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Warm superdeformed nuclei:

Probes of Nuclear Structure and Tunneling Processes At the Onset of Chaos

Oslo WS – May 2009

Outline:

1- INTRO: Warm Superdeformed Nuclei

2- Experimental Analysis

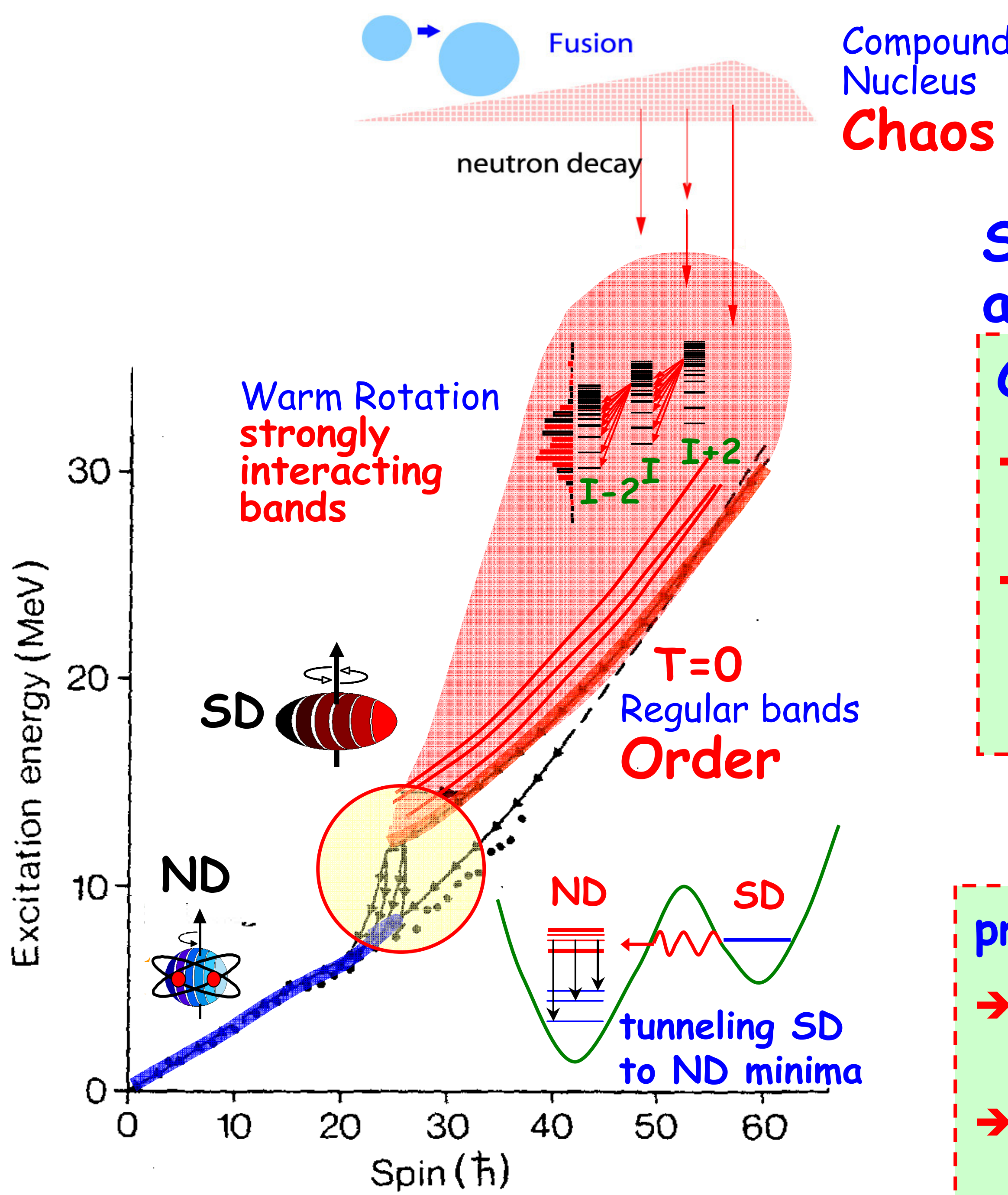
^{151}Tb & ^{196}Pb EUROBALL IV data

3- Theoretical Modelling

Microscopic Monte Carlo simulation

4- OUTLOOK:

Probes of Nuclear Structure
& Potential Barriers



Superdeformation at Finite Temperature

Challenging topic

➔ experiment:
focus on ~1% γ-decay

➔ theory:
cranking at T≠0
coupled to
tunneling to ND well

present status

➔ experiment:
partial infos on ^{143}Eu, ^{152}Dy, ^{194}Hg

➔ theory:
schematic OR many parameters

Aim of this work:

Step forward in Experiment & Theory

EXPERIMENT:

Extensive Study of warm rotation in A=150 and 190: ^{151}Tb and ^{196}Pb

Evaluation of **several** independent experimental oservables

⇒ stringent test of γ-decay flow

THEORY:

Development of new Monte Carlo model

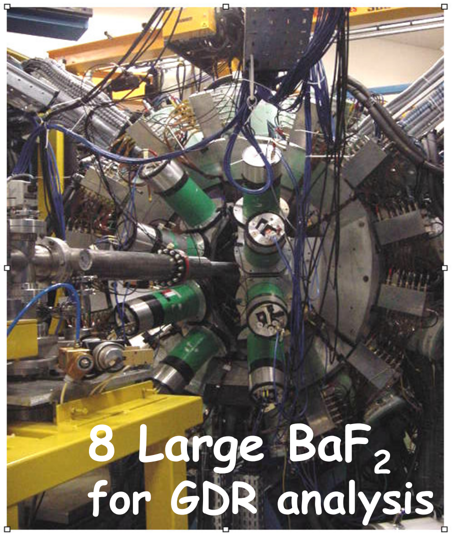
Based on **microscopic calculations**

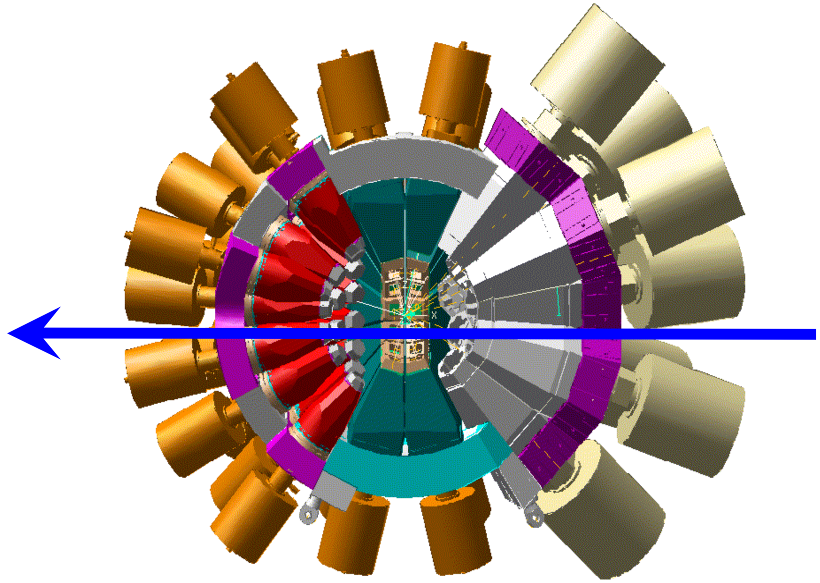
⇒ Towards a parameter "free" model

1- The ^{151}Tb and ^{196}Pb experiments

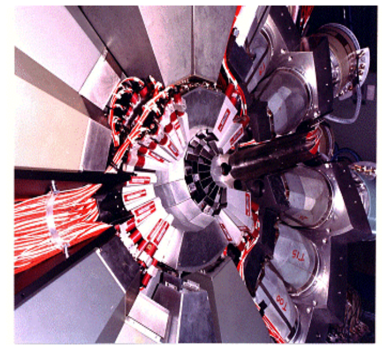
Two High Statistics EUROBALL-IV Experiments
^{151}Tb and ^{196}Pb

HECTOR





BGO INNER BALL
210 detectors



$^{30}Si + ^{170}Er \rightarrow ^{196}Pb + 4n$

Thin target, E_{beam} = 148 MeV, $L_{max} \sim$ 53 $\hbar$

Statistics: 8 days

$\sim 2 \times 10^8$ $\langle F_{Ge} \rangle = 3$

$\langle F_{\gamma} \rangle = 10$

Goals: warm rotation in SD well
(S. Leoni et al., in print in PRL)
GDR in A = 190
(D. Montanari et al., in preparation)

$^{27}Al + ^{130}Te \rightarrow ^{151}Tb + 6n$

Thin target, E_{beam} = 155 MeV, $L_{max} \sim$ 80 $\hbar$

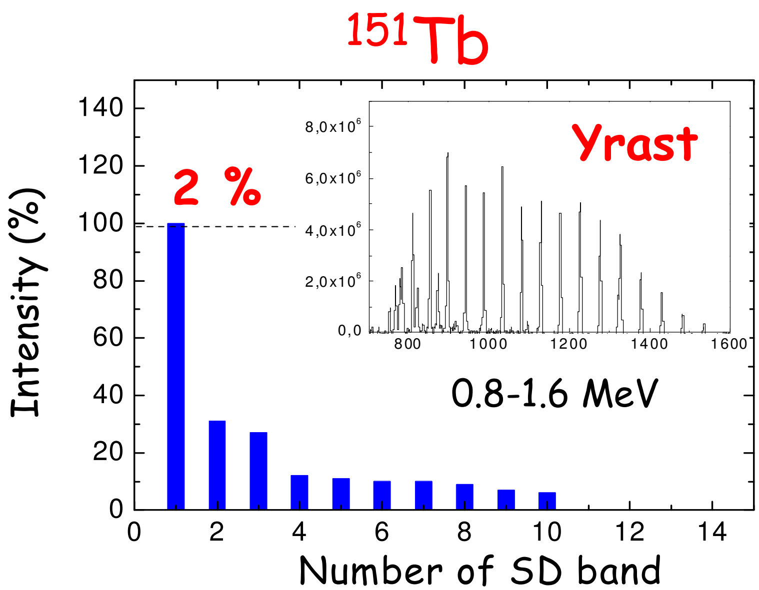
Statistics: 17 days

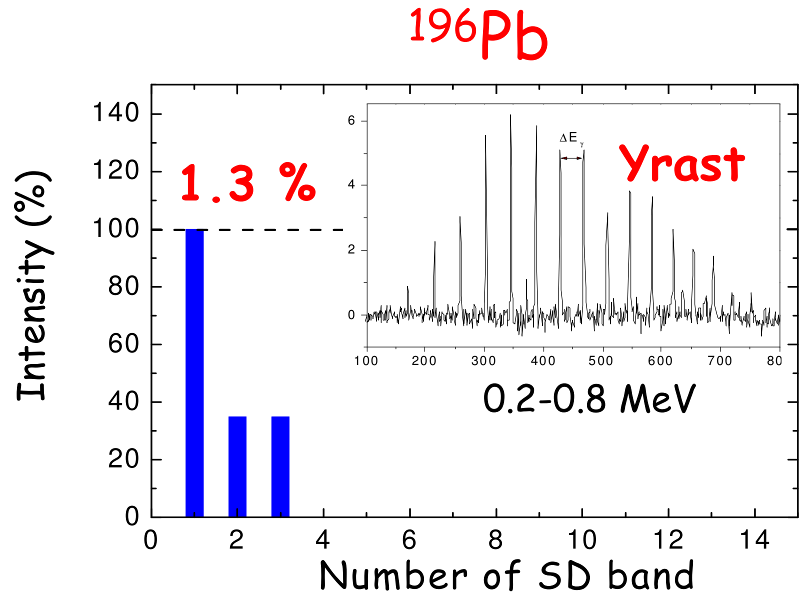
$\sim 9 \times 10^9$ $\langle F_{Ge} \rangle = 5$

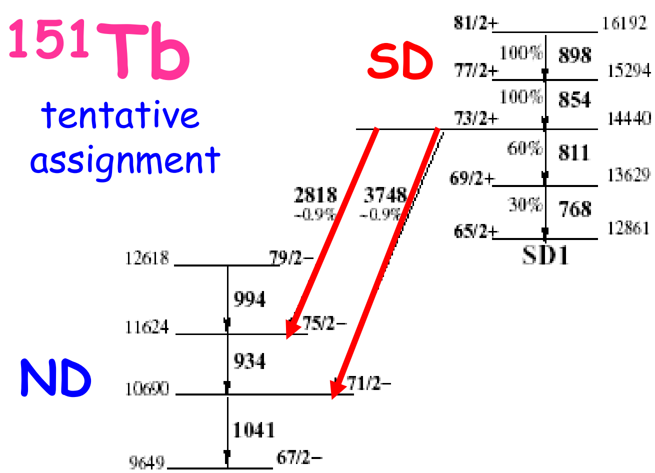
$\langle F_{\gamma} \rangle = 22$

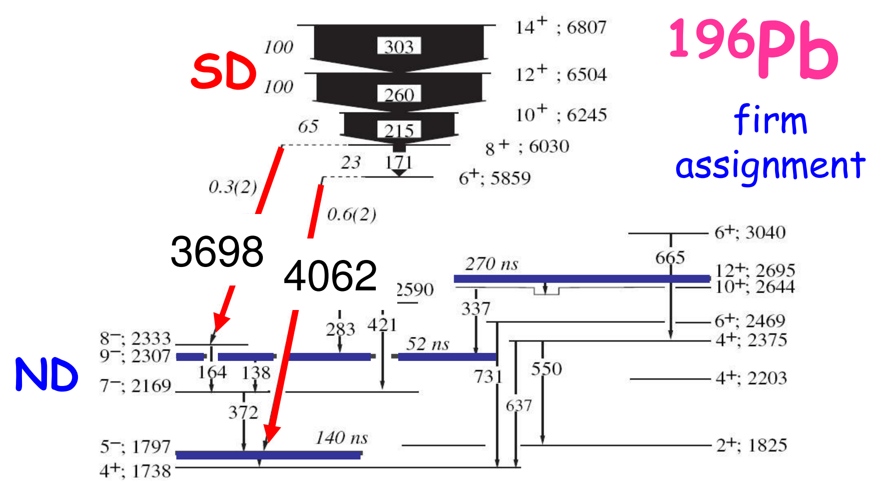
Goals: discrete spectroscopy in SD well
(J. Robin et al., PRC77, 014308(2008)
search for linking transitions SD $\rightarrow$ ND
(J. Robin et al., PRC78(2008)034319)

Discrete Spectroscopy Info's





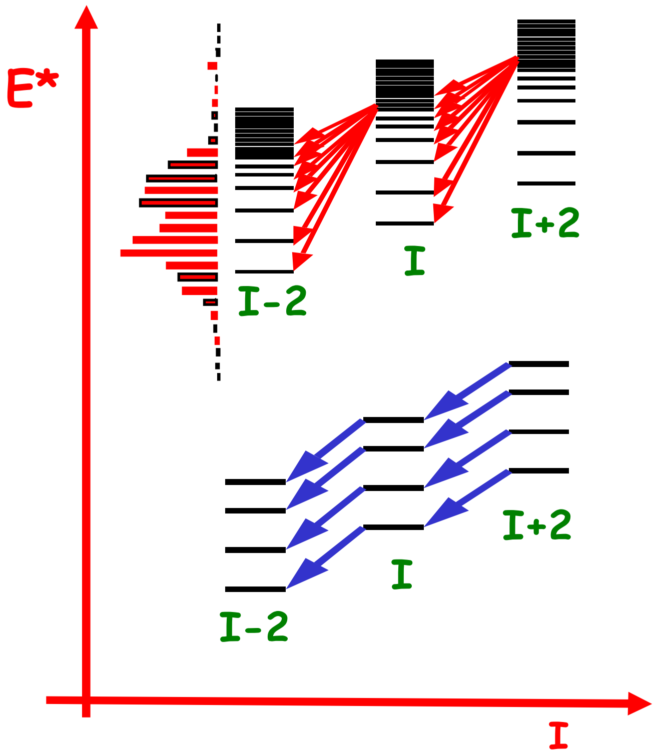


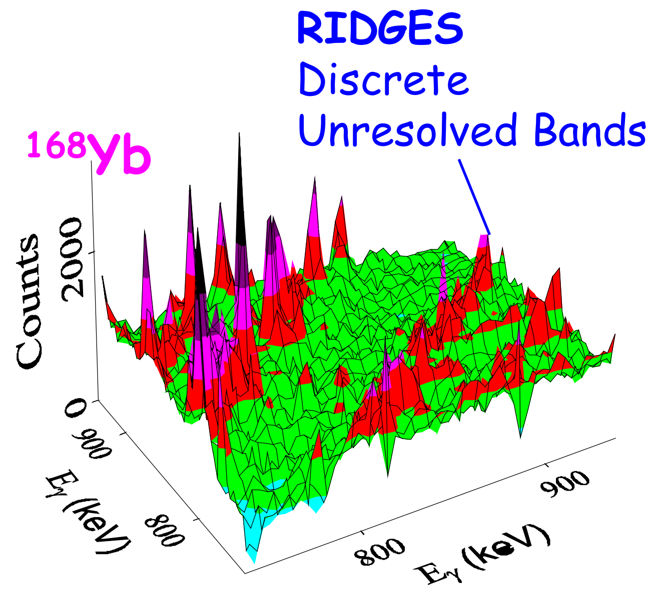


J. Robin et al., Pys. Rev. C78(2008)034319

A.N. Wilson et al., Phys. Rev. Lett. 95 (2005)

