

Breaking of axial symmetry in excited heavy nuclei as identified by experimental data

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Fermi gas \longleftrightarrow statistical physics

State & level densities \longleftrightarrow collective enhancement

Electric dipole (IVGDR) \longrightarrow radiative strength

\longrightarrow Neutron capture data (Maxwellian averages)

\longrightarrow Is axiality generally broken in most heavy nuclei ?

State density $\omega(E_x)$ in intrinsic nuclear system \rightarrow **level density $\rho(E_x)$ in lab**

Fermi gas (FG) above t_{pt} (known from quantum statistics) and **CT** at low energies

$$\omega_{FG} \propto e^{2 \cdot \tilde{a} \cdot t}; \quad t^2 = \frac{E_x - E_{bs}}{\tilde{a}}$$

$$\tilde{a} \approx a_{nm} \cong \frac{\pi^2 A}{4 \varepsilon F} \approx \frac{A}{13} \gg \frac{A}{8}$$

“level density parameter”

phase transition (pt)

$$E(t_{pt}) = \tilde{a} \cdot t_{pt}^2 + E_{bs}$$

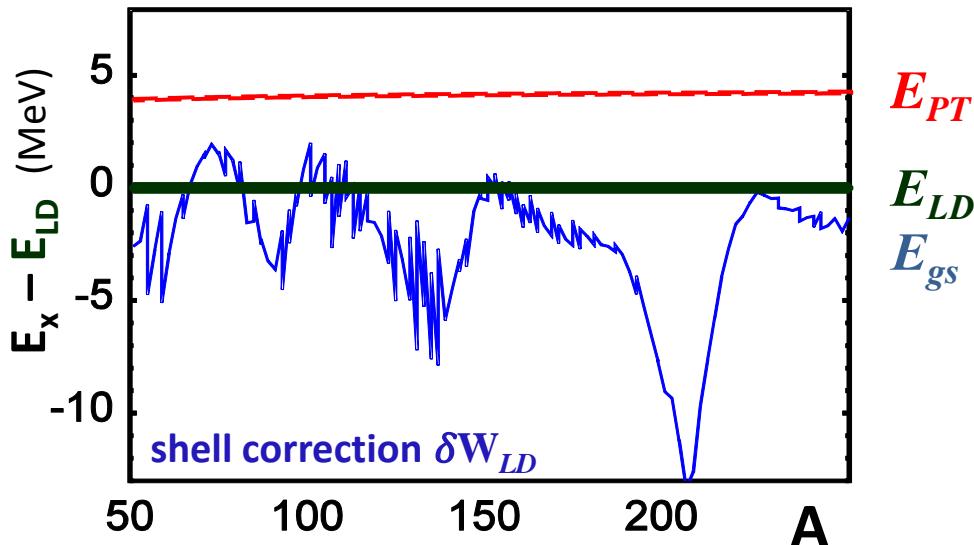
$$t_{pt} = \Delta_0 \cdot e^c / \pi = 0.567 \cdot \Delta_0$$

$$\omega_{CT} \propto e^{E/T}$$

↑ simulates BCS

slope change at pt

$E_{bs} = E_{LD} + E_{pc}$ backshift (bs) defined by liquid drop (LD) and pairing condensation:



$$\omega_{qp}(E_x) = \frac{\sqrt{\pi} \exp\left(2\sqrt{\tilde{a}} \cdot (E_x - E_{bs})\right)}{12\tilde{a}^{1/4} (E_x - E_{bs})^{5/4}} \quad \text{for } E_x \geq E_{pt}$$

$$\omega_{qp}(E_x) = \omega_{qp}(0) \cdot \exp\left(\frac{E_x}{T}\right) \quad \text{for } E_x < E_{pt}$$

The intrinsic **quasi-particle state density** in a finite nucleus $\omega_{\text{qp}}(E_x)$ is not yet the observable density of nuclear levels with well defined spin $\rho(E_x, J = I_{\text{rot}} + j, \pi)$.

