The Scissors Mode: A Building Block of Low-Energy Nuclear Structure

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- A bit of history
- Salient features
- Systematics
- Scissors mode in vibrational nuclei
- Scissors mode in the quasicontinuum

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A bit of history

Discovery of the Scissors Mode

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G.F. Bertsch, Nature 280, 263 (1979)

Review article on nuclear giant resonances

What is the likelihood of discovering more vibrations? The possibility of more complex motion always exists, and other vibrations can be calculated in RPA. However, all the other modes of particle displacement have a higher mean frequency. …Thus it is unlikely that a coherent mode, containing most of the sum rule, will be resolved as a distinct peak.

yet ……

Discovery of the Scissors Mode at DALINAC

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D. Bohle et al., Phys. Lett. B 137, 27 (1984)

From (e,e‘) from factor → **M1 transition**

Peak at 3 MeV!

Volume 137B, number 1,2 PHYSICS LETTERS 22 March 1984

NEW MAGNETIC DIPOLE EXCITATION MODE STUDIED IN THE HEAVY DEFORMED NUCLEUS ^{156}Gd BY INELASTIC ELECTRON SCATTERING ☆

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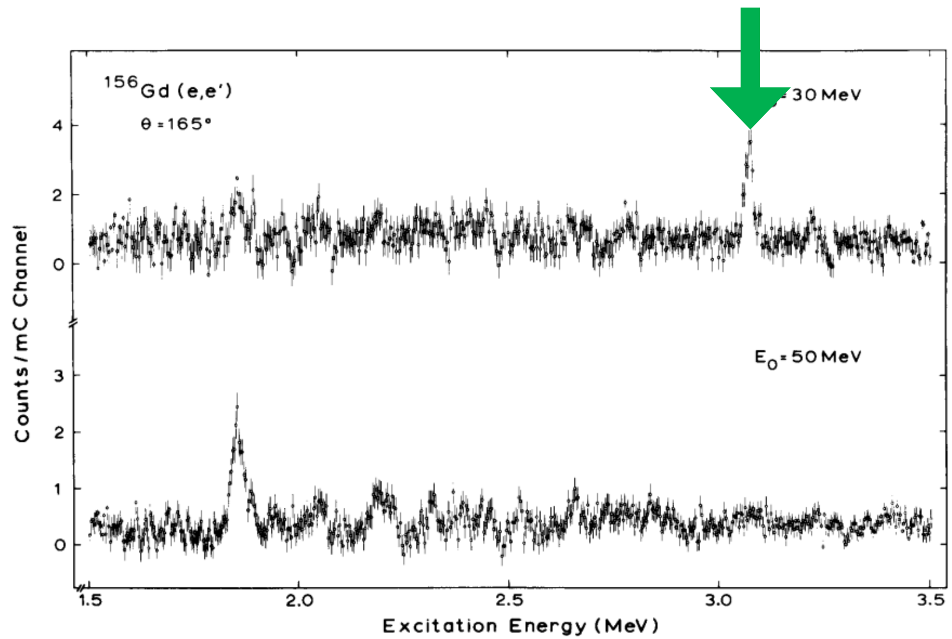
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824-1321, USA

