Spectroscopy of the Heaviest Elements

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Outline

Heavy Elements

- What are they
- Why are they interesting

Heavy Element Detection

Spectroscopy Techniques

- In-beam spectroscopy
- Decay spectroscopy
  - K-isomers
  - SHE spectroscopy

Question

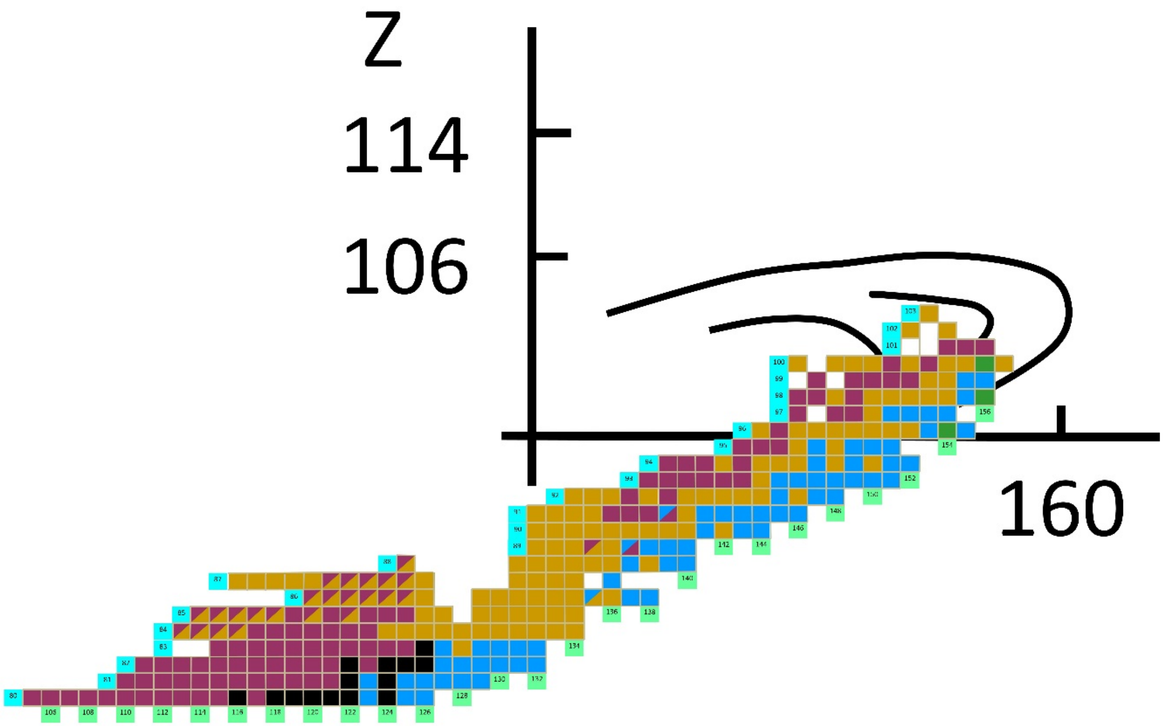
What is the atomic number of Flerovium?

a) 112
b) 114
c) 116
d) 118
e) 120

Upper End of Chart of Nuclides: 1966

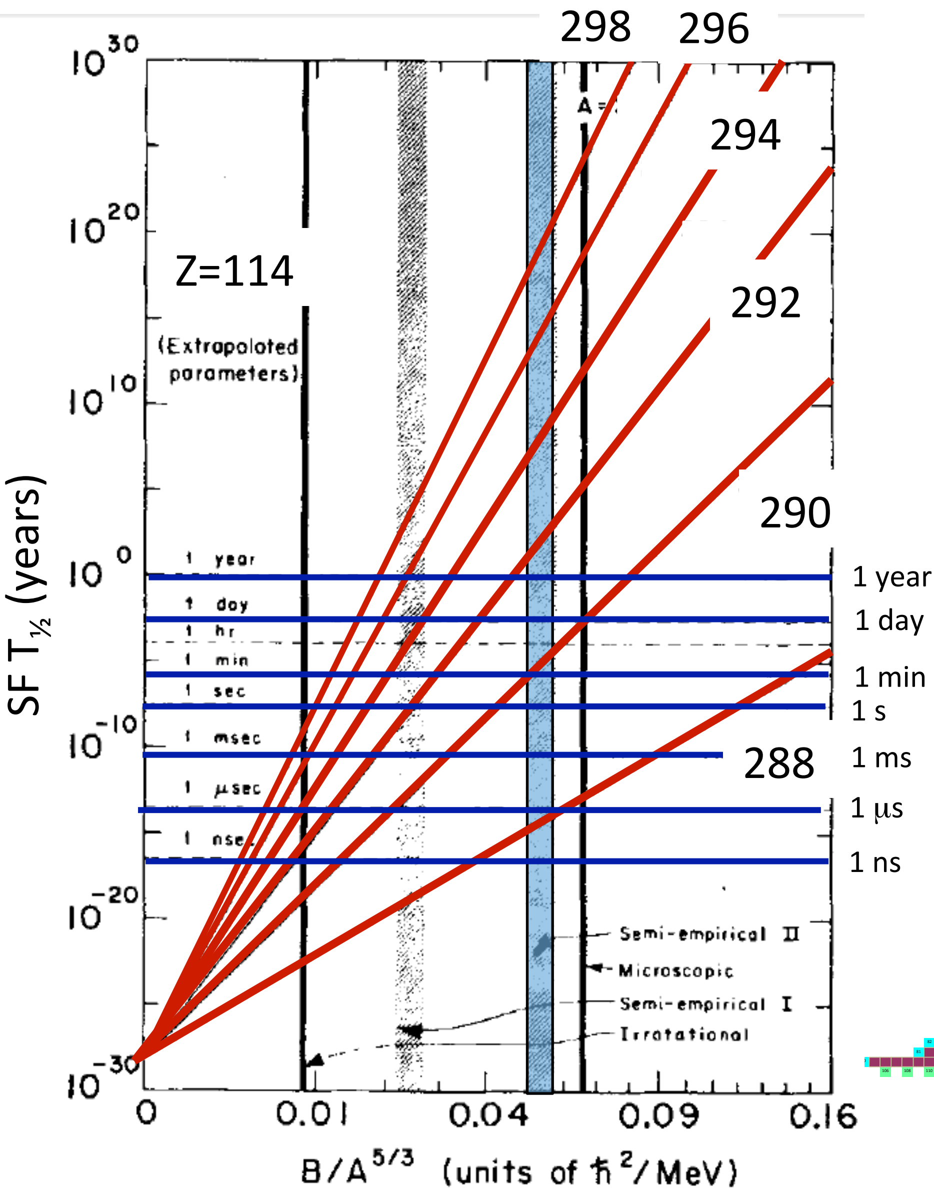
- Predictions without shell effects:

  Z=104 last element stable against SF



Myers and Swiatecki: Nucl. Phys. **81** (1966) 1
Patyk: Nucl. Phys. A **502** (1989) 591c

What about the lifetimes?



$^{288}114$: 100 ns

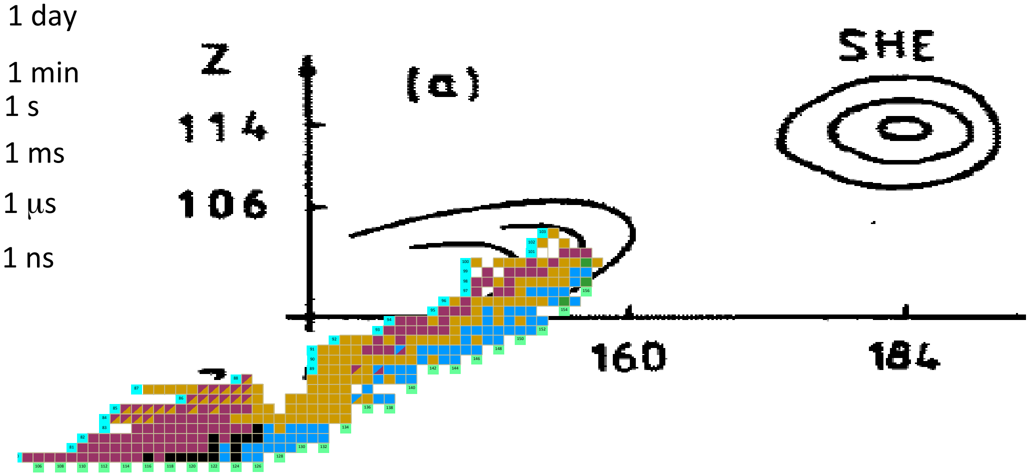
$^{290}114$: 1 min

$^{292}114$: 100 years

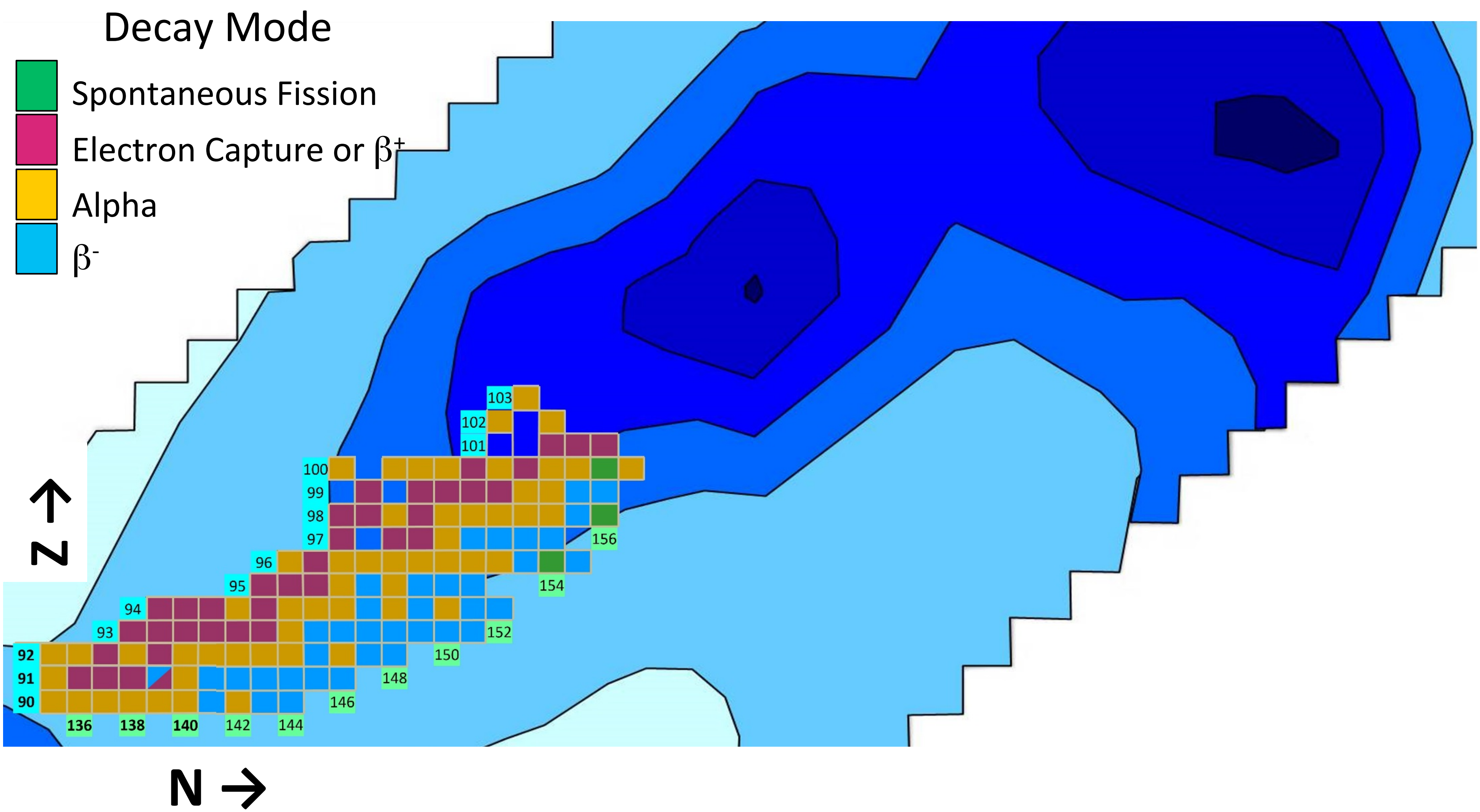
$^{294}114$: 10^8 years

$^{296}114$: 10^{14} years

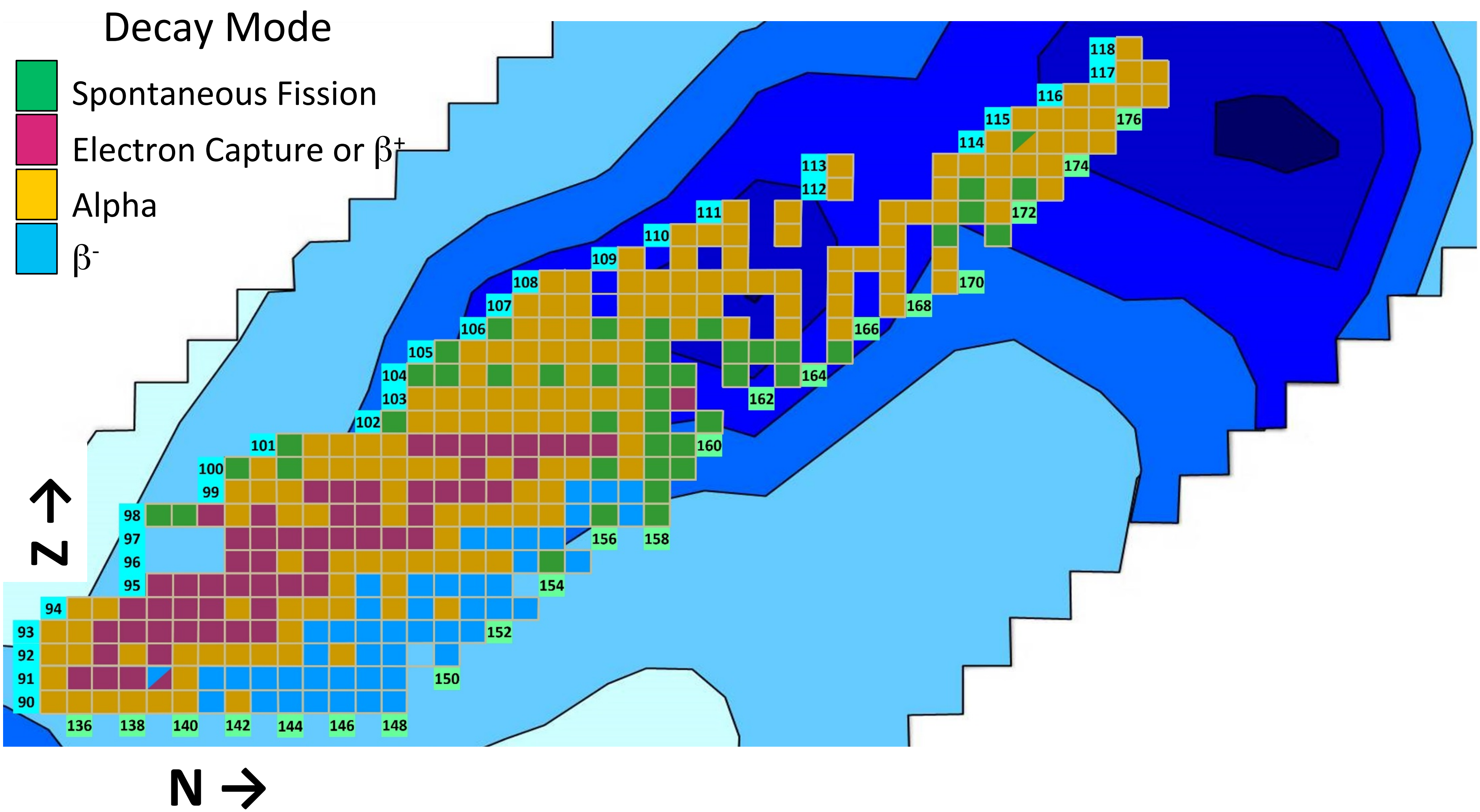
$^{298}114$: 10^{19} years



S.G. Nilsson et al. Nucl. Phys. A **115** (1968) 545
Patyk: Nucl. Phys. A **502** (1989) 591c



Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306



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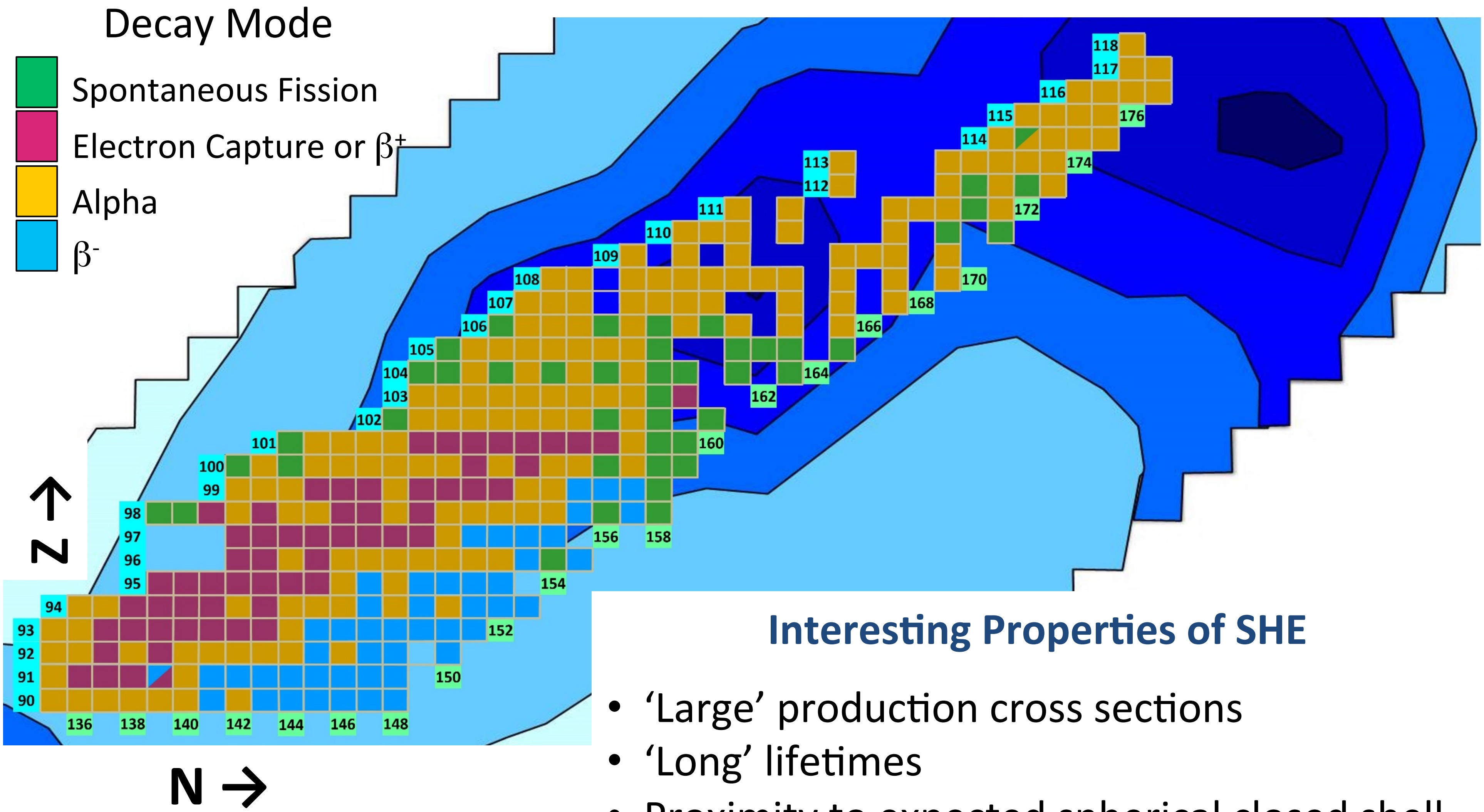
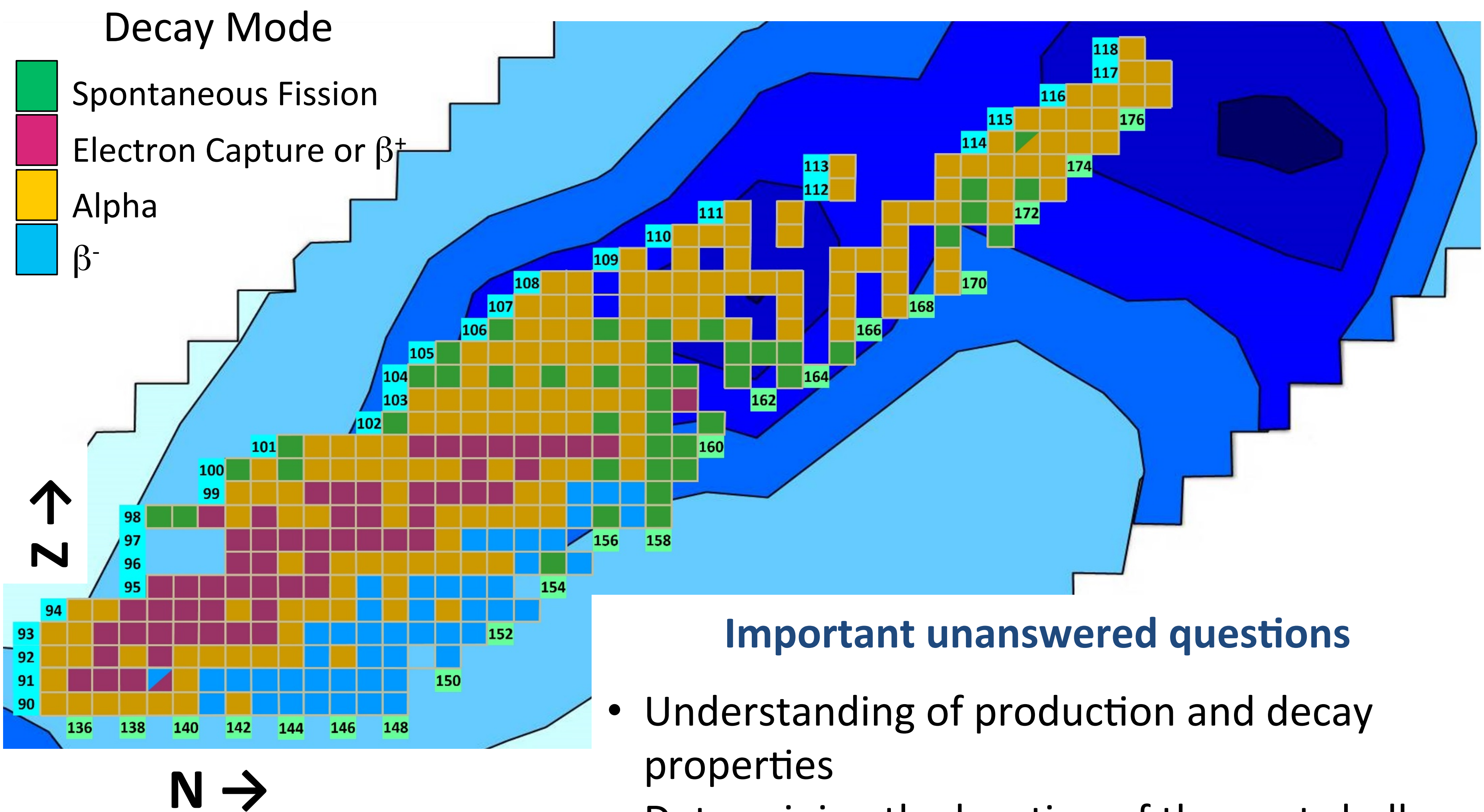


Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

Interesting Properties of SHE

- ‘Large’ production cross sections
- ‘Long’ lifetimes
- Proximity to expected spherical closed shell
- Change from spherical to deformed

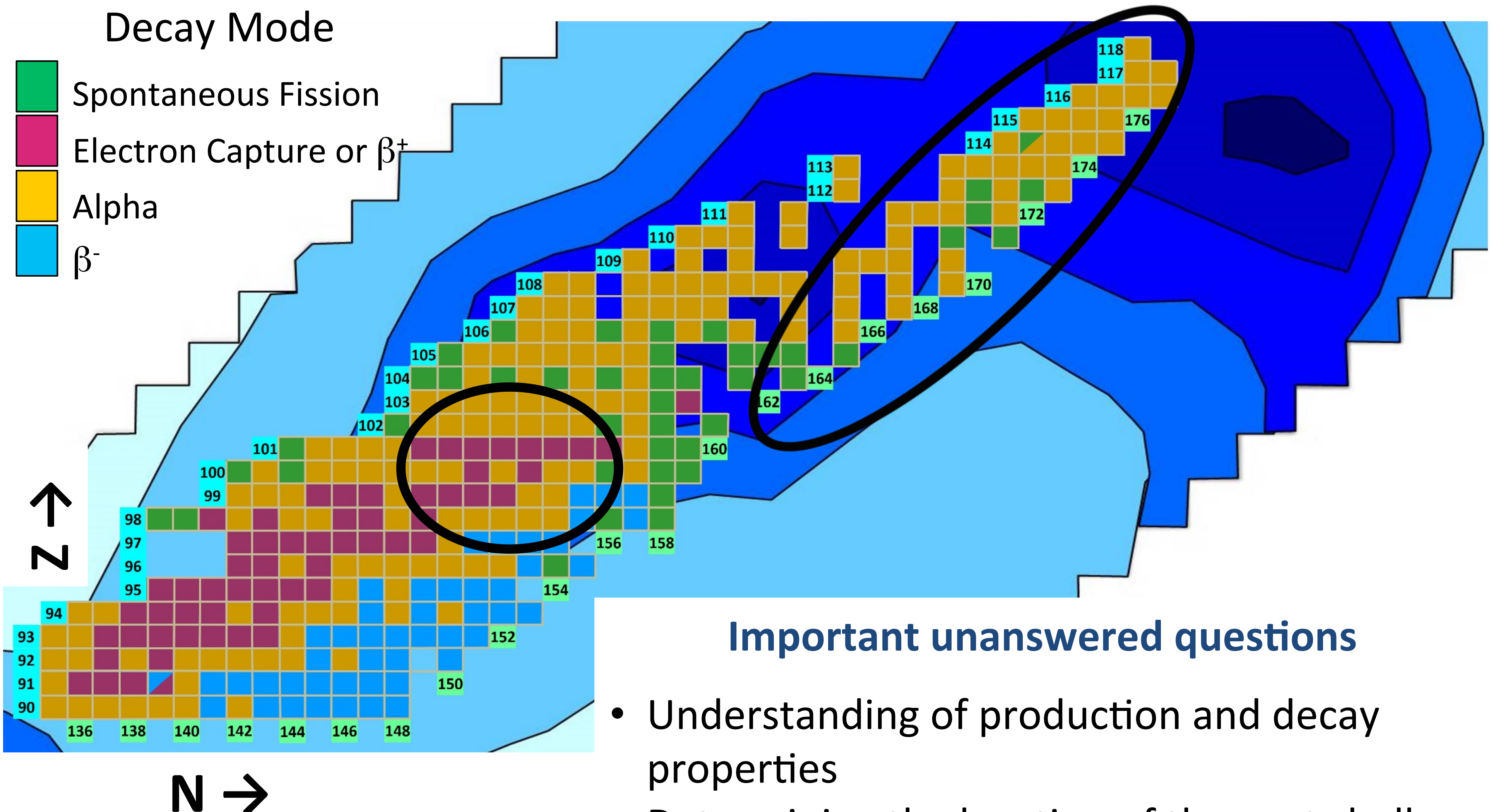


Shell effects from Sobiczewski et al: Phys. Rev. C 63 (2001) 034306

Important unanswered questions

- Understanding of production and decay properties
- Determining the location of the next shells
- Evolution of shape
- Confirmation of assigned A and Z

Regions of Study



Shell effects from Sobiczewski et al:
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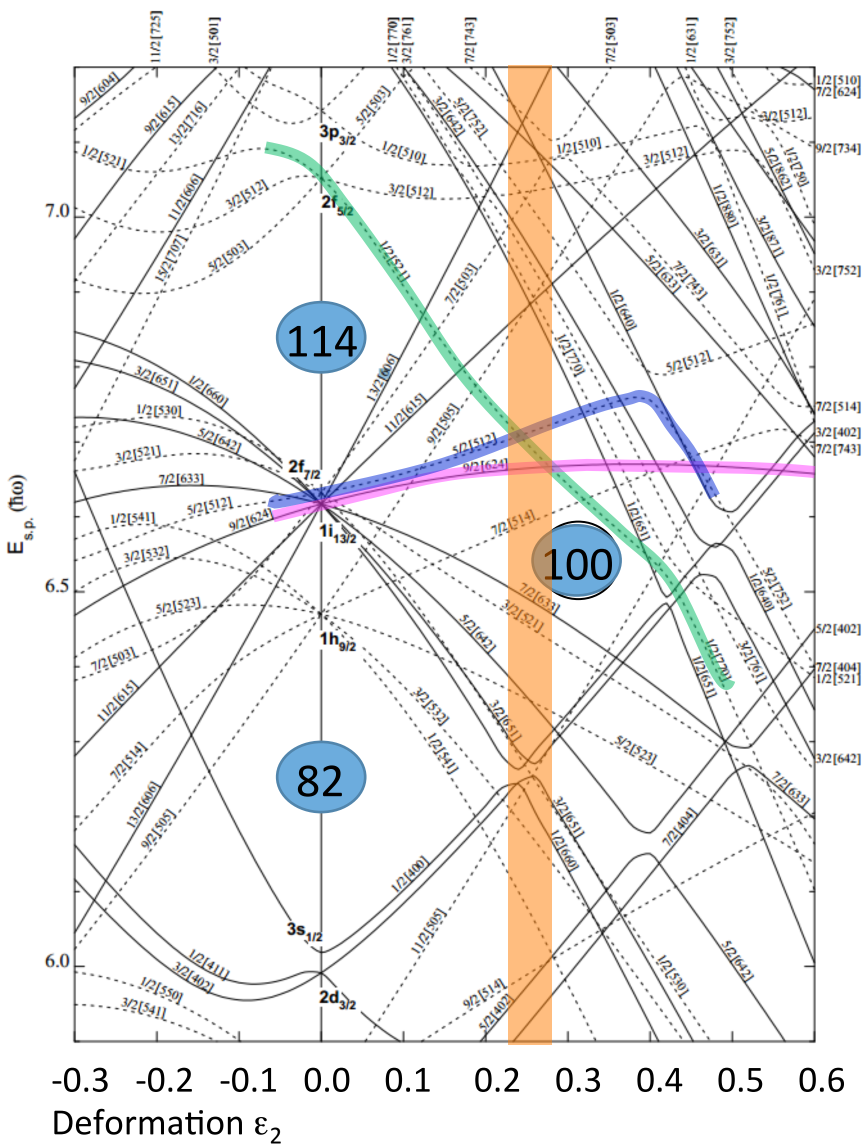
Single-Particle States Responsible for SHE



Nilsson diagram for protons with Z≥82

We can learn about the single-particle states responsible for the stability of superheavy elements in two ways:

1) States which are near the ground state in deformed nuclei near *Z*=102 are also near the ground state for spherical SHE. We can study these states in *Z*=102-104 with production rates of up to atoms per second.

2) We can produce SHE at rates of nearly 1 atom per day. New capabilities allow us to perform spectroscopy directly with SHE.

Spectroscopy of Heavy Elements - Challenges

Low cross sections:

Z~100: μb to nb — 1 heavy element per 10^{12-14} beam particles and 10^{5-7} unwanted reaction products

Z~114: pb — 1 heavy element per 10^{17} beam particles and 10^{11} unwanted reaction products

Every aspect of spectroscopy dominated by background

What you need for spectroscopy:

High-intensity beams (pμA)

Way to tell when you actually make something interesting

Two techniques recently developed:

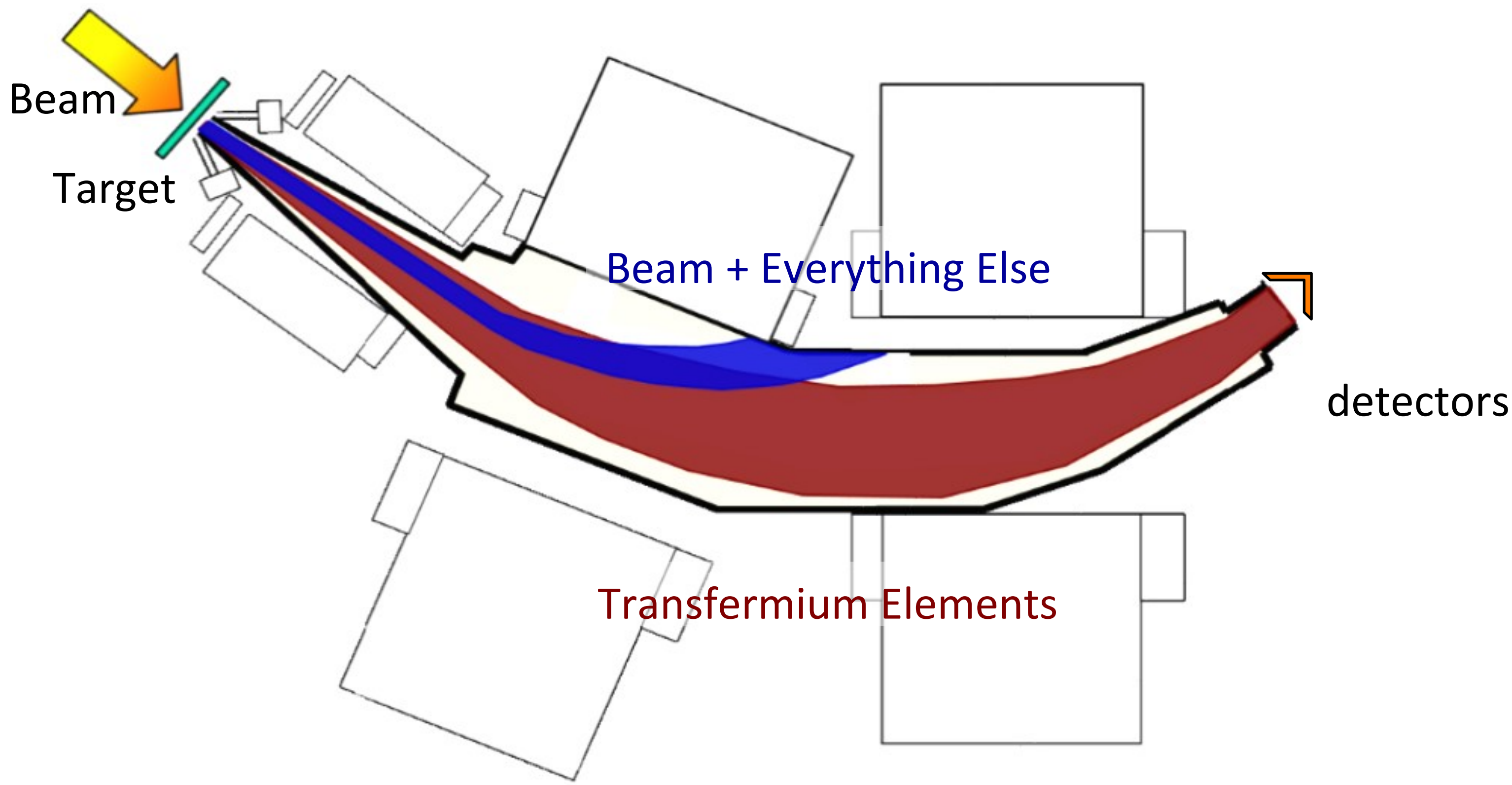
In-beam spectroscopy

Decay spectroscopy

Decay Spectroscopy – How

Technique to access Nuclear Structure in Heavy Element Isotopes

1) Produce heavy element
2) Separate and implant in focal plane detector
3) Observe decay in same detector pixel
4) Used known time of recoil and decay to gate on γ-rays



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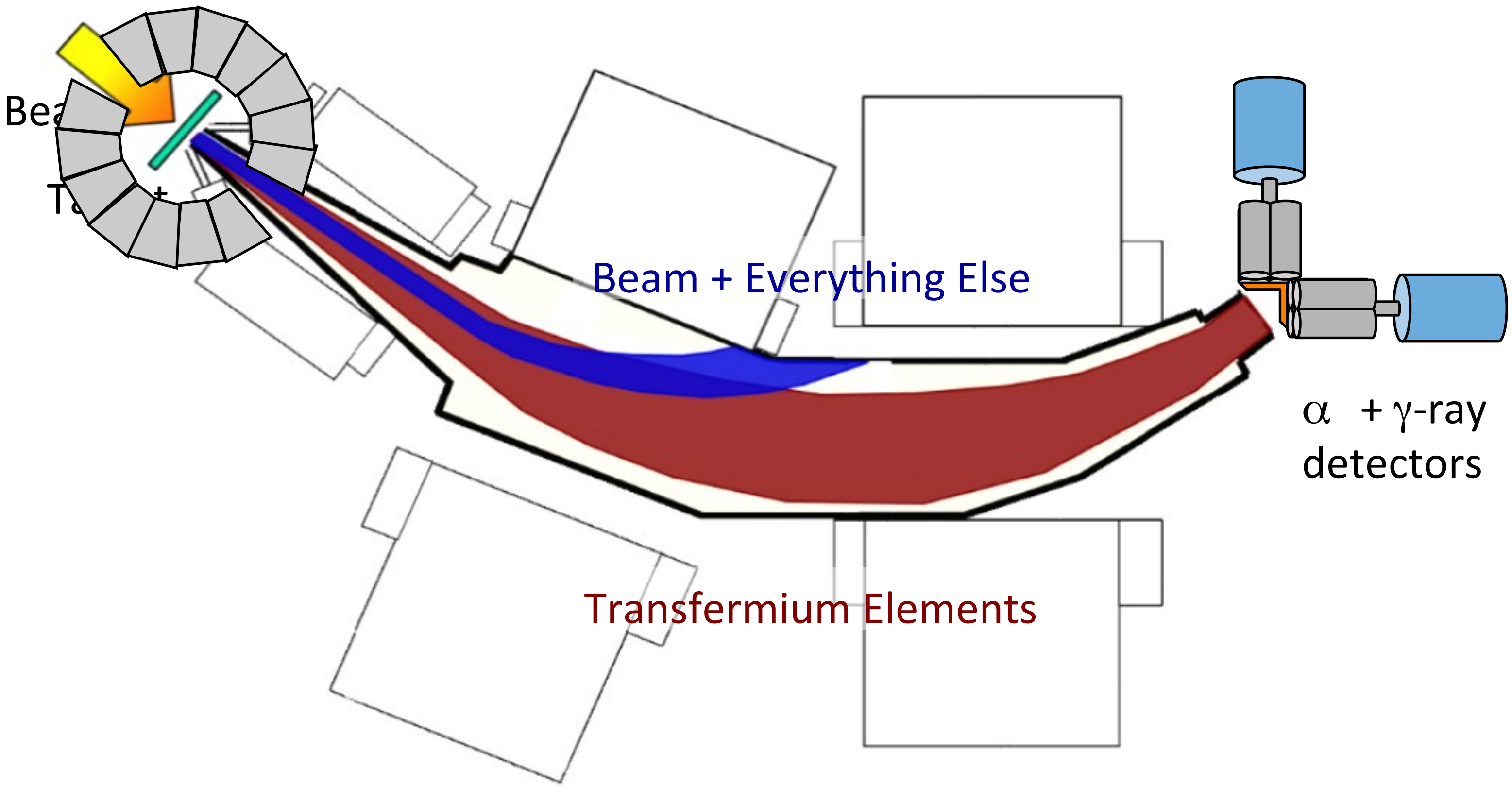
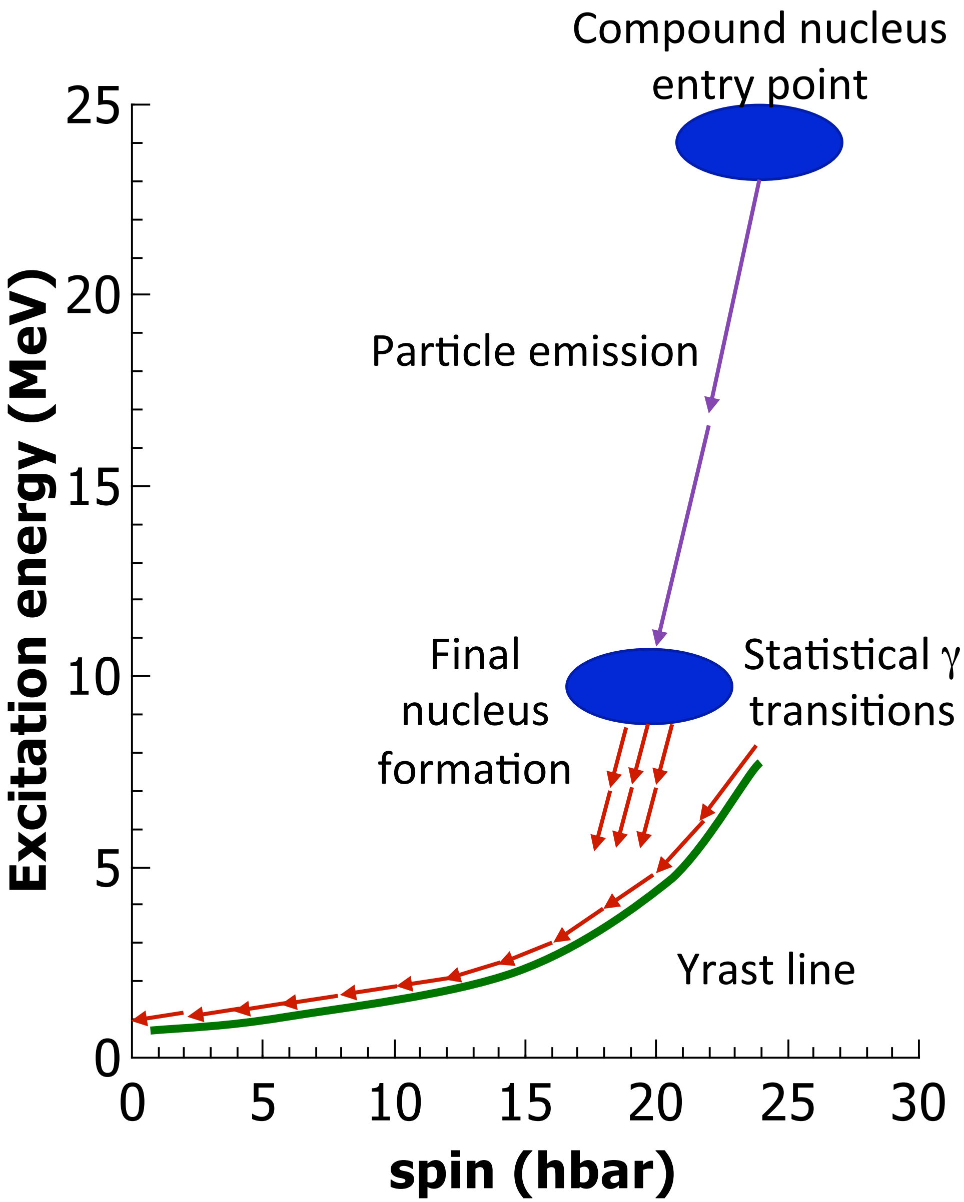


