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

A.R. Junghans [1)], E. Grosse [2)], R. Massarczyk [1*)]

1) Helmholtz-Zentrum Dresden-Rossendorf, Germany

2) Institut für Kern- und Teilchenphysik, TU Dresden, Germany

*present address: Los Alamos National Laboratory, NM, U.S.A.

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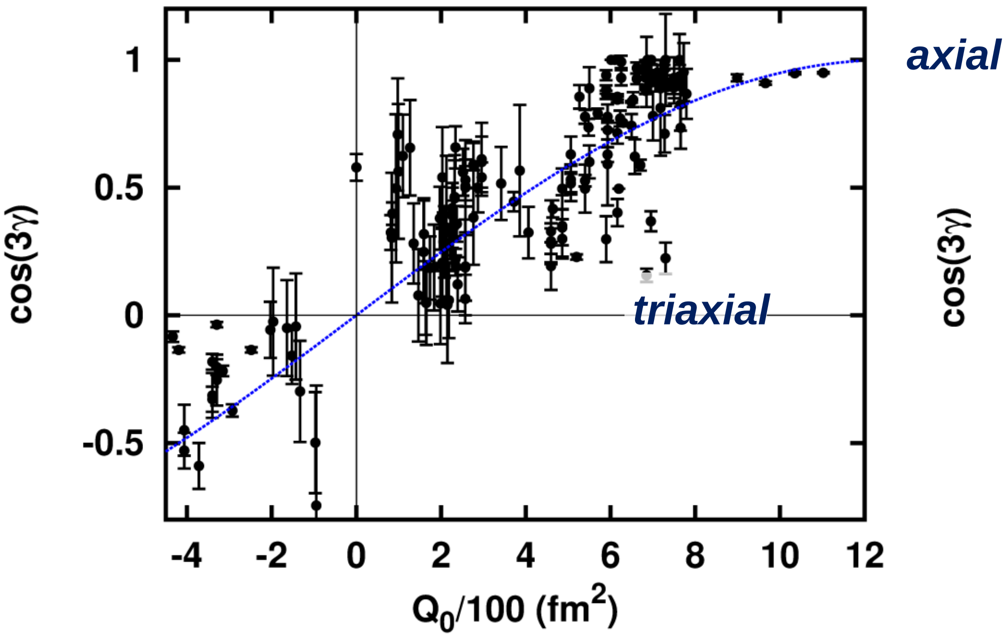
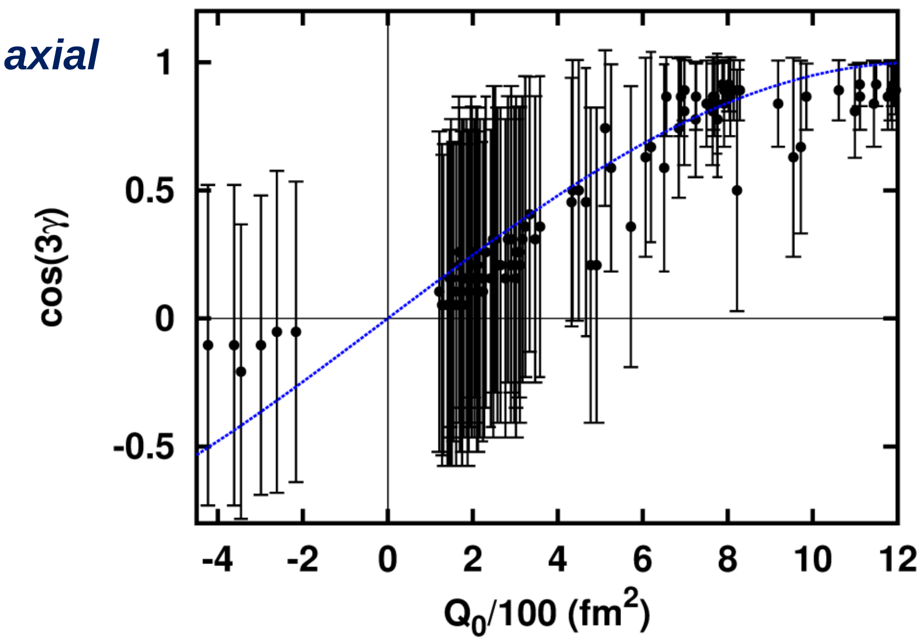
- Breaking of axial symmetry evidenced in Coulomb excitation
- Global GDR without assumption of axial symmetry
- Level density without axial symmetry
- Averaged neutron capture cross sections

