Alpha-gamma and high-resolution α fine-structure spectroscopy for the heaviest nuclei

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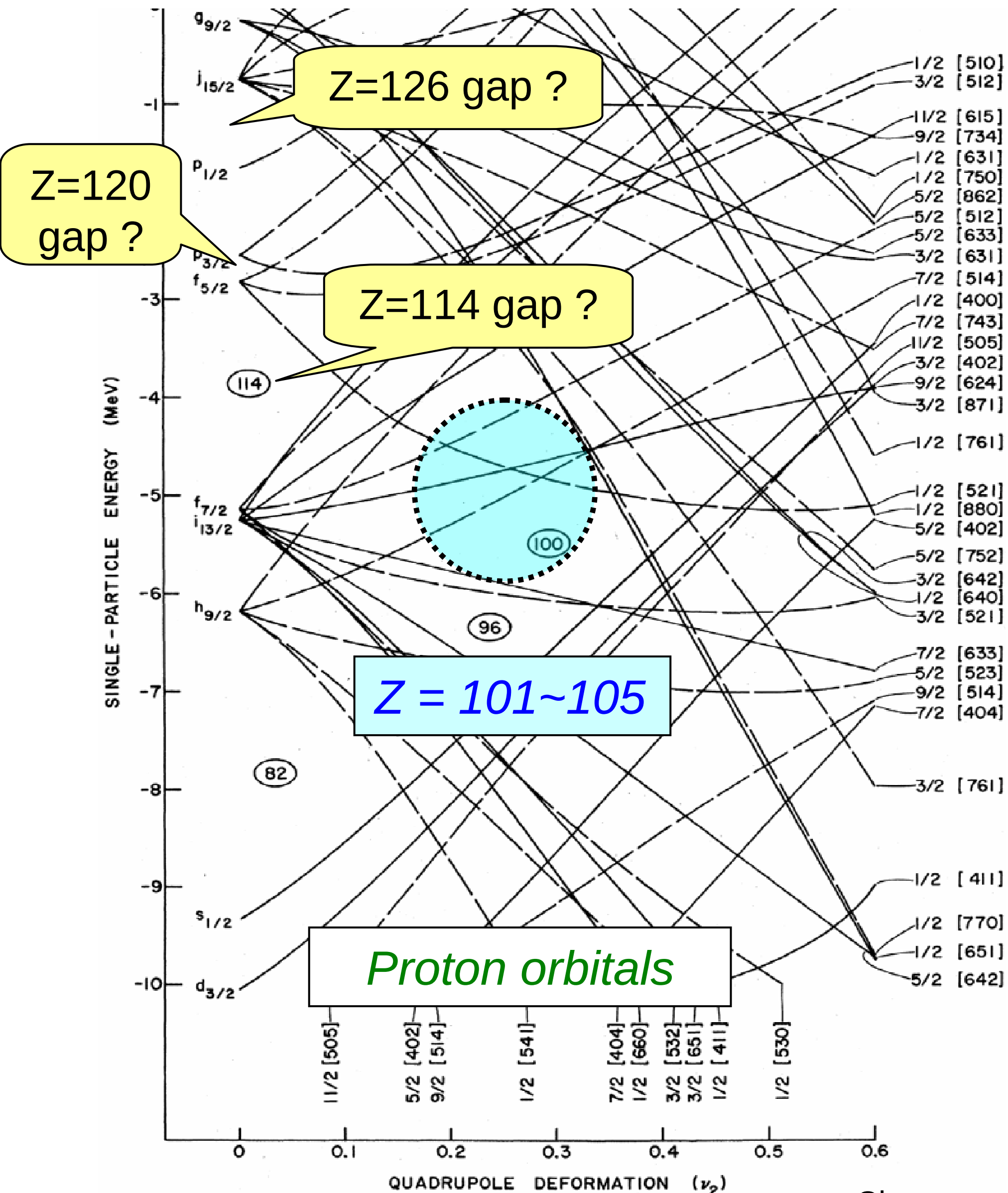
1. α-γ coincidence spectroscopy of ^{259}Rf (Z=104) using a mixed Cf target
2. High-resolution α fine-structure spectroscopy of odd-mass Lr isotopes (Z=103)

Physics motivation: Shell structure of superheavy nuclei



Chasman et al., Rev. Mod. Phys. 49 (1977) 833.

Shell structure of superheavy nuclei

↑

Energy spacings and order of single-particle orbitals

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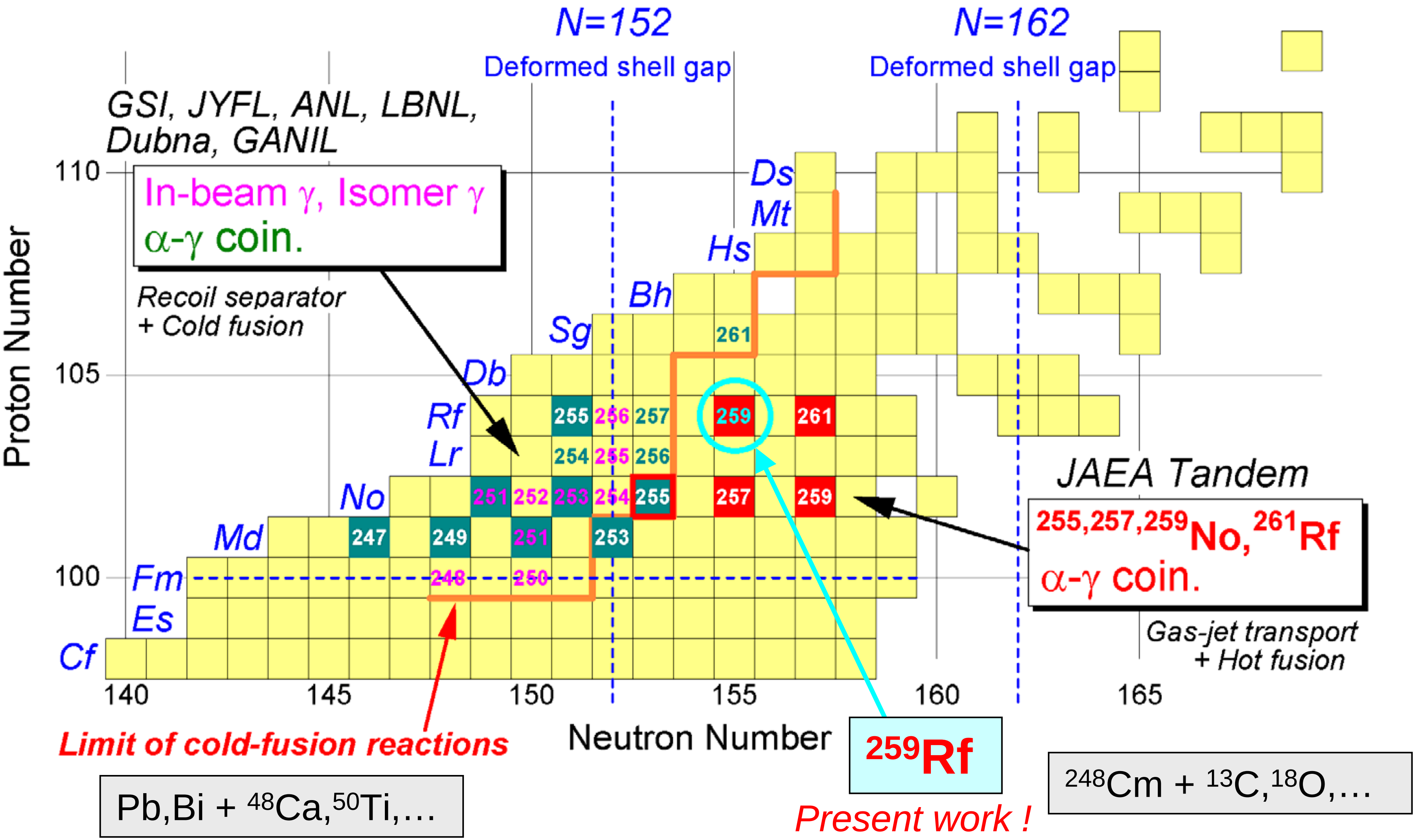
Experimental assignments of single-particle states in odd-mass superheavy nuclei

- Spin-parity
- Single-particle configuration

Current status of spectroscopic studies for superheavy nuclei



Spin-parity and configuration assignments are very scarce ! especially in the region of $Z > 101$ and $N > 153$

Production of ^{259}Rf

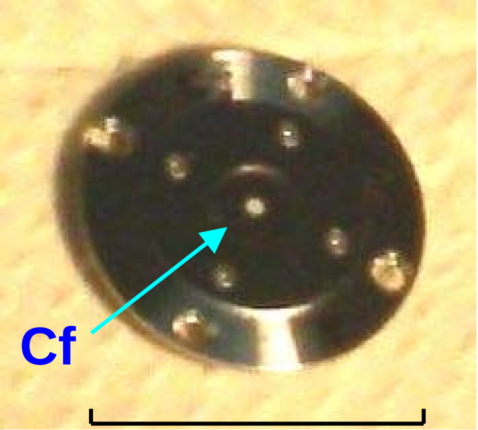
- $^{249}Cf(^{13}C,3n)^{259}Rf$ ~ 6 nb
- $^{248}Cm(^{16}O,5n)^{259}Rf$ ~ 5 nb
- $^{251}Cf(^{12}C,4n)^{259}Rf$ ~ 100 nb (HIVAP calc.)

