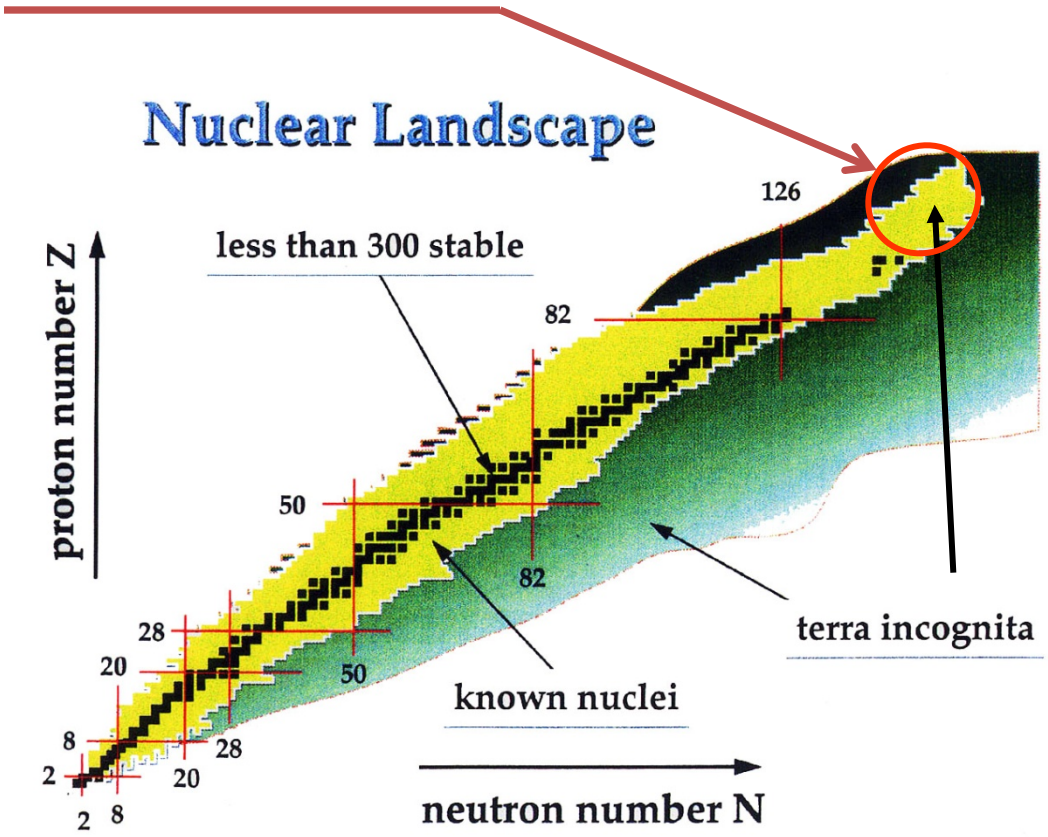
Stability of superheavy nuclei at high spin: shell energy, fission barrier, & single-particle spectrum

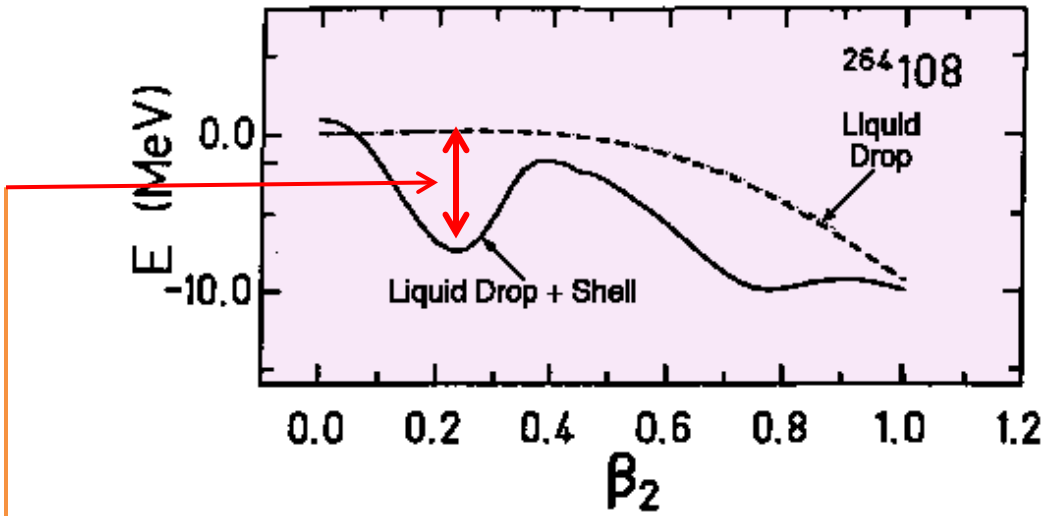
T. L. Khoo, Argonne National Laboratory

Pb heaviest stable element

Extension beyond last stable element
104/82=1.27
118/82=1.44

Opportunity to study nuclei at *3 simultaneous limits of Z, I, E**





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

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

Superheavy nuclei are ***at the limits of Coulomb stability***;
would fission instantaneously,
but ***shell-correction energy*** lowers the ground state, thereby creating a ***barrier against fission.***

Extra binding from $\mathbf{E_{shell}}$ &

fission barrier, $\mathbf{B_f} = E_{saddle} - E_{gs}$, enable existence of SHN.

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

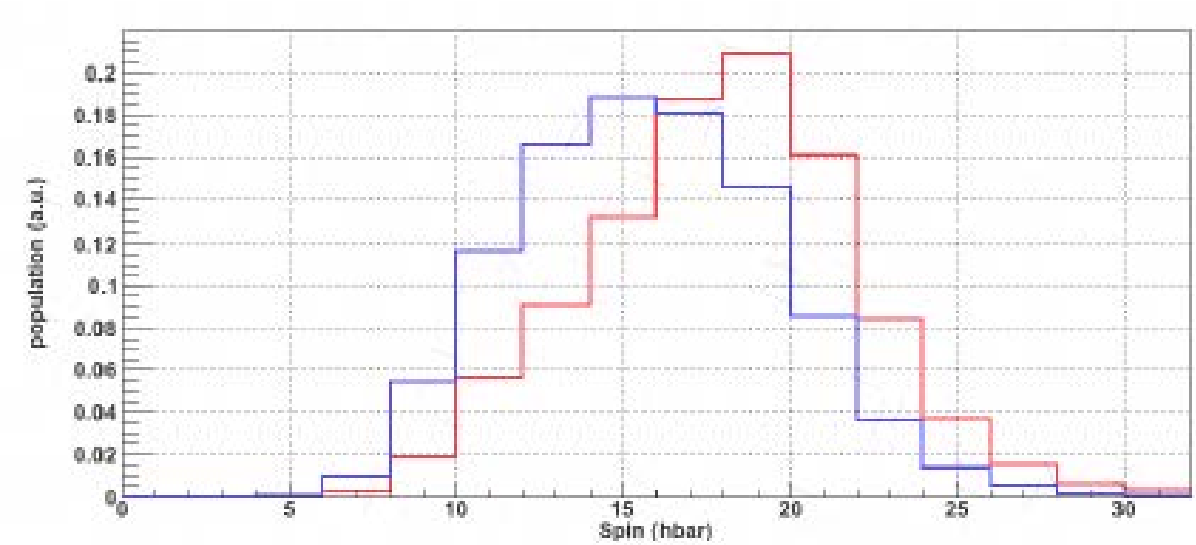
All properties can, in principle, be calculated once the spectrum is established.

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

Why are high-spin properties important?

- *If E_{shell} were to disappear at finite spin I, we would not be able to make SHN!*
- *The bulk of σ(ER) at high I.*
- Not so long ago, experts believed that SHN could exist at only low (zero) spin.

