Decoherence of collective motion in warm nuclei.

S. Frauendorf

Department of Physics

University of Notre Dame

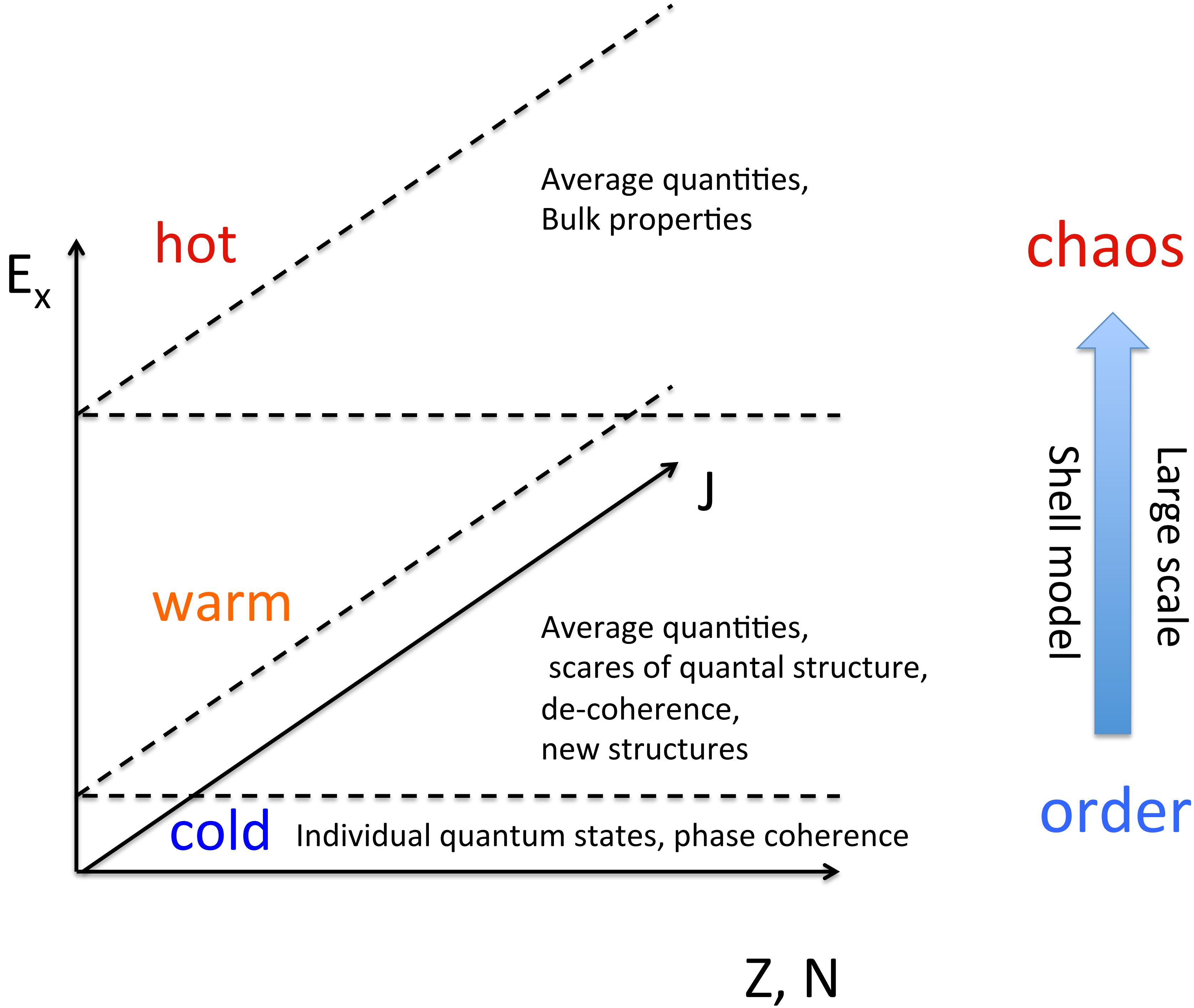
In collaboration with:

C. Petrache, Universite de Sud, Paris

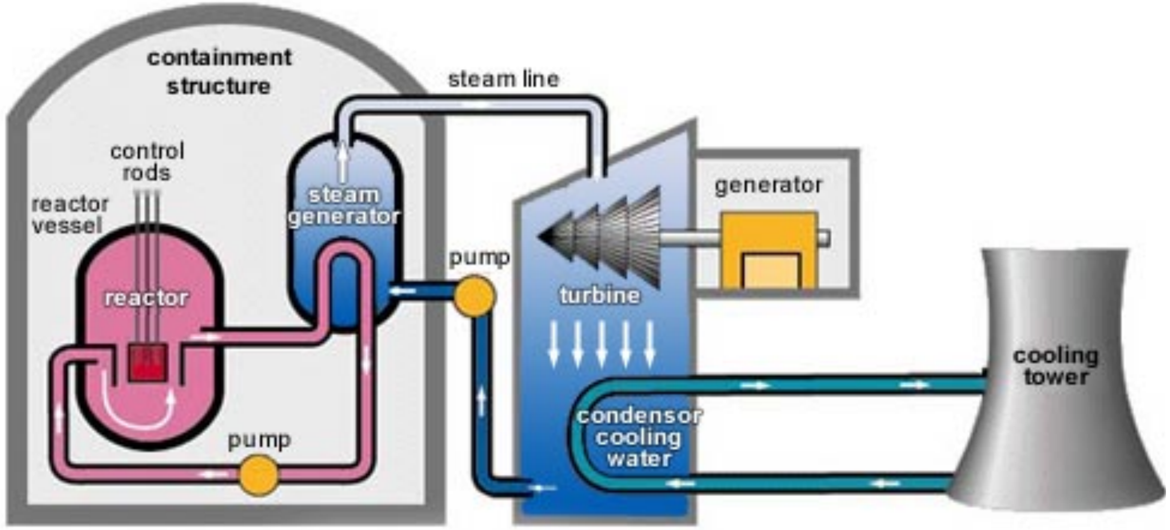
R. Schwengner, HZDR, Dresden

B. A. Brown, Michigan State University

K. Wimmer, University Tokyo

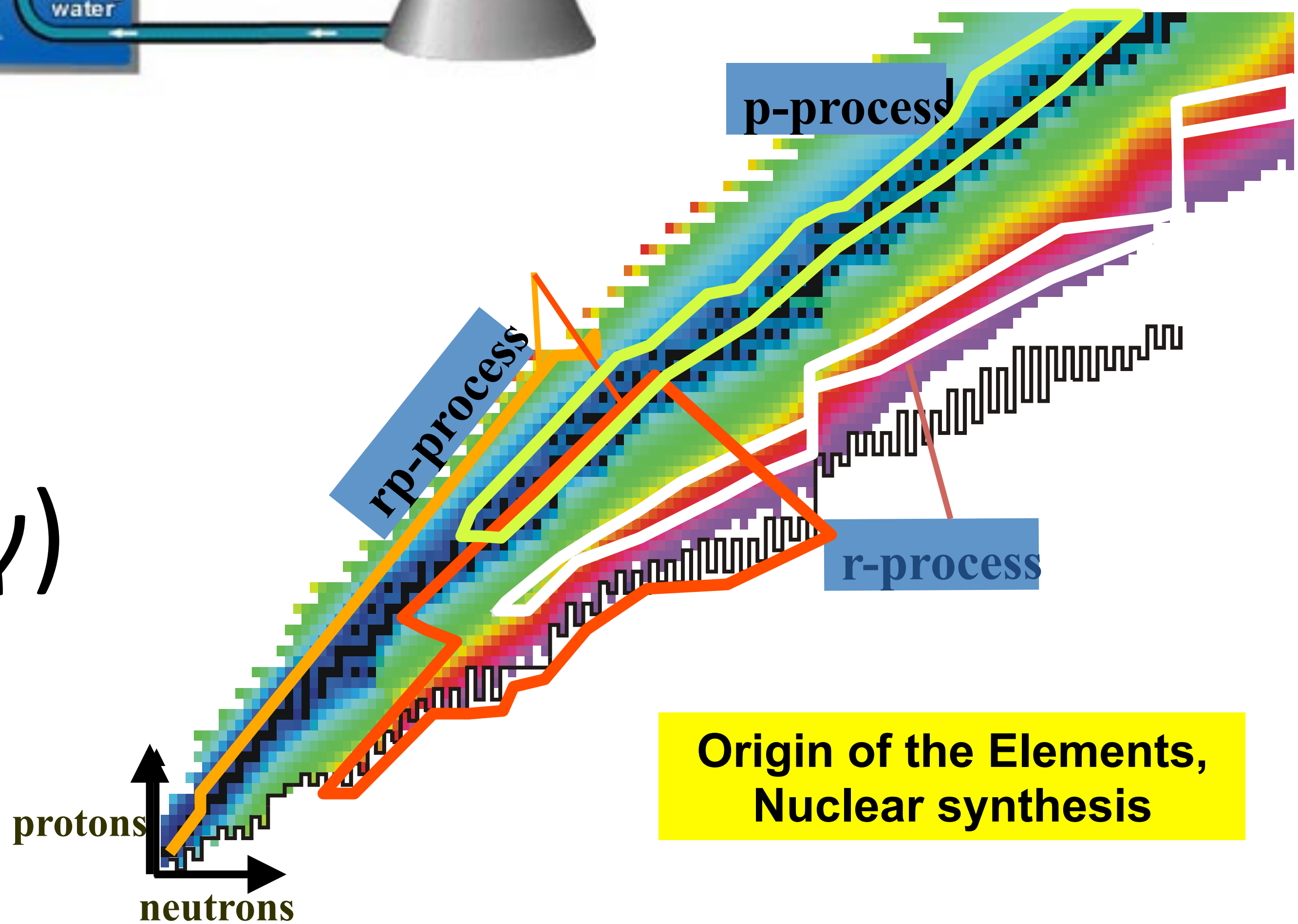


Average quantities,
Bulk properties
hot
E_x
chaos
J
Shell model
Large scale
warm
Average quantities,
scares of quantal structure,
de-coherence,
new structures
cold
Individual quantum states, phase coherence
order
Z, N



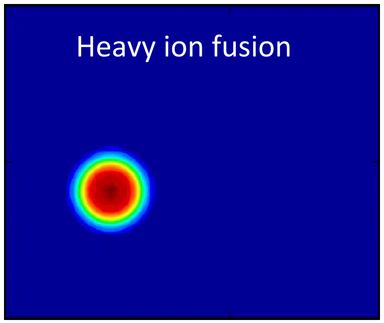
Nuclear technology

needed:
(n,γ)
(light ion,γ)

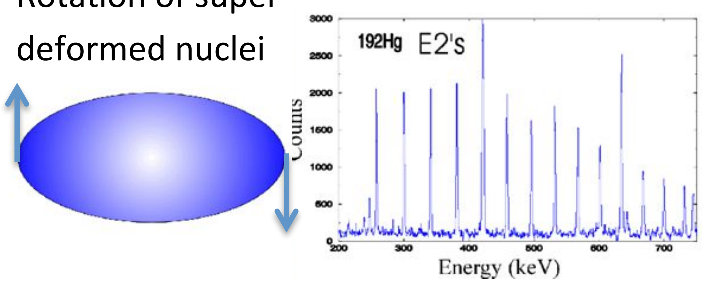


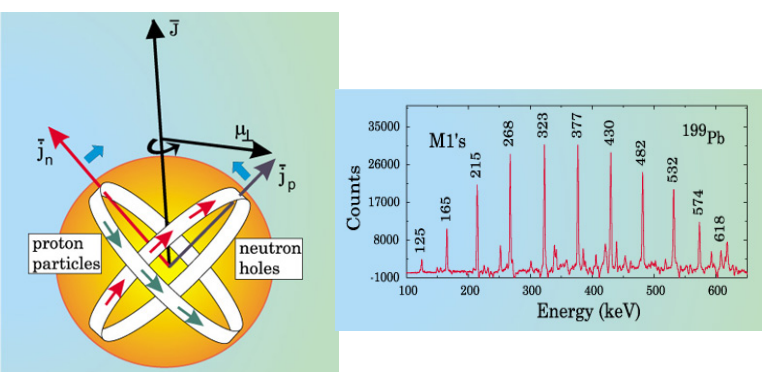
Origin of the Elements,
Nuclear synthesis

	"collective"	"coherent"
	Many nucleons participate in the mode	A wave function $\Psi(\alpha)$ describes the mode, where α is the "collective coordinate" that is directly related to an "order parameter" (measurable physical quantity).
Heavy ion fusion	**yes**	**no**
Rotation of super deformed nuclei	**yes**	**yes** op: charge quadrupole moment
(bottom figures)	**4-6**	**yes** op: magnetic dipole moment



Rotation of super deformed nuclei





Coherence length-decoherence

Coherence length: $\Delta\alpha: \quad |\langle \alpha | \alpha' \rangle|^2 \approx \exp[-\frac{(\alpha-\alpha')^2}{(\Delta\alpha)^2}]$

Minimal distance between two collective coordinate points.
Length scale on which the collective wave function emerges.
Wave length must be larger than coherence length.

$$\pi_{\max} \sim \hbar / \Delta\alpha$$

Limiting momentum that the coherent collective motion can carry.

Transition order to chaos:

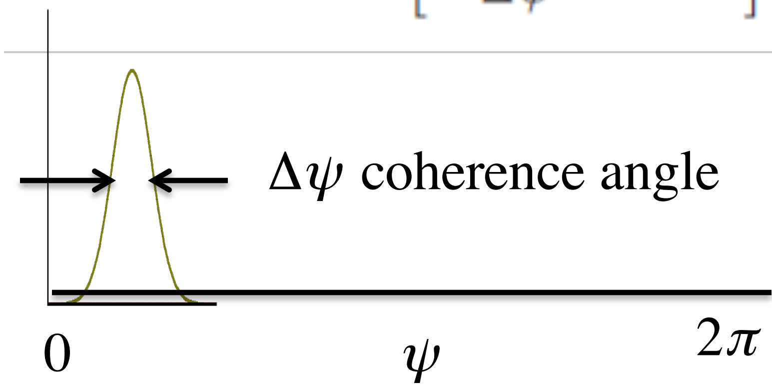
Above a certain excitation energy one cannot expect a one-to-one correspondence between properties of the individual experimental and theoretical states. Element of randomness enter the description.

→ statistical concepts: level density, strength functions

The coherence length increases until the collective wave function
Can no longer live on the system: decoherence

Uniform rotation

$$|\langle \mathcal{R}_z(\psi)\rangle|^2 \sim \exp\left[-\frac{1}{\Delta\psi^2}\sin^2(\psi)\right]$$



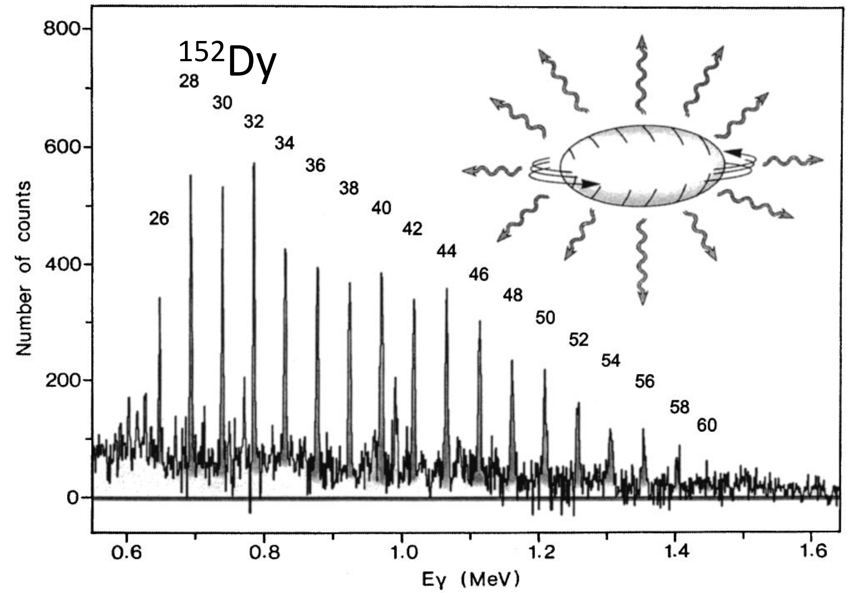
$$\Delta\psi\Delta J \sim 1$$

$$\Delta\psi \approx \Delta J^{-1} \ll 2\pi.$$

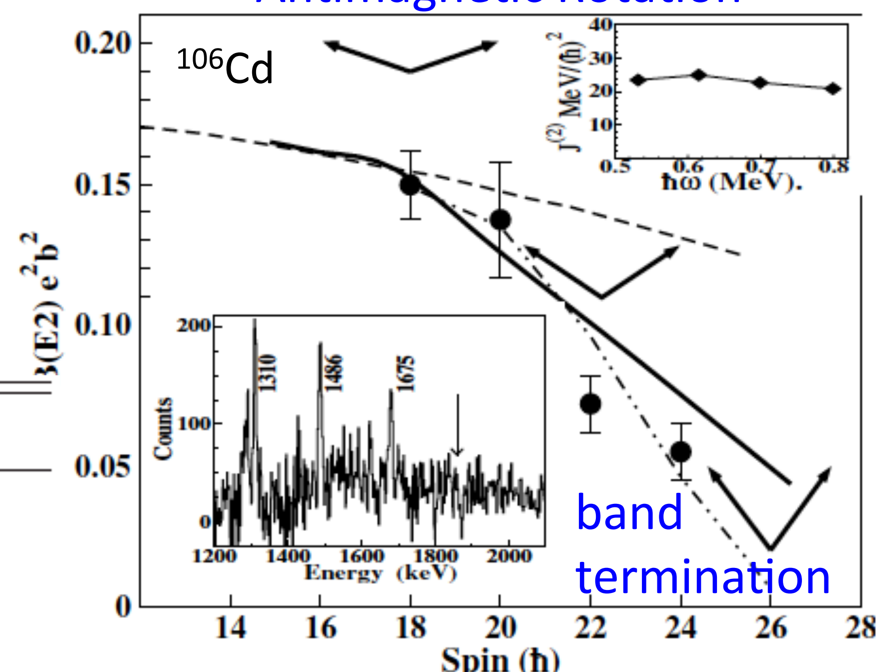
$\sim 2\pi\Delta J$ length of the rotational band

Deformation	Super	Normal	Weak
$\mathcal{J}^{(2)}$	97	56	14
ΔJ	14	7.1	2.9
$\Delta\psi$	4°	8°	20°

Superdeformed bands



Antimagnetic Rotation



Loss of coherence (order -> chaos) by warming up

Electric quadrupole moments – collective quadrupole mode

-Rotational damping

-Islands of order in the sea of chaos

Magnetic dipole moments – magnetic rotation

-Low Energy Magnetic Radiation (no coherence)

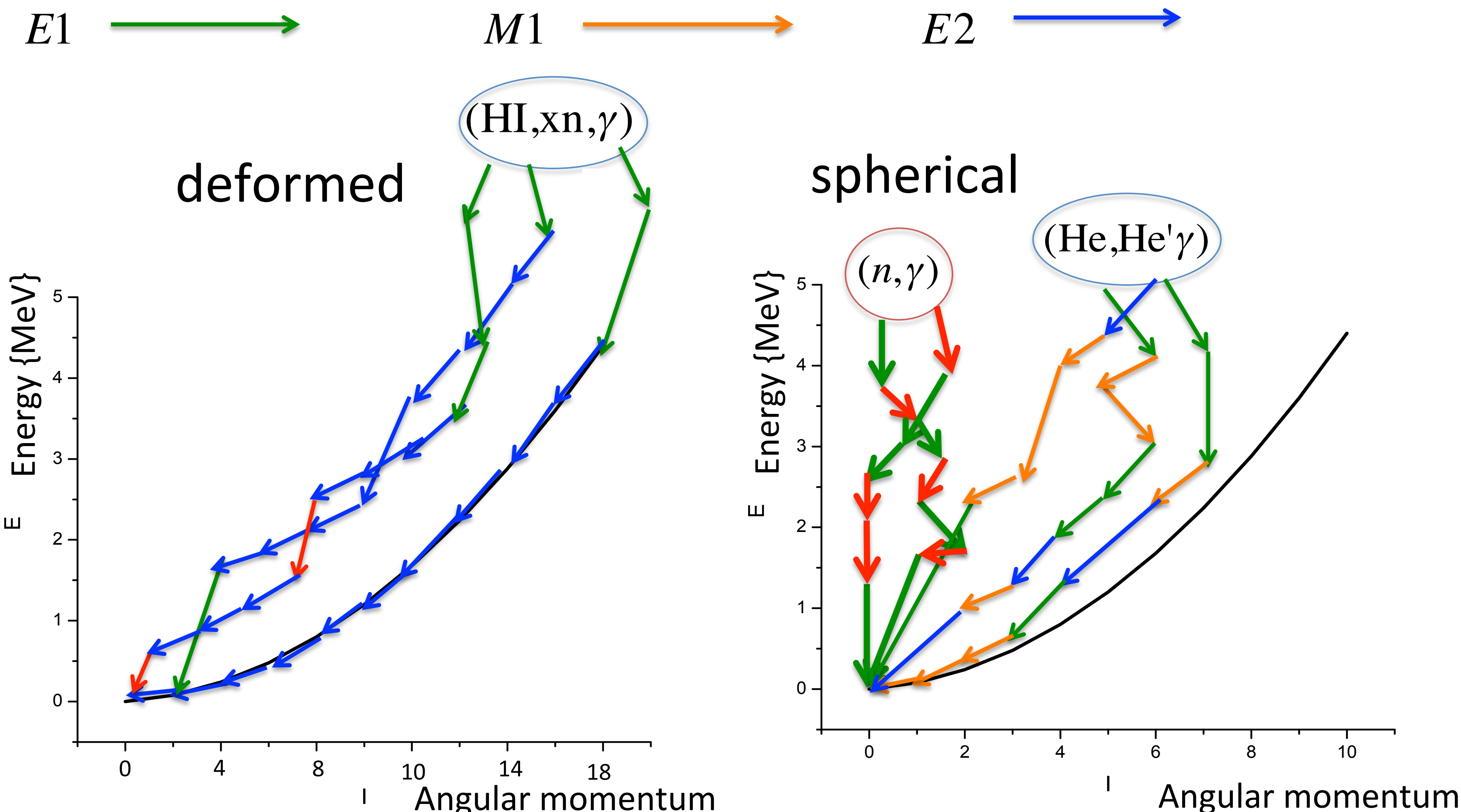
-Bimodal structure of M1 strength (onset of coherence)

-Consequences for element synthesis

Average reduced transition probability/state $\bar{B}(E1, M1, E2, E_\gamma, E_i)$

Radiative strength function $\Gamma_\gamma(E1, M1, E_\gamma, E_i) / 2\pi E_\gamma^3 \propto \bar{B}(E1, M1, E_\gamma, E_i)\ \rho(E_i)$

Number states /energy unit $\rho(E)$



Decoherence by warming: rotational damping

Experiment: Copenhagen/Milano collaboration

Theory: T. Dossing, M. Matsuo, K. Yoshida

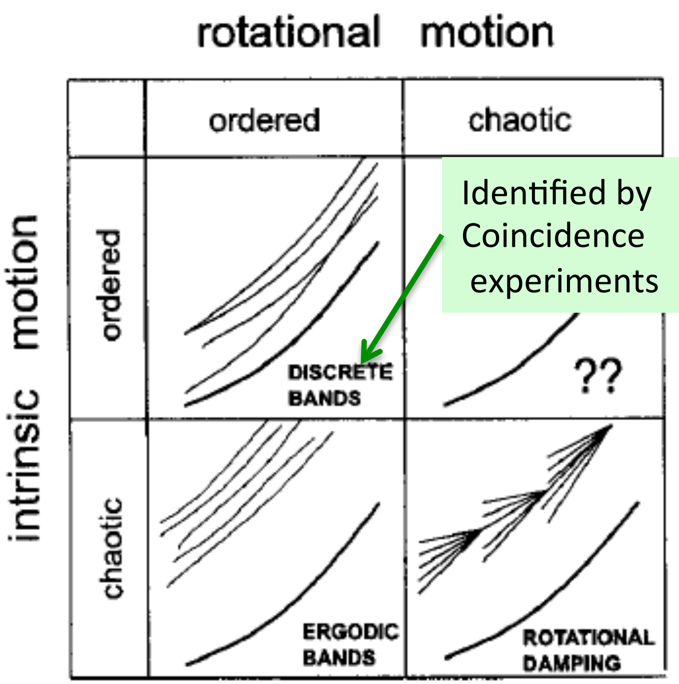
Cranked mean field configurations $(h_{def} - \omega j)|\omega,i\rangle = E'|\omega,i\rangle$ basis

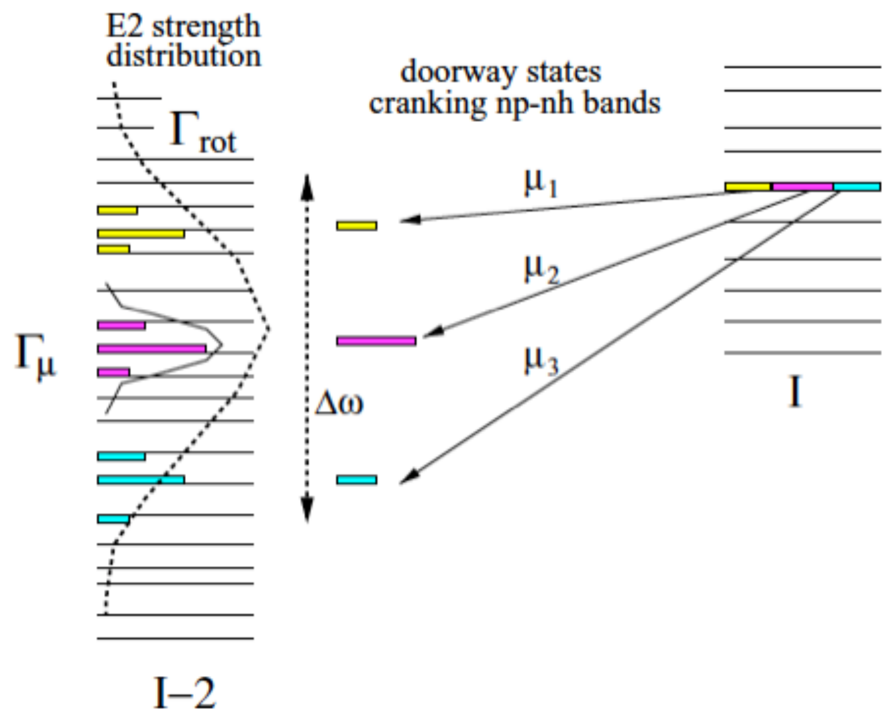
Diagonalization of $H = h_{def} + V_{\text{int}}$ in the basis $|\omega,i\rangle$ mixing

