Quasiparticle Structure - Experiment

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Outline

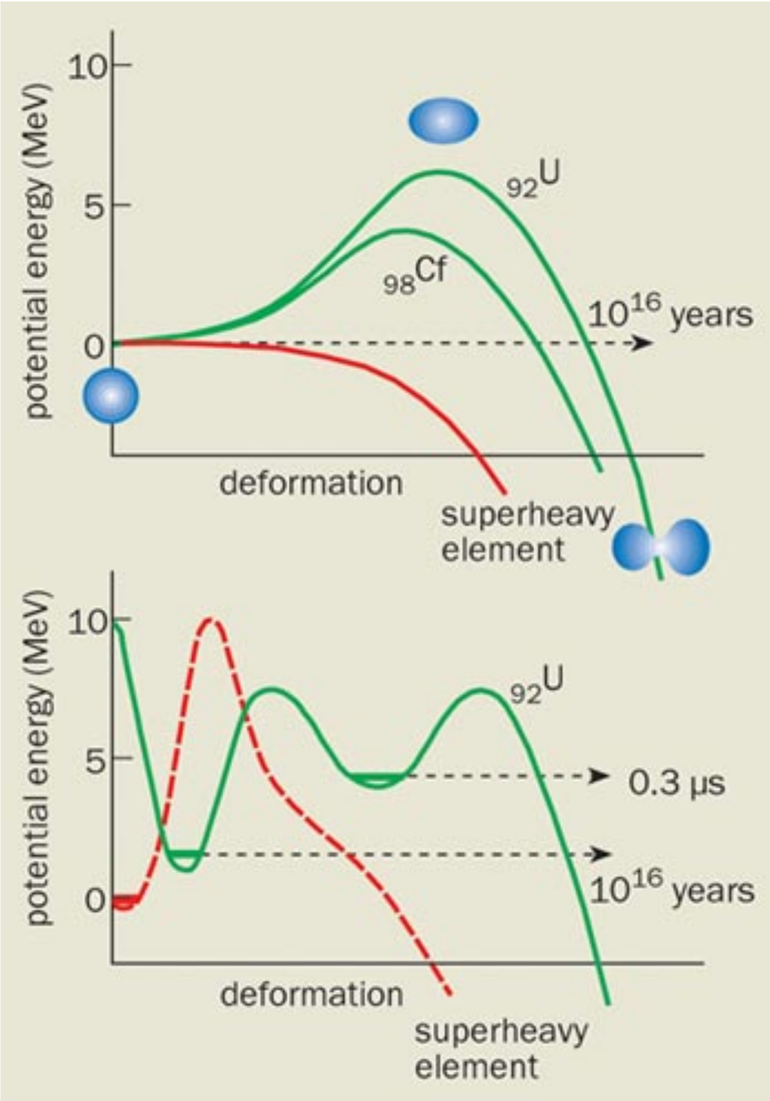
1) Introduction
   - The questions to be answered
   - The experimental aims

2) State-of-play
   - What is known experimentally?
   - How well do theories describe experiment?

3) Opportunities
   - Techniques and methods
   - What will we know in the next few years?

4) Future
   - New capabilities and directions

The Questions



Y. Oganessian, Physics World, July 2004

1) What are the "magic numbers" for the spherical super-heavy nuclei?

➔ Locating the center of the "island of stability"

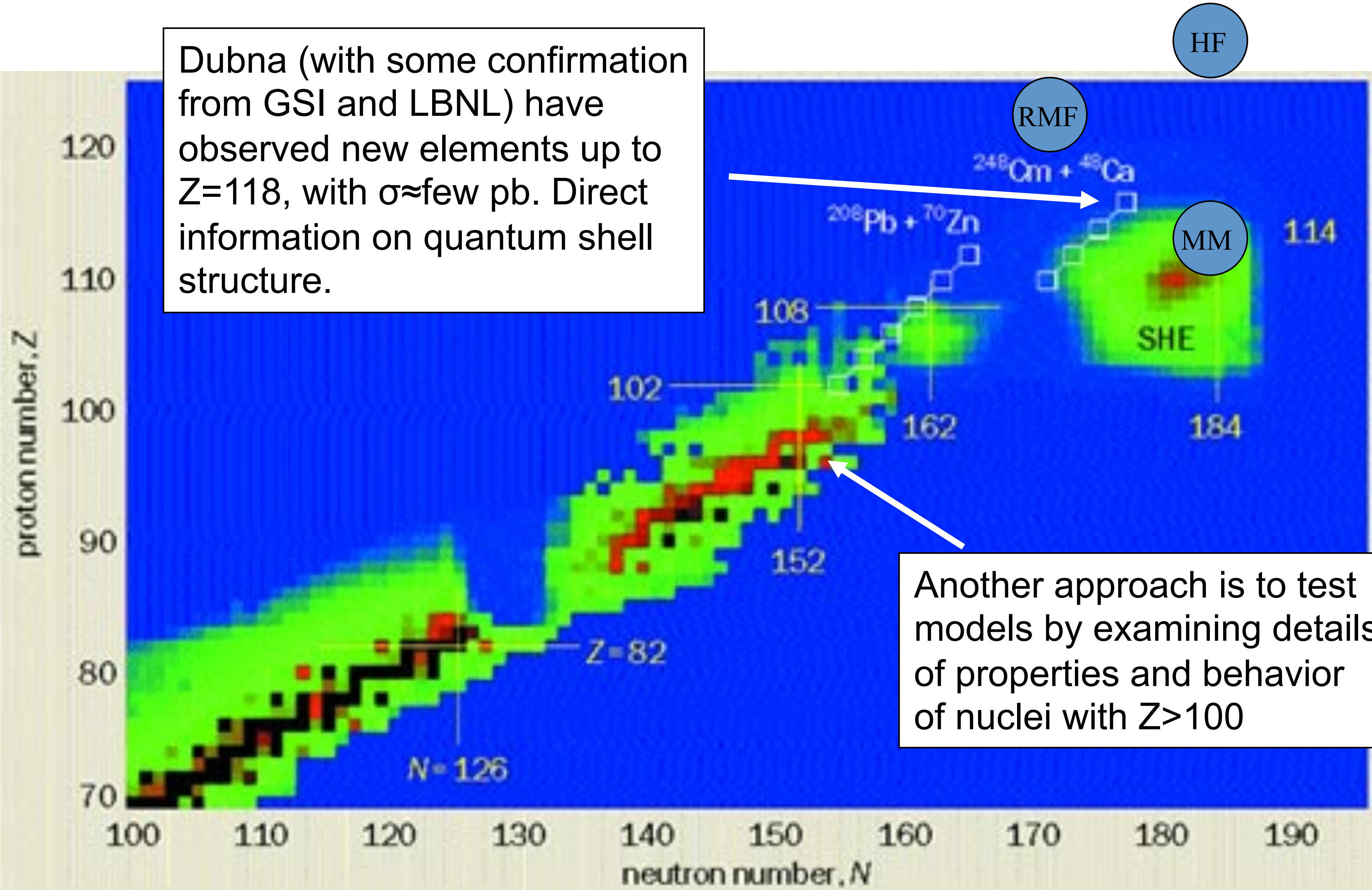
2) What are the magnitudes of the shell effects?

➔ Extent of the island and relative stability against fission

The same questions can be asked of the deformed gaps (Z=108, N=162).

Different Theories, Different Shell Gaps

Dubna (with some confirmation from GSI and LBNL) have observed new elements up to Z=118, with σ≈few pb. Direct information on quantum shell structure.



Another approach is to test models by examining details of properties and behavior of nuclei with Z>100

Experimental Goal

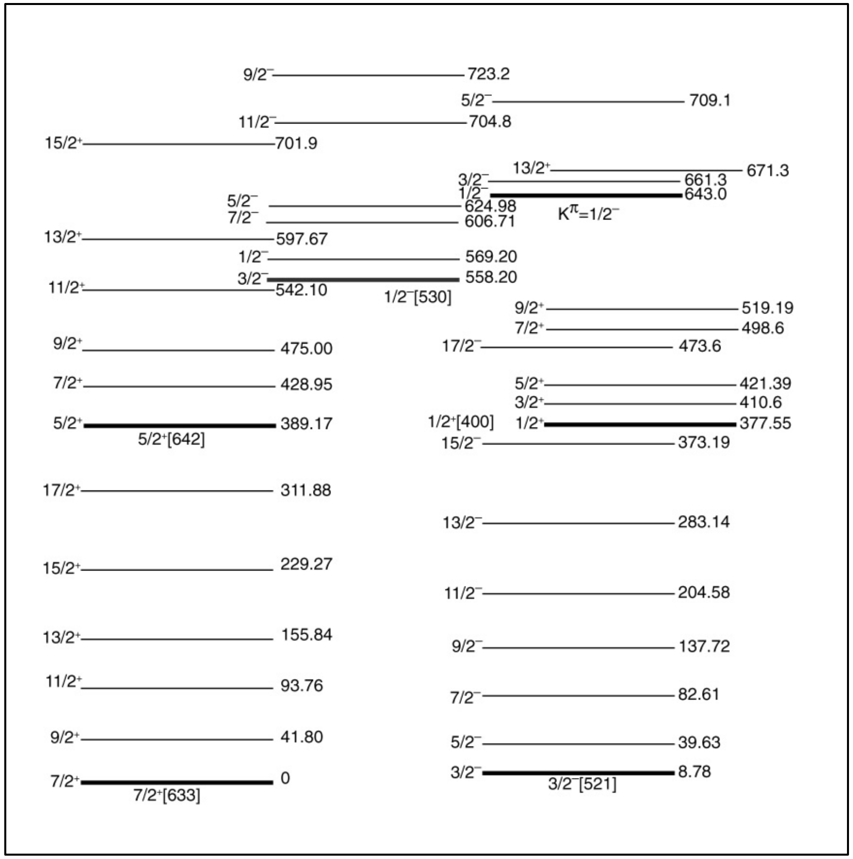
Investigate the structure of nuclei with the largest Z and N

➔Push the Fermi level towards the major shell gaps

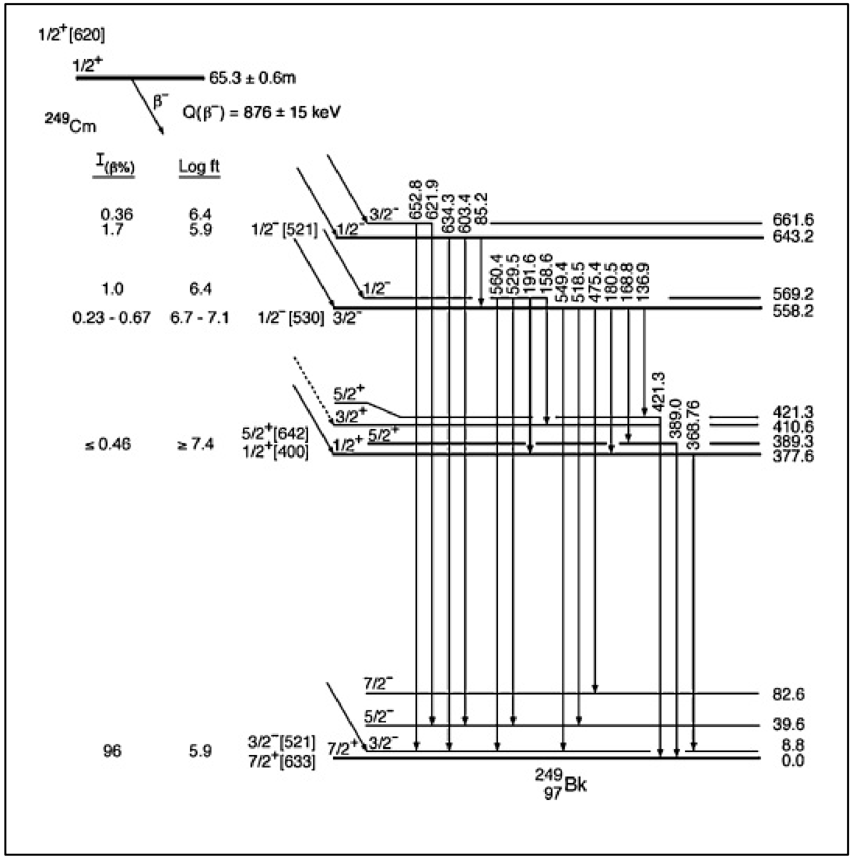
Experimental Status 1

A lot is known about the structure of nuclei up to Z~100.

An example is ^{249}Bk from I. Ahmad et al., Phys. Rev. C 71 (2005) 054305.