> *It is almost impossible to obtain a large amount of isotopically enriched ^{251}Cf material !*

Mixed Cf target

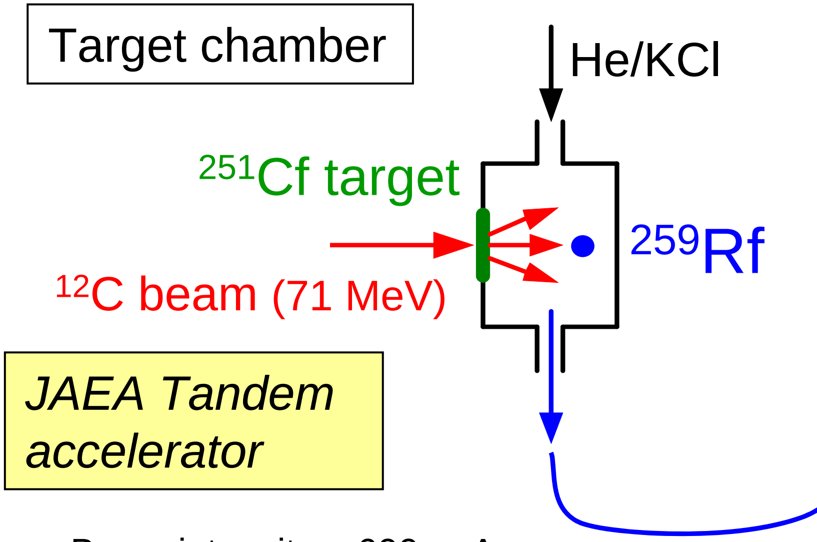
- $^{249}Cf(62\%)$, $^{250}Cf(14\%)$, $^{251}Cf(24\%)$
- Residue of 40-year-old ^{252}Cf neutron source
- Small-size target : φ1.4 mm x 420 μg/cm^2 = 6.5 μg
- Total radioactivity : 4.1 MBq