CHANDA SOLVING CHALLENGES IN NUCLEAR DATA FOR THE SAFETY OF EUROPEAN NUCLEAR FACILITIES
SEVENTH FRAMEWORK PROGRAMME

Triaxiality in Coulomb Excitation / HFB theory





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

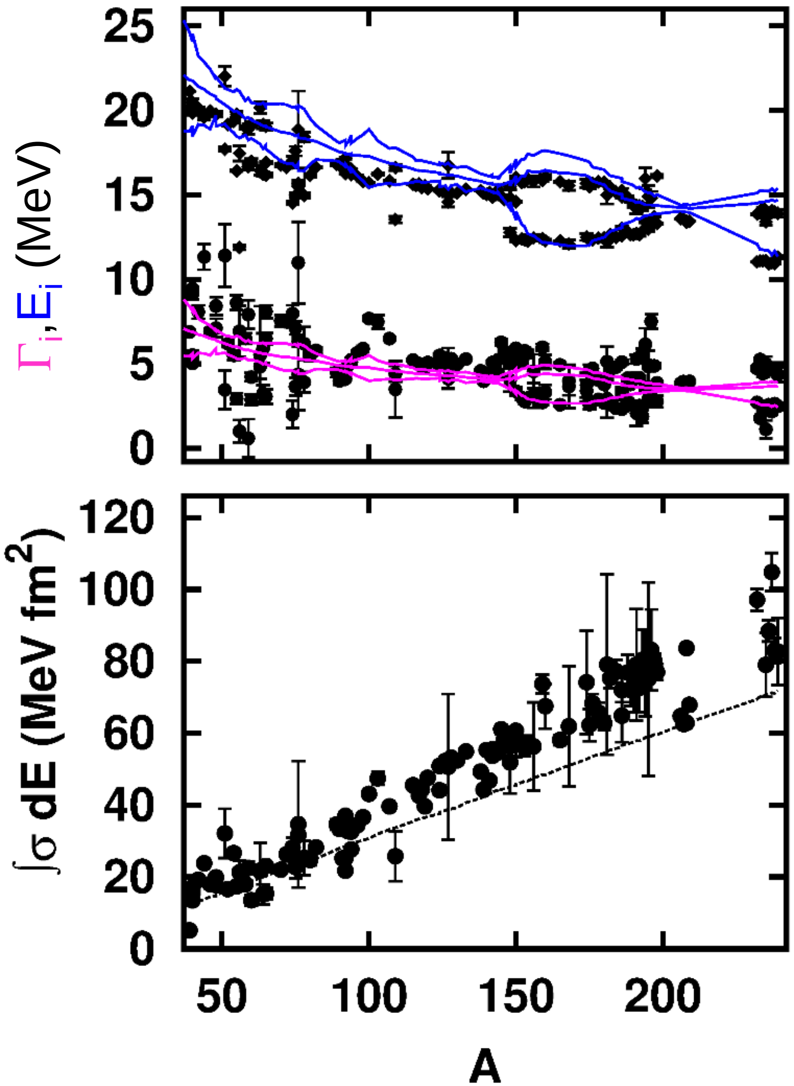
Triaxiality predicted by HFB-theory with account for nucleon pairing and a variation <u>after</u> projection to find minimum energy in lab-frame.

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

Hayashi, Hara and Ring, Phys. Rev. Lett. 53 (1984) 337
Bertsch et al., Phys. Rev. Lett. 99 (2007) 032502
Delaroche et al., Phys. Rev. C 81 (2010) 014303

Triaxiality not only a rare property of some exotic nuclei

Global GDR description without assumption of axial symmetry



1. Triple Lorentzian Parametrisation TLO

$$E_k = \frac{R_0}{R_k} E_0$$

E_0 from Droplet Model (Myers, 1977)
axes ratios, charge radii based on CHFB-5DCH
Delaroche et al., Phys. Rev. C 81 (2010) 014303

