Leda and the Swan, copy by Cesare da Sesto after a lost original by Leonardo, 1515–1520,

Impact of superheavy element research on theory

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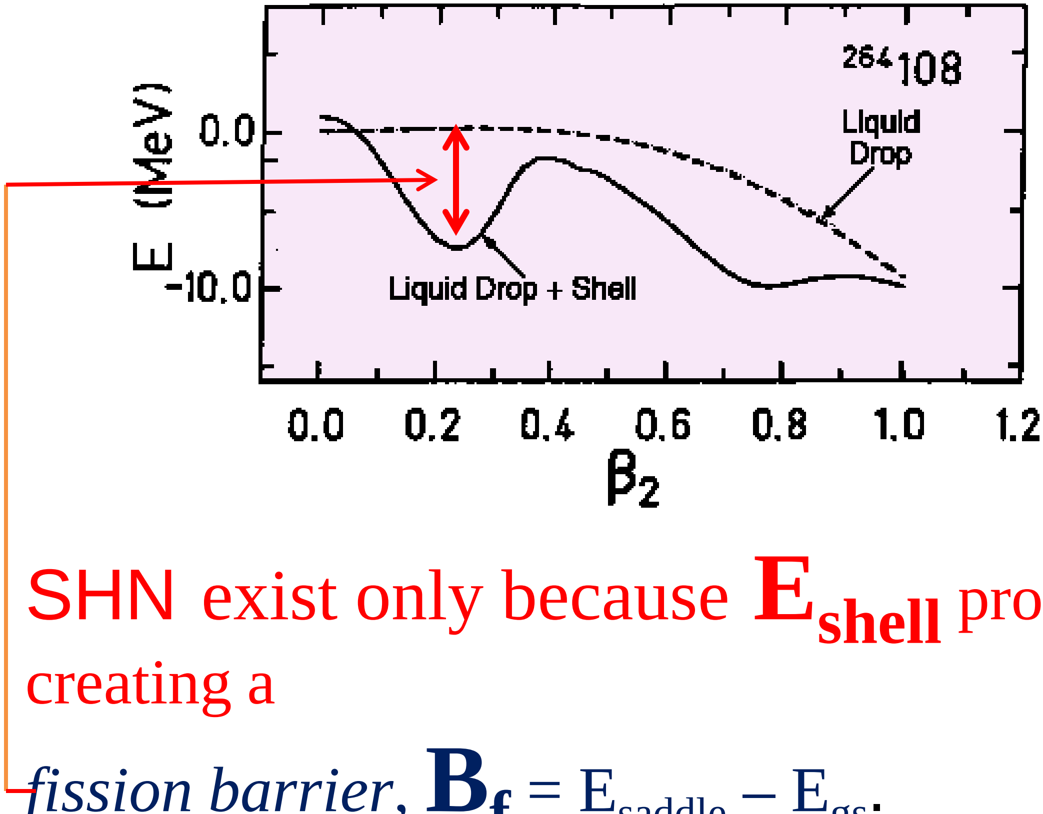
- Nuclei at three simultaneous limits: ***Z*, *I*, *E****
- Models anchored on nuclei where data available for parameter fits.
- Calculations of superheavy elements (SHE) -- & superdeformed nuclei -- represent true predictions, rather than descriptions.

Why SHN do exist?



E=E(LD) + E(shell) + E(pair) + E(deformation)

$T_{sf}(exp)/T_{sf}(LD) > 10^{13}$

SHN exist only because $\mathbf{E_{shell}}$ provides extra binding, creating a *fission barrier*, $\mathbf{B_f} = E_{saddle} - E_{gs}$.

$\mathbf{E_{shell}}$ arises from gaps in the **single-particle spectrum.**

All properties can, in principle, be calculated once the spectrum is established.

$\mathbf{E_{shell}}$, $\mathbf{B_f}$, **single-particle spectrum**: each & every one necessary for existence of SHN, **essential** aspects of the field.

