Overview of recent and future experiments of transfermium nuclei in the deformed region around N=152

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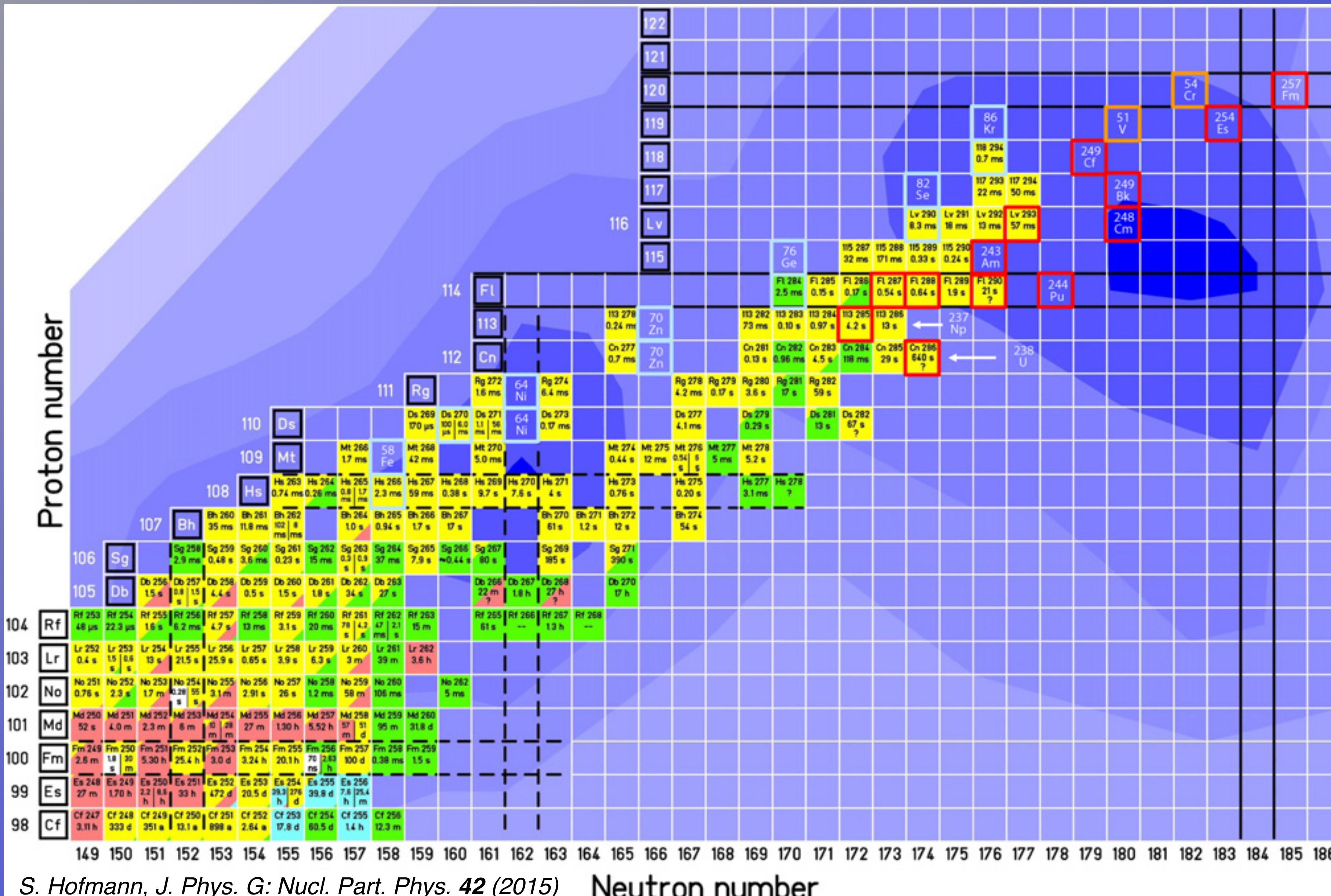
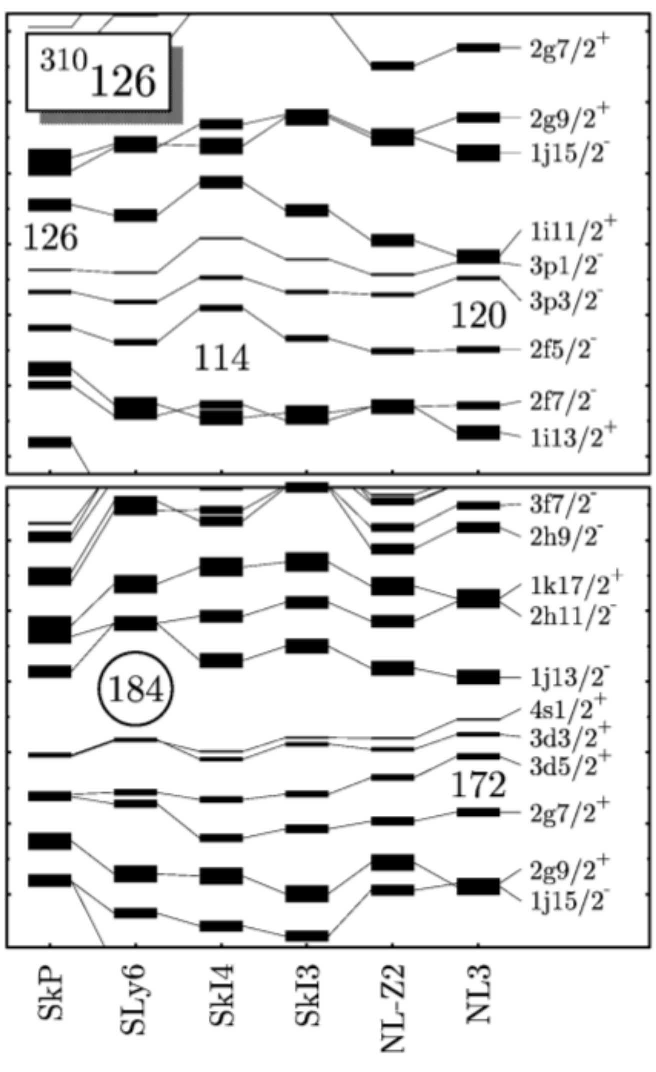
ESNT Workshop, Saclay, 16 – 19 November 2015

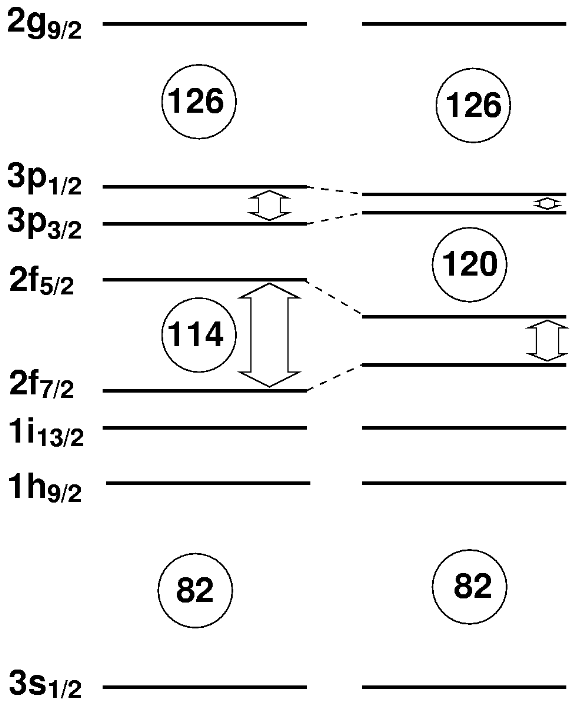
The super heavy landscape



S. Hofmann, J. Phys. G: Nucl. Part. Phys. ***42*** *(2015)*

SHE – Shell correction and single-particle levels



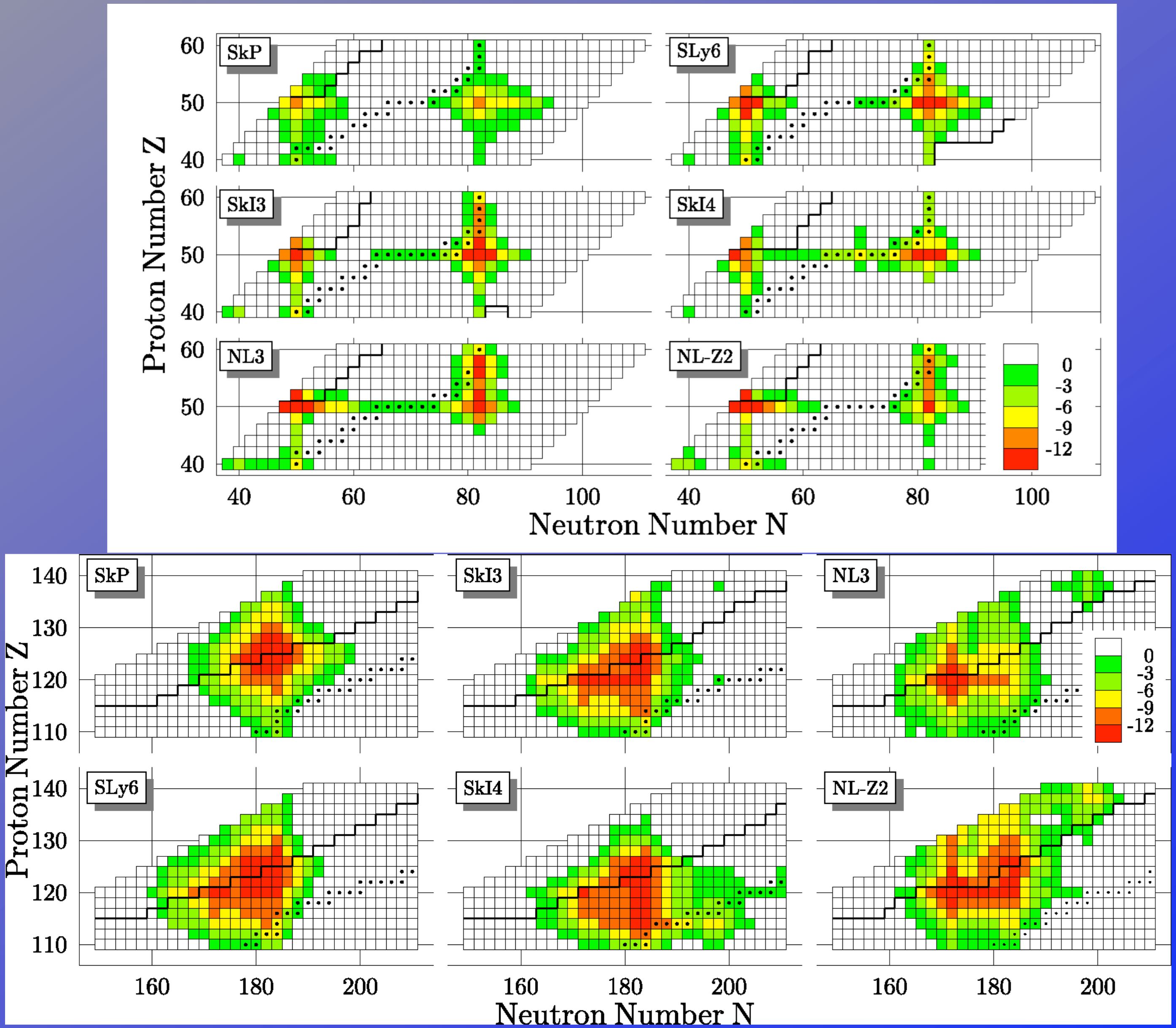


Self-Consistent Theories

- Calculations based on realistic effective nucleon–nucleon interaction
- Allows results to be traced back to interaction
- Difficult in Macroscopic–Microscopic calculations
- Need experimental data to determine correct ordering
- Will provide better predictions of properties of SHE

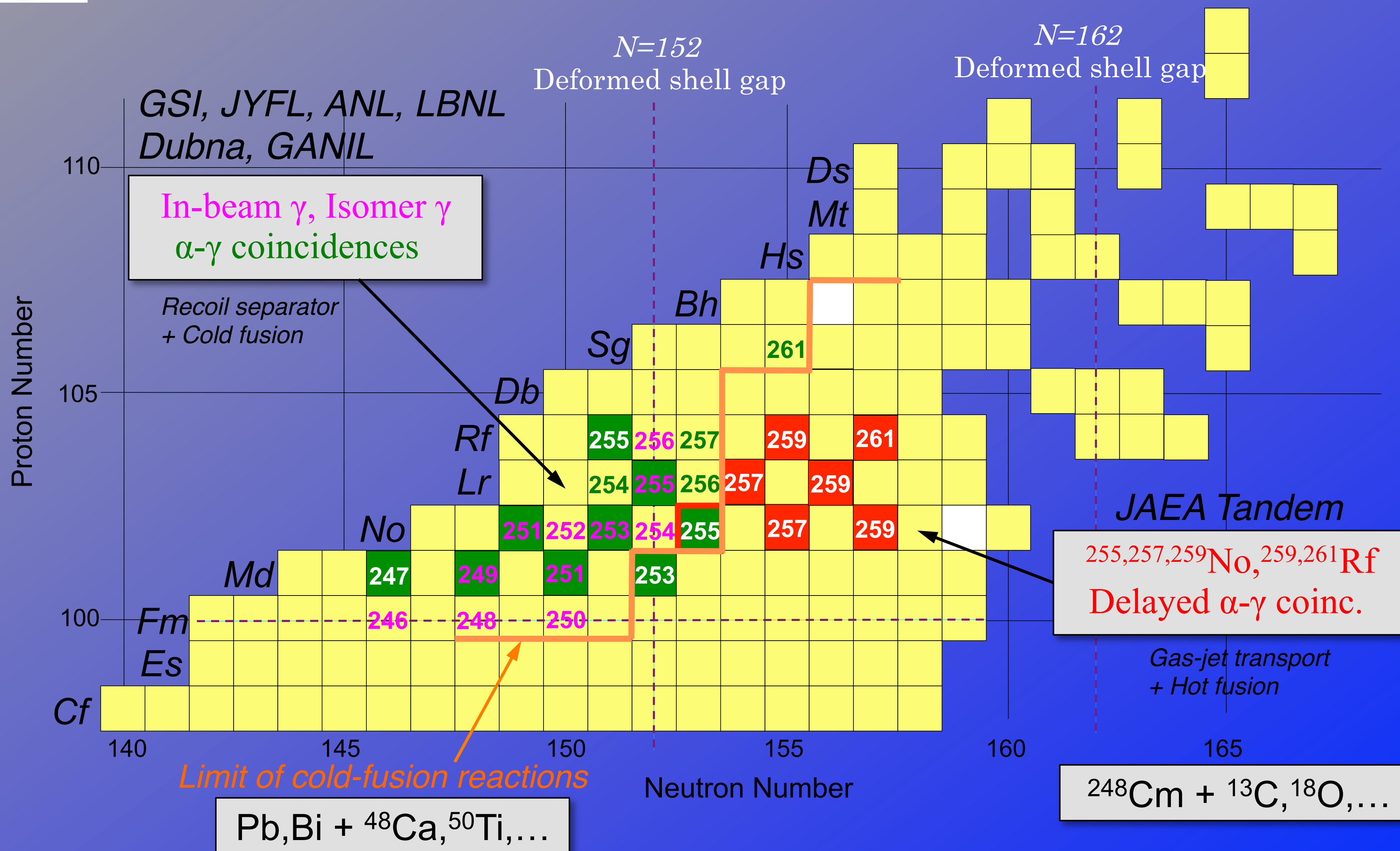
*M .Bender, W. Nazarewicz, P.-G. Reinhard, PLB **515**, 42 (2001)*