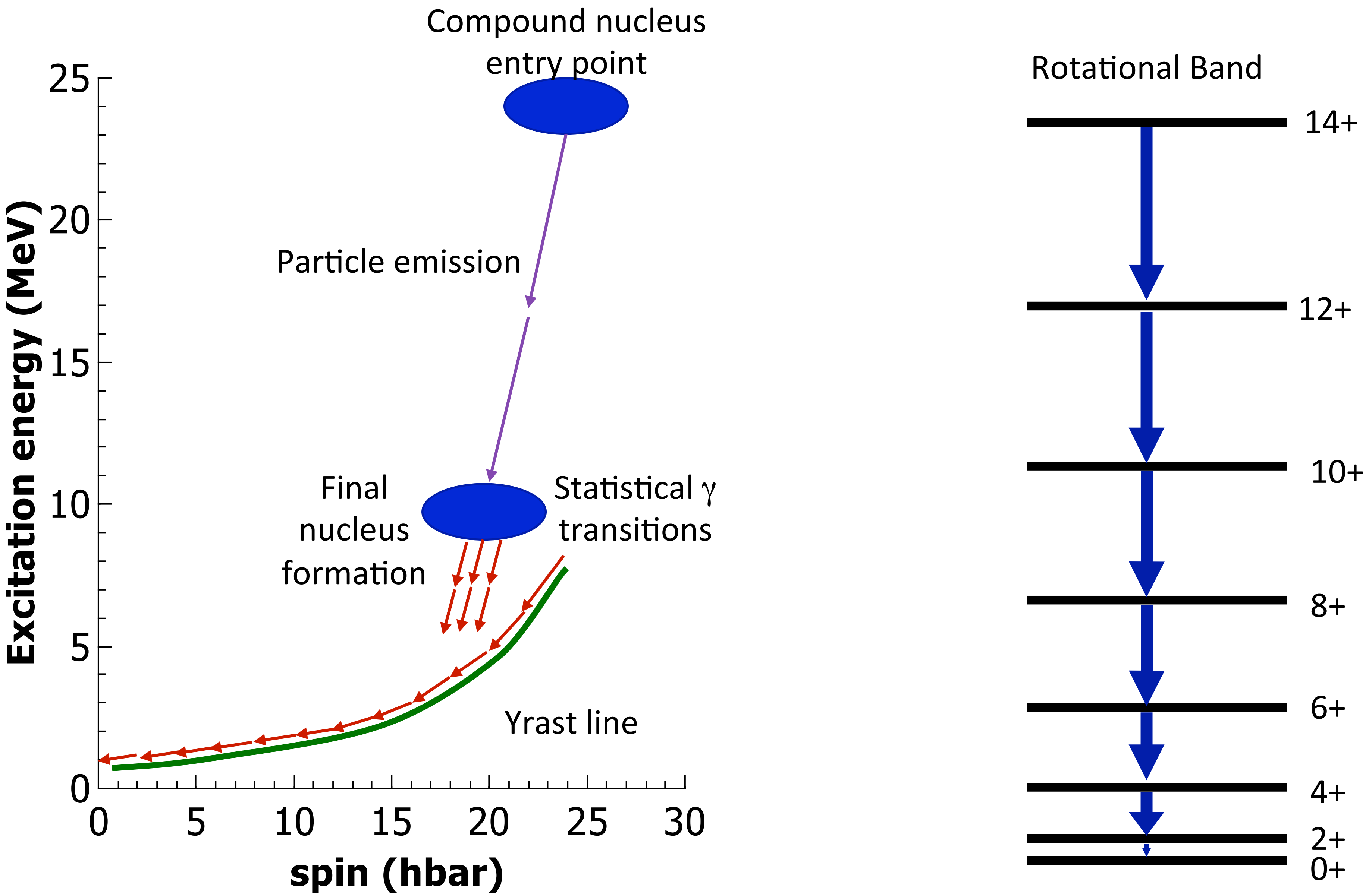
In-beam Spectroscopy - Why



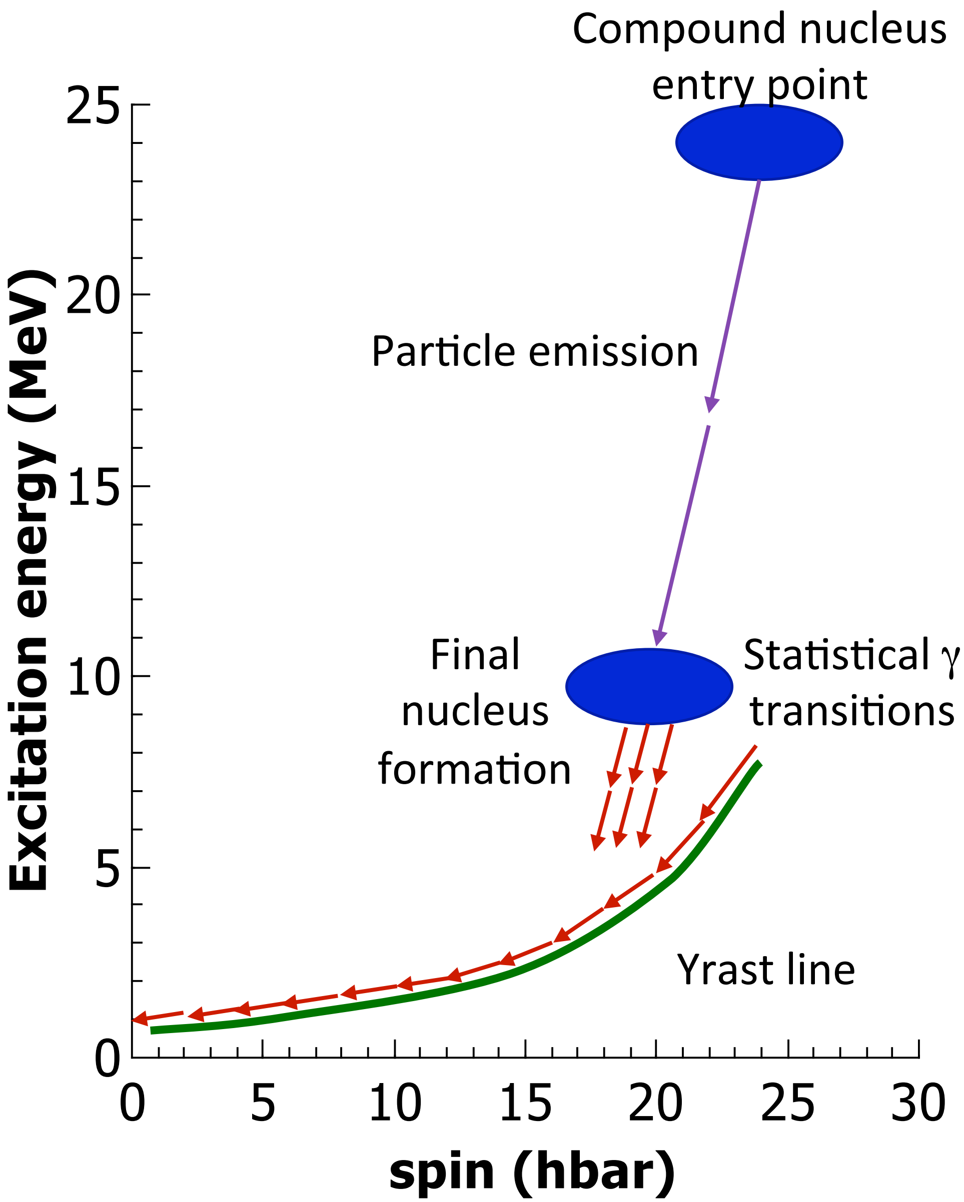
Observing γ-rays that occur during the de-excitation process directly after a compound nucleus is formed

- Heavy element compound nuclei formed at coulomb barrier beam energies
- De-excite through combination of particle and γ-ray emission
- Process takes 10^{-15} to 10^{-13} s

In-beam Spectroscopy - Why



In-beam Spectroscopy - Why



Rotational bands

- Deformation
- how centrifugal force causes shape changes by stressing nuclei at high spin

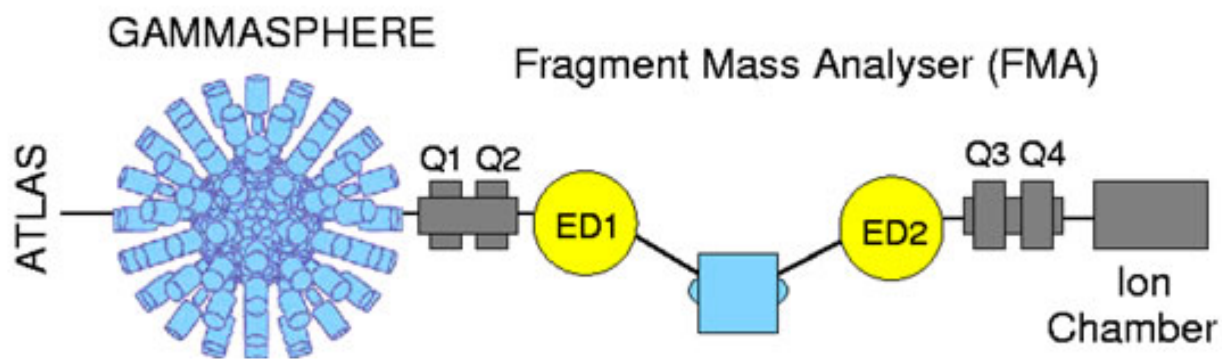
Single-particle states

Vibrational and octupole bands

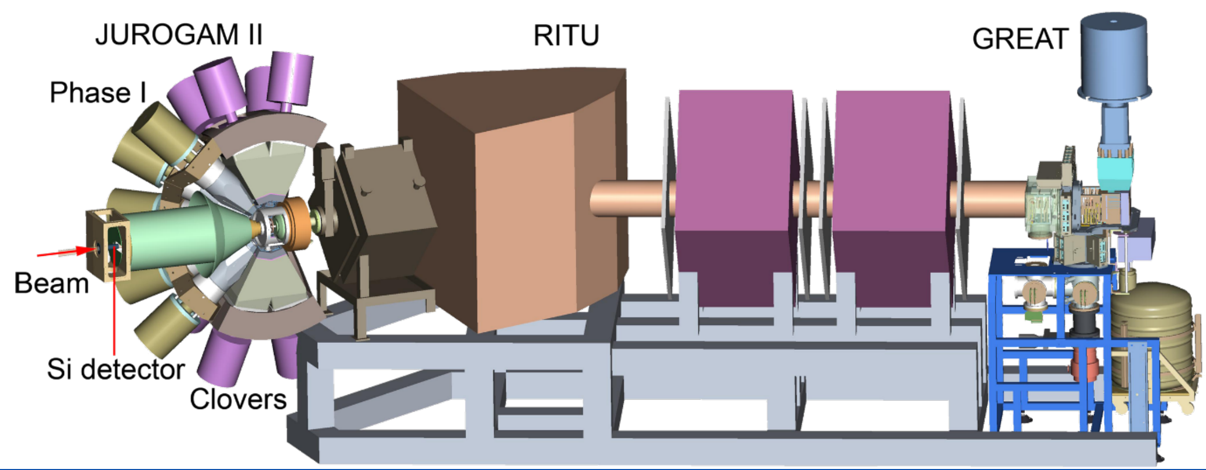
All these can be used to put strong constraints on nuclear models, and improve our understanding of nuclei in this region at the high-Z limit of nuclear stabiltiy.

Places with In-Beam Spectroscopy Setups

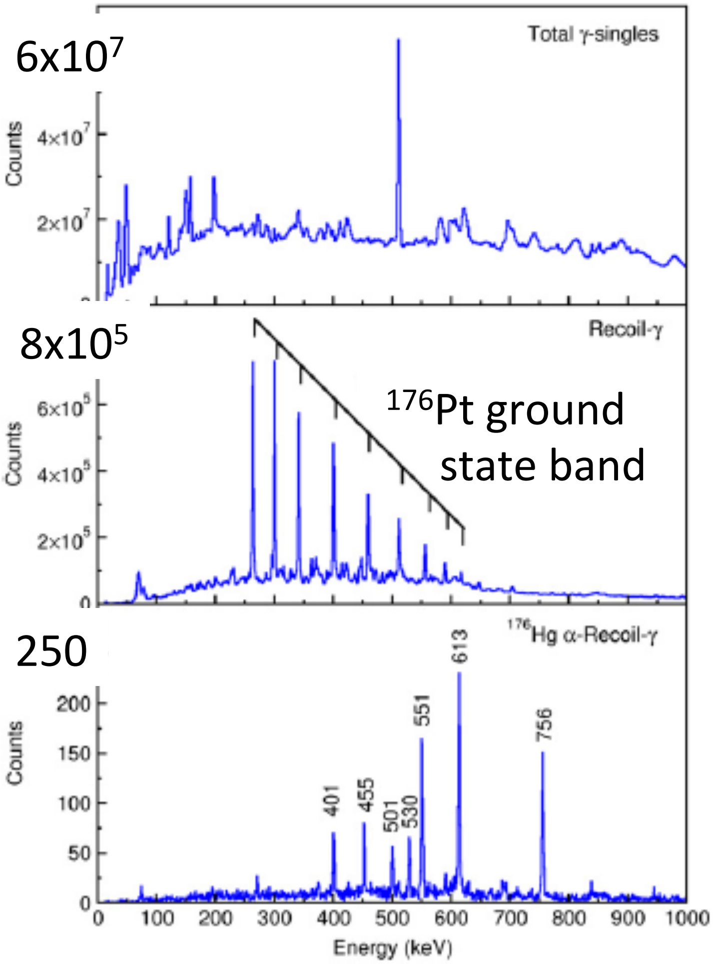
GAMMASPHERE +
Fragment **M**ass **A**nalyzer at
Argonne National
Laboratory



JUROGAM +
Recoil **I**on **T**ransport **U**nit
at the University of
Jyväskylä



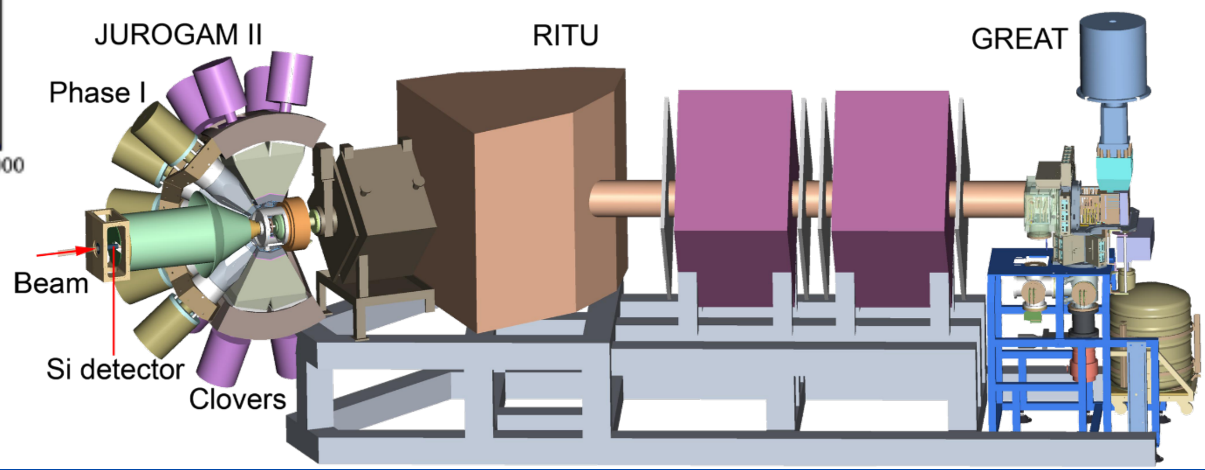
In-beam Spectroscopy – $^{144}Sm(^{36}Ar,4n)^{176}Hg$



Sum gamma spectrum

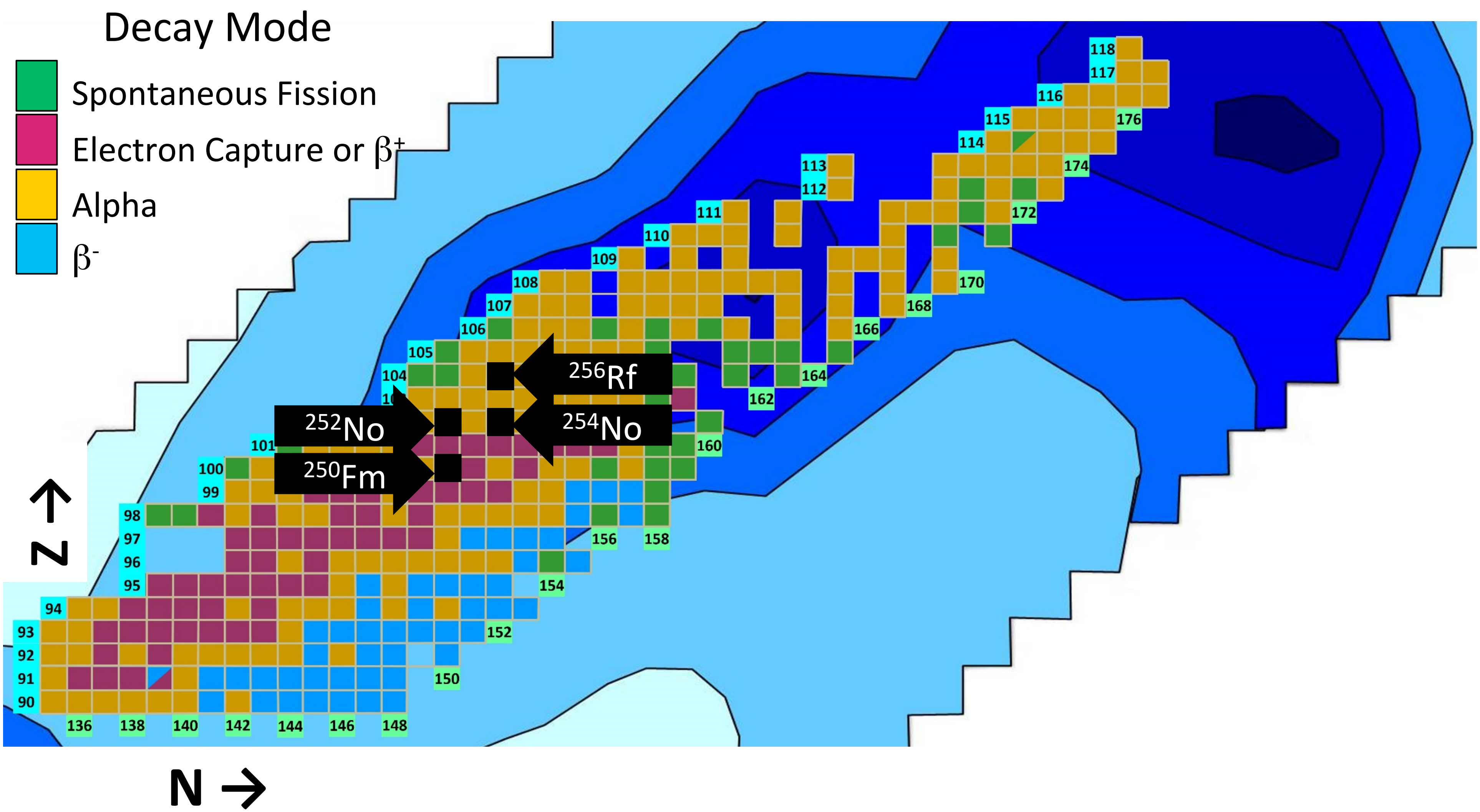
Gamma spectrum – gated on all recoils

Gamma spectrum – gated on all recoils followed by ^{176}Hg α



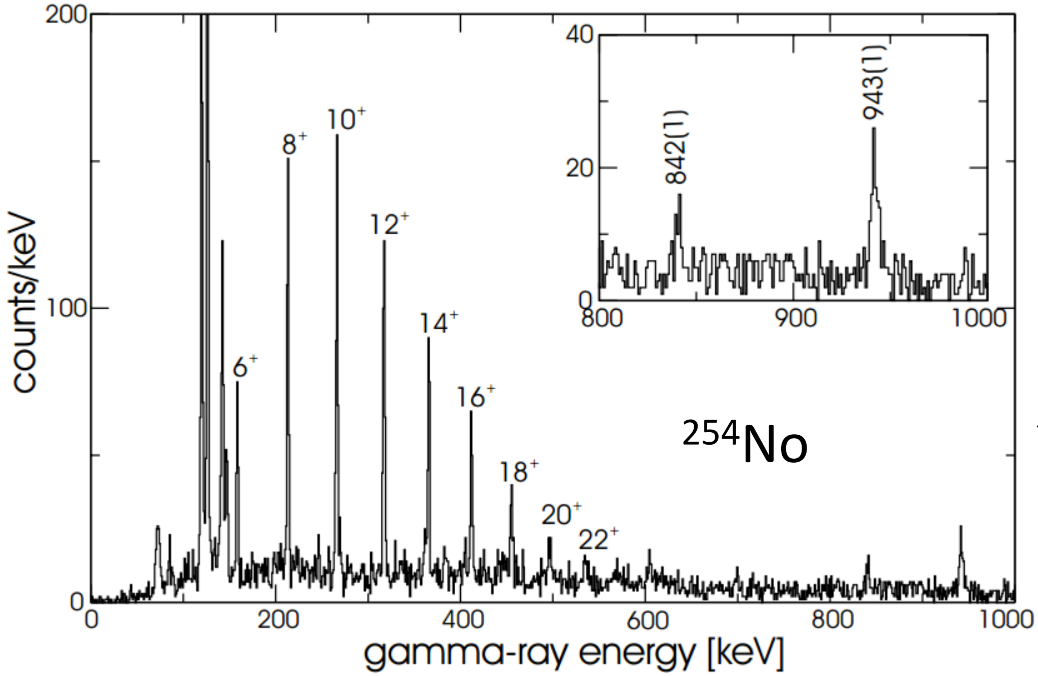
R.-D. Herzberg:
Prog. in Part. Phys. **61** (2008) 674

In-Beam Spectroscopy – What has been done

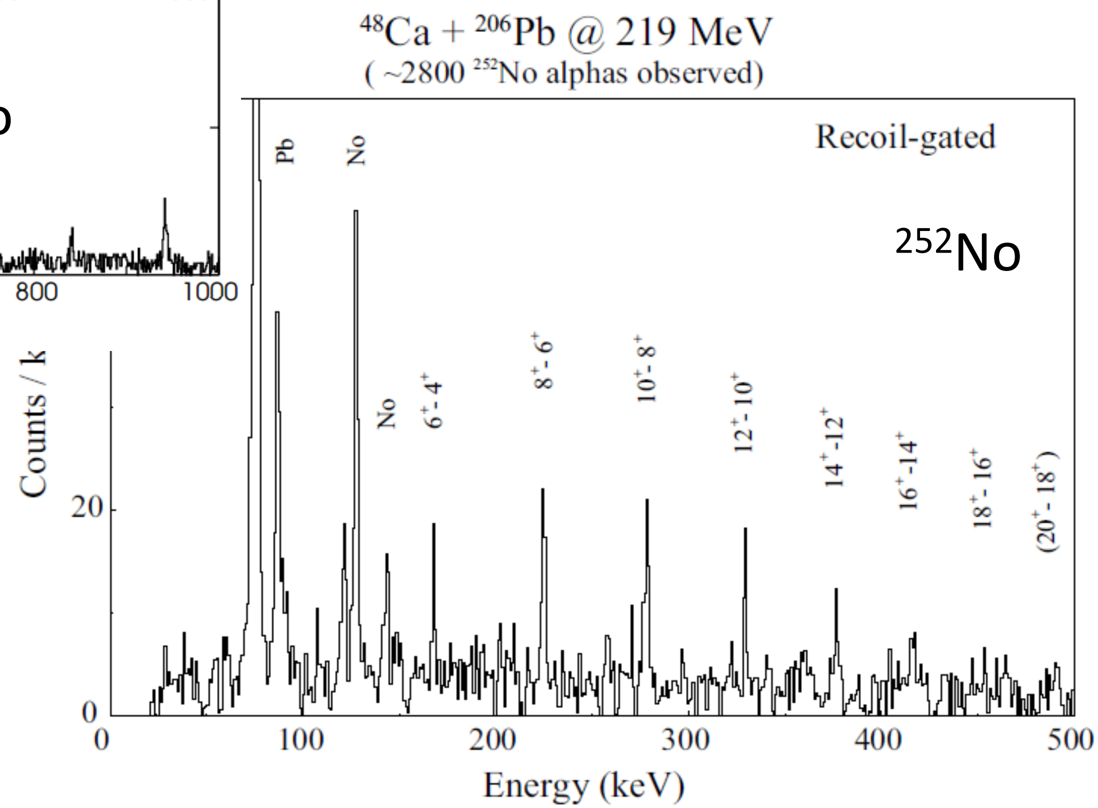


Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

^{252}No and ^{254}No from ^{208,206}Pb(^{48}Ca,2n)