σ(*I*)



G. Henning *et al.*

Shell energy E_{shell} at high spin I

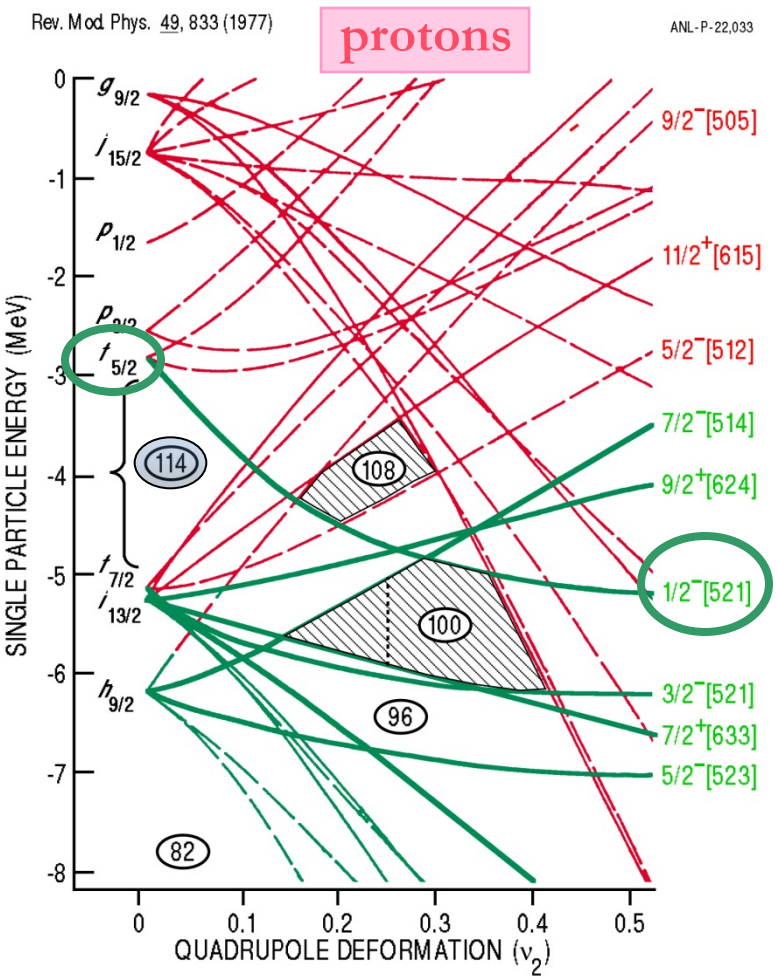
- Search for ever heavier superheavy nuclei[a]: an exciting (& glamorous) frontier in nuclear physics.
- The underlying physics: *how E_{shell} persists at large Z[b], i.e.* ***$E_{shell}(Z)$***. Magic numbers of SHN?
- $E_{shell}(I,Z,N)$ → more insight. Tests theory as function of several variables, is sensitive to shell gaps and alignments of high-*j* orbitals.

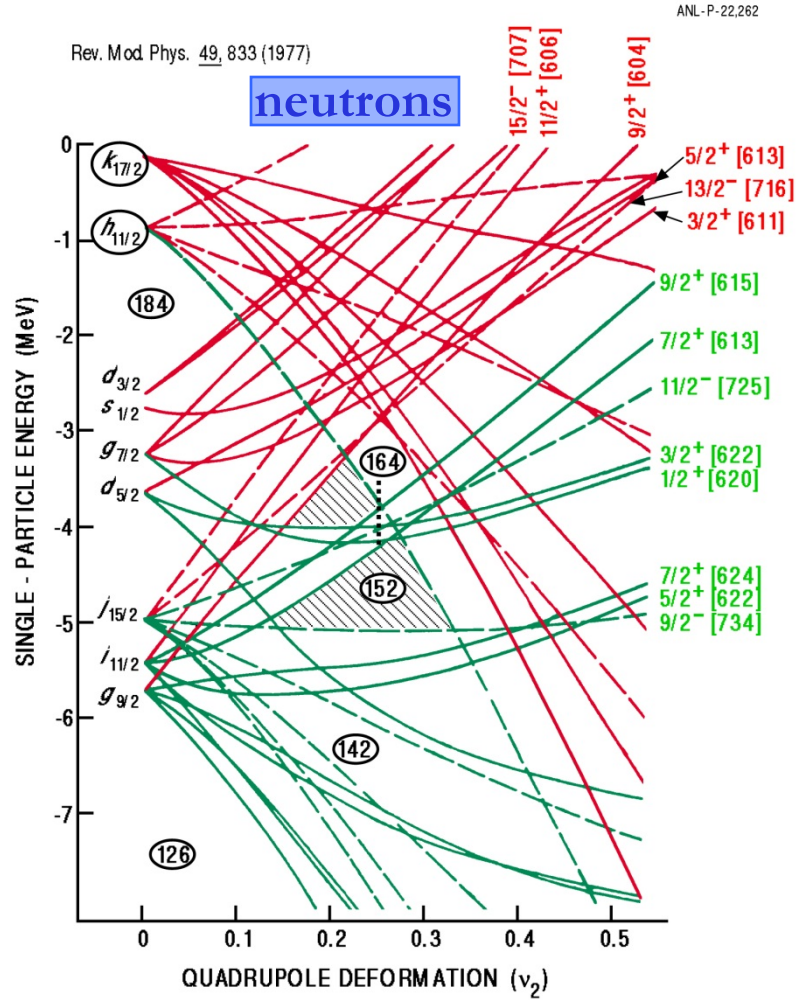
[a]Oganessian, Stoyer NS12 talks; [b]Henning NS12 poster, "Z from X rays?".

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)



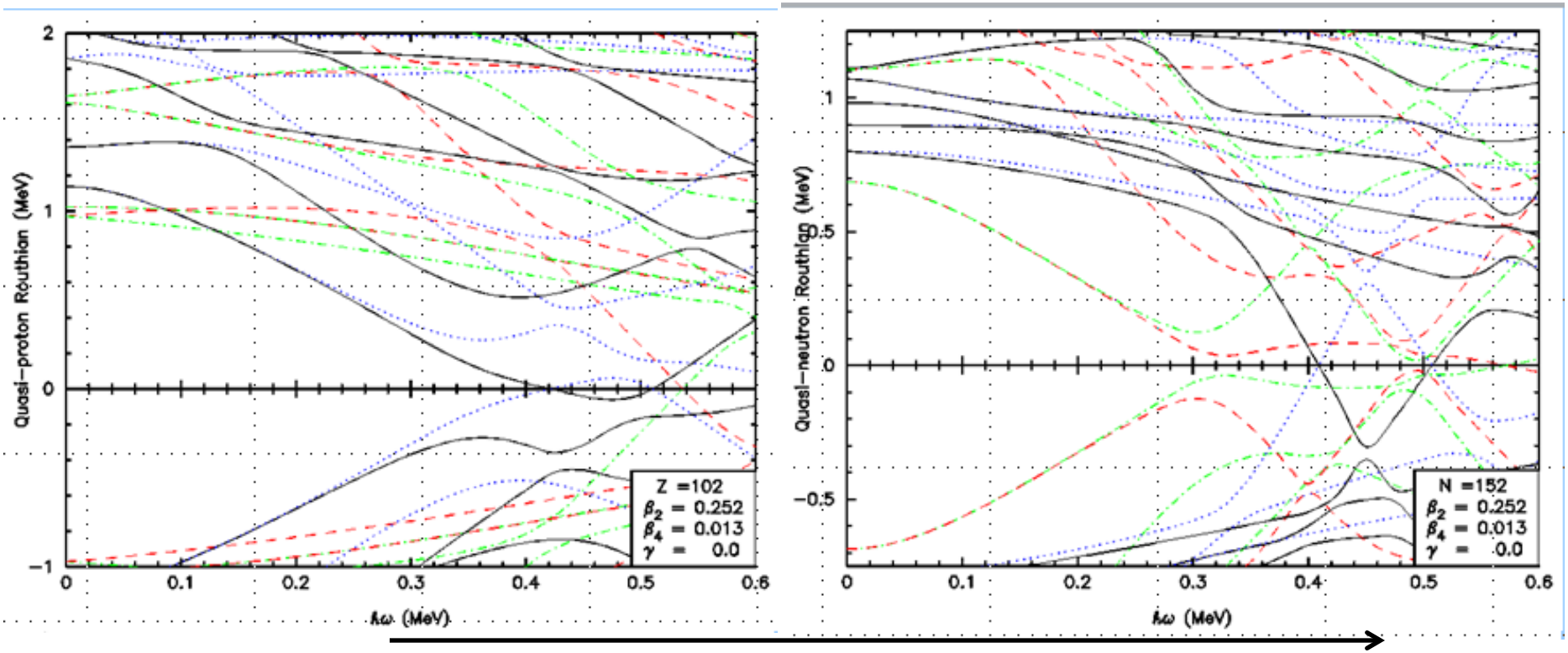


R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

Rotation decreases E(qp)

especially for high-j orbitals

protons ^{254}No neutrons



β_2, β_4, β_6 from energy minimization

frequency ħΩ (MeV)

Courtesy M. P. Carpenter

Summary of recent results (very brief)

- *In beam spectroscopy*

a. **Rotational bands** up to I ~ 32 in Pu, Cm, Cf[a], Fm, Md, No, Lr, Rf[b] (Z = 94 – 104); fusion, inelastic & transfer reactions.

a. **Entry distributions in (I, E)**, the starting distribution of γ decay to ground state.

b. **Nuclei deformed** with rotational bands.

c. **Survive to high spin (I~>24)** , where the bulk σ(EvapResidue) lies in fusion reactions.

- *Decay spectroscopy*

a. **High-K isomers** (2-, 4- & 6-qp); hindrance by K selection rules.

b. **Nuclei prolate & axially symmetric**, with **good K** quantum number.

c. **Theory predicts b.**

d. **Energies of 1, 2-qp states test & discriminate** among models.