SHE – Shell correction and single-particle levels



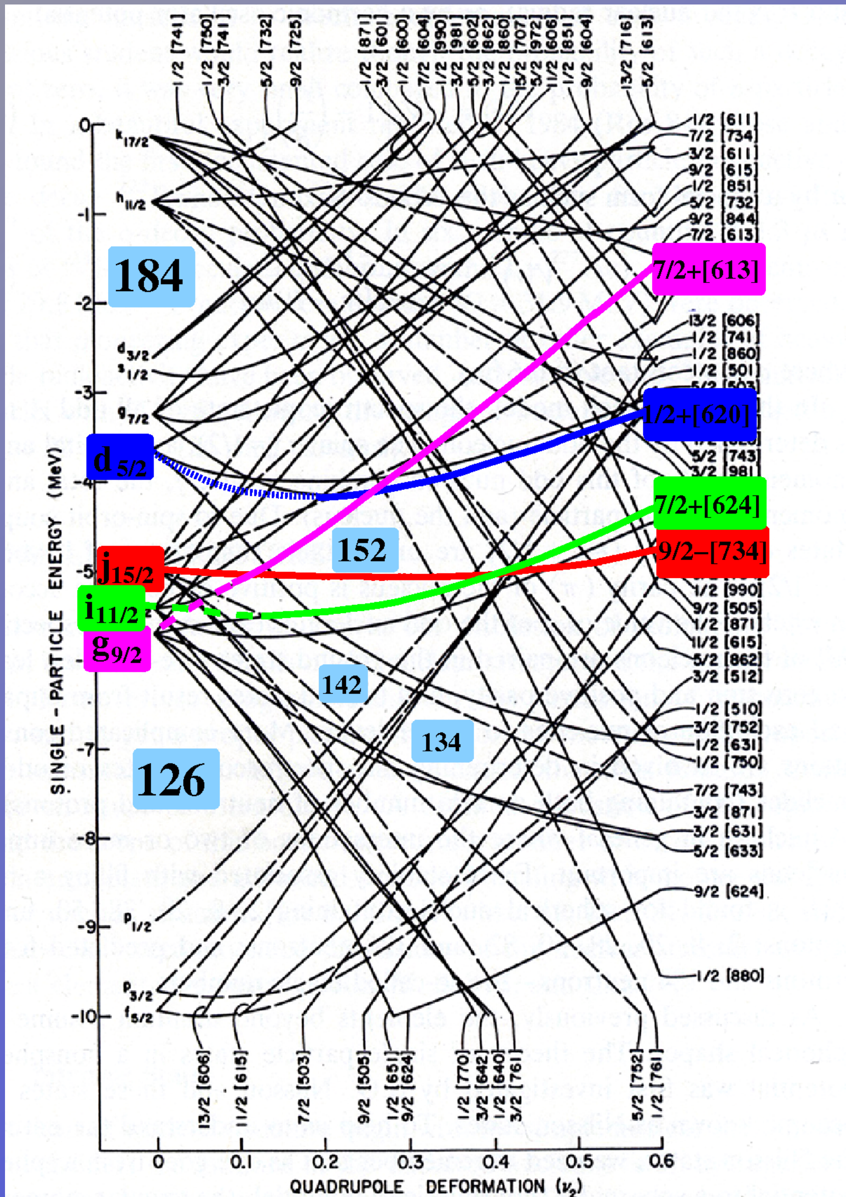
*M .Bender, W. Nazarewicz, P.-G. Reinhard, PLB **515**, 42 (2001)*

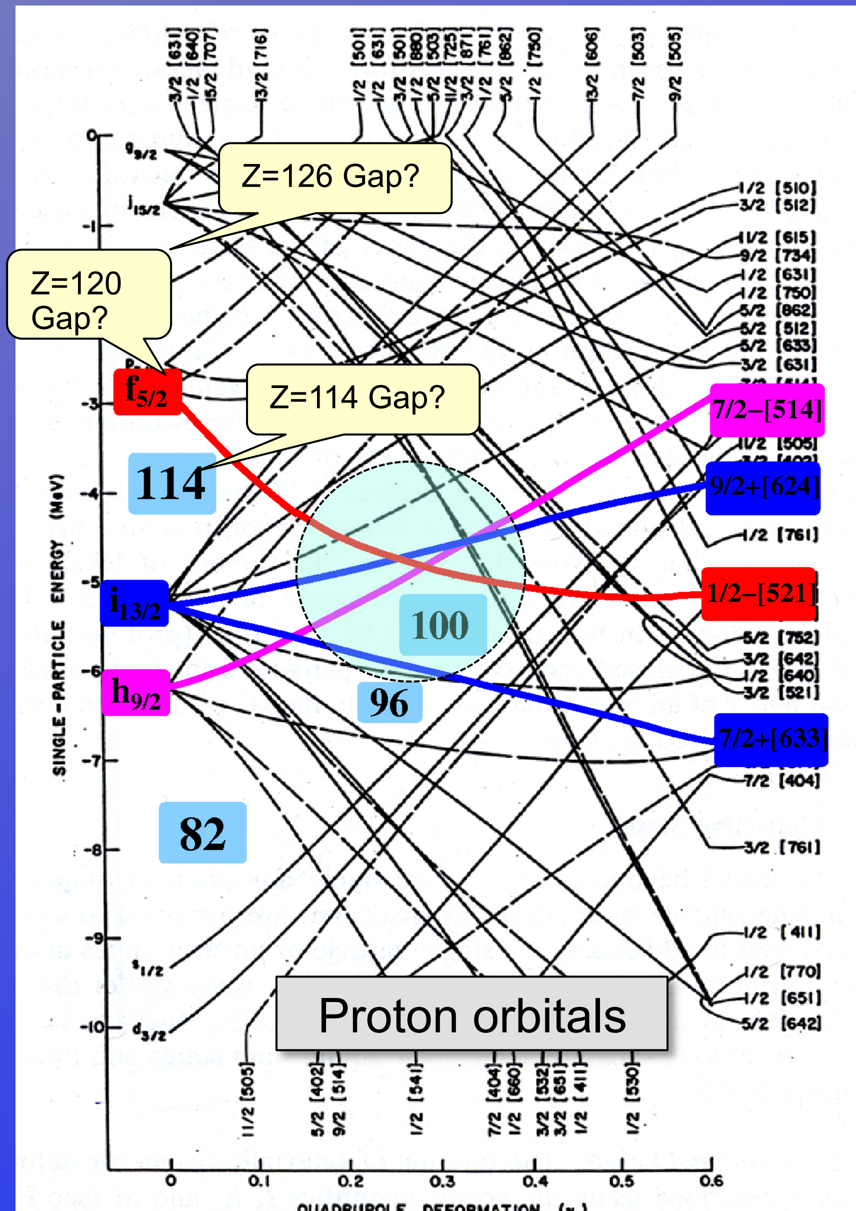
Current status of spectroscopic studies for SHN



Spin-parity and configuration assignments are very scarce!
Especially in the region Z >100 and N > 153

Single particle orbitals in the region



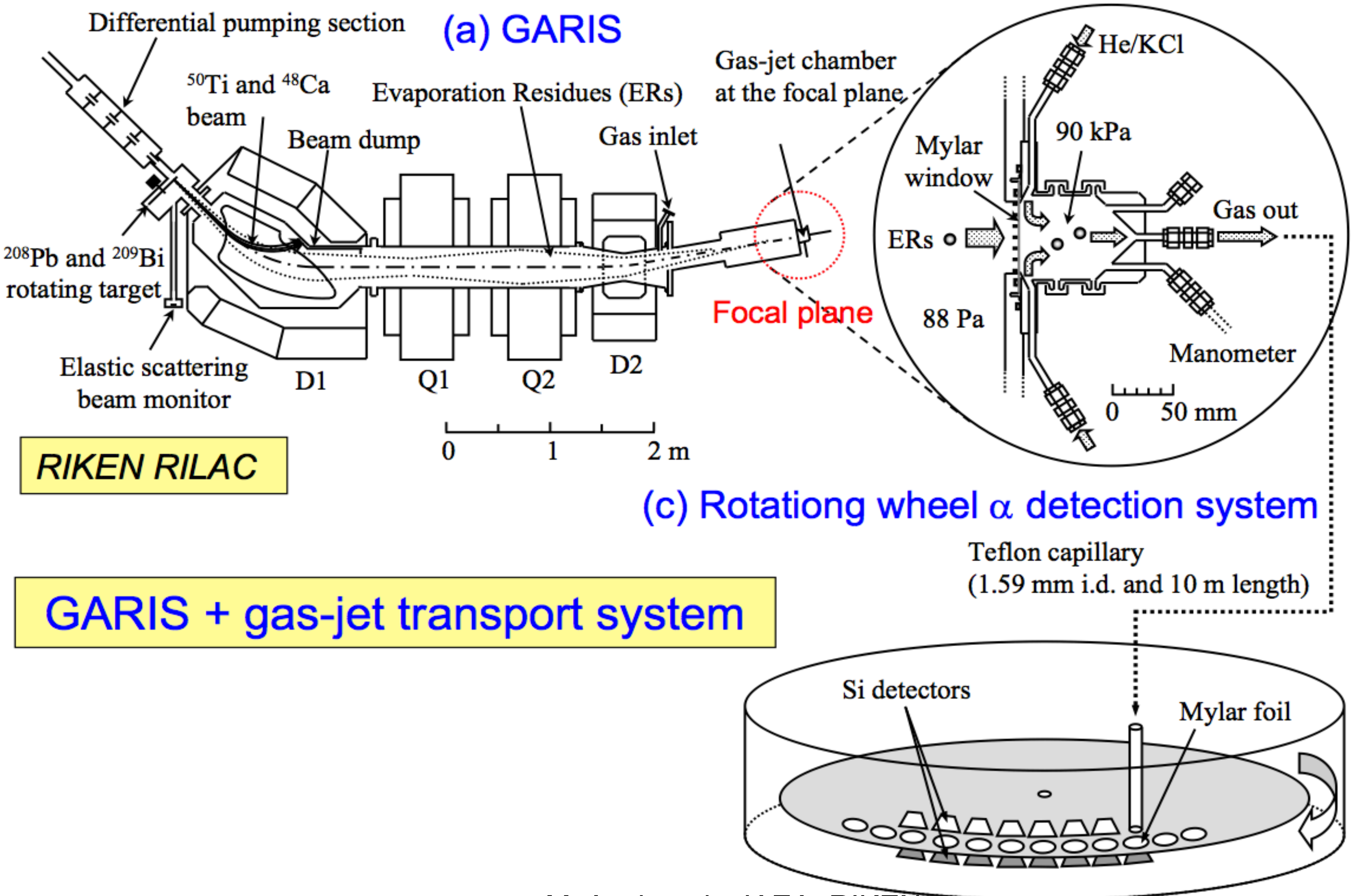


R.R Chasman et al., Rev. Mod. Phys. ***49****, 833 (1977)*

Experimental approaches

Experimental setup (2)

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

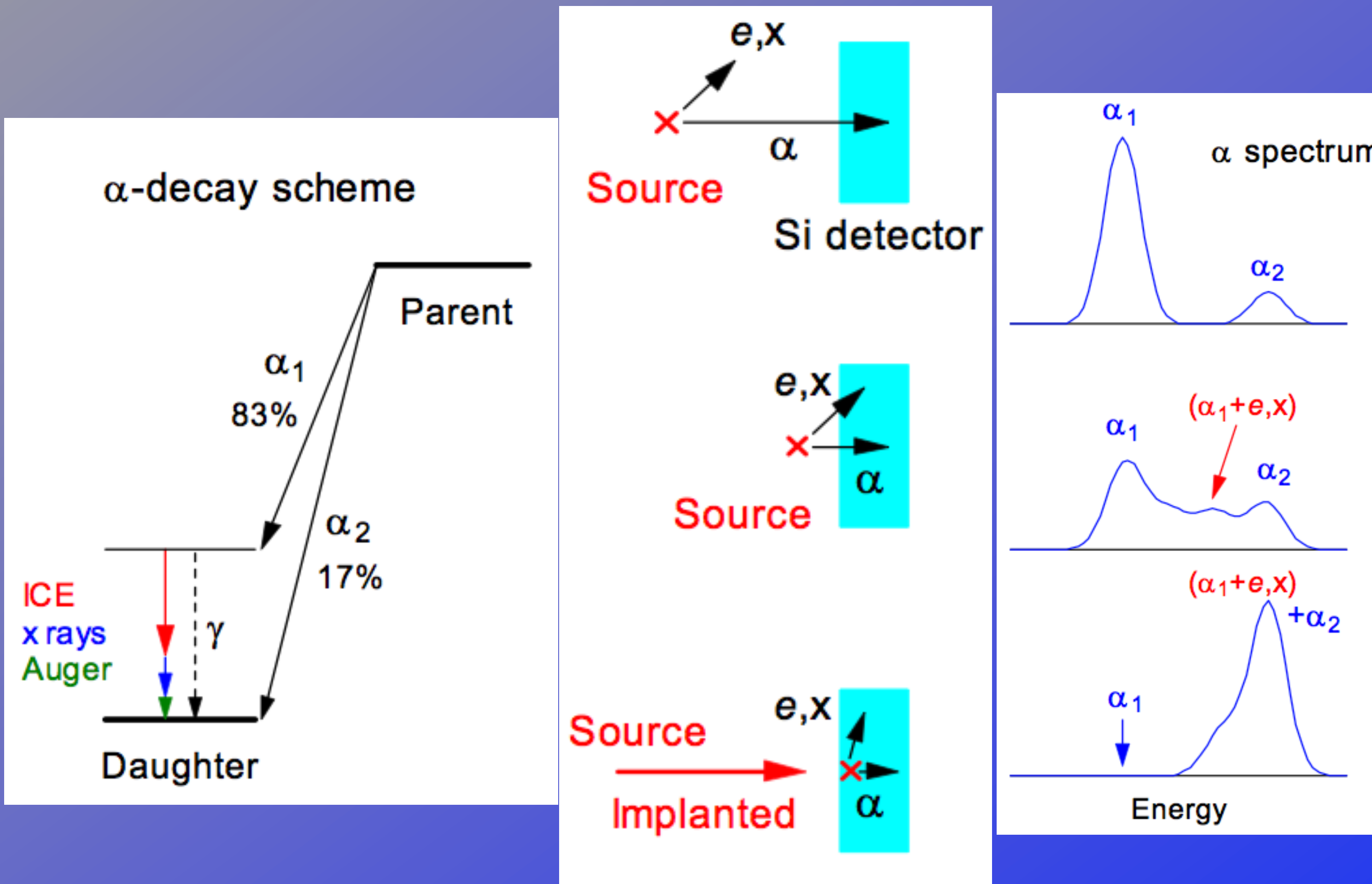


RIKEN RILAC

GARIS + gas-jet transport system

M. Asai et al., JAEA, RIKEN

Distortion of α-energy spectrum by coincidence summing effects



True and real!

Relatively long source-to-detector distance

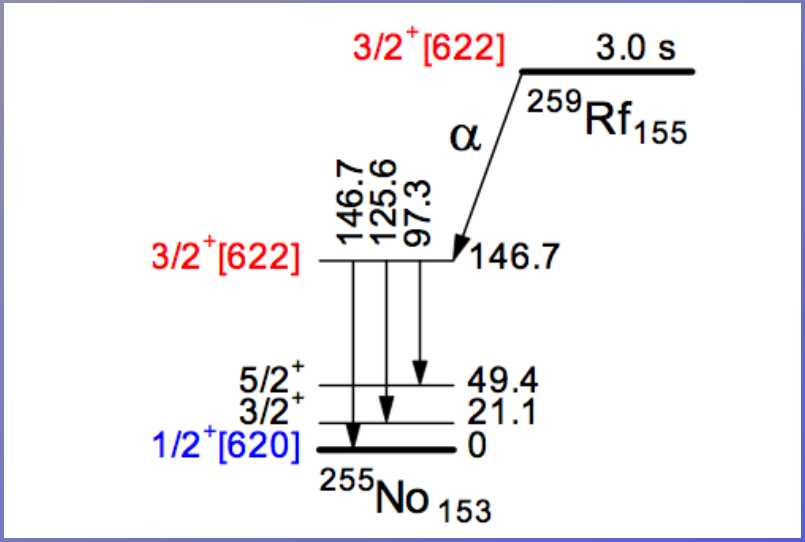
Distorted!

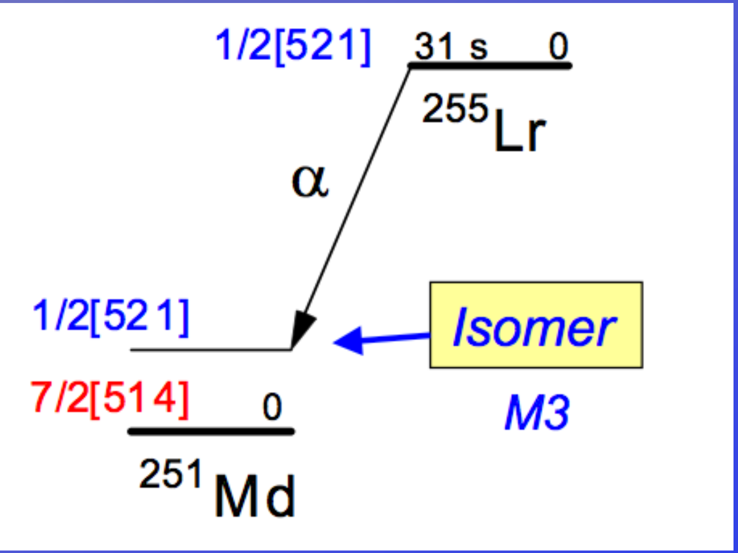
Close geometry

Implanted using a recoil separator

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

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





α-γ spectroscopy needs γ-ray emission!