To fix J the underlying collective symmetry has to be introduced:

1. *spherical*

\Rightarrow only *q-p states*

↙ small J limit

$$\rho(E_x, J, \pi) \xrightarrow{\quad} \frac{2J+1}{2\sqrt{8\pi}\sigma^3} \omega_{\text{qp}}(E_x)$$

2. *axial*

\Rightarrow *q-p states & rotation \perp axis*

$$\rho \xrightarrow{\quad} \frac{2J+1}{2\sqrt{8\pi}\sigma} \omega_{\text{qp}}(E_x)$$

3. non-axial (triax) \Rightarrow *q-p states & rotation about any axis*

$$\rho \xrightarrow{\quad} \frac{2J+1}{2 \cdot 4} \omega_{\text{qp}}(E_x)$$

4. no reflection symmetry \Rightarrow *q-p states & octupole deform.*

$$\rho \xrightarrow{\quad} \frac{2J+1}{2} \omega_{\text{qp}}(E_x)$$

Thomas-Fermi Model



$$\sigma^2 = \frac{\tilde{a} \cdot t}{11} A^{2/3} \approx \frac{A^{5/3}}{143} \cdot t$$

↗ 1 parity

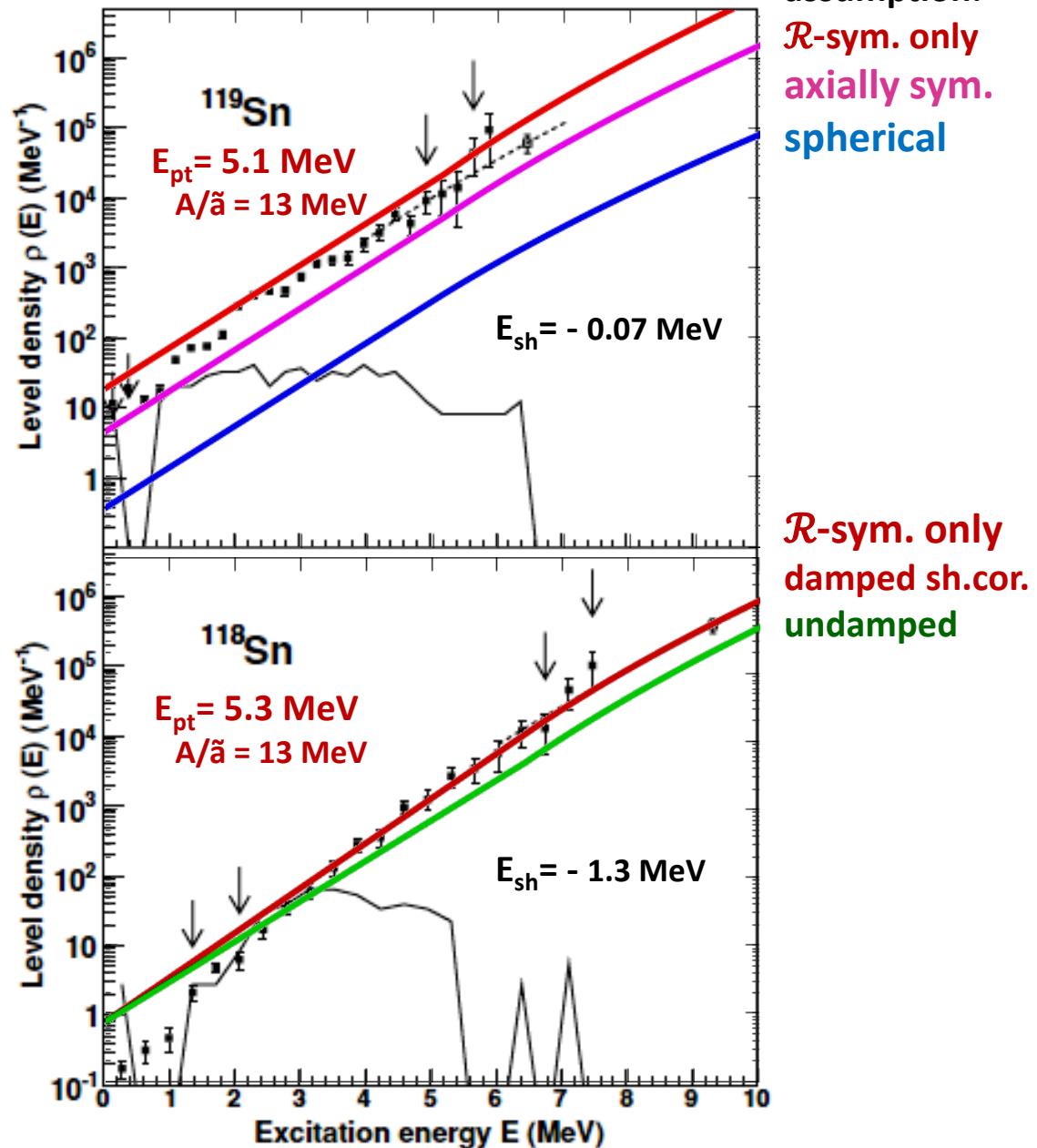
Density of levels

as determined at Oslo cyclotron
with $(^3\text{He}, \alpha\gamma)$ & $(^3\text{He}, ^3\text{He}\gamma)$
- coincidences.