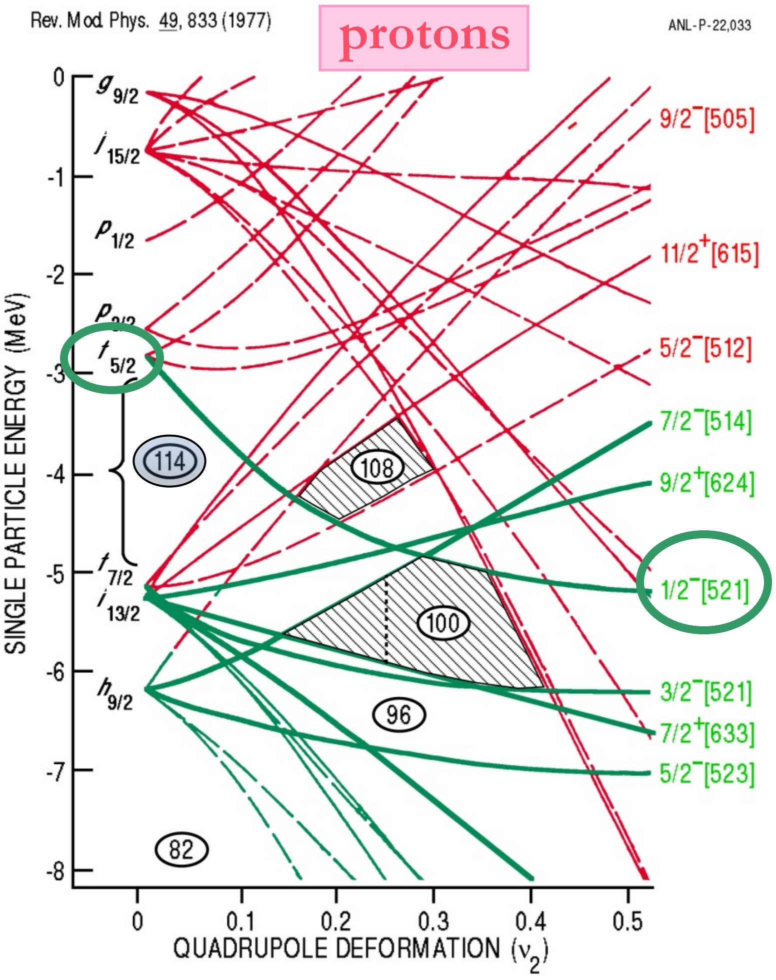
Shell energy E_{shell} at high spin I

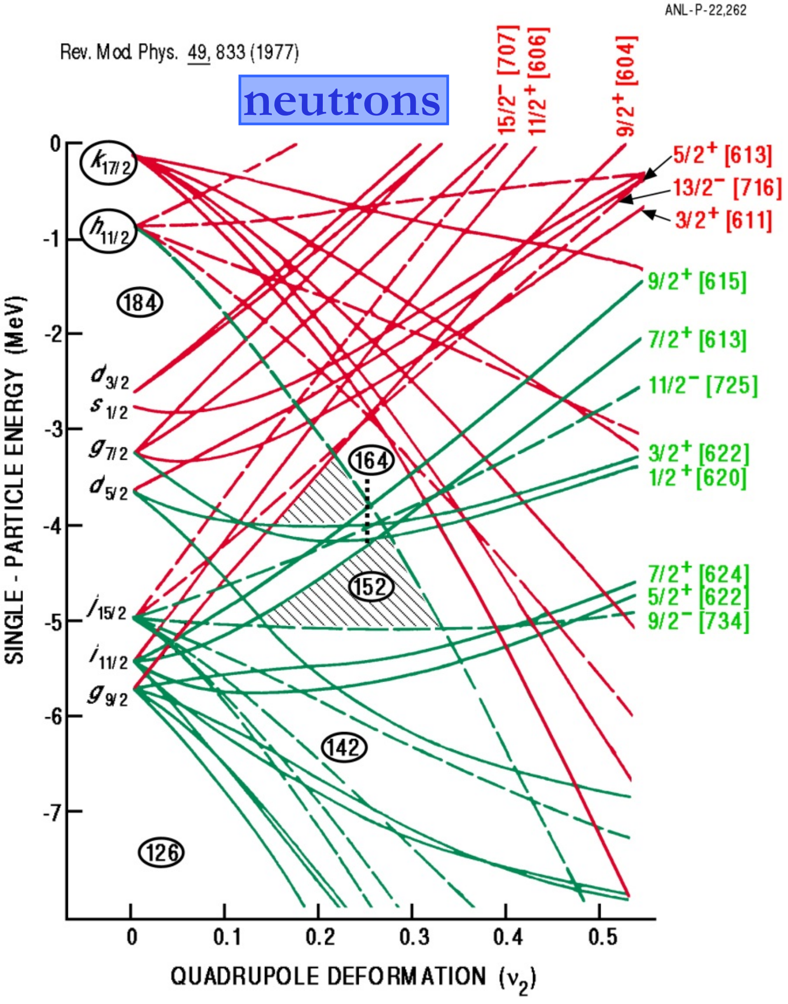
- Search for ever heavier superheavy elements: an exciting (& glamorous) frontier in nuclear physics.
- The underlying physics: *how E_{shell} persists at large Z, i.e.* ***$E_{shell}(Z)$***. Magic numbers of SHN?
- $E_{shell}(I,Z,N)$ → more insight.

Effect of **deformation** & **rotation** on orbital energy

- Deformation & rotation lower sub-states of high-lying *j* shells towards Fermi level.
- Shells become **accessible** which otherwise would not be (if nucleus were spherical).

Proton and neutron single-particle energies (Woods-Saxon potential)





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

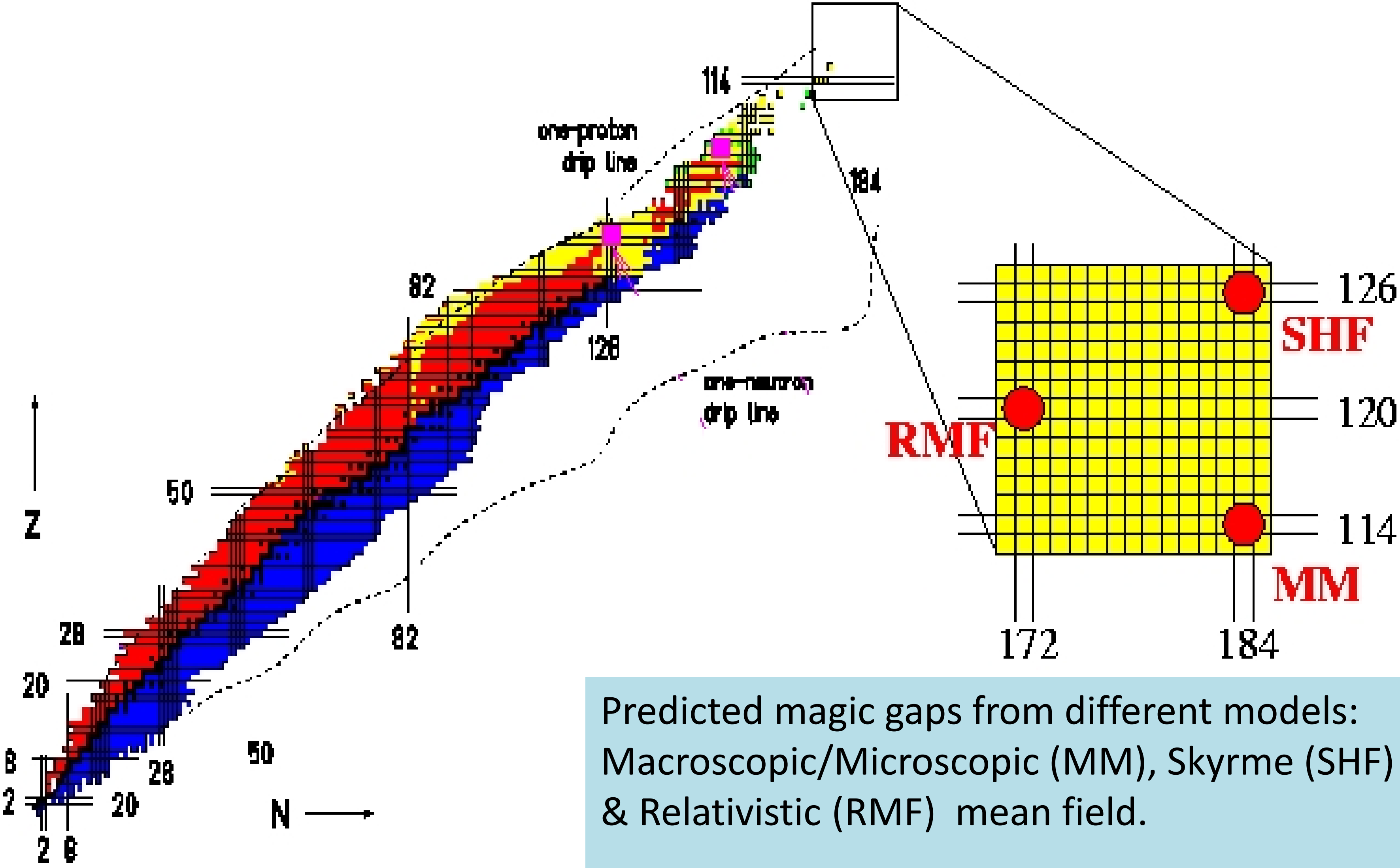
Spectroscopy, mass and reaction data

- Combine **spectroscopic, mass and reaction data** to develop a more complete, consistent description.
- Especially when data is sparse, as for SHN.
- **SPE** from spectroscopy, mass.
- Entry distribution ⟷ Fission barrier $\mathbf{B_f}$, formation mechanism.
- $\mathbf{E_{shell}}$(I) from mass & yrast line.

1. Single-particle energies (SPE) of SHE:

- Shell energy originates from single-particle spectra, particularly from gaps.
- **SPE represent the core from which all follows: existence, mass, shell energy, fission barrier.**
- Accurate predictions require accurate SPE.
- Different models have discrepant SPE.
- Can predictions be accurate without accurate SPE?

Where are the magic gaps for superheavy nuclei?



Predicted magic gaps from different models: Macroscopic/Microscopic (MM), Skyrme (SHF) & Relativistic (RMF) mean field.

SPE must be different; therefore testable.

