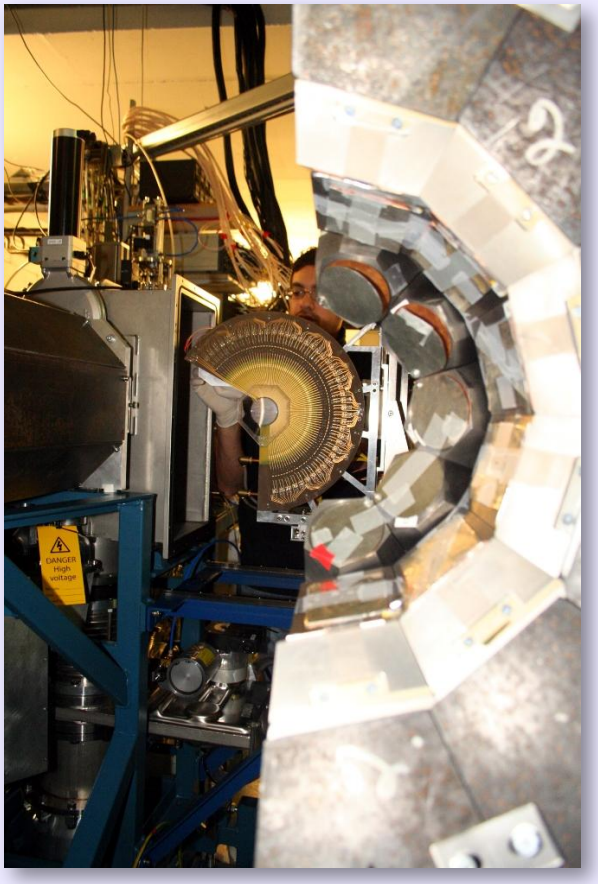
Spectroscopy of heavy nuclei



R-D Herzberg

4th International Conference
on the Chemistry and Physics
of the Transactinide Elements

Sochi, Russia, 6-10 Sept 2011

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Overview

- Introduction
- Isomer Spectroscopy
- Analysis Methods
- In-beam Spectroscopy
- Electron Spectroscopy: SAGE
- Summary

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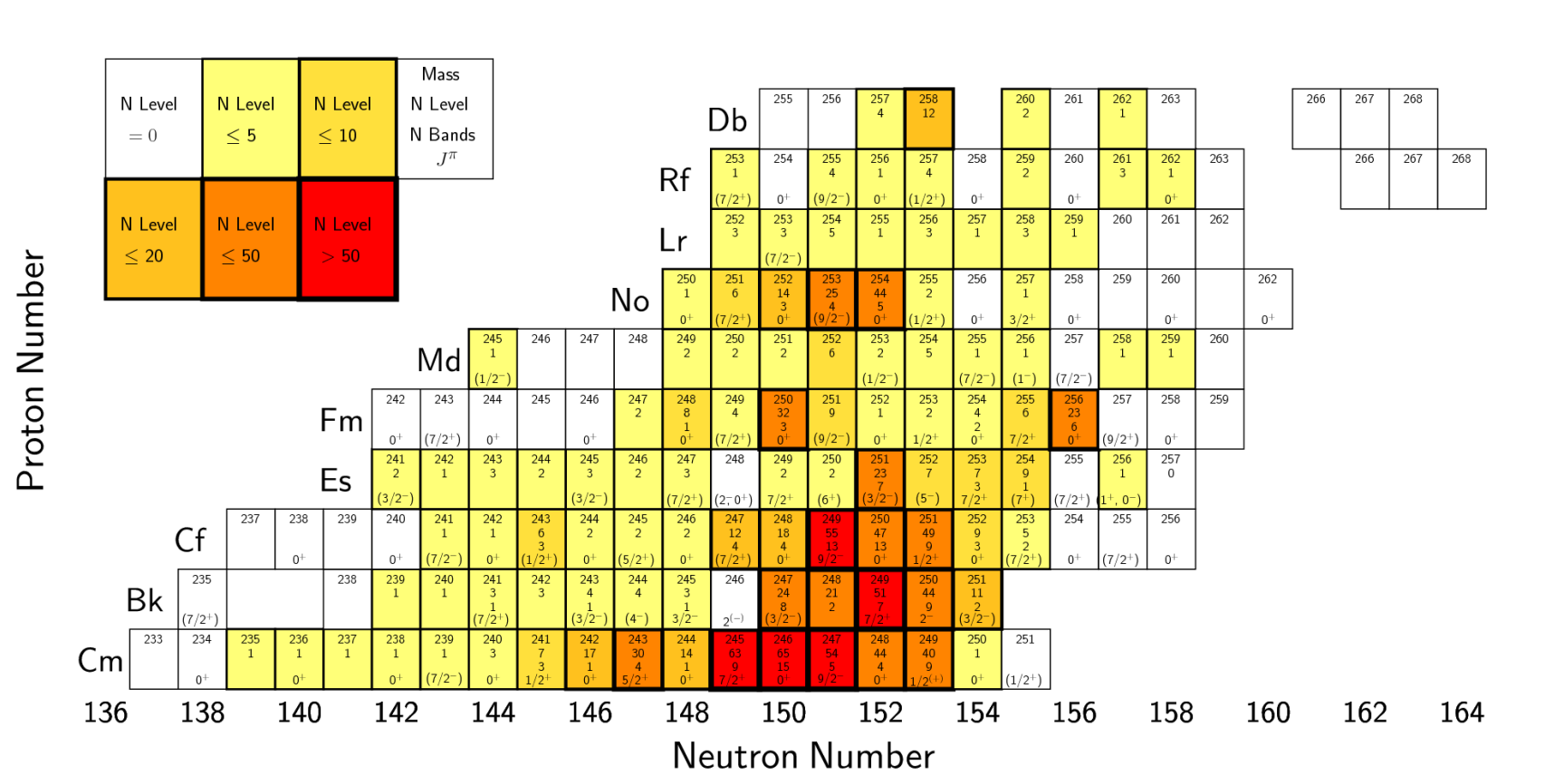
Data known today



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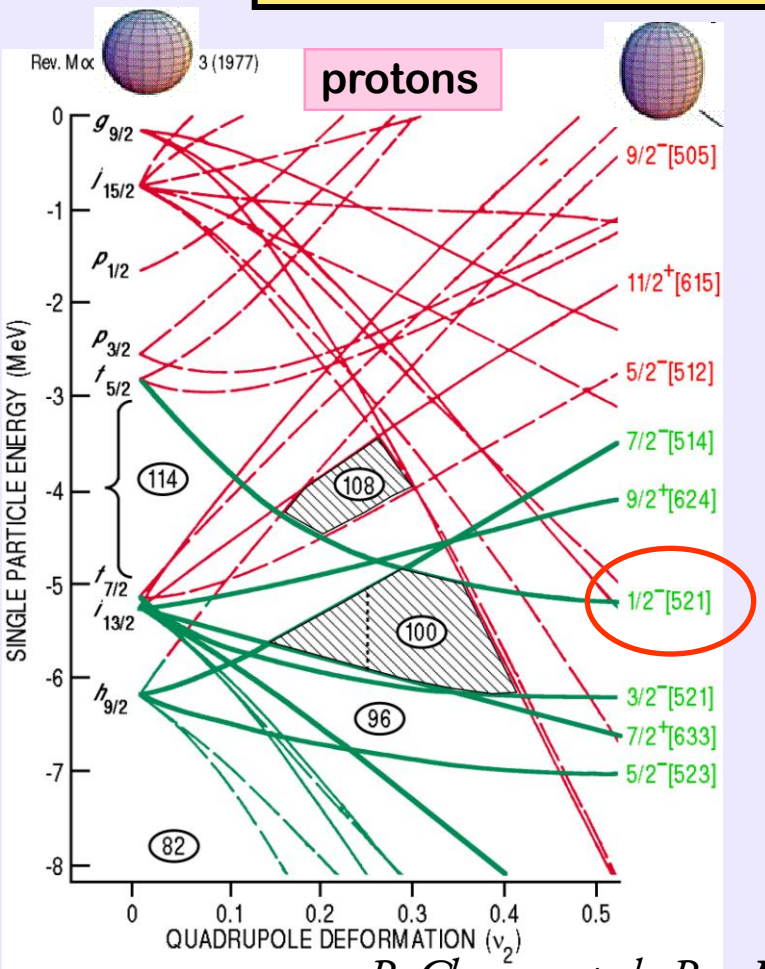
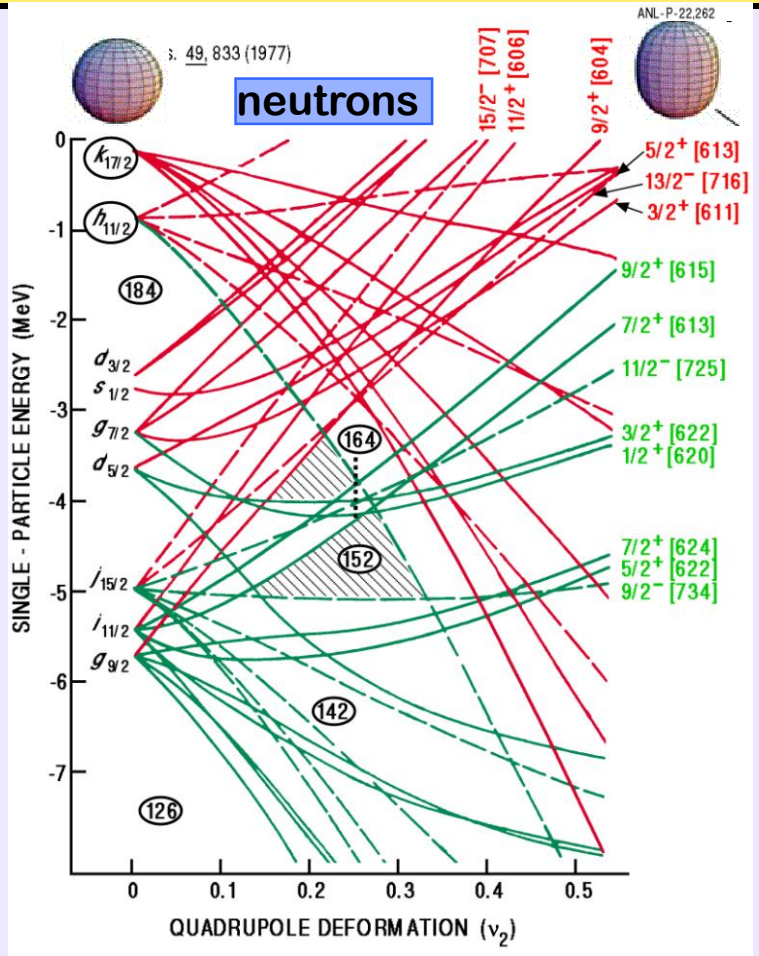
Deformed Single Particle Orbitals





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

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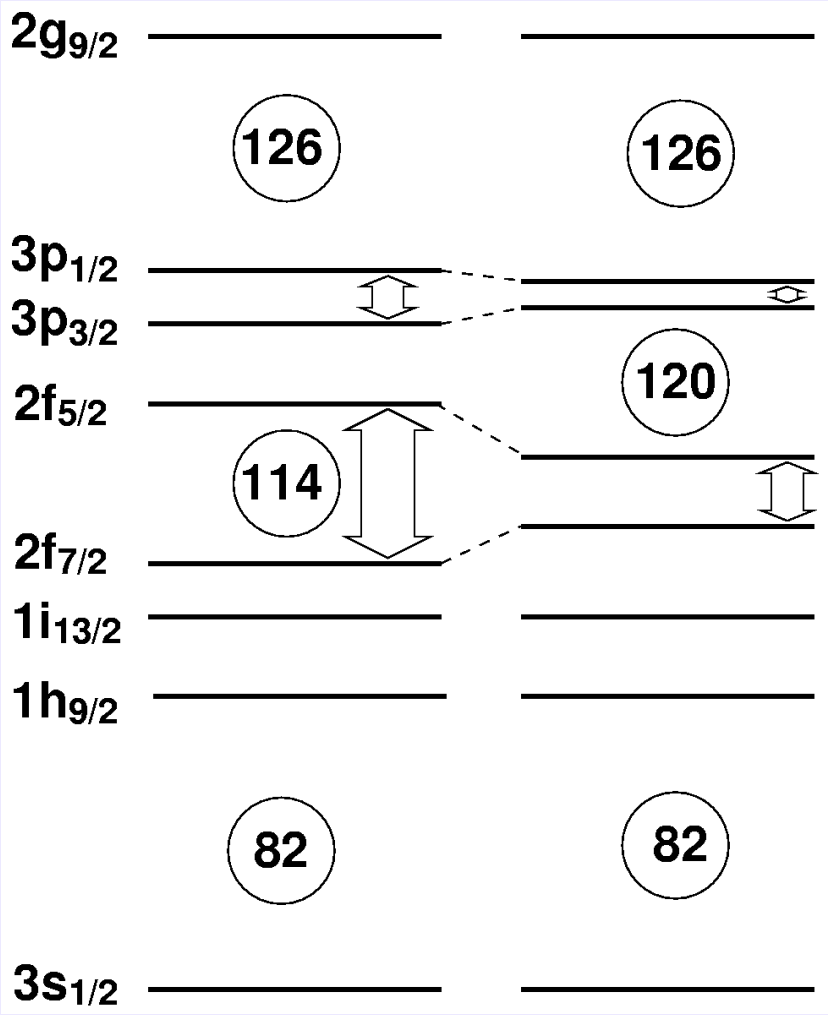
Spin-Orbit Interaction

Strong



Weak

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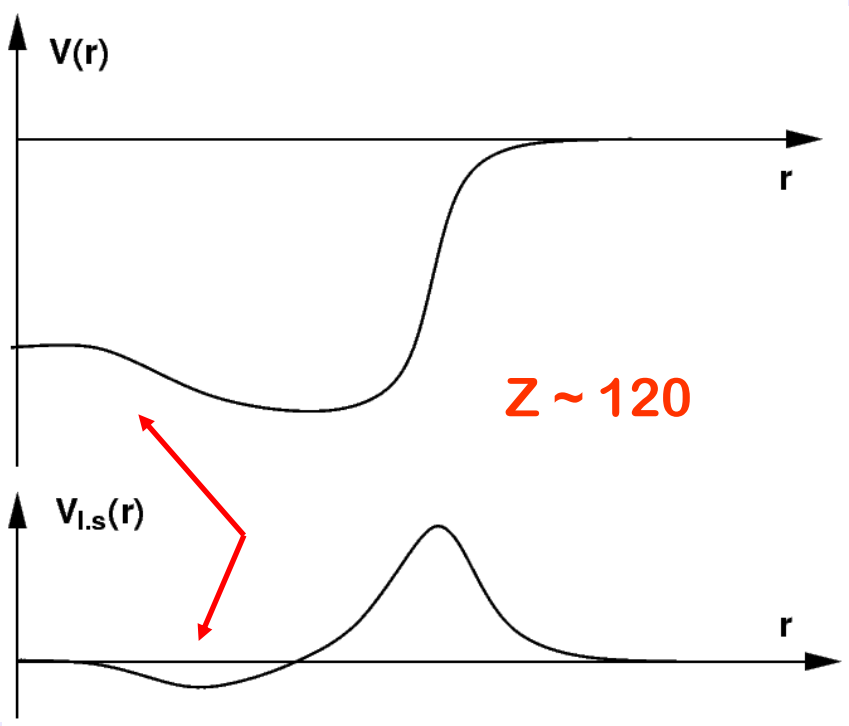
Spin-Orbit



Phenomenological:

$$V_{l.s}(r) = -\frac{1}{r}\frac{\partial V(r)}{\partial r}$$

Regardless of details,
V_{ls} is density dependent.

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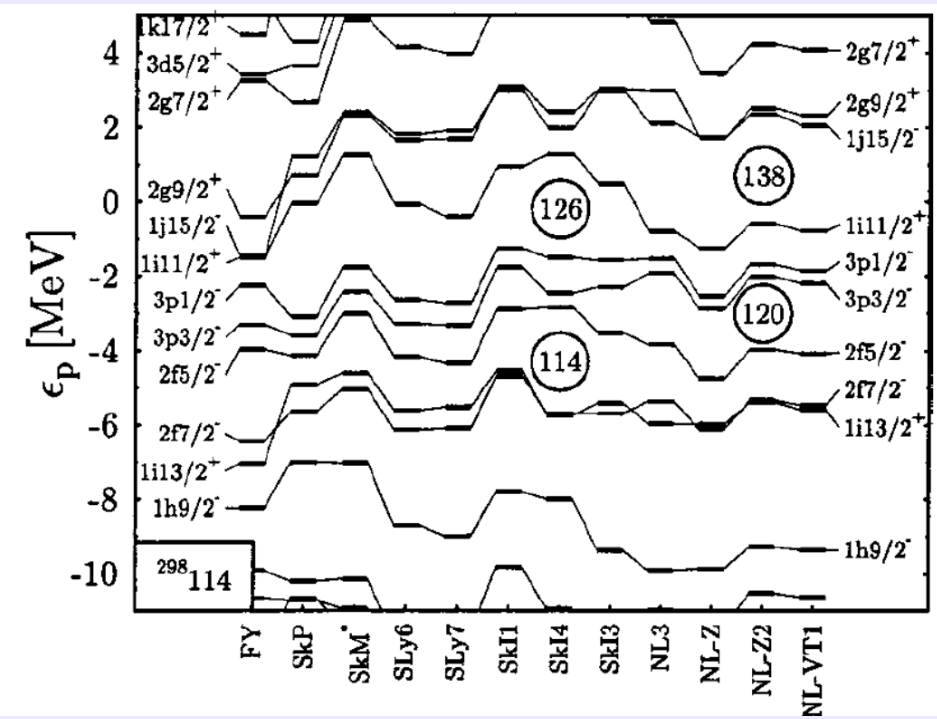
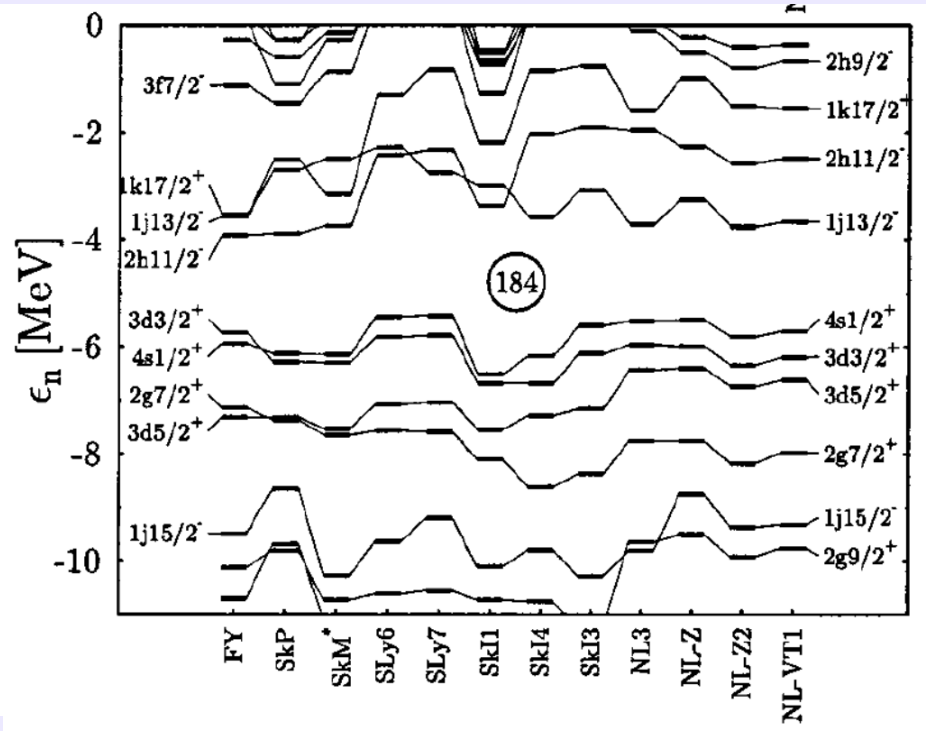
Shell Positions for $^{298}114$





