Structure of hot nuclear states

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Argonne National Laboratory

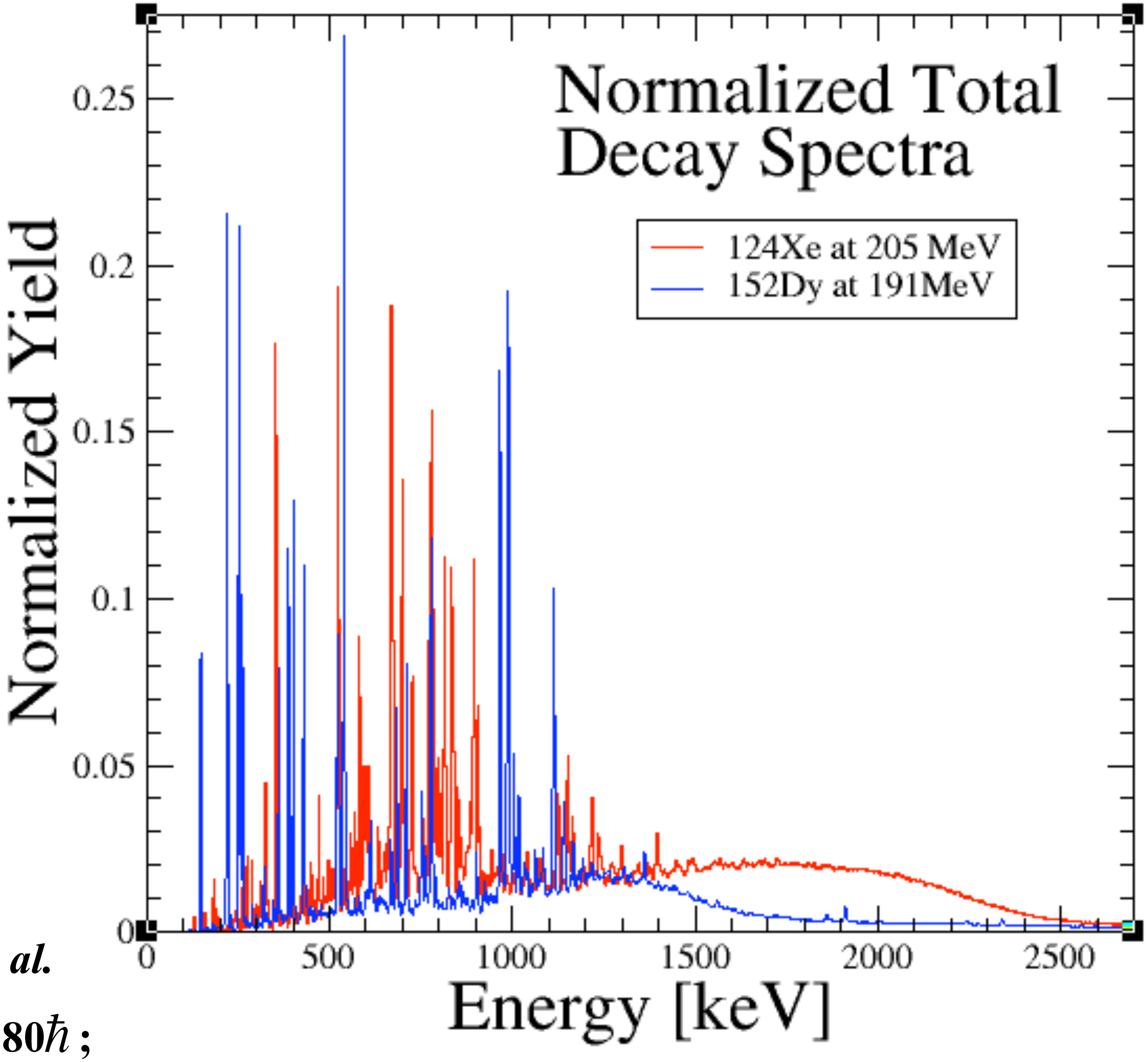
2nd Workshop on
Level Density and Gamma Strength
Oslo, May 11 - 15, 2009

Samuel Taylor Coleridge
The Rime of the Ancient Mariner

And the Albatross begins to be avenged.

Water, water, every where,
And all the boards did shrink ;
Water, water, every where,
Nor any drop to drink.

γs, γs every where,
And all the spectra did shrink ;
γs, γs every where,
Nor any physicist to drink.



Lauritsen *et al.*

^{124}Xe, $l_{max} \sim 80\hbar$;

~1/2 of γs unresolved, from hot states.

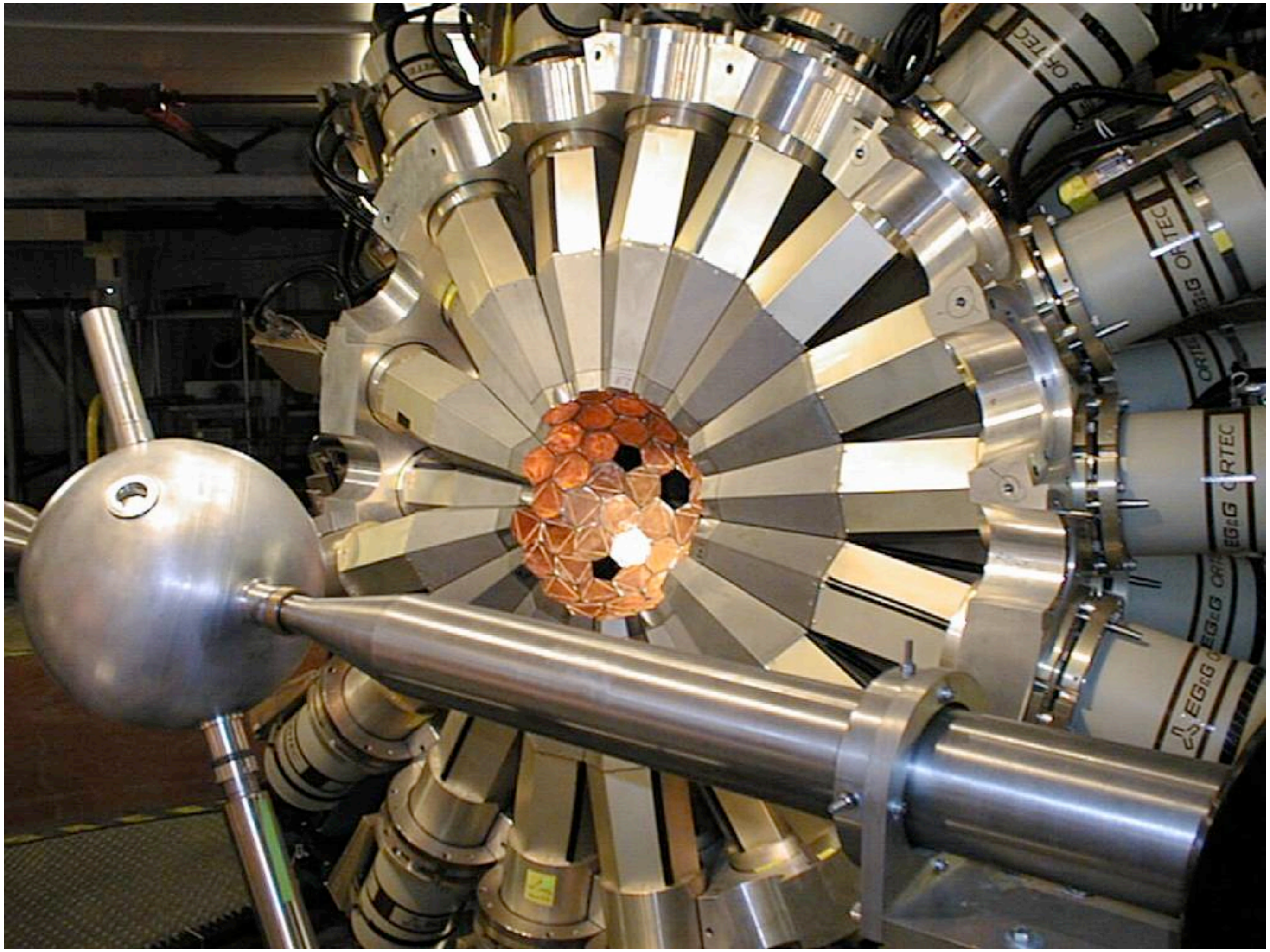
Topics

- Phase transitions
- Fission barriers and l_{max} in Superheavy Nuclei
- Order to chaos transition in superdeformed nuclei
- Ergodic superdeformed bands

Information extracted from γ spectra.

Theoretical description of γ spectrum requires knowledge of ρ & S_γ.