[a.] Hota et al, NS12 talk; [b.] Greenlees et al, NS12 talk.

Ground-state shell energy

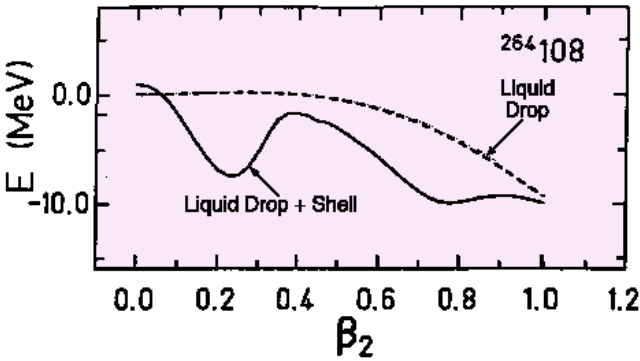
M_{saddle}

M_{mac}(sphere)

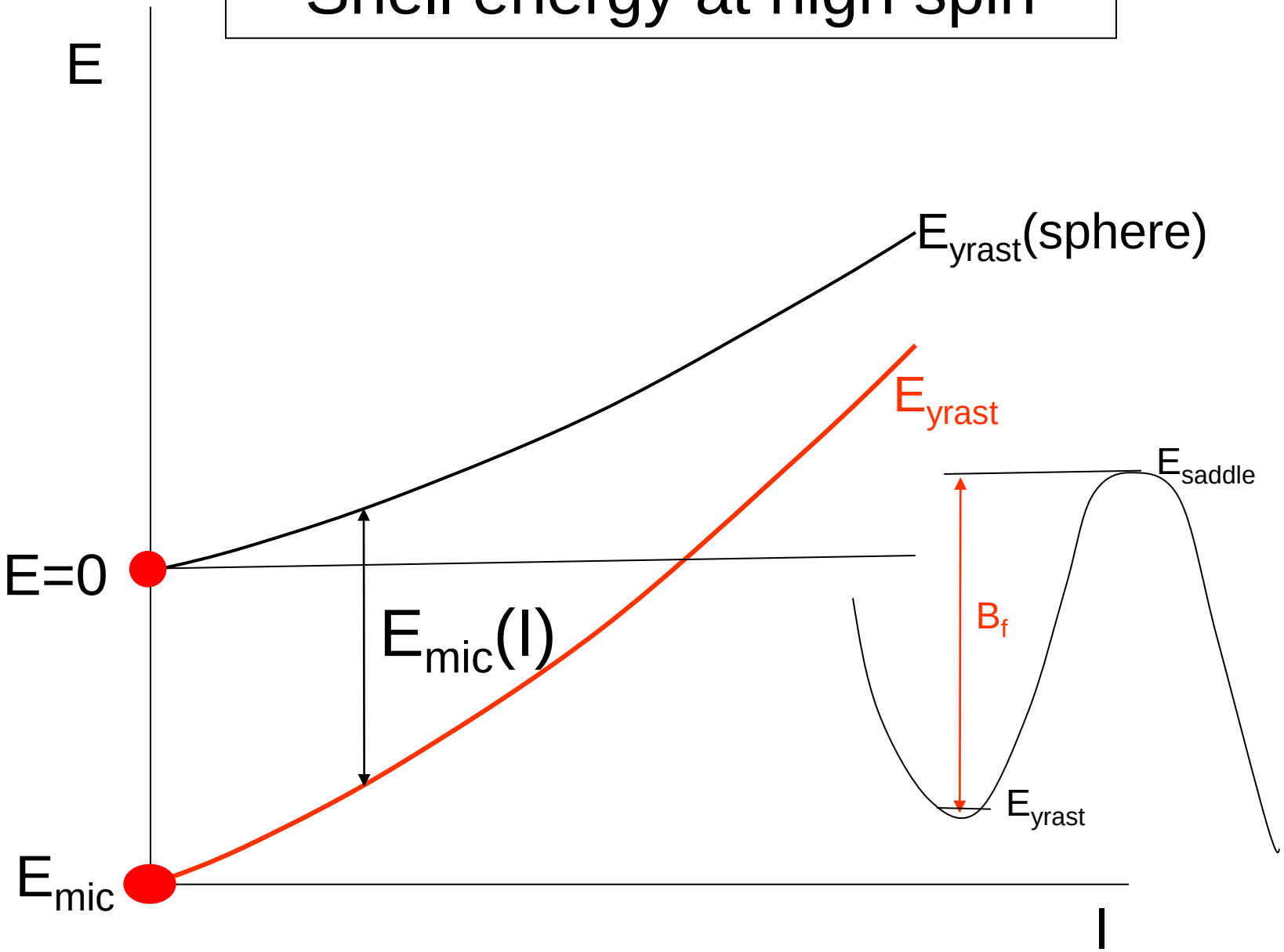
B_f fission barrier

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

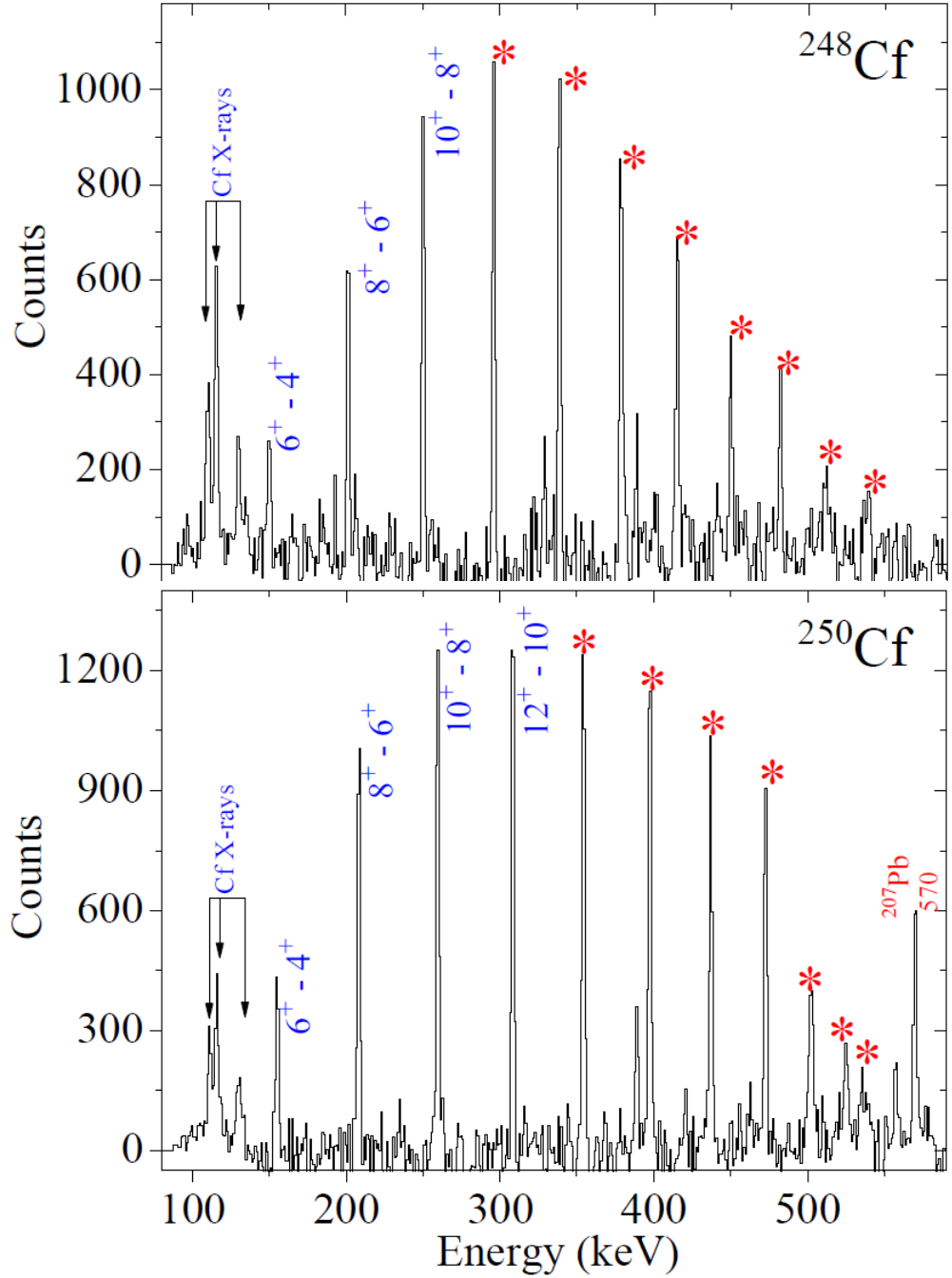
$M_{ground\ state}$ (expt)