From M. Bender et al., PRC 60 (1999) 034304

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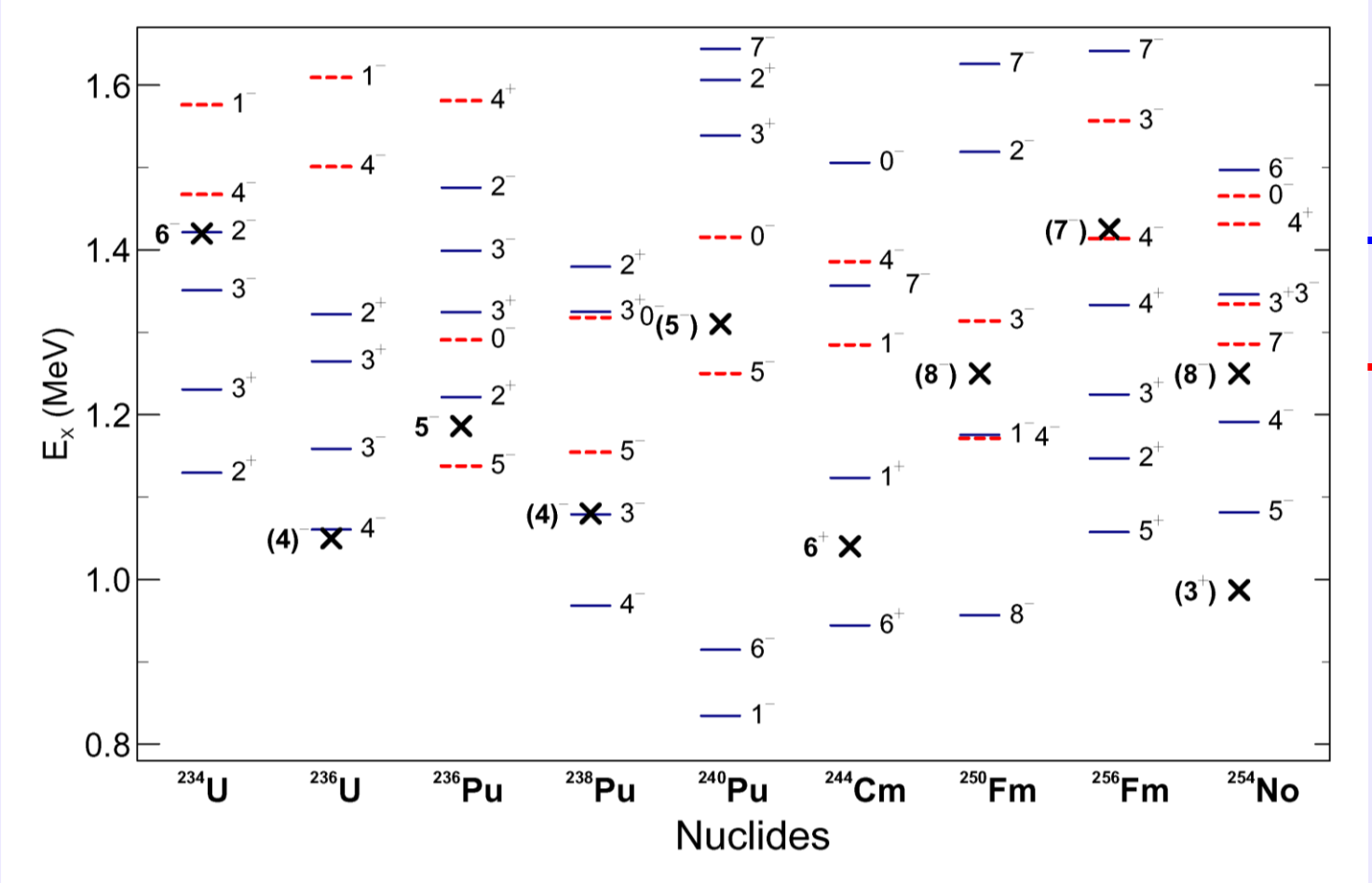
HFB Gogny Calculation



X Data

neutrons

protons

J.P. Delaroche et al., NPA 771 (06) 103

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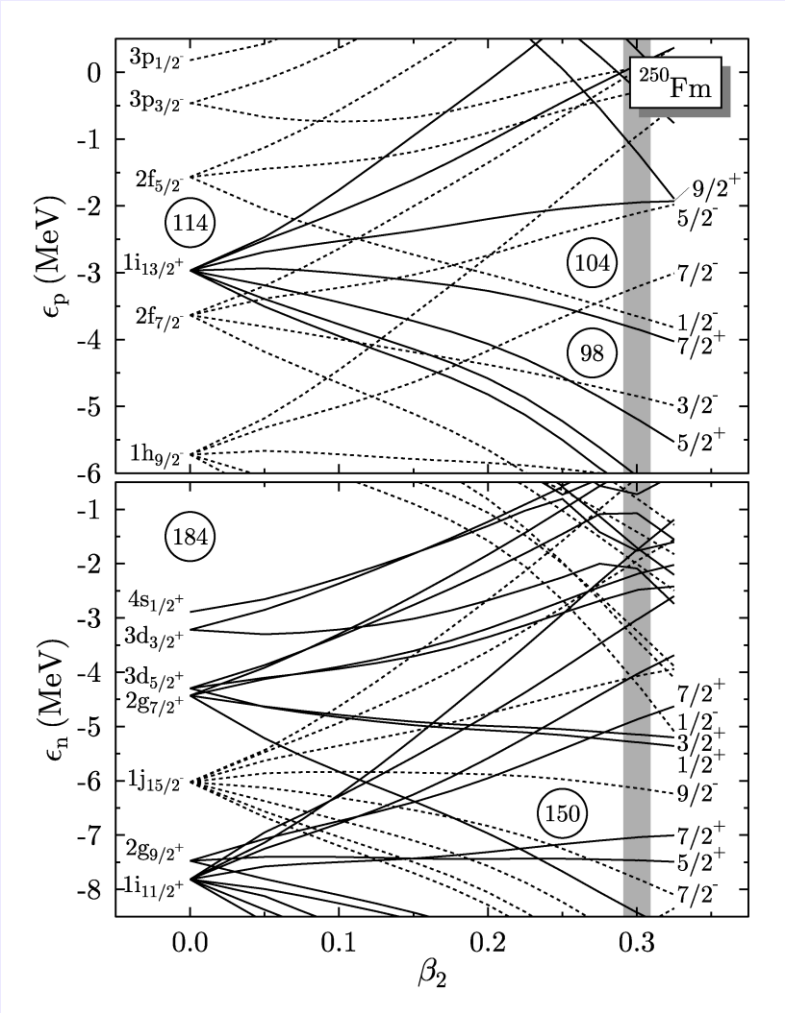
Deformed orbitals



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

Trace to position of high-l Orbitals?

p $i_{13/2}$ n $j_{15/2}$

M Bender, e.g. in
A. Chatillon et al, EPJA30, 06, 397

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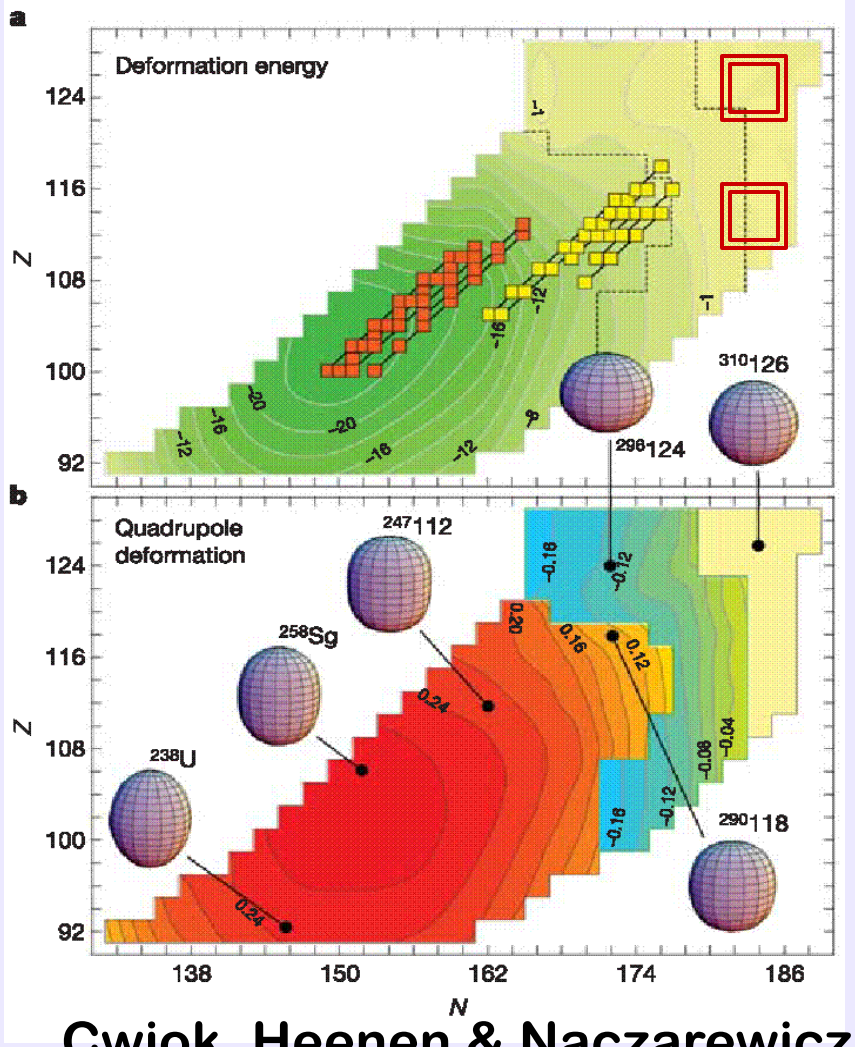
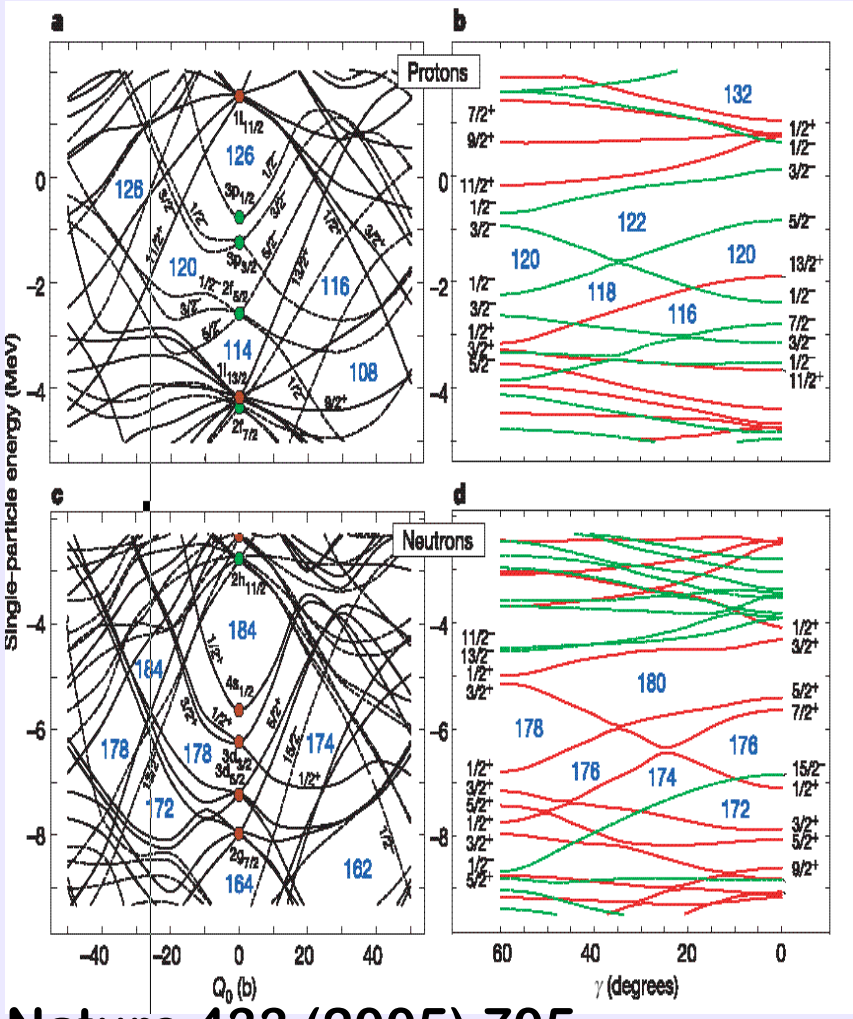
Shape is important!





Cwiok, Heenen & Naczarewicz, Nature 433 (2005) 705
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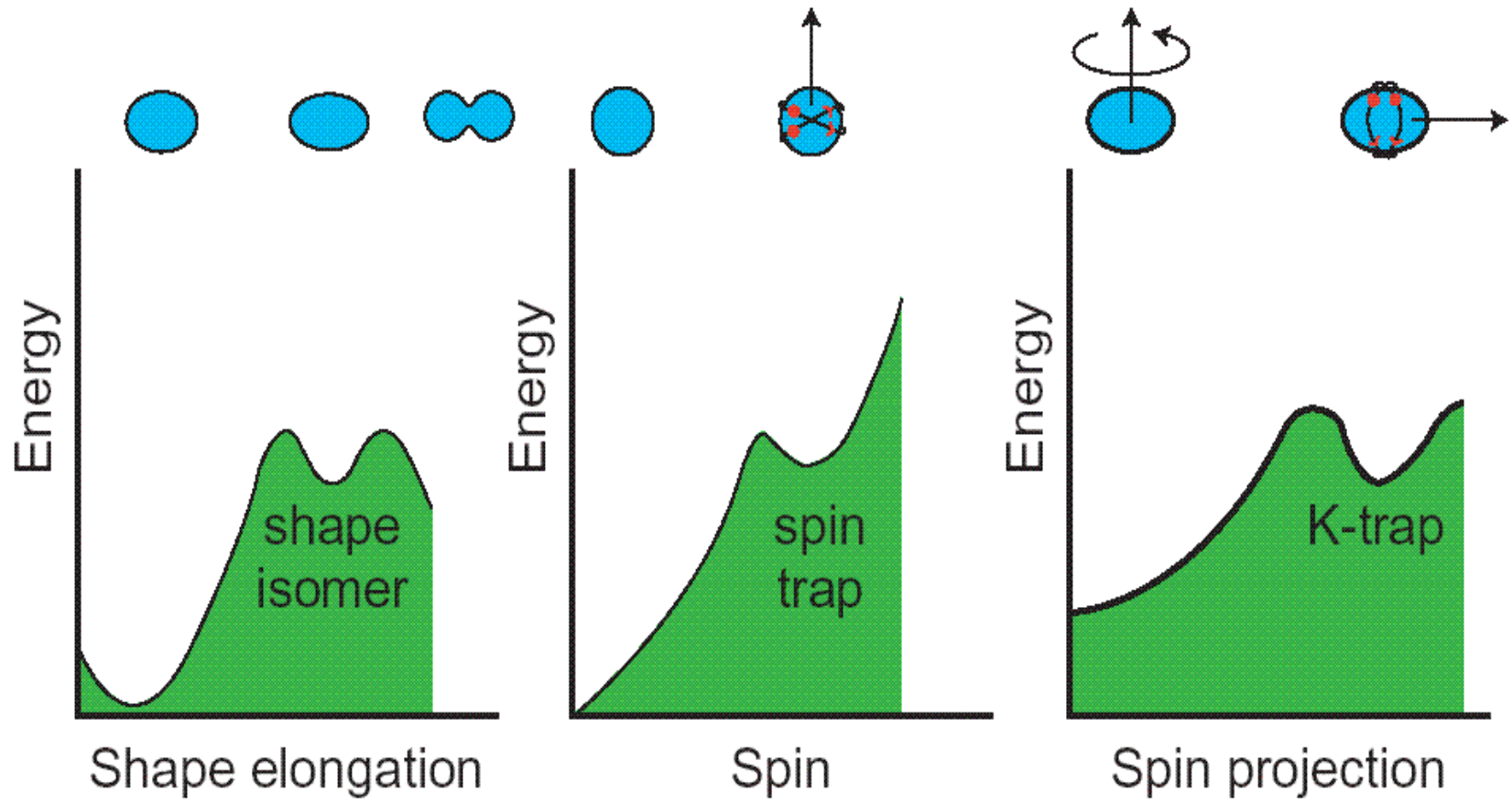
Summary

- Structure is very important.
- Position of high-l orbitals is crucial
- Isomer spectroscopy is ideal to locate these positions experimentally
- Systematic approach needed

Isomers



Walker & Dracoulis, Nature 399 (1999) 35
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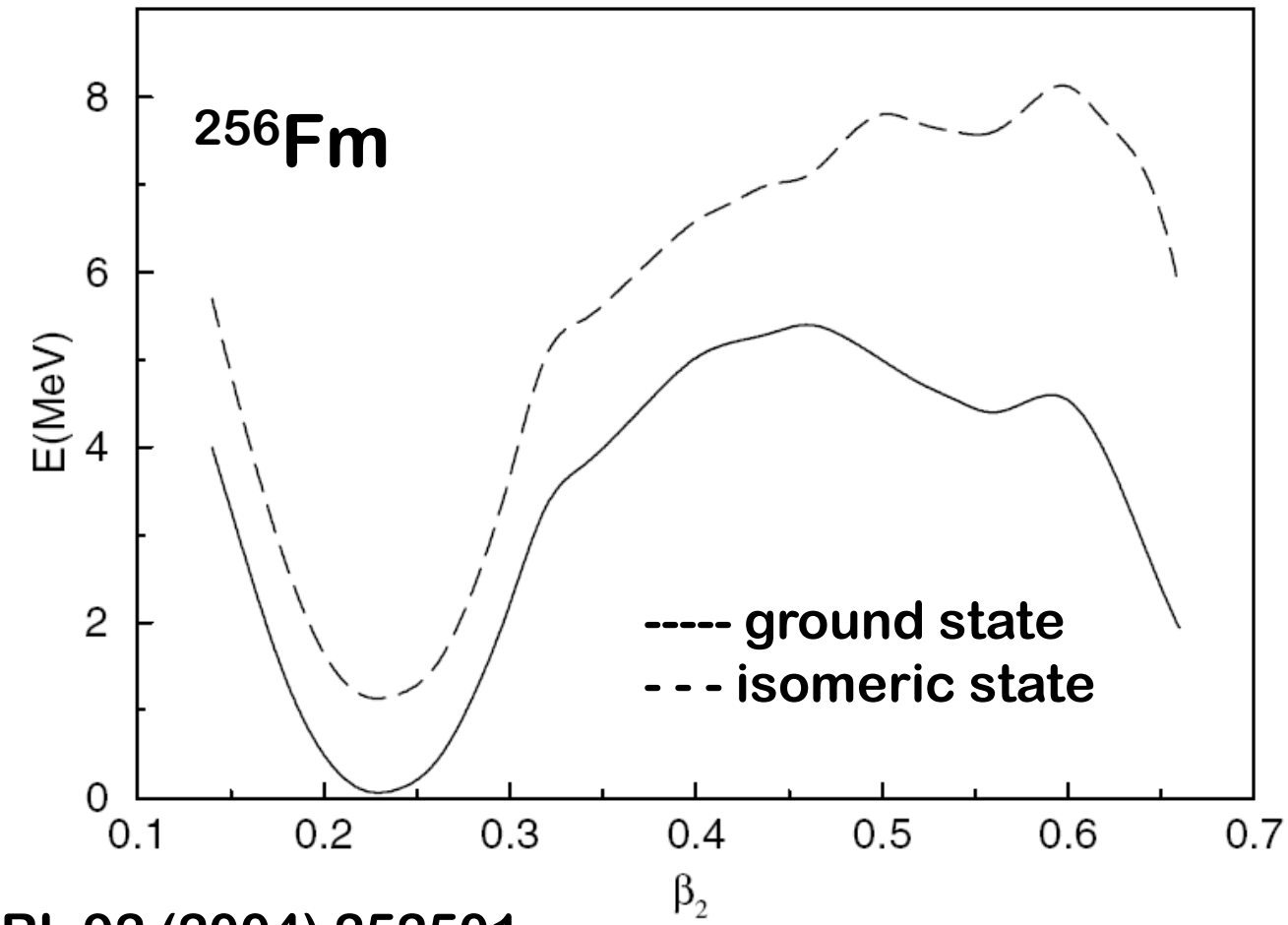
Fission Barrier