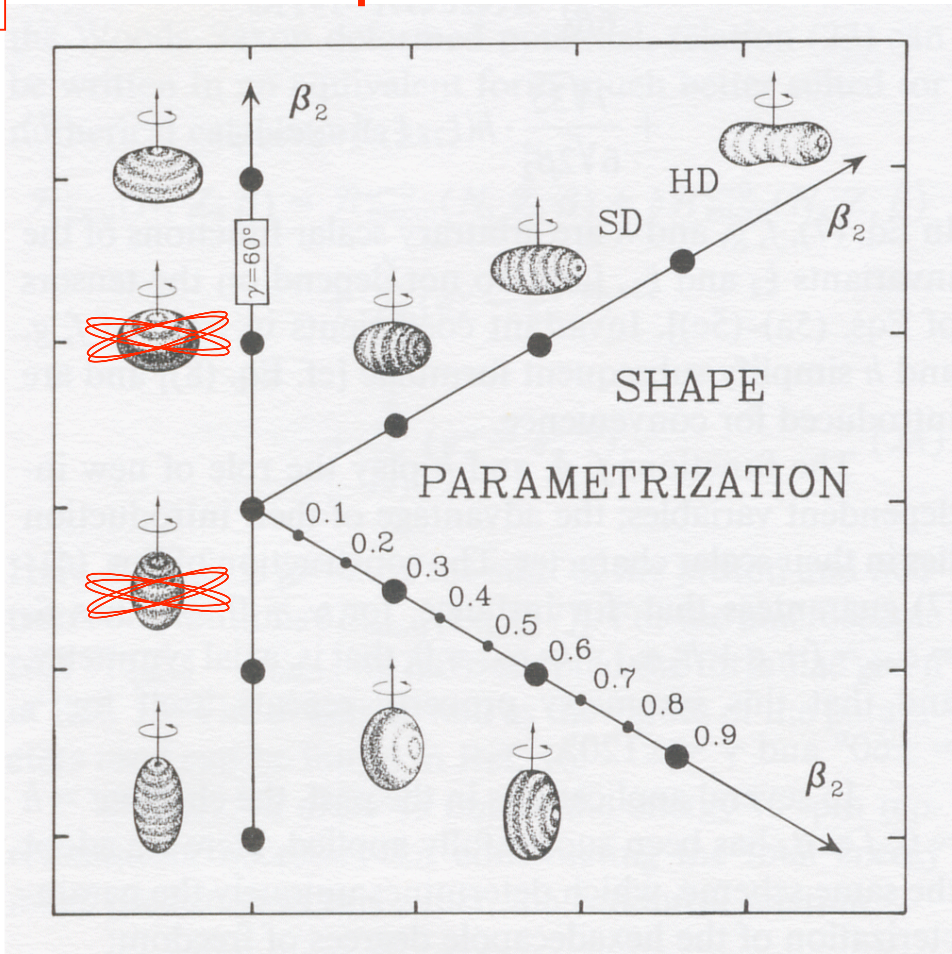
γs detected with Gammasphere
@Argonne & Berkeley



Adventures in the $\beta\gamma$ plane & above

"Rotation" around symmetry axis

Oblate s.p.



prolate

$J \sim J_0(1 + 0.6\beta)$

$J_0 = J_{rigid\ sphere}$

$J \sim J_0(1 - 0.6\beta)$

Collective oblate

prolate s.p.

Collective & aligned-particle rotation of nuclei

symmetry broken

ordered phase

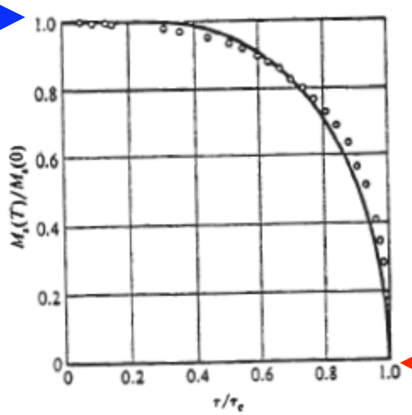


Figure 10.16 Saturation magnetization of nickel as a function of temperature, together with the theoretical curve for spin ½ on the mean field theory.

Magnetization *vs.* T/T$_c$

deformed

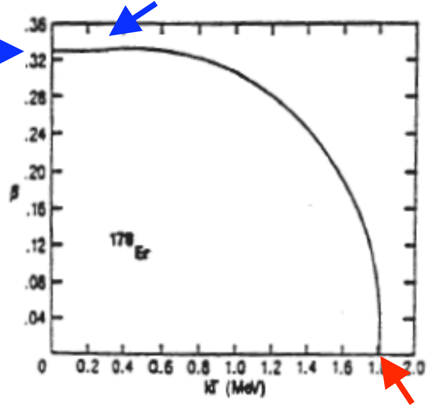


Fig. 9. The quadrupole deformation vs the temperature for ^{170}Er.

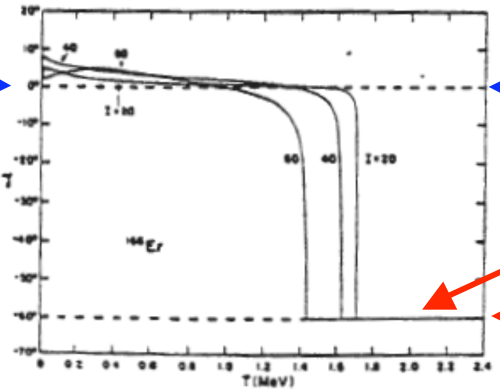
β *vs.* T, I=0

^{170}Er, Goodman

symmetry restored

disordered phase

spherical



γ = 0^0, prolate

γ = 60^0, oblate

γ *vs.* T, I=60, 40, 20 ħ

^{164}Er, Goodman

Universality class

Critical exponent β

Order param ∝ (1 – T/T$_c$)$^{\beta}$

Phase Transitions

LUME 84, NUMBER 26 PHYSICAL REVIEW LETTERS 26 JUNE 20

Phase Transitions above the Yrast Line in ^{154}Dy

W. C. Ma,[1] V. Martin,[2] T. L. Khoo,[3] T. Lauritsen,[3] J. L. Egido,[4] I. Ahmad,[3] P. Bhattacharyya,[5]
M. P. Carpenter,[3] P. J. Daly,[5] Z. W. Grabowski,[5] J. H. Hamilton,[6] R. V. F. Janssens,[3] D. Nisius,[3] A. V. Ramayya,[6]
P. G. Varmette,[1] and C. T. Zhang[5]

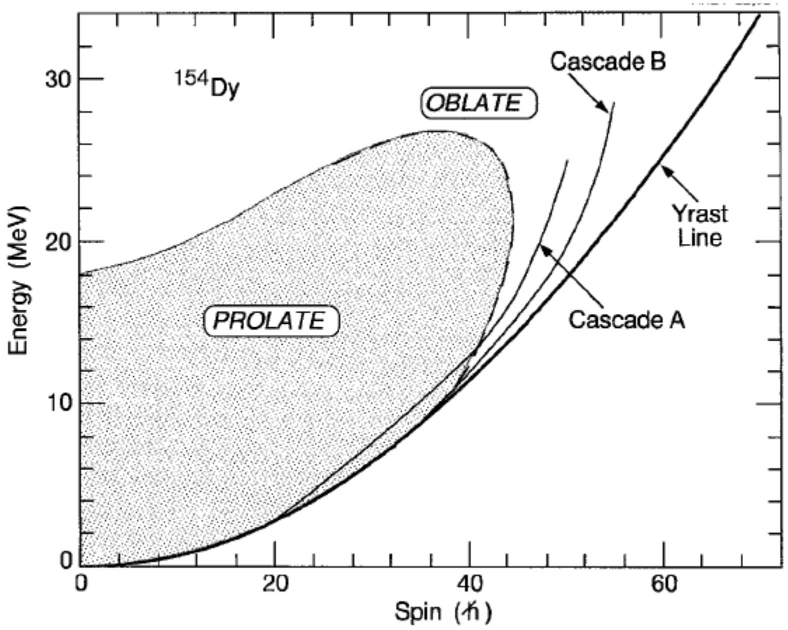
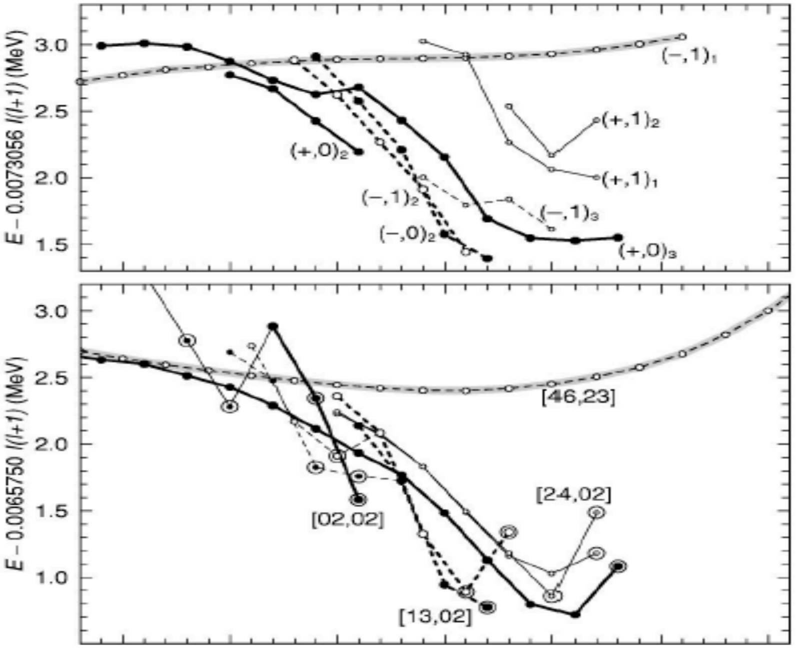