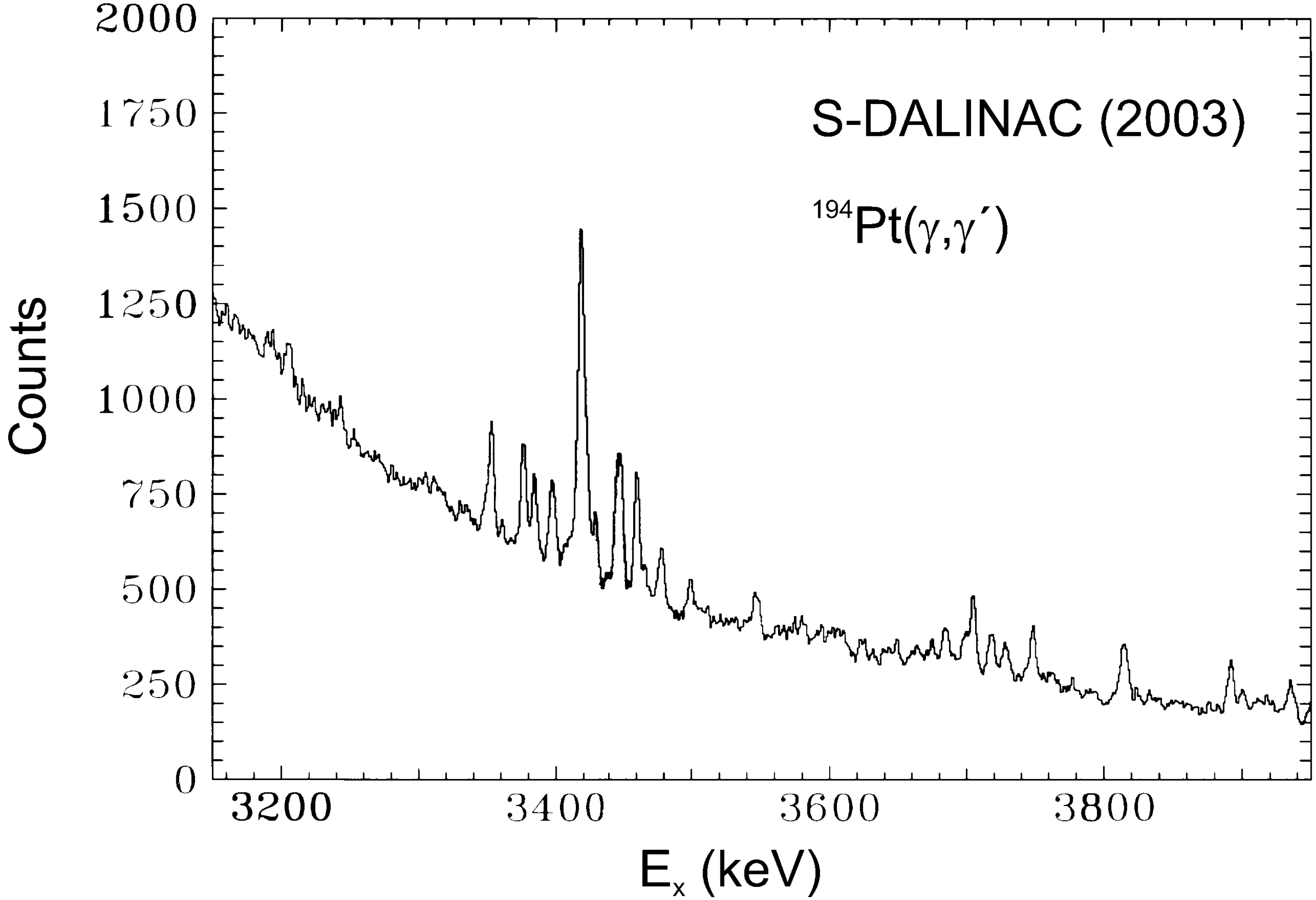


Web of Science: about 730 citations!

Salient Features

Fragmentation

A. Linnemann et al., Phys. Lett. B 554, 15 (2003)

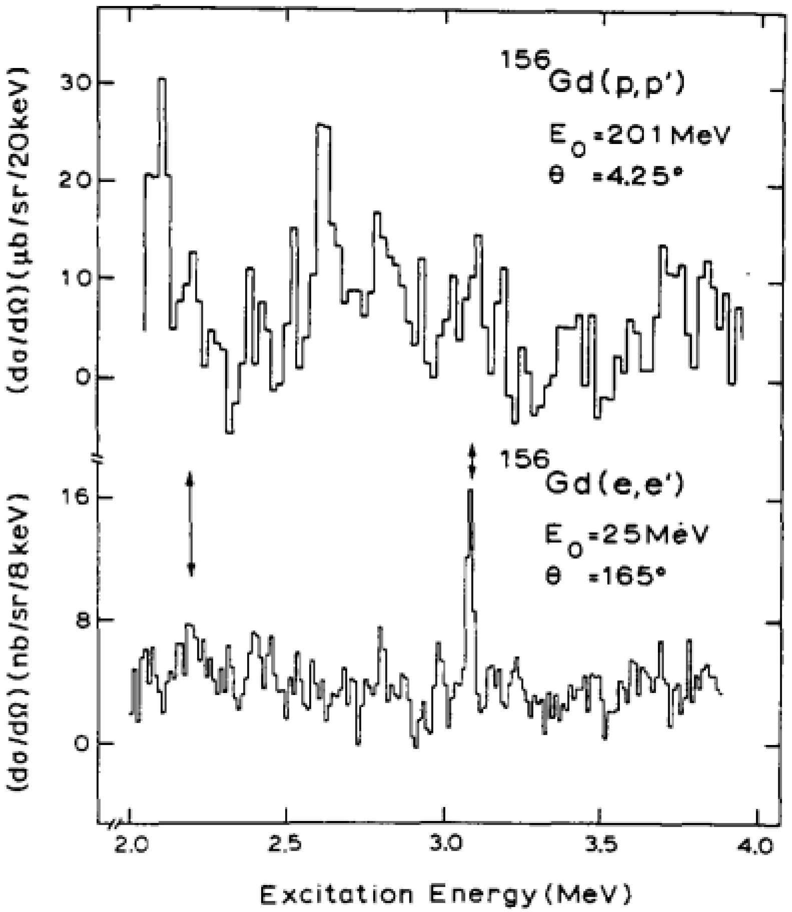


Orbital Nature

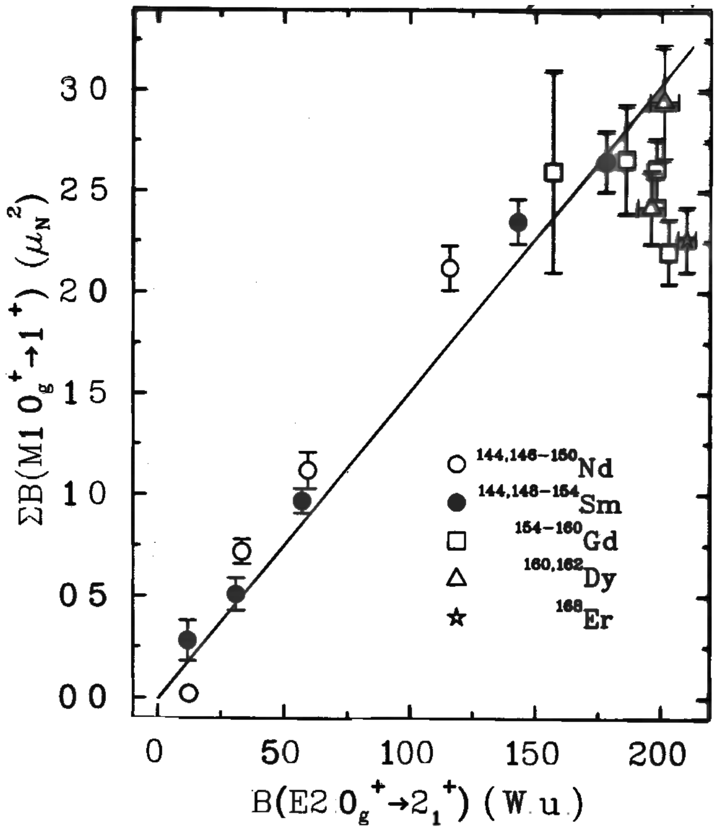
C. Djalali et al., Phys.Lett. B 164, 269 (1985

