Shape Coexistence Beyond the N=104 Midshell -Studies of ${}^{180}_{79}\mathrm{Au}_{101}$ by decay spectroscopy

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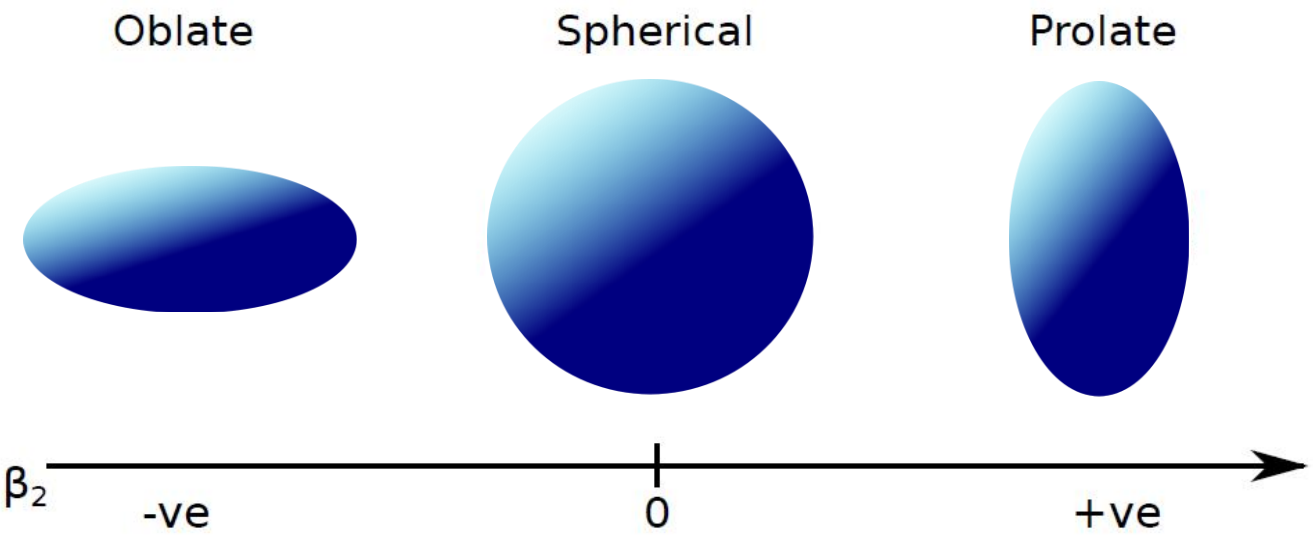
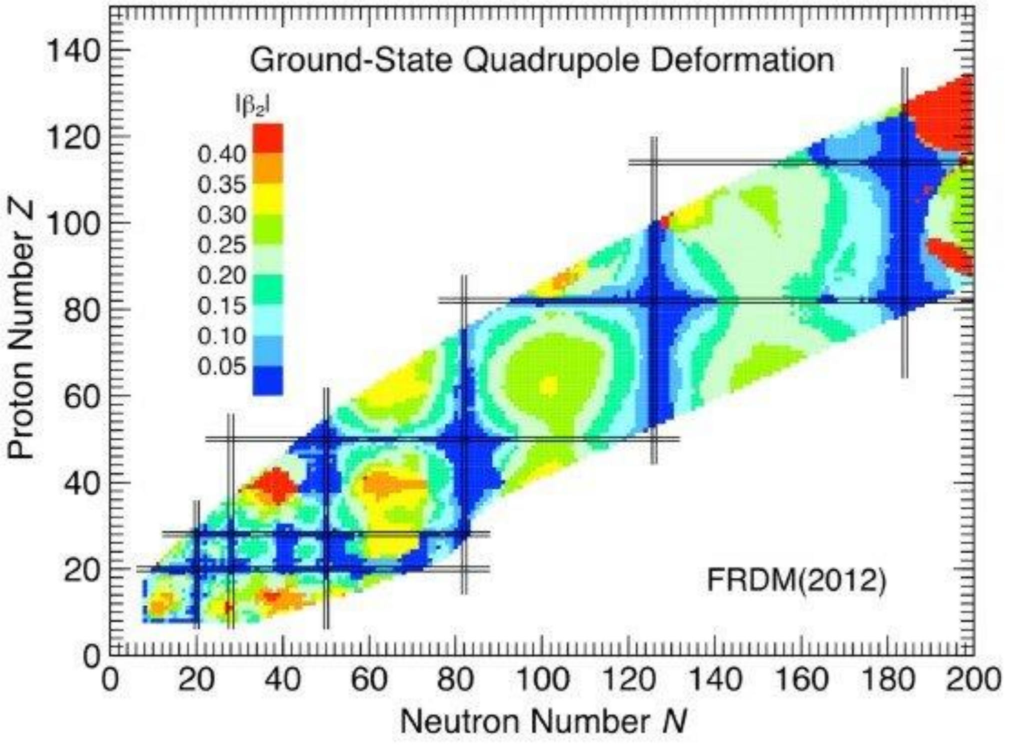
Shape of nuclei

-Spherical ground state configurations are energetically favorable in nuclei near shell closures.

-Modifying the nucleon number of a doubly closed-shell nuclei will increase the deformation of the ground state until the midshell, where deformation is maximal.

-Excited states can display different configurations from ground states.





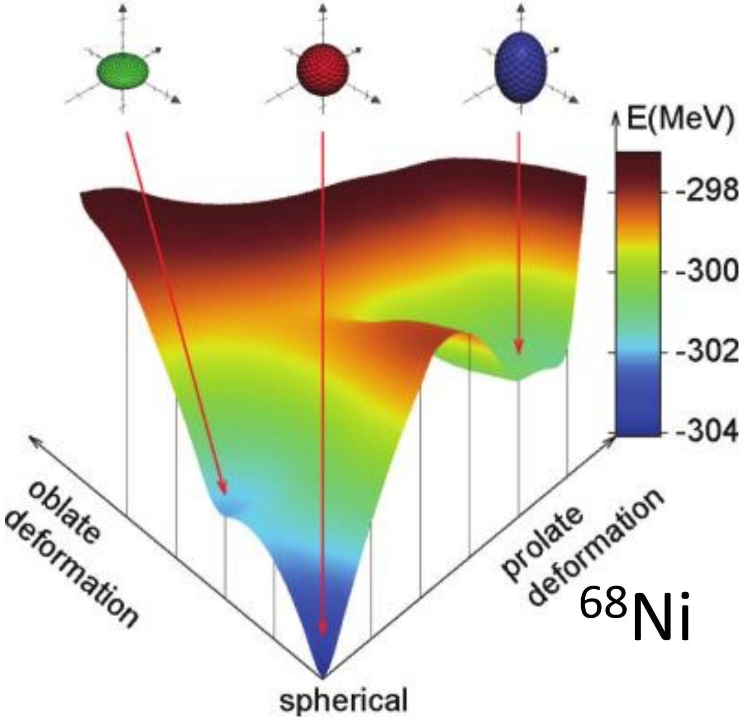
Möller, P., et al. Atomic Data and Nuclear Data Tables 109 (2016): 1-204.

Low energy shape coexistence

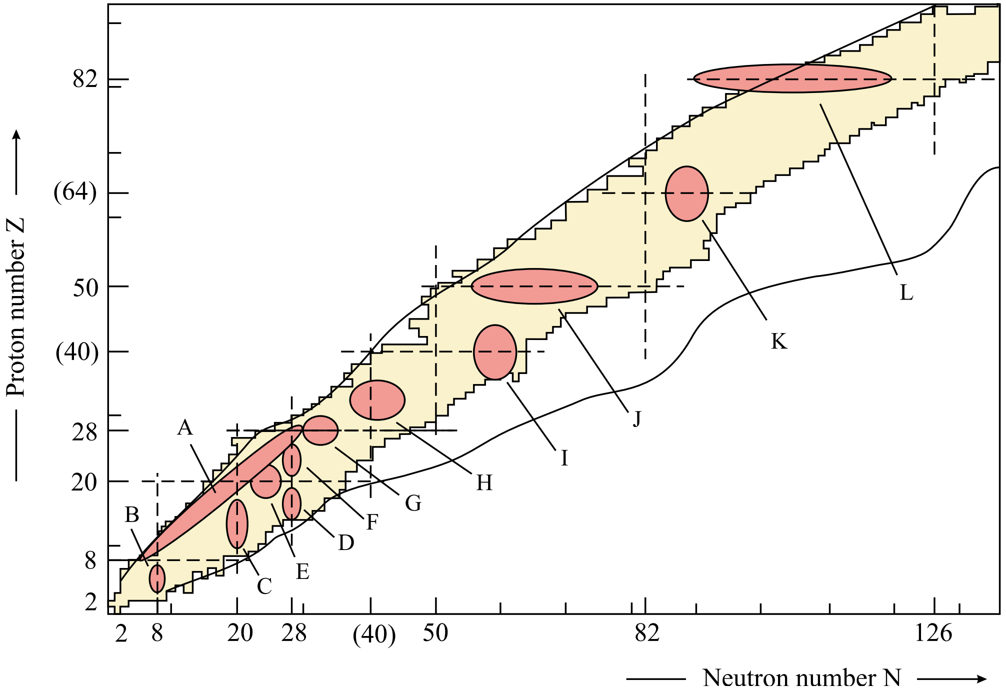
-Regions where one type of nucleon lies near a shell closure and the other near midshell lead to competition between spherical and deformed shapes (e.g., Z = 82, N = 104).

-Different configurations are said to coexist within a single nuclei.

-Spherical and deformed configuration can be separated by only a few hundred KeV. (^{186}Pb)



Suchyta, Scott, et al. Physical Review C 89.2 (2014): 021301.



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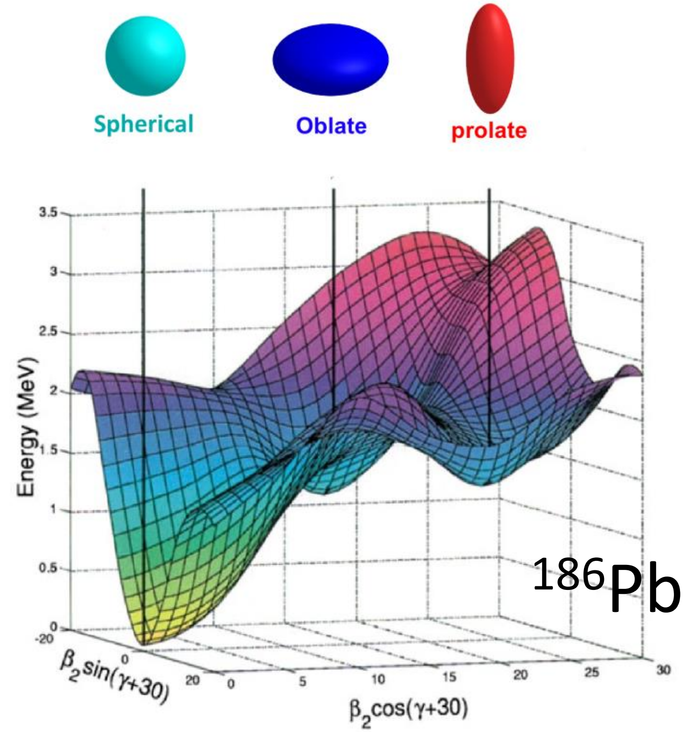

Andreyev, A. N., et al. *Nature* 405.6785 (2000): 430-433

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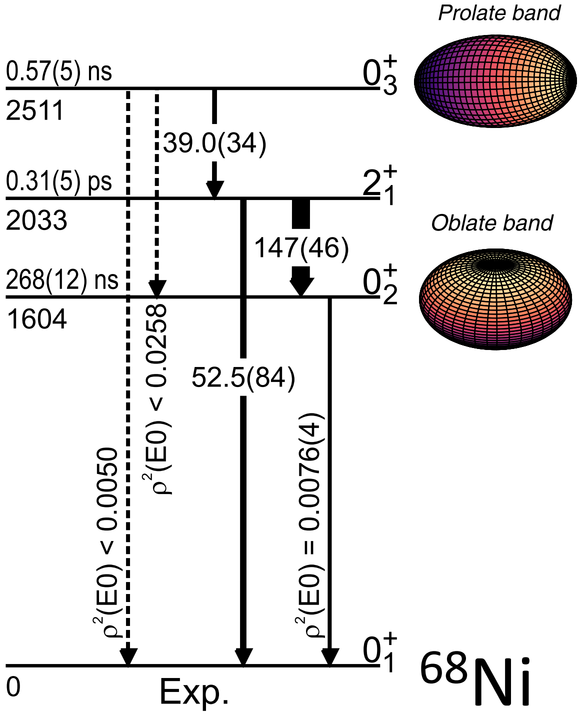