2. GDR width $\Gamma_k = 0.045\, E_k^{1.6}$
hydrodynamical model
Bush, Alhassid, Nucl. Phys. A 531 (1991) 27

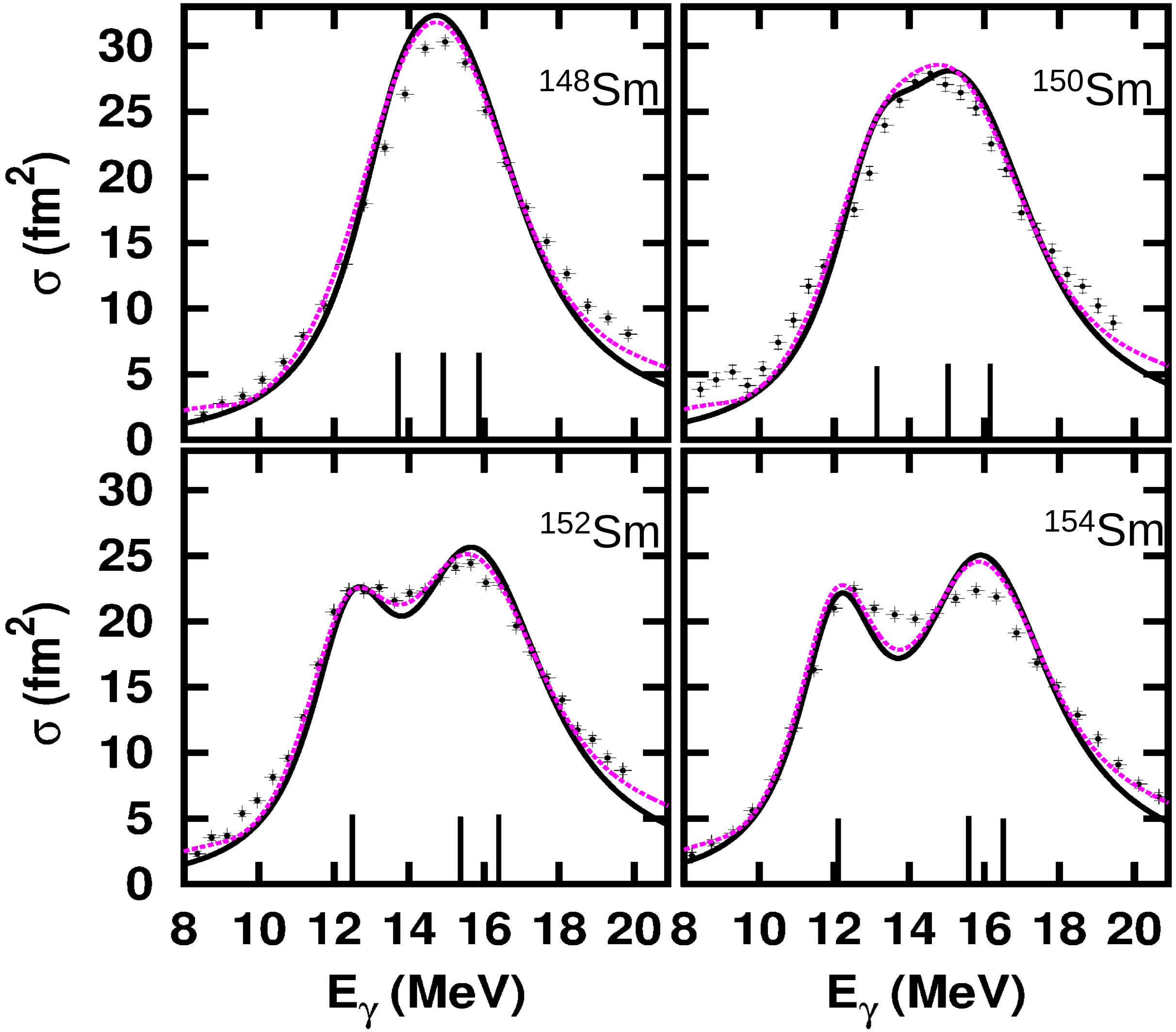
3. TRK Sum rule for normalization of the GDR region
Gell-Mann et al., Phys. Rev. 95 (1954) 1612

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

Junghans, et al. PLB 670 (2008) 200

data points: local 1,2 Lorentzian fits(RIPL-3)
strong variations in width ➔ overshoot TRK sum rule by a large fraction
TLO: smooth A dependence modulated by shape

TLO Description of the GDR



Instantaneous Shape Sampling small influence on the GDR shape

CHFB 5DCH
def. parameters too large for nuclei at magic numbers

$$\beta \rightarrow \beta(0.4 + (\mathrm{N} - \mathrm{N}_{\mathrm{shell}})/20$$

Exp. data scaled by 0.9 in accordance with
Berman et al. Phys. Rev C 36 (1987) 1286

exp. data: Carlos et al. Nucl. Phys. A 225 (1974) 171

Empirical parametrisation of Minor Strength

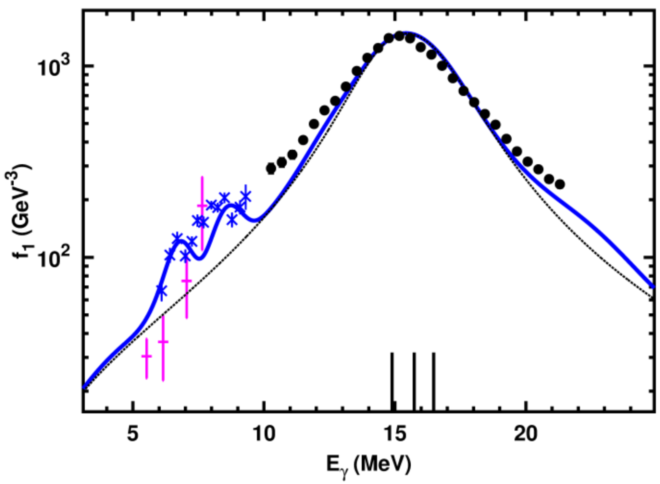
Component parameter(units)	multi-polarity	E_c (MeV)	I_c ($\mathrm{fm}^2\mathrm{MeV}$)	σ_c (MeV)
low E_x pigmy mode	E1	$0.43E_0$	$7\ \frac{Z(N-Z)}{A}$	0.6
high E_x pigmy mode	E1	$0.55E_0$	$13\ \frac{Z(N-Z)}{A}$	0.5
$0^+ \leftrightarrow (2^+ \times 3^-)_{1-}$	E1	$\frac{140}{N}(1+\frac{107}{Z})$	$0.006ZA\beta$	0.6
orbital (scissors) mode	M1	$0.21E_0$	$0.033ZA\beta$	0.4
isoscalar spin-flip	M1	$42A^{-1/3}$	17	0.8
isovector spin-flip	M1	$47A^{-1/3}$	27	1.3
low E_x quadrupole	E2	$19A^{-1/3}$	$0.1\ \frac{\alpha_e(\pi R_c E_\gamma)^2 Z^2}{(3Am_pc^2)}$	1.0
ISGQR	E2	$63A^{-1/3}$	$2\ \frac{\alpha_e(\pi R_c E_\gamma)^2 Z^2}{(3Am_pc^2)}$	1.0
IVGQR	E2	$48A^{-1/6}$	$\frac{\alpha_e(\pi R_c E_\gamma)^2 Z^2}{(3Am_pc^2)}$	1.8