α-γ coincidence study of 253Es



β- decay study of ^{249}Cm

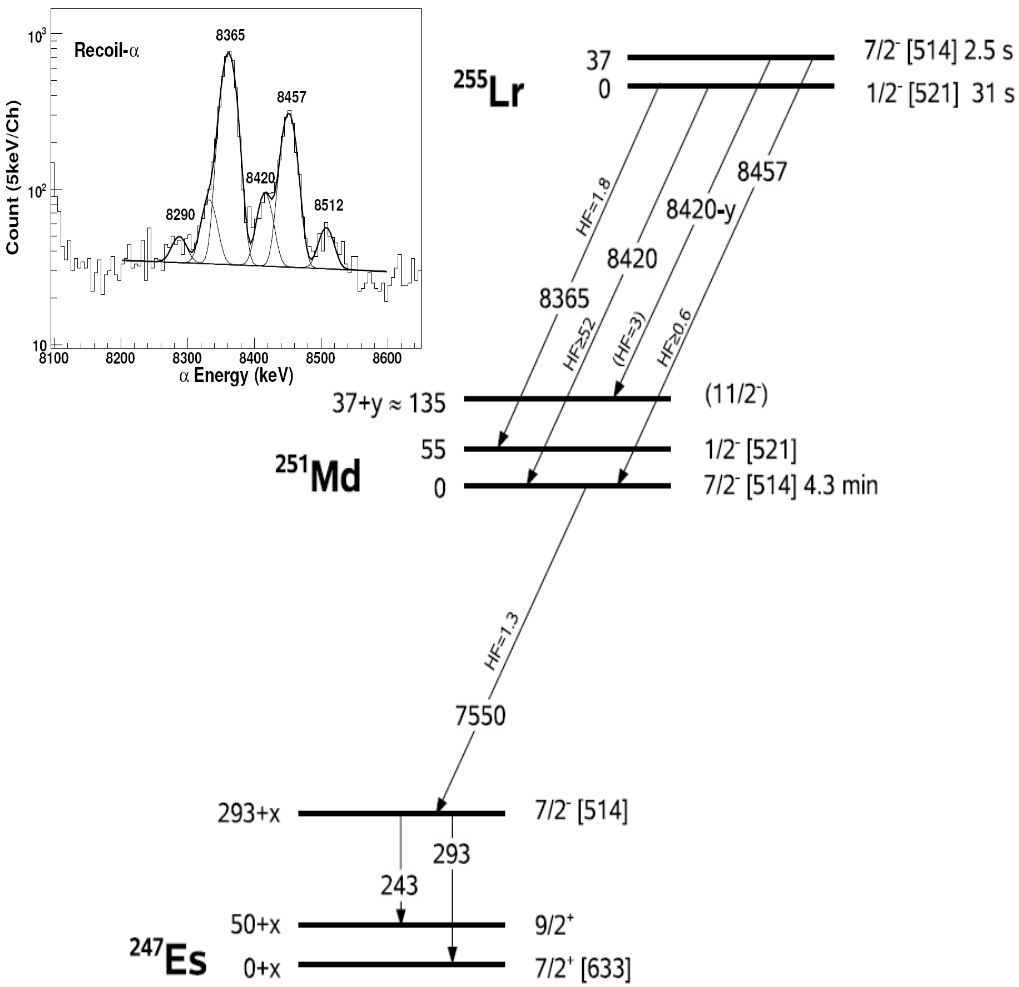
Many single-qp states and associated rotational bands are firmly established

Experimental Status 2

A lot of recent activity on nuclei from Fm (Z=100) to Rf(Z=104)

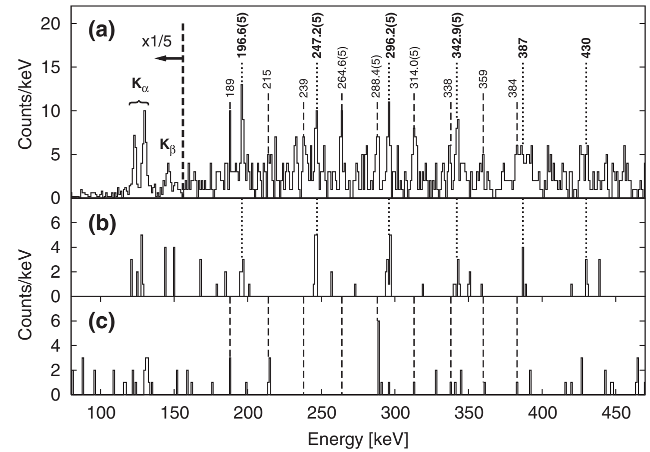
^{255}Lr

α-decay spectroscopy



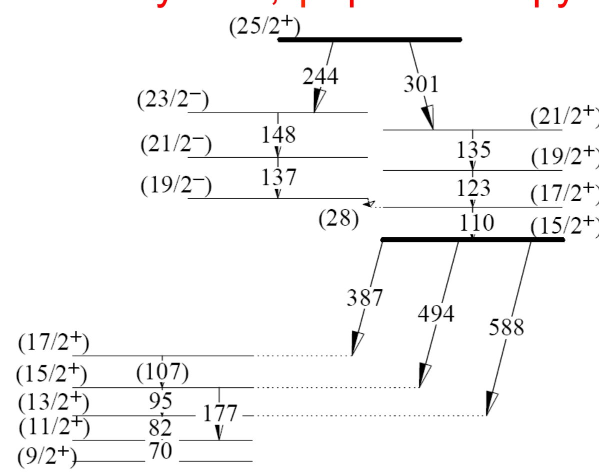
A. Chatillon et al., EPJ A 30 397 (2006)

Prompt γ spectroscopy



S.Ketelhut et al., PRL 102 212501 (2009)

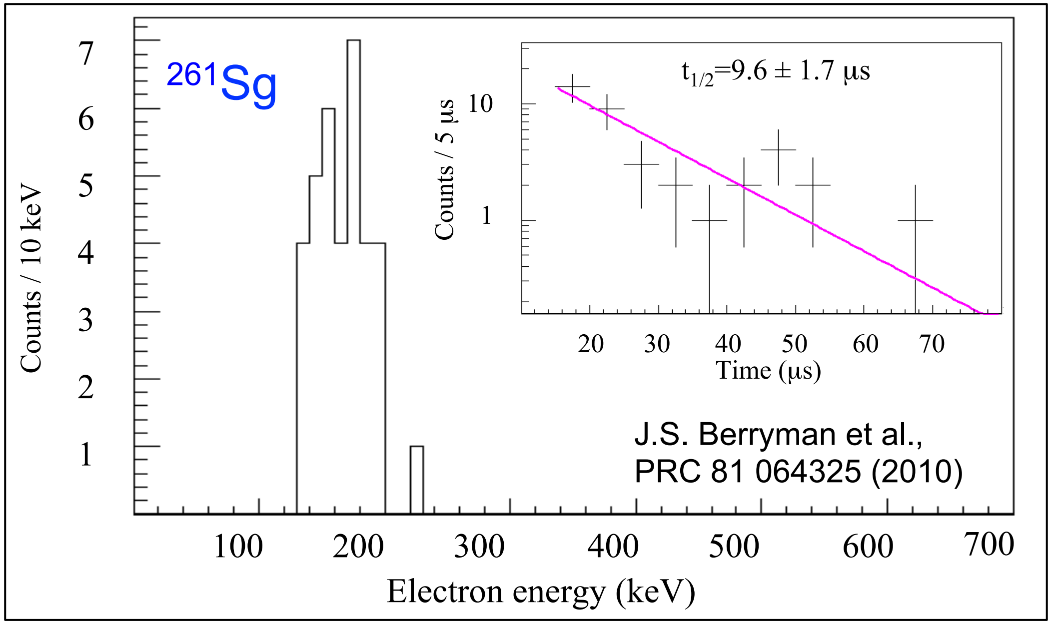
Delayed e-, γ spectroscopy

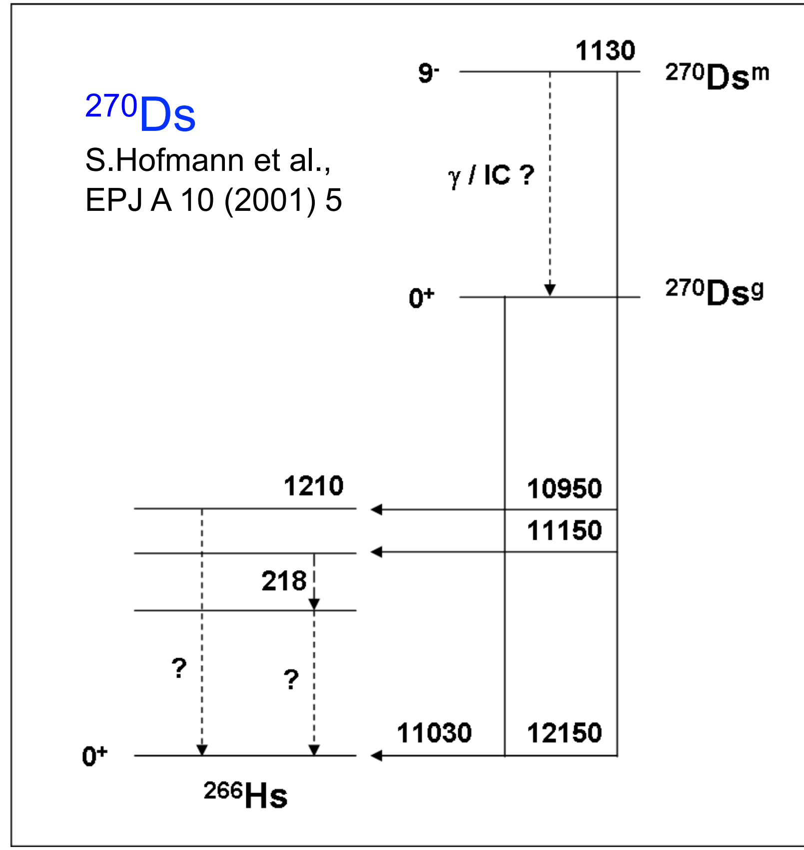


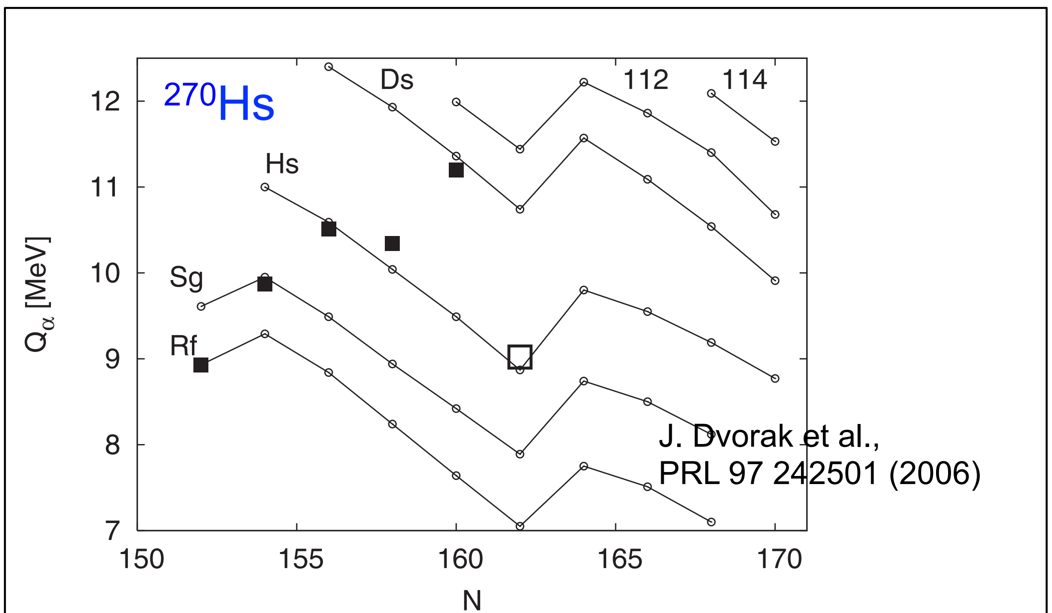
H.B. Jeppesen et al., PRC 80 034324 (2009)
K. Hauschild et al., PRC 78 021302(R) (2008)
S. Antalic et al., EPJ A38 219 (2008)

Experimental Status 3

We are attempting to push to nuclei with Z>104. Little is known.







Comments on Theory

Two broad categories of theory:

1) Microscopic-Macroscopic (MM)
   - traditional approach refined to a great degree
   - "tuned" to reproduce experimental data
   - excellent local predictive power (e.g. doubly magic nucleus ^{270}Hs Z=108, N=162)
   - how well does MM extrapolate?

2) Self-consistent microscopic approaches (DFT)
   - examples are HF+Skyrme/Gogny, RMF
   - interactions usually fitted to bulk properties of a few key nuclei (e.g., ^{48}Ca, ^{208}Pb)
   - self-consistency might imply reliable extrapolations
   - how well does DFT work on what we know?

Comments on Theory

To be a useful tool for a spectroscopy a theory must:

a) quantitatively reproduce the large body of estabished data for $93<Z<100$ (e.g., the single qp states in ^{249}Bk).

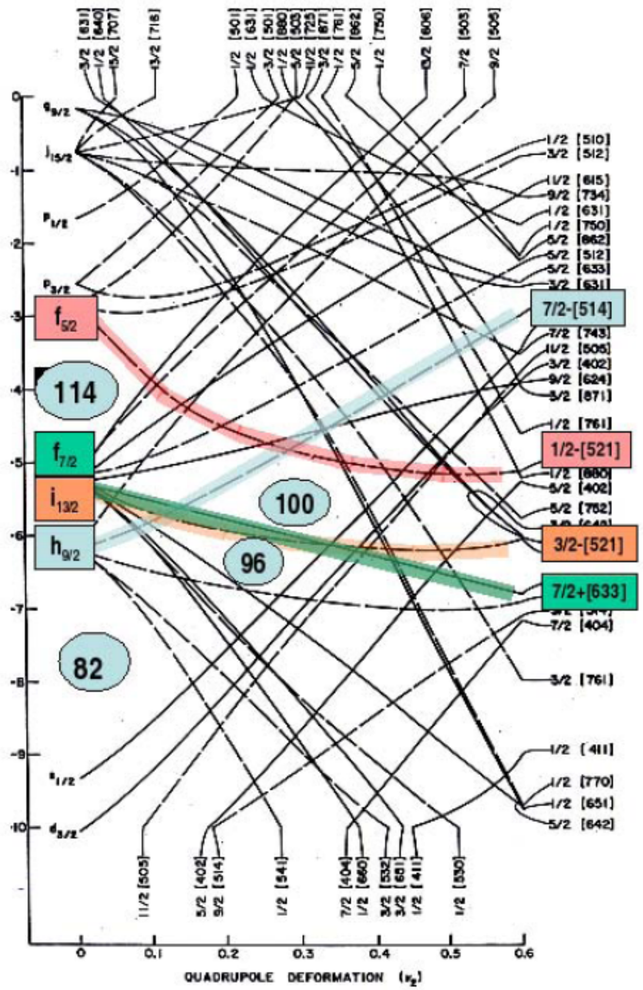
b) aid the interpretation of the emerging data for $99<Z<105$ (e.g., the single qp states in ^{255}Lr).

c) Provide testable predictions for $Z>105$ (e.g., the doubly-magic nature of ^{270}Hs).