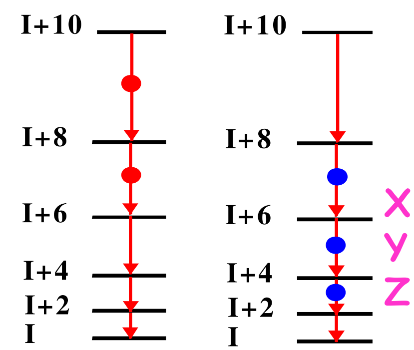
Quasi-Continuum Spectroscopy: Warm Rotation

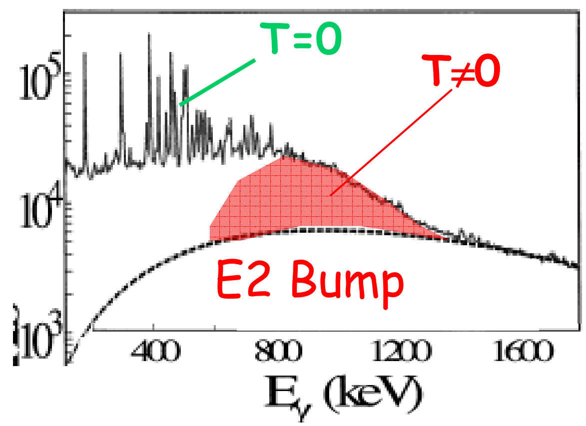




γ–γ spectra
&
rotational planes

$x+y = 2z \pm \delta$





γ spectra

Total E2
Quasi-Continuum

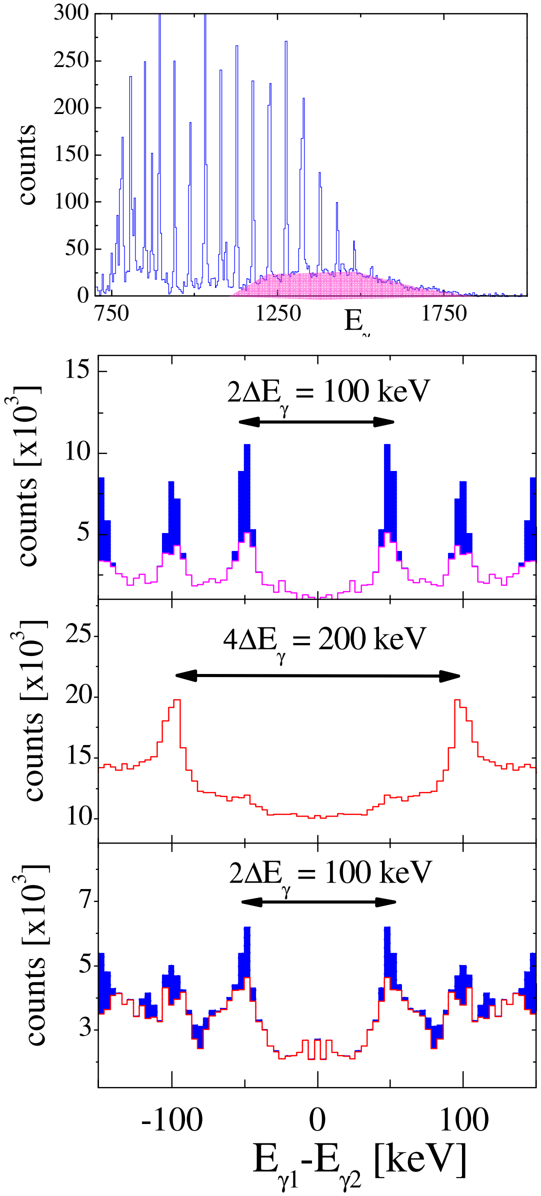
^{151}Tb Analysis

SD gated
γ–spectrum
E2 Bump

SD gated γ–γ
1st Ridge

Rot-Plane
2nd Ridge

Total γ–γ
1st Ridge



Analysis Techniques

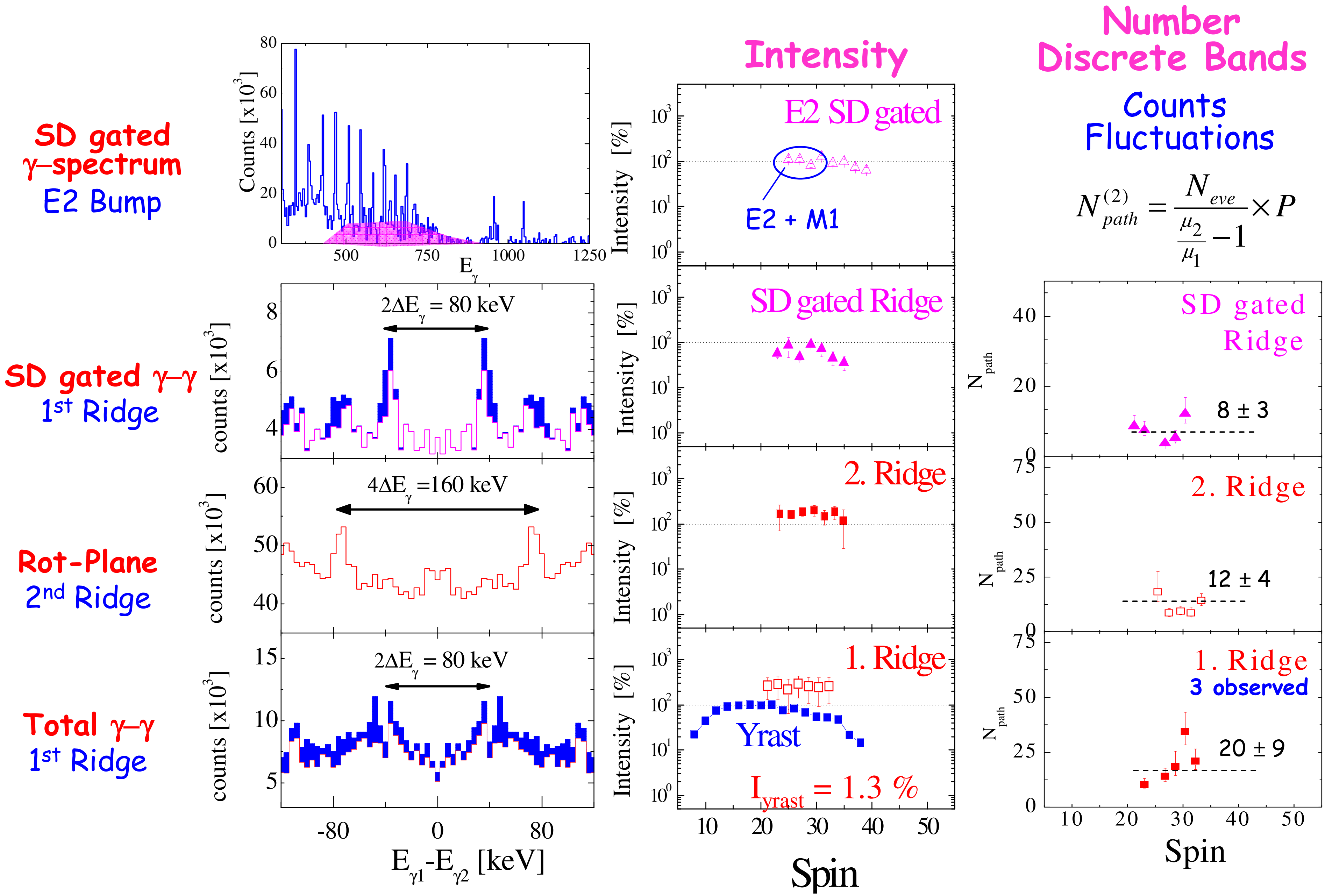
1. **Spectrum Intensity**:
   population

2. **Spectrum Fluctuations**:
   number of bands

Properties of γ-decay flow of SD nucleus

^{196}Pb Analysis

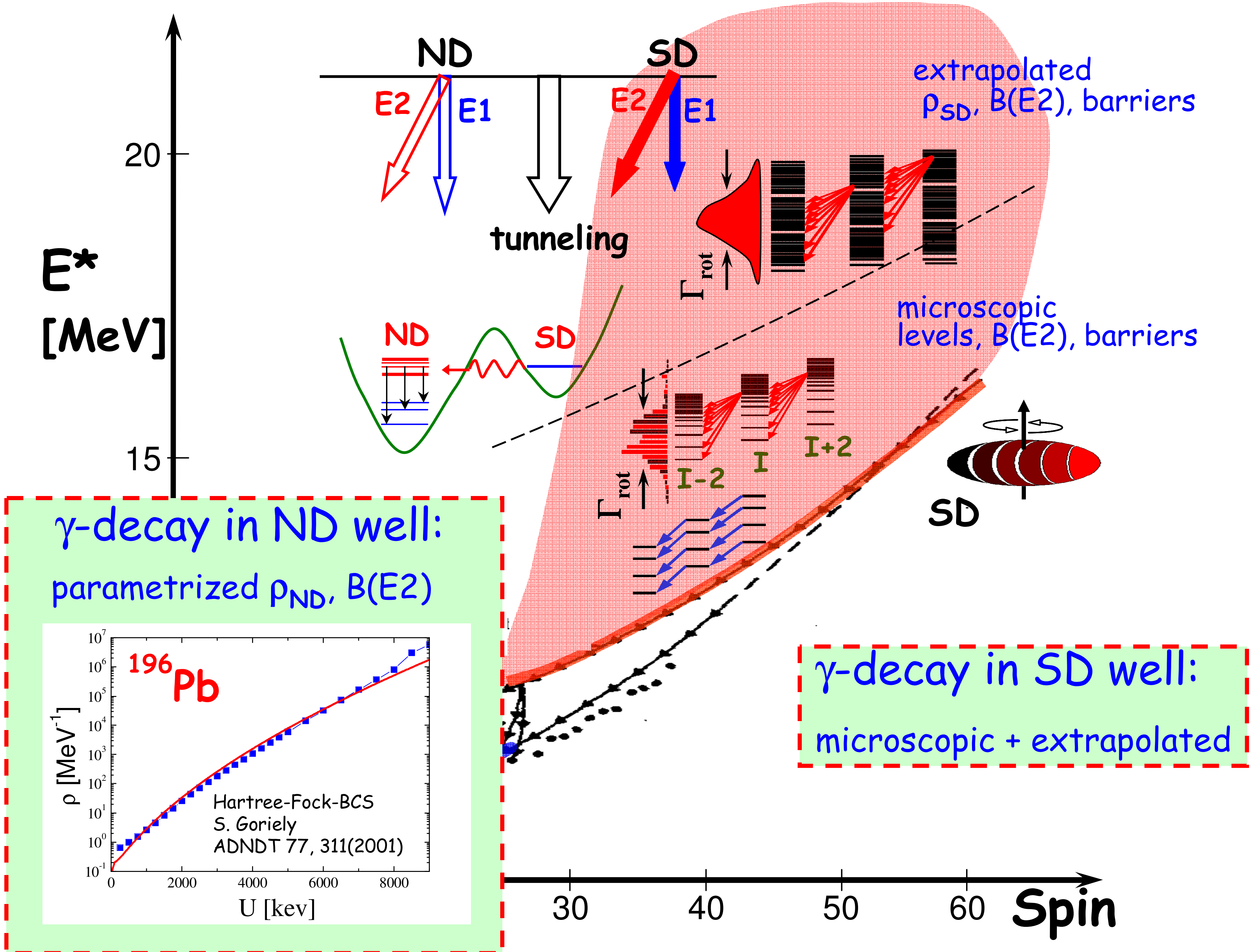
8 independent observables



2- The Interpretation of the DATA

a <u>Monte Carlo</u> simulation of the γ-decay based on <u>microscopic calculations:</u>

Towards a parameter "free" model



ND
SD
E2
E1
E2
E1
tunneling
extrapolated
ρ_{SD}, B(E2), barriers
E*
[MeV]
20
15
ND
SD
Γ_{rot}
Γ_{rot}
microscopic
levels, B(E2), barriers
I-2
I
I+2
SD
γ-decay in ND well:
parametrized ρ_{ND}, B(E2)
^{196}Pb
ρ [MeV^{-1}]
Hartree-Fock-BCS
S. Goriely
ADNDT 77, 311(2001)
U [kev]
γ-decay in SD well:
microscopic + extrapolated
30
40
50
60
Spin

Microscopic calculations entering the Monte Carlo:

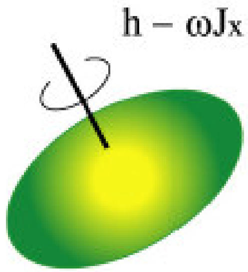
1. Interacting cranked shell model

   K. Yoshida, M. Matsuo, NPA612(1997)126

2. Microscopic Barriers & Tunneling Actions

   K. Yoshida, M. Matsuo and Y. Shimizu, NPA696, 85(2001)

Cranked Shell Model at T≠ 0



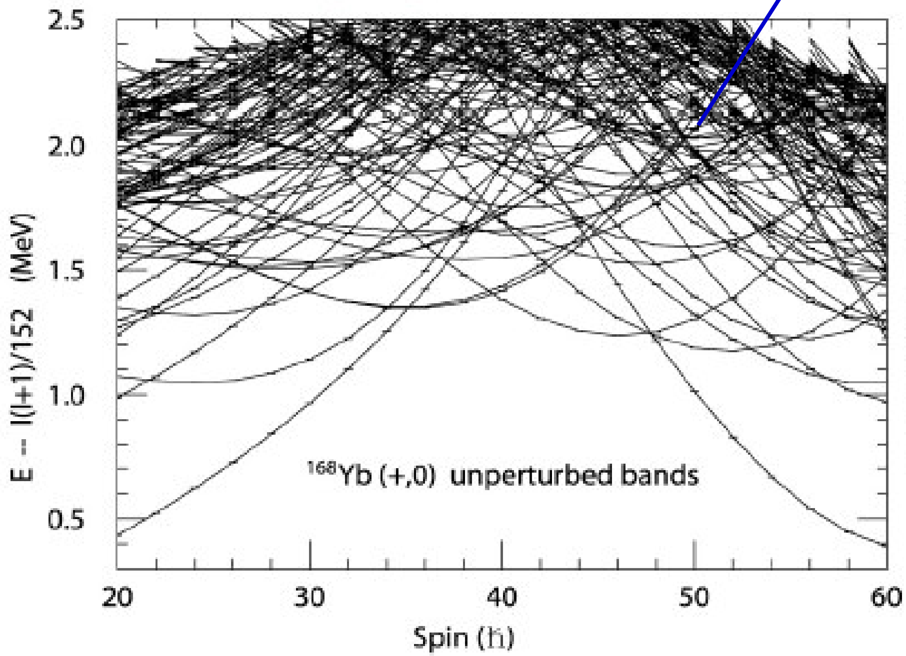
- Cranked Nilsson potential
- Surface delta interaction