The arrows indicate the regions
used to normalize the absolute
values and the slope

Fermi-gas with \tilde{a} from n.m.
& const. T below E_{pt}
no parity dependence
absolute scale
not fitted to data

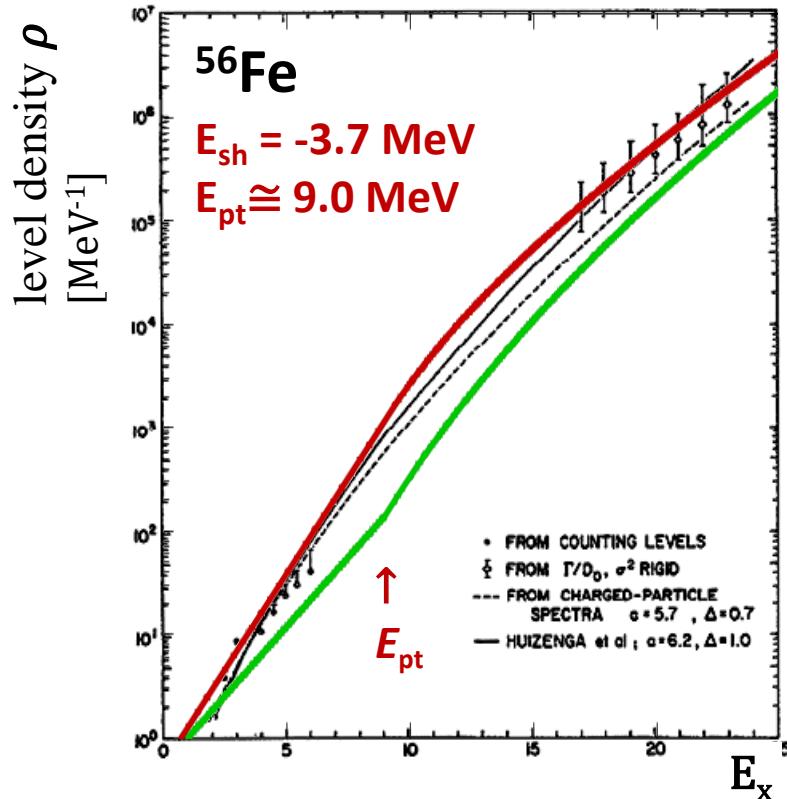
shell correction damped
with increasing t



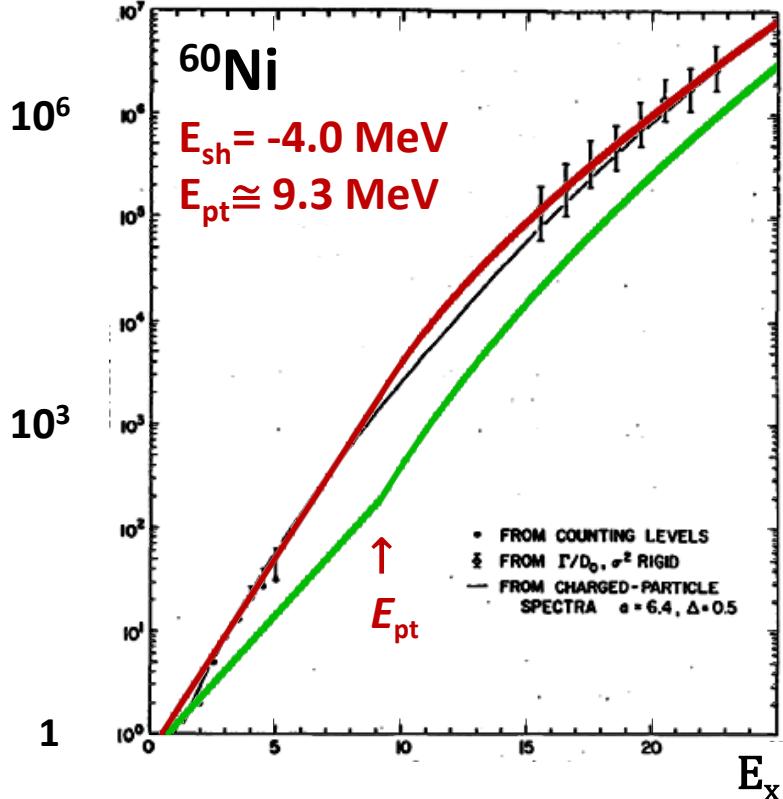
$^{59}\text{Co} (\text{p}, \alpha_{0-2}) ^{56}\text{Fe}$ to isolated levels and $^{60}\text{Ni}(\alpha, \alpha') ^{60}\text{Ni}$ & $^{63}\text{Cu}(\text{p}, \alpha) ^{60}\text{Ni}$

combined data analysis:

average cross sections $\rightarrow \Gamma \cdot \rho(E_x)$ & cross-section fluctuations \rightarrow width Γ \rightarrow level density ρ



