Order to chaos transition and extreme deformations

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- Random Matrix Theory + quantum « chaos »
- level statistics + decay widths
- « chaos »-assisted tunneling
- rotational damping
- motional narrowing + ergodic bands

Workshop on Physics with AGATA ORSAY 2004

Random Matrix Theory:

developped to explain complex fission resonance spectra

Wigner: resonance energies = eigenvalues of a random matrix sharing the same properties as the Hamiltonian of the nucleus

no preferred basis for the random matrix => Gaussian probability densities

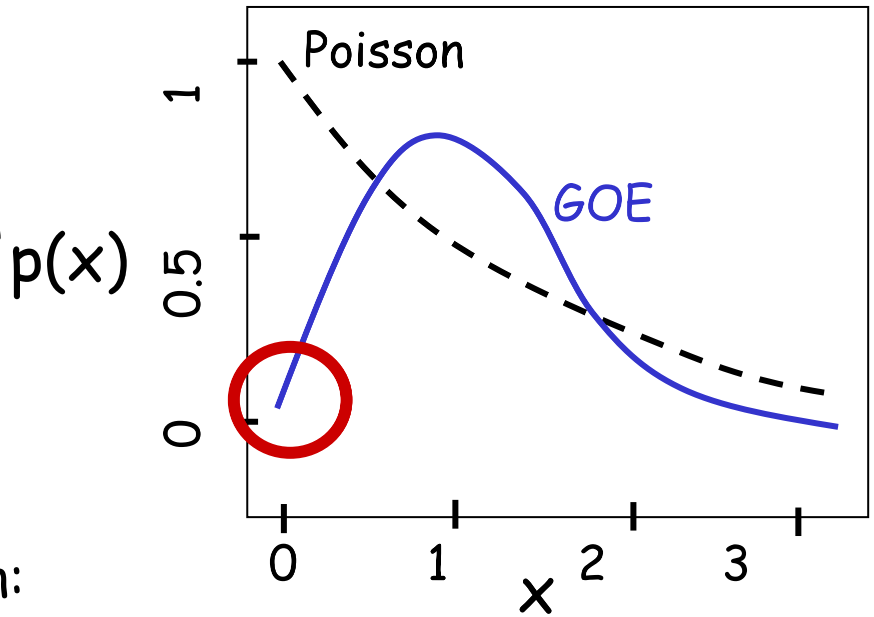
Dyson & Mehta: time-reversal invariant systems are described by GOE and GSE

GOE:

Nearest Neighbour Spacing distribution (for sequence with same I, π):

$$p(x) = \pi x/2 \exp(-\pi x^2/4)$$

$x=s/d$ ← unfolding procedure

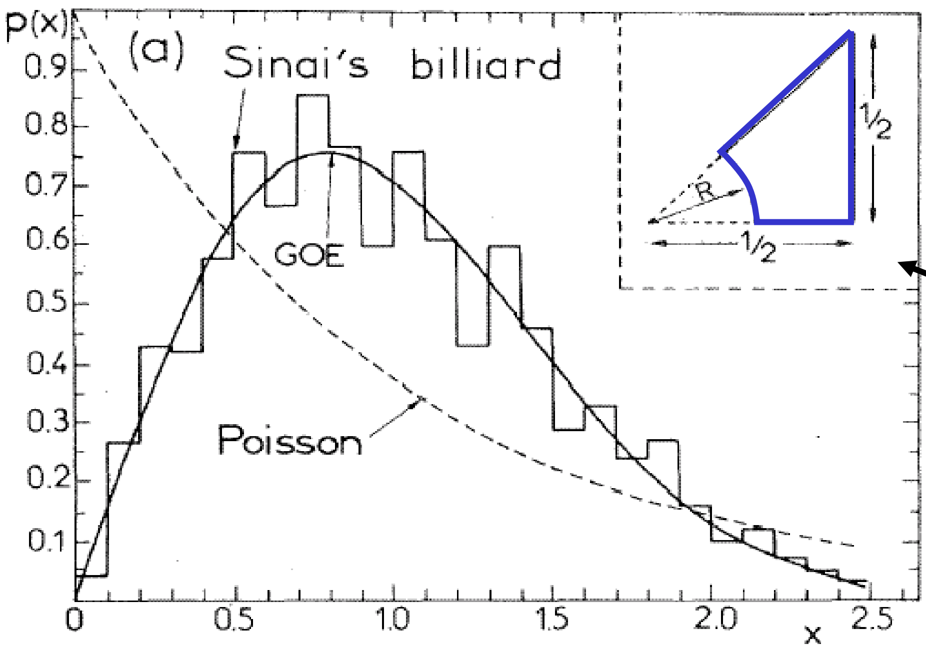


reduced transition strength distribution:

Porter-Thomas distribution: $p(\xi) = (\xi/2\pi)^{-1/2} \exp(-1/2\ \xi)$

$\xi = B/\langle B\rangle$

Quantum « chaos »:



1-particle quantum system exhibits random matrix statistics !

2D billiard = classically chaotic : hypersensitive to initial conditions

O. Bohigas et al., PRL 52 (1984)

Bohigas, Giannoni and Schmit conjecture:

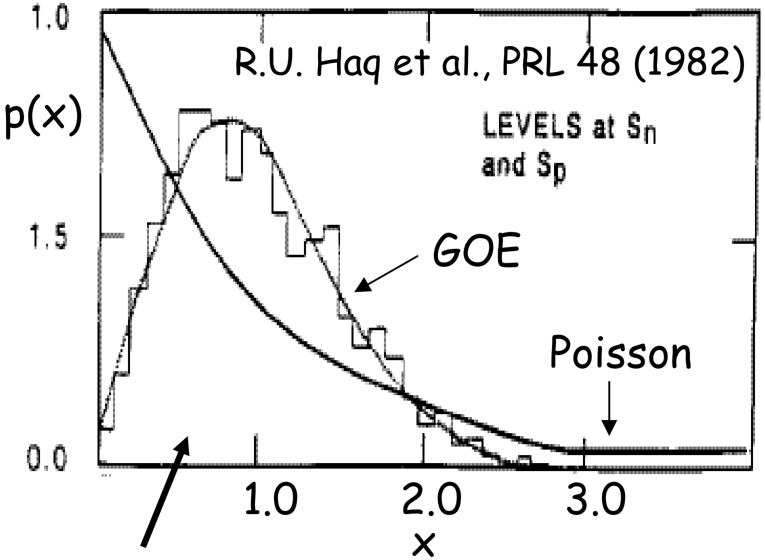
Spectra of systems whose classical analogues are fully chaotic show correlation properties as modeled by the Gaussian Ensembles

=> association of RMT with « chaos »

=> universality of the laws of level fluctuations ?

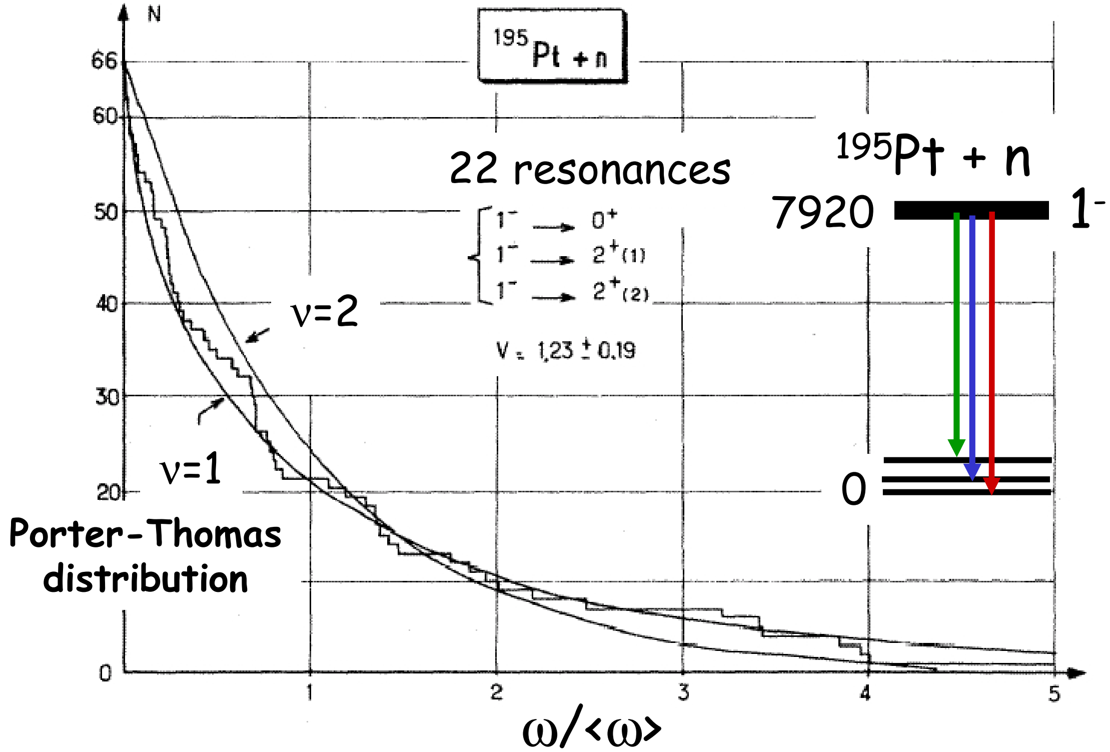
Resonance region : « chaotic » regime

NDE: 1047 resonances
30 sequences of 27 nuclei



for each nucleus, the sequence of levels must be complete and pure

H. Jackson *et al.* PRL 17 (1966)



What happens at lower E* ?
Does « chaos » coexist with « order » ?
Is there a transition from « order » to « chaos » ?
When does the transition occur ?
What is the spin, deformation & mass dependence of the transition ?

