DE LA RECHERCHE À L'INDUSTRIE

INVESTIGATION OF GROUND STATE BAND AND HIGH K STATES IN TRANSFERMIUM ELEMENTS

ESPACE DE STRUCTURE ET DE RÉACTIONS NUCLÉAIRES THÉORIQUE

NOVEMBER 16TH-19TH 2015

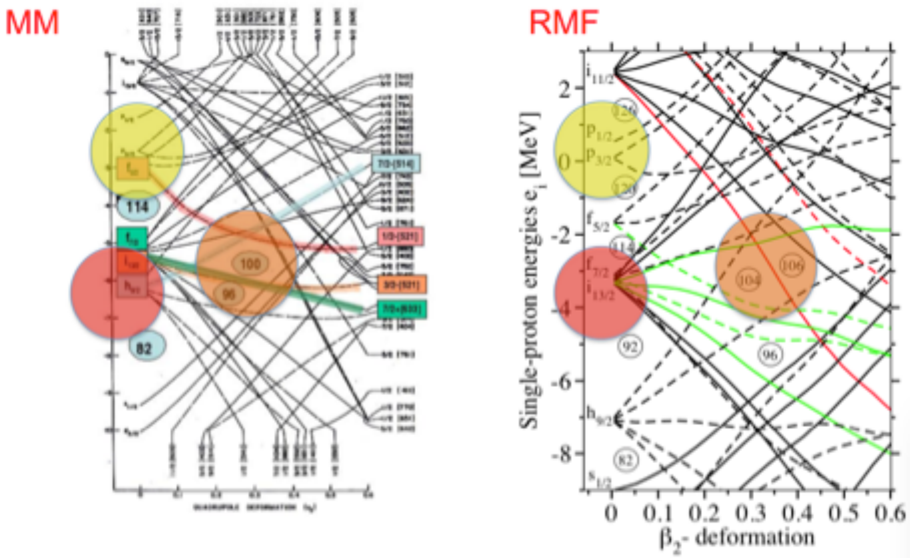
Barbara Sulignano *CEA SACLAY*

Outlook

- Motivation
- Few Results: even even nuclei; Isomeric high K states; prompt electron spectroscopy
- Experimental Observables & Comparison with the theory
- Conclusion & perspectives

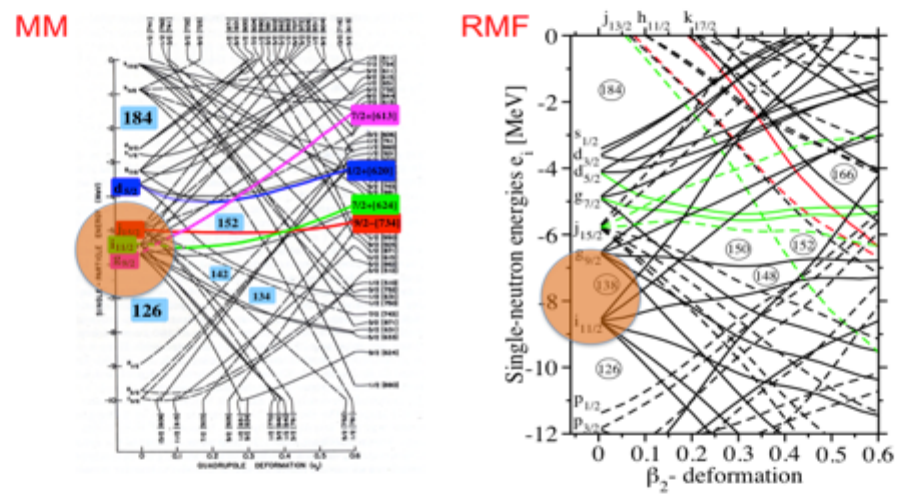
MOTIVATION: CONSTRAINING THEORY

Nilsson Diagram: Protons



- ➢ Microscopic-Macroscopic models based on a liquid drop model (Z=114)
- ➢ Relativistic mean field models (Z=120,126)
- ➢ Hartree-Fock-Bogoliubov –Skyrme or Gogny Interaction (Z=120,126 N=184)

Nilsson Diagram: Neutrons



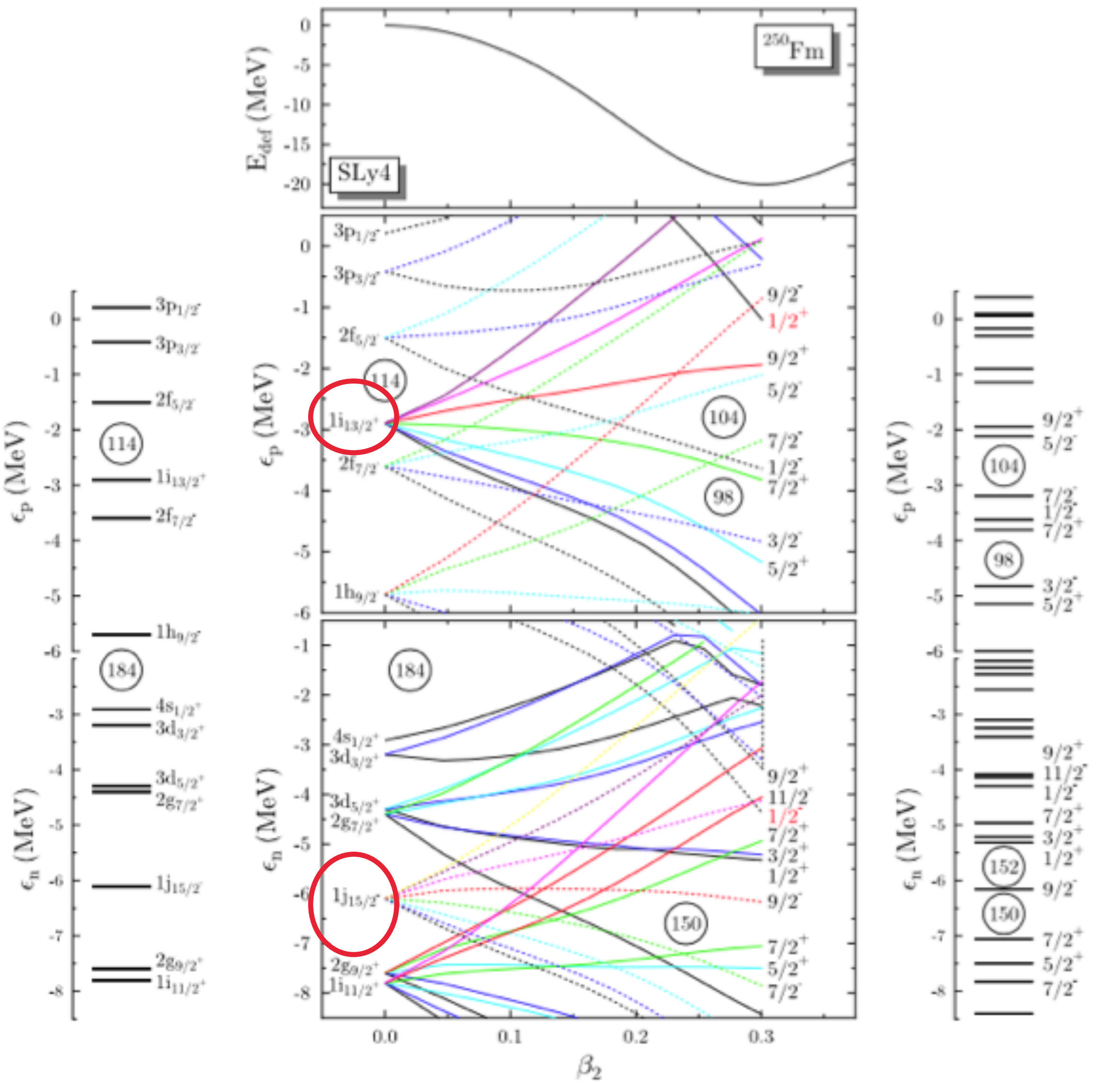
Similar differences seen for neutron level structure

MOTIVATION: CONSTRAINING THEORY

- Differences in single-particle structure reflected in the shell gaps for both spherical and deformed systems

Problems:
No gap at Z=100 or 102
No gap at N=152

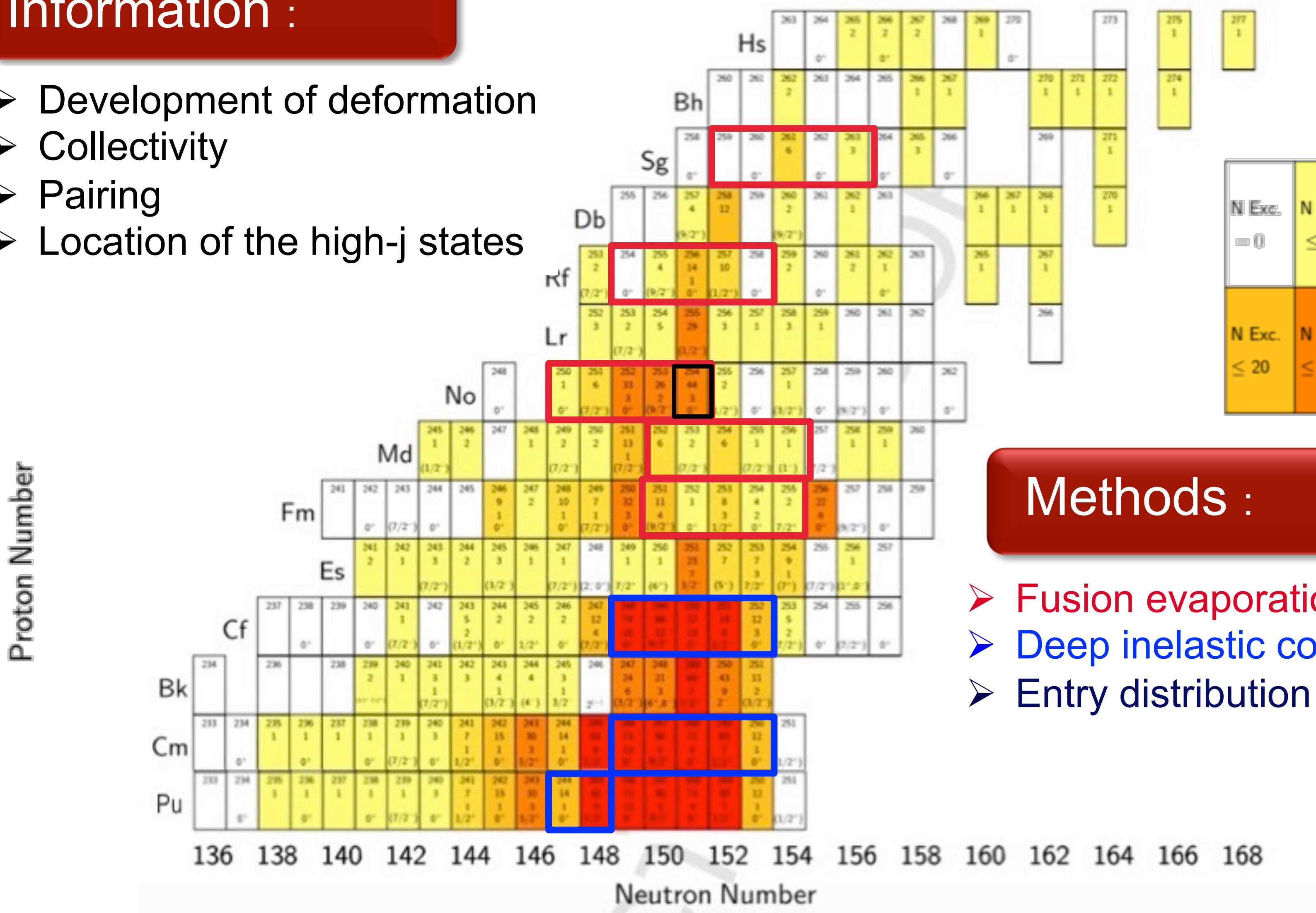
Trace to position of high-j Orbitals? π $i_{13/2}$ and ν $j_{15/2}$

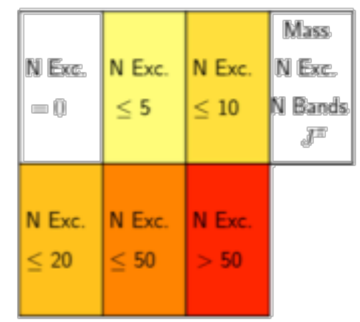


WHY IN BEAM TECHNIQUES TO STUDY HEAVY NUCLEI?

Information :

- Development of deformation
- Collectivity
- Pairing
- Location of the high-j states

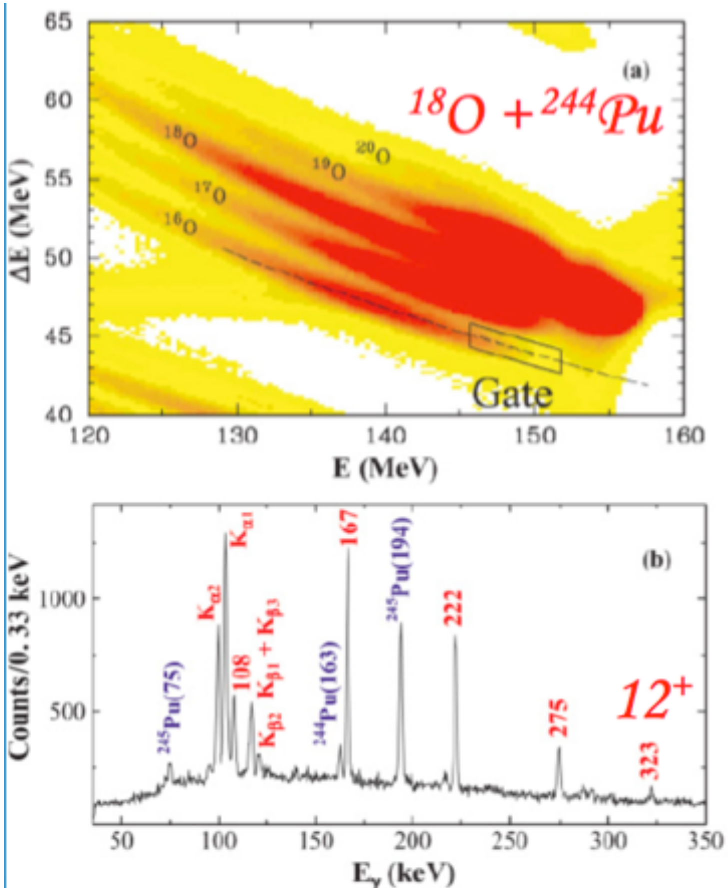




Methods :

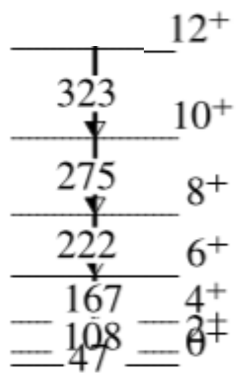
- Fusion evaporation reaction
- Deep inelastic collision
- Entry distribution

TRANSFER REACTIONS G.S BAND N=152 : ^{246}PU

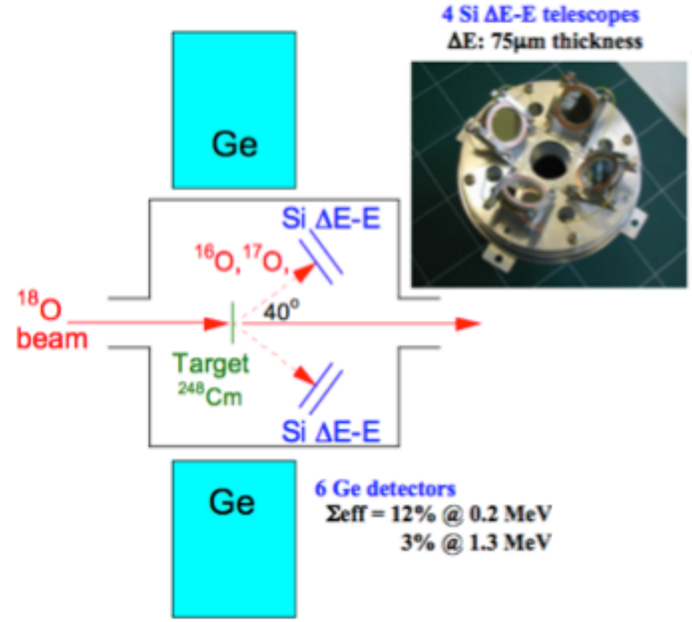


H. Makii et al., PRC 76, 081301(R) (2007)

$^{18}O + ^{244}Pu$



$^{246}Pu_{152}$



Transfer reaction @ TOKAI tandem JAEA:

- Light ions beams
- Outgoing projectile-like particles detected by Si ΔE − E detectors.
- γ rays were measured by Ge detectors, in coincidence with outgoing particles.