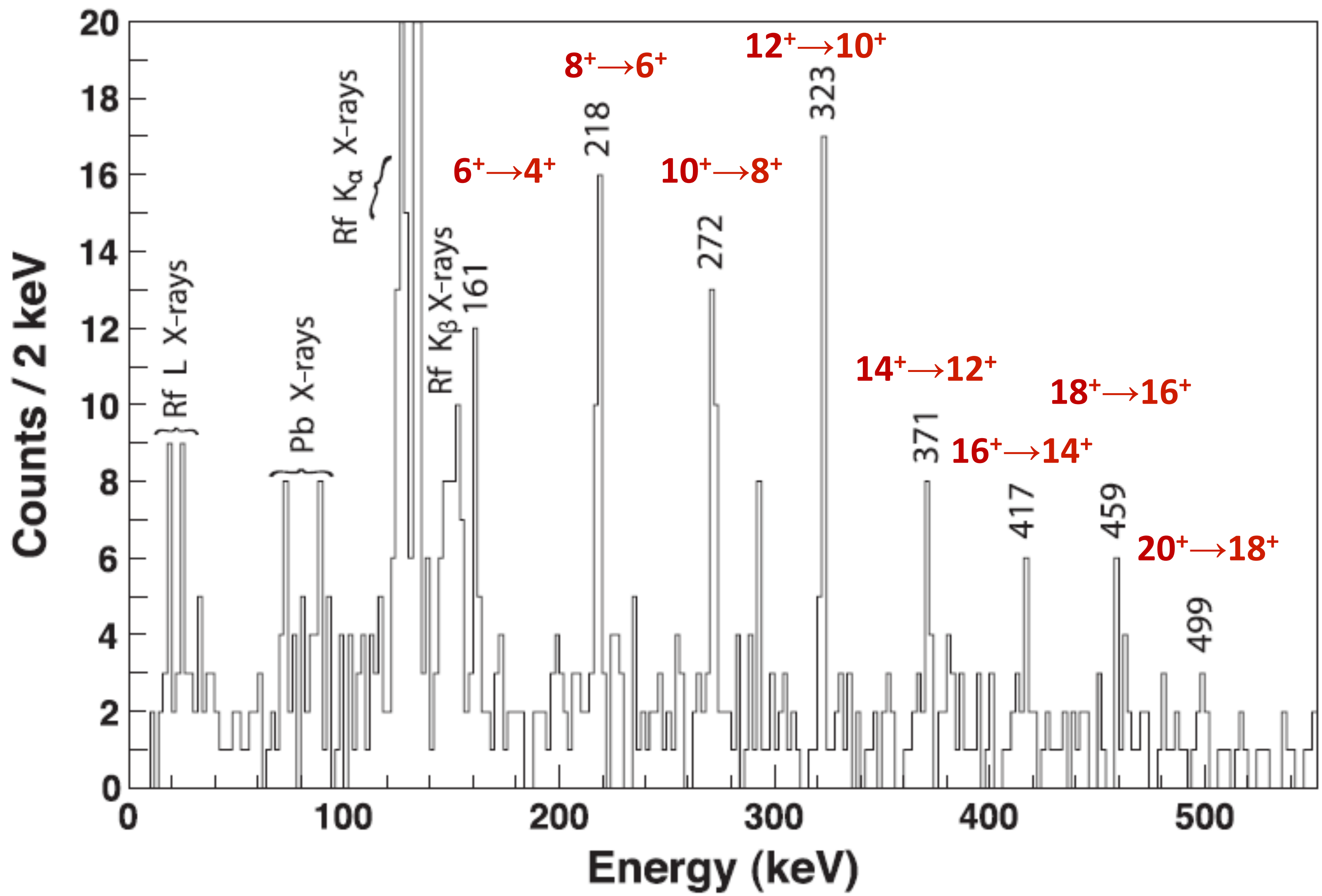


Eeckhaudt: Eur. Phys. J. A **25** (2005) 605



Greenlees: Eur. Phys. J. A **20** (2004) 87

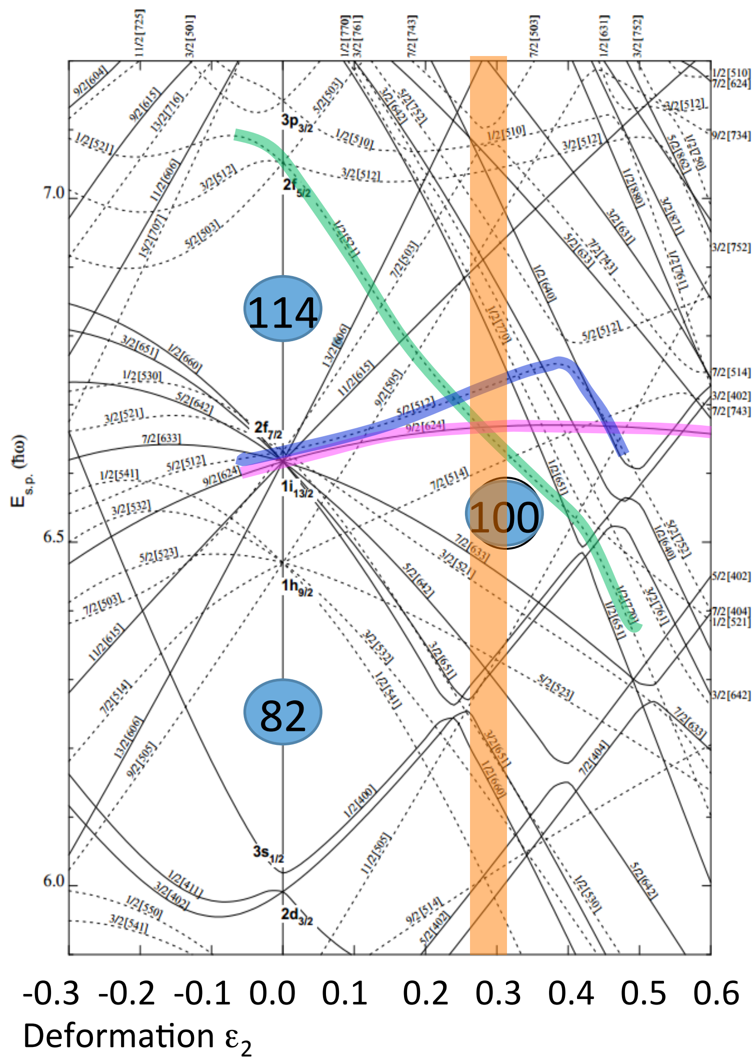
^{256}Rf from $^{208}Pb(^{50}Ti,2n)$



Greenlees: Phys. Rev. Lett. **109** (2012) 012501

In-beam Spectroscopy – What we have learned

Deformation parameters for ^{252,254}No ≈ 0.29

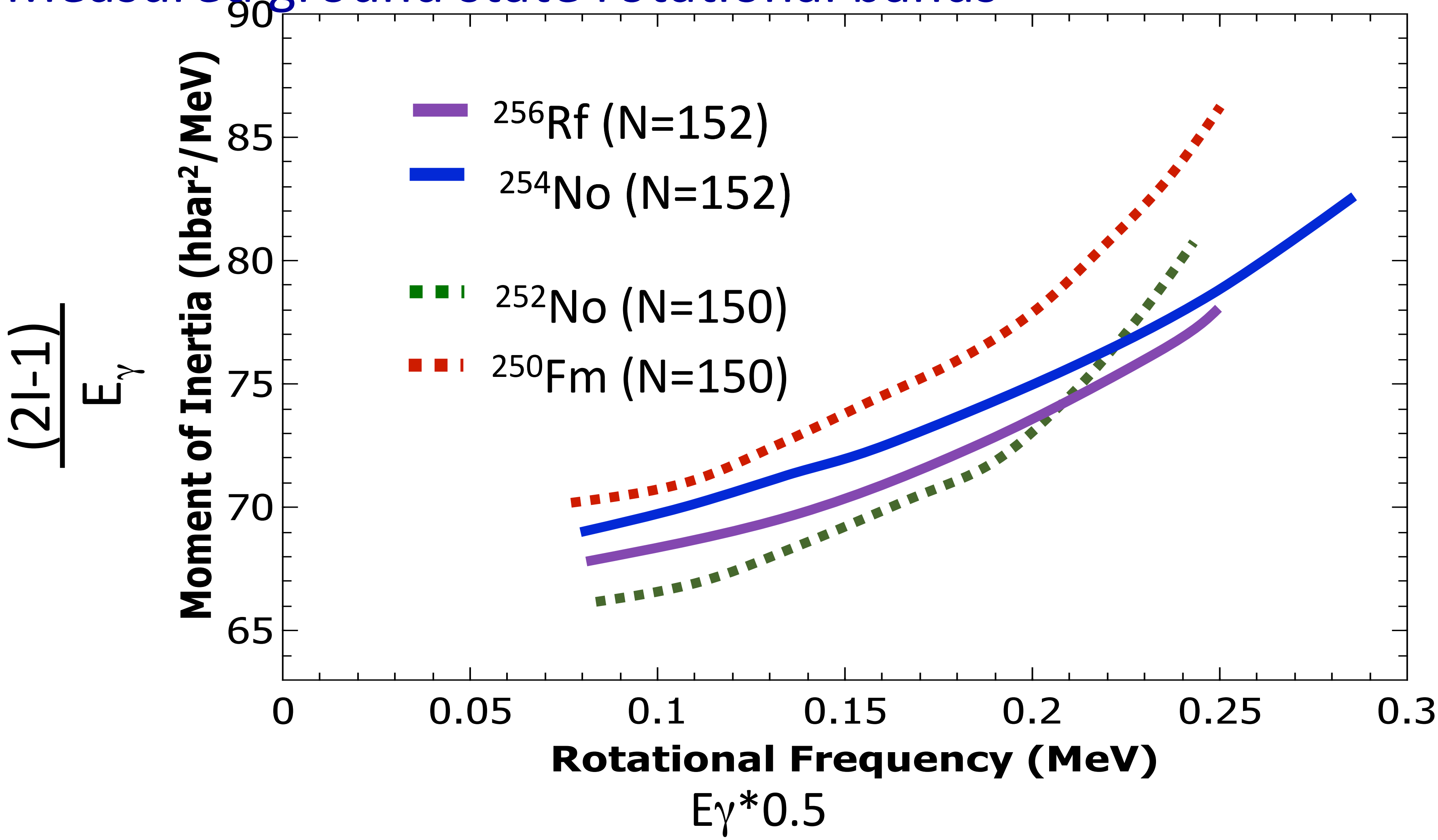


Nilsson diagram for protons with Z≥82

In-beam Spectroscopy – What we have learned

Deformation parameters for ^{252,254}No ≈ 0.29

Measured ground state rotational bands

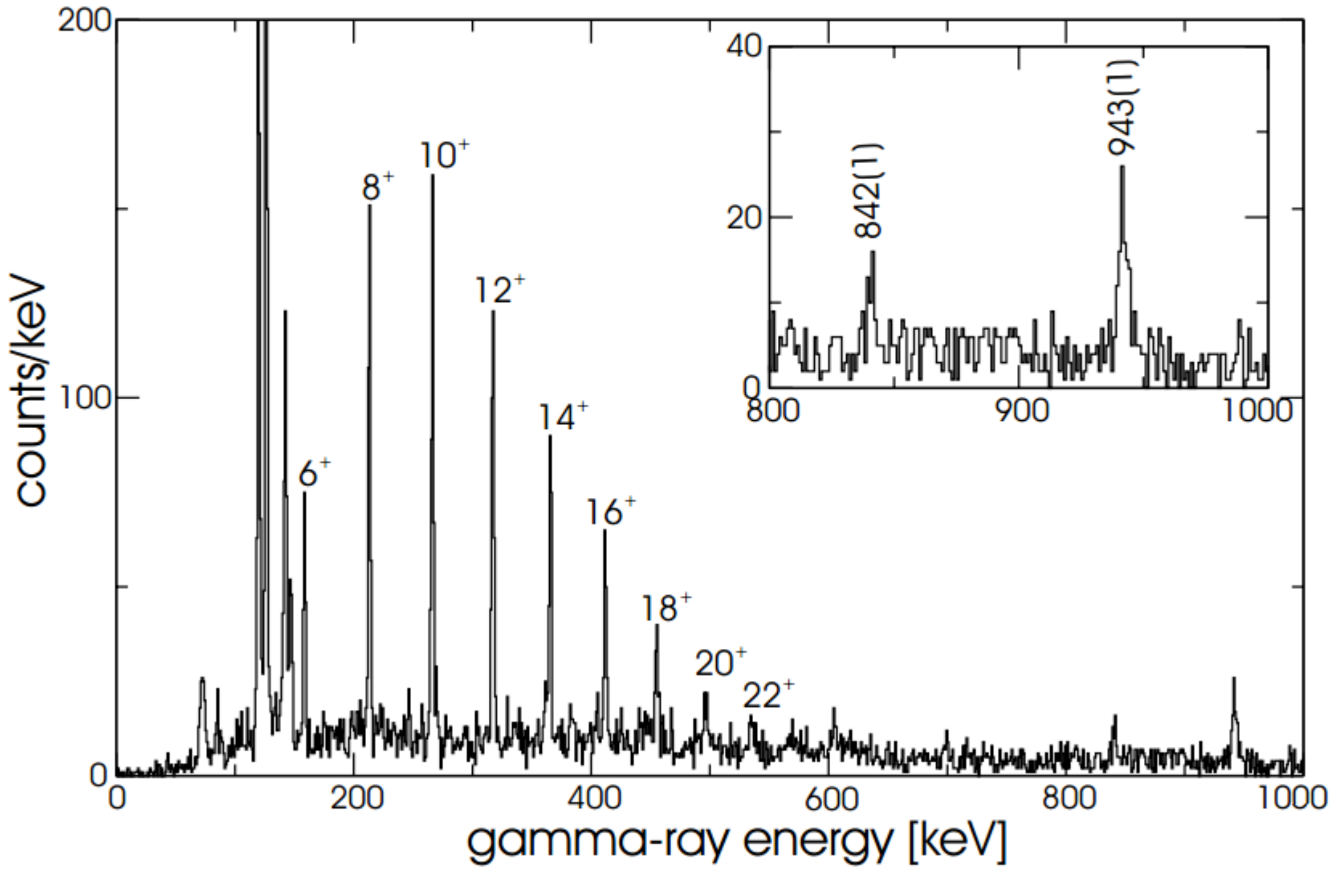


In-beam Spectroscopy – What we have learned

Deformation parameters for ^{252,254}No ≈ 0.29

Measured ground state rotational bands

Decay from states above the yrast line



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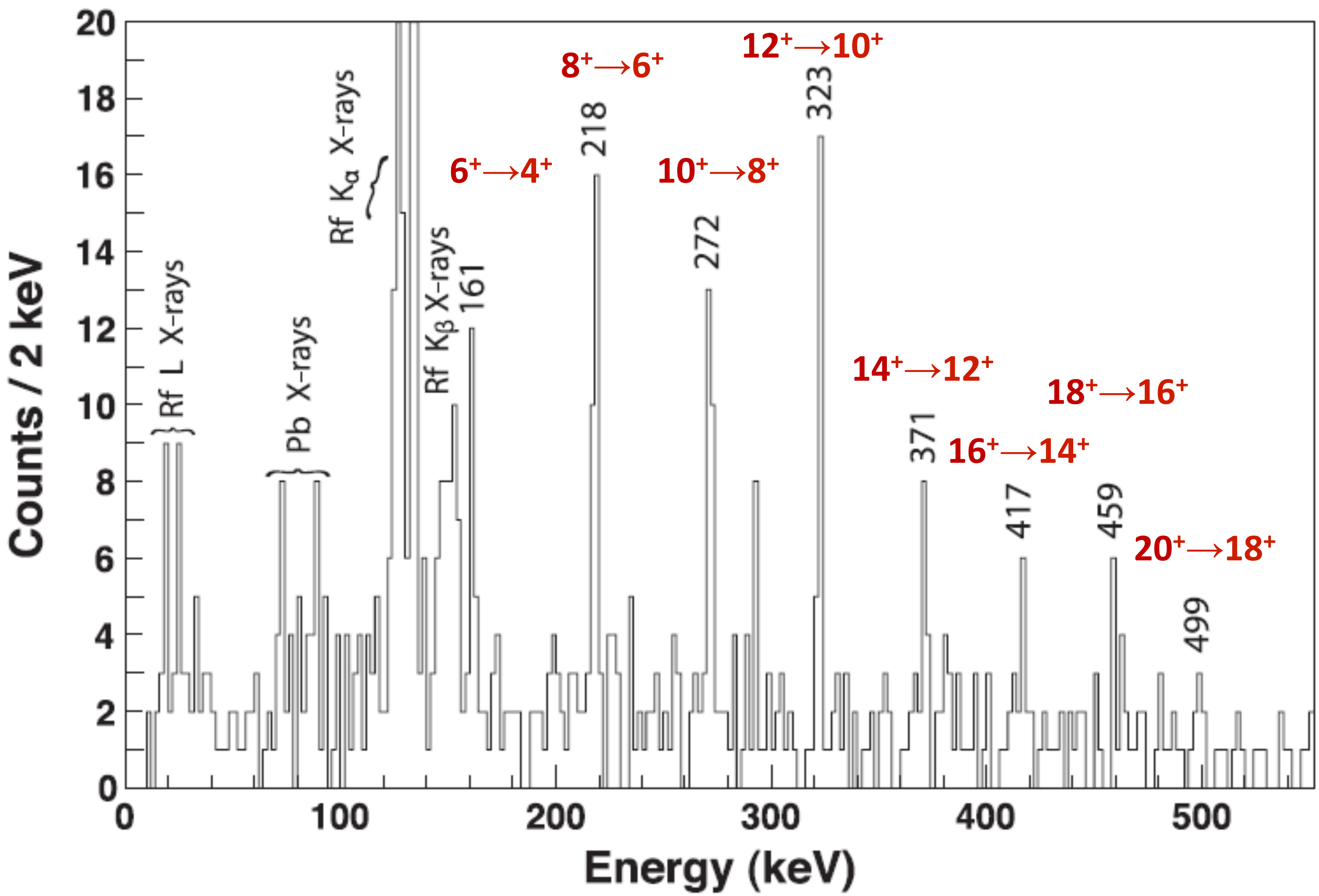
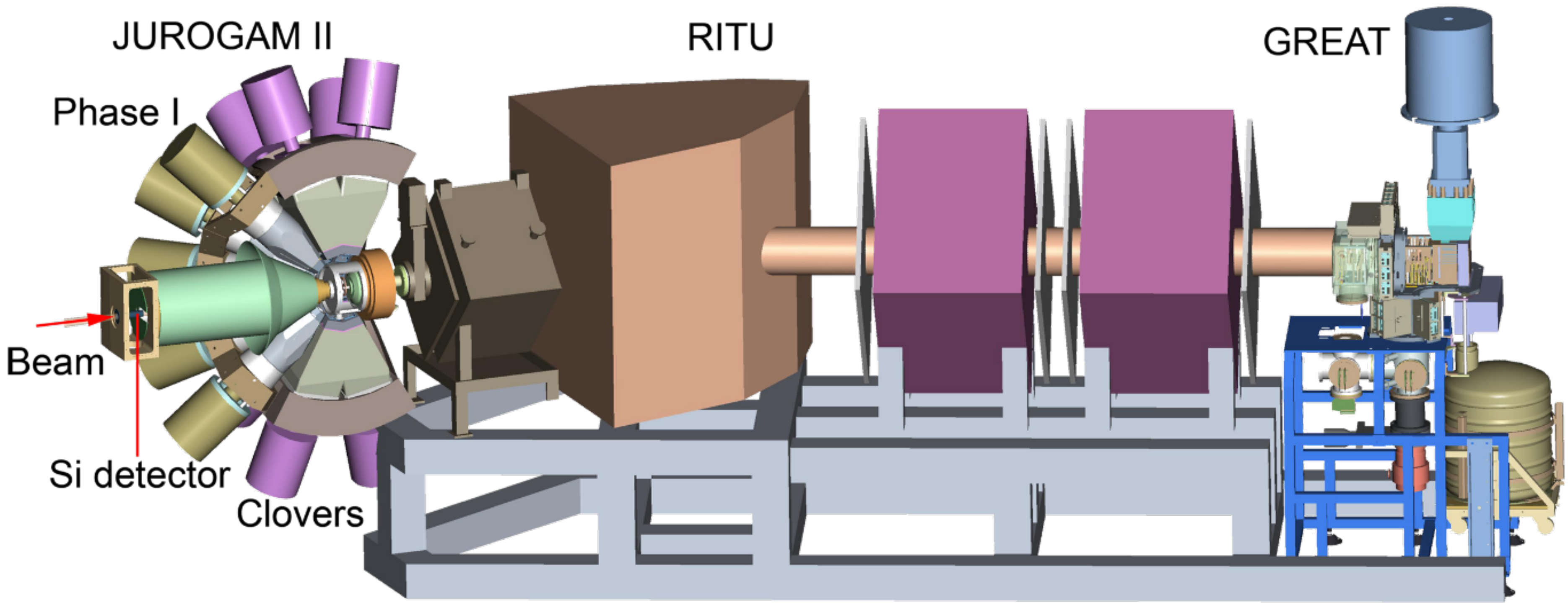


Greenlees: Phys. Rev. Lett. **109** (2012) 012501

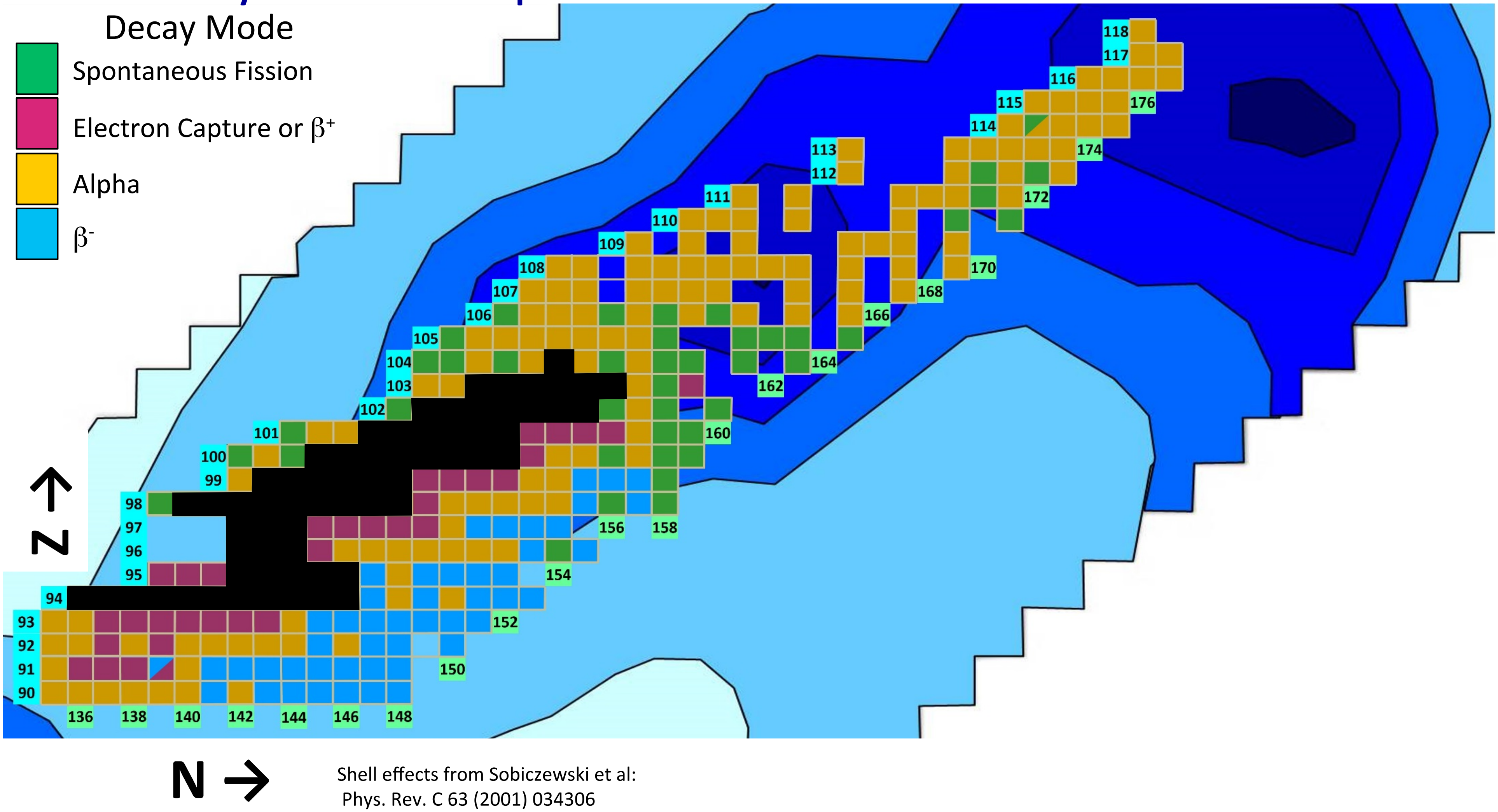
In-beam Spectroscopy - Challenges

- Rate in Ge-detectors surrounding target limit beam intensity to ~20-50 pnA $\rightarrow$ σ>20 nb