Strongly observed with
electromagnetic probes
but not with hadronic probe

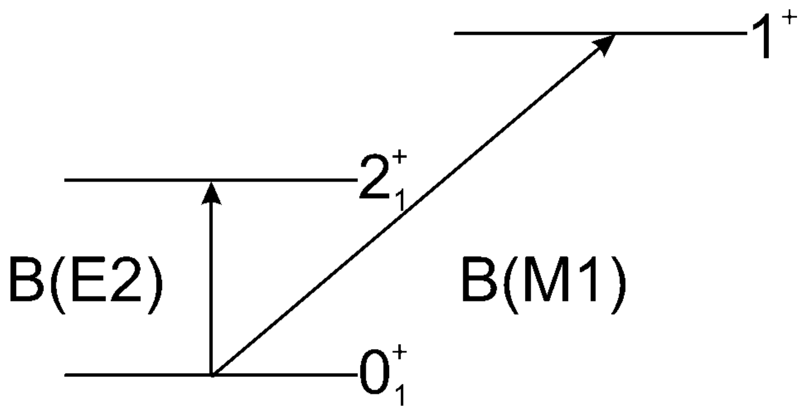
→ **orbital excitation**



Correlation between B(M1) and B(E2) strengths



C. Rangacharyulu et al.,
Phys. Rev. C43, R949 (1991)

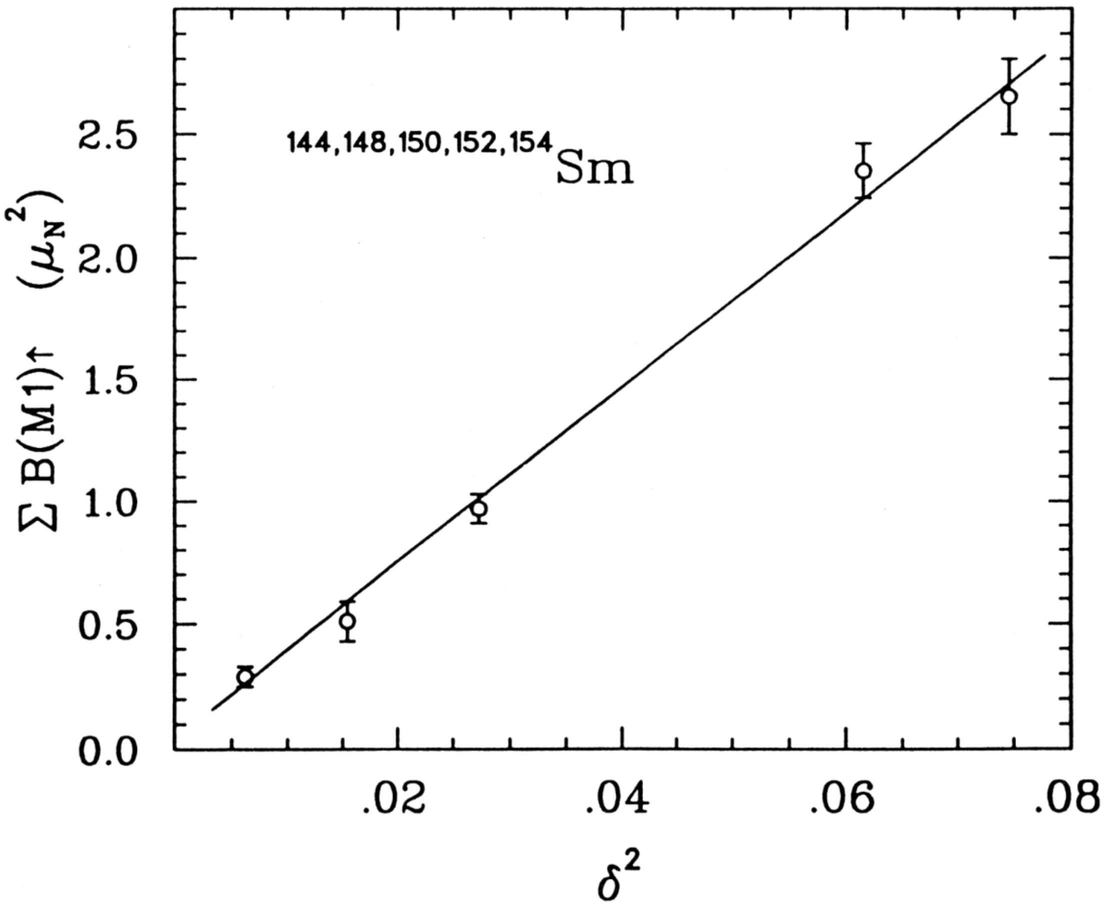


B(E2) ~ δ^2 → strong dependence of scissors mode on deformation

Expectation: B(M1) ~ δ^2

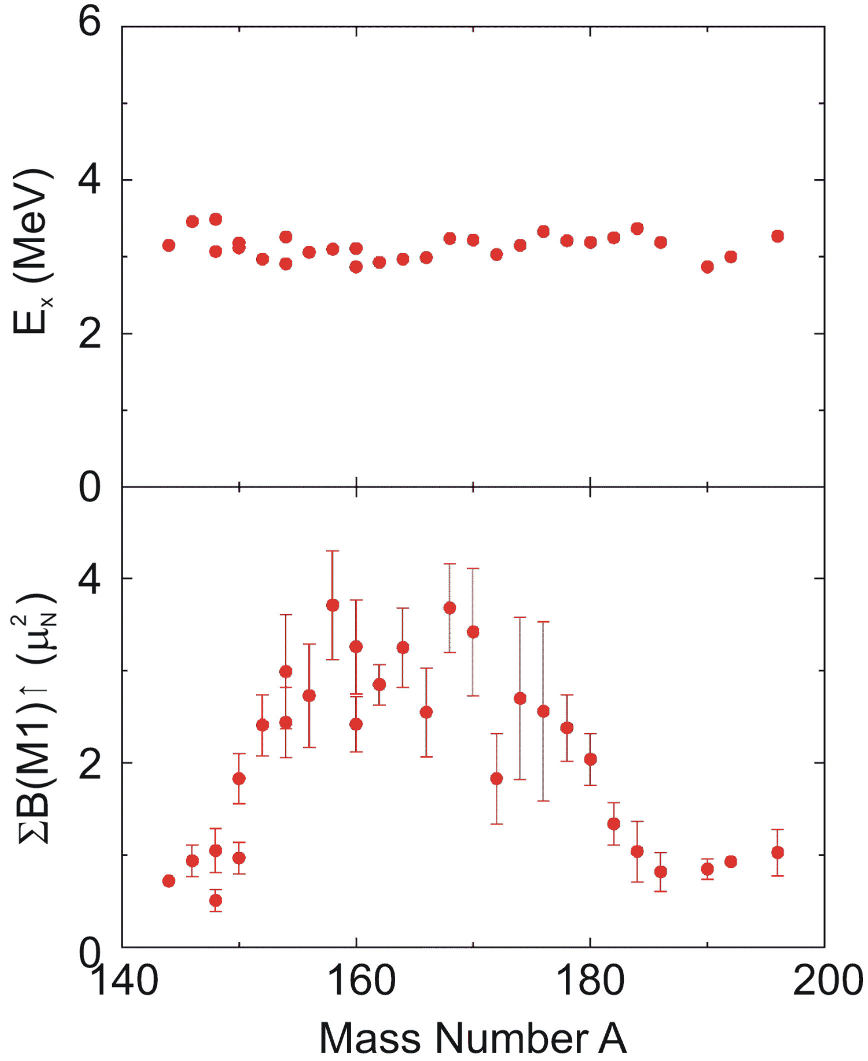
Deformation Dependence

W. Ziegler et al., Phys. Rev. Lett. 65, 2515 (1990)



Systematics

Systematics in Rare-Earth Nuclei



Excitation energy approximately constant, independent of deformation

Strength depends strongly on deformation: B(M1) ~ δ^2 ~ B(E2)

Sum-Rule Approach

E. Lipparini and S. Stringari, Phys. Rep. 175, 103 (1989)

- Sum rules $$S_j(\mathcal{M}) = \sum_i B_i(\mathcal{M})\, E_{xi}^j$$

$$S_{+1}(M1) = \frac{3}{5\pi}\, r_0^2\, A^{5/3}\, \delta^2\, E_{GDR}^2\, m_N\, g_{IV}^2$$