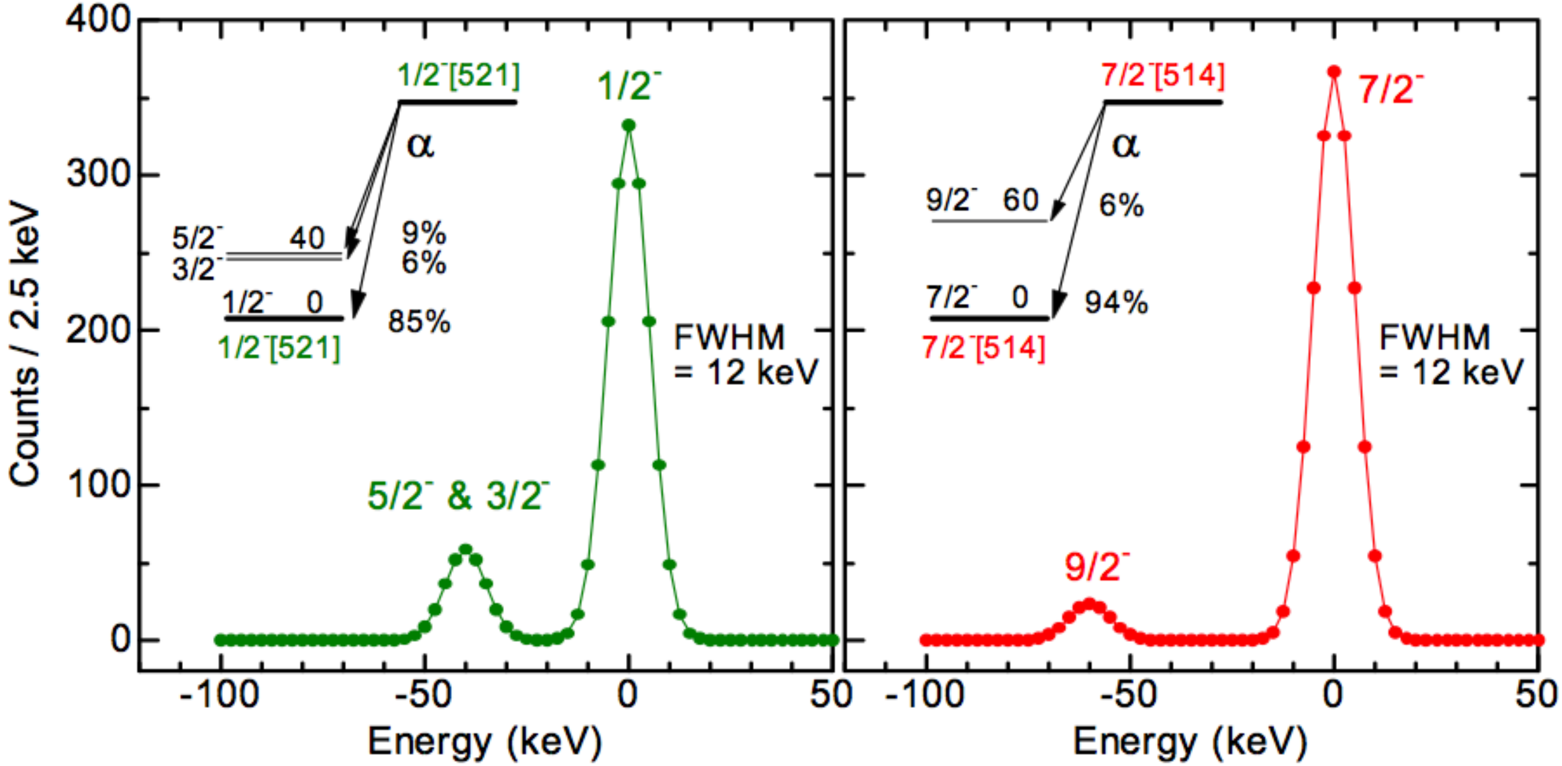
If the α-decay populates the ground or isomeric state, there is no γ-rays observed.

However, γ-ray intensity is very weak in SHN.
Internal conversion is dominant

High-resolution α fine-structure spectroscopy needed

How do we assign spin-parities and configurations?

Expected α fine-structure spectra

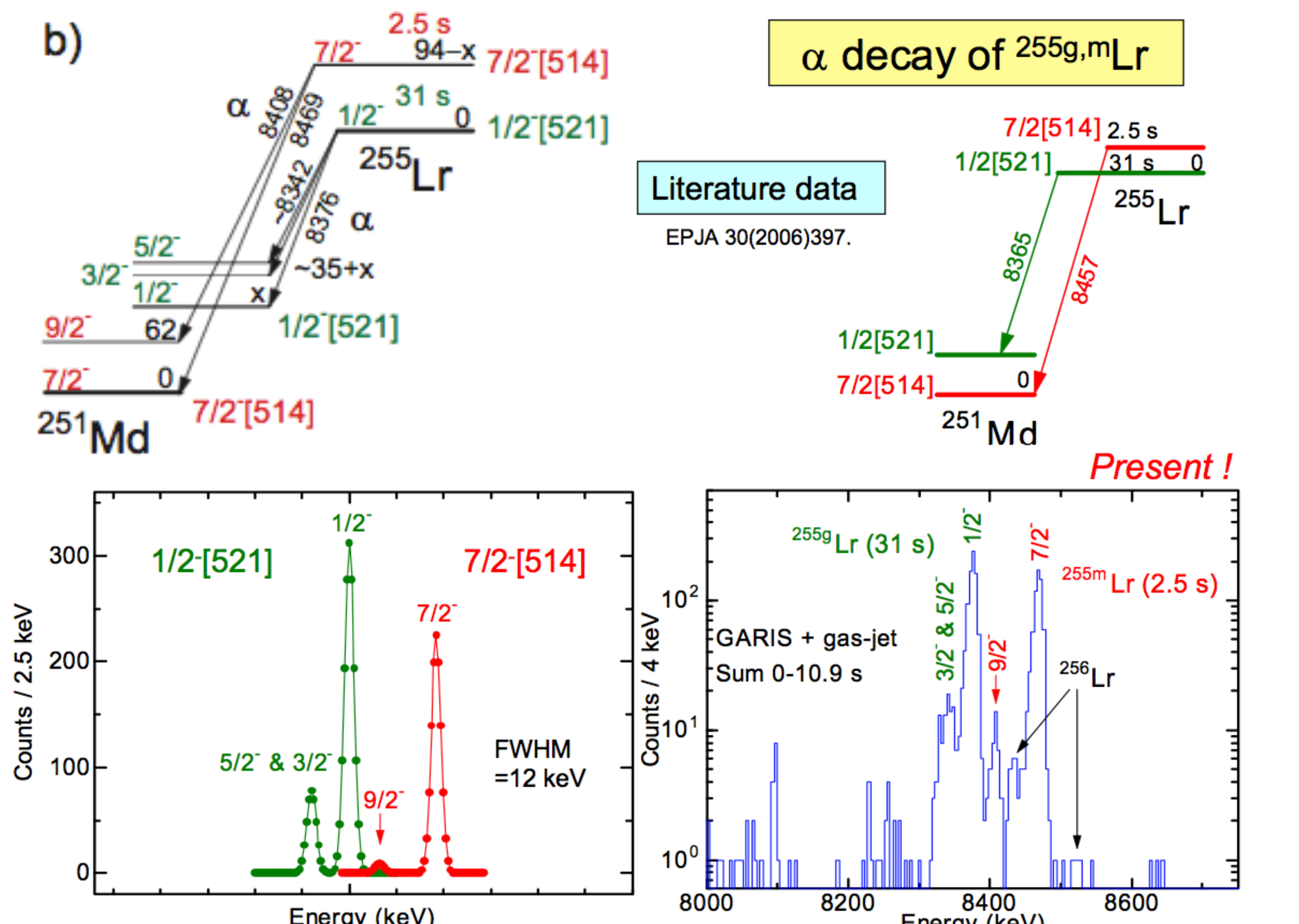


- Rotational band energies
- α intensities

→ Single-particle configuration

α energy resolution ~ 10 keV

High-resolution α fine-structure spectroscopy



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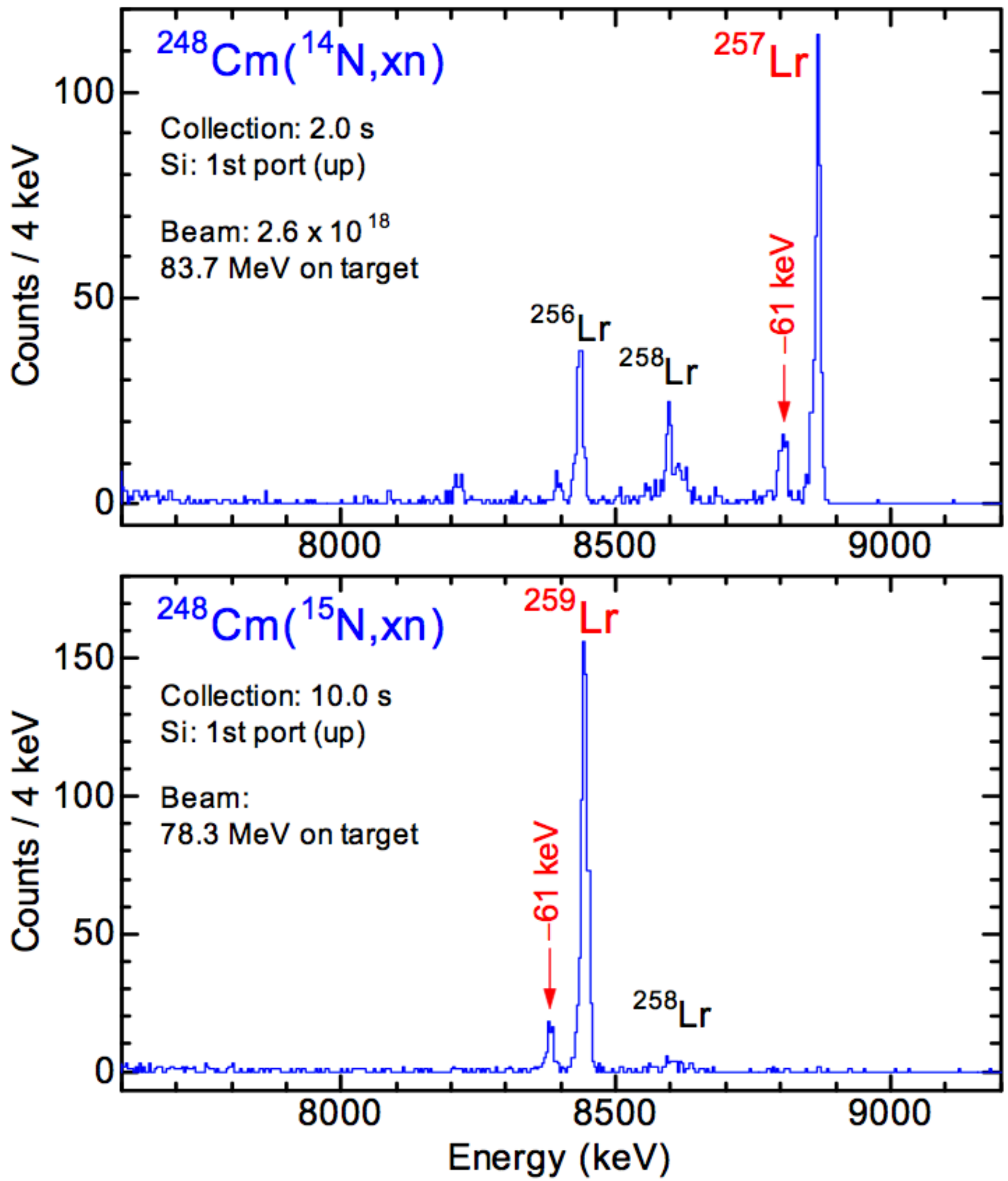
High-resolution α fine-structure spectroscopy



α decay of ^{257}Lr

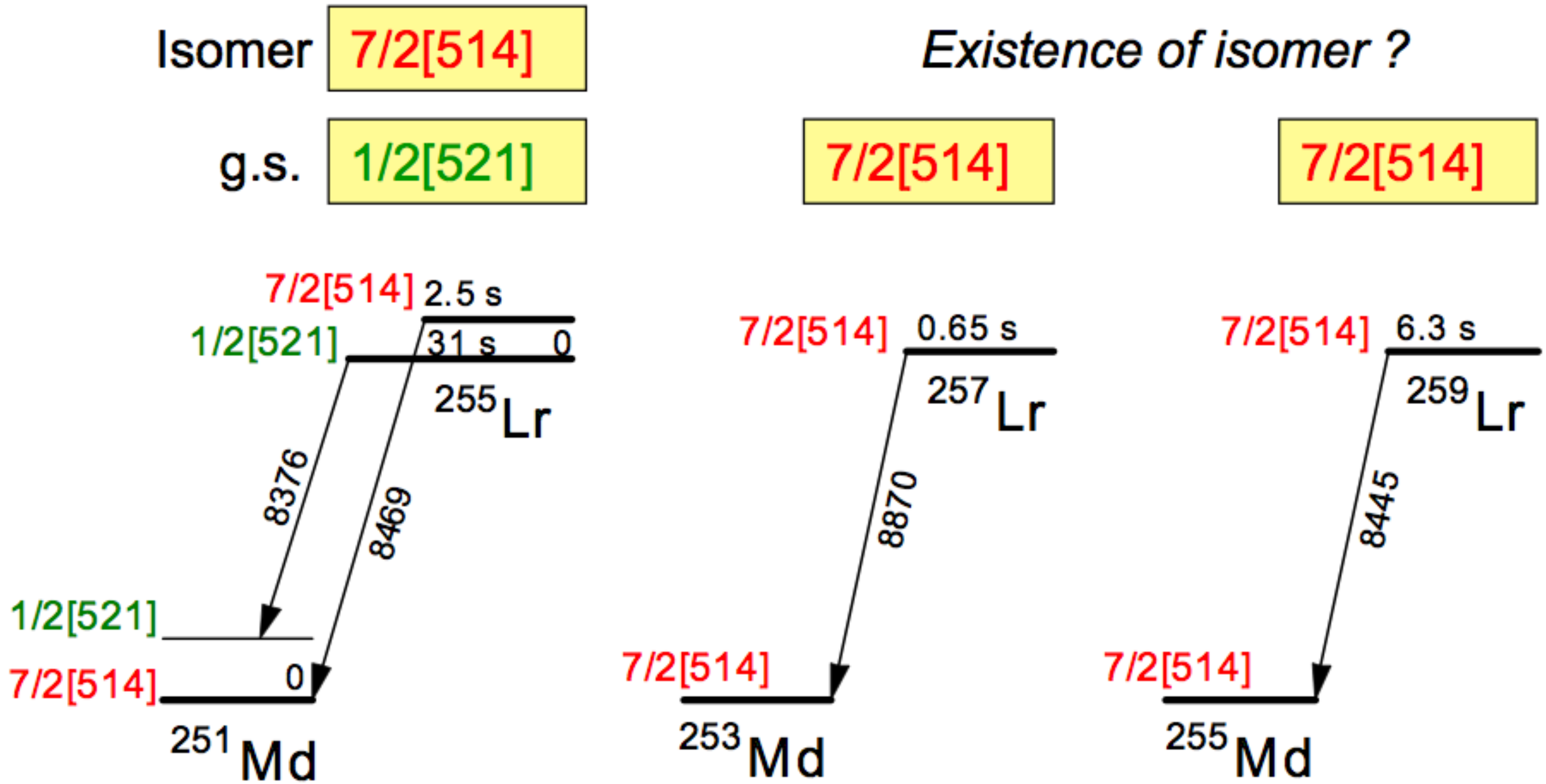
Energy difference of 61 keV is very consistent with the 7/2$^-$[514] assignment,

α decay of ^{259}Lr

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

M. Asai et al., JAEA, RIKEN

Proton single-particle configurations in Lr isotopes



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

M. Asai et al., JAEA, RIKEN

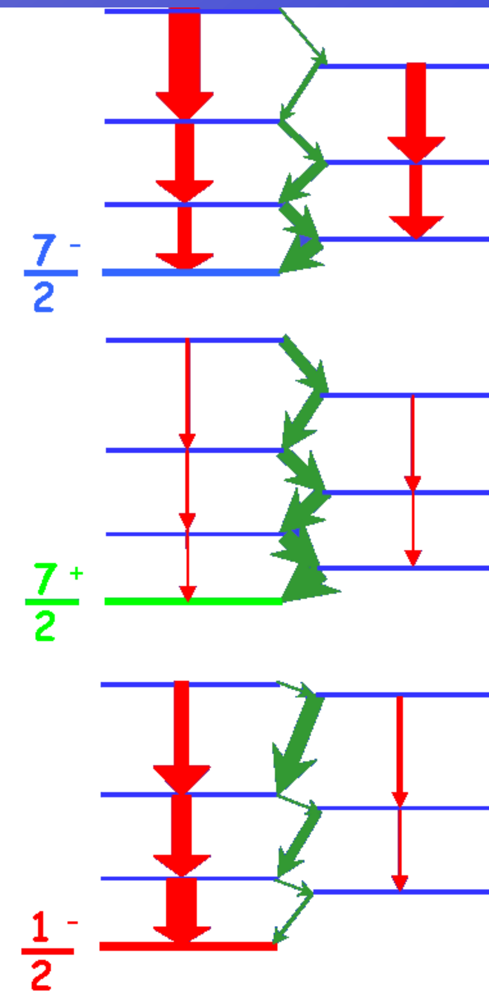
Electromagnetic properties from rotational band structures