Low-lying level statistics

light -> heavy

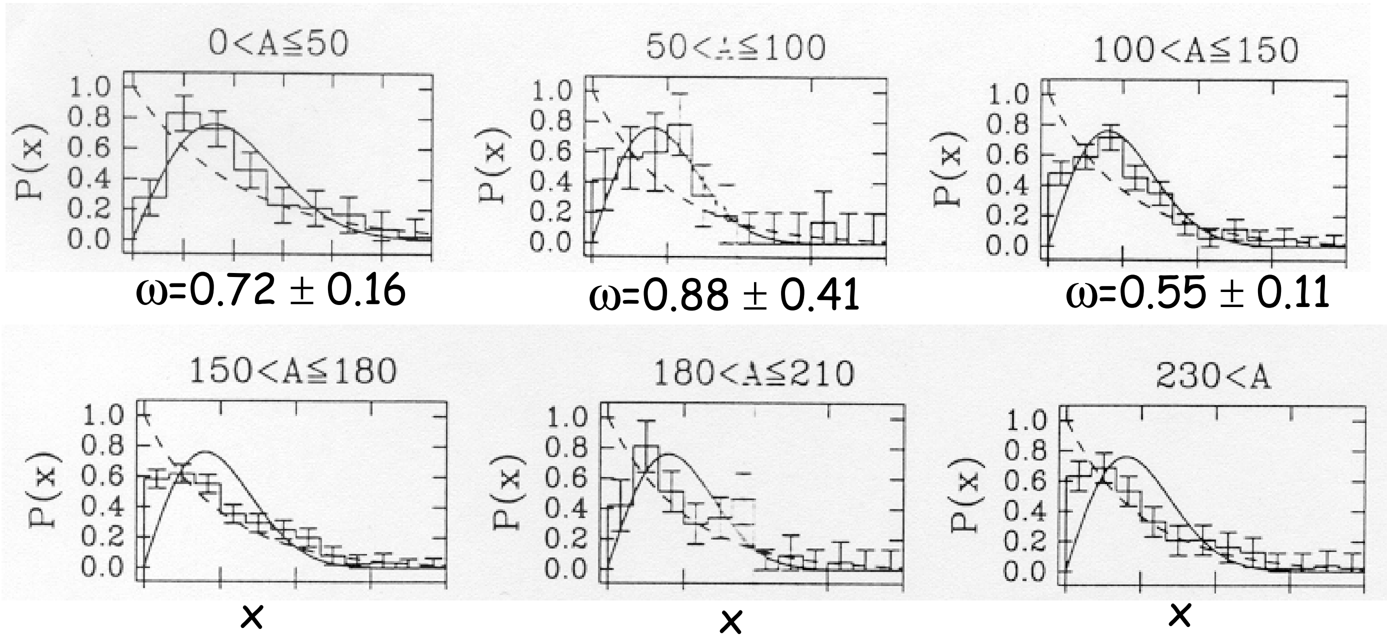
988 spacings from 90 nuclides from ^{24}Na to ^{244}Am

J.F. Shriner et al., ZPA 339 (1991)

Brody parameter ω : interpolation between 2 extreme distributions

ω = 0 : Poisson

ω = 1 : GOE



ω=0.72 ± 0.16 ω=0.88 ± 0.41 ω=0.55 ± 0.11

ω=0.33 ± 0.07 ω=0.43 ± 0.17 ω=0.24 ± 0.11

=> trend from GOE to Poisson as the mass increases

spherical -> deformed

$\beta_2/\beta_{2(sp)} > 12$ => deformed $\omega = 0.30 \pm 0.06$

$\beta_2/\beta_{2(sp)} < 7$ => spherical $\omega = 0.60 \pm 0.08$

=> NNS distribution of deformed nuclei closest to Poisson

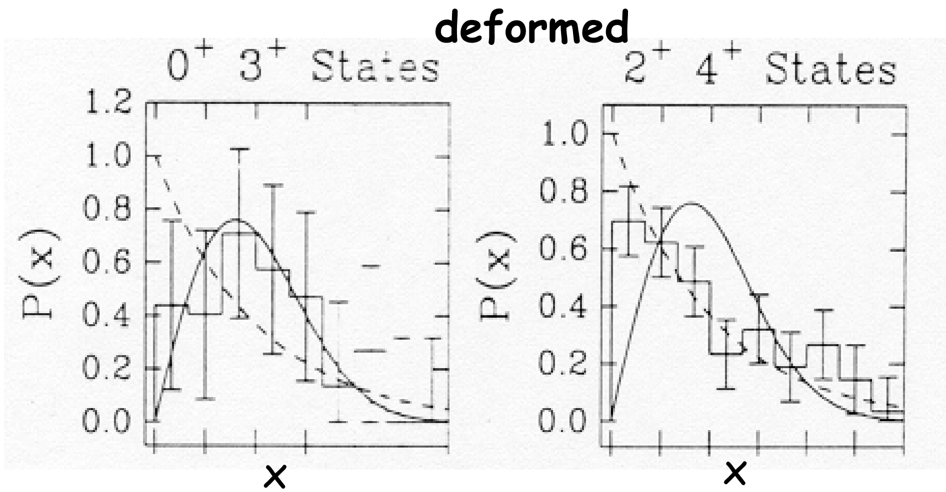
spin dependence (e-e nuclei)

spherical $0^+,3^+$: $\omega=0.52 \pm 0.21$

$2^+,4^+$: $\omega=0.52 \pm 0.15$

deformed $0^+,3^+$: $\omega=0.74 \pm 0.52$

$2^+,4^+$: $\omega=0.16 \pm 0.13$



shortage of data => no definite conclusions

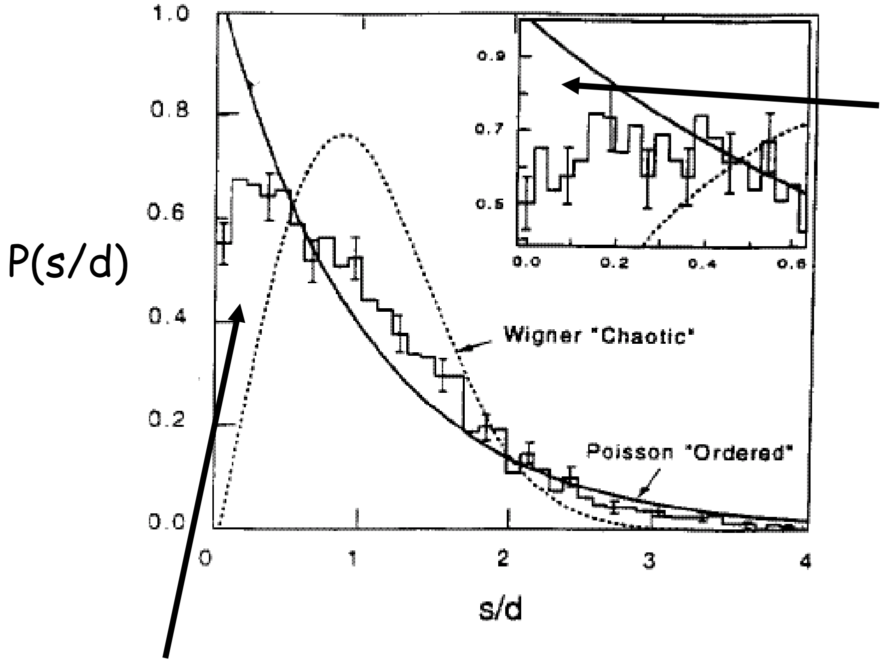
=> more extensive data in a single nuclide is required:

- phase transition
- neglected symmetries ?

Towards regularity or influence of K quantum number ?

3130 near yrast spacings of e-e and odd A rare earth nuclei

J. Garrett et al., PLB 392 (1997)



deviation from Poisson (independent of I,π and nuclear type):

mixing of closely spaced states with the same quantum numbers => level repulsion ?

80% of closely spaced levels (with known K-values) correspond to states that differ in K by 2 or more units

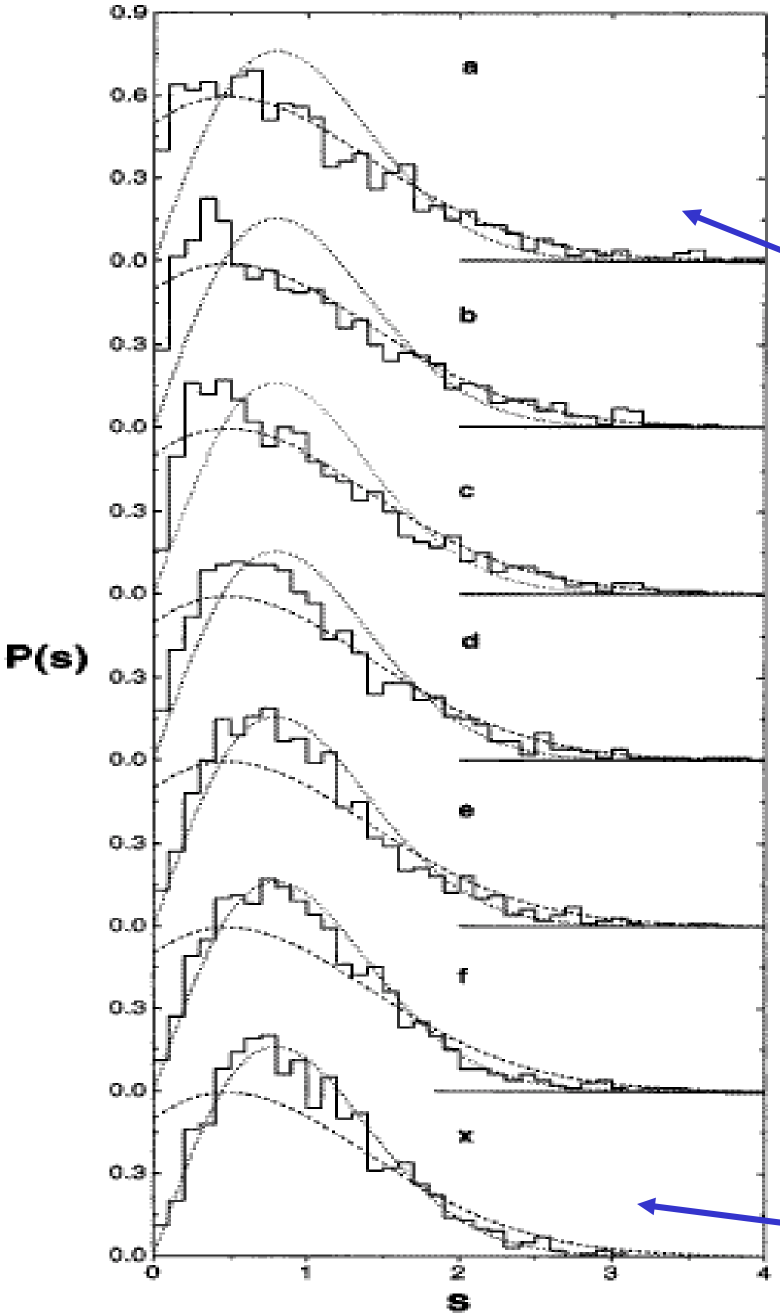
=> K quantum number = good quantum number for classifying deformed states

=> superposition of unrelated sequences ?