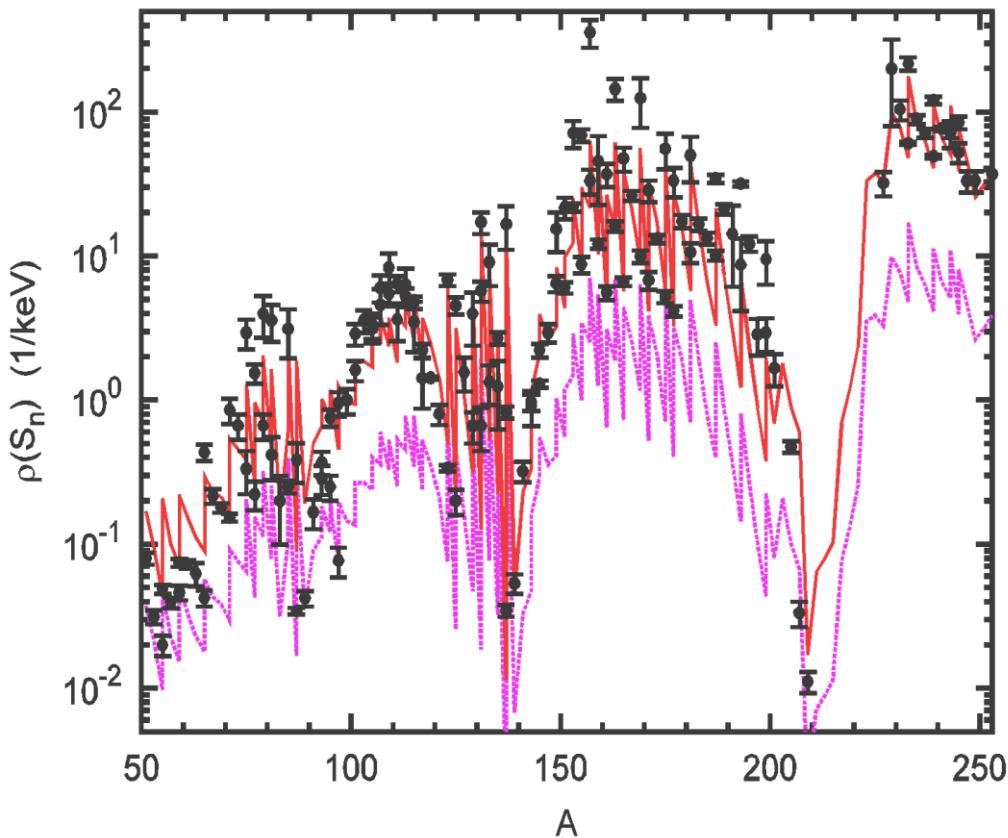
damped vs. undamped shell correction



Fermi-gas with $\tilde{\alpha}$ from n.m.
& const. T below E_{pt}
no parity dependence
absolute scale
not fitted to data

Level density just above n-binding energy S_n (even A targets)

measured by counting neutron capture resonances ($J = \frac{1}{2}^+$)



Fermi-gas theory & CTM

are transformed into lab-frame;