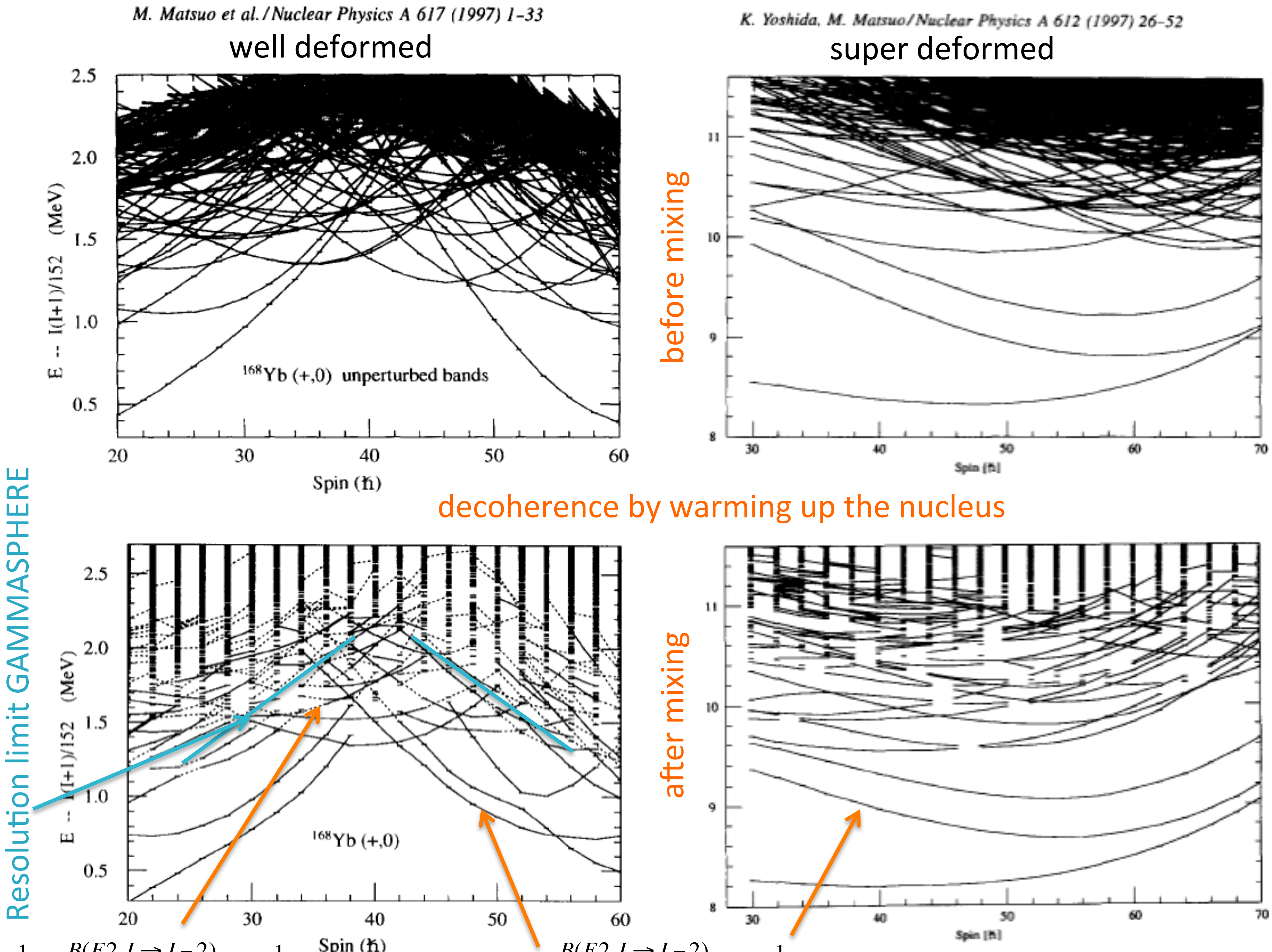
V_{int} surface delta interaction

ordered = coherent motion

give up one-to-one correspondence
use statistical concepts





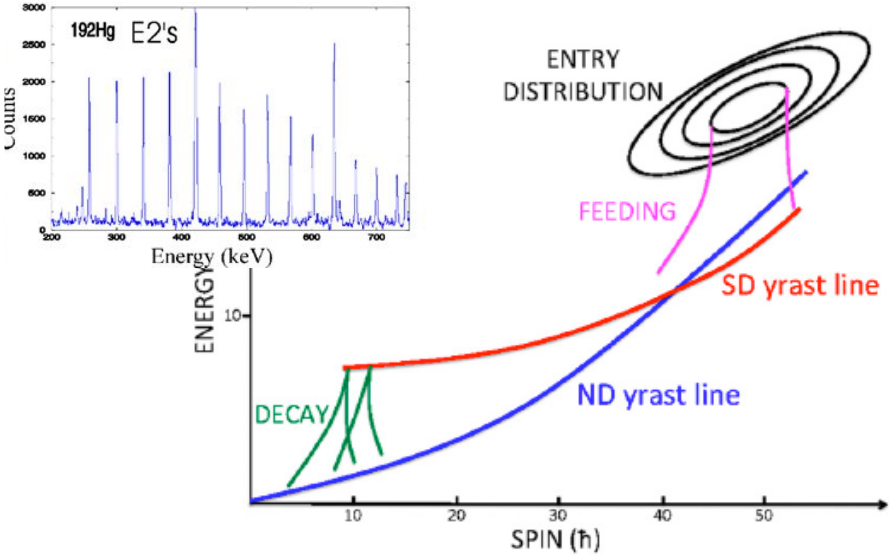


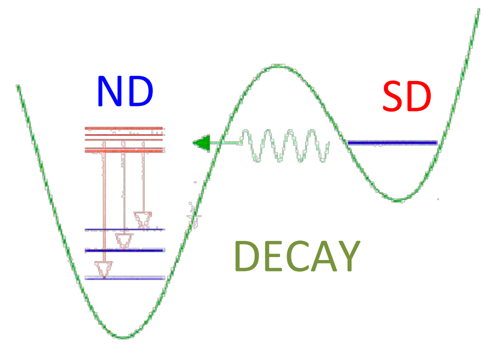
$$\frac{1}{\sqrt{2}} > \frac{B(E2, I \rightarrow I-2)_{after}}{B(E2, I \rightarrow I-2)_{before}} > \frac{1}{2}$$

$$\frac{B(E2, I \rightarrow I-2)_{after}}{B(E2, I \rightarrow I-2)_{before}} > \frac{1}{\sqrt{2}}$$

Superdeformed bands

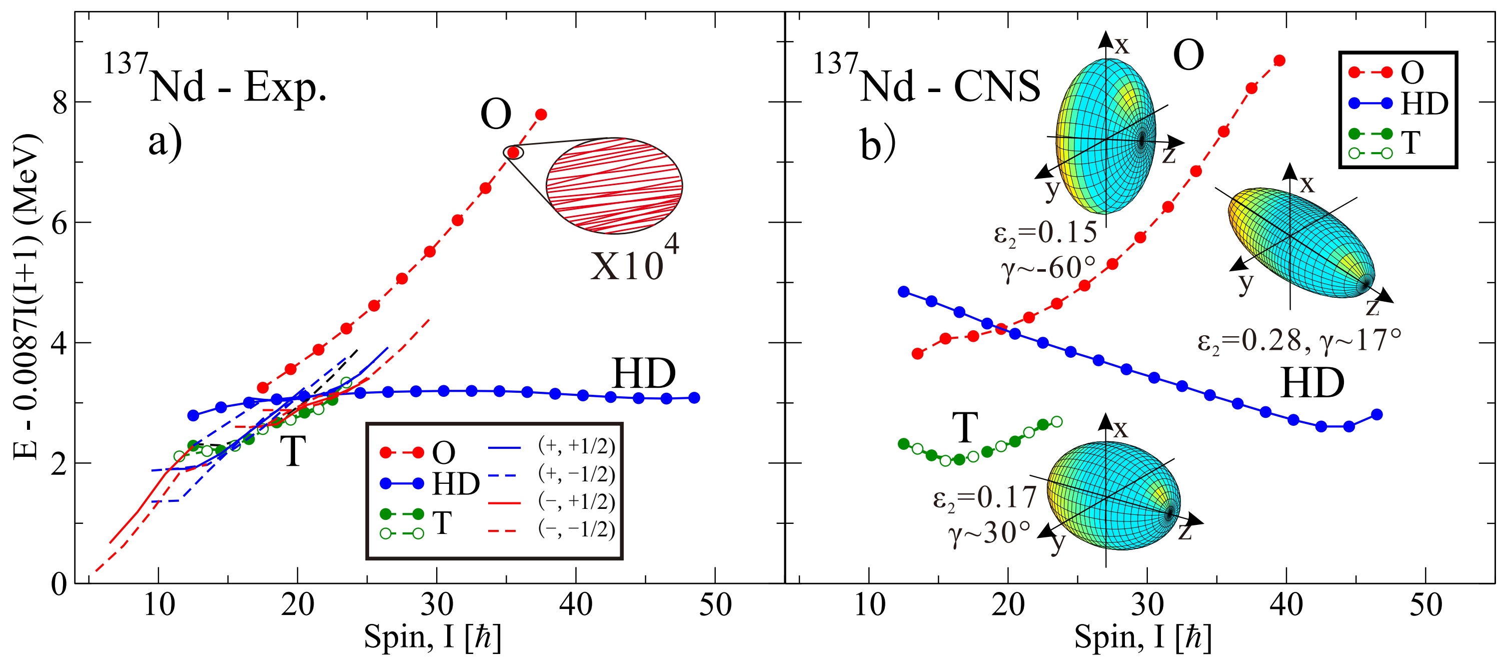
Islands of order in the sea of chaos





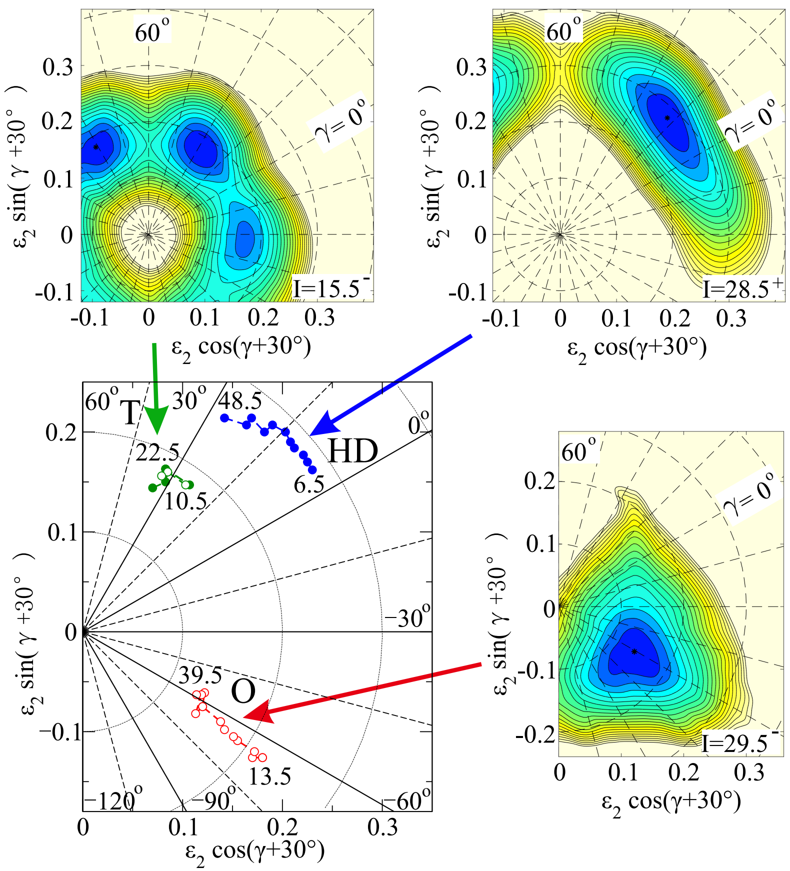
S Leoni, A Lopez-Martens, Phys. Scr. 91 (2016) 063009

Oblate band

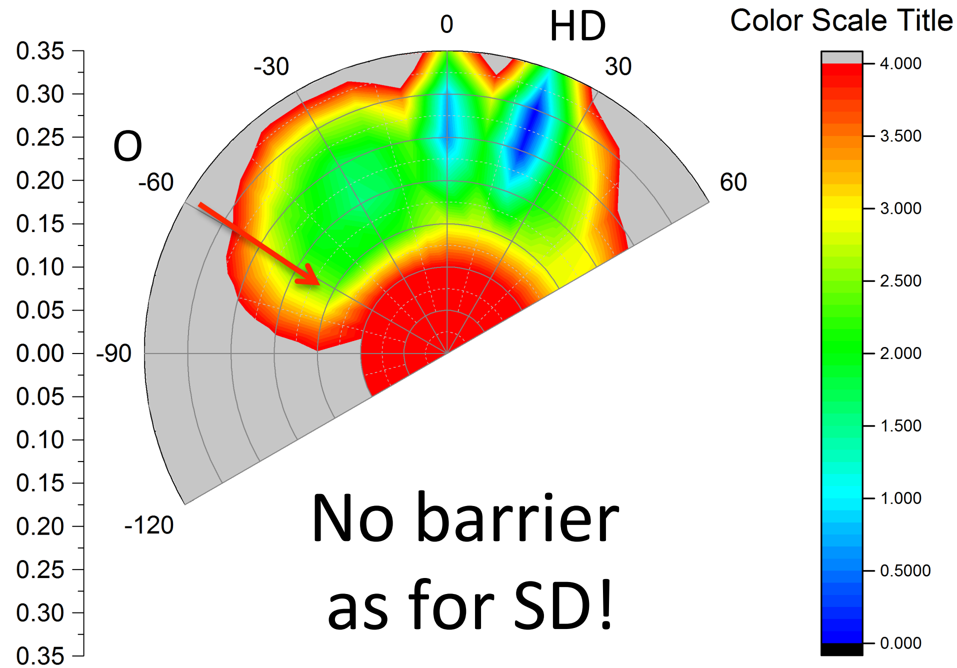


C. M. Petrache, S. F. et al. , Phys. Lett. B accepted

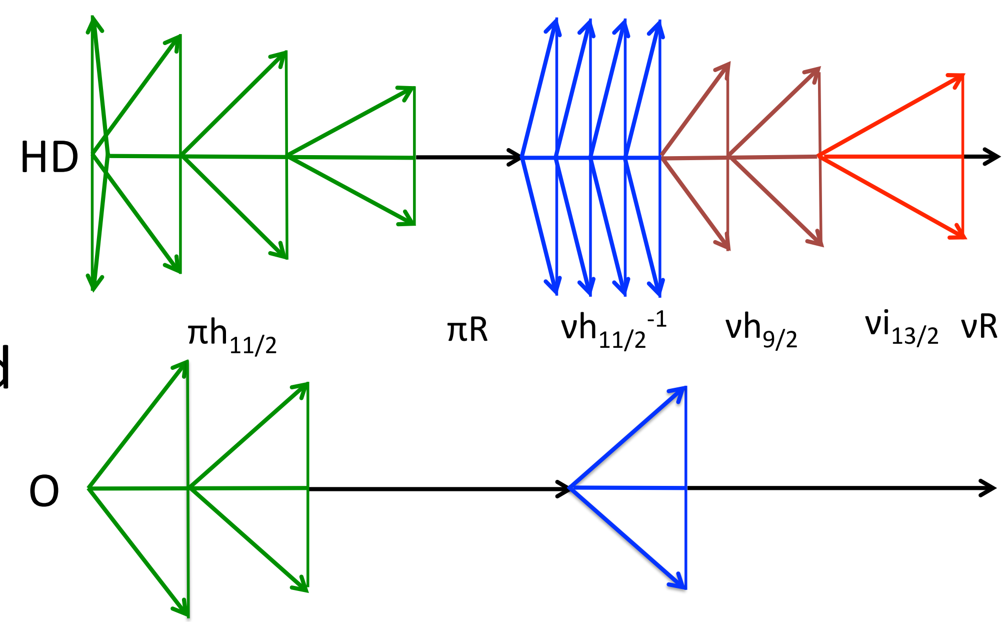
configuration constraint CNS



yrast configuration TRS ω=0.4 MeV



No barrier
as for SD!



Structure inhibited

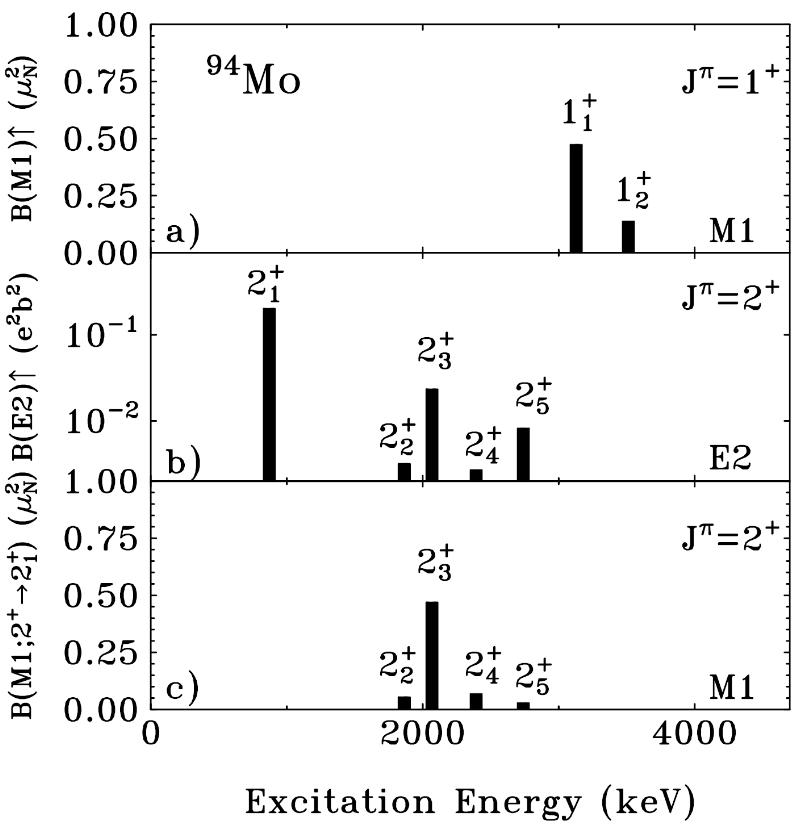
Warming up the nucleus

- Coherence of rotational motion is attenuated
- Special configurations are screened: superdeformed bands by a potential wall
- oblate bands in Nd by a substantial rearangment of single particle orbitals

Emergence of the LEMAR spike:
chaotic M1 radiation in spherical nuclei
Loss of the pair field

Dipole strength in ^{94}Mo

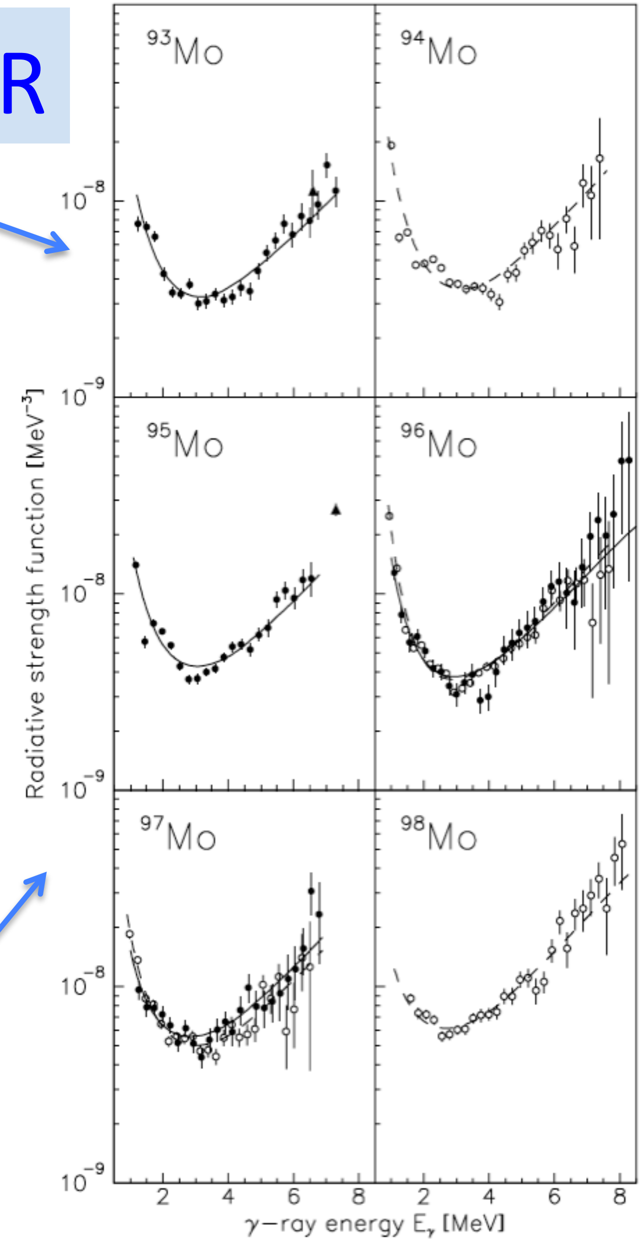
LEMAR



Absorption from the ground state

N. Pietralla et al. PRL 83 (1999) 1303

? ? ?



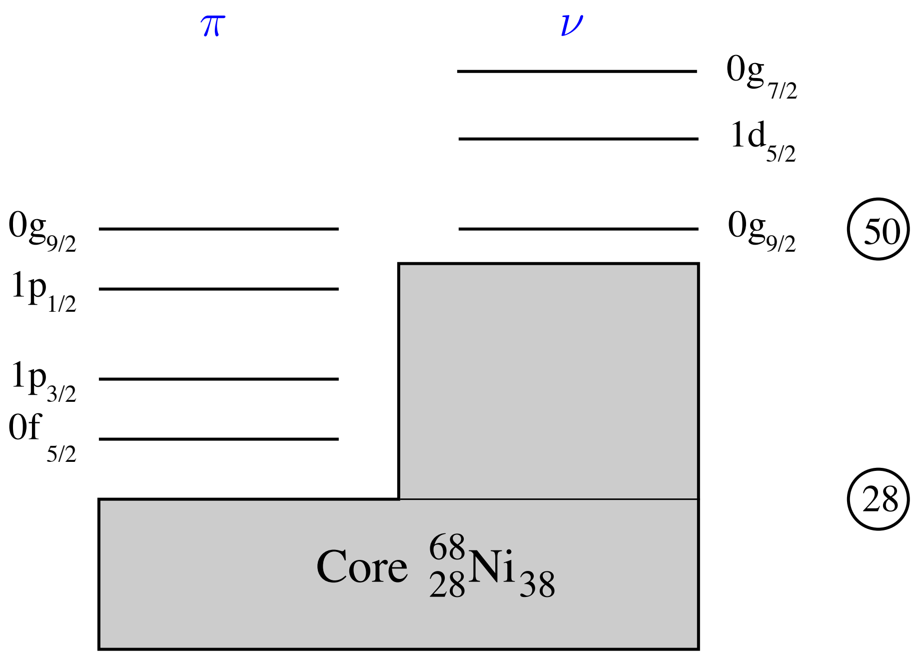
M. Guttormsen et al.
PRC 71 (2005) 044307

Low-energy dipole radiation
What is it? Assumption M1

Shell-model calculations around N = 50

R. Schwengner et al.
PRL 111, 232504 (2013)

Configuration space SM2:



Code: RITSSCHIL

Two-body matrix elements:

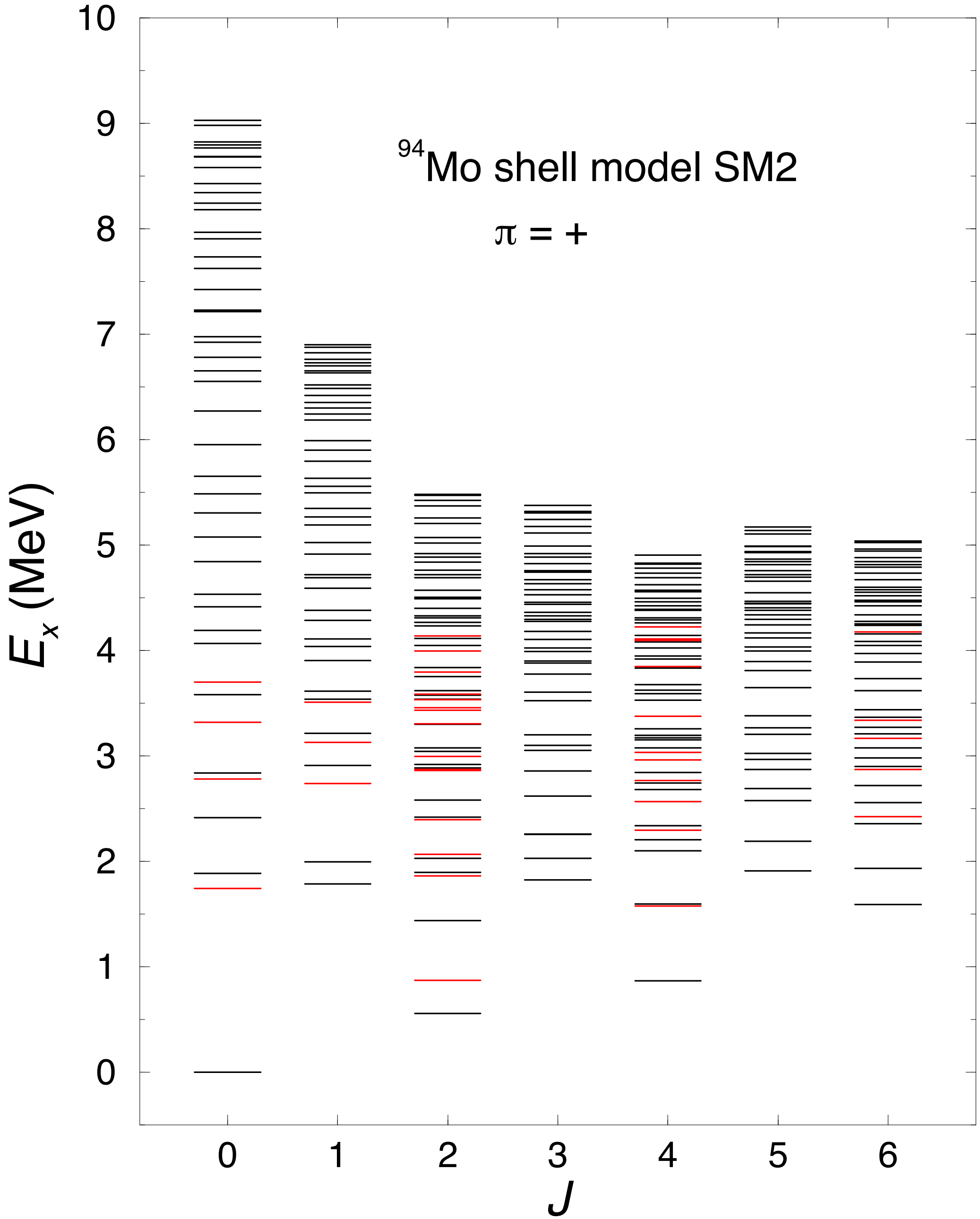
$\pi\pi$:
empirical from fit to N=50 nuclei, ^{78}Ni core;
X. Ji, B.H. Wildenthal, PRC 37 (1988) 1256

$\pi\nu, \nu\nu$ $(0g_{9/2}, 1p_{1/2})$:
emp. from fit to N=48,49,50 nuclei, ^{88}Sr core;
R. Gross, A. Frenkel, NPA 267 (1976) 85

$\pi\nu$ $(\pi 0f_{5/2}, \nu 0g_{9/2})$:
experimental from transfer reactions;
P.C. Li et al., NPA 469 (1987) 393

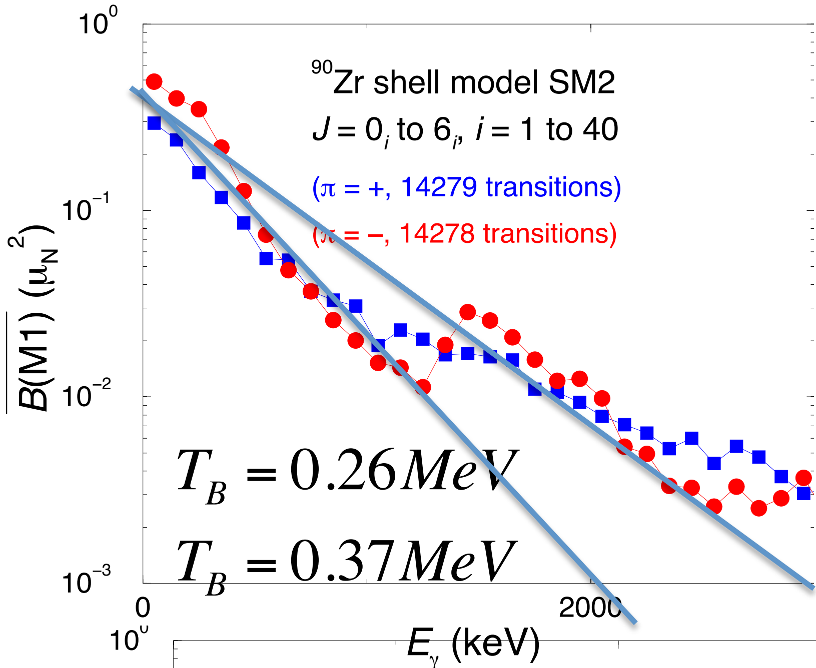
$\nu\nu$ $(0g_{9/2}, 1d_{5/2})$:
exp. from energies of the multiplet in ^{88}Sr;
P.C. Li, W.W. Daehnick, NPA 462 (1987) 26

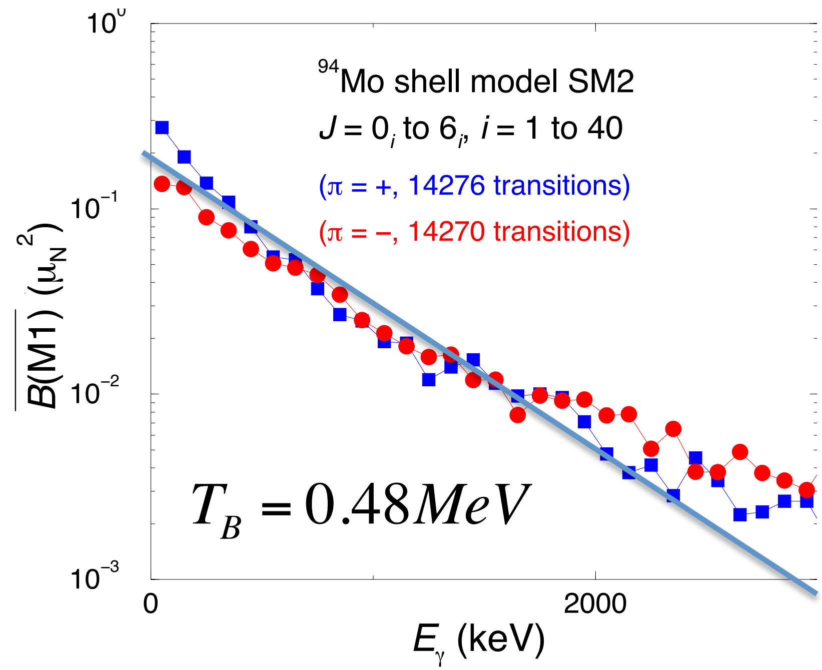
remaining:
MSDI;
K. Muto et al., PLB 135 (1984) 349

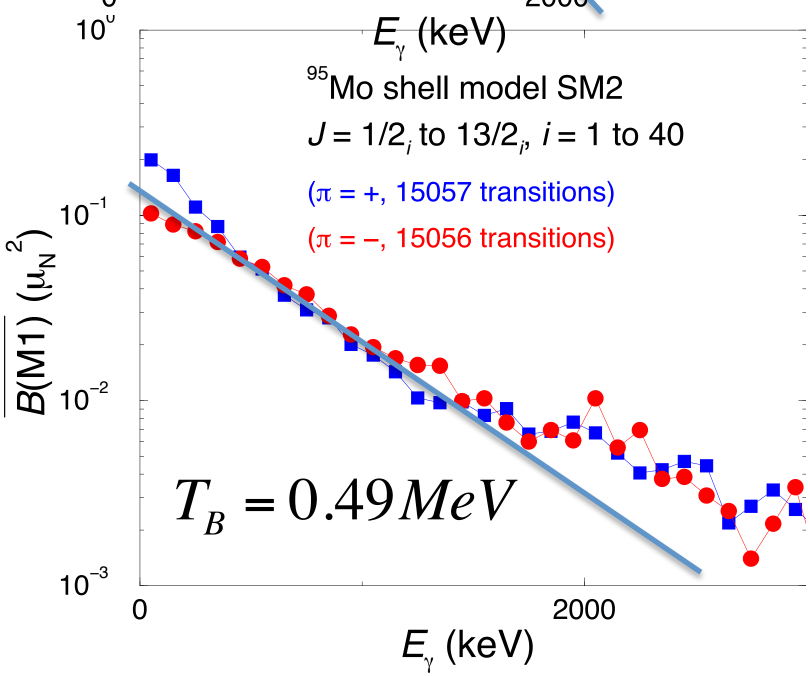


Average B(M1):
Calculate all possible M1 transitions within every 100keV bin of transition energy.
Sum the B(M1) values and
divide by the number of
possible transitions.