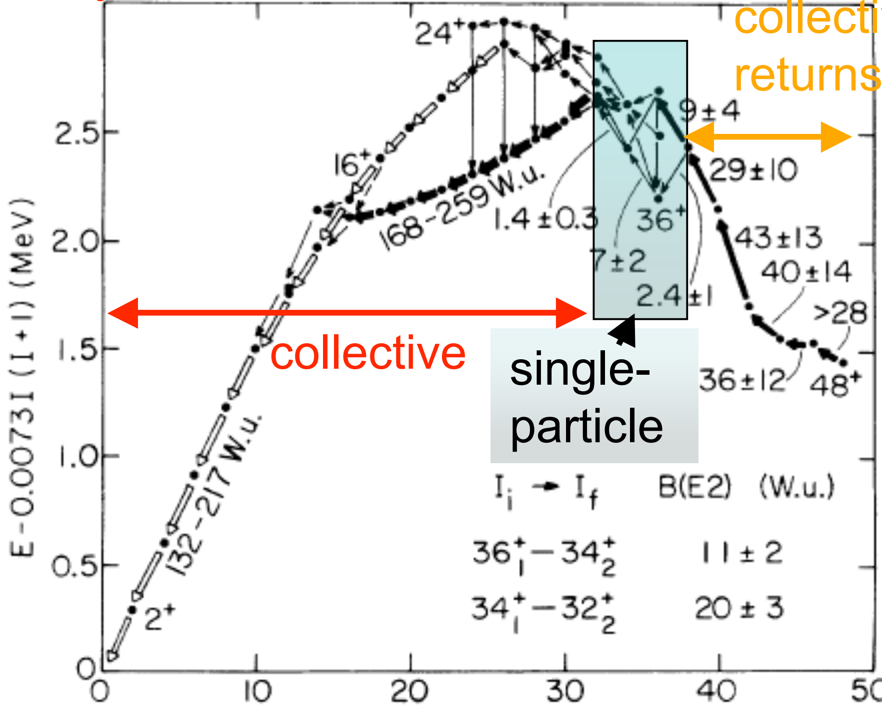
FIG. 1. Theoretical yrast line and regions of prolate (dotted) and oblate phases in ^{154}Dy. The phase boundary (dashed line) corresponds to the $\gamma = -60°$ line in finite-temperature Hartree-Fock-Bogoliubov calculations without fluctuations [4]. Sketches of two cascade paths (A, B) are shown, which connect the experimental entry and exit points for cascades feeding into two selected regions of the yrast line, $I = (16-22)\hbar$ and $I = (34-36)\hbar$.

Prolate ($\gamma=0^0$) & oblate ($\gamma=60^0$) states in N=88, 90 nuclei

- N ≤ 86, e.g. ^{152}Dy. Particle alignment ($\gamma=60^0$, oblate), yrast isomers.
- **N = 88, 90, e.g. ^{154,156}Dy. Both prolate & oblate →rotational & terminating bands.**
- N ≥ 92, e.g. ^{158}Dy, prolate rotors ($\gamma=0^0$).



^{154}Dy, Ma et al., PRL **61**, 46 (1988), PRC **70**, 034315 (2004)



collectivity returns

collective

single-particle

OLUME 84, NUMBER 26 PHYSICAL REVIEW LETTERS 26 JUNE 200

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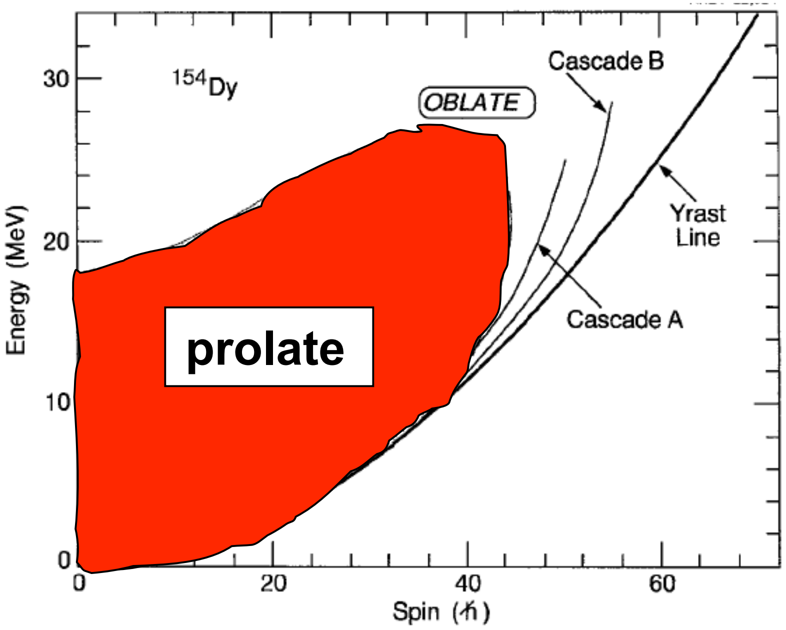

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Cascade A

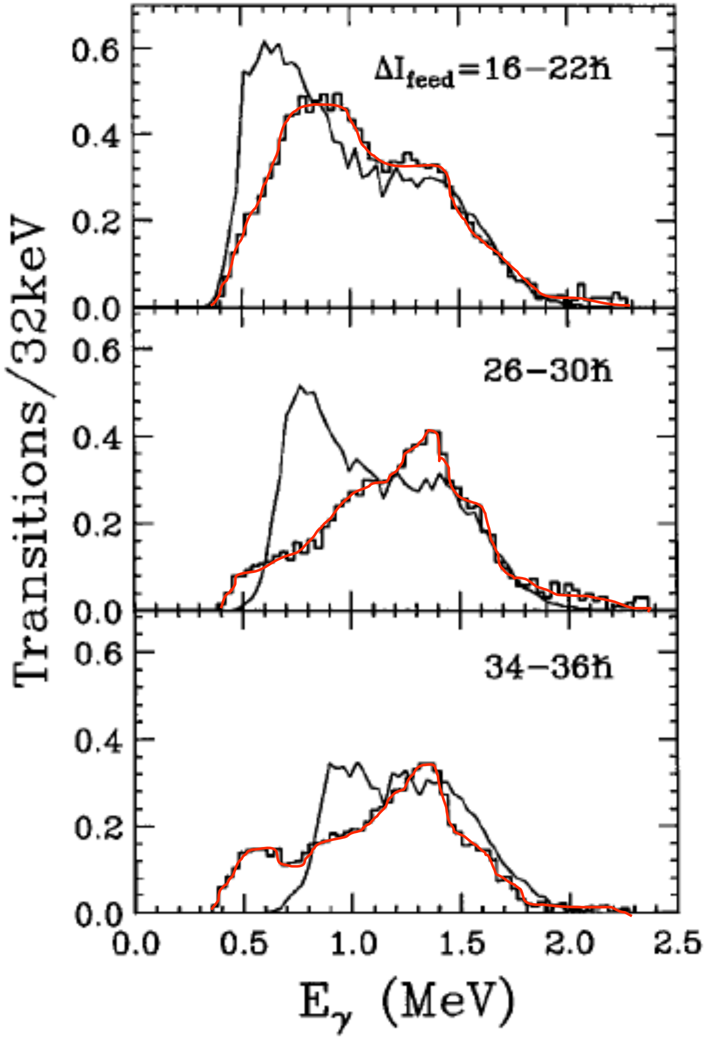
oblate & prolate zones → ***2 peaks***

Theory THFB

Experiment

Cascade B

oblate zone → ***1 peak***



Ma et al., PRL **84**, 5967 (2000)

Remanent signatures of phase transition at finite temperature in a mesoscopic system

FIG. 3. Differential $E2$ spectra feeding into the yrast line *only* in the indicated spin region ΔI_{feed}. Histograms and solid lines correspond to experiment and theory. The approximate decay pathways corresponding to the top and the bottom spectra are shown as cascades *A* and *B*, respectively, in Fig. 1.