⇒ 'rotational' enhancement,

3 axes ↔ broken axial symmetry

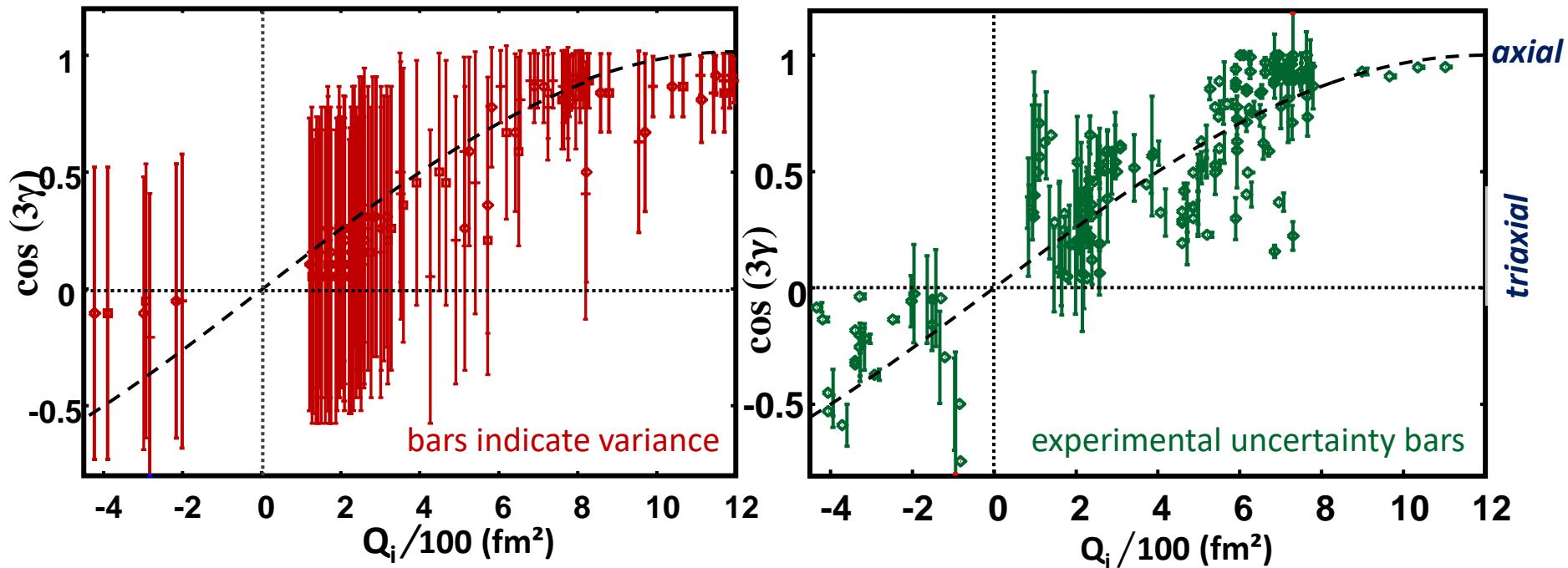
2 axes of rotation (axial symmetry)

$$\tilde{a} \approx a_{nucl\ matt}$$

A broken symmetry causes an extra degree of freedom =>

Rotational enhancement of level density – in agreement to data on absolute scale

*non-relativistic HFB - calculations and multiple coulomb excitation data
for nuclei in the valley of stability*



Triaxiality is predicted by BHF-theory with account for nucleon pairing and a GCM-approx. projection to minimum energy in lab-frame.

Bertsch et al., PRL 99 (2007) 032502
Delaroche et al., Phys. Rev. C 81 (2010) 014303

Triaxiality as deduced from complex analysis of experimental data for multiple Coulomb excitation

Kumar, Phys. Rev. Lett. 28 (1972) 249
Cline, Ann. Rev. Nucl. Part. Sci. 36 (1986) 683
Srebnry et al., Int. J. of Mod. Phys. E 20 (2011) 422