Deviations from GOE & hidden symmetries

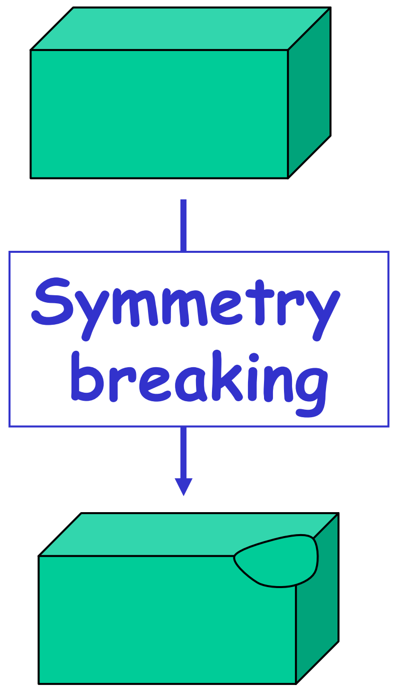
1400 accoustic resonances in quartz blocks (with 1 point-group symmetry)

C. Ellegaard et al., PRL 77 (1996)



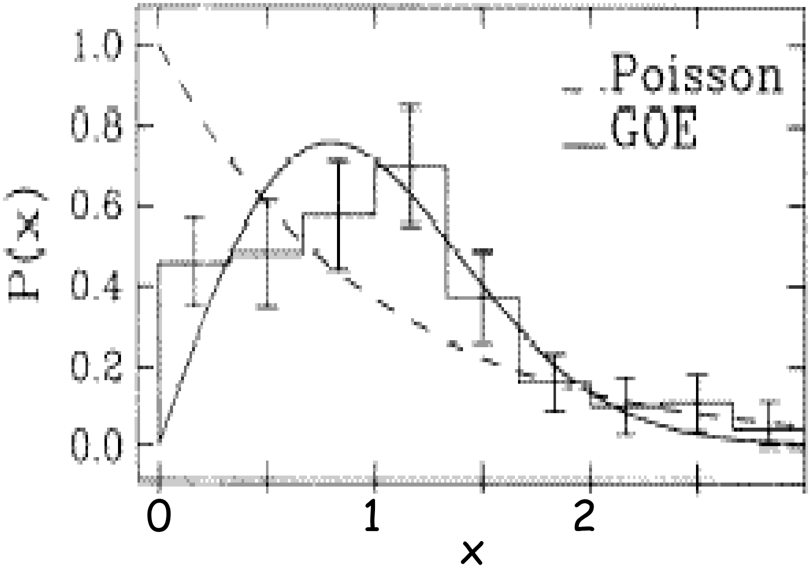
2 noninteracting spectra from 2 GOE matrices

GOE



1st 100 +parity levels in ^{26}Al (E*= 0-8 MeV)

G. E. Mitchell et al., PRL 61 (1988)



N=Z odd-odd nucleus: T=0 & T=1 states coexist at all energies

=> NNS distribution intermediate between 1 & 2 GOE

Coupled random matrix calculations:

=> 3% isospin mixing
=> <Coulomb matrix element>~20 keV

T. Guhr, H.A. Weidenmüller, Ann. Phys. (1990)
M.S. Hussein, M.P. Pato, PRC 47 (1993)

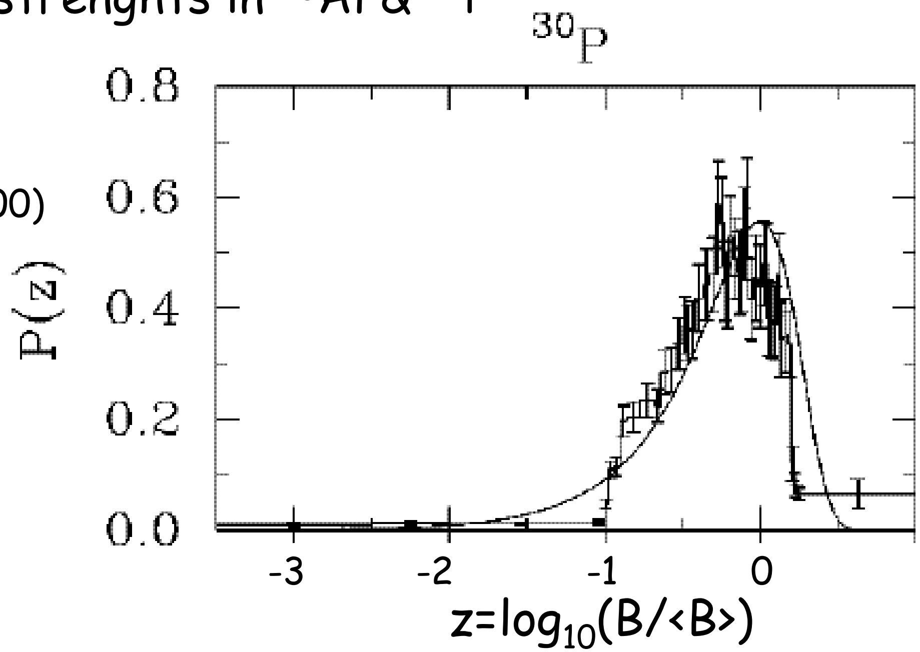
distribution of electromagnetic transition strenghts in ^{26}Al & ^{30}P

=> deviation from Porter-Thomas

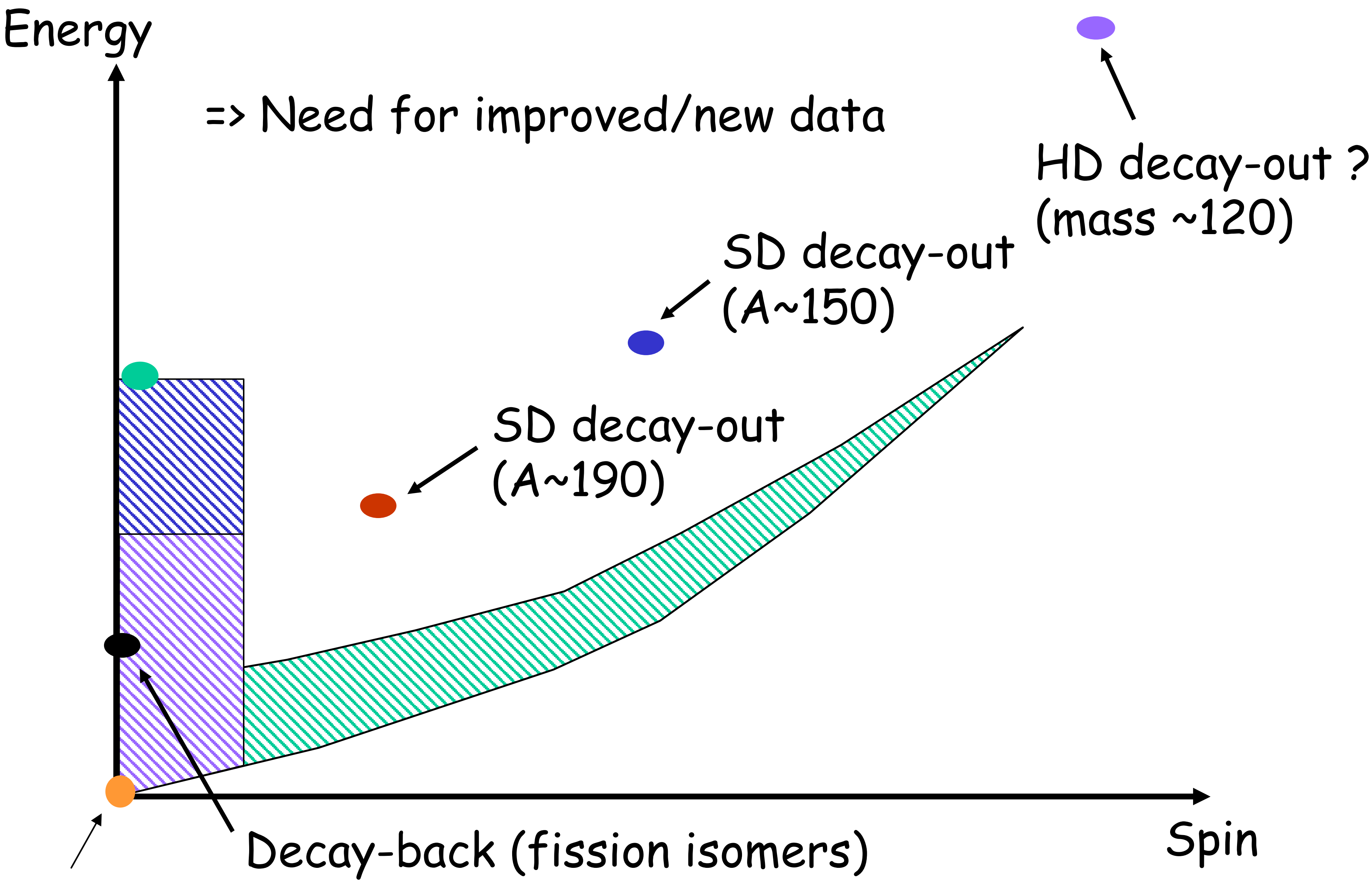
A.A. Adams et al., PLB 422 (1998)
J.F. Shriner, C.A. Grossmann, G.E. Mitchell, PRC62 (2000)

Consitent with recent theoretical work

C.I. Barbosa, T. Guhr, H.L. Harney, PRE 62 (2000)
M.S. Hussein, M.P. Pato, PRL 84 (2000)