GOALS OF THE EXPERIMENTS

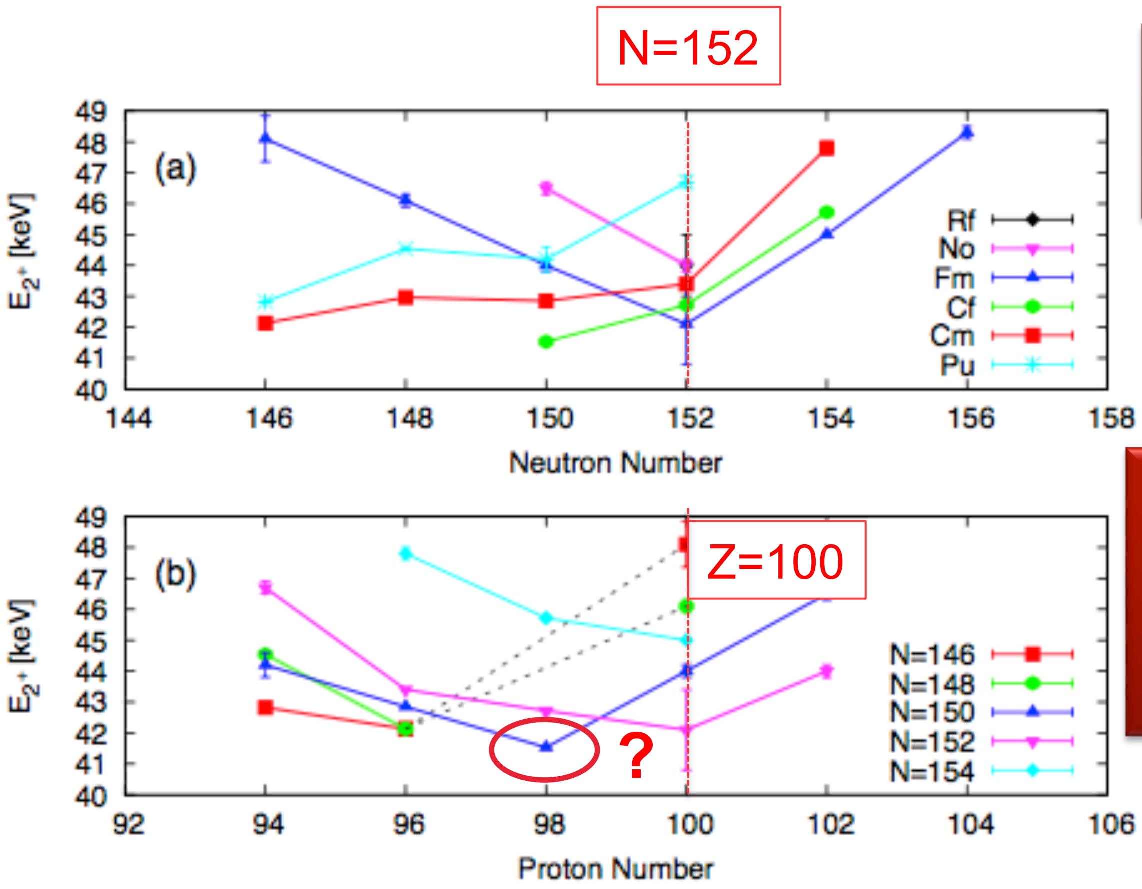
Observables

- Excitation energies, spins, parities
- Moment of inertia
- Rotational alignment
- Isomeric states

Goals

- Shell effect
- Pairing correlations
- Collective modes
- Quasi particle configuration

SYSTEMATICS OF THE EXPERIMENTAL 2+ ENERGY



The E2+ are sensitive to the deformation and to the shell effect

- Experimental shell gap N=152 & Z=100
- Reduction of shell gap for ^{246}Pu
- More data are needed
- Strong collective effect in Cf

Ch.Theisen, P.T.Greenlees et al. EPJ(2015)

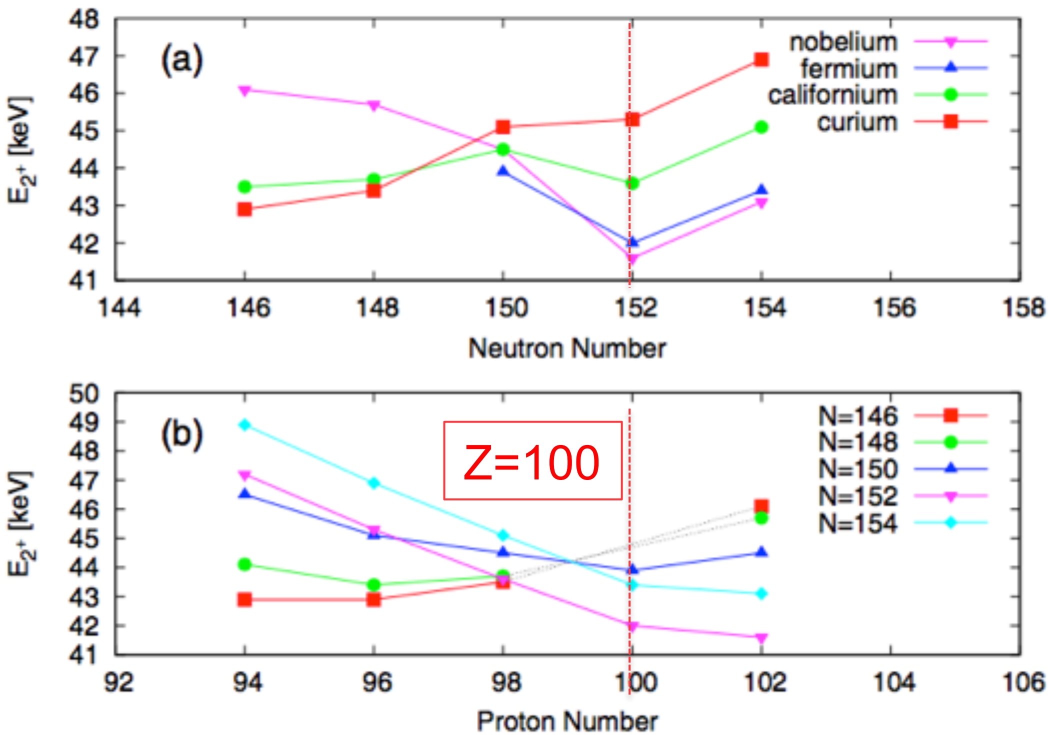
SYSTEMATICS OF THEORETICAL 2^+ ENERGY

Pairing correlation are reduced at a deformed shell gap

→ Larger Moment of Inertia → smaller E_{2+}

Sobiczewski, Muntian, Patyk. PRC 63, 034306 (2001)

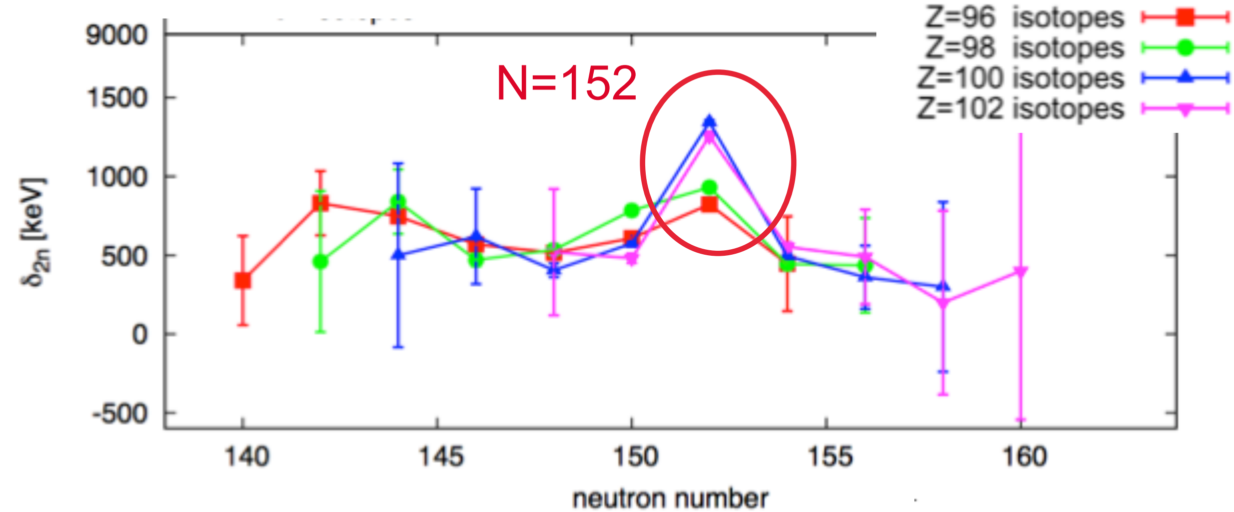
N=152



- The calculated E2 values reproduce the systematics around N=152 very well
- The Z = 100 gap is present but less pronounced.
- There is no minimum at Z = 98

CORRELATION TO MASSES

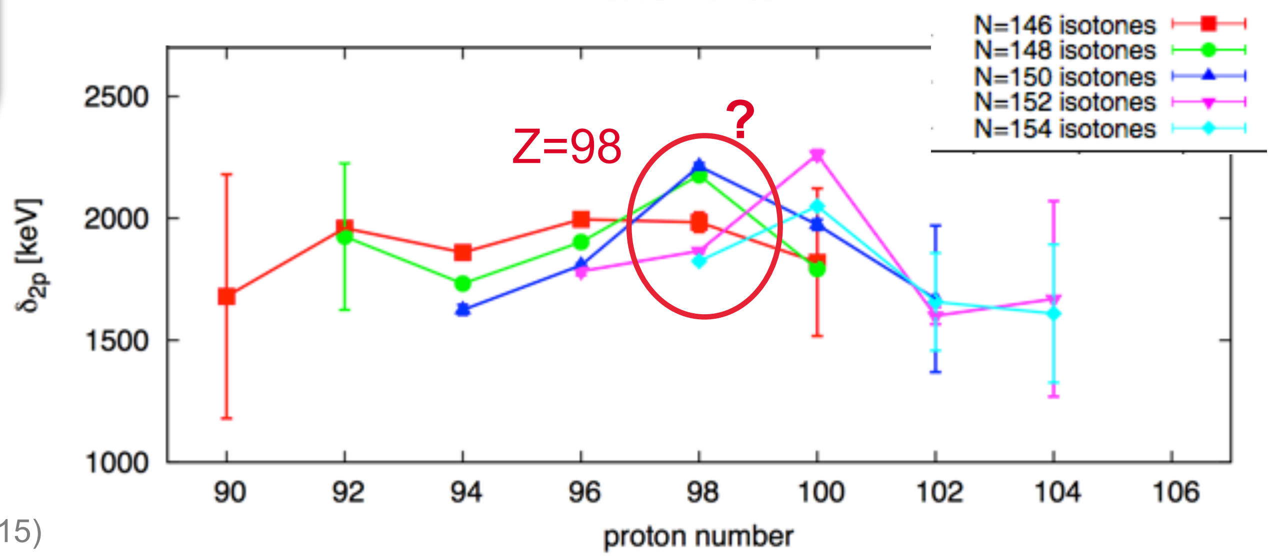
$$\text{AME2003: } S_{2n}(Z,N) = B(Z,N) - B(Z,N-2),\ \delta_{2n}(Z,N) = S_{2n}(Z,N) - S_{2n}(Z,N+2)$$



Shell gap parameter

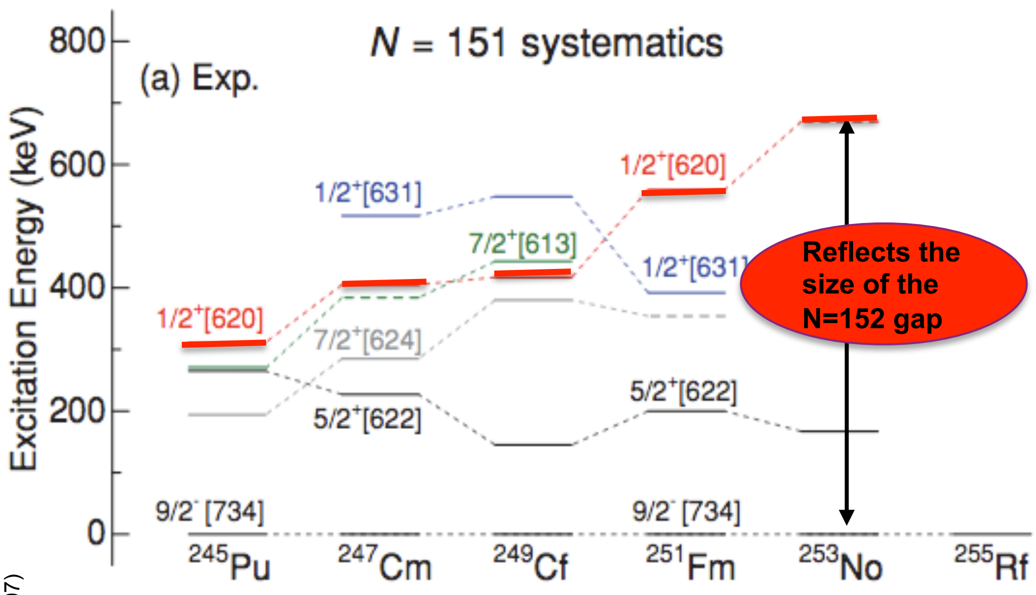
There is a correlation between the masses and the effect at Z=98