$$S_{-1}(M1) = \frac{3}{16\pi}\, \Theta_{M1}\, g_{IV}^2$$

$$E_x = \sqrt{S_{+1}/S_{-1}}$$

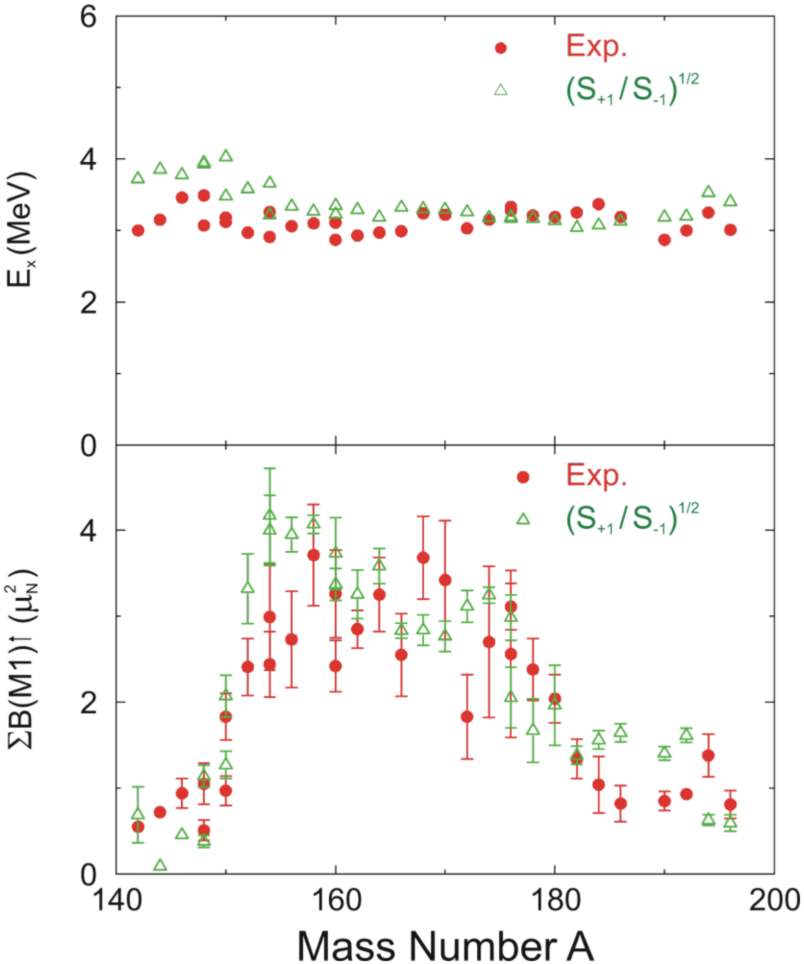
$$B(M1) = \sqrt{S_{+1} \cdot S_{-1}}$$

- Sum rules depend on two parameters:

$$g_{IV} \approx g_{IS} = g(2_1^+) \qquad \Theta_{IV} = \Theta_{IS} = 3\hbar^2/E_{2_1^+}$$

Parameter-Free Sum Rule Description

J. Enders et al., Phys. Rev. C 71, 014306 (2005)



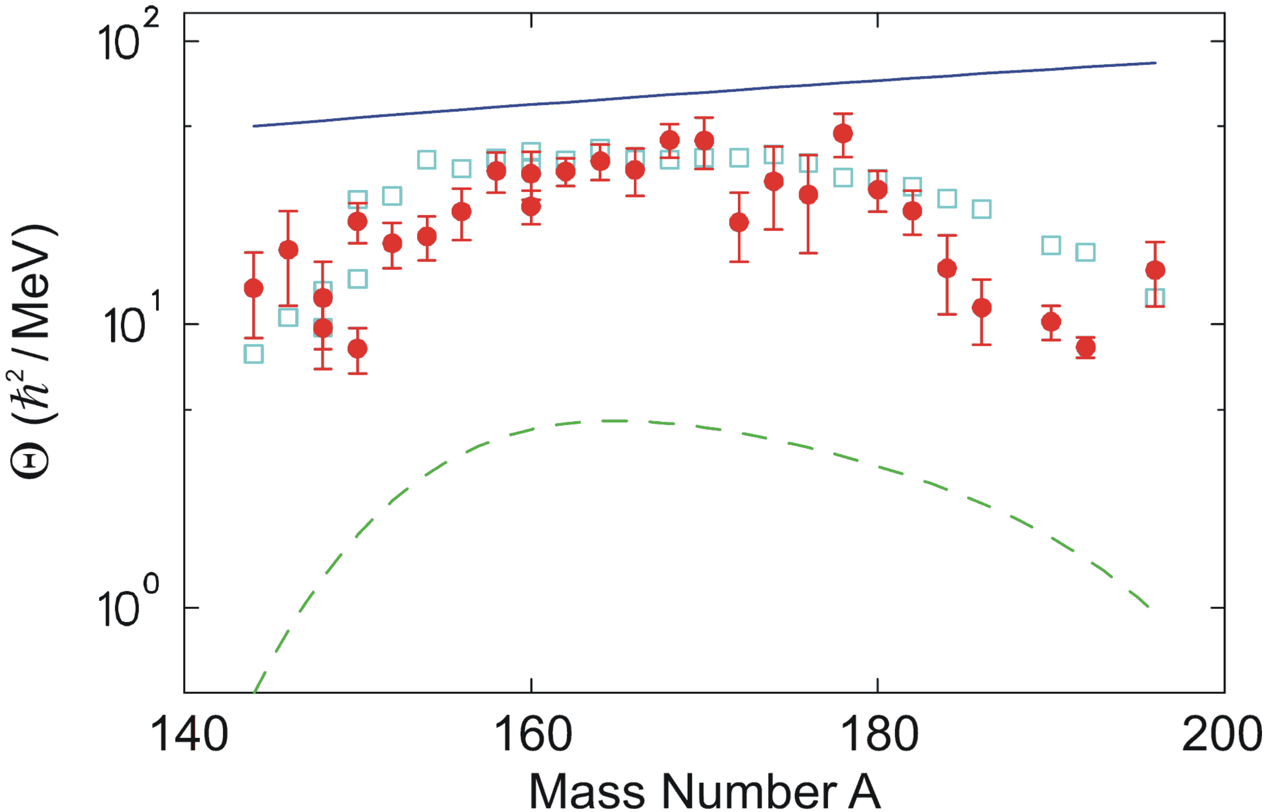
$$E_x \sim \sqrt{E_{2_1^+}} \cdot \delta \approx const.$$