Shell energy at high spin



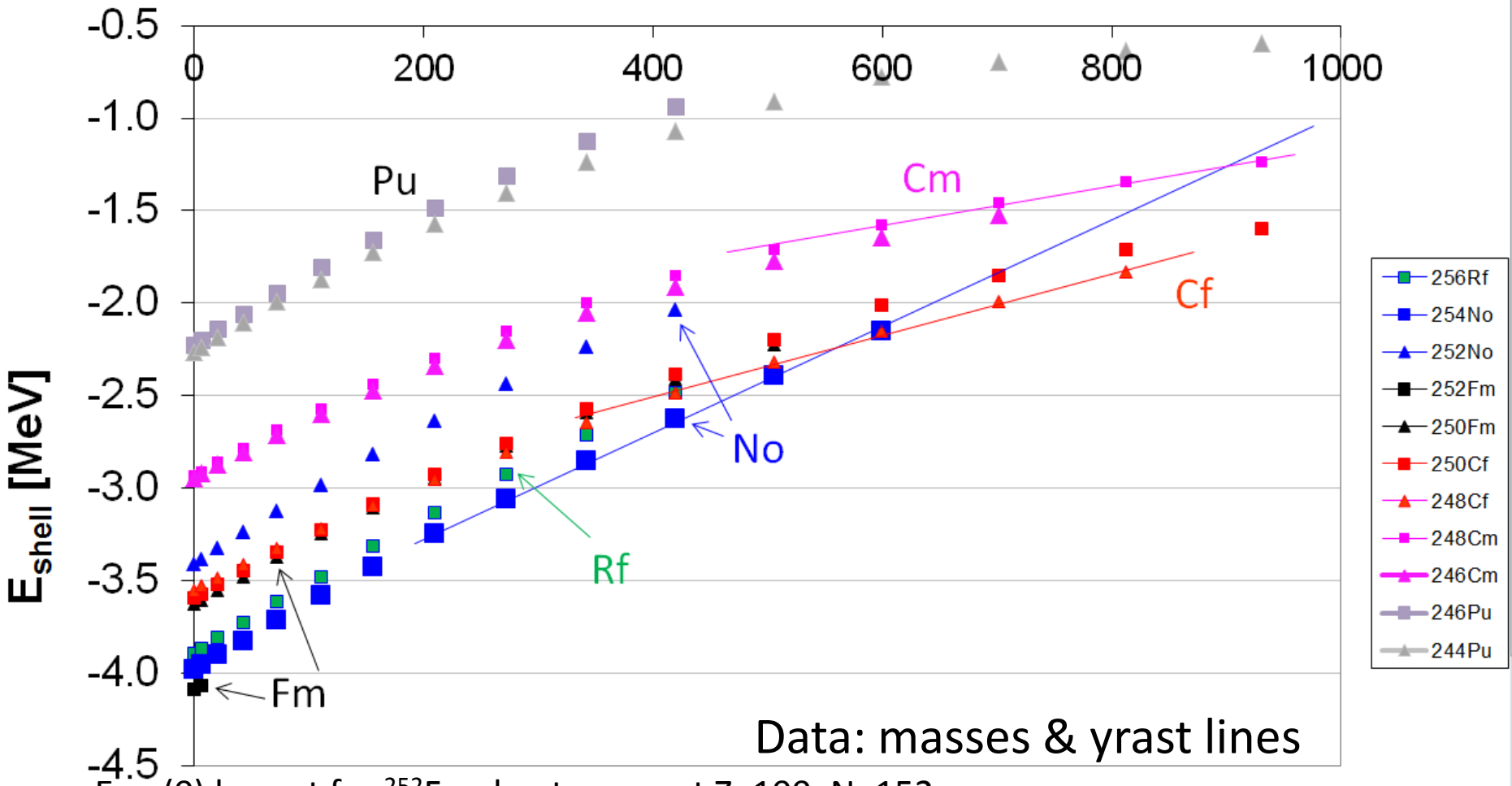
High spin states (I≤32) in ^{248,250}Cf from transfer reactions in ^{208}Pb + ^{249}Cf



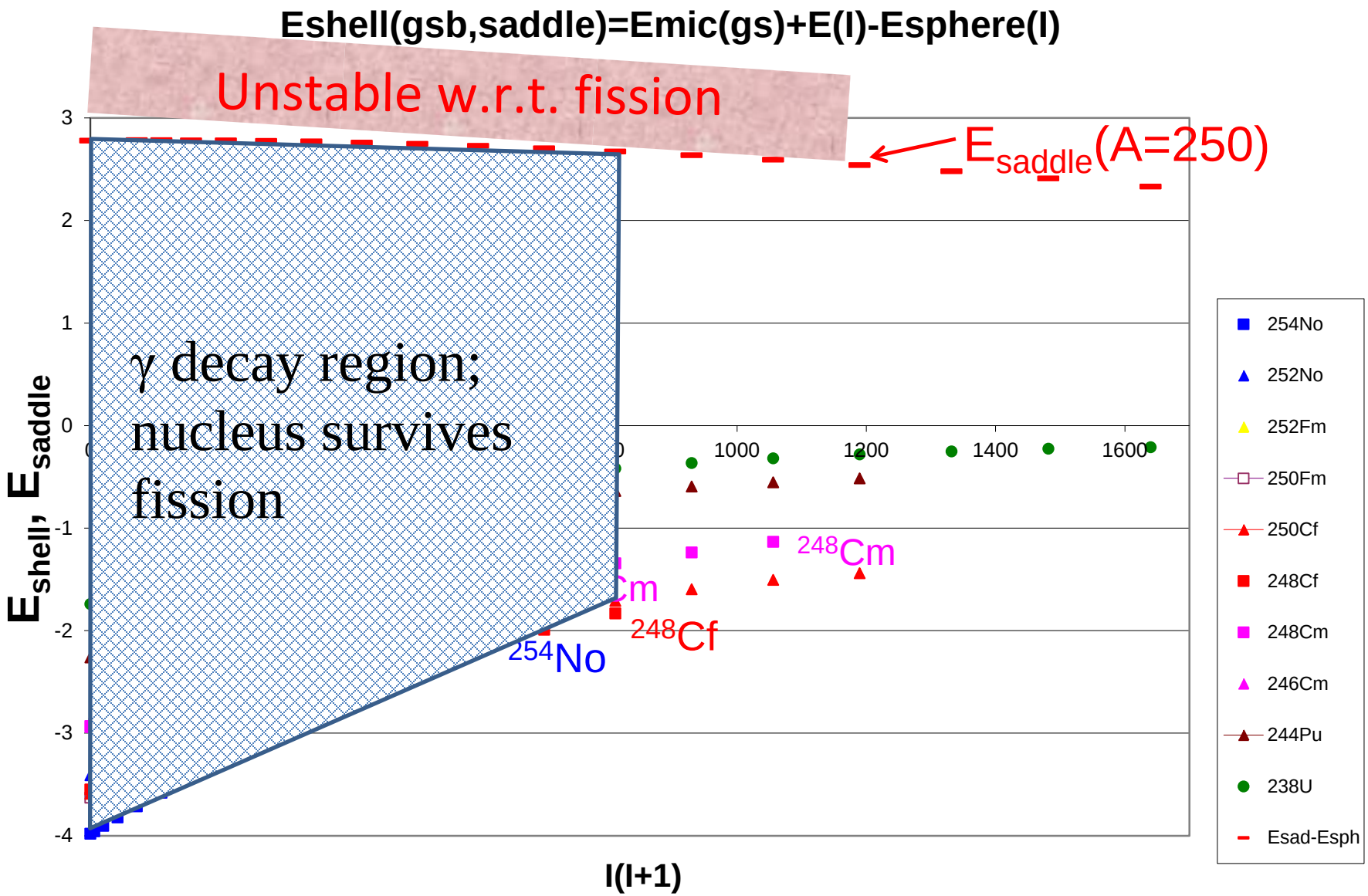
S. Hota et al., U. Mass Lowell, Ph. D. thesis, ^{208}Pb + ^{249}Cf