Anomaly in Cf isotopes

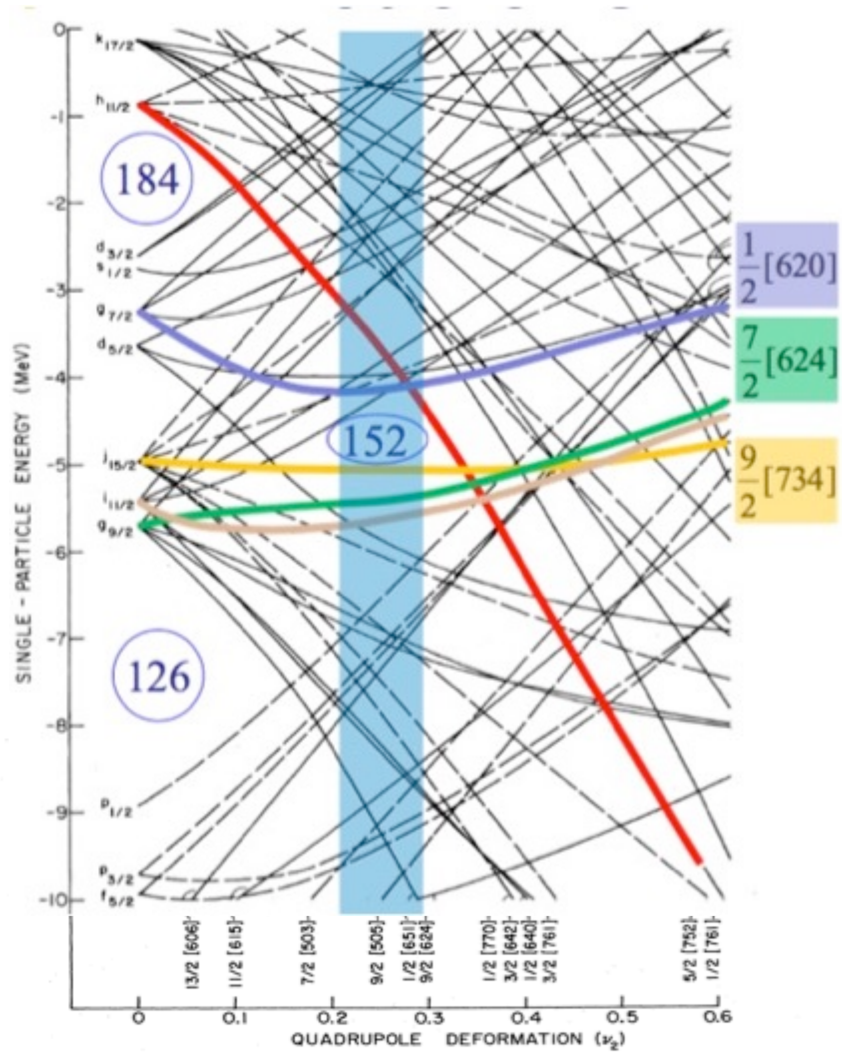


Ch.Theisen, P.T.Greenlees et al. EPJ(2015)

SYSTEMATICS OF ONE QUASIPARTICLE LEVELS IN N=151 ISOTONES - SHELL GAP N=152

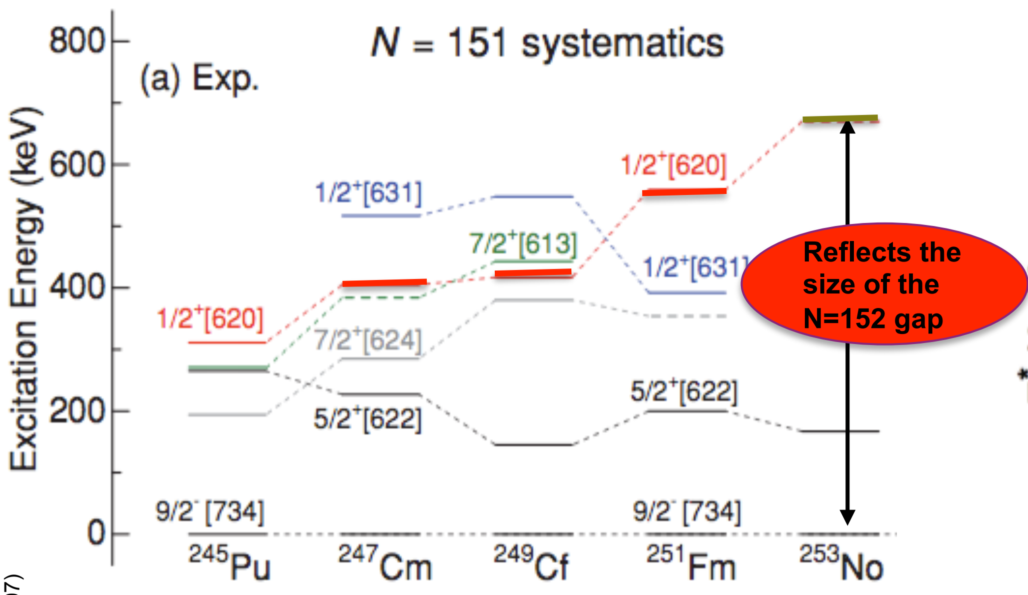


H. Makii prc 76(2007)

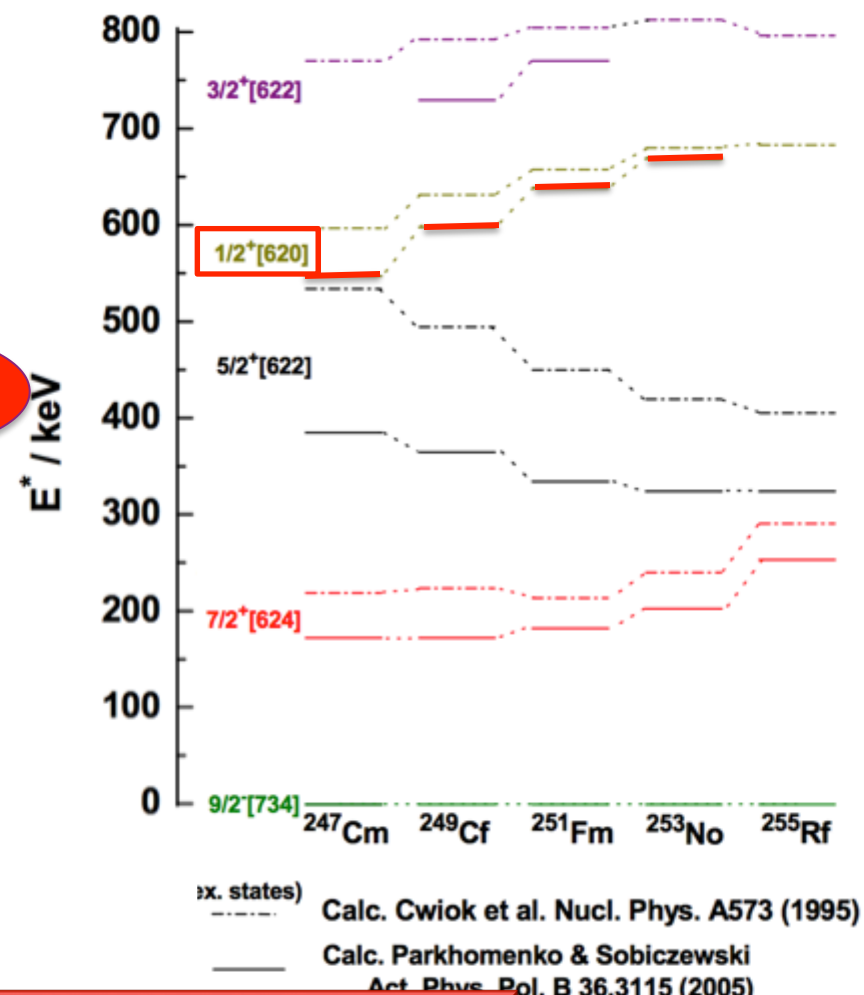


➢ N=152 gap energy increases with the atomic number

SYSTEMATICS OF ONE QUASIPARTICLE LEVELS IN N=151 ISOTONES COMPARISON THEORY



H. Makii prc 76(2007)



- N=152 gap energy increases with the atomic number
- The MM theory does not reproduce the energy of the ½(620) single particle level

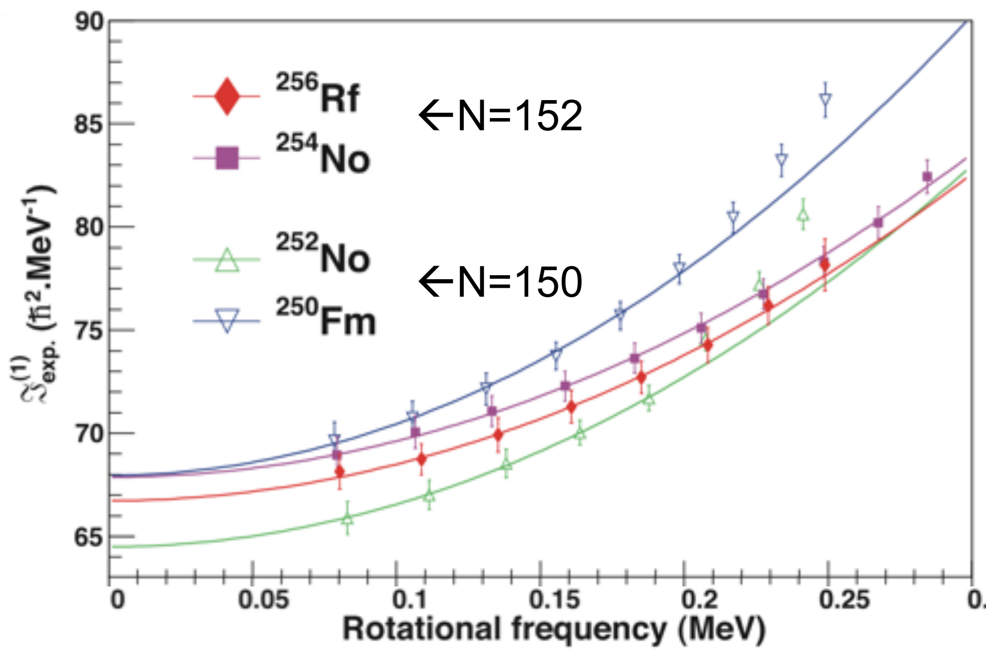
WHAT WE CAN LEARN FROM MOMENT OF INERTIA

Moments of inertia are related to (deformed) shell gaps & pairing correlations

- ✧ Alignment faster for N=150 as compared to N=152
- ✧ At a shell gap, pairing correlations are weakened, resulting in larger moments of inertia

→ Gaps at Z=100 (Fm) and N=152 (^{254}No)

→ No gap at Z=104



Ch.Theisen, P.T.Greenlees et al. EPJ(2015)

N=150

N=152

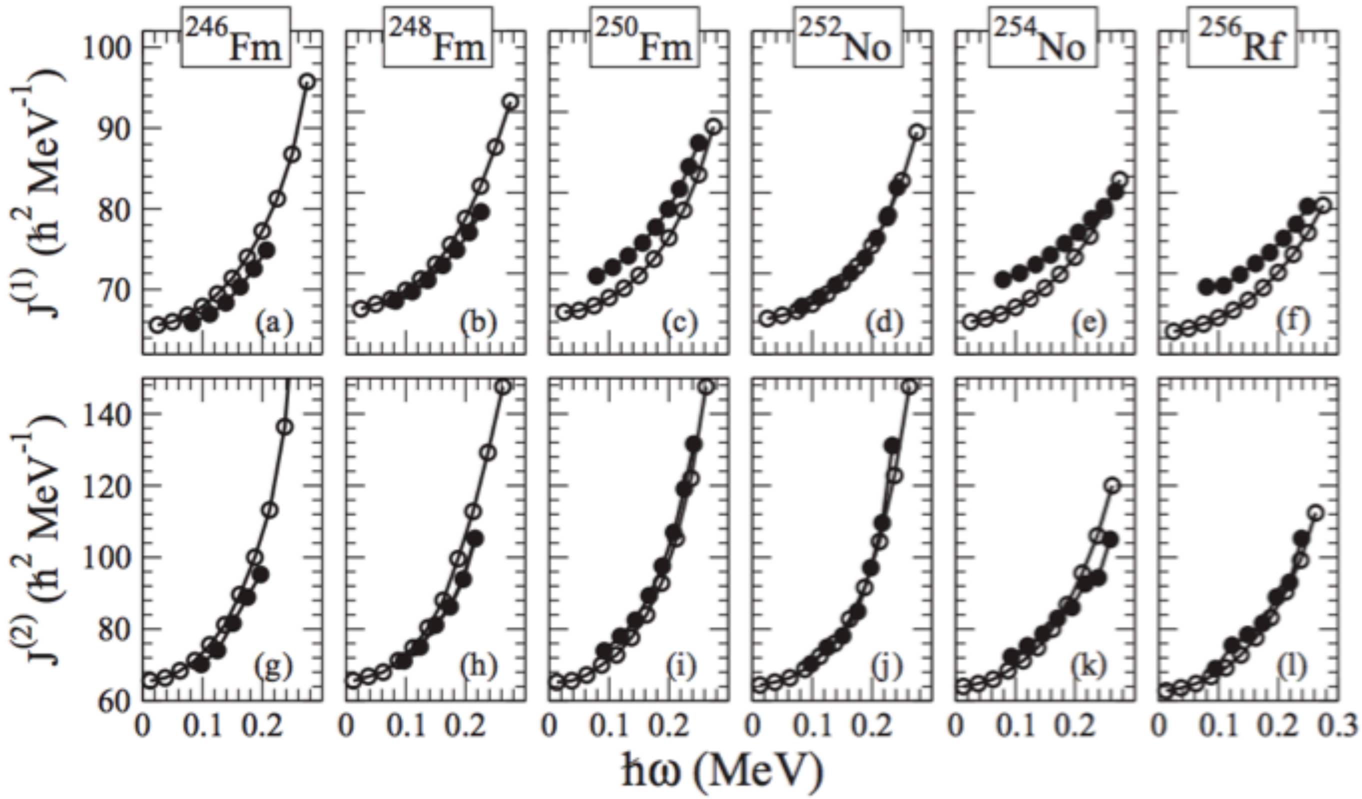
WHAT HFB MODEL SAYS?