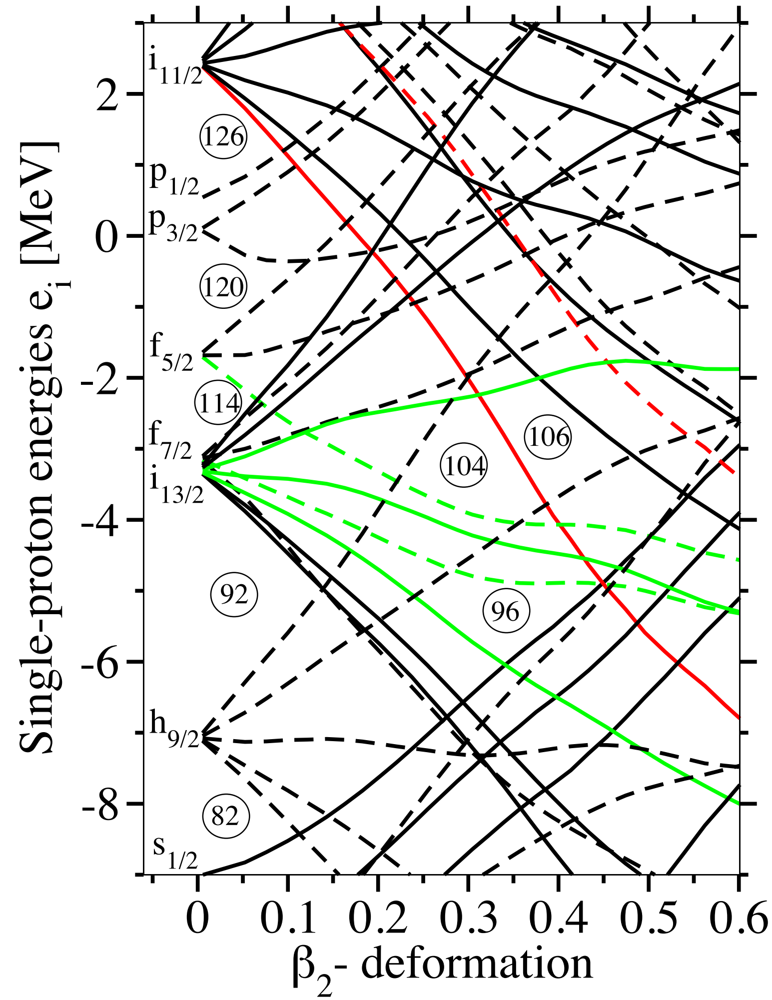
How do the different types of theory perform today?

Nilsson Diagram: Protons

MM



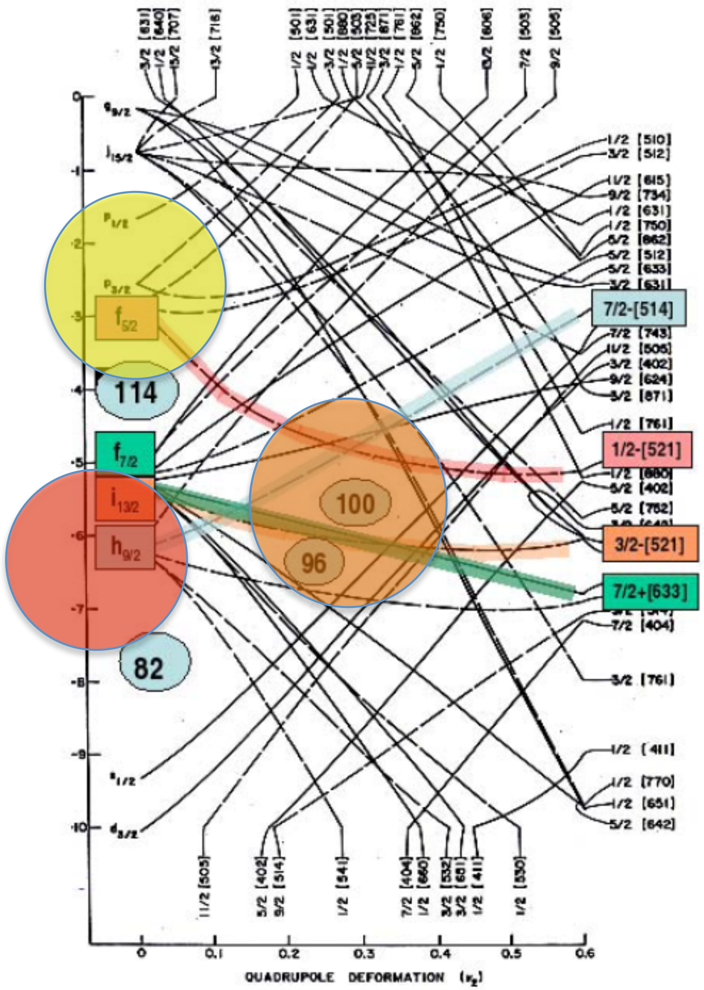
RMF



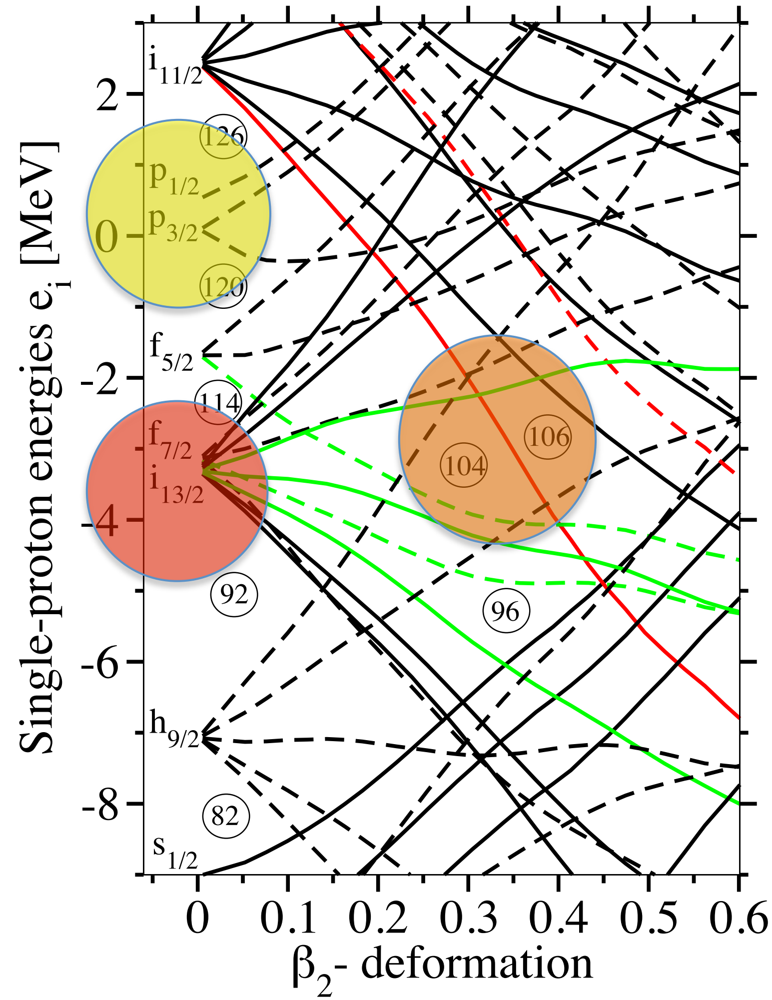
Differences in single-particle structure reflected in the shell gaps for both spherical and deformed systems.

Nilsson Diagram: Protons

MM



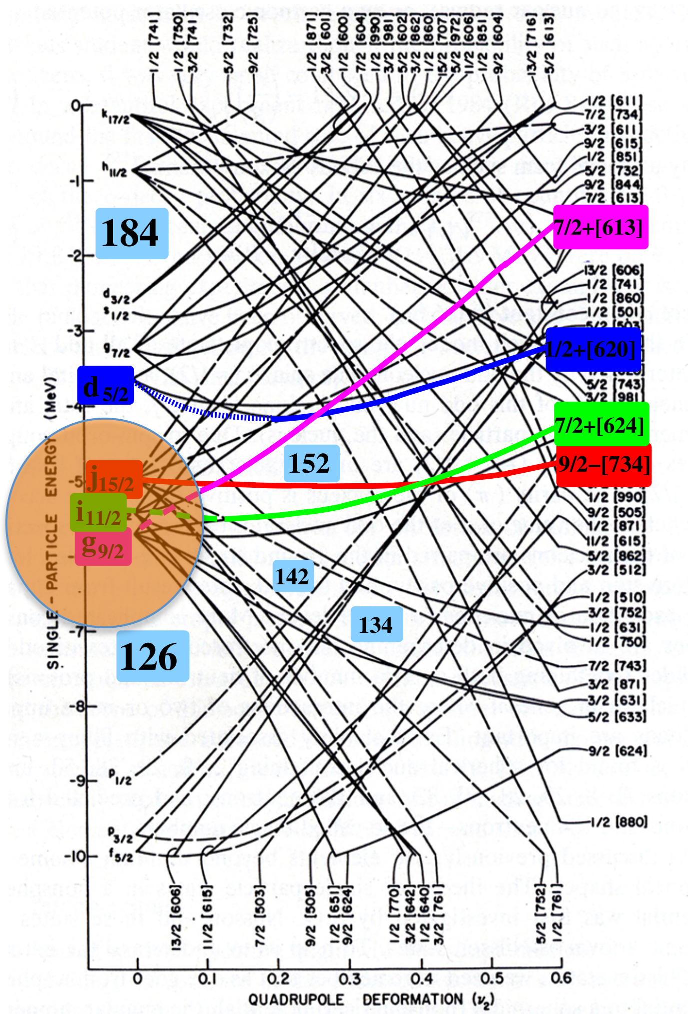
RMF



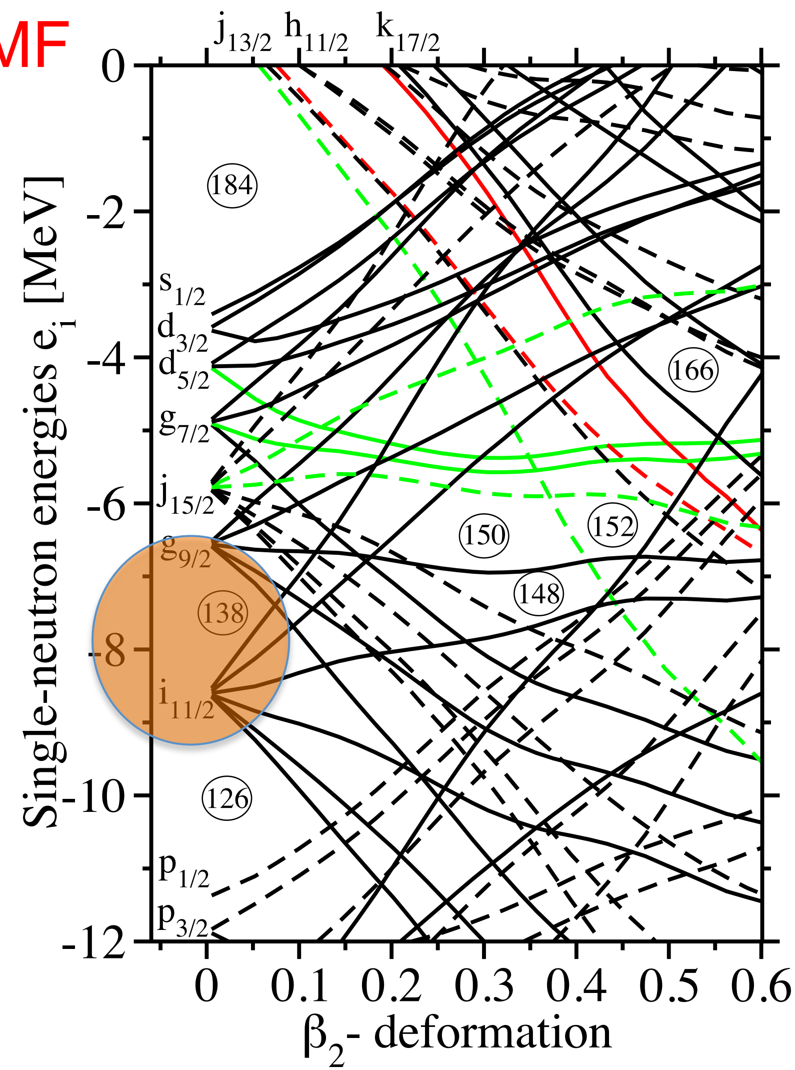
Differences in single-particle structure reflected in the shell gaps for both spherical and deformed systems.