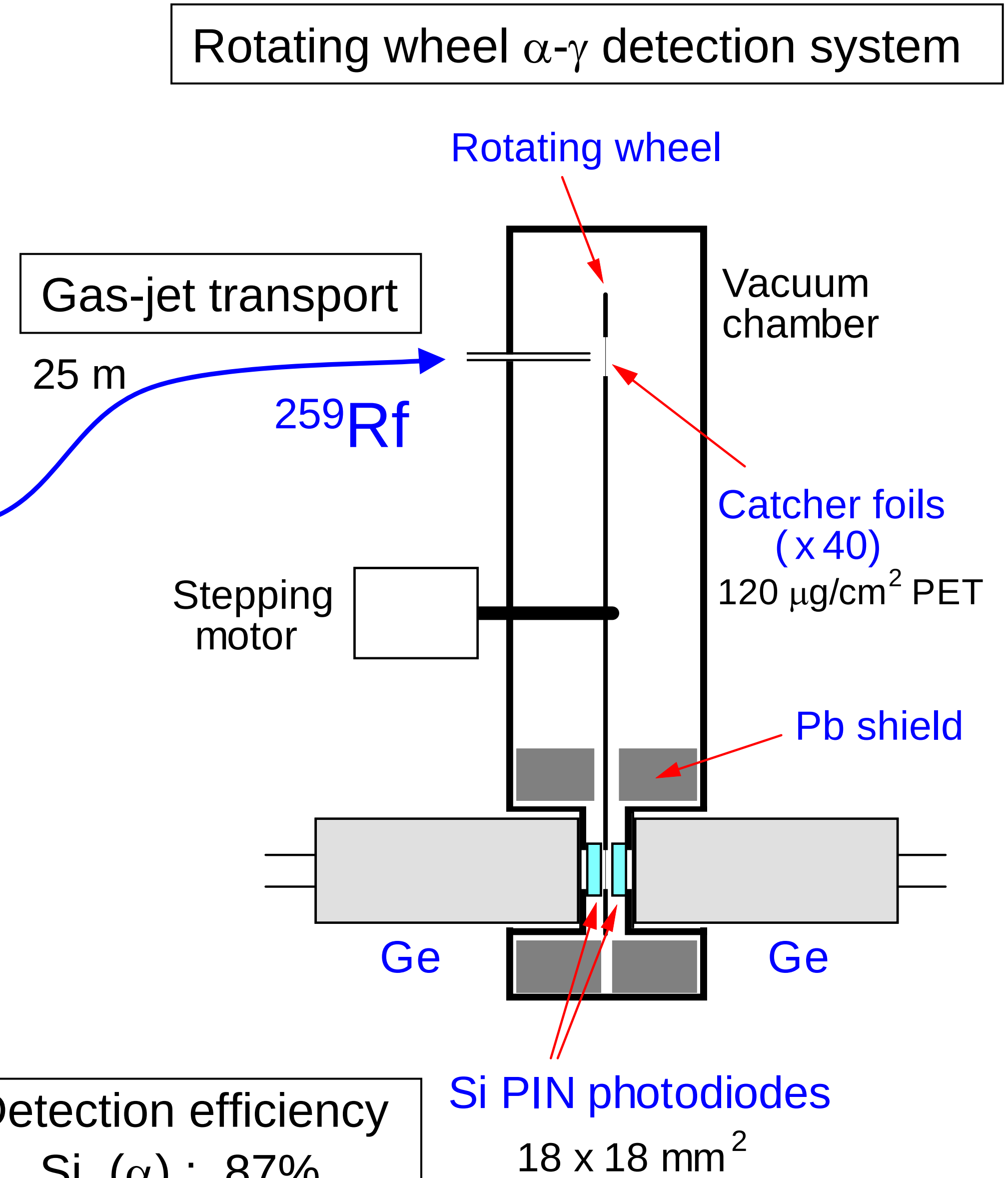
φ1.4-mm Cf target



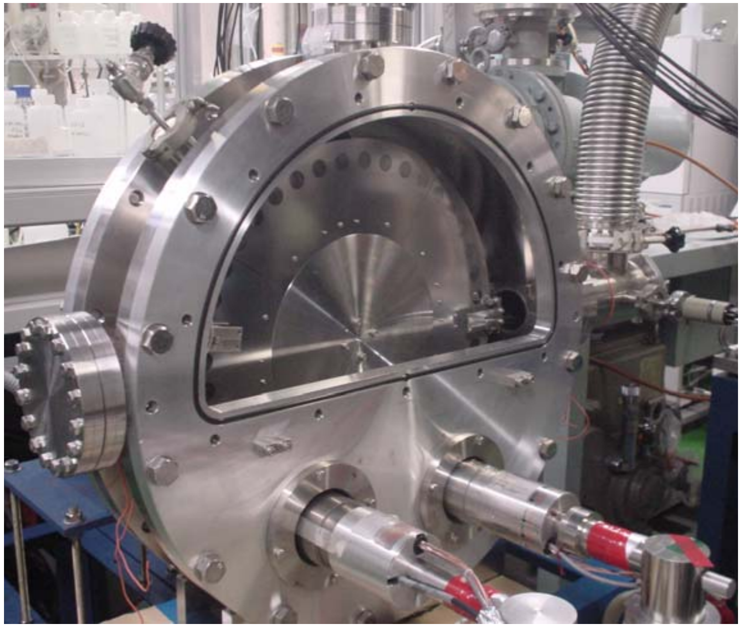
3 cm

Experimental setup



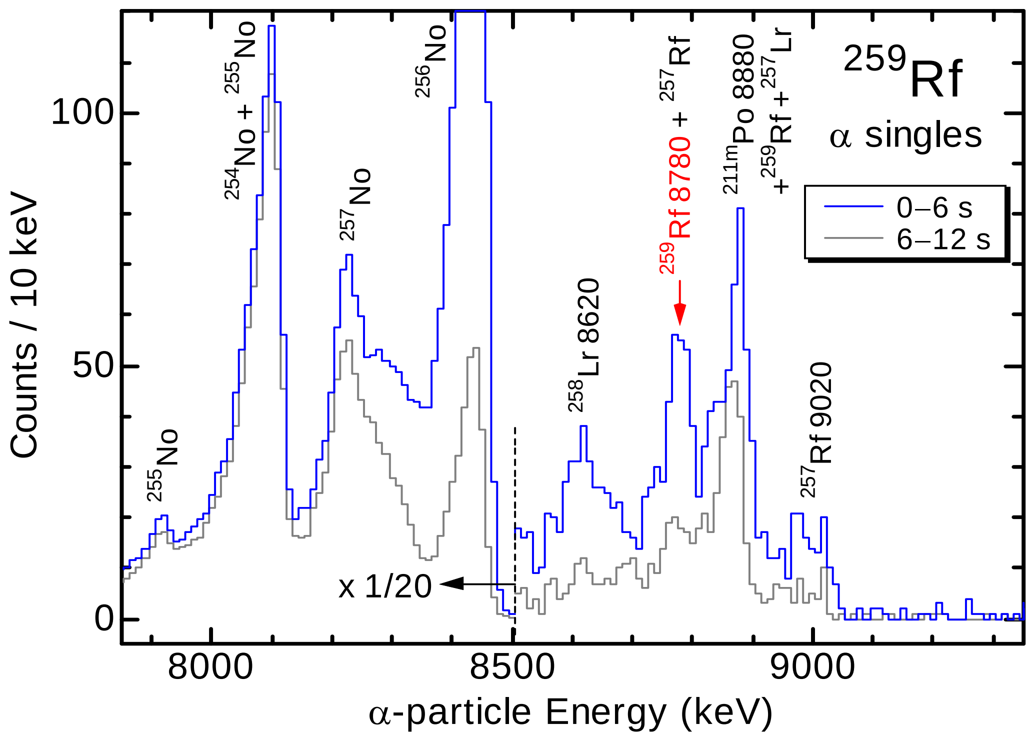


- Beam intensity: ~600 pnA
- Total beam time: 14 days

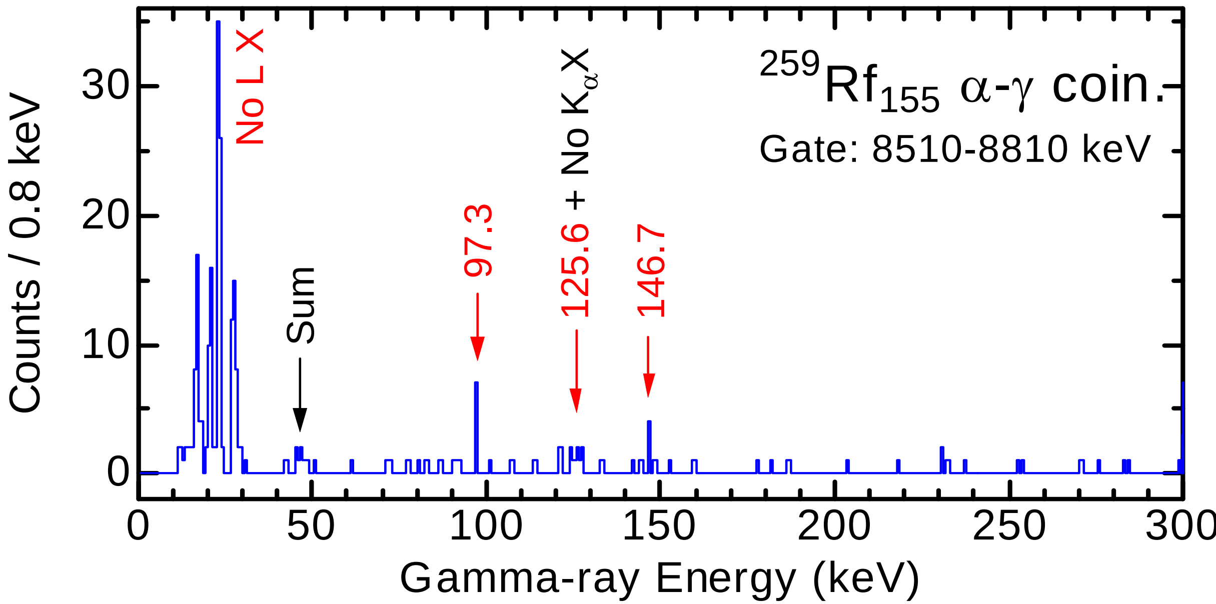


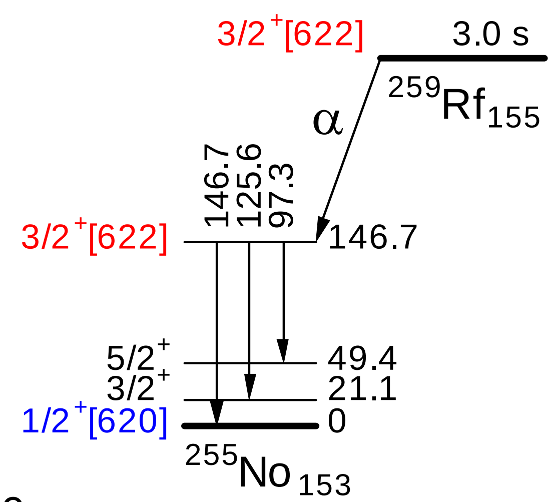
Detection efficiency
Si (α) : 87%
Ge (γ) : 30%

α-singles spectrum

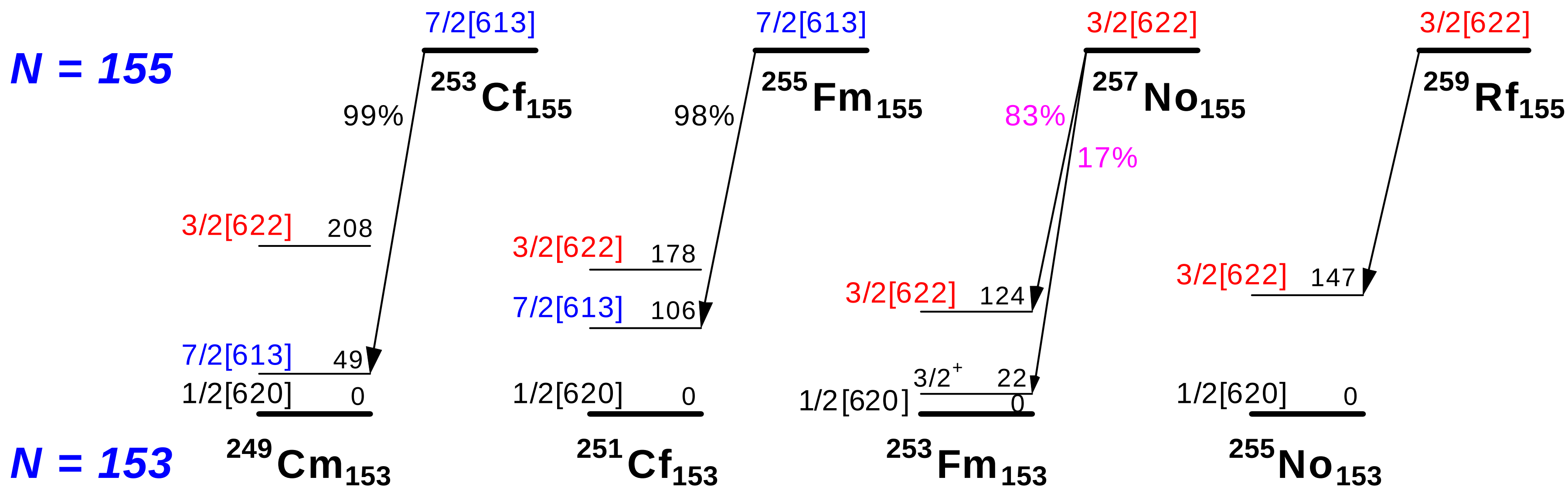


α-γ coincidence spectrum

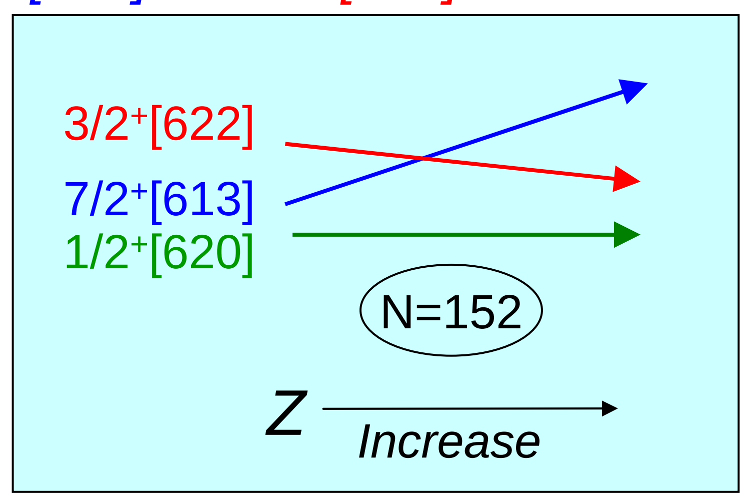




α decays of N=155 isotones and levels in N=153 daughters



7/2[613] and 3/2[622] are Inverted !