contributions from deformation and moment of inertia cancel each other

$$B(M1) \sim \frac{\delta}{\sqrt{E_{2_1^+}}} \sim \delta^2$$

“δ^2 law” results from an interplay of deformation and the moment of inertia

Moments of Inertia



$$\Theta_{M1} = \frac{4\pi S_{-1}}{3 g_{IV}^2}$$

$$\Theta_{gsb} = \frac{3\hbar^2}{E_{2_1^+}}$$

$$\Theta_{rig} = \frac{2}{5} M R^2$$

$$\Theta_{irrot} = \Theta_{rig} \cdot \delta^2$$

Ground-state correlations reduce MoI with respect to rotational limit

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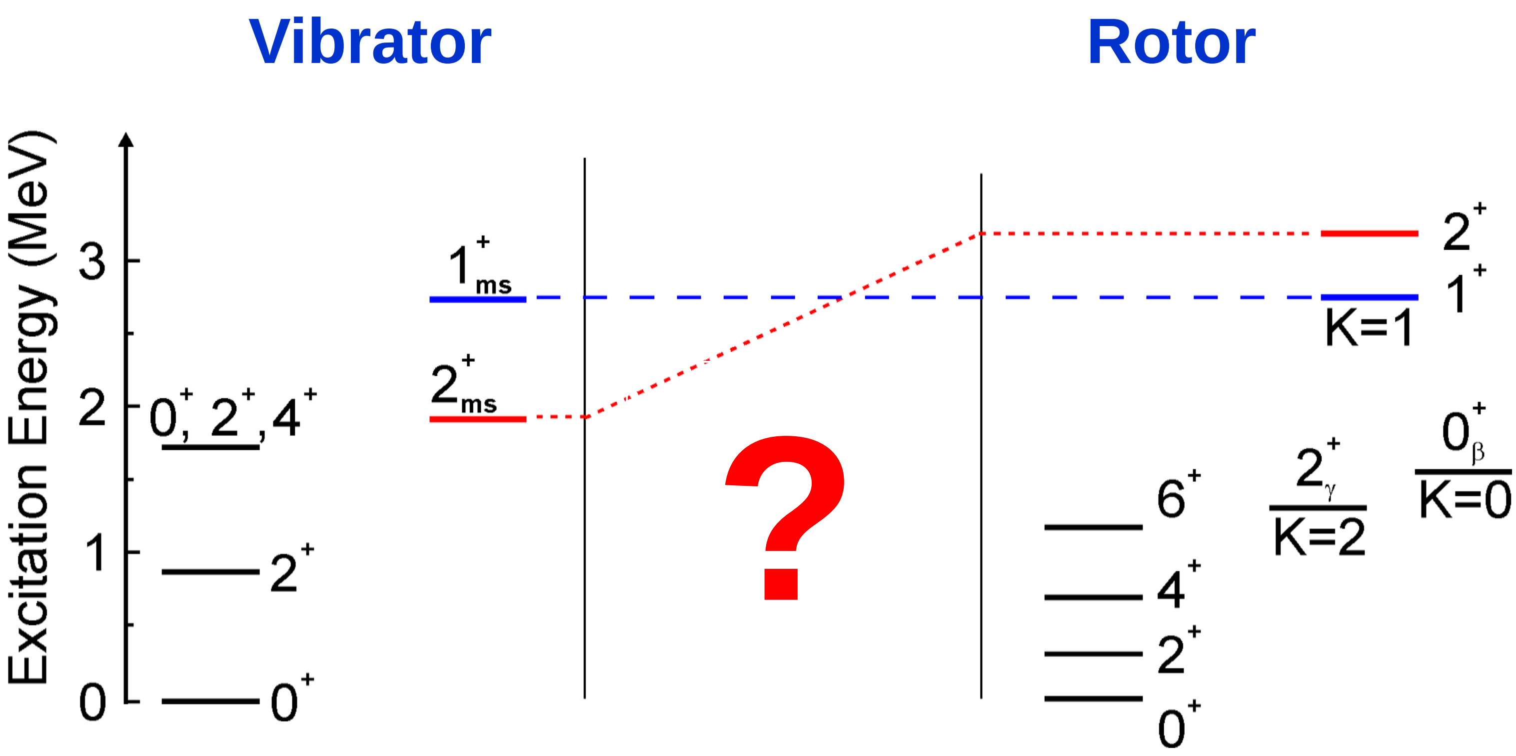
Scissors mode in vibrational nuclei