Superheavy nuclei: at the limits of Z,I,E^*
What are the limits?

Physics questions.

- $B_f(I,E^*,Z,N)$ & $E_{shell}(I,E^*,Z,N)$.

- Variation with I, E* (as well as Z, N) → incisive tests of shell structure.

- Spectroscopy → detailed tests of
E_{sp}, $e(\omega)$, $E_{band}(I)$, $J^{(1,2)}$ (i.e. $\partial E/\partial I$, $\partial^2 E/\partial^2 I$).

ρ, S_γ in SHN

- ρ, S_γ in SHN with transfer reactions,

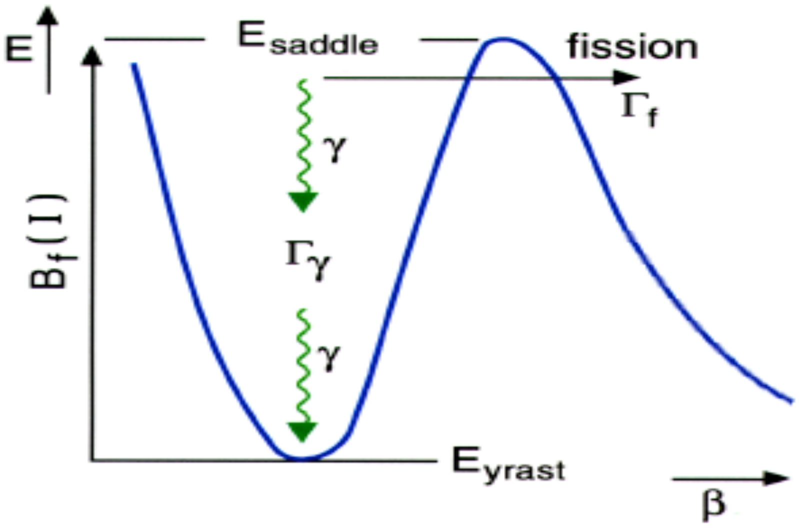
e.g. ^{249}Cf(d,p), (α,^{3}He), (d,t), (^{3}He,α)

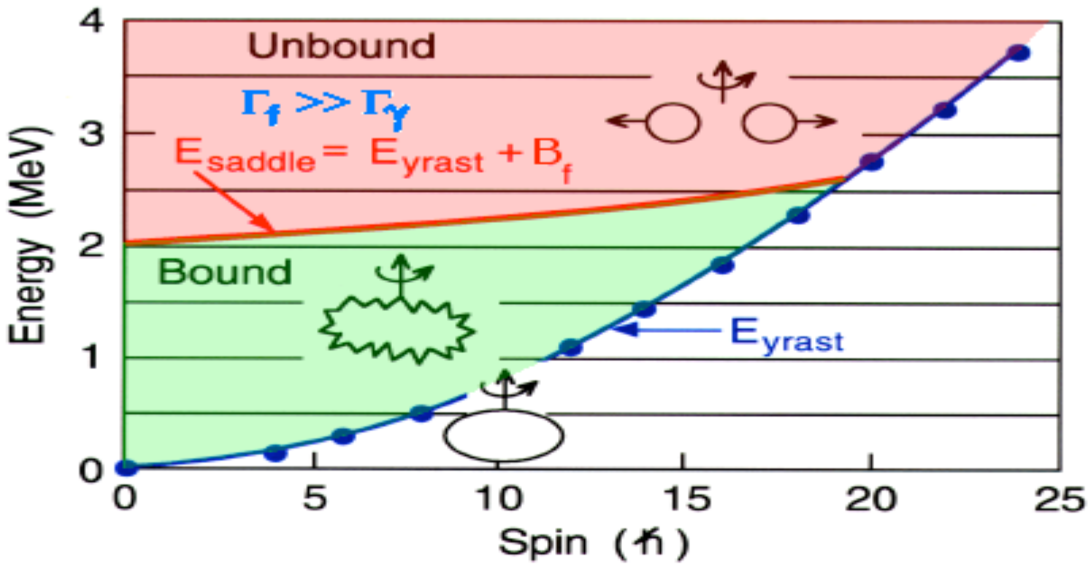
- Any new aspects, e.g. near top of fission barrier?

How delicate are superheavy nuclei?

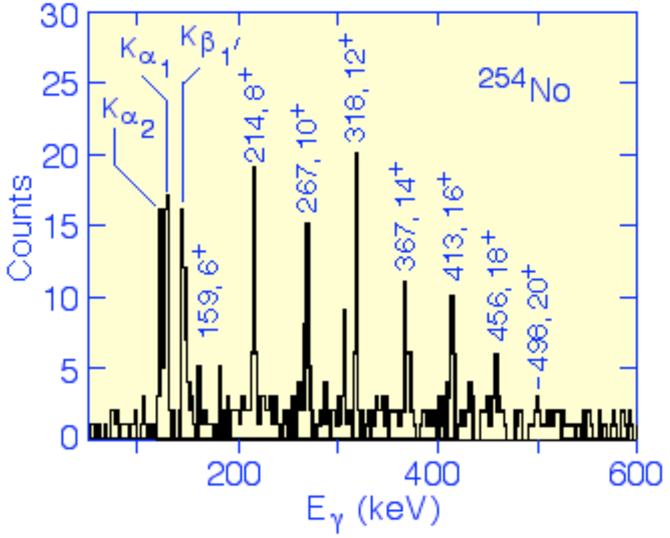
- How fragile are these loosely-bound nuclei, barely held together shell-created barriers?
- If you tickle them, will they “laugh” and fall apart?
- If you spin them, will they fission immediately?

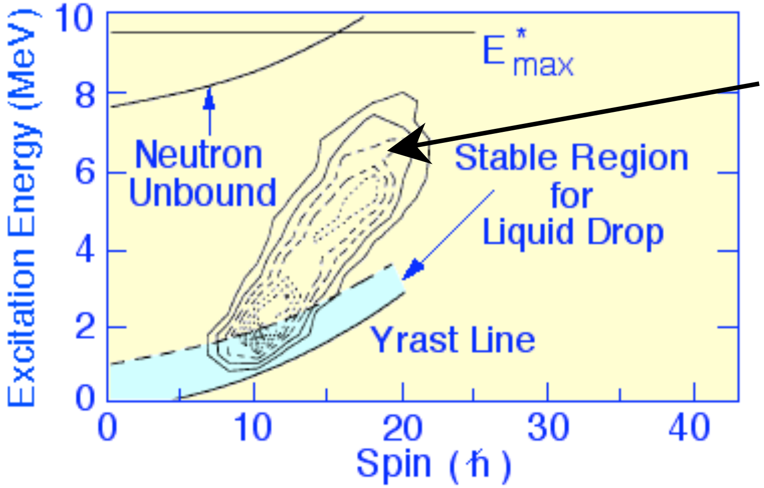
$\Gamma_f >> \Gamma_\gamma$





Limits of Stability in Spin and Energy





Initial states for γ decay to g.s.

^{254}No is stable up to at least spin $22\hbar$ and 8 MeV energy -- much more robust than expected.