“possible” means:
all transitions that conserve energy, angular momentum, parity







Dependence on γ − energy

nearly exponential decrease

$$B(M1, E_\gamma) \approx B_0 \exp(-E_\gamma / T_B)$$

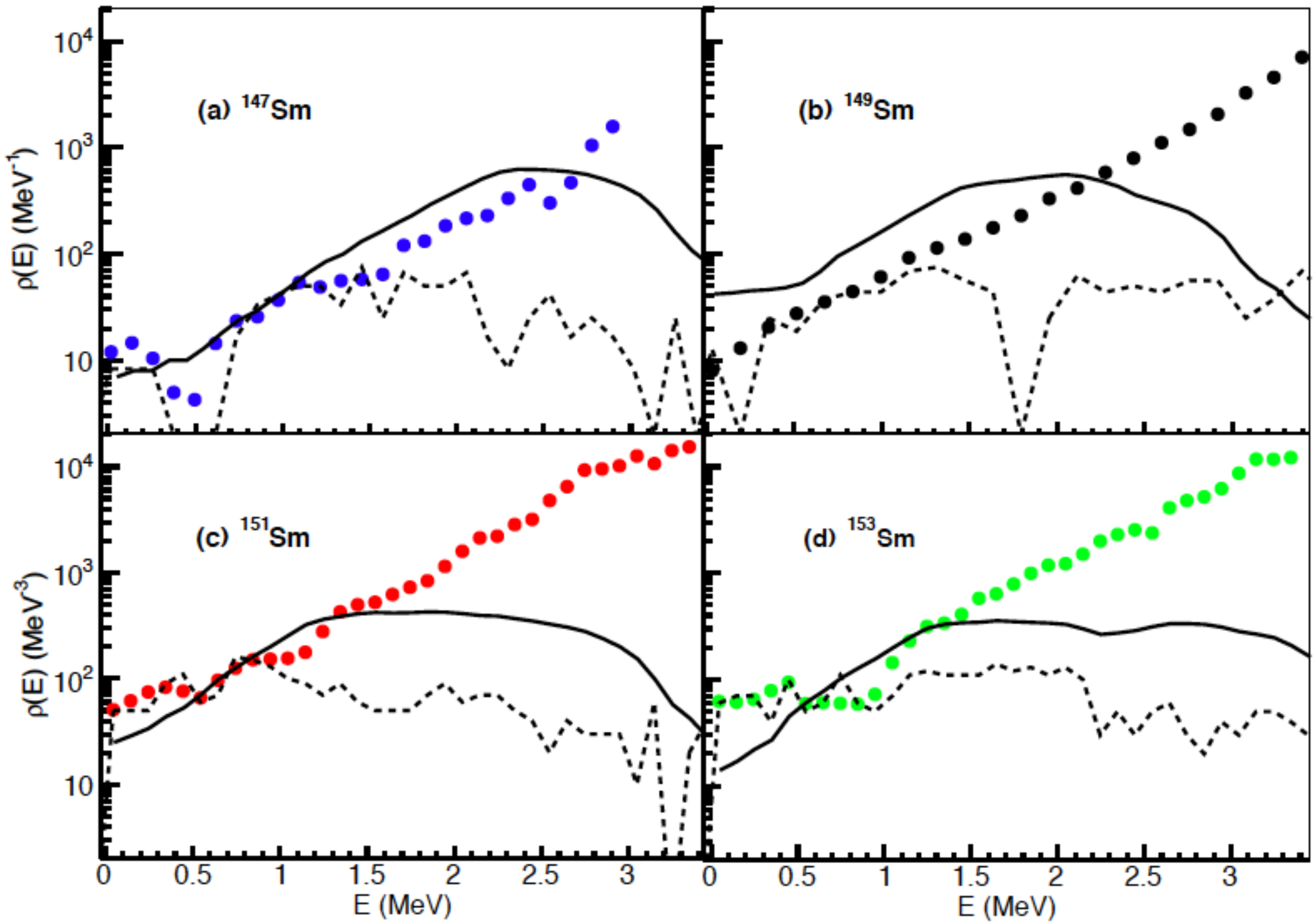


FIG. 6. Level density functions for all four Sm isotopes: solid symbols - data extracted using the Oslo method, solid line - level density from shell-model calculations, dashed line - known levels.

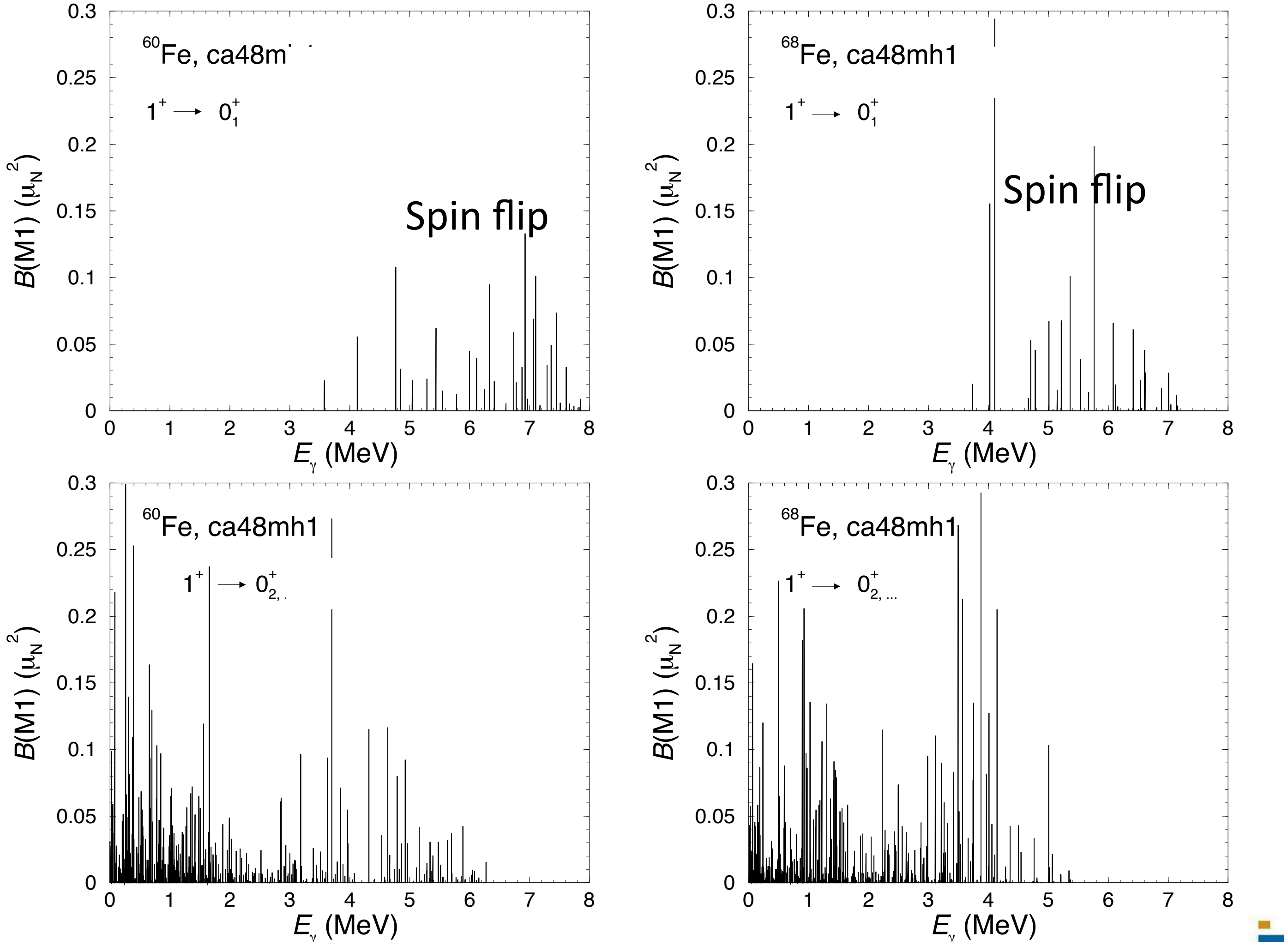
jj56pn model space with the jj56pna Hamiltonian using the code NuShellX@MSU [45]. The model space

$$\rho(E^*) \propto \exp[E^* / T]$$

melting of the pair correlations

F. Naqvi, A. Simon, M. Guttormsen, R. Schwengner, S. Frauendorf, C.S. Reingold, J.T. Burke, N. Cooper, R.O. Hughes, P. Humby, J. Koglin, S. Ota, and A. Saastamoinen, Phys. Rev. C, accepted

Transitions from 1^+ states



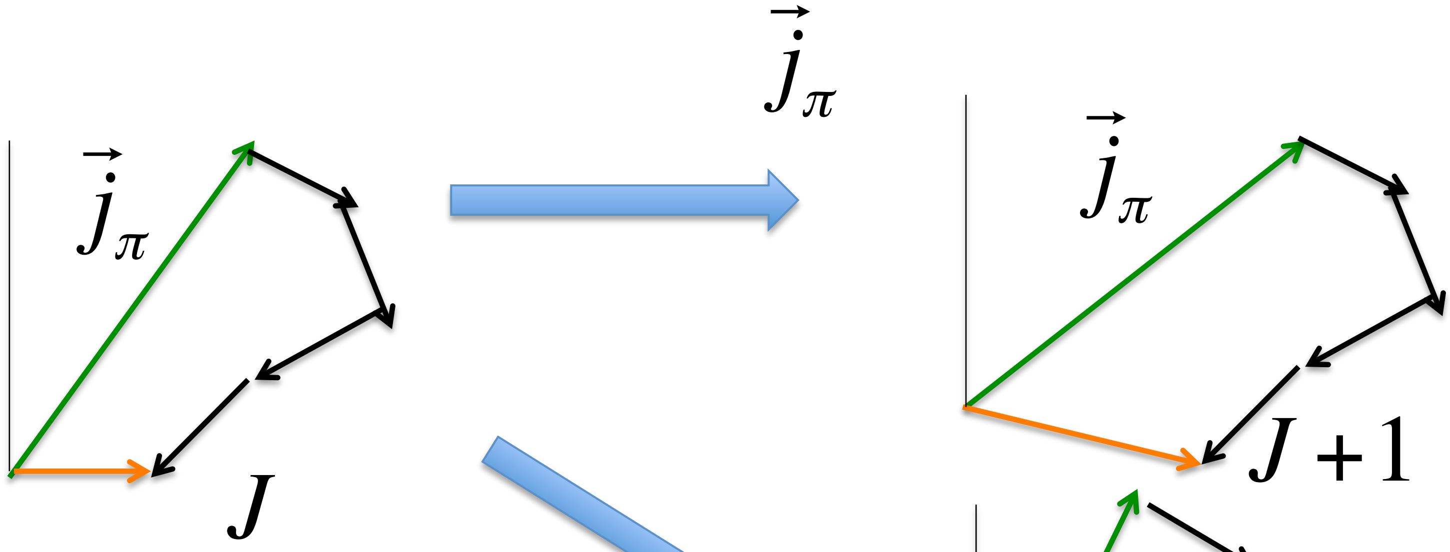
Warming up the nucleus (going to higher excited states) destroys the pairing correlations, which thaws frozen orientation of the magnetic dipoles

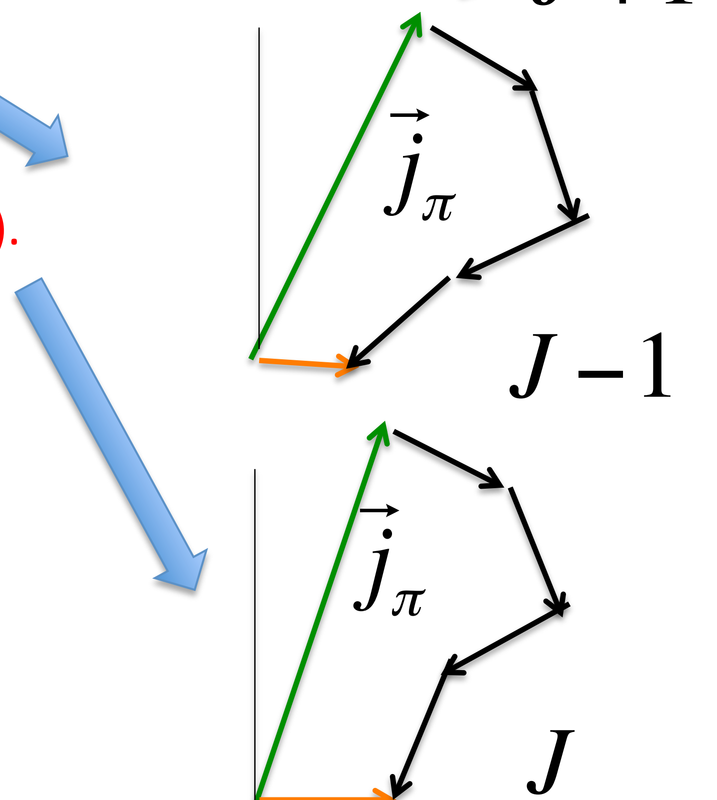
Mechanism which generates the M1 radiation

Configurations that generate large M1 transition strengths (active orbits with $j_\pi \neq 0$ and $j_\nu \neq 0$):

- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^2_{5/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^2_{5/2})$
- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^1_{5/2}\ 0g^1_{7/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^1_{5/2}\ 0g^1_{7/2})$
- $\pi = +$: $\pi(0g^2_{9/2})$ $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$
  $\pi = -$: $\pi(1p^{-1}_{1/2}\ 0g^3_{9/2})$ $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$.
- $\pi = +$: $\nu(1d^2_{5/2}\ 0g^{-1}_{9/2}\ 0g^1_{7/2})$

Large matrix elements between different states of one and the same configuration that are related by mutual re-alignment of the angular momenta of the active high-j orbitals.

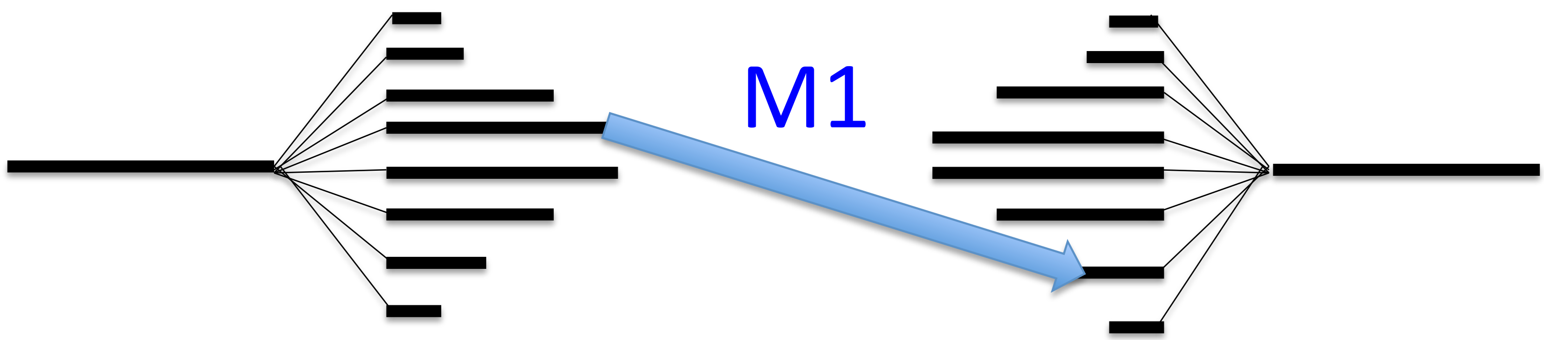




Reorientation of high-j orbitals within the same configuration generates large B(M1). Without residual interaction it does not cost energy.

$$B(M1) \sim A_i g_\pi^2 \left| \vec{j}_\pi - \vec{j}_\pi ' \right|^2 \mu_N^2$$

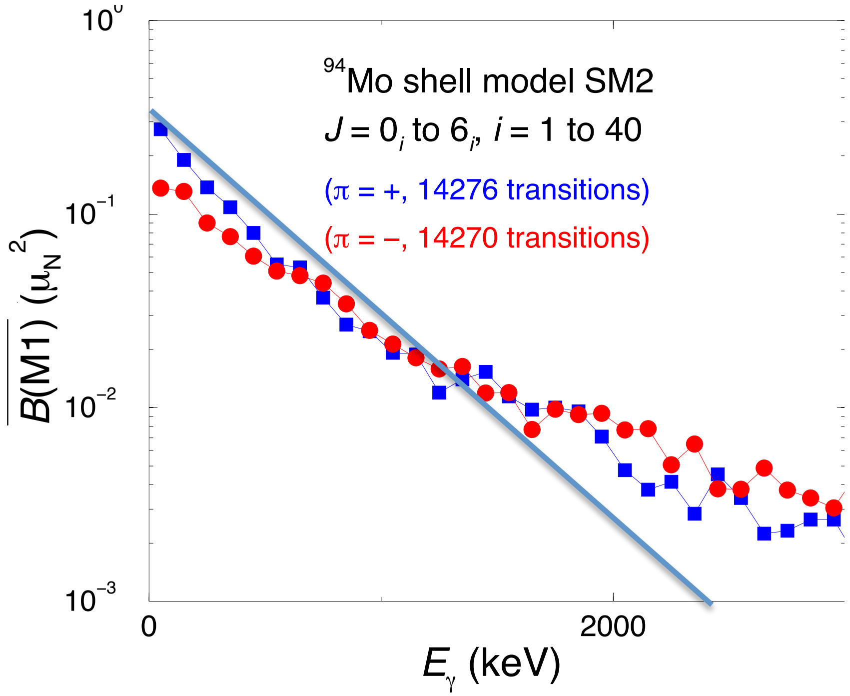
A_i: stochstic angular momentum coupling factor

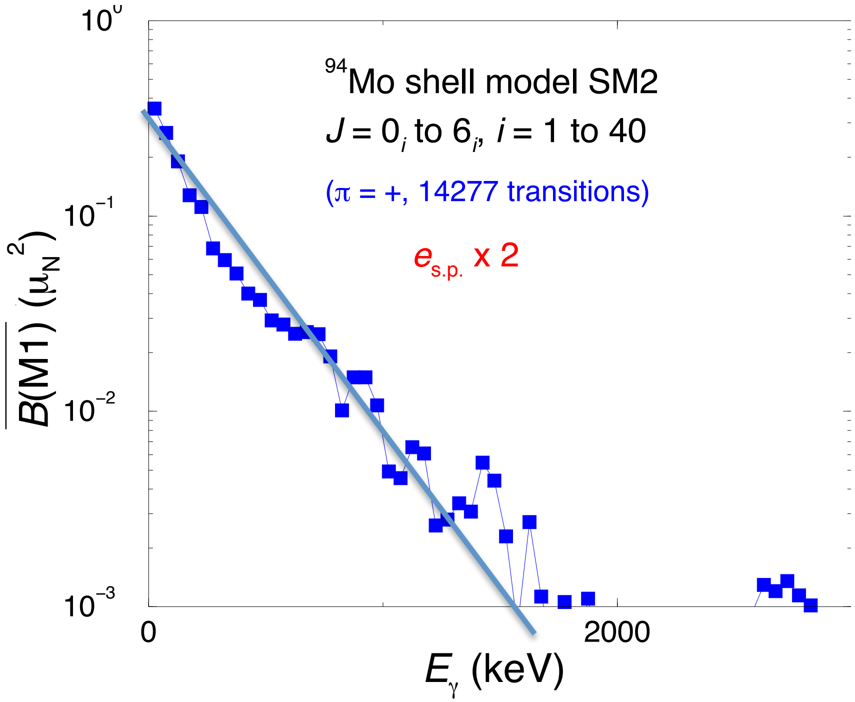


Large matrix elements between different sates of one and the same configuration that are related by mutual re-alignment of the spins of the active high-j orbitals.

Without residual interaction the states have the same energy
-> no radiation

Residual interaction mixes the states in a chaotic way and generates energy differences between them
->radiation





full interaction strength

$T_B = 0.49 MeV$

half interaction strength

$T_B = 0.24 MeV$

no interaction $T_B = E_\gamma = 0$

The residual interaction is the only energy scale

Strong M1 by re-alignment of high-j orbital

$$\mu_+ = g(j)\sqrt{(j-m)(j+m+1)}c^+_{m+1}c_m$$

$$\left|i\right\rangle = \sum_r a^i_r \left|r\right\rangle, \quad \left|f\right\rangle = \sum_r a^f_r \left|r\right\rangle,$$

The states are chaotically distributed over a number d of multi quasiparticle configurations, which reduces

$$\left\langle f\right|\mu_+\left|i\right\rangle \sim g(j)\sqrt{(j-m)(j+m+1)}/\sqrt{d}$$

with $d = \exp[S(E_i)]$, relative level distance

S entropy, $1/T = dS/dE$ inverse temperature

$$S(E_i) = S(E_f + E_\gamma) = S(E_f) + E_\gamma / T$$

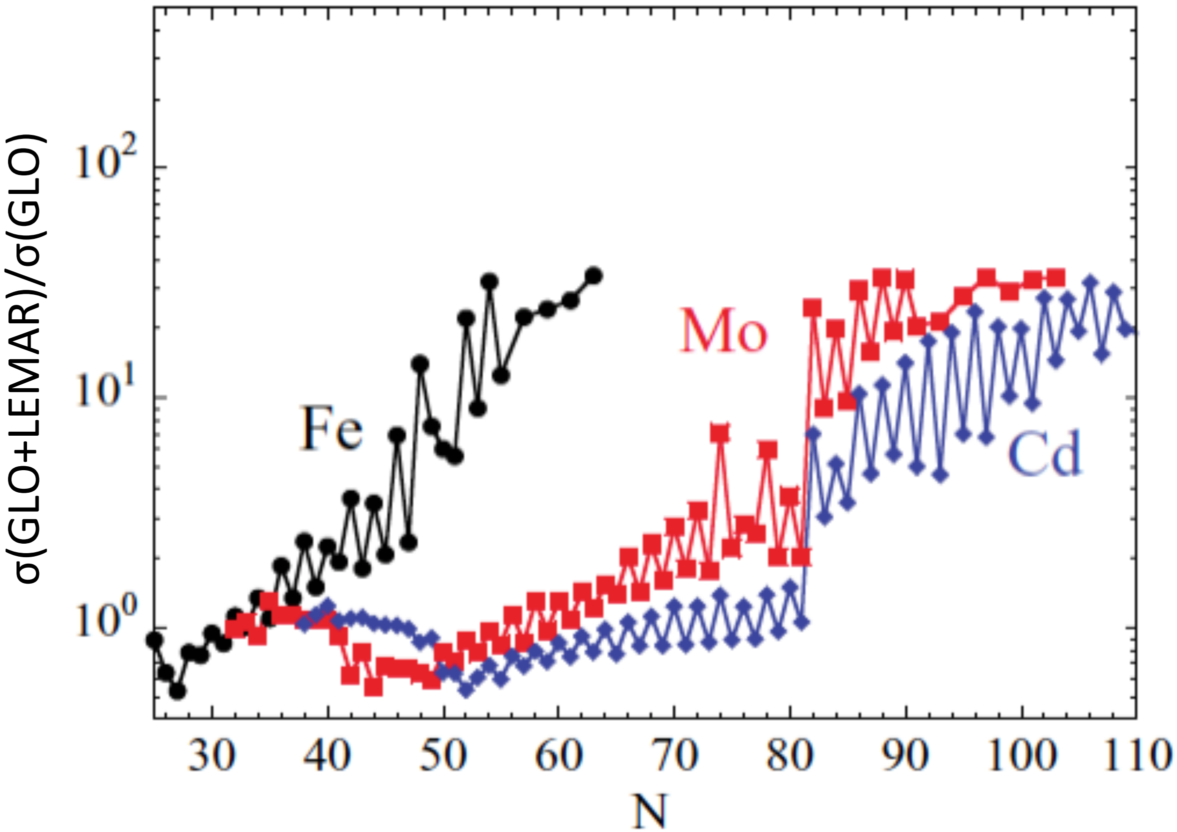
$$B(M1) = B_0 \exp[-E_\gamma / T]$$

See Zelevinsky, Volya
Phys. Rep. 391 (2004) 311

The increasing complexity of generates the exponential fall-off.

The temperature appearing in the level density and in the B(M1) are the same.
(information entropy thermodynamic entropy are the same).