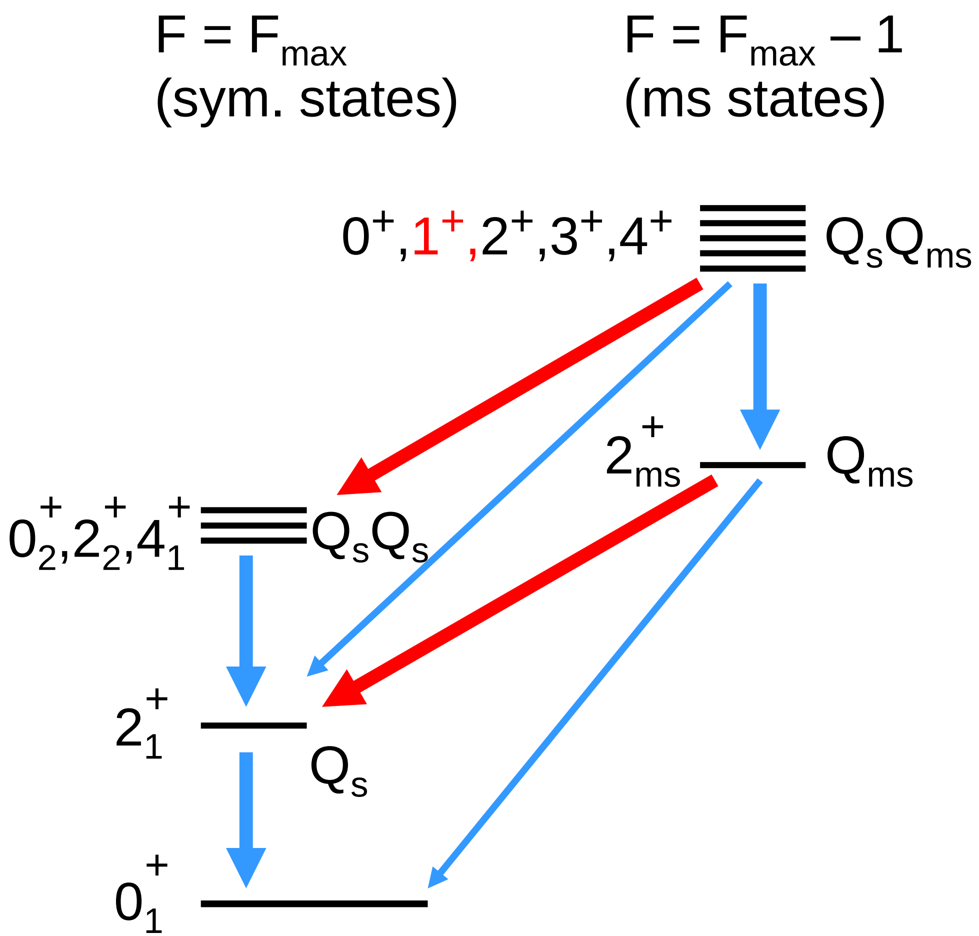
Transition Deformed-Spherical Nuclei

What happens to the scissors mode when approaching spherical nuclei?



Interpretation in terms of Interacting Boson Model 2

Mixed-Symmetry States in Vibrational Nuclei



Strong E2 transitions for decay of symmetric Q-phonon

Weak E2 transitions for decay of ms Q-phonon

Strong M1 transitions for decay of ms states to symmetric states

M1 transitions are orbital because of operator $(\boldsymbol{L_p} - \boldsymbol{L_n})$

Demonstrated for ^{94}Mo: N. Pietralla et al., Phys. Rev. Lett. 83, 1303 (1999)