$\boxed{B_f(\ell) > 5\text{ MeV}}$ $\ell \geq 10\,\hbar$

Gammasphere at ANL Reiter et al. PRL 84, 3542 (2000)

UME 84, NUMBER 16 PHYSICAL REVIEW LETTERS 17 APRIL 20

Entry Distribution, Fission Barrier, and Formation Mechanism of ${}^{254}_{102}$No

P. Reiter,[1,2] T. L. Khoo,[1] T. Lauritsen,[1] C. J. Lister,[1] D. Seweryniak,[1] A. A. Sonzogni,[1] I. Ahmad,[1] N. Amzal,[3] P. Bhattacharyya,[4] P. A. Butler,[3] M. P. Carpenter,[1] A. J. Chewter,[3] J. A. Cizewski,[1,5] C. N. Davids,[1] K. Y. Ding,[5] N. Fotiades,[5] J. P. Greene,[1] P. T. Greenlees,[3] A. Heinz,[1] W. F. Henning,[1] R.-D. Herzberg,[3] R. V. F. Janssens,[1] G. D. Jones,[3] H. Kankaanpää,[7] F. G. Kondev,[1] W. Korten,[6] M. Leino,[7] S. Siem,[1,8] J. Uusitalo,[1] K. Vetter,[9] and I. Wiedenhöver[1] M. Asai[1,10], D. Grayson[1]

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(Received 3 January 2000)

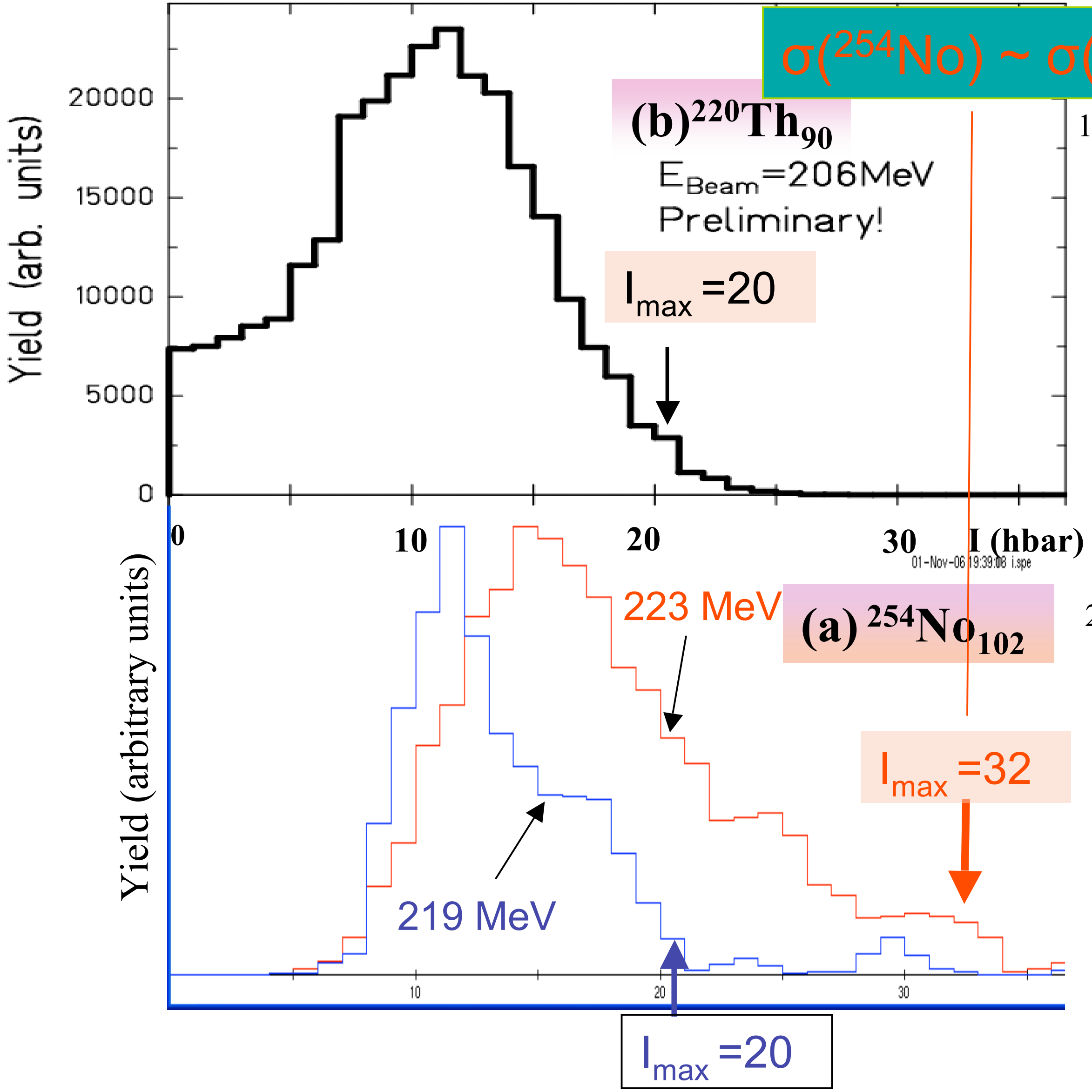
The entry distribution in angular momentum and excitation energy for the formation of ^{254}No has been measured after the ^{208}Pb(^{48}Ca, $2n$) reaction at 215 and 219 MeV. This nucleus is populated up to spin $22\hbar$ and excitation energy $\gtrsim 6$ MeV above the yrast line, with the half-maximum points of the energy distributions at ~ 5 MeV for spins between $12\hbar$ and $22\hbar$. This suggests that the fission barrier is $\gtrsim 5$ MeV and that the shell-correction energy persists to high spin.

$I_{max}(^{254}No) > I_{max}(^{220}Th)$!

$B_f(^{254}No) > B_f(^{220}Th)$

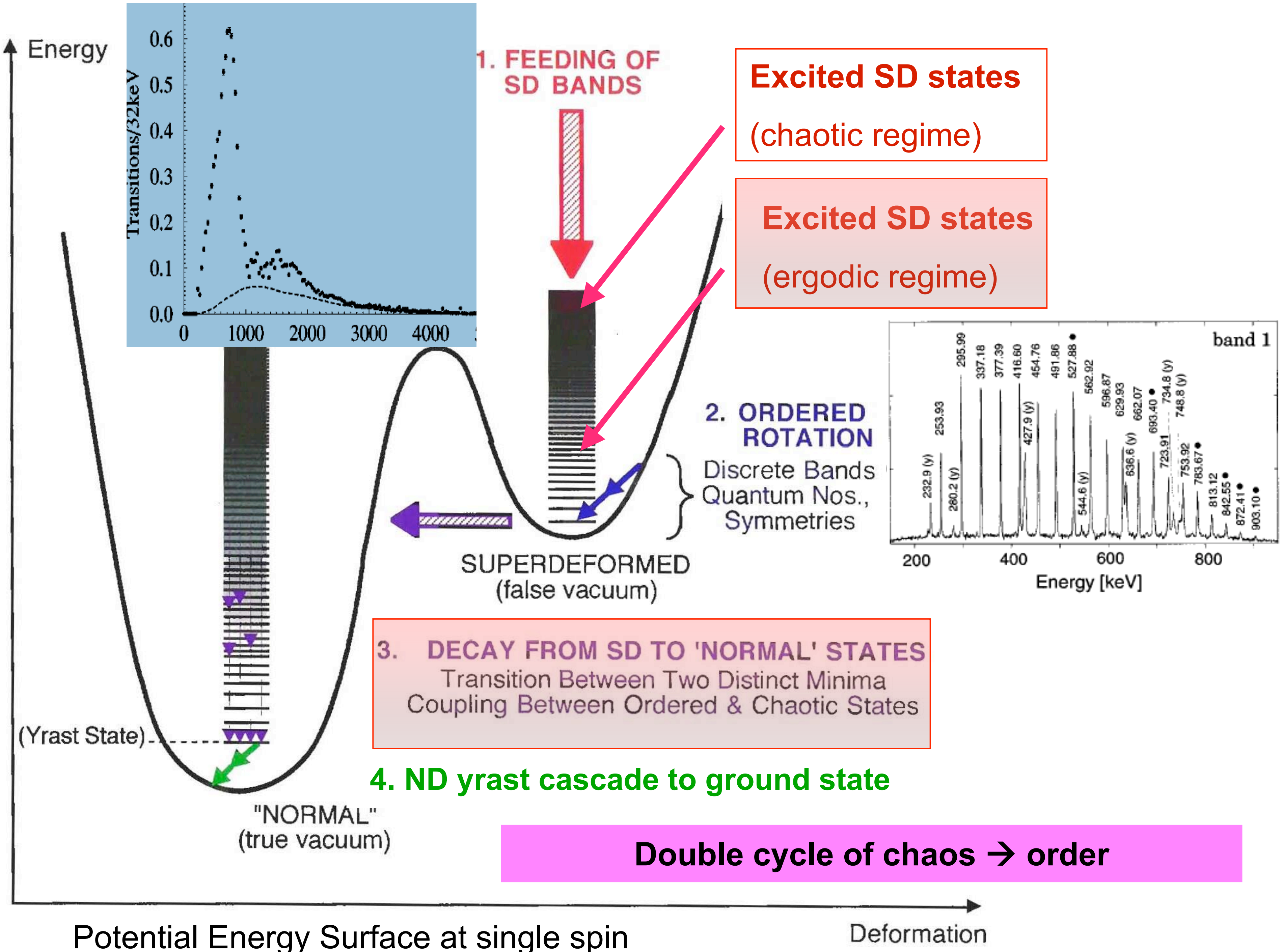
>5 MeV ~8 MeV

$\sigma(^{254}No) \sim \sigma(^{220}Th)/10^3$



$^{176}Yb(^{48}Ca,4n)$

$^{208}Pb(^{48}Ca,2n)$



1. FEEDING OF SD BANDS

Excited SD states

(chaotic regime)