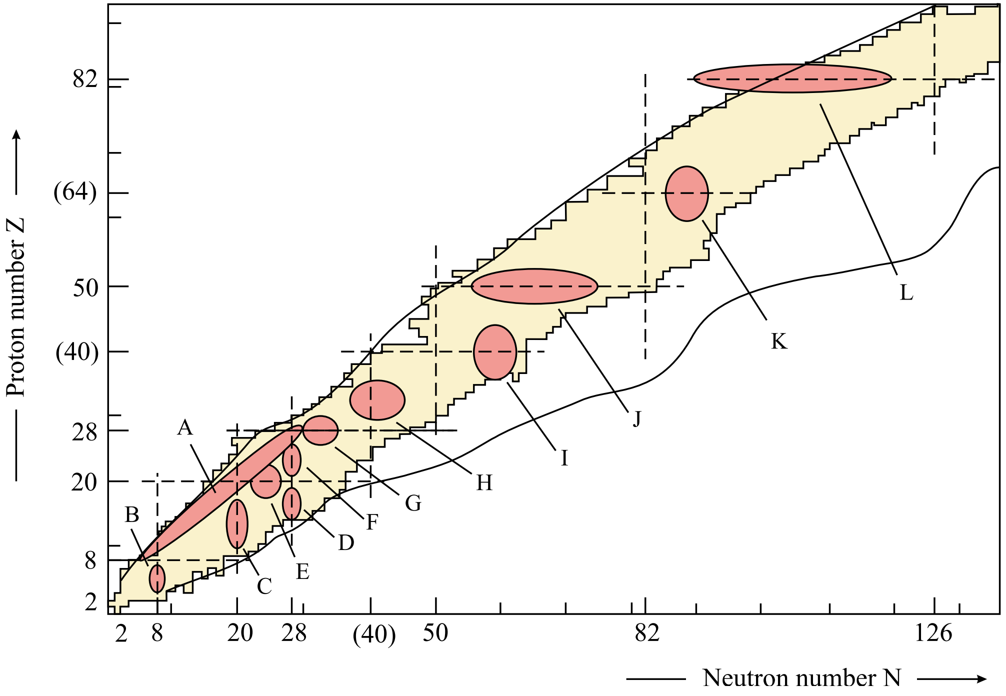

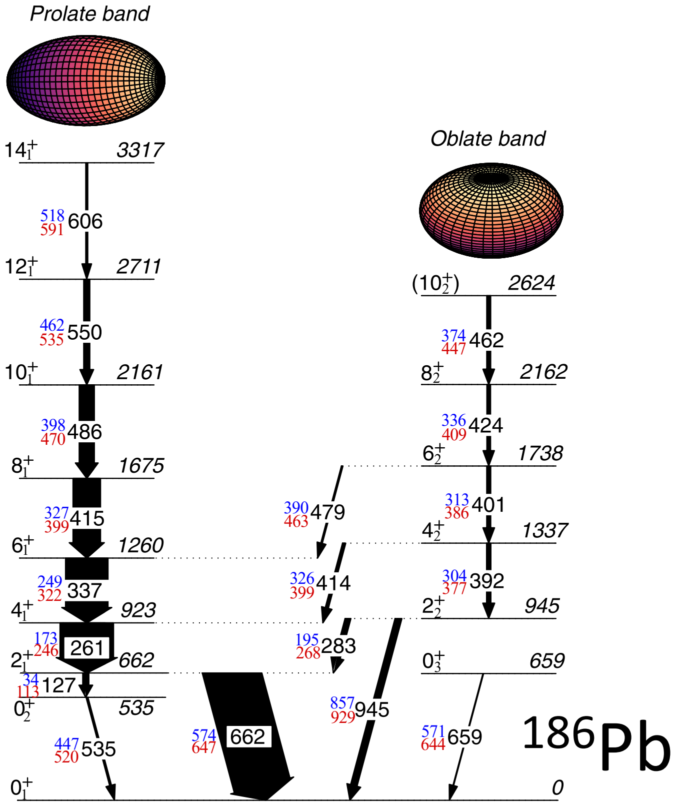

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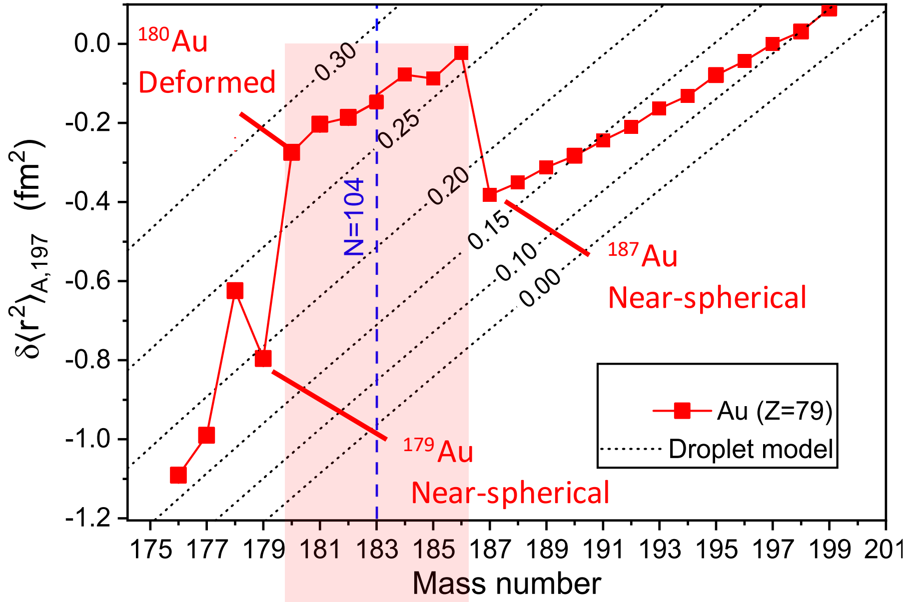
Ojala, J. *et al. Commun Phys* **5**, 213 (2022).

Low energy shape coexistence

-Describing this behavior in a consistent manner is a big challenge for theory.

-To constrain our models, experimental data on these structures is required.

-Some of the first evidence of shape coexistence came from laser spectroscopy in the region of Z=82 and N=104.



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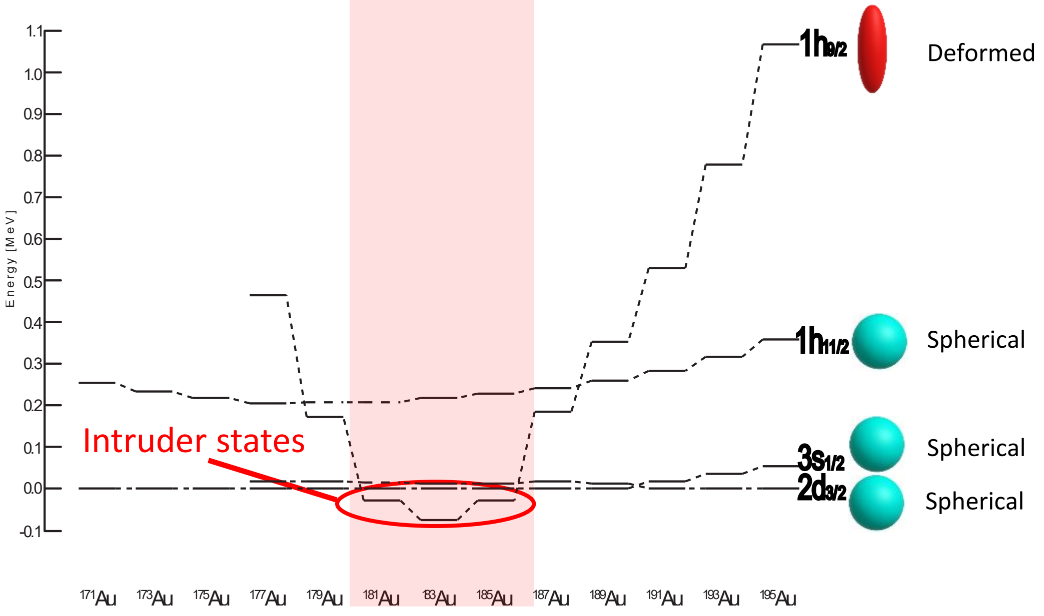

Venhart. M, Phys. G 44, 074003 (2017)

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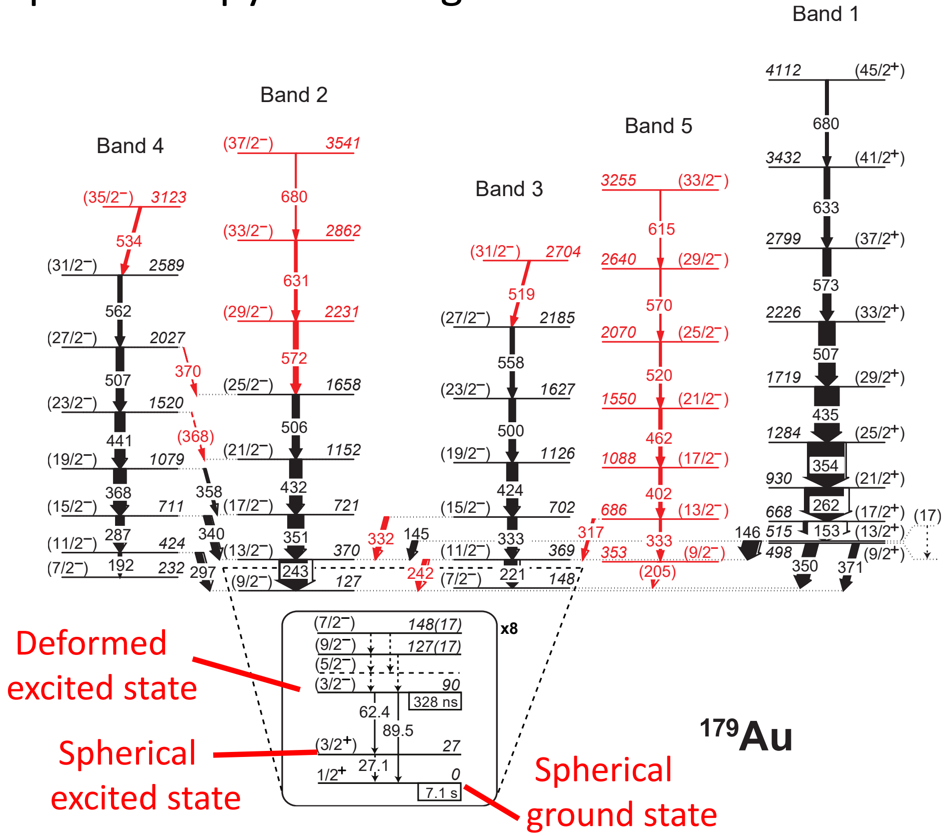
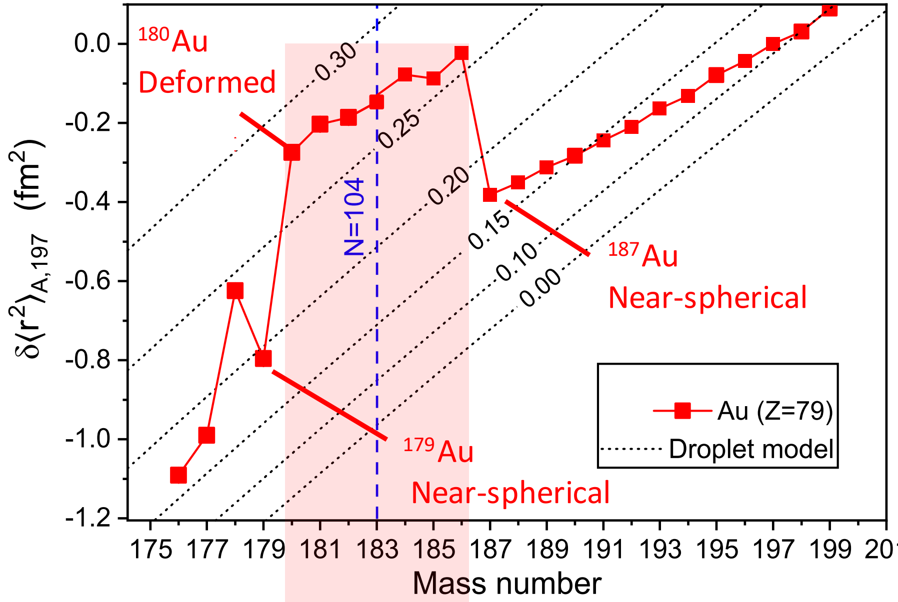


Balogh, M., et al. Physical Review C 106.6 (2022): 064324.



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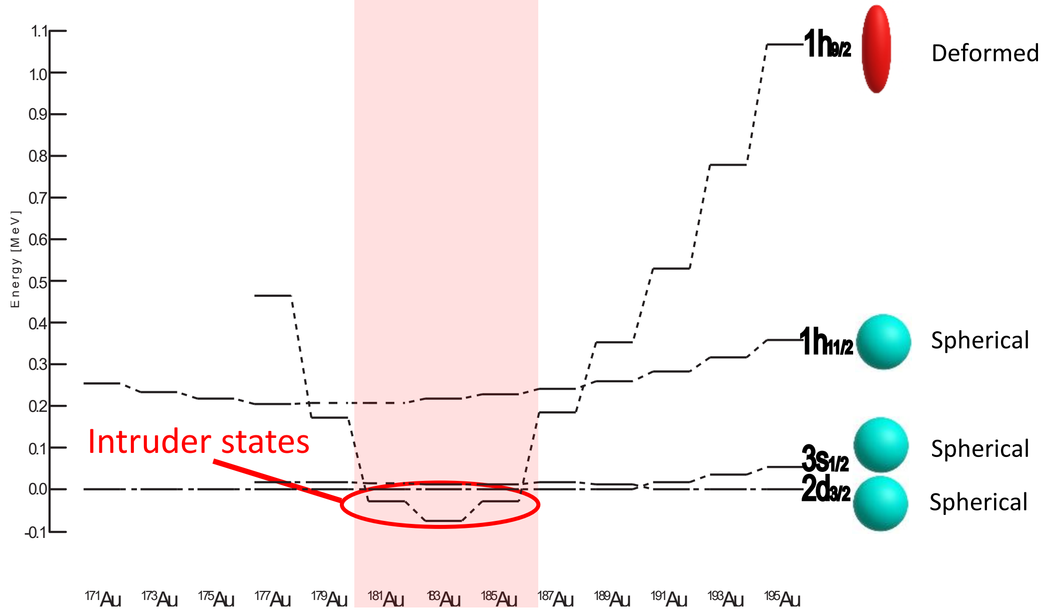