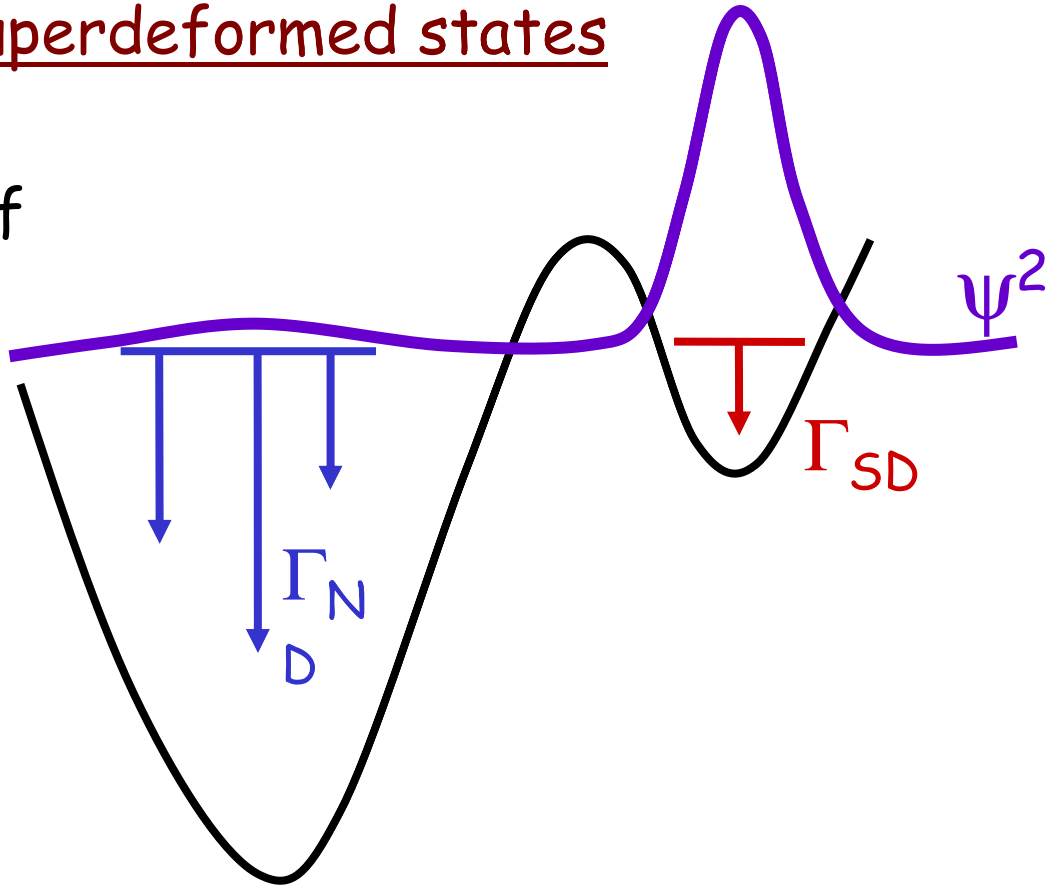
Status of « chaoticity » investigations



O. Bohigas and P. Leboeuf, PRL 88 (2002)

Decay from superdeformed states

decay-out occurs because of weak coupling to ND states through a potential barrier



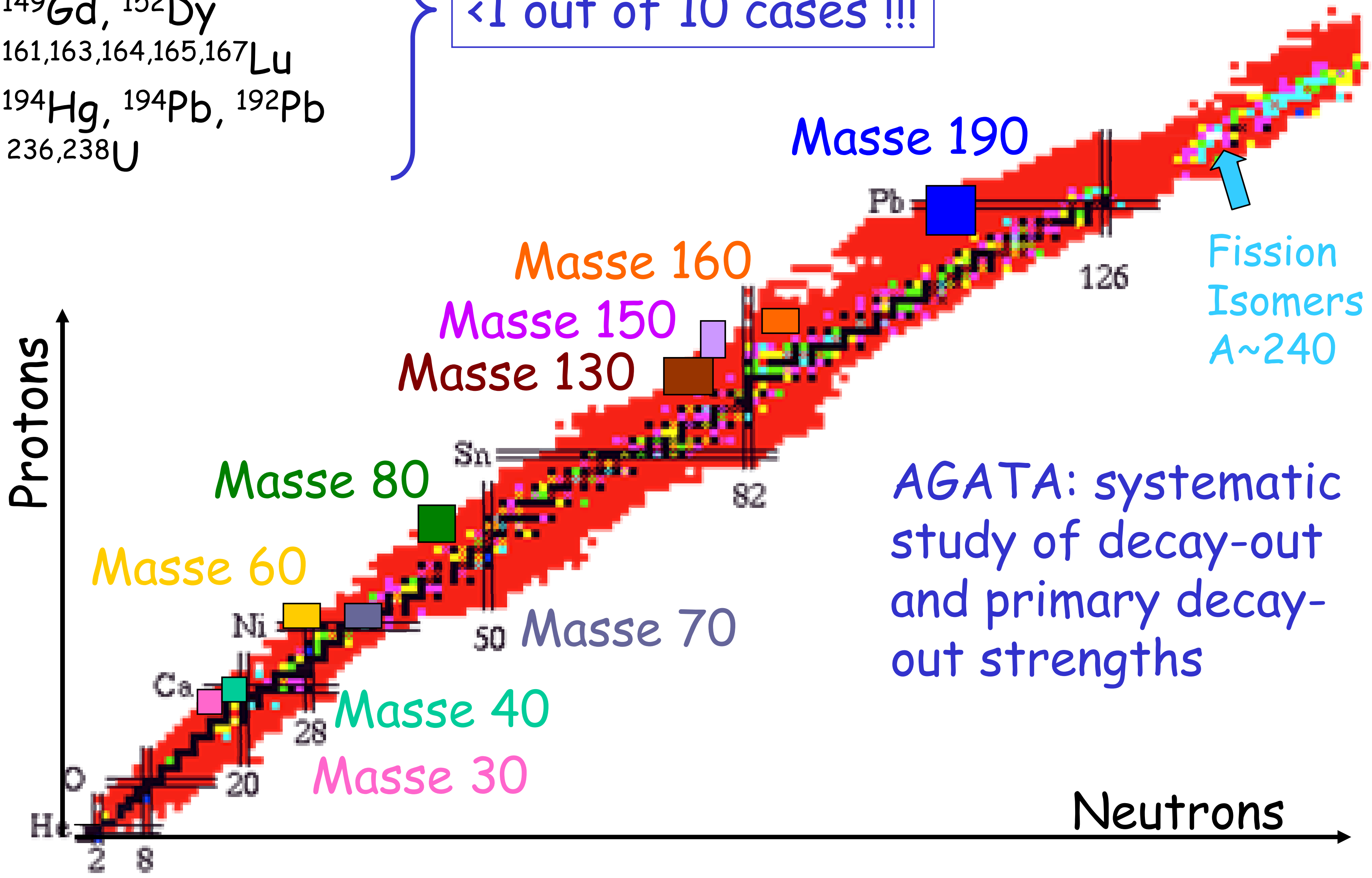
=> what is observed is the decay of excited ND states

highly deformed rotational bands provide states of well defined (E,I,π) which can act as probes of the ND spectrum

Cases for which $(E,I,\pi)_{SD}$ is known from γ-ray spectroscopy:

- ^{36}Ar, ^{40}Ca
- ^{60,61}Zn, ^{58,59}Cu, ^{56}Ni
- $^{132-137}$Nd
- ^{149}Gd, ^{152}Dy
- ^{161,163,164,165,167}Lu
- ^{194}Hg, ^{194}Pb, ^{192}Pb
- ^{236,238}U

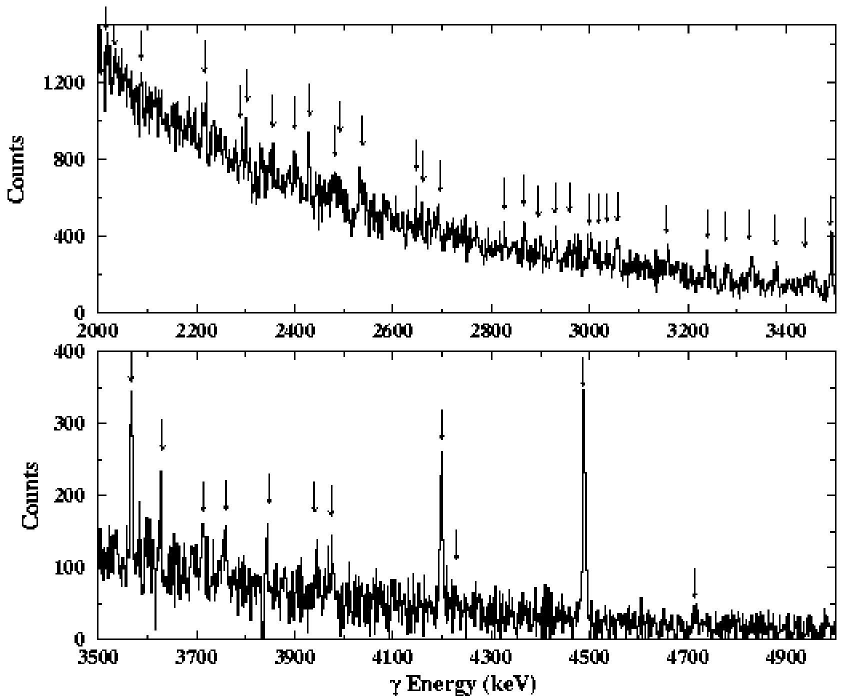
<1 out of 10 cases !!!



AGATA: systematic study of decay-out and primary decay-out strengths

Primary decay-out strength analysis in ^{194}Hg

(high statistics Gammasphere experiment)



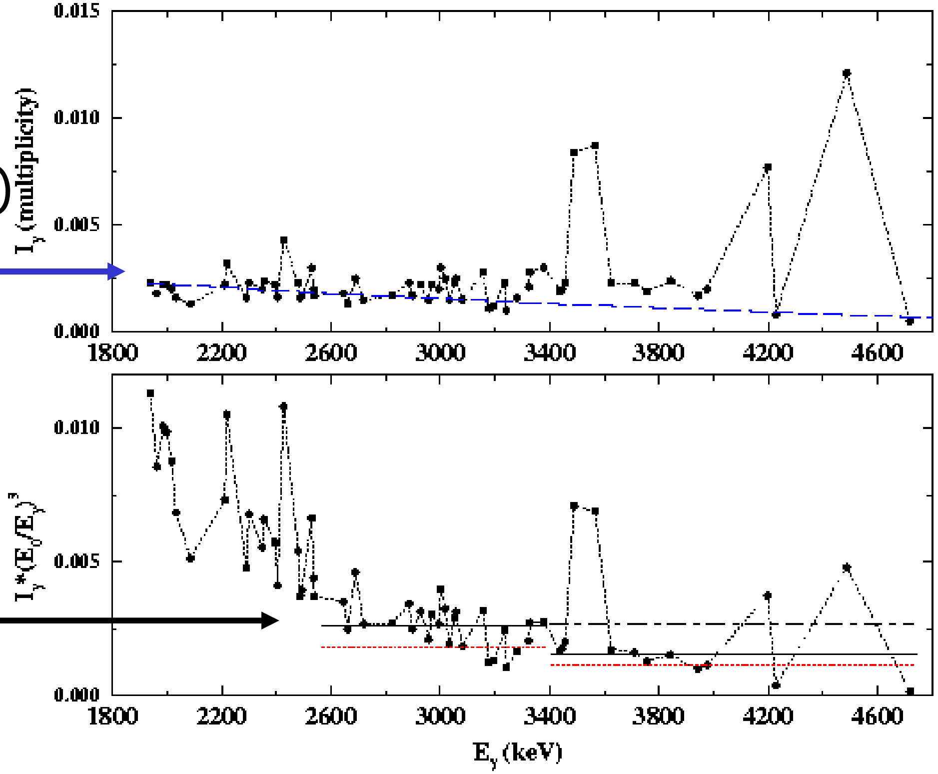
ideally, one should identify primary lines from their coincidences and determine their E&M nature and multipolarity