Excited SD states

(ergodic regime)

2. ORDERED ROTATION

Discrete Bands
Quantum Nos.,
Symmetries

SUPERDEFORMED
(false vacuum)

3. DECAY FROM SD TO 'NORMAL' STATES

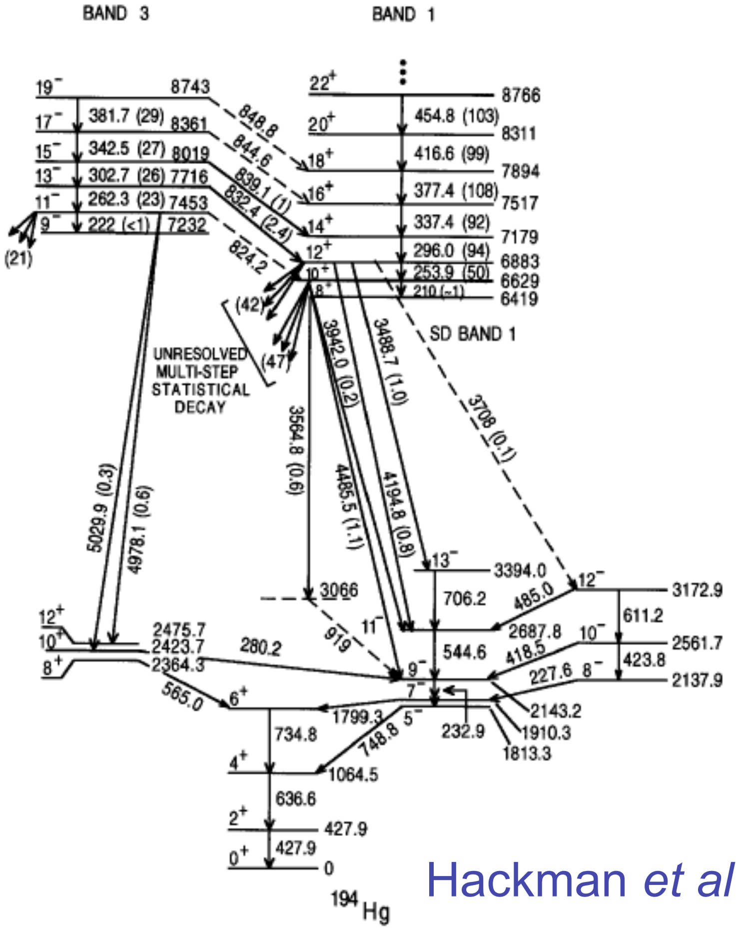
Transition Between Two Distinct Minima
Coupling Between Ordered & Chaotic States

4. ND yrast cascade to ground state

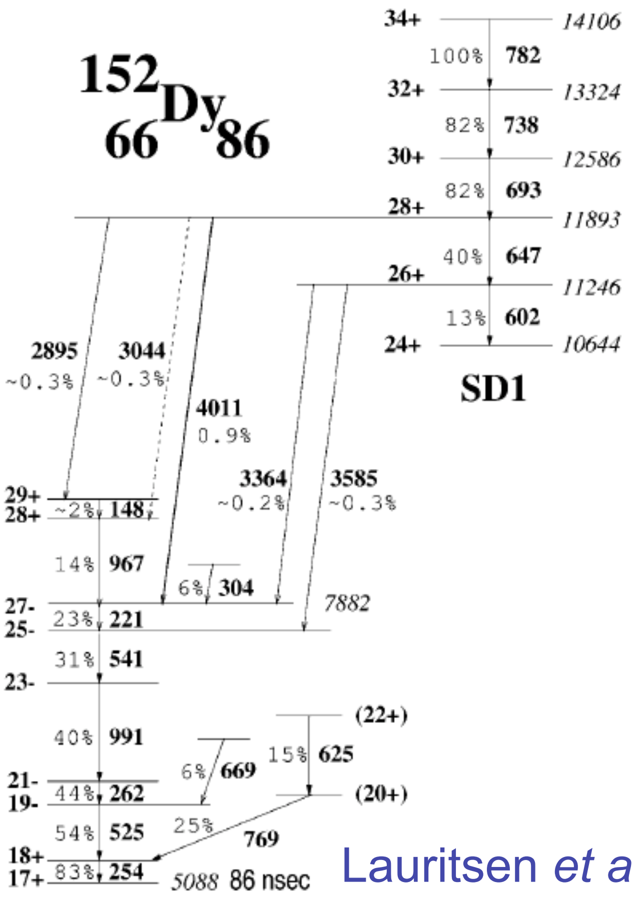
"NORMAL"
(true vacuum)