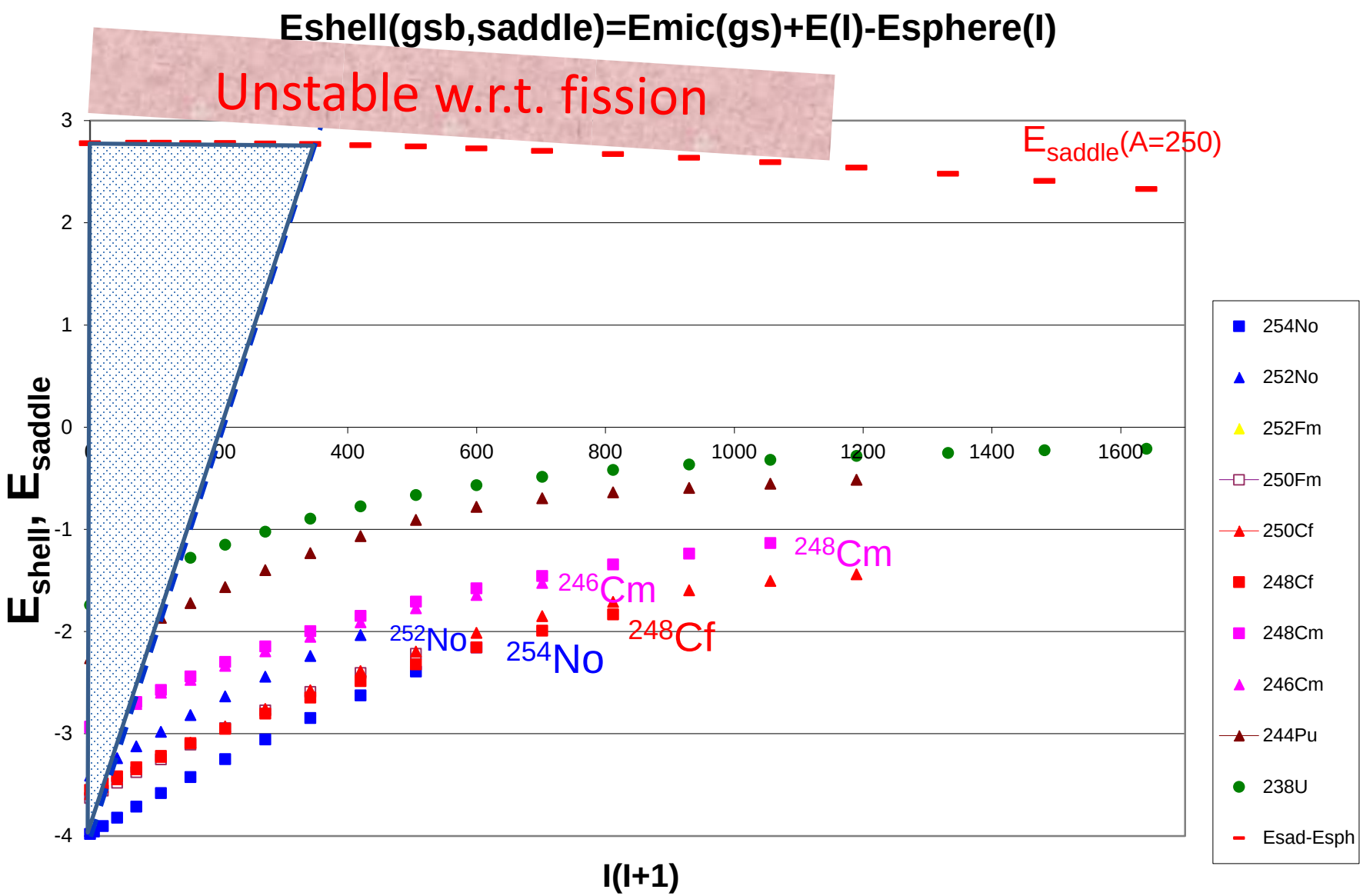
E_{shell} *vs.* I(I+1)

N =150, 152; Z = 94-104



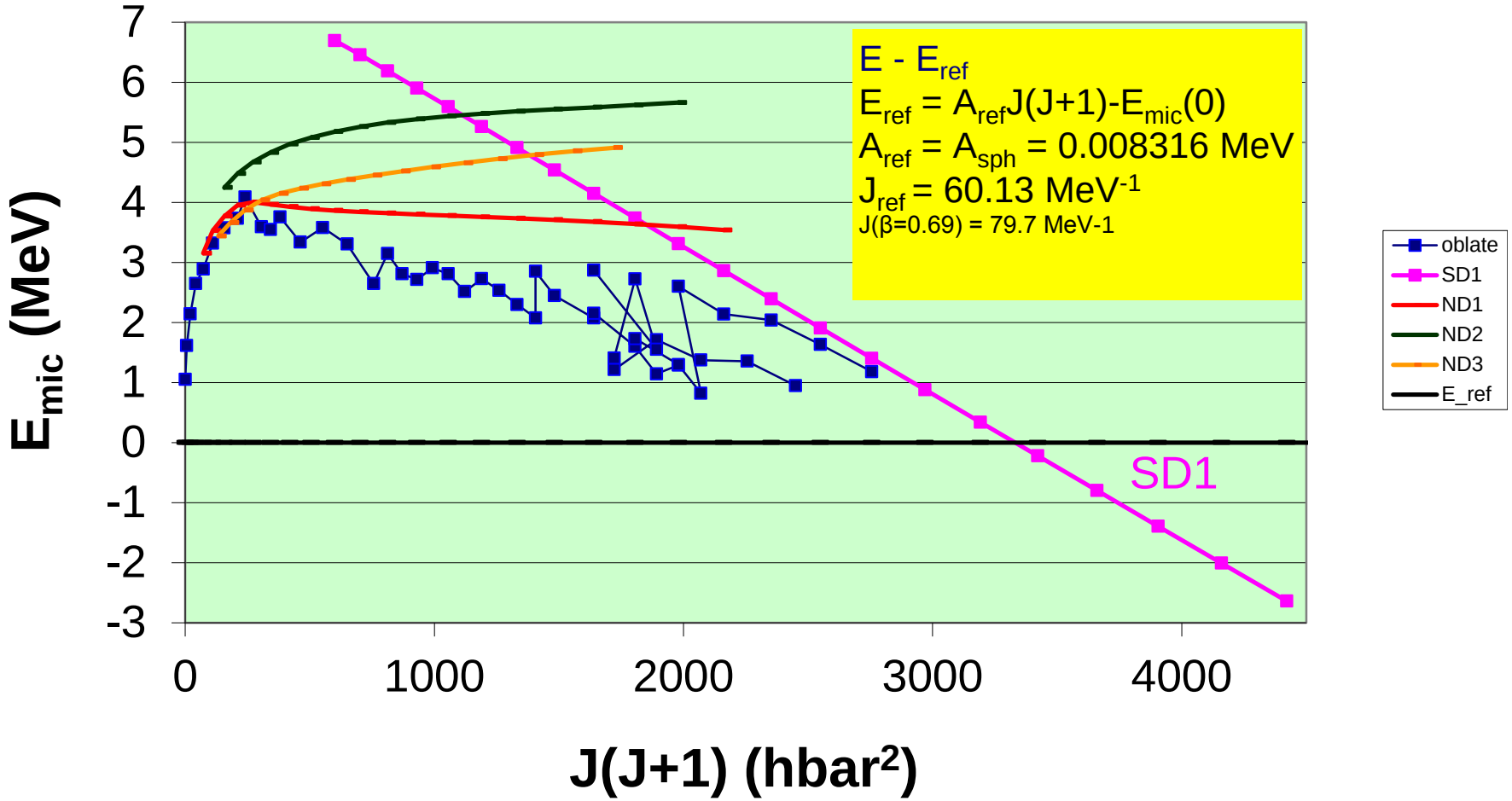
- $E_{shell}(0)$ largest for ^{252}Fm due to gaps at Z=100, N=152
- E_{shell} decreases with I.
- Rate of decrease depends on moment of inertia, backbend.
- For I ≥ 24, E_{shell} in ^{248}Cf has more negative than ^{254}No.


Eshell(gsb,saddle)=Emic(gs)+E(I)-Esphere(I)
Unstable w.r.t. fission
E_{saddle}(A=250)
γ decay region;
nucleus survives
fission
E_{shell}, E_{saddle}
I(I+1)
3
2
1
0
-1
-2
-3
-4
1000
1200
1400
1600
^{248}Cm
^{248}Cf
^{254}No
254No
252No
252Fm
250Fm
250Cf
248Cf
248Cm
246Cm
244Pu
238U
Esad-Esph