GDR's and deformation

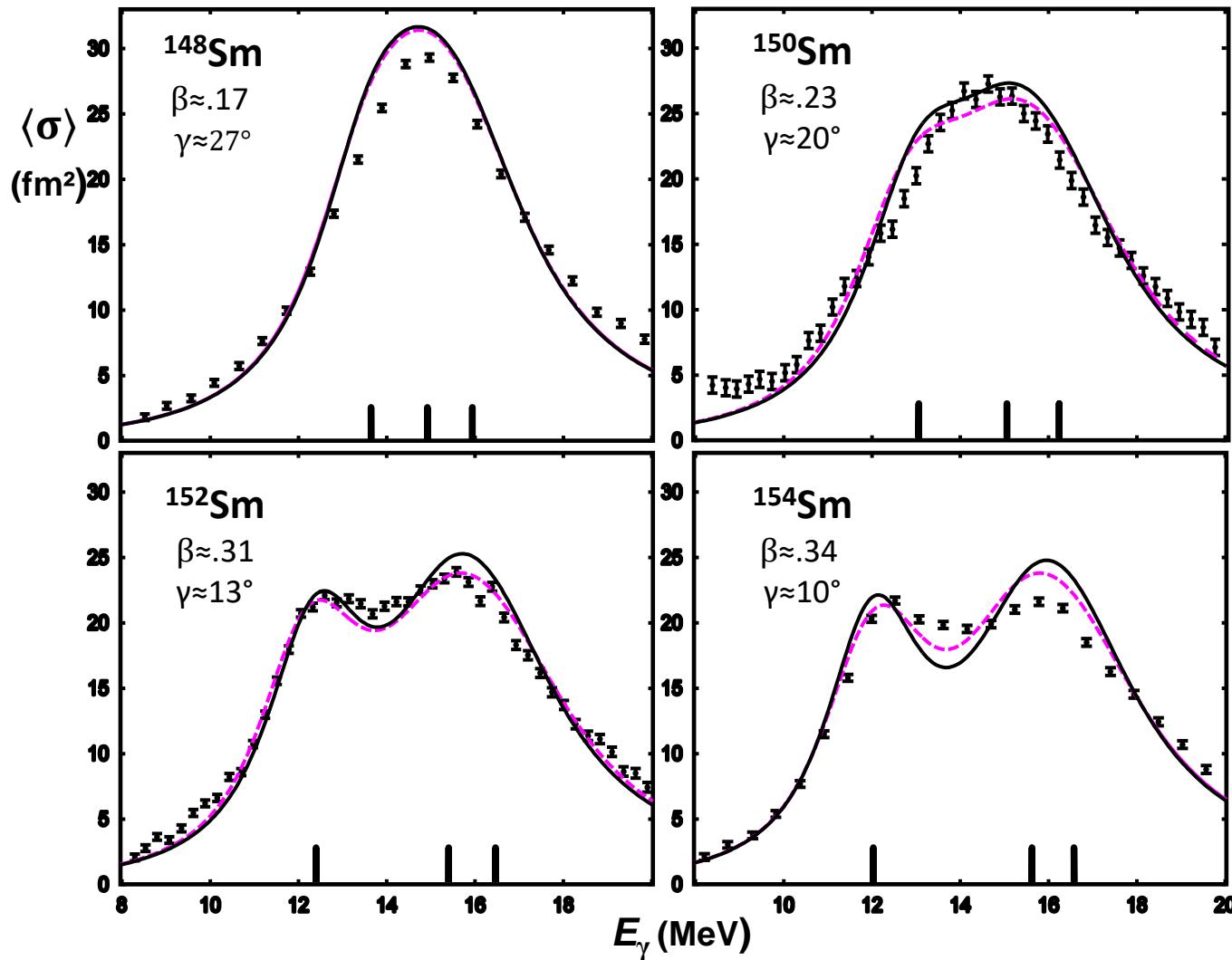
Apparent width of GDR:

1. 3 deformation axes

$$LDM \rightarrow E_{pole} \rightarrow E_k$$

A. Junghans et al.,

Phys.Lett. B 670 (2008) 200



2. many body dynamics

$$\text{hydro} \rightarrow \Gamma_k = \mathbf{c}_w \cdot \mathbf{E}_k^{1.6}$$

B. Bush and Y. Alhassid,
Nucl. Phys. A 531 (1991) 27

3. quantum effects (shape sampling)

M. Erhard et al.,

Phys. Rev. C 81 (2010) 34319

$$\text{TLO: } \sigma_{\text{abs}}^{\text{E1}}(E_\gamma) \cong 4\pi \frac{\alpha \hbar^2}{3m_N} \frac{\text{ZN}}{A} \sum_{k=1}^3 \frac{E_\gamma^2 \Gamma_k}{(E_k^2 - E_\gamma^2)^2 + E_\gamma^2 \Gamma_k^2} \text{ fm}^2$$