YUE SHI, J. DOBACZEWSKI, AND P. T. GREENLEES PHYSICAL REVIEW C **89**, 034309 (2014)

PHYSICAL REVIEW C **86**, 011301(R) (2012)

Understanding the different rotational behaviors of ^{252}No and ^{254}No

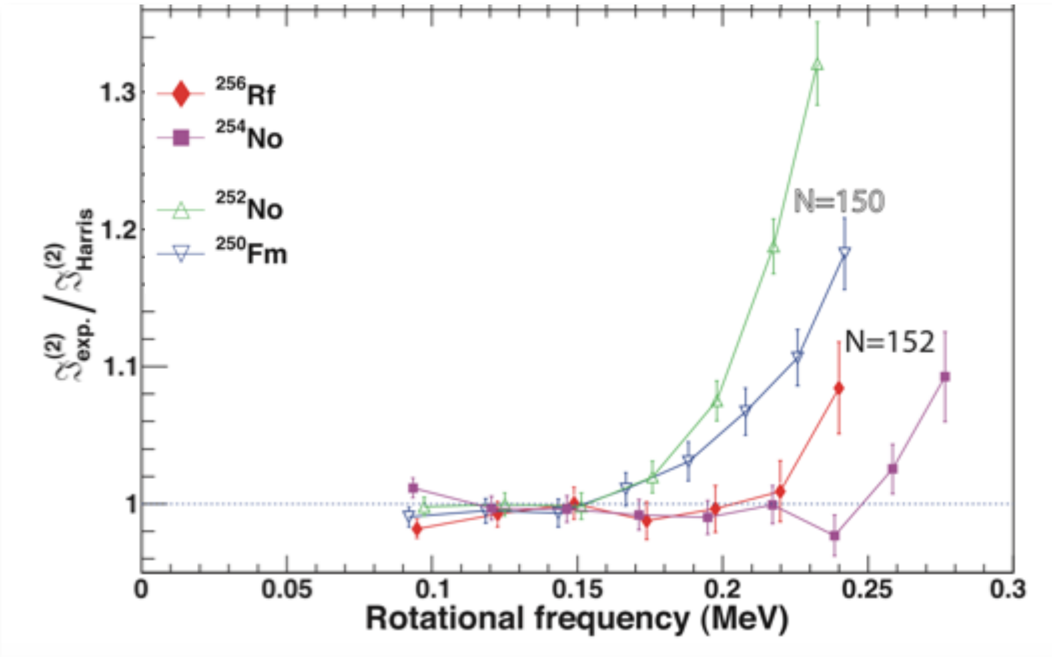
- The parity strength was increased to reproduce the experimental data
- The agreement is not so good as the proton or neutron number is changed



WHAT WE CAN LEARN FROM ALIGNEMENT

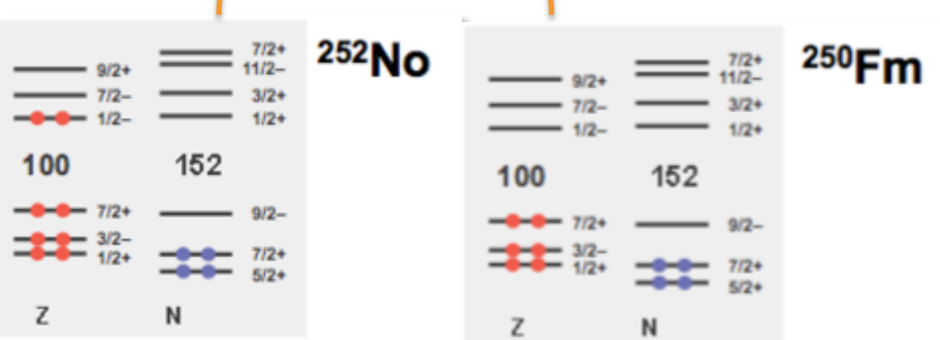
- Alignement effect in N=150 and N=152
- Alignment later in N=152 isotones than N=150

→competition $\pi\ i_{13/2}$ and $\nu\ j_{15/2}$ orbitals



Ch.Theisen, P.T.Greenlees et al. EPJ(2015)

N=150

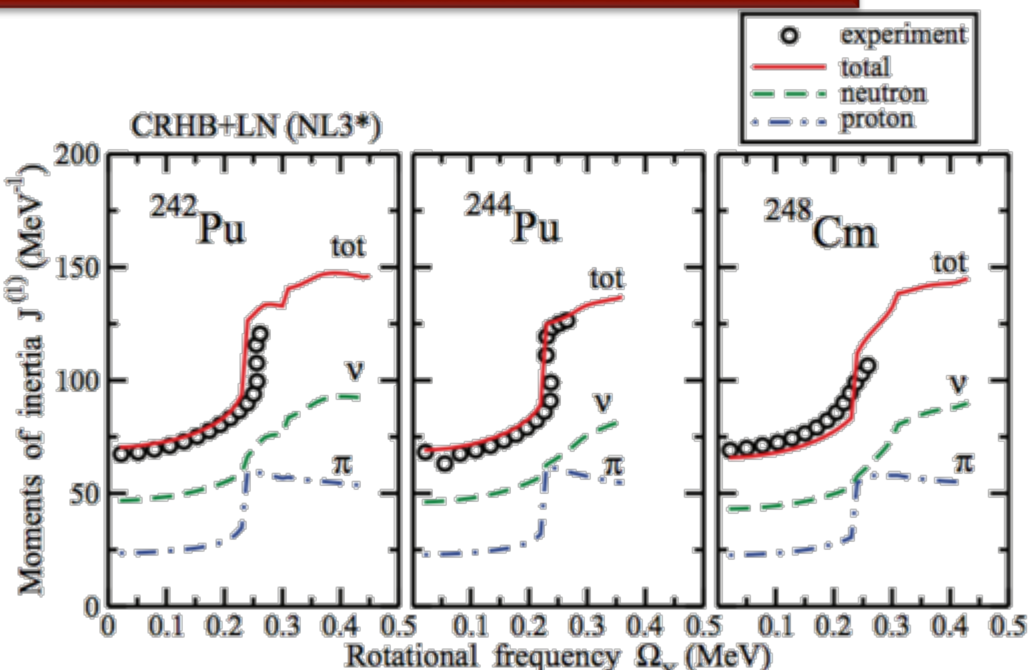


N=152

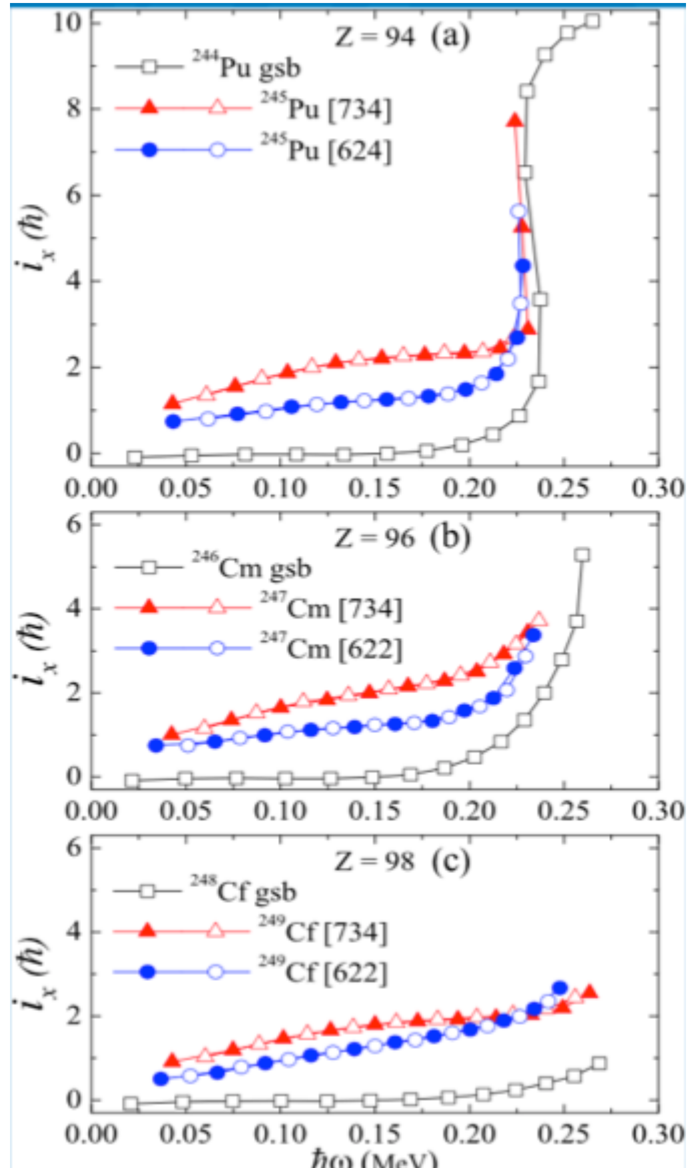
ROTATIONAL ALIGNMENT

- $j_{15/2}$ neutron alignment
- Blocked in ν 9/2- [734] band (red)
- Allowed in ν 7/2+ [624] band (blue)
- Proton alignment confirmed experimentally!

N=151



A. Afanasjev PRC 88, 014230(2013)



Hota et al Phy Lett B 739(2014)

- $i_{13/2}$ proton and $j_{15/2}$ neutrons predicted to align at comparable frequencies

CONCLUSION COLLECTIVITY

- ✧ In-beam now feasible down to a cross section of 10nb;
- ✧ Relatively few in-beam studies beyond plutonium have been performed;
- ✧ High spin data can been produced using inelastic scattering or transfer reactions → actinide targets are needed

  →Limiting factors: lifetime and high gamma ray counting rates
- ✧ Need to push to Z=108 and N=162 to investigate states from above Z=120, N=184

- ➢ The correlation between the 2+ energies and the masses and the effect @ Z=98 is no yet understood
- ➢ No $j_{15/2}$ neutron alignment has been unequivocally observed in these heavy elements. Calculations always predict neutron crossings before proton crossings, but in reality the $i_{13/2}$ protons align
- ➢ Pairing strengths?? → poor agreement between experiments and theory

ISOMERS

- Provide clean information on quasi-particle states
- Several researches in GSI, JYFL, ANL and Berkley

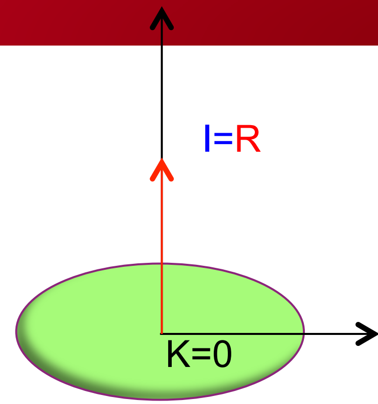
ISOMERIC STATES IN EVEN EVEN NUCLEI

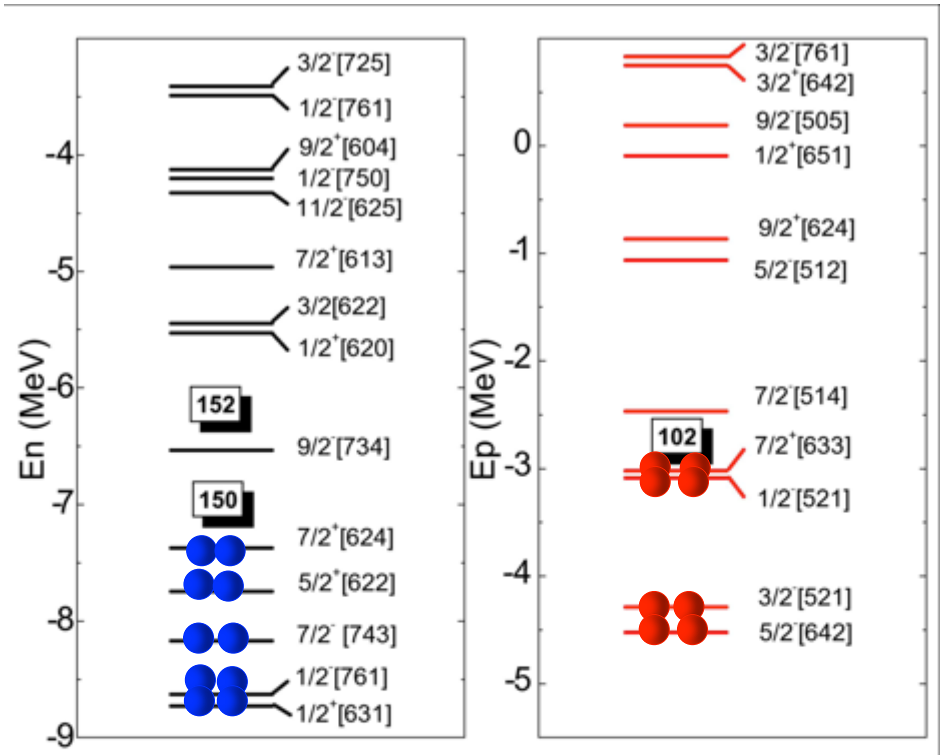
Why K isomers occur?

- Deformed nucleus
- Selection rule for electromagnetic transition $\lambda \geq \Delta K$ is not fulfilled
- Breaking of particle pairs at Fermi Surface
- Excitation energy of quasi-particle: $E = \sqrt{(\varepsilon - \lambda)^2 + \Delta^2}$

What we can learn?

- Information about Nilsson level energy gaps
- Influence on stability of super heavy elements
- The pairing interaction





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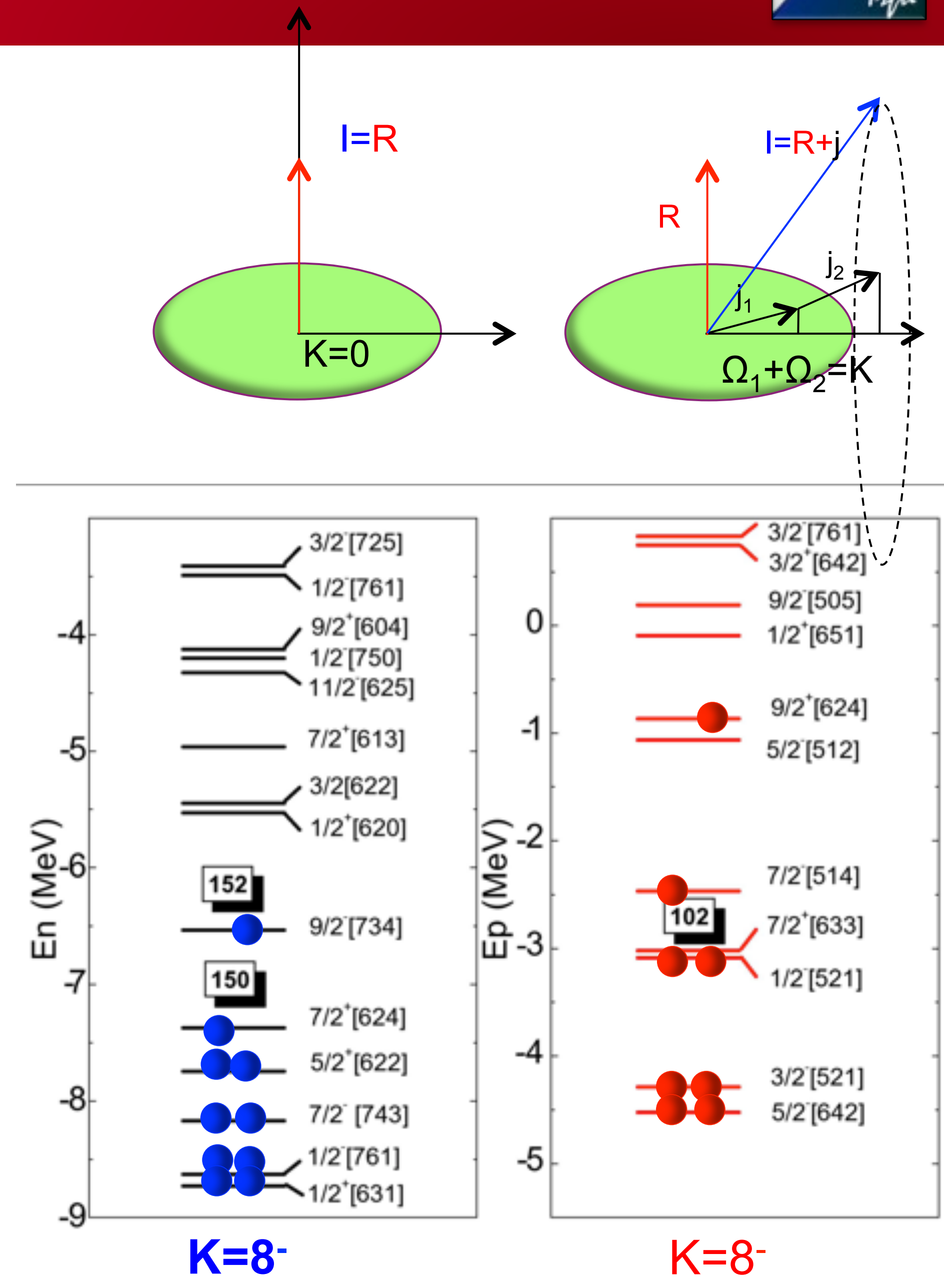