Impact of LEMAR on (n,γ) reaction cross sections

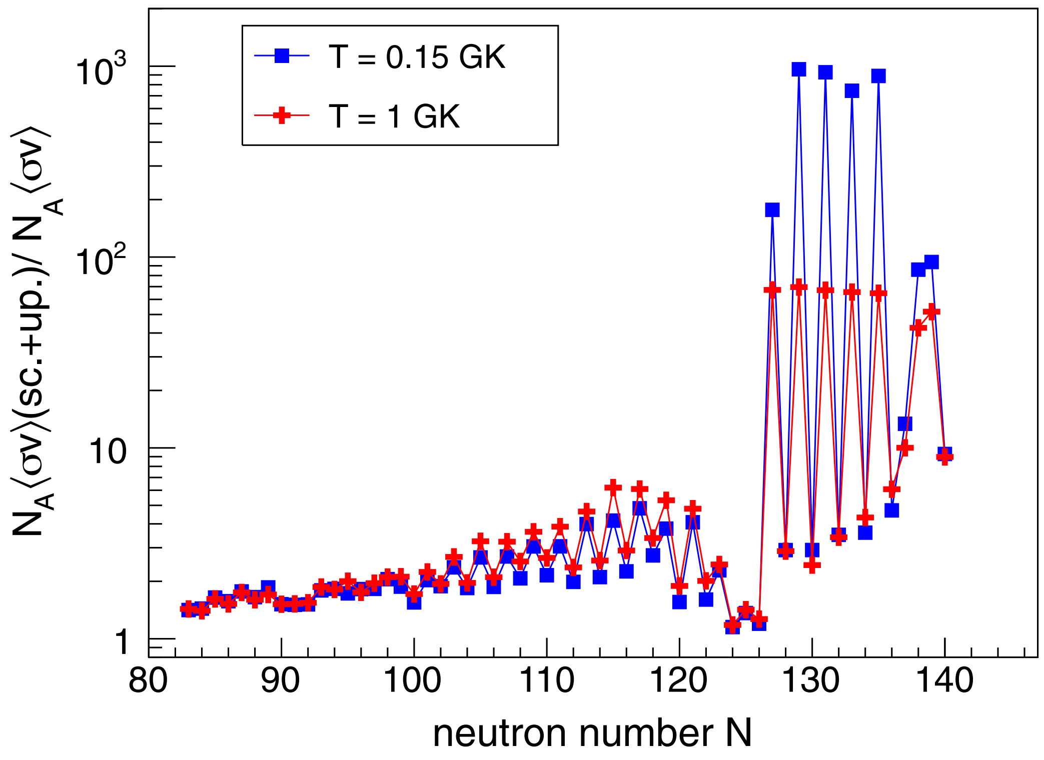


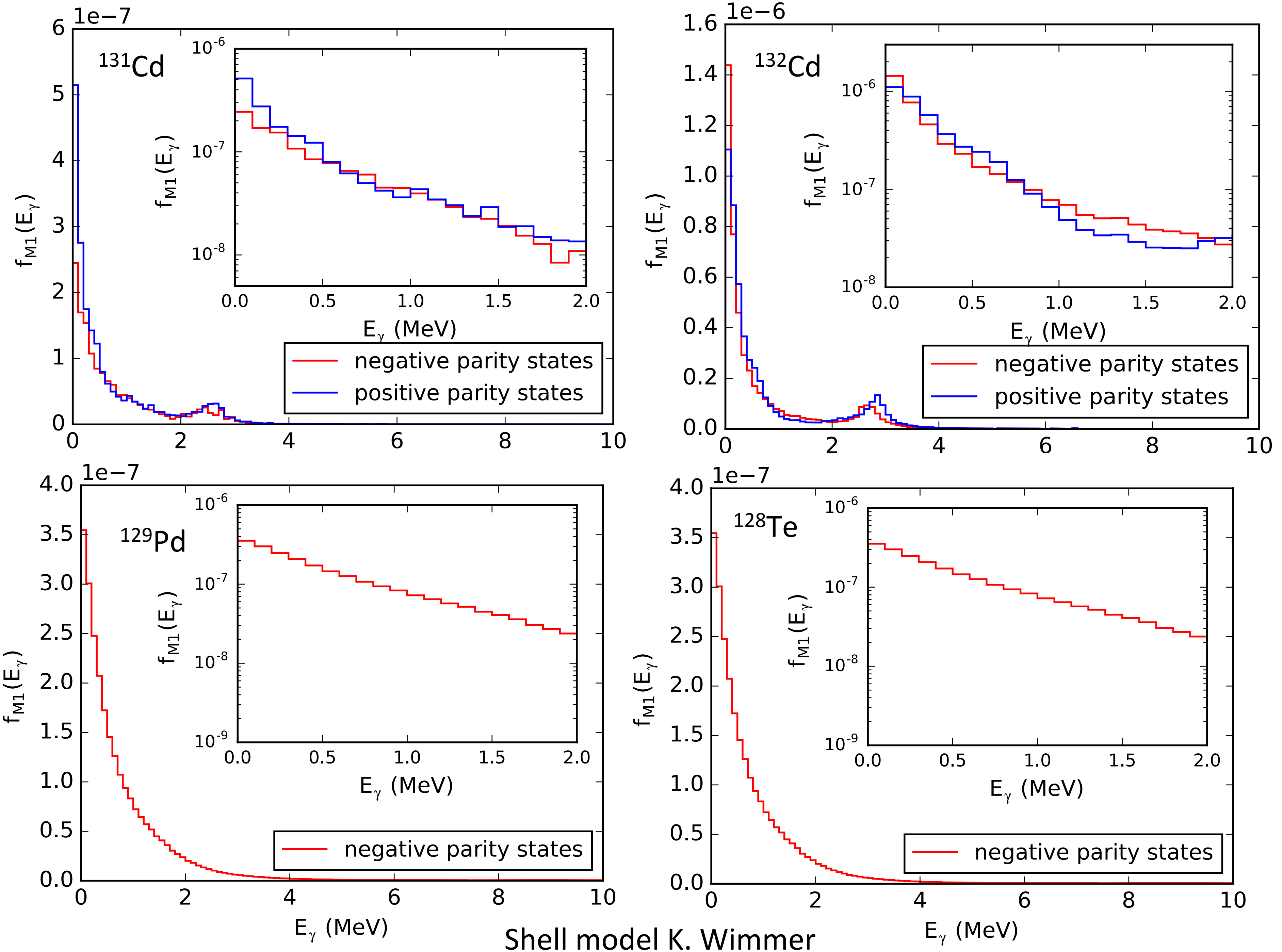
A.C. Larsson and S. Goriely
PRC 82 (2010) 014318

LEMAR enhances the cross section up to a factor of 100

A. Simon et al. , Phys. Rev. C 93, 034303 (2016)

Sm istopes





Shell model K. Wimmer

Warming up the nucleus

- Quenching pairing generates Low Energy Magnetic Radiation LEMAR
- The transition strength falls of exponentially

$$B(M1) \propto \exp[-E_\gamma / T_B]$$

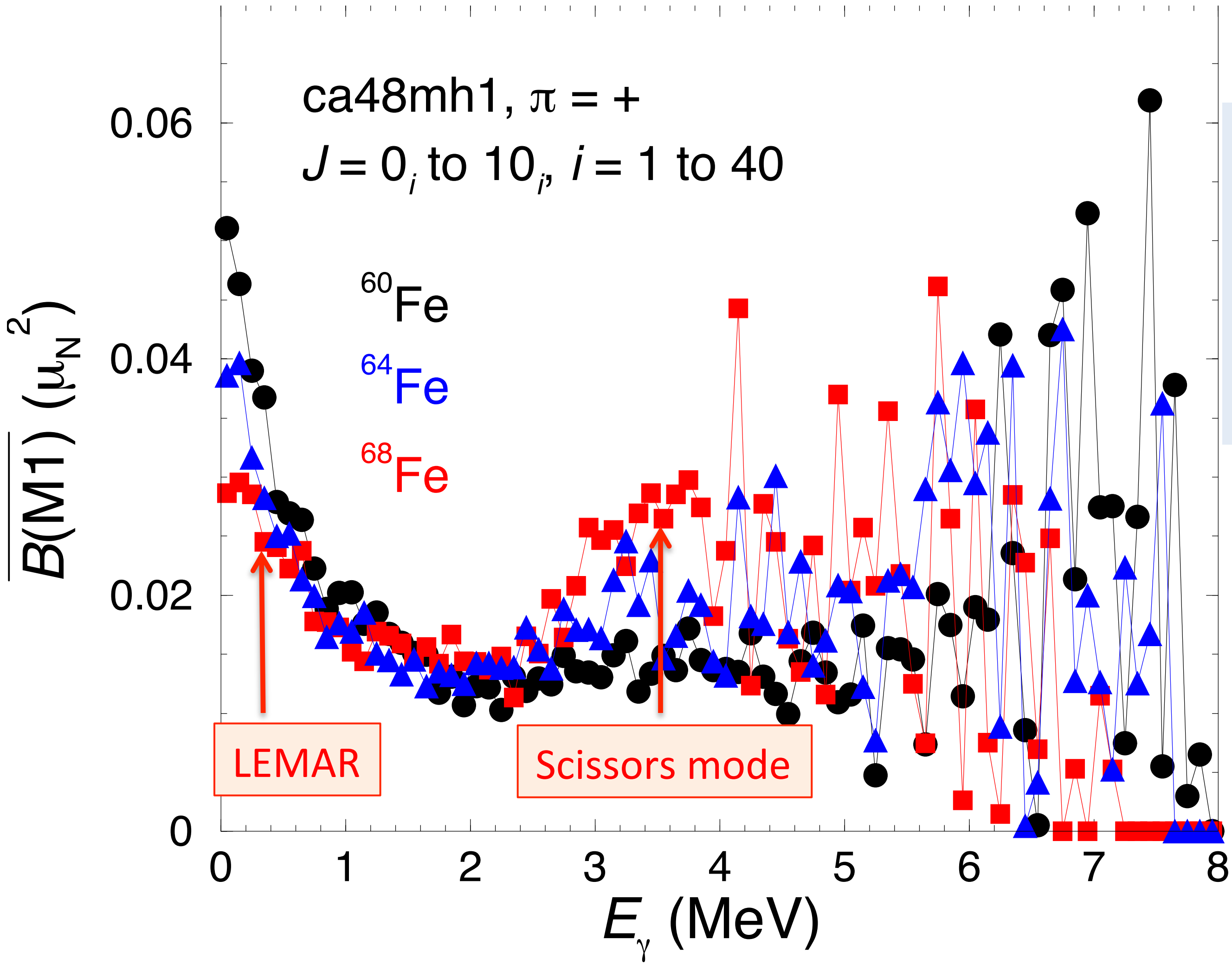
- LEMAR expected near closed shells
- LEMAR may increase the (n,gamma) cross-sections in the r-process by several orders of magnitude.

Bimodal structure: onset of coherence
Consequences of deformation

Bimodal structure

Shell Model calculations for $^{60,64,68}Fe$
R. Schwengner , S. F., B. A. Brown,
Phys. Rev. Lett. 118, 092502 (2017)

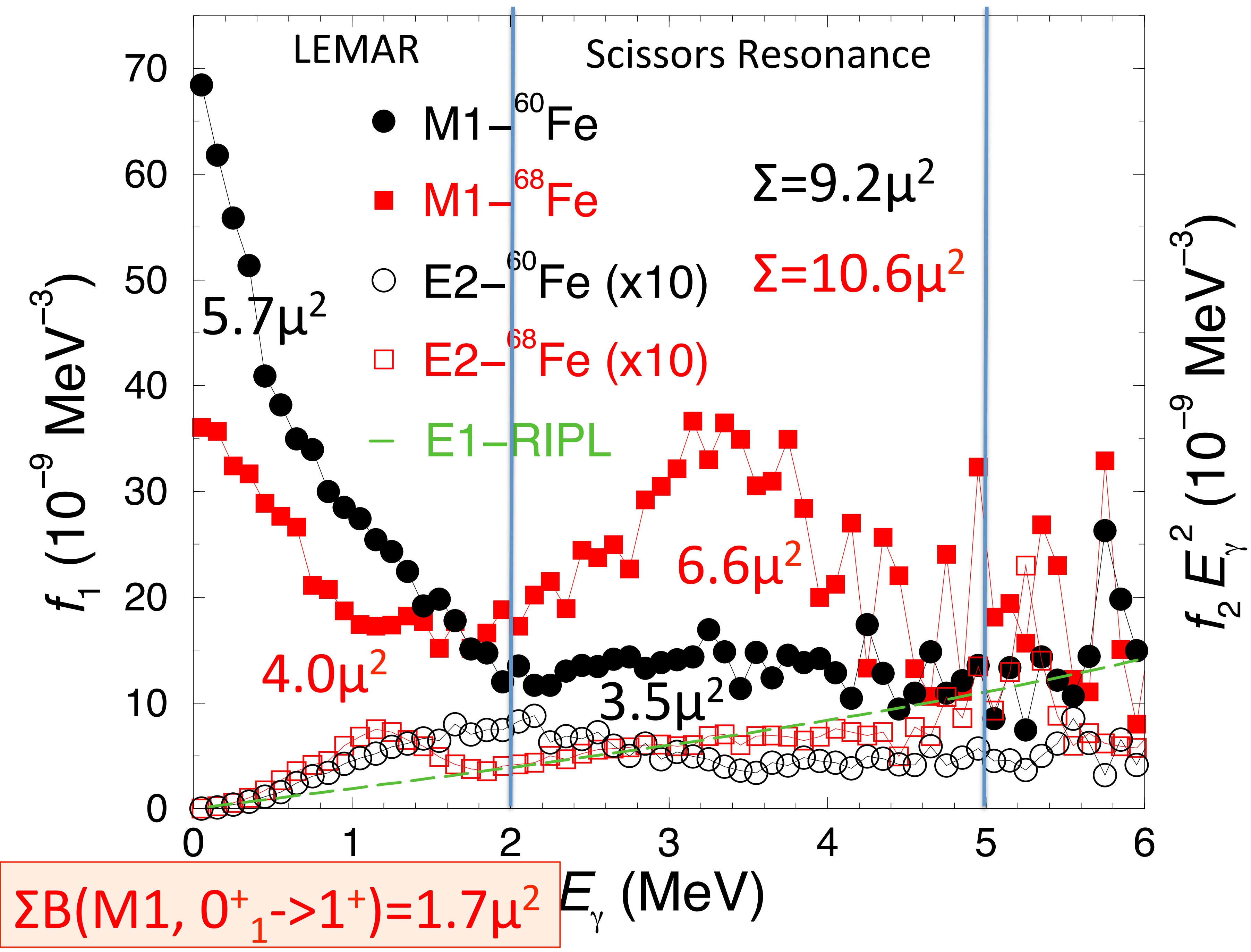
Newshell code
4n in $g_{9/2}$ for A=60,64, 6n in $g_{9/2}$ for A=68
rest in pf, p in pf, GPFX1A Hamiltonian



With increasing deformation

-LEMAR becomes less spiky
-Scissors Resonance appears

A	60	64	68
$E(2^+_{exp})[keV]$	823	746	522
$E(2^+_{SM})[keV]$	779	589	616
$B(E2)_{exp}[e^2 fm^2]$	190	344	450
$B(E2)_{SM}[e^2 fm^2]$	368	406	406
$\sqrt{\langle \beta^2 \rangle_{exp}}$	0.33	0.45	0.51
$\sqrt{\langle \beta^2 \rangle_{SM}}$	0.46	0.49	0.49



LEMAR
Scissors Resonance
M1–60Fe
M1–68Fe
E2–60Fe (x10)
E2–68Fe (x10)
E1–RIPL
Σ=9.2μ²
Σ=10.6μ²
5.7μ²
4.0μ²
6.6μ²
3.5μ²
f1 (10⁻⁹ MeV⁻³)
f2 Eγ² (10⁻⁹ MeV⁻³)
Eγ (MeV)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
ΣB(M1, 0⁺1->1⁺)=1.7μ²

A	148	150	152	154
N	86	88	90	90
$E(2^{+}_{\text{exp}})[keV]$	570	334	122	82
$B(E2)_{\text{exp}}[e^2 fm^4]$	720	1350	3460	4360
$\sqrt{\langle \beta^2 \rangle_{\text{exp}}}$	0.14	0.19	0.30	0.34

Total M1 strength $B(M1, E_\gamma < 5MeV) \sim 8\mu_N^2$ for all isotopes.

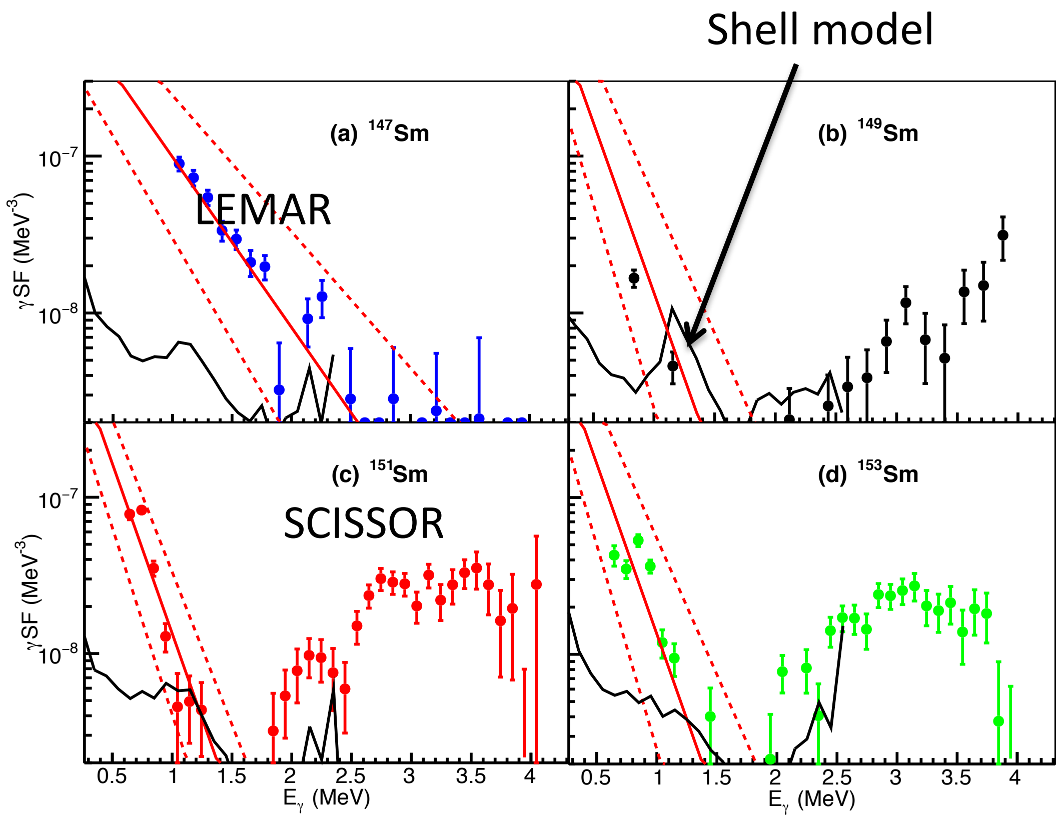


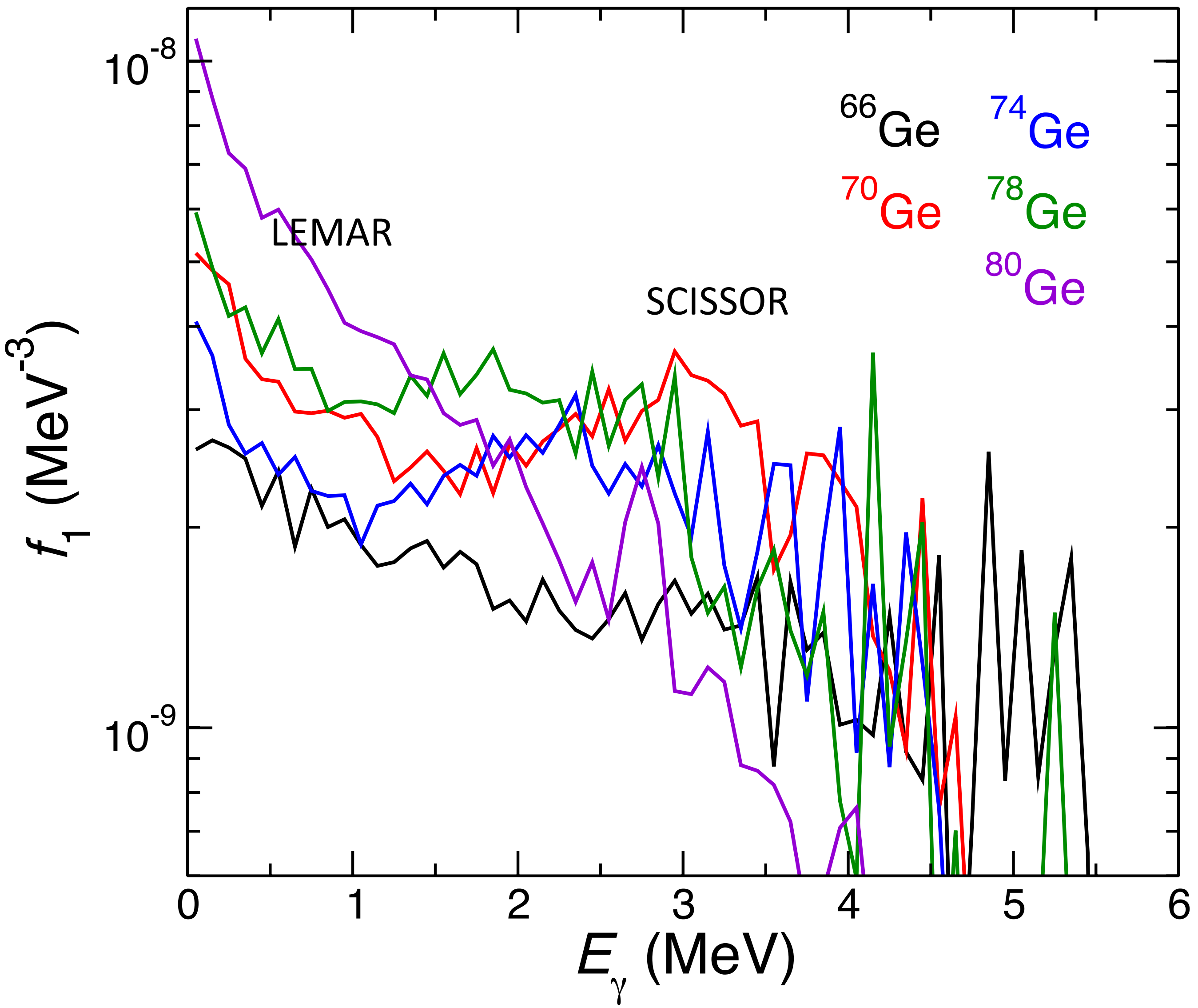
FIG. 5. γ-ray strength functions for all four Sm isotopes with the GDR contribution subtracted. Solid line indicates the fit to the upbend region, while the dashed lines show the fit uncertainty. The results are compared with shell model calculations (black solid line).

TABLE II. Parameters for resonances and the upbend for ^{147,149}Sm isotopes from the current work and for ^{151,153}Sm taken from [30].

Nucleus	Giant dipole 1 and 2 resonances							Spin-flip M1			Upbend		Scissors resonance			
	$\omega_{E1,1}$ (MeV)	$\sigma_{E1,1}$ (mb)	$\Gamma_{E1,1}$ (MeV)	$\omega_{E1,2}$ (MeV)	$\sigma_{E1,2}$ (mb)	$\Gamma_{E1,2}$ (MeV)	T_f (MeV)	ω_{M1} (MeV)	σ_{M1} (mb)	Γ_{M1} (MeV)	C (MeV^{-3})	η (MeV^{-1})	ω_{SR} (MeV)	σ_{SR} (mb)	Γ_{SR} (MeV)	B_{SR} (μ_N^2)
^{147}Sm	13.8	200	3.8	15.5	230	5.6	0.55	8.1	2.3	4.0	10(5)10^{-7}	3.2(10)	-	-	-	-
^{149}Sm	12.9	180	3.9	15.7	230	6.5	0.47	7.7	2.6	4.0	20(10)10^{-7}	5.0(10)	-	-	-	-
^{151}Sm	12.8	160	3.5	15.9	230	5.5	0.55	7.7	3.8	4.0	20(10)10^{-7}	5.0(5)	3.0(3)	0.6(2)	1.1(3)	7.8(34)
^{153}Sm	12.1	140	2.9	16.0	5.2	232	0.45	7.7	3.3	4.0	20(10)10^{-7}	5.0(10)	3.0(2)	0.6(1)	1.1(2)	7.8(20)

F. Naqvi, A. Simon, M. Guttormsen, R. Schwengner, S. Frauendorf, C.S. Reingold, J.T. Burke, N. Cooper, R.O. Hughes, P. Humby, J. Koglin, S. Ota, and A. Saastamoinen, Phys. Rev. C, accepted

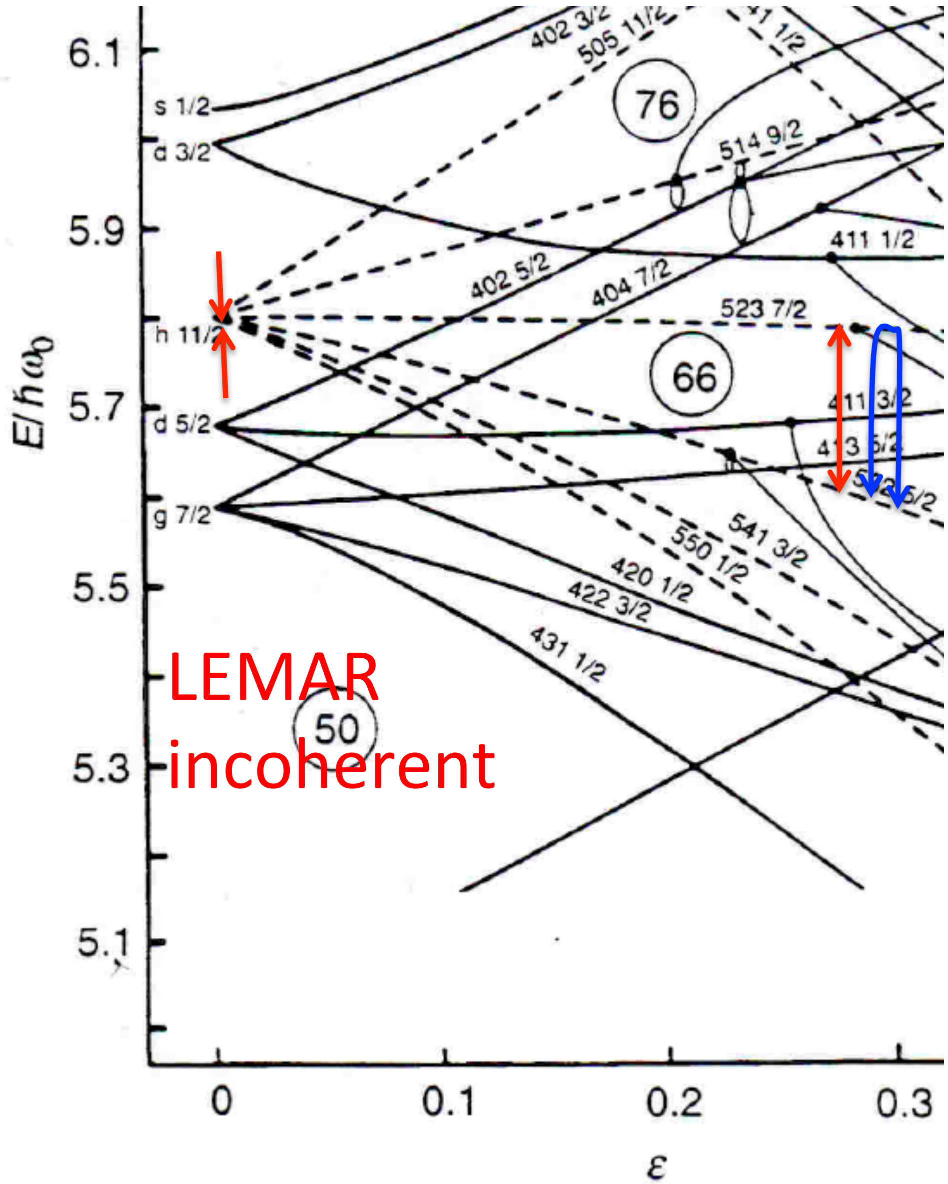
Shell model, full pf shell, R. Schwengner, SF., to be published



deformation β_{exp}	
$^{66}Ge_{34}$	0.17
$^{70}Ge_{38}$	0.22
$^{74}Ge_{42}$	0.28
$^{78}Ge_{46}$	0.22(sys)
$^{80}Ge_{50}$	0

monomodal

bimodal

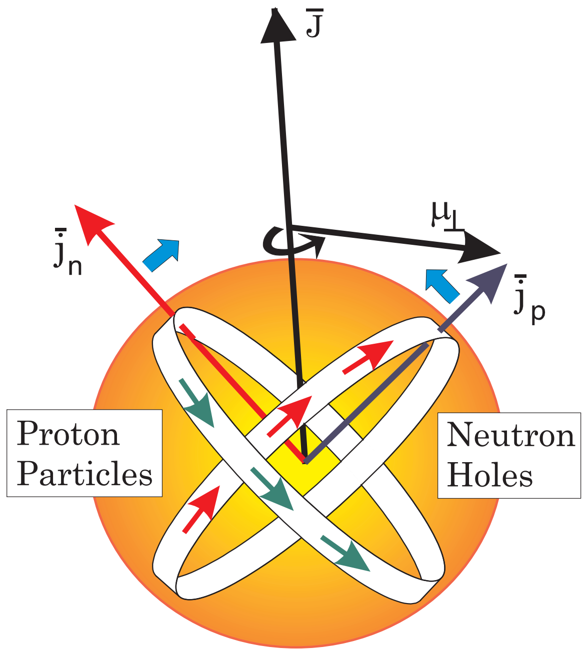


LEMAR
incoherent

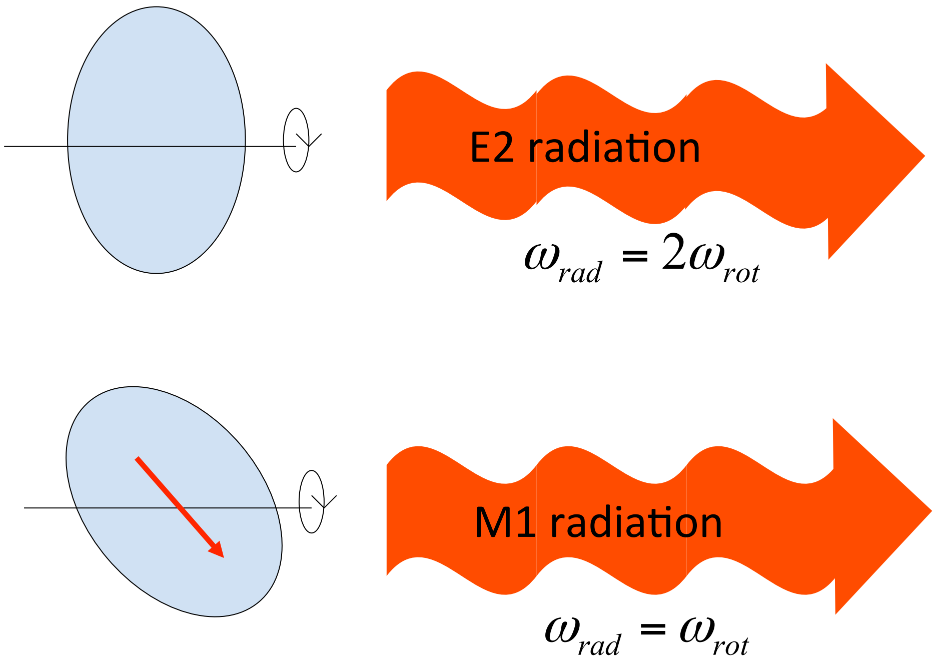
Scissors Resonance:
real transitions
coherent ?