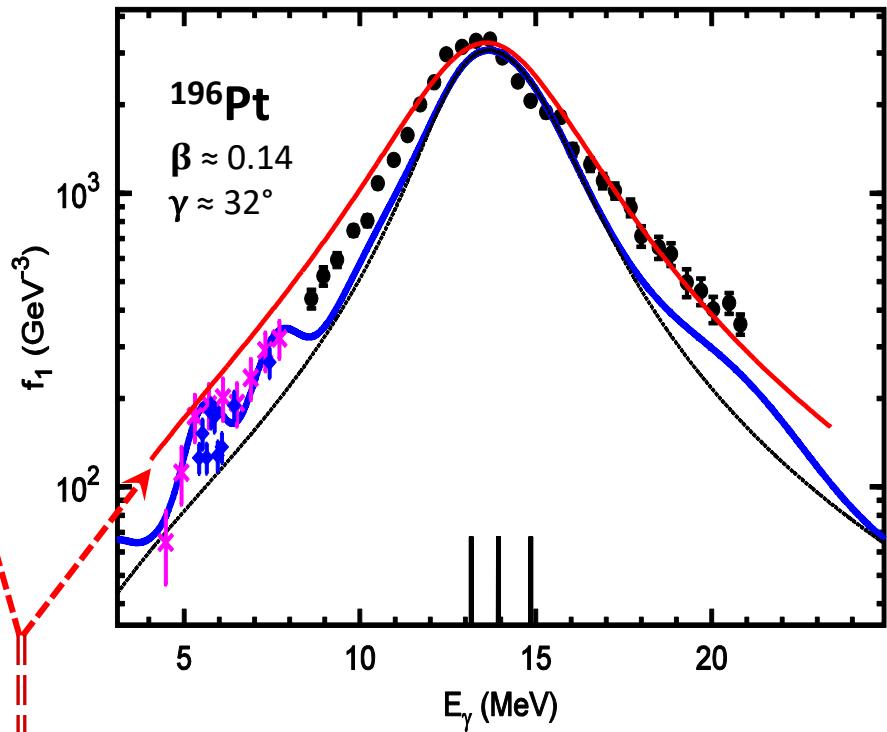
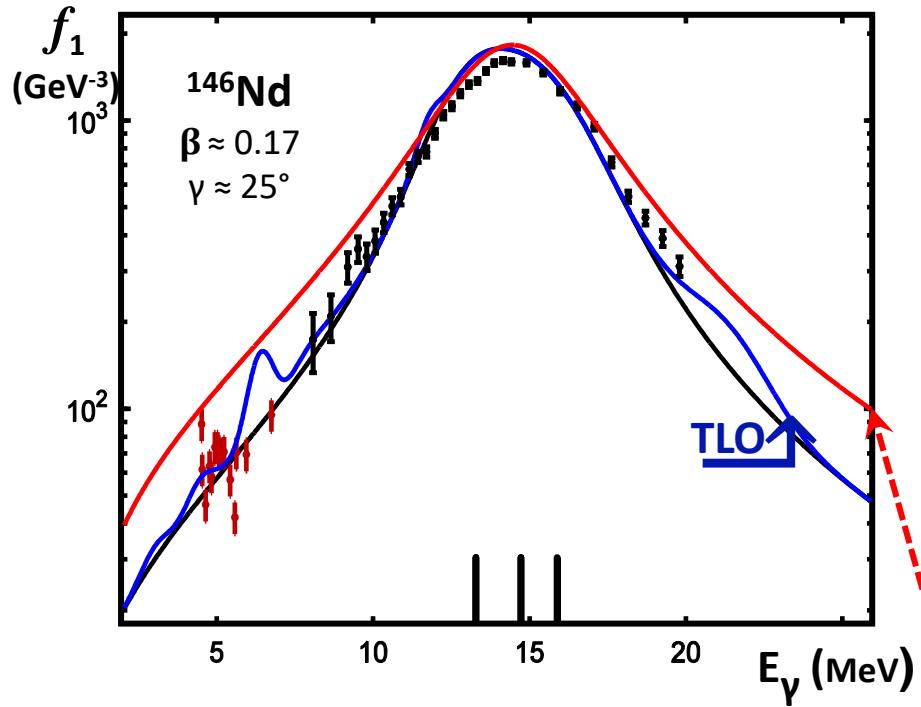
↓ TRK sum rule

one global width parameter

+ sum rule

⇒ agreement on ***absolute scale***

*Without widening induced by triaxial deformation
fits to GDR result in too high integral and yield in the tails.*