Xu et al, PRL 92 (2004) 252501

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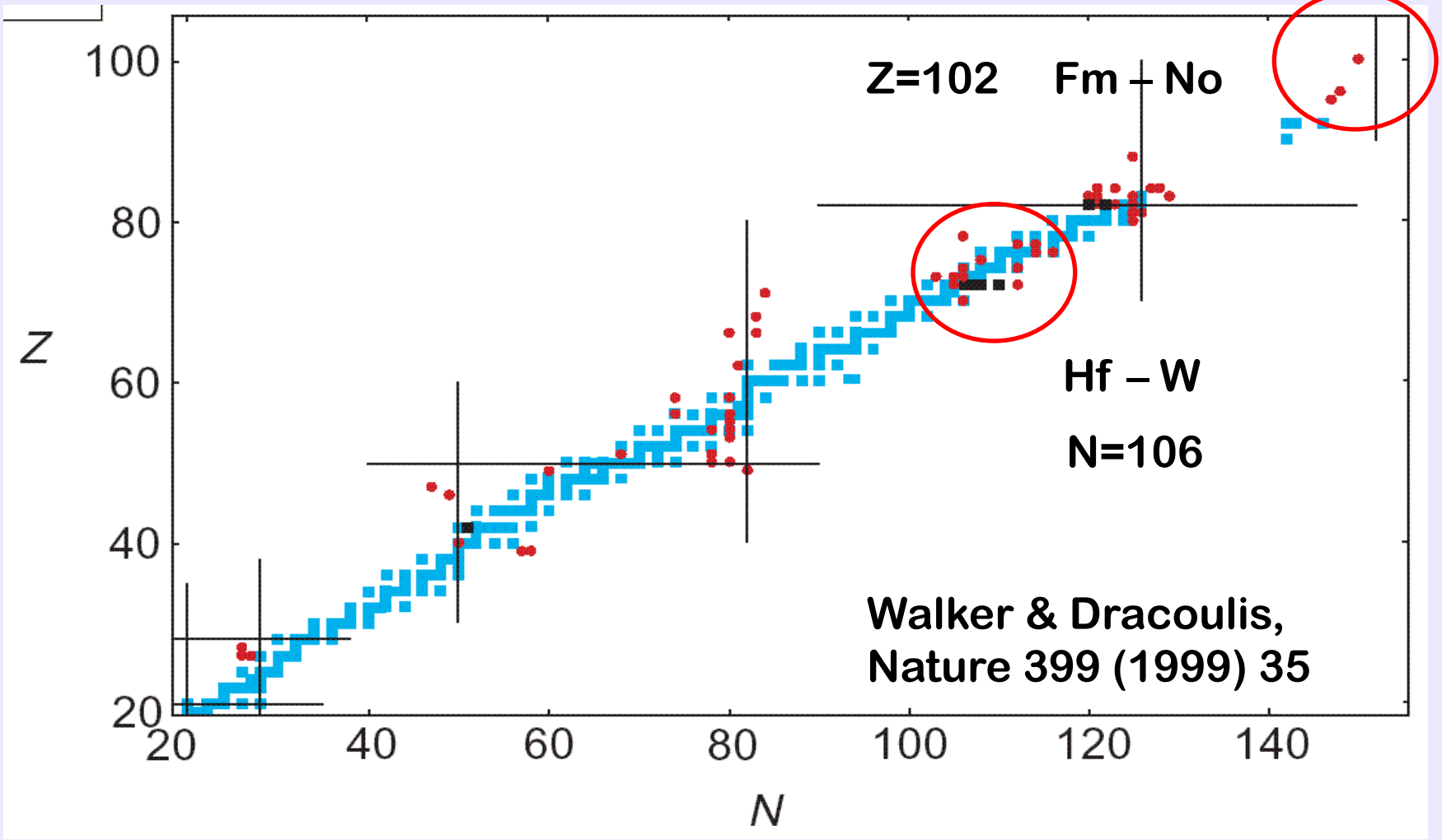
Isomer Hunting Grounds



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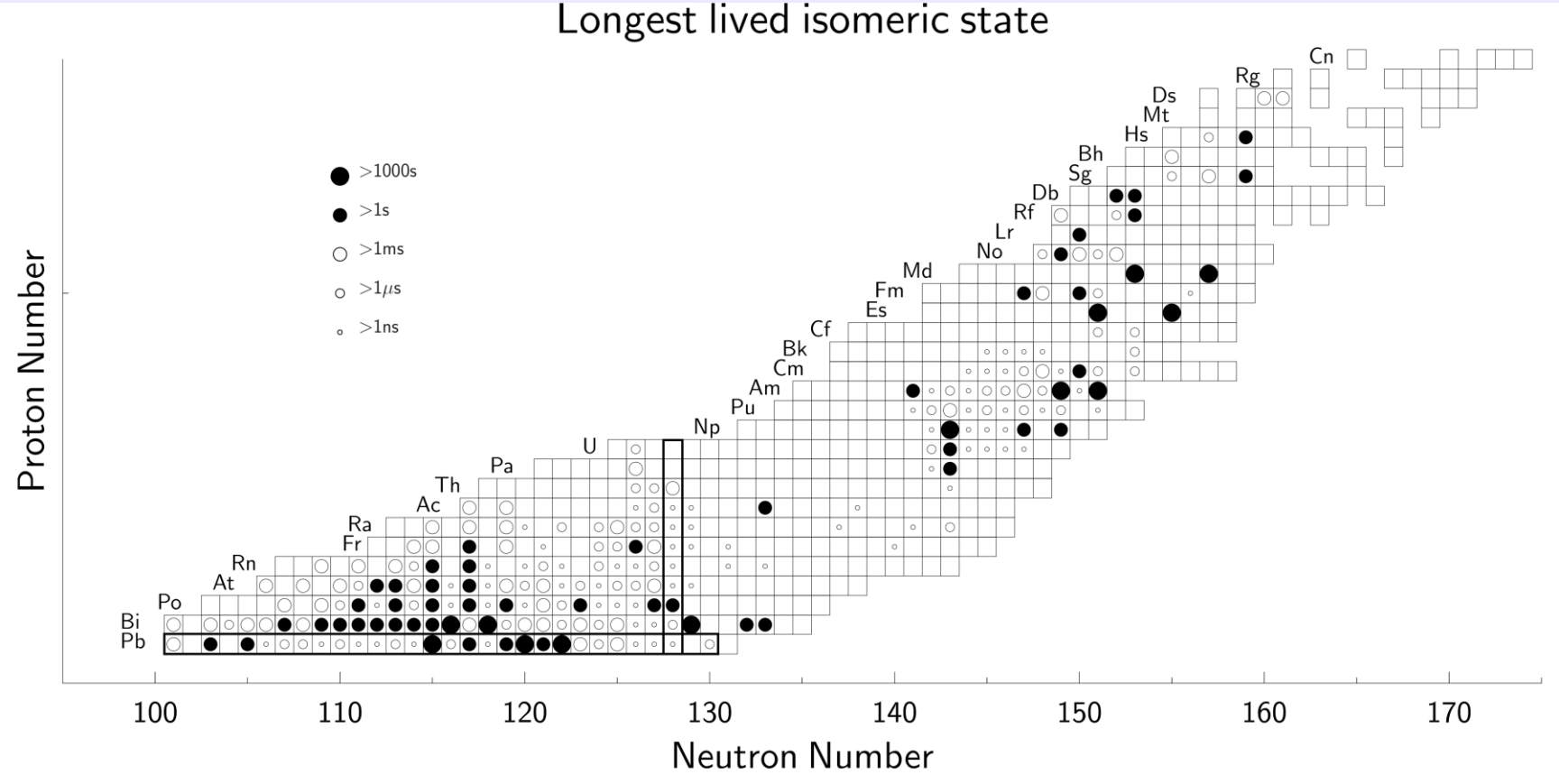
Isomers



RDH & DM Cox, RCA 99, 441, (2011)

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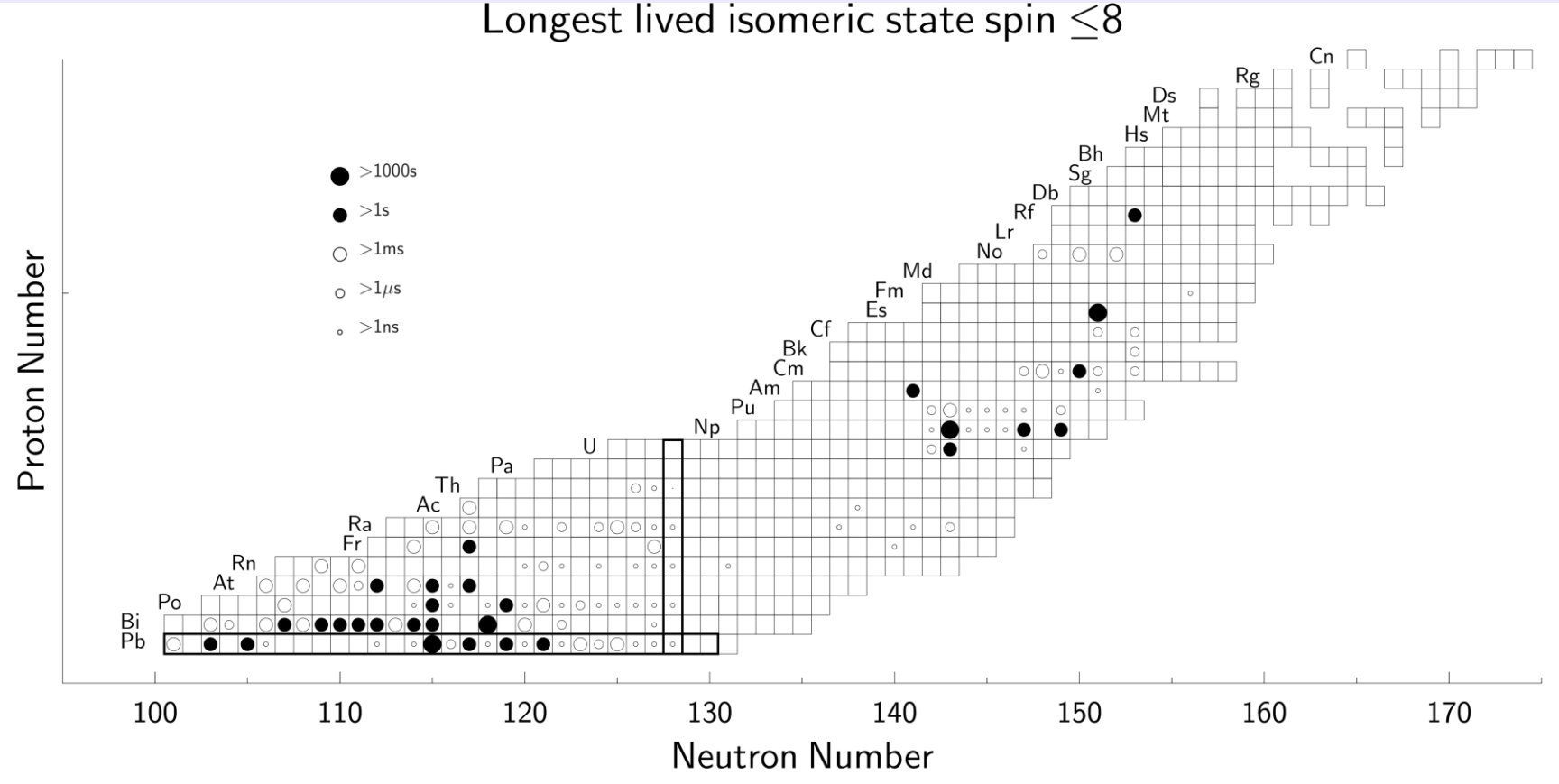
Isomers J≤8



RDH & DM Cox, RCA 99, 441, (2011)

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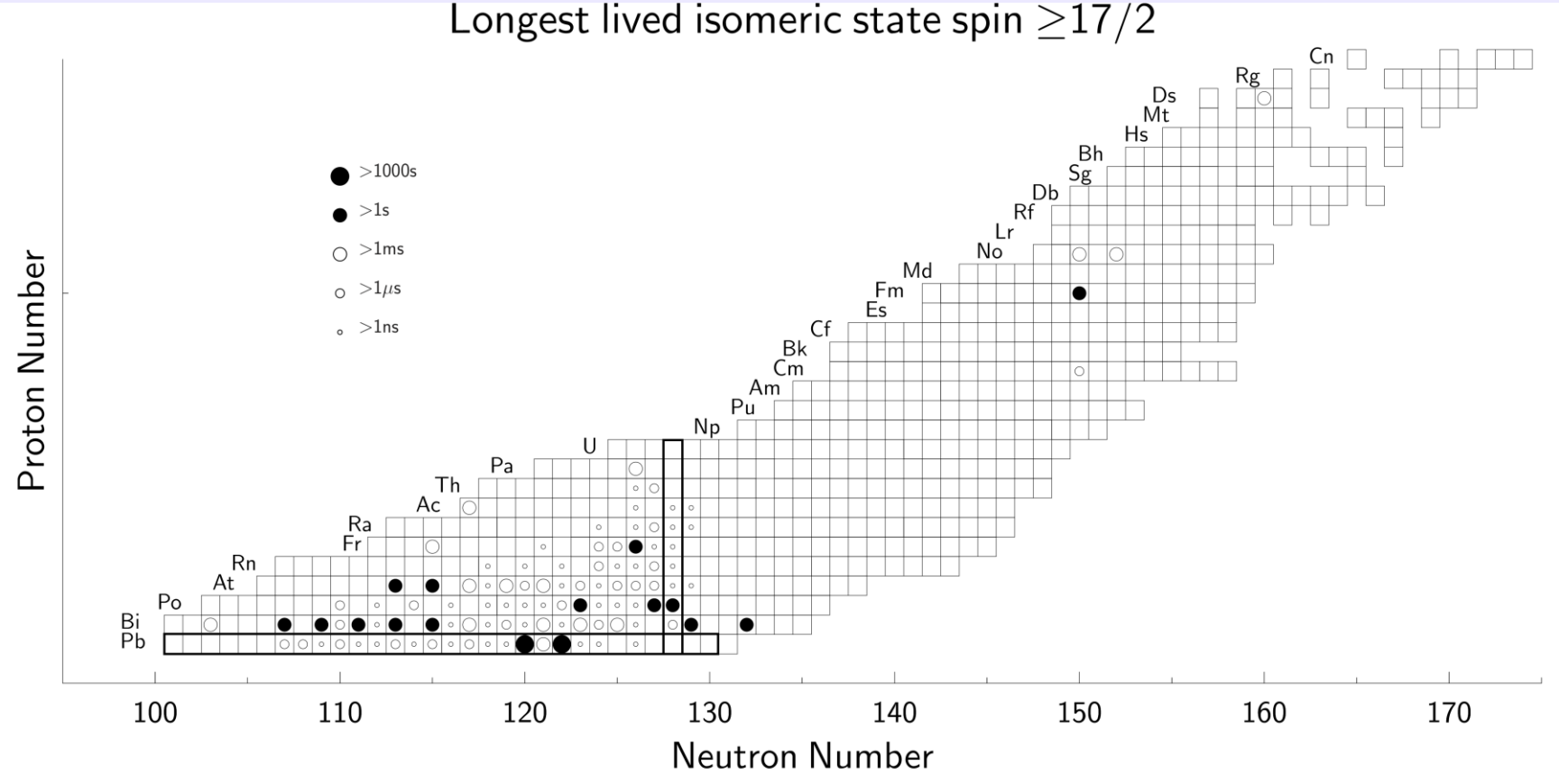
Isomers J>8



RDH & DM Cox, RCA 99, 441, (2011)

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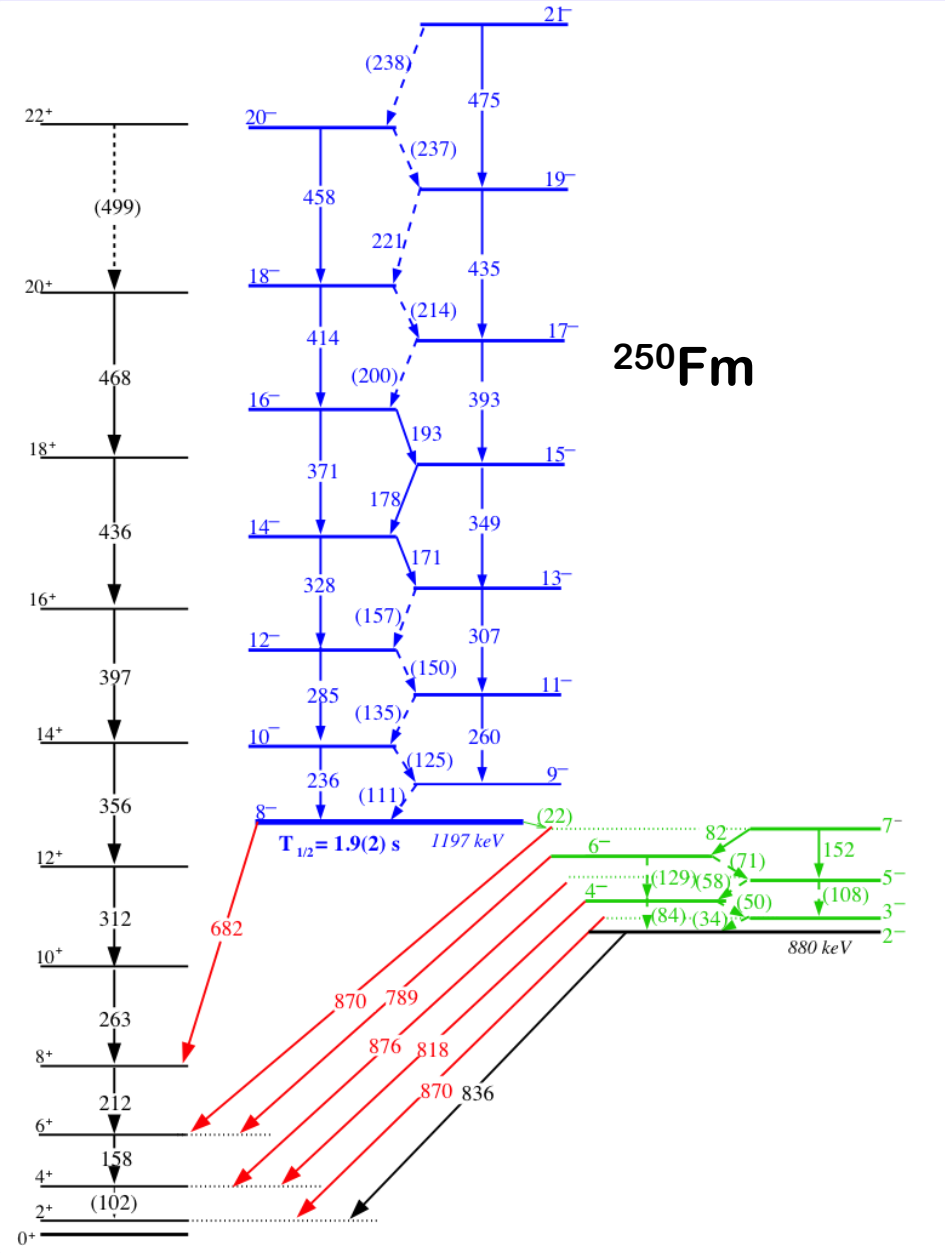
^{250}Fm

- Greenlees et al, PRC78 (08) 021303R

- Delayed gamma rays leading to energies of K=2 and K=8 bands

- Half life of isomeric K=8 band head



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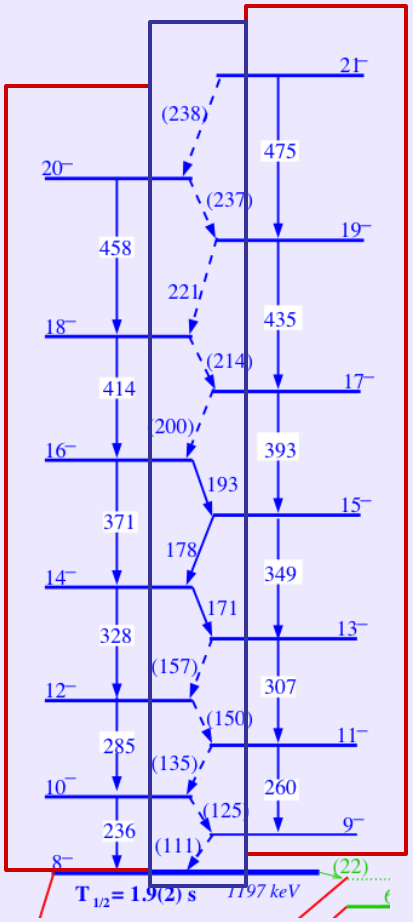
Branching Ratios