Damped Magnetic
Rotation:
virtual transitions
^{68}Fe:
$\overline{BM1}/\overline{BE2} \sim 6(\mu/eb)^2$

Generation of M1 radiation by a rotating magnetic dipole



$B(\mathrm{M1}) \sim \mu_\perp^2$



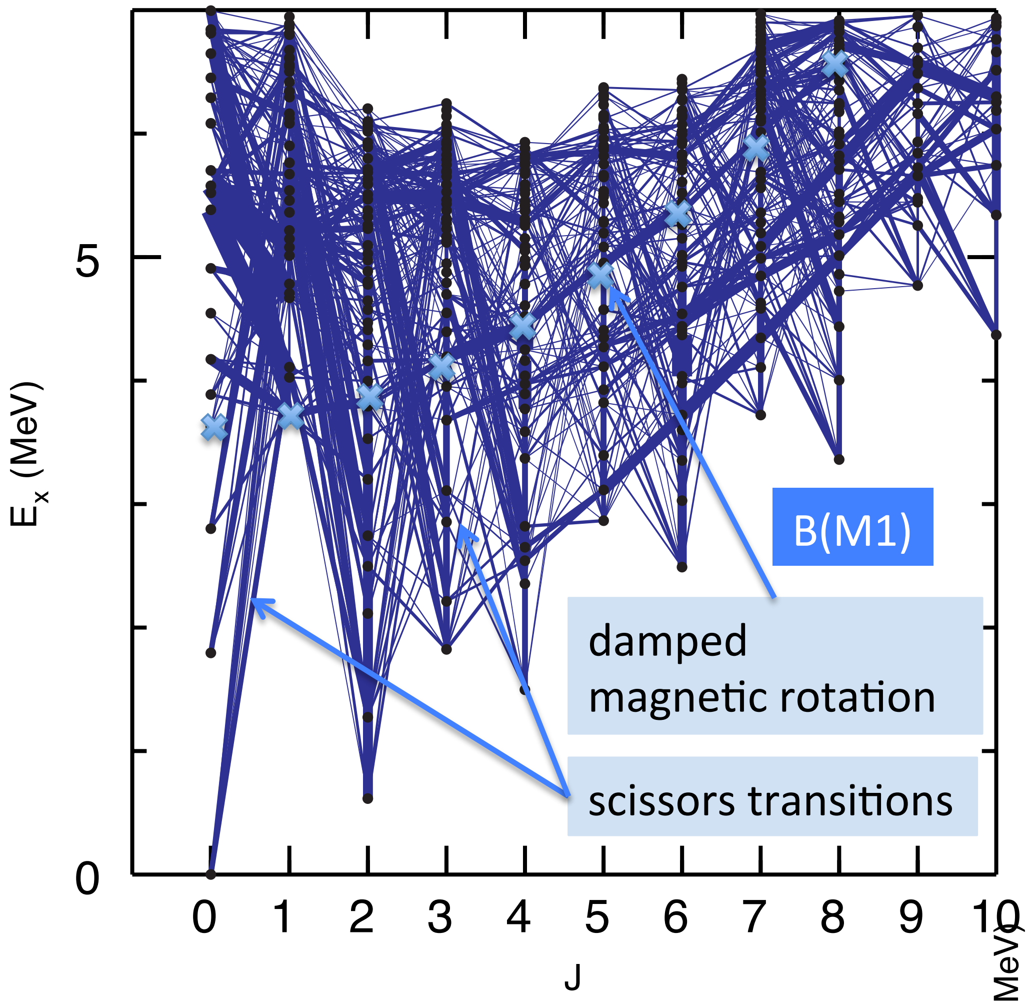
Magnetic Rotation

Ordinary Rotation

Warming up the nucleus

- Deformation generates a scissors resonance around 3MeV
- It acquires part of the LEMAR M1 strength, while the sum stays about the same

Coherence: E2 versus M1



threads $E(threads) = J(J+1)/2\Theta$

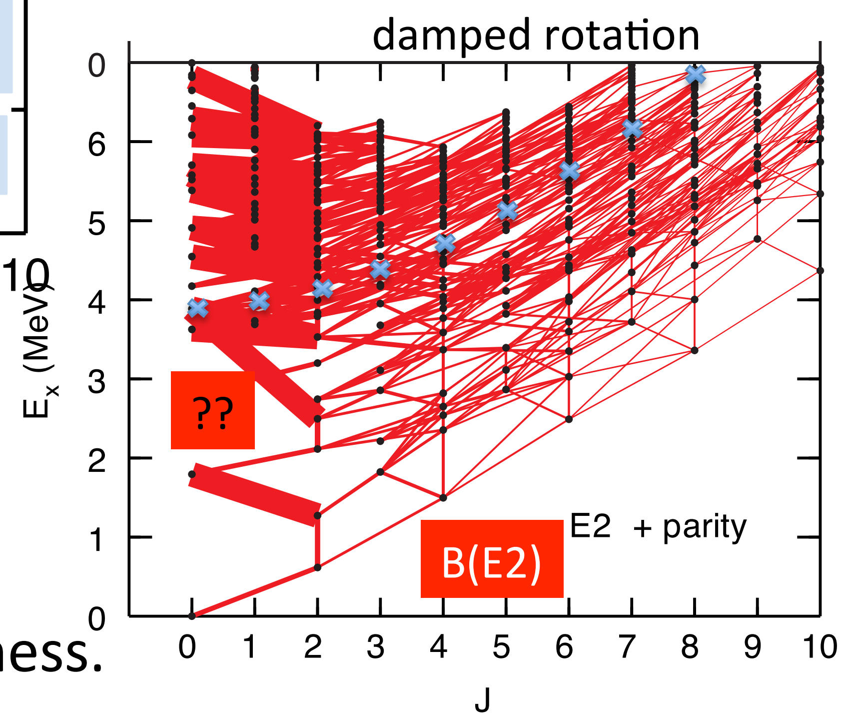
moment of inertia $\Theta = 14 MeV^{-1}$

rigid body value $\Theta = 17 MeV^{-1}$

cranking T=1.2 MeV spherical $\Theta = 14 MeV^{-1}$

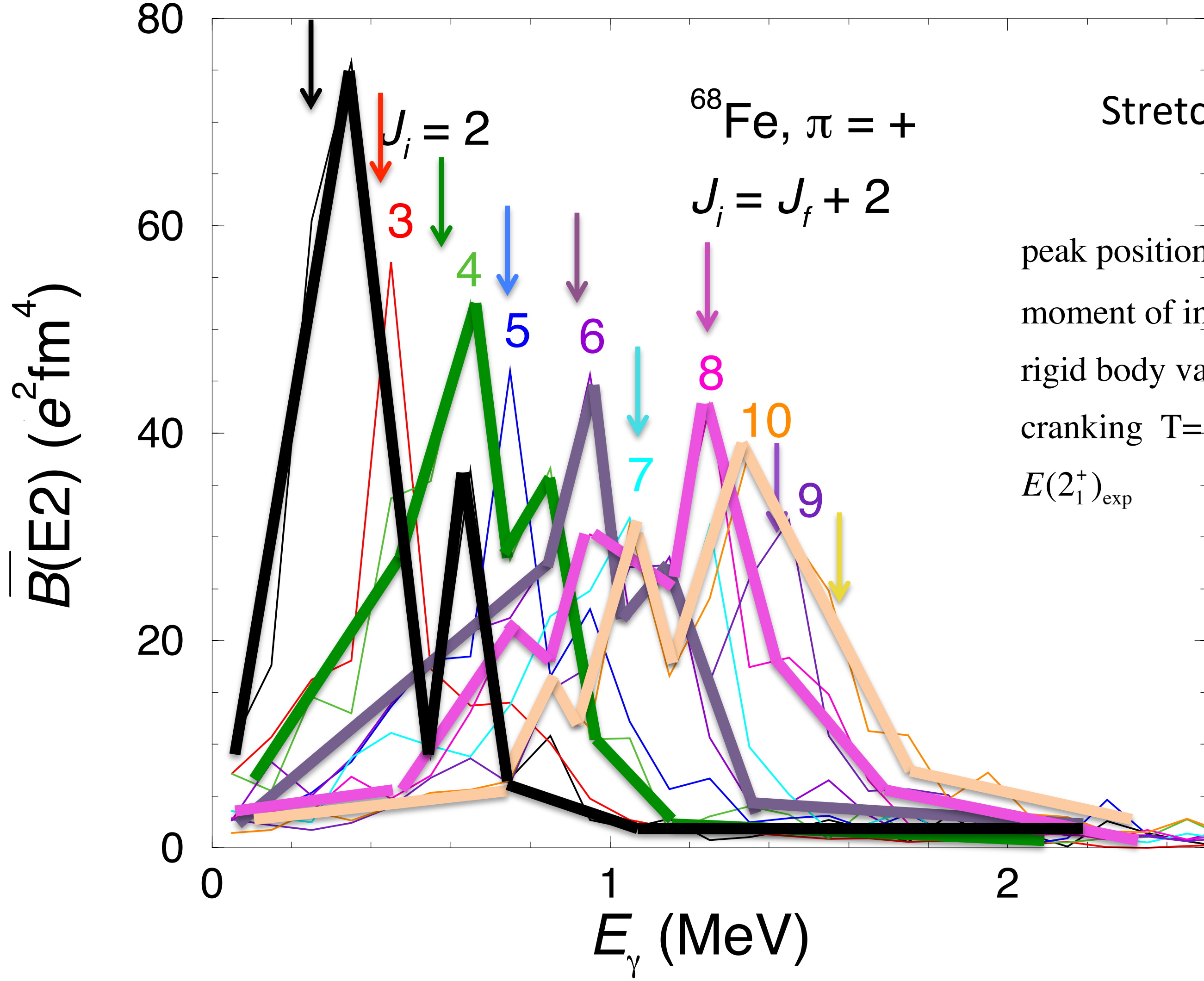
$E(2_1^+)_{exp}$ $\Theta = 5.74 MeV^{-1}$

M1 scares of coherence
E2 rotational



^{68}Fe, $\pi = +$

B(M1),B(E2) proportional to line thickness.



Stretched BE2

peak position $E_\gamma(peak) = 2\omega = (2J_i - 1)/\Theta$

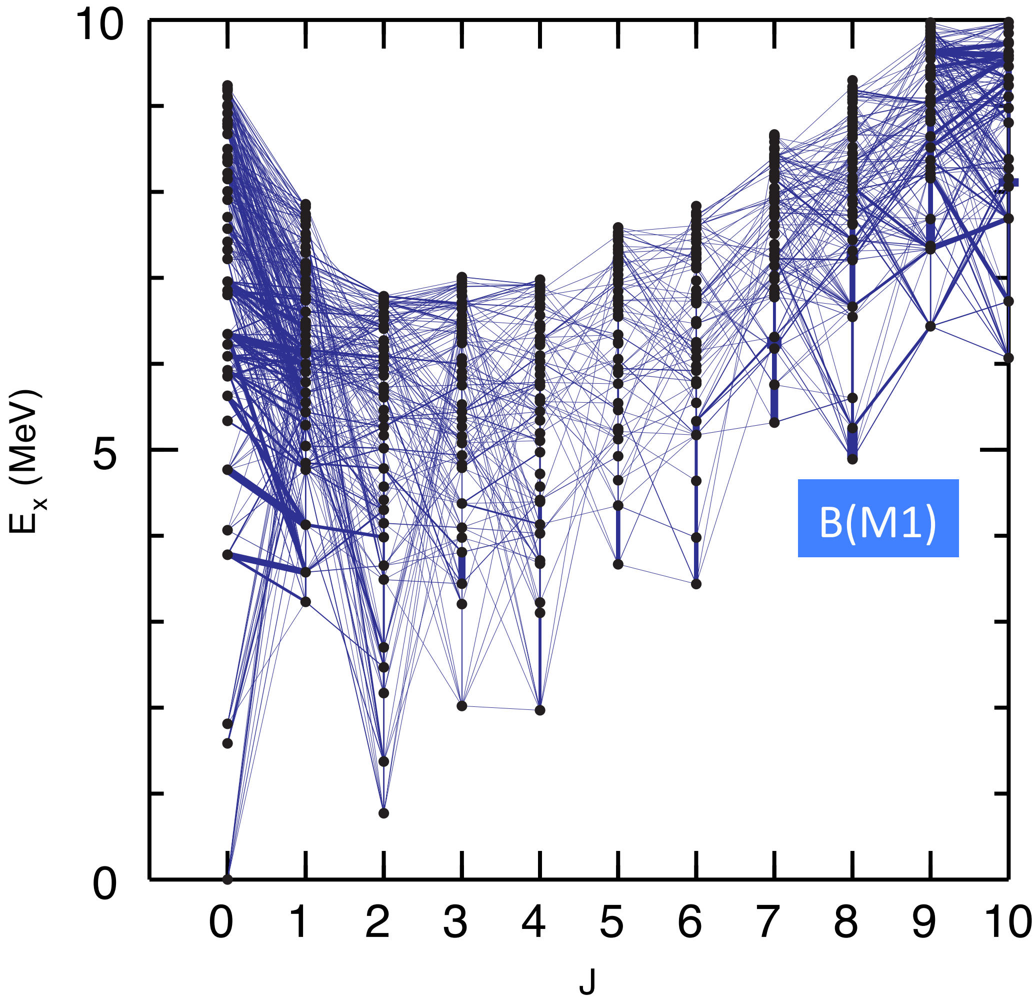
moment of inertia $\Theta = 12\hbar^2 \mathrm{MeV}^{-1}$

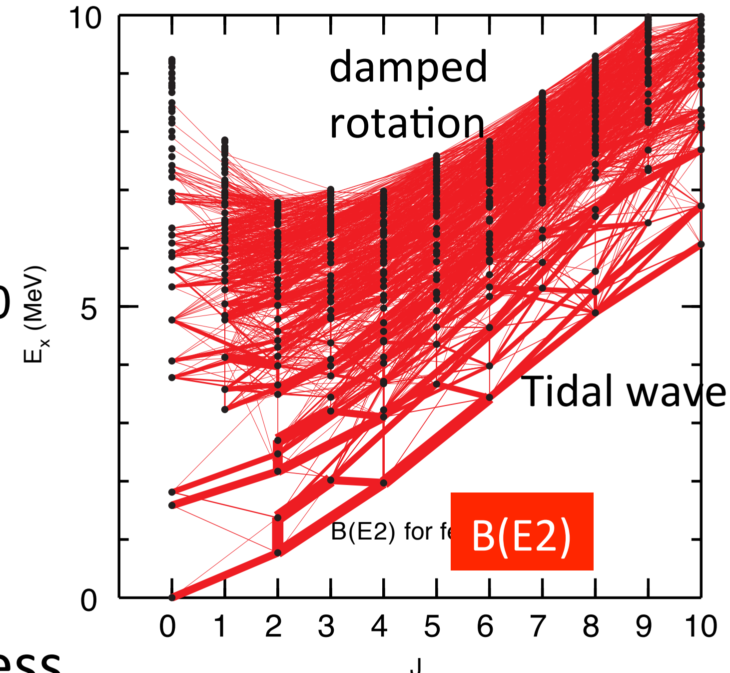
rigid body value $\Theta = 17\hbar^2 \mathrm{MeV}^{-1}$

cranking T=1.2 MeV spherical $\Theta = 14\hbar^2 \mathrm{MeV}^{-1}$

$E(2_1^+)_{\mathrm{exp}}$ $\Theta = 5.74\hbar^2 \mathrm{MeV}^{-1}$

Quantal coherence sets in.

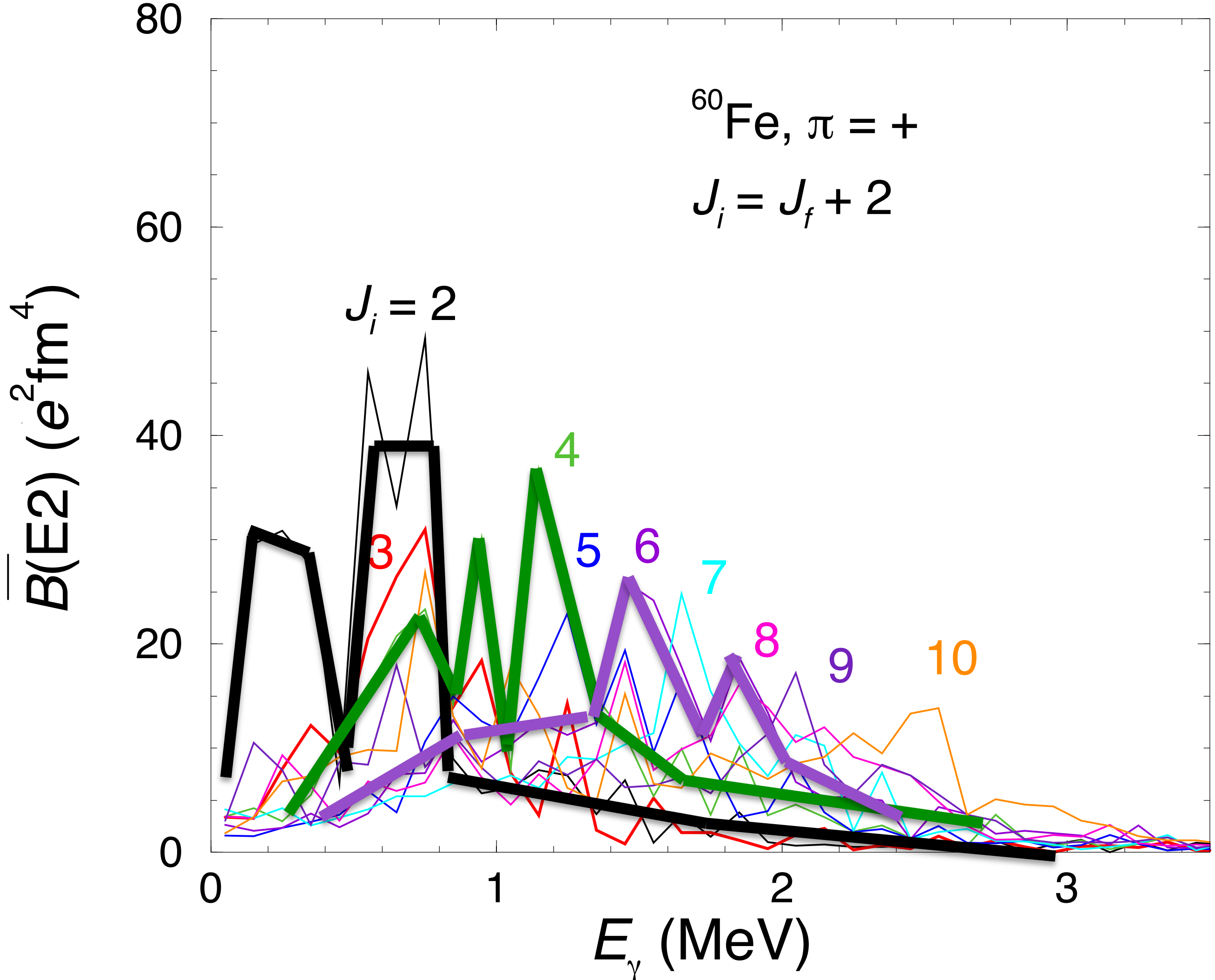




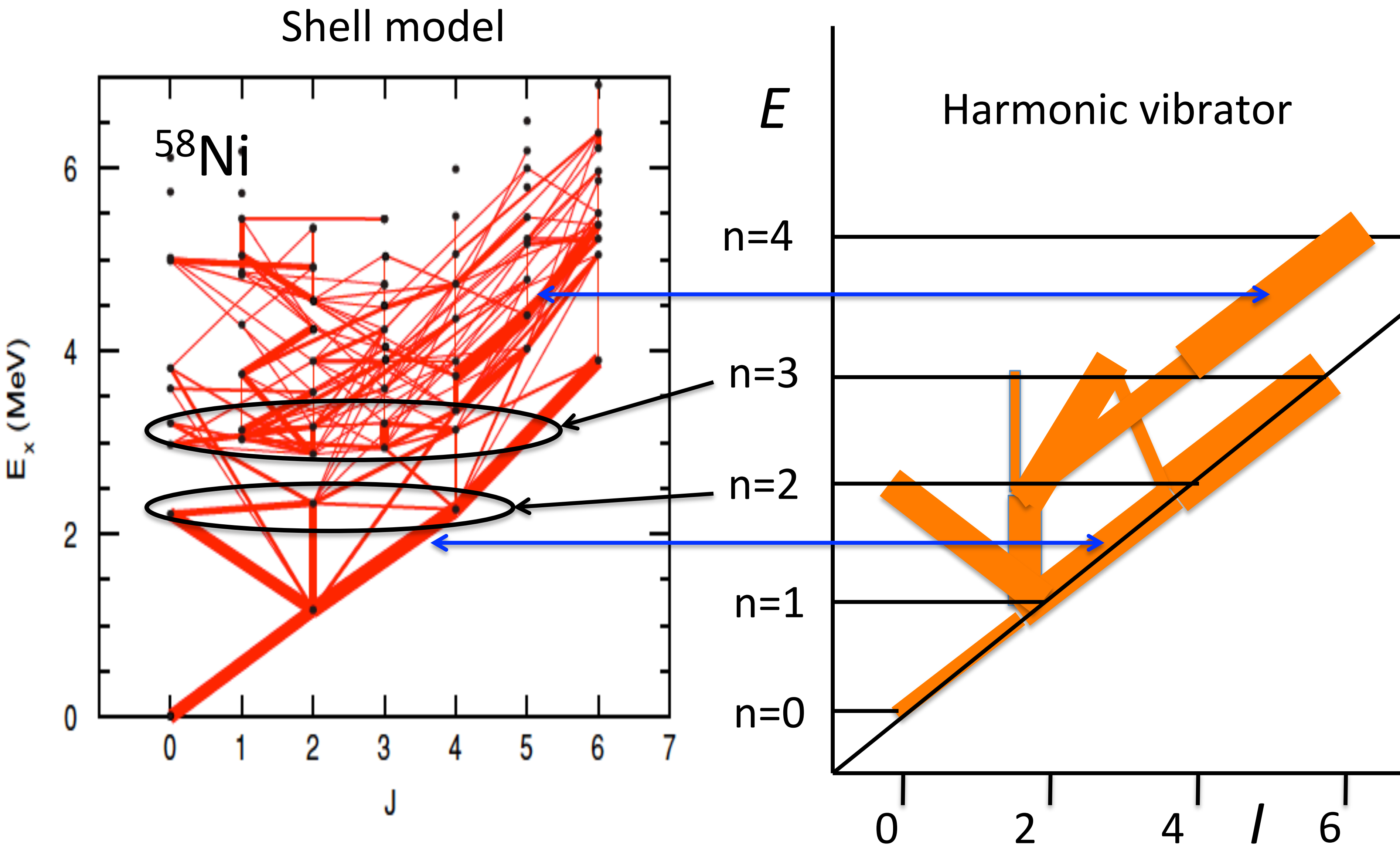
^{60}Fe, π=+

M1 chaotic
E2 rotational

B(M1),B(E2) proportional to line thickness.

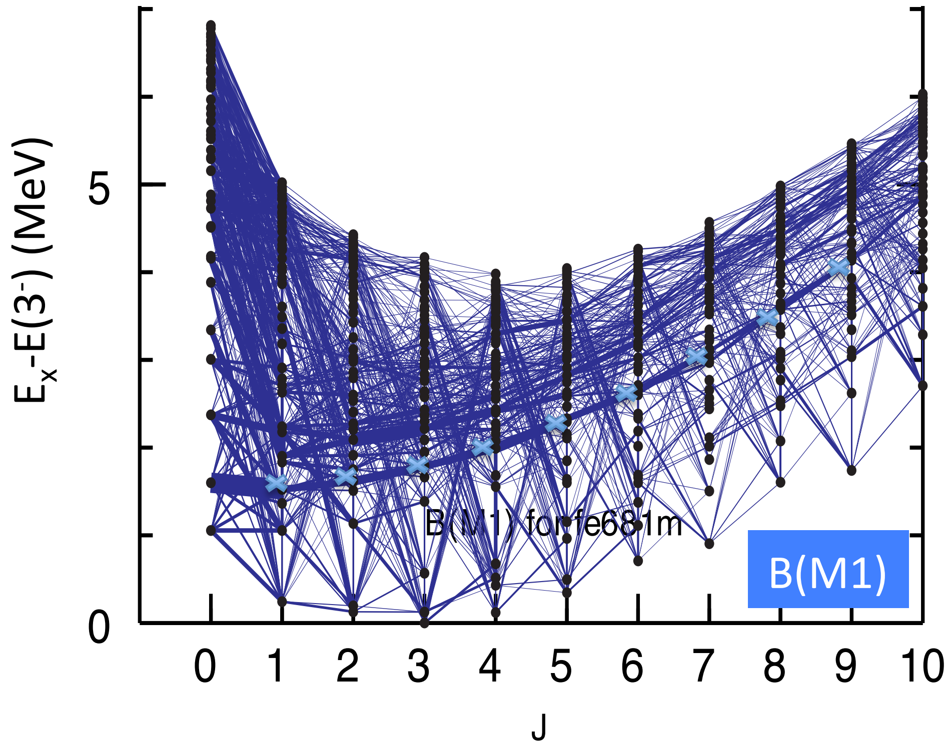


Weak/no coherence, overdamped



A. Chakroborty et al. PHYSICAL REVIEW C 83, 034316 (2011)

B(E2) proportional to line thickness.