Upper limit description by gaussian peaks E_c, σ_c, I_c
GQR modes (photon absorption) proportional to charge radius squared

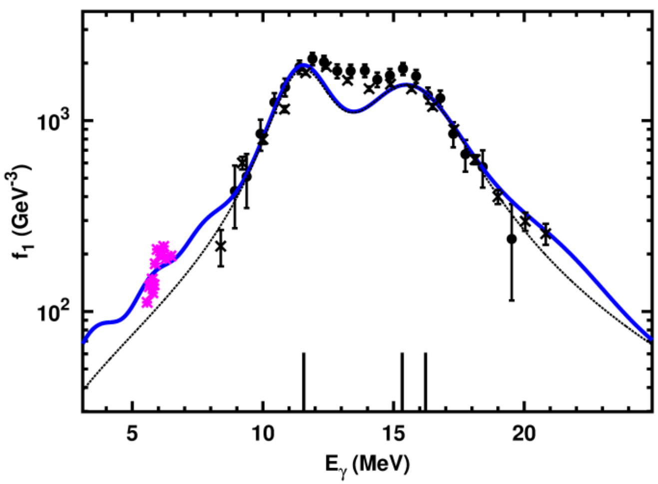
E.Grosse, A.R. Junghans in Landolt-Börnstein New Series (2012) I/25D 4
K. Heyde, P. von Neumann-Cosel, A Richter, Rev. Mod. Phys. 82 (2010) 2365
U. Kneissl, H.Pitz, A.Zilges, Prog. Part. Nucl. Phys. 37 (1996) 349
and references therein…

TLO + minor strength

^{118}Sn



^{168}Er



TLO **without** minor strength, minor strength **included**

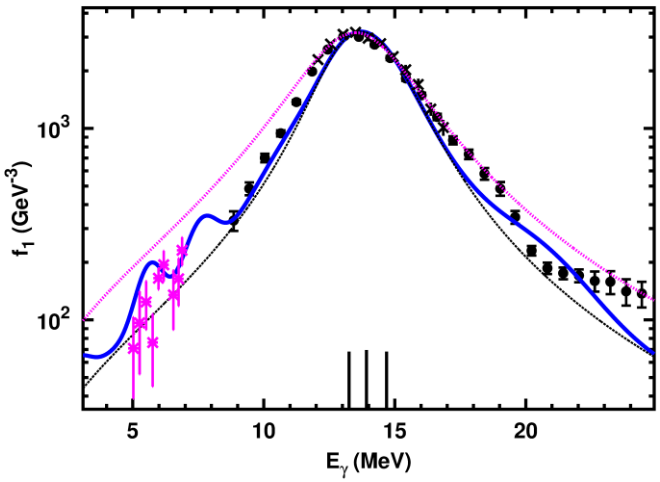
(γ,n) data (scaled with 0.9): A. Lepretre et al., Nucl. Phys. A 219 (1974) 39
(γ,tot) : P. Axel et al., Phys. Rev. C2 (1970) 689
(^{3}He,^{3}Heγ): H. K. Toft Phys. Rev. C 81 (2010) 064311

TLO **without** minor strength, minor strength **included**

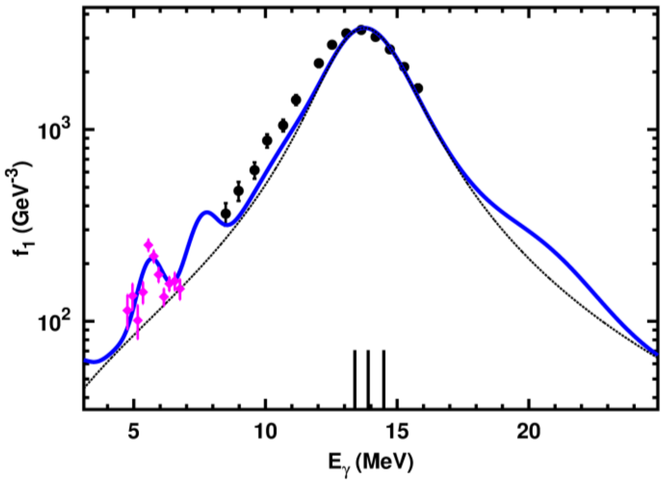
x (γ,n) data (scaled with 0.9): H. Bergére Nucl. Phys. A 133 (1969) 417
o (σ_{tot}) : G.M. Gurevich et al., Nucl. Phys. A 351 (1981) 257
(ARC Average resonance capture): S.F. Mughabghab, Phys. Lett. B 487 (2000) 155