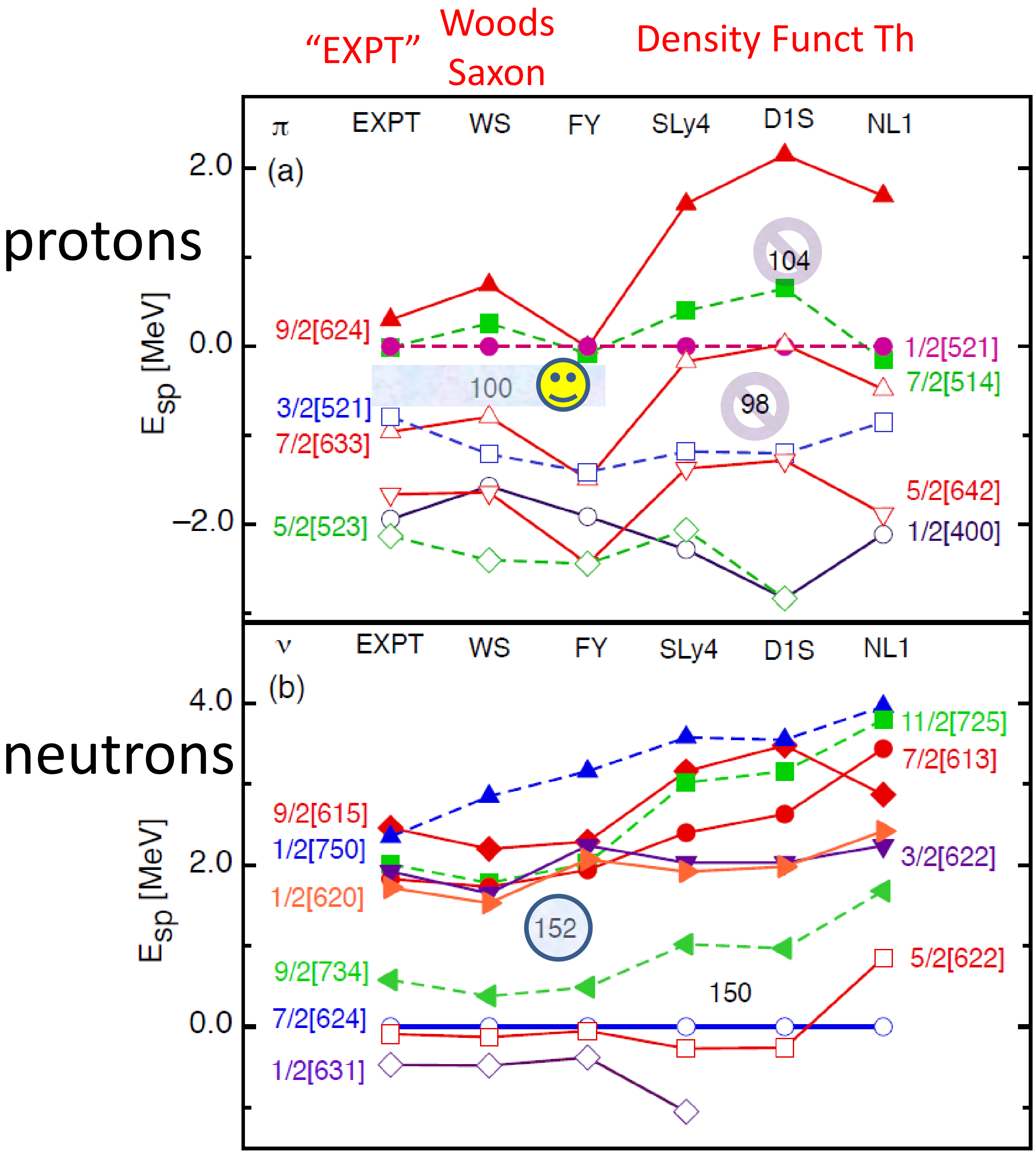
Single-particle energies (SPE) of SHN:

decisive test of theory

Extract a set of **SPE**, which give **E(1qp)** equal to measured energies in ^{247,249}Bk, ^{251}Es & ^{247}Cm, ^{251}Cf.

- Trial set of SPE.
- Calculate E(1qp), using LN procedure for pairing.
- Iterate until E(1qp) reproduce experiment.

E(2qp) provide complementary tests.



“SPE” (deduced from E_{1qp})
Expt. vs. theory

Spectrum directly reflected in E_{1qp}, E_{2qp} & masses.

Degeneracies in SPE → $\Delta E_{1qp} < 9$, 55 keV.

Gaps at Z=100, N=152 → largest E_{shell} at ^{252}Fm; also reflected in δS_{2n}, $\delta\ S_{2p}$.

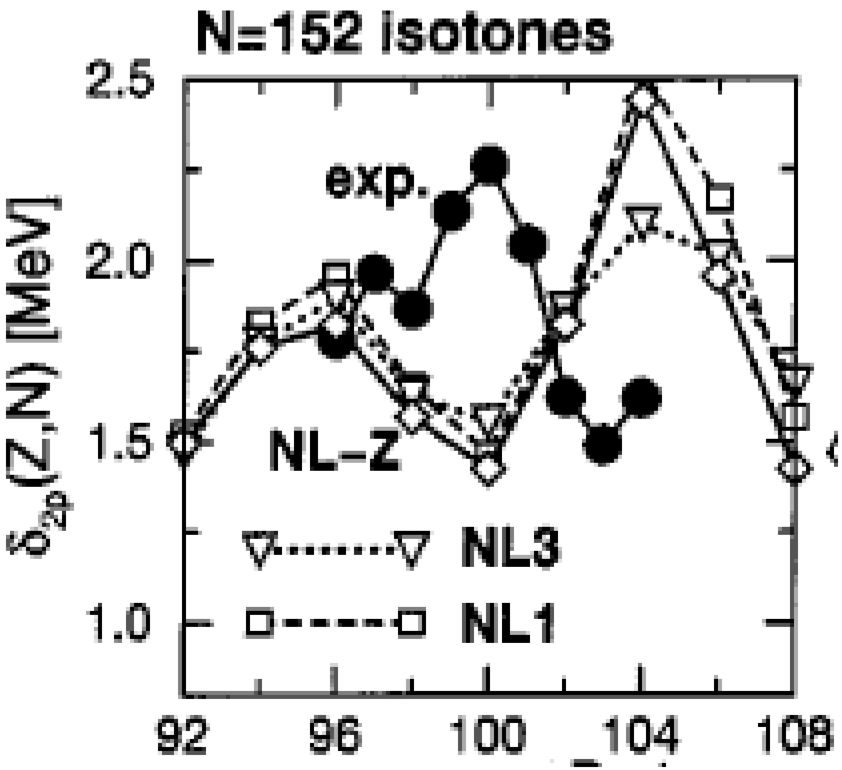
Errors in $E_{1qp,2qp}$(DFT) traced to too high E(high-j); ΔE up to 1.4 MeV!