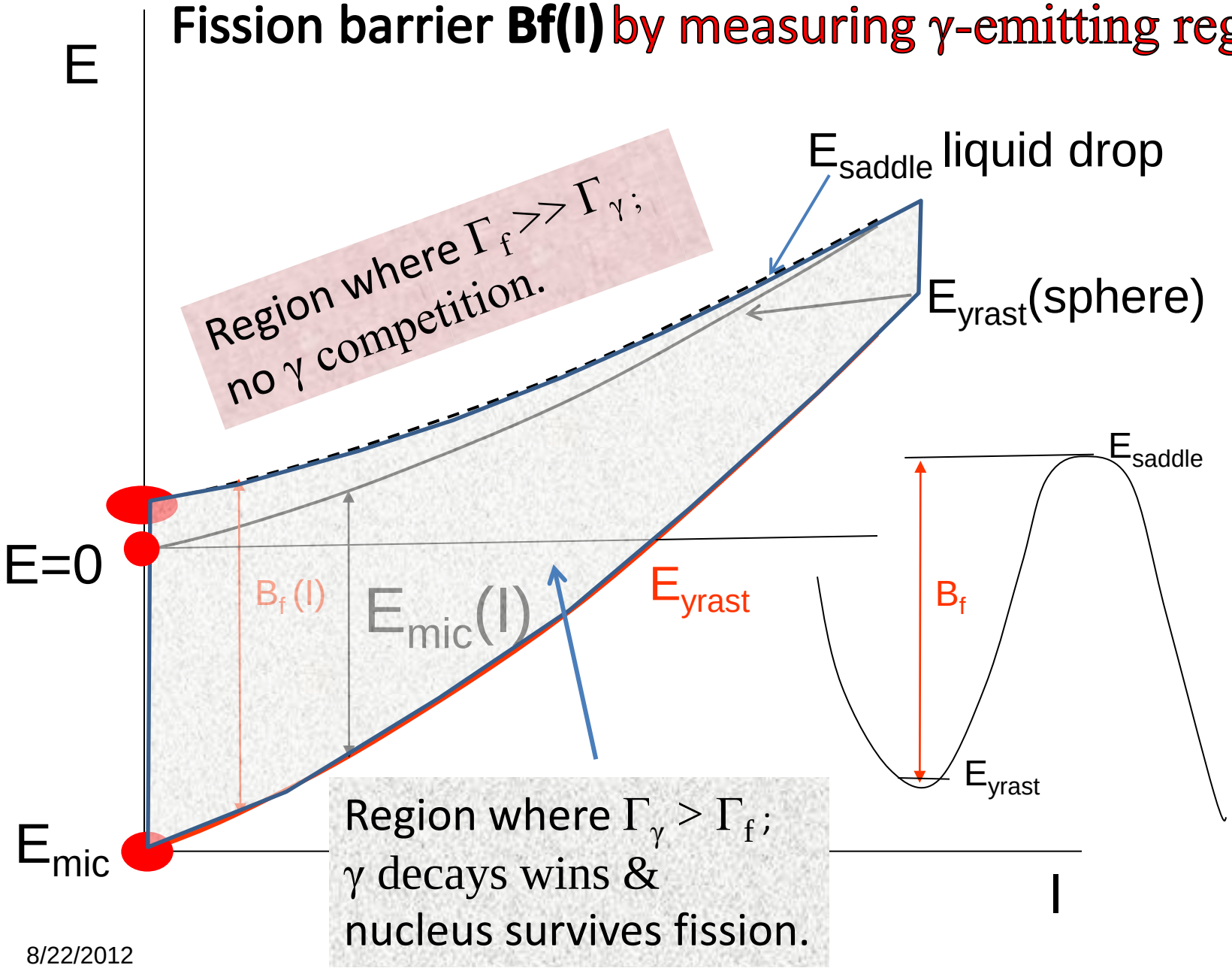

Eshell(gsb,saddle)=Emic(gs)+E(I)-Esphere(I)
Unstable w.r.t. fission
Esaddle(A=250)
Eshell, Esaddle
I(I+1)
3
2
1
0
-1
-2
-3
-4
400
600
800
1000
1200
1400
1600
252No
254No
246Cm
248Cf
248Cm
254No
252No
252Fm
250Fm
250Cf
248Cf
248Cm
246Cm
244Pu
238U
Esad-Esph

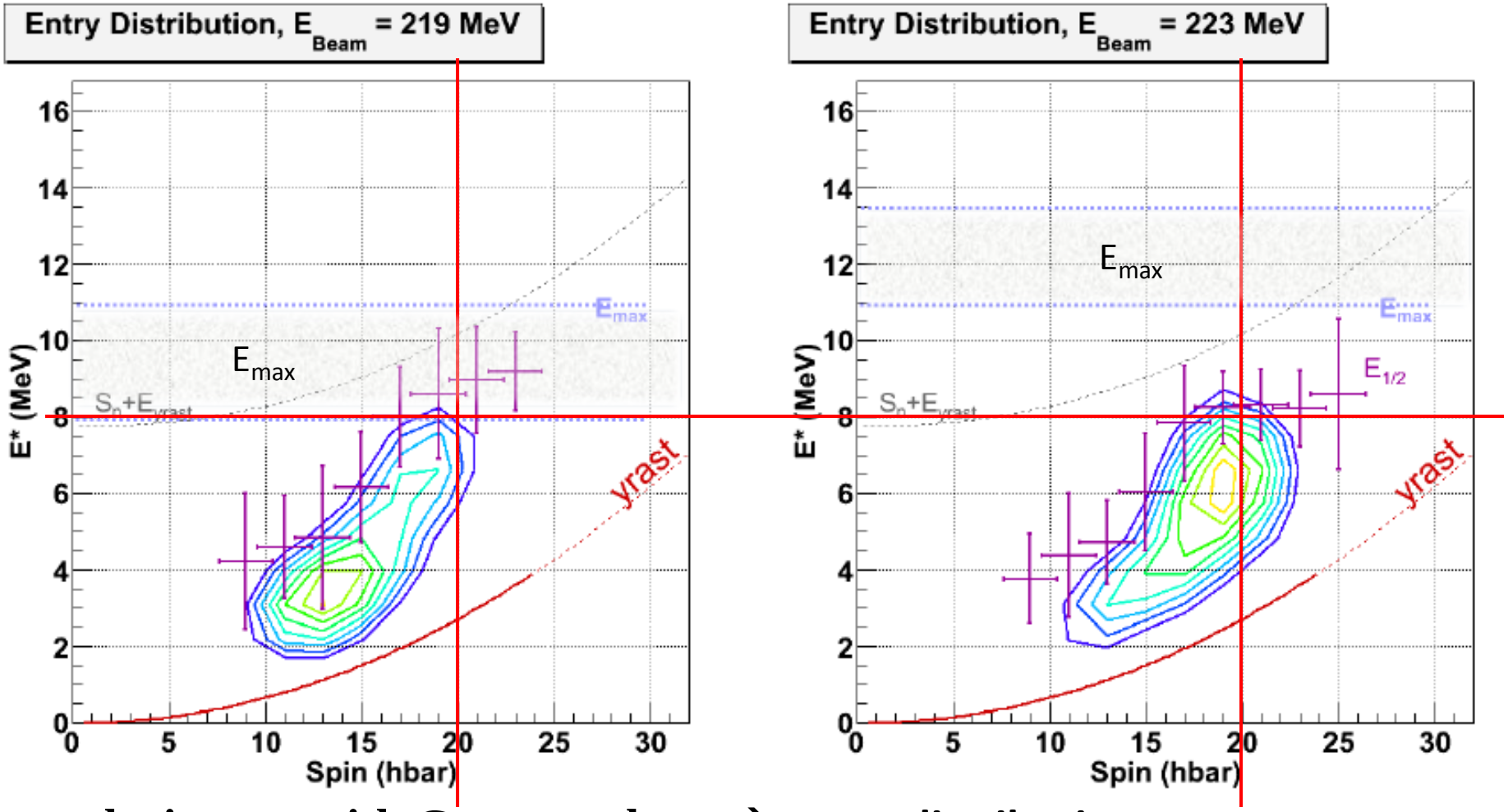
SD minimum gains E_{shell} at high I.

