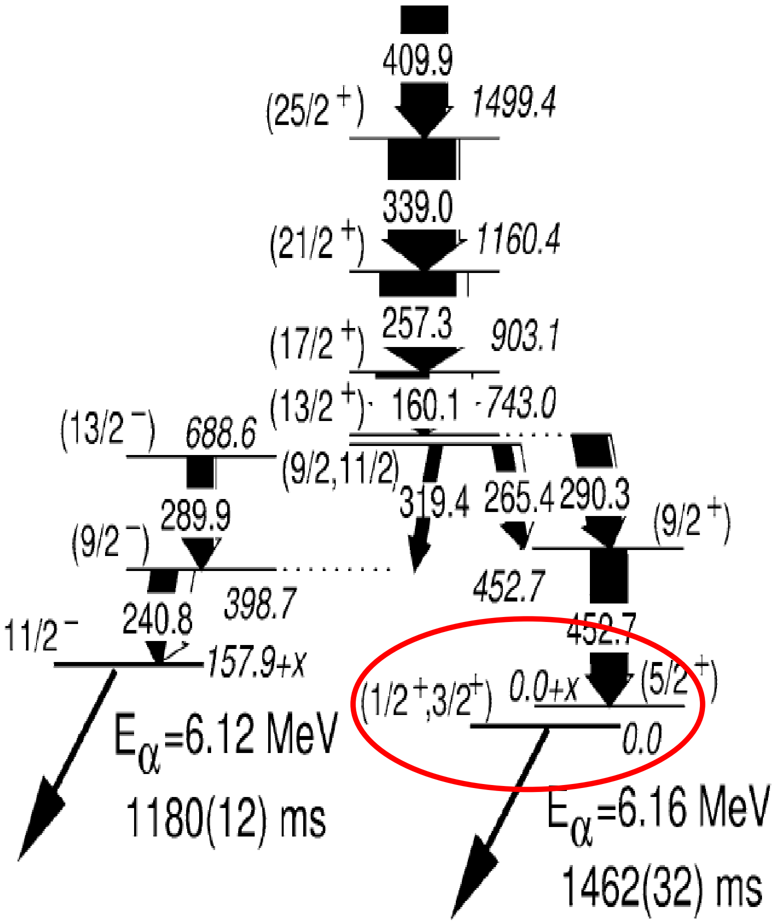
RITU: A. Andreyev et al., R35 experiment (+ISOLDE data)
M. Venhart et al, PLB 695, 82 (2011)



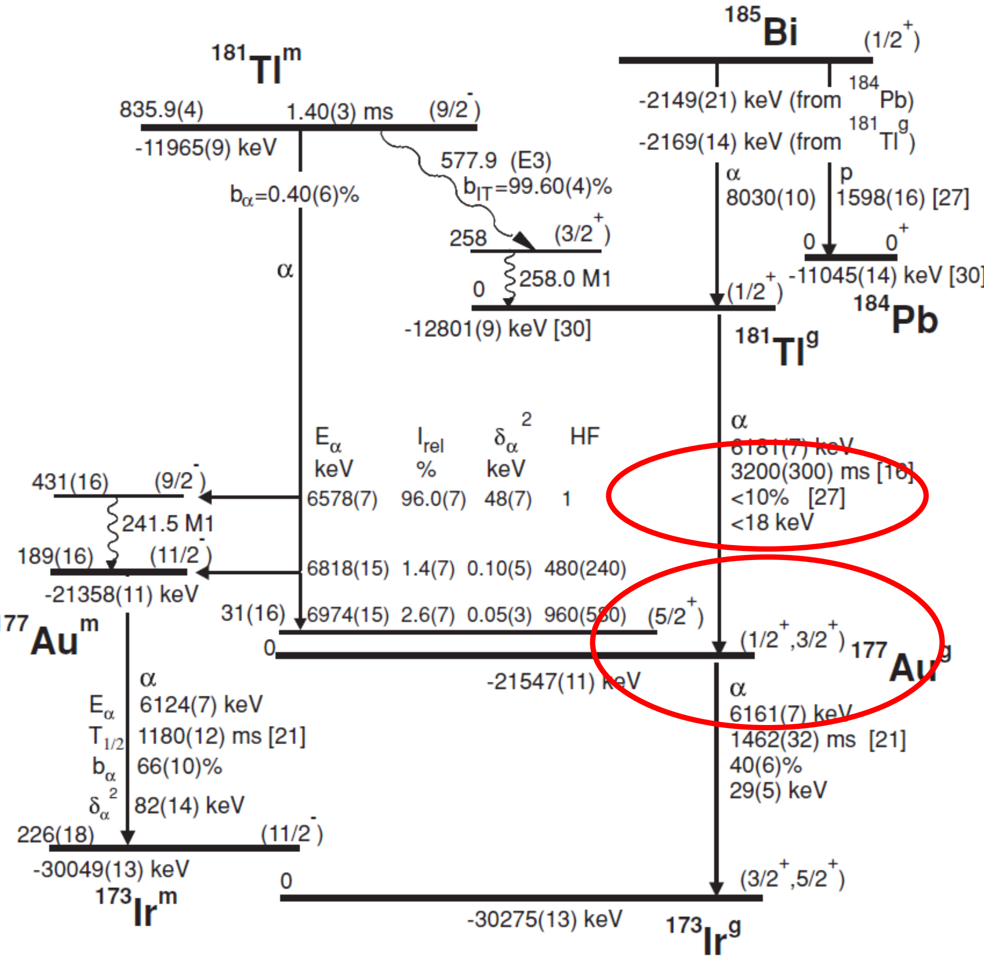
Extensive ISOLDE data for g.s. of ^{183}Tl are available, analysis underway

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

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



SHIP: 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