$E2 \sim Q_o^2$

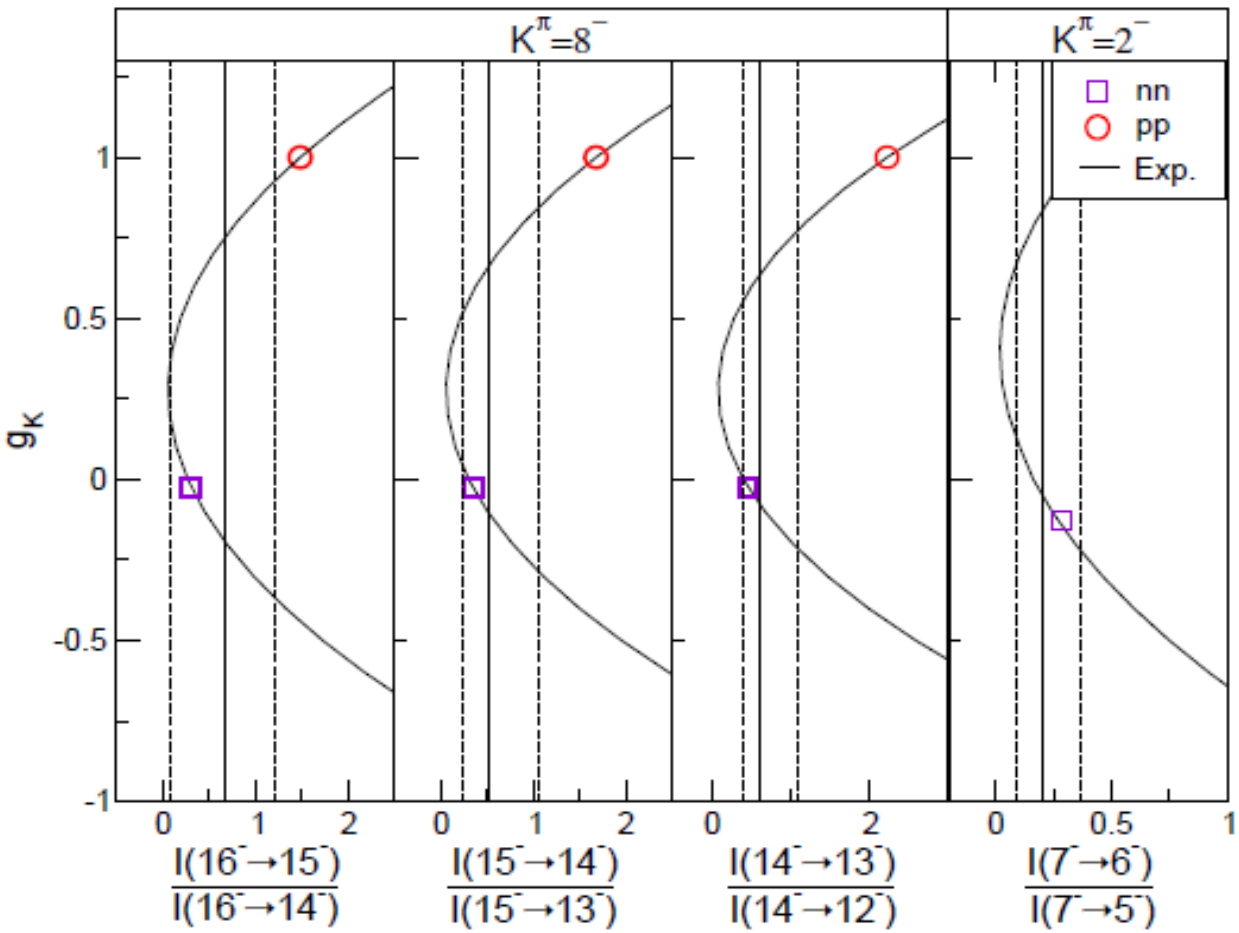
$M1 \sim (g_k - g_R)^2$

Stretched: E2 only

Interband: mixed E2 + M1

Branching ratios sensitive to $[(g_k - g_R)/Q_o]^2$

g-factors in ^{250}Fm



Test:

pp:
$8^-\{9/2^+[624]\times7/2^-[514]\}$
$g_K=1.001$

nn:
$8^-\{7/2^+[624]\times9/2^-[734]\}$
$g_K=-0.0225$

D. Rostron

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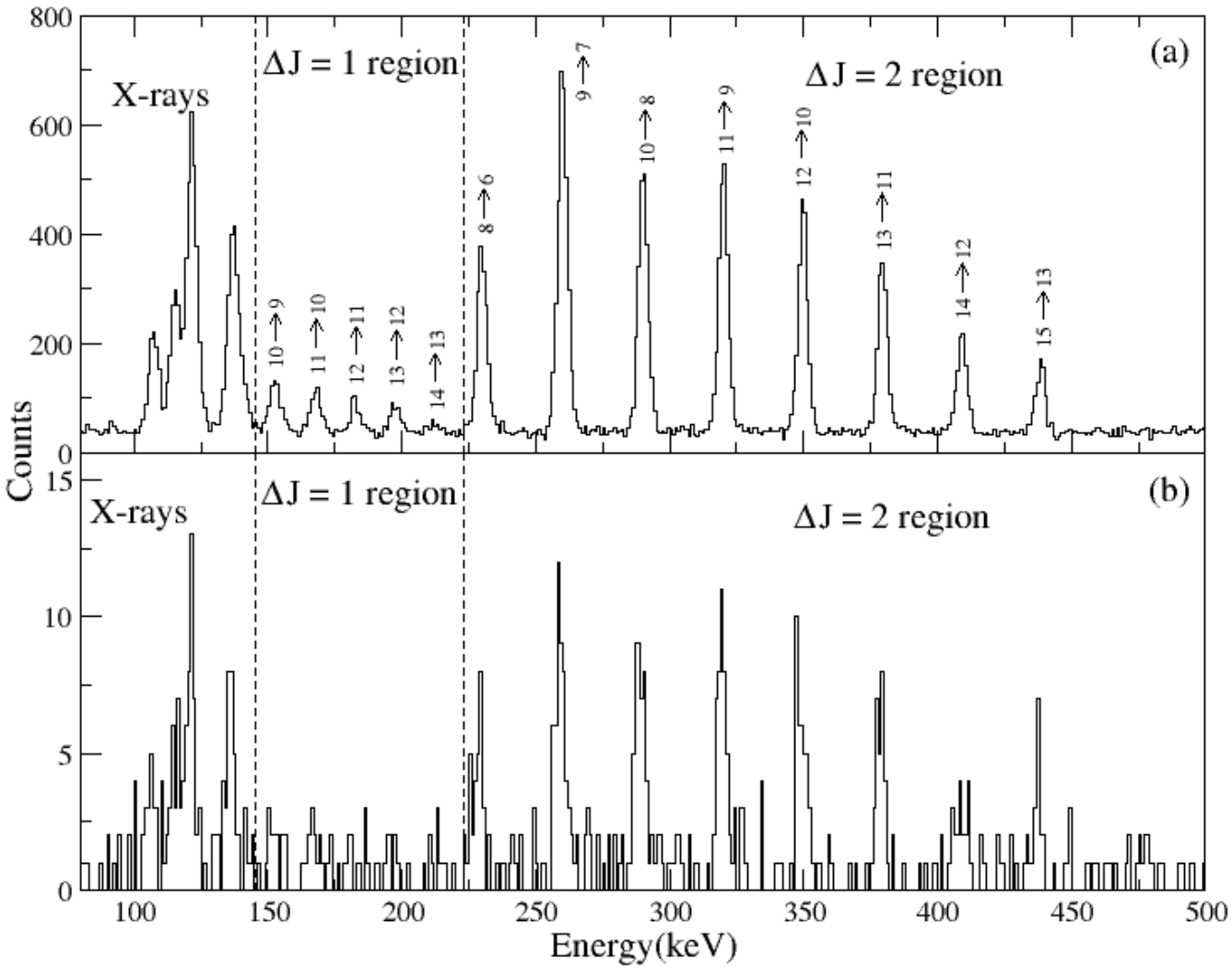
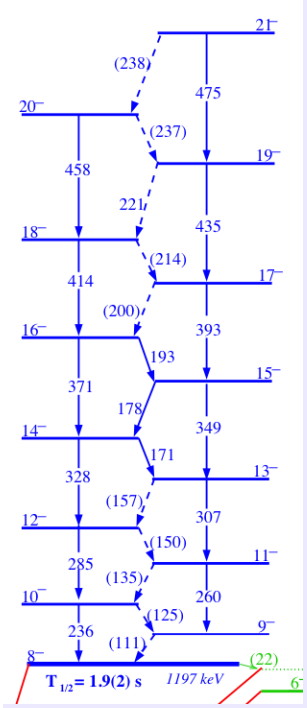
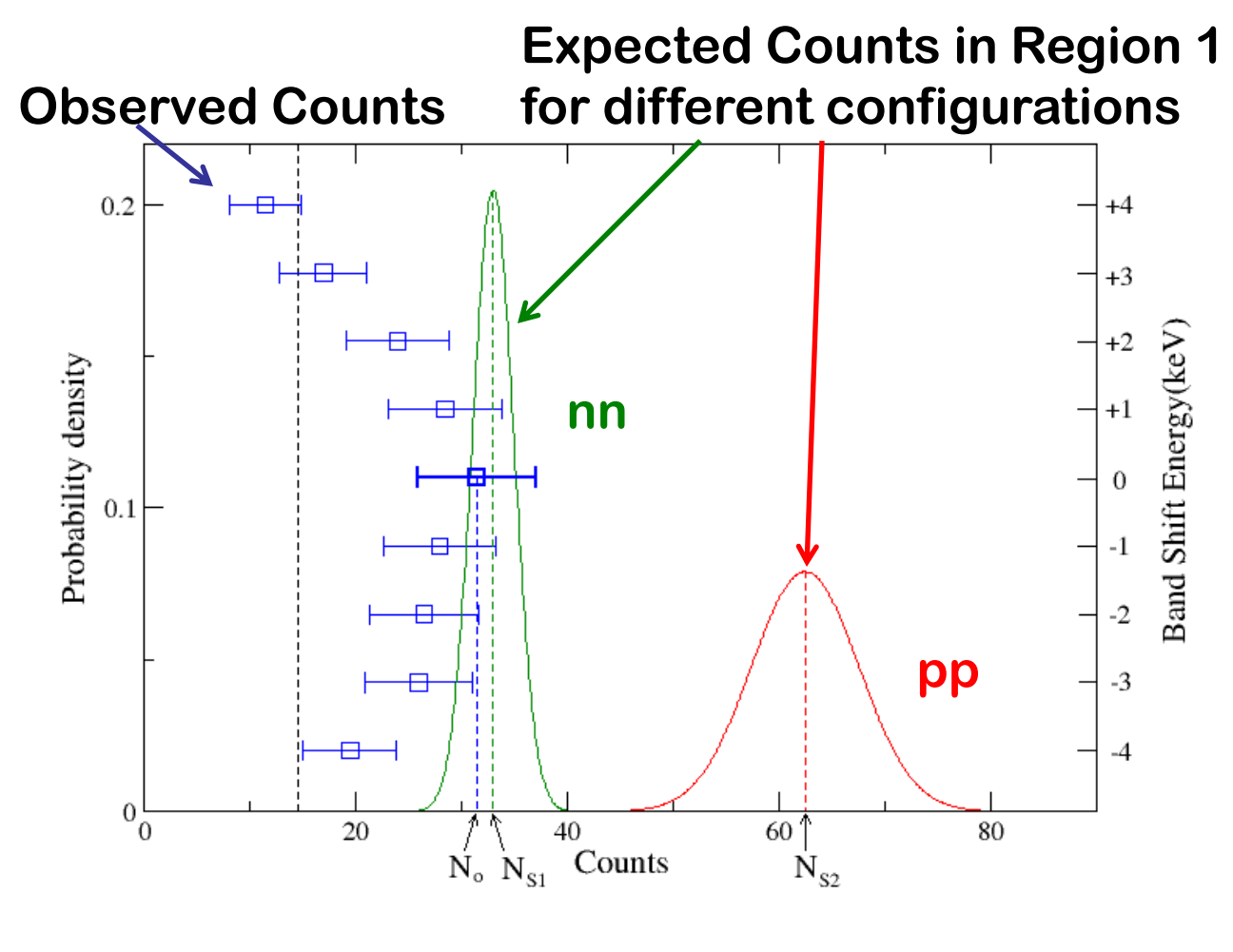
If statistics is low:





Use Region 2 to predict counts in region 1

In Practice : ^{250}Fm



E. Parr thesis
& in prep.

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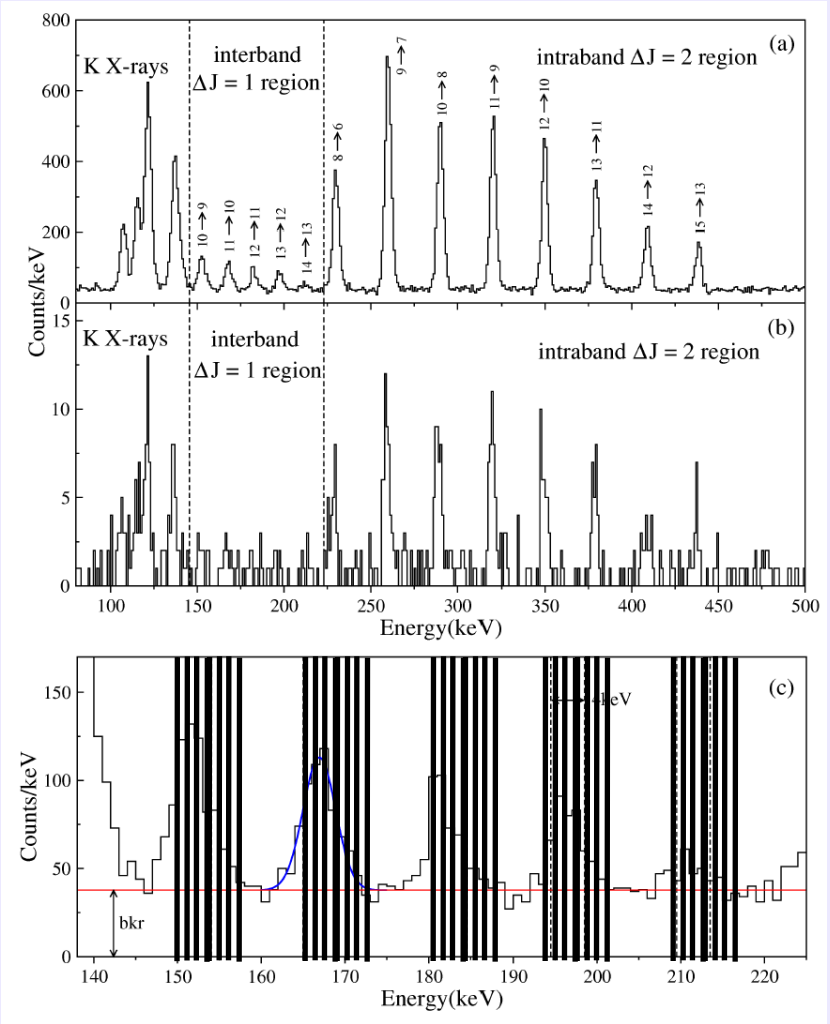
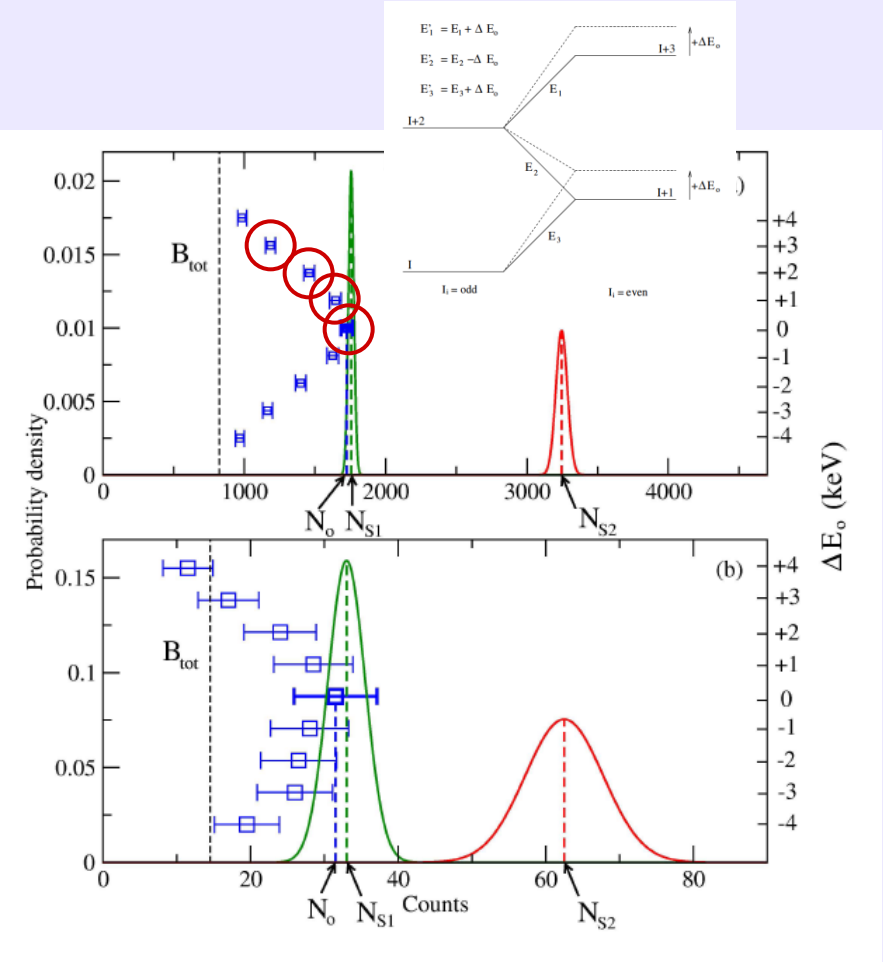
A test case





E.Parr, in preparation

Quenching

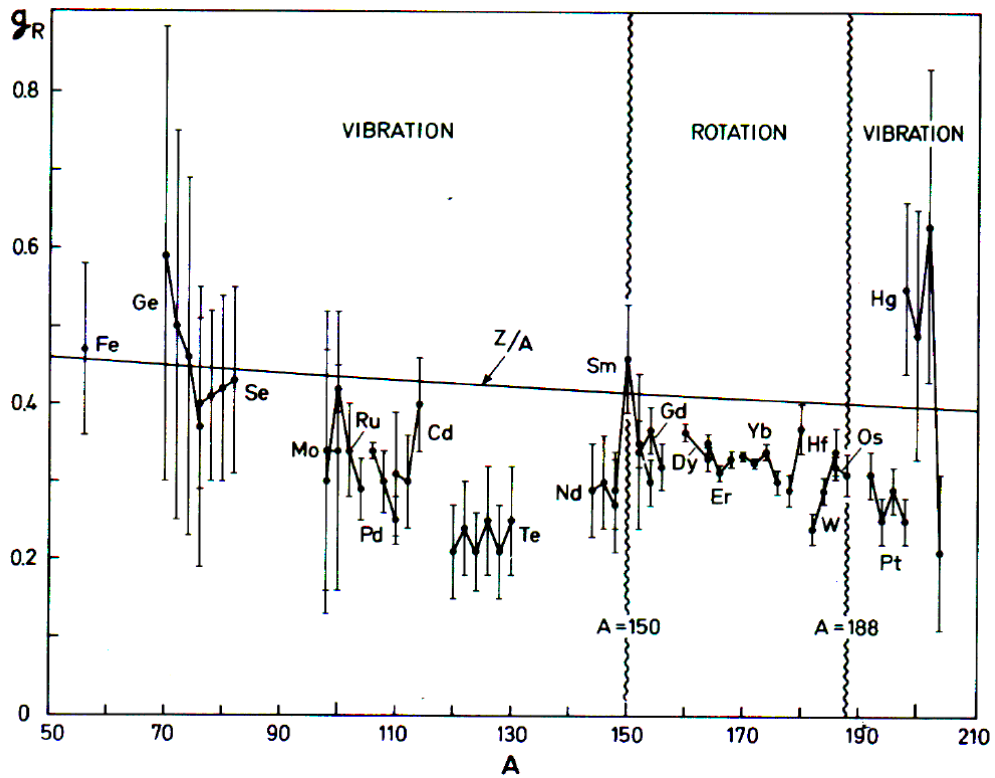


Figure 4-6 *g* factors for first excited 2+ states in even-even nuclei. The figure is based on the experimental data given by G. M. Heestand, R. R. Borchers, B. Herskind, L. Grodzins, R. Kalish, and D. E. Murnick, *Nuclear Phys.* **A133**, 310 (1969) and on the review by Grodzins (1968). We are indebted to L. Grodzins, B. Herskind, and S. Ogaza for help in the preparation of the figure.