Nilsson Diagram: Neutrons

MM



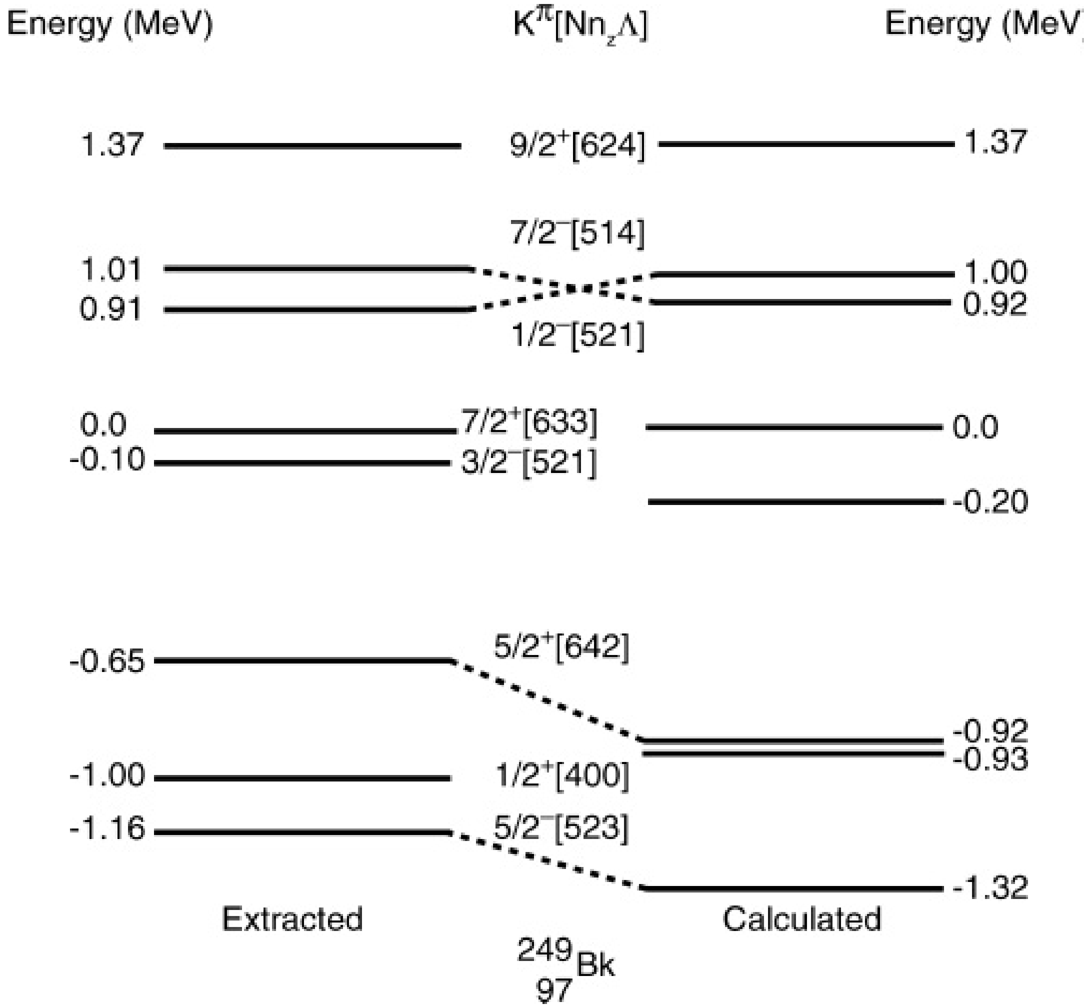
RMF



Similar differences seen for neutron level structure

MM Theory and Experiment: ^{249}Bk

Experimental single-particle energies extracted after removing contribution of pairing correlations via a Hamiltonian containing a density-dependent interaction.



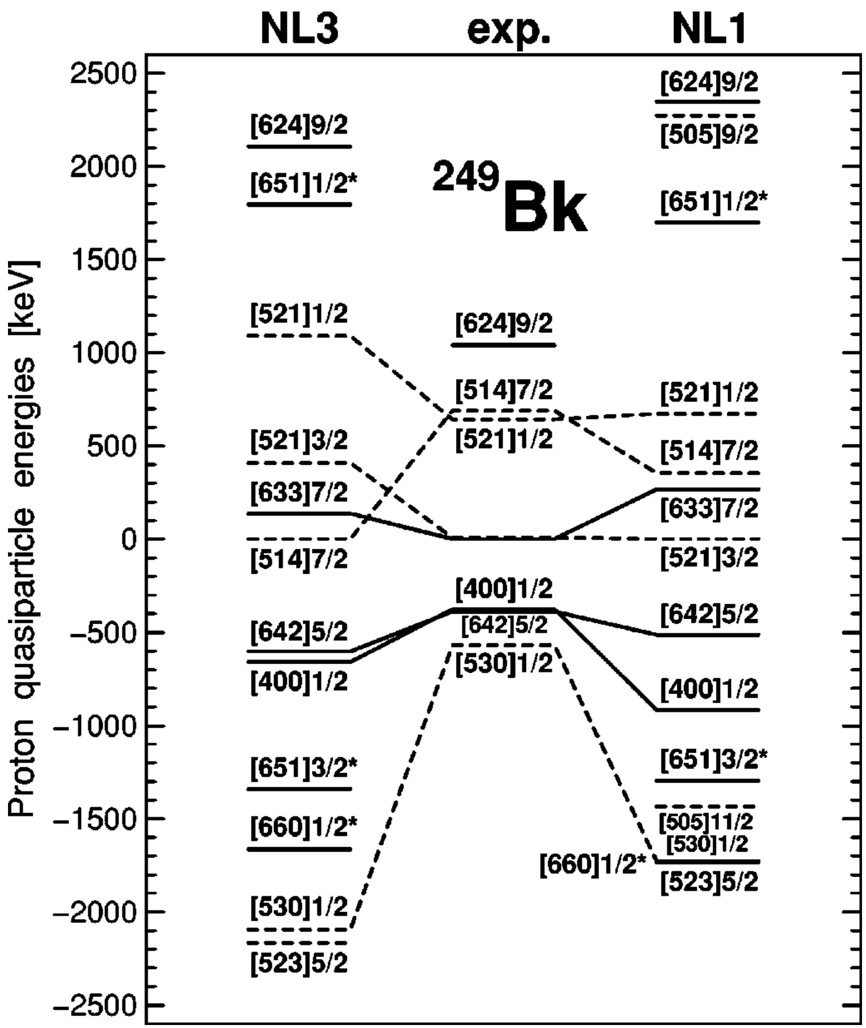
I. Ahmad et al.,
PRC 71 054305 (2005).

Calculated energies from Woods-Saxon potential with parameters tuned to reproduce experiment - agreement is excellent.

DFT and Experiment: ^{249}Bk

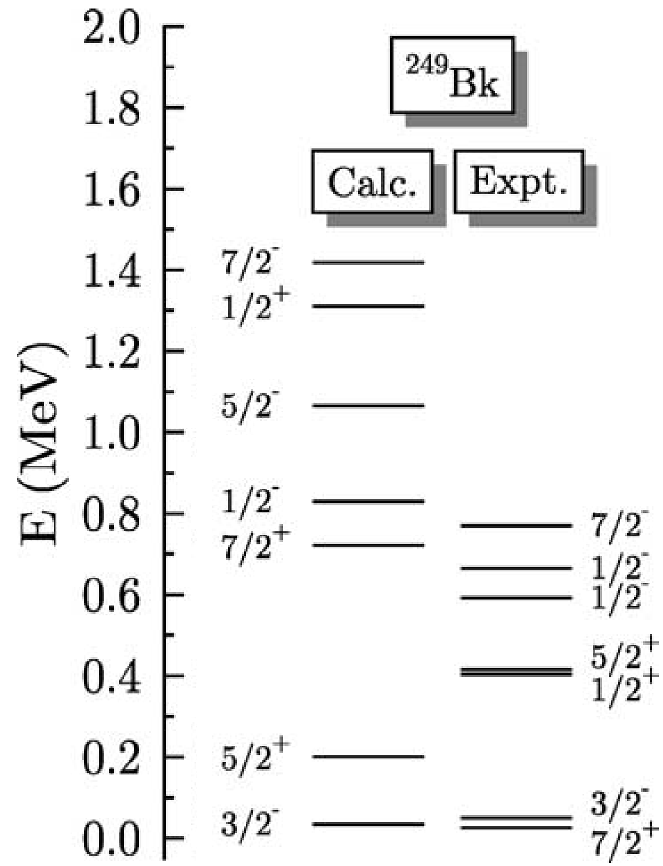
RMF

A. Afanasjev et al., PRC 67 024309 (2003)



HFB+SLy4

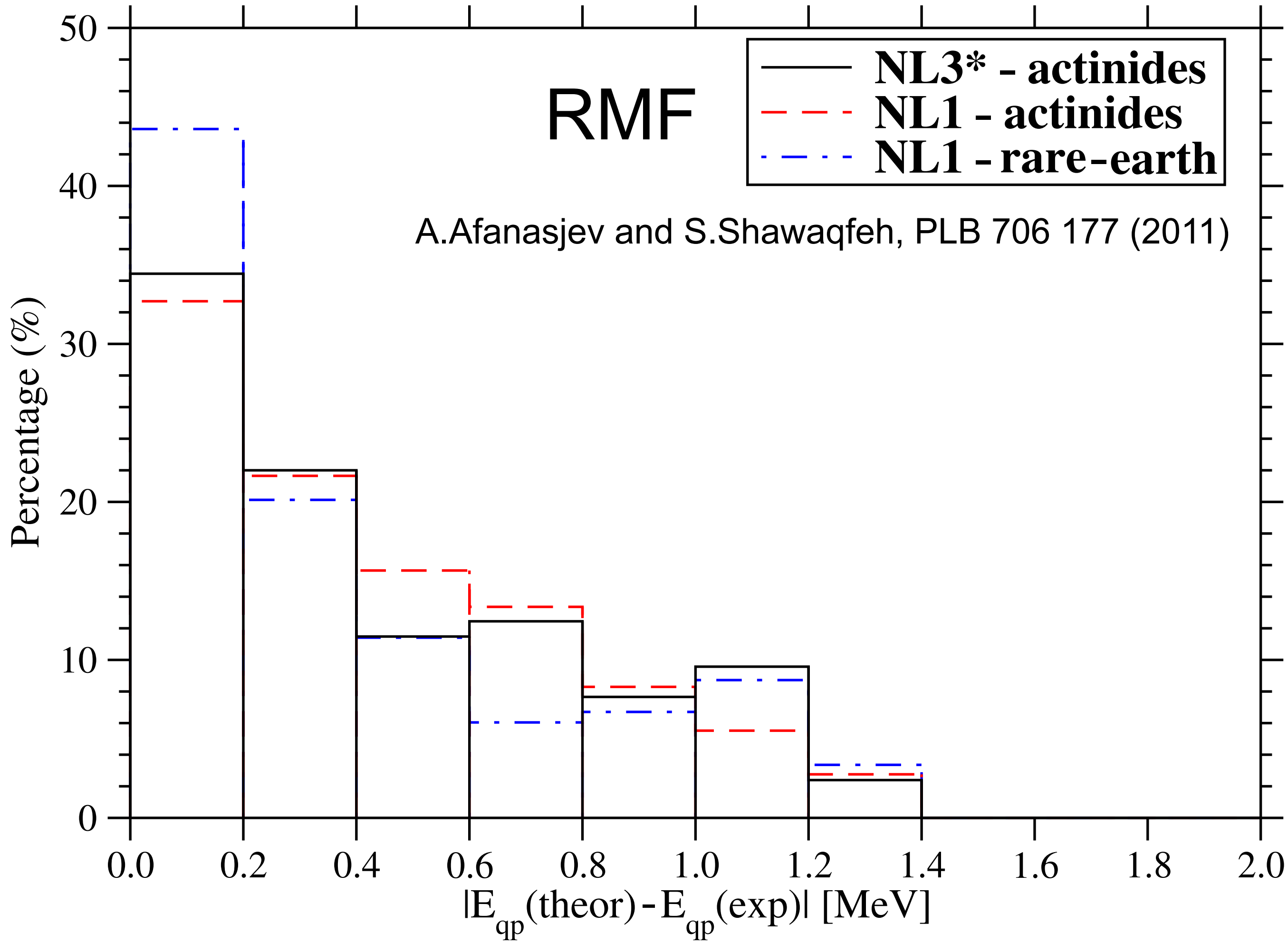
M. Bender et al., NPA 723 354 (2003)



Agreement is much worse with certain states off by ~1 MeV. Note the apparent compression of the experimental spectrum compared to the theoretical ones.

Theory Compared With Experiment

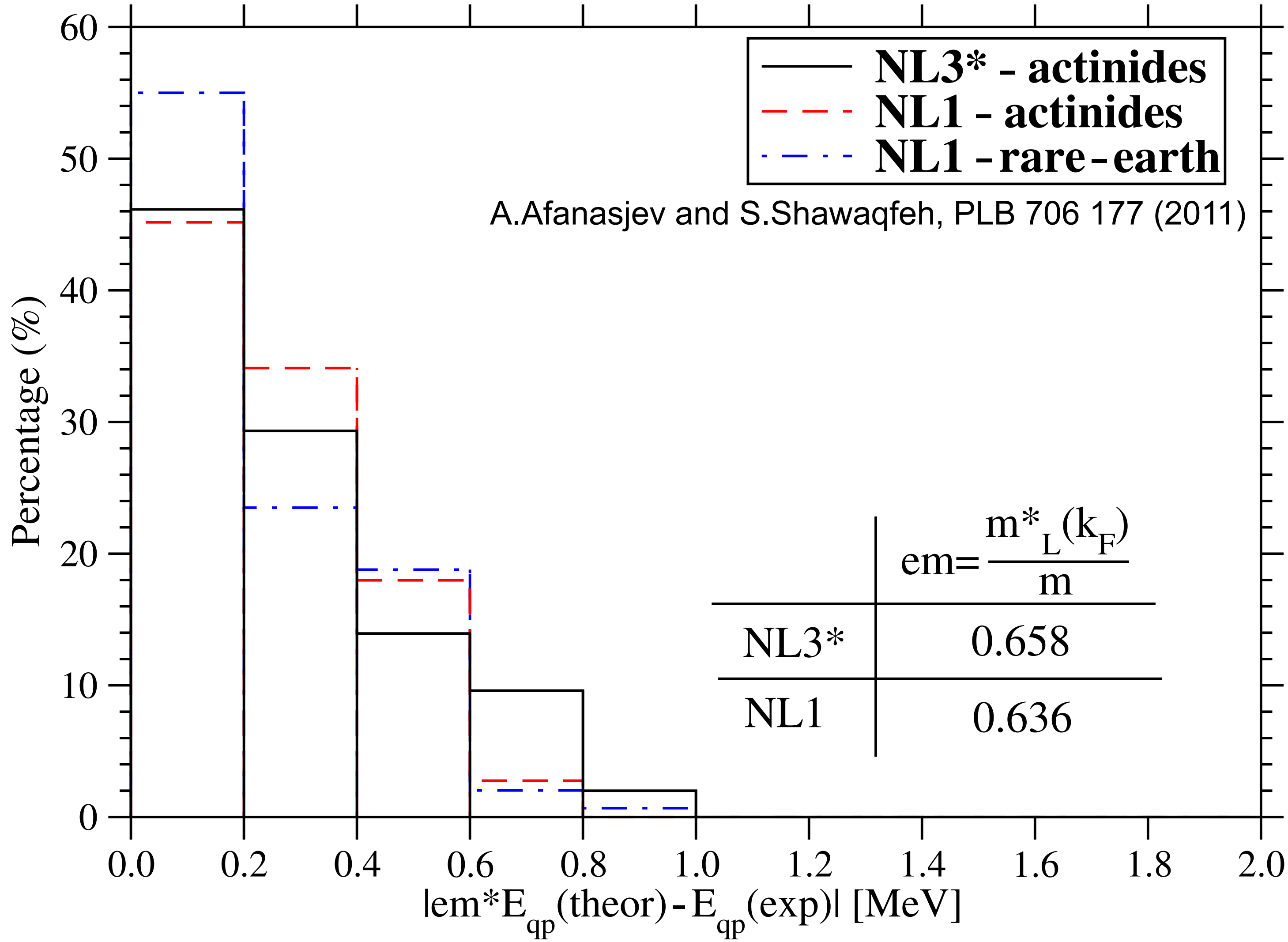
1-qp spectra calculated for 21 odd-N and 23 odd-Z nuclei with Z=89-100



- About 1/3 of 1-qp states are calculated to within 200 keV.
- There are many calculated states where discrepancy can approach 1 MeV.
- It would be interesting to see same plot for other DFT's.