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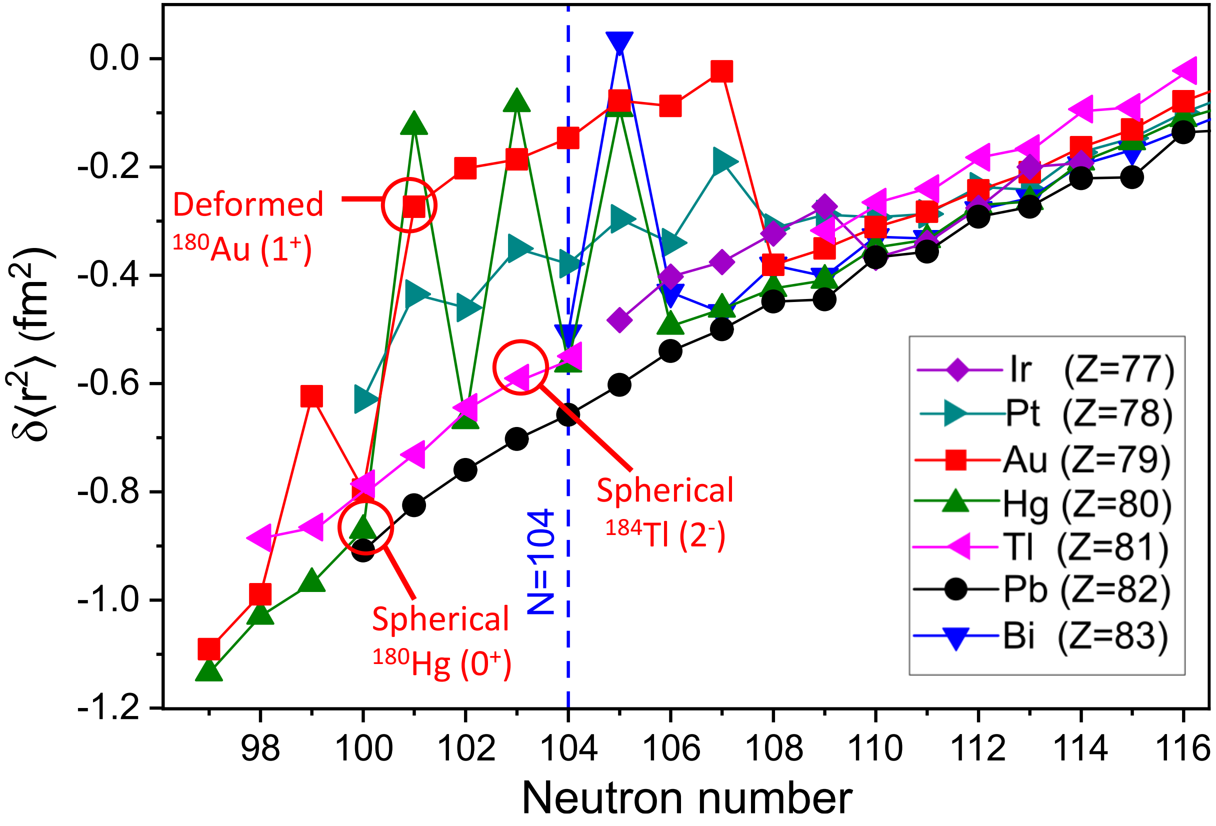
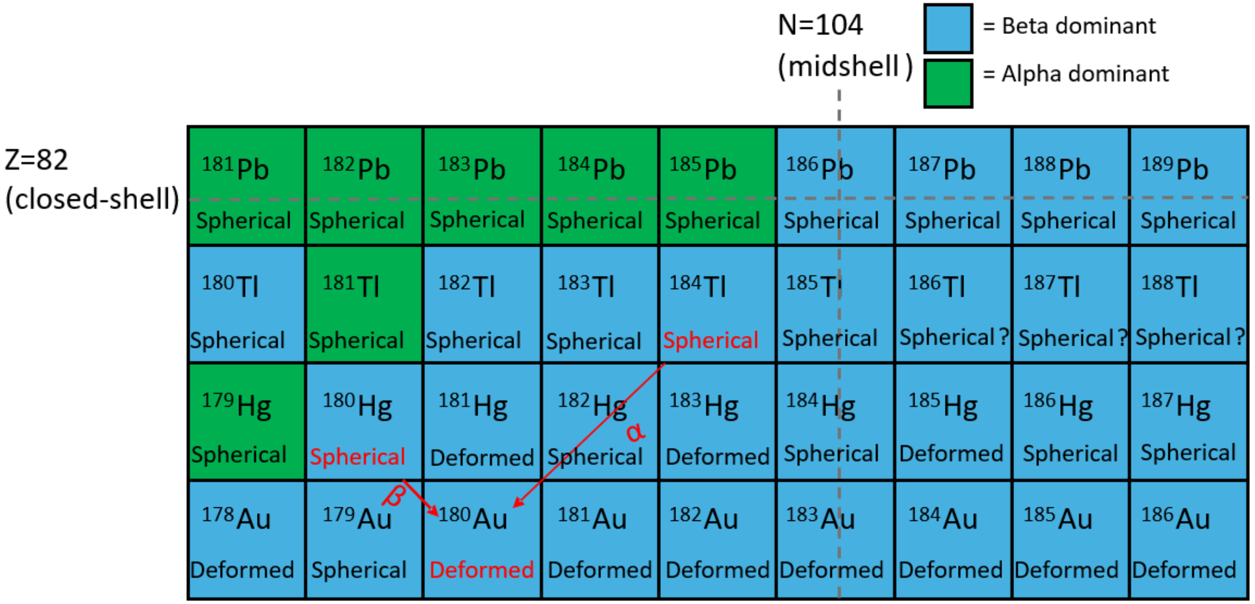
Low energy shape coexistence

-Alpha decay $^{184}Tl \rightarrow ^{180}Au$.

-Beta decay $^{180}Hg \rightarrow ^{180}Au$.





The time for decay spectroscopy

-Whilst laser spectroscopy has been successful in displaying hints of shape coexistence, it is limited in what it can show.

-Different decay channels will populate different states. (Alpha vs Beta)

-Two major previous studies of the low-lying structure of ^{180}Au were conducted.

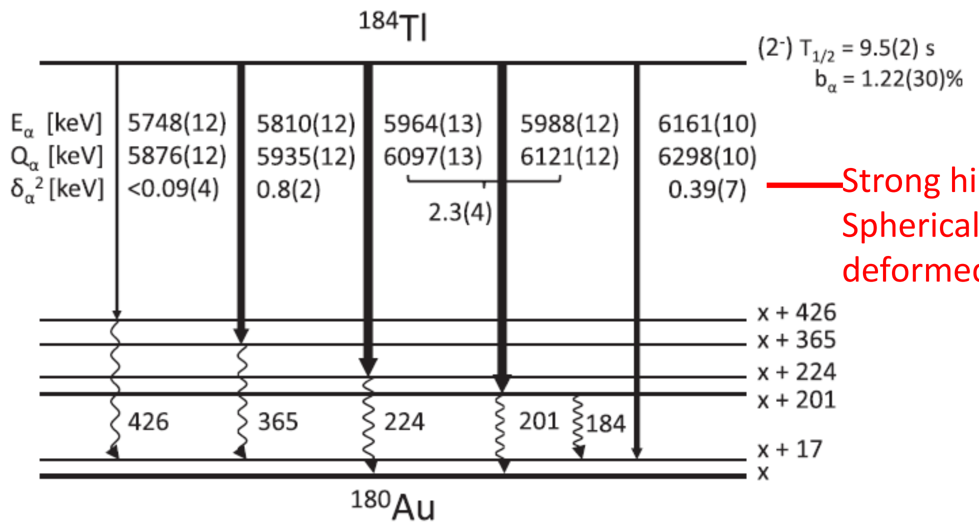
-Beta-gamma decay study in 1977

-Alpha-gamma study in 2016

-Different selection rules of decay processes allow complementary studies.

E_γ	I_γ
^{x}125.0 *4*	9.7 *20*
^{x}300.5 *3*	100
^{x}381.2 *4*	69 *14*
^{x}405.0 *5*	≈17
^{x}450.5 *5*	≈16
^{x}479.9 *4*	23.0 *45*

All gammas are unplaced and a decay scheme is unable to be constructed

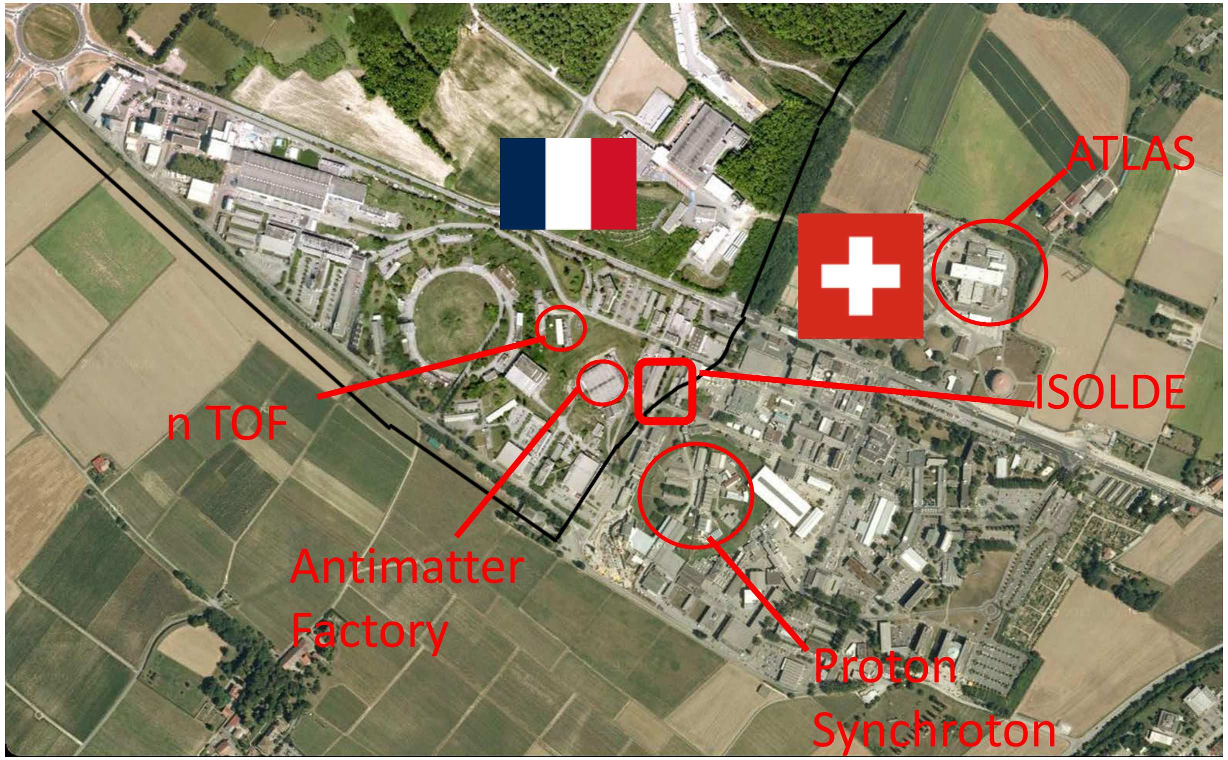


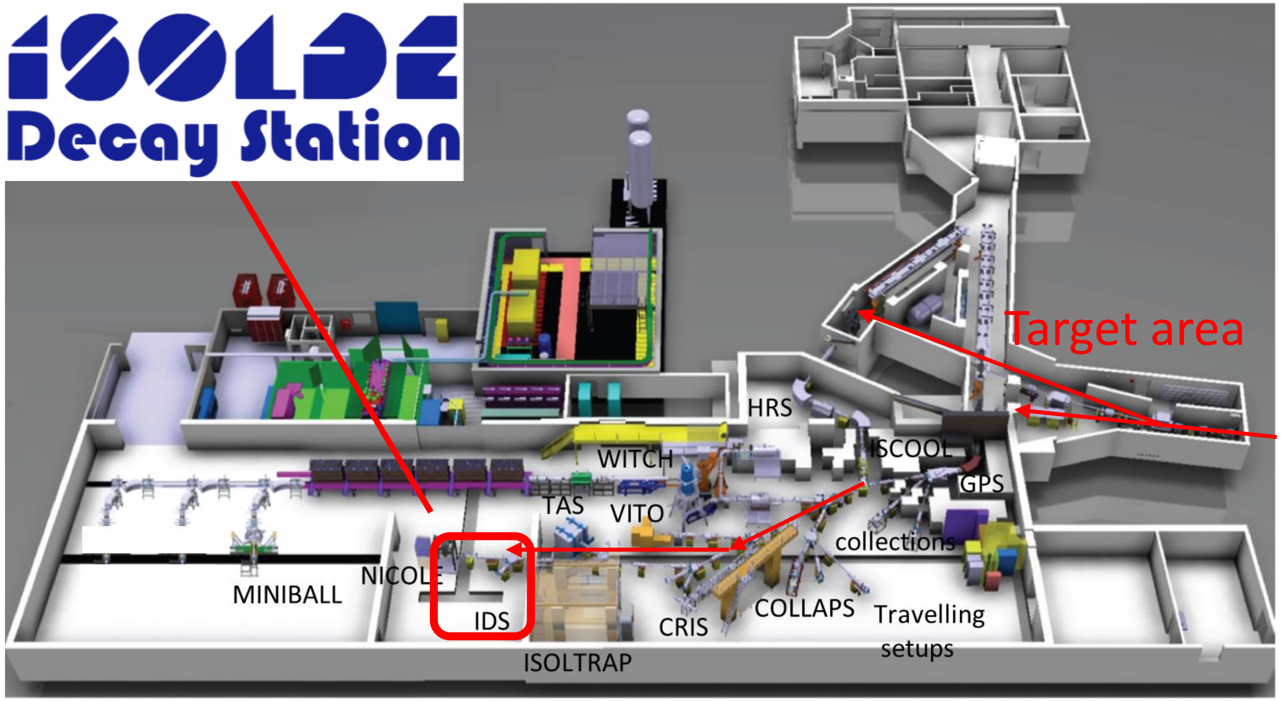
Strong hinderance Spherical G.S to deformed G.S

Husson, J. P. ,et al. *Journal de Physique Lettres* 38.13 (1977): 245-248.