^{152}Dy $E_{mic}(J) = E_{mic}(0) + E(J) - E_{sph}(J)$



Fission barrier **Bf(I)** by measuring γ-emitting region





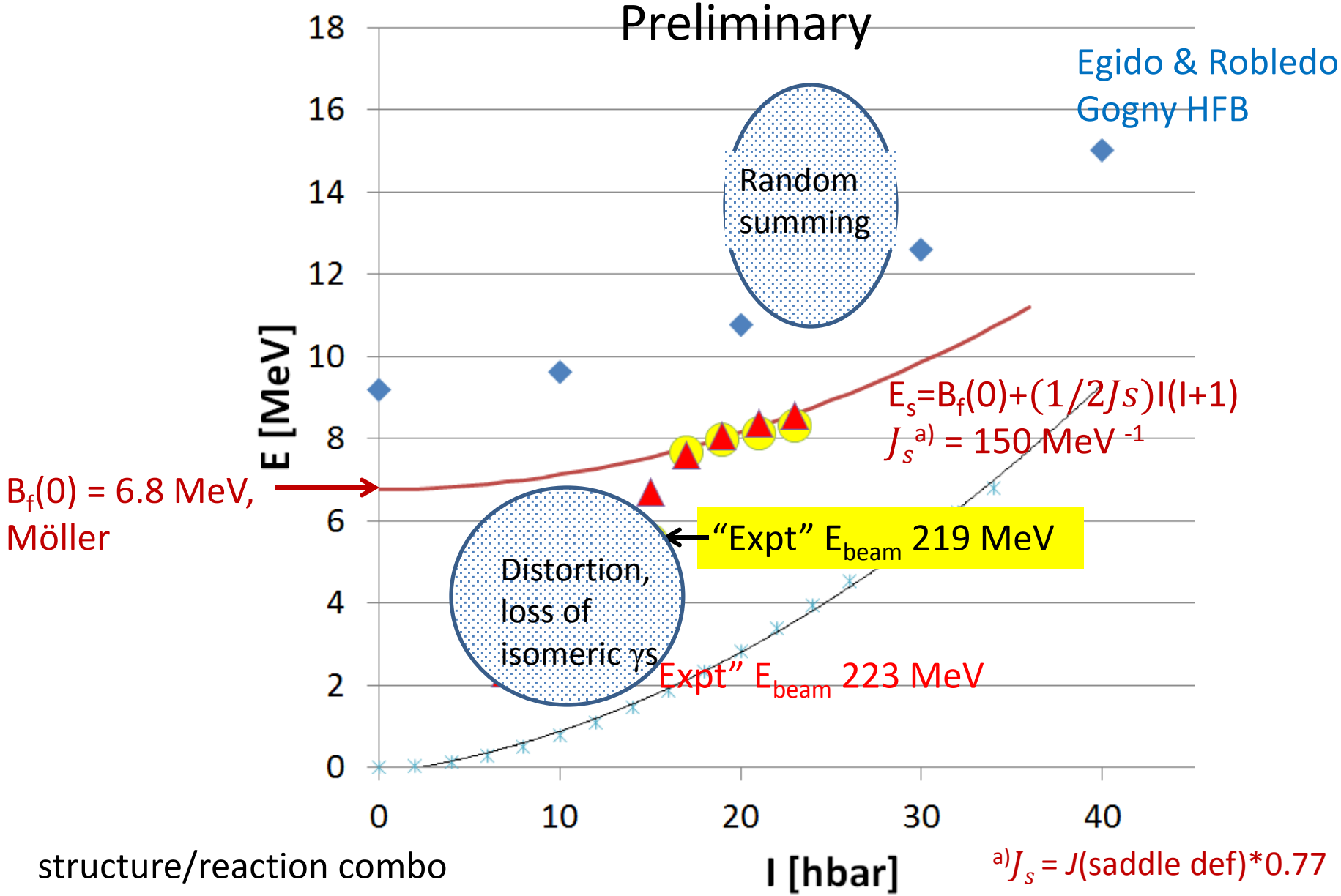
γ calorimetry with Gammasphere → entry distribution

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.

$B_f(I{\sim}20) \sim 5$ MeV.

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

E_{saddle} vs. I
Preliminary



structure/reaction combo

a) J_s = J(saddle def)*0.77

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.

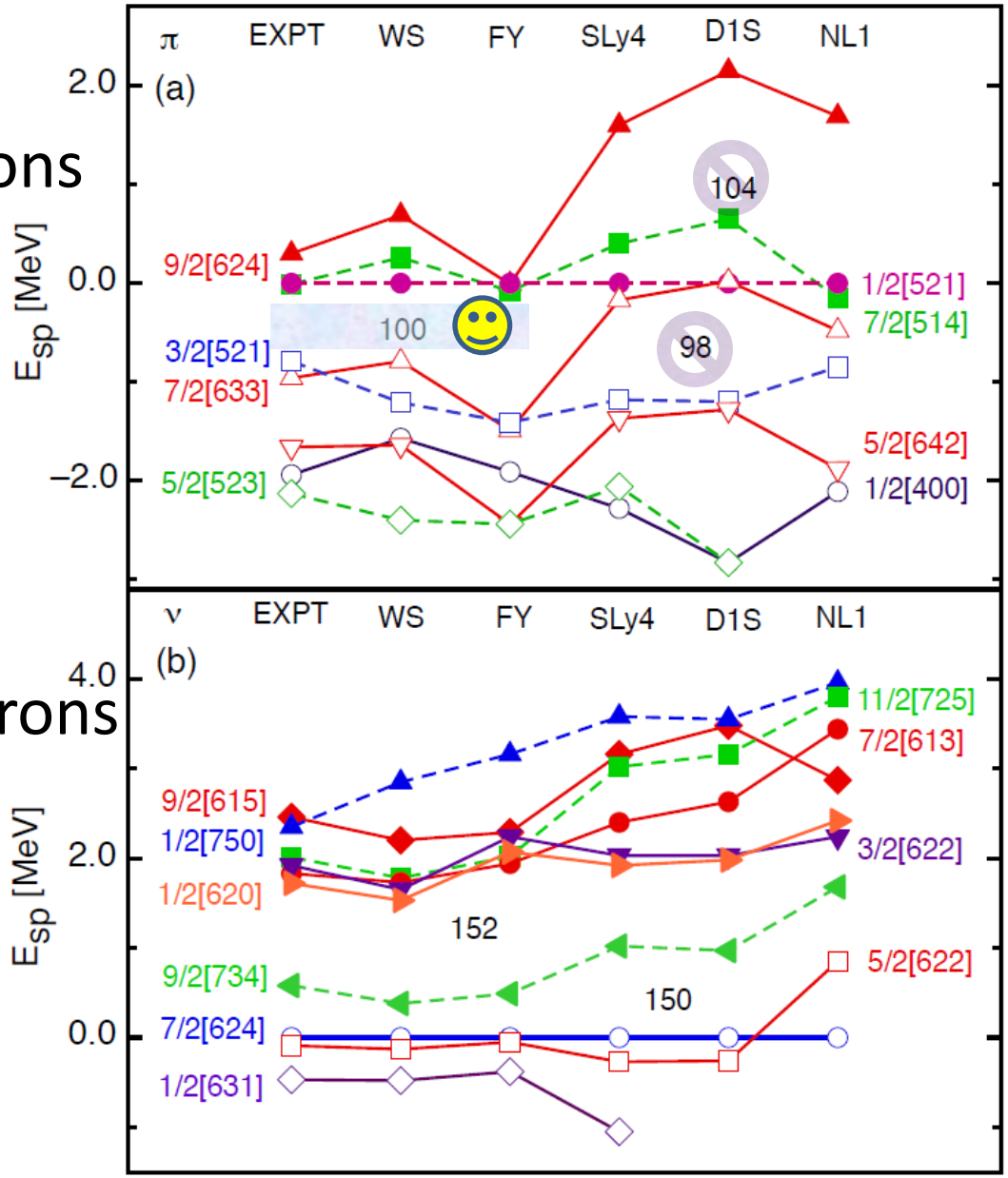
- Trial set of SPE.
- Calculate E(1qp), using LN procedure for pairing.
- Iterate until E(1qp) reproduce experiment.

E(2qp) provide complementary tests.

"EXPT" Woods Saxon Density Func Th

protons

neutrons



"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; reflected in S_{2n}, S_{2p}.

Spectroscopy, mass

Comments on theory

- DFT[a)] require improved effective interactions.
- Woods-Saxon (WS) potential gives reasonable (best) spe.
- Deformed orbitals originate from spherical shells, so energies interconnected.
- Different s.p. spectra due to different $E_{sph\ shell}$ → discrepant predictions of magic gaps at Z = 114 & ~~120,126~~ (from models which give wrong deformed gaps).
- Z = 114, N = 184 (~2.1 MeV from WS) most likely.

[a)] Afanasjev, NS12 talk

Summary

- E_{shell} (I) persists to high spin.
- Decreases by half at I ~ 26 hbar for deformed SHN.
- Nevertheless, B_f(I) survives to high spin.
- SHN robust & populated predominantly at high spin.
- Single-particle energies described by Woods Saxon potential, which suggests magic gaps at Z=114, N=184 (~2.1 MeV).