From Bohr & Mottelson

$g_R = q\ Z/A$

Typically used:

$q \sim 0.7$

We always test

$q = 1$ and $q = 0.7$

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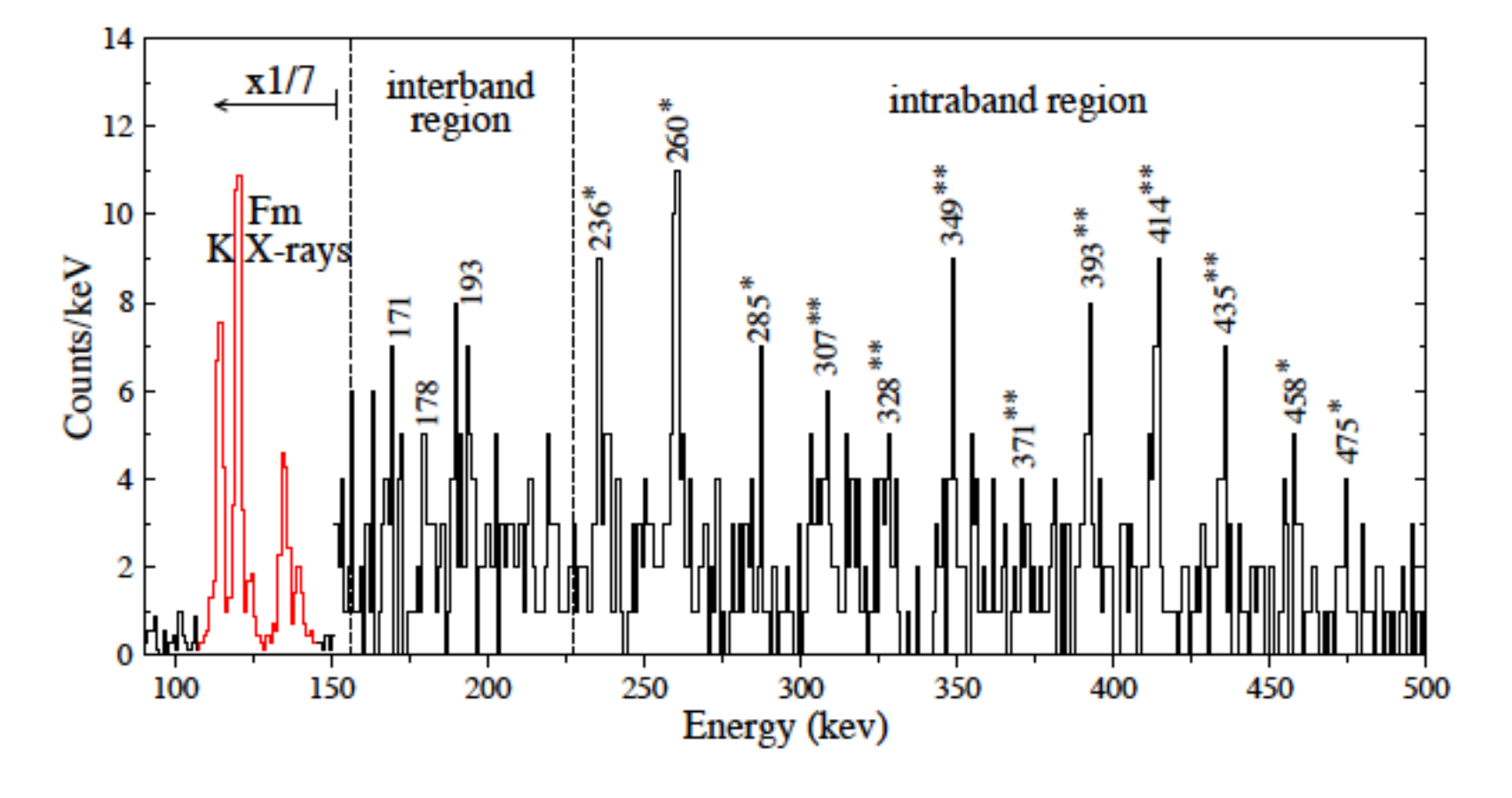
^{250}Fm 8$^-$ isomer

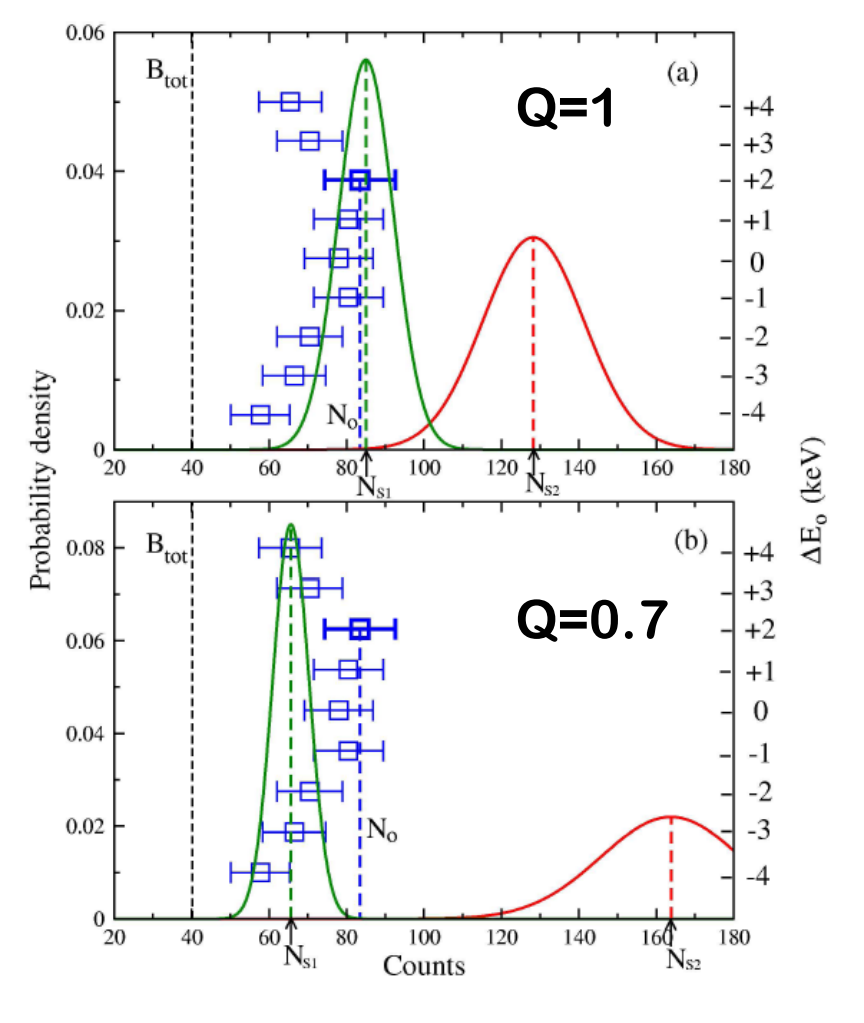


^{250}Fm 8$^-$ isomer

7/2+[624] x 9/2-[734] nn

7/2-[514] x 9/2+[624] pp

Clearly a two-neutron state



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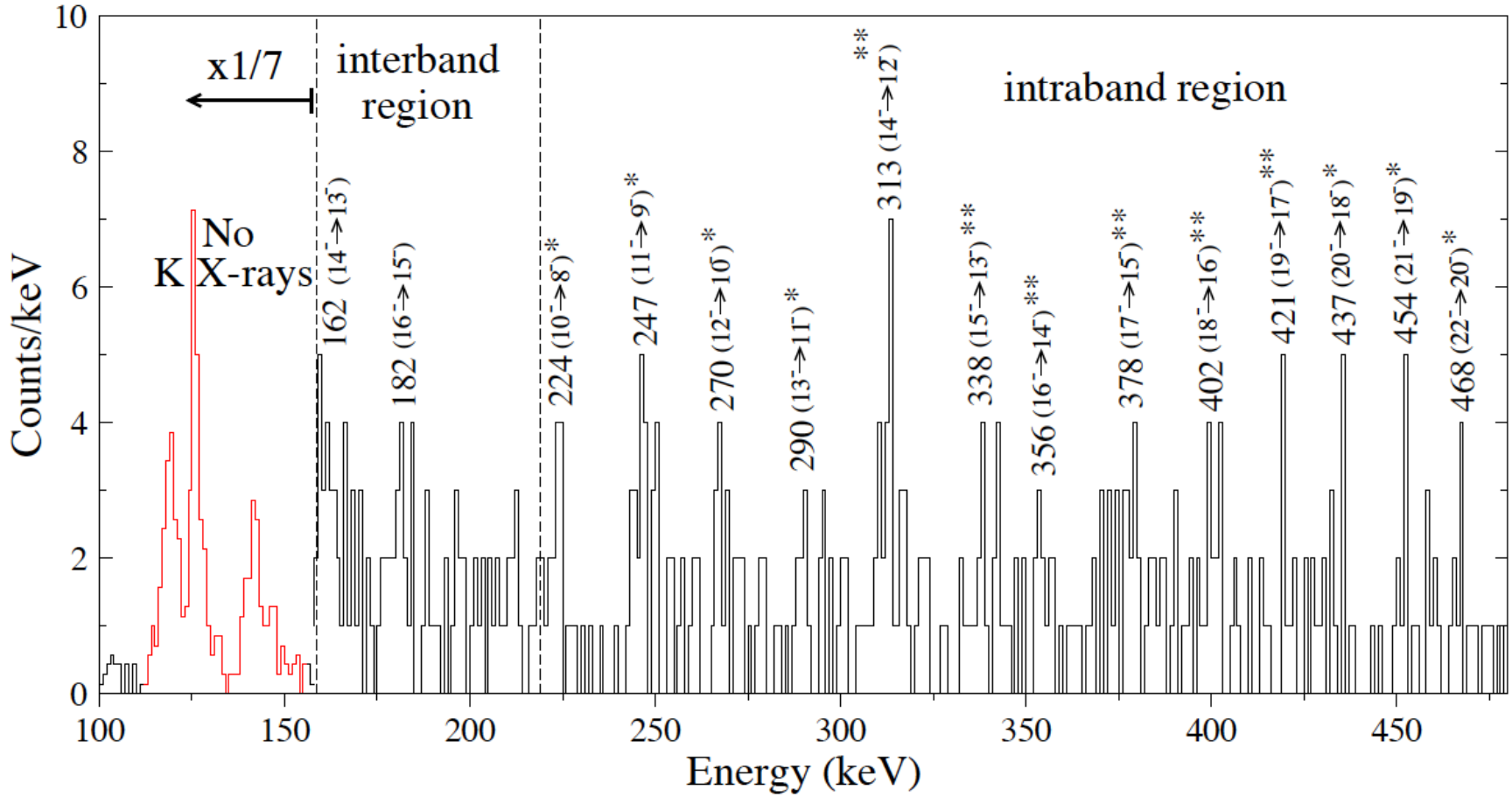
^{252}No 8$^-$ isomer

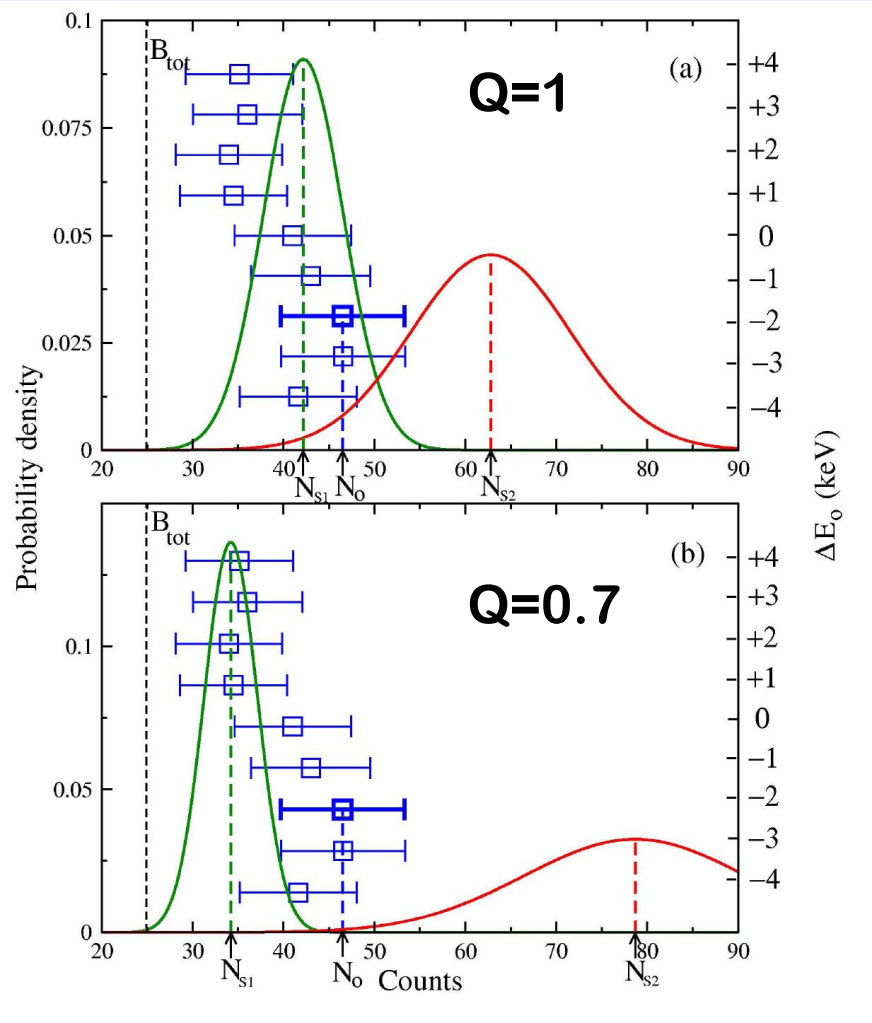


B Sulignano, E Parr, in preparation

^{252}No 8^- isomer

7/2+[624] x 9/2-[734] nn

7/2-[514] x 9/2+[624] pp



Clearly a two-neutron state

B Sulignano, E Parr, in preparation

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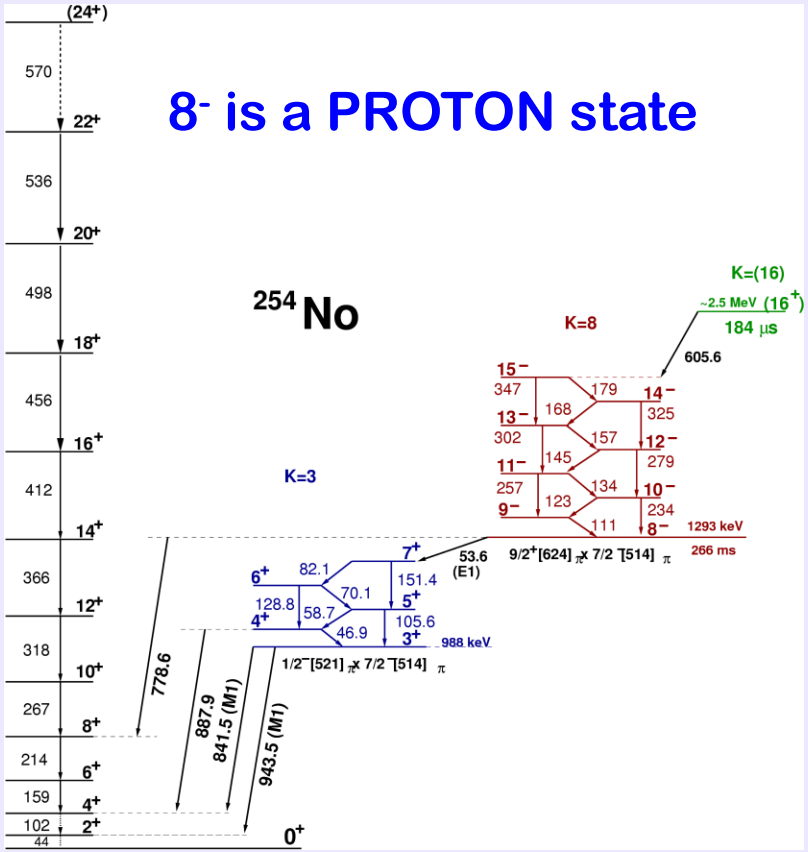
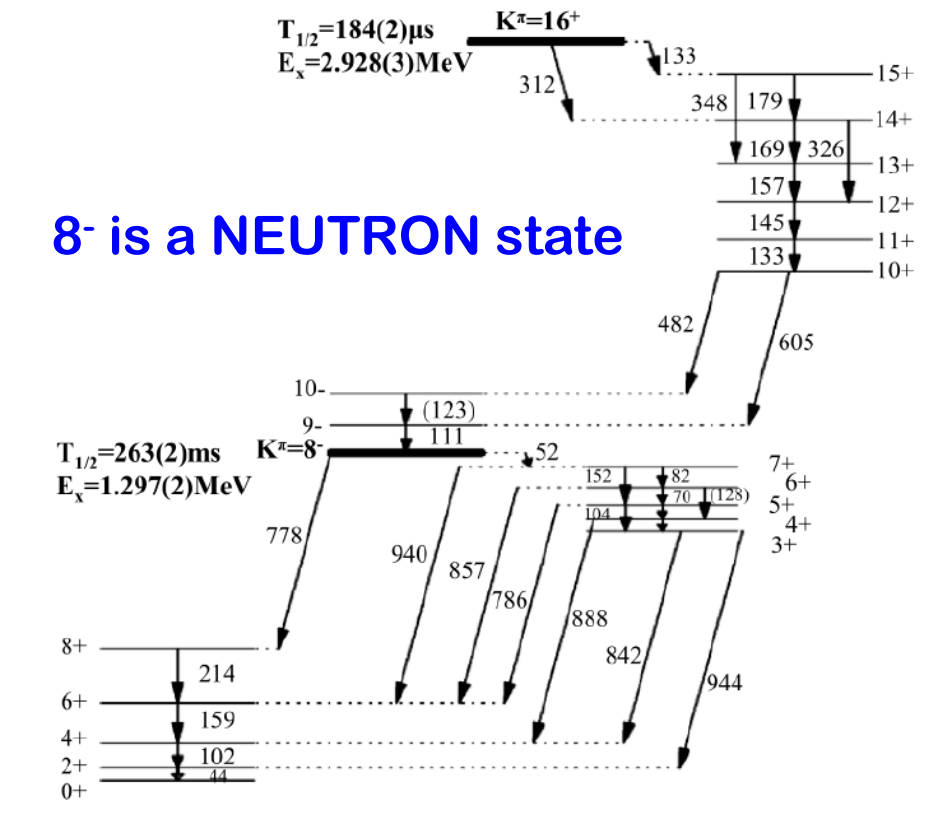
^{254}No 8$^-$ isomer

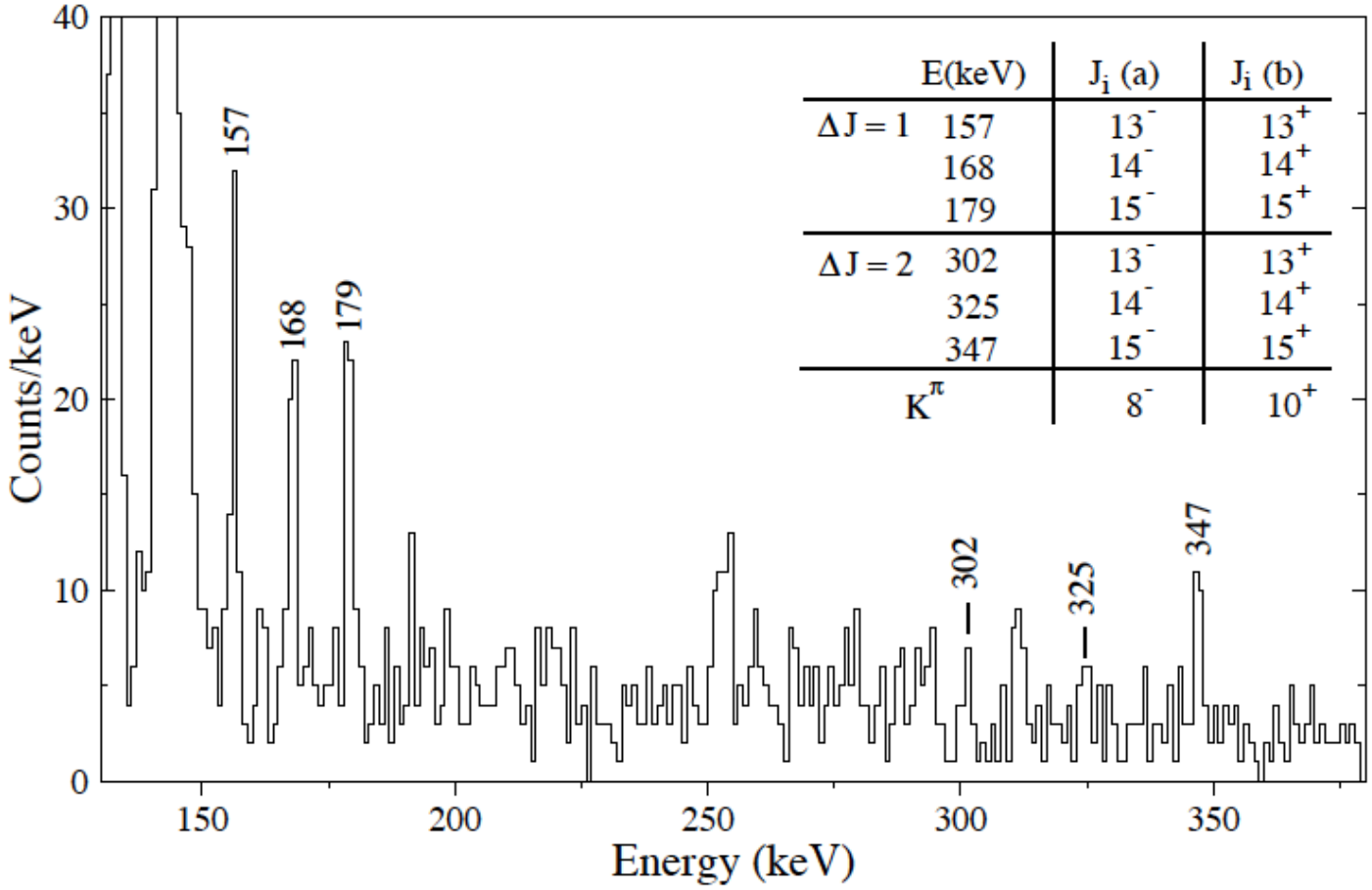




New Data:
F.P. Hessberger, EPJ43, 55 (10)
C Gray-Jones, thesis

R.M. Clark et al., PLB690, 610 (09)