Spectroscopy, mass

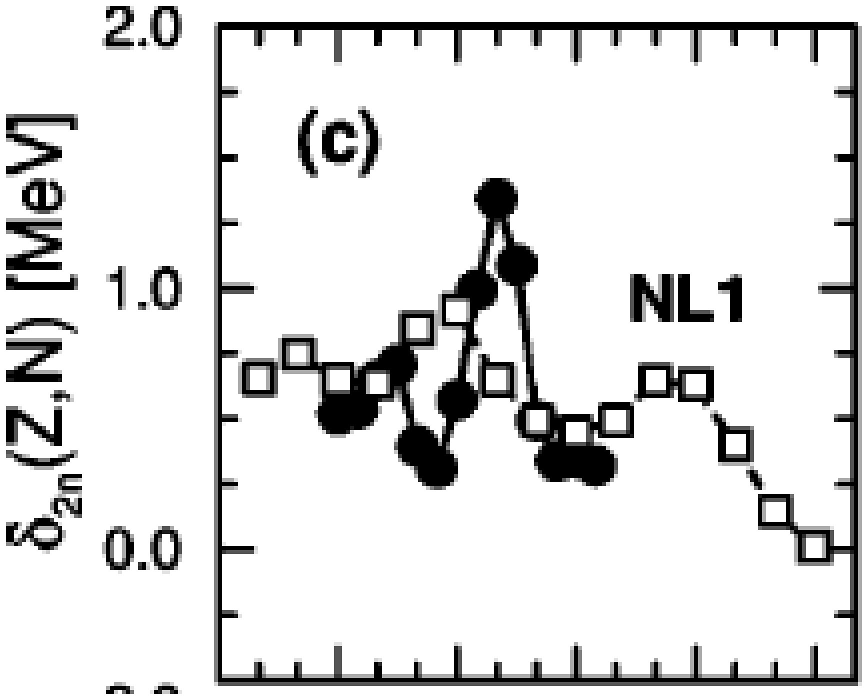
Single-particle spectra directly manifest in binding energy, hence **mass & δS_{2n}, δS_{2p}.**

Also governs **B_f.**

Z=100



N=152



Afanasvej et al, PR **C67**, 024309 (2003)

Comments on theory

- DFT[a)] require improved effective interactions.
- Predict gaps at Z = ~~120,126~~, but give wrong deformed gaps.
- Woods-Saxon (WS) potential gives reasonable (best) spe. Gap at Z=114.
- **High-K 2-qp isomers** establish configurations & support above conclusions.

2. Fission Barrier B_f

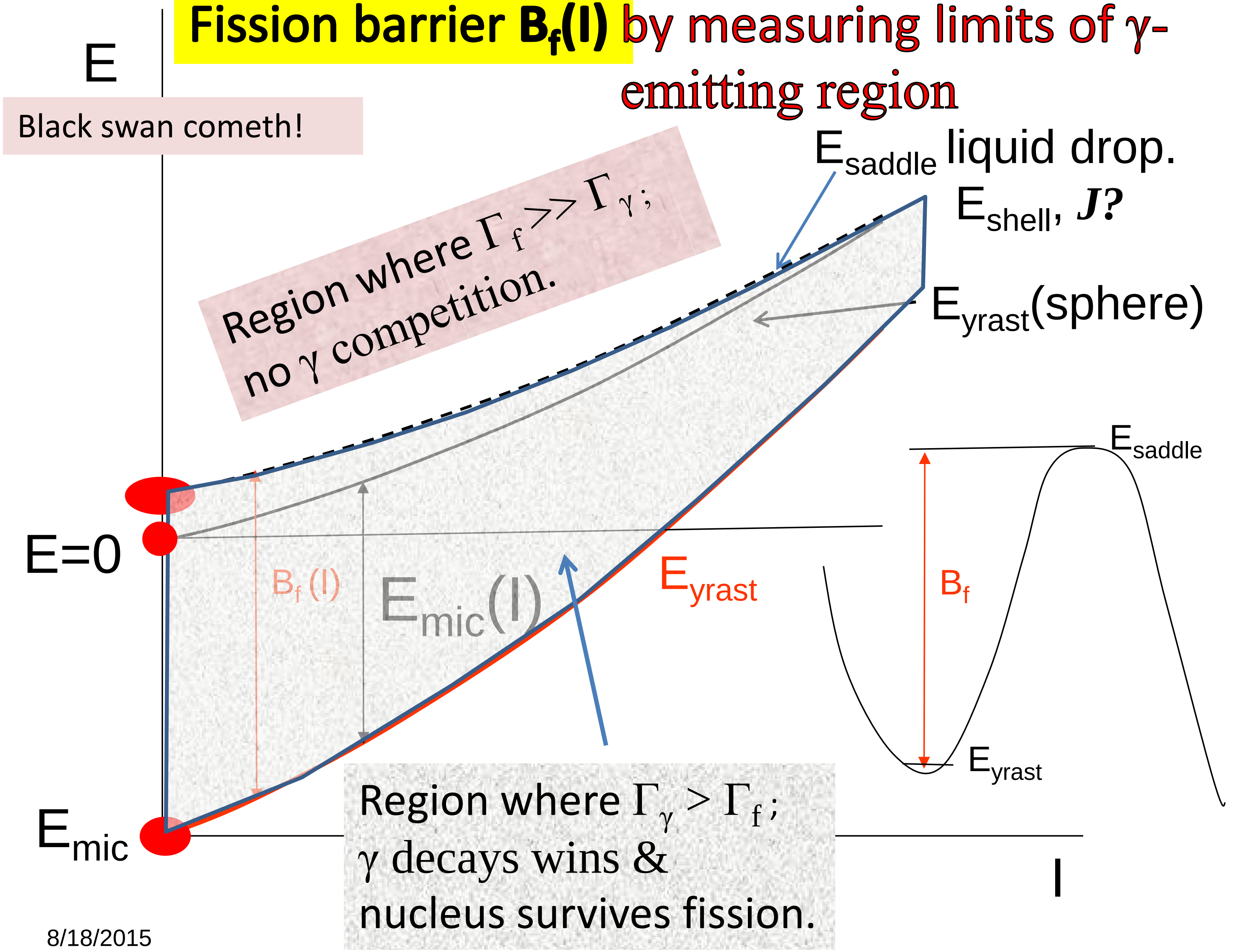
B_f in ^{254}No. How does it test theories that predict properties of SHE?

- ^{254}No shell-stabilized, like SHE.
- **Dominant contribution to B_f from shell energy, which depends on single-particle spectrum (spe).**
- Theoretical approaches have different spe, hence, different B_f. (Mic-mac: 6.76 MeV; DFT: 6 – 12.5 MeV.)

- Classical & most direct method: **fission threshold** after transfer reactions.
- Up to Cf (Z=98). **No results for heavier Z for >40 y** due to lack of stable target, so we **need a new method**.
- $\Gamma_\gamma/(\Gamma_\gamma + \Gamma_f) \rightarrow 0$ **at fission threshold,** below S_n, (where only γ & fission channels open).
- **γ calorimetry with Gammasphere → entry distribution** (starting points for γ decay to ground state)
- **E^*_{cutoff} of entry distribution →** $E_{saddle}(I)$, $B_f(I)$.
- **$B_f(I\sim15) \sim 6.6\ (5)$ MeV; $B_f(I=0) \sim 6.0\ (9)$ MeV.**