threads $E(threads) = (J + 1/2 - 1)^2 / 2\Theta$

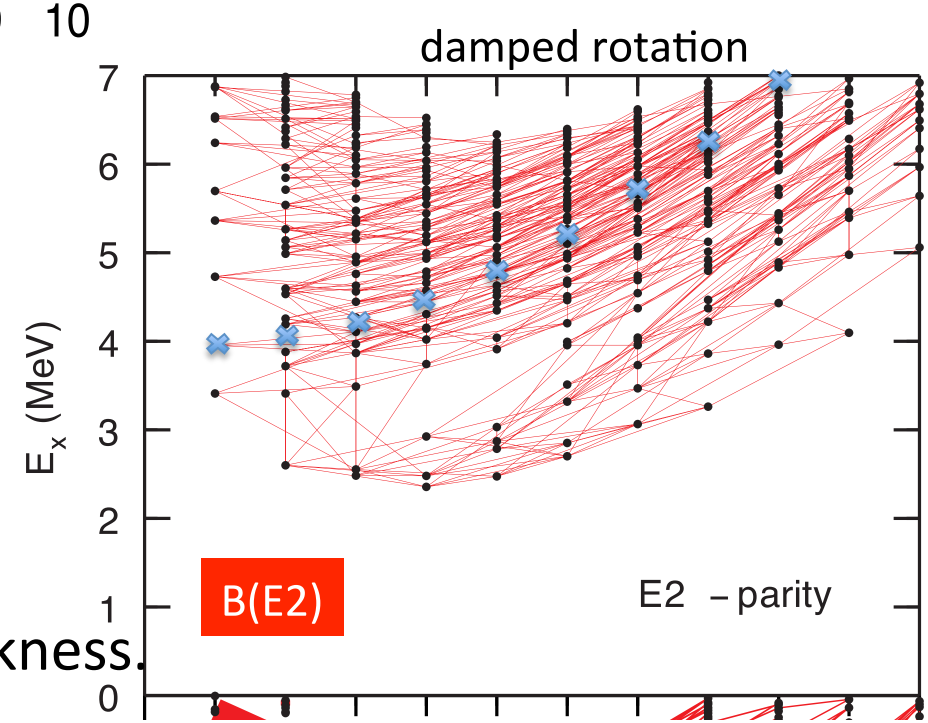
moment of inertia $\Theta = 14 MeV^{-1}$

rigid body value $\Theta = 17 MeV^{-1}$

cranking T=1.2 MeV spherical $\Theta = 14 MeV^{-1}$

$E(2_1^+)_{exp}$ $\Theta = 5.74 MeV^{-1}$

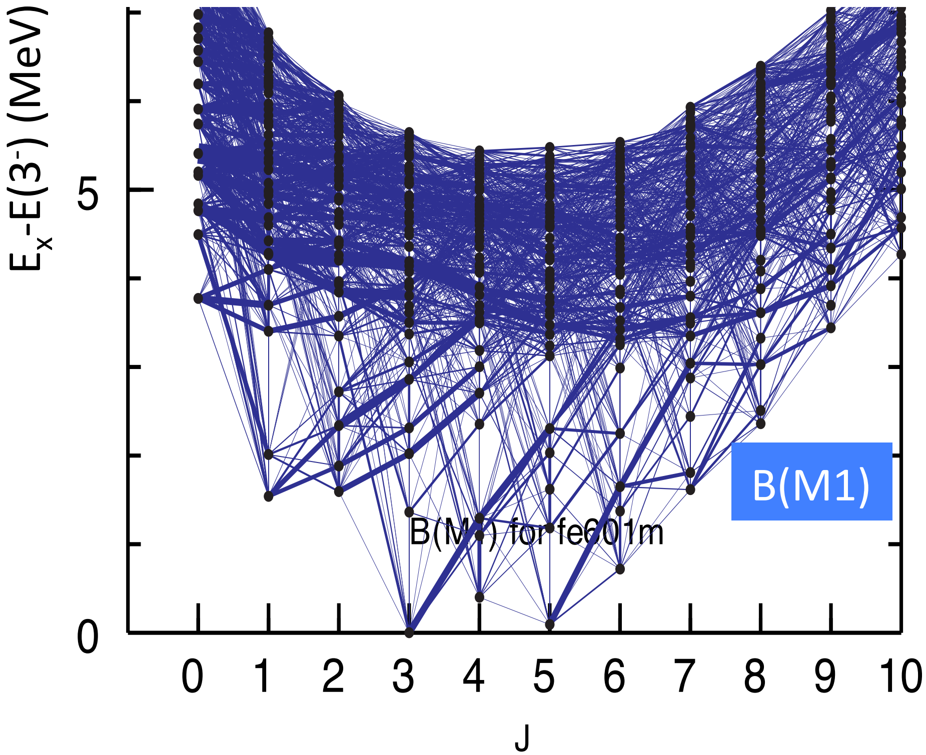
M1 scares of coherence
E2 rotational

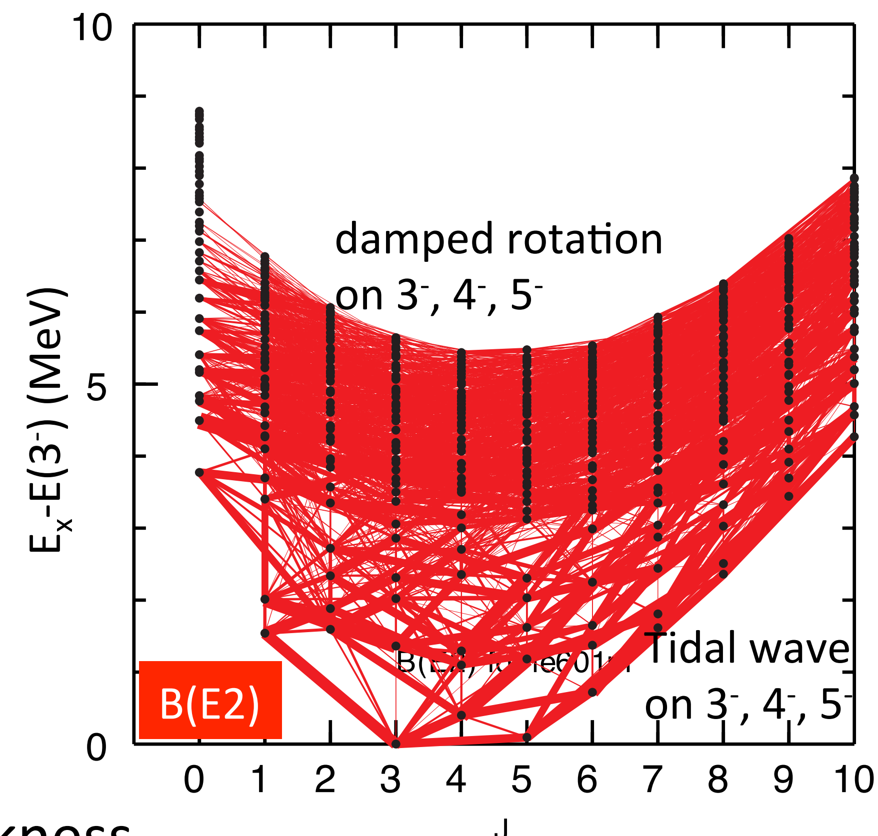


^{68}Fe, π=-

B(M1),B(E2) proportional to line thickness.

M1 chaotic, scars of coherence
Similarity M1←→E2 ???
E2 rotational





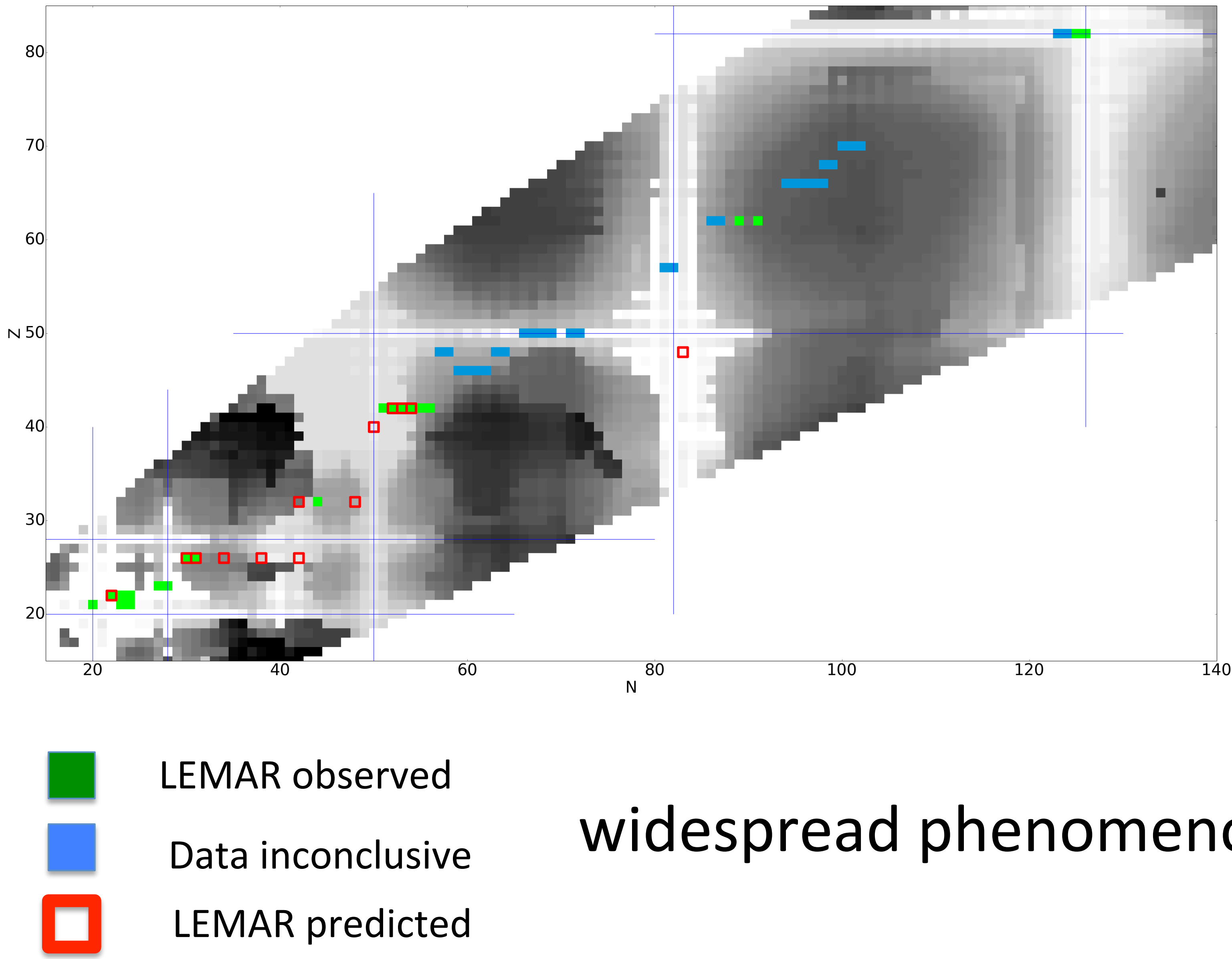
^{60}Fe, π=-

B(M1),B(E2) proportional to line thickness.

Warming up the nucleus

- Coherence of rotational motion is attenuated
- Special configurations are screened: superdeformed bands, oblate bands in Nd
- Quenching pairing generates Low Energy Magnetic Radiation $B(M1) \propto \exp[-E_\gamma / T_B]$
- Deformation generates a scissors resonance which acquires part of the LEMAR M1 strength
- LEMAR may increase the (n,gamma) crossections in the r-process by several orders of magnitude.

LEMAR is generated by realignment of high-j orbitals at the Fermi surface. This is the case for the majority of nuclei.



widespread phenomenon

^{68}Fe π=-

bimodal

scars of coherence

threads $E(threads) = J(J+1)/2\Theta$

moment of inertia $\Theta = 14 MeV^{-1}$

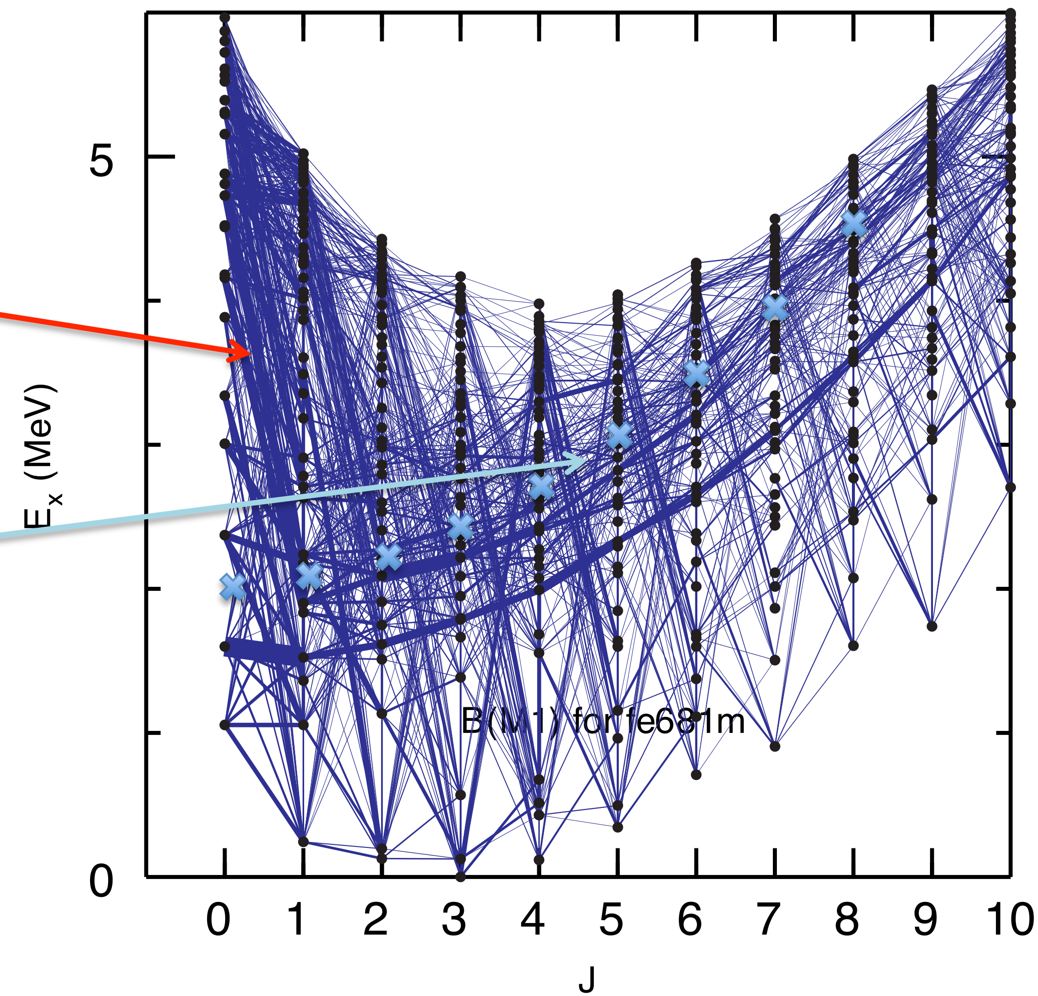
rigid body value $\Theta = 17 MeV^{-1}$

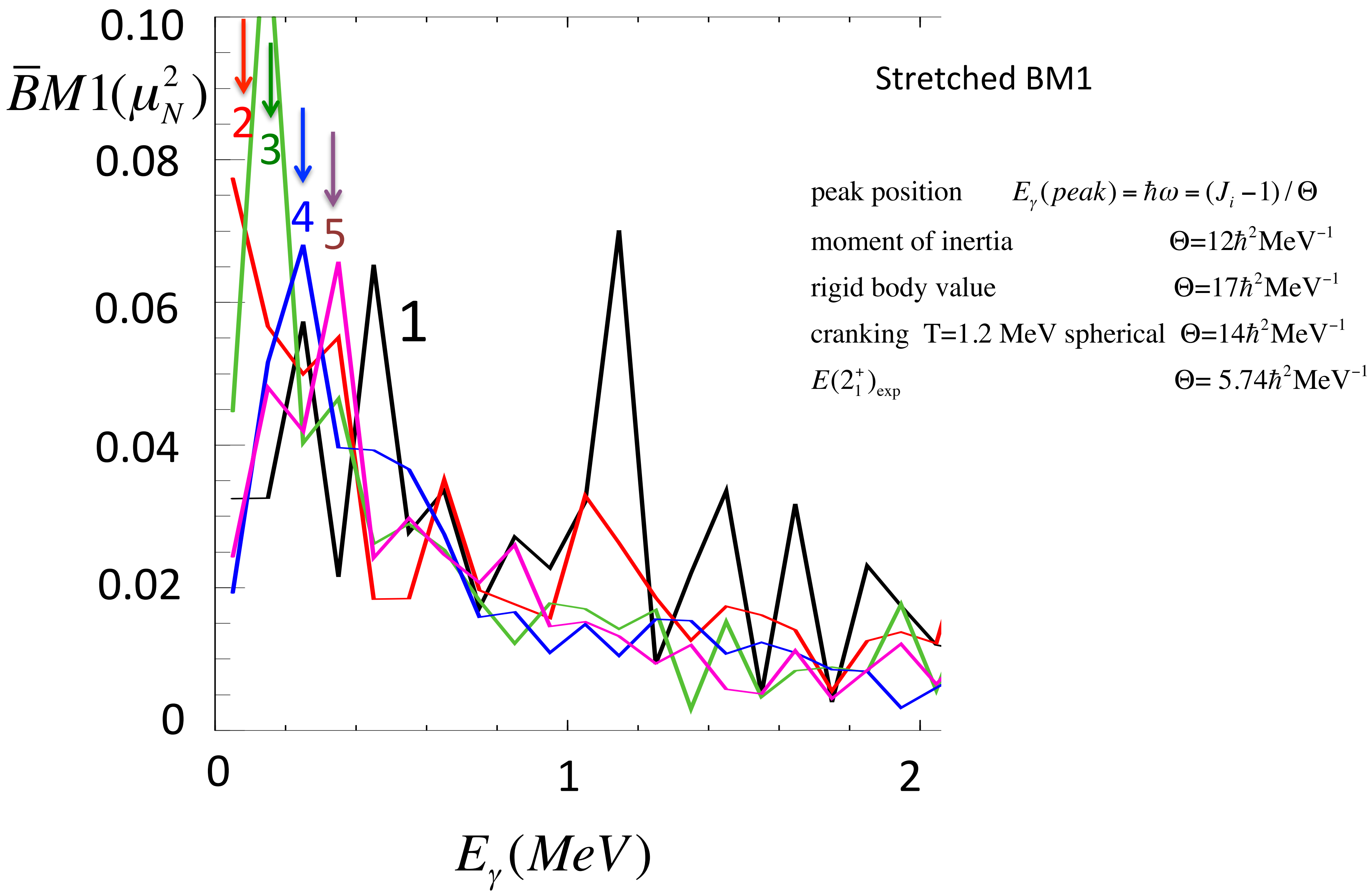
cranking T=1.2 MeV spherical $\Theta = 14 MeV^{-1}$

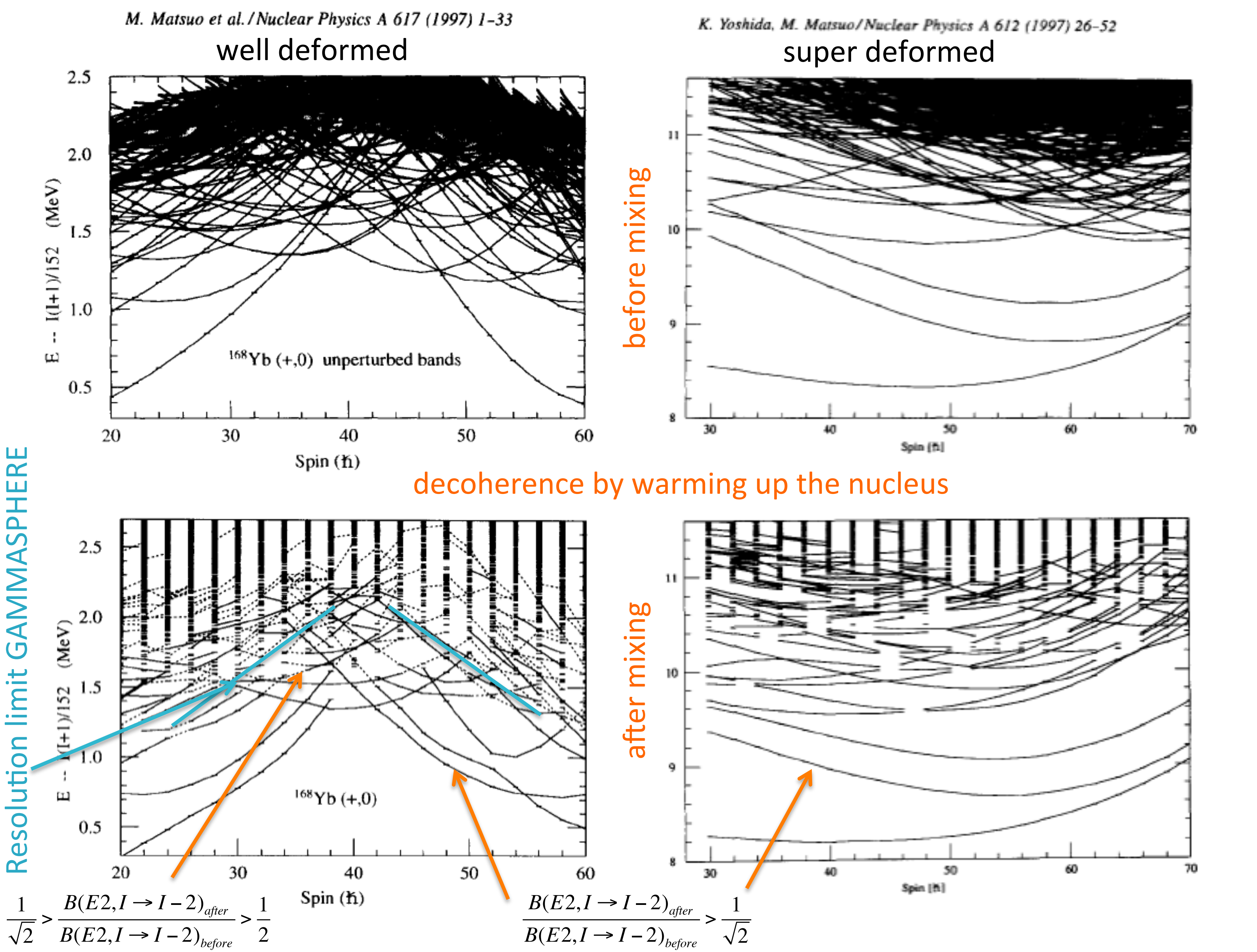
$E(2_1^+)_{exp}$ $\Theta = 5.74 MeV^{-1}$

Scissors Resonance:
real transitions

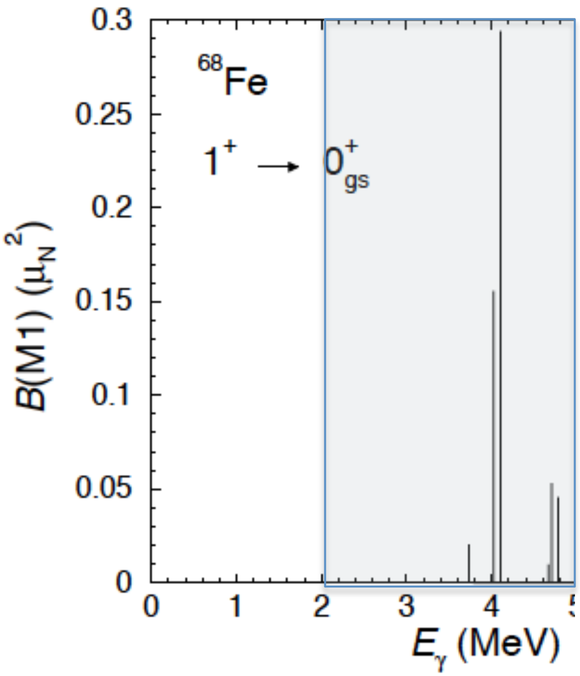
Damped Magnetic Rotation:
$BM1/BE2 \sim 6(\mu/eb)^2$




Stretched BM1
$\bar{B}M1(\mu_N^2)$
0.10
0.08
0.06
0.04
0.02
0
0
1
2
$E_\gamma(MeV)$
1
2
3
4
5
peak position $E_\gamma(peak) = \hbar\omega = (J_i - 1)/\Theta$
moment of inertia $\Theta=12\hbar^2\mathrm{MeV}^{-1}$
rigid body value $\Theta=17\hbar^2\mathrm{MeV}^{-1}$
cranking T=1.2 MeV spherical $\Theta=14\hbar^2\mathrm{MeV}^{-1}$
$E(2_1^+)_{exp}$ $\Theta= 5.74\hbar^2\mathrm{MeV}^{-1}$

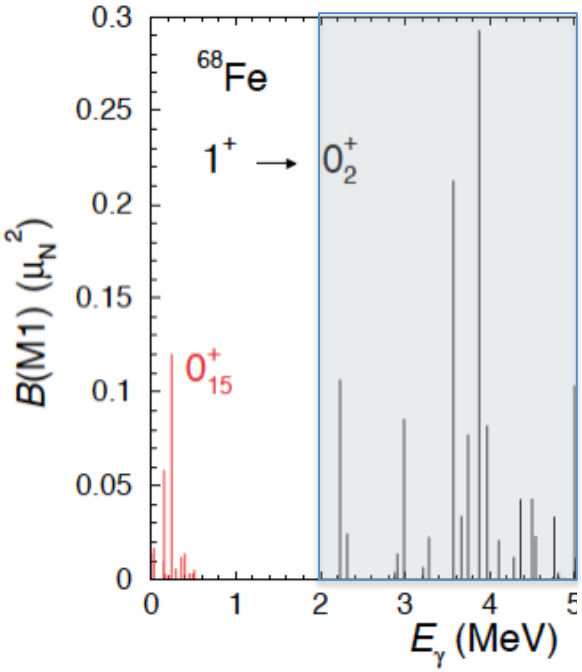


M. Matsuo et al. / Nuclear Physics A 617 (1997) 1–33
well deformed
K. Yoshida, M. Matsuo / Nuclear Physics A 612 (1997) 26–52
super deformed
E -- I(I+1)/152 (MeV)
Spin (ħ)
^{168}Yb (+,0) unperturbed bands
before mixing
Spin [ħ]
decoherence by warming up the nucleus
Resolution limit GAMMASPHERE
^{168}Yb (+,0)
after mixing
$\frac{1}{\sqrt{2}} > \frac{B(E2, I \rightarrow I-2)_{after}}{B(E2, I \rightarrow I-2)_{before}} > \frac{1}{2}$
$\frac{B(E2, I \rightarrow I-2)_{after}}{B(E2, I \rightarrow I-2)_{before}} > \frac{1}{\sqrt{2}}$



$$\Sigma B(M1, 1^+ \rightarrow 0^+_1) = 0.56\mu_N^2$$

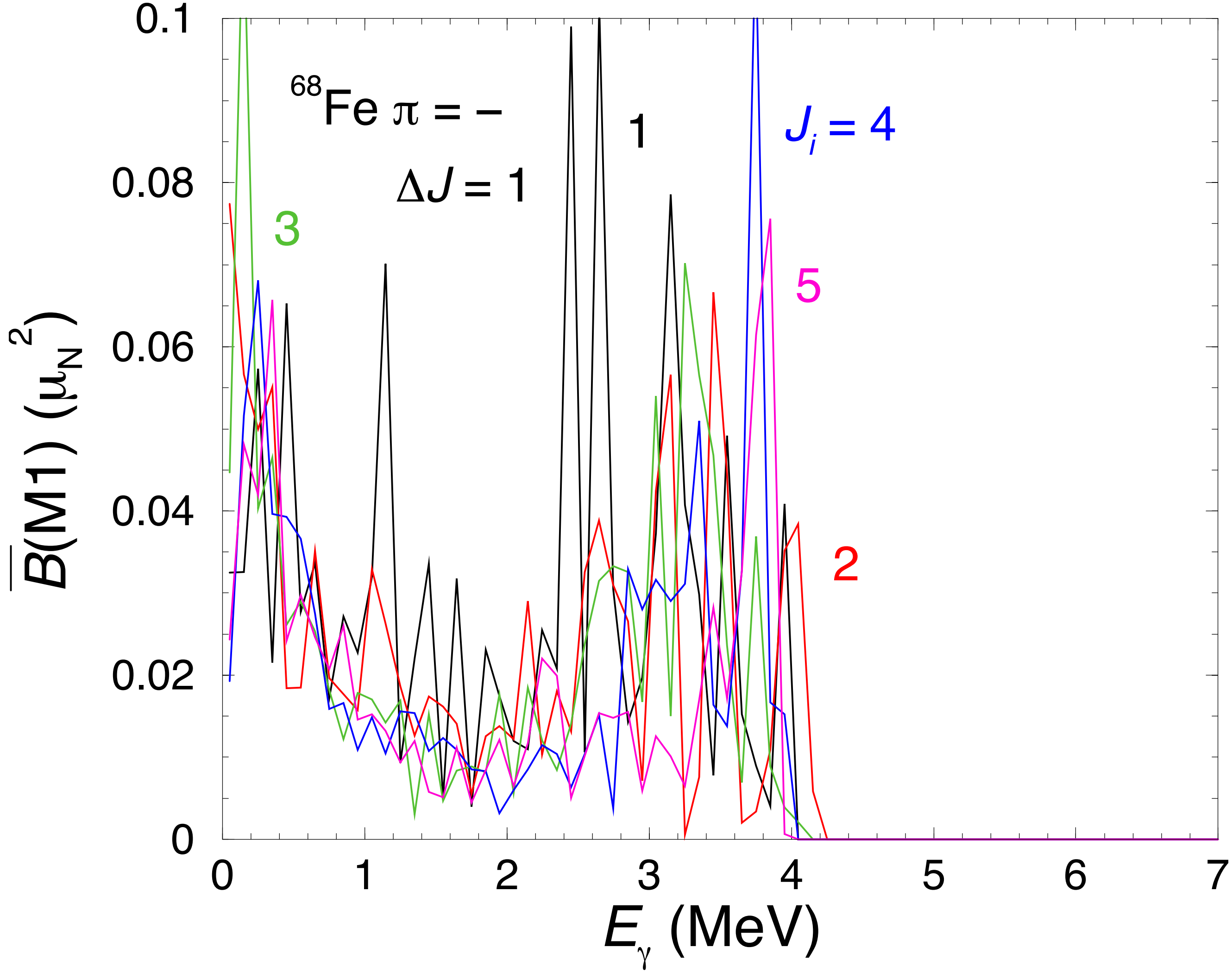
Warming up the nucleus
(going to higher excited states)
thaws degrees of freedom
frozen by correlations (pairing)