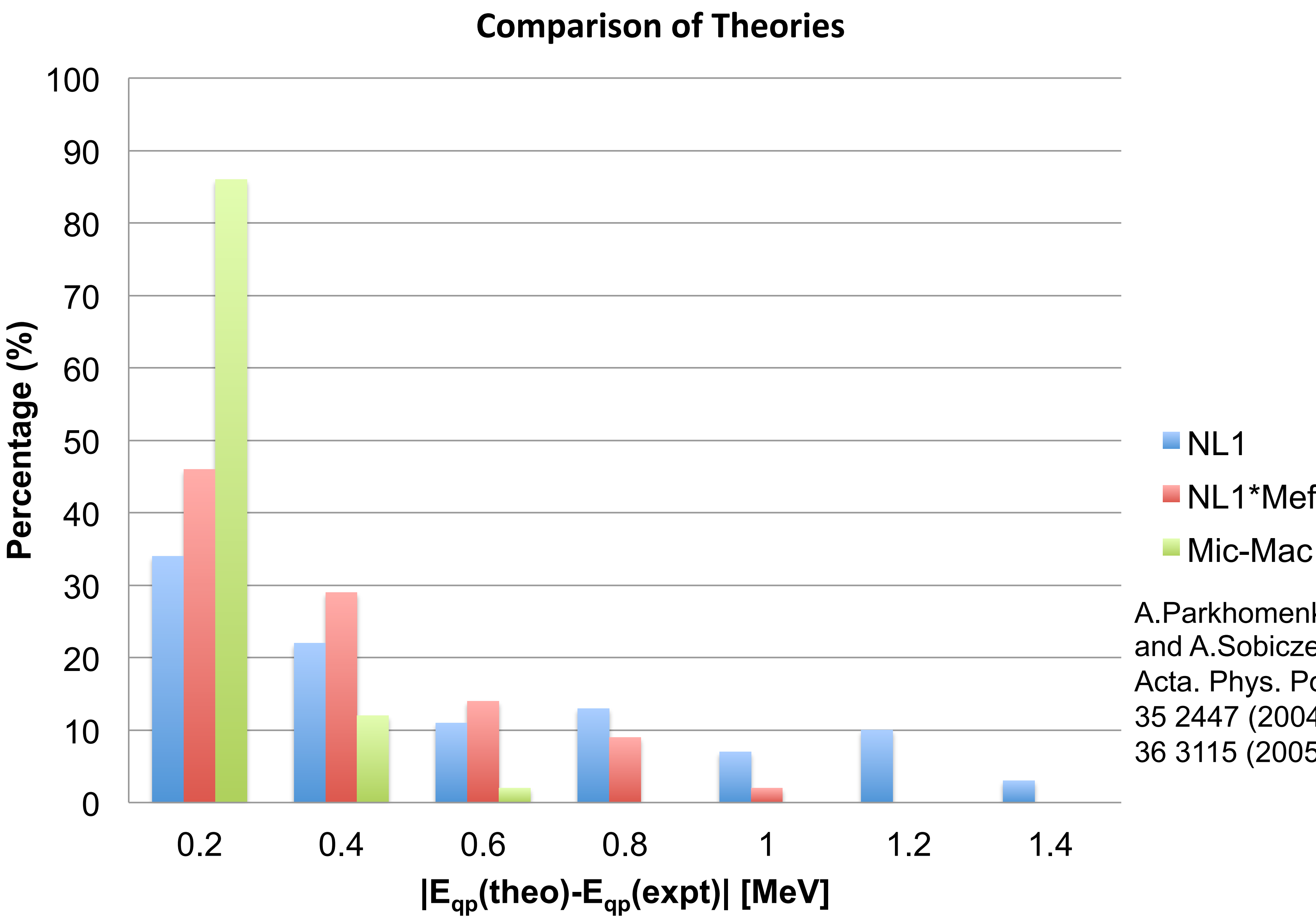
Improving DFT

The “stretching” of the calculated spectrum can be related to low effective mass (and calculated single-particle level density) in DFT’s. Scaling improves agreement.



Physical basis for scaling the effective mass may lie with proper treatment of particle-vibration coupling [E.V.Litvinova and A.Afanasjev, PRC 84 014305 (2011)].

MM vs DFT



A.Parkhomenko and A.Sobiczewski, Acta. Phys. Pol. B 35 2447 (2004) 36 3115 (2005)

Comments on Theory

MM theories, which are often tuned to reproduce experiment, provide the best description of single-qp states.

The role of higher-order deformation β_2, β_4, β_6, β_8 crucial

The argument remains concerning how certain can we be of the extrapolations to the Z=114, N=184 major spherical gaps.

Self-consistent DFT, with interaction parameters fitted mainly to bulk properties of doubly magic nuclei:

- correctly predict most of the orbitals near the Fermi surface
- accuracy for many single-qp states within 600 keV

However, major discrepancies exist (some states off by ~1MeV) which lead to incorrect predictions of known deformed gaps and, presumably, the major spherical gaps.

Experimental Opportunities

Deformation brings orbitals involved from above major spherical shell gaps close to the Fermi surface.

Rotation decreases the energy of qp states, especially for high-j orbitals.

➔Spectroscopy of deformed transfermium nuclei near Z=100 provides important testing ground of models.

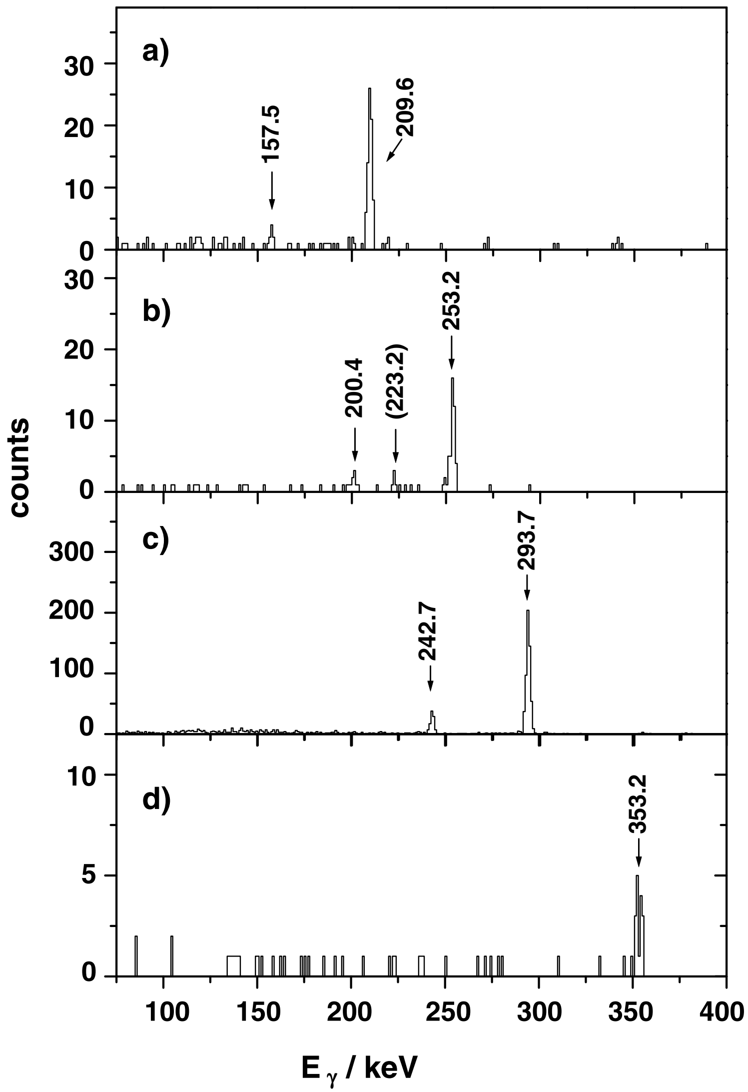
Variety of techniques being applied to these studies:

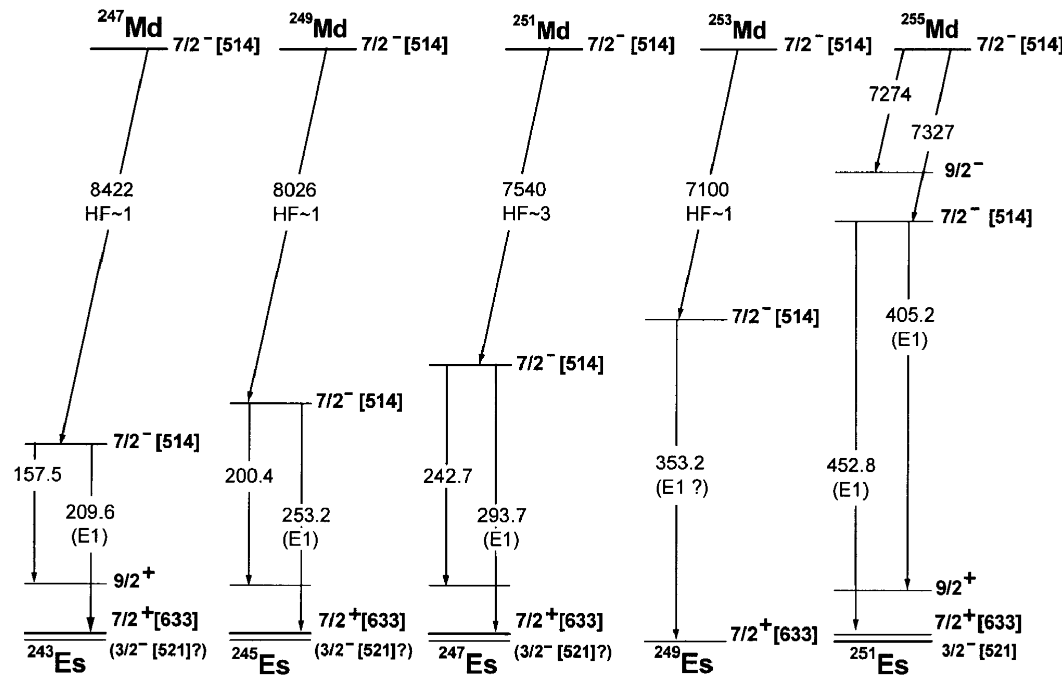
- alpha-gamma spectroscopy
- isomer spectroscopy
- prompt gamma spectroscopy via RDT

What can we do and how far can we push these techniques?

Alpha-Gamma Decay Spectroscopy

Needs a firm assignment as a starting point. Hindrance of alpha decay indicates which states have a similar character. Gamma-rays give finer details in daughter. Excellent data up to Z=99, becomes patchy for higher Z.