- *Odd-proton orbitals in ^{251}Md*
- *B(M1)/B(E2) depends on $(g_k - g_R)/Q_0$*

[514] $\frac{7^-}{2}$ $g_K \sim 0.7$ Mainly E2

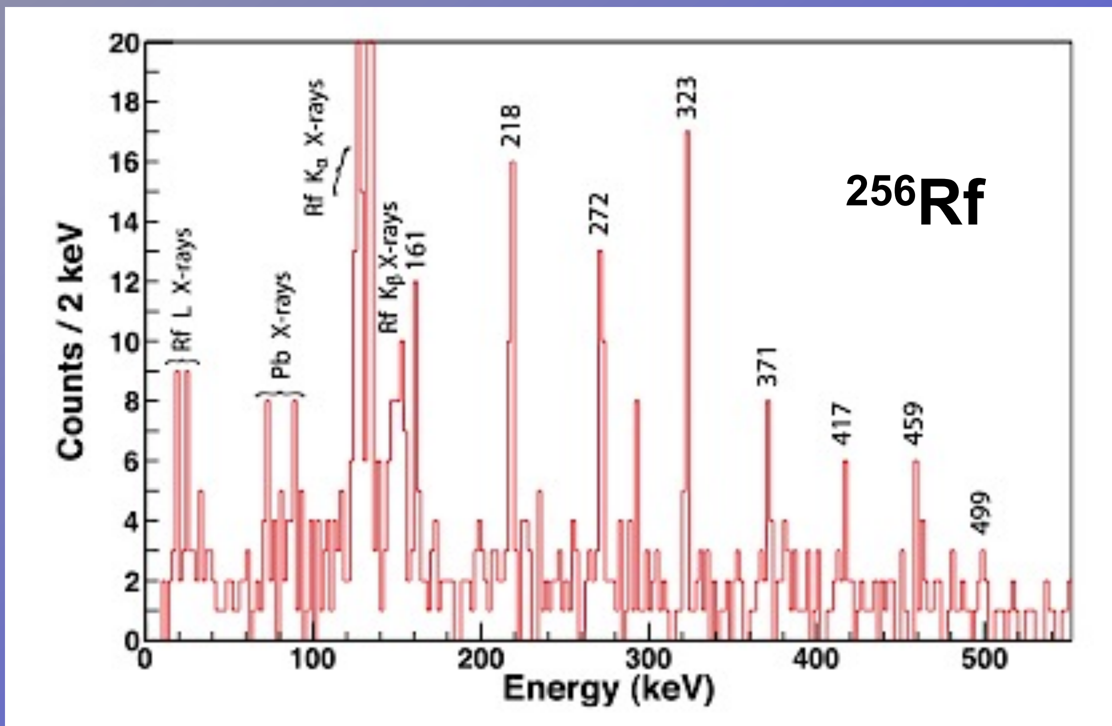
[633] $\frac{7^+}{2}$ $g_K \sim 1.3$ Mainly M1

[521] $\frac{1^-}{2}$ $a \sim 0.9$: $g_K \sim -0.55$ Mainly E2

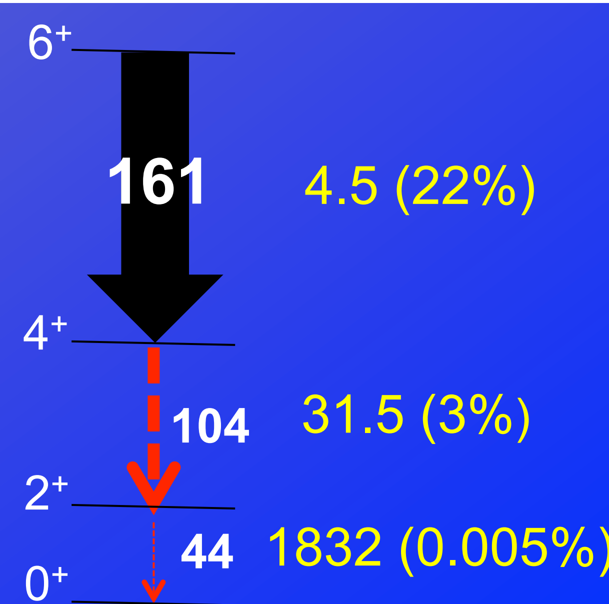


Why we need to measure conversion electrons?

Eγ (keV)	Transition assignment	Relative intensity (%)
44±1	$(2^+ \to 0^+)$	
104±1	$(4^+ \to 2^+)$	
161±1	$(6^+ \to 4^+)$	100 ± 30
218±1	$(8^+ \to 6^+)$	80 ± 20
272±1	$(10^+ \to 8^+)$	53 ± 12
323±1	$(12^+ \to 10^+)$	49 ± 11
371±1	$(14^+ \to 12^+)$	22 ± 8
417±2	$(16^+ \to 14^+)$	20 ± 7
459±2	$(18^+ \to 16^+)$	18 ± 7
499±2	$(20^+ \to 18^+)$	16 ± 7



P. Greenlees et al., Phys. Rev. Lett. 109, 012501 (2012)

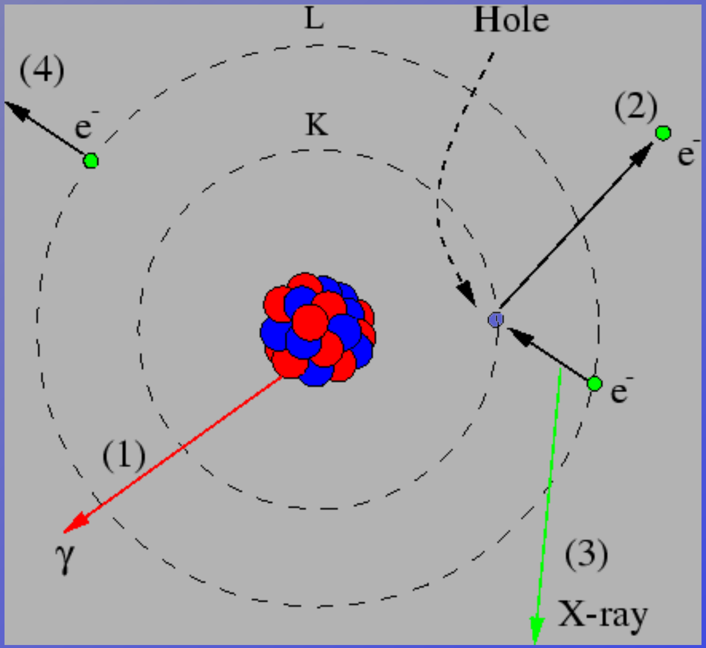


$$\alpha \propto \frac{Z^3}{E^*} \qquad \alpha = \frac{N_e}{N_\gamma}$$

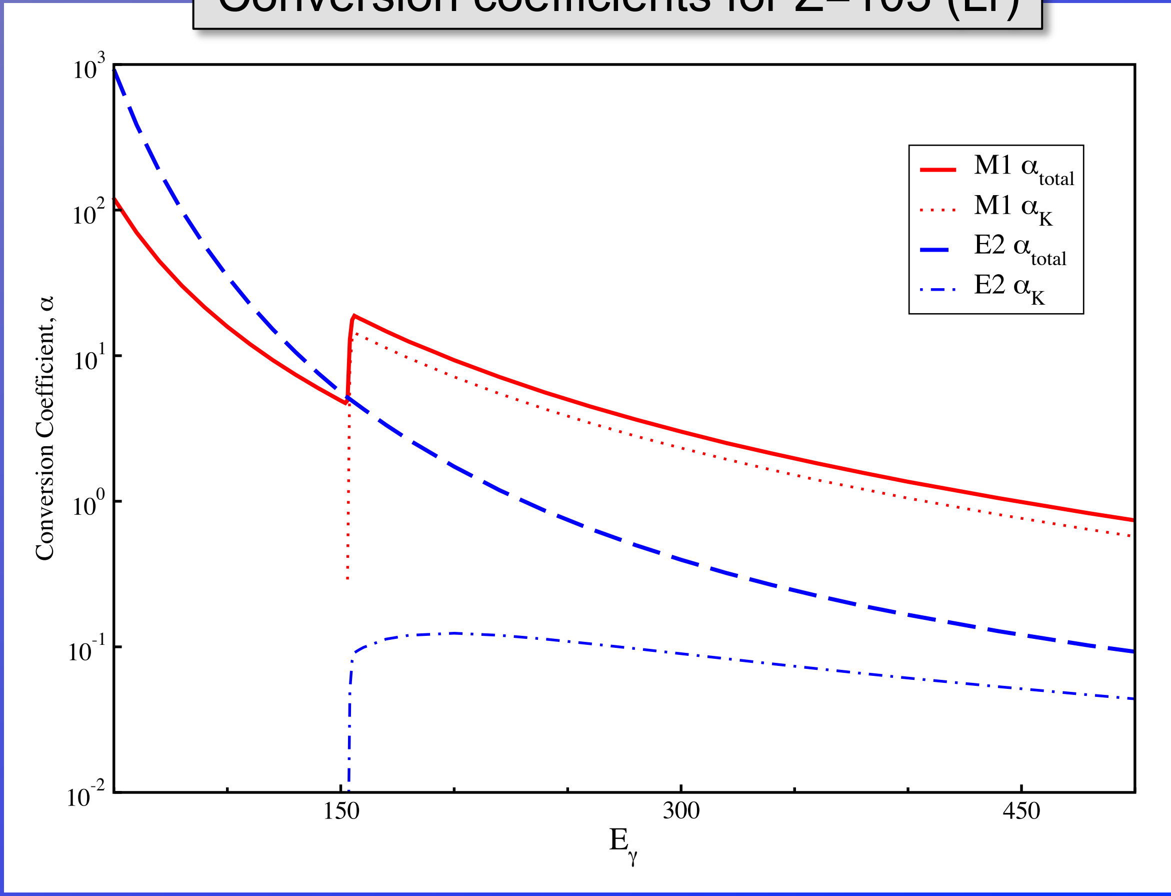
Internal conversion

- $\alpha_{tot} = N_\gamma/N_e = \alpha_k + \alpha_L + \ldots$
- *α increases strongly with multipolarity*
- *α larger for magnetic transitions*

$$\alpha \propto \frac{Z^3}{E^*}$$

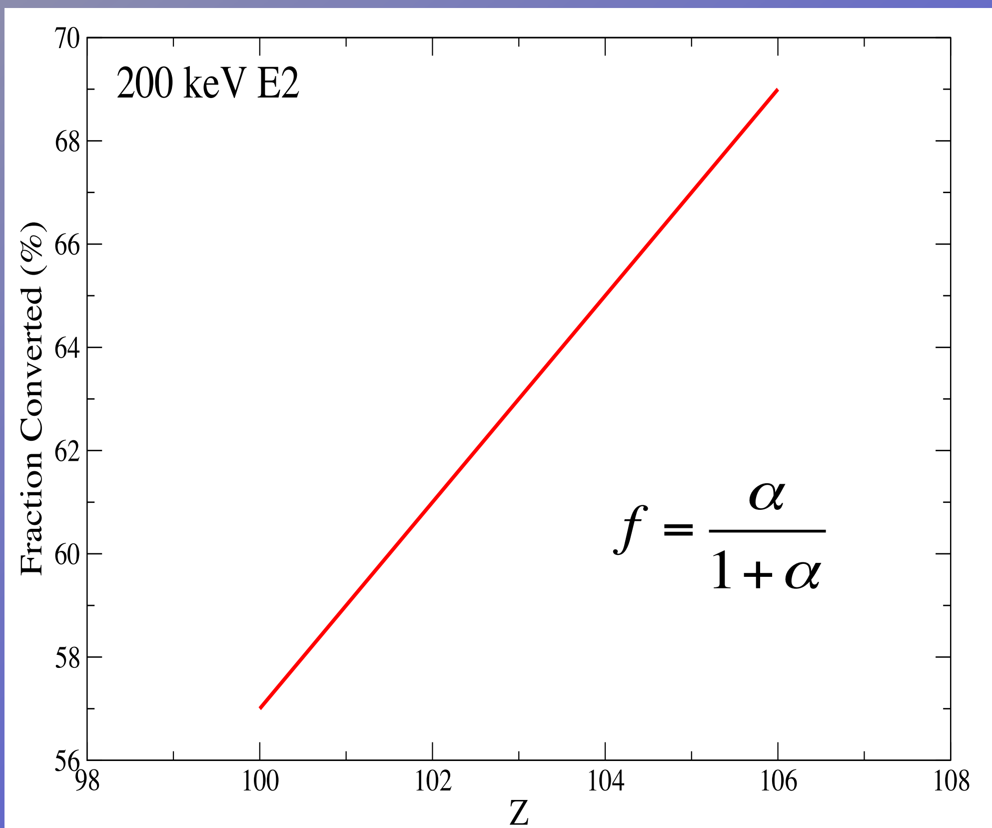


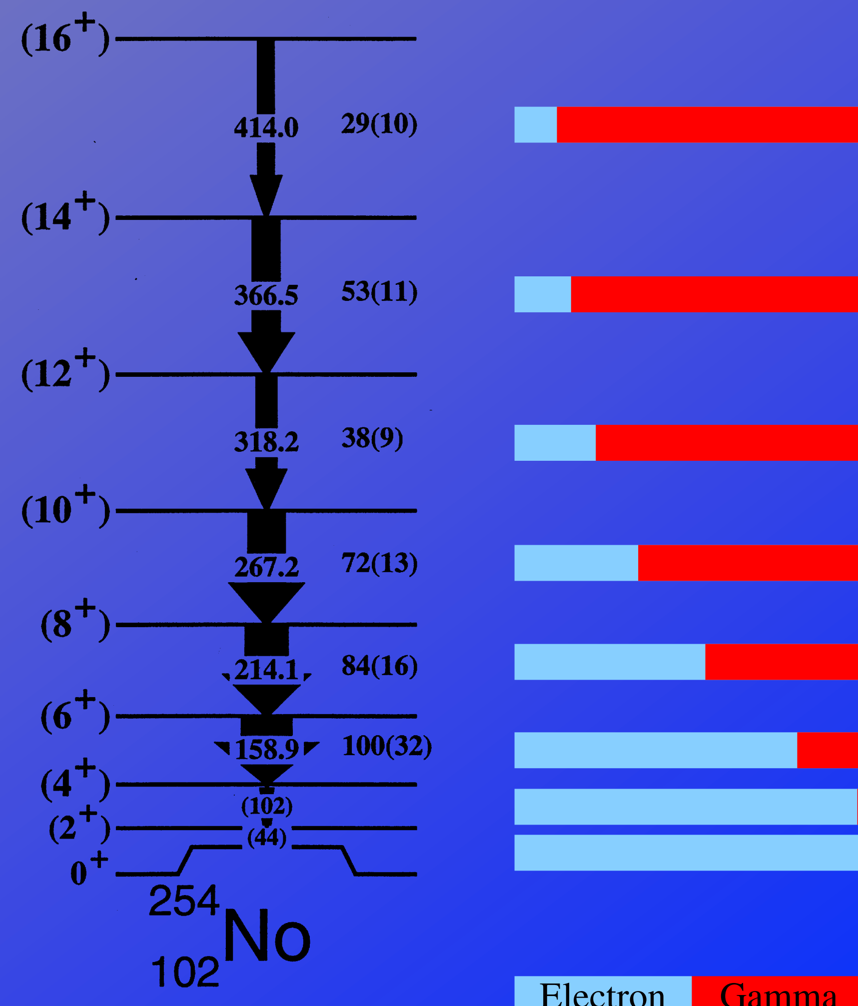
Conversion coefficients for Z=103 (Lr)