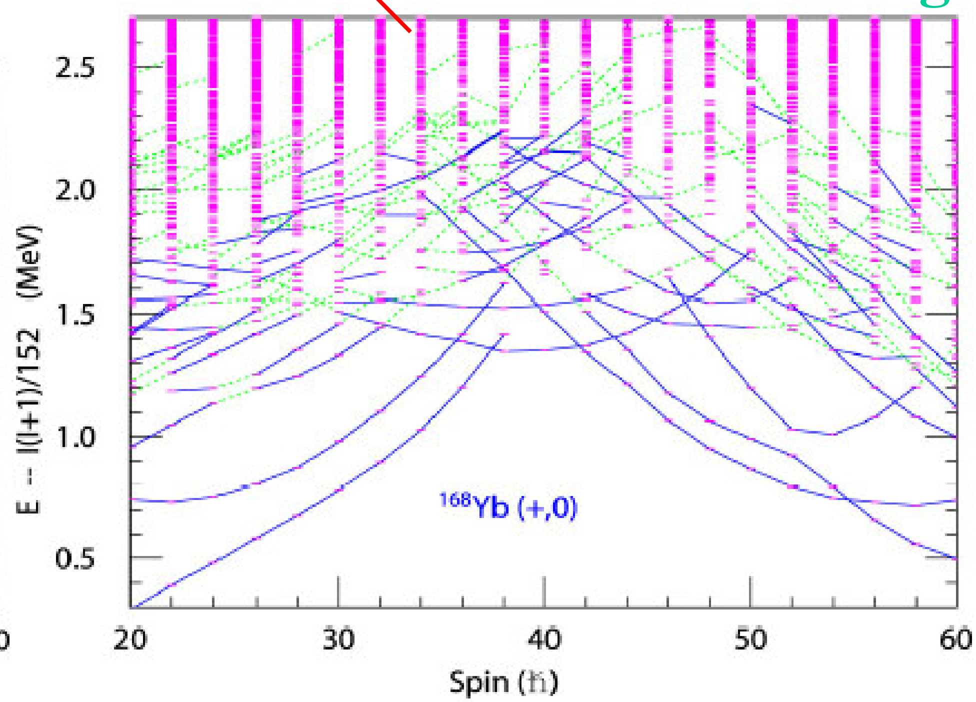
M. Matsuo et al. Nucl. Phys. A617(1997)1

$$H = H_{def} - \omega J_x + V_{res}$$

Cranking np-nh basis bands

Configuration mixing

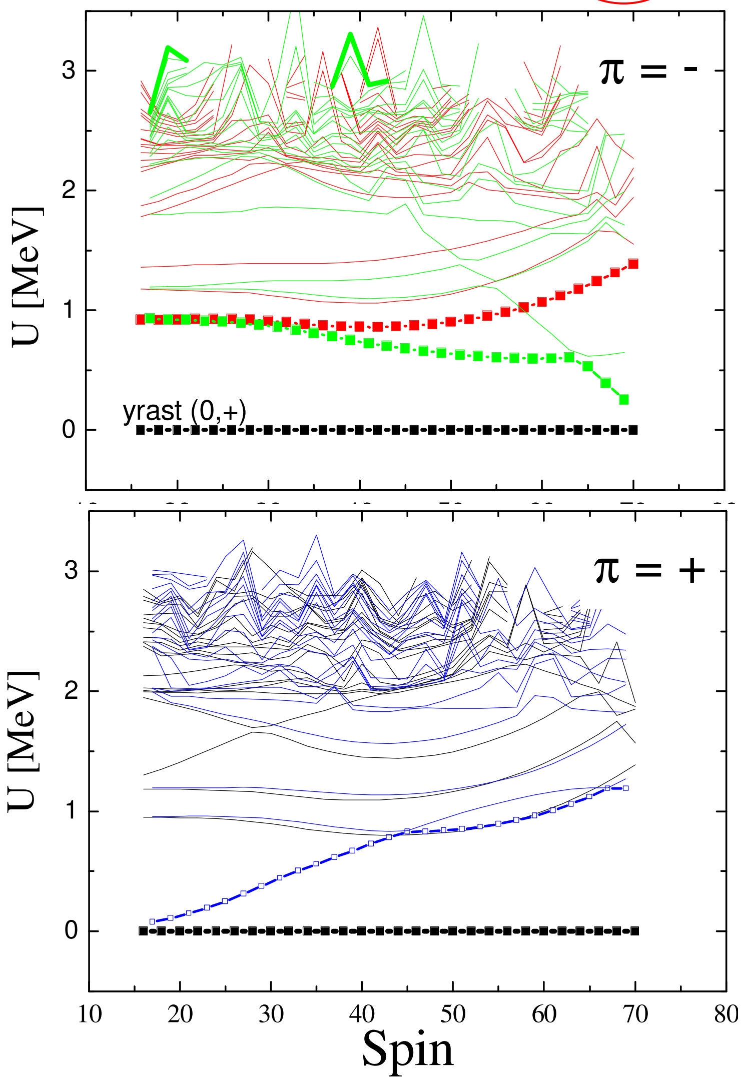




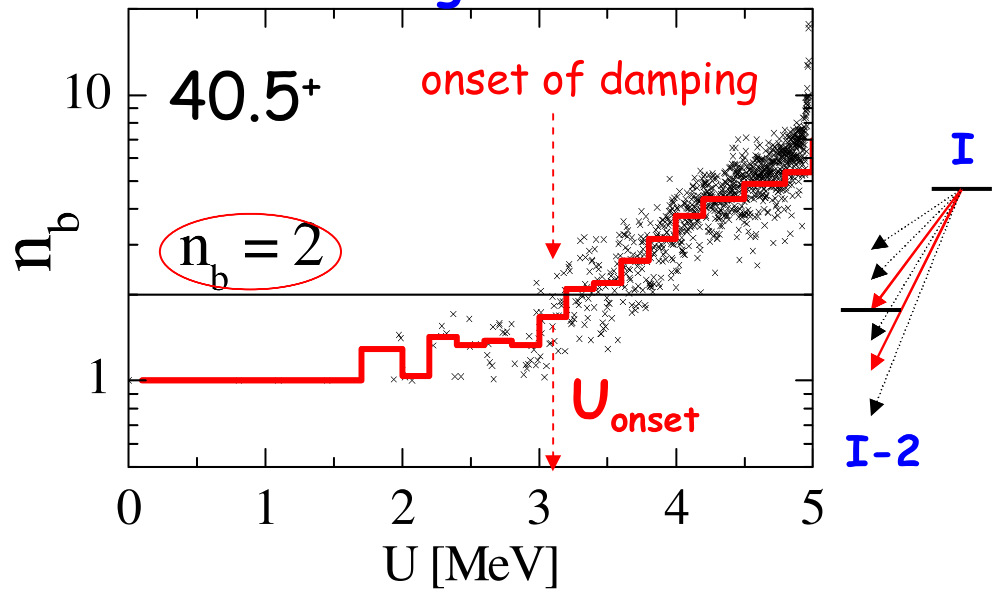
^{151}Tb microscopic calculations

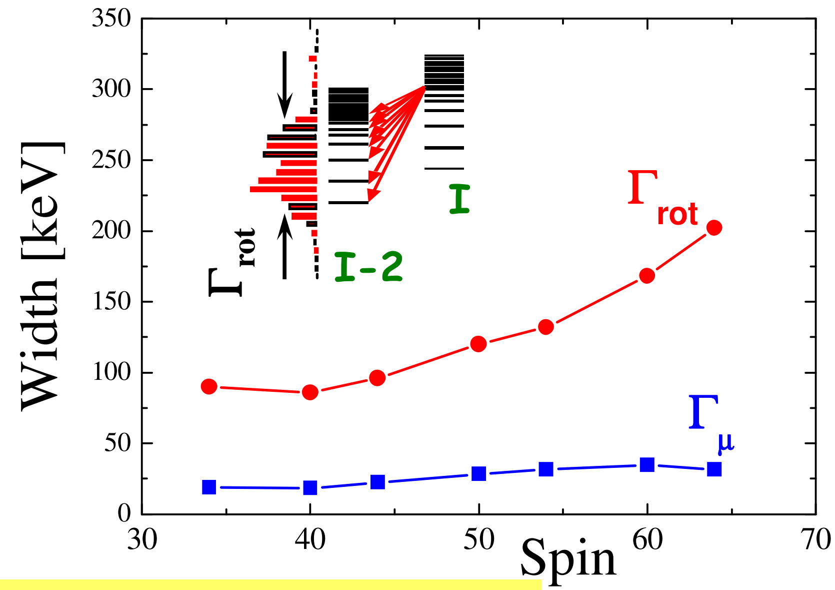
Cranked shell model at T≠ 0

$$H = H_{def} - \omega J_x + V_{res}$$



E2 fragmentation



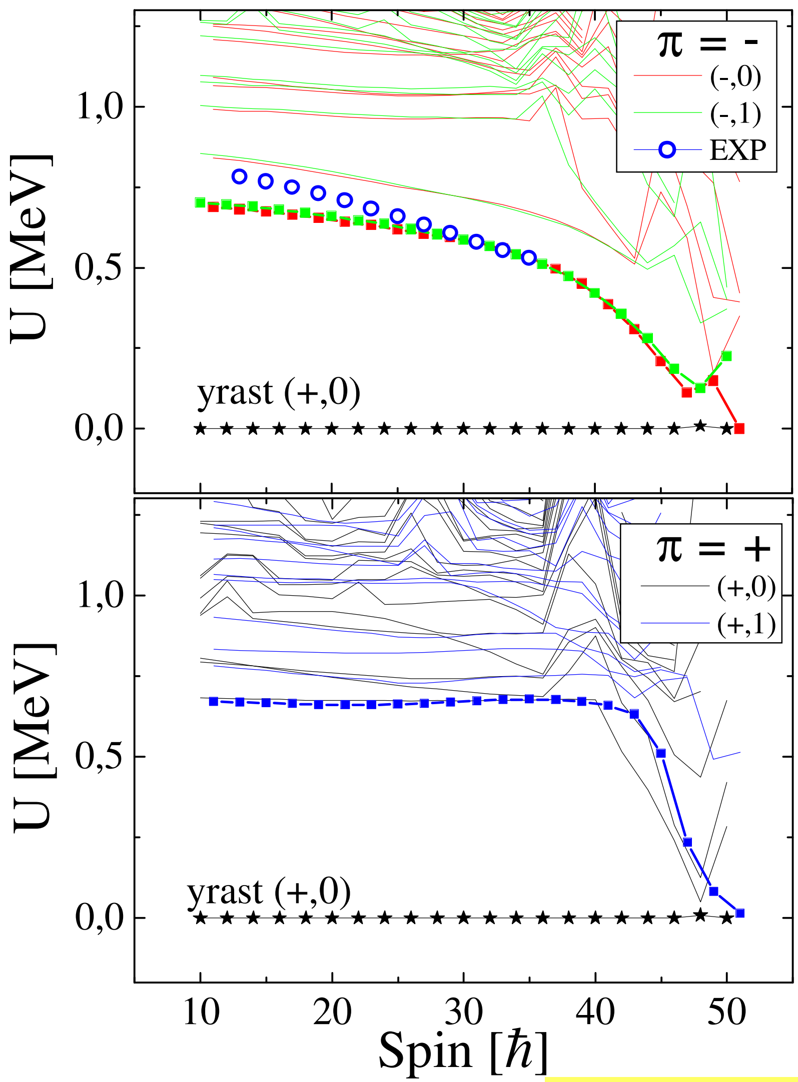


K. Yoshida, M. Matsuo, NPA612(1997)126

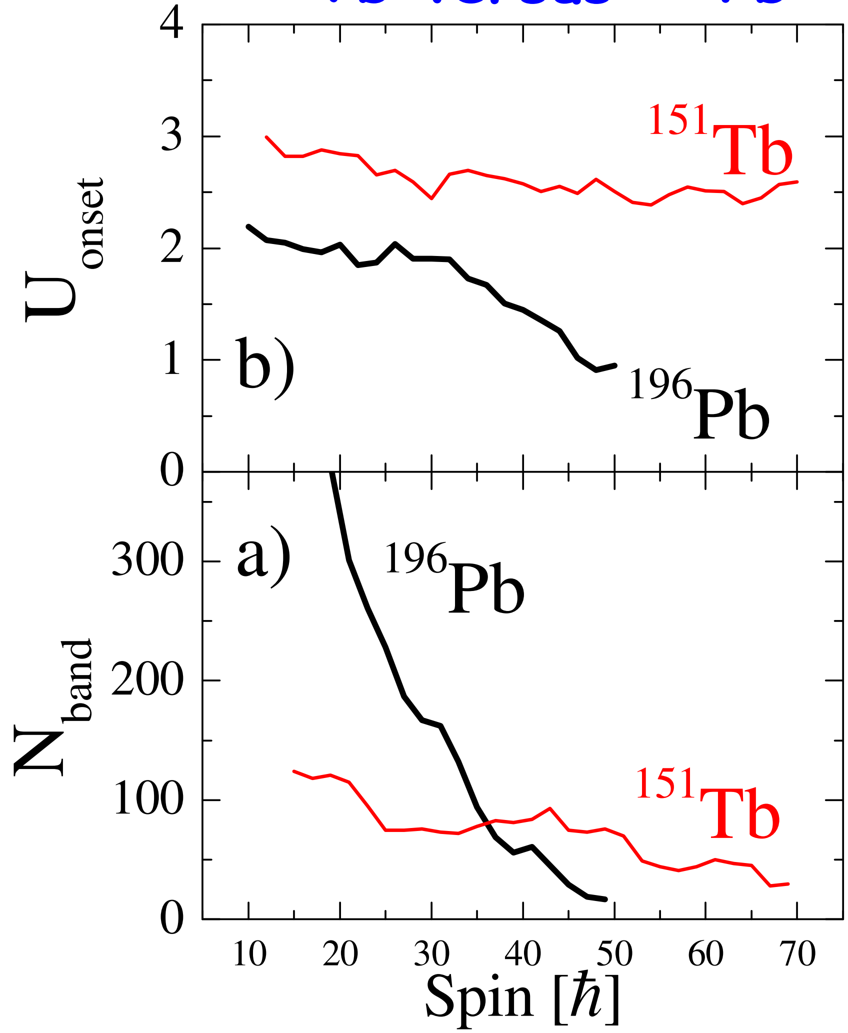
^{196}Pb microscopic calculations

Cranked shell model at T≠ 0

$$H = H_{def} - \omega J_x + V_{res}$$



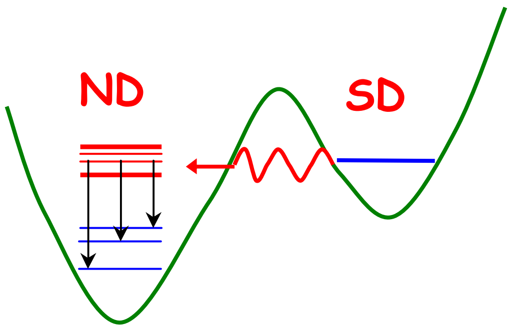
^{151}Tb versus ^{196}Pb



K. Yoshida, M. Matsuo, NPA612(1997)126

microscopic calculations for decay-out at T≠0

K. Yoshida, M. Matsuo and Y. Shimizu, NPA696, 85(2001)



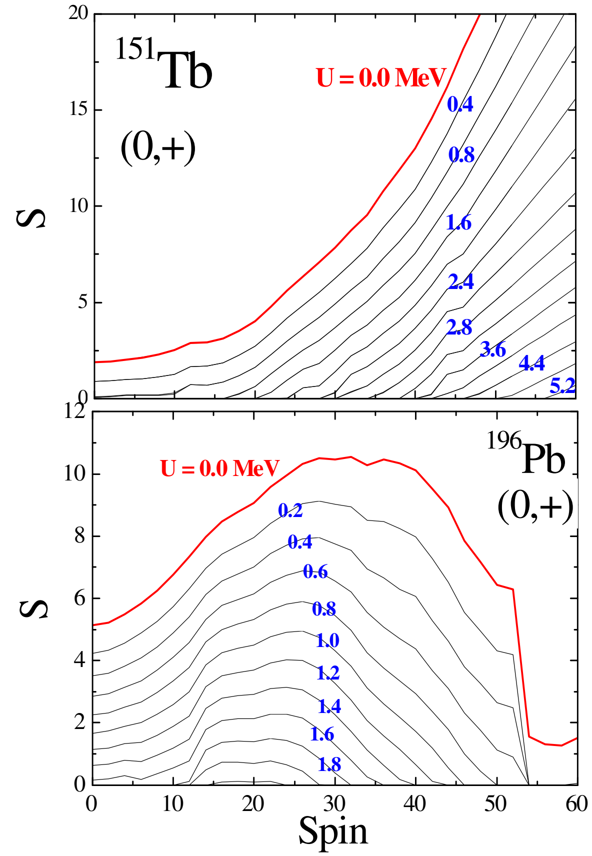
$$\Gamma_t = \frac{\hbar\omega_{SD}}{2\pi}\frac{D_{SD}}{\hbar\omega_{SD}}(1+e^{2S})^{-1}$$