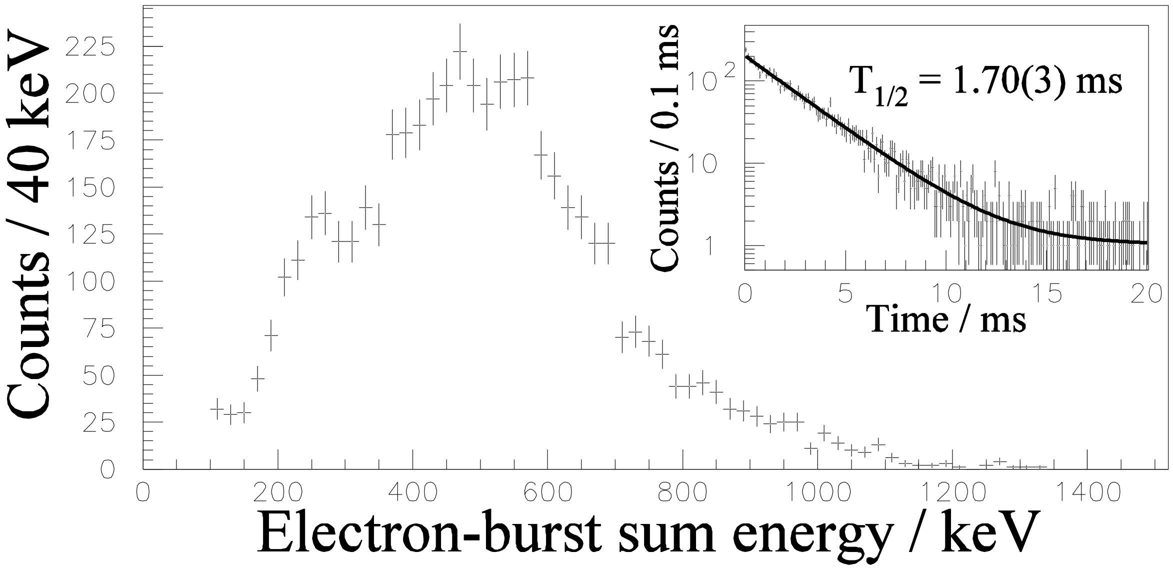
Proton states from four spherical subshells:

1/2[521] (f5/2) — Spin-orbit pair on both sides
3/2[521] (f7/2) — of Z=114 gap in MM
7/2[514] (h9/2)
7/2[633] (i13/2) — Troublesome in DFT

F. Hessberger et al., Eur. Phys. J. A 26 233 (2005).

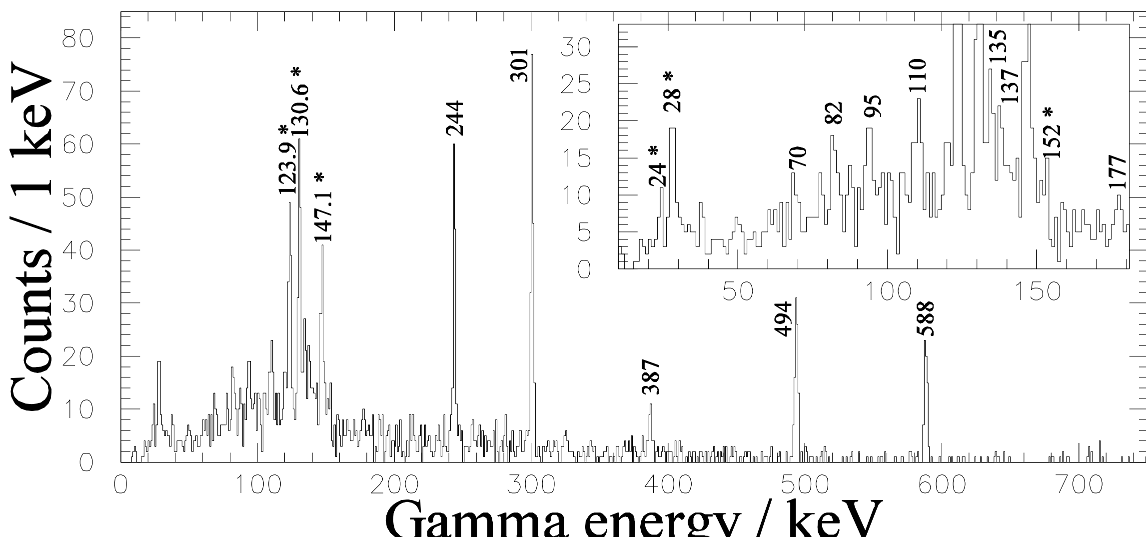
K-Isomer Spectroscopy

Single- and multi-quasiparticle states can become metastable (K hindered) and their delayed decays, via conversion electron and gamma transitions, can give detailed info.

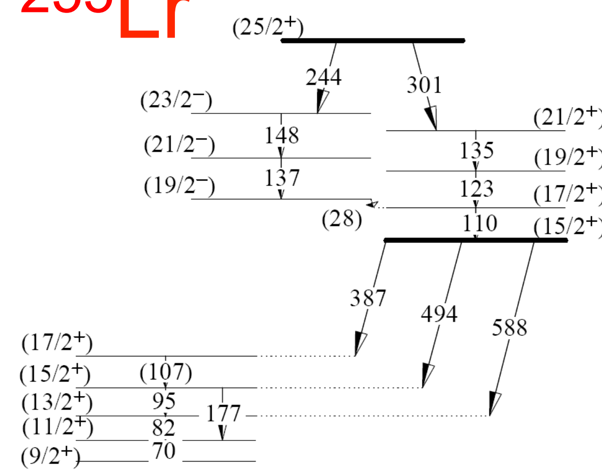


- Maximum energy of isomer (gamma+electron) ≈ 1500 keV
- Regular pattern of low-energy gamma-rays indicative of a rotational band.

$$E_{rot} = \frac{\hbar^2}{2\Im}\left[I(I+1)\right] + E_K$$



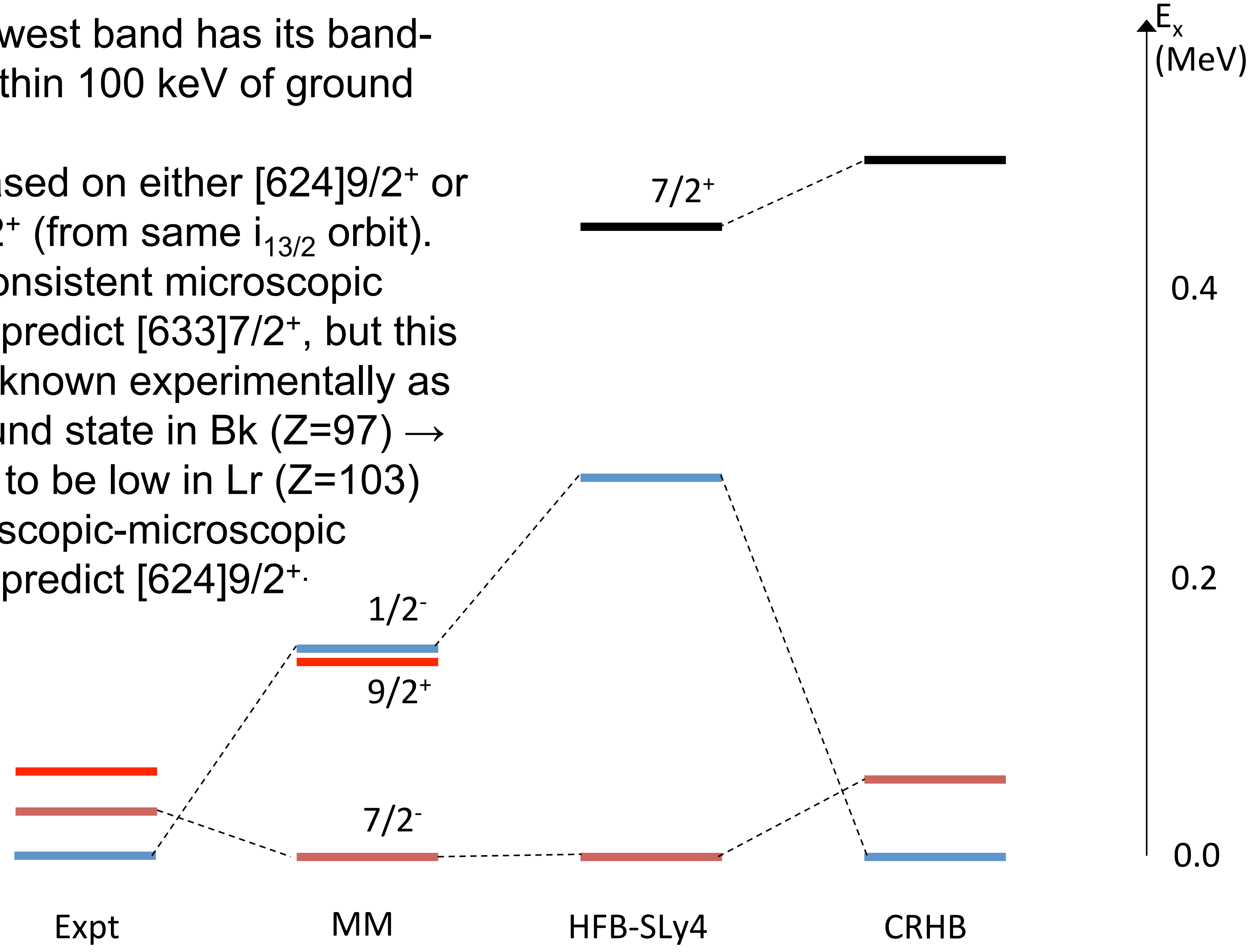
^{255}Lr



H.B. Jeppesen et al., PRC 80 034324 (2009)

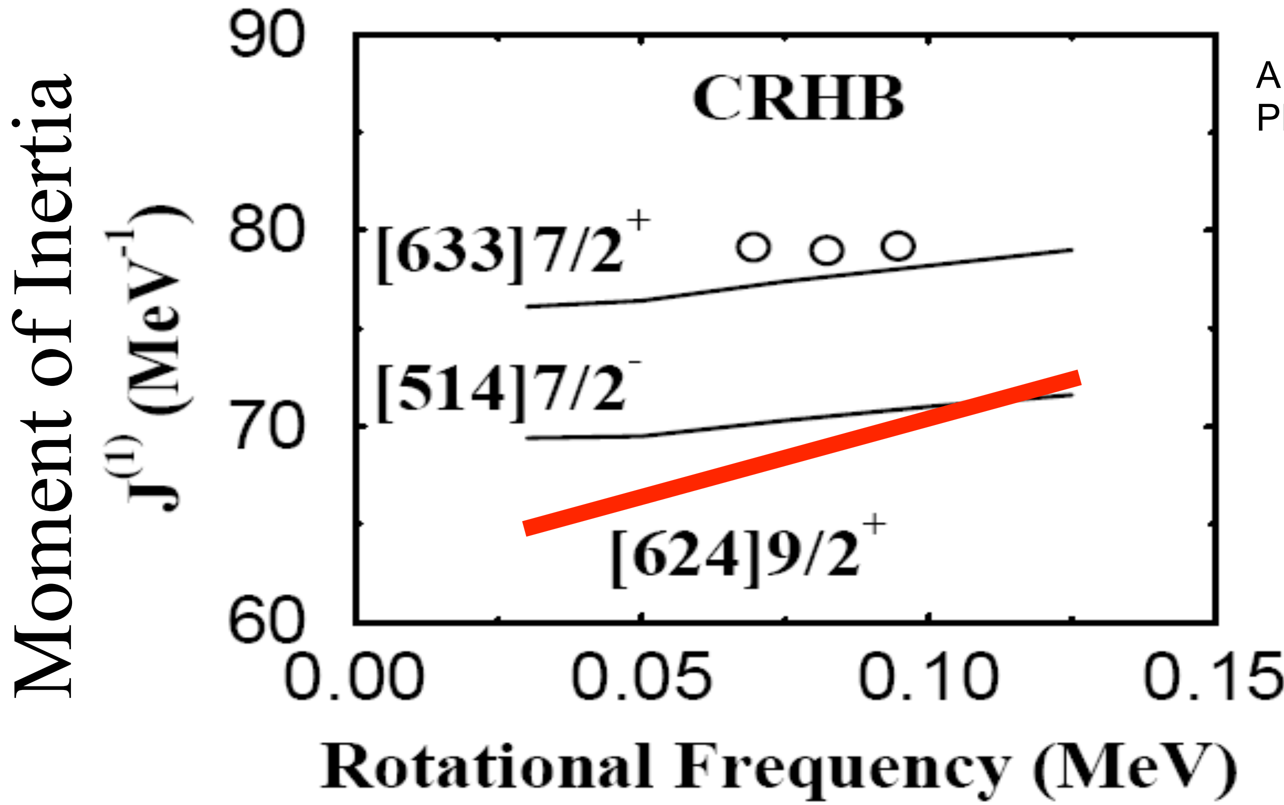
Comparison With Theories

- The lowest band has its band-head within 100 keV of ground state.
- It is based on either [624]9/2$^+$ or [633]7/2$^+$ (from same $i_{13/2}$ orbit).
- Self-consistent microscopic models predict [633]7/2$^+$, but this state is known experimentally as the ground state in Bk (Z=97) → unlikely to be low in Lr (Z=103)
- Macroscopic-microscopic models predict [624]9/2$^+$.



Rotational Response

• If band is based on [624]9/2$^+$ as suggested by MM models then self-consistent models fail to reproduce the moment of inertia – a 20% discrepancy is not usual.