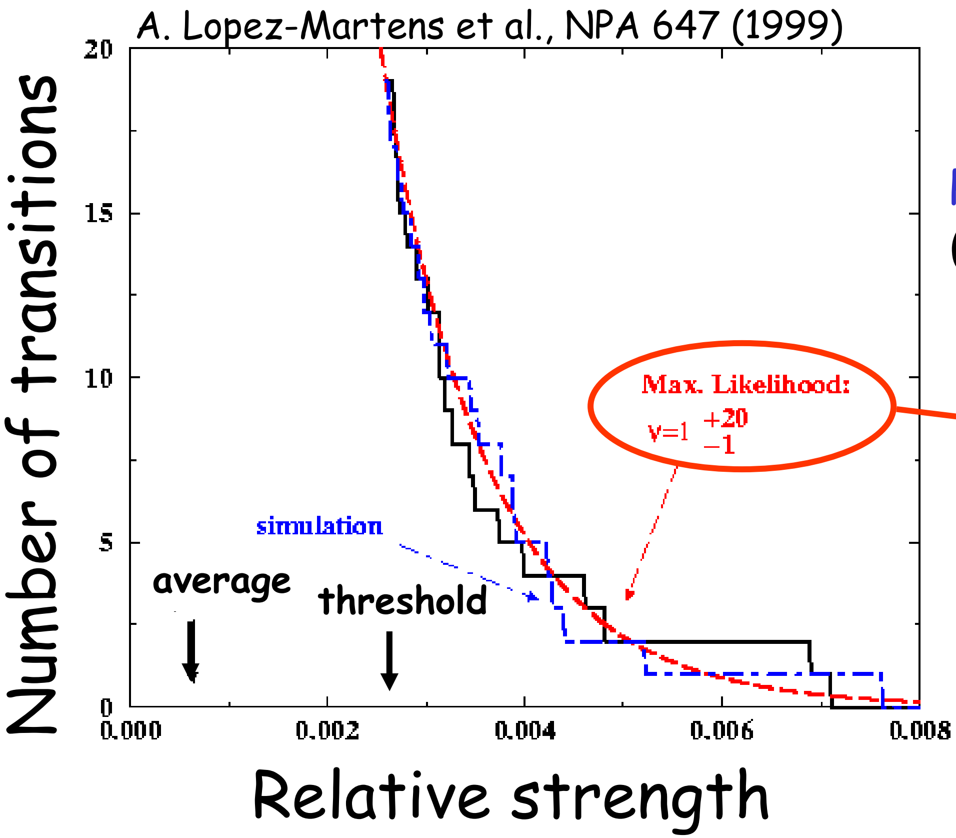
lack of statistics in ^{194}Hg
=> all discrete lines > 2.6 MeV = primary E1's

40 lines identified
(Fluctuation Analysis => 600 primary lines)

32 > 3σ limit

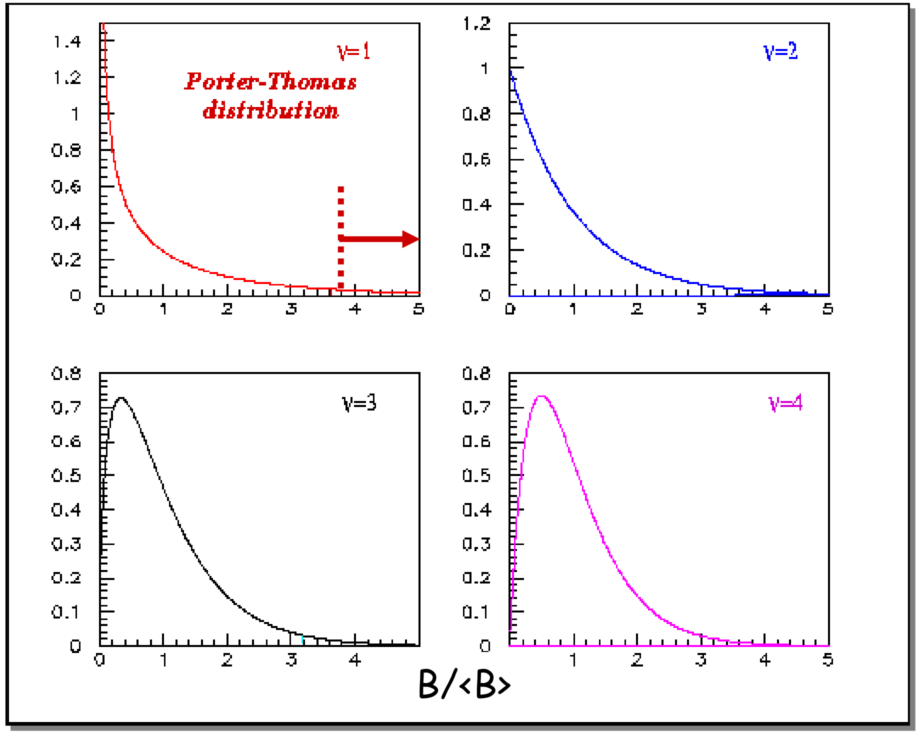
19 > strength threshold





Porter-Thomas distribution: most likely
(extrapolation of most likely distribution
to the origin => 400 primary lines)

Large error bar !

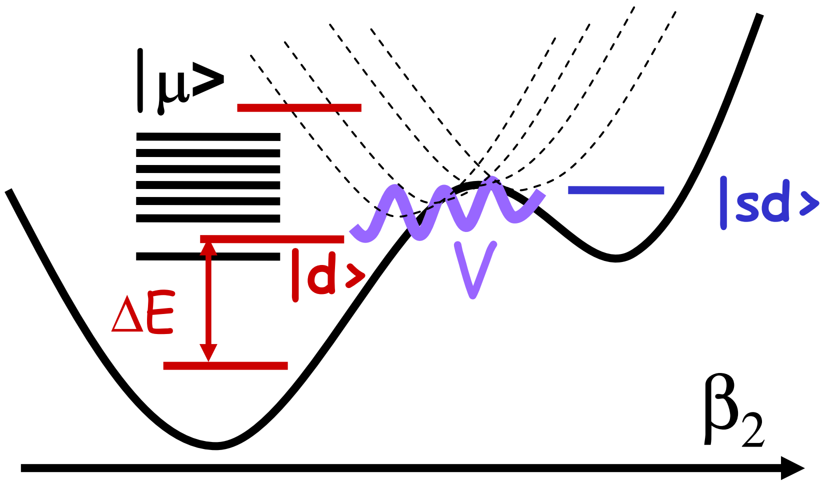


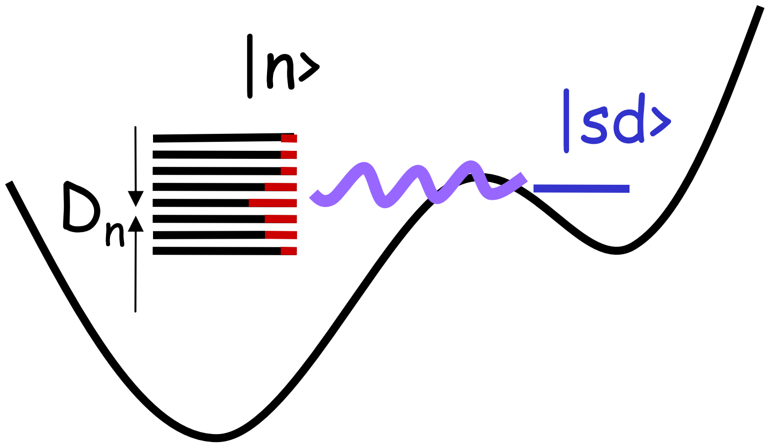
threshold = 3.8 x average strength

=> Only the tail of the distribution is accessible

Onset of « Chaos » & tunneling enhancement

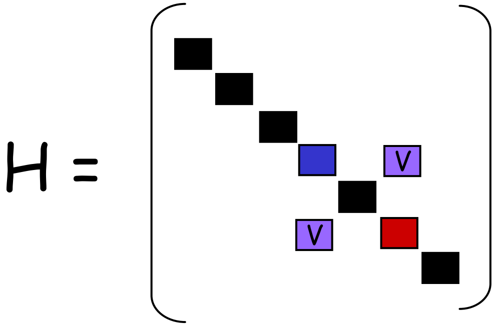
S. Åberg, PRL 82 (1999)