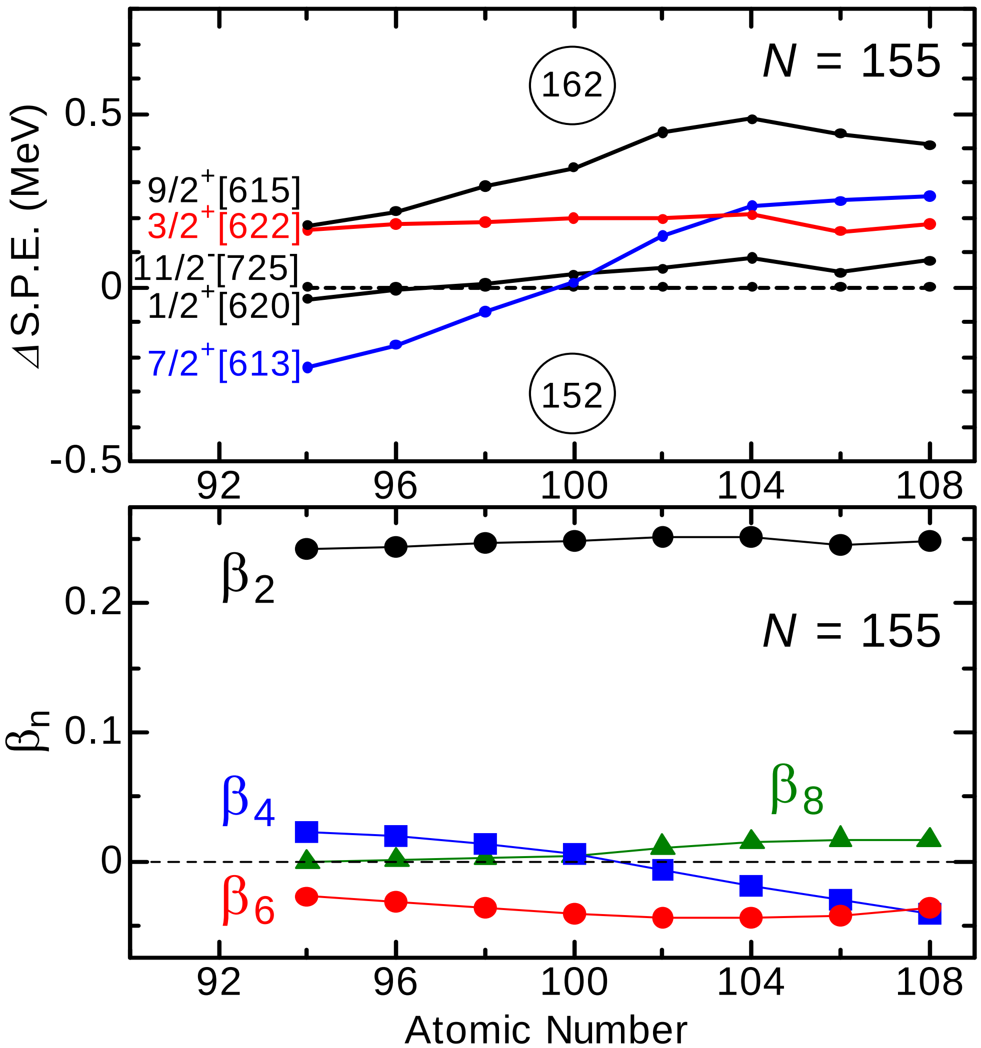


Ground states of N=155 isotones

- Z = 98,100 --- 7/2+[613]
- Z = 102,104 --- 3/2+[622]

Inversion of $7/2^+[613]$ *and* $3/2^+[622]$ *orbitals*

Macroscopic-microscopic model calculation (by T. Ichikawa)



FRLDM + Folded-Yukawa single-particle potential

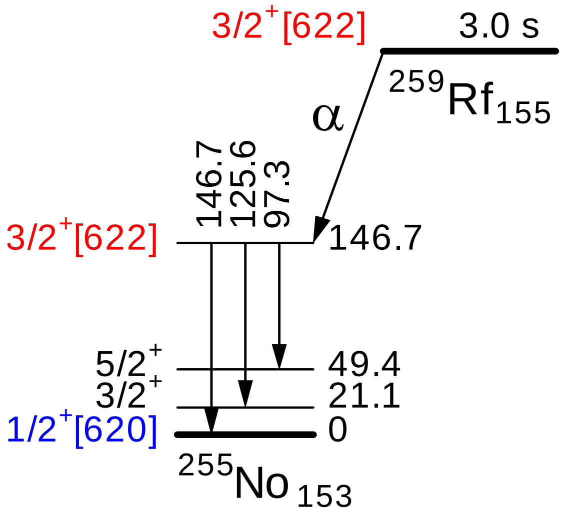
$7/2^+[613]$ and $3/2^+[622]$ energies are inverted at Z > 102

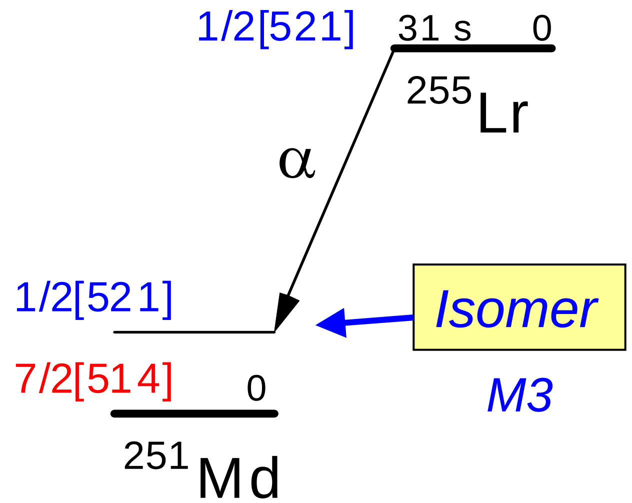
Reproduced well !

- Z = 98,100 --- $7/2^+[613]$
- Z = 102,104 --- $3/2^+[622]$

β_4 and β_6 largely contribute to this inversion

High-resolution α fine-structure spectroscopy of odd-mass Lr isotopes





α-γ spectroscopy needs γ-ray emission !

If α transition populates ground state or isomeric state, no γ-ray is observed.

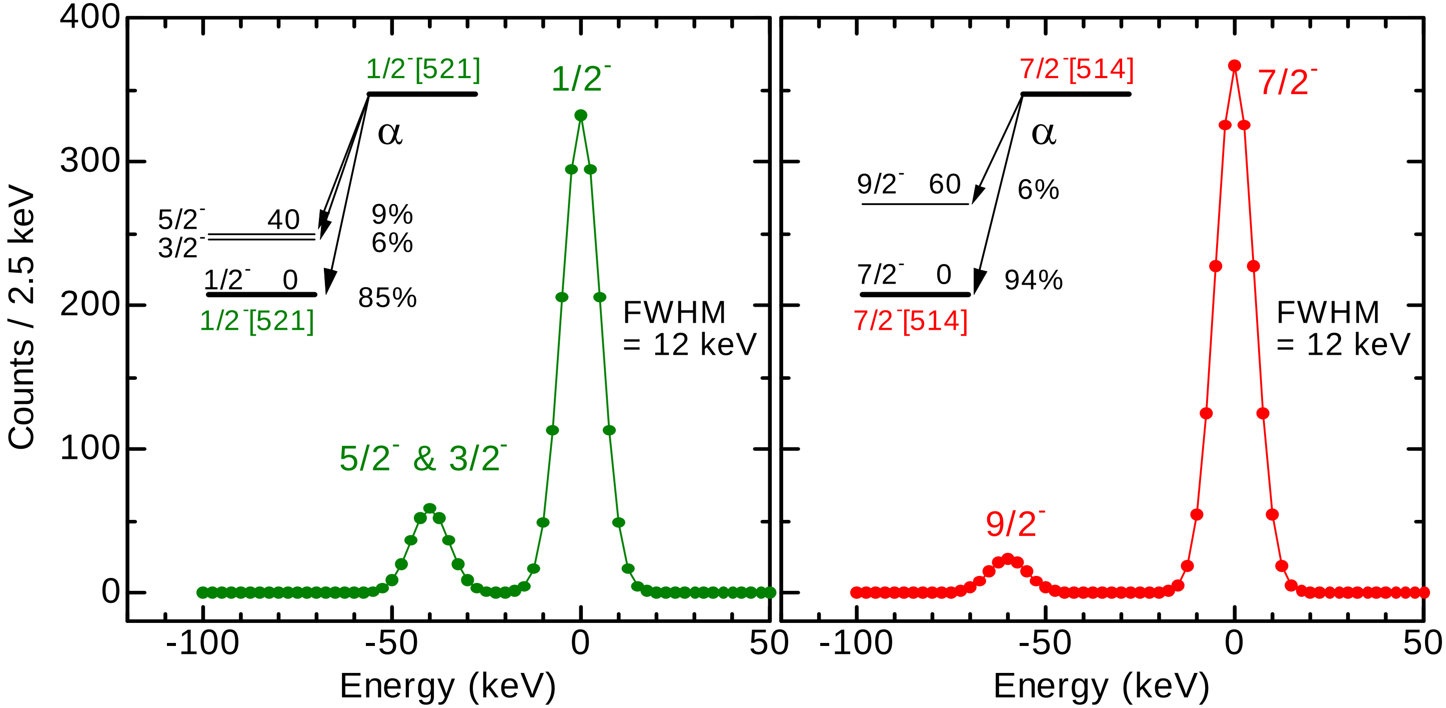
However, γ-ray intensity is very weak in the α decay of SHN.

Internal conversion is dominant.

High-resolution α fine-structure spectroscopy

How do we assign spin-parities and configurations?