A.V.Afanasjev et al., PRC 67 024309 (2003)

EITHER

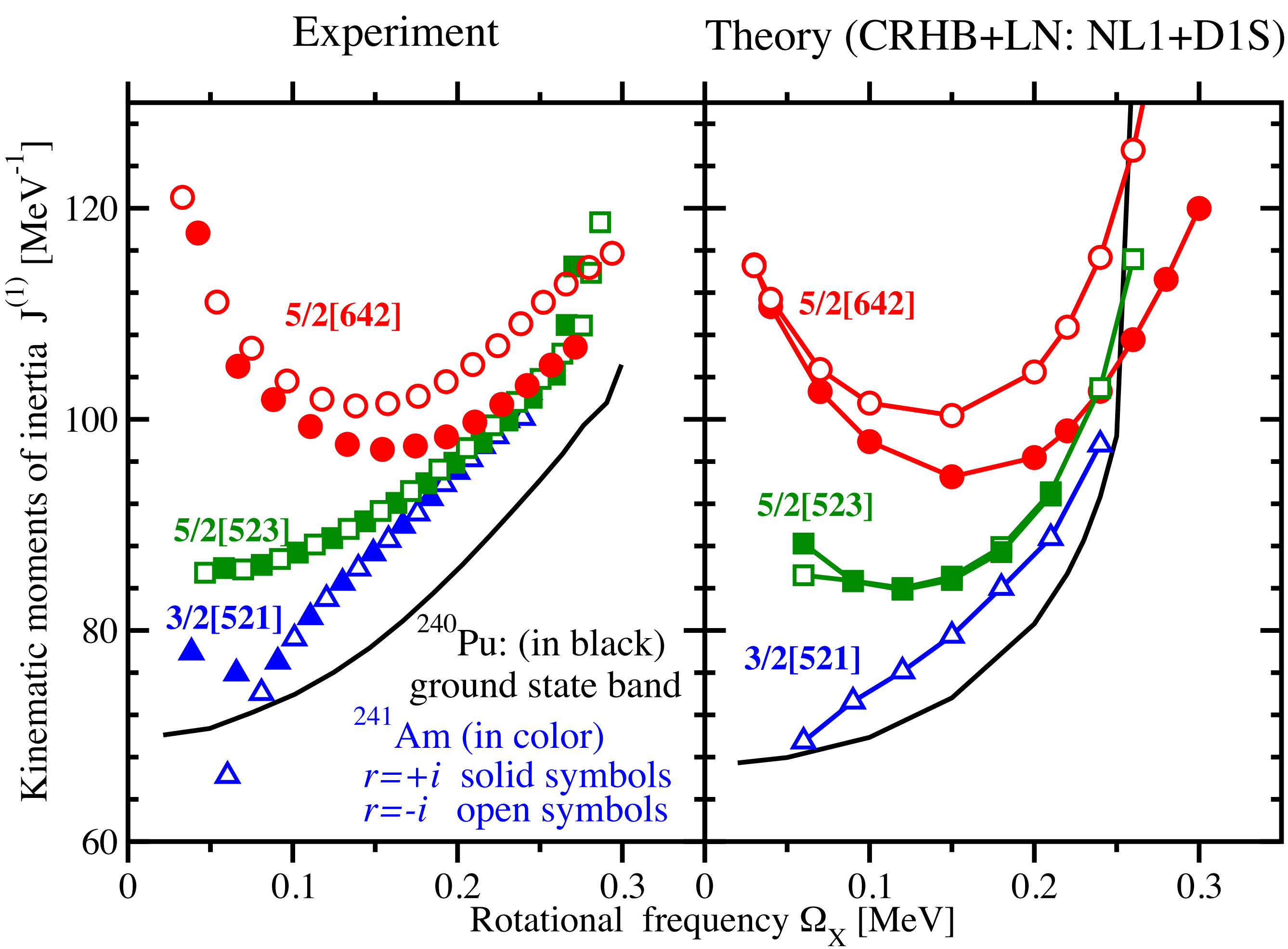
MM models have got single-particle energies wrong (affecting entire region)

OR

Self-consistent microscopic models fail to reproduce rotational response

Rotational Properties of Odd-A Nuclei

Moments of inertia, signature splitting, relative alignment all give important information for orbital assignments.

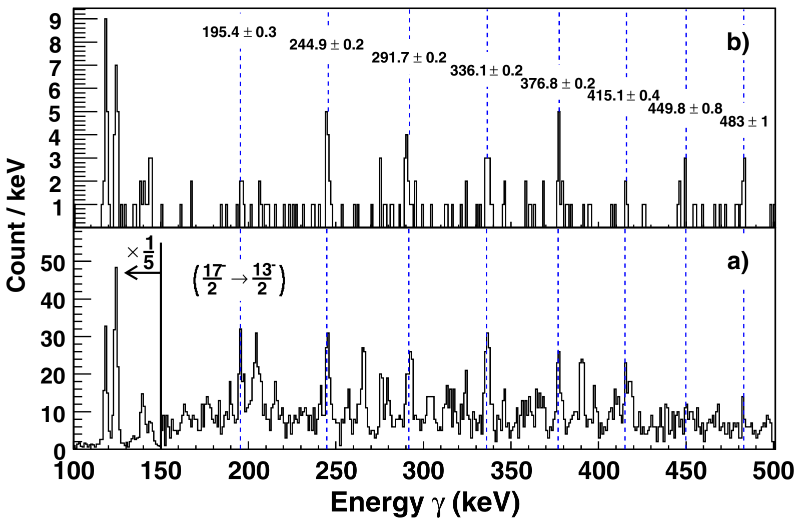


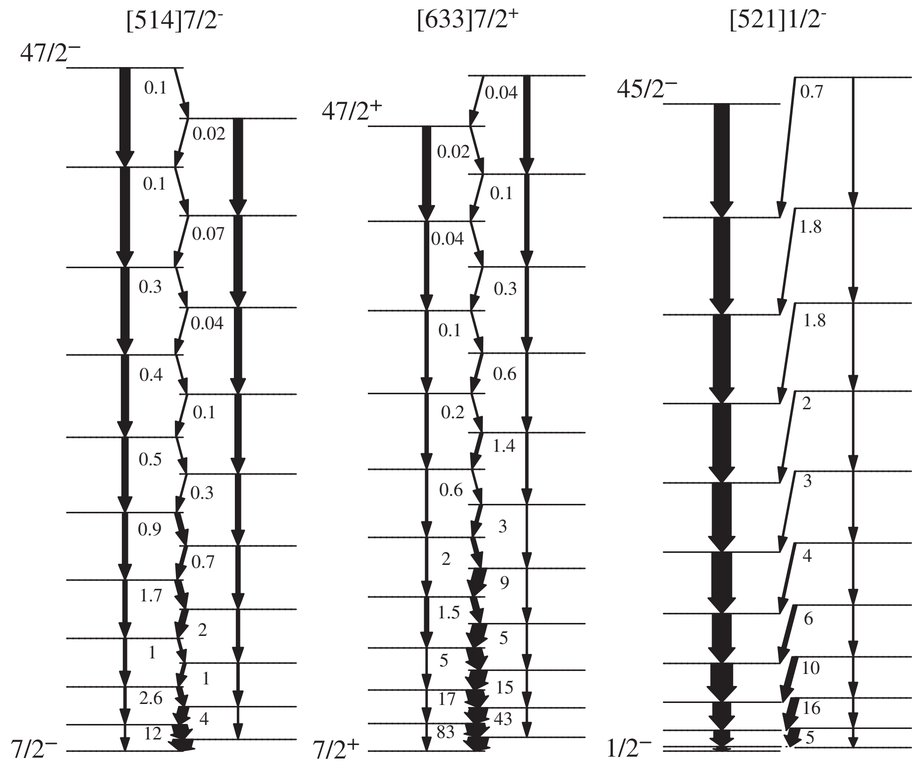
RMF

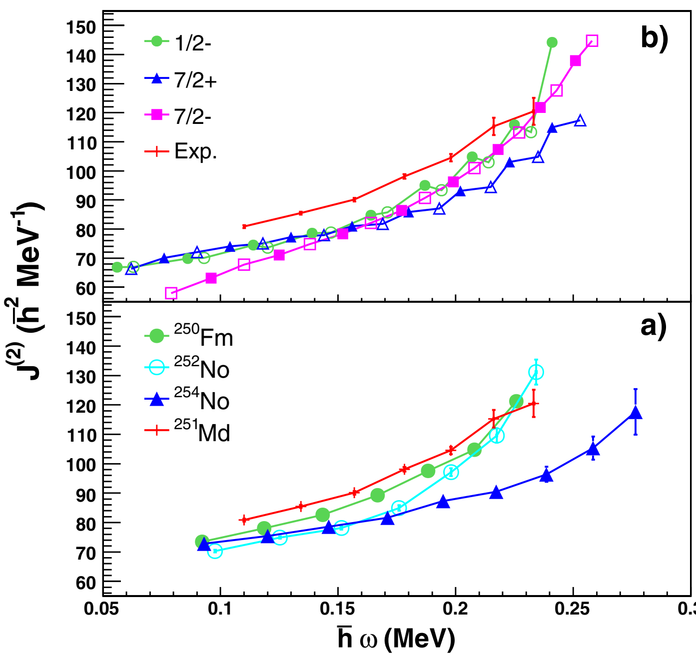
A.V.Afanasjev et al., J. Phys Conf. Ser. 312 09204 (2011)

EM Decay of Rotational Bands

EM properties of rotational bands give important information on the nature of the quasi-particle band-head. Example of ^{251}Md and identifying the ½[521] ($f_{5/2}$) state.



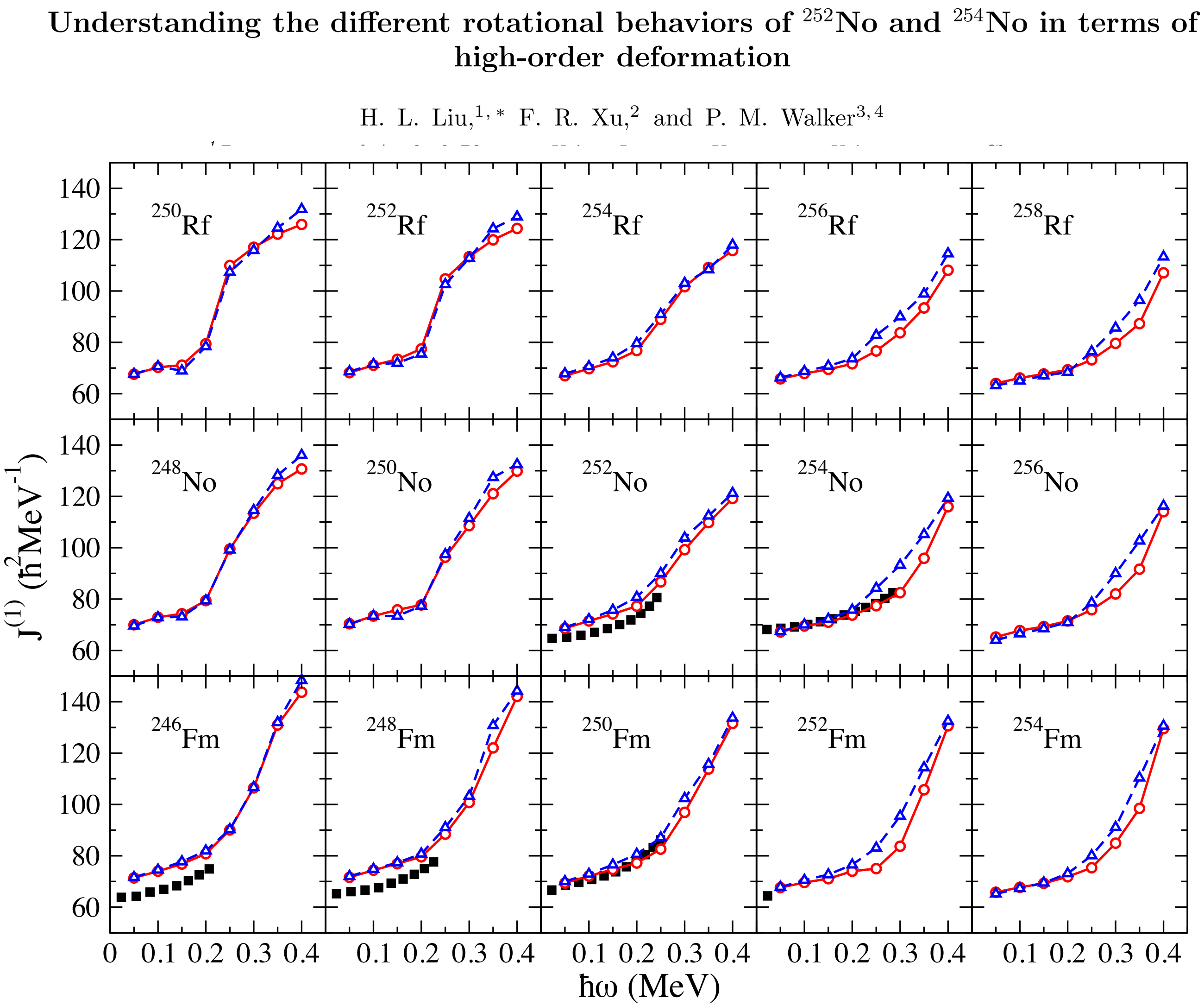




The moment of inertia may not be enough.
M1/E2 ratios ➔ (gK-gR) ➔ configuration

A. Chatillon et al., PRL 132503 (2007)

Rotational Response in Even-Even Nuclei



Properties of even-even rotational bands also give info on structure. For ^{252,254}No the $\pi i_{13/2}$ and $\nu j_{15/2}$ must align simultaneously. Could we even find traces of $\nu k_{17/2}$ alignments at highest spins?

Looking to the Future

Experimental Advances

a) Accelerator upgrades are planned which will give beam currents 1pμA < I_{BEAM}< 10 pμA.

One Example:
- 88-Inch Cyclotron at LBNL coupled with VENUS ECR source should give >1pμA 48Ca beams.

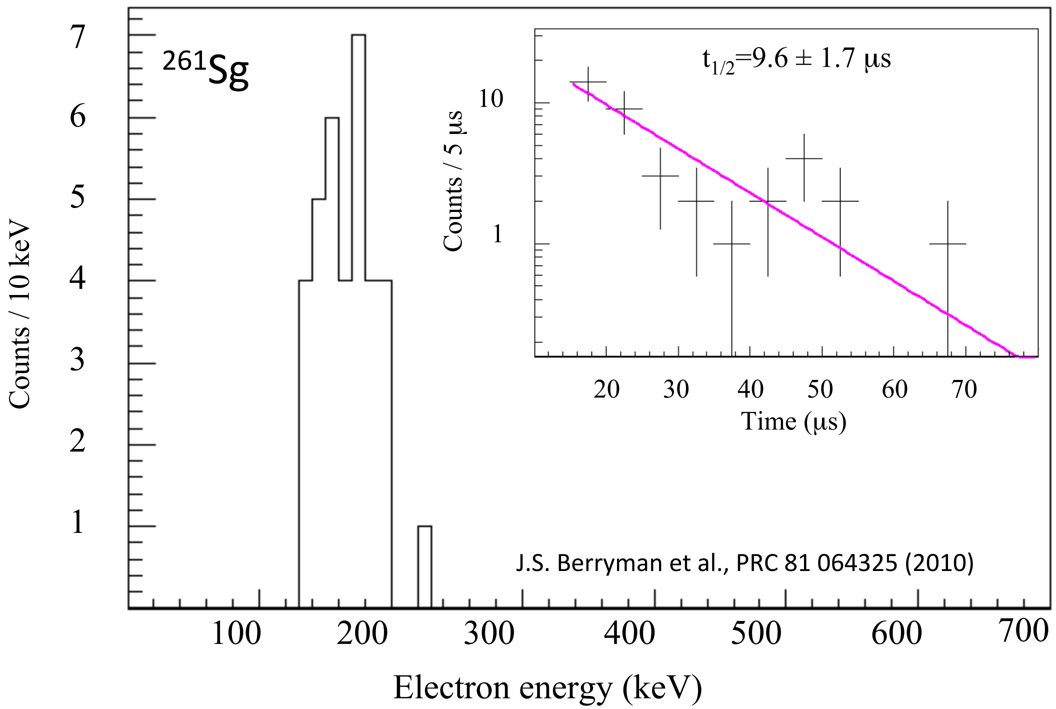
b) Improvement in detector systems will yield higher efficiency for alpha-, electron-, and gamma-spectroscopy.