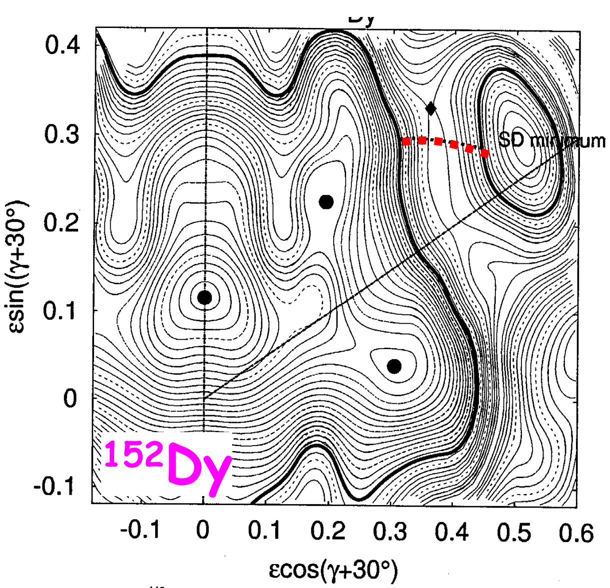
action integral
along tunneling path

$$S(E) = \int_{path} ds\sqrt{2M_0(V(q(s))-E)}$$

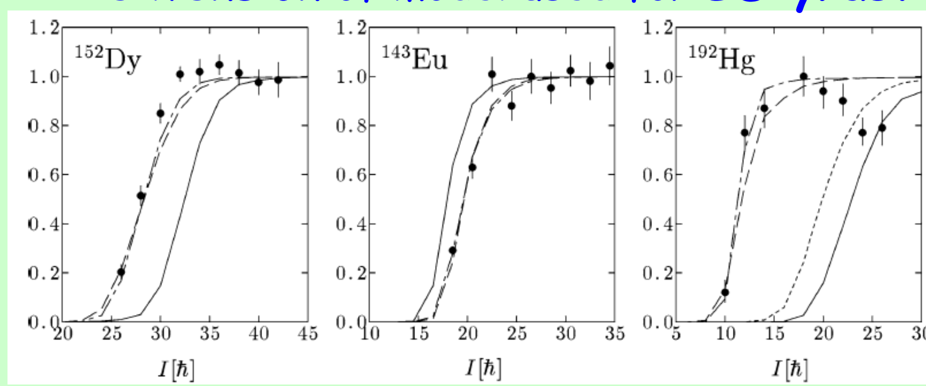
$$M_0 \approx \frac{1}{\Delta^2}$$

driven by pairing





extension of model used for **SD yrast**



Microscopic Calculations in SD well

Energy levels, E2 strengths, actions S

↓

Microscopic Monte Carlo Simulation:

1. Drastic reduction of Number of parameters:
   - entry distribution
   - E1 strength in SD & ND well
   - level density in ND well

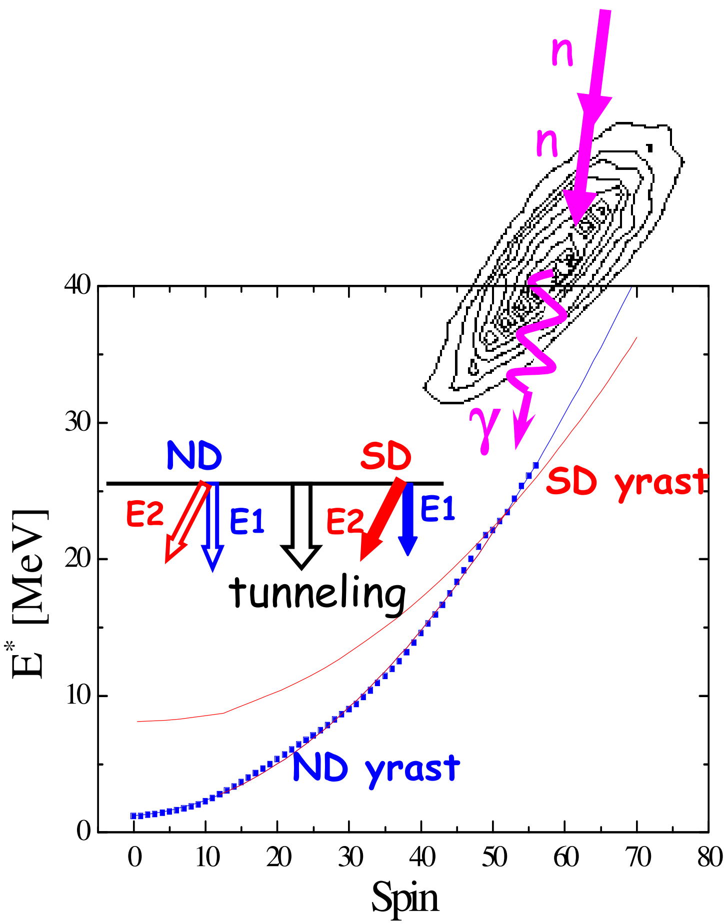
2. Quantitative analysis of
   Spectrum Intensity and Fluctuations

The simulation parameters

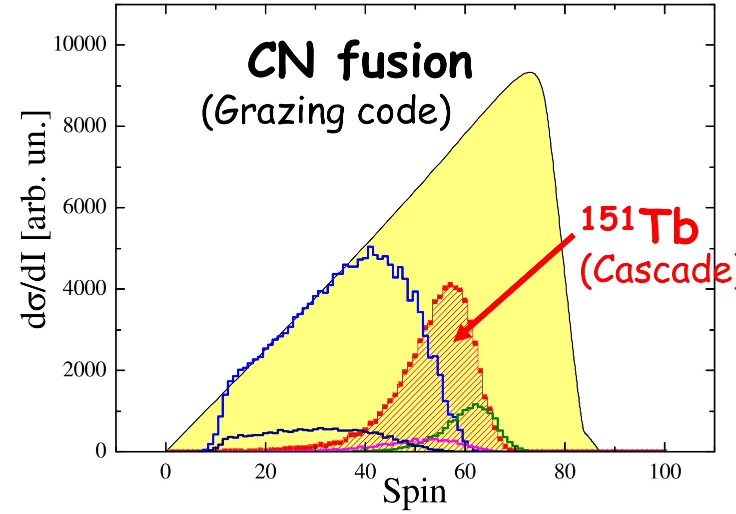
1. The Entry Distribution:

it is NOT a real parameter

(it can be measured or calculated)



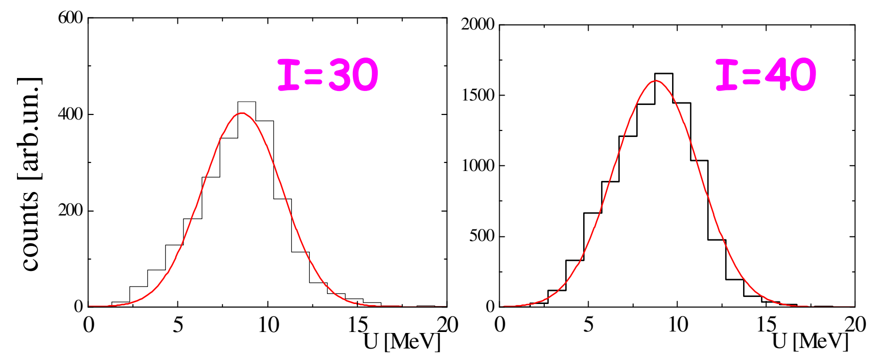
$^{27}Al + ^{140}Te$ @ E_{lab}=152 MeV



Entry ^{151}Tb

<I> = 58 ℏ ± 8 ℏ

<U> = 8.3 ± 2.5 MeV

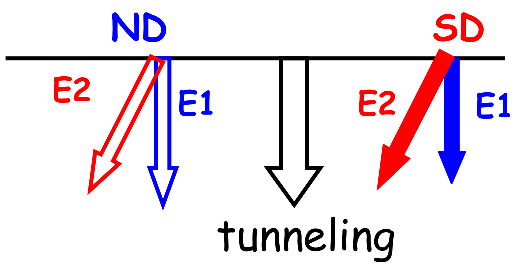


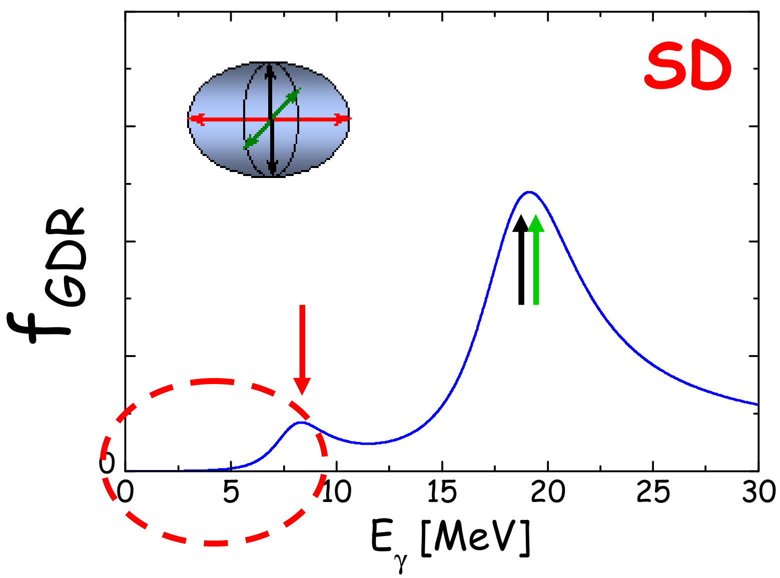
A. Winther, Nucl. Phys. A594, 203(1995)
F. Pulhofer, Nucl. Phys. A280, 267 (1977)

The simulation parameters

2. The E1 decay strength:

the tail of the GDR





f_{GDR} = Sum of 3 Lorentzian

$$T(E1) = H_{1n} \times K_{E1} \, B(E1) \times E_\gamma^3$$

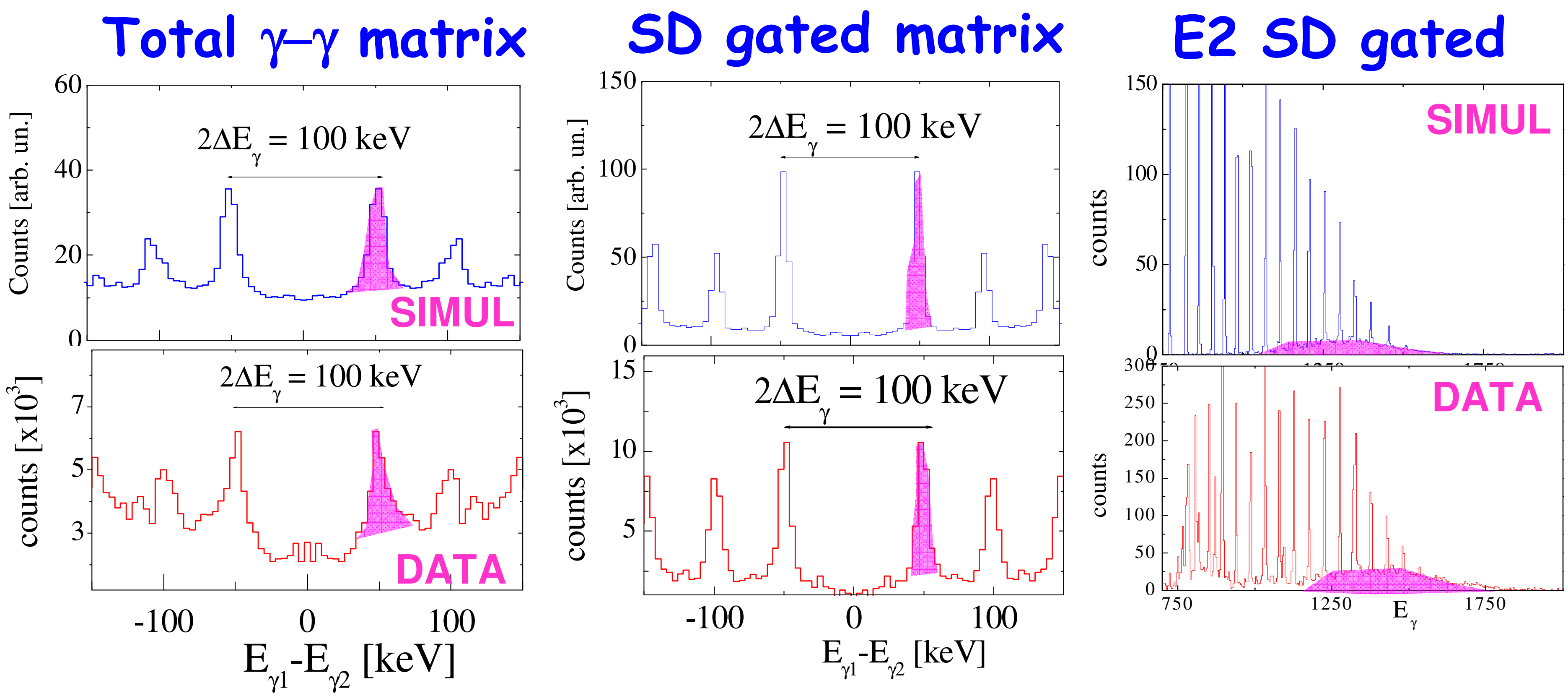
Hindrance factor ~ 10^{-2}

(tuned to reproduce the intensity of the yrast band)

K.E.G. Lobner, Phys. Lett. 26B, 369(1968)