^{254}No 8$^-$ isomer



Data:
F.P. Hessberger, EPJ43, 55 (10)
C Gray-Jones, thesis

^{254}No 8$^-$ isomer

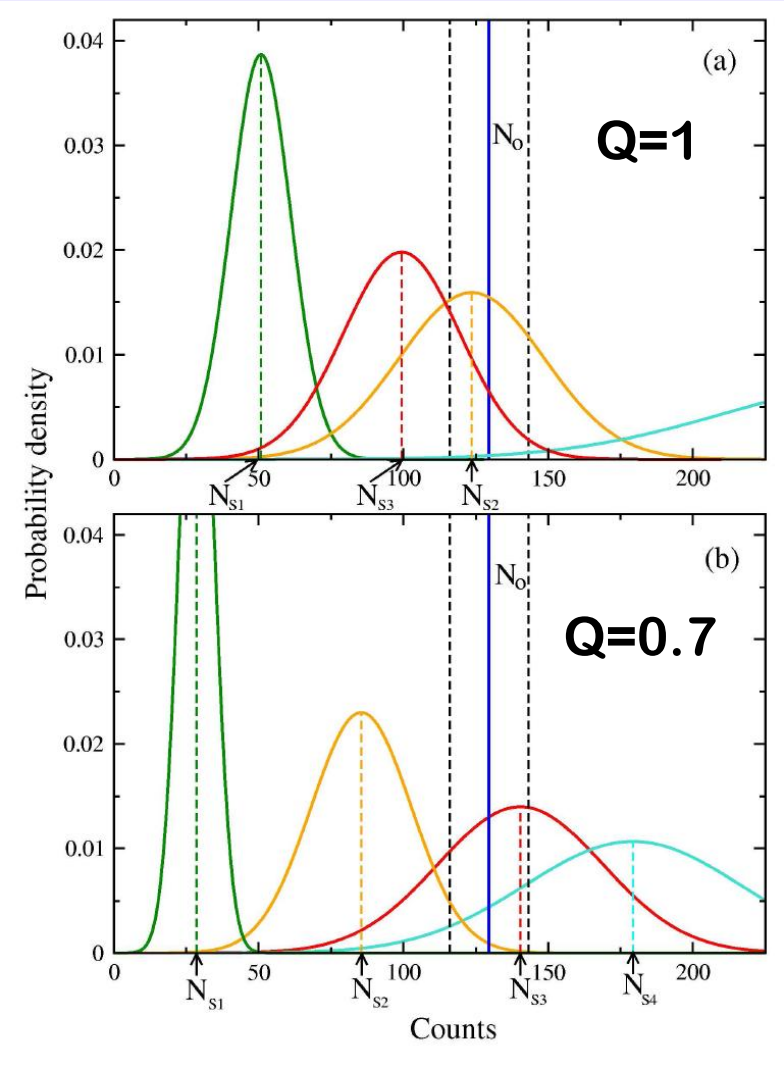
7/2+[624] x 9/2-[734] nn

7/2+[613] x 9/2-[734] nn

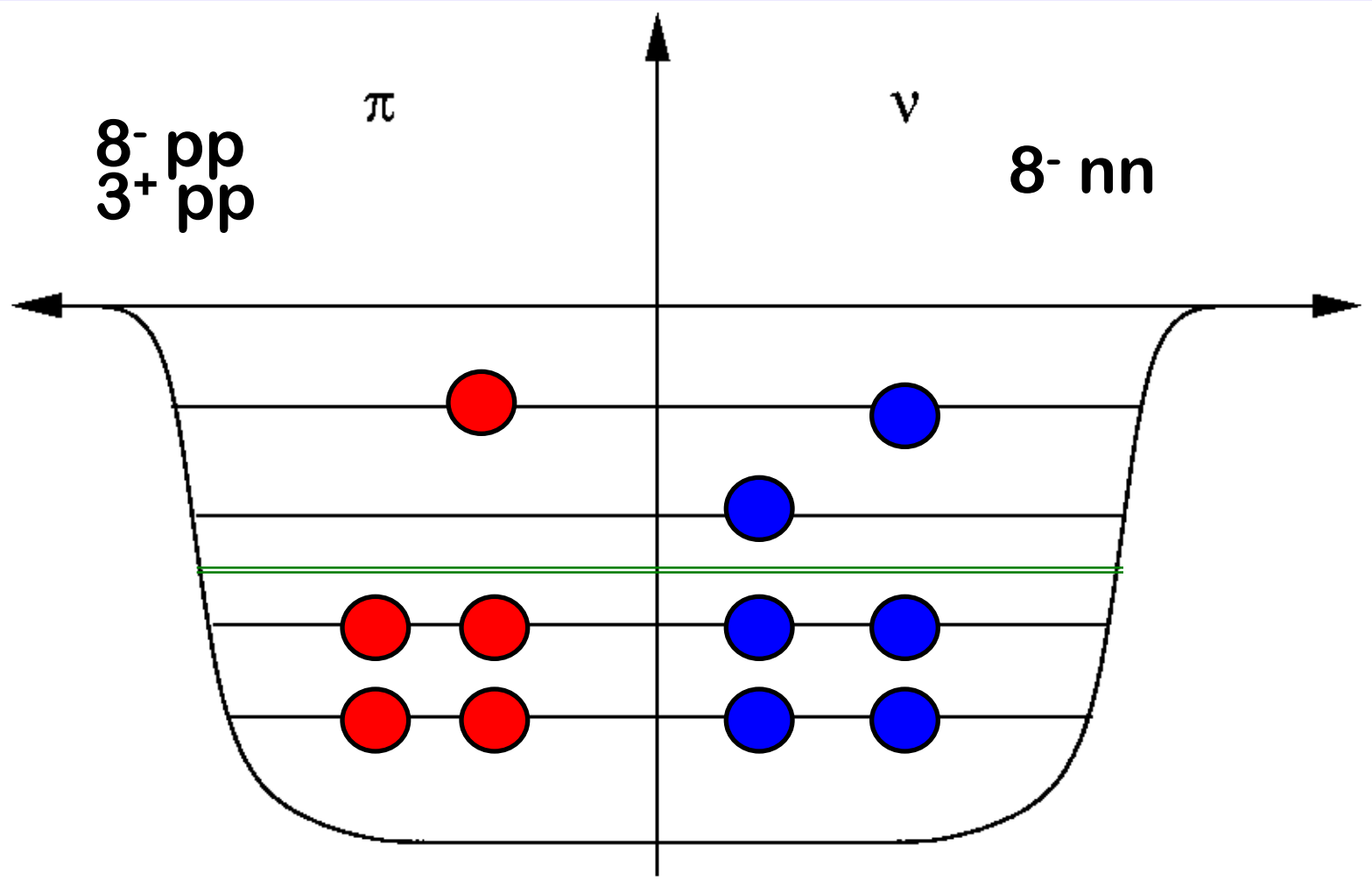
7/2-[514] x 9/2+[624] pp

11/2-[725] x 9/2-[734] nn

Depending on quenching, either configuration is possible.



Transitions



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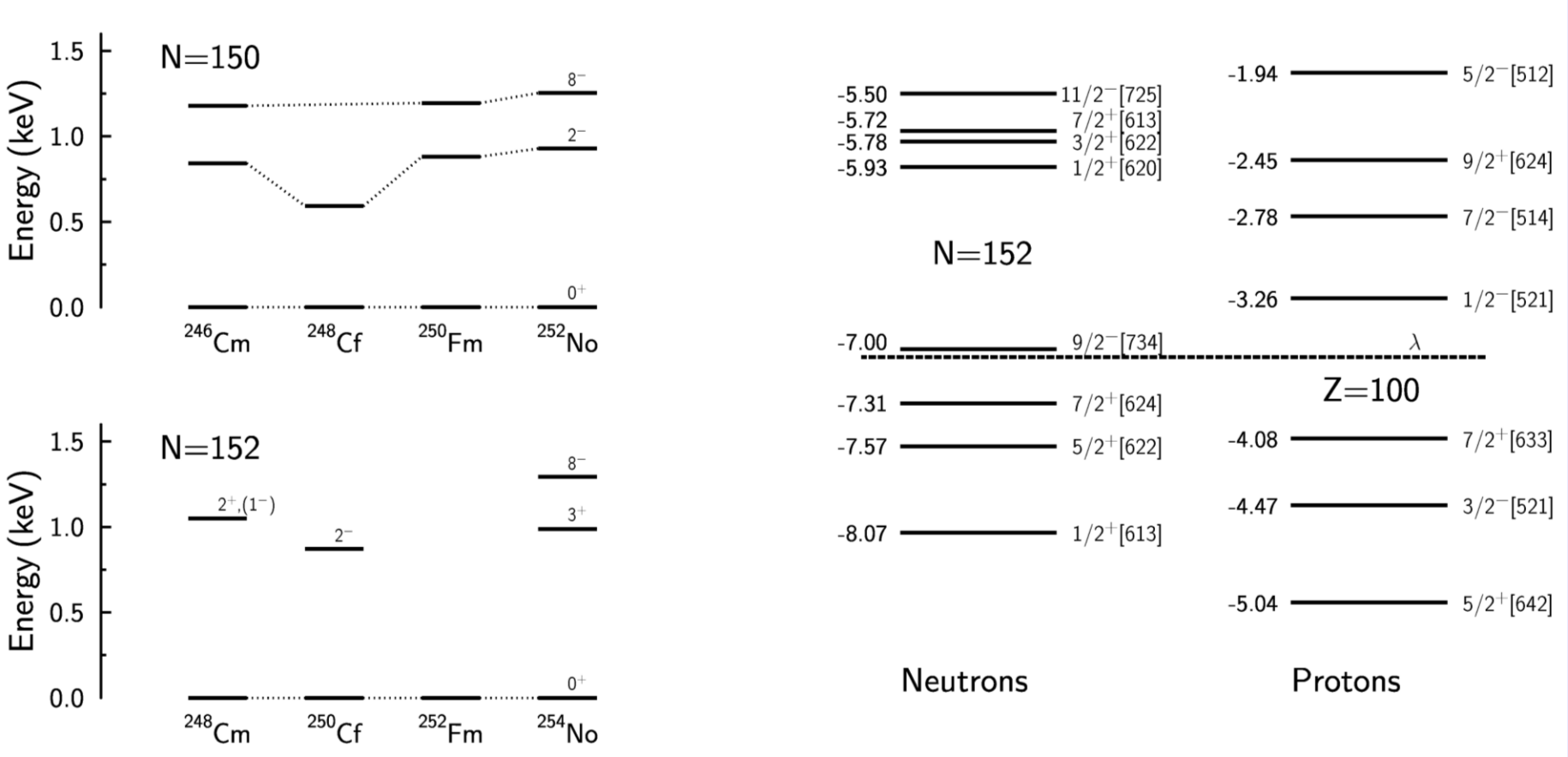
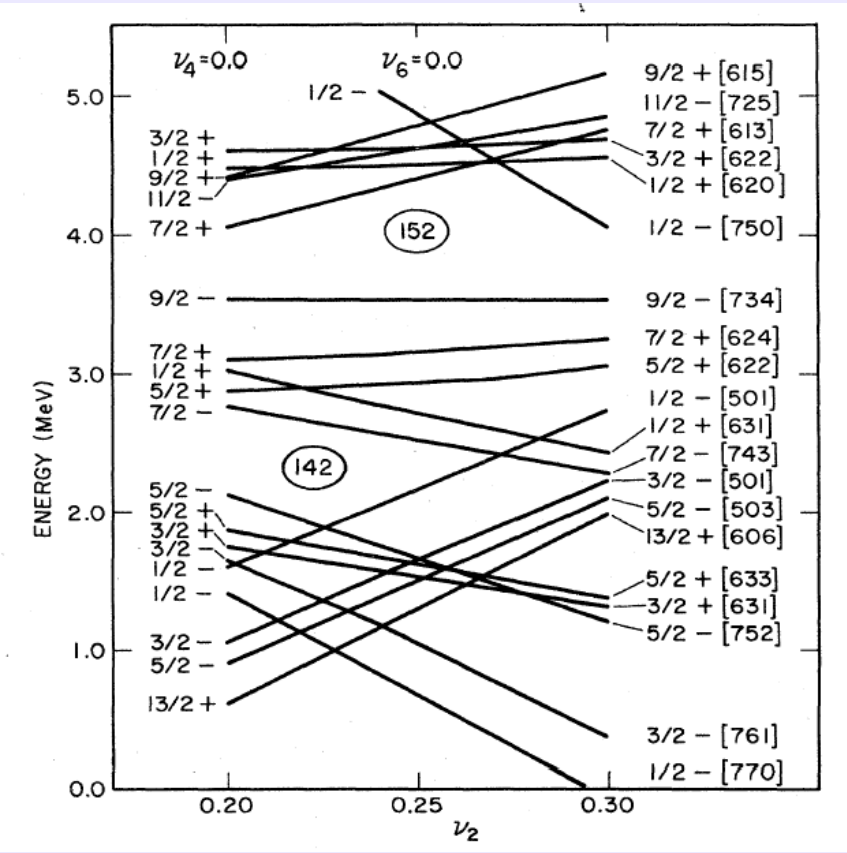
Systematics



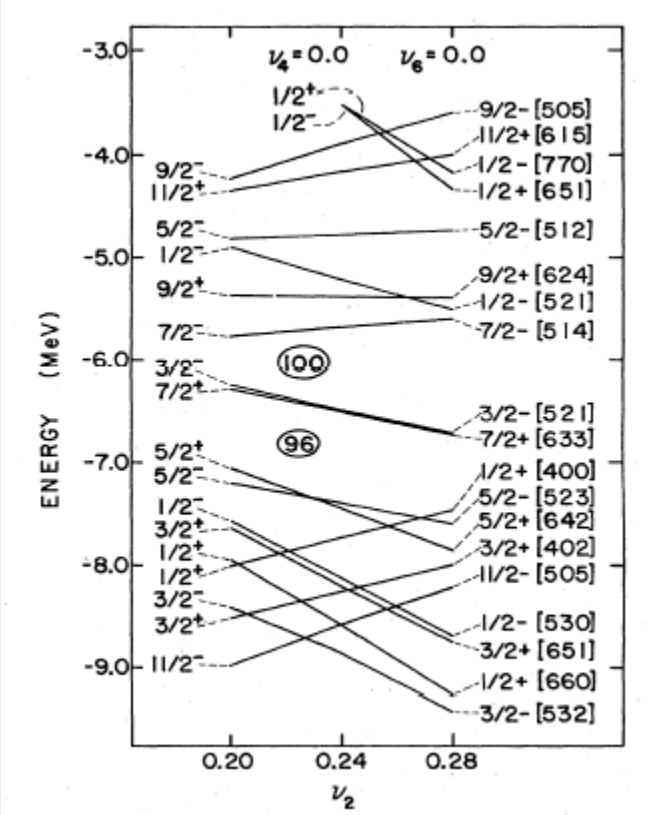
R-D Herzberg

Deformed gaps

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



Gap at N=152



Gap at Z=100

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Conclusions

- 8^- isomers in ^{252}No and ^{250}Fm are neutron states
- 3^+ state in ^{254}No is a proton state
- 8^- isomer in ^{254}No needs more study
- What quenching is appropriate in this region?

We see many isomers – do we really understand their structure?

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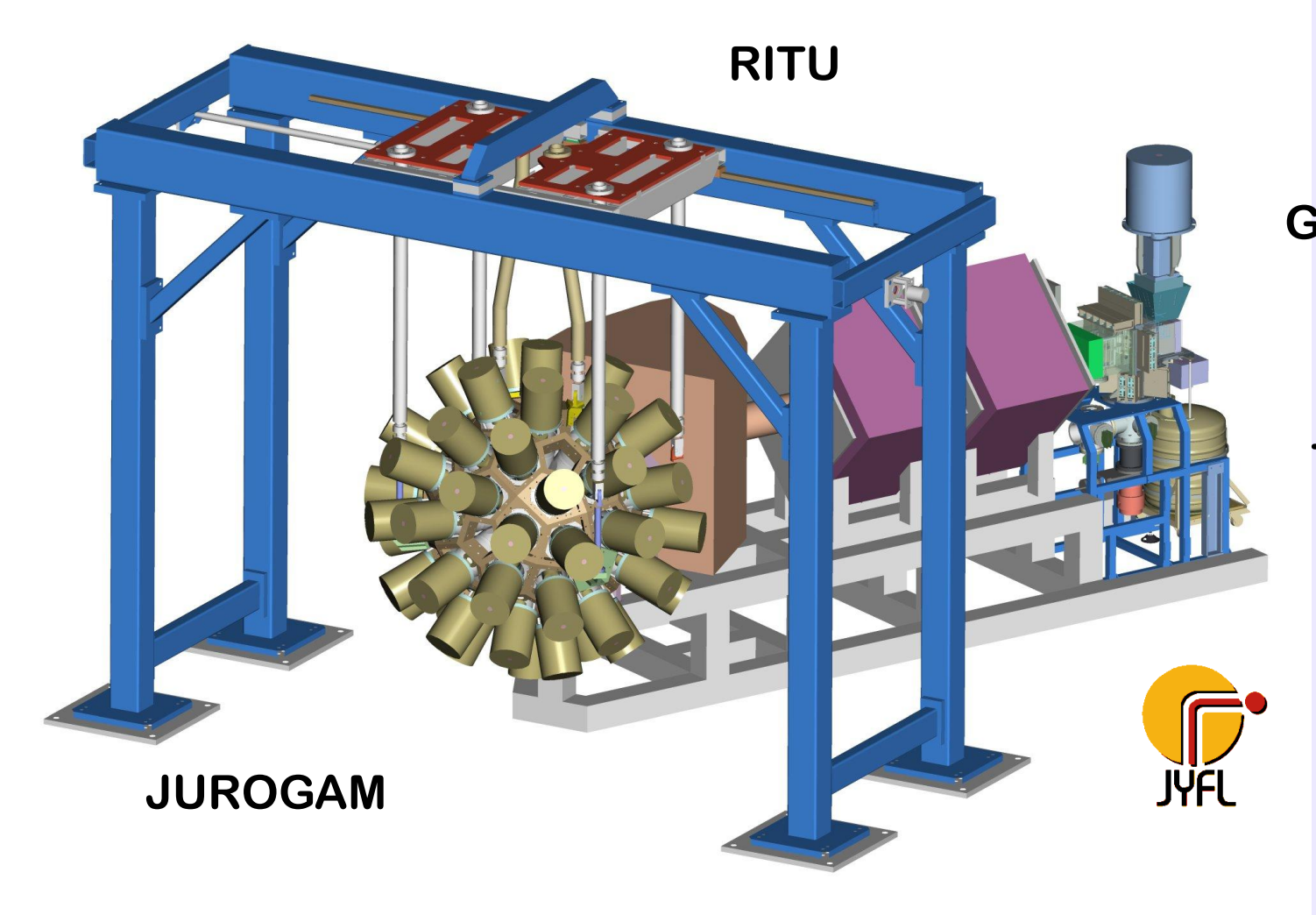
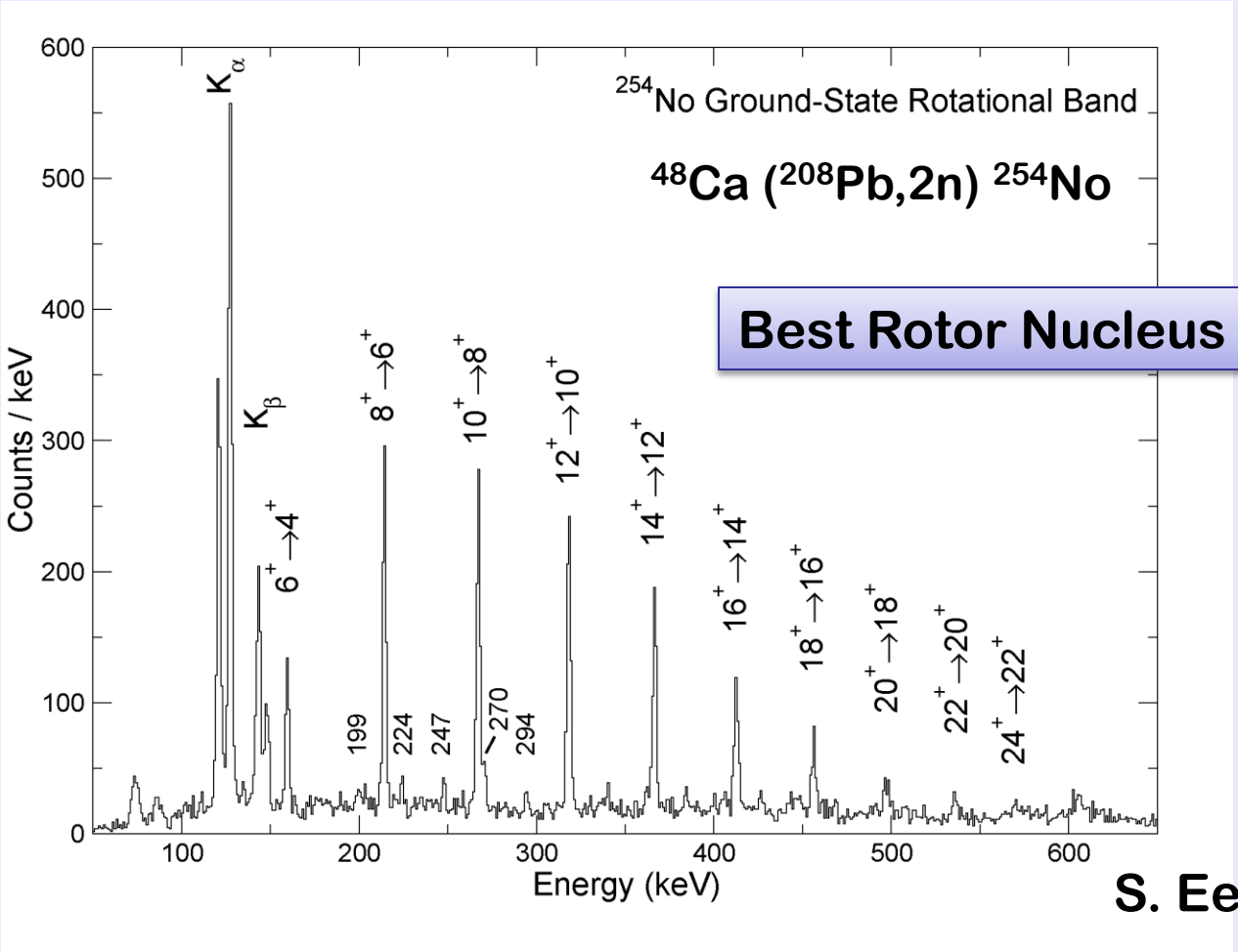
In-beam Spectroscopy