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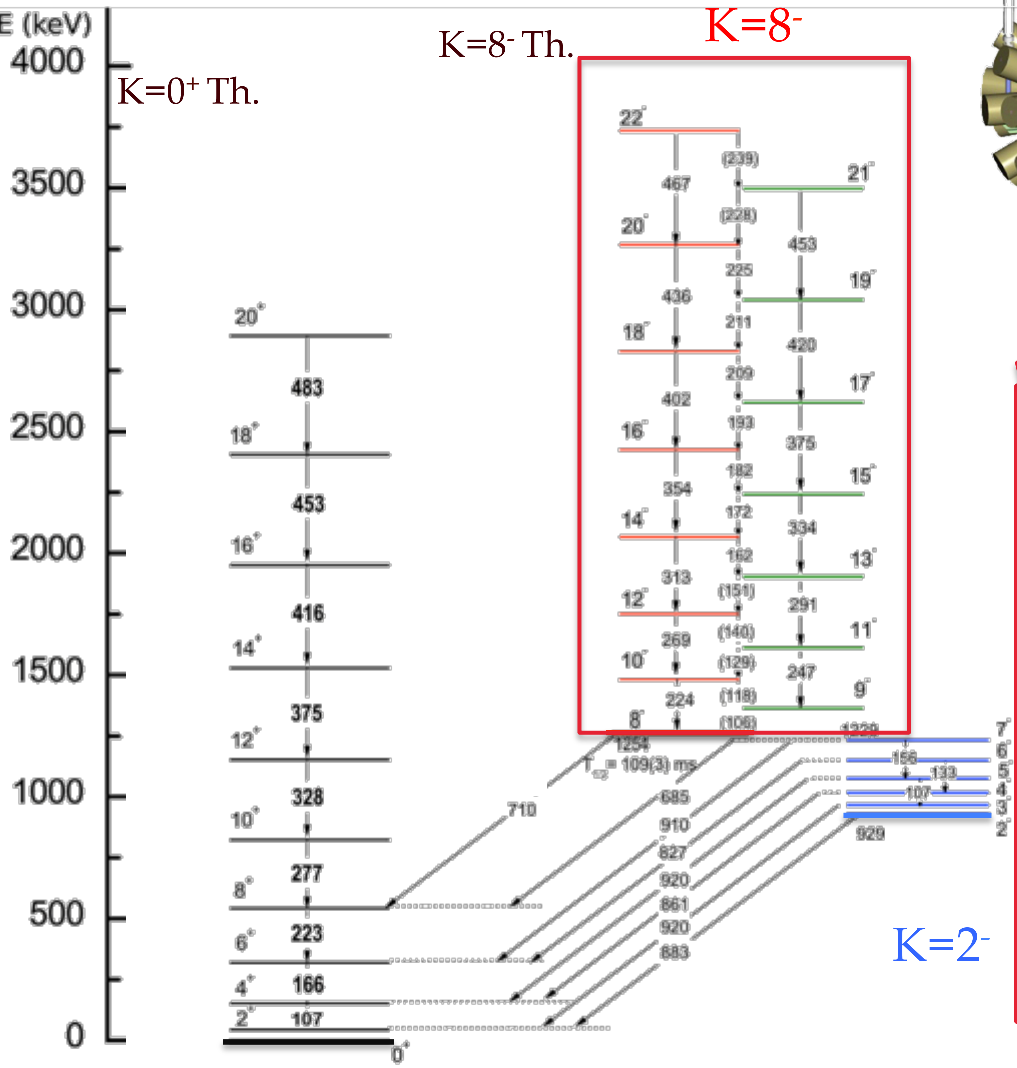
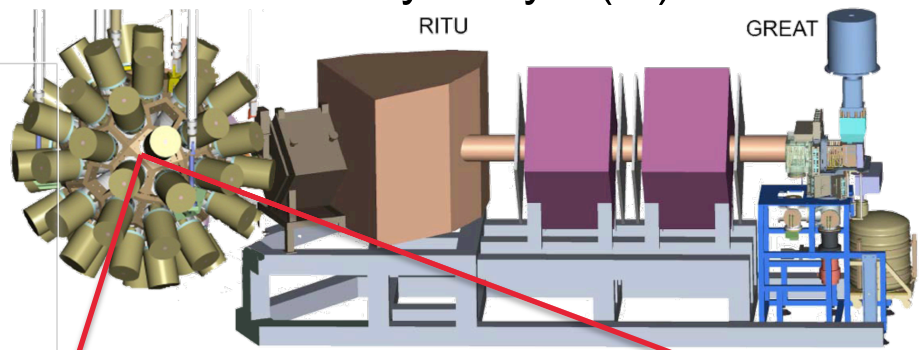
K ISOMER IN ^{252}NO

^{252}No

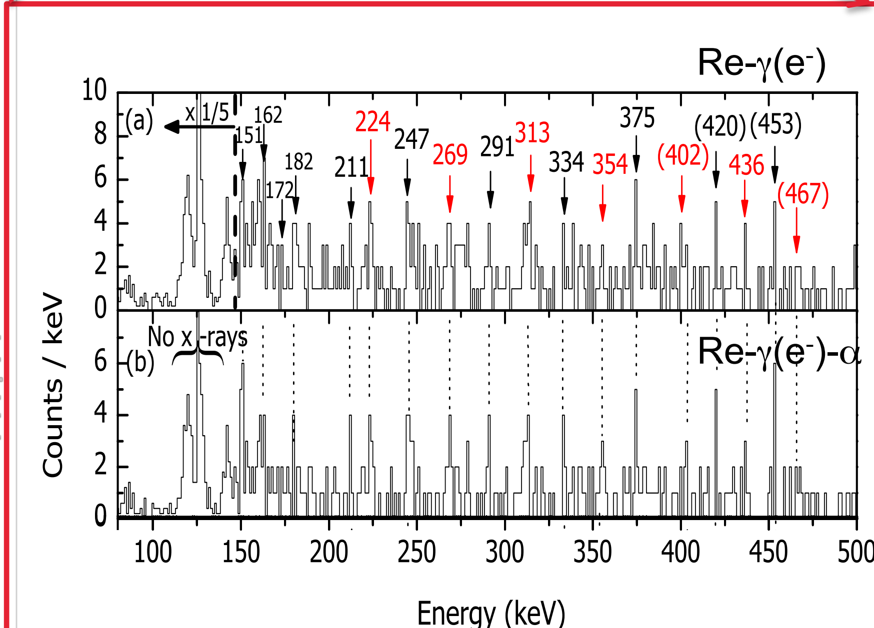


K=0+

Jyväskylä (FI)



K=8-

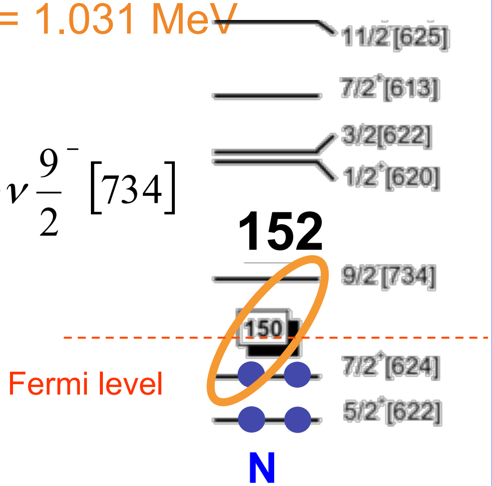


B. Sulignano et al. Eur. Phys. J. 33 (2007), 327; B. Sulignano et al. Phys. Rev. C 86 (2012), 44138

NEUTRON SINGLE PARTICLE STATES FOR ^{252}NO

Calculated configuration:
$K_\pi=8^-$ E_{exc} = 1.031 MeV

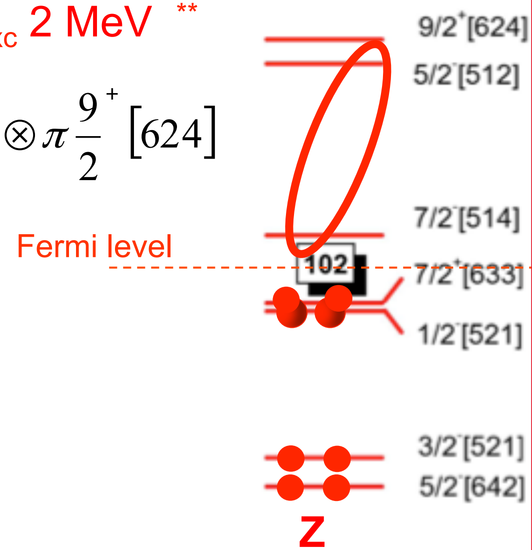
$$\nu\frac{7}{2}^{+}[624]\otimes\nu\frac{9}{2}^{-}[734]$$



g_k νν(th.)
0.01

Calculated configuration:
$K_\pi=8^-$ E_{exc} 2 MeV **

$$\pi\frac{7}{2}^{-}[514]\otimes\pi\frac{9}{2}^{+}[624]$$

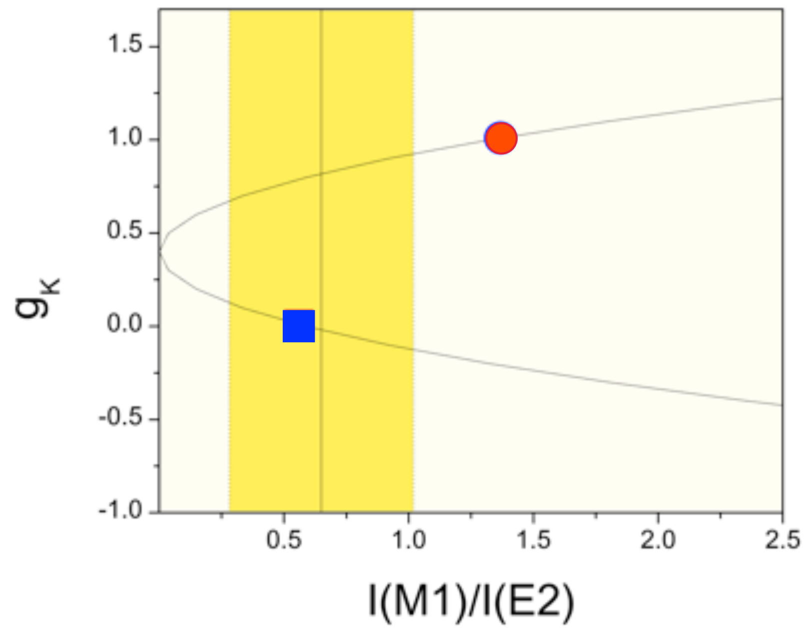


g_k ππ(th.)
1.001

Branching ratio

$$R_{\exp} = I_\gamma(J\rightarrow J-1)/I_\gamma(J\rightarrow J-2)$$

$$R_{th} = \frac{T(M1)}{T(E2)} = \frac{1.76[E_\gamma(M1)]^3 B(M1)s^{-1}}{1.22[E_\gamma(E2)]^5 B(E2)s^{-1}};\propto \frac{(g_K-g_R)^2}{Q_0^2}$$



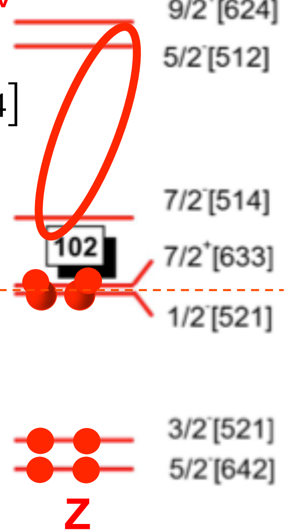
The isomer K=8⁻ is based on 2-qn excitation

NEUTRON SINGLE PARTICLE STATE IN ^{250}FM

Calculated configuration:

$K_\pi=8^-$ E_{exc} = 2 MeV

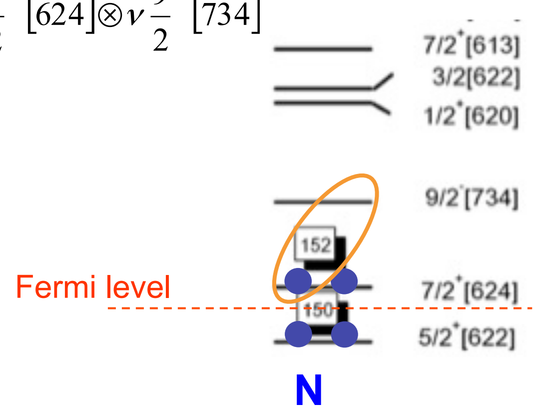
$$\pi\frac{7}{2}^-[514]\otimes\pi\frac{9}{2}^+[624]$$



Calculated neutron configuration:

$K_\pi=8^-$ E_{exc} = 1.029 MeV

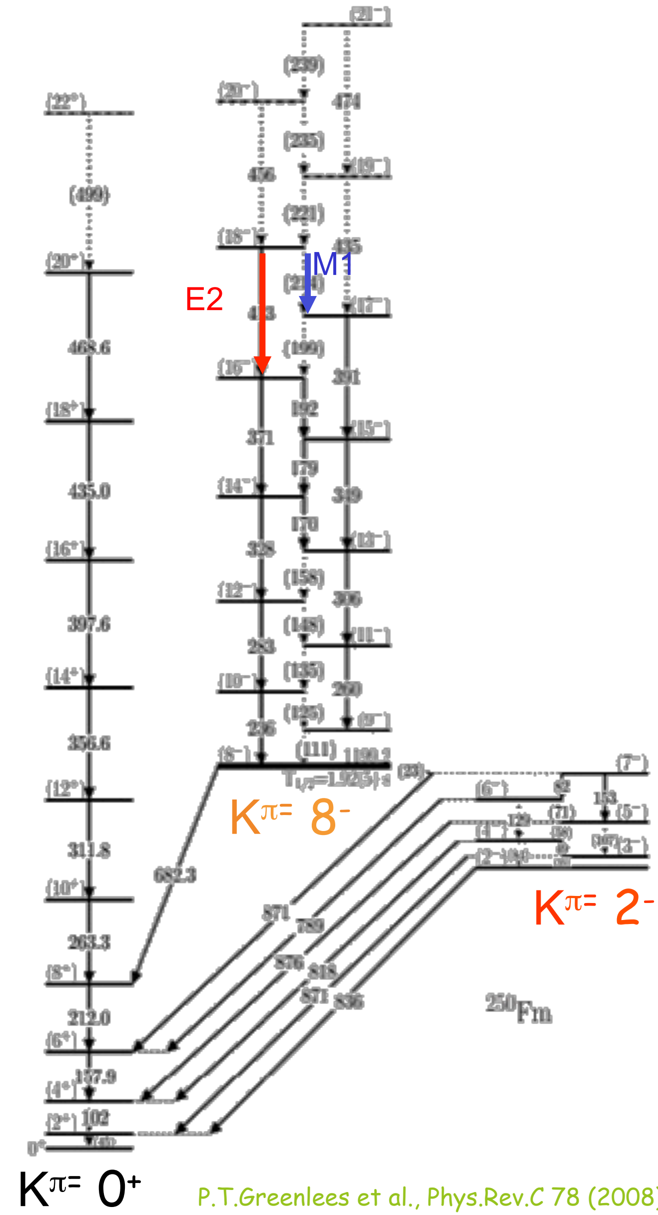
$$\nu\frac{7}{2}^+[624]\otimes\nu\frac{9}{2}^-[734]$$



g_k ππ(th.)= 1.001

g_k (exp.)= 0.09

g_k νν(th.)= - 0.025



P.T.Greenlees et al., Phys.Rev.C 78 (2008)

PROTON SINGLE PARTICLE STATE FOR ^{254}NO

Two-quasi-particle proton states: ???