G. Henning et al., PRL 113, 262505 (2014)

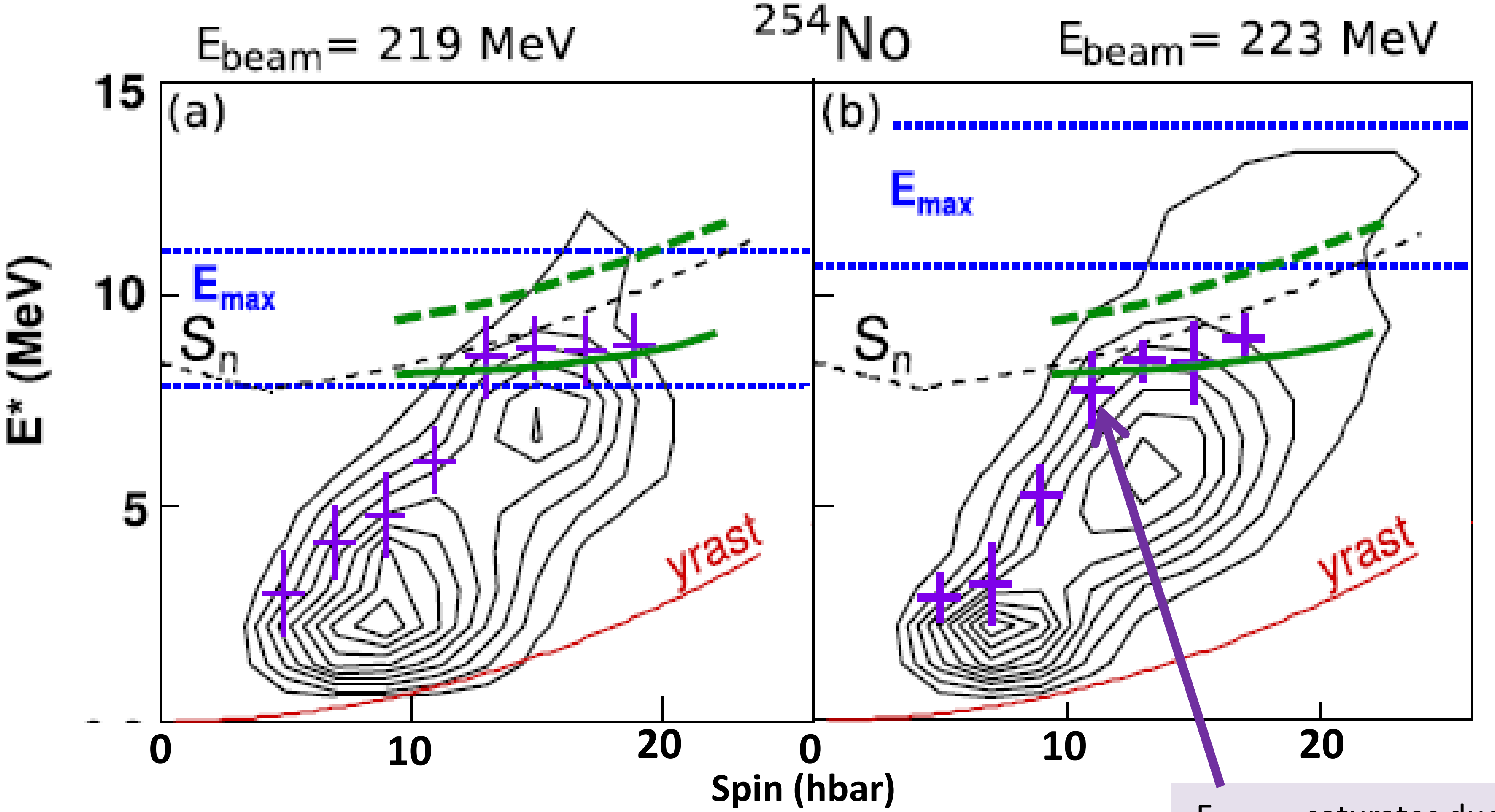
Fission barrier $B_f(I)$ by measuring limits of γ-emitting region



Black swan cometh!

Region where $\Gamma_f >> \Gamma_\gamma$;
no γ competition.

Region where $\Gamma_\gamma > \Gamma_f$;
γ decays wins &
nucleus survives fission.



$E_{1/2max}$; saturates due to fission cut-off

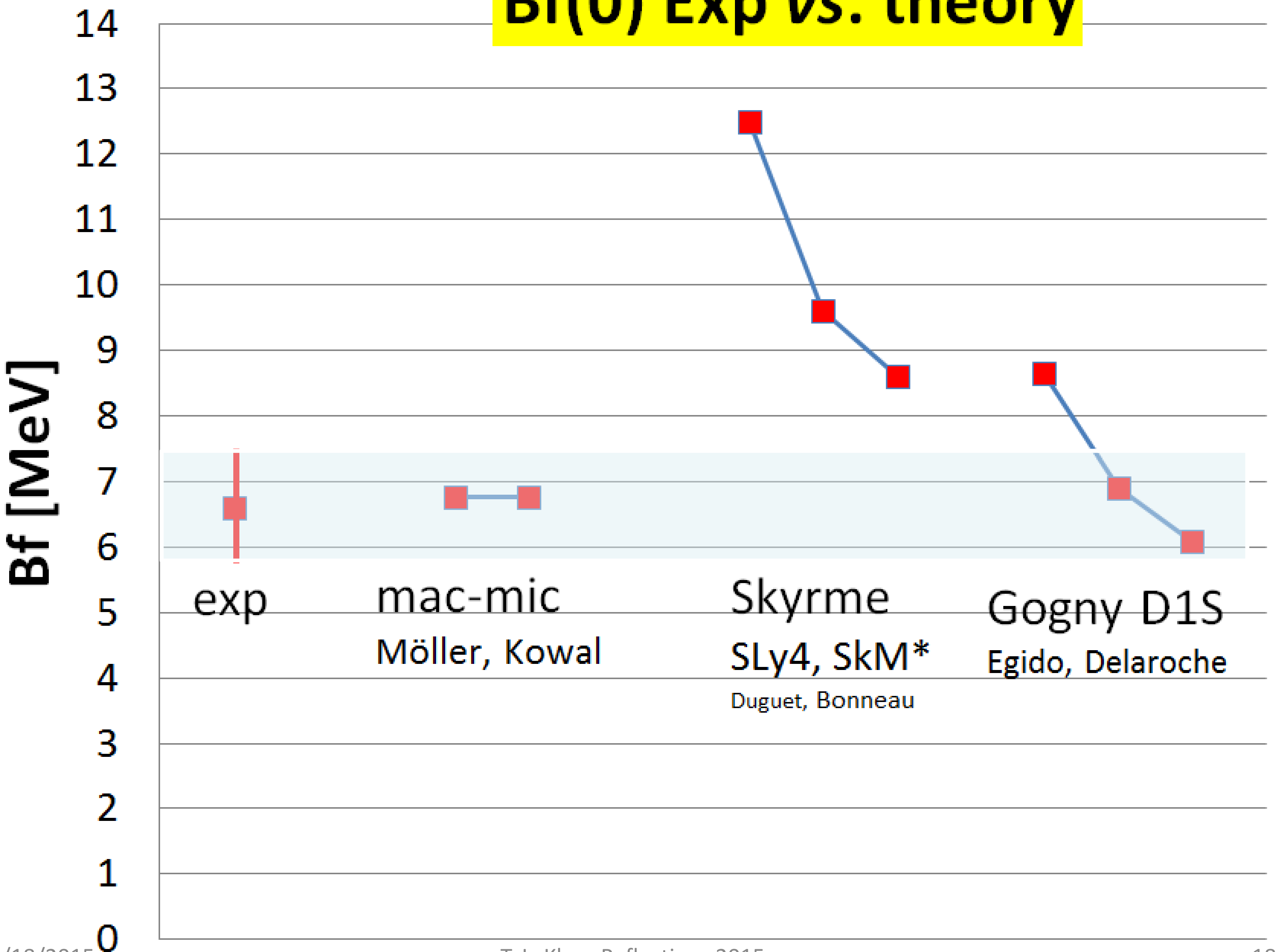
γ calorimetry with Gammasphere → entry distribution

Measure $E_{saddle}(I)$, $B_f(I)$ by inspecting where, in excited states of ^{254}No, fission dominates γ decay and truncates the entry distribution.