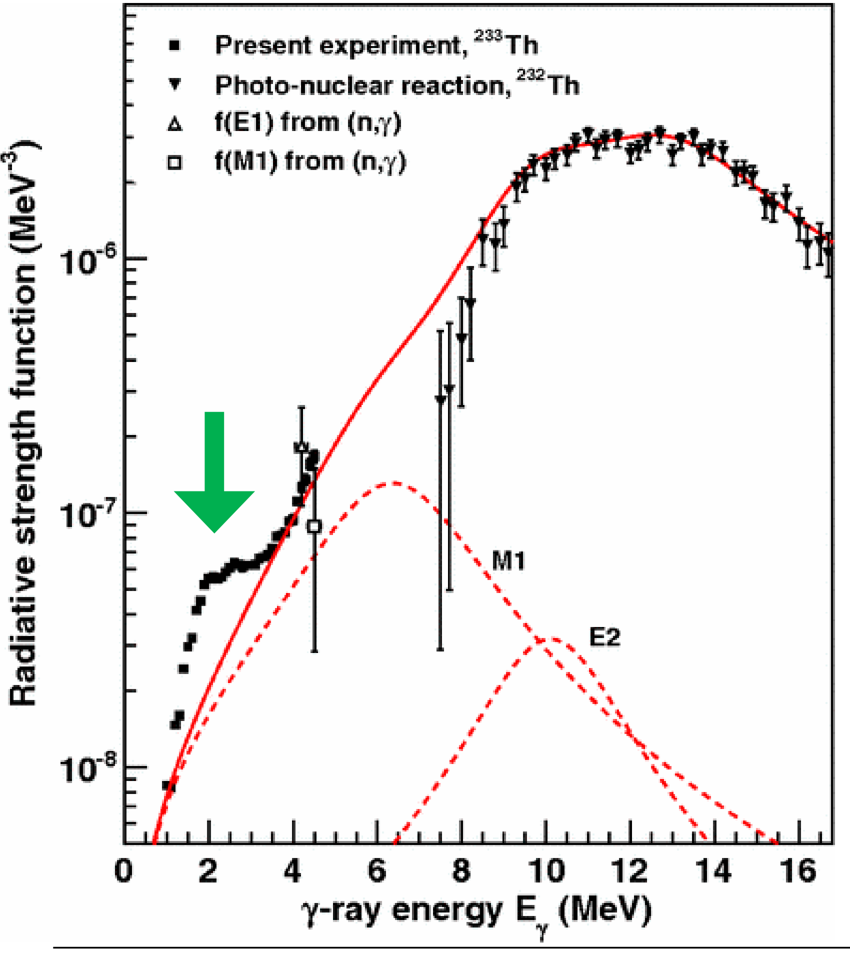
Further reading

K. Heyde, P. von Neumann-Cosel and A. Richter,
Rev. Mod. Phys. 82, 2365 (2010)

Scissor mode in the quasicontinuum

Observation in Quasicontinuum γ Decay

M. Guttormsen et al., Phys. Rev. Lett. 109, 162503 (2012)

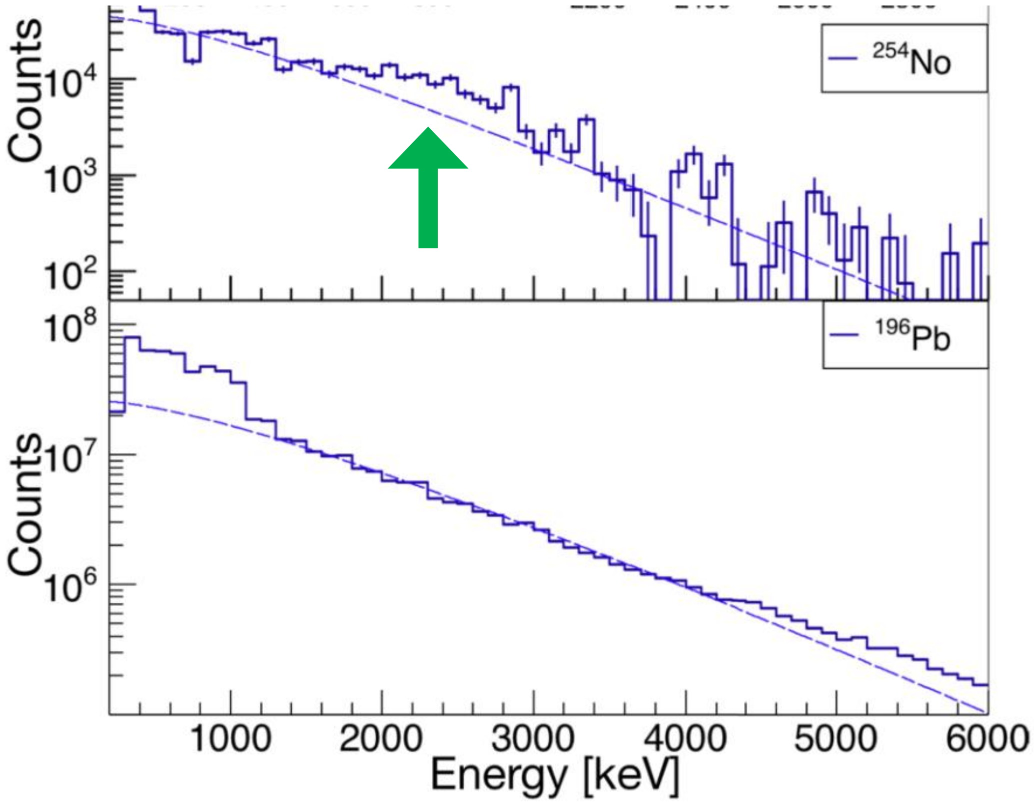


Oslo experiment on ^{233}Th