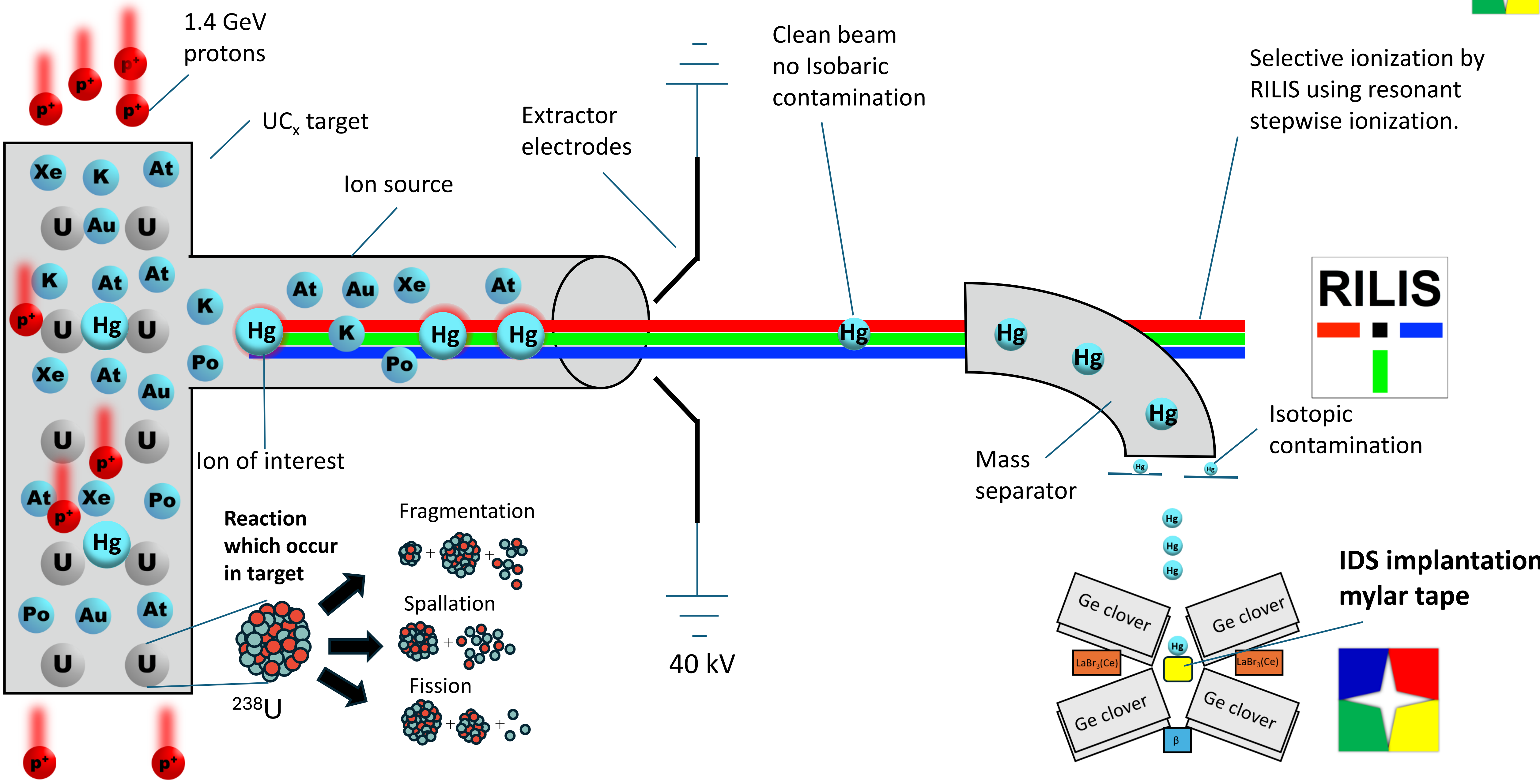
Van Beveren, C, et al *J of P G: Nuclear and Particle Physics* 43.2 (2016): 025102

Decay spectroscopy at the ISOLDE facility

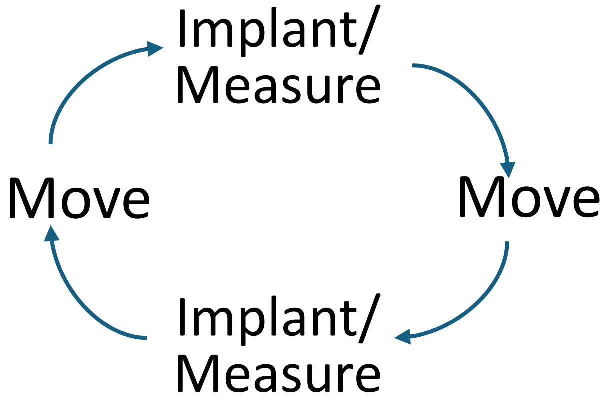


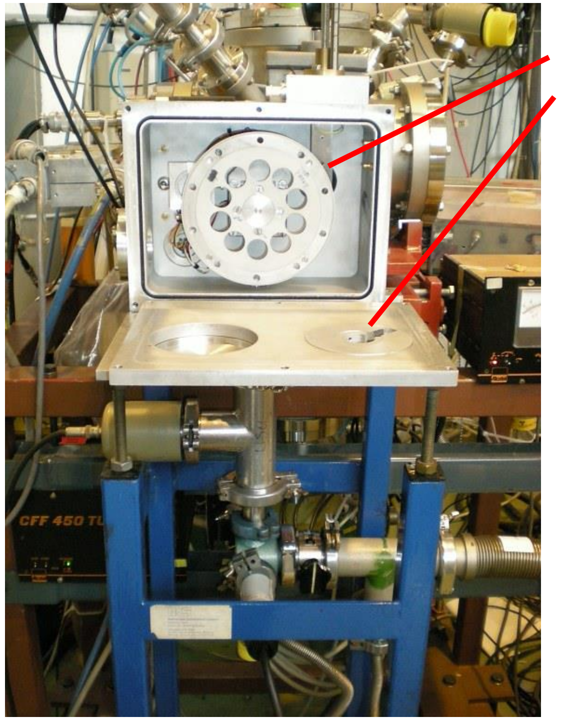


Rare isotope beam production at ISOLDE

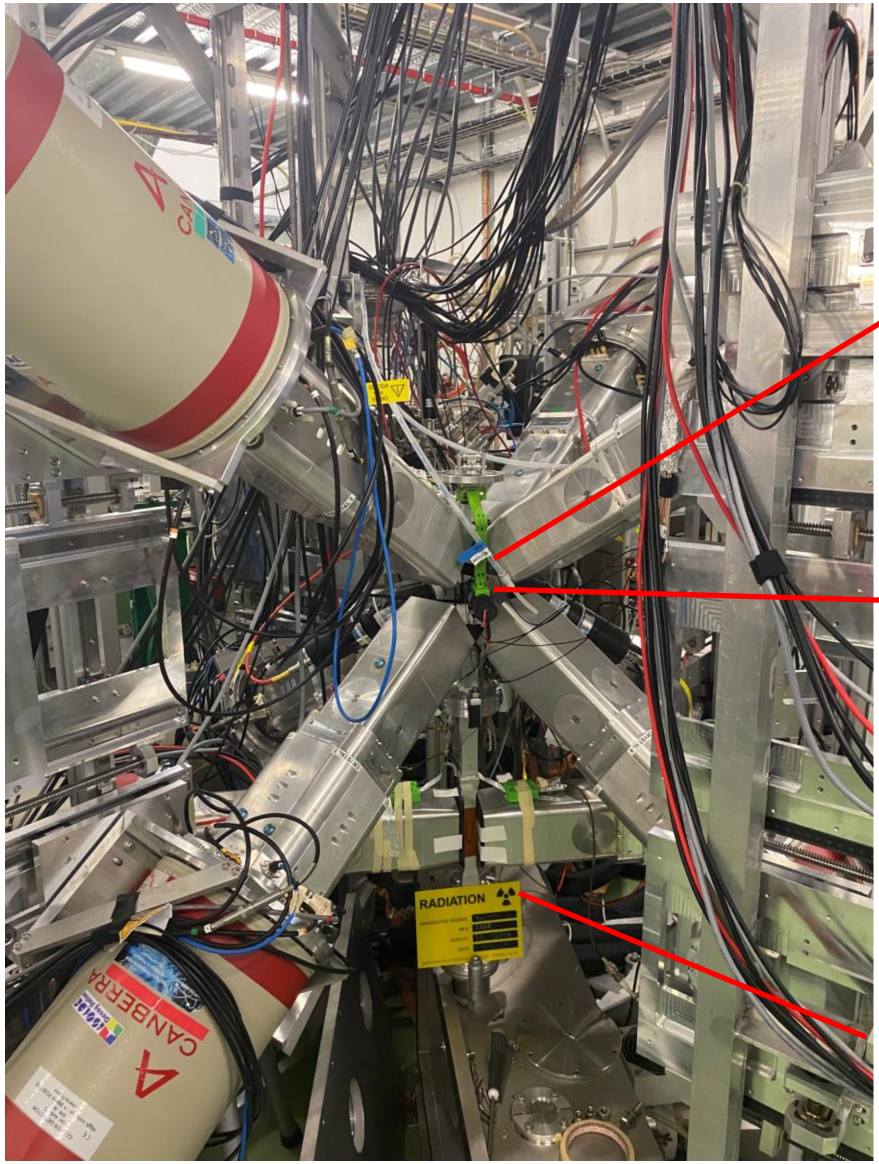


Windmill versus ISOLDE Decay station





Previous experimental set-up using 2 silicon detectors and 1 germanium



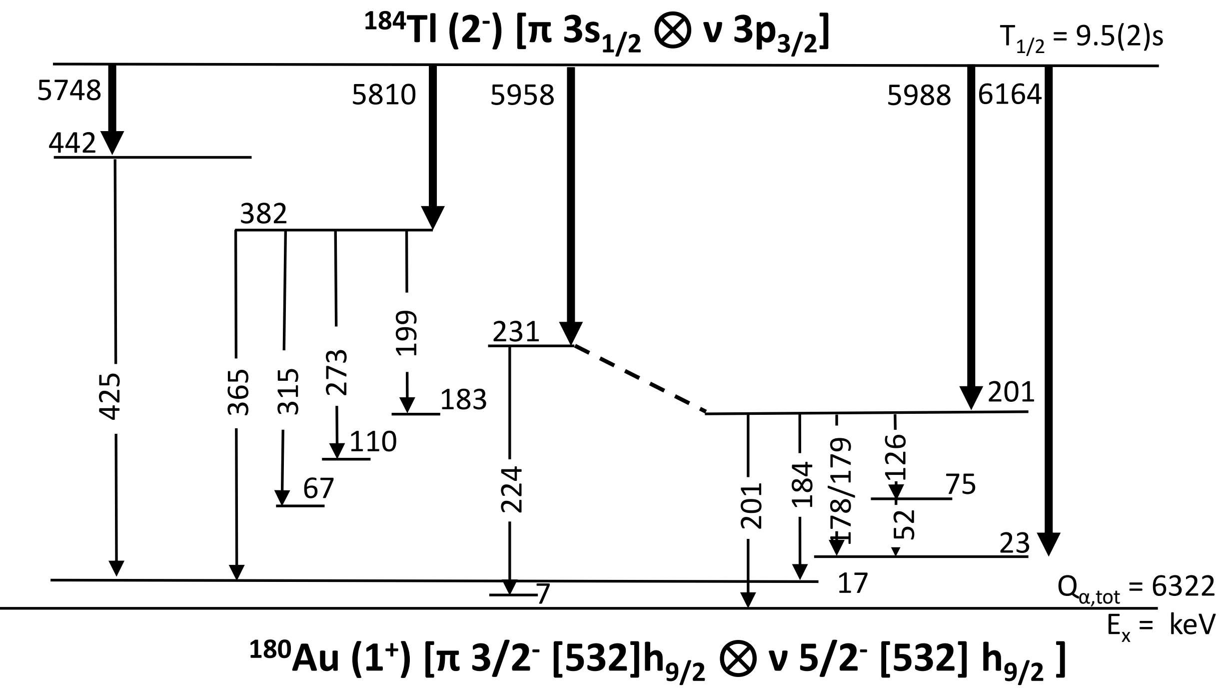
Plastic scintillators have a high beta particle detection efficiency β^+/EC with 70% coverage for beta-tagging.

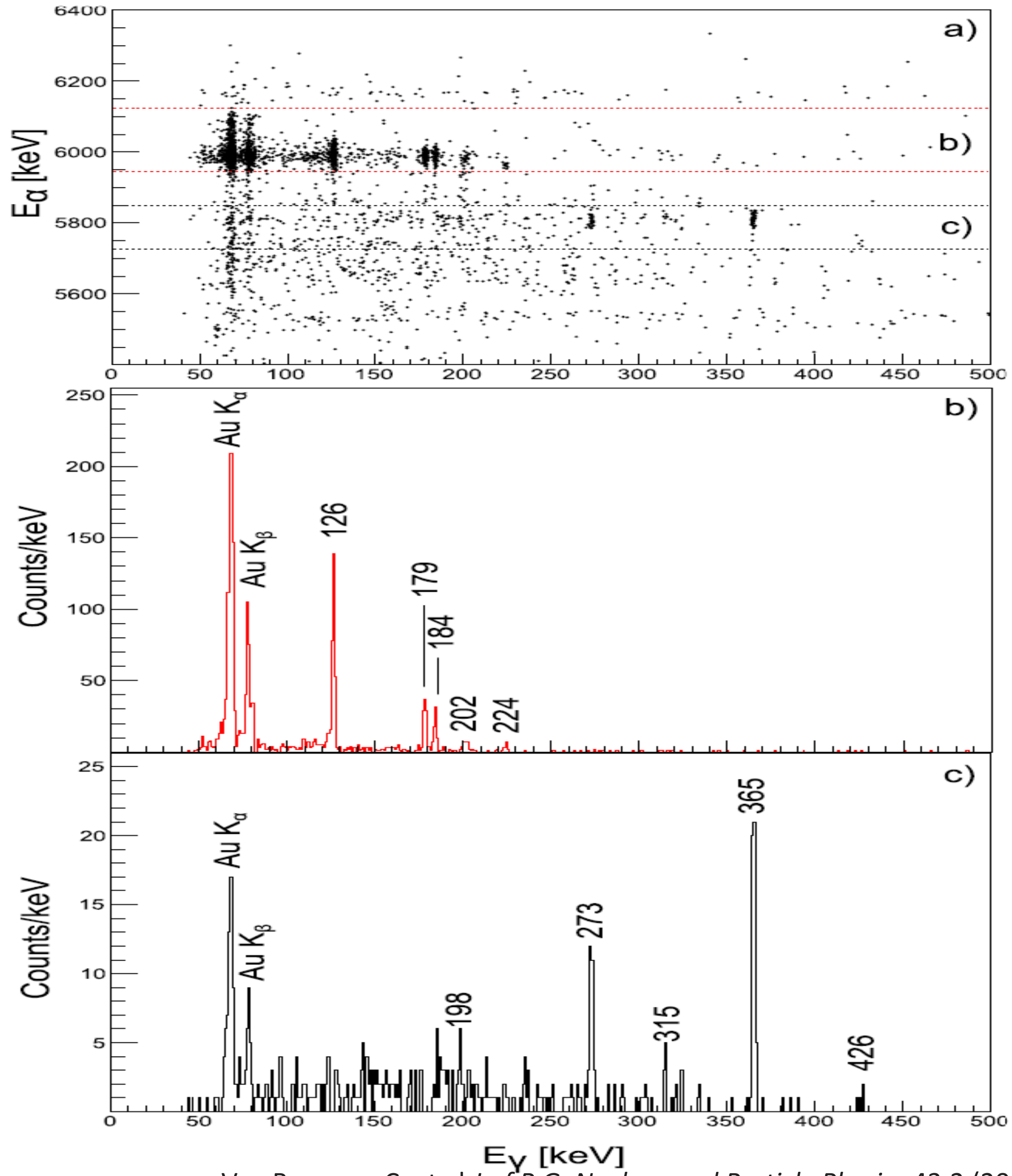
IDS implantation mylar tape is surrounded by 8 Ge clovers for high gamma efficiency.