$B_f(I\sim15) = 6.0(5)$ MeV.

G. Henning et al., PRL 113, 262505 (2014)

Bf(0) Exp *vs.* theory



SHN formed at high spin.
No yield at *l* = 0.
If $E_{shell}(I)$ ~0, no SHE.

$\sigma(l)$ ^{254}No

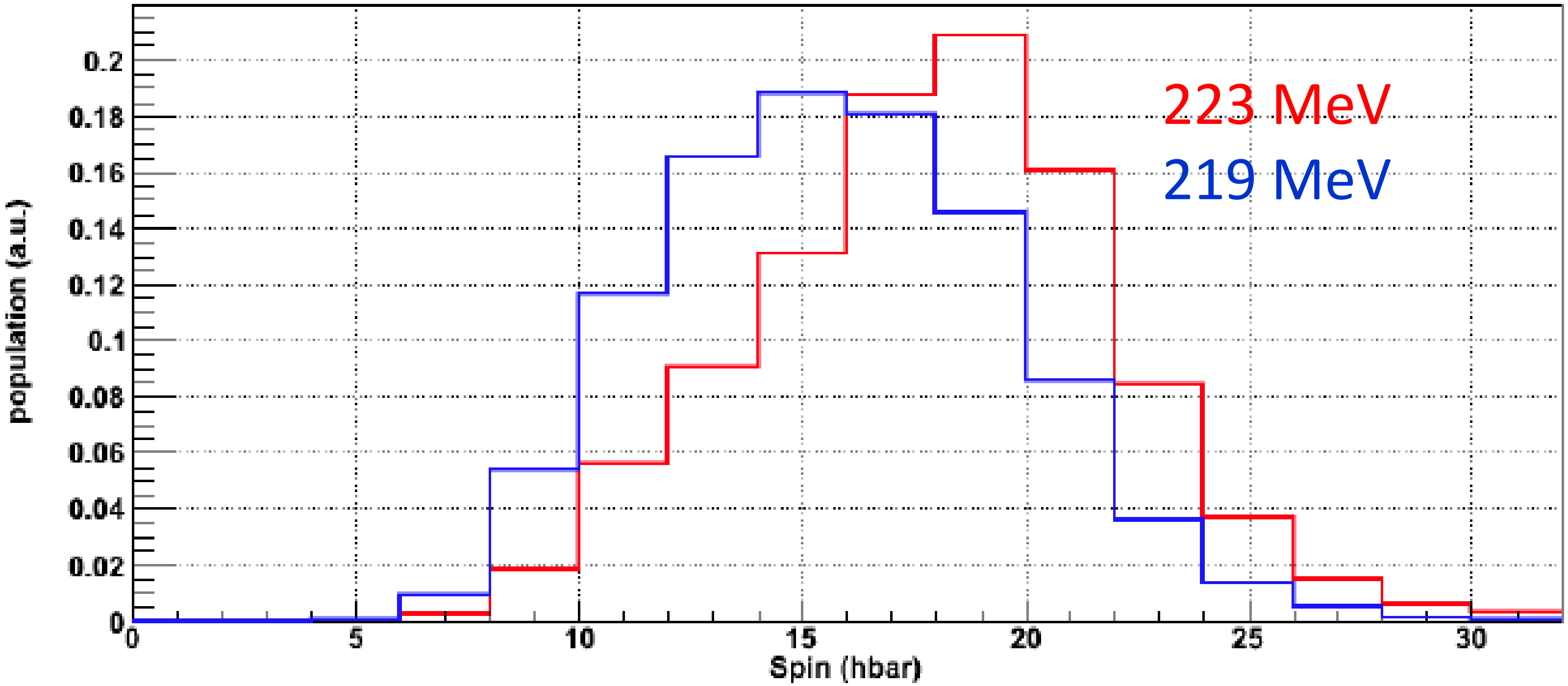
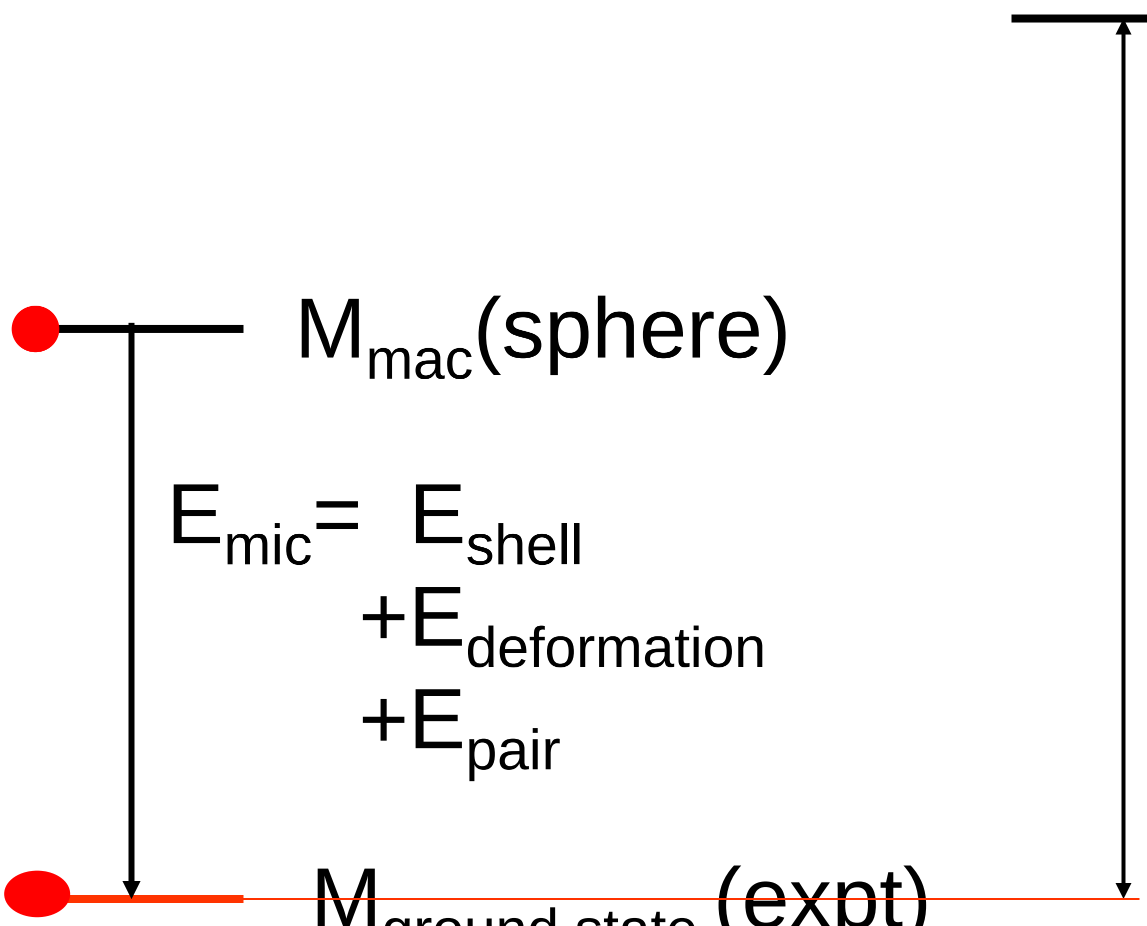


Figure 6.4: Spin distribution profile for $E_{\mathrm{Beam}} = 219$ MeV recoil gated (blue) and $E_{\mathrm{Beam}} = 223$ MeV recoil gated (red).

structure/reaction
B_f, $\sigma(l)$ ↔ formation mechanism.