(1/2$^-$[521] 7/2$^-$[514]) 3$^+$ - 988 keV

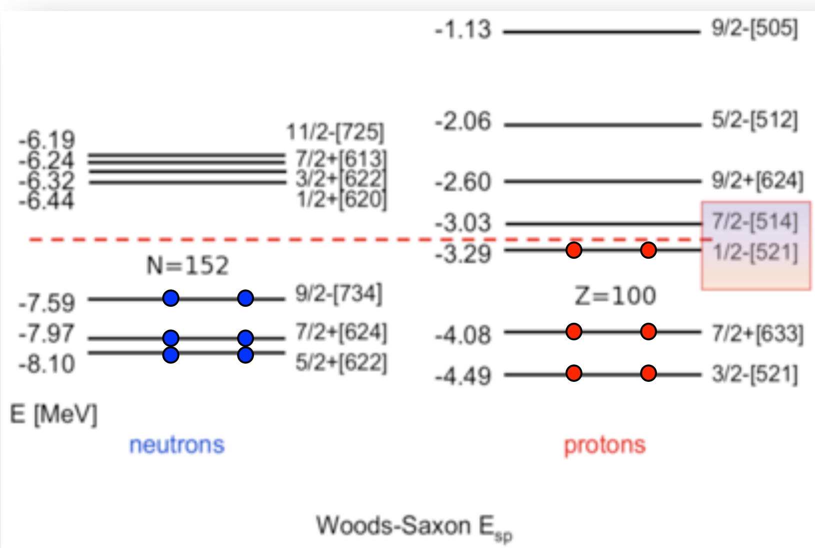
(9/2$^+$[624] 7/2$^-$[514]) 8$^-$ - 1293 keV

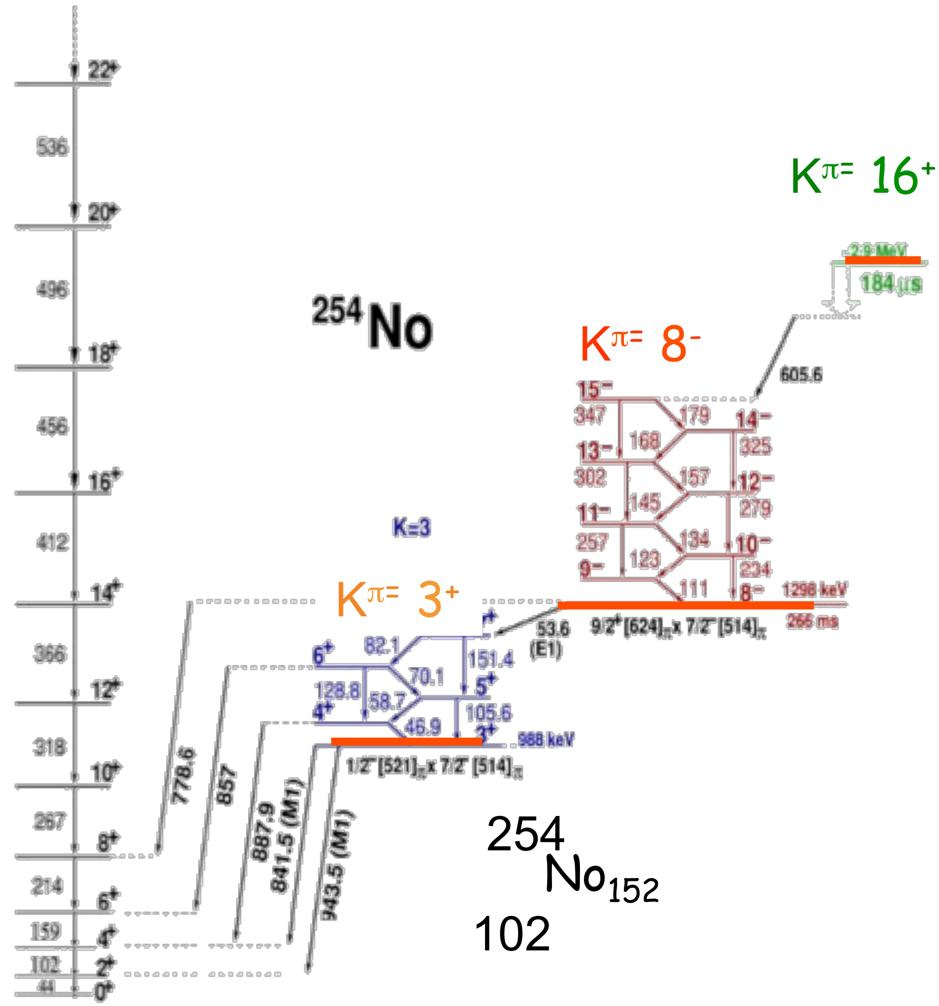
or

two-quasi-neutron state: ???

9/2-[734] ⊗ 7/2+[613] 8$^-$

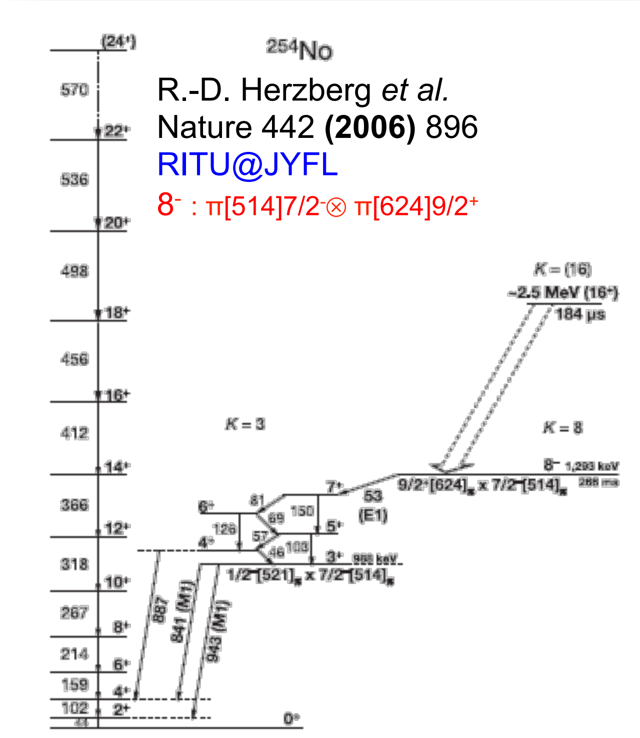
7/2+[624] ⊗ 9/2-[734] 8$^-$



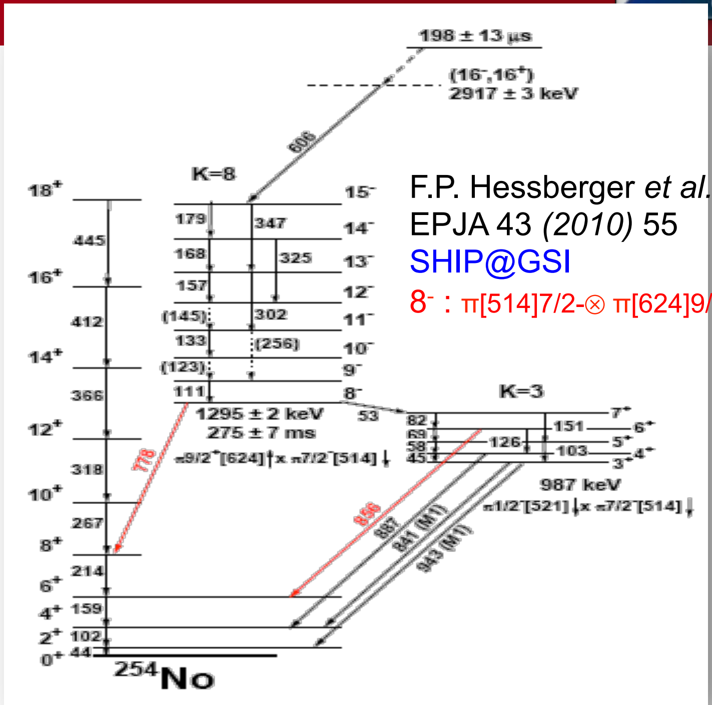


R.-D. Herzberg et al. Nature 442, 896 (2006)
S. Tandel et al., Phys. Rev. Lett. 97 (2006) 082502

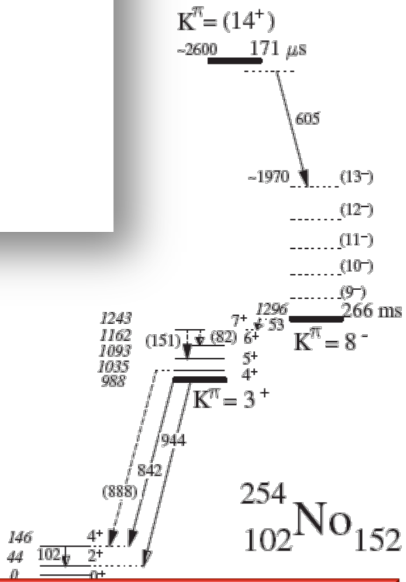
HIGH-K ISOMERS IN ^{254}NO



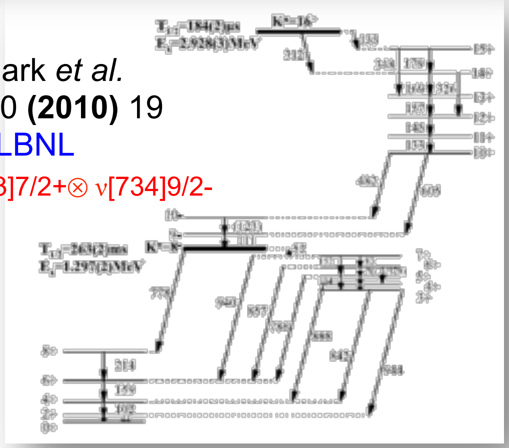
R.-D. Herzberg *et al.*
Nature 442 **(2006)** 896
RITU@JYFL
8^- : π[514]7/2- ⊗ π[624]9/2+



F.P. Hessberger *et al.*
EPJA 43 *(2010)* 55
SHIP@GSI
8^- : π[514]7/2- ⊗ π[624]9/2+



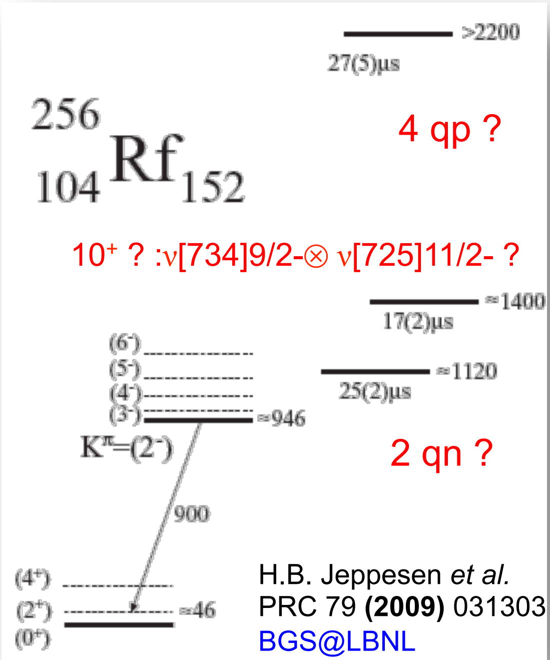
S.K. Tandel *et al.*
PLR 97 **(2006)** 082502
FMA@ANL
8^- : π[514]7/2- ⊗ π[624]9/2+



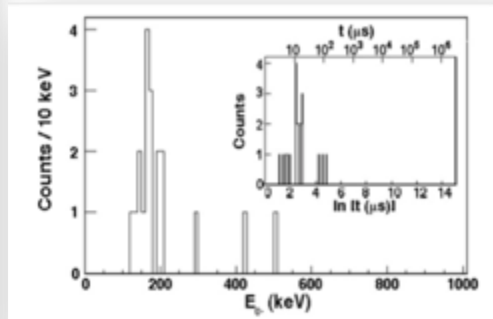
R.M. Clark *et al.*
PLB 690 **(2010)** 19
BGS@LBNL
8^- : ν[613]7/2+ ⊗ ν[734]9/2-

no agreement concerning an 2qp K isomer at ~1,3 MeV

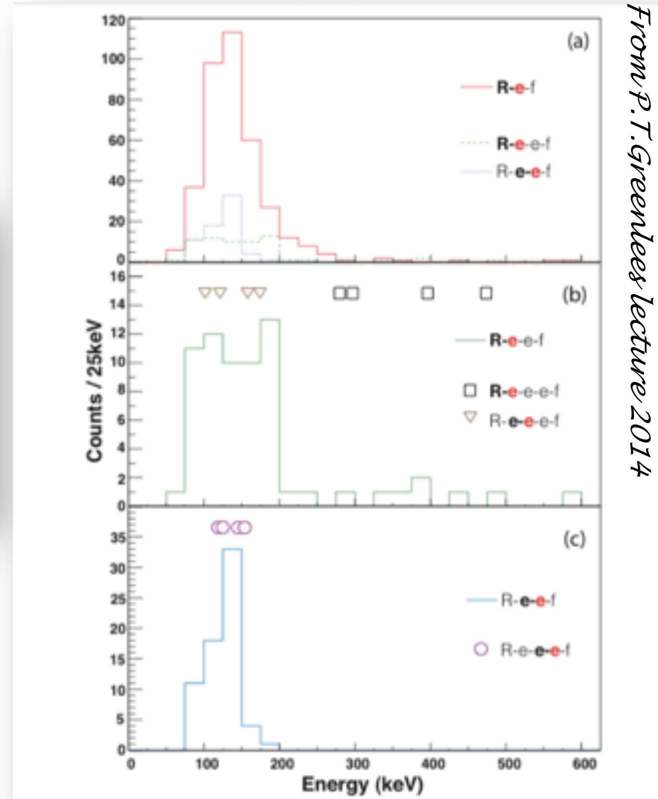
K ISOMERISM IN ^{256}RF



H.B. Jeppesen *et al.*
PRC 79 **(2009)** 031303
BGS@LBNL



A.P. Robinson *et al.*
PRC 83 **(2011)** 064311
FMA@ANL
Only one isomer 17(5) μs 4qp ?