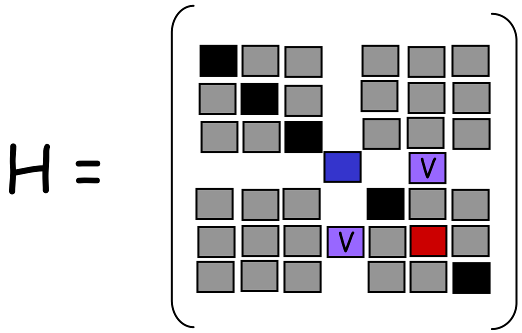




off diagonal elements = 0

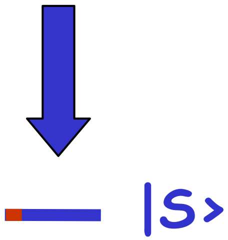
off diagonal elements = GOE

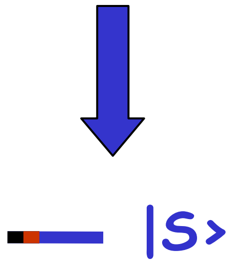




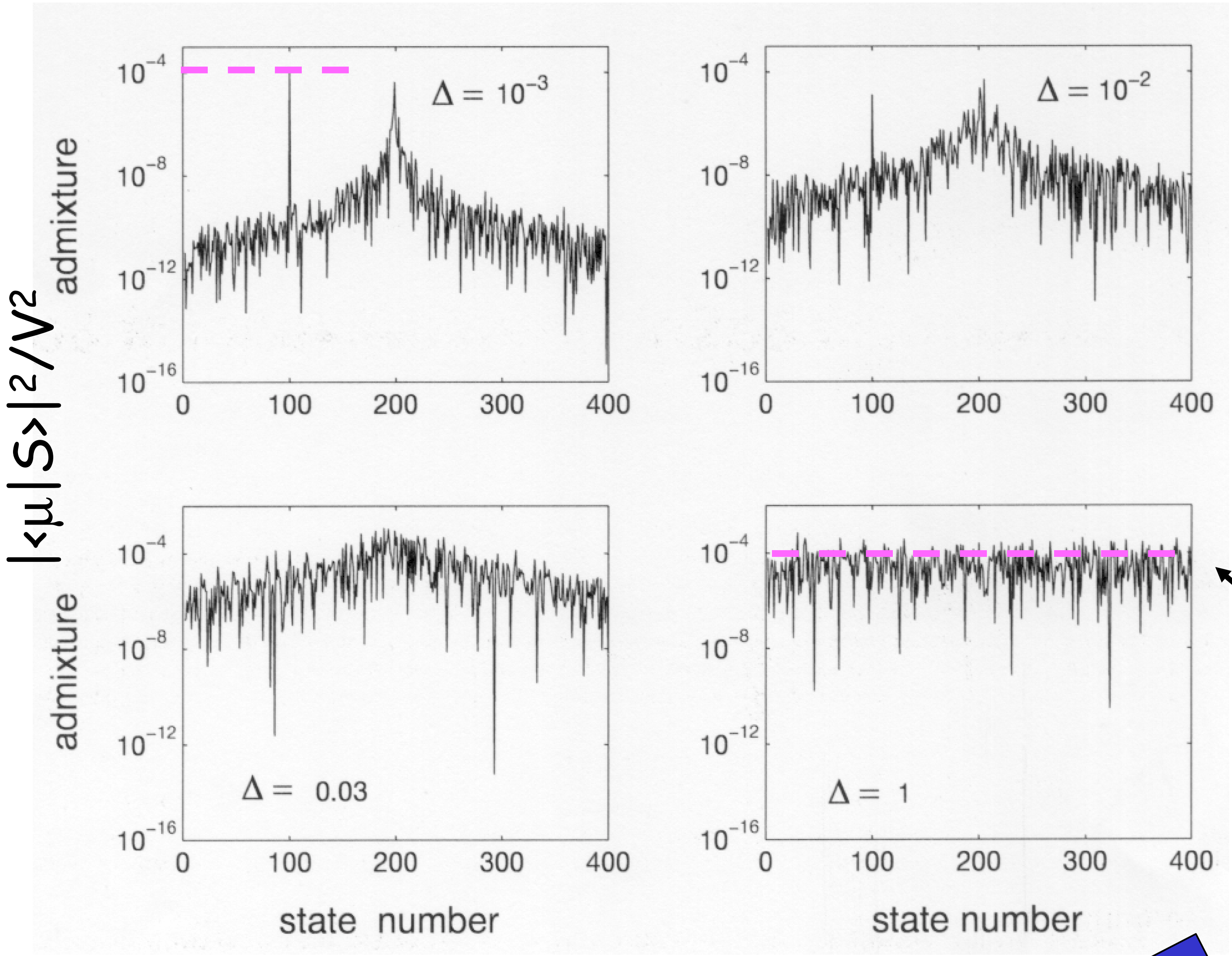
size =NxN

$\Delta = 0$ ⟶ $\Delta = 1$





T. Døssing et al.

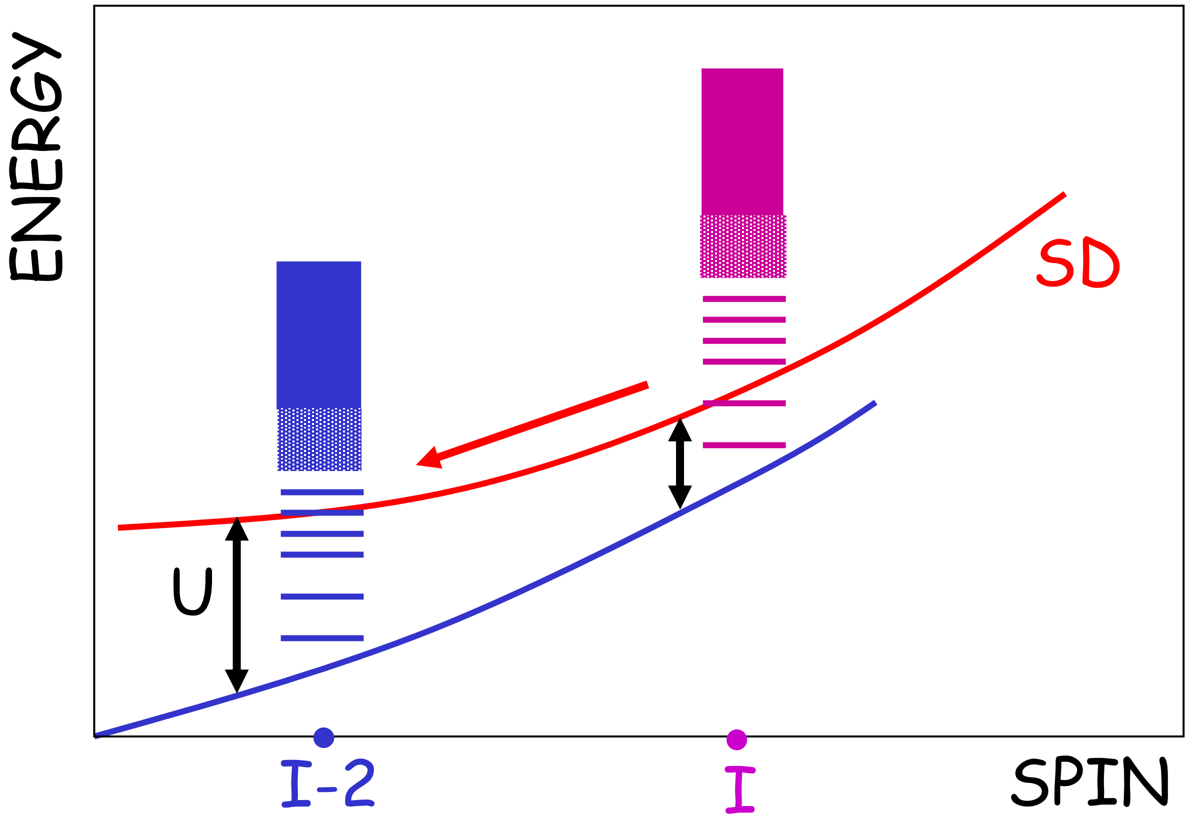


$N_{SD}=N/2$
$N_{door}=N/4$

N states contribute with the same admixture

« Chaos » assisted tunneling

Consequences of the onset of « chaos »



- increasing tunneling probability as I -> I-2
- large decay-out strength fluctuations

=> analysis of decay-out strengths at 2 consecutive spins

=> alternative explanation for the sudden decay out ?

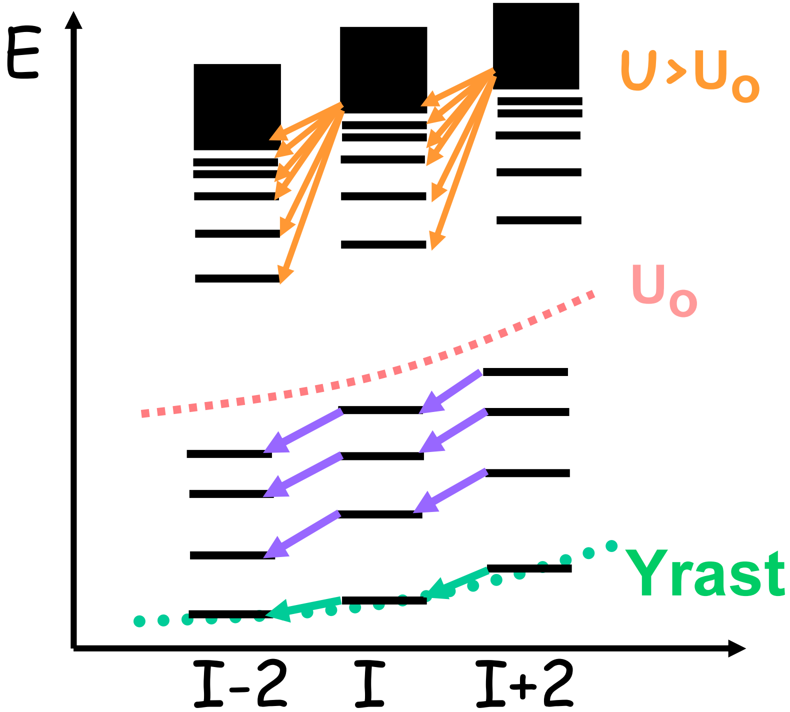
Onset of « chaos » & rotational damping

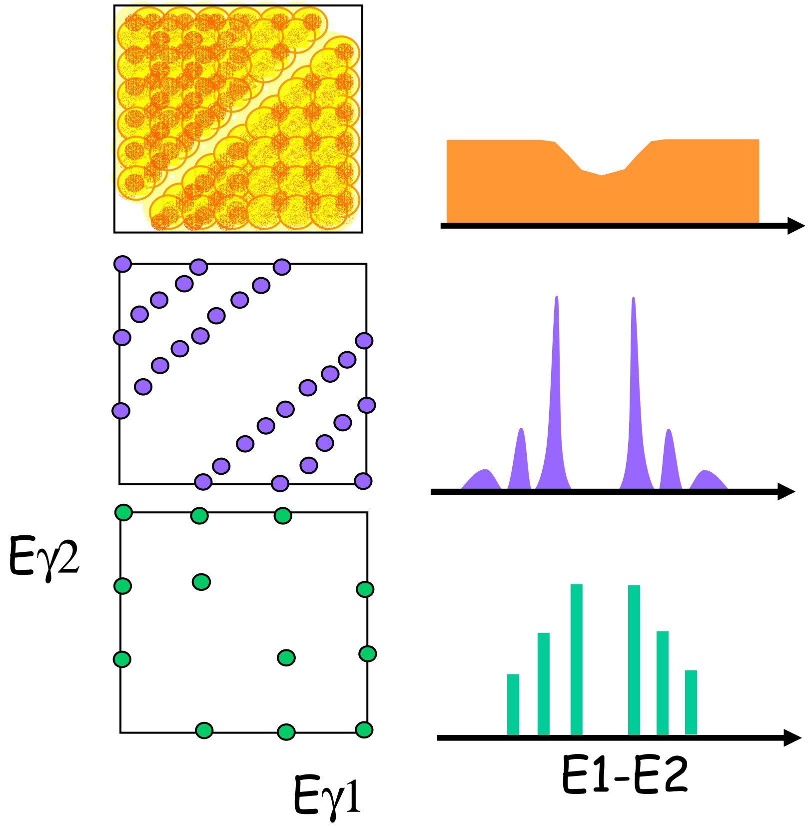
quasicontinuum γ-ray spectroscopy:

• « E2 bump » studies => rotational motion with full collective strength extends to very high I