TLO + minor strength

^{197}Au



^{202}Hg



TLO **without** minor strength, minor strength **included**

(γ,n) data (scaled with 0.9): A. Lepretre et al., Nucl. Phys. A 219 (1974) 39
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TLO **without** minor strength, minor strength **included**

(γ,n) data (scaled with 0.9): A. Veyssiere et al., Jour. de Physic Lettres 36 (1975) L267
(γ, γ): R.M. Laszewski, P. Axel, Phys. Rev. C 19 (1979) 342

Level density in nuclei without axial symmetry

- Intrinsic level density $\omega_{qp}(E_x)$: Constant Temperature description below and backshifted Fermi-Gas above pairing phase transition

$$\omega_{qp}(E_x) = \omega_{qp}(0)\exp(\frac{E_x}{T_{ct}}) \quad \text{for} \quad E_x < E_{pt}$$

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

In the following the parameters $\tilde{a}$, $\mathrm{E_{bs}}$, $\mathrm{E_{pt}}$ will **not** be fitted to experimental data

- Level density for spherical and deformed nuclei (collective enhancement)
  Bjørnholm, Bohr Mottelson, Rochester 1973 IAEA-SM-174/205

$$\rho_{sph}(E_x, J^\pi) \cong \frac{2J+1}{2\sqrt{8\pi}\sigma^3}\exp\left(-\frac{(J+1/2)^2}{2\sigma^2}\right)\omega_{qp}(E_x)$$

$$\xrightarrow{\text{small} J} \frac{2J+1}{2\sqrt{8\pi}\sigma^3}\omega_{qp}(E_x) \text{ with } \sigma = \sqrt{\frac{\Im t}{\hbar^2}}$$

Gaussian m-substate distribution with width σ around 0.
Spin-cutoff parameter σ depending on nuclear moment of inertia $\Im$

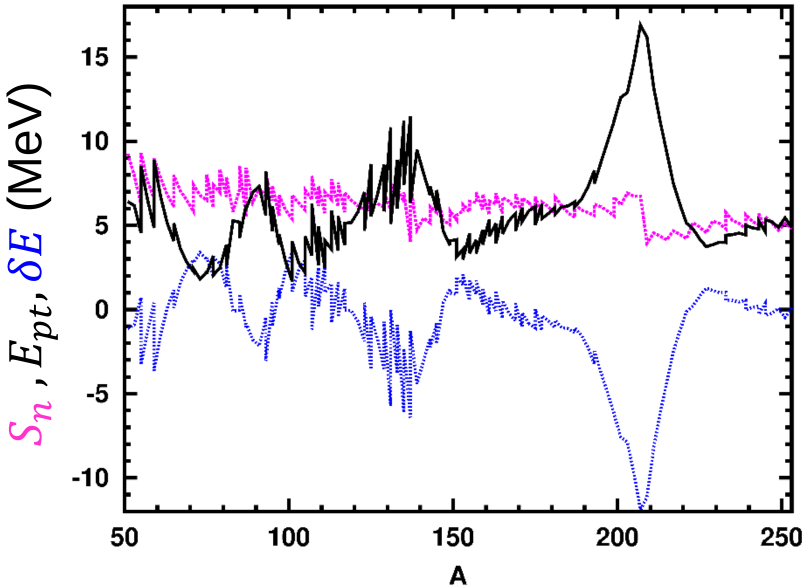
$$\rho_{axial}(E_x, J^\pi) \xrightarrow{\text{small J}} \frac{2J+1}{2\sqrt{8\pi}\sigma}\,\omega_{qp}(E_x)$$

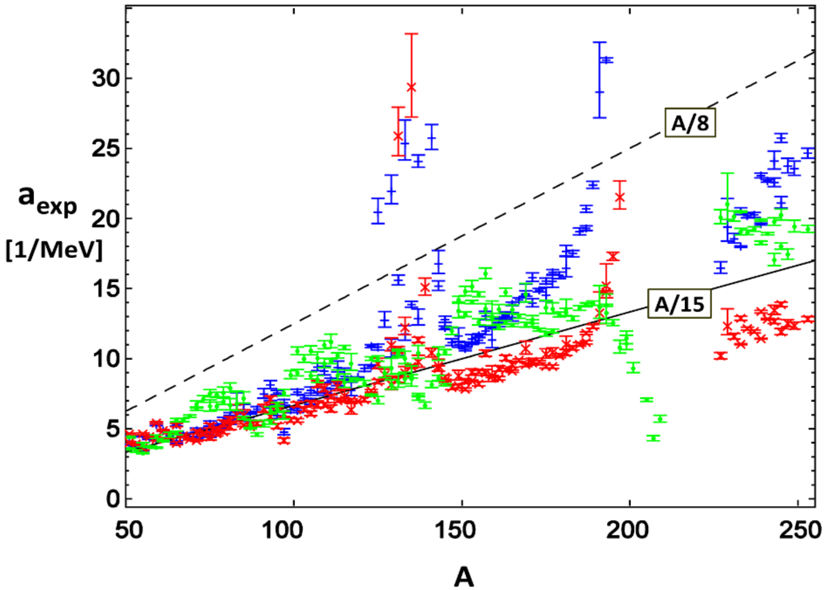
$$\rho_{triaxial}(E_x, J^\pi) \xrightarrow{\text{small J}} \frac{2J+1}{2\cdot 4}\,\omega_{qp}(E_x)$$