Expected α fine-structure spectra

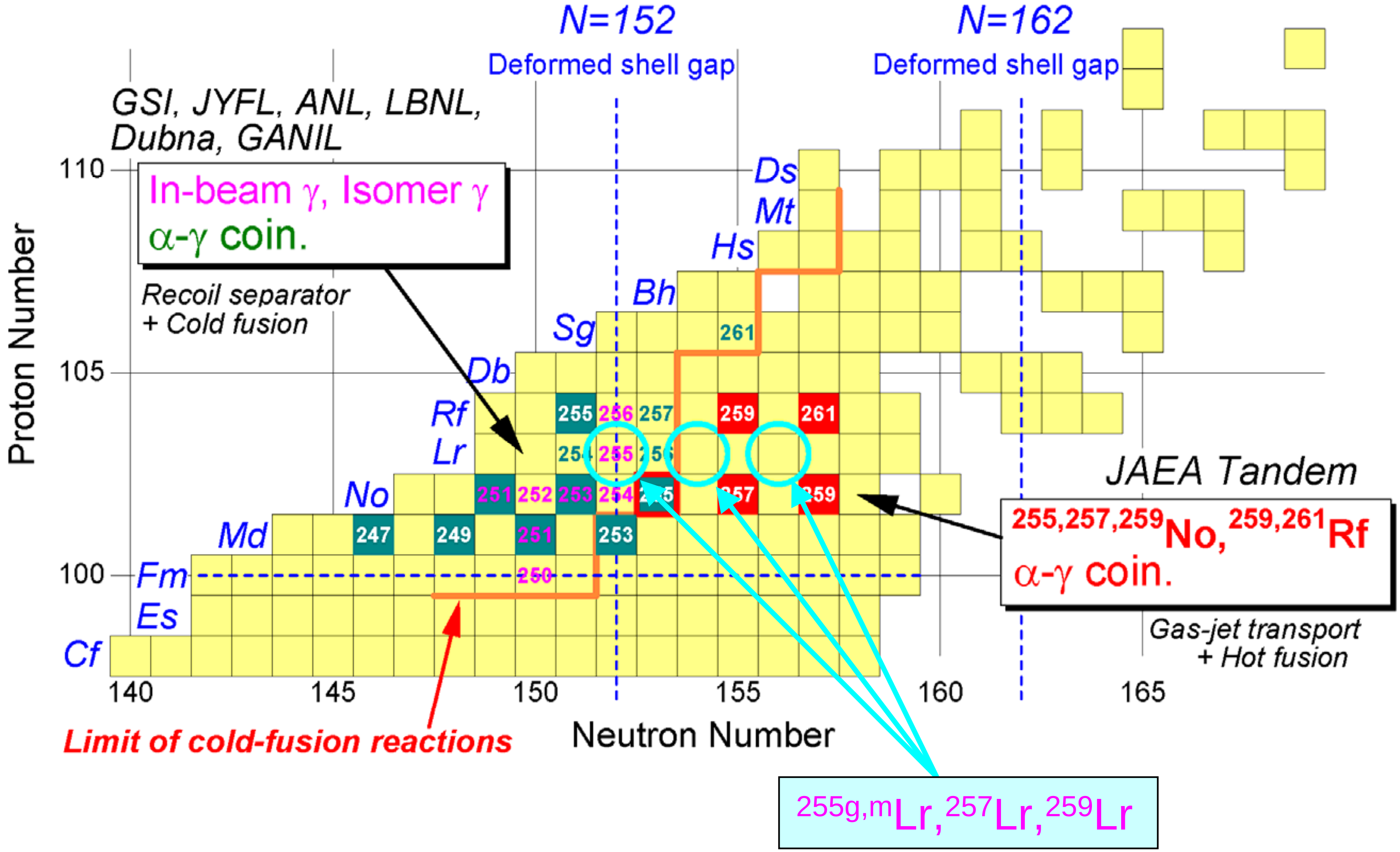


- Rotational band energies
- α intensities

→ Single-particle configuration

α energy resolution ~ 10 keV

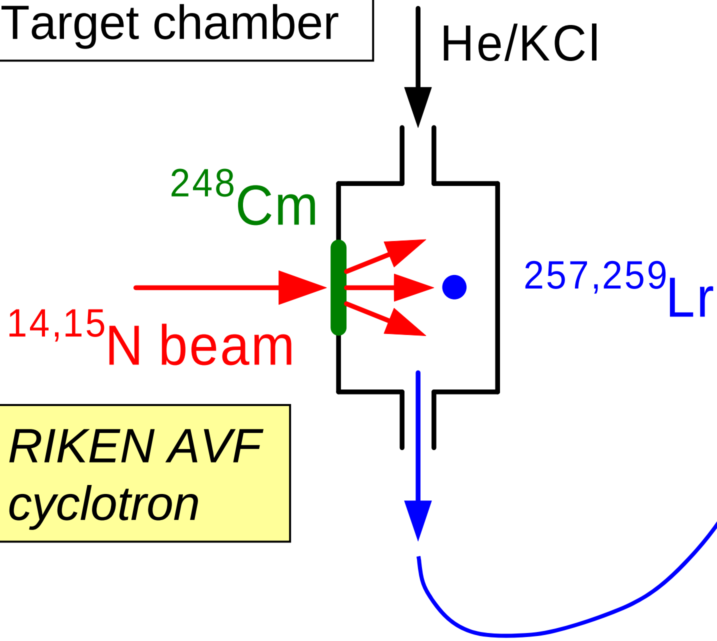
Current status of spectroscopic studies for superheavy nuclei



Experimental assignments of proton single-particle states in Z ≥ 103 nuclei

Experimental setup (1) $^{248}Cm + ^{14,15}N \rightarrow ^{257,259}Lr$

Target chamber

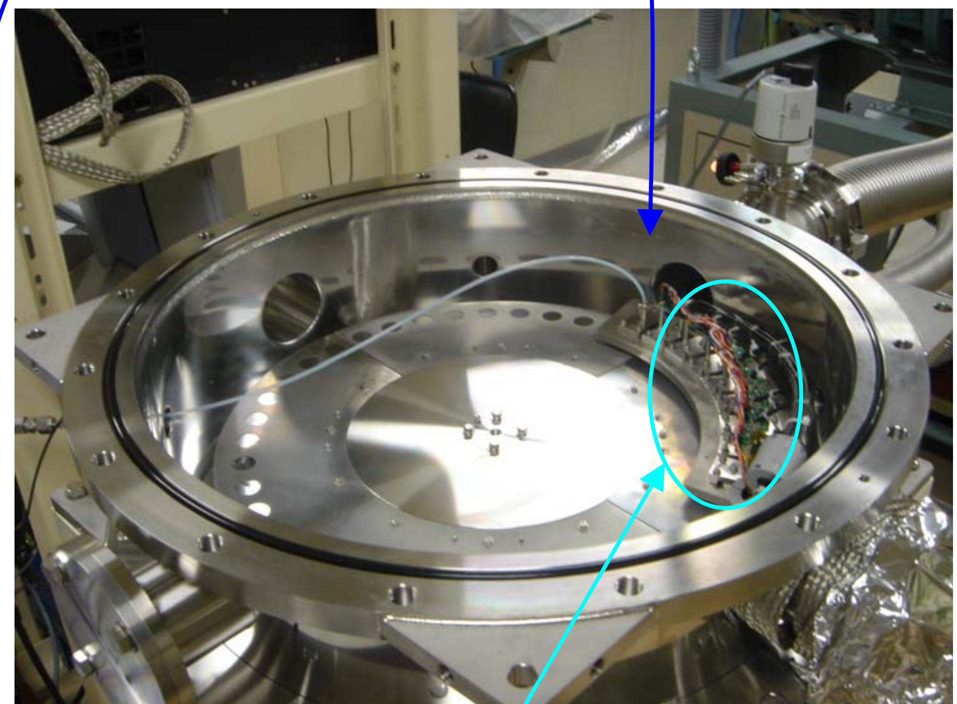


RIKEN AVF cyclotron

Gas-jet transport

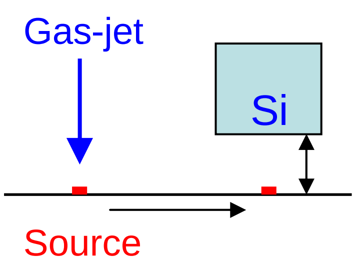
- Transport time: ~0.4 s
- Transport efficiency: ~50%

Capillary (11 m)