From P.T.Greenlees lecture 2014

Observed decays **BGS**

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	5400	6.67(9) ms
R-e-F	985 (18%)	25(2) μs
R-e-e-F	147 (2.7%)	17(2) μs
R-e-e-e-F	7 (0.13%)	27(2) μs

Observed decays **ANL**

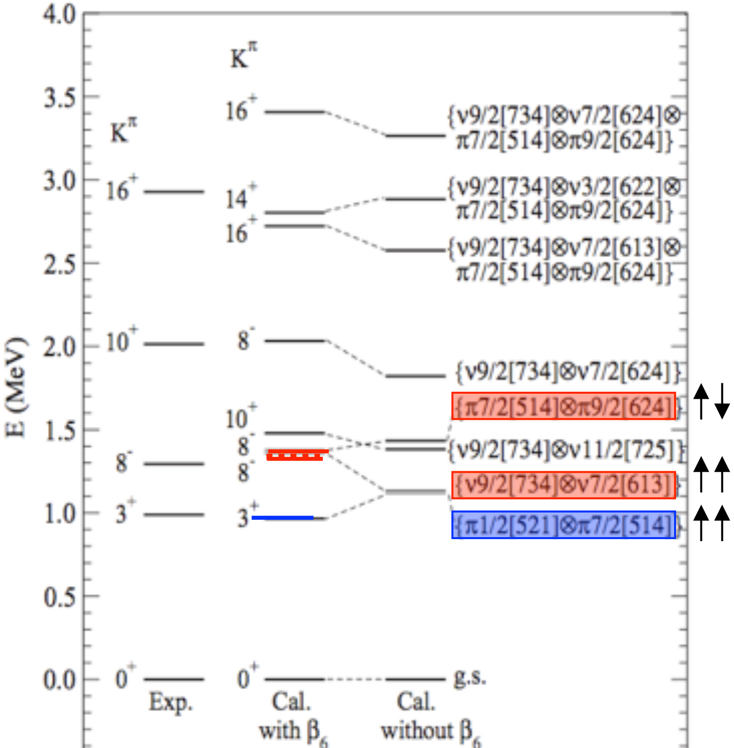
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	1322	6.9(4) ms
R-e-F	19 (1.4%)	17(5) μs

Observed decays **JYFL**

Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	2210	6.9(2) ms
R-e-F	382 (17%)	23 μs
R-e-e-F	67 (3.0%)	17 μs
R-e-e-e-F	4 (0.18%)	27 μs

Experimental differences difficult to reconcile
→ An order of magnitude in statistics is required σ=15nb

THEORIES

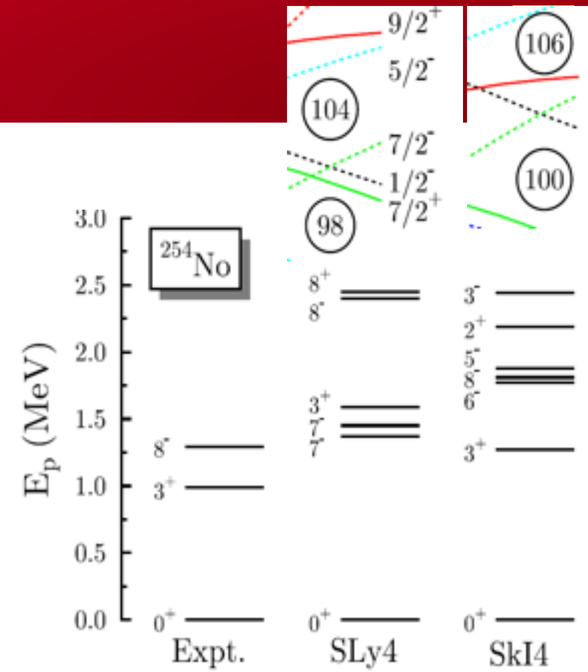


H.L. Liu, F. R. Xu, P.M. Walker and C.A. Bertulani, Phys. Rev. C 83 (2011) 011303(R)

Including higher order deformation strengthens the N=152 and Z=100 gaps

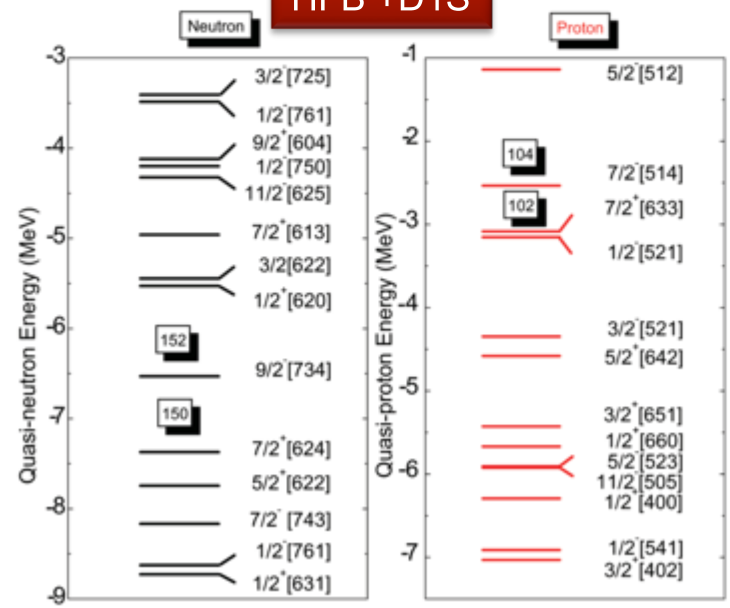
Spin-spin coupling will push the unfavoured 2 quasineutron state up in energy

More experimental data are needed to solve the discrepancies



P.-H. Heenen, from http://nuclear1.paisley.ac.uk/SHEworkshop

HFB +D1S



J.P. Delaroche et al.

CONCLUSION ISOMERS

- 8^- isomer in ^{252}No and in ^{250}Fm are neutron states
- 3^+ state in ^{254}No is a proton state
- 8^- isomer in ^{254}No needs more study
- Systematics study are necessary to draw a clear picture of the region
- We see many isomers we do really understand their structure?

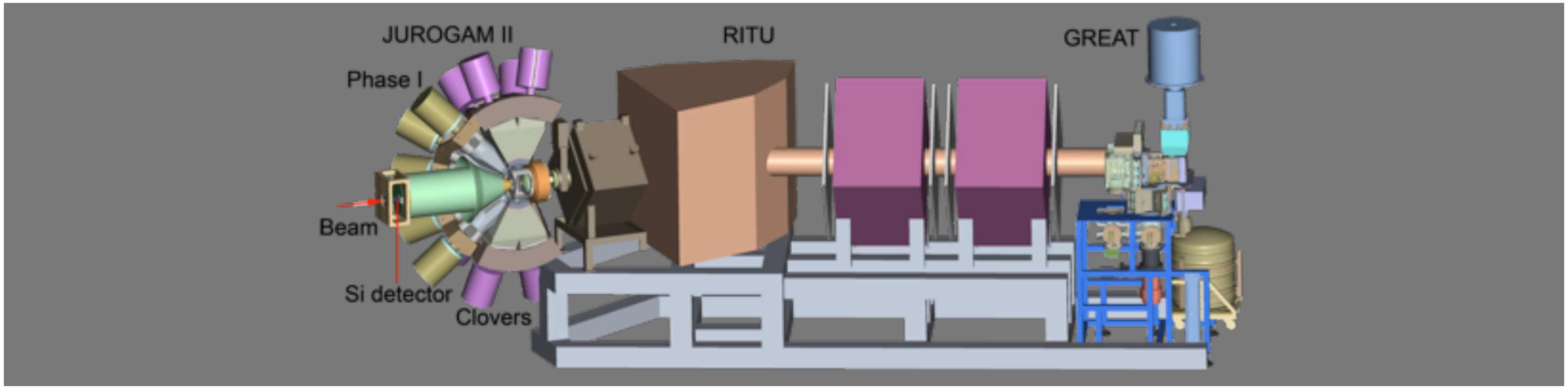
- Very few theoretical works are devoted to rational bands built on high K isomer

  → Only HFB using D1S Gogny Force & CCTRS
- Large spread in predictions for $K^{\pi} = 8^-$ in ^{254}No proton and neutron energies
- No proton deformed shell gap is predicted at Z=100 for HFB+Gogny force and Skyrme Sly4 force
- Needs calculations of the magnetic moments for the isomeric states

PROMPT ELECTRON SPECTROSCOPY ^{251}MD

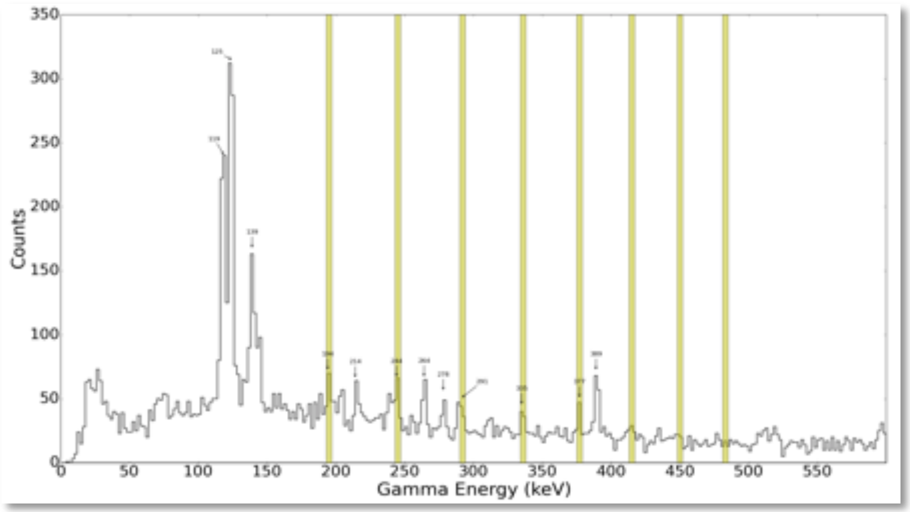
$^{205}Tl(^{48}Ca,2n)^{251}Md$

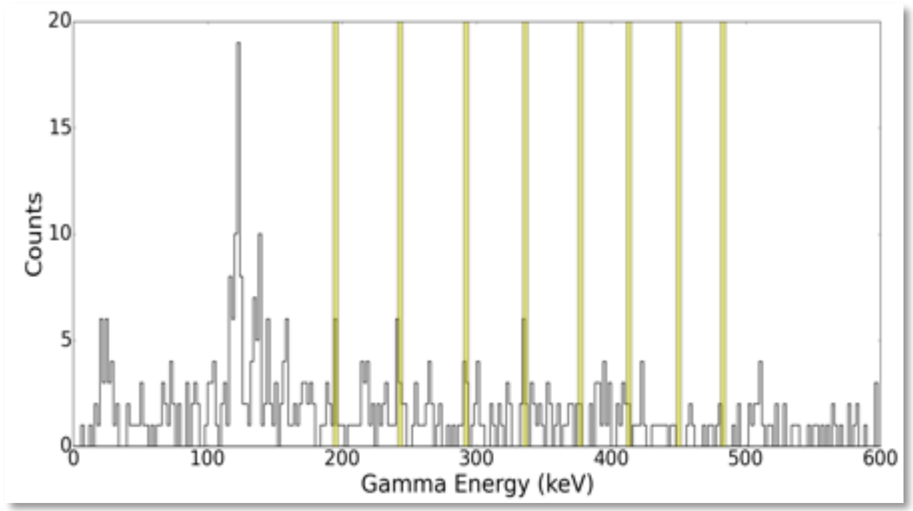
$\sigma \sim 760$ nb



Recoil Tagging

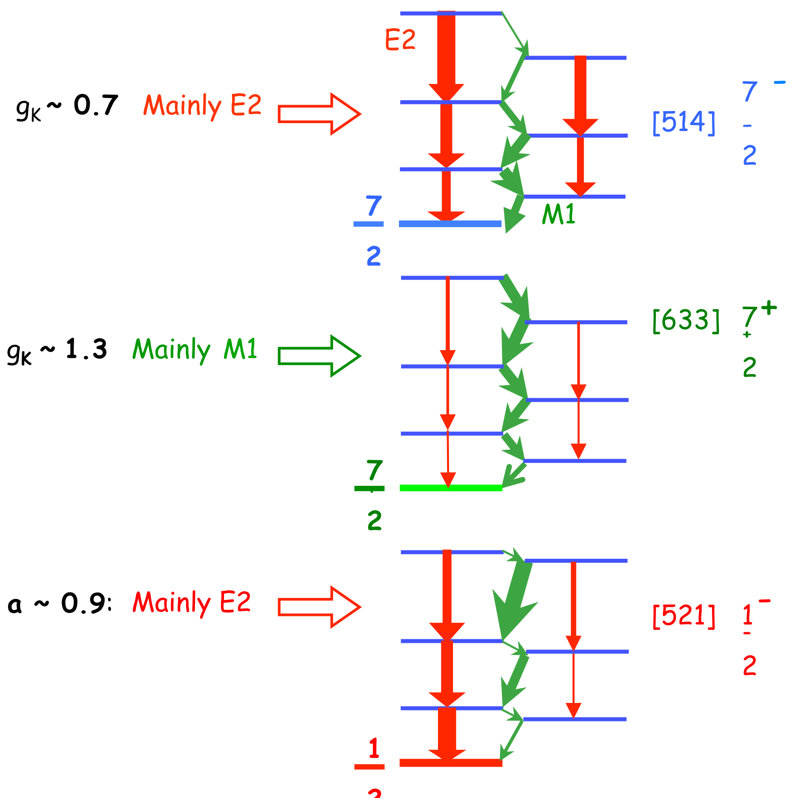
Recoil Decay Tagging

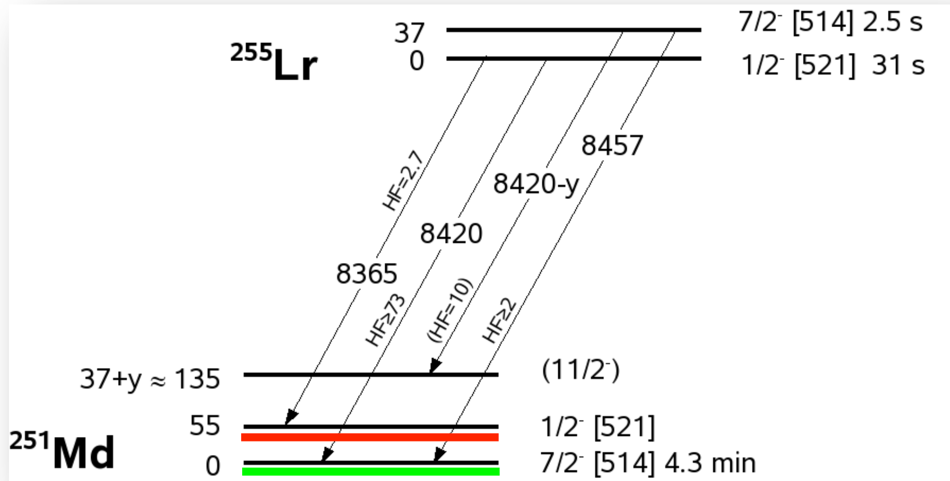




ELECTROMAGNETIC PROPERTIES

^{251}Md





$$B(M1)/B(E2) \propto K^2(g_K-g_R)^2/Q_0^2$$

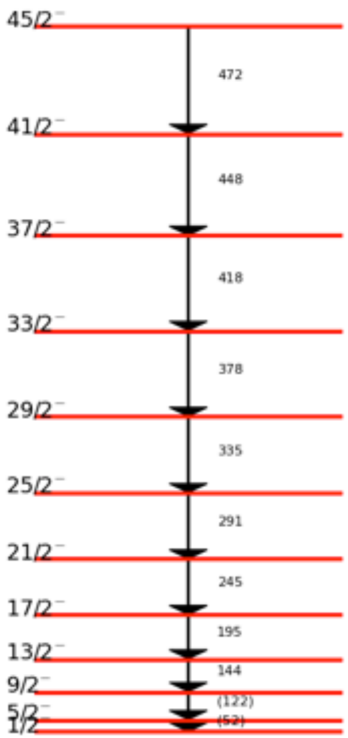
Ch. Theisen et al.