G. Leander, PRC38, 728(1988)

^{151}Tb: simulated γ-spectra



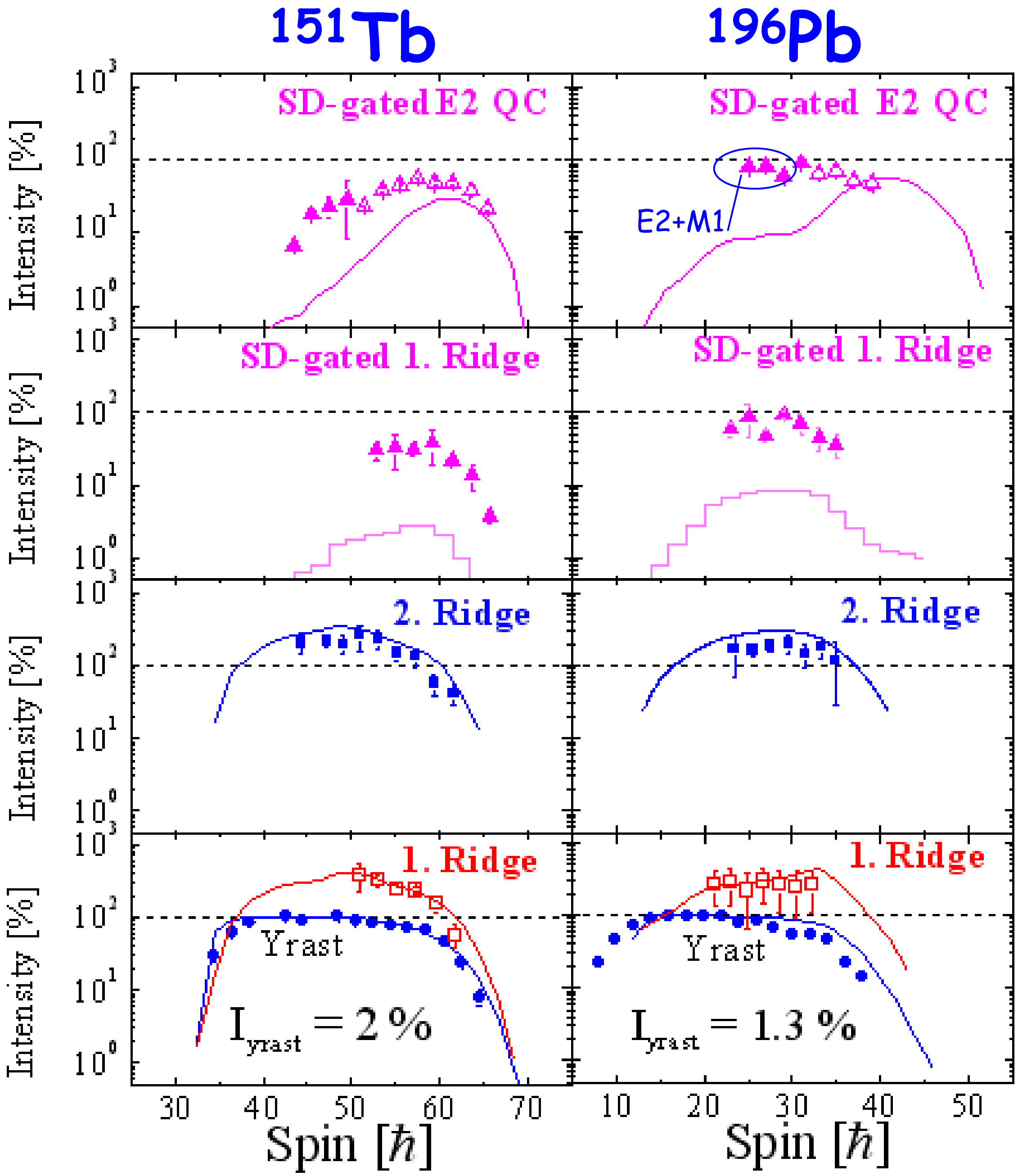
Analysis of Simulated Spectra: Spectrum Intensity (population)
Fluctuations (number of bands)

Exp. versus Theory

Analysis of Intensities

exclusive quantities
⇓
SD gated decay-flow

inclusive quantities
⇓
average decay-flow



SD gated γ–spectrum
E2 Bump

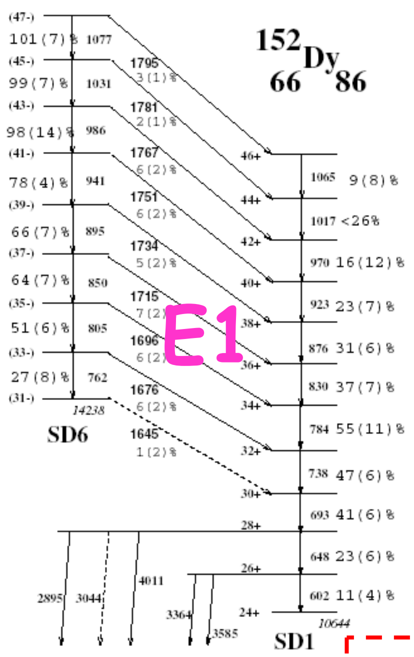
SD gated γ–γ
1st Ridge

Rot-Plane
2nd Ridge

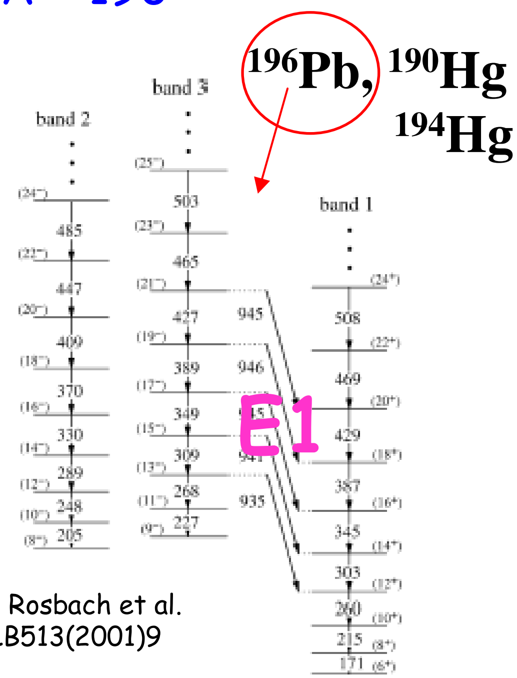
Total γ–γ
1st Ridge

SD gated quantities are sensitive to E1/E2 balance

Enhanced **octupole vibrations** have been observed in A= 150 and A = 190

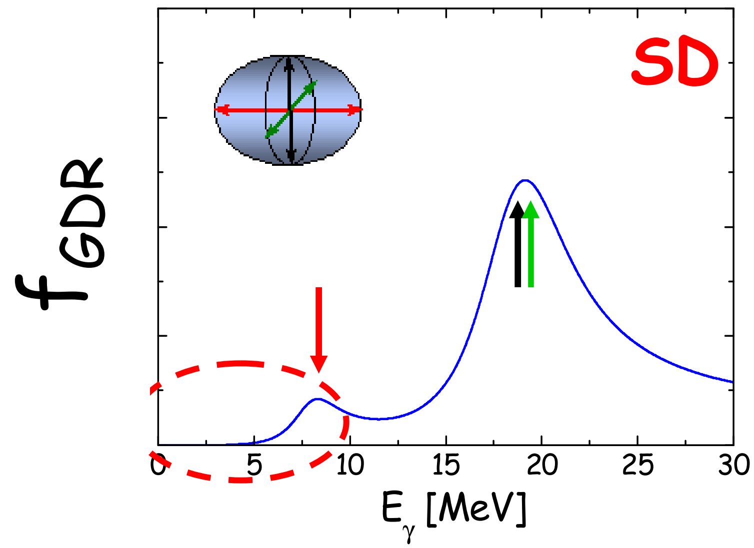


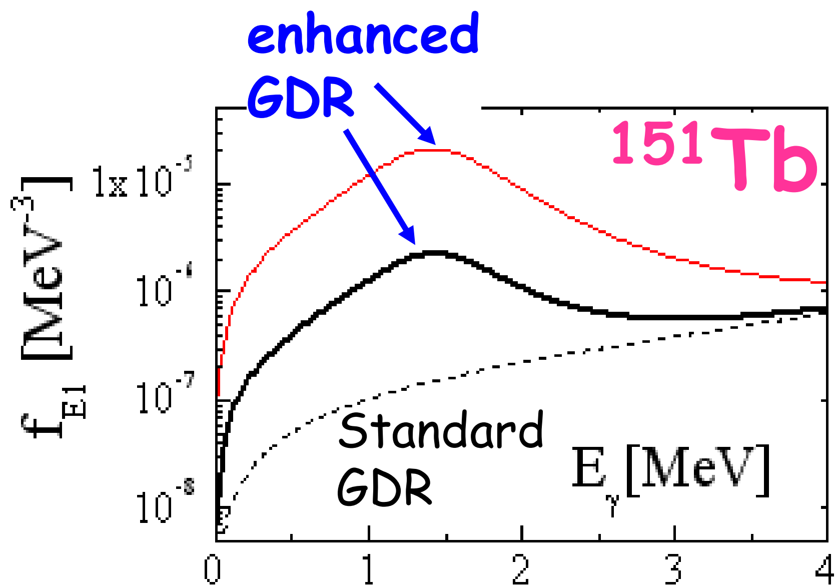
T. Lauritsen et al., PRL89(2002)282501



D. Rosbach et al. PLB513(2001)9

B(E1) ~ 10^{-4}-10^{-3} W.u.
10 to 100 times stronger



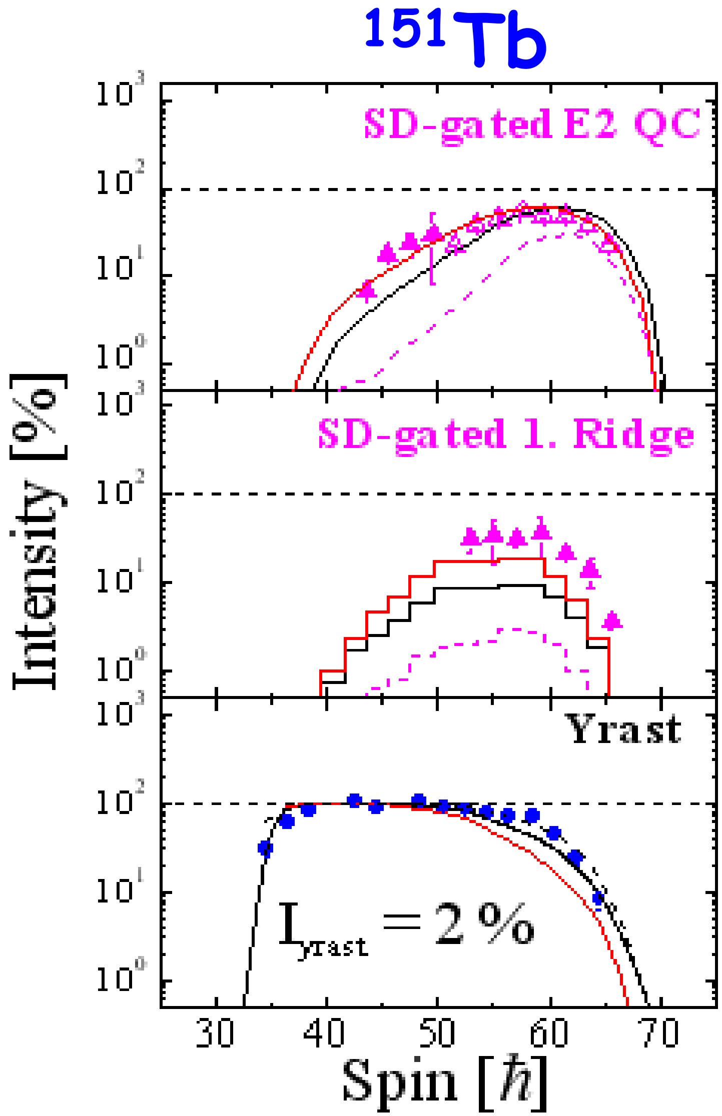


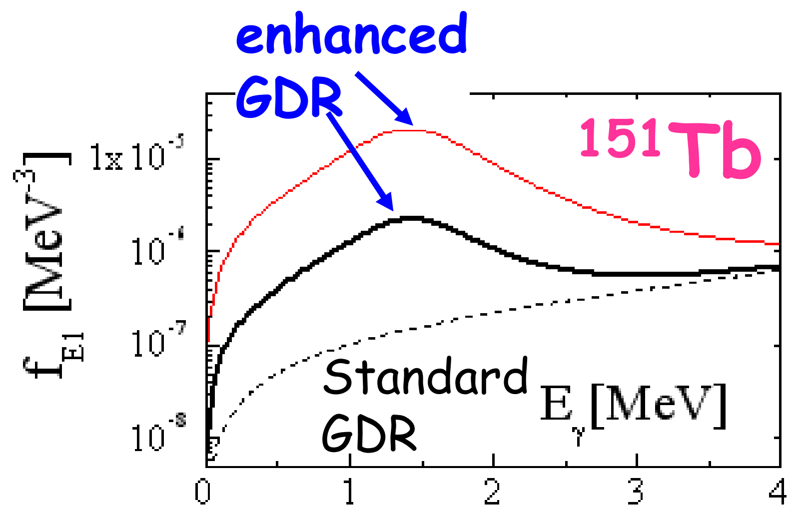
Theory: Nilson + QRPA
J. Kvasil, N. LoIudice et al., PRC75 (2007)034306
T. Nakatsukasa et al., PLB343(1995)19

Exp. versus Theory: Intensities

exclusive quantities
⇓
SD gated decay-flow

inclusive quantities
⇓
average decay-flow





other types of enhancement my be possible
M1's ...

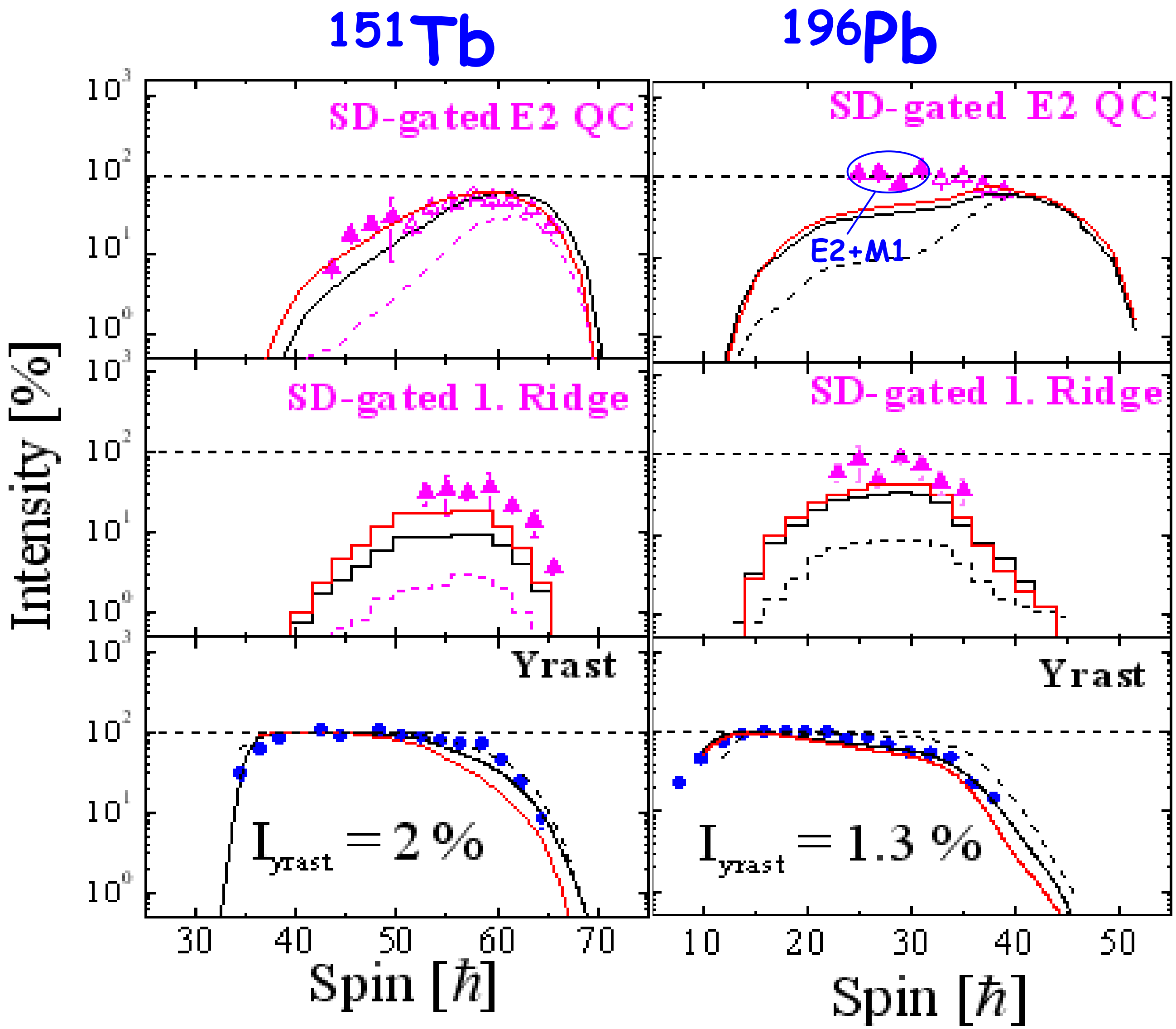
Good agreement with data in both A=150 and 190 region

S. Leoni et al. PRL101(2008)142502

Exp. versus Theory: Intensities

exclusive quantities
⇓
SD gated decay-flow

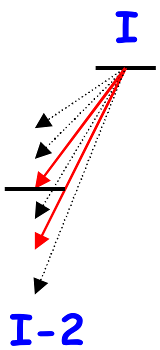
inclusive quantities
⇓
average decay-flow