Mylar tape is cycled to decay position to reduce daughter products build up and study daughters with 2 Ge Clovers.

Alpha decay (^{184}Tl->^{180}Au)

-Reanalysis of previous alpha data revealed new gamma transitions.
-Lack of ground state to ground state alpha decays indicates strong hinderance and large difference in structure.
-Presence of several low energy levels due to p-n multiplets.





Van Beveren, C, et al *J of P G: Nuclear and Particle Physics* 43.2 (2016): 025102

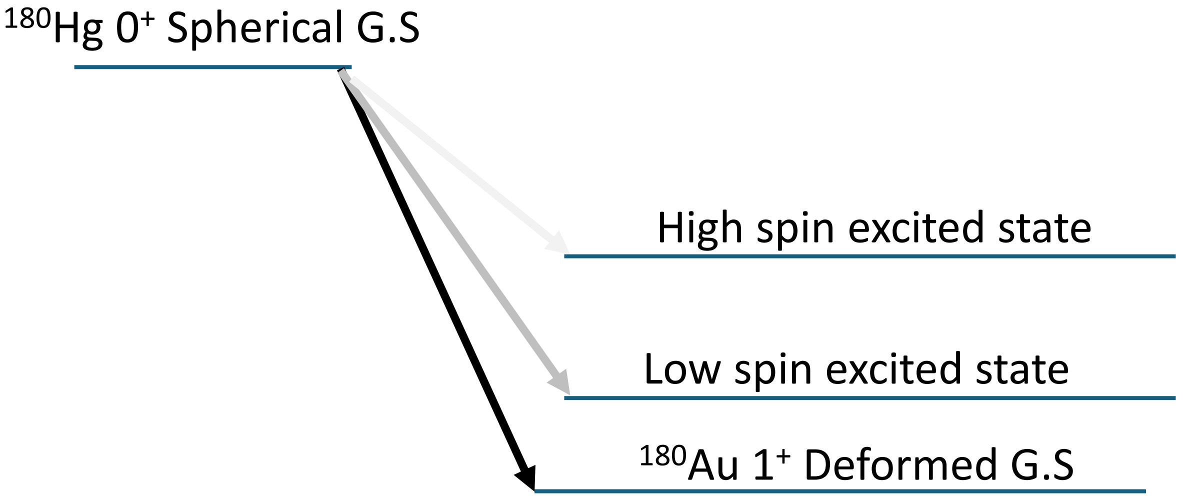
Difficulties with beta decay (^{180}Hg->^{180}Au)

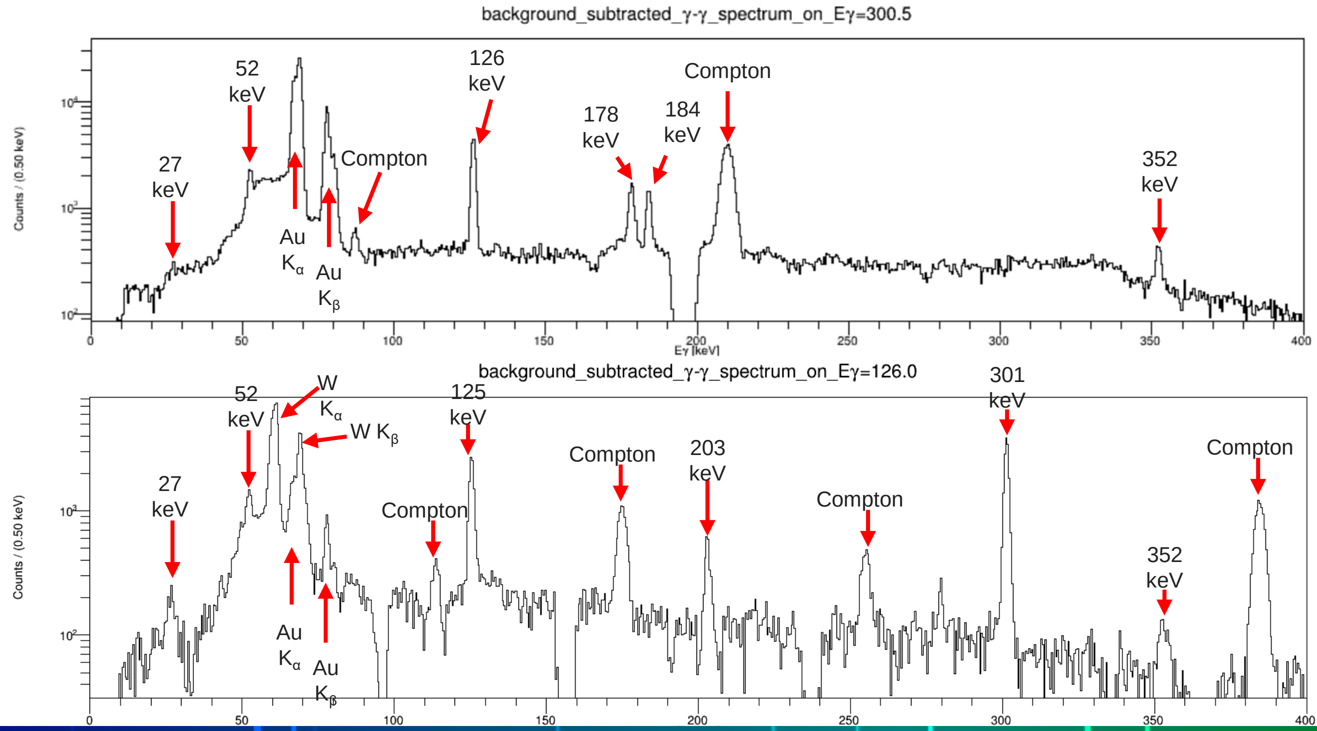
-Allowed Gamow-Teller beta decay ($0^+ \rightarrow 1^+$)
-Ground state to ground state will be a common transition i.e no gamma rays.
-Small Q_{EC} of 5.4 MeV compared to neighboring nuclei.
-A large number of Compton scatters.
-Daughter product build-up cause gamma-ray energies to appear to shift.
-Many weak and low energy transitions exist, so multiple techniques will need to be used.

E_γ	I_γ
^{x}125.0 *4*	9.7 *20*
^{x}300.5 *3*	100
^{x}381.2 *4*	69 *14*
^{x}405.0 *5*	≈17
^{x}450.5 *5*	≈16
^{x}479.9 *4*	23.0 *45*

Collected over a 24 hour period, on the order of a few hundred counts, for strongest peak.

Our data, 1.6 million counts in 1 hour, for strongest peak.





^{180}Au via beta decay

-We have been able to produce the following decay scheme based on both the previous and our own study.
-We have identified peaks from previous study, as well as some new peaks.
-We see no population of high-E states, and no high-E gamma rays, so far. (Q_{EC}=5375 keV)

E_γ	I_γ
^{x}125.0 *4*	9.7 *20*
^{x}300.5 *3*	100
^{x}381.2 *4*	69 *14*
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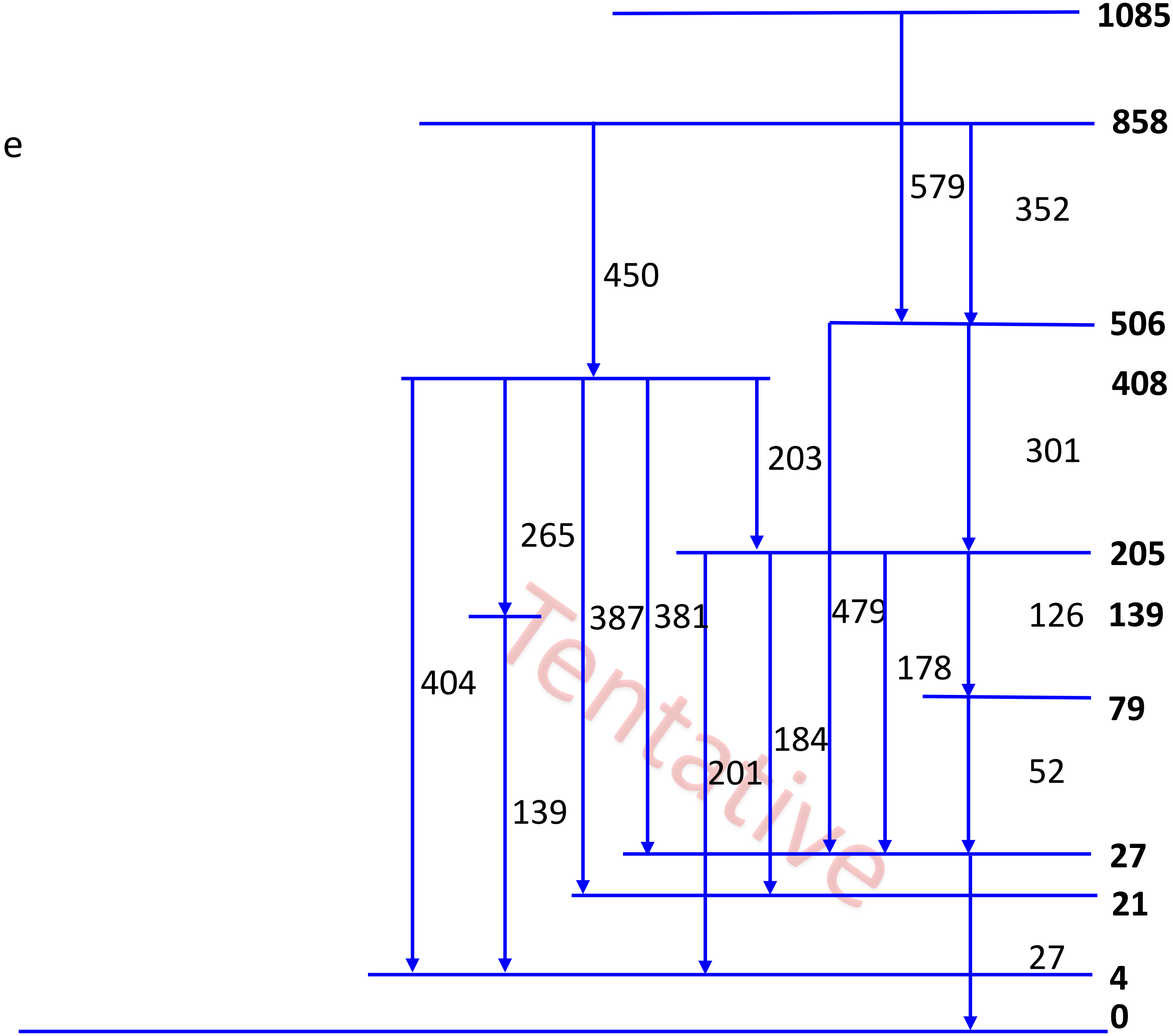
^{x} γ ray not placed in level scheme.

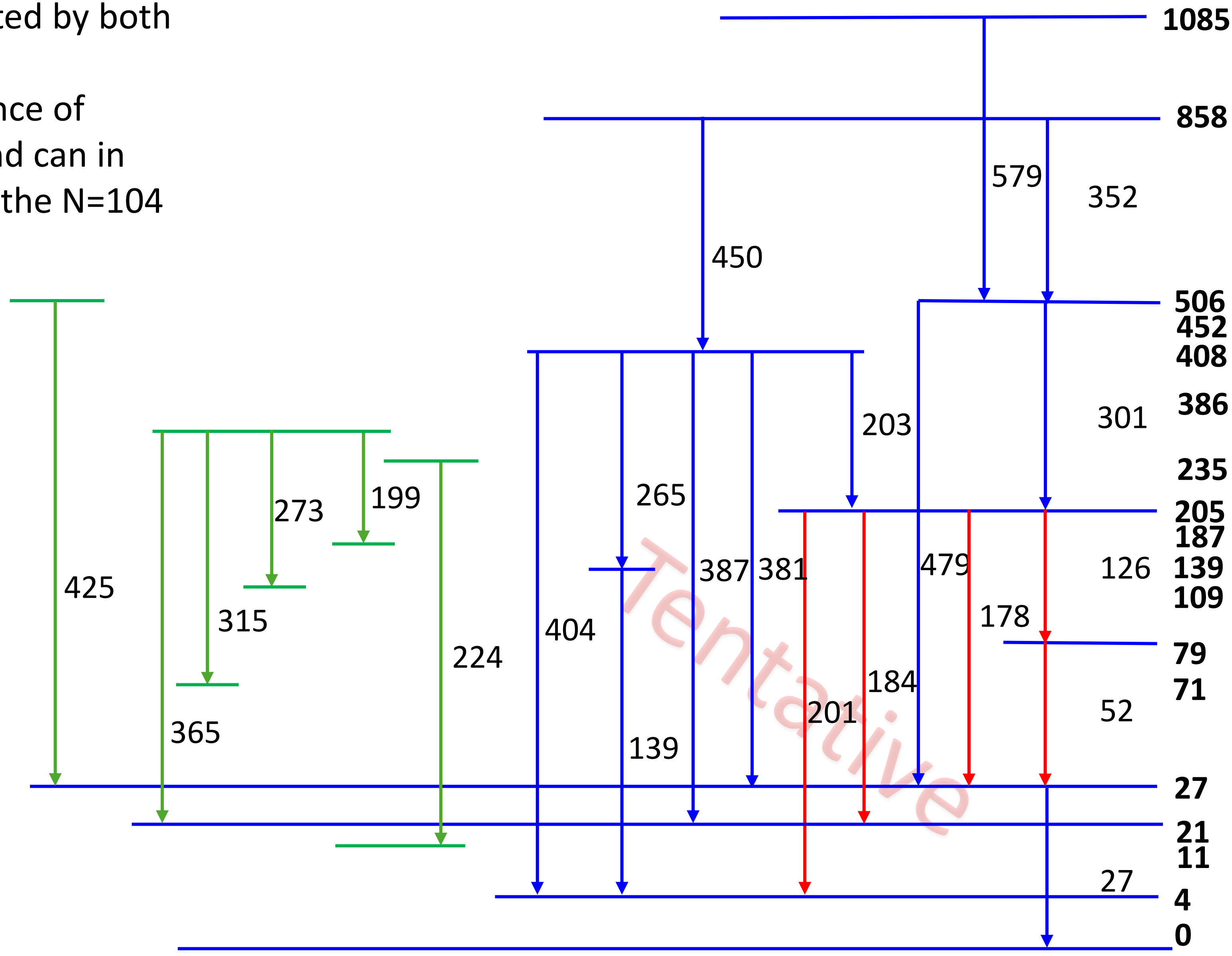
Husson, J. P. ,et al. *Journal de Physique Lettres* 38.13 (1977): 245-248.