Rotating-wheel α-detection system

7 pairs of Si detectors



- Thin source

\+

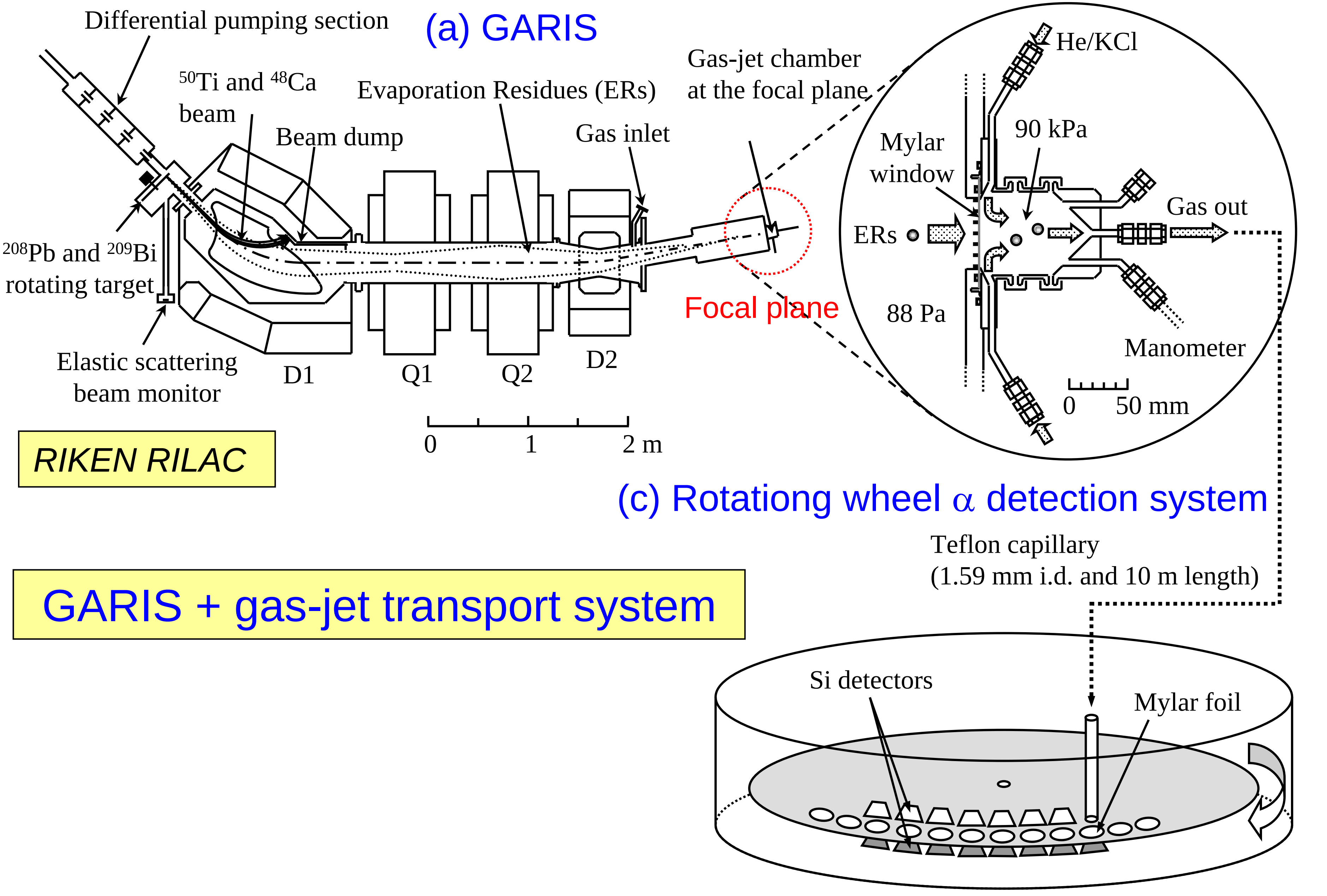
- Small Si detector 8 mmϕ
- Source-to-detector distance ~4 mm
- Detection efficiency ~15%

Good α-energy resolution !

FWHM ~ 10 keV

Experimental setup (2)

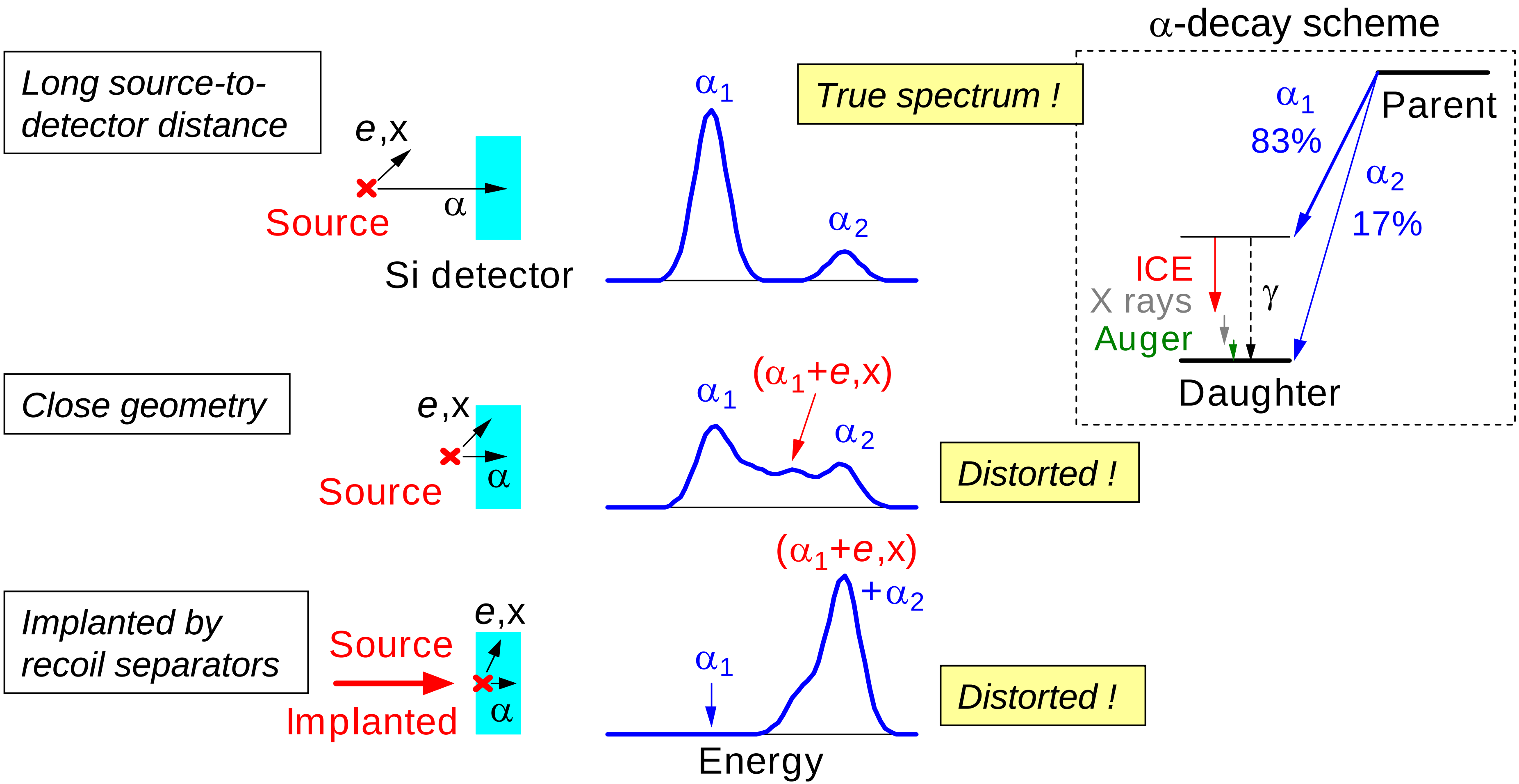
$^{209}Bi + ^{48}Ca \rightarrow ^{255}Lr$



RIKEN RILAC

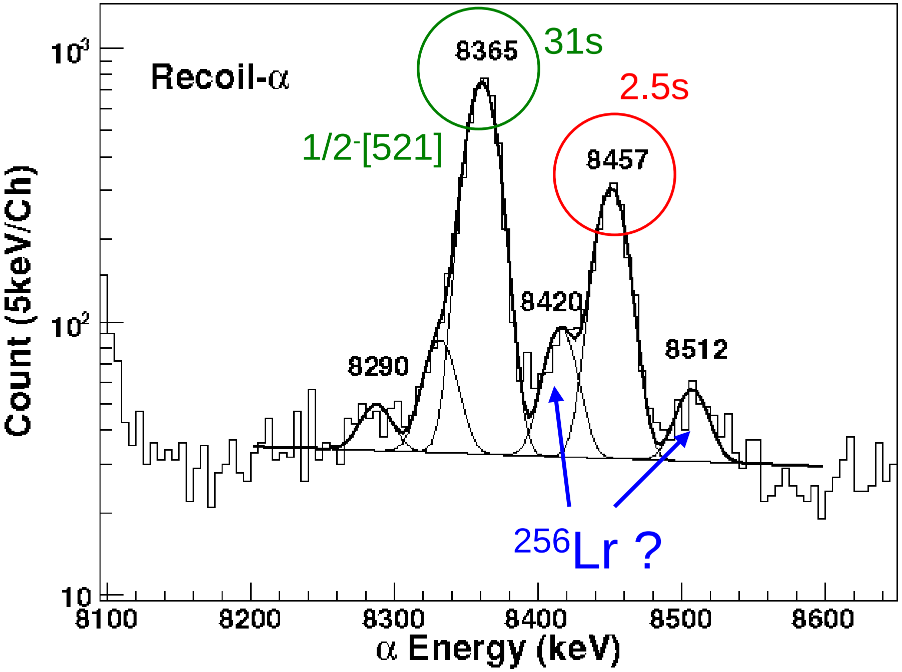
GARIS + gas-jet transport system

Distortion of α-energy spectrum by coincidence summing effect



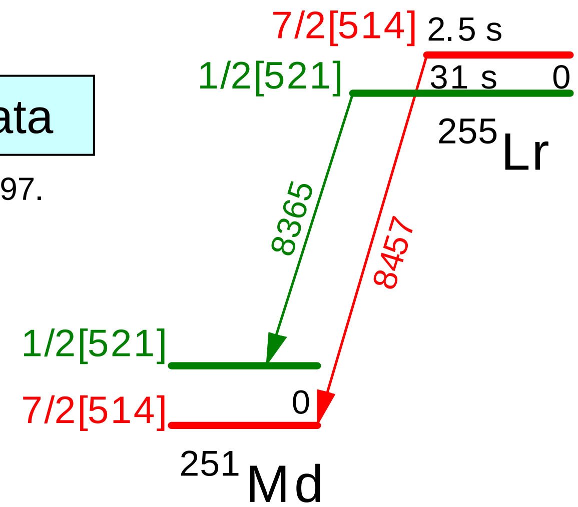
It is almost impossible to derive α energies and intensities precisely !
at close geometry, and by implantation