Good agreement with data in both A=150 and 190 region

S. Leoni et al. PRL101(2008)142502

Exp. versus Theory: Number of Discrete Bands



Cranking

Onset of Damping
(Chaos)
$n_{branch} < 2$

+

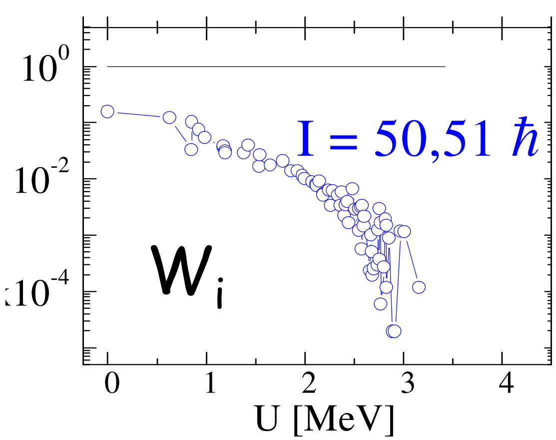
decay-out

(tunnel through potential barrier)

+

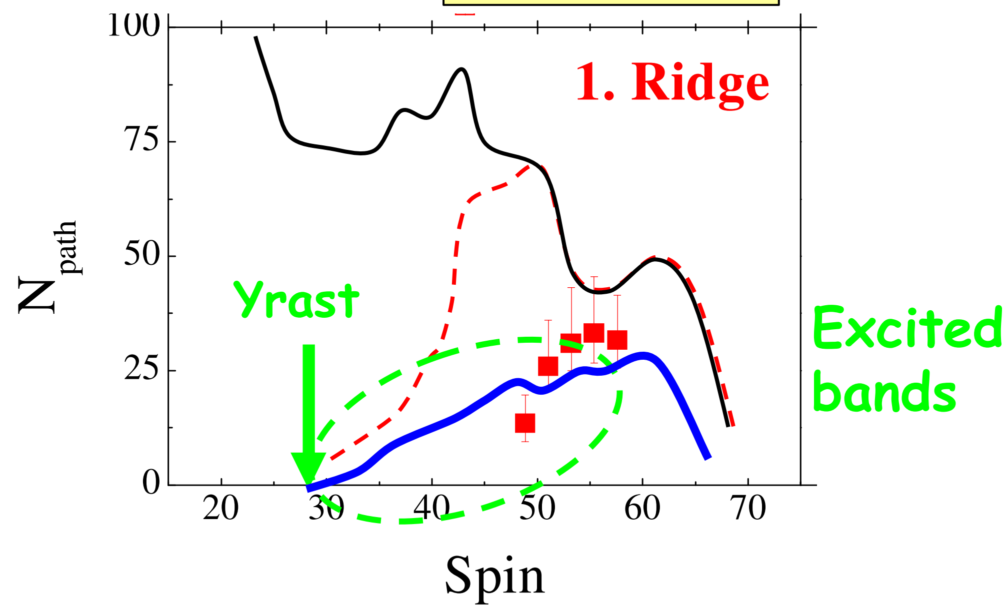
Population

decay-flow
($N_{path} = 1/\Sigma w_i^2$)



^{151}Tb

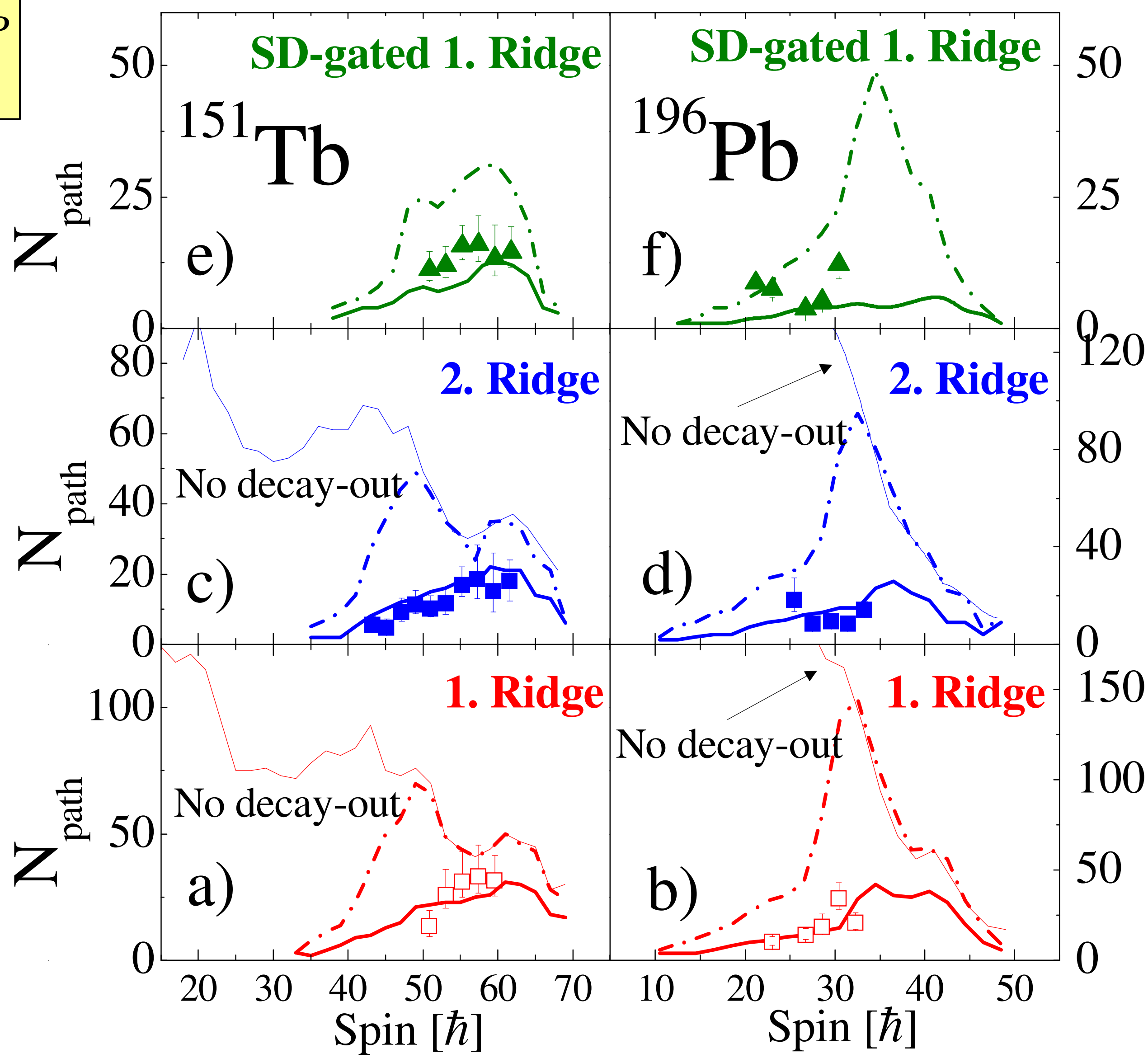
$$N^{(2)}_{path} = \frac{N_{eve}}{\frac{\mu_2}{\mu_1} - 1} \times P$$



- the **flow** bias strongly the population probability

- TEST of nuclear structure & tunneling model over wide range of I and U

$$N^{(2)}_{path} = \frac{N_{eve}}{\frac{\mu_2}{\mu_1} - 1} \times P$$



Good agreement with data in both A=150 and 190 region

S. Leoni et al. PRL101(2008)142502

OUTLOOK:

Probes of Nuclear Structure and Tunneling

1. Strength of two-body interaction

2. Mass parameter in action S

3. ND level density

Sensitivity mostly in A = 190 region

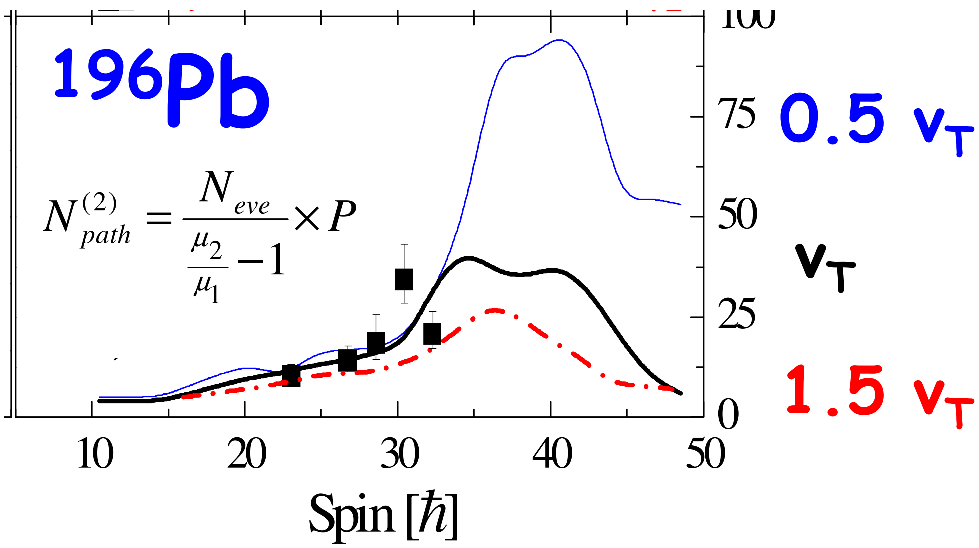
Probes of Nuclear Structures

1. Sensitivity to two-body interaction Strength

Cranked shell model at $T \neq 0$

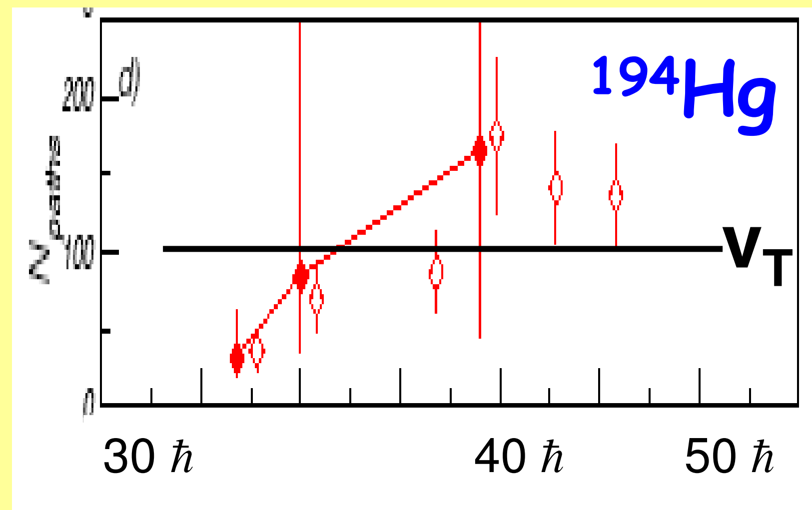
$$H = H_{def} - \omega J_x + V_{res}$$

$$V_{res}(1,2) = v_T \, \delta(x_1 - x_2)$$



Number of discrete SD bands

S. Leoni et al. Submitted to PRC

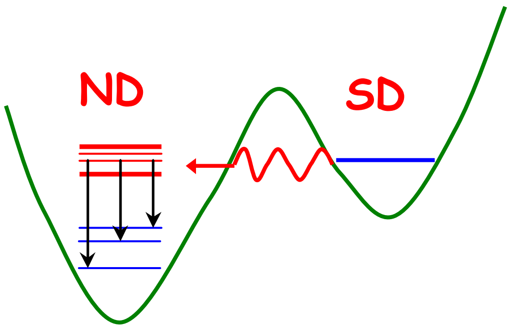


$\geq$ 100 Regular bands of chaotic nature

A. Lopez-Martens, PRL100(2008)102501

Probes of Nuclear Structures

2. Sensitivity to Mass Parameter in Action S



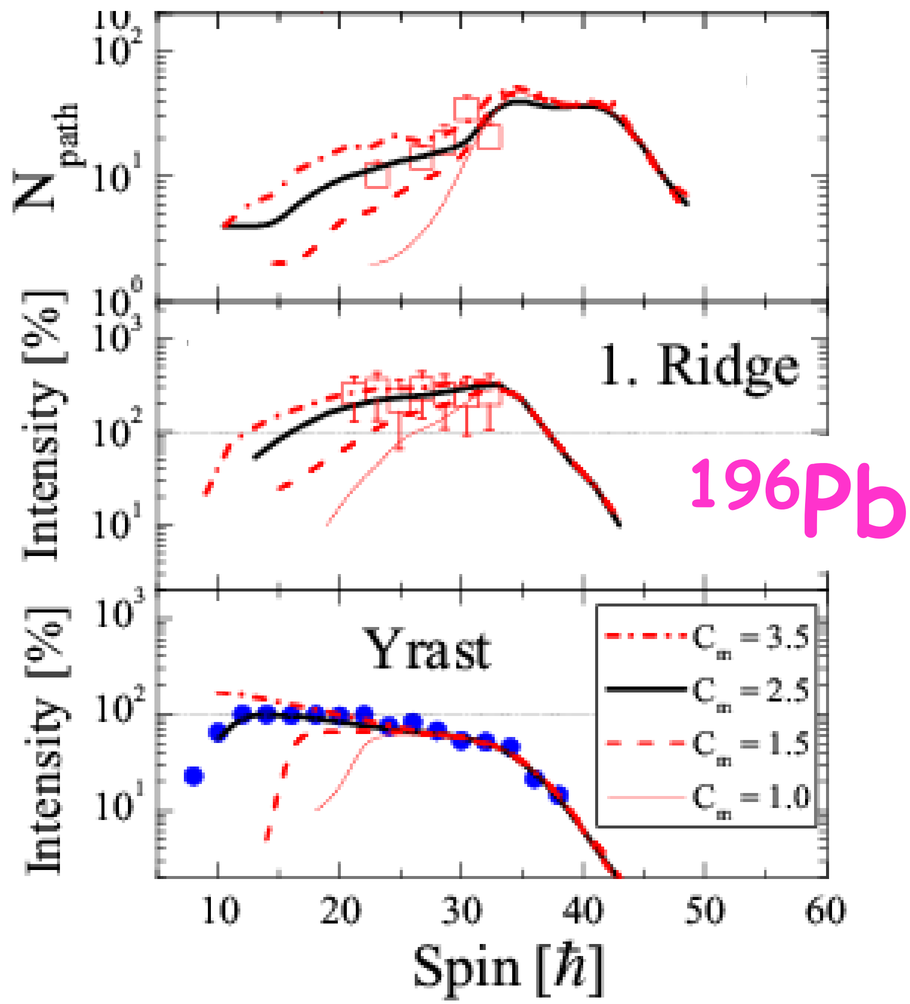
$$\Gamma_t = \frac{\hbar\omega_{SD}}{2\pi}\frac{D_{SD}}{\hbar\omega_{SD}}(1+e^{2S})^{-1}$$