Internal conversion

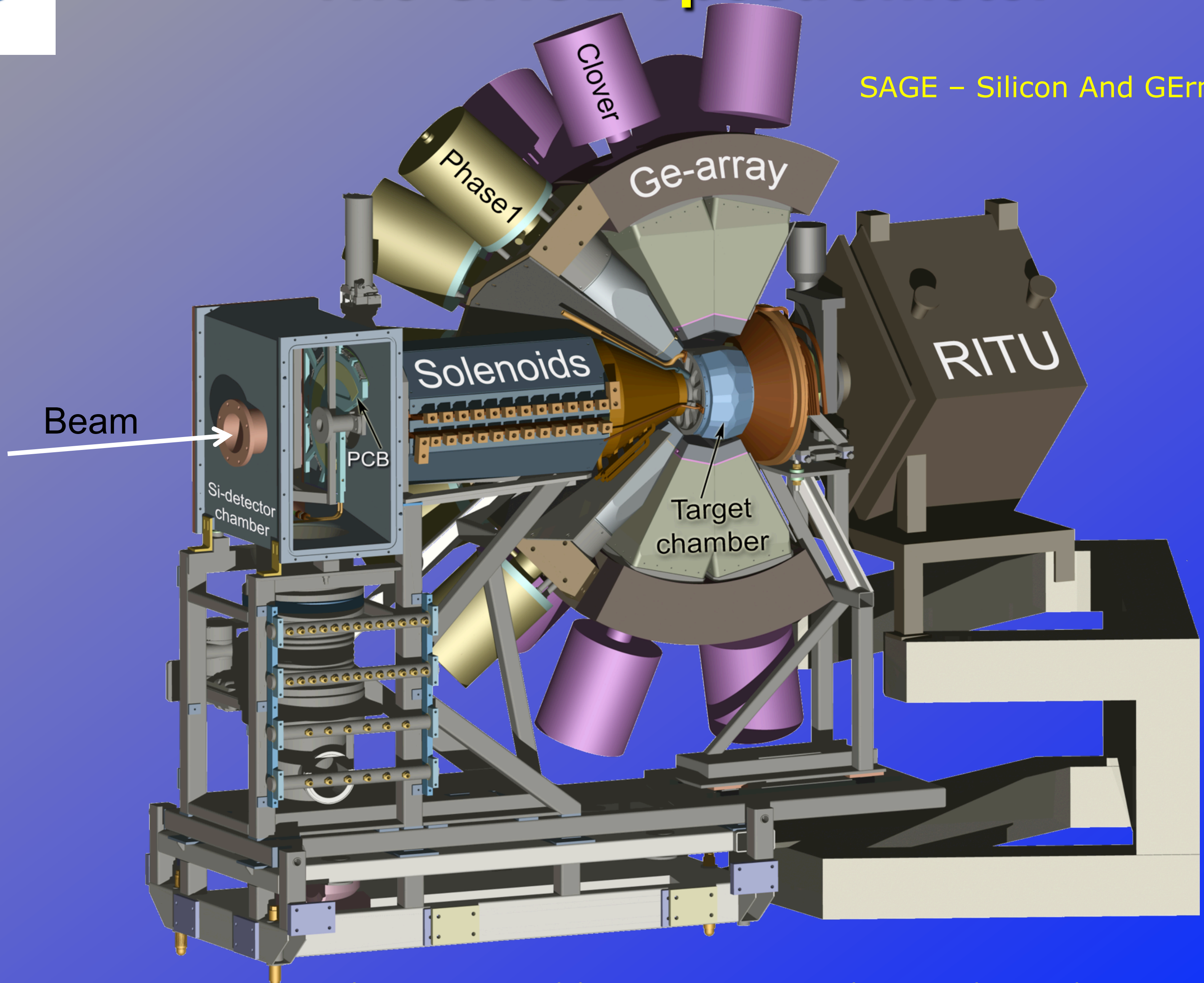
Fraction of 200 keV E2 converted





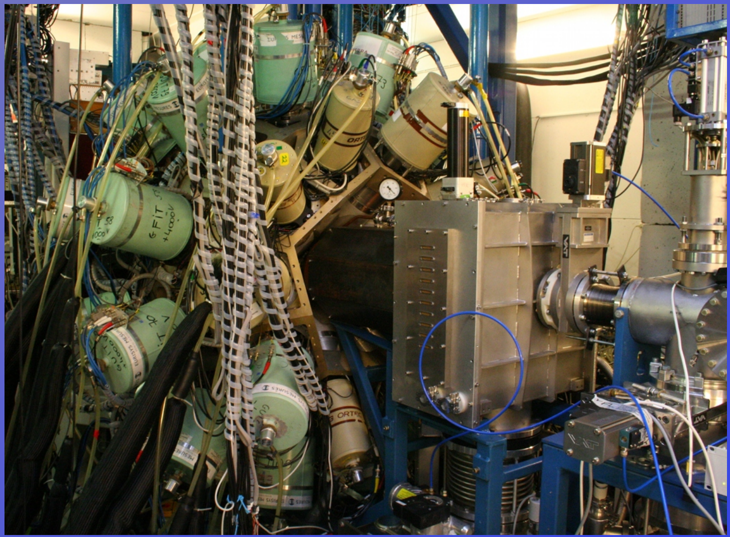
The SAGE spectrometer

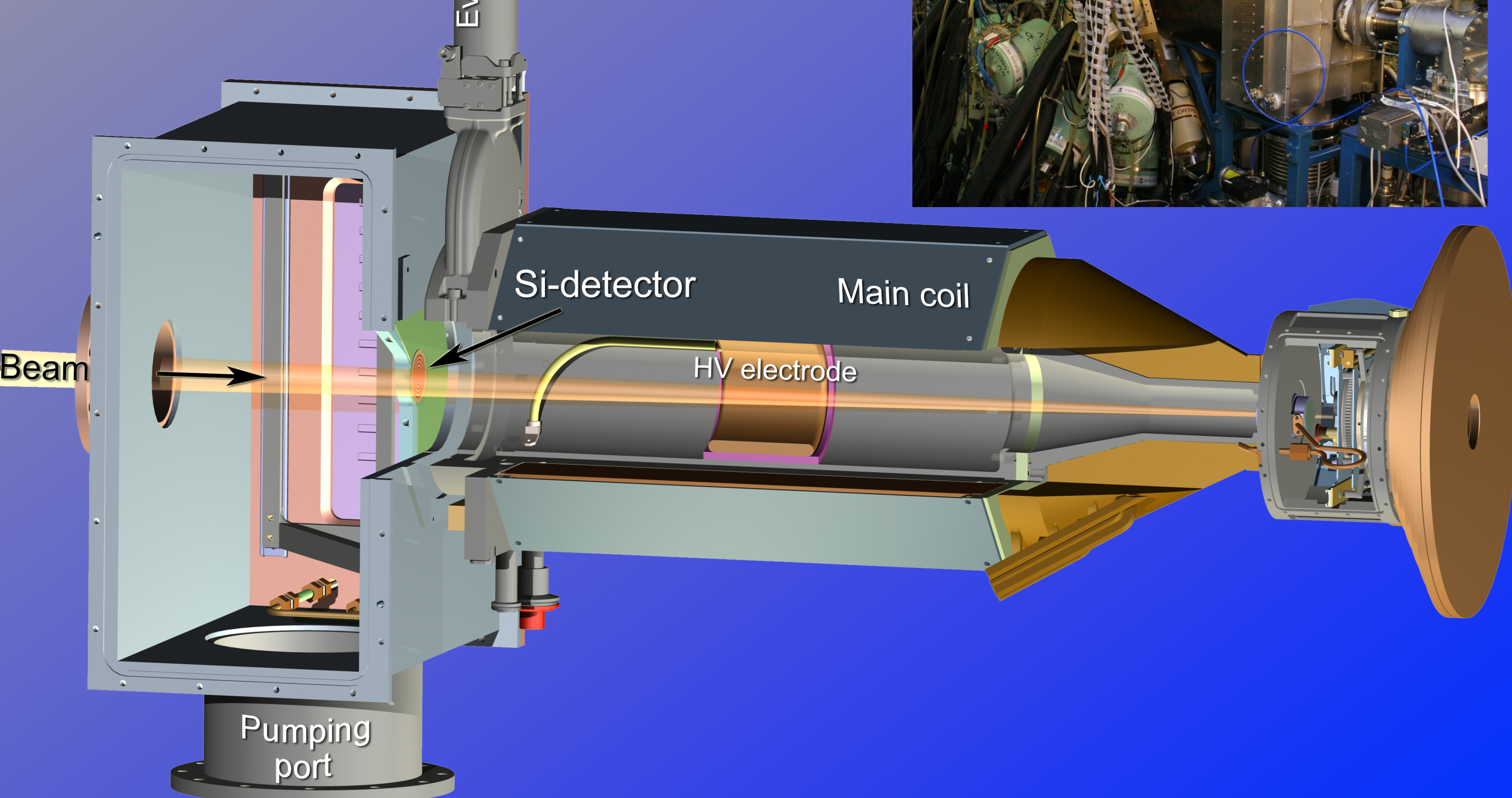
SAGE – Silicon And GErmanium



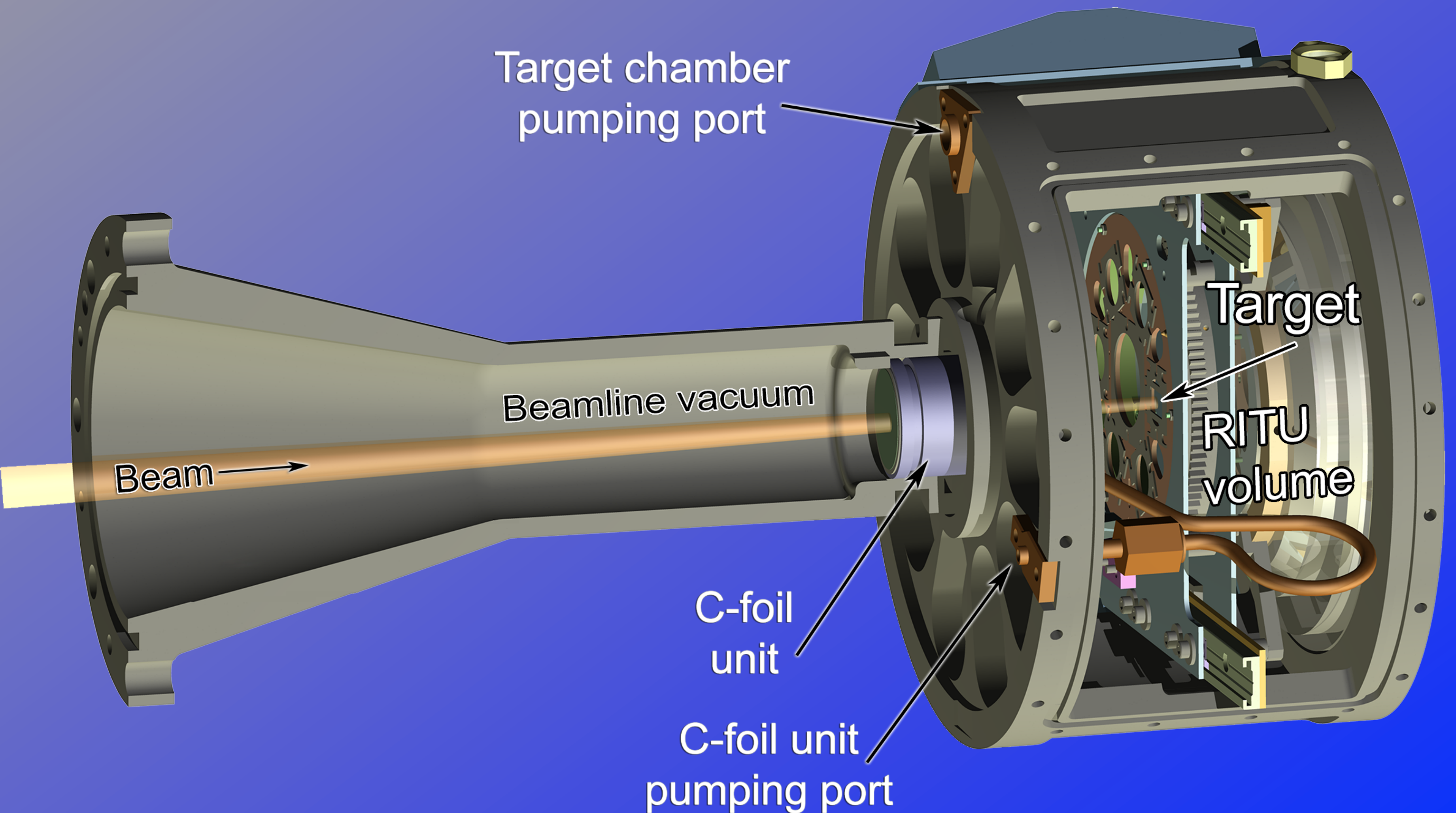
J. Pakarinen, P. Papadakis, J. Sorri, R.D. Herzberg, *et al.*, Eur. Phys. J. A 50 (53) 2014

SAGE

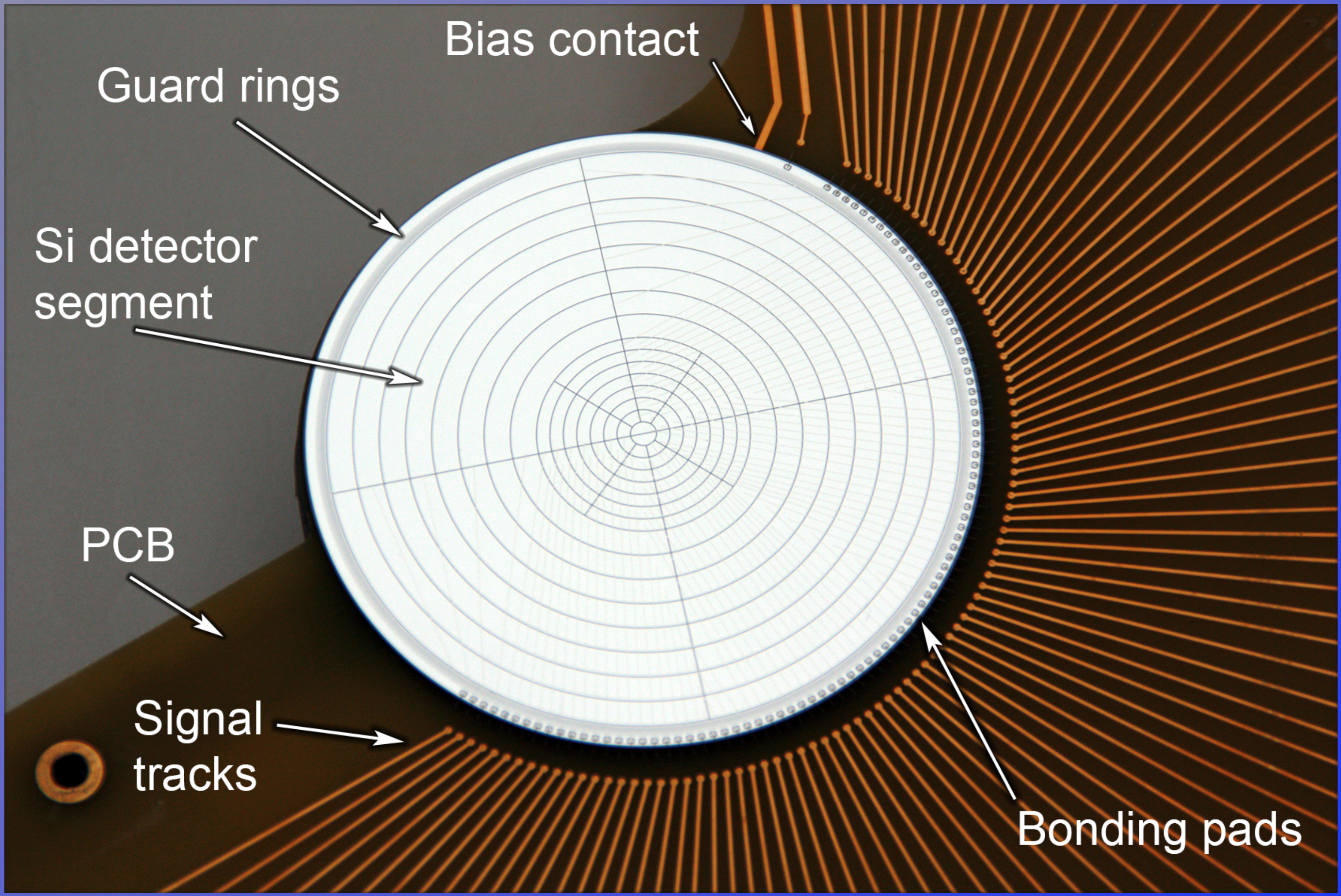



Evacuation valve
Si-detector
Main coil
Beam
HV electrode
Pumping port

SAGE


Target chamber
pumping port
Beamline vacuum
Beam
Target
RITU
volume
C-foil
unit
C-foil unit
pumping port