Double cycle of chaos → order

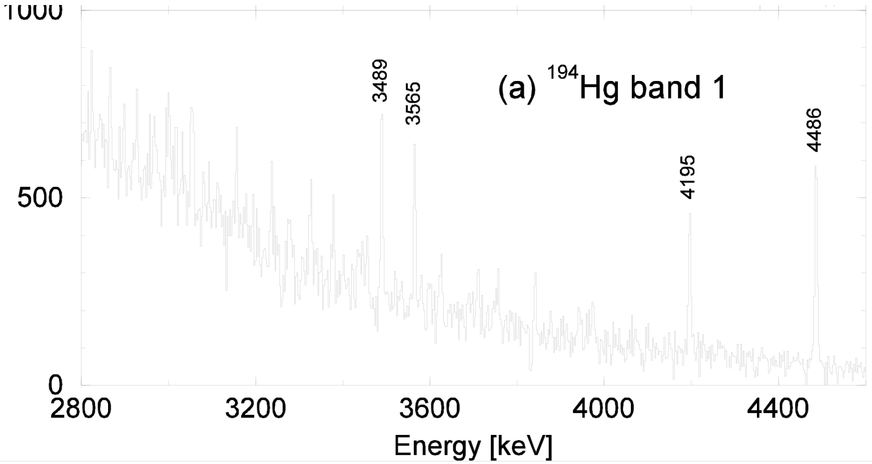
Potential Energy Surface at single spin

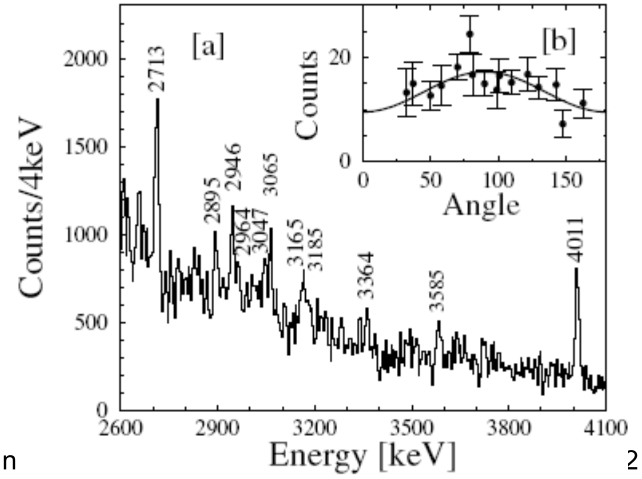


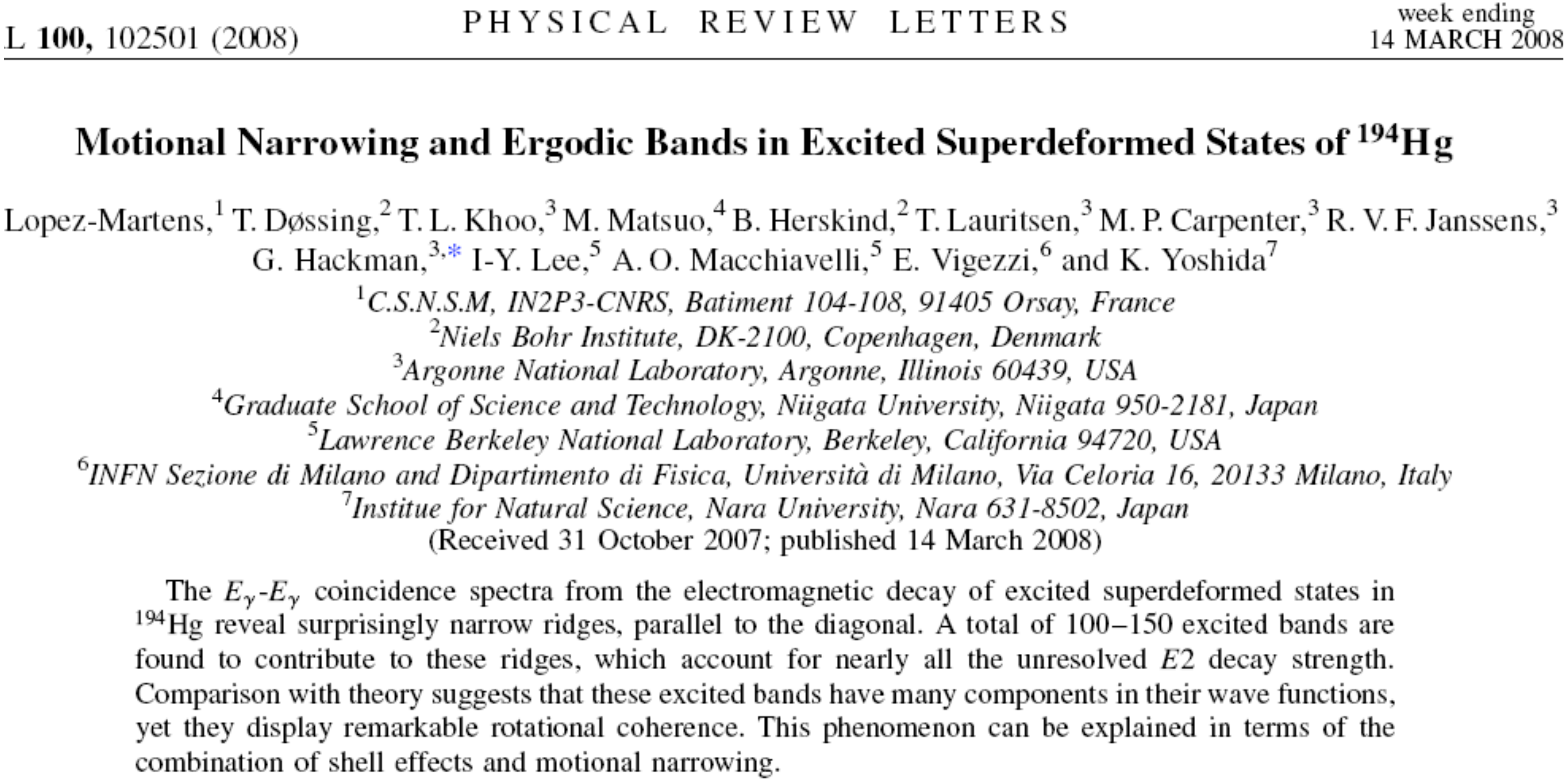
Hackman *et al.*



Lauritsen *et al.*







L **100,** 102501 (2008) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2008

Motional Narrowing and Ergodic Bands in Excited Superdeformed States of ^{194}Hg

Lopez-Martens,[1] T. Døssing,[2] T. L. Khoo,[3] M. Matsuo,[4] B. Herskind,[2] T. Lauritsen,[3] M. P. Carpenter,[3] R. V. F. Janssens,[3] G. Hackman,[3,*] I-Y. Lee,[5] A. O. Macchiavelli,[5] E. Vigezzi,[6] and K. Yoshida[7]
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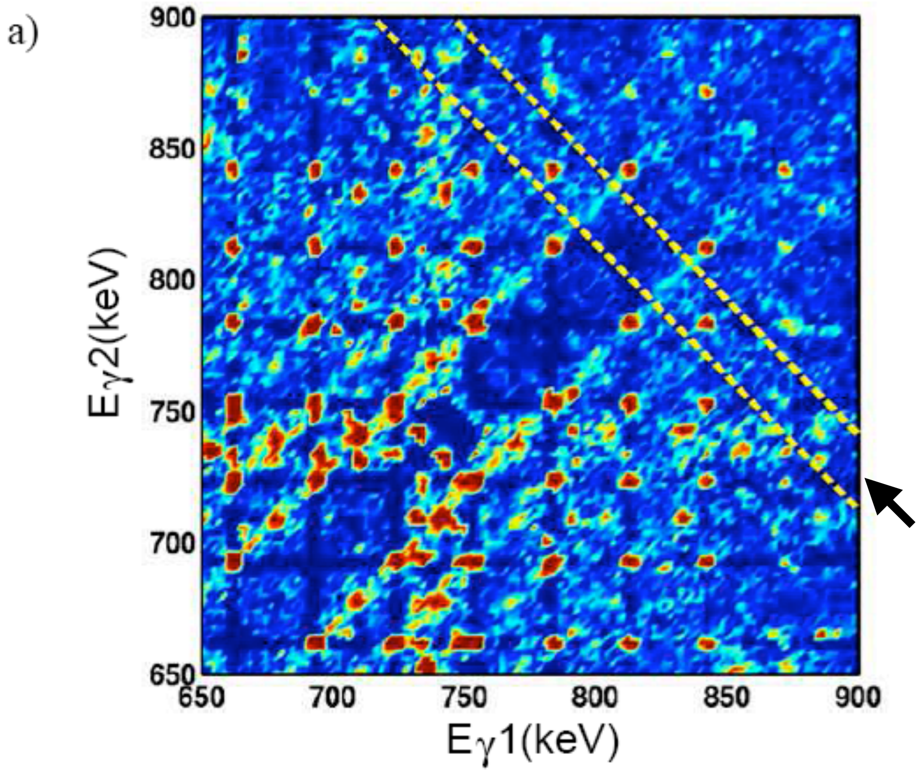
The E_γ-E_γ coincidence spectra from the electromagnetic decay of excited superdeformed states in ^{194}Hg reveal surprisingly narrow ridges, parallel to the diagonal. A total of 100–150 excited bands are found to contribute to these ridges, which account for nearly all the unresolved $E2$ decay strength. Comparison with theory suggests that these excited bands have many components in their wave functions, yet they display remarkable rotational coherence. This phenomenon can be explained in terms of the combination of shell effects and motional narrowing.

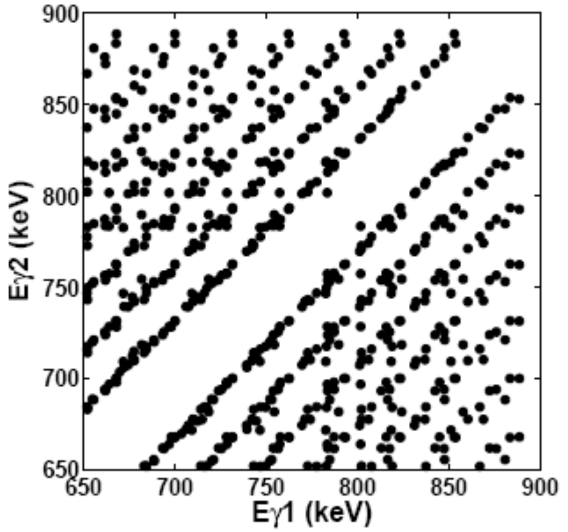
^{194}Hg SD gated

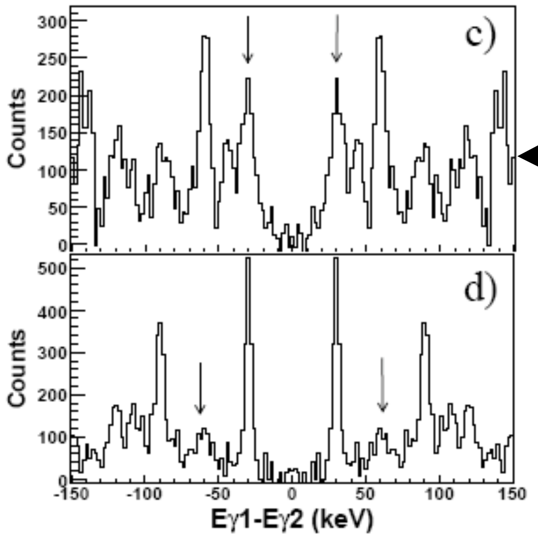
Lopez-Martens *et al.*

E_γ E_γ correlations



Slice c)