Isotopes with Suitable Cross Sections

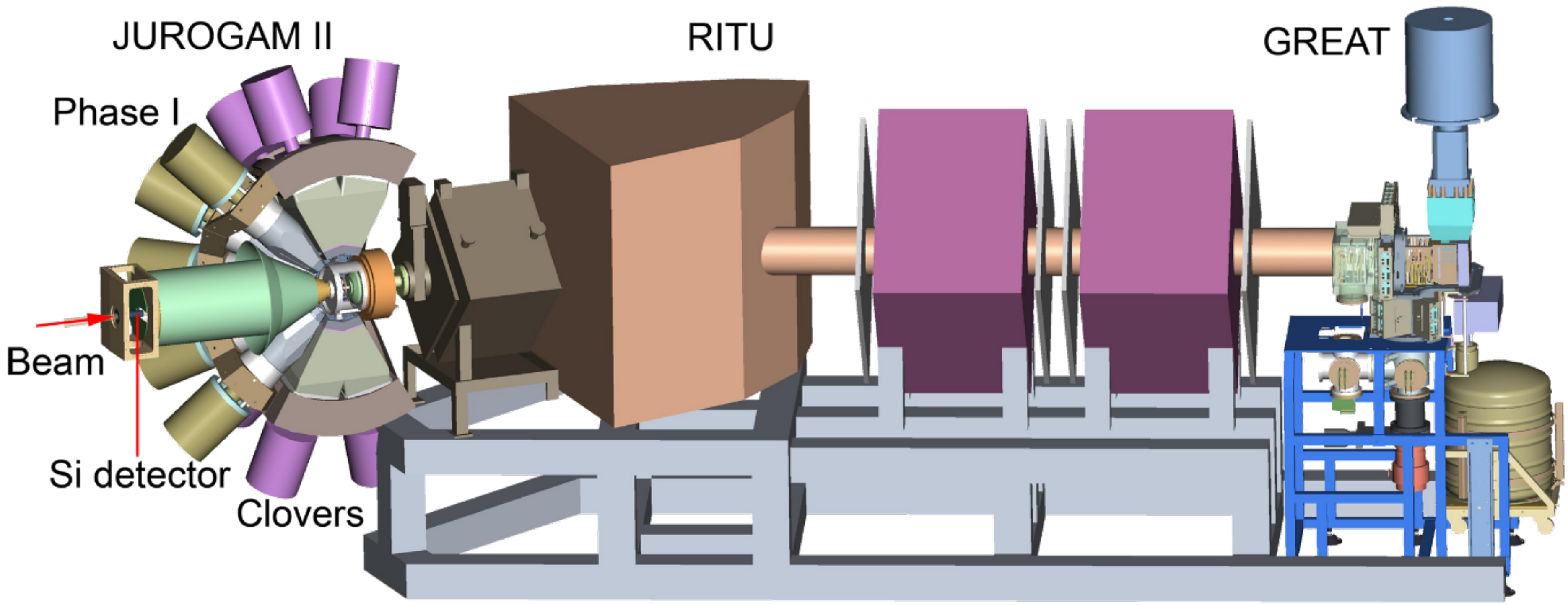
- Rate in Ge-detectors surrounding target limits beam intensity to ~20-50 pnA → σ>20 nb



Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

In-beam Spectroscopy - Challenges

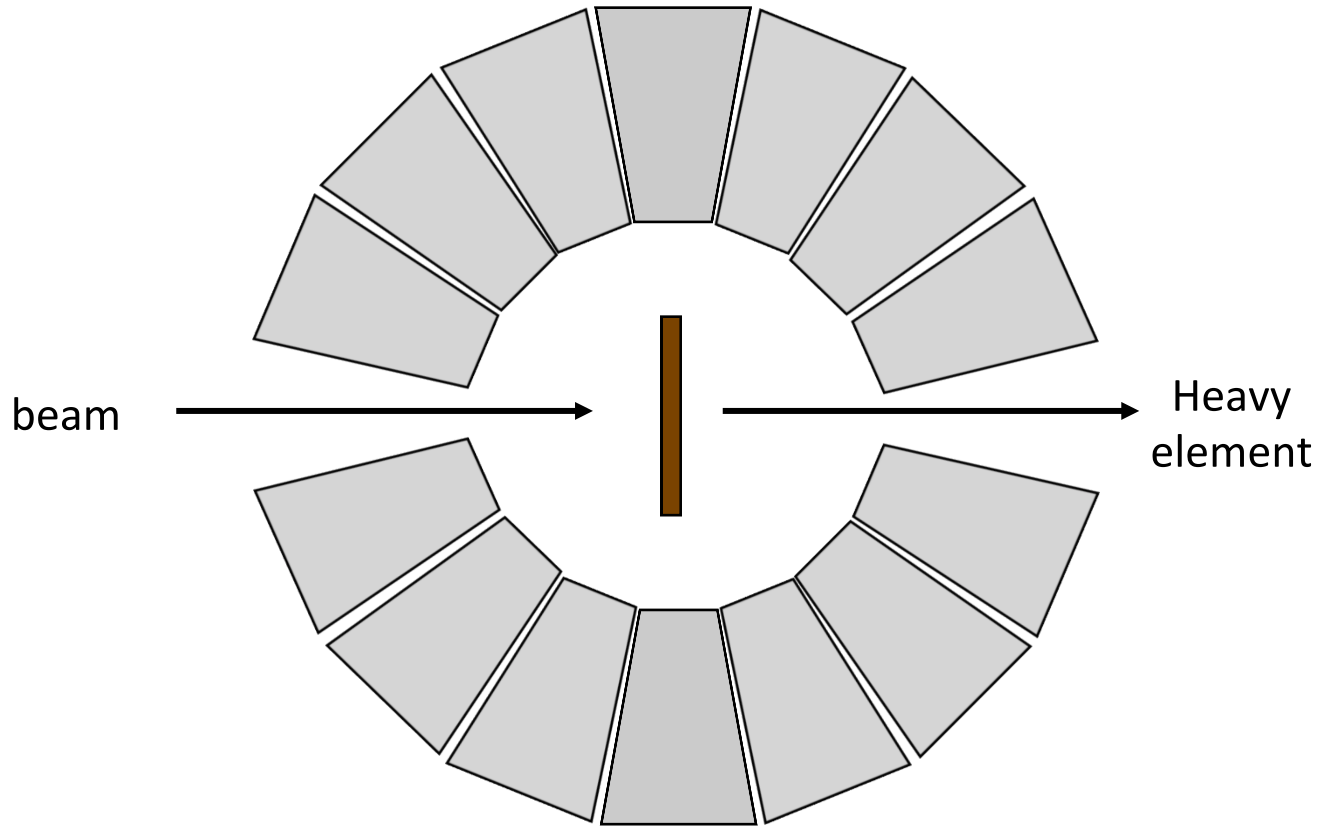
- Rate in Ge-detectors surrounding target limits beam intensity to ~20-50 pnA → σ>20 nb
- Isomers



Question

Heavy elements are formed with 20-50 MeV of kinetic energy, or about 1-2% the speed of light. Given that most in-beam spectroscopy setups have radii of <30 cm, how long does it take a heavy element to exit the spectrometer?

A) <0.1 ns
B) 0.1-1 ns
C) 1-10 ns
D) 10-100 ns
E) >100 ns



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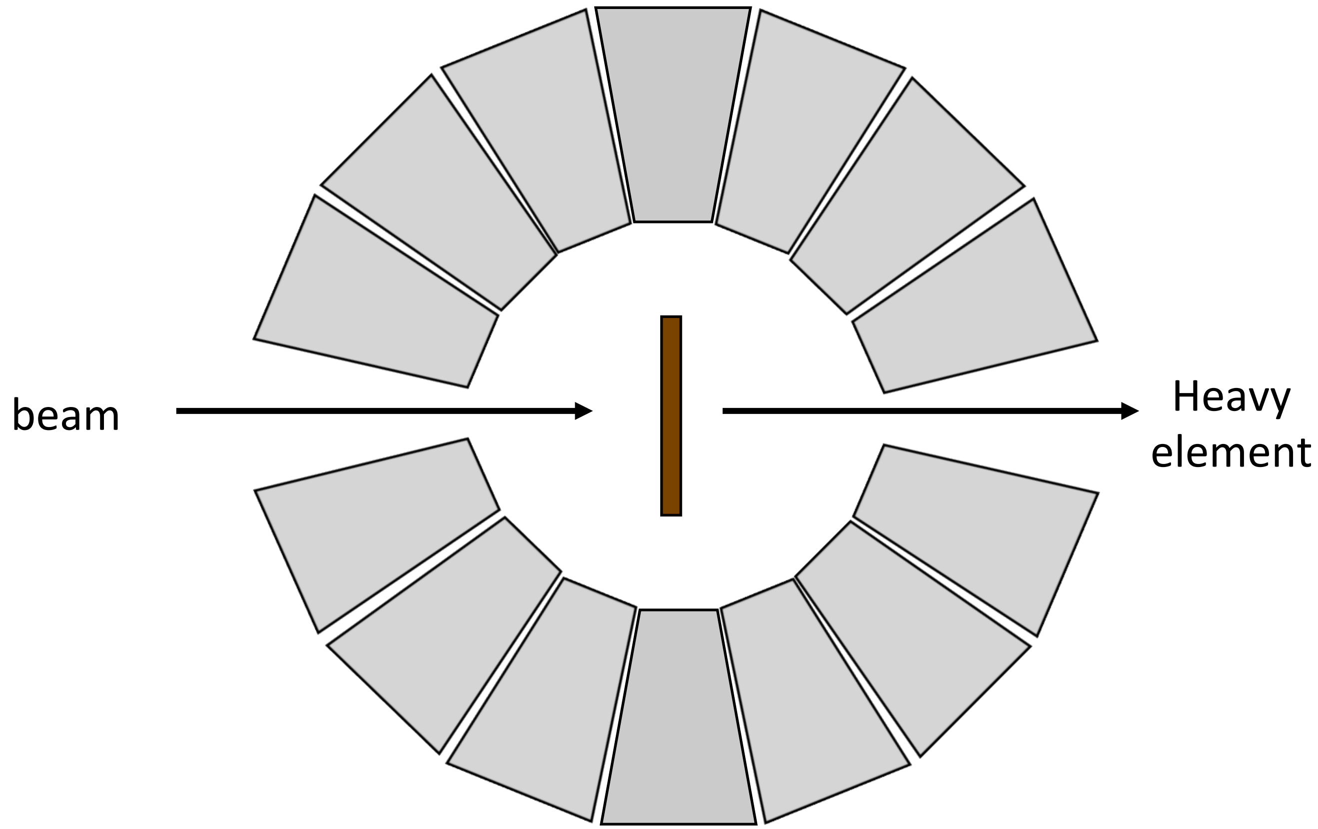
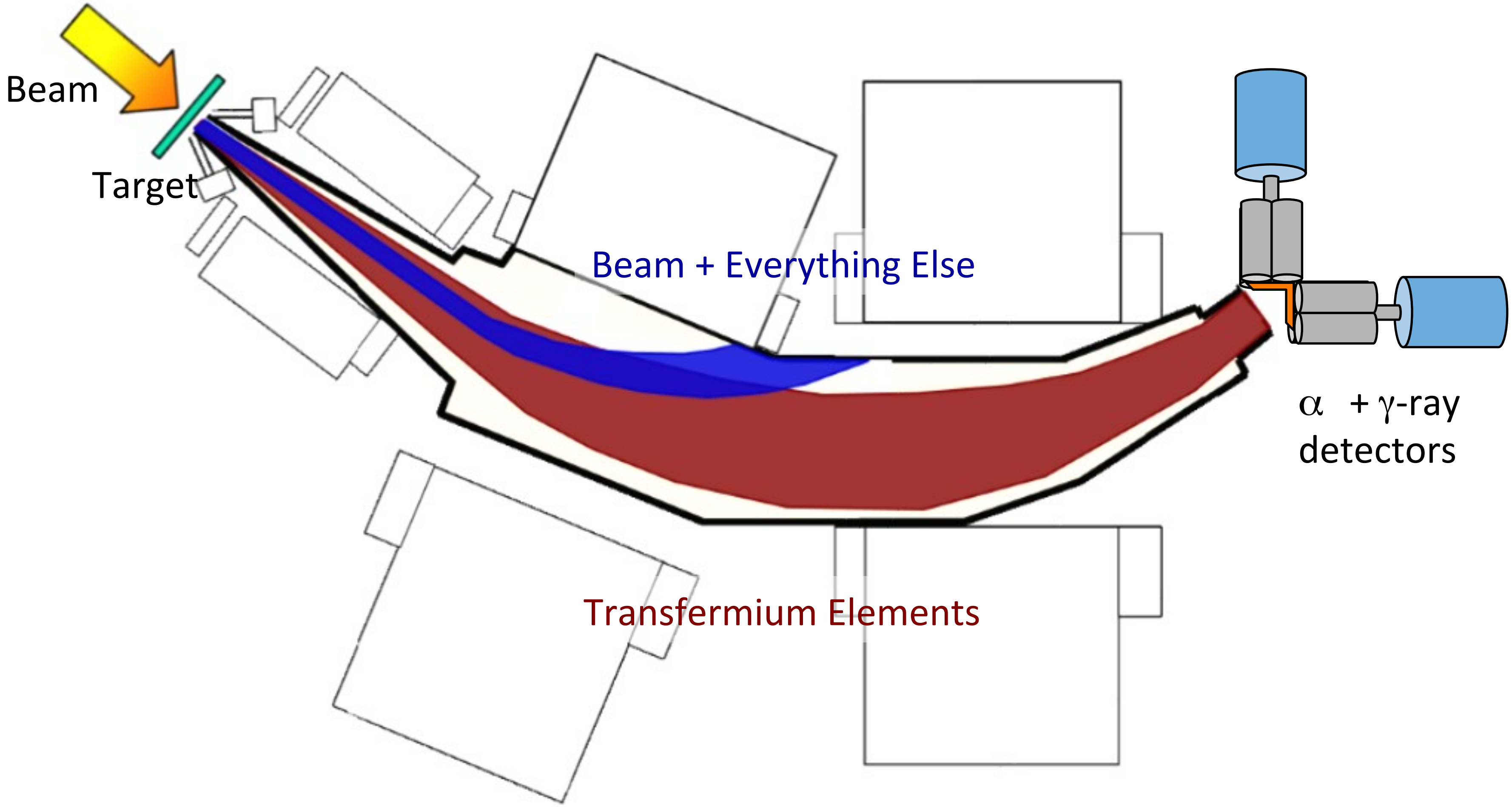


Decay Spectroscopy – How



Technique to access Nuclear Structure in Heavy Element Isotopes

1) Produce heavy Element Isomers

2) Separate and implant in focal plane detector

Decay Spectroscopy – How

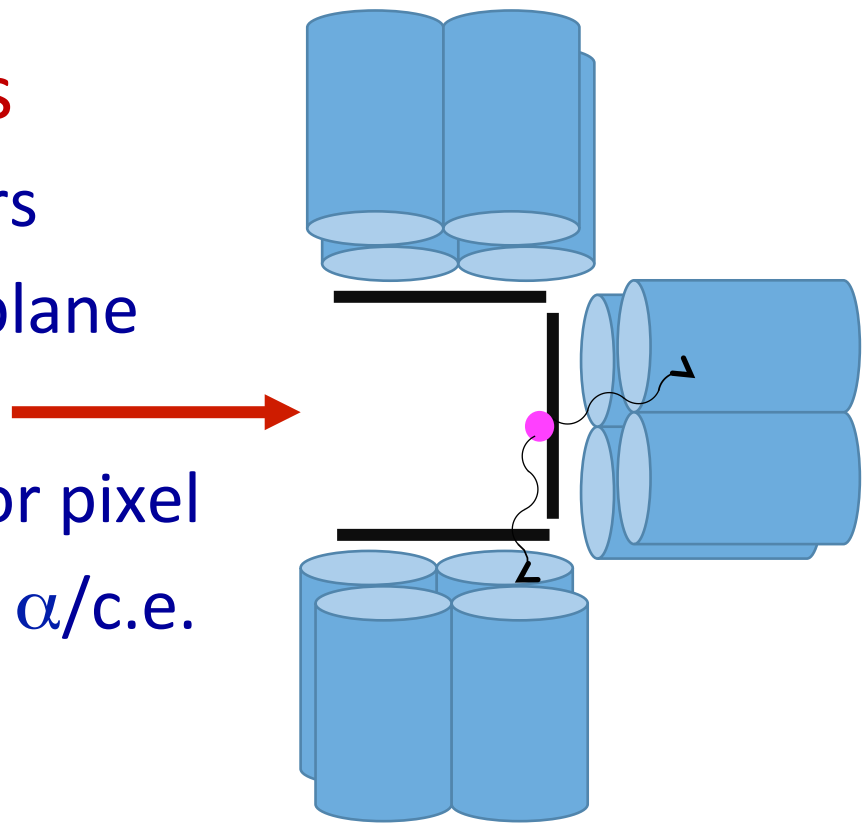
New Technique to access
Nuclear Structure in
Heavy Element Isotopes

1) Produce heavy Element Isomers

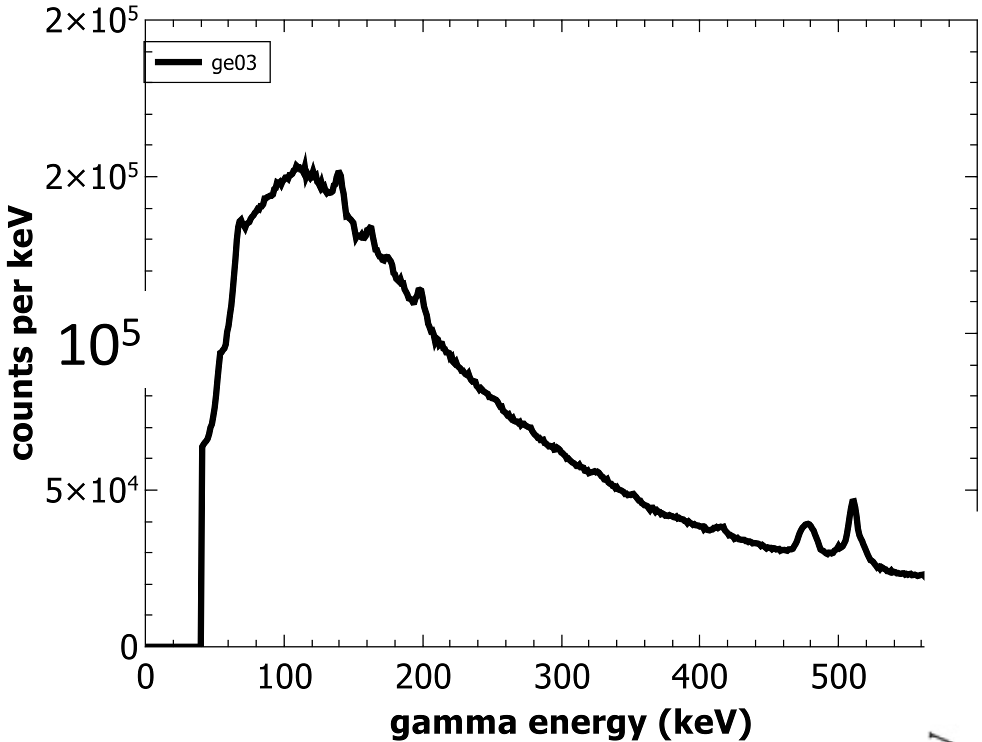
2) Separate and implant in focal plane detector

3) Observe decay in same detector pixel

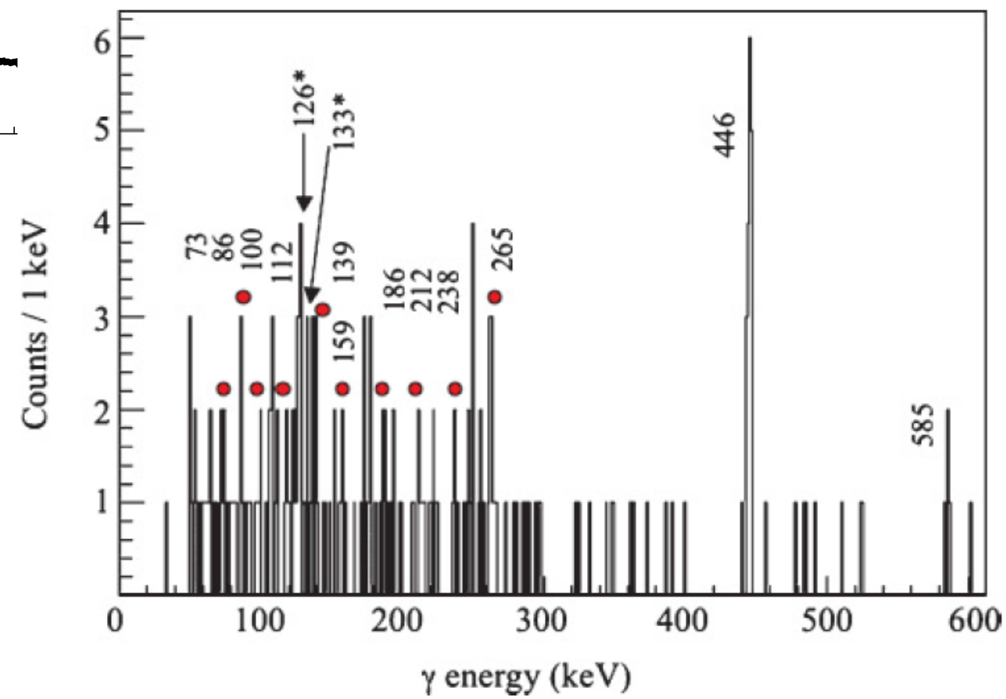
4) Observe γ-rays coincident with α/c.e.