G. Henning et al., Ph. D. thesis, U. Paris Sud

Ground-state shell energy



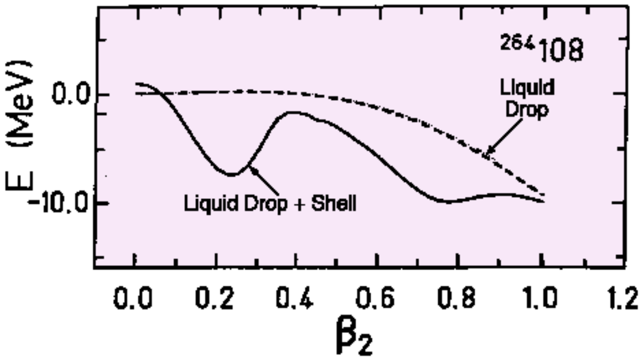
M_{saddle}

M_{mac}(sphere)

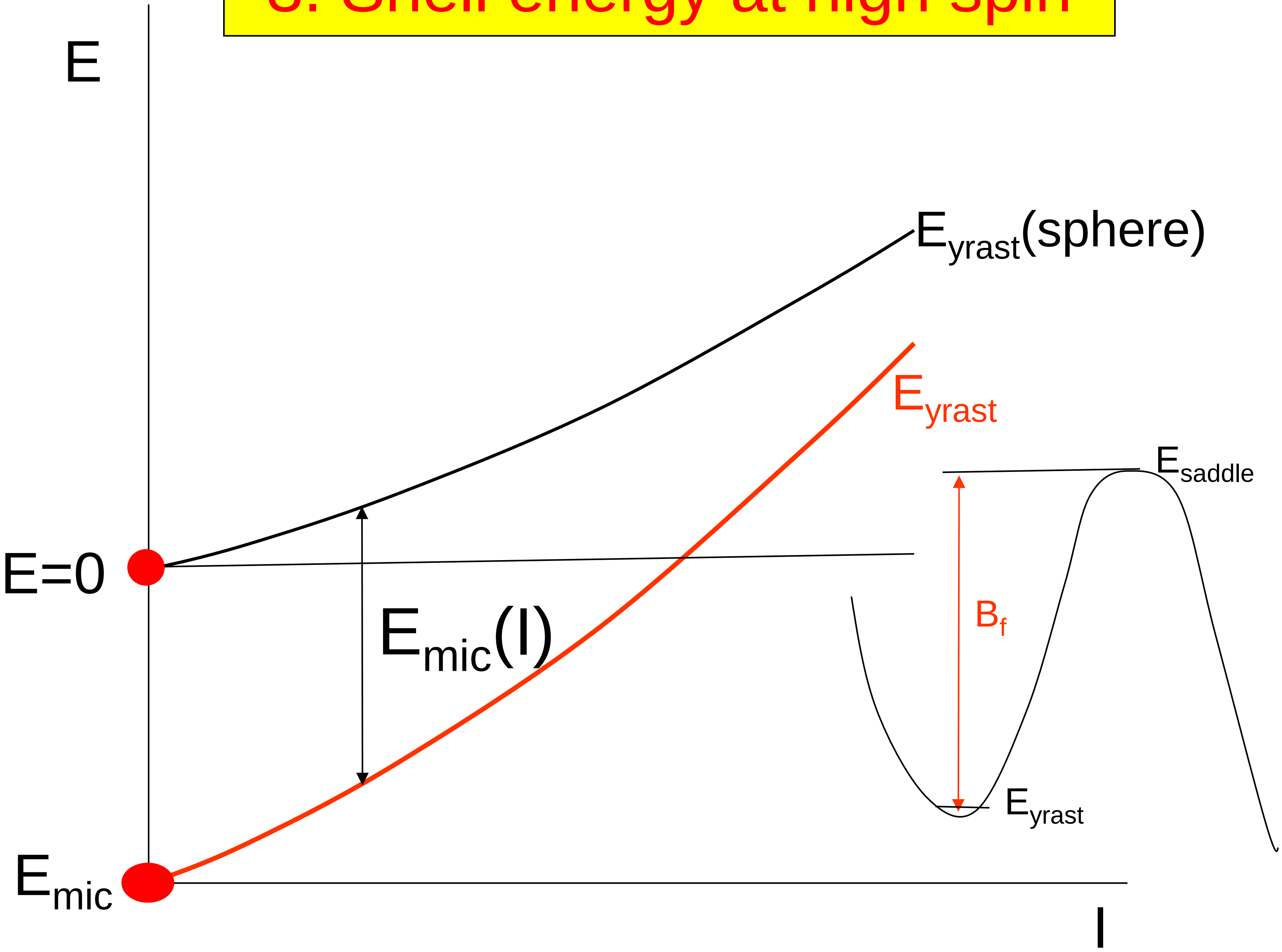
B_f fission barrier

$E_{mic} = E_{shell}$
$+E_{deformation}$
$+E_{pair}$

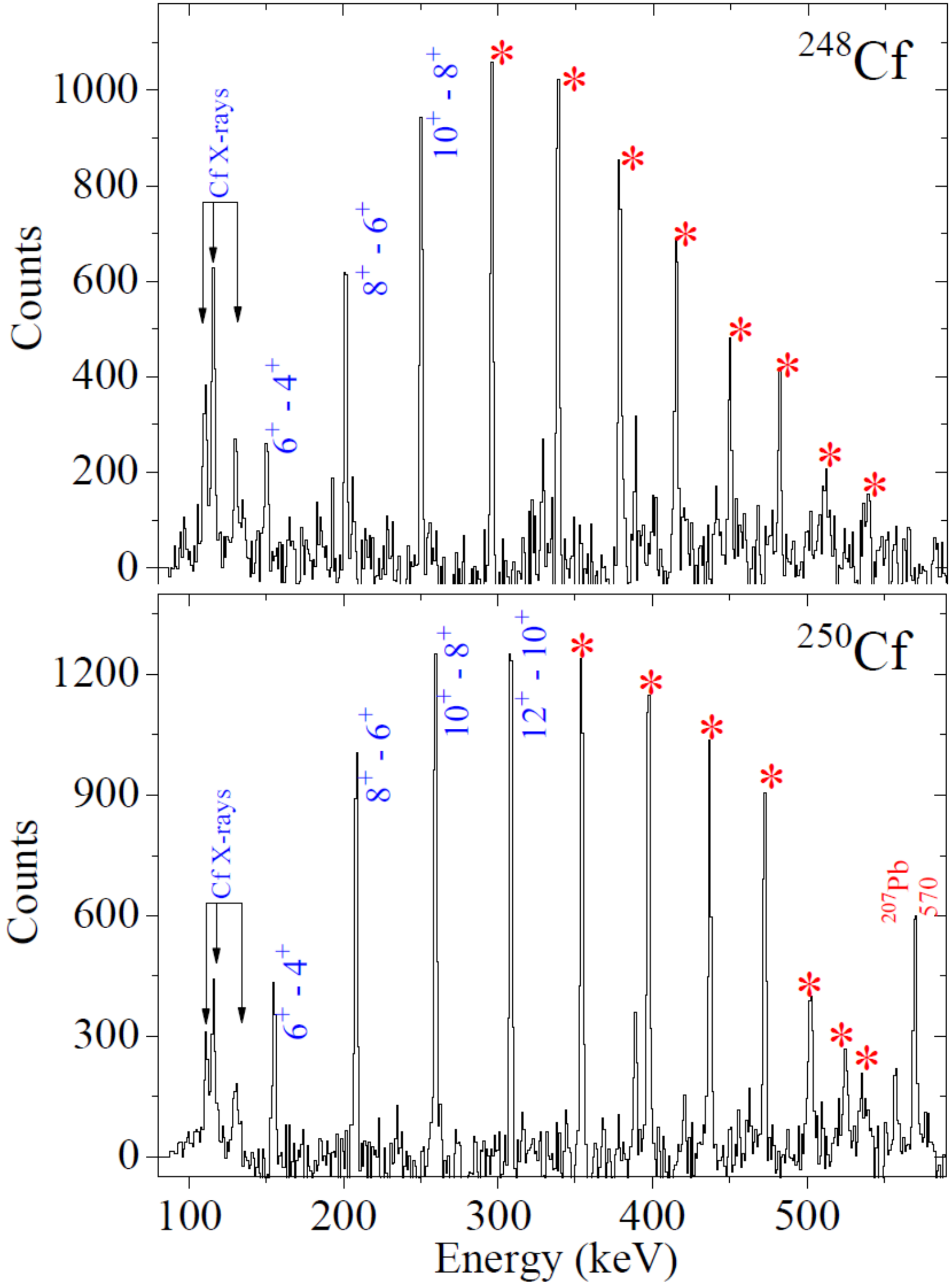
$M_{ground\ state}$ (expt)



3. Shell energy at high spin



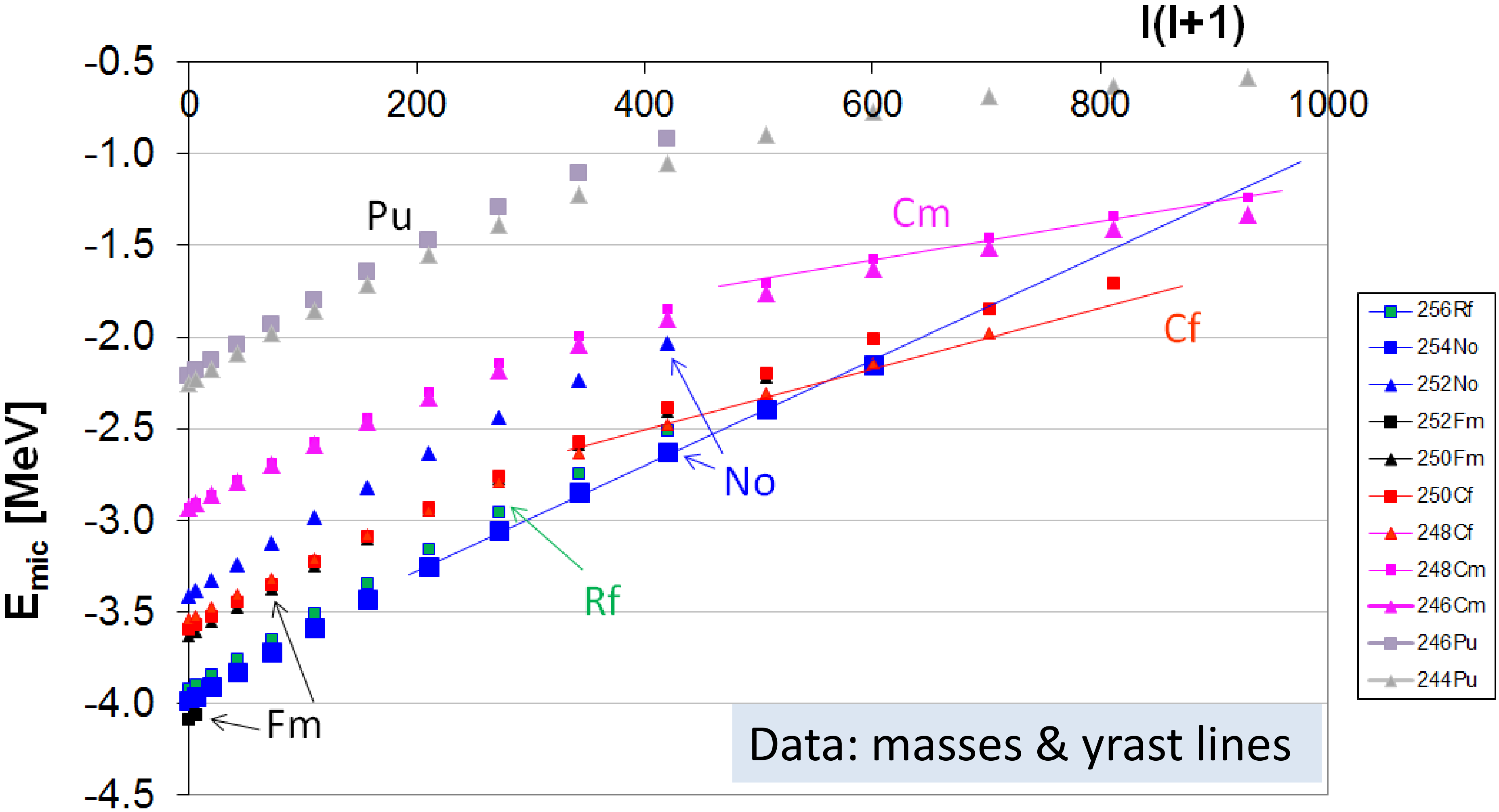
High spin states (I≤32) in ^{248,250}Cf from transfer reactions in ^{208}Pb + ^{249}Cf



S. Hota et al., U. Mass Lowell, Ph. D. thesis, ^{208}Pb + ^{249}Cf

E_{mic} vs. $I(I+1)$

N =150, 152; Z = 94-104



Data: masses & yrast lines

- $E_{shell}(0)$ largest for ^{252}Fm due to gaps at Z=100, N=152
- E_{mic} decreases with I.
- Rate of decrease depends on moment of inertia, backbend.
- For I ≥ 24, E_{shell} in ^{248}Cf is more negative than in ^{254}No.

- No calculation yet which simultaneously describes g.s. and yrast mass at high spin.

Summary
Theoretical description of SHN

A good model should describe **all** properties:

- single-particle spectra (proton and neutron gaps),
- $E_{shell}(I)$,
- masses of ground &saddle states,
- fission barriers.

Microscopic-macroscopic models (with WS or folded Yukawa potentials) almost satisfy this criterion.

DFT is limited by the hunt for a good effective interaction.

SHN robust & *populated predominantly at high spin*.

collaborators

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The end!

- Thank you for your attention.
- Thank ye.
- Diolch i chi.
- Go raibh maith agaibh.

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