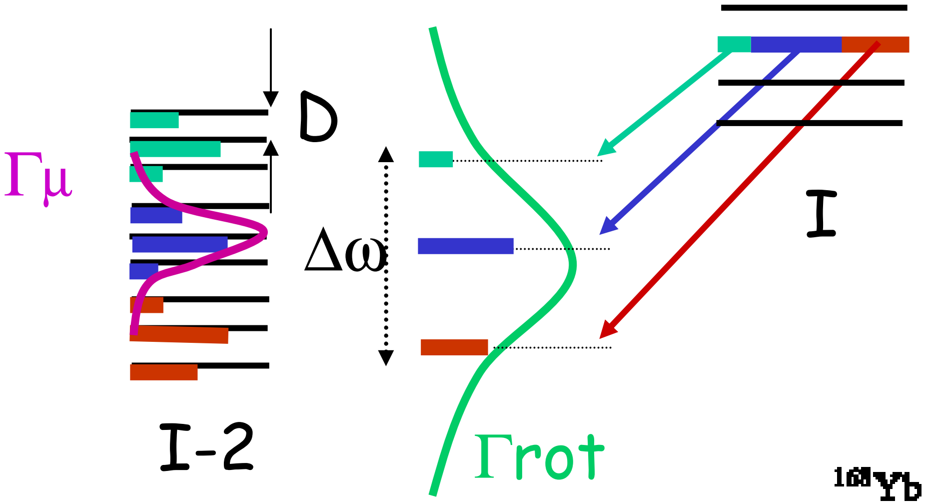
• 2-D Eγ1.Eγ2 correlations: weaker correlations in the quasicontinuum => damping of rotational motion

* 3-D correlations + count fluctuation + covariance analyses => better picture of the γ-decay of rotating nuclei





Microscopic origin of rotational damping



As U increases, ρ(U) ↗

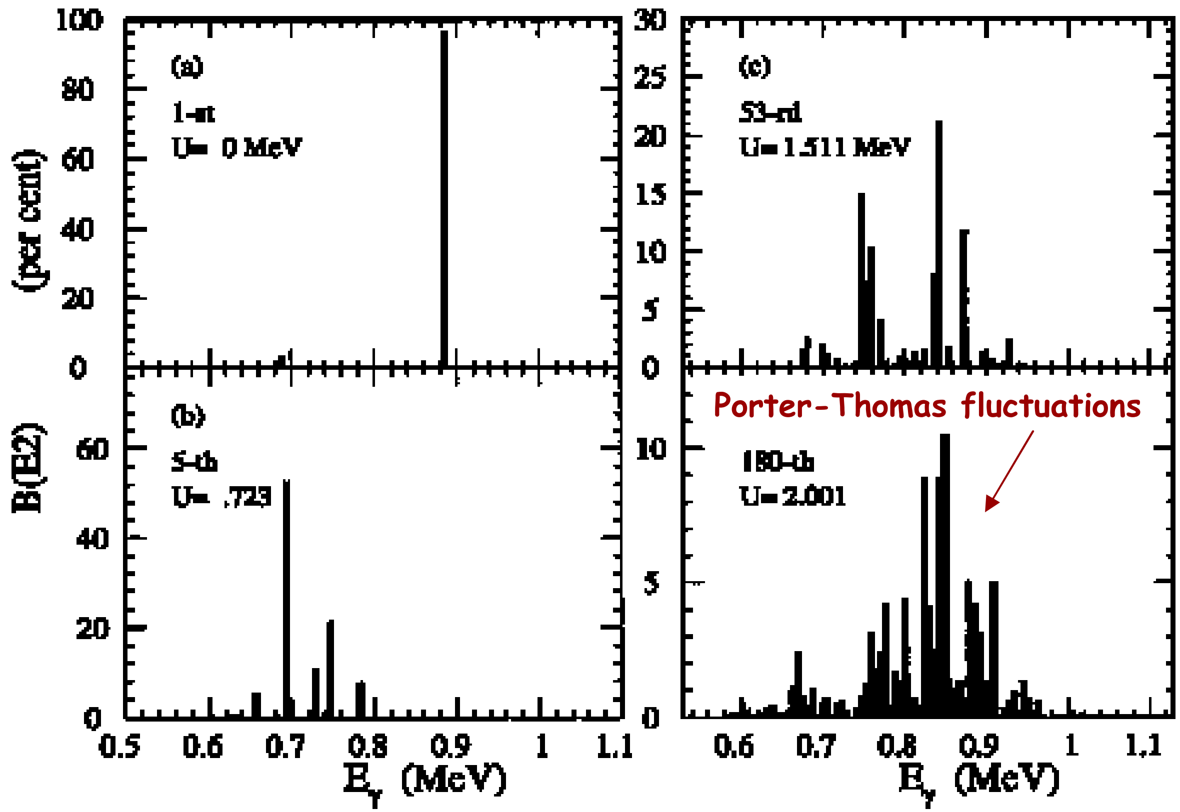
=> residual interaction mixes np-nh states with different rotational properties

=> fragmentation of the E2 strength

Cranked Nilsson mean field
+
SDI
(residual 2-body interaction force)

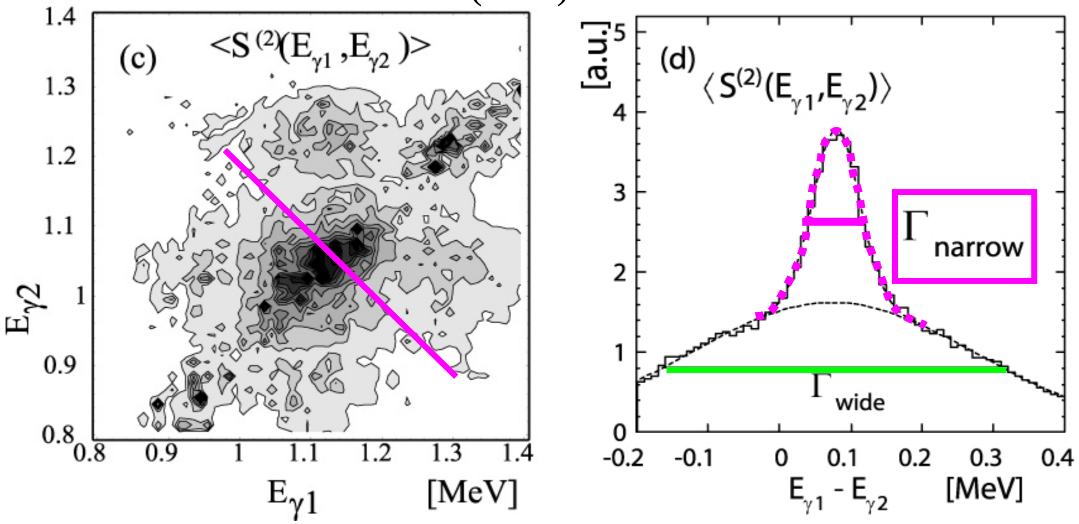
=> Γμ and Γrot have different physical origins

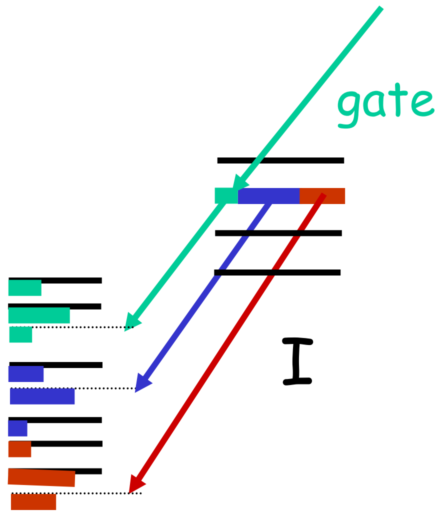
^{168}Yb $I^{\pi}=30^{+}$ M. Matuso, RIKEN Review No. 23 (1999)



Evidence for the effect of Γμ in γ–γ correlations

M. Matsuo et al. PLB 465 (1999)





doorway states maintain the rotational correlation (Γμ < Γrot)
but the correlation is smeared by Γμ

=> can measure both Γrot and Γμ

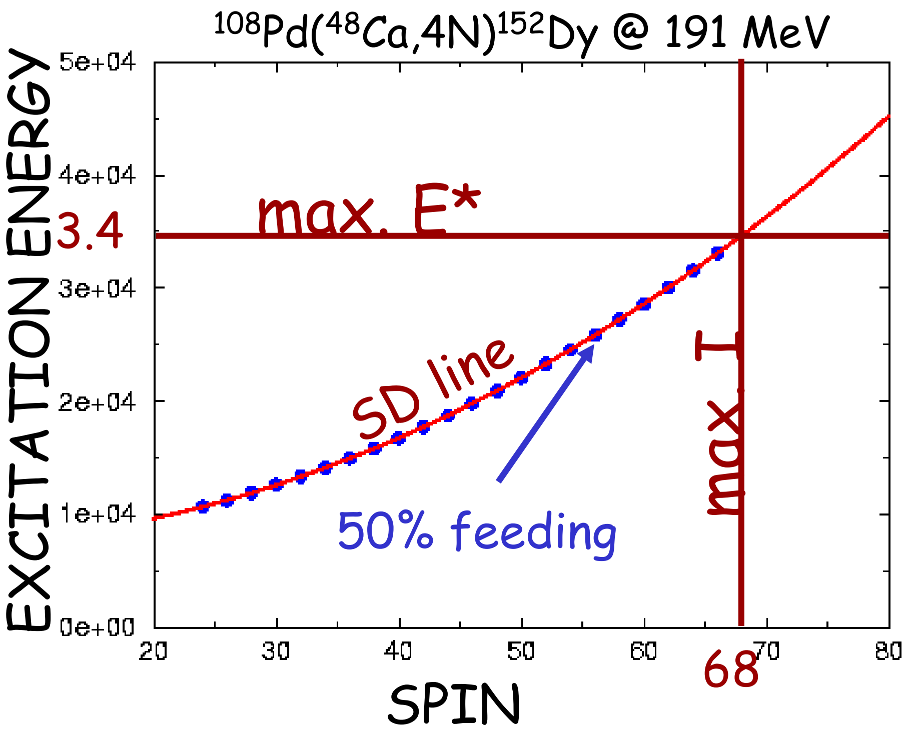
recent example of ^{168}Yb

S. Leoni et al EPJ A4 (1999)
F. Stephens et al., PRL 88 (2002), Frontiers of Nuclear Structure, AIP (2003)

=> can simulate the γ-decay of the warm rotating nucleus with a measured entry distribution