Gammas

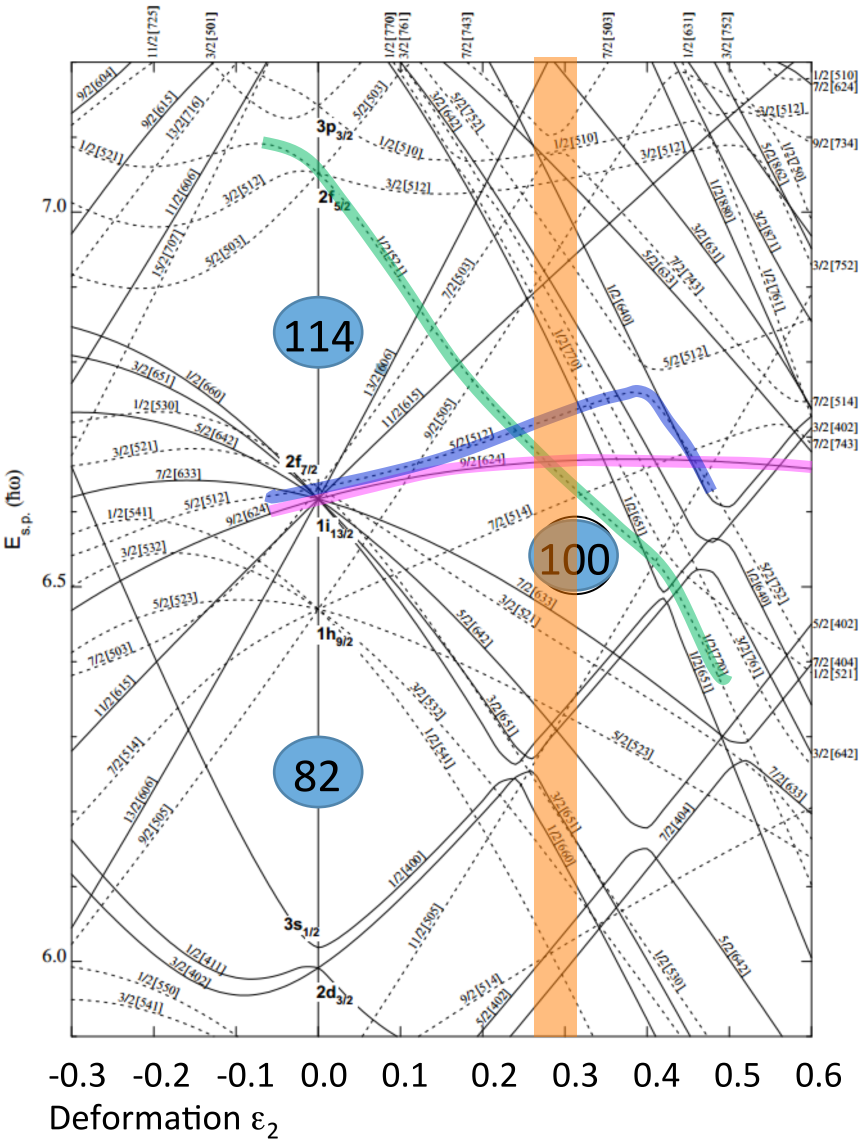


ge03
counts per keV
gamma energy (keV)
2×10⁵
2×10⁵
10⁵
5×10⁴
0
0
100
200
300
400
500



Counts / 1 keV
γ energy (keV)
126*
133*
446
73
86
100
112
139
159
186
212
238
265
585
0
100
200
300
400
500
600
1
2
3
4
5
6

Decay Spectroscopy – Why



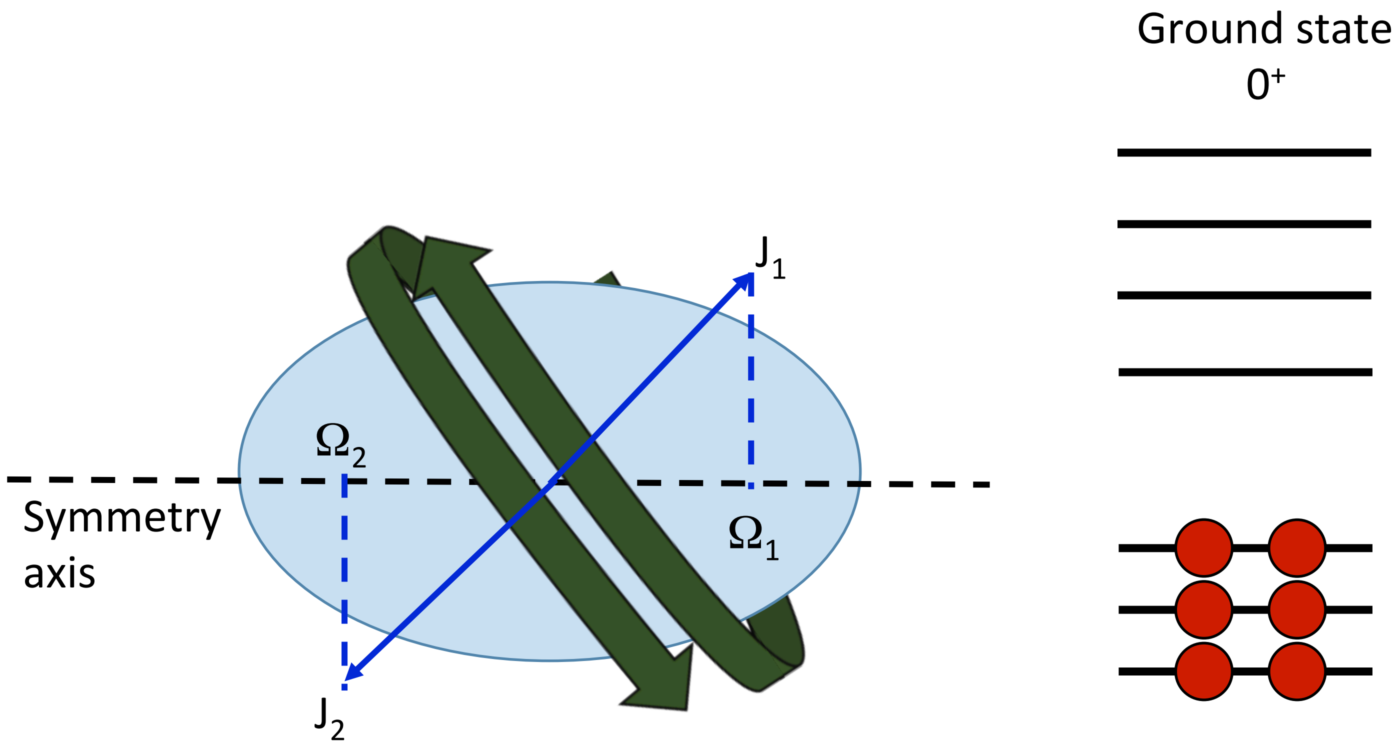
Nilsson diagram for protons with Z≥82

- Single-particle/multi-quasiparticle states
- measurement of rotational, vibrationonal and octupole bands

Investigation of K-isomers in Z~100

K-Isomers – What

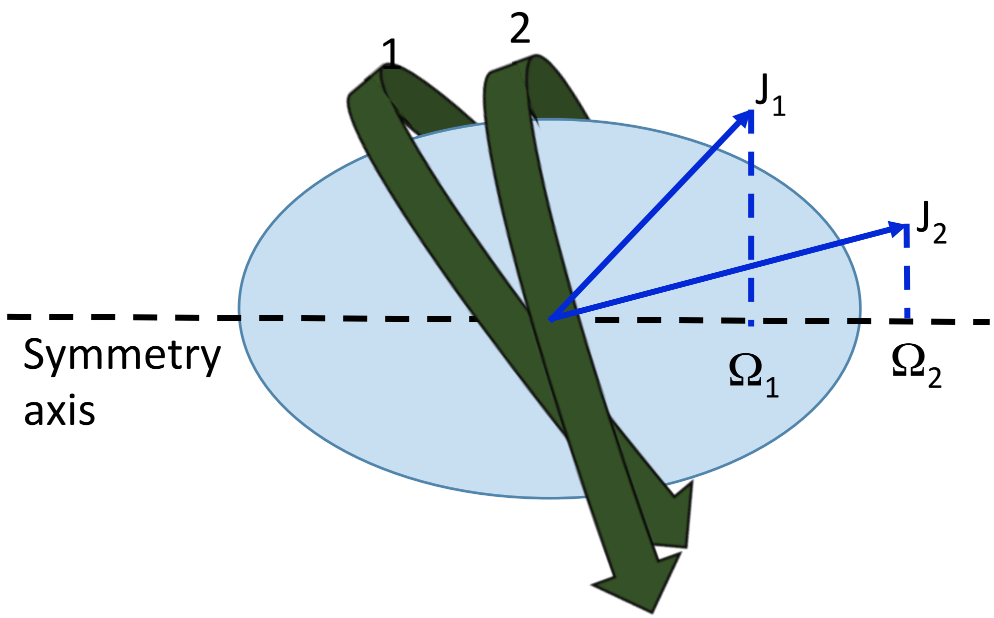
- K is the angular-momentum projection on the nuclear symmetry axis

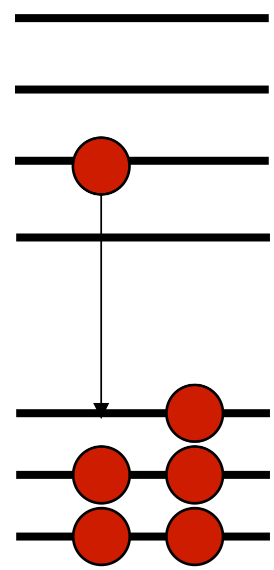


$K = \Omega_1 + \Omega_2$

K-Isomers – What

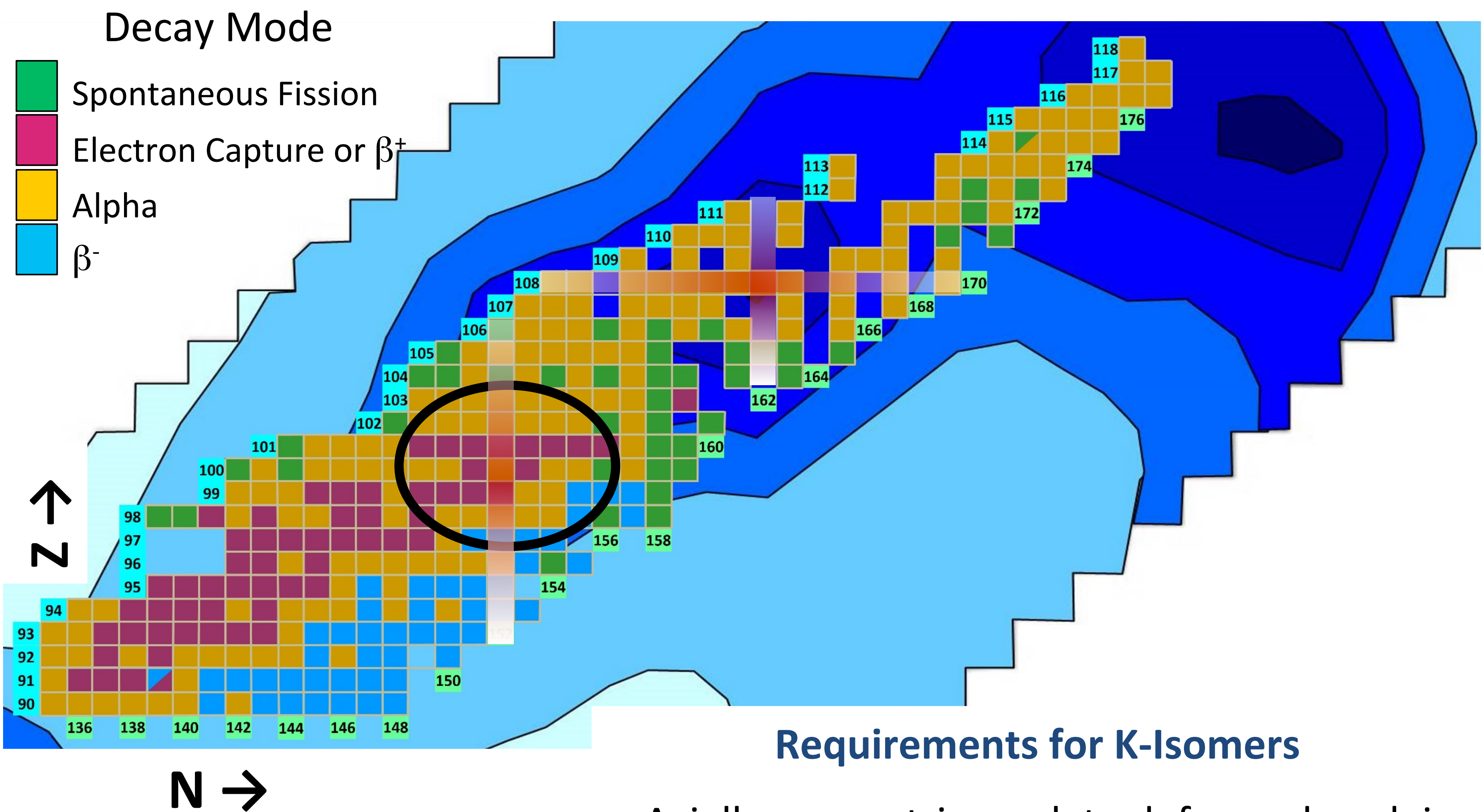
- K is the angular-momentum projection on the nuclear symmetry axis
- K selection rules are similar to J selection rules: transitions with lower ΔK are favored





$K=\Omega_1+\Omega_2$

K-Isomers – Where are they found

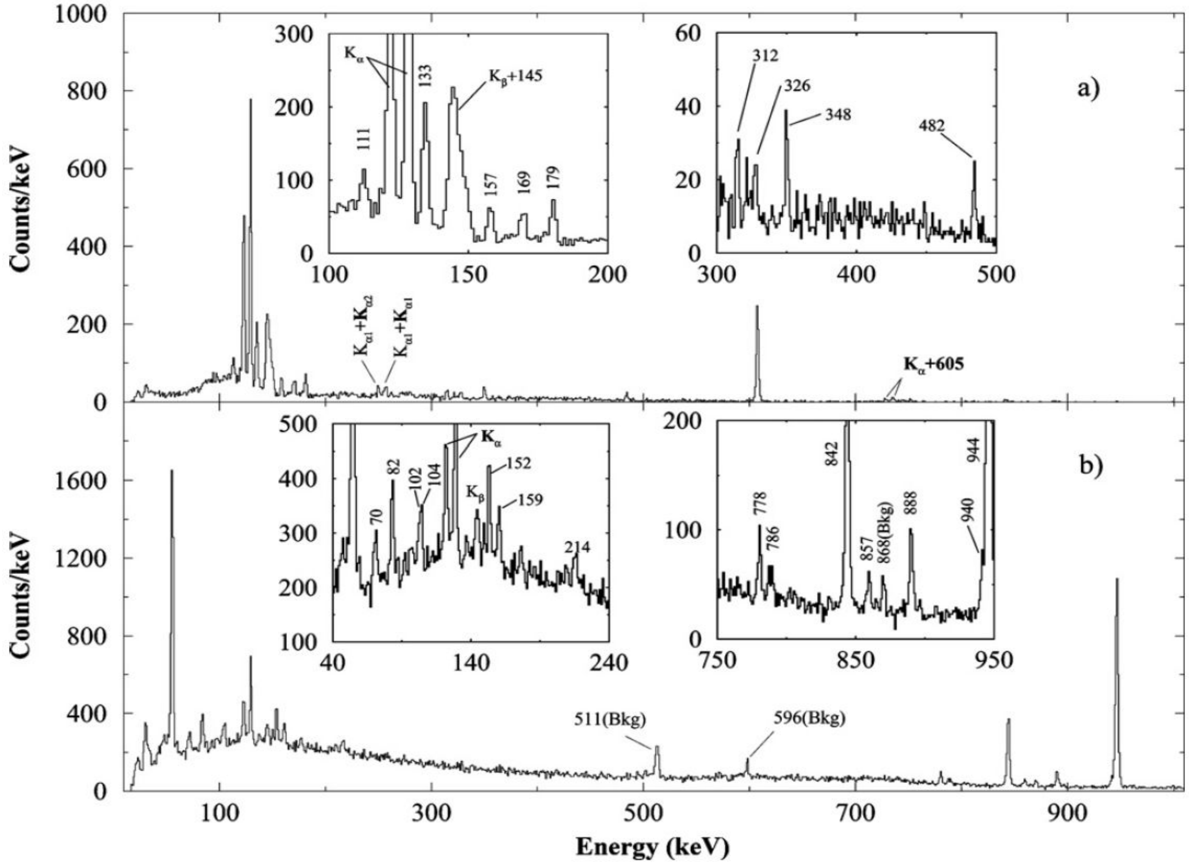


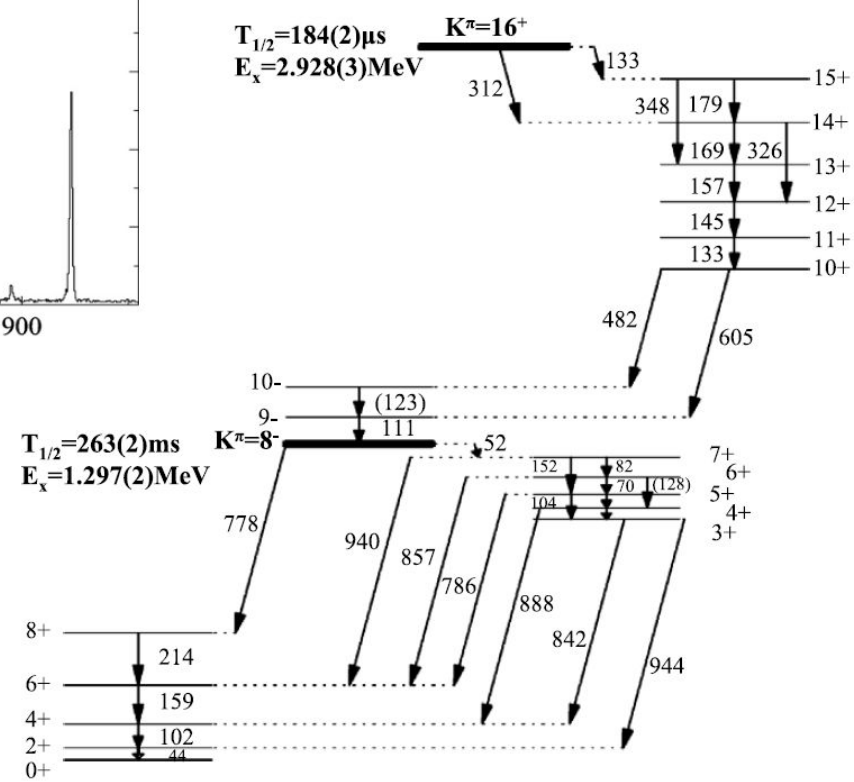
Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

Requirements for K-Isomers

- Axially symmetric, prolate deformed nuclei well away from spherical shells

^{254}No Isomers





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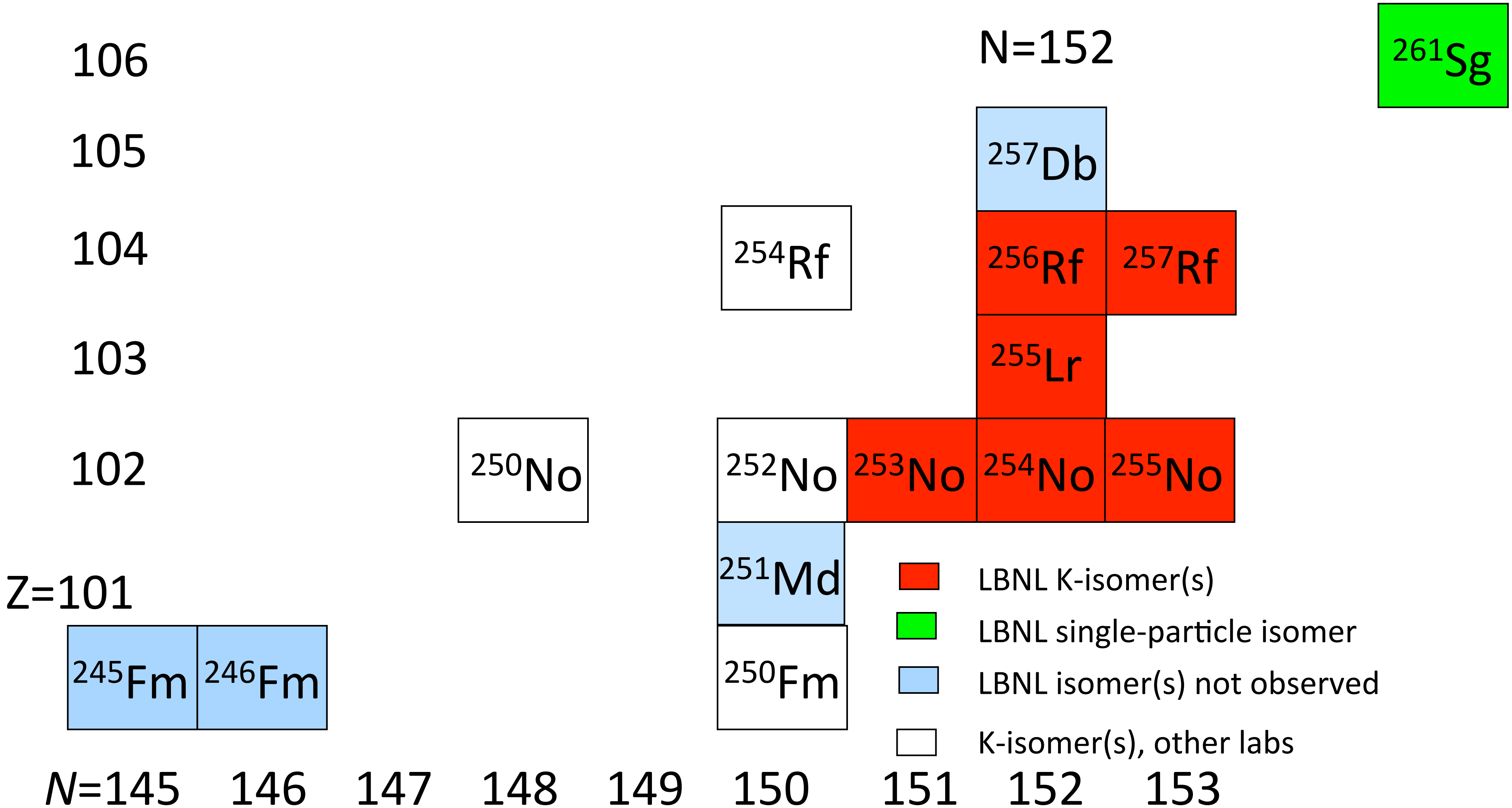
High-K multi-quasiparticle states in ^{254}No