^{180}Au (1^+) – [$\pi 3/2^-(532)h_{9/2} \otimes \nu 5/2^-(512)\ h_{9/2}$]

Combined Decay Scheme

-Combine data, displays states which can be populated by both alpha and beta decay, as well as those that can not.
-This can be used to show evidence or lack of evidence of coexisting structure inside the low lying structure and can in turn give a suggestion of shape coexistence beyond the N=104 midshell.



^{180}Au (1^{+}) – [π3/2^{-}(532)h$_{9/2}$⊗ν5/2^{-}(512) h$_{9/2}$]

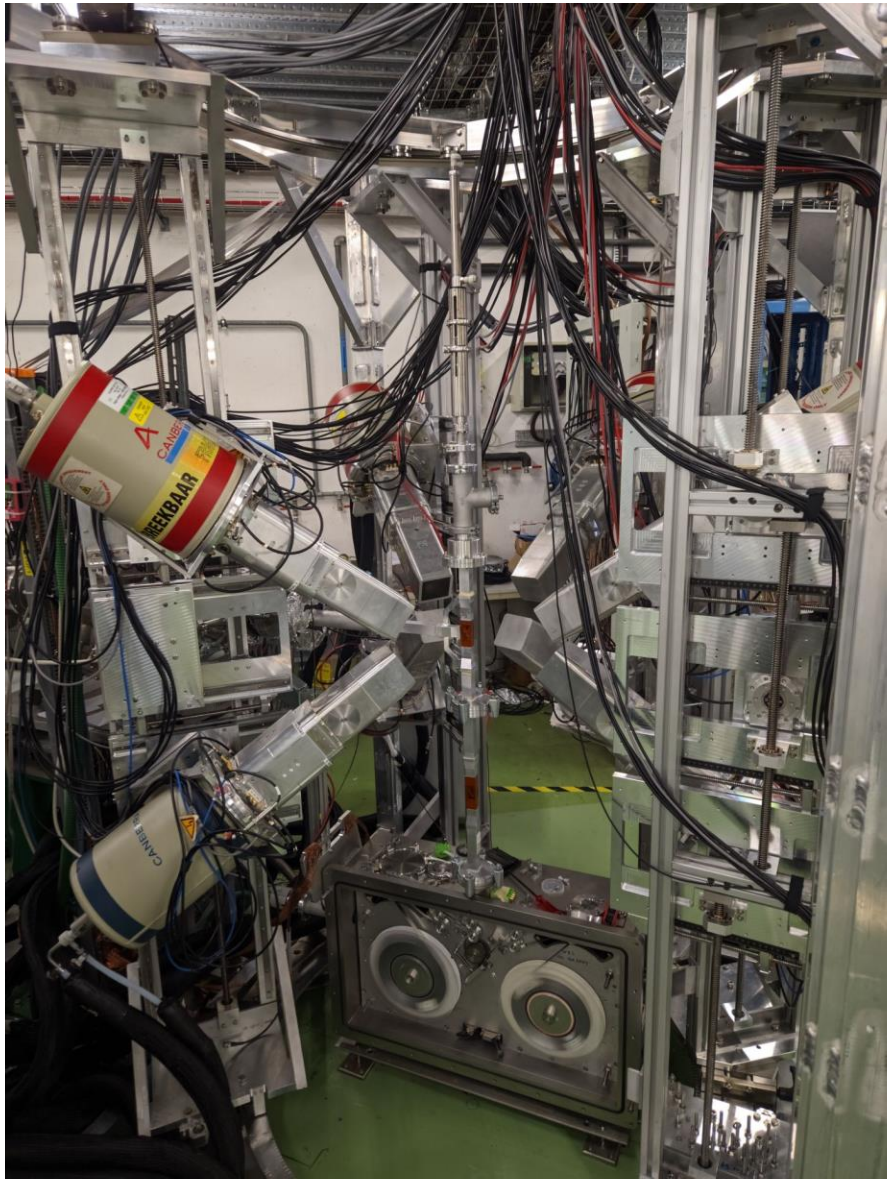
=seen in alpha decay
=seen in beta decay
=seen in both

Summary and outlook

We have been able to produce more ^{180}Hg, than previously due to upgrade techniques since the original studies.
-We have been able to reveal low-lying levels of ^{180}Au, and construct an initial decay scheme.

-Work to do

-Place remaining gamma rays.
-Calculate ground state feeding.
-Assignments of multipolarities of gamma rays.
-Compare with data from other nuclides.
-Ponder over the lack of high energy gamma rays and other expected features.
-Understand whether we see the shape coexistence, we were promised from laser spec.



Thank you

Literature list

- Möller, P., et al. Atomic Data and Nuclear Data Tables 109 (2016): 1-204. – Quadrupole deformation
- Suchyta, Scott, et al. Physical Review C 89.2 (2014): 021301. ^{68}Ni
- Wood, J. et al. Rev. Mod. Phys. 83, 1467 (2011)
- Andreyev, A. N., et al. *Nature* 405.6785 (2000): 430-433
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- Cubiss, J. G., et al. *Physical review letters* 131.20 (2023): 202501.
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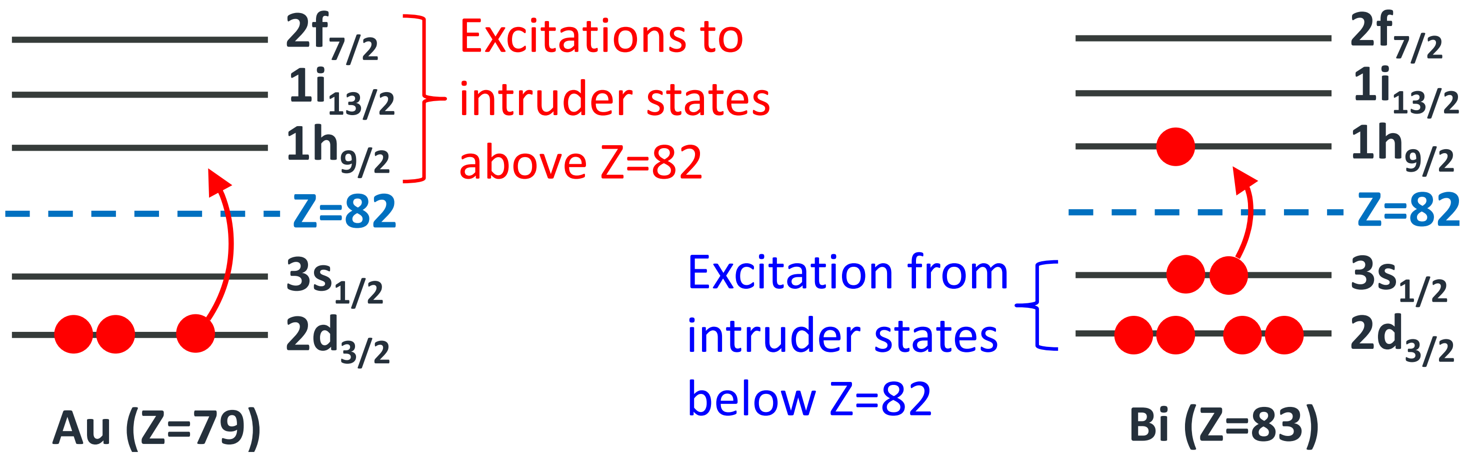
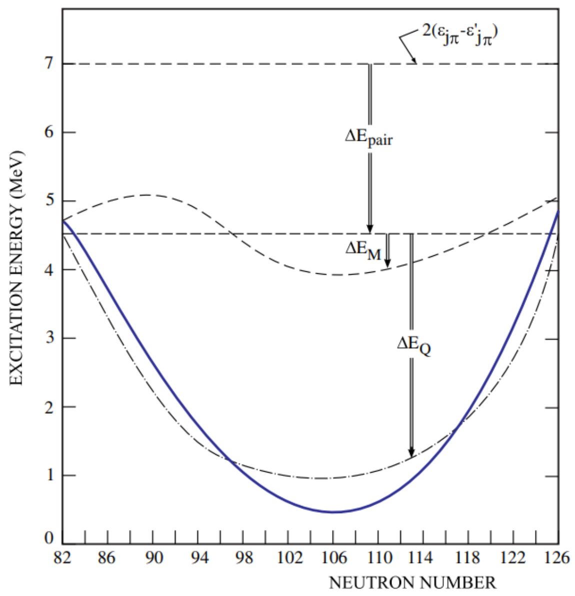
Shape Coexistence

- Shape coexistence is defined as the occurrence within a single atomic nucleus of multiple low-lying quantum states that are characterized by significantly different intrinsic shapes, existing at similar excitation energies.
- The microscopic origin of shape coexistence can be justified from the spherical shell model by excitation of nucleons across energy gaps associated with shell or sub-shell.
- Promoting one or more pairs of nucleons (protons or neutrons) from orbitals below a shell gap to orbitals above it creates multi-particle-multi-hole (e.g., 2p-2h, 4p-4h) configurations relative to the normal, ground-state configuration (often considered 0p-0h).
- These excited configurations are our "intruder states".
- If the gain in energy is comparable to the shell gap, multiple competing shapes can coexist.
- The energy required to form this np-nh excitation, can be offset by a gain in correlation energy from quadrupole-quadrupole valence nucleon interactions, which drive deformation and thus a deformed shape.
- The excitation energy of intruding states tends to follow a parabolic shape, with a centroid at the mid-shell.





$$E_{\text{intr}}(0^+) = 2(\varepsilon_{j_\pi} - \varepsilon_{j'_\pi}) - \Delta E_{\text{pair}} + \Delta E_M + \Delta E_Q,$$

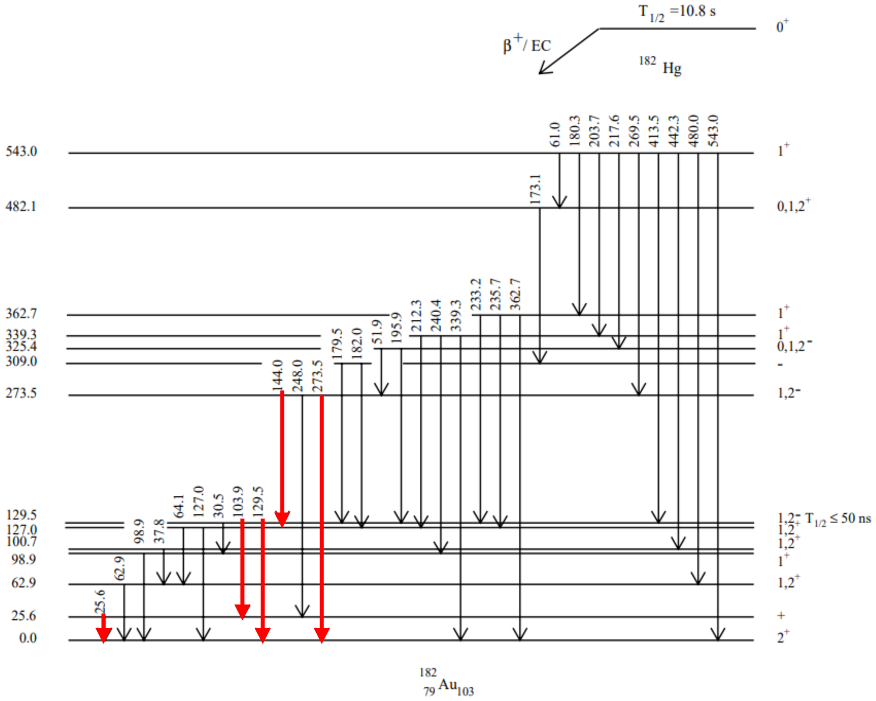
Gap — Pairing — residual p-n energy

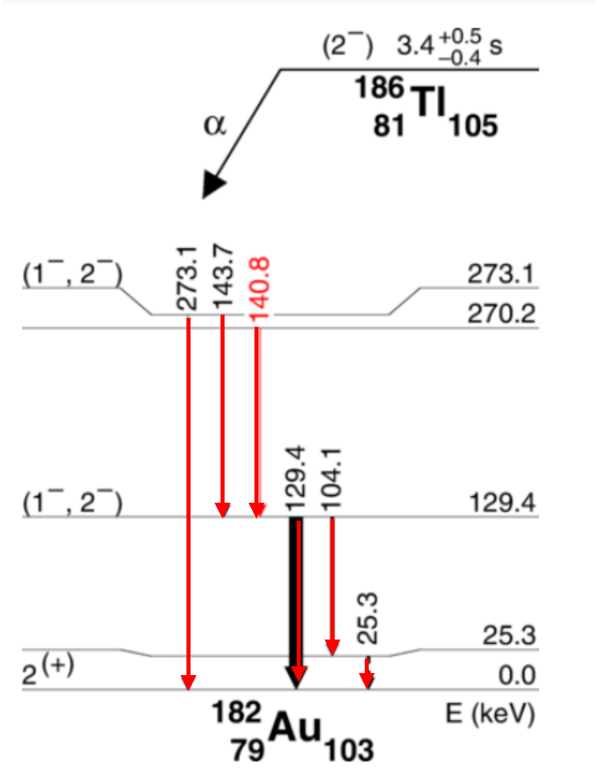
How to investigate shape coexistence with different techniques

- In-beam γ-ray spectroscopy can investigate rotational bands, and high-spin structures.
- Β-decay can selectively populate the low-spin states, beta-feeding to daughters and logft values can provide help with structural assignments.
- Laser spectroscopy can observed relative changes in nuclear charge distribution between isotopes.
- α-decay can investigate fine structure probing energy levels of band-heads especially for 0^+ states, as well as reduced widths and hinderance being sensitive probes for changes in nuclear configuration and deformation between parent and daughters .
- Coulex can investigate the collectivity of transitions in low-spin states.
- Lifetime measurements can reveal transition rates and help characterize states.
- Conversion electrons studies especially in conjunction with in-beam studies can reveal E0 transitions from bandheads.
- Laser spectroscopy can identify the existence of isomers, arising from proton-neutron coupling due to intruder orbitals, this in conjunction with alpha decay will constrain the allowed configurations and shapes.