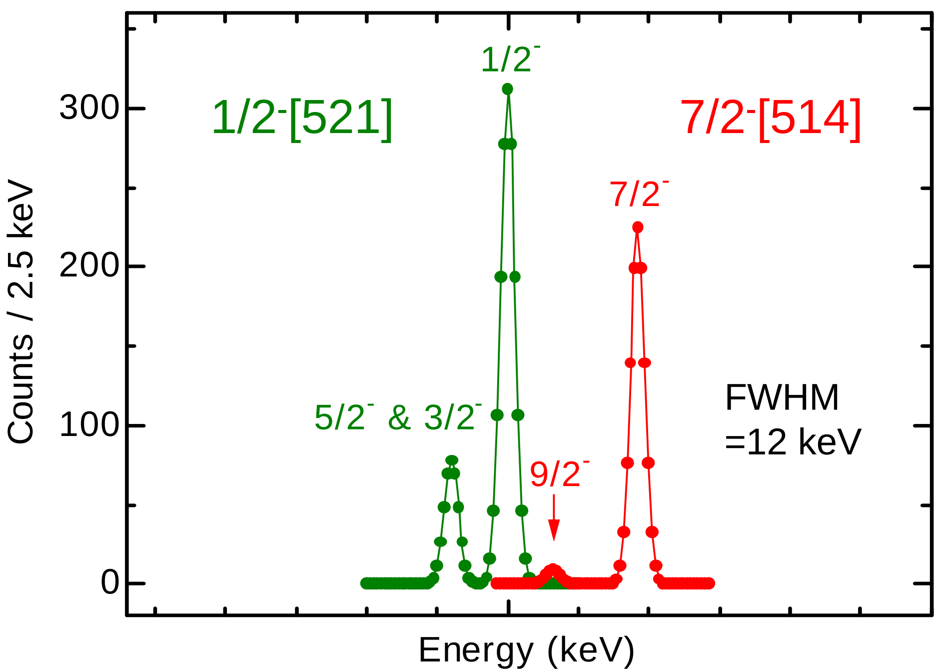
α decay of ^{255g,m}Lr



Literature data

EPJA 30(2006)397.





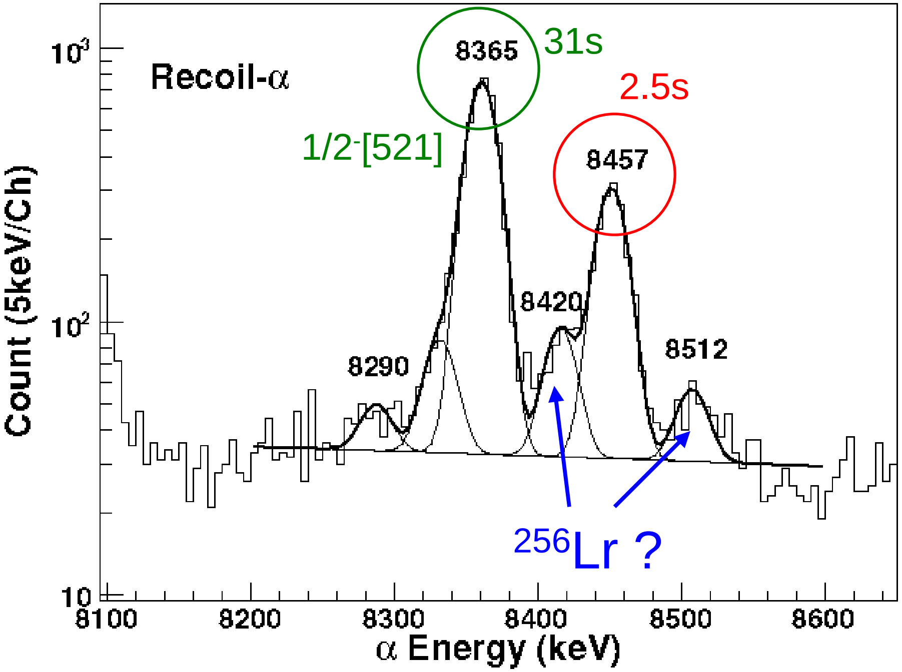
These configuration assignments seem reasonable, but no experimental evidence

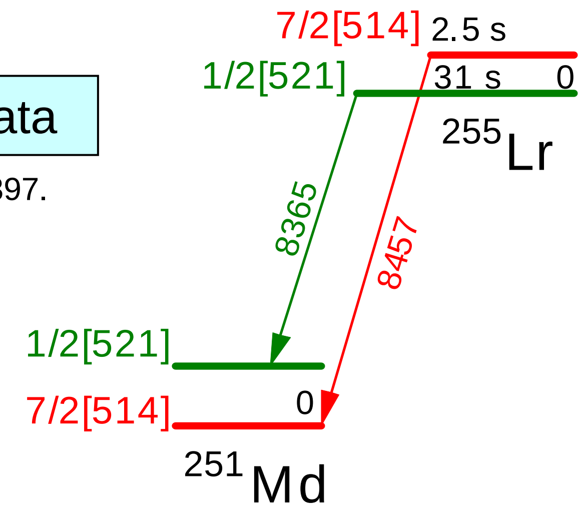
If the above configuration assignments are correct, α fine-structure spectrum should be observed like this.

α decay of ^{255g,m}Lr

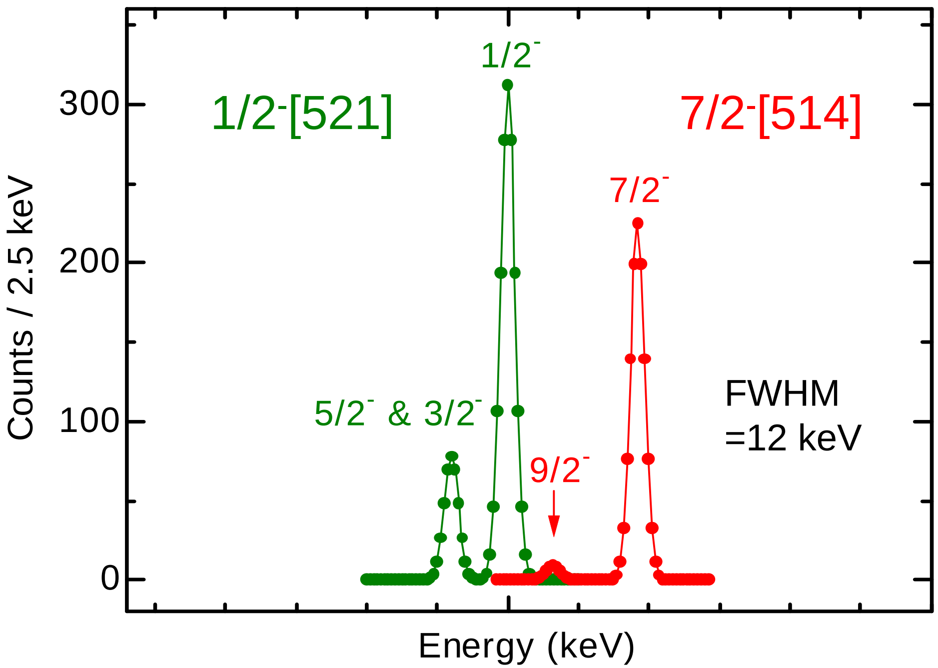
Literature data

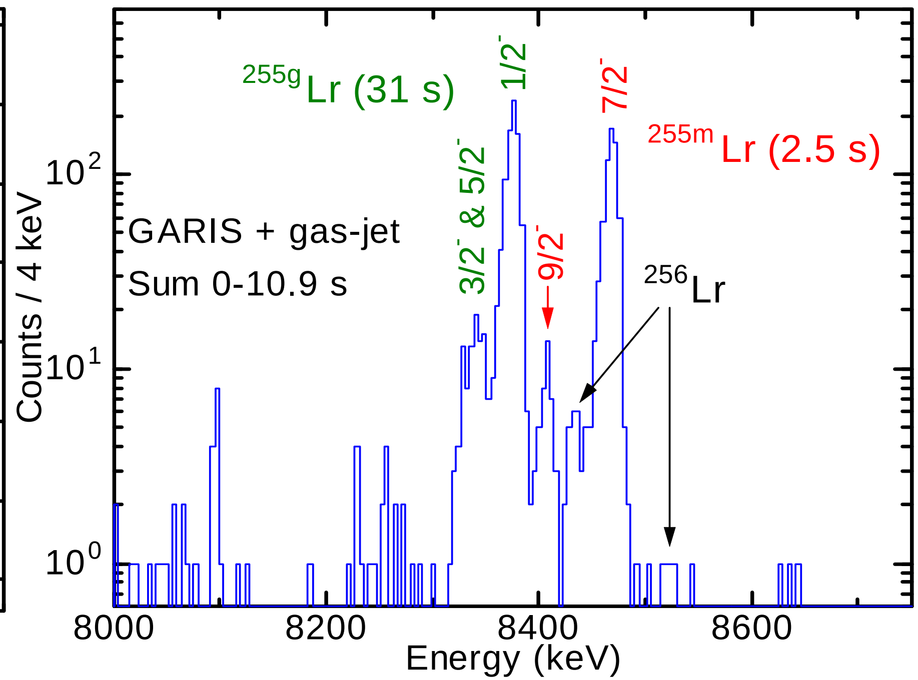
EPJA 30(2006)397.