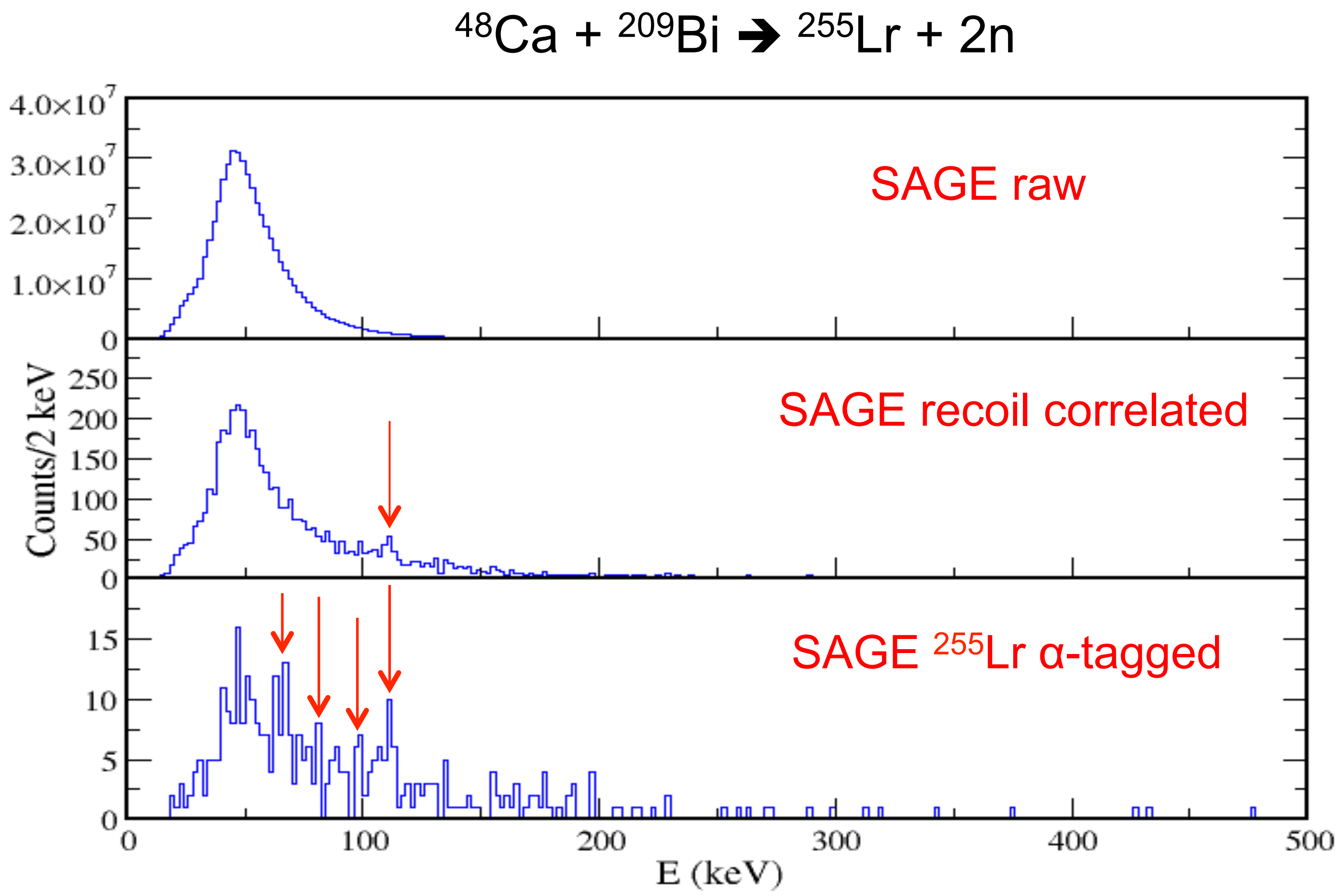
SAGE silicon detector



Consists of 90 active pixels

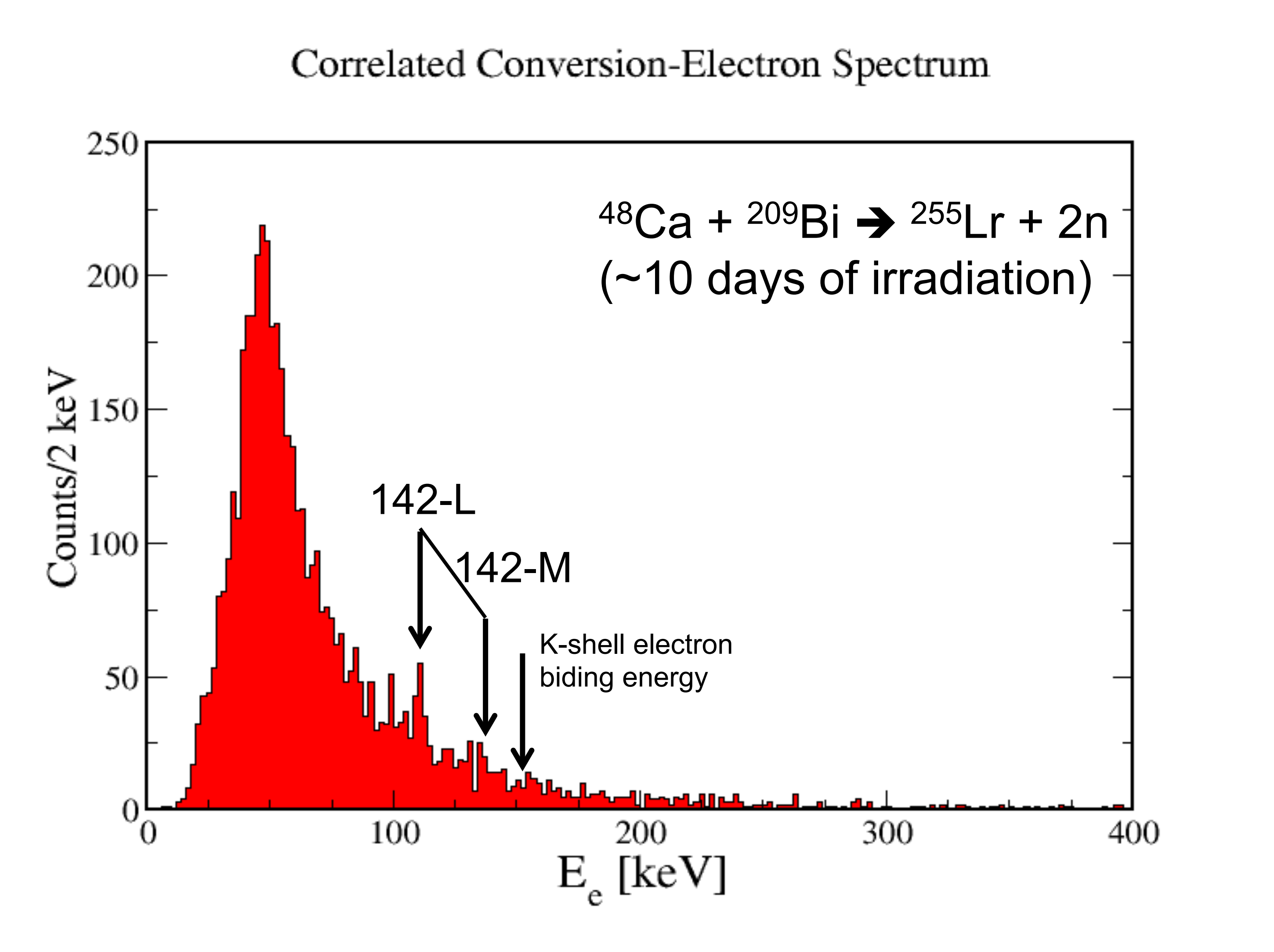
1 mm thick, 50 mm wide

Prompt conversion electron spectra



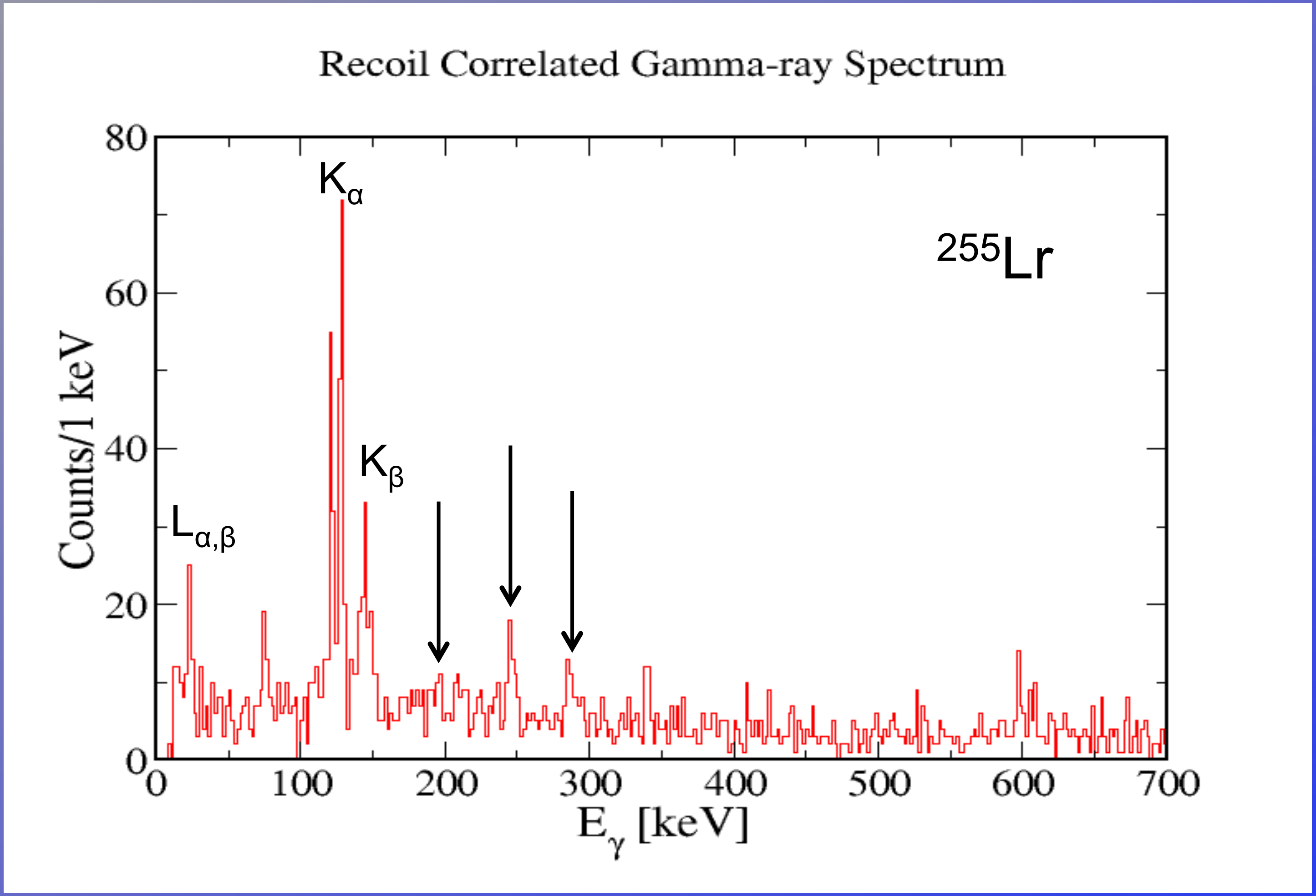
A tag necessary for distinguishing any features in the spectrum

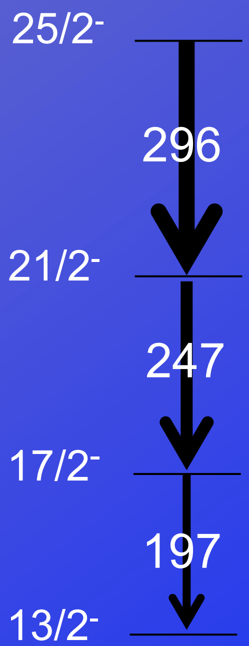
Singles electron spectrum



The recoil gated electron spectrum is sufficiently clean

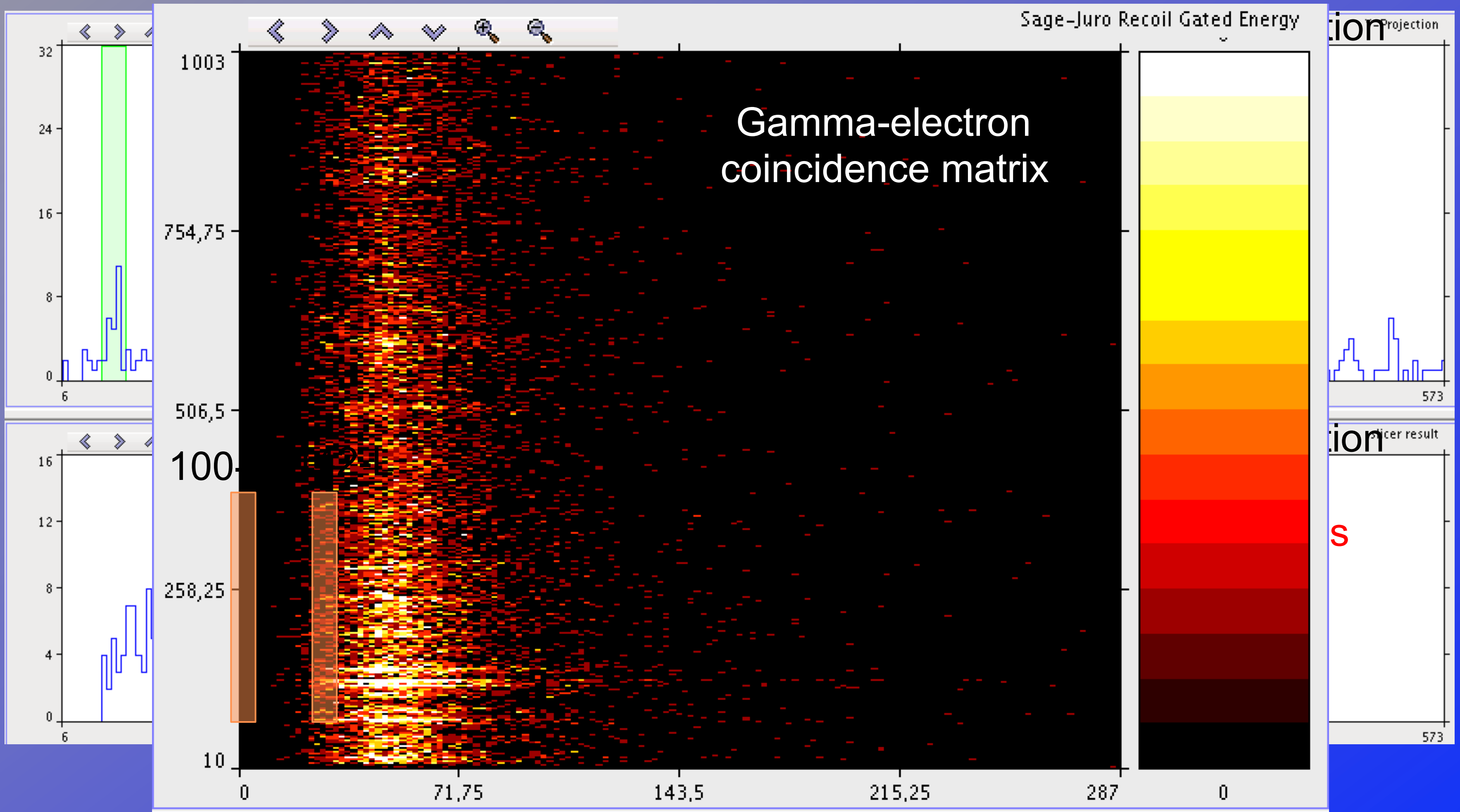
Singles gamma-ray spectrum





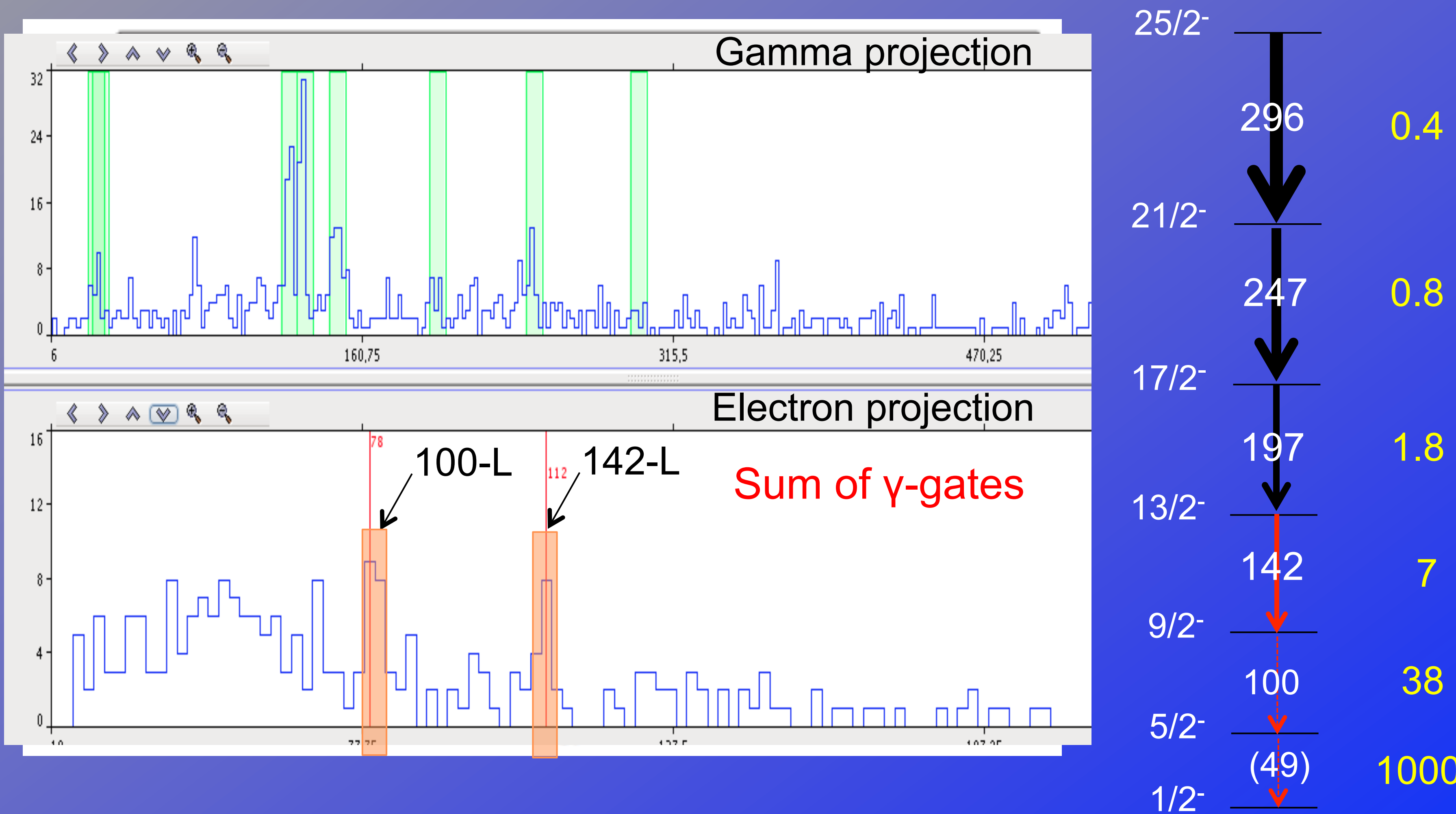
Transitions are visible from the favoured signature band built upon the 1/2⁻ ground state, i.e. the ½⁻[521] orbital