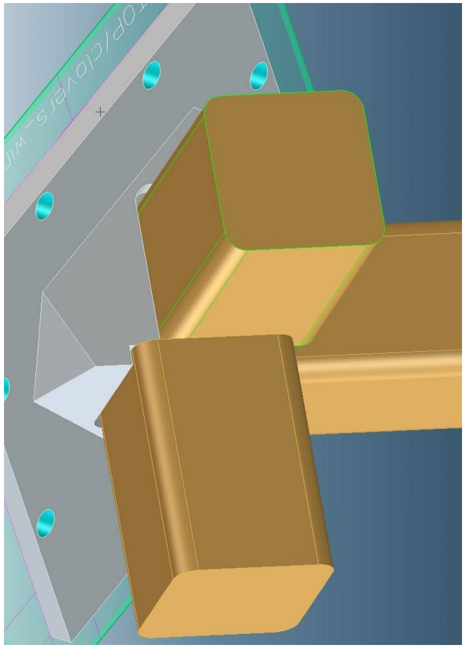
Decay Spectroscopy Example
- New focal-plane detectors for BGS at 88-Inch Cyclotron.

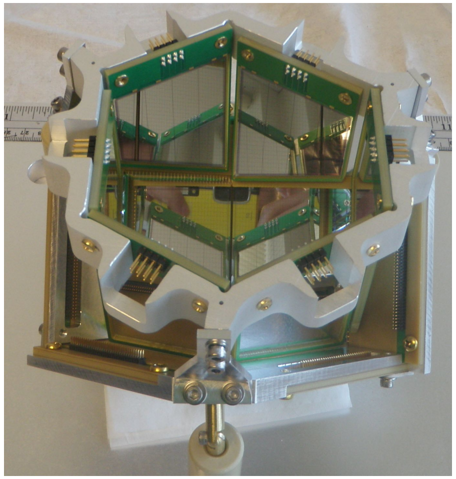
Prompt Spectroscopy Example
- The new tracking arrays GRETINA/GRETA and AGATA

New Focal Plane Detector System at LBNL

Seaborgium (Z=106) is the current limit for spectroscopy

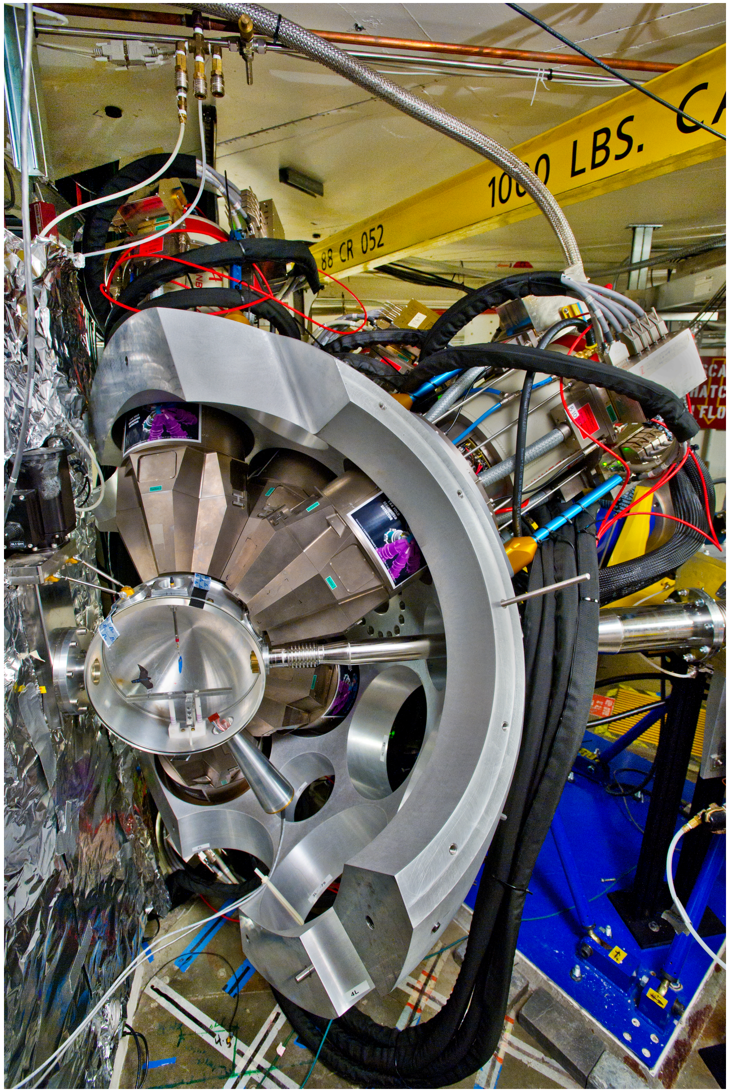


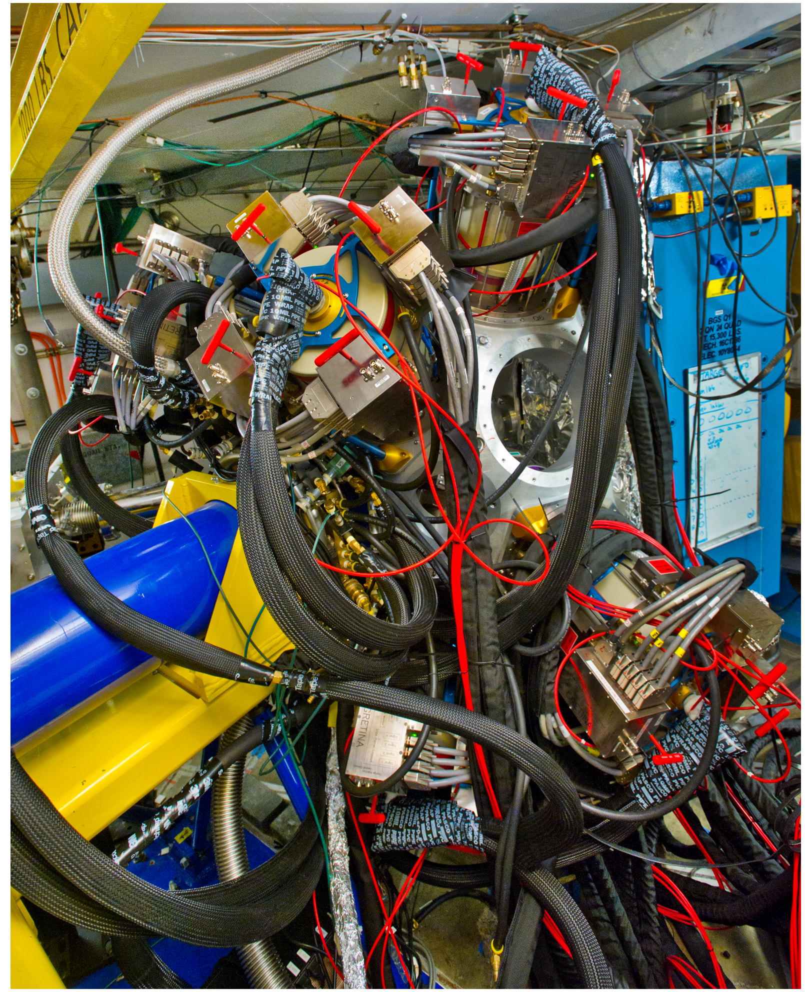




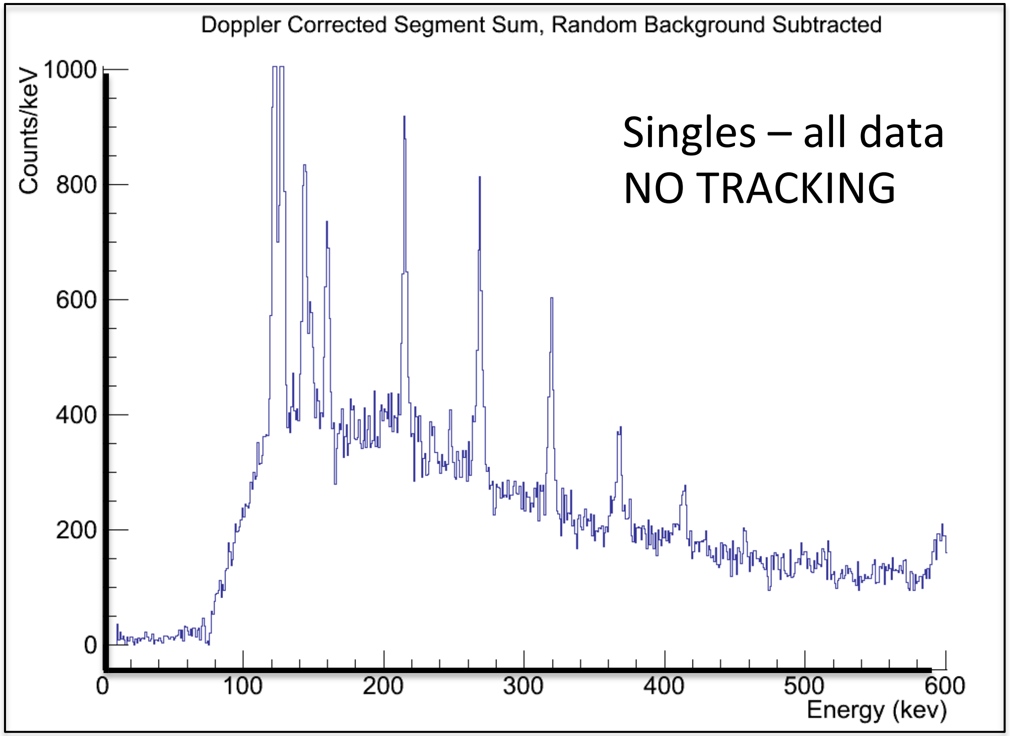
- New focal-plane detector system C^3 (> factor 6 in r-γ-α efficiency)
- Cyclotron intensity upgrade (> factor 4 for ^{48}Ca)
- Improved sensitivity for isomer studies (> factor 10)
  - → detailed γ spectroscopy of Rf (Z=104)
  - → first γ spectroscopy of Sg (Z=106)
  - → first observation of isomers in Hs (Z=108)

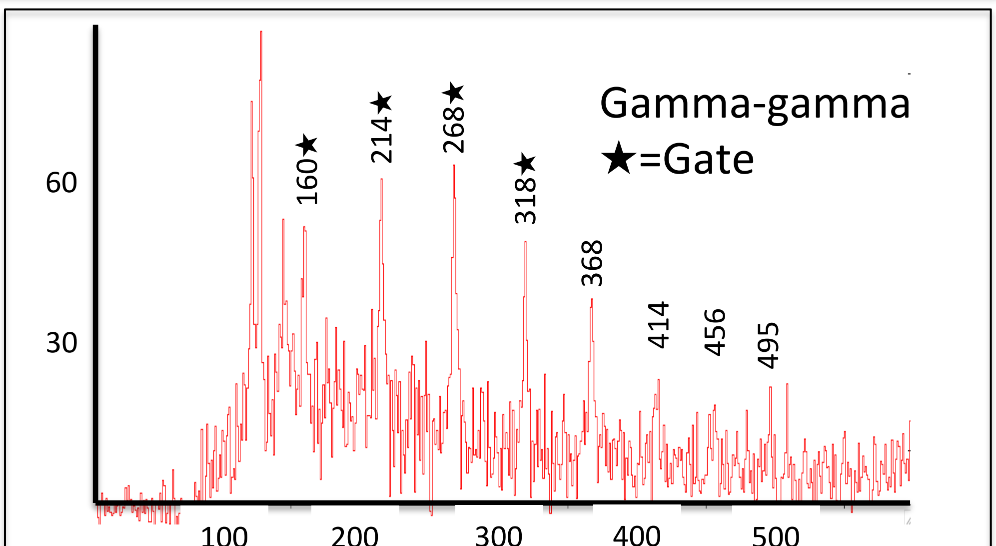
GRETINA at Target Position of BGS





Prompt Spectroscopy of ^{254}No (Z=102, N=152)





$^{208}Pb(^{48}Ca,2n)^{254}No$

Benchmark reaction with potential for new physics.

Harsh conditions for GRETINA:
- Low transition energies
- High crystal rates, 25-45K
- Low external trigger rate (~0.1/s)

~355,000 total recoils

Ongoing work:
- Final non-linearity corrections
  (better resolution)
- Tracking
  (background reduction)

Expect new results from our data (e.g. transitions above isomers).

Summary

Increased beam intensities and better focal-plane detector systems will lead to many experimental advances in decay spectroscopy (detailed spectroscopy from Z=100-104, pushing towards Z=108).

Advanced detector systems like GRETINA and AGATA when coupled to efficient recoil detectors offer unique opportunities for high-spin spectroscopy (rotational bands) perhaps to Z=106.

For now, MM theories are the best theoretical aid to spectroscopy. Local predictions are excellent but the question of extrapolation always remains.

DFT is beginning to approach spectroscopic quality and holds the promise of more reliable extrapolation.

Thanks !