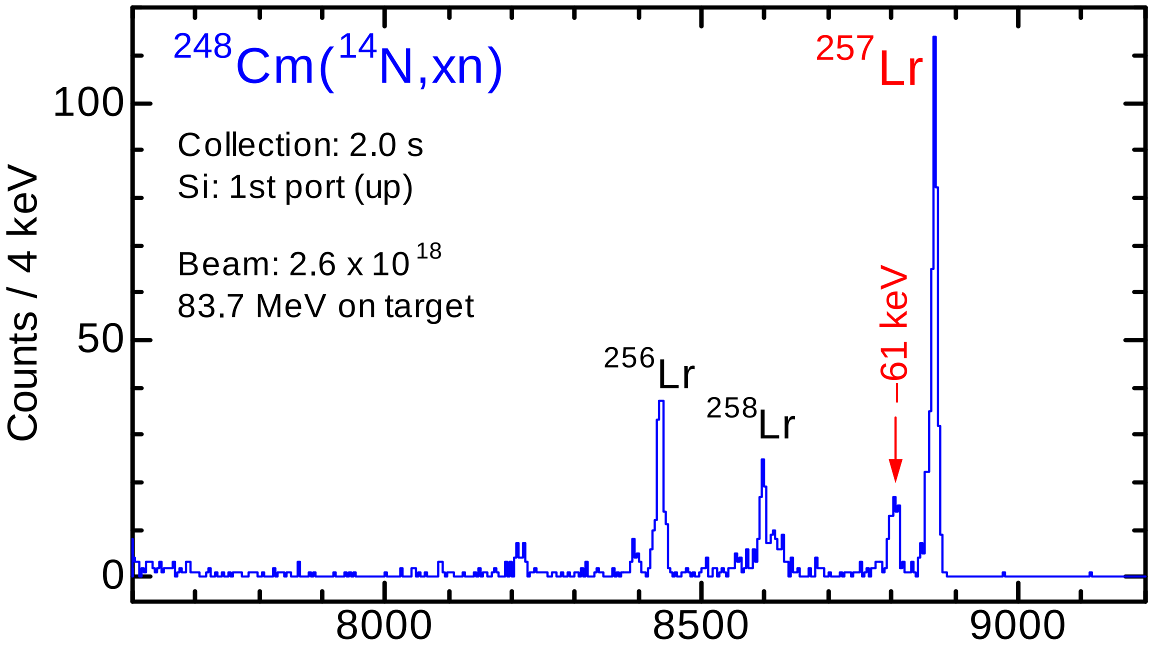
Present !





α decay of ^{257}Lr

Energy difference of 61 keV is very consistent with the 7/2$^-$[514] assignment



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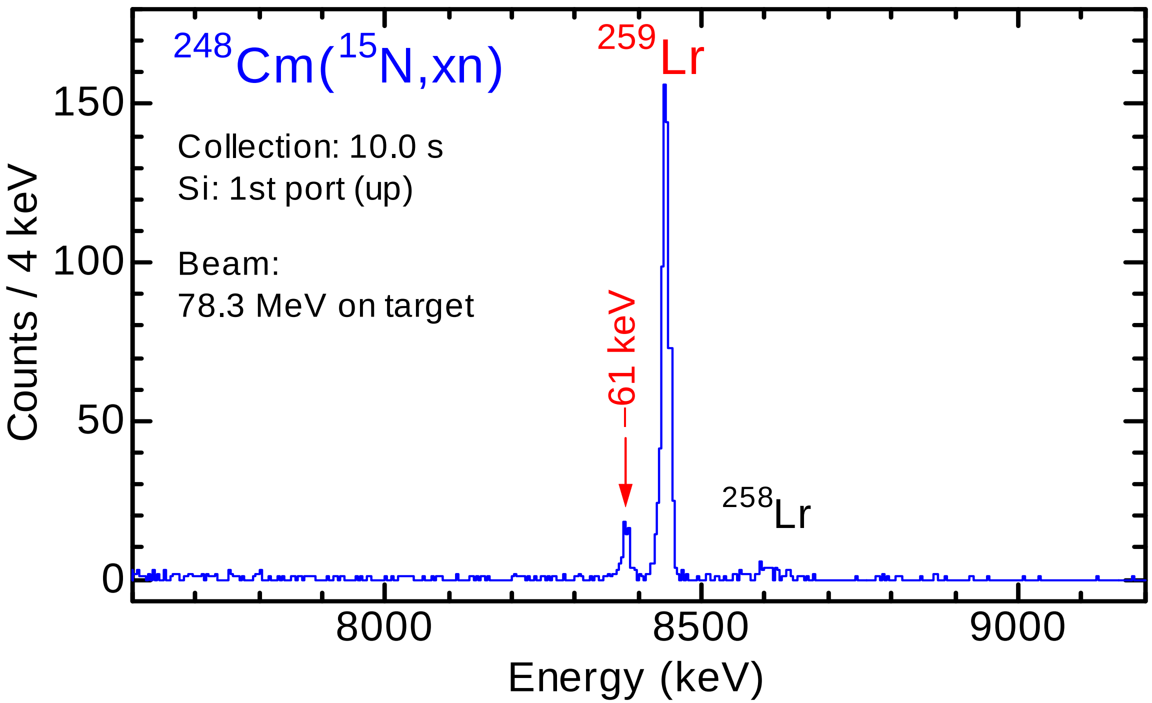
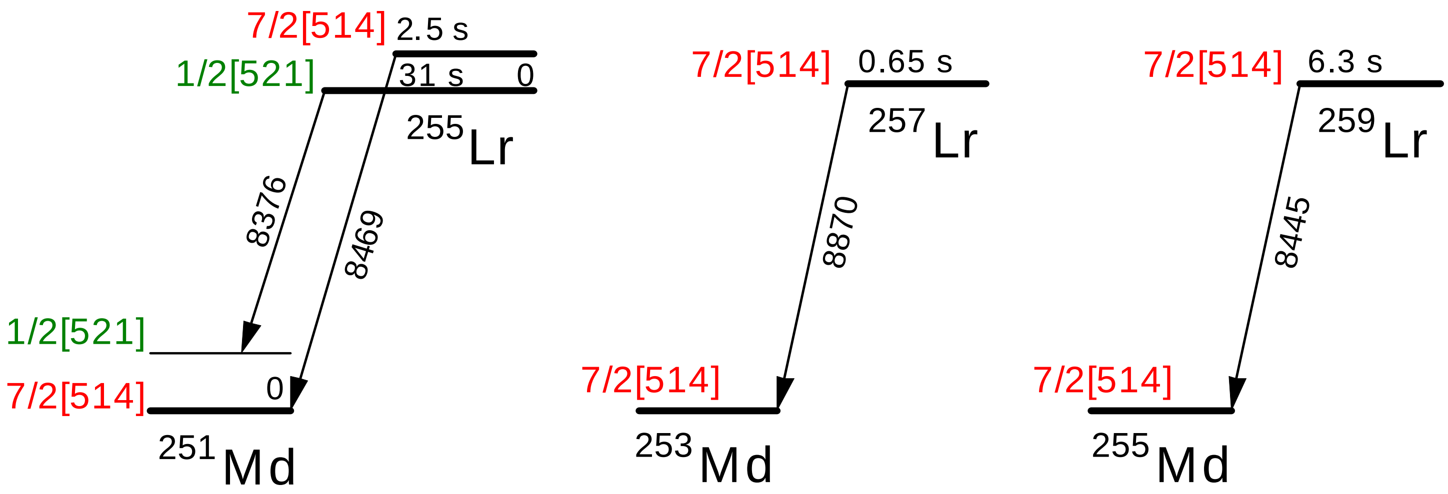


Summary of the Lr experiments

		Existence of isomer ?	
Isomer	7/2[514]		
g.s.	1/2[521]	7/2[514]	7/2[514]



First definite identification of proton single-particle configurations in Z ≥ 103 isotopes

Summary

- γ rays following the α decay of ^{259}Rf were observed for the first time.
- The ground-state configuration of ^{259}Rf was assigned to be $3/2^+$[622].
- Neutron orbitals of $7/2^+$[613] and $3/2^+$[622] were found to be inverted in N=155 isotones.
- The evolution of higher-order deformation parameters (β_4 and β_6) largely contributes to this inversion.
- Proton configurations of ^{255g,m}Lr, ^{257}Lr, and ^{259}Lr were definitely identified through a high-resolution α fine-structure spectroscopy.

Future plans

- High-resolution α fine-structure spectroscopy of ^{257}Rf
- α-γ coincidence spectroscopy of ^{261}Db