Gamma-electron coincidences



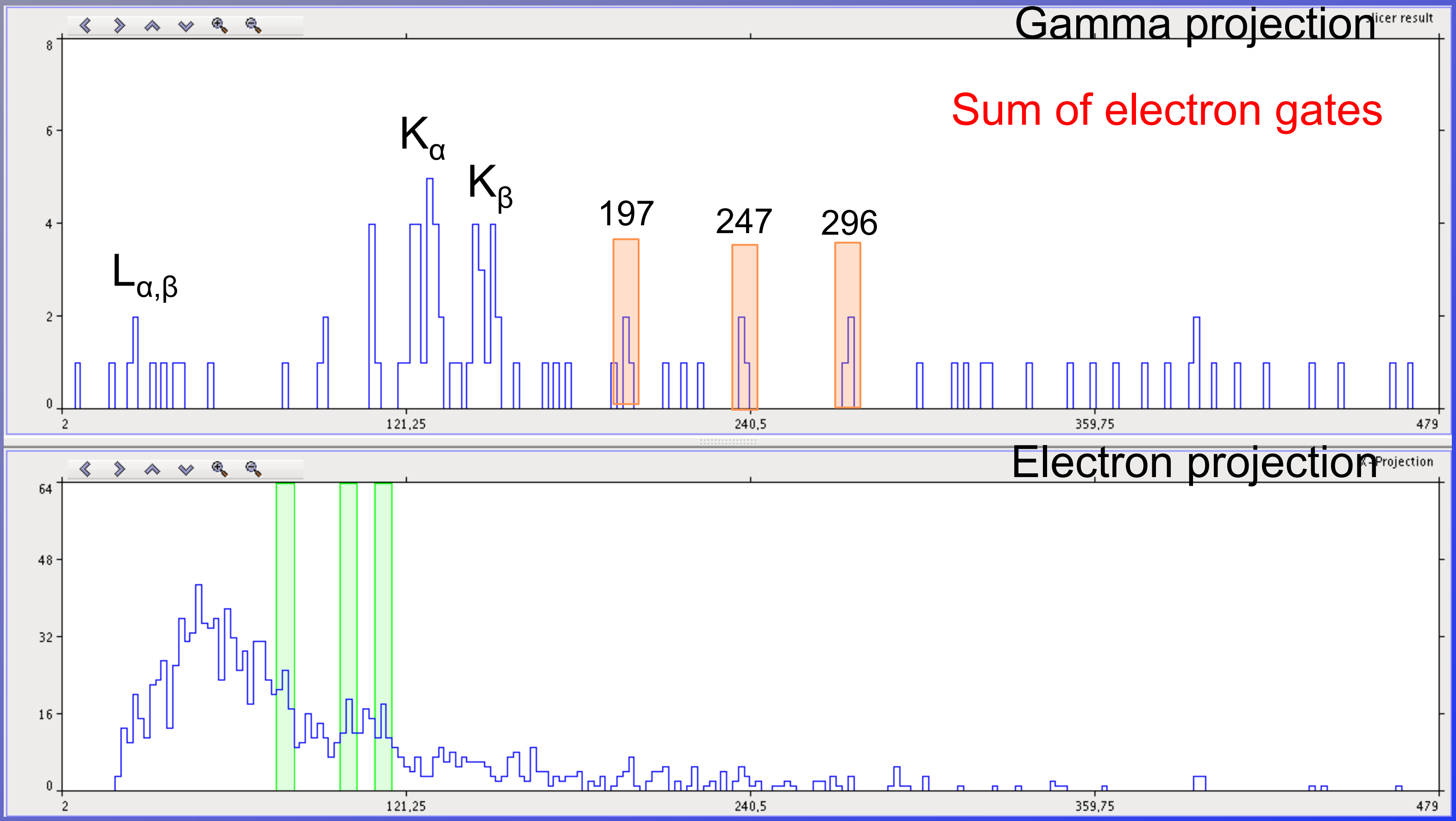
With the gamma-electron coincidences the low-lying members of the gs band can be elucidated

Gamma-electron coincidences in ^{255}Lr



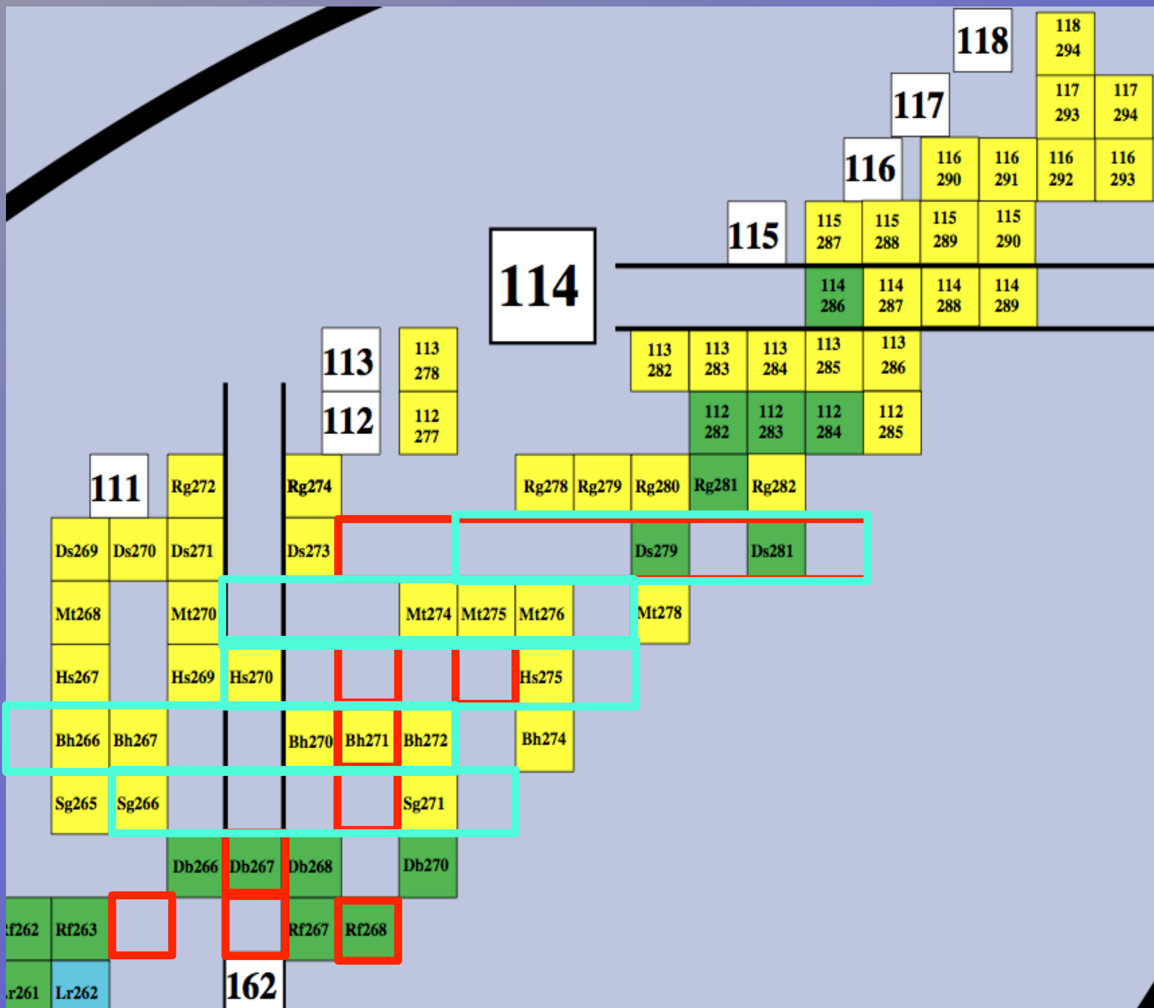
Are essential!

Electron-gamma coincidences



Prompt in-beam conversion-electron and gamma-ray spectroscopy is possible down to ~250 nb level!

Possibilities with RIBs



Around N=152/162

$^{90-94}Kr + {}^{164}Dy \rightarrow {}^{254-258}No^*$

$^{90-94}Kr + {}^{160}Gd \rightarrow {}^{250-254}Fm^*$

$^{132}Sn + {}^{137}Cs \rightarrow {}^{267}Db^*$

$^{132}Sn + {}^{132,134,136}Xe \rightarrow {}^{264,266,268}Rf^*$

$^{132}Sn + {}^{138}Ba \rightarrow {}^{270}Sg^*$

$^{132}Sn + {}^{139}La \rightarrow {}^{271}Bh^*$

$^{132}Sn + {}^{140,142}Ce \rightarrow {}^{272,274}Hs^*$

$^{132}Sn + {}^{142-150}Nd \rightarrow {}^{274-282}Ds^*$

$^{90-96}Kr + {}^{181}Ta \rightarrow {}^{271-277}Mt^*$

$^{90-96}Kr + {}^{186}W \rightarrow {}^{276-282}Ds^*$

$^{90-96}Kr + {}^{180}Hf \rightarrow {}^{270-276}Hs^*$

$^{90-96}Kr + {}^{175,176}Lu \rightarrow {}^{265-272}Bh^*$

$^{90-96}Kr + {}^{176}Yb \rightarrow {}^{266-272}Sg^*$

Towards N=184?

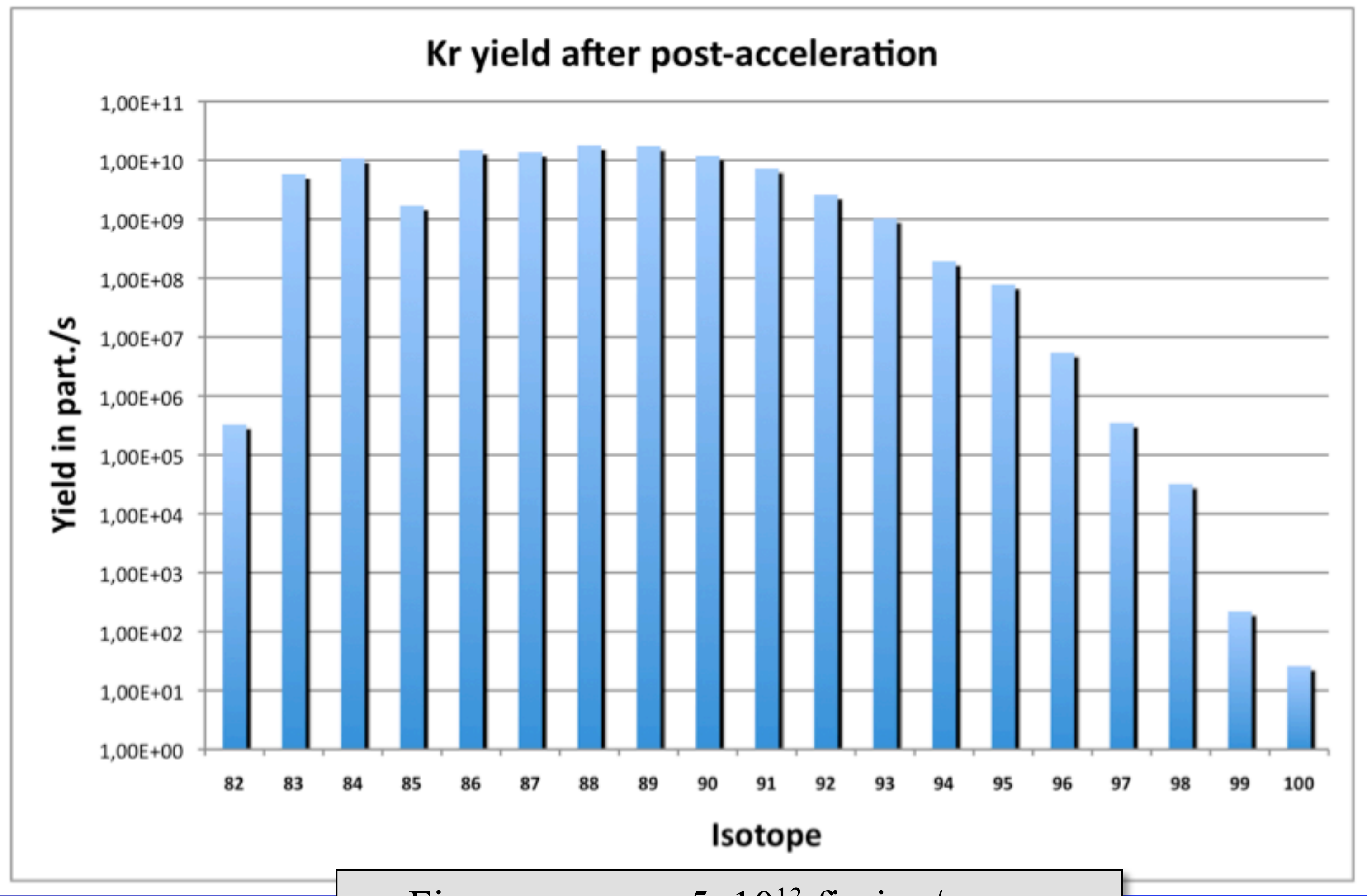
Difficult even with radioactive beams

$^{90-95}Kr + {}^{208}Pb \rightarrow {}^{298-303}118^*$

$^{132}Sn + {}^{170}Er \rightarrow {}^{302}118^*$

$^{132}Sn + {}^{176}Yb \rightarrow {}^{308}120^*$

SPIRAL2 predicted intensities



- Figure assumes 5×10^{13} fission/sec
- Phase2 Day1, 50 kW d beam: e.g. ^{92}Kr 6.2 MeV/u 2.6×10^{8} pps

EURISOL predicted intensities

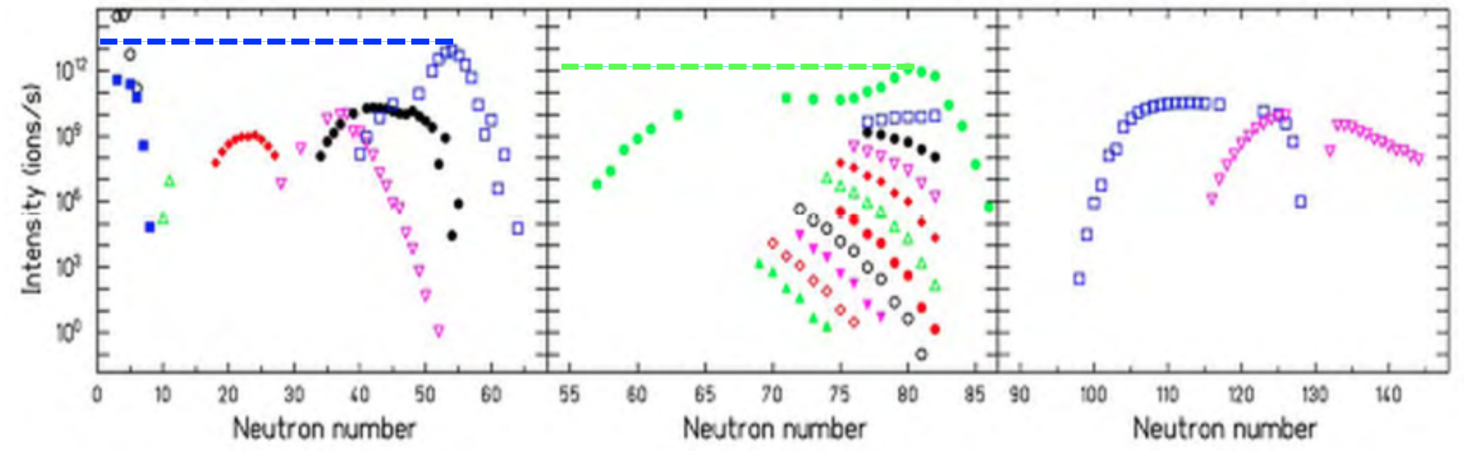


Fig. 13: Predicted EURISOL intensities of several nuclides:

Left: *Be (black open dots),*
Li (blue filled squares),
Mg (open green triangles),
Ar (red filled rhomboids),
Ni (magenta open triangles),
Ga (black filled dots),
Kr (open blue squares);

Centre: *Zr (filled green triangles),*
Nb (open red diamonds),
Mo (magenta filled triangles),
Tc (black open dots),
Ru (red filled dots)
Rh (green open triangles),
Pd (red filled diamonds)
Ag (magenta open triangles)
Cd (filled black dots),
In (open blue squares),
Sn (green filled dots);

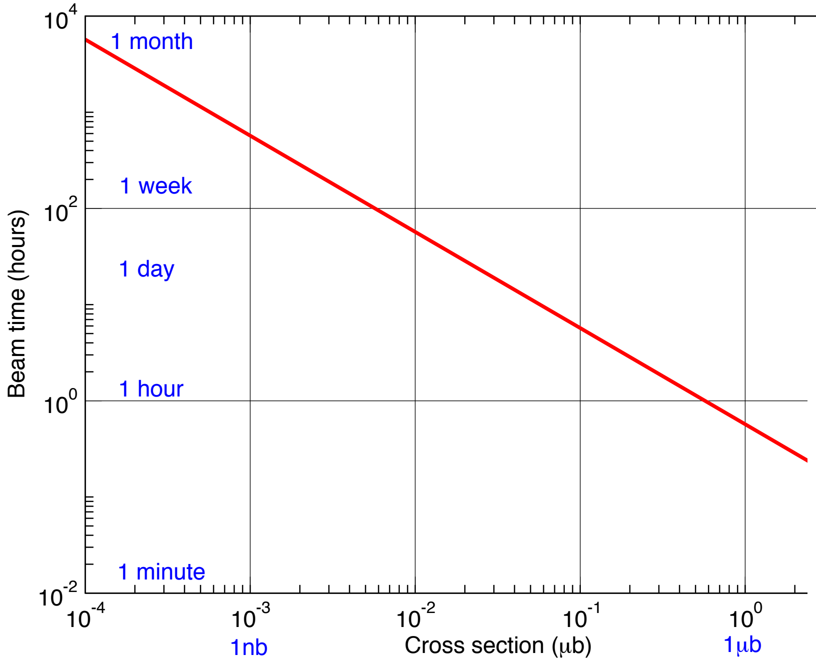
Right: *Hg (squares)*
Fr (triangles)