Previous even mass studies in this region

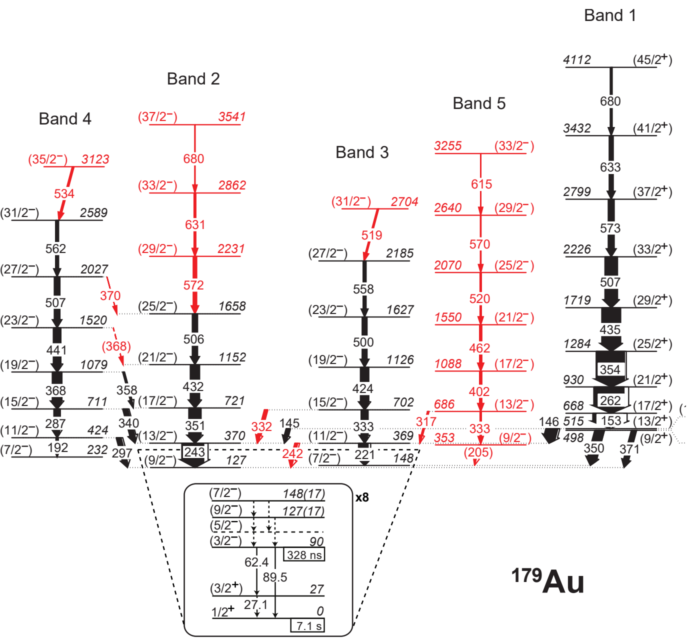
- Similar studies have been performed with neighbouring nuclei ^{178}Au and ^{182}Au, as well as ^{184}Au which may have a similar excitation energy due to parabolic shape and this has been used in past to find connections between certain nuclei.
- Odd-odd nuclei posses both two unpaired nucleons , coupling between these leads to a higher density of low-lying states, as they are sensitive to single-particle configurations and deformation.

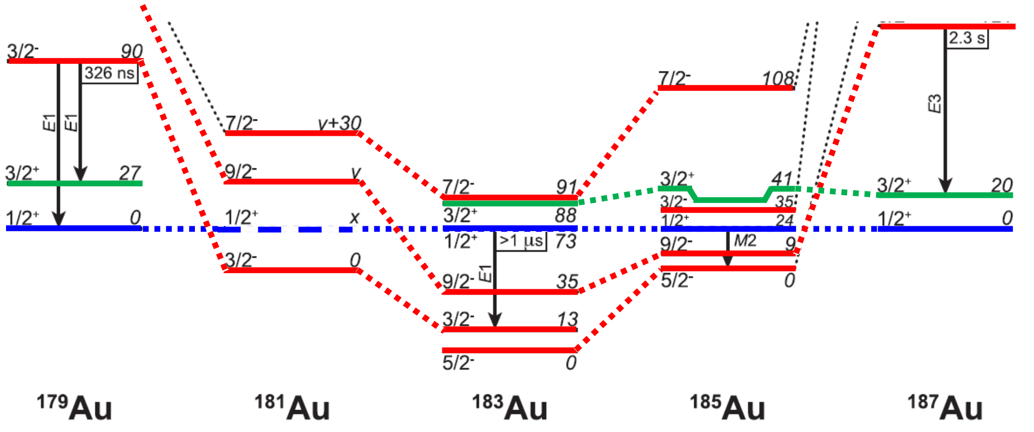


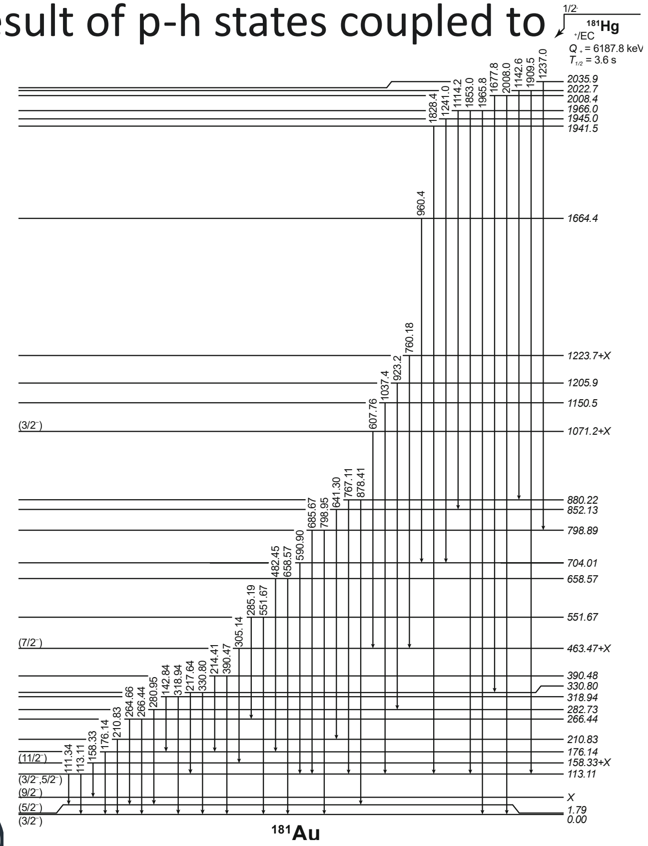


Previous studies of neighboring odd mass nuclei

- Similar studies have been performed with neighbouring nuclei ^{179}Au and ^{181}Au.
- The study of the neighboring odd-A nuclei is method by which single-particle states present can be identified suggests the neutron-proton configurations.
- Studies of neighboring odd-A Au isotopes have already established the presence of coexisting structures, often involving competition between low-j proton hole states (e.g., πs1/2, πd3/2) and high-j intruder particle states (e.g., πh9/2, πi13/2).
- A prolate band built on the πh9/2, while oblate structure have been built on nano second isomers in this region.
- The πh11/2 states remain almost constant in energy, these are believed to be the result of p-h states coupled to even-even Hg cores, while πh9/2 are coupled to even-even Pt cores.



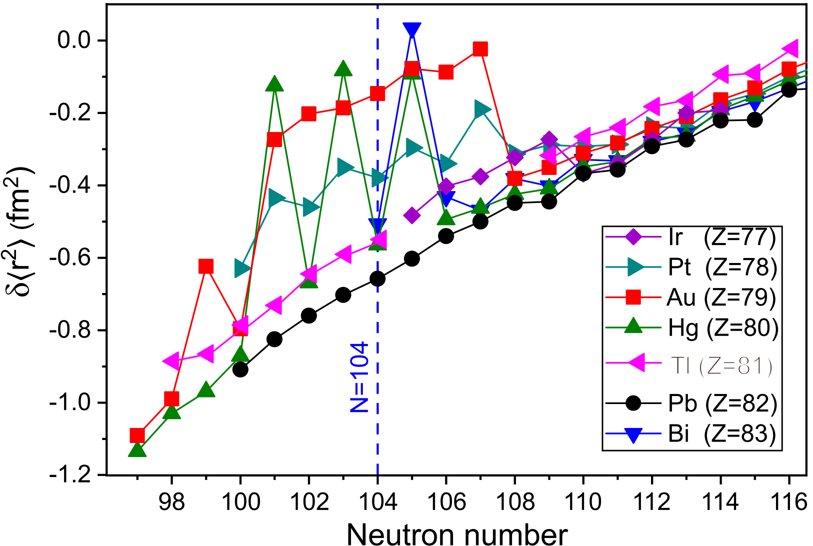




M. Venhart *et al.*, J. Phys. G **44**, 074003 (2017)

Shape Coexistence (Lead region)

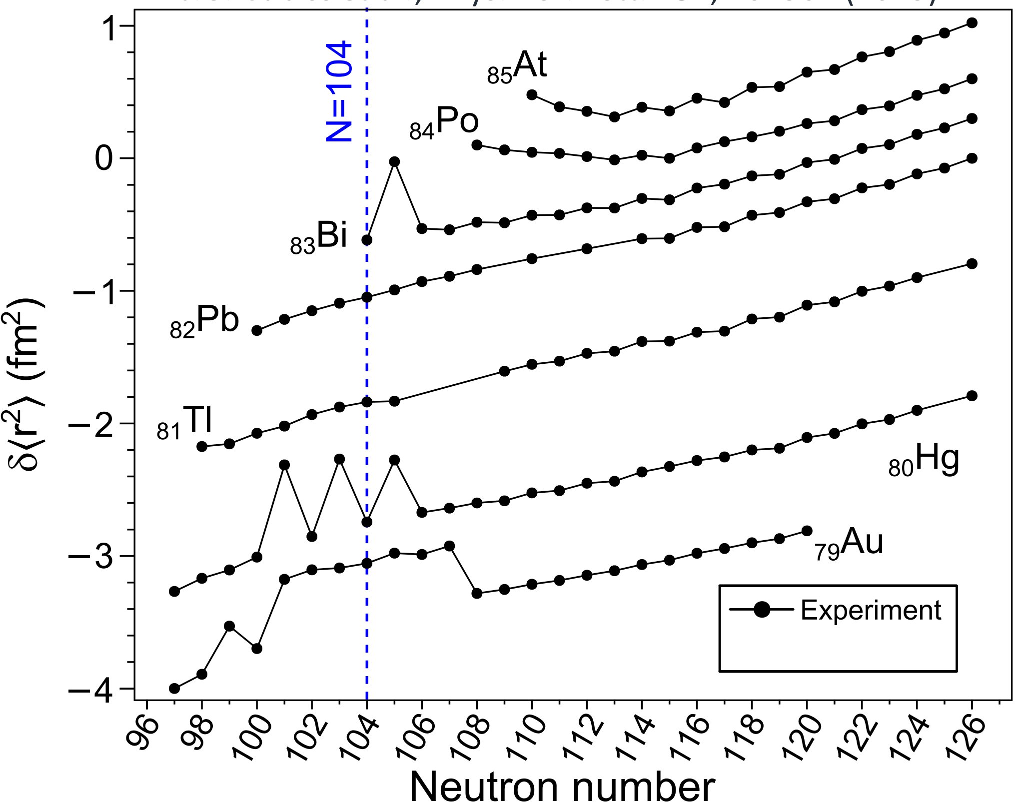
- The midshell lead region has been one of the most successful regions of the chart for exploring low energy shape coexistence.
- The first evidence coming from hyperfine structure measures of Hg, which showed large variations between odd and even mass nuclei.
- The lead isotopes have displayed shape coexistence with multiple low-lying excited 0^+ states, occurring in species near the mid-shell, which have been accompanied with the studied of E0 transitions between.
- Radioactive decay between even mass Hg to Pt nuclides have displayed a large hinderance factor which suggest a great change in the 0^+ states.
- Alpha decay has indicated that a strongly deformed ground state may exist within Po isotopes, which does not exist in higher Z isotopes.



Shape Coexistence- Odd-odd case

- Shape coexistence has been a constant challenge for nuclear theory.
- Modern DFT, and shell model calculation work very well for most even-even nuclei in the Z=82, N=104 region.
- Odd-A, and especially odd-odd nuclei are a major challenge for our nuclear theories.
- Begin by selecting states with correct spins, and calculating ground states.
- Theory predicts odd-even staggering for Au, experiment does not.
- For most nuclear theory, a lack of experimental data hampers the models ability to predict.

J.G. Cubiss *et al.*, Phys. Rev. Lett. **131**, 202501 (2023)