collaborators

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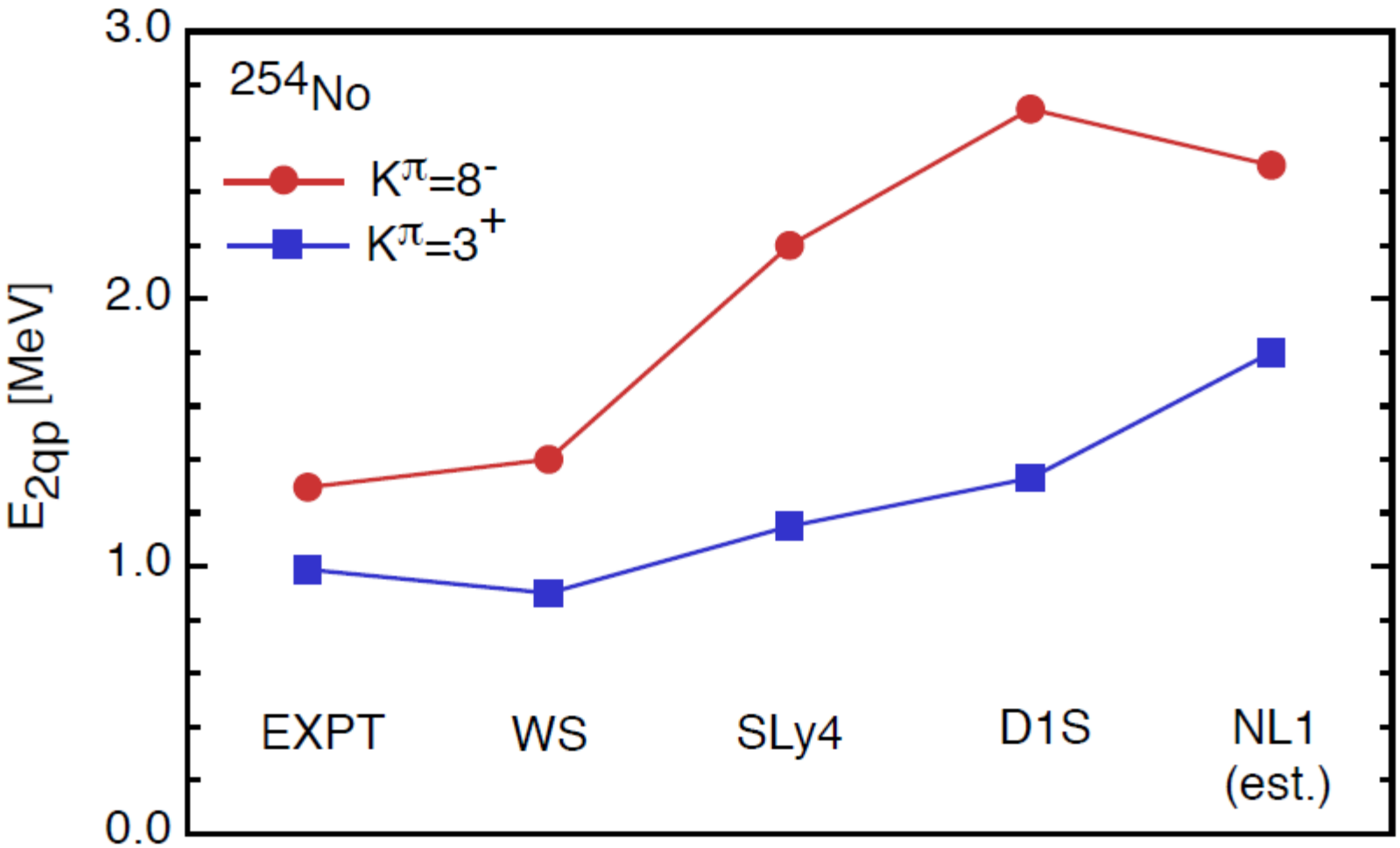
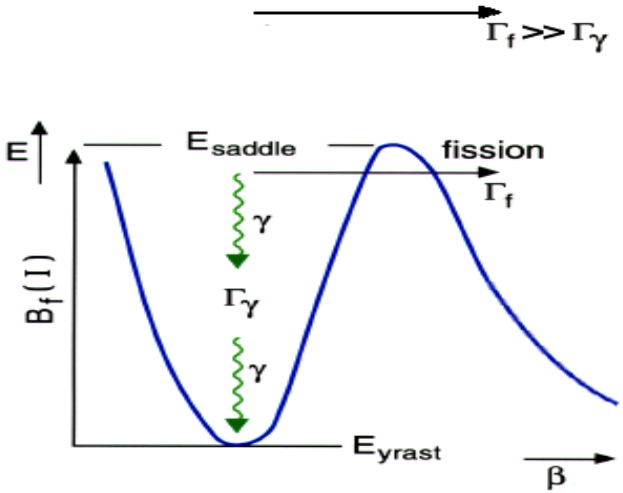
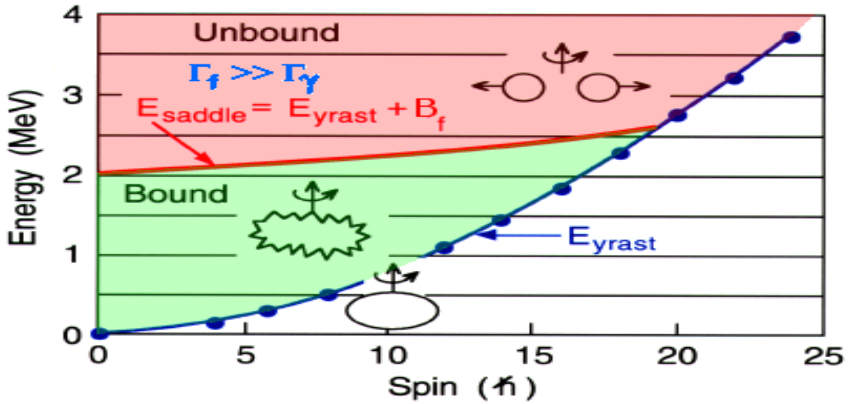
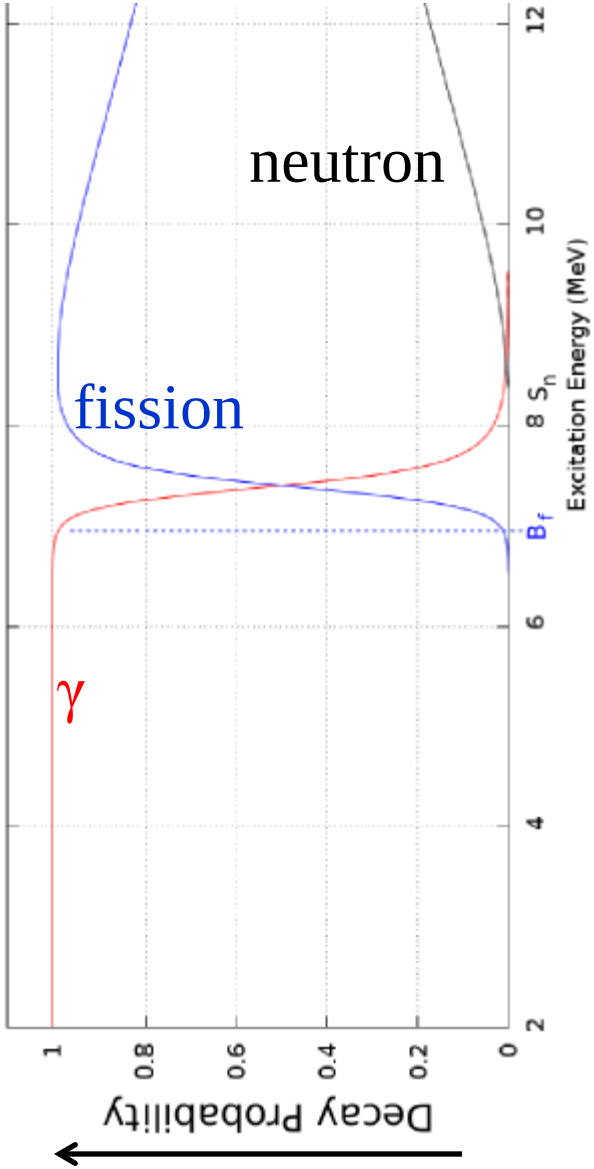
The end!

- Thanks for your attention (if you did pay attention).
- Merci pour votre attention.
- Danke für Ihre Aufmerksamkeit.
- Grazie per la vostra attenzione.
- Gracias por su atención.
- Dziękujemy za uwagę.
- Спасибо за внимание.
- Kiitos huomiota.
- Tak for din opmærksomhed.
- Takk for oppmerksomheten.
- Köszönöm Figyelmüket.
- 感謝您的關注。
- あなたの注意をありがとう。
- आपका ध्यान के लिए धन्यवाद.
- شكرا لاهتمامكم.
- Terima kaseh atas perhatian Anda.


3.0
2.0
1.0
0.0
E_{2qp} [MeV]
^{254}No
$K^{\pi}=8^{-}$
$K^{\pi}=3^{+}$
EXPT
WS
SLy4
D1S
NL1
(est.)


$\Gamma_f >> \Gamma_\gamma$
E
E_{saddle}
fission
Γ_f
γ
Γ_γ
γ
$B_f(I)$
E_{yrast}
β


Unbound
$\Gamma_f >> \Gamma_\gamma$
$E_{saddle} = E_{yrast} + B_f$
Bound
E_{yrast}
Energy (MeV)
Spin (ħ)
0
1
2
3
4
0
5
10
15
20
25


neutron
fission
γ
B_f
S_n
Excitation Energy (MeV)
Decay Probability
2
4
6
8
10
12
0
0.2
0.4
0.6
0.8
1