E. Grosse et al., Phys. Lett. B739 (2014) 425

DRESDEN concept HZDR

Level density parameters





$$E_{con} = \frac{3}{2\pi^2} a_{nm} \Delta_0^2$$

$$E_{bs} = E_{con} - \delta E(Z, A)$$

$$E_{pt} = \tilde{a} t_{pt}^2 + E_{bs}$$

$$\mathrm{t_{pt}} = 0.567\Delta_0$$

$$\mathrm{a_{nm}} = \frac{\pi^2 A}{4\, \epsilon_F} \approx \frac{A}{15};$$

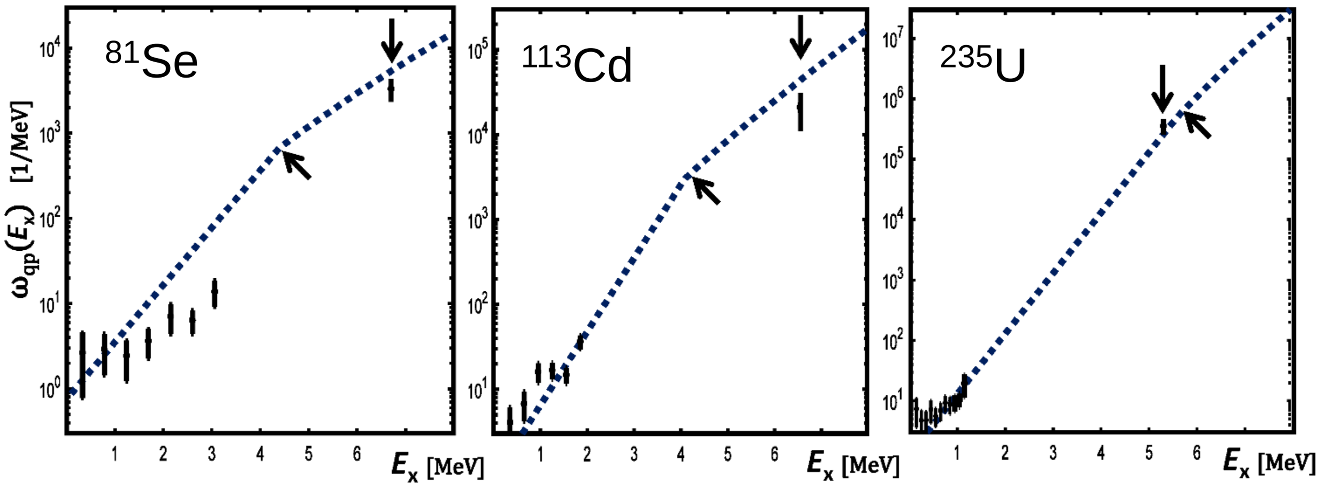
$$\tilde{a} = a_{nm} + \delta\alpha; \;\; \delta\alpha = \alpha A^{\frac{2}{3}}$$

no shell correction
shell corr. Myers, Swiatecki Nucl. Phys. 81 (1966) 1
shell corr. Myers, Swiatecki, Ark. Fizik 36 (1967) 343