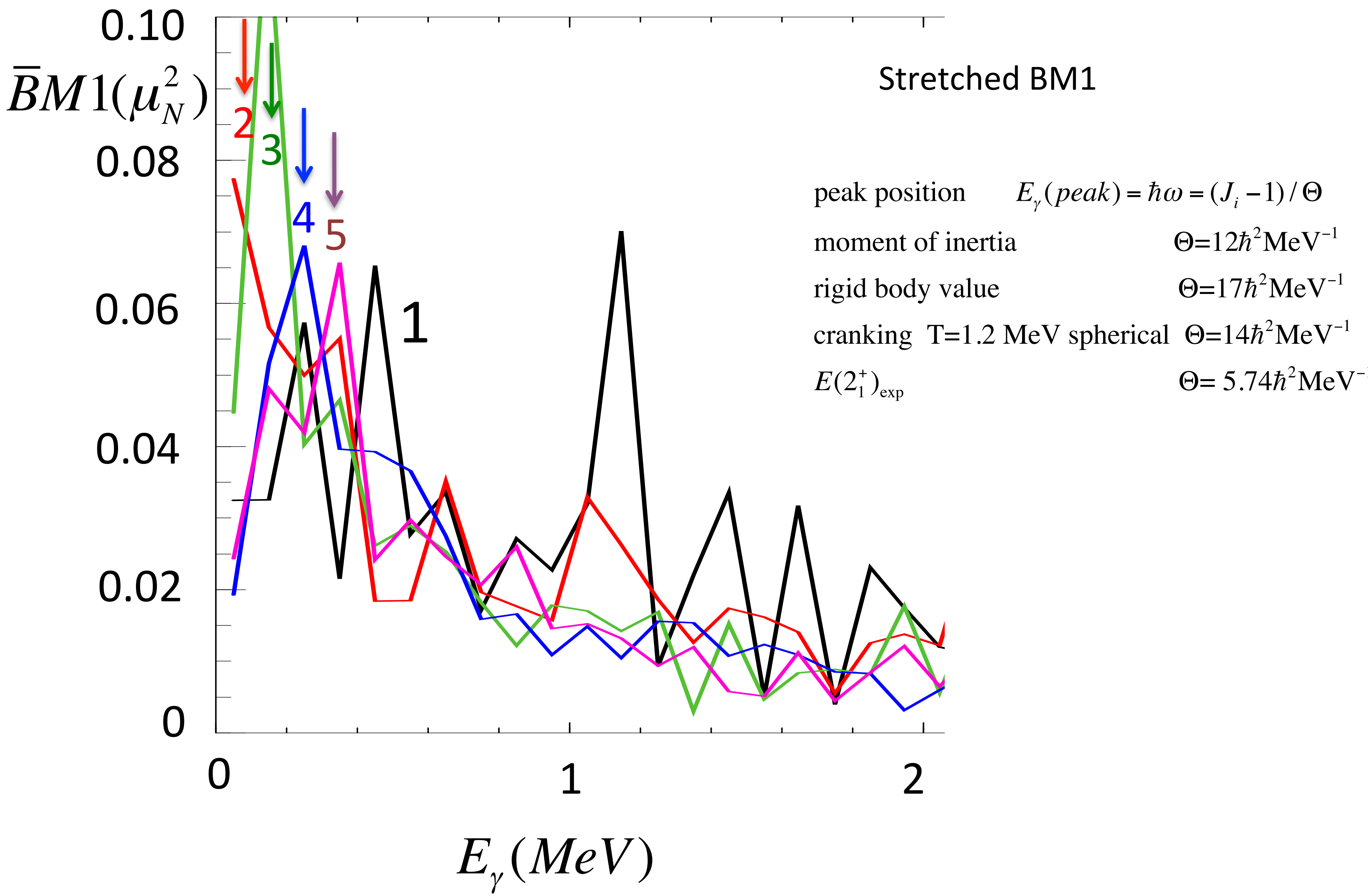
$$\Sigma B(M1, 1^+ \rightarrow 0^+_2) = 1.15\mu_N^2$$

Summary

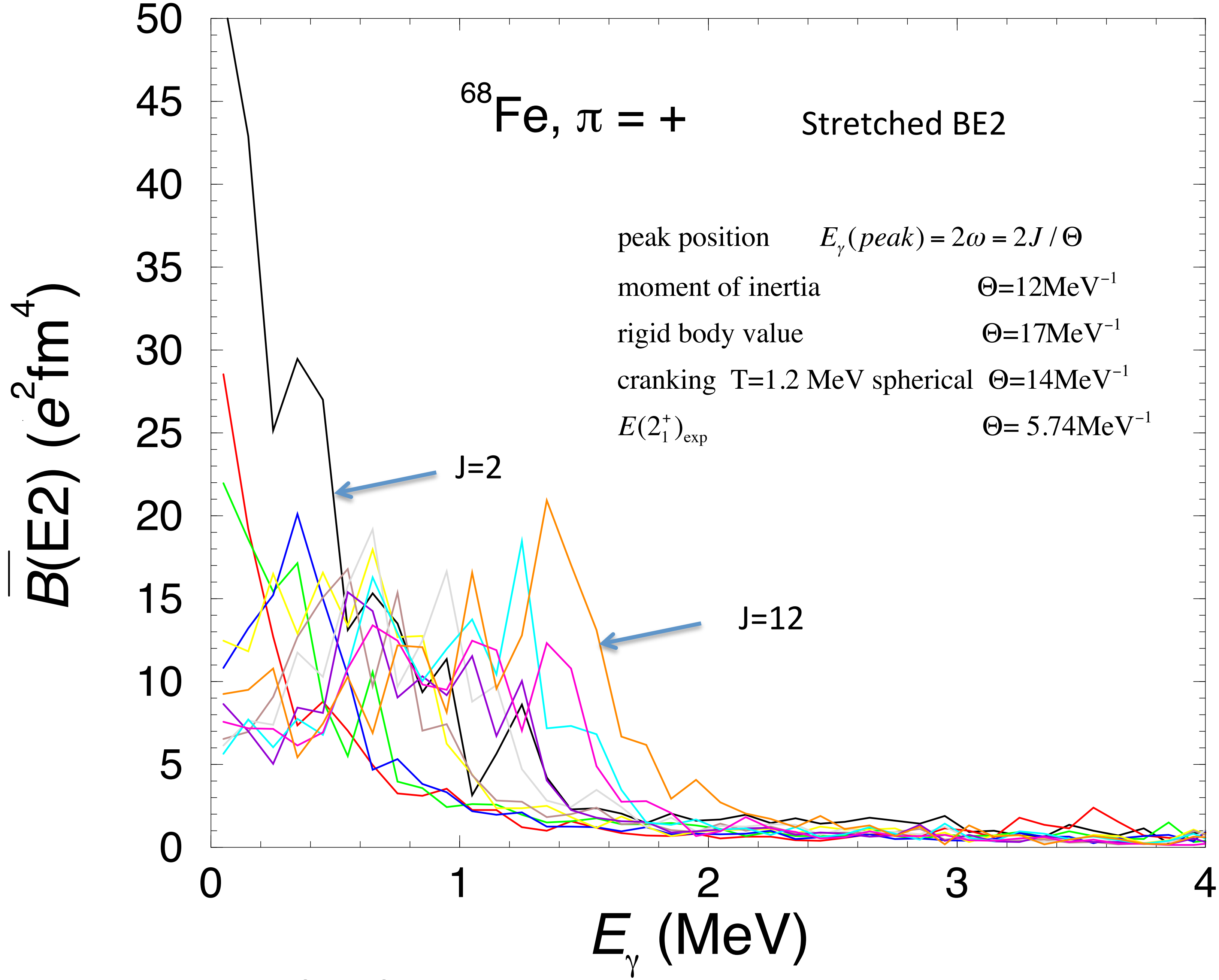
- LEMAR is a spike in the M1 radiation strength at zero Eγ, which arises by warming the nucleus.
- LEMAR appears pervasively in the nuclear chart and increases the astrophysical (n,γ) reaction rates of neutron-rich nuclei (>100).
- Near closed shells, LEMAR is radiation of thermally agitated magnetic dipoles with strength proportional to exp(-Eγ/T).
- Into the open shell it acquires the character of damped magnetic rotation causing moderate deviations from exp(-Eγ/T).
- The LEMAR M1 strength depends on the presence of high-j orbitals. Are the SM estimates accurate? Are there simpler and more robust estimates?
- Into the open shell a bimodal structure builds up. The Scissors Resonance takes M1 strength from LEMAR such that the total strength stays nearly constant.
- The M1 strength of the Scissors Resonance in warm nuclei is twice the strength in cold.



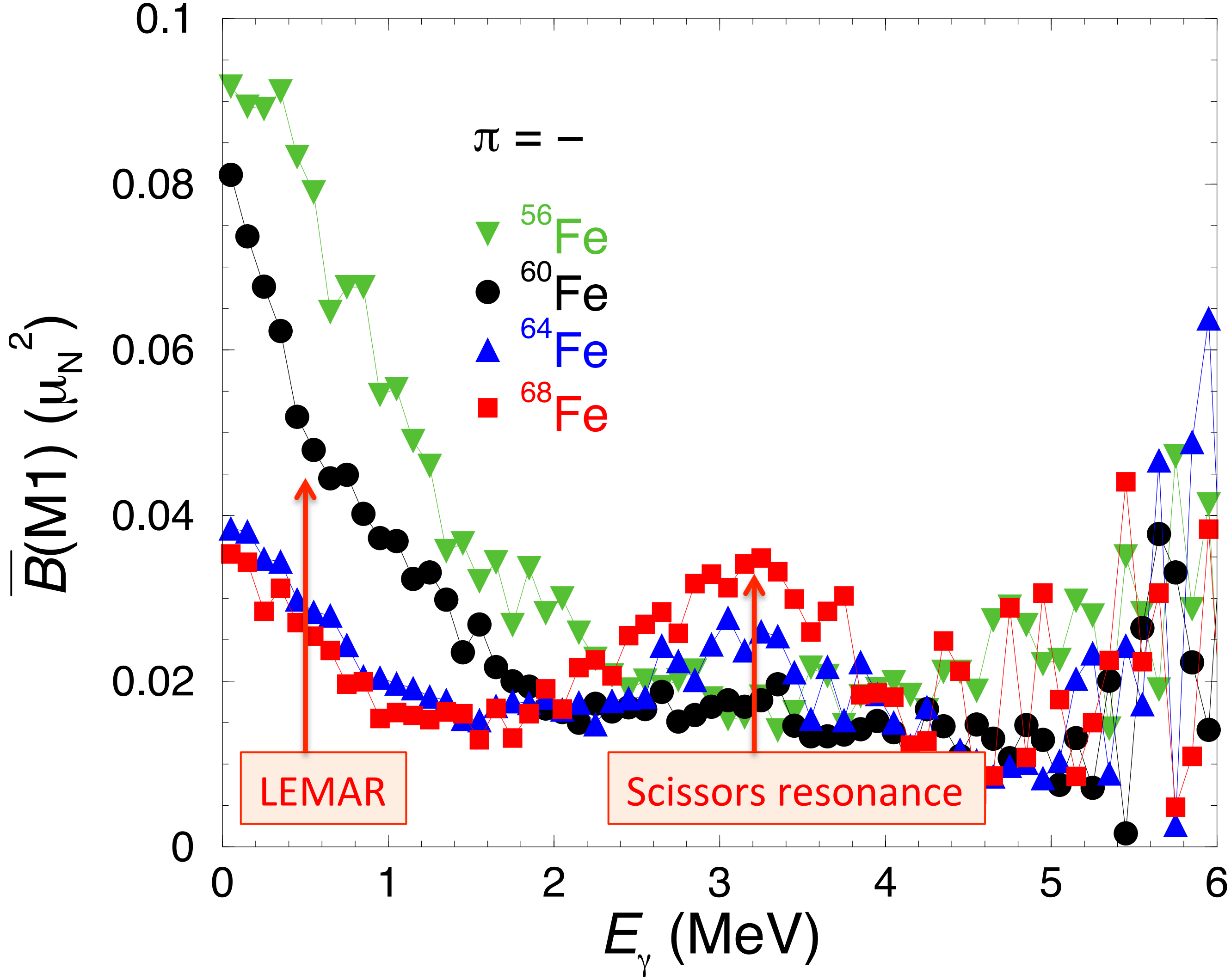
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6
7
$\overline{B}$(M1) (μ_N^2)
E_γ (MeV)
^{68}Fe π = −
ΔJ = 1
1
J_i = 4
3
5
2

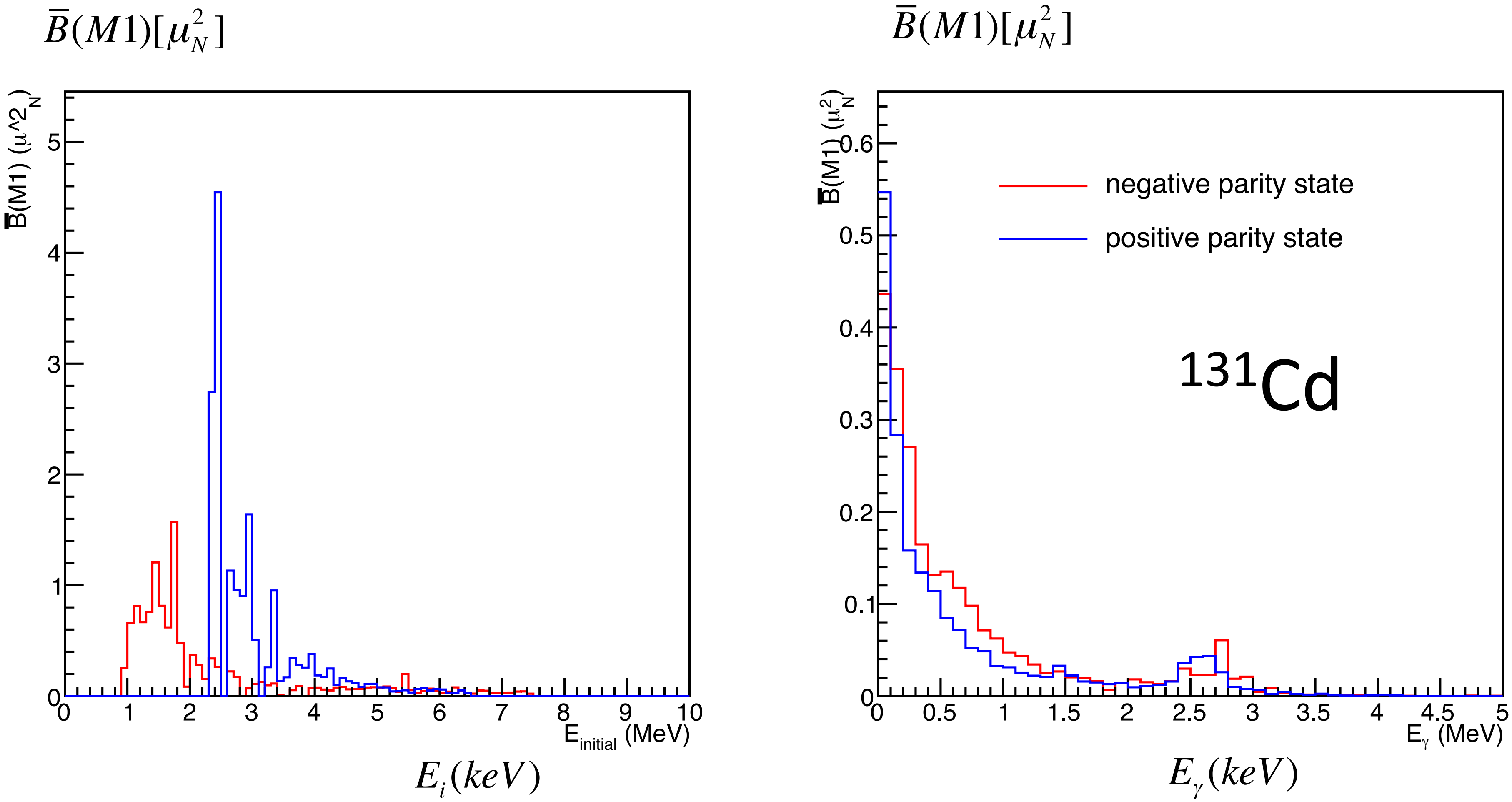


0.10
0.08
0.06
0.04
0.02
0
$\bar{B}M1(\mu_N^2)$
2
3
4
5
1
0
1
2
$E_\gamma(MeV)$
Stretched BM1
peak position $E_\gamma(peak) = \hbar\omega = (J_i - 1)/\Theta$
moment of inertia $\Theta = 12\hbar^2 MeV^{-1}$
rigid body value $\Theta = 17\hbar^2 MeV^{-1}$
cranking T=1.2 MeV spherical $\Theta = 14\hbar^2 MeV^{-1}$
$E(2_1^+)_{exp}$ $\Theta = 5.74\hbar^2 MeV^{-1}$



Quantal coherence sets in.


π = −
56Fe
60Fe
64Fe
68Fe
LEMAR
Scissors resonance
B̄(M1) (μN2)
Eγ (MeV)
0.1
0.08
0.06
0.04
0.02
0
0
1
2
3
4
5
6

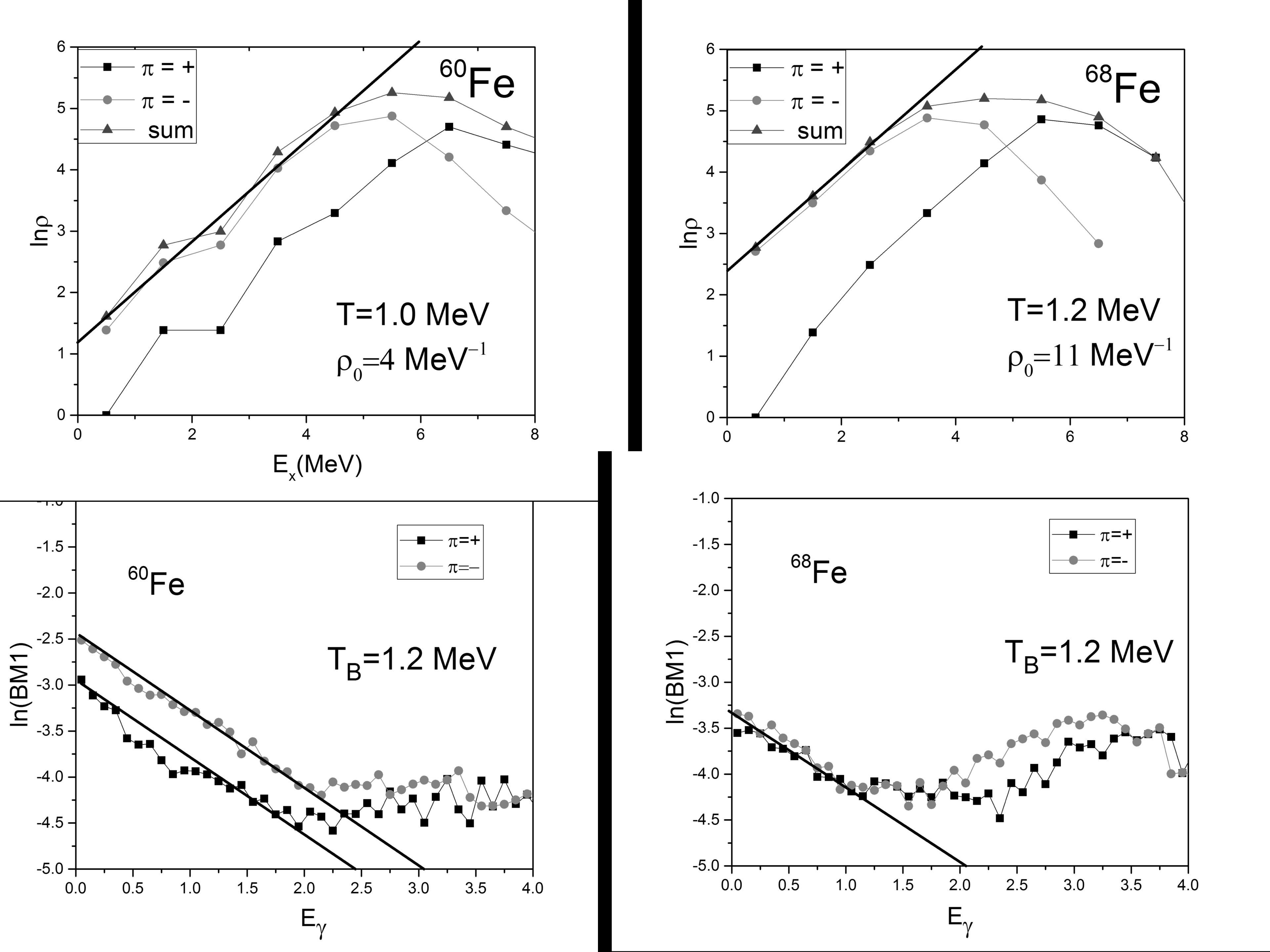


Shell model with Z=50 and N=82 core

valence orbitals:

proton holes $1p_{3/2}, 0f_{5/2}, 1p_{1/2}, 0g_{9/2}$ neutron particles $0h_{9/2}, 1f_{5/2}, 2p_{3/2}, 2p_{1/2}$

G-matrix derived from CD-Bonn NN interaction



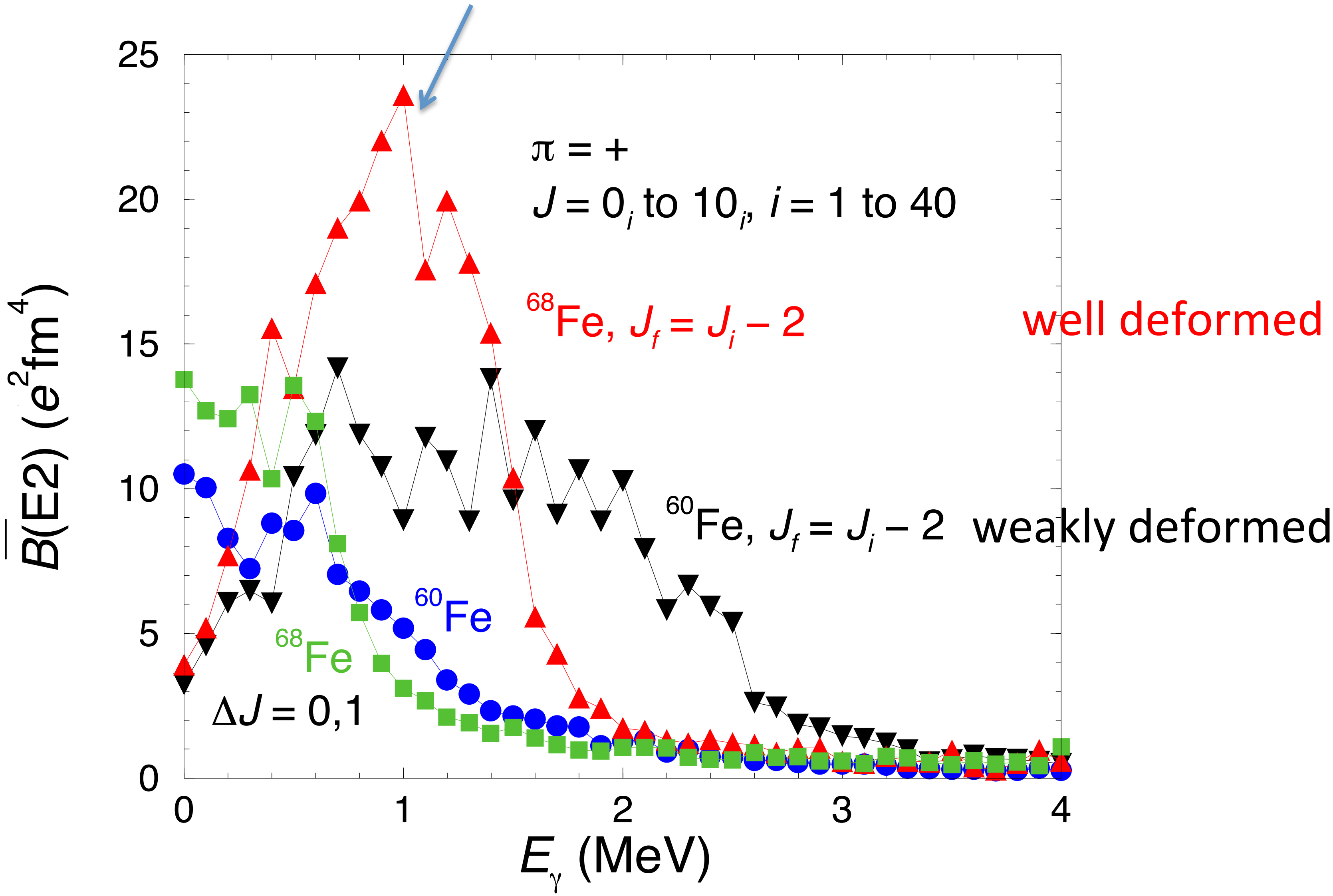
π = +
π = -
sum
60Fe
lnρ
T=1.0 MeV
ρ0=4 MeV−1
Ex(MeV)
π = +
π = -
sum
68Fe
lnρ
T=1.2 MeV
ρ0=11 MeV−1
π=+
π=−
60Fe
ln(BM1)
TB=1.2 MeV
Eγ
π=+
π=-
68Fe
ln(BM1)
TB=1.2 MeV
Eγ

peak position $E_\gamma(peak) = 2\omega = 2J/\Theta$

moment of inertia Θ=12MeV^{-1}

$J = 0,\ 1,\ \ldots\ 12$

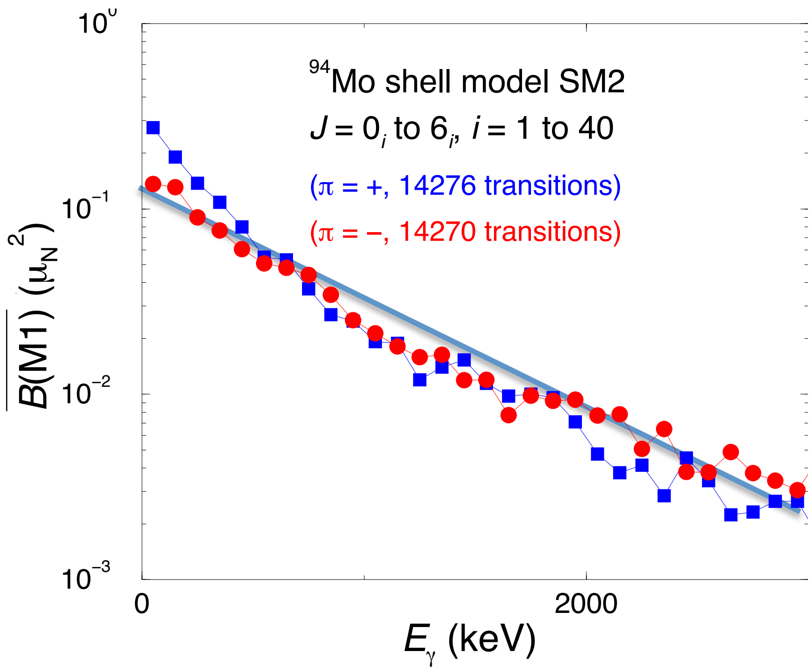
$E_\gamma(peak) = 2\omega = 2x6/12 = 1MeV$



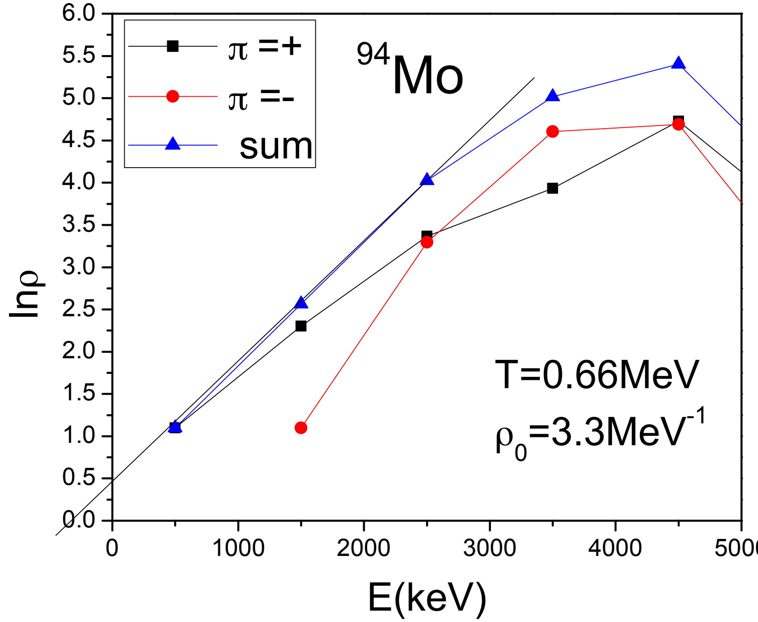
Thermal radiation?