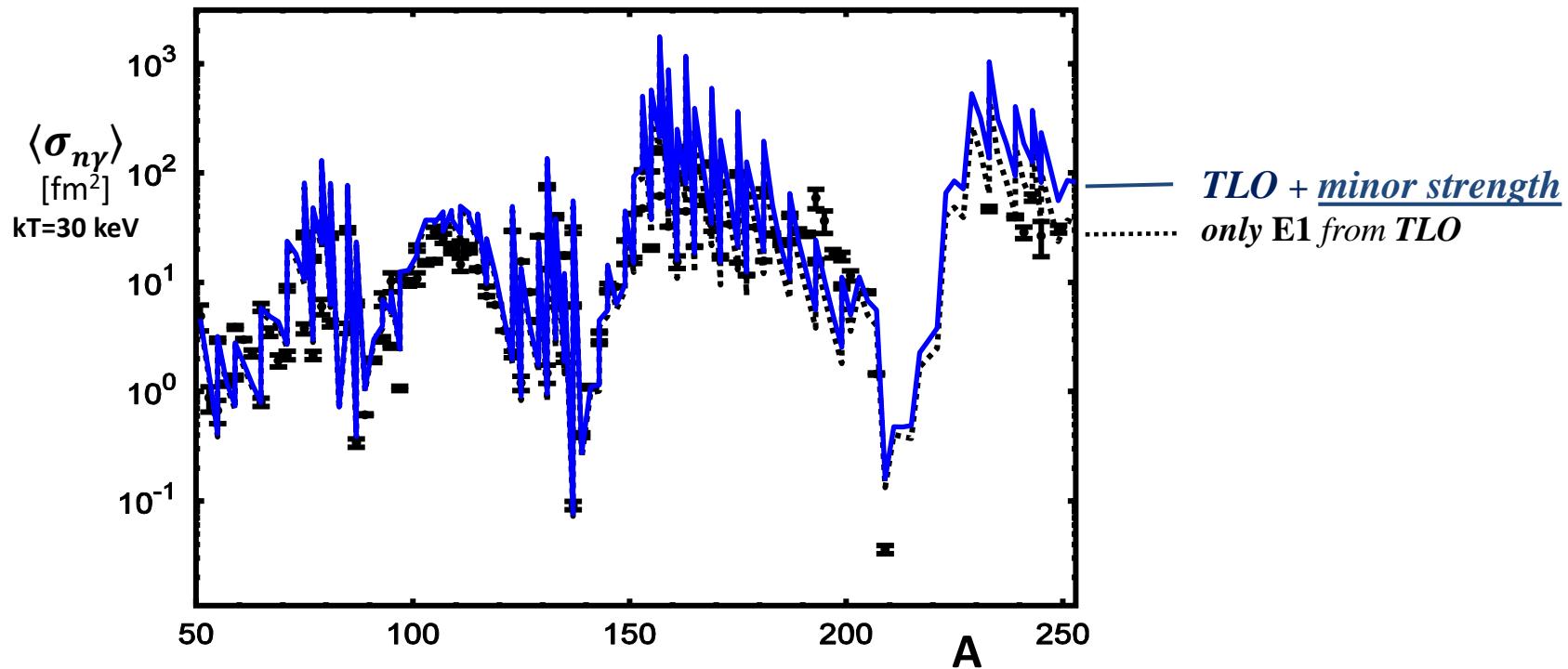


One-pole fit integral exceeds dipole sum rule by $\gtrsim 30\%$

The yield in the tails is directly proportional to
prediction for radiative capture cross section

*Maxwellian average capture cross-sections, calculated from global predictions for average level densities $\rho(E_r)$ and photon widths for radiative neutron capture at stellar temperatures of $3 \cdot 10^8$ K
 => test of the triple Lorentzian photon strength $f_1(E_\gamma)$ and the level density prediction for broken axiality .*

$$\langle \sigma_{n,\gamma} \rangle_r \cong 2\pi^2 \lambda_n^2 \cdot \sum_{\ell_n} (2\ell_n+1) \cdot \left\langle \frac{\Gamma_n \cdot \bar{\Gamma}_\gamma}{\Gamma_n + \bar{\Gamma}_\gamma} \right\rangle_r \cdot \rho(E_r, J_r); \quad \bar{\Gamma}_\gamma = \sum_{J_b} g \frac{f_1(E_\gamma) E_\gamma^3}{\rho(E_r, J_r)}; \quad E_r \cong S_n + kT$$



*absolute agreement for >130 nuclei (s-capture via overlapping resonances) =>
 good global predictions are possible, as $\langle \sigma \rangle$ depends mainly on
 $\rho(A, Z, E_r)$ & $f_1(E_\gamma)$, i.e. on ϵ_F , shell correction and sum rule, if broken axiality is used.*

Conclusions:

A symmetric configuration is not necessarily the one with lowest energy!

For most heavy nuclei several facts indicate broken axial symmetry :

1. *Hartree-Fock-Bogolyubov calculations* with
mapping onto a 5-dim. collective quadrupole Hamiltonian
 2. *Multiple Coulomb excitation* analyzed via rotation invariants
 3. *Split of the giant dipole resonance indicates triaxiality*
 4. *Level densities* well predicted with $\tilde{\alpha} = \frac{\pi^2 \cdot A}{4 \varepsilon_F} + \alpha \cdot A^{2/3}$; $\alpha < 0.1$
 5. *Neutron capture cross sections* are well described for $70 < A < 240$
with only one (global) fit parameter for spreading widths.
- *Is axiality generally broken in most heavy nuclei ?*