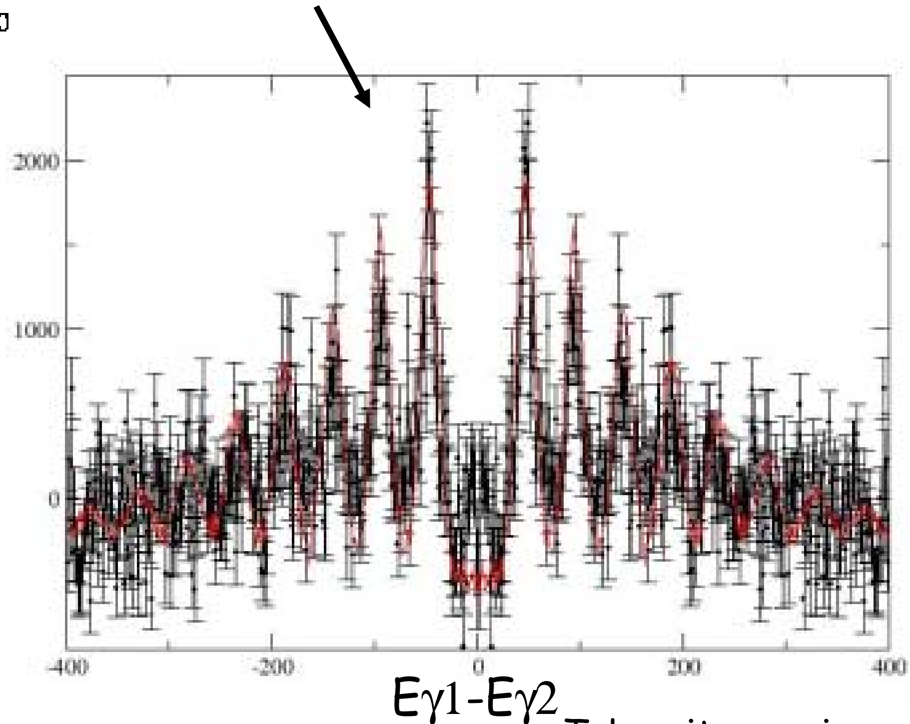
(AGATA=total absorption & multiplicity spectrometer)

Feeding of yrast superdeformed states in 152Dy



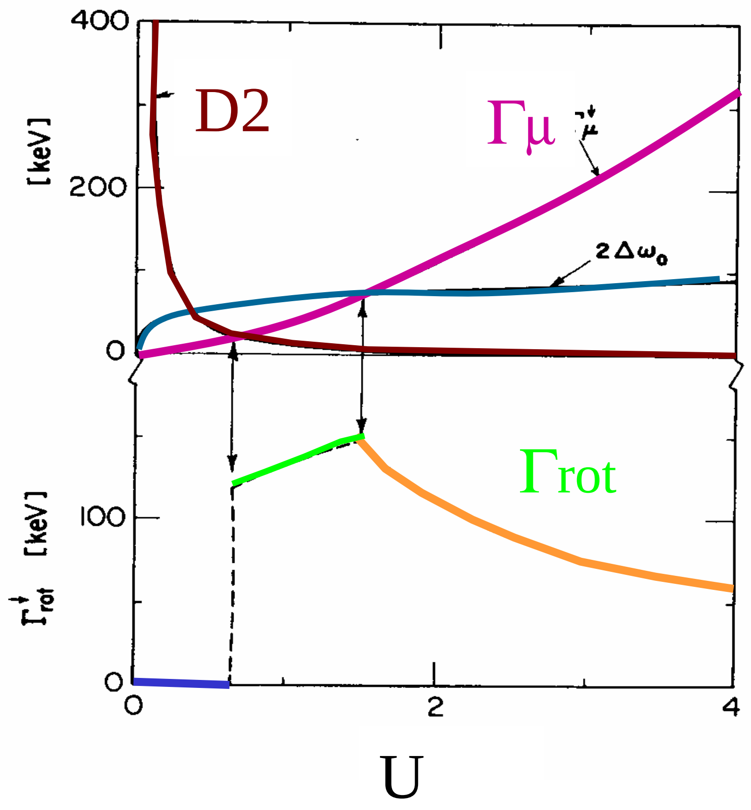
=> would not expect many ridges in coincidence with the yrast SD band

4-5 ridges sitting on a wider structure are observed in coincidence with the SD band !!



T. Lauritsen priv. comm.

=> need to know the entry distribution to understand the population + ridge/valley structure



Γμ < D2 discrete bands

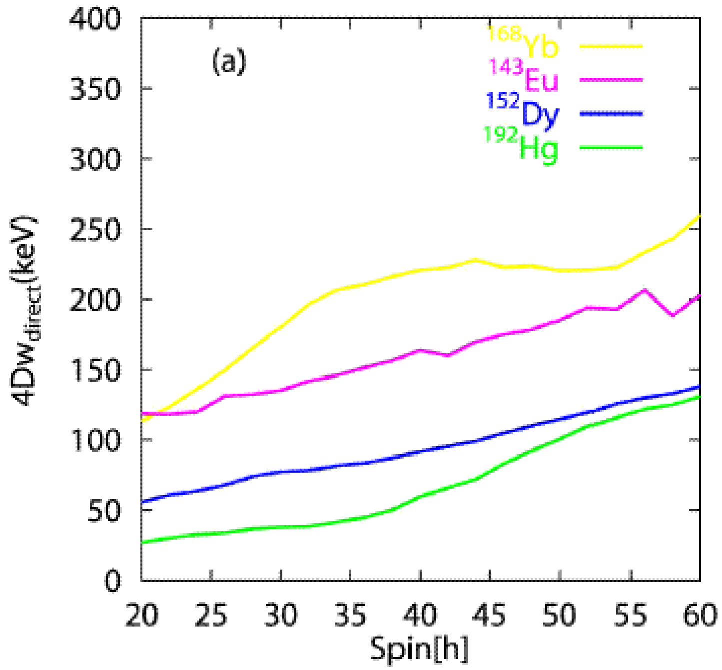
Γμ > D2 onset of mixing

Γμ > 2Δω motional narrowing

Γμ/D >>1 & Γrot/D < 1 **Ergodic bands**

B. R. Mottelson, NPA 557 (1993)
S. Åberg, ZPA 358 (1997)

K. Yoshida and M. Matsuo, NPA A636 (1998)



Where to look for ergodic bands ?

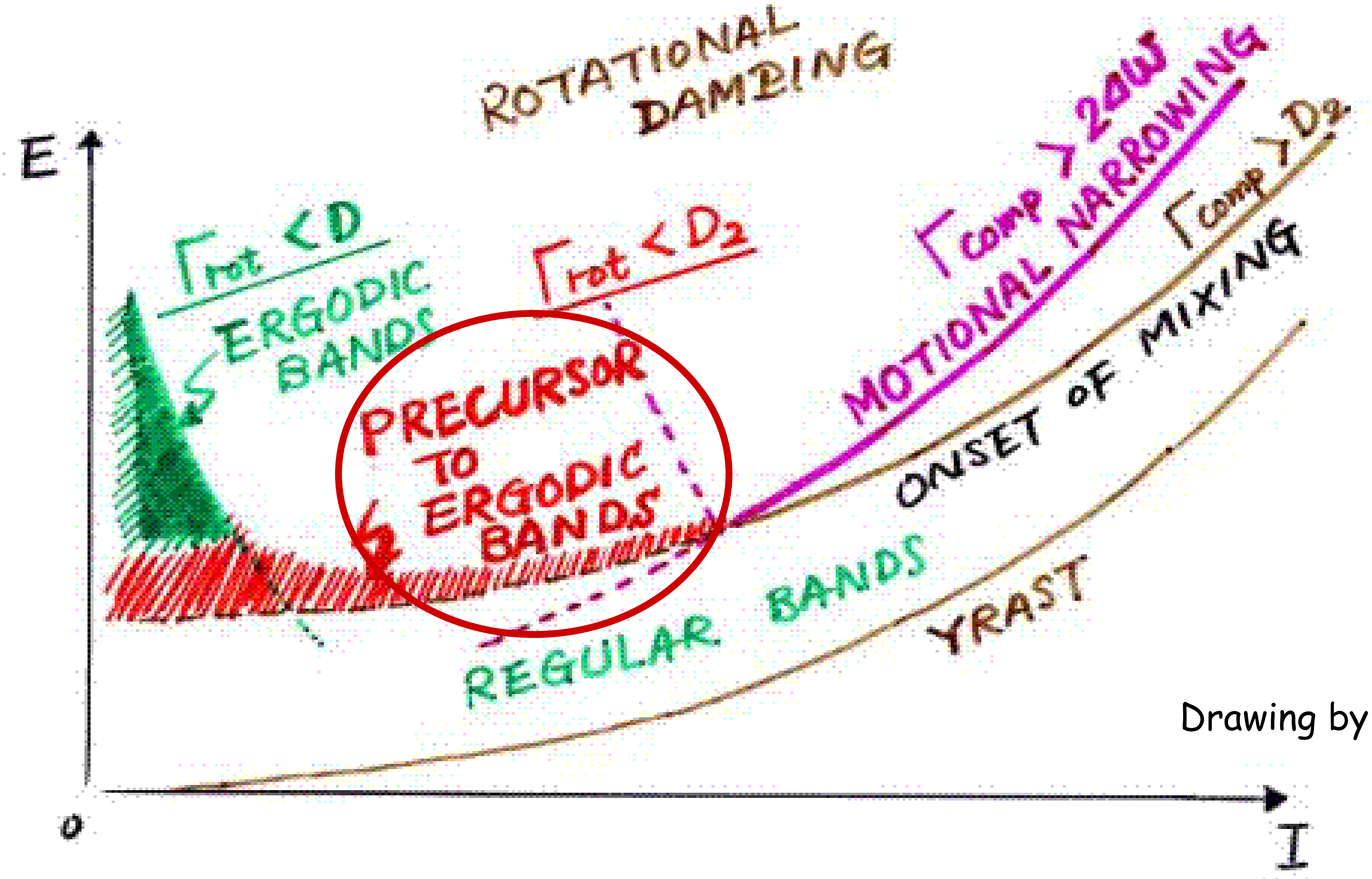
shell effects (level density & alignements)

=> hyperdeformation = favourable case ?
S. Åberg ZPA 358 (1997)

spin effects

Precursor to ergodic bands in 194Hg ?

Gammasphere experiment: 2-3 ridges in coincidence with the yrast SD band
100-150 bands contribute to the ridge
narrow ridges, no or little E2 branching



Drawing by M. Matsuo

Conclusions & perspectives

- ❒ Need for Improved technology to perfom COMPLETE spectroscopy
  => wealth of new data on level spacings and transition strengths
- ❒ Fluctuation properties => order-> « chaos » transition symmetry breaking, microscopic origin of quantum « chaos »,...
- ❒ Decay-out of SD (and HD) bands : new regions of (E,I) to study transition strength statistics & possibility of « chaos »-assisted tunneling
- ❒ Damping of rotational motion: extraction of the compound width & rotational damping width
- ❒ Understand and simulate the features of the γ-cascades emitted from fast rotating nuclei
- ❒ Motional narrowing and ergodic rotational bands