In-beam Spectroscopy



Best Rotor Nucleus known

S. Eeckhaudt et al

R-D Herzberg

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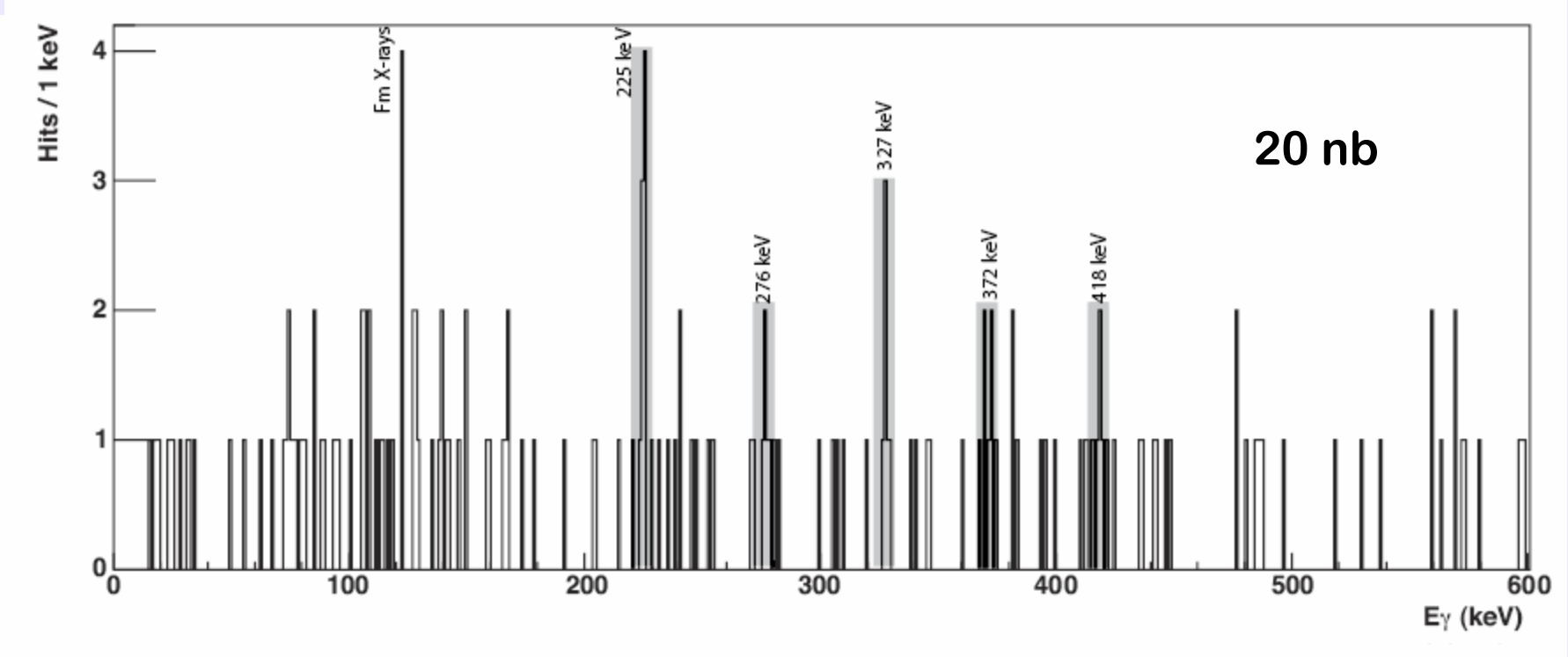
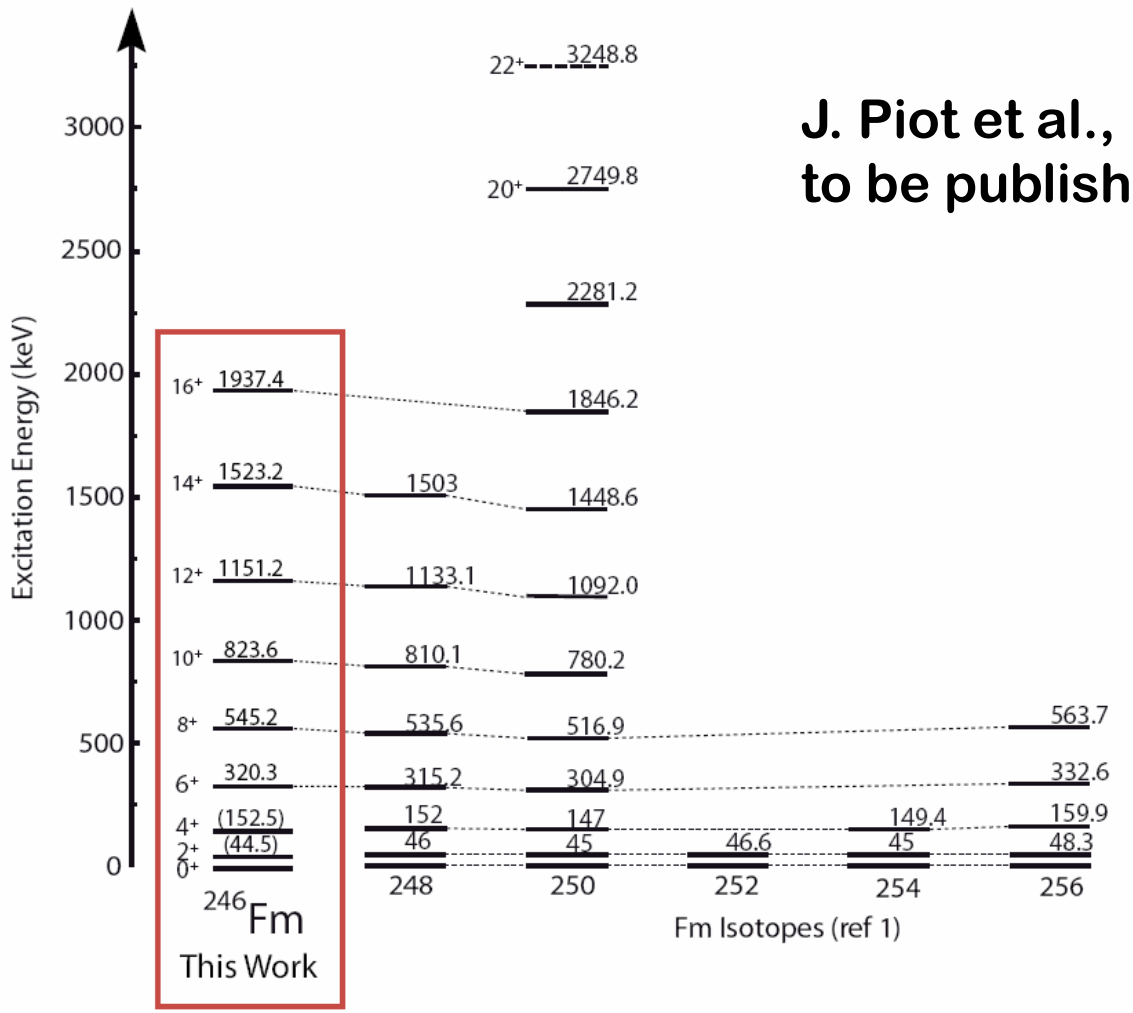
New record: ^{246}Fm



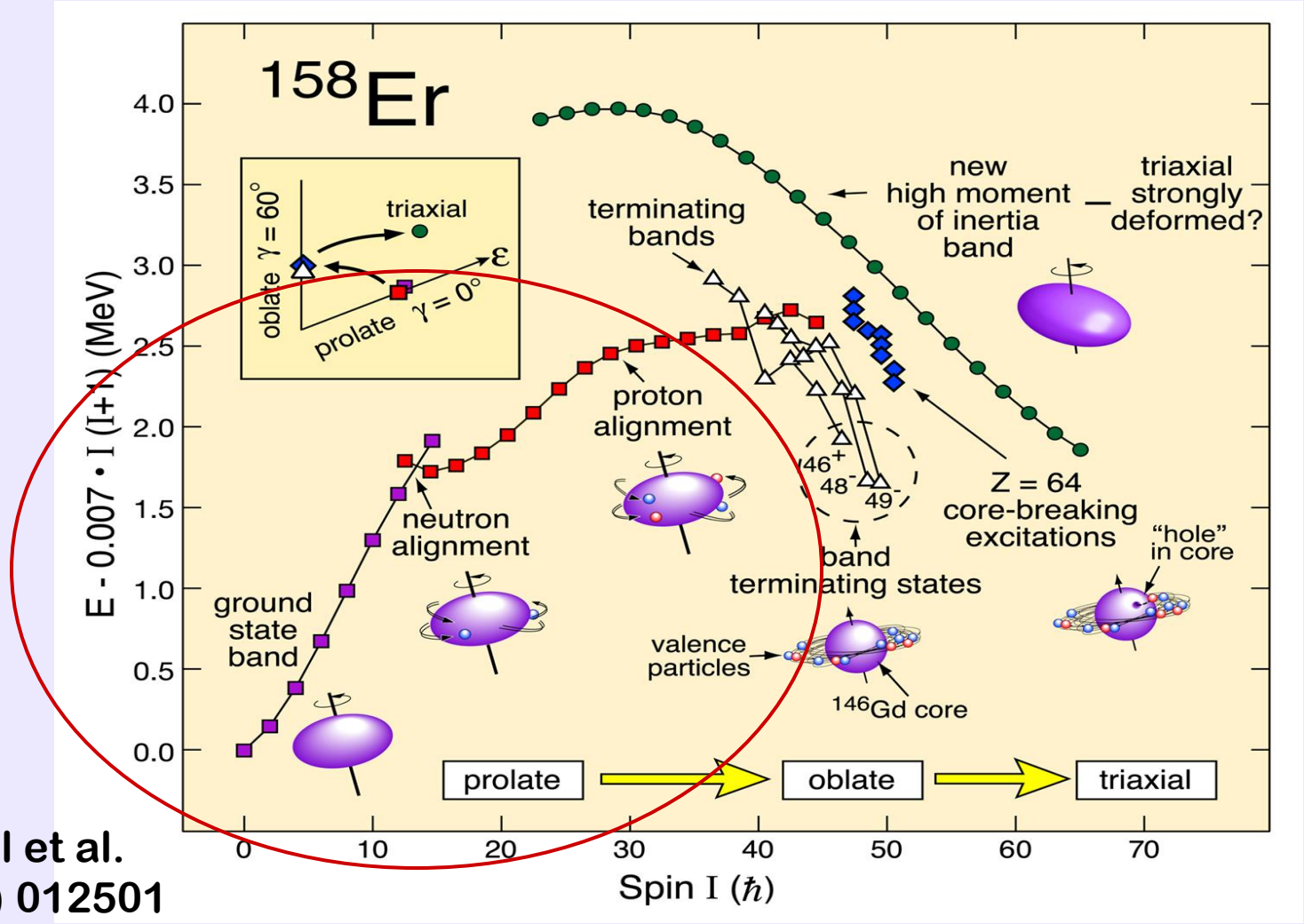
J. Piot et al., to be published

Fm rotational bands



J. Piot et al.,
to be published

Alignment



From E.S. Paul et al.
PRL 98 (2007) 012501

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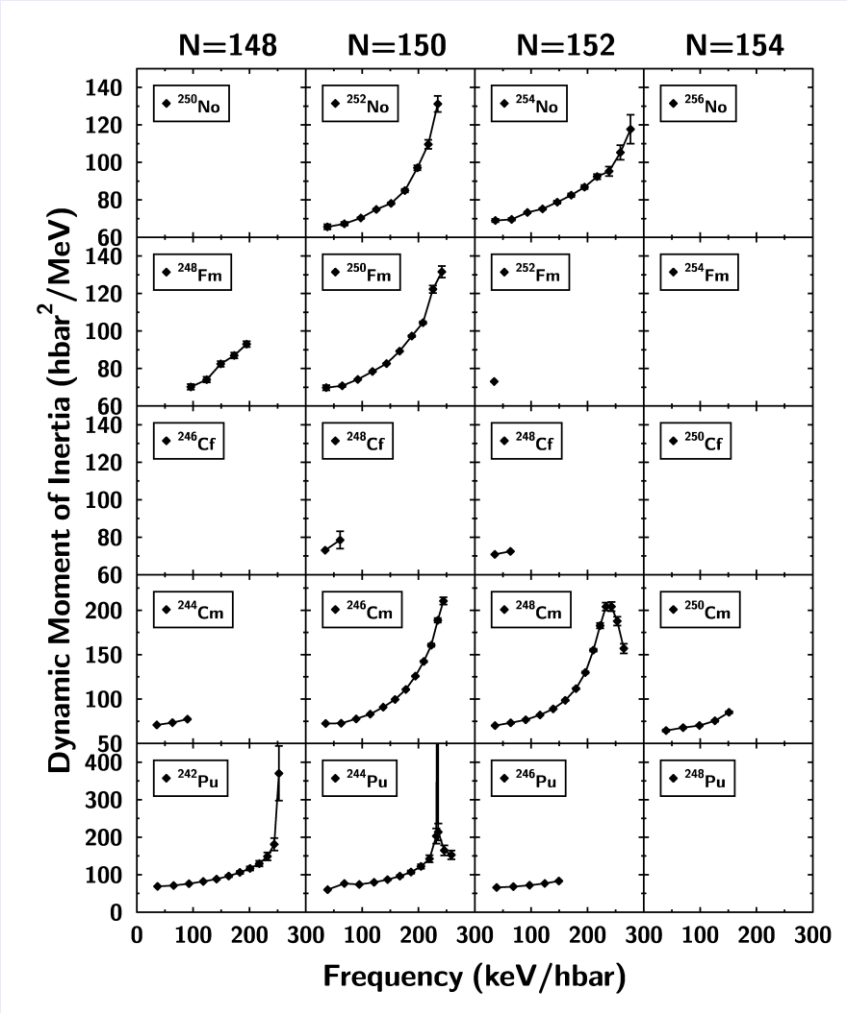
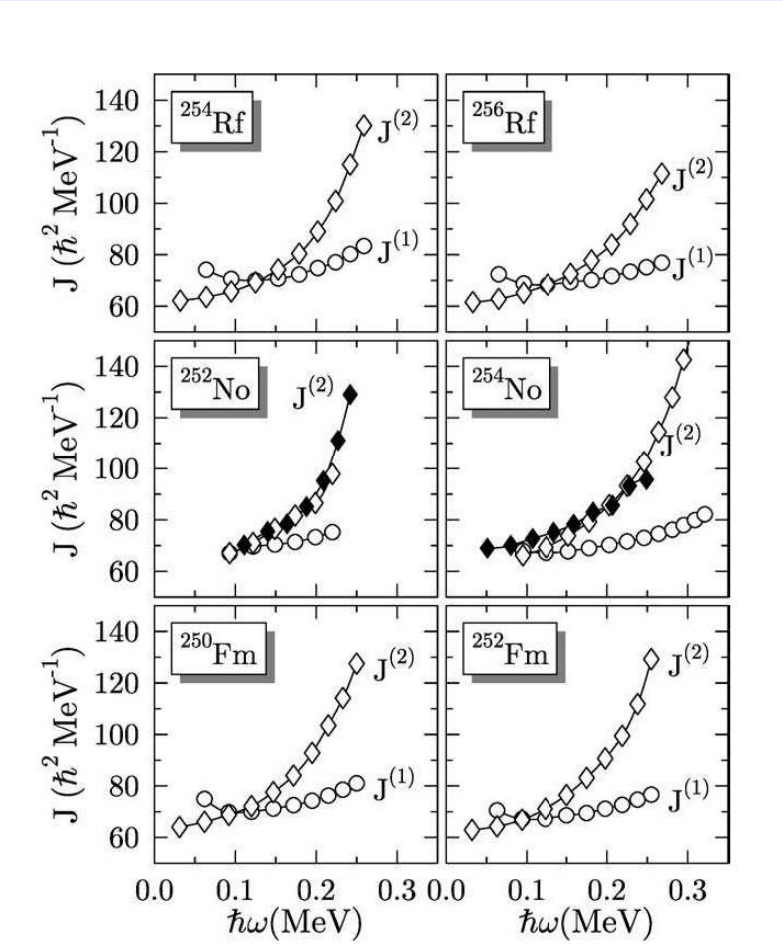
Systematics





Bender et al, NPA723 (03) 354

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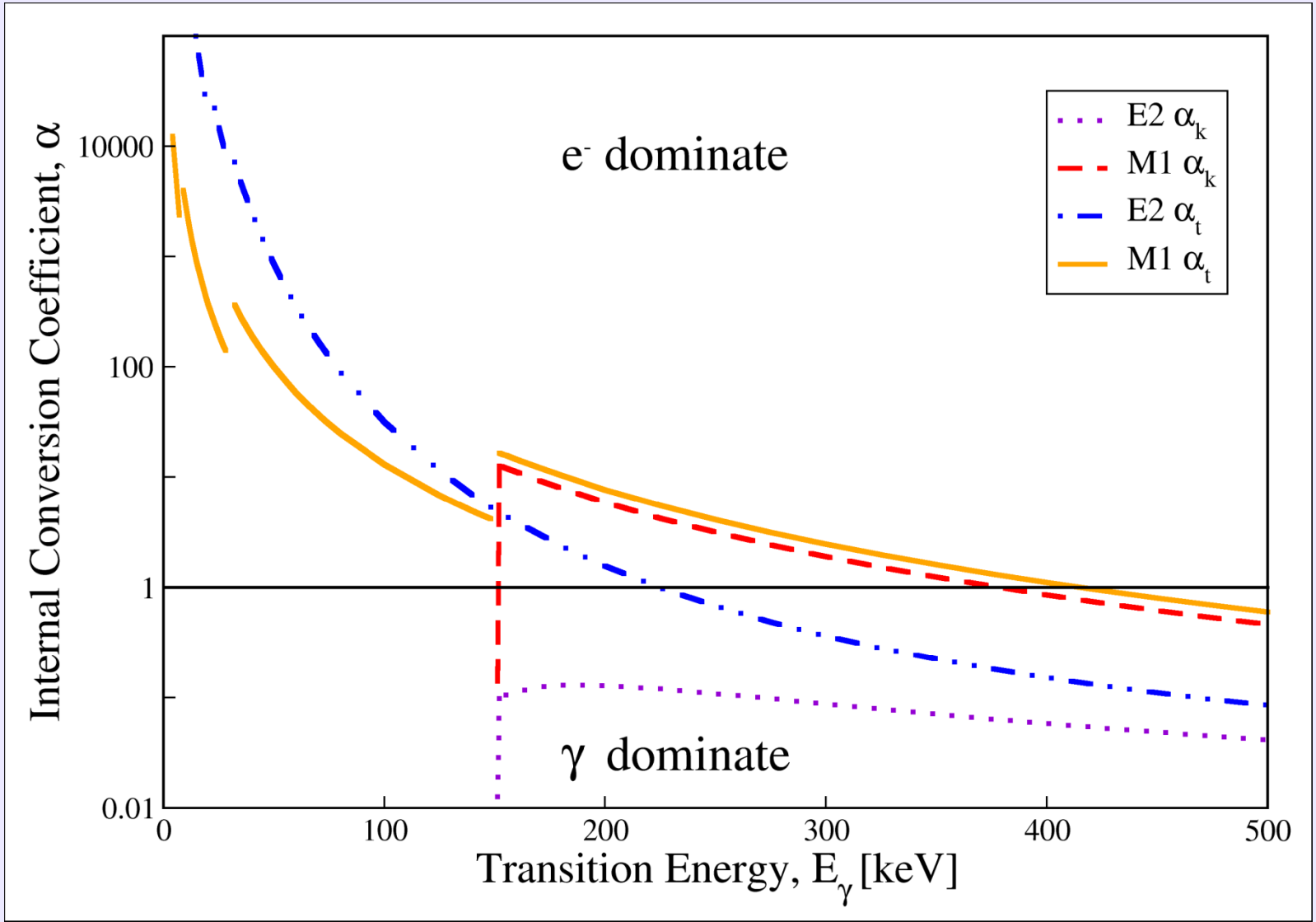
Internal Conversion