action integral along tunneling path

$$S(E) = \int_{path} ds\sqrt{2M_0(V(q(s))-E)}$$

$$M_0 \approx \frac{1}{\Delta^2}$$ driven by pairing

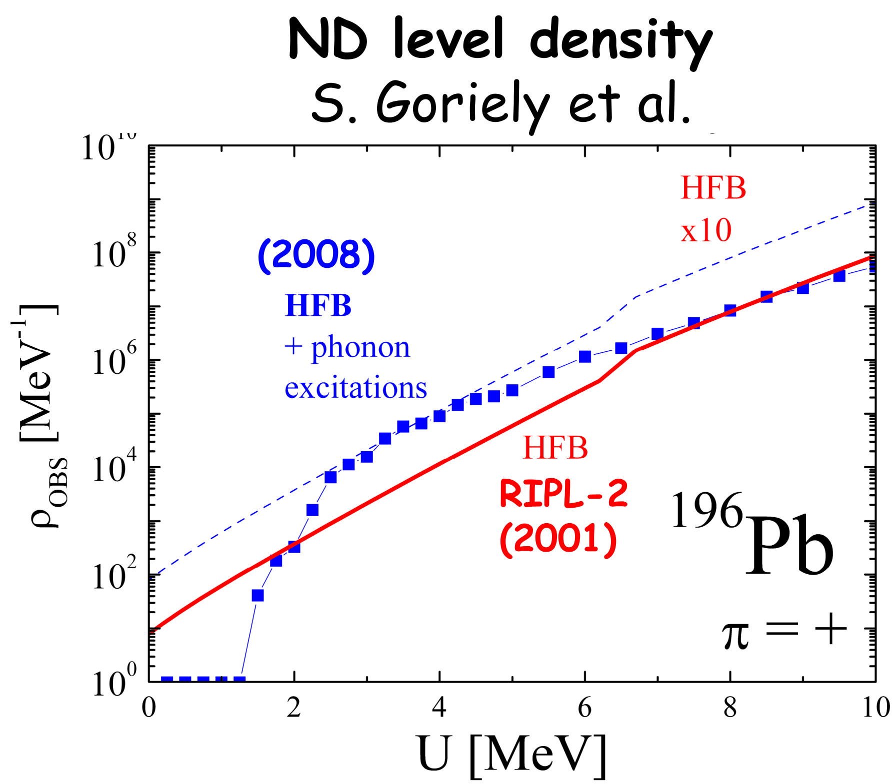
$M_0 \rightarrow C_m M_0$

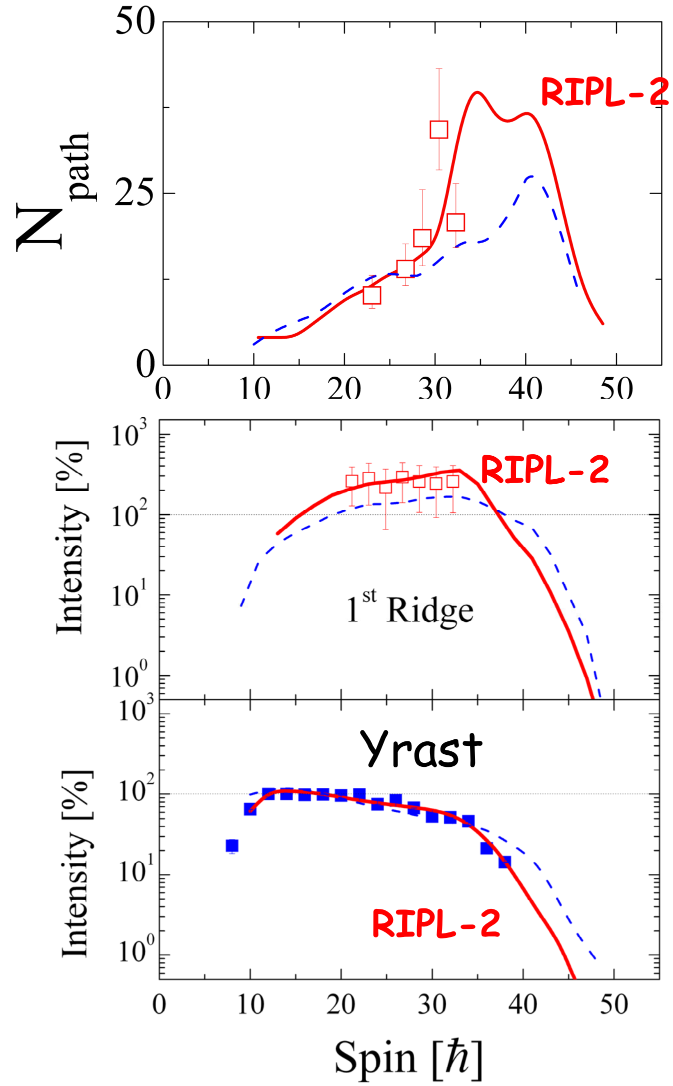


S. Leoni et al. Submitted to PRC

Probes of Nuclear Structures

3. Sensitivity to level density in ND well





Region of interest

U ≤ 7 MeV

CONCLUSIONS:

Warm Rotation in Superdeformed nuclei is a test bench for

1. cranked shell model at finite temperature
2. tunneling through potential barrier

Experimental analysis ^{151}Tb & ^{196}Pb:
Intensities and Fluctuations of Quasi-continuum spectra

Data interpretation:
Microscopic Monte Carlo simulation, almost parameter "free"

➔ Evidence for nuclear structure effects:
enhanced E1 strength @ E_γ = 1-2 MeV

➔ Sensitivity to V_{res}, Inertial Mass and ND level density

Ideal physics case for
intense Stable/Radioactive beams
&
new generation detector arrays (AGATA & GRETA)

Collaborators →

Participants to the Experiments

Milano University & INFN:
A. Bracco, G. Benzoni, N. Blasi, S. Brambilla, F. Camera, F. Crespi, A. DeConto, S. Leoni, P.Mason, D. Montanari, B. Million, M. Pignanelli, O. Wieland

IRES, Strasbourg:
G.Duchene, J.Robin, D. Curien, Th.Bysrki, F.A.Beck et al.,

Krackow, Poland:
A.Maj, M. Kmiecik, P.Bednarczyk, W. Meczynski, J. Styczen, et al.

NBI, Copenhagen:
B. Herskind, G. Hagemann, G. Sletten et al.

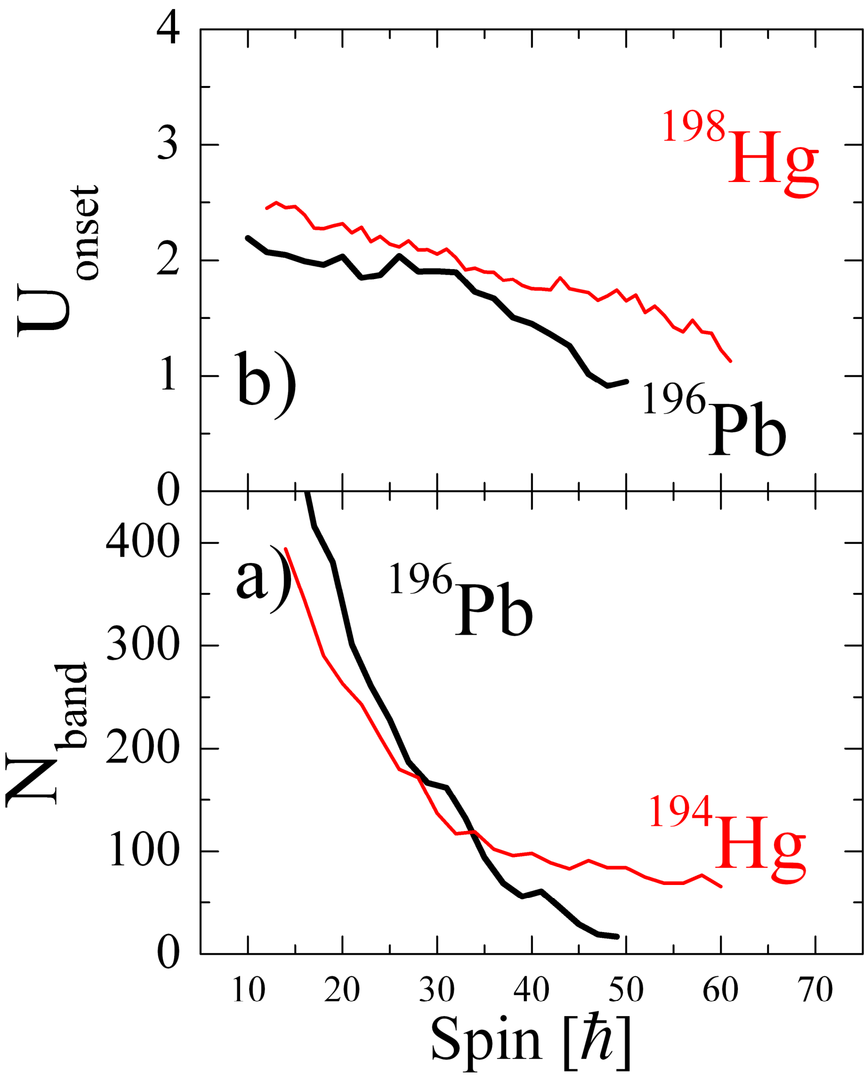
Oliver Lodge Laboratory, University of Liverpool:
P.J.Twin

KTH, Stockholm:
A.Odahara, K.Lagergren

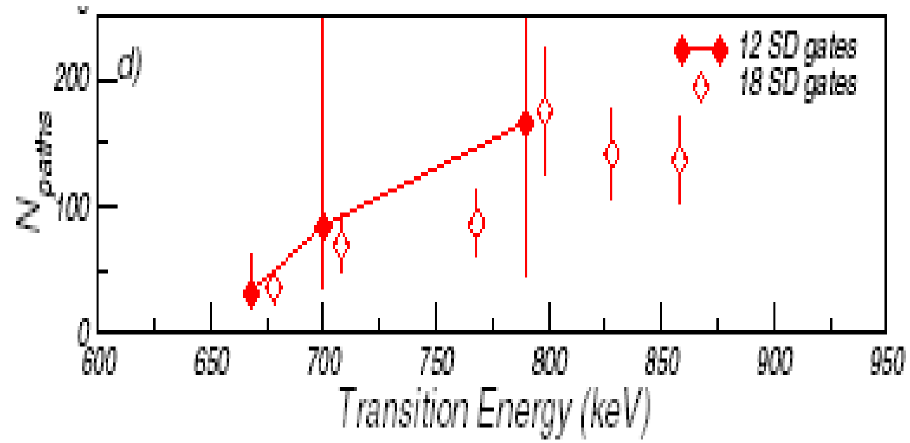
+ ***EUROBALL*** *collaborations*

Theory: E.Vigezzi (**Milano University & INFN**)
M.Matsuo (**Niigata University**), Y.R.Shimizu (**Kyushu University**) et al.

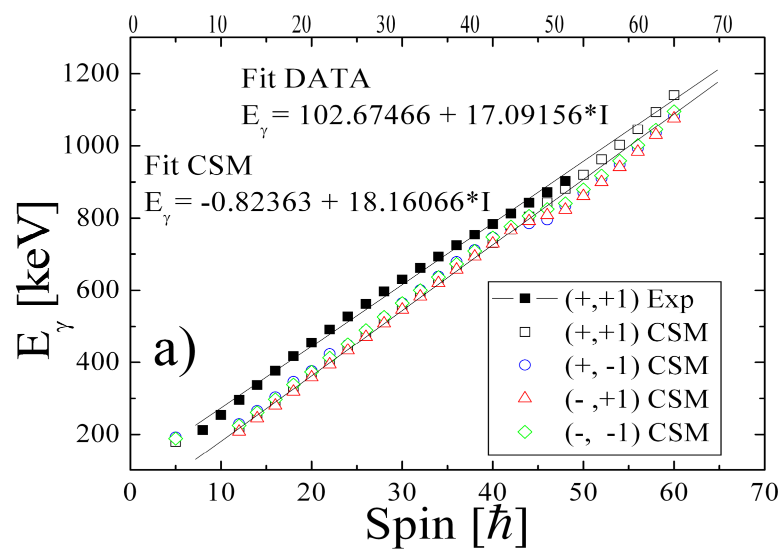
^{194}Hg



U onset
198Hg
196Pb
b)
N band
a)
196Pb
194Hg
Spin [ħ]
0
10
20
30
40
50
60
70



d)
12 SD gates
18 SD gates
N paths
Transition Energy (keV)

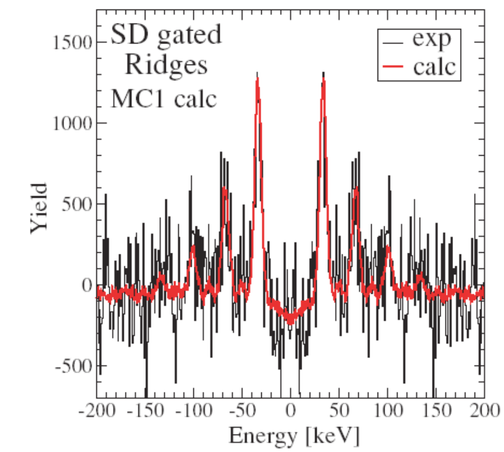


Fit DATA
Eγ = 102.67466 + 17.09156*I
Fit CSM
Eγ = -0.82363 + 18.16066*I
Eγ [keV]
a)
(+,+1) Exp
(+,+1) CSM
(+, -1) CSM
(- ,+1) CSM
(-, -1) CSM
Spin [ħ]

Outlook: detailed analysis of other cases

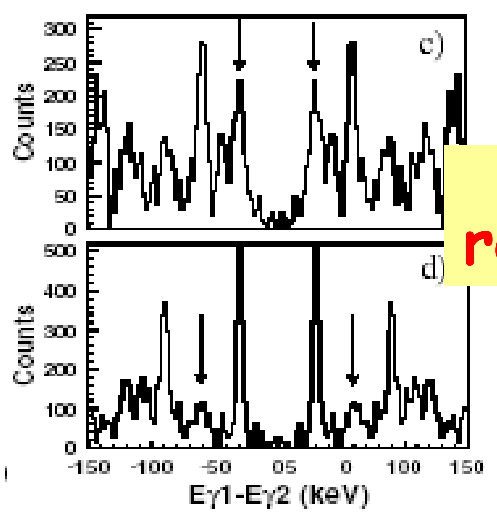
1. The SD NUCLEUS ^{152}Dy

So far investigated in details via a parameter dependent model
T.Lautitsen et al., PRC75(2007)064309