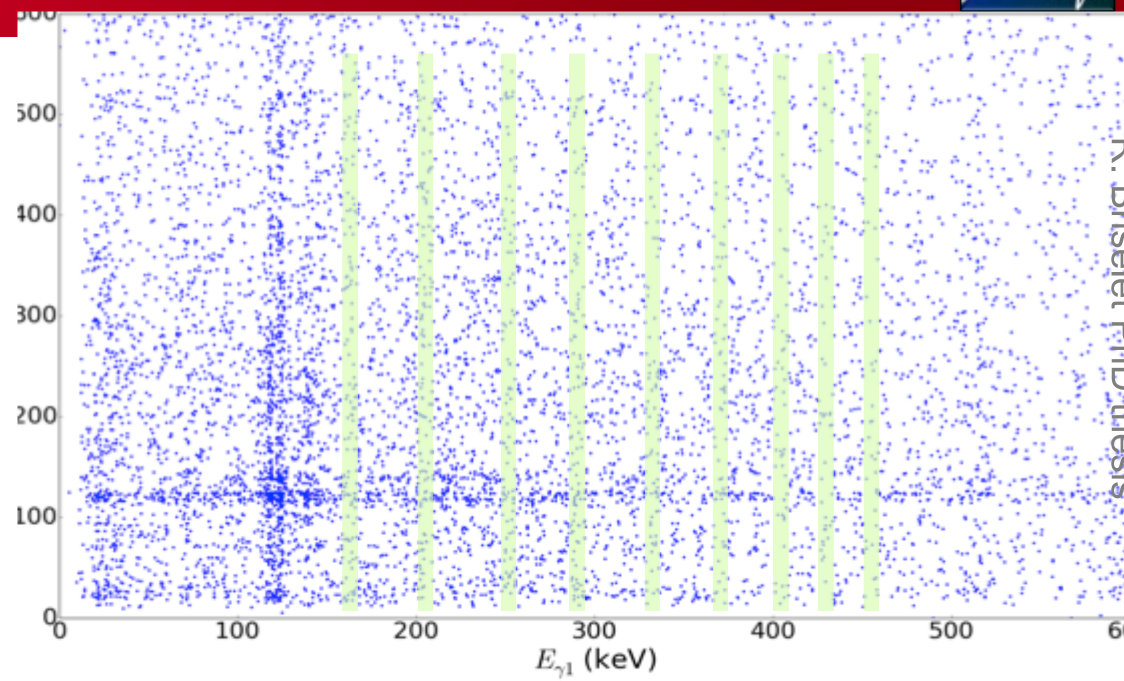
- In odd nuclei , the rotational bands are decoupled in two signature partners.
- The intensity ratio strongly depends on the single particle structure
- The decay path is a unique finger print to deduce the s.p. structure via its magnetic moment

GAMMA GAMMA COINCIDENCES

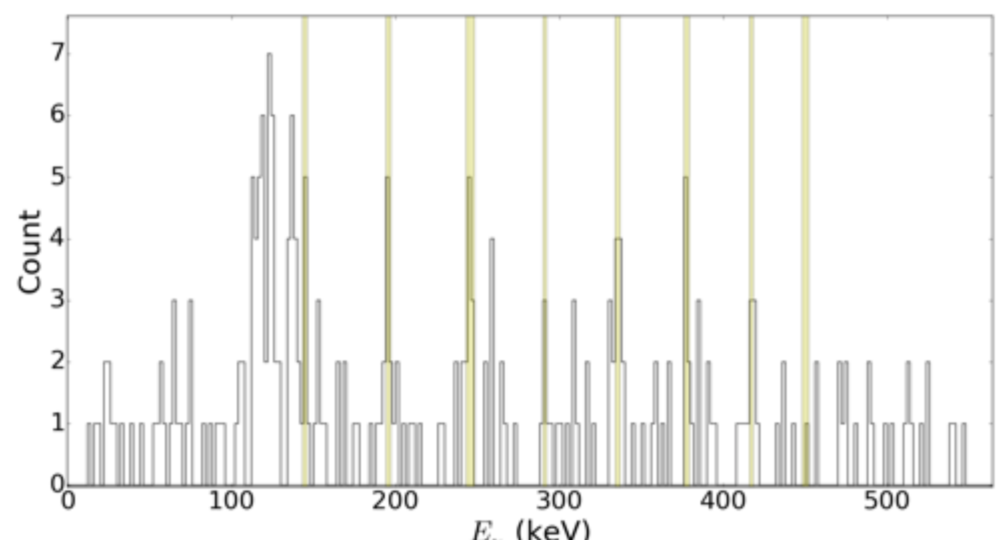
Band 1

No signature partner





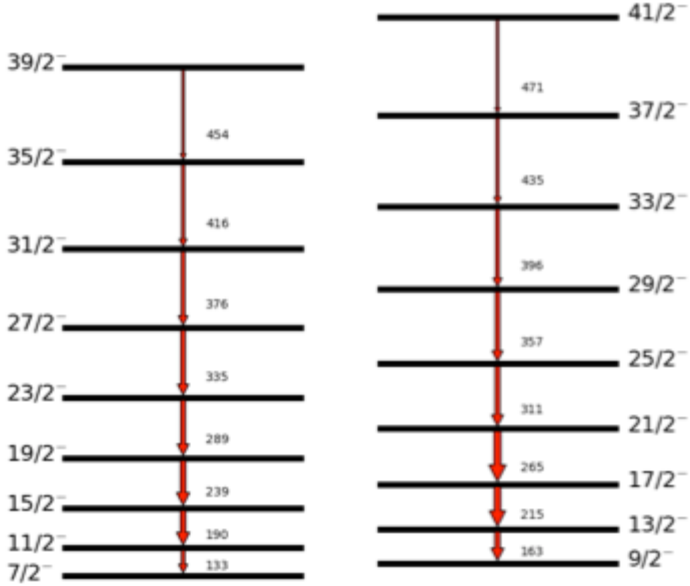
R. Briselet PhD thesis

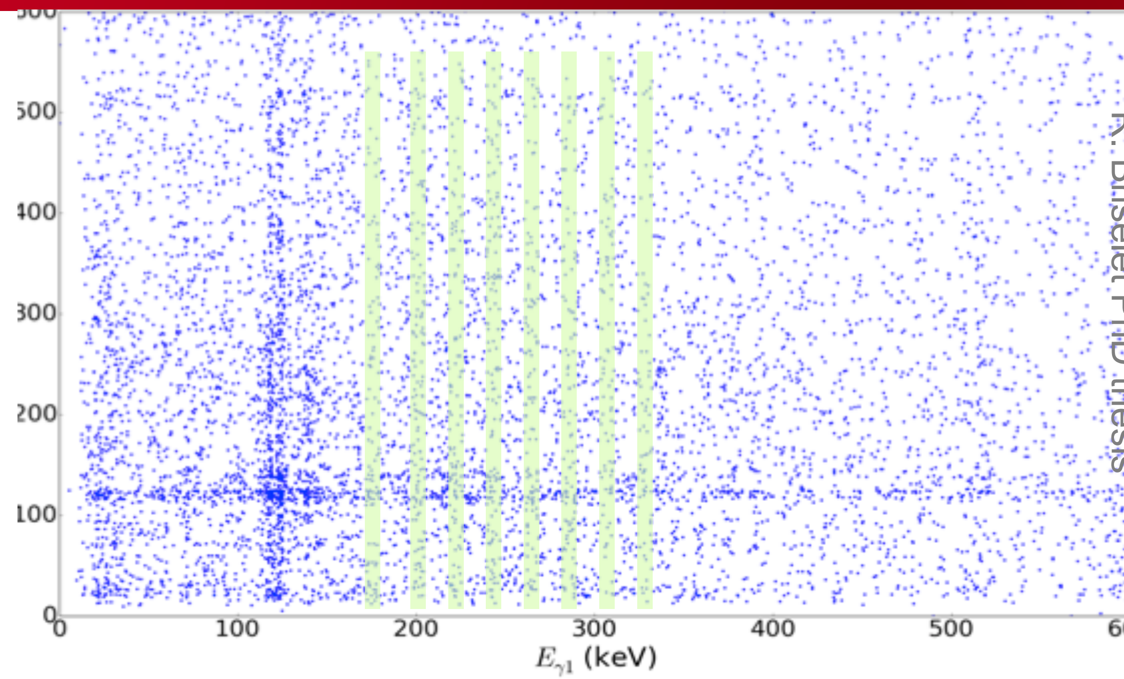


Electromagnetic properties HFB
→ Band 1 = [521] ½⁻

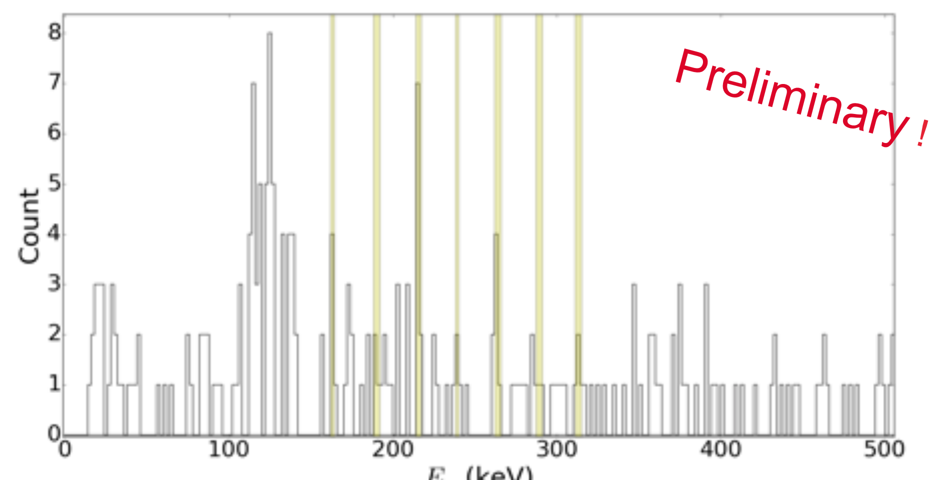
GAMMA GAMMA COINCIDENCES

Band 2





R. Briselet PhD thesis



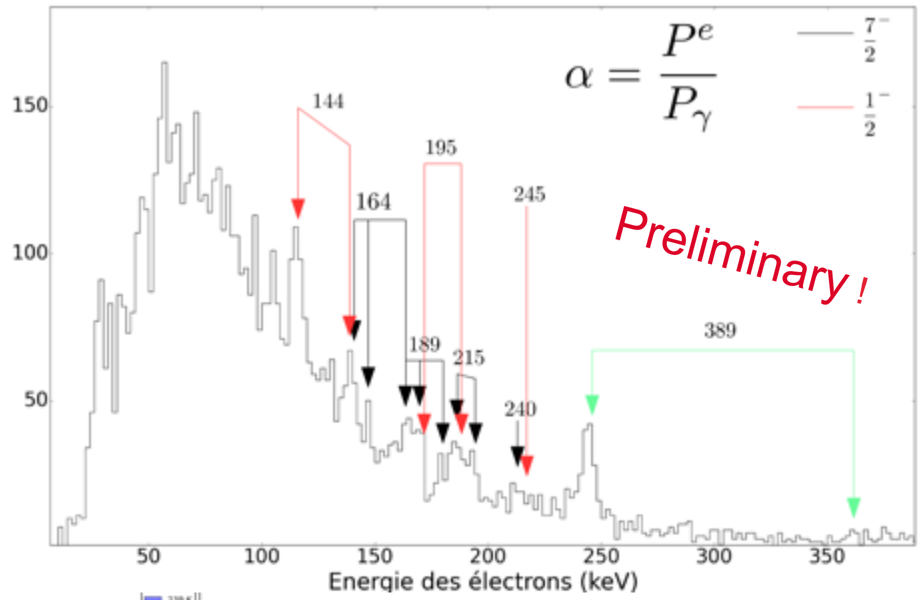
Electromagnetic properties HFB
→ Band 2 = [514] 7/2$^-$

M1 TRANSITIONS

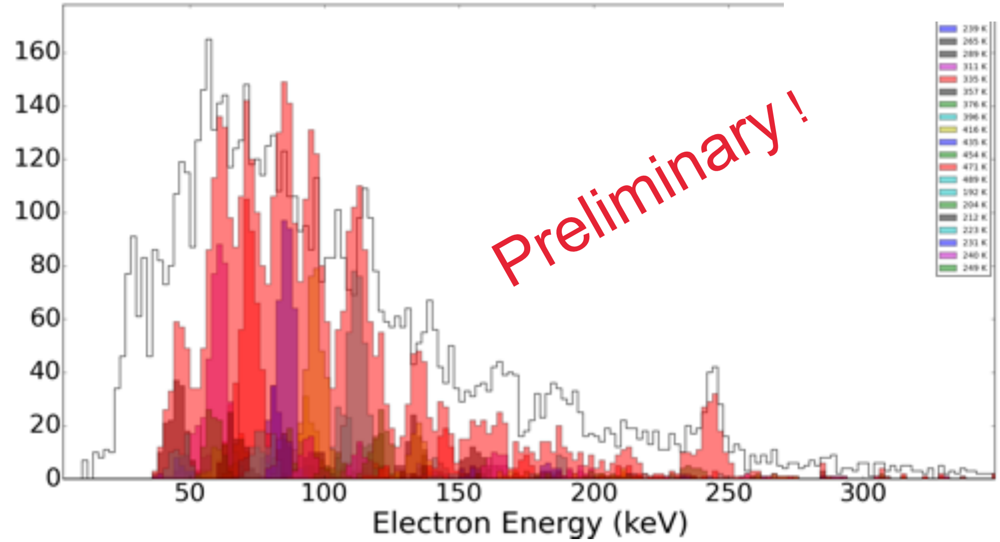
Experimentally M1 not seen in gamma spectroscopy

→ Look what's happen with electrons

Where are the M1 transitions?



R. Briselet PhD thesis



R. Briselet PhD thesis

Example of simulation including 1/2$^-$ and 7/2$^-$ bands, M1 and E2 transitions

→ Very difficult analysis

PERSPECTIVES

Near Future:

- VAMOS GAS FILLED Mode and AGATA spectrometer.
- RITU coupled with Sage spectrometer allows electron conversion measurements

→ e.g. ^{254}No,^{249}Md(April 2016)

Further into the future

- Asymmetric hot fusion reactions using actinide targets, ^{238}U(^{18}O,4n)^{252}Fm;
- Deep inelastic reactions e.g. ^{18}O, ^{86}Kr or ^{136}Xe beams on a ^{248}Cm target

Thanks!