R. Schwengner +SF to be published

$$\ln[B(M1)] = \ln B_0 - E_\gamma / T_B$$



$$\ln \rho = E / T_\rho + \ln \rho_0$$



The B(M1) distributions can be modeled by a thermal photon distribution → T_B

The level density can be modeled by the constant temperature expression → T_ρ

$$T_B \approx T_\rho$$

Spectral distribution of thermal radiation

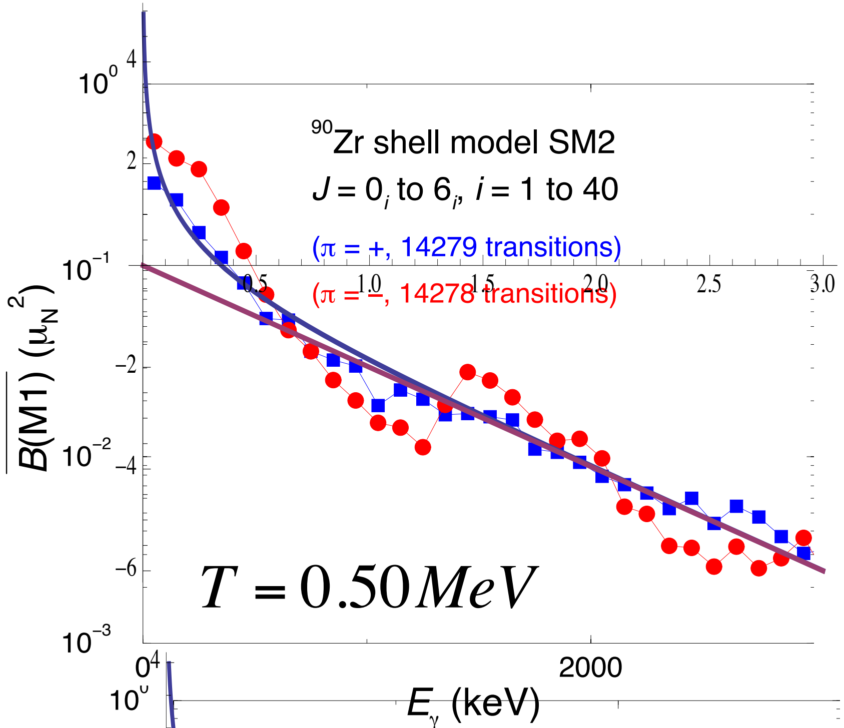
$$P \propto E_\gamma^3 B(M1, E_\gamma)$$

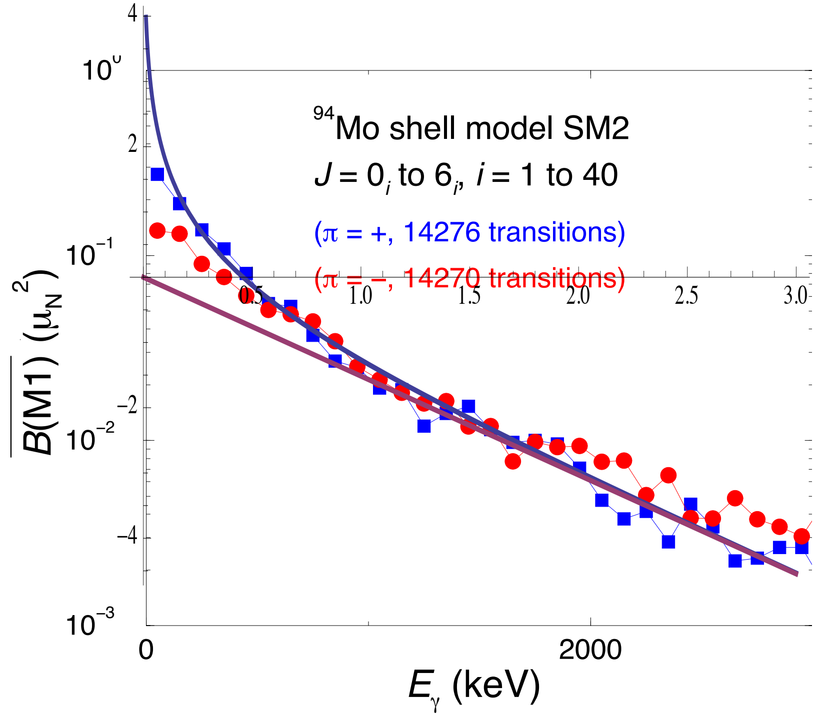
$$P(E_\gamma) = P_0 \frac{E_\gamma^3}{\exp(E_\gamma / T) - 1}$$

$$\text{classical: } \frac{1}{T} = \frac{dS}{dU} = \frac{d \ln \rho}{dE^*}$$

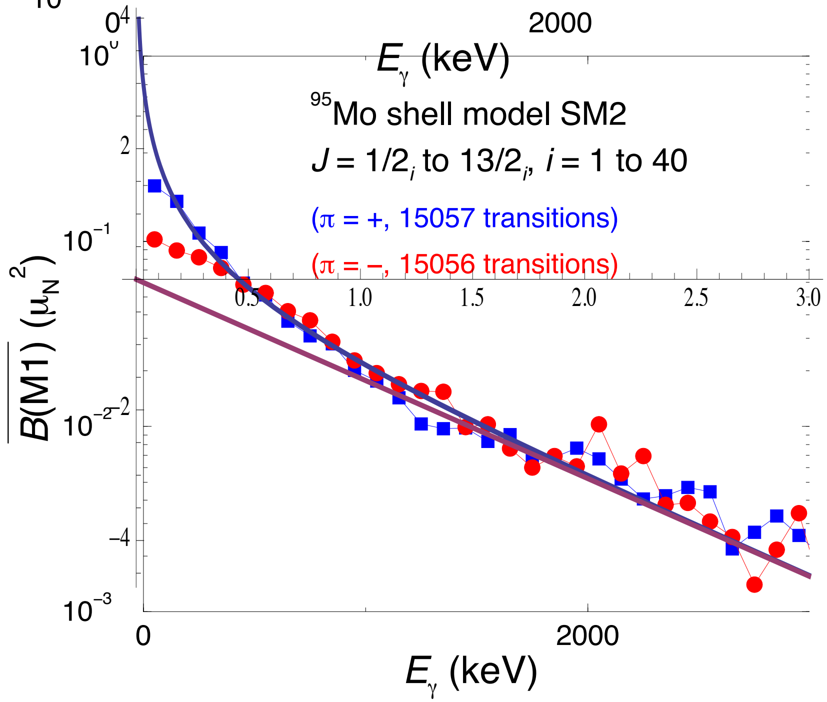
take T from level density

Planck's Law for black body radiation.
For absolute radiation intensity the emission (or absorption) coefficient of the radiating body Is required.





$T = 0.66\,MeV$ from level density



$T = 0.59\,MeV$ from level density

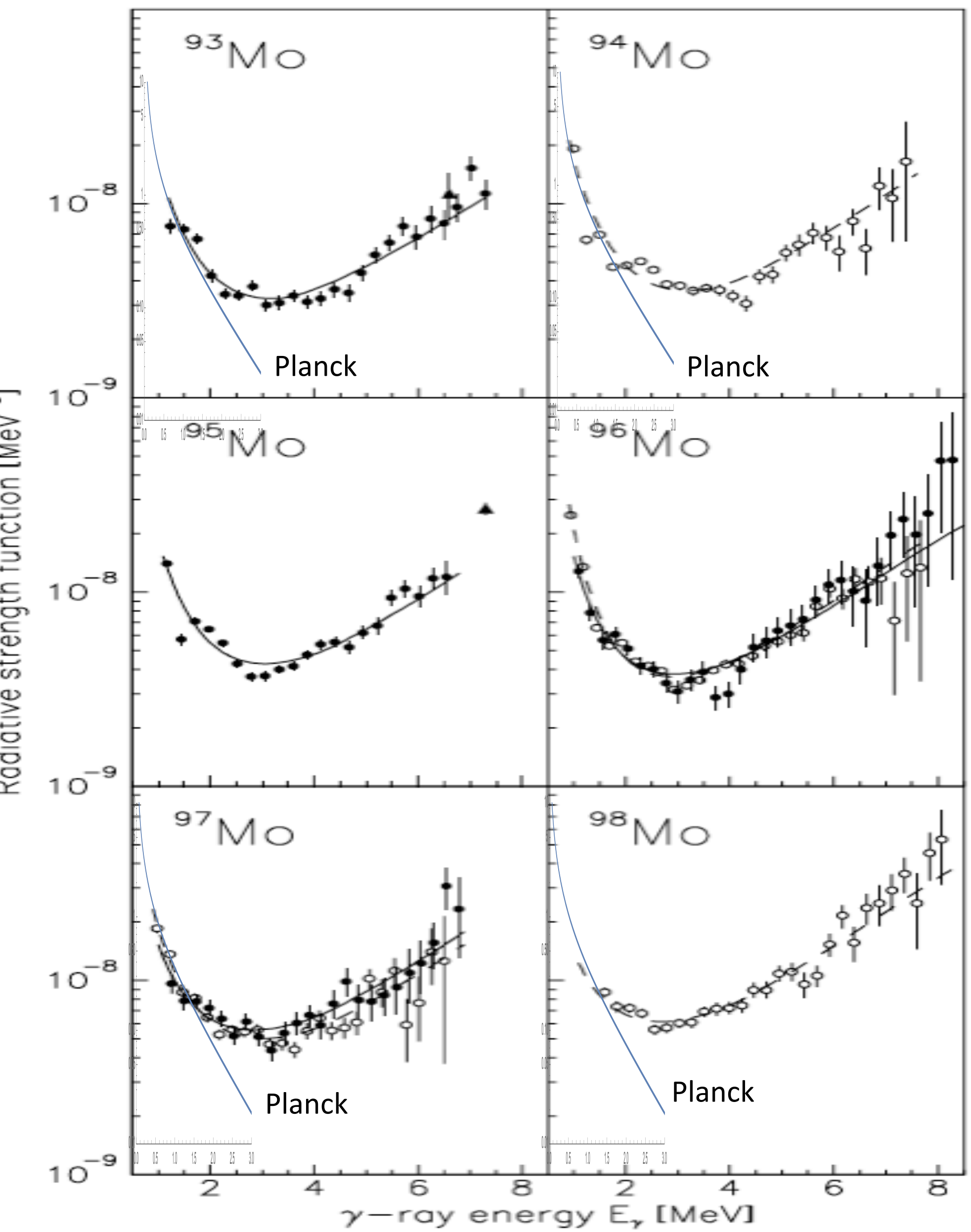
Better described by

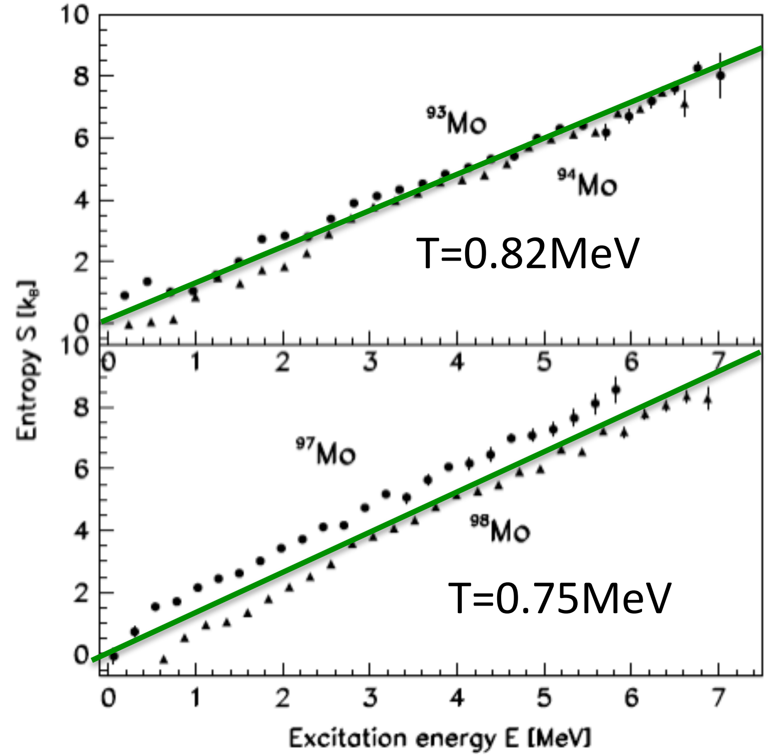
$$B(M1, E_\gamma) = \frac{B_0}{\exp(E_\gamma / T) - 1}$$

T from level density

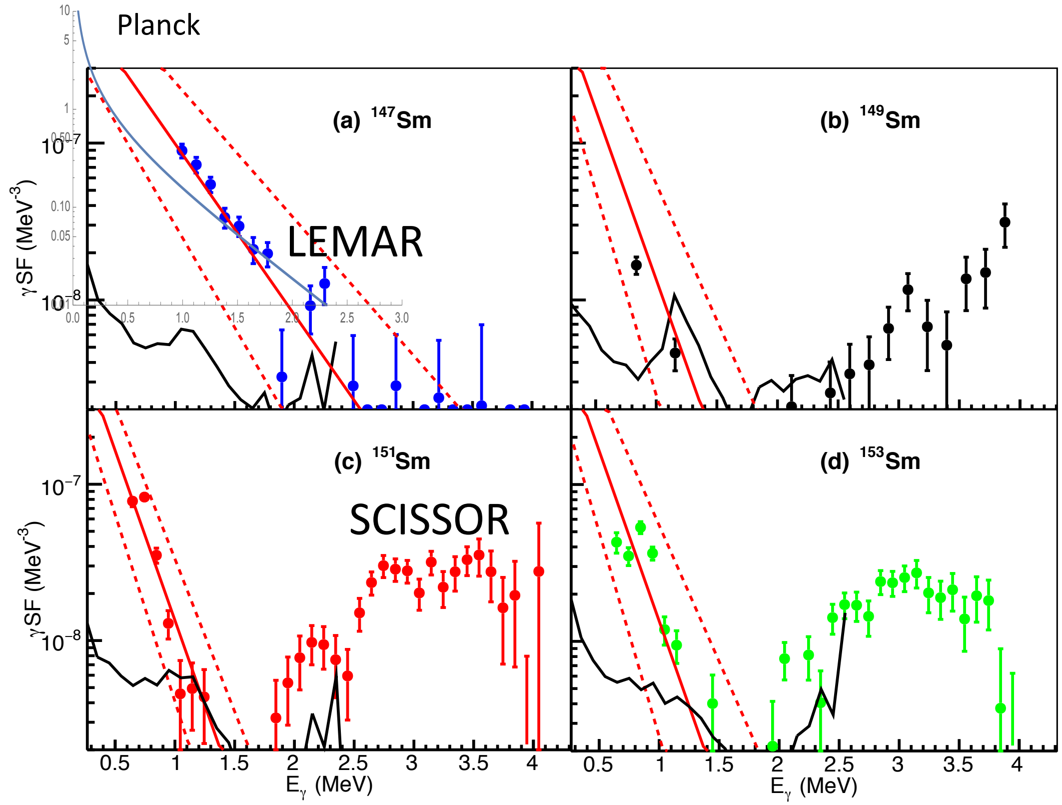
"thermal temperature"

Chankova et al. PRC 73 (2006) 034311





Not conclusive



$T_\rho \approx 0.5 MeV$

$T_B = 0.2 - 0.3 MeV$

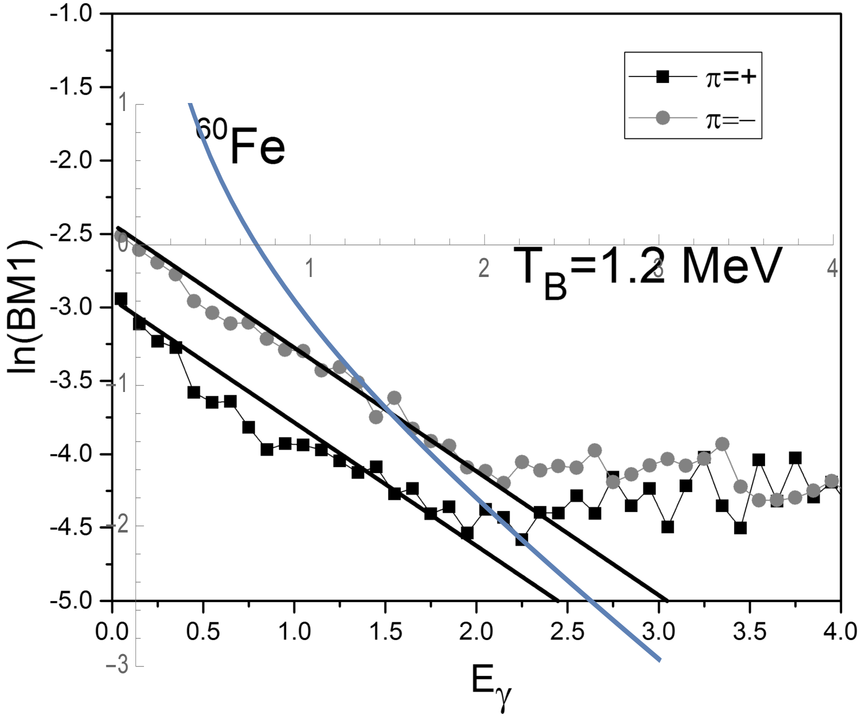
Planck does not work

FIG. 5. γ-ray strength functions for all four Sm isotopes with the GDR contribution subtracted. Solid line indicates the fit to the upbend region, while the dashed lines show the fit uncertainty. The results are compared with shell model calculations (black solid line).

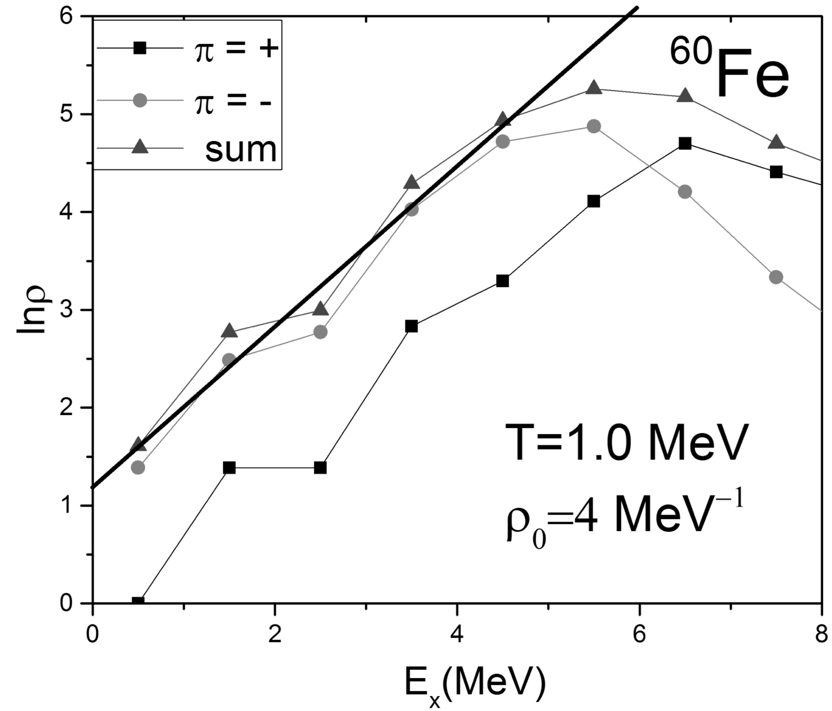
TABLE II. Parameters for resonances and the upbend for ^{147,149}Sm isotopes from the current work and for ^{151,153}Sm taken from [30].

Nucleus	Giant dipole 1 and 2 resonances							Spin-flip M1			Upbend		Scissors resonance			
	$\omega_{E1,1}$ (MeV)	$\sigma_{E1,1}$ (mb)	$\Gamma_{E1,1}$ (MeV)	$\omega_{E1,2}$ (MeV)	$\sigma_{E1,2}$ (mb)	$\Gamma_{E1,2}$ (MeV)	T_f (MeV)	ω_{M1} (MeV)	σ_{M1} (mb)	Γ_{M1} (MeV)	C (MeV^{-3})	η (MeV^{-1})	ω_{SR} (MeV)	σ_{SR} (mb)	Γ_{SR} (MeV)	B_{SR} (μ_N^2)
^{147}Sm	13.8	200	3.8	15.5	230	5.6	0.55	8.1	2.3	4.0	10(5)10^{-7}	3.2(10)	-	-	-	-
^{149}Sm	12.9	180	3.9	15.7	230	6.5	0.47	7.7	2.6	4.0	20(10)10^{-7}	5.0(10)	-	-	-	-
^{151}Sm	12.8	160	3.5	15.9	230	5.5	0.55	7.7	3.8	4.0	20(10)10^{-7}	5.0(5)	3.0(3)	0.6(2)	1.1(3)	7.8(34)
^{153}Sm	12.1	140	2.9	16.0	5.2	232	0.45	7.7	3.3	4.0	20(10)10^{-7}	5.0(10)	3.0(2)	0.6(1)	1.1(2)	7.8(20)

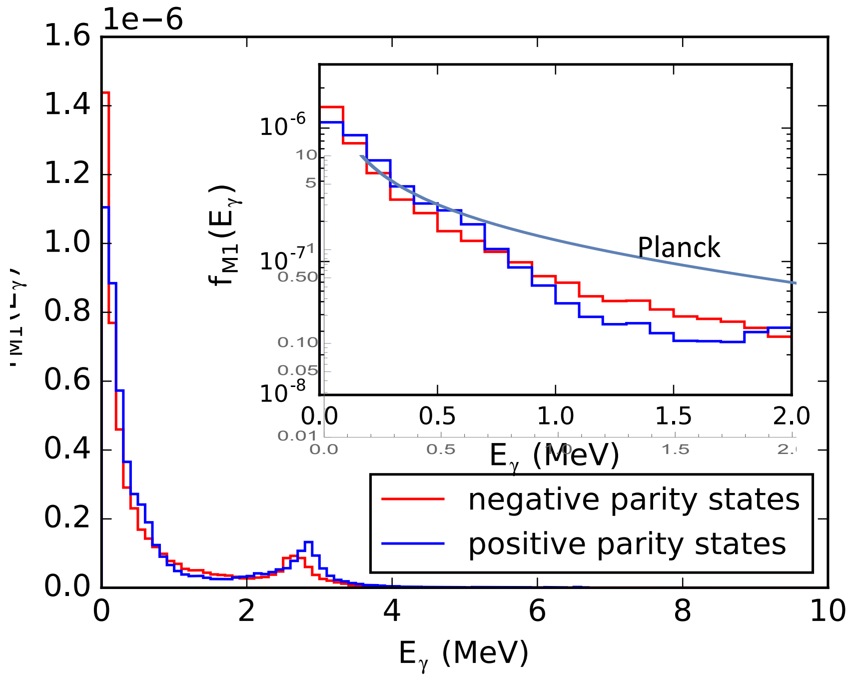
F. Naqvi, A. Simon, M. Guttormsen, R. Schwengner, S. Frauendorf, C.S. Reingold, J.T. Burke, N. Cooper, R.O. Hughes, P. Humby, J. Koglin, S. Ota, and A. Saastamoinen, Phys. Rev. C, accepted



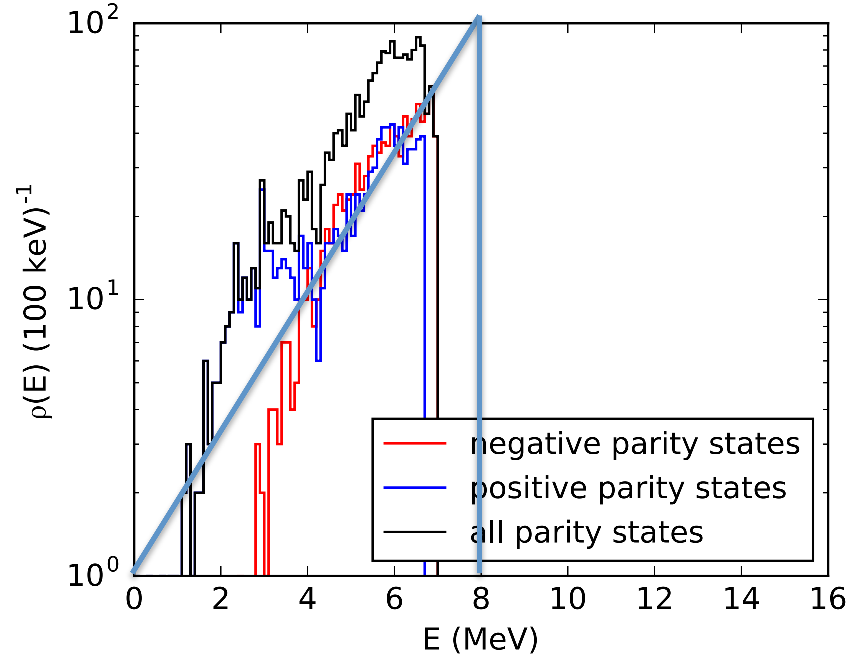
ln(BM1)
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
E_γ
π=+
π=−
^{60}Fe
T_B=1.2 MeV



lnρ
0
1
2
3
4
5
6
0
2
4
6
8
E_x(MeV)
π = +
π = -
sum
^{60}Fe
T=1.0 MeV
ρ_0=4 MeV^{-1}



1e−6
Planck
negative parity states
positive parity states
Eγ (MeV)
fM1(Eγ)

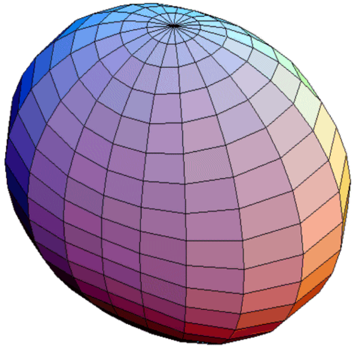


negative parity states
positive parity states
all parity states
E (MeV)
ρ(E) (100 keV)-1

T=1.7MeV

The quadrupole mode

late decoherence

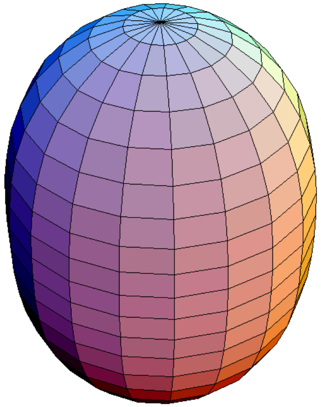


uniform rotation

quadrupole mode

different solutions of BH (multiplet members)

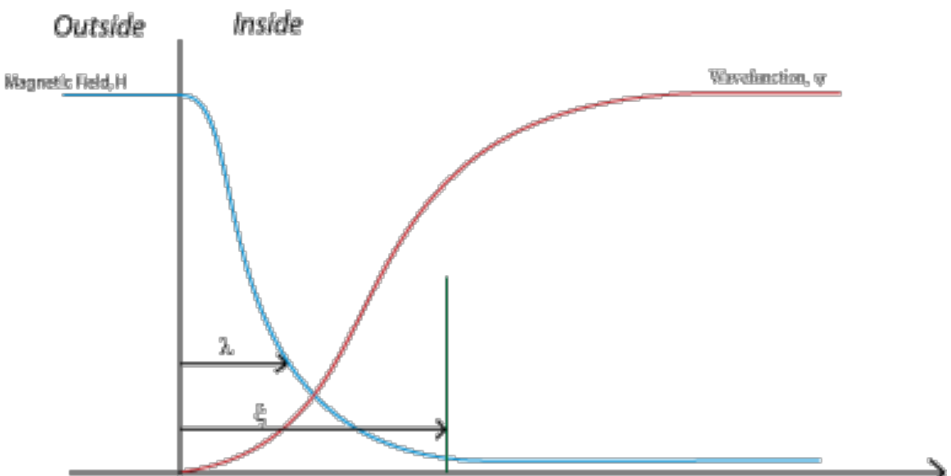
early decoherence



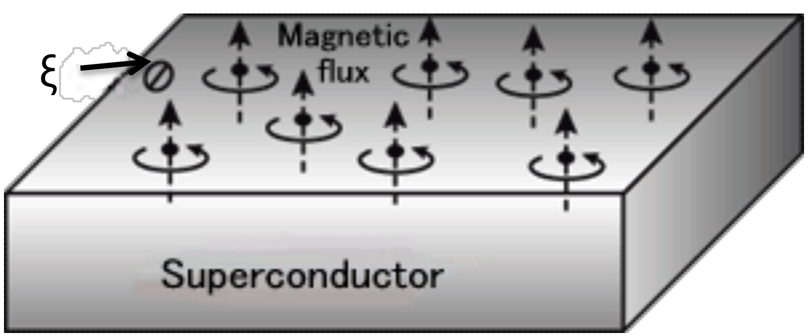
axial vibration

Coherence length

superconductor Type I



Coherent collective phenomena:
Meissner effect, flux quantization,
Josephson effect, super current



Collective condensate wave function $\Psi(\mathbf{r})$

Changes of Ψ appear only on a length scale

larger than the coherence length $\xi = \dfrac{\hbar v_f}{\pi\Delta}$,

which is the spatial extension of a Cooper pair.

Maximal momentum density carried by Ψ

$$p_{\max} = \frac{\hbar}{\xi} = \frac{\pi\Delta}{v_f} \qquad v_{\max} = \frac{\pi\Delta}{p_f}$$

$v_{\max}$ is maximal velocity the condensate

$$j_{\max} = \rho v_{\max} \qquad (10^3 - 10^4 A/m^2)$$

maximal super current at $T = 0$

warming up: $T \to T_C, \quad \Delta \to 0, \quad \xi \to \infty$

no more coherence and pertaining phenomena