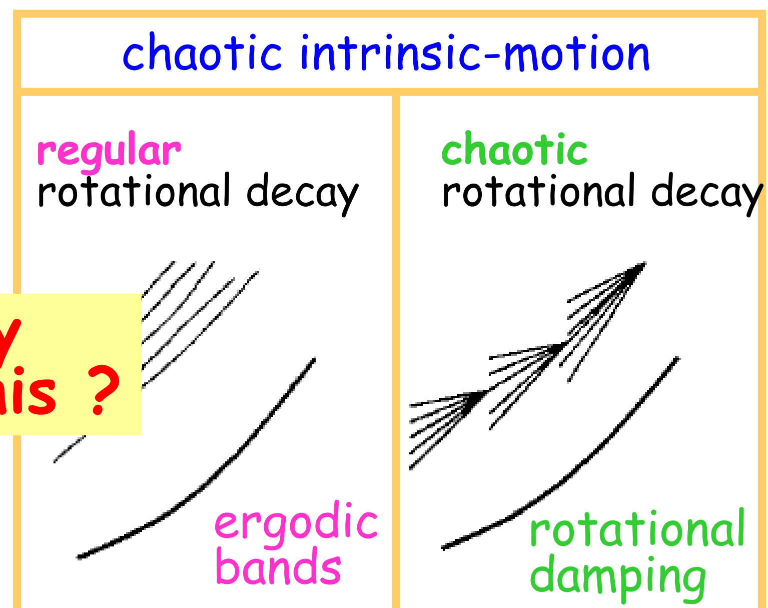


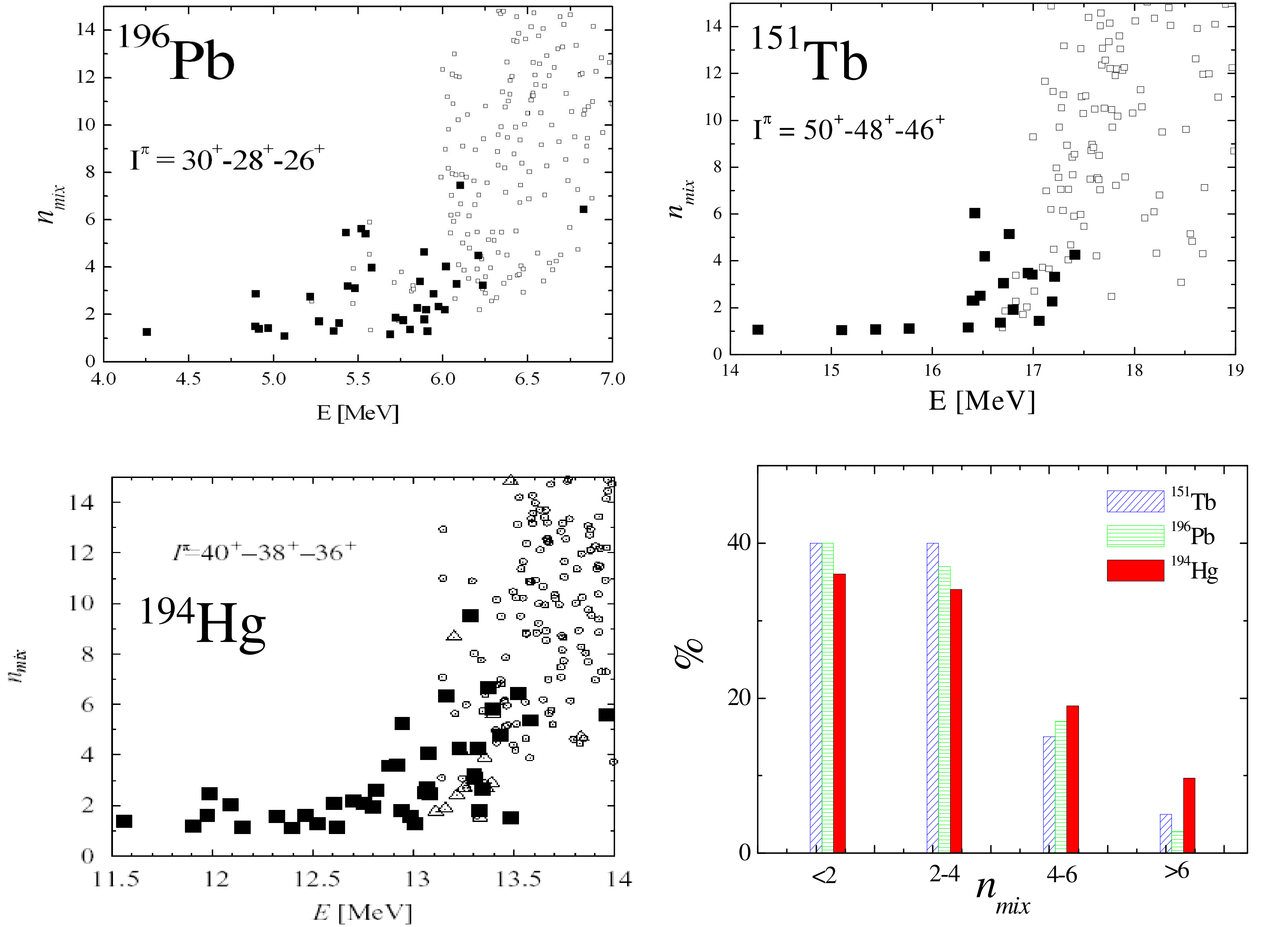
2. The PECULIAR case of ^{194}Hg

≥ 100 Regular bands of chaotic nature
A. Lopez-Martens, PRL100(2008)102501

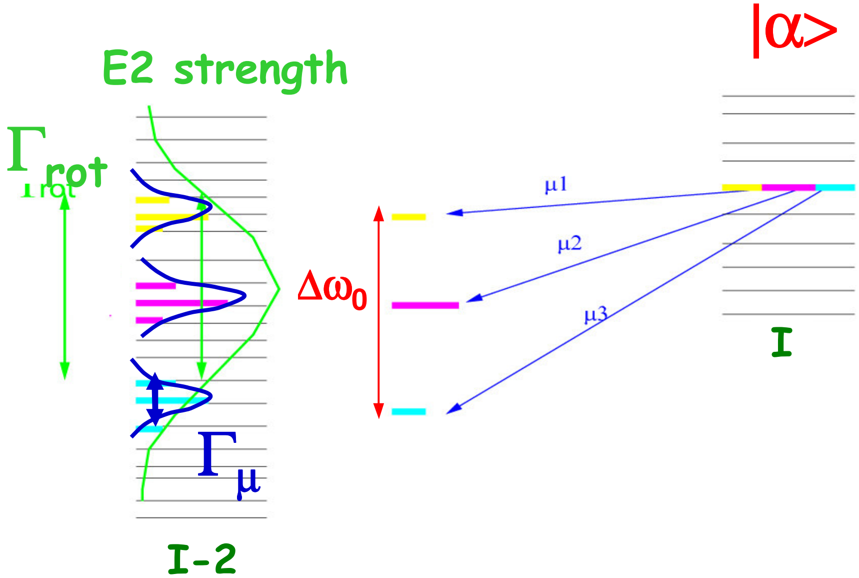


Can theory reproduce this ?

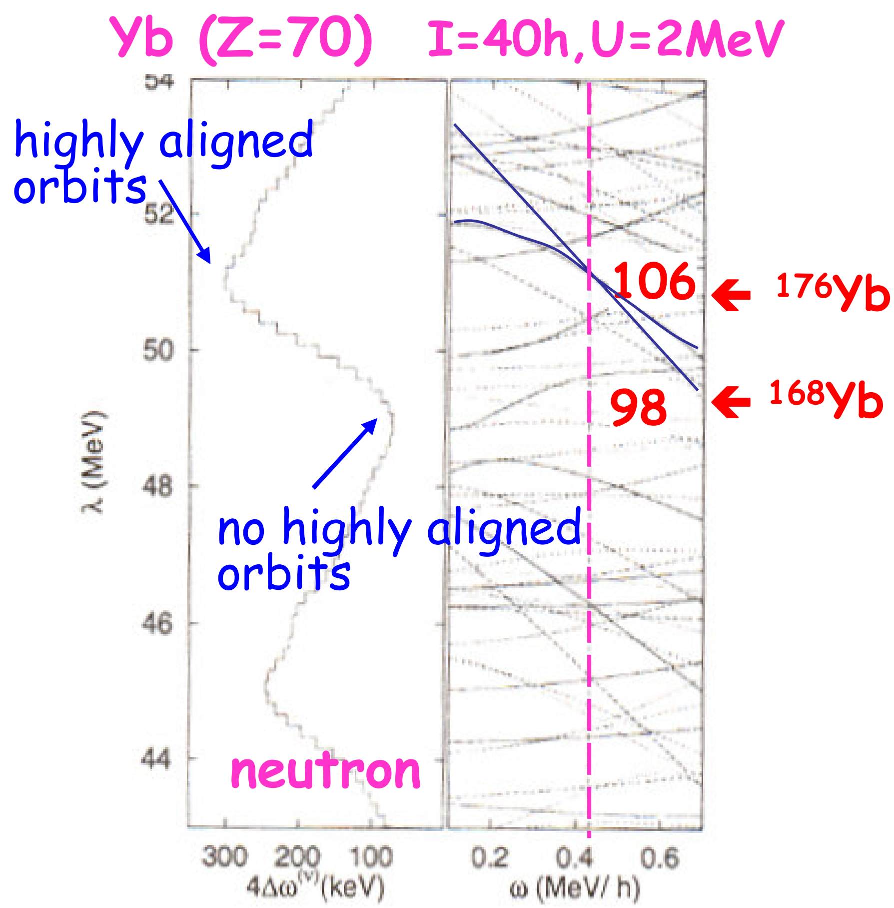




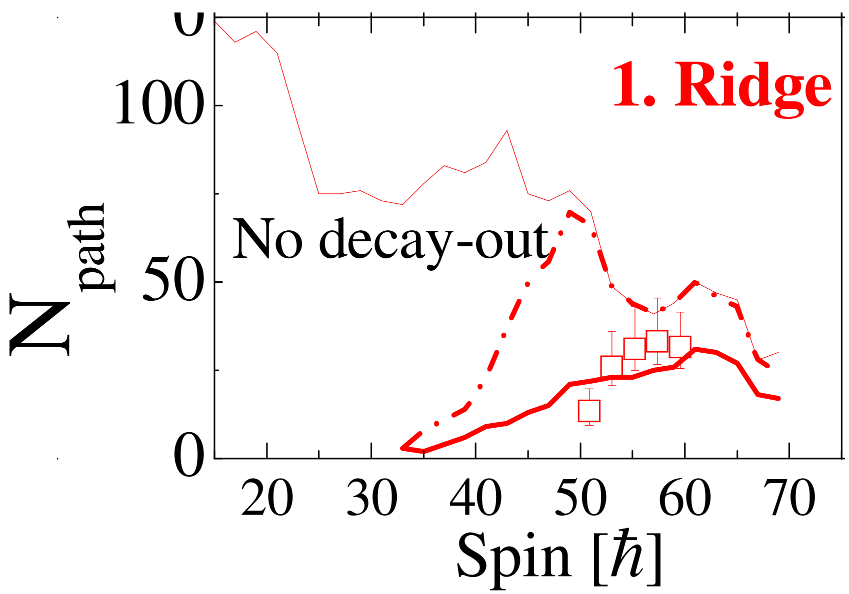
196Pb
Iπ = 30+-28+-26+
n_mix
E [MeV]
151Tb
Iπ = 50+-48+-46+
n_mix
E [MeV]
194Hg
Iπ=40+–38+–36+
n_mix
E [MeV]
151Tb
196Pb
194Hg
%
<2
2-4
4-6
>6
n_mix

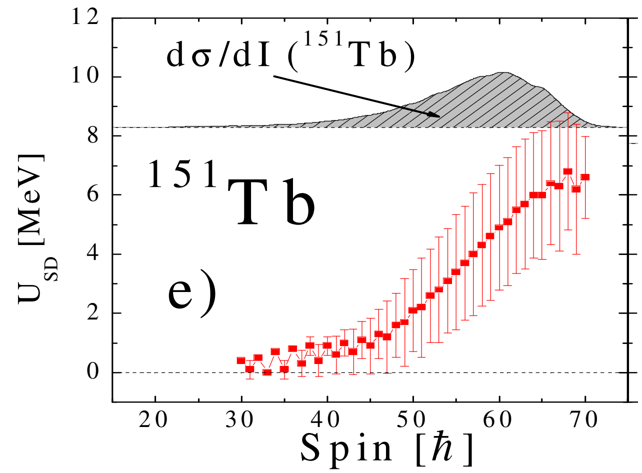


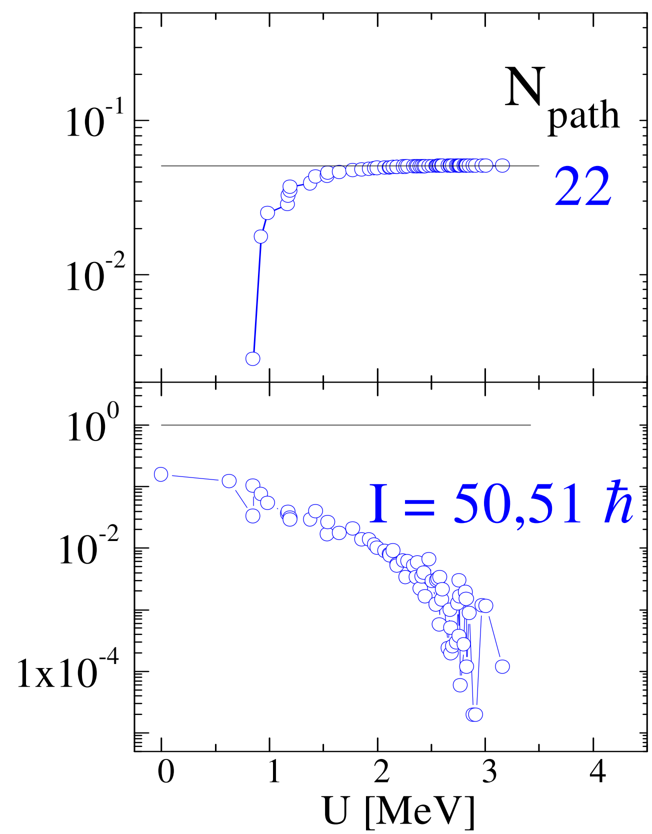
$$\Gamma_{rot} = 2(2\Delta\omega_0) \text{ for } U \leq 2 \text{ MeV}$$



$$\Delta\omega_0 = \sqrt{(\Delta\omega_0{}^N)^2 + (\Delta\omega_0{}^P)^2}$$







ΣW_i^2

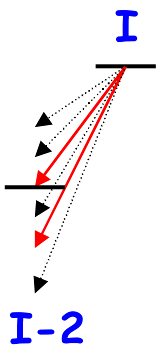
W_i

$$N_{path} = 1/\Sigma W_i^2$$

the flow bias strongly
the population probability

Exp. versus Theory

Number of Discrete Bands



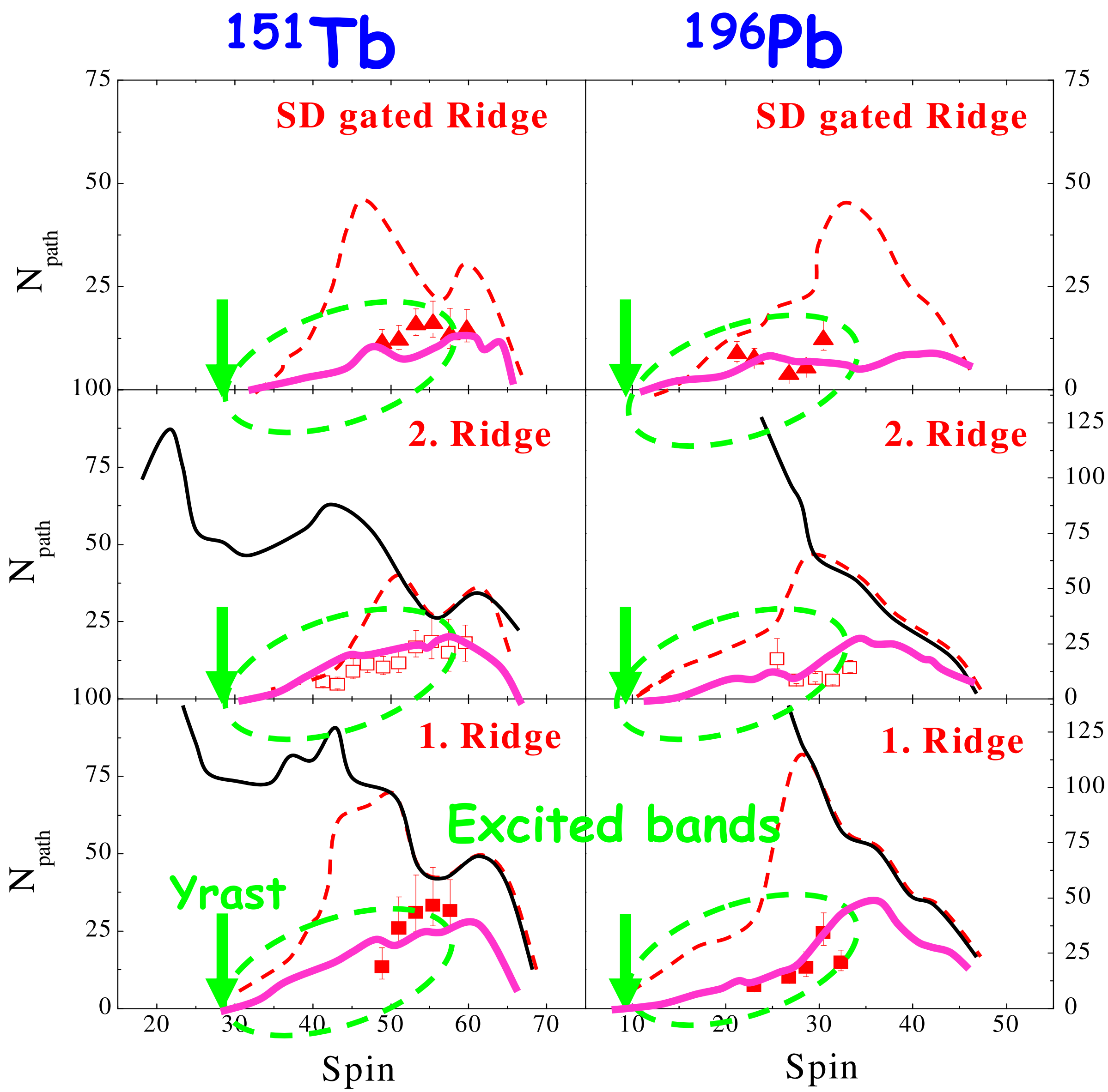
Cranking
Onset of Damping
(Chaos)
$n_{branch} < 2$

+

decay-out
(barriers and pairing)

+

Population
decay-flow
($N_{path} = 1/\Sigma w_i^2$)



Monte Carlo simulation: TEST of theory over wide spin range !