E. Grosse et al., Phys. Lett. B739 (2014) 425

DRESDEN concept

Level density in nuclei without axial symmetry

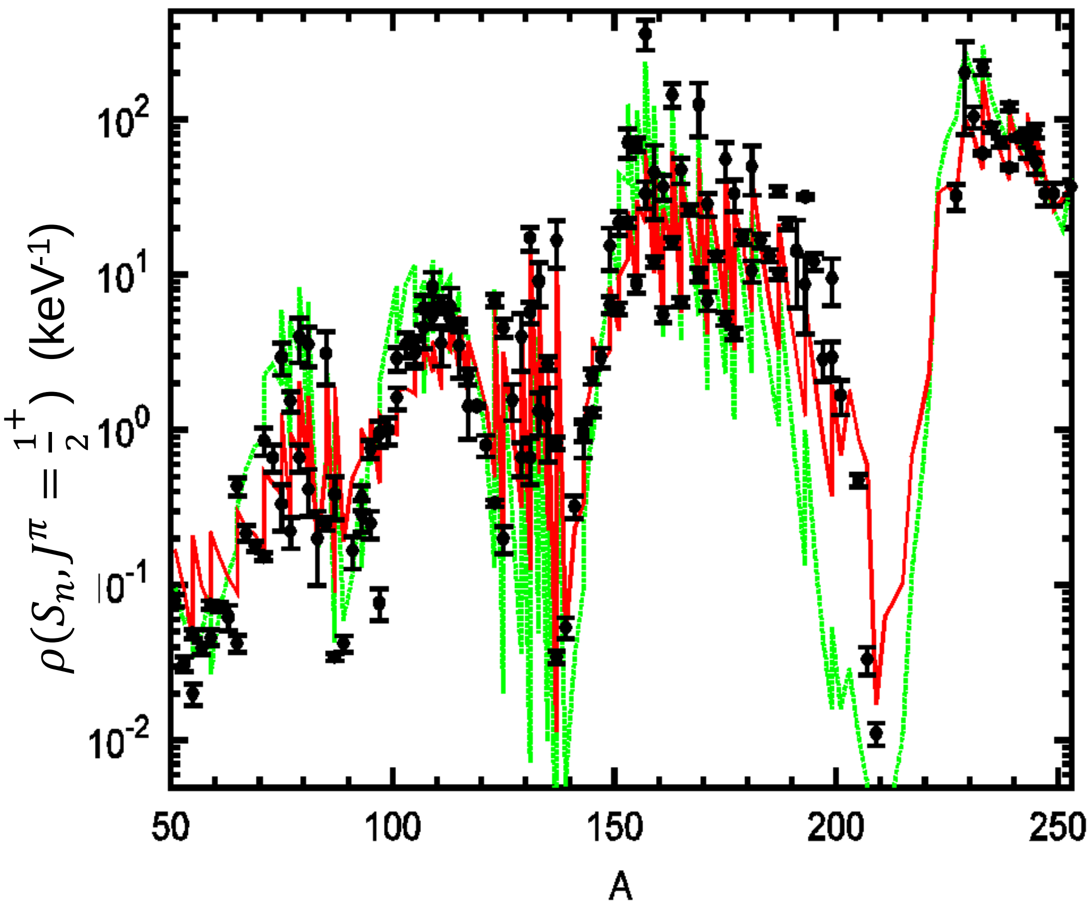


- $\omega_{qp}(S_n)$deduced from average s-wave spacing inverted

$\frac{1}{D_0} = \rho_{triaxial}(E_x, J^\pi) = \frac{2J+1}{2 \cdot 4}\ \omega_{qp}(E_x)$ with $J = \frac{1}{2}$

- reasonable description of the level density for $J = \frac{1}{2}$ up to S_n

Density at S_n for ½+ levels



without damping of shell correction

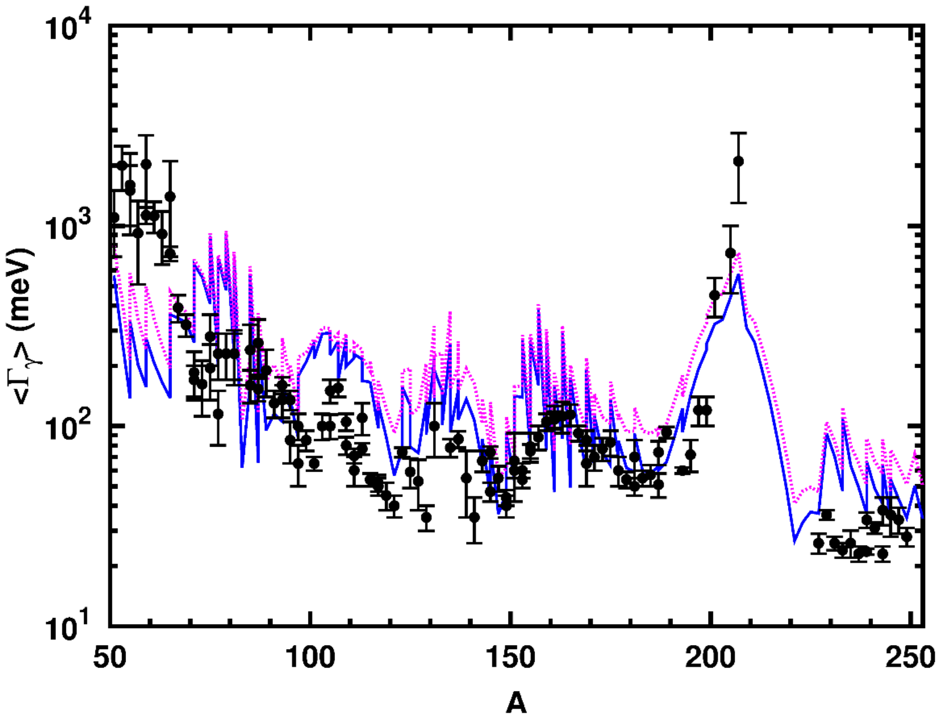
with damping of shell correction

Influence of shell damping is significant.