Discrete SD bands, A~190

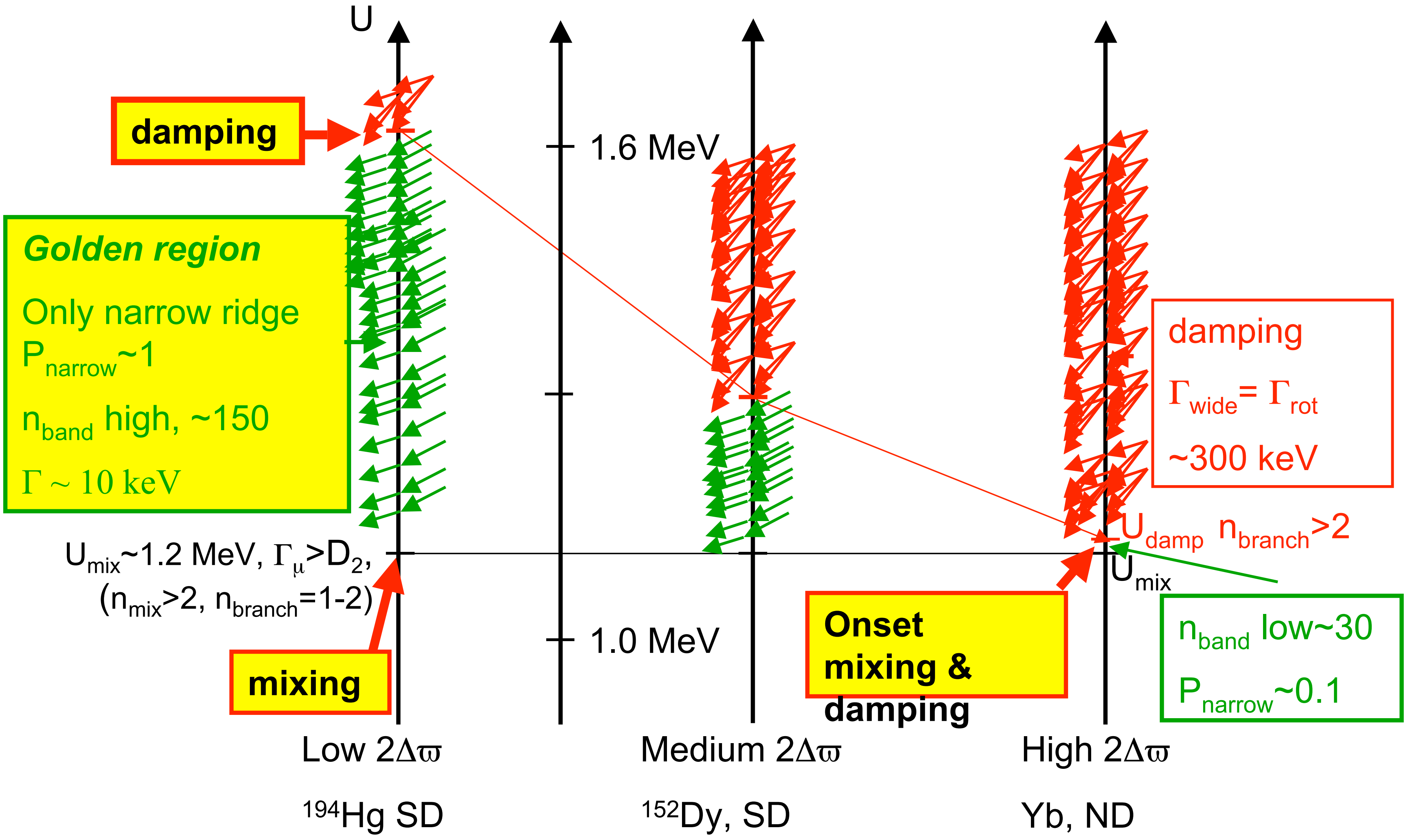
Cuts perpendicular to diagonal

Observations: ***new phenomenon***

- Exceptionally narrow SD ridges ~~(~10 keV *vs.* ~50 keV for ND).~~
- Ridge exhausts ~100% of E2 total strength (*vs.* ~10% for ND).
- No detectable broad component with rotational damping Γ_{rot} ~300 keV.
- ***Number of bands contributing to the ridge ~150* (*vs.* ~30 for ND).**
- Cf. $FWHM_{SD}$ ~ 10 keV *vs.* $FWHM_{ND}$ ~ 350 keV

- Narrow ridge implies E2 transitions flow within parallel rotational bands with nearly identical $J^{(2)}$.
- $J^{(2)}$ identical to that of SD band 1.
- Theory
  - predicted narrow ridges (Matsuo and Yoshida).
  - suggests that ~2-8 (4, average) basis configurations in excited SD states; from U=1.2-1.6 MeV.

- Predicted by Mottelson



damping

Golden region

Only narrow ridge

P_{narrow}~1

n_{band} high, ~150

$\Gamma \sim 10$ keV

U_{mix}~1.2 MeV, Γ_{μ}>D_2,

(n_{mix}>2, n_{branch}=1-2)

mixing

Onset mixing & damping

damping

$\Gamma_{wide} = \Gamma_{rot}$

~300 keV

U_{damp} n_{branch}>2

U_{mix}

n_{band} low~30

P_{narrow}~0.1

Low 2Δϖ

^{194}Hg SD

Medium 2Δϖ

^{152}Dy, SD

High 2Δϖ

Yb, ND

$$\Gamma_{E2} < D < \Gamma_{\mu}$$

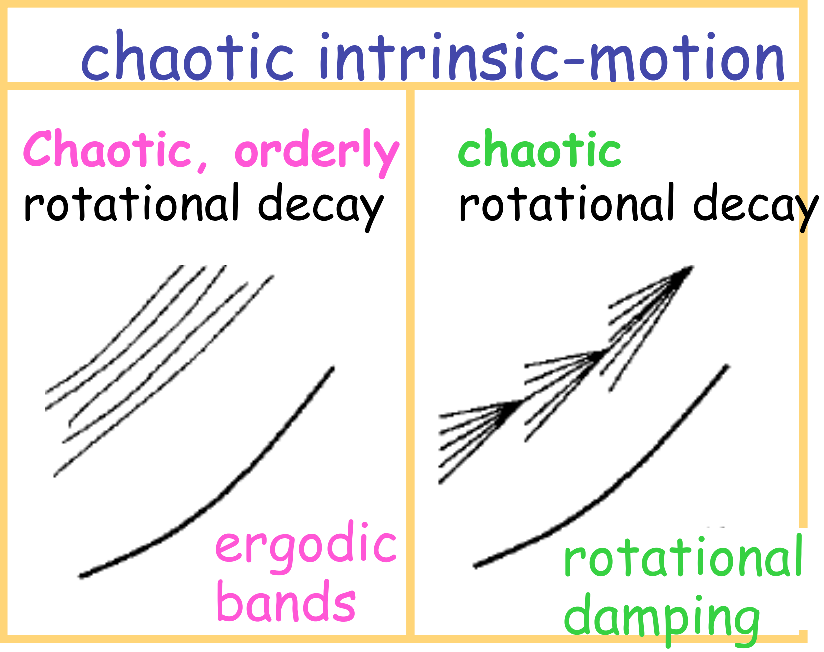
~10 ~20 ~40 keV

Ergodic condition

$$2\Delta\omega < \Gamma_{\mu}$$

~25 ~40 keV

Motional narrowing



chaotic intrinsic-motion

Chaotic, orderly rotational decay

chaotic rotational decay

ergodic bands

rotational damping

n_{branch} ~1 >2

conditions for ergodic bands

small $\Delta\omega_0 \approx \frac{\Delta i}{\mathfrak{I}}$ → large ε, K

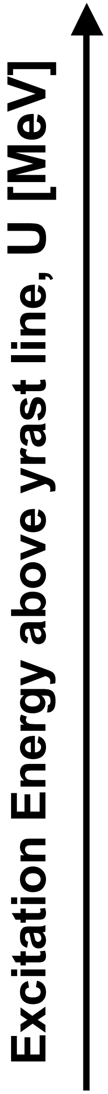
→ Large ε, A

SD states in A ~190

small Coriolis intn.

- Small $\Delta\varpi$ → ~identical $J^{(2)}$ →“identical” bands.
- Ergodic and identical bands intimately connected.

From Order to Chaos



Excitation Energy above yrast line, U [MeV]

Chaotic

Quantum numbers lost (except I, π) → ***no selection rules***.

Statistical spectrum.

Transitions strengths unpredictable, governed by Porter-Thomas fluctuations.

Ergodic

Mostly chaotic, with:

(a) complicated wavefunctions and

(b) Porter-Thomas fluctuations in all transitions except collective E2 transitions, with rotational band structure preserved. Unique in ^{194}Hg.

Ordered

Good quantum numbers → ***selection rules***.

Well-defined spectrum; equi-spaced (picket-fence) sharp lines from rotation of a cold SD object.

Summary

1. Phase transitions along and above the yrast line.
2. Superheavy nuclei:

   survive to I = 32 hbar;

   shell structure robust to high spin.
3. Superdeformed bands:

   double cycle of chaos-to-order transition;

   new ergodic regime with “orderly” E2 flow in chaotic states.