The Limits

Minimum requirement for in-beam studies

Beam time required to accumulate 10 full-energy alpha decays

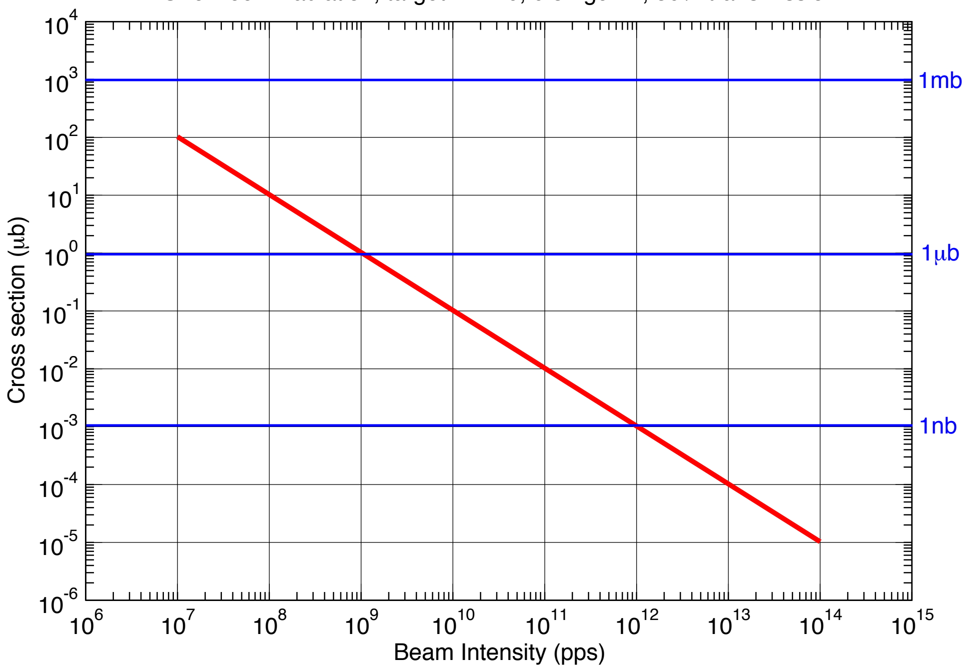
Target A=170, 0.5mgcm^{-2}, 50% transmission, $I_{beam}=10^{10}$pps



Minimum requirement for decay/ reaction mechanism studies

Cross section required to accumulate 300 full-energy alpha decays

One week irradiation, target A=170, 0.5mgcm^{-2}, 50% transmission

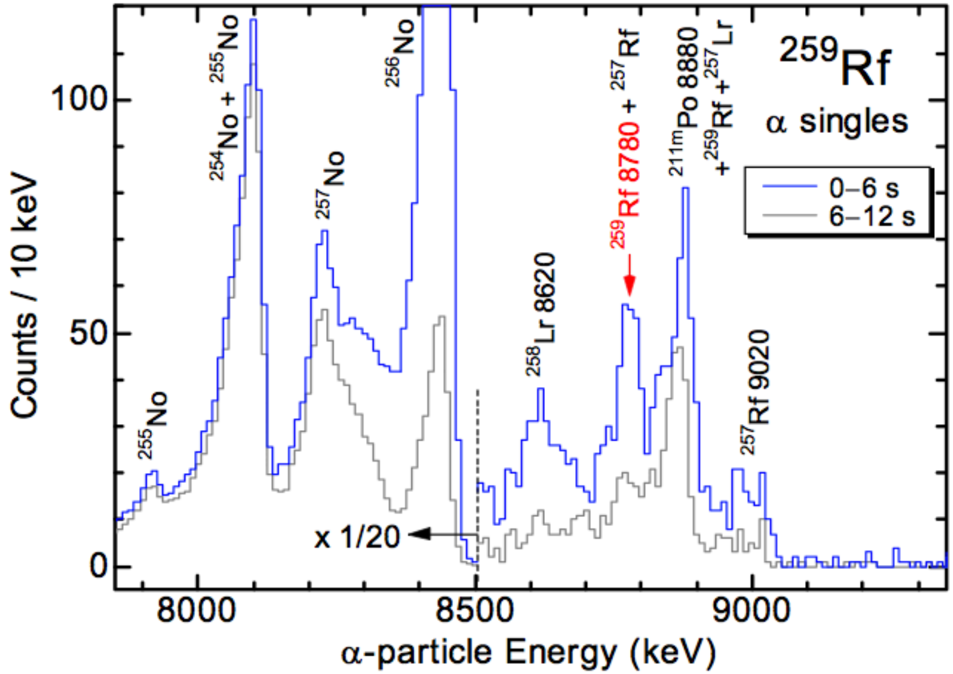


Summary

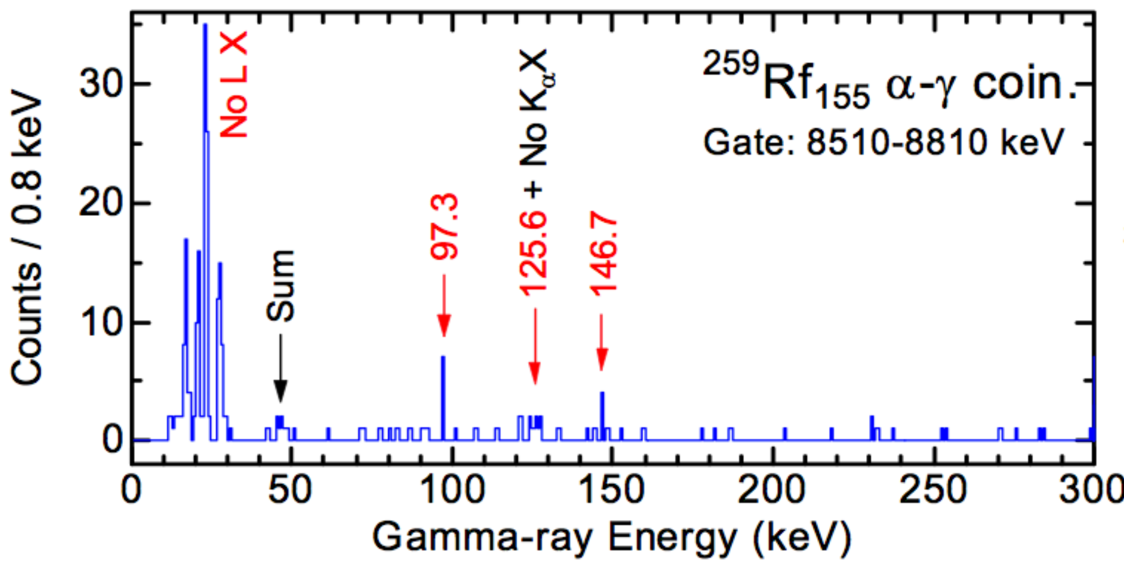
- Determination of single-particle orbital energy spacing is crucial for understanding the shell structure of SHN
- Prompt conversion-electron and gamma-ray coincidences are essential in order to unveil low-lying transitions in heavy nuclei
- A cross section of at least several hundreds of nb needed for prompt gamma-electron coincidence spectroscopy
- For spectroscopic studies on the region Z>108 and N=162-184 new technology is needed to obtain sufficient statistics within reasonable beam time

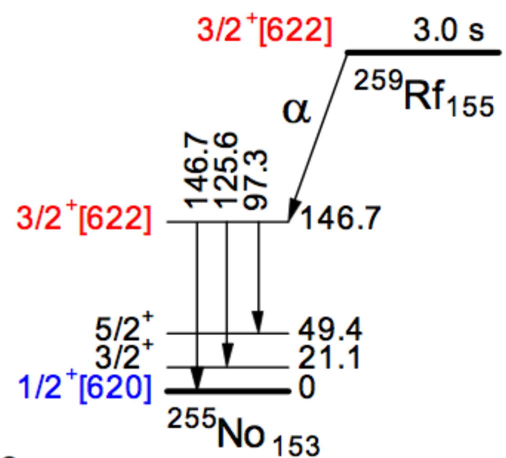
α-γ coincidence decay spectroscopy of ^{259}Rf

α-singles spectrum



α-γ coincidence spectrum





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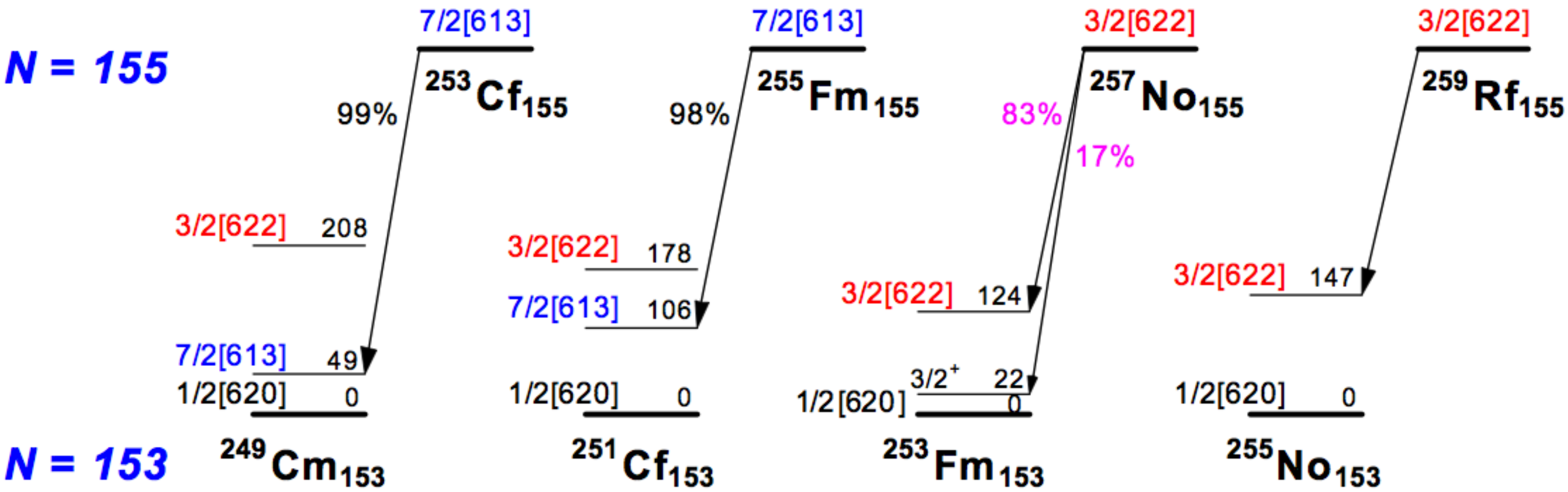
Single-particle N=153 systematics

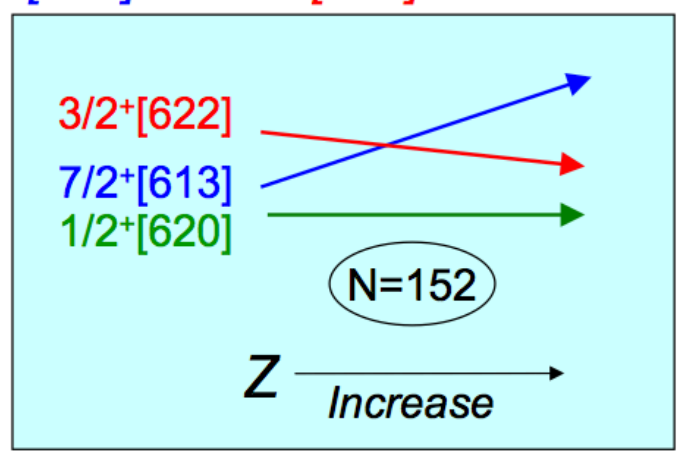
α decays of N=155 isotones and levels in N=153 daughters



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]



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Acknowledgements

SAGE

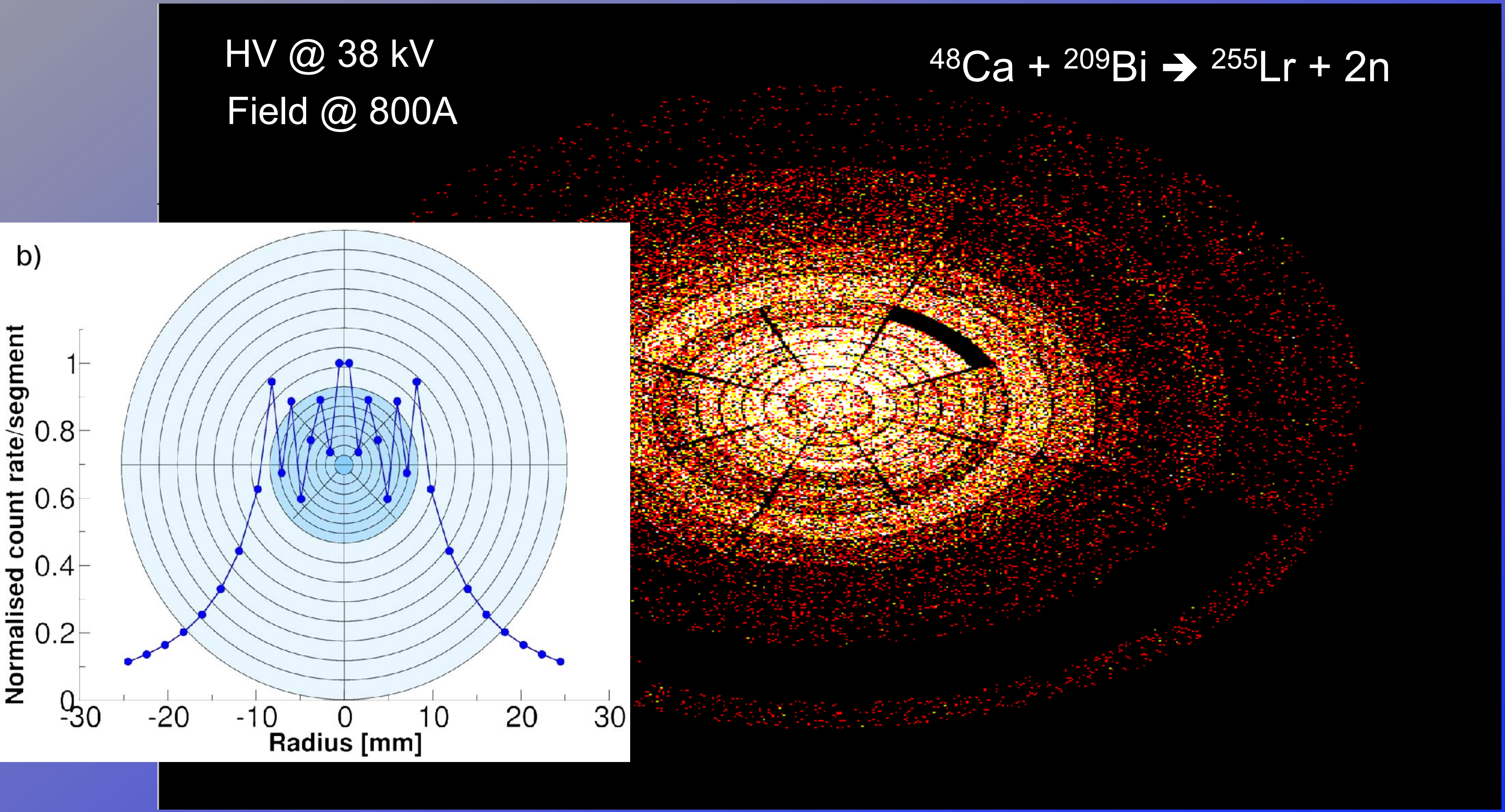
J. Pakarinen, P. Papadakis, J. Sorri , **R.-D. Herzberg**, **P.T. Greenlees**, P.A. Butler, P.J.Coleman-Smith, D.M. Cox, J.R. Cresswell, P. Jones, R. Julin, J. Konki, I.H. Lazarus, S.C. Letts, A. Mistry, R.D. Page, E. Parr, V.F.E. Pucknell, P. Rahkila, J. Sampson, M. Sandzelius, D.A. Seddon, J. Simpson, J. Thornhill, D. Wells

GAMMAPOOL

MATERIAL

K. Ranttila, J. Tuunanen, R.-D. Herzberg, P. Papadakis, J. Pakarinen, L.I. Pakarinen, S.K. Pakarinen

Conversion Electron Distribution



Central pixels are more exposed than outer ones, typical count rates are 25-35 kHz per pixel/channel