Data from: A.V. Ignatyuk, RIPL-3 IAEA TECDOC 1506 (2006)

shell damping: S.K. Kataria et al. Phys. Rev. C 18 (1978) 549

Average radiative capture widths



$$\bar{\Gamma}_\gamma = \sum_{b\in\Delta_b} \Gamma_\gamma(r \to b)$$
$$\cong \int_{\Delta_b} \rho(E_b, J_b)\langle\Gamma_\gamma(r \to b)\rangle dE_\gamma$$
$$\cong \int_{\Delta_b} \frac{\rho(E_b, J_b)}{\rho(E_r, J_r)} f_1(E_\gamma)E_\gamma^3 dE_\gamma$$

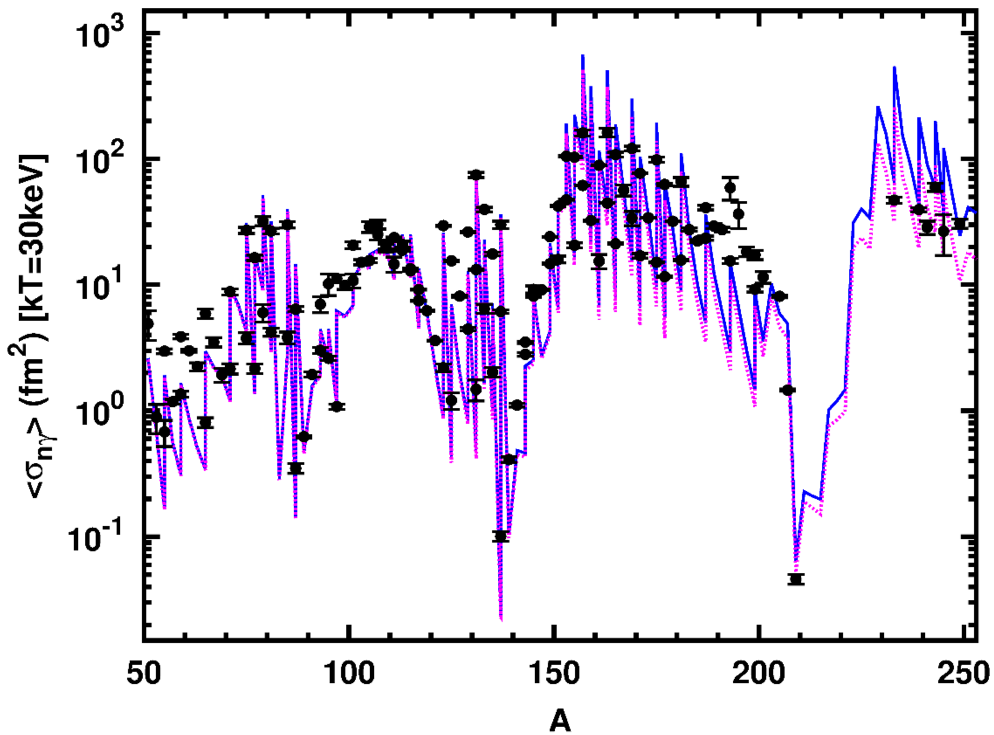
shown here: $J_r^\pi = \frac{1}{2}^+$ only

Spin 0 targets for neutron capture

satisfactor agreement on absolute scale

Data from: A.V. Ignatyuk, RIPL-3 IAEA TECDOC 1506 (2006)

Maxwellian averaged cross sections



S-wave capture on Spin 0 targets
no effects of spin-cut off parameter

$E_n > 1$ keV $< \Gamma_n > \gg \bar{\Gamma_\gamma}$ and

$$\langle \frac{\Gamma_n \bar{\Gamma}_\gamma}{\Gamma_n + \bar{\Gamma}_\gamma} \rangle_r \cong \bar{\Gamma}_\gamma$$

$$D \gg \Gamma_r > \Gamma_{r\gamma}$$

➔ Maxwellian averaged cross sections are not strongly affected by Porter-Thomas fluctuations

$$\sigma_{capt}(E_n) \equiv \langle \sigma(n,\gamma) \rangle_r$$

$$\cong 2\pi^2 \lambda\!\!\!^{-}{}_n^2 \sum_{l,J_b} (2l+1) \cdot \int_0^{Er} f_1(E_\gamma) E_\gamma^3 \rho(E_b, J_b) dE_\gamma$$

Reasonable agreement on an absolute scale using TLO and level density for nuclei without axial symmetry
Minor strength has only small influence

Data from:
I. Dillmann et al., PRC 81 (10) 015801;
B. Pritychenko et al., ADNDT 96 (10) 645

Conclusion:

- Triaxial nuclear shapes seem to be a common feature in many nuclei
- Phenomenological parameterisations for the dipole strength function and level density allowing for breaking of axial symmetry
  ➔ global description of GDR cross sections (without local fits)
  ➔ maxwellian average capture cross sections described reasonably for spin 0 target nuclei