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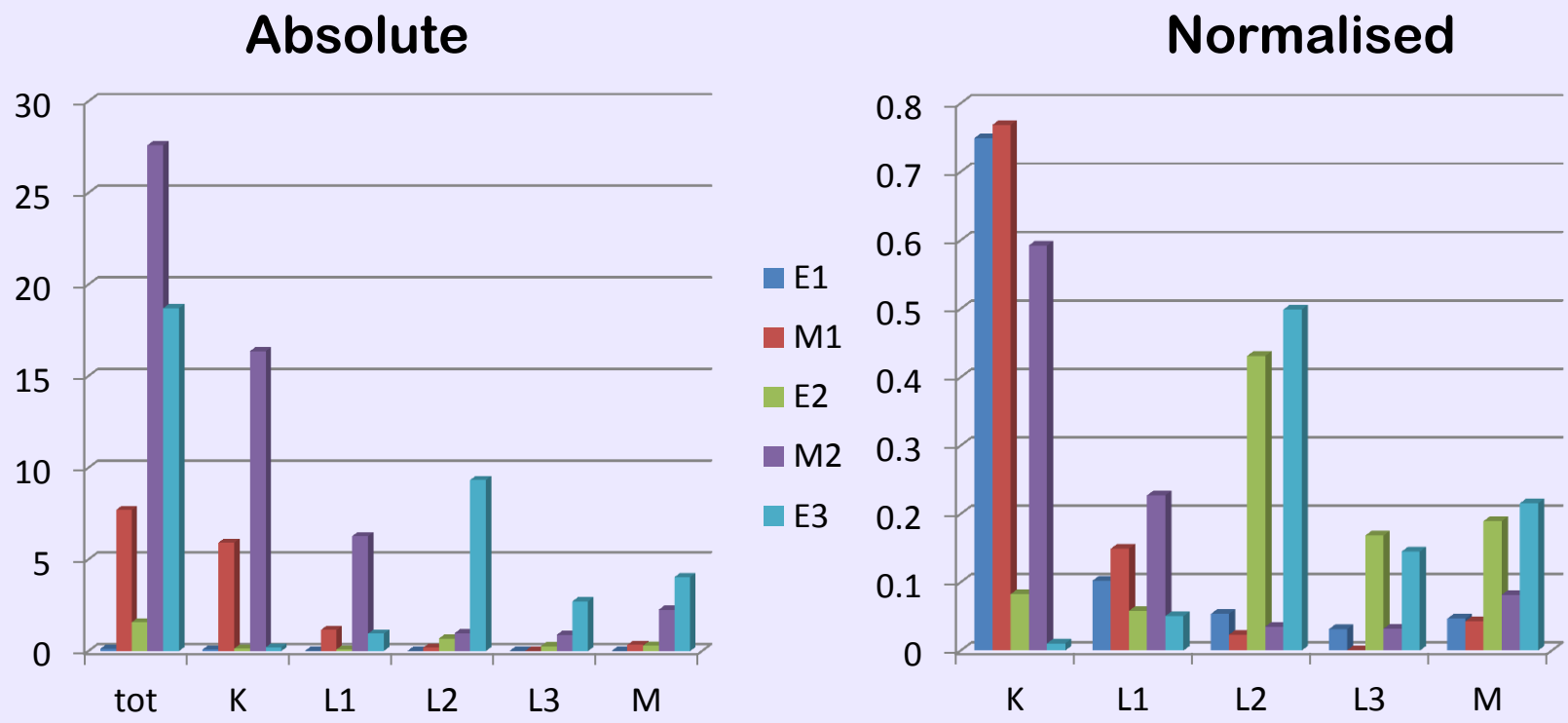
Conversion Coefficients



E = 200 keV Z= 102 BrICC (T. Kibédi et al., NIMA 589 (2008) 202)

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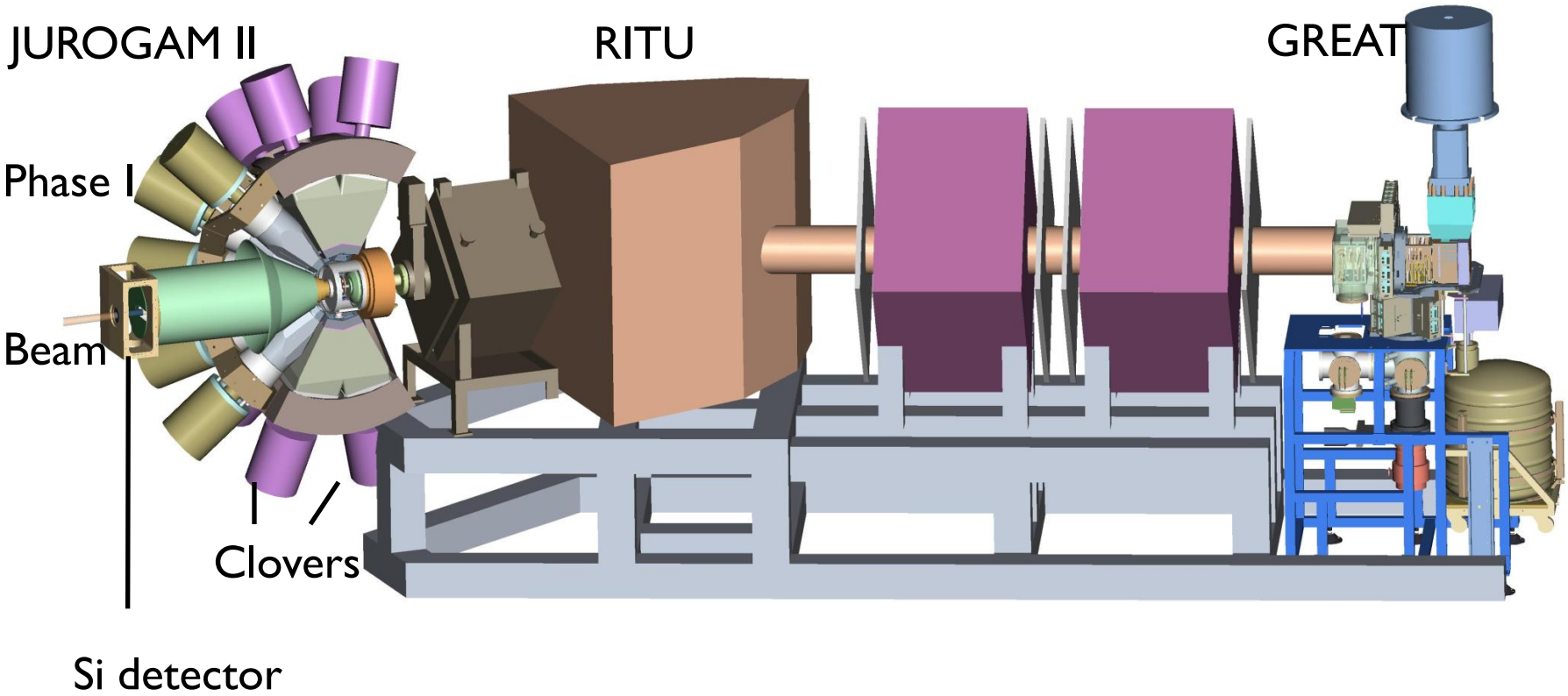
S(ilicon) A(nd) GE(rmanium) spectrometer



Fully instrumented with digital electronics

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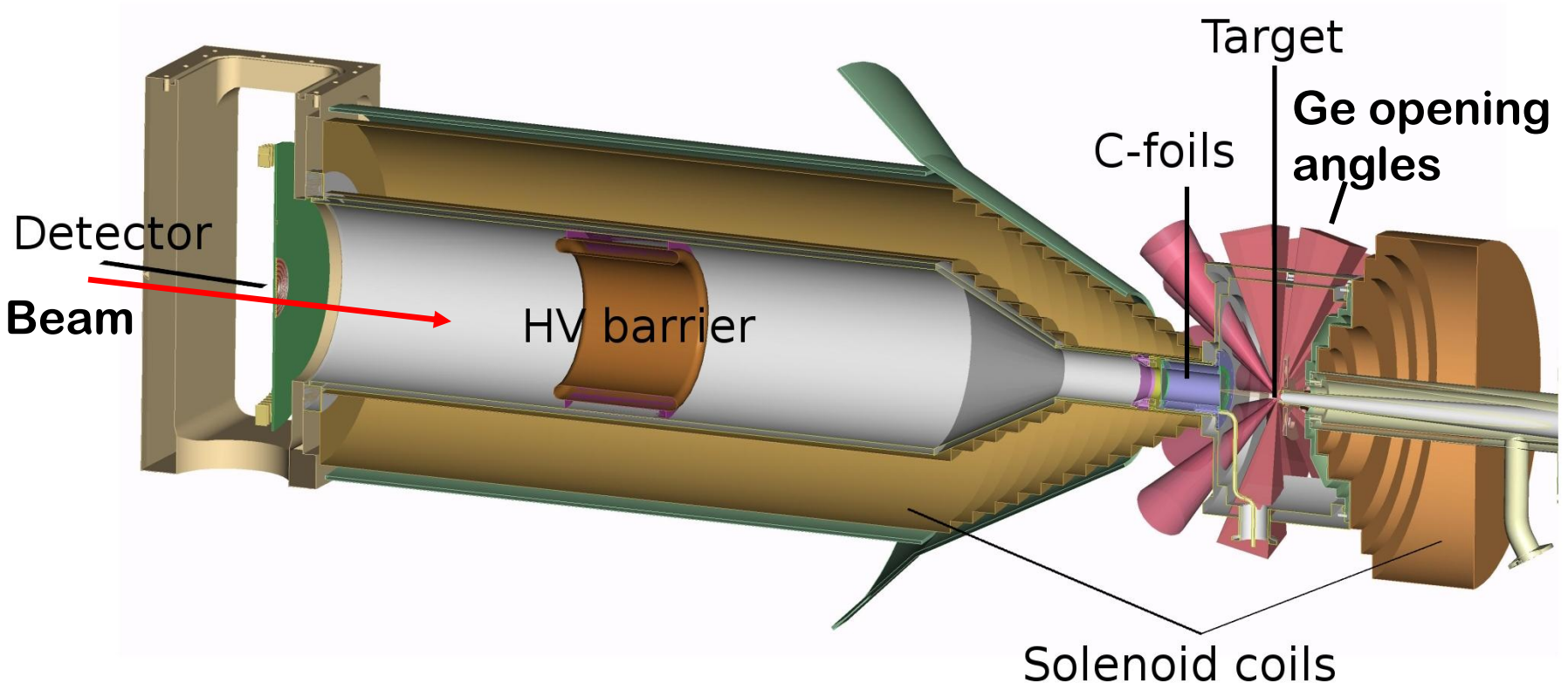

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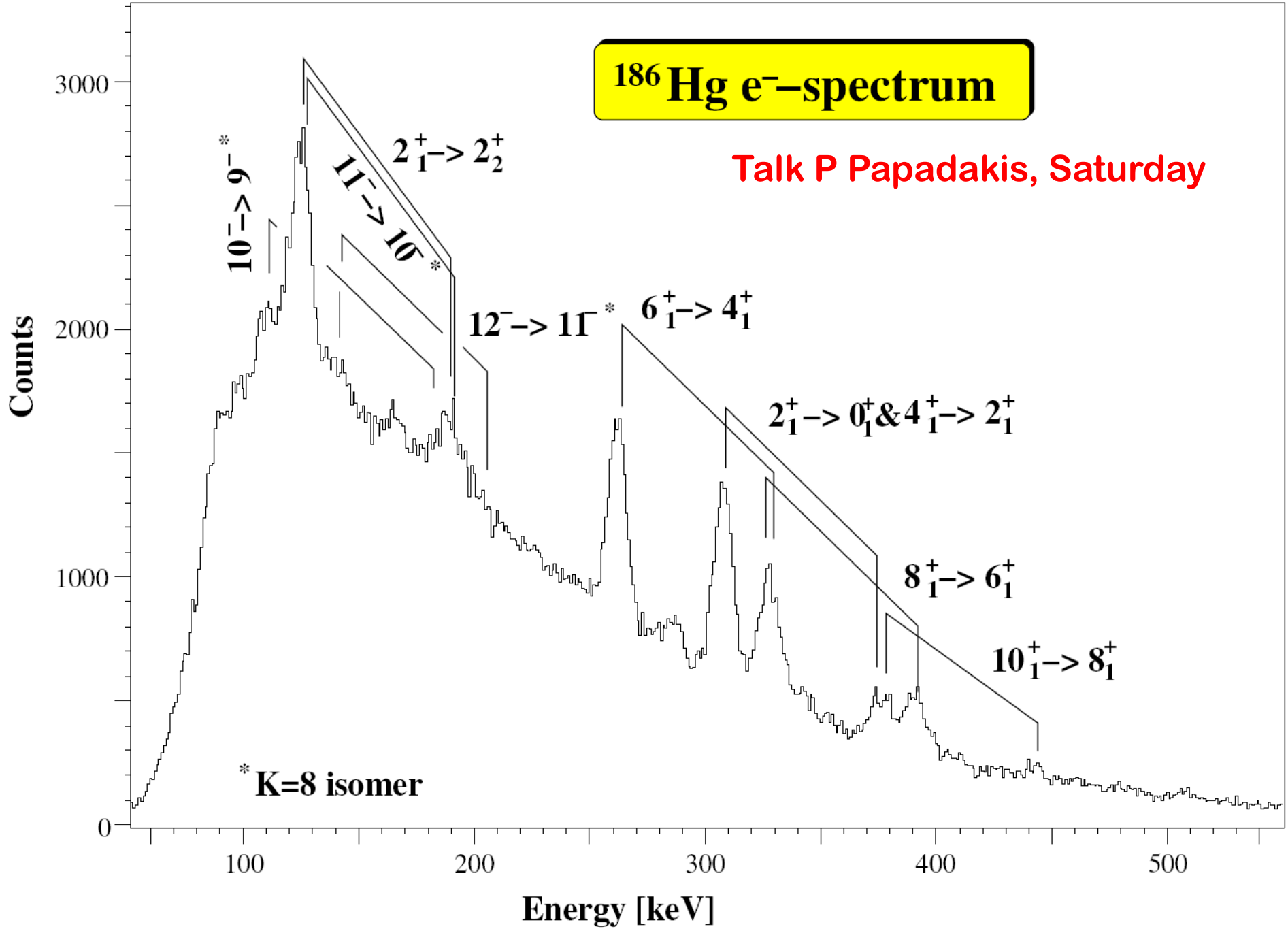
^{186}Hg e$^-$–spectrum
Talk P Papadakis, Saturday
$10^-_1 \to 9^-_1$ *
$11^- \to 10^-$ *
$2^+_1 \to 2^+_2$
$12^- \to 11^-$ *
$6^+_1 \to 4^+_1$
$2^+_1 \to 0^+_1$ & $4^+_1 \to 2^+_1$
$8^+_1 \to 6^+_1$
$10^+_1 \to 8^+_1$
* K=8 isomer
Counts
Energy [keV]
0
1000
2000
3000
100
200
300
400
500

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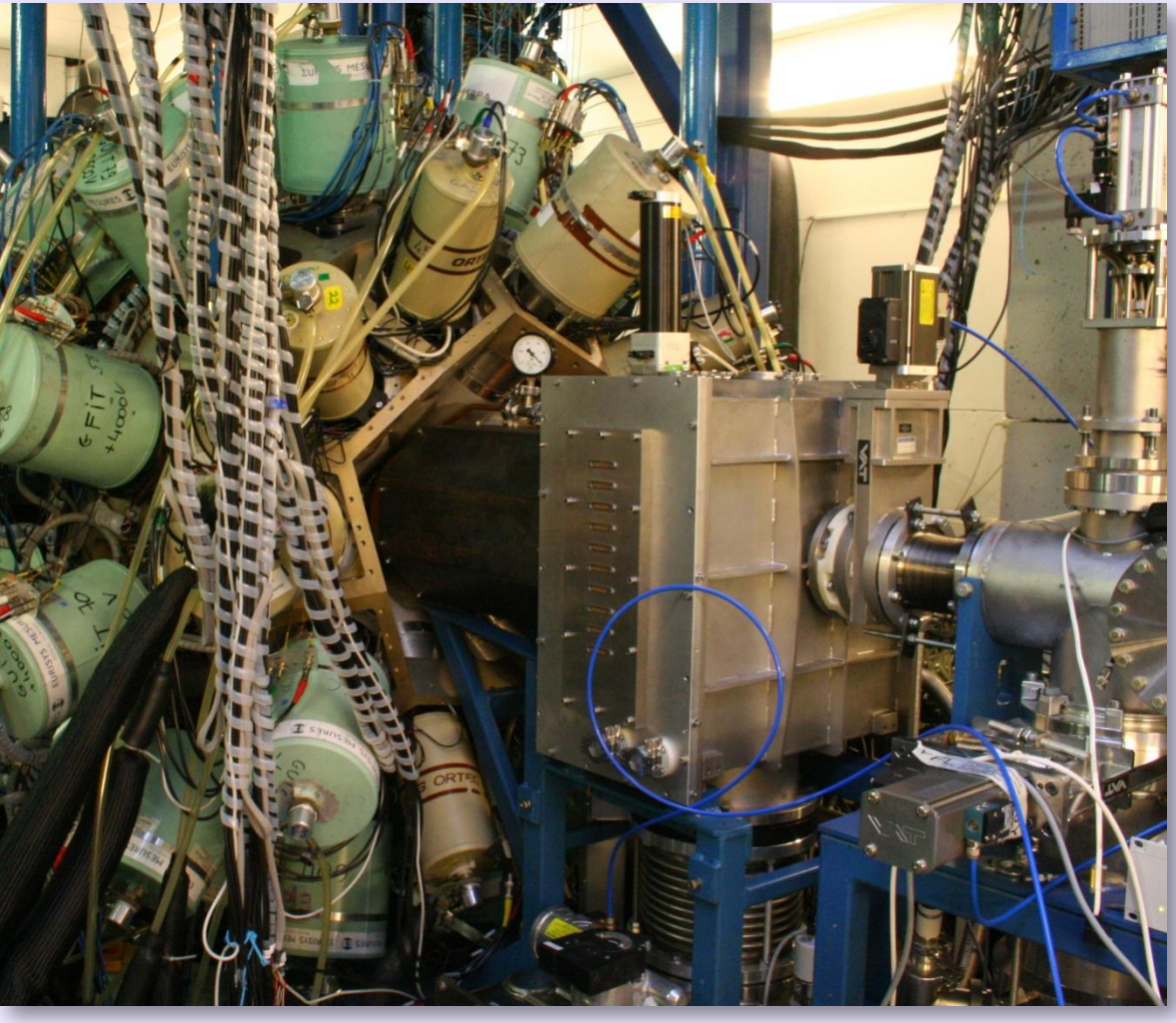

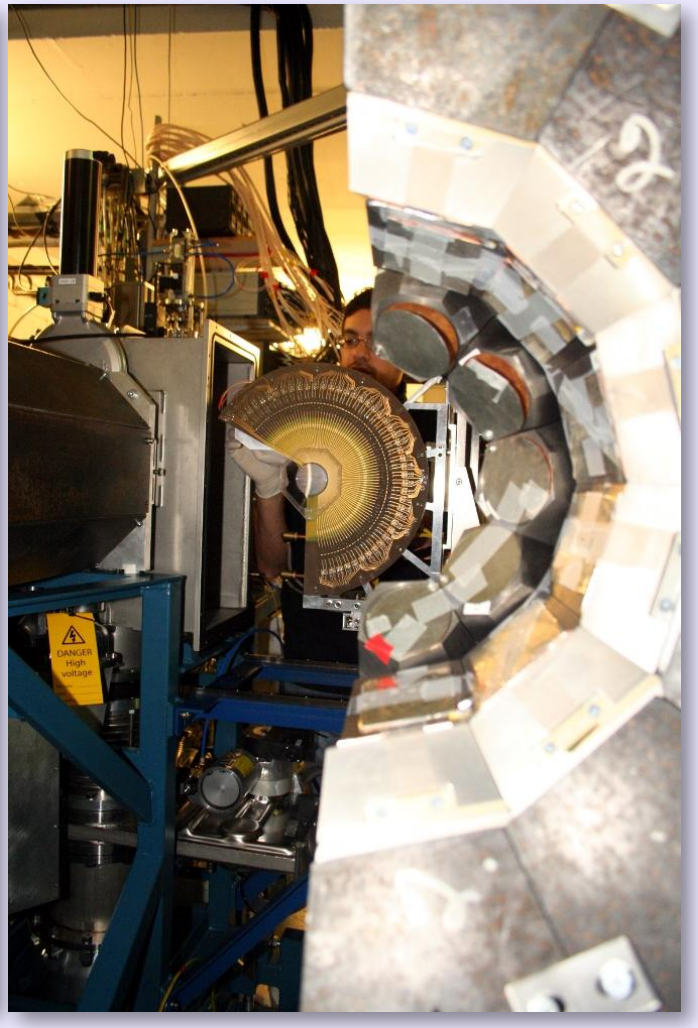

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Summary

- A variety of experimental probes is available for structure investigations in heavy nuclei
- Study high-l orbitals, which pose a challenge to theory
- Isomers are great
- Need to reach more neutron rich systems
- Systematic studies under way in many places
- Combined Gamma and conversion electron spectroscopy is the next step

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Collaboration

UNIVERSITY OF JYVÄSKYLÄ

cea

IKP

ARGONNE NATIONAL LABORATORY

GSI

THE UNIVERSITY of LIVERPOOL

HELSINGIN YLIOPISTO

CCLRC

ISOLDE CERN

iReS Institut de Recherches Subatomiques STRASBOURG