R.M. Clark [a,*], K.E. Gregorich [a], J.S. Berryman [a], M.N. Ali [a,b], J.M. Allmond [c], C.W. Beausang [c], M. Cromaz [a], M.A. Deleplanque [a], I. Dragojević [a,b], J. Dvorak [a], P.A. Ellison [a,b], P. Fallon [a], M.A. Garcia [a,b], J.M. Gates [a,b], S. Gros [a], H.B. Jeppesen [a], D. Kaji [d], I.Y. Lee [a], A.O. Macchiavelli [a], K. Morimoto [d], H. Nitsche [a,b], S. Paschalis [a], M. Petri [a], L. Stavsetra [a], F.S. Stephens [a], H. Watanabe [d], M. Wiedeking [e]

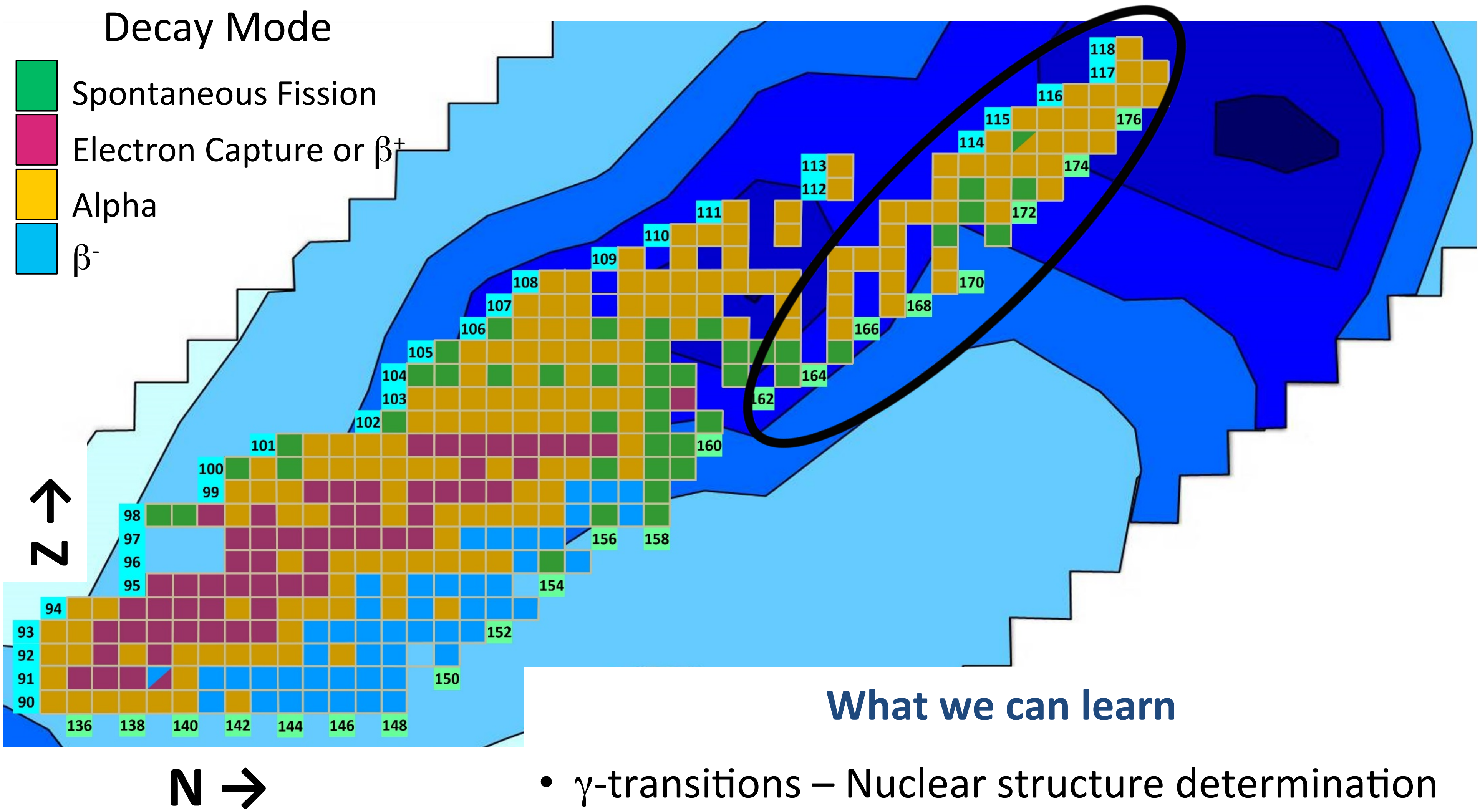
K-Isomer Studies – What we have done

Known excited isomeric states in elements with Z>100



A new generation of experiments is underway addressing the fundamental issue of the maximum limit of nuclear mass and charge.

Going to higher Z – Spectroscopy of SHE



Shell effects from Sobiczewski et al:
Phys. Rev. C 63 (2001) 034306

What we can learn

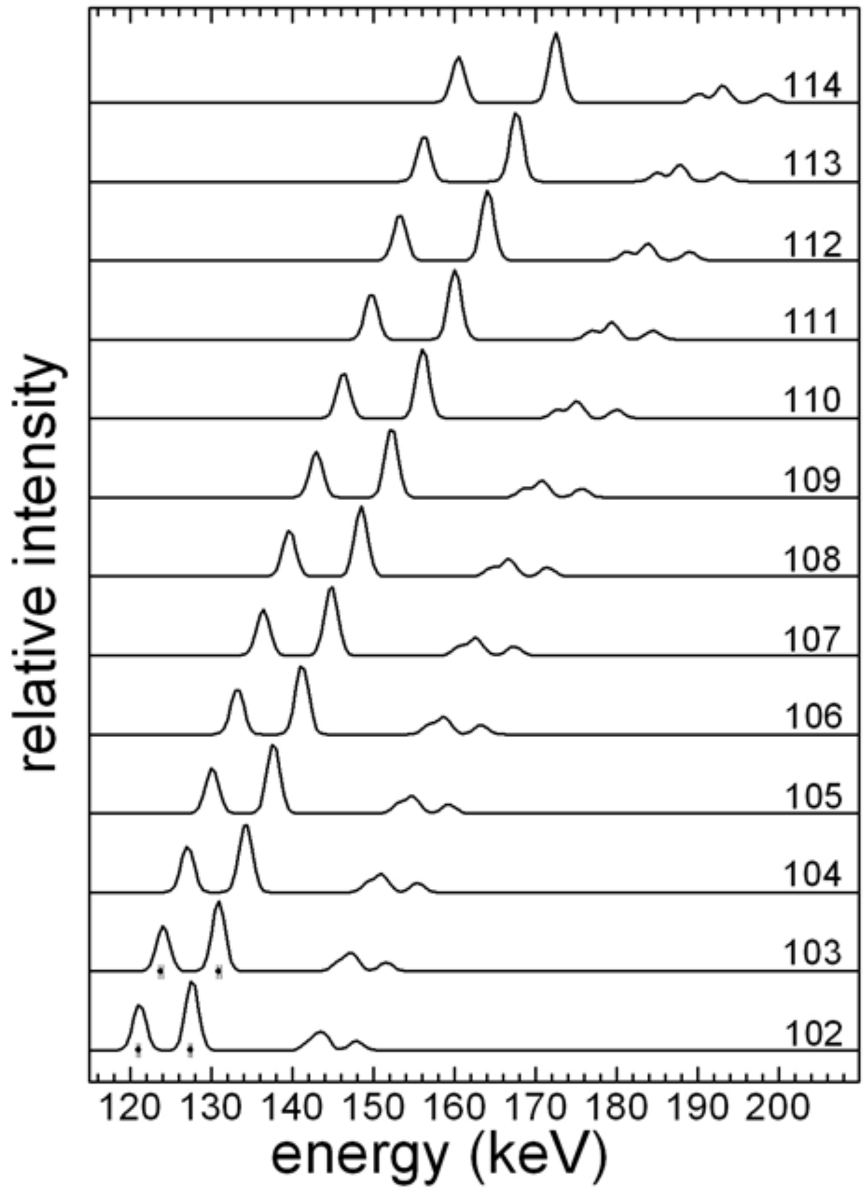
- γ-transitions – Nuclear structure determination
- K X-rays – Z determination
- rotational spectrum – Shape determination

Question

What is the difference between a γ-ray and an x-ray?

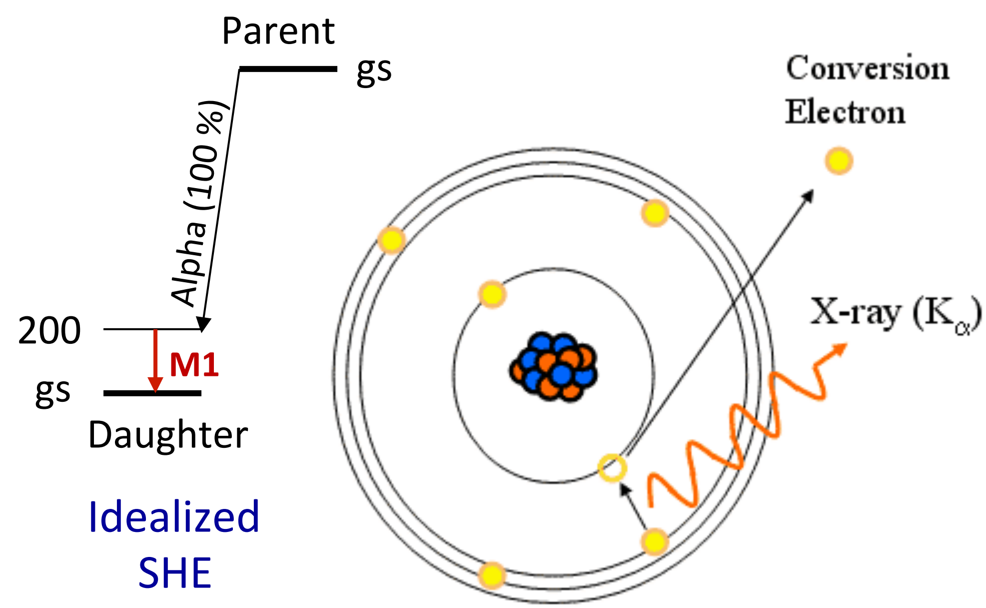
a) X-rays are atomic transitions, γ-rays are nuclear transitions
b) X-rays are nuclear transitions, γ-rays are atomic transitions
c) X-rays are lower energy than γ-rays
d) No difference

What is needed for a Z identification



Dirac-Fock-Slater prediction of K x-ray energies –
(B. Fricke, G. Soff, At. Data Nuc. Data Tab, **19**, 83 (1977)

Observation of 3 Kα X rays can provide unambiguous Z identification – in the absence of background

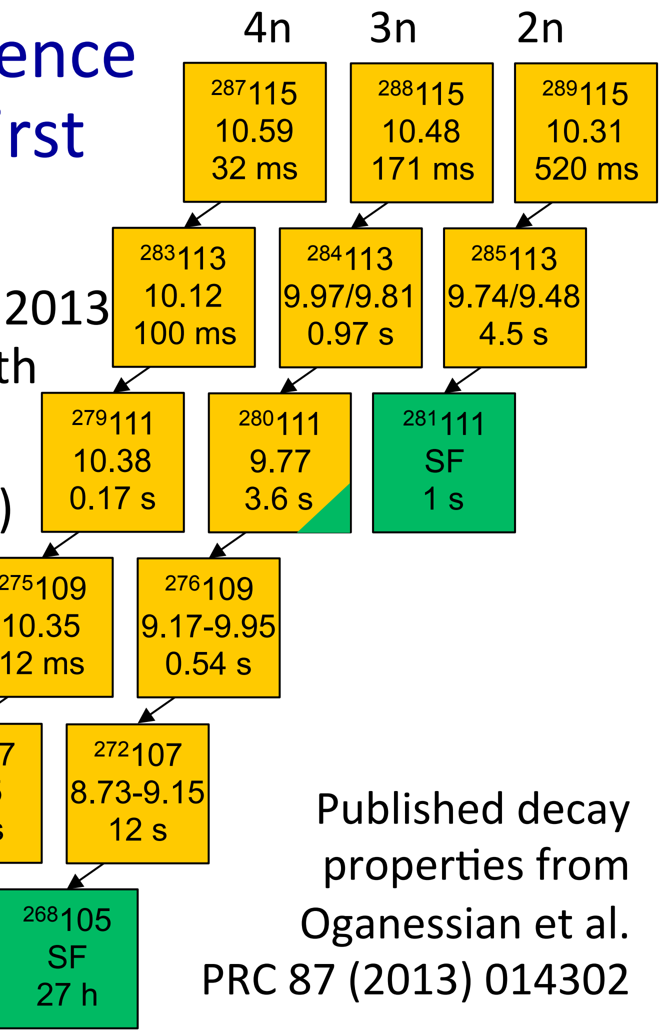


Idealized SHE Decay

Toward Decay Spectroscopy of E115

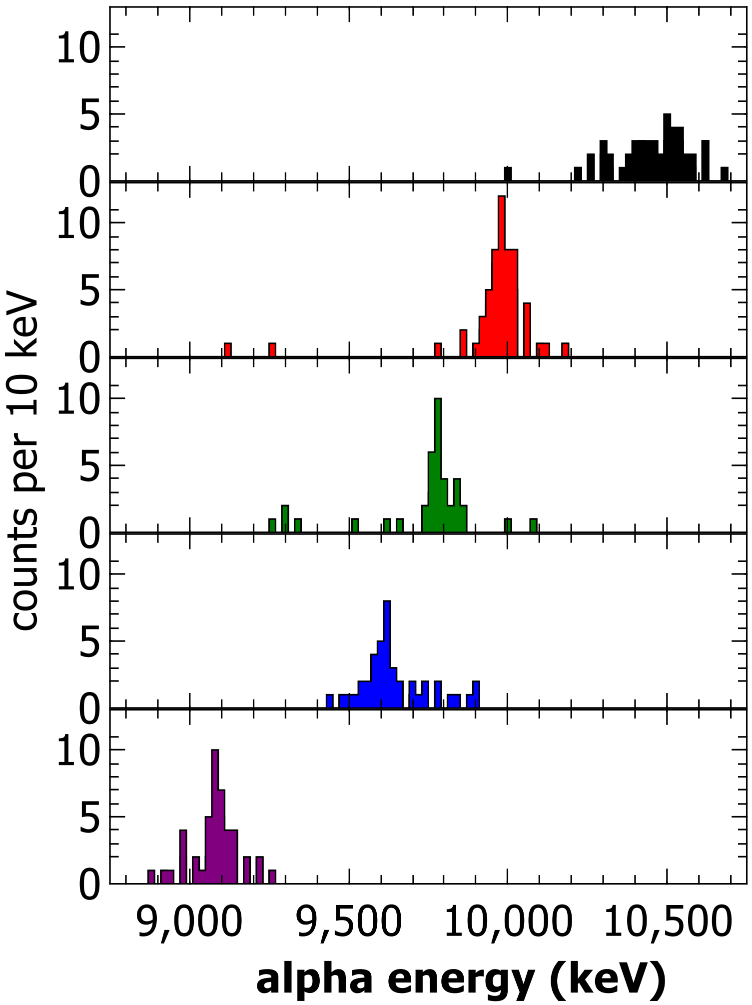
observing characteristic x-rays in coincidence with α-particle decays would provide first confirmation of SHE proton number

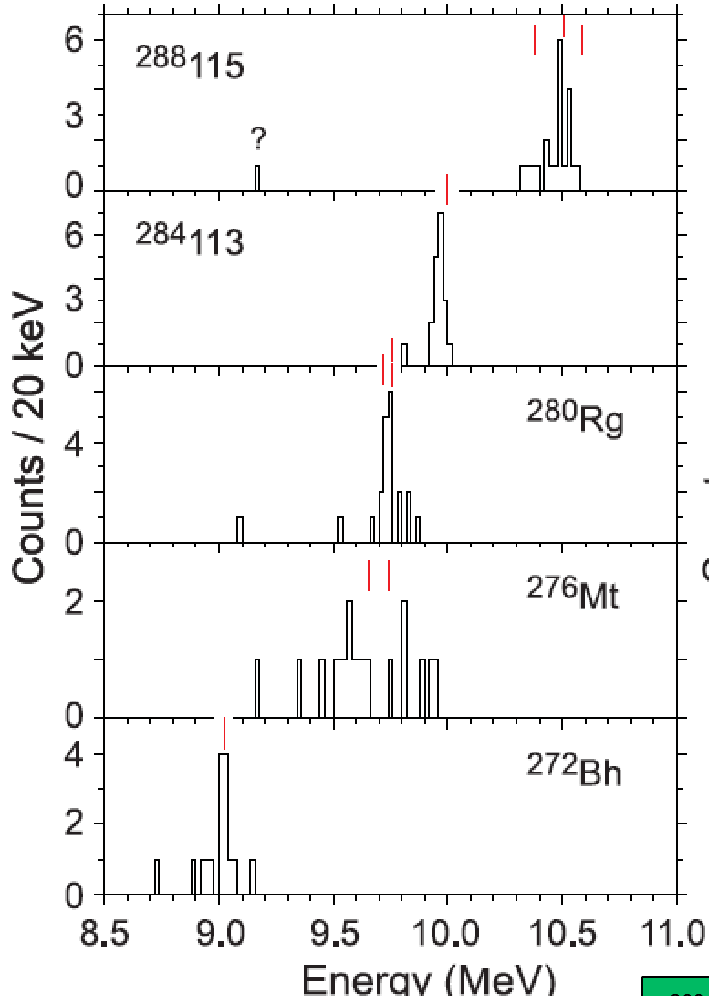
- ^{48}Ca + ^{243}Am experiments performed at GSI in Nov-Dec 2013 and continued at LBL in April-June 2013 and studied with TASISpec (GSI) and C3 (LBL)
- Average beam intensity on target was 1 pμA (6×10^{12} s^{-1})
- 46 events of element 115 were observed at LBL and 30 events of 115 observed with TASISpec
- Multiple α-photon coincidences were observed between the two experiments