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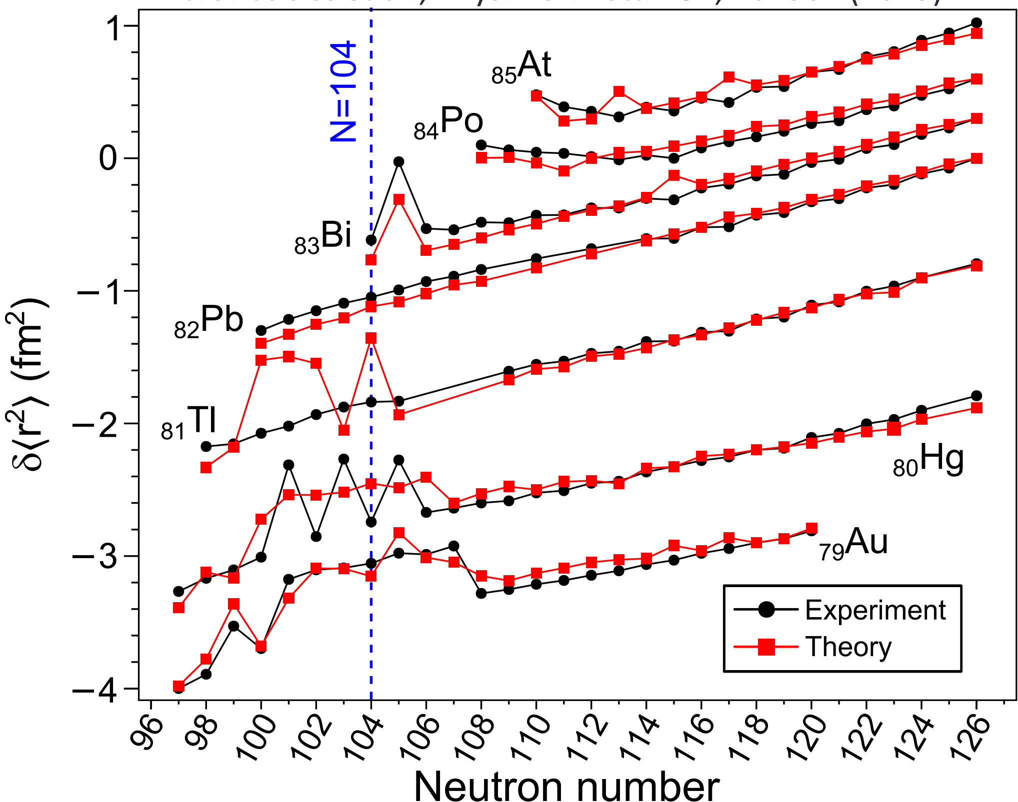
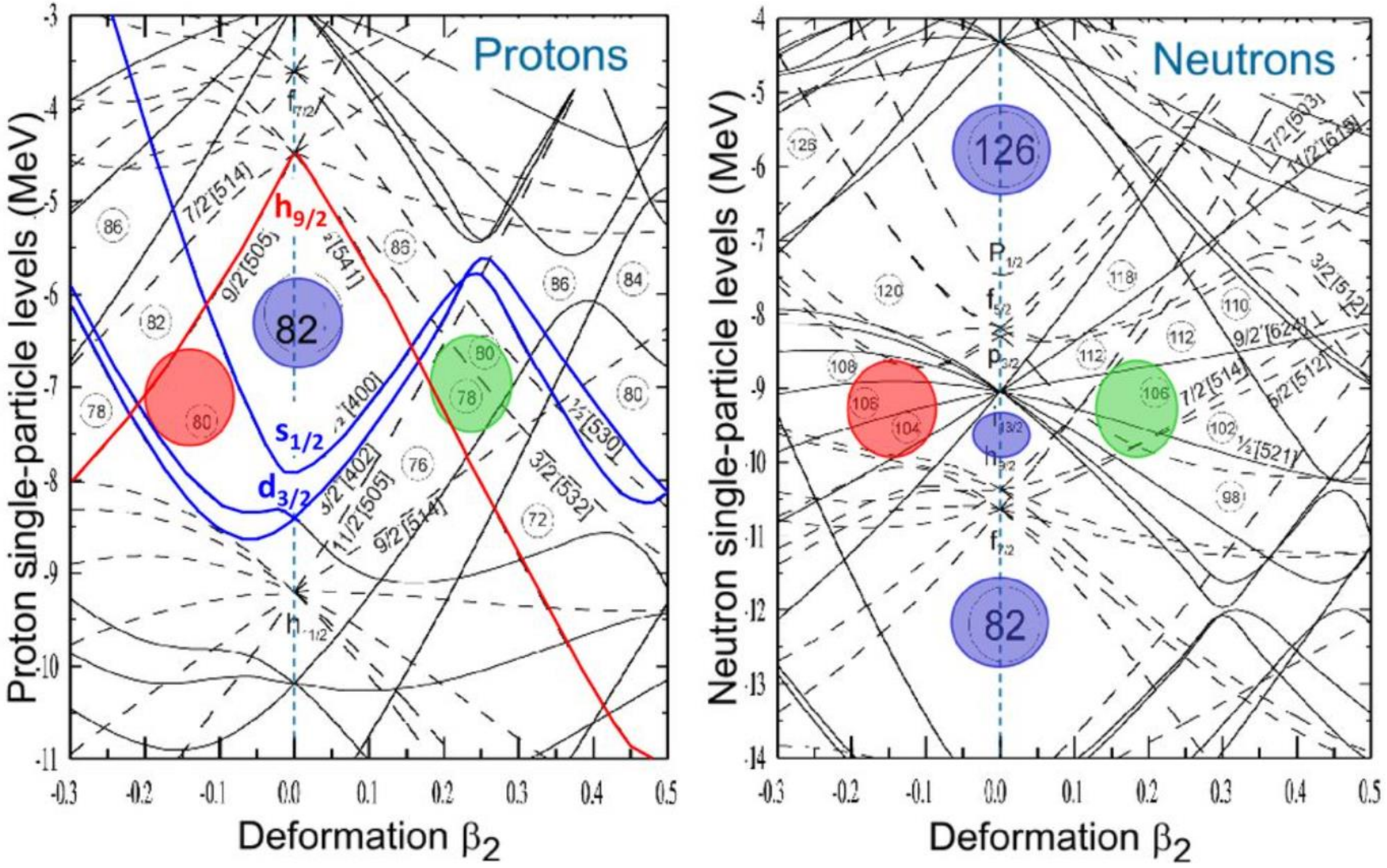
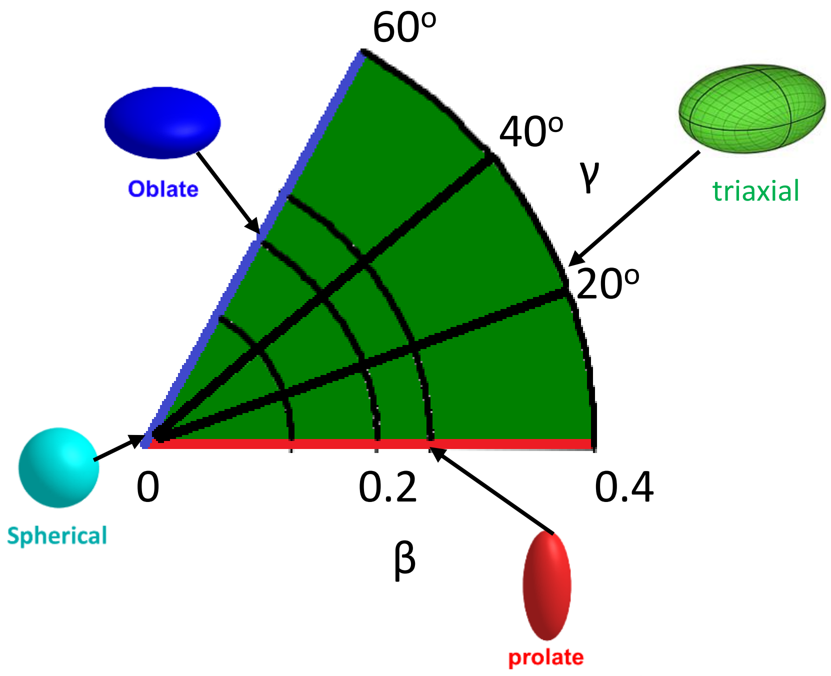


Shape Coexistence- Pb region



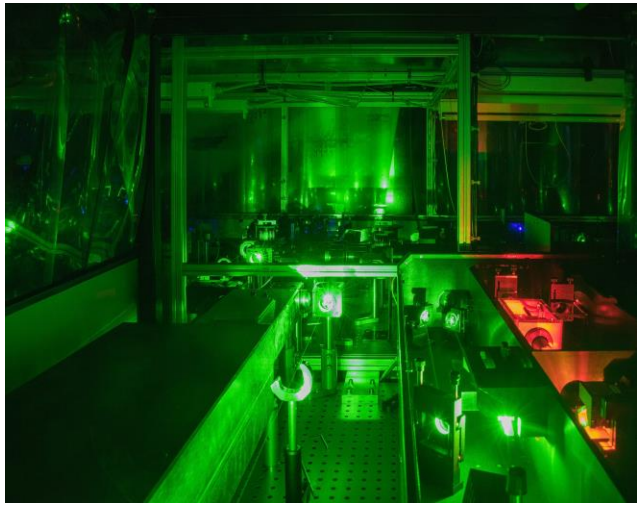
Other Deformation

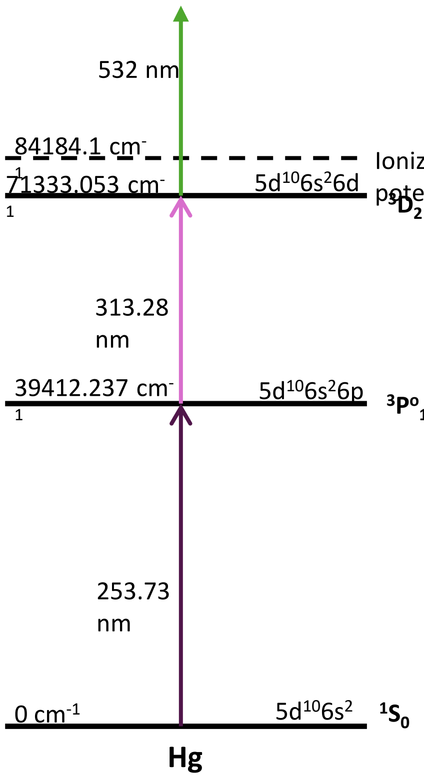
- An extension of the purely axial symmetric deformation discussed is the idea of triaxial deformation introducing a new parameter gamma, by the rigid triaxial rotor model of Davydov and Filippov.
- **Spherical Shape:** $\beta_2=0$.
- **Prolate Shape:** $\beta_2>0$, $\gamma=0\circ$.
- **Oblate Shape:** $\beta_2>0$, $\gamma=60\circ$. Previously represented as $\beta_2<0$ with $\gamma=0\circ$).
- **Triaxial Shape:** $\beta_2>0$, $0\circ<\gamma<60\circ$. Lacks axial symmetry.
- Triaxial deformation has been suggested as a feature in this region of the chart adding additional triaxial bands ^{180}Os.
- Octupolar deformation and other higher order effects may also play a role in shape coexistence in this region.



Resonance ionization spectroscopy (RIS)

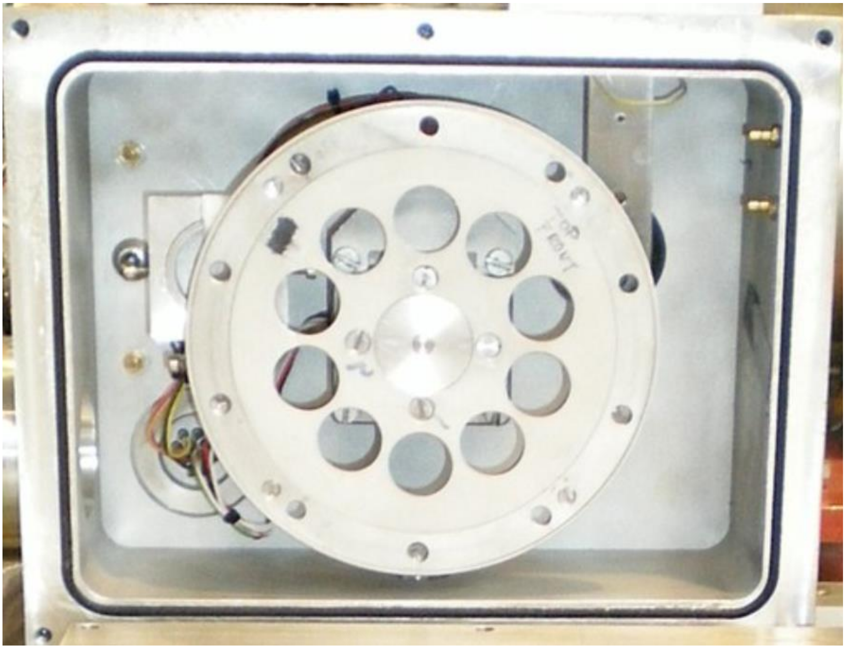
- RIS, is a technique used to liberate isotopes from the target and transfer line.
- All chemical elements have a unique energy level scheme, which can be excited in a unique way using a laser.
- Multiple lasers can be used to excite in a stepwise manner to liberate a valence electron from the element of interest.
- Ionization is maximize by saturating the atomic transitions.
- At ISOLDE this is performed by the RILIS experiment.
- The selectivity of RILIS is achieve by multiple excitation of valence electrons in an element specific way.
- The atomic transitions are saturated.
- Ionization can occur via an autoionizing state, which is a prefer pathway due to a higher efficiency compare to alternatives.
- RILIS covers a wide range of wavelengths from UV to IR, which in turn allows the ionization of nearly all naturally occurring elements.

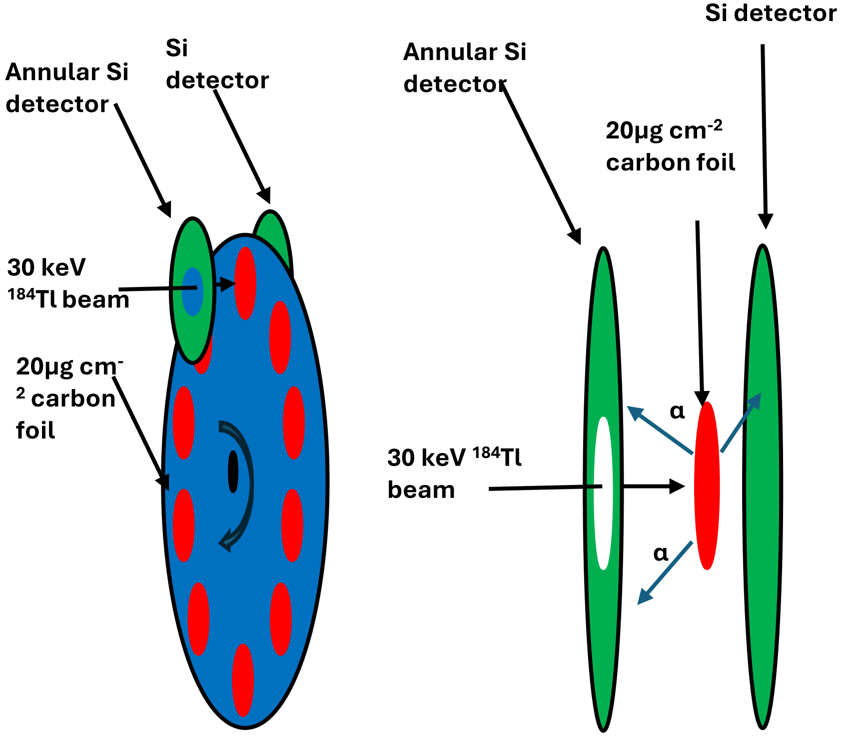




The Windmill detector

- The windmill detector was a set-up used to look at the decay spectroscopy of nuclides at ISOLDE.
- The Windmill detector consists of a rotating wheel containing 10 thin carbon foils (20 μg/cm2).
- A RIB passes through the hole in an annular silicon detector and is impinged on the target and implants, since the foils are thin, alpha particles can escape.
- Escaping alphas will be detected by silicon detectors placed in front of and behind the foils with a germanium detector located near to catch gamma rays.
- Once enough contamination has built up or a new isotope of interest is looked at, the wheel is rotated and process repeated.





Laser spectroscopy-charge radii, isotope shift, and moments

- Laser spectroscopy is a key tool for mapping evolving structures of ground states and isomers.
- Laser spectroscopy is used to measure the hyperfine structure of nuclei along isotopic chains.
- A key measurement is the isotopic shift, the energy required for a specific atomic transition is observed to shift between different isotopes of the same element.
- Laser spectroscopy can determine the spin, and moments of nuclei in a model independent way.
- The mean-squared charge radii is of fundamental importance to nuclear structure, defining the extent of a nuclei.
- The change in mean-squared charge radius between different isotopes can be extracted from experimental measurements of the isotope shift.
- These shifts, result from the change in mass and size between isotopes, equally they can also have changes between the same isotope, but different states known as isomeric shifts.
- Charge radii and electromagnetic moments of exotic nuclei provide important information on their deformation and underlying nuclear structure and this can be extracted from laser spectroscopy data.