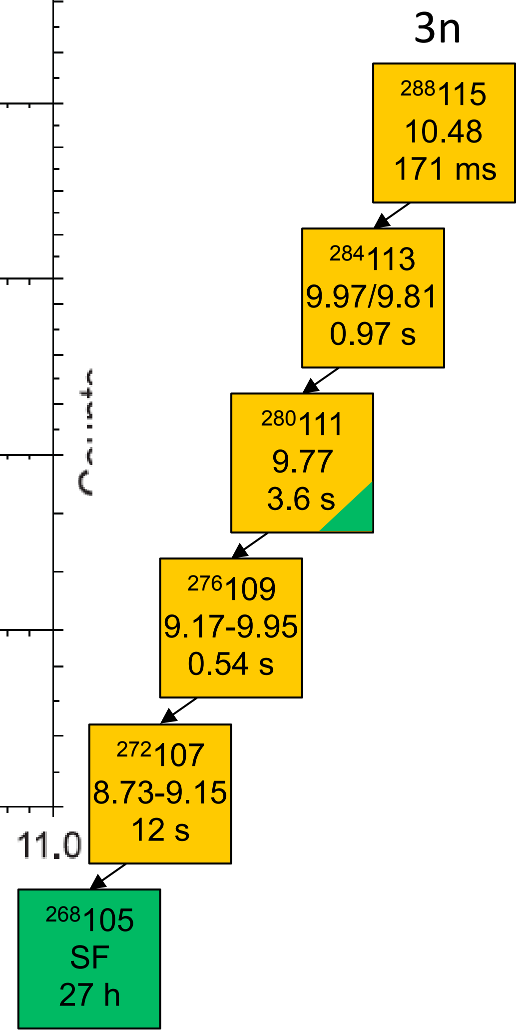


Published decay properties from Oganessian et al. PRC 87 (2013) 014302

Spectrum of α-decays from E115 and daughters

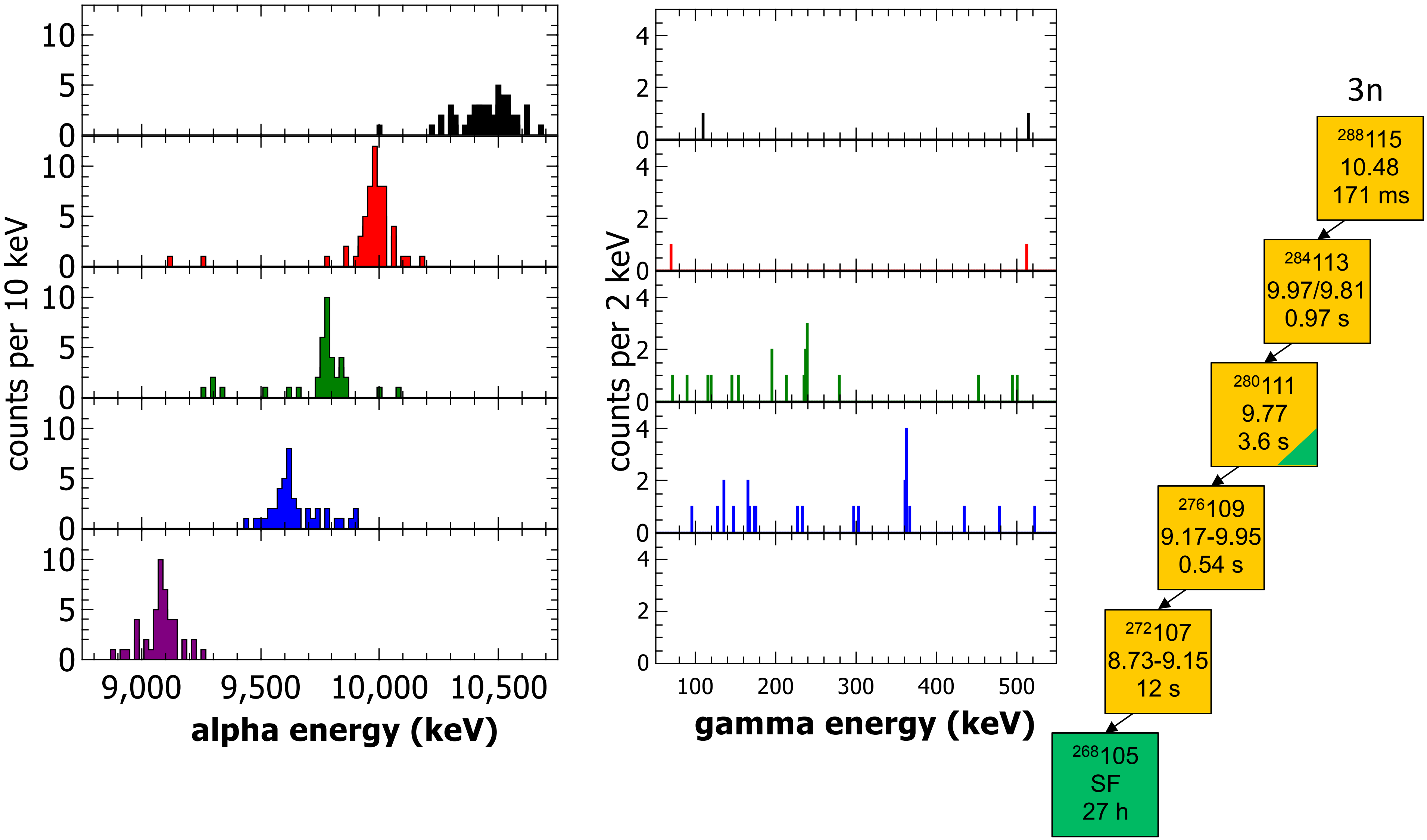




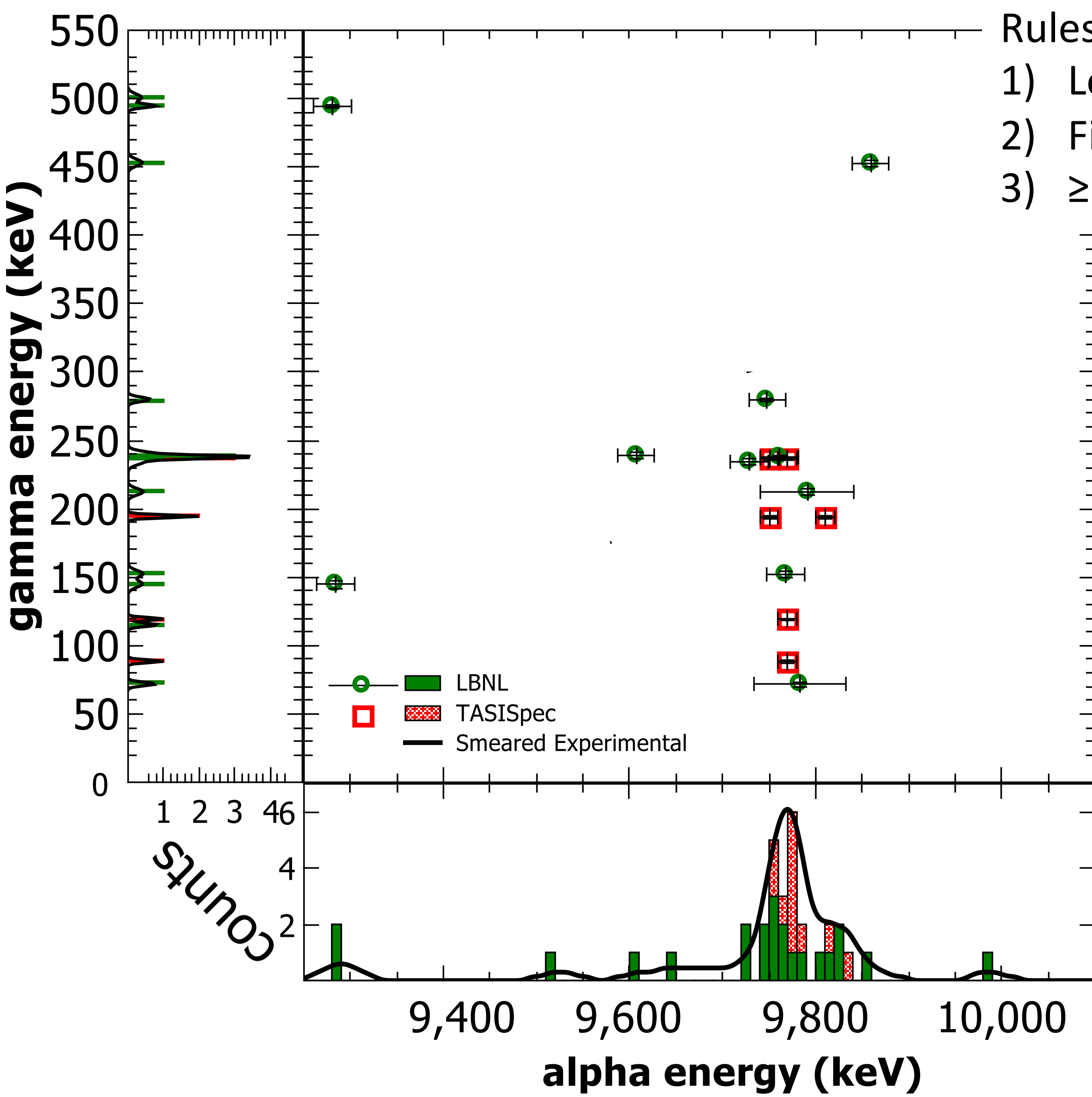


Oganessian et al:
PRC 87 (2013) 014302

α and γ spectrum from decay of E115 and daughters

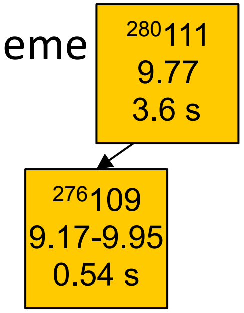


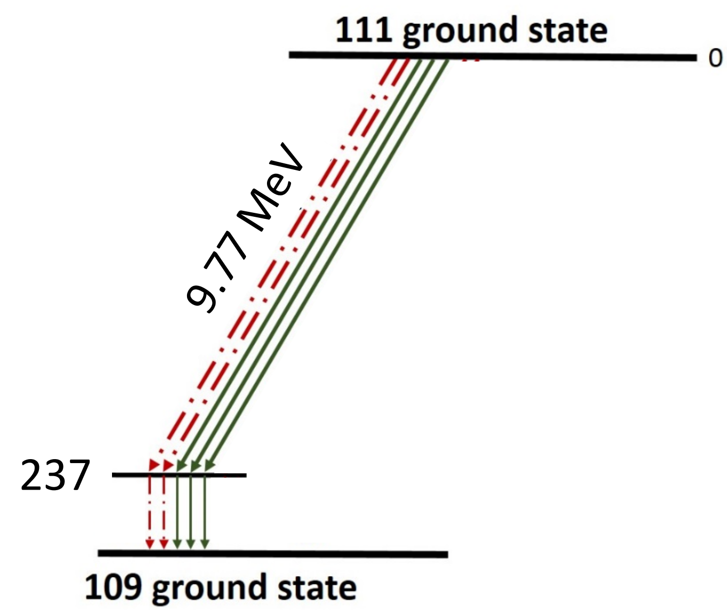
γ-like events Coincident with ‘^{280}111’ Decays



Rules for building the level scheme

1) Lots and lots of events
2) Fits on a diagonal
3) ≥ 2 α-γ coincidences



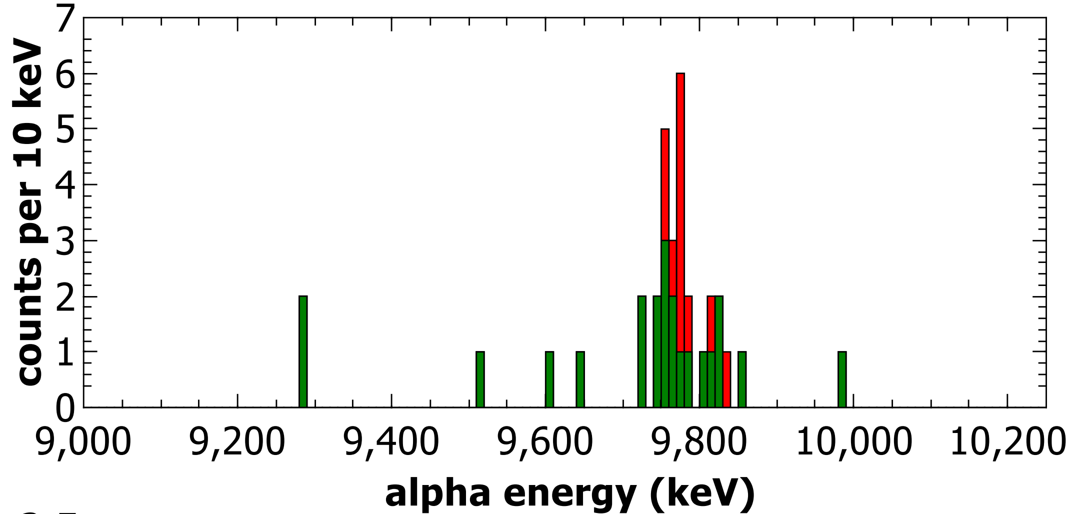


Proposed level scheme from Rudolph et al: PRL 111 (2013) 112502

Question

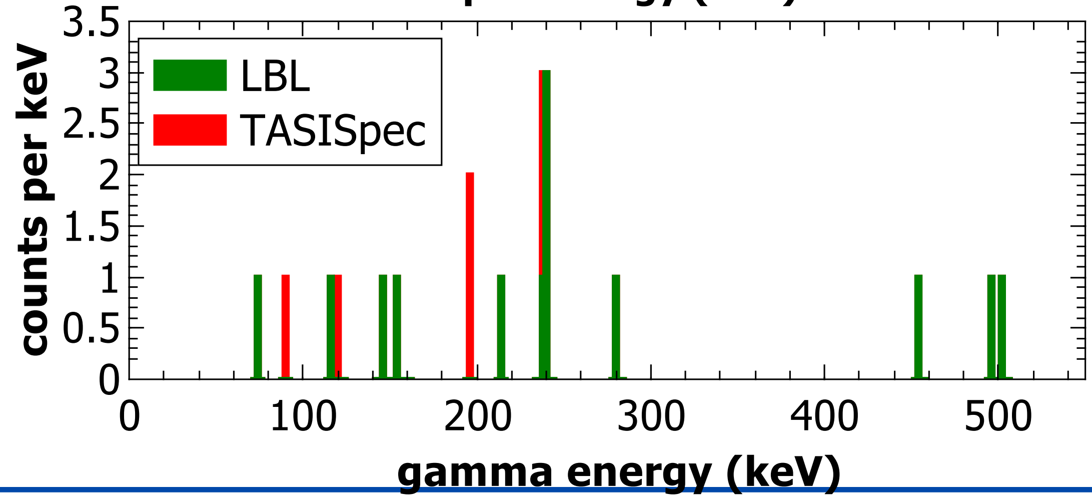
Given the α and γ spectra and ratios of emitted conversion electrons to γ-rays below, can we determine the multipolarity of the 237-keV transition? If so, what is it?

A) No
B) Yes, M1
C) Yes, E1
D) Yes, E2



Conversion Electron/γ-ray:

M1: 9.33
E1: 0.0929
E2: 1.493



Question

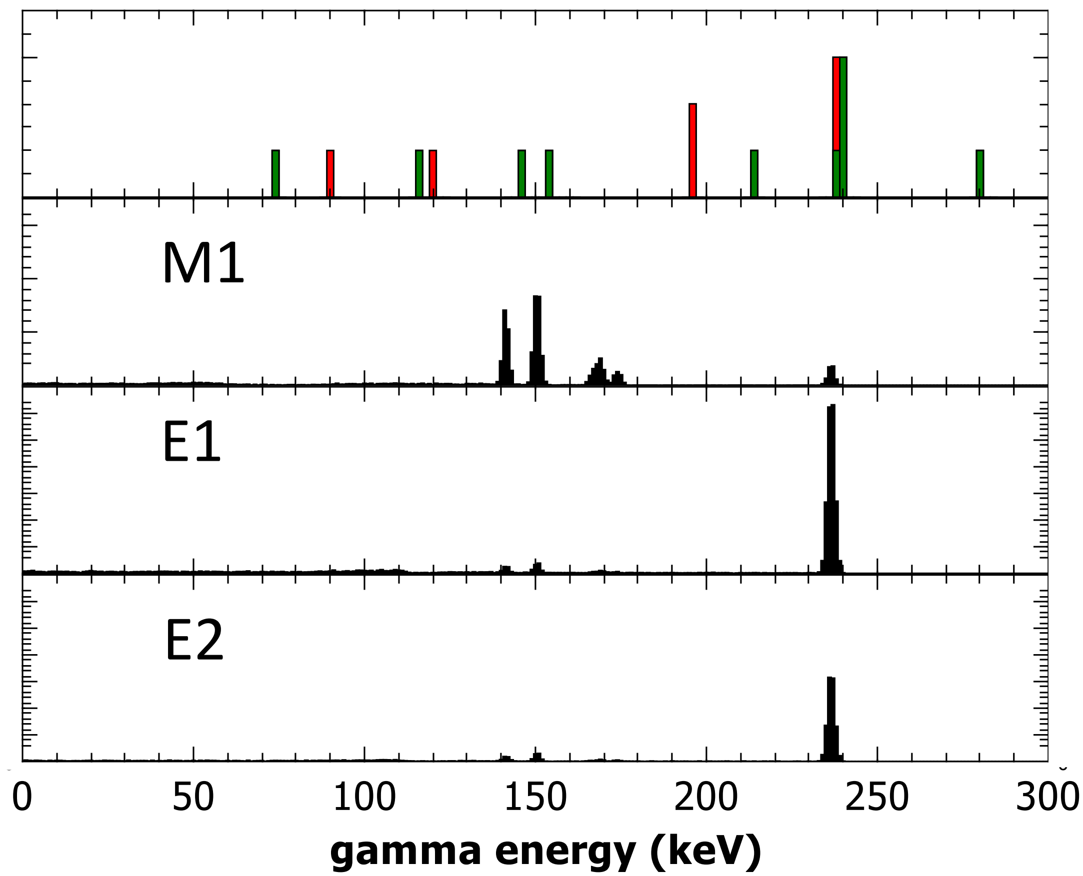
Given the α and γ spectra and conversion coefficients below, can we determine the multipolarity of the 237-keV transition? If so, what is it?

A) No

B) ~~Yes, M1~~

C) Yes, E1

D) Yes, E2



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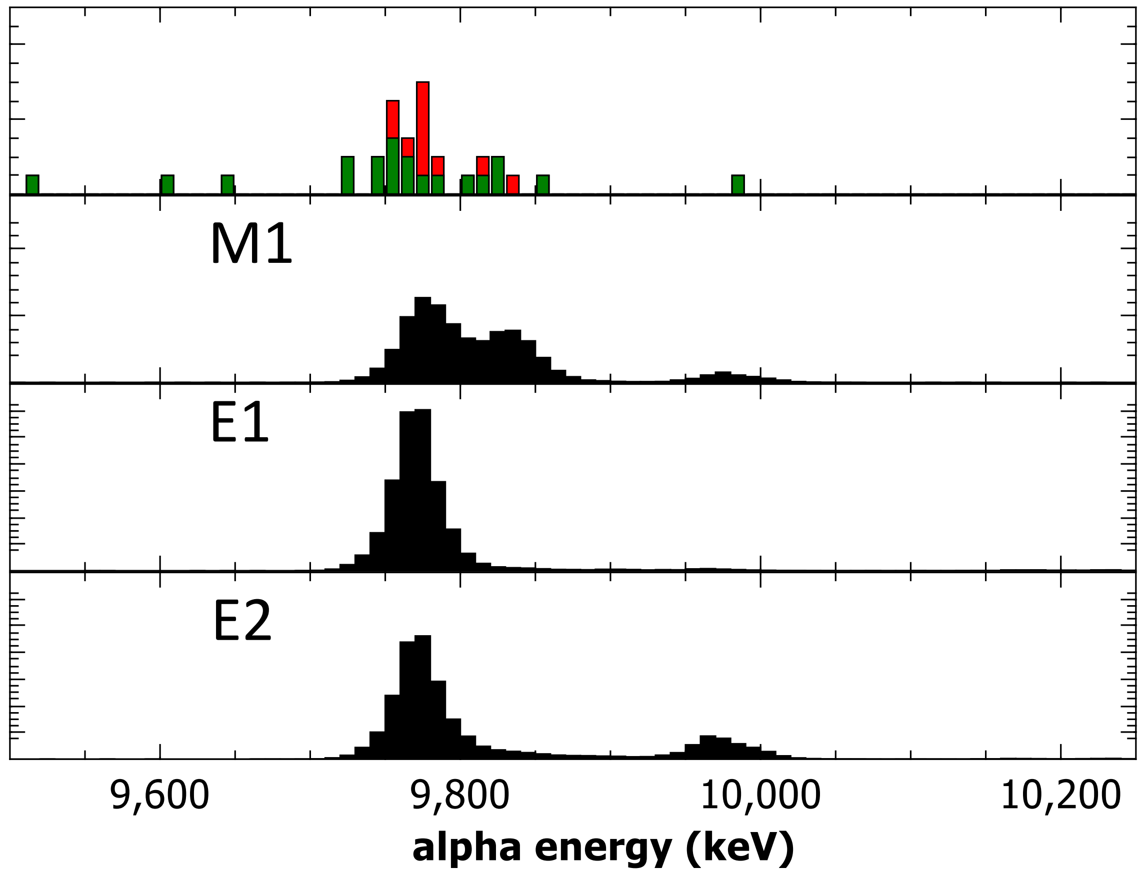
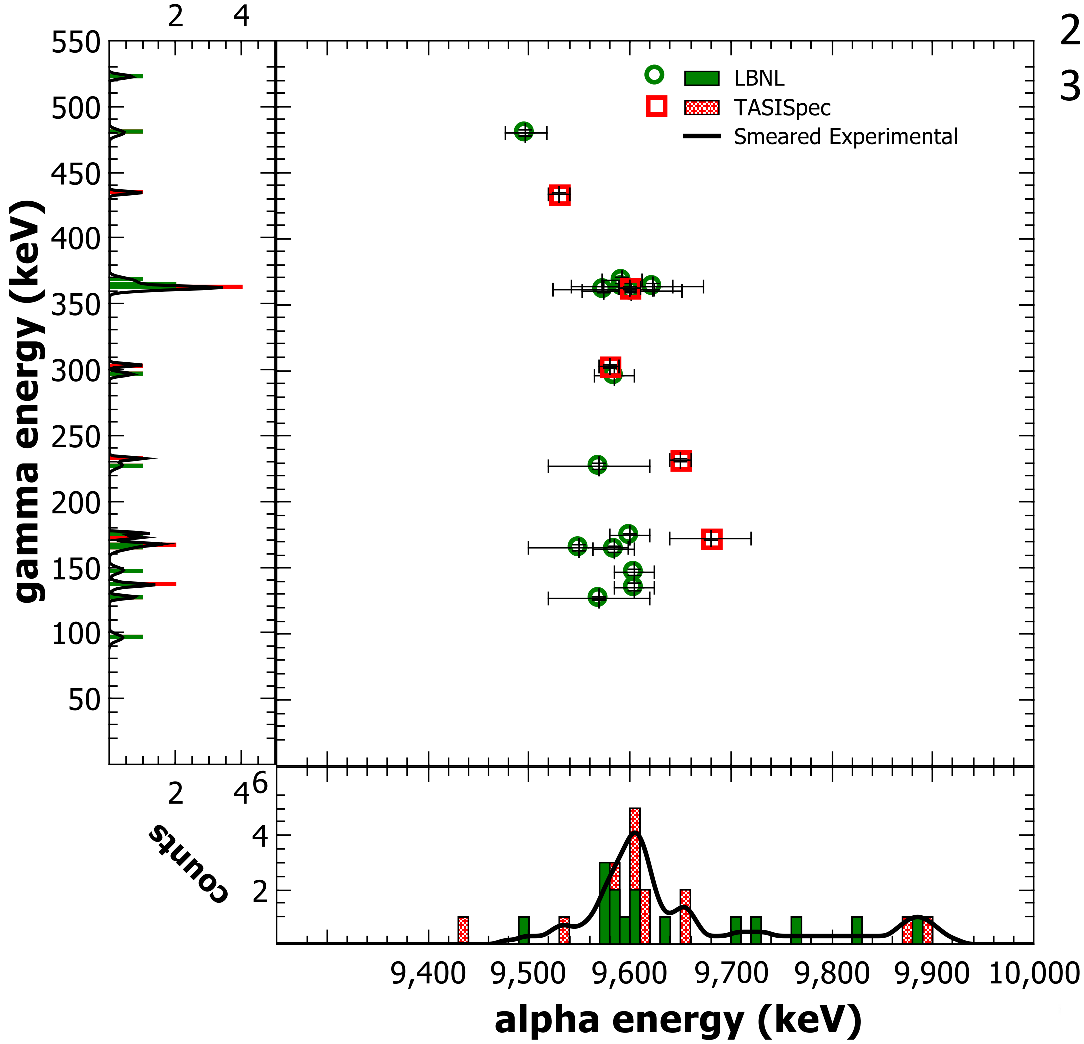


Conversion Electron/γ-ray:

M1:	9.33
E1:	0.0929
E2:	1.493

γ-like events Coincident with ‘^{276}109’ Decays



Rules for building the level scheme

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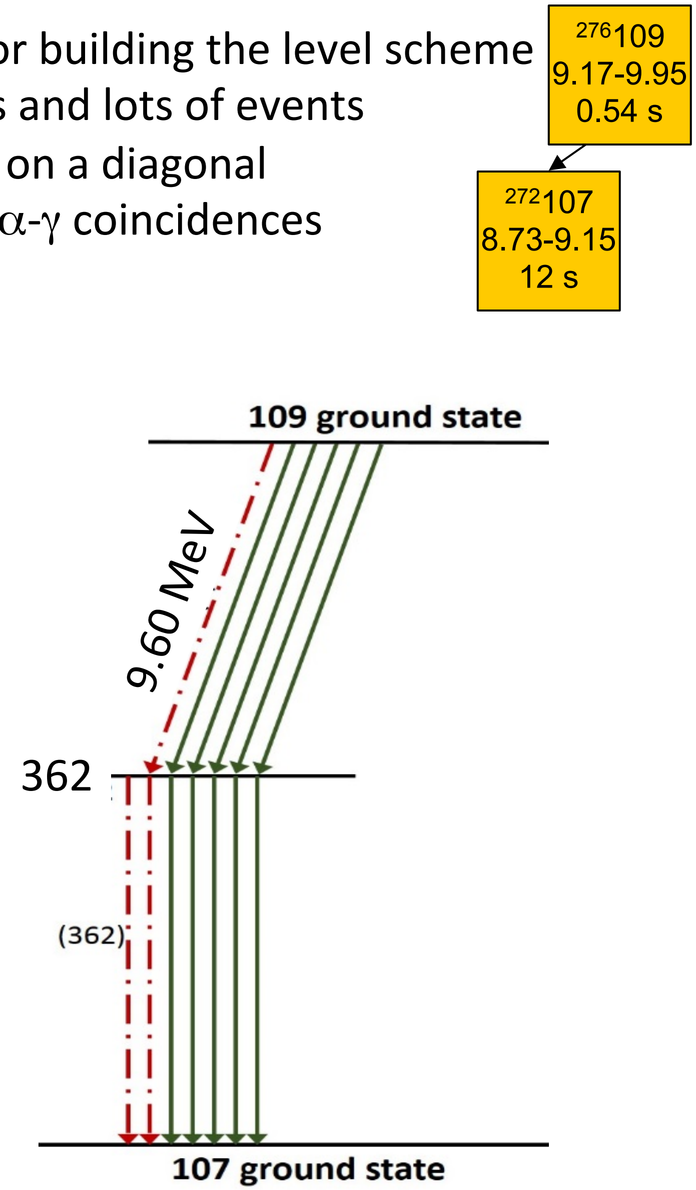
2) Fits on a diagonal
3) ≥ 2 α-γ coincidences



Summary

In-Beam Spectroscopy has been performed on Fm, No and Rf isotopes

- Ground state rotational bands
- Deformation
- Hints of higher lying states

K-Isomer studies

- Ground state rotational bands
- Where K-isomers exist
- Higher lying states

E115 Spectroscopy

- one excited state each in $^{280}111$ and $^{276}109$

B E R K E L E Y , C A L I F O R N I A