Enhancement on top of the GSF extrapolated to low γ energies around 2.5 MeV interpreted as scissors mode resonanance

Scissors Mode in Superheavy ^{254}No

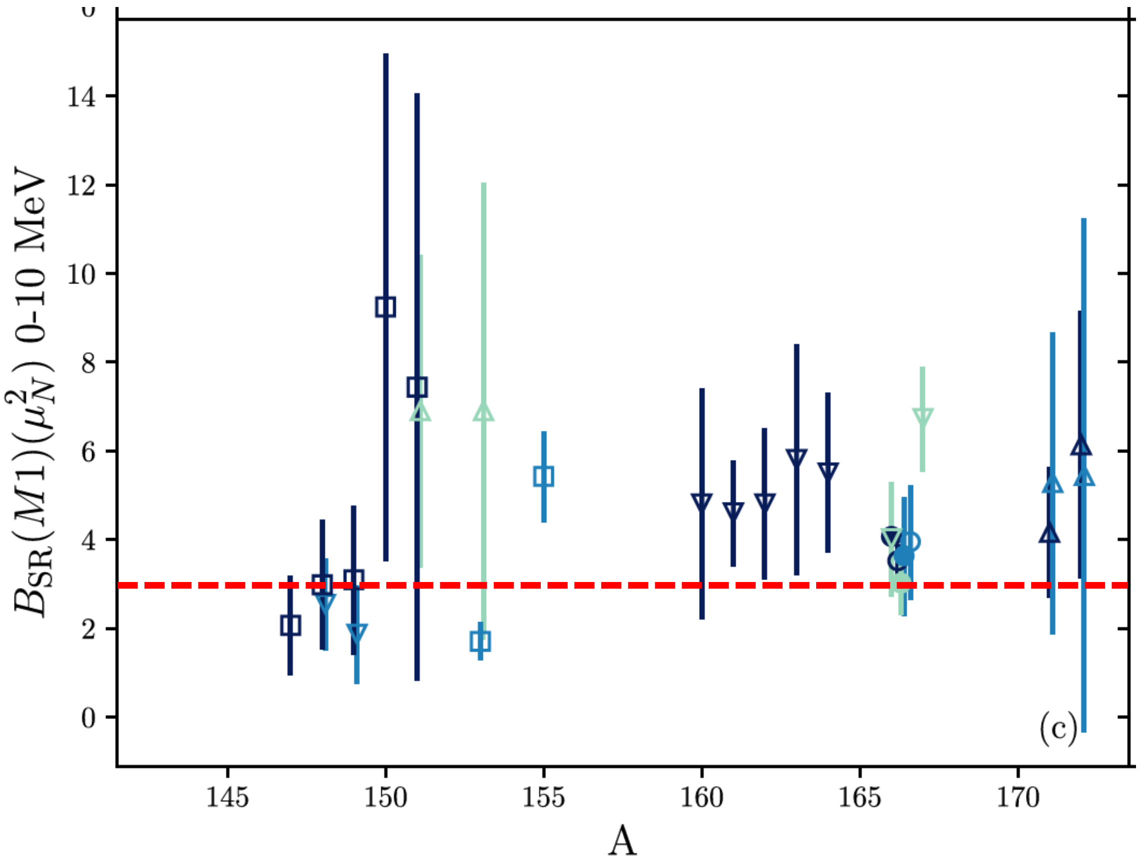
F.L. Bello Garotte et al., Phys. Lett. B 834, 137479 (2022)



M1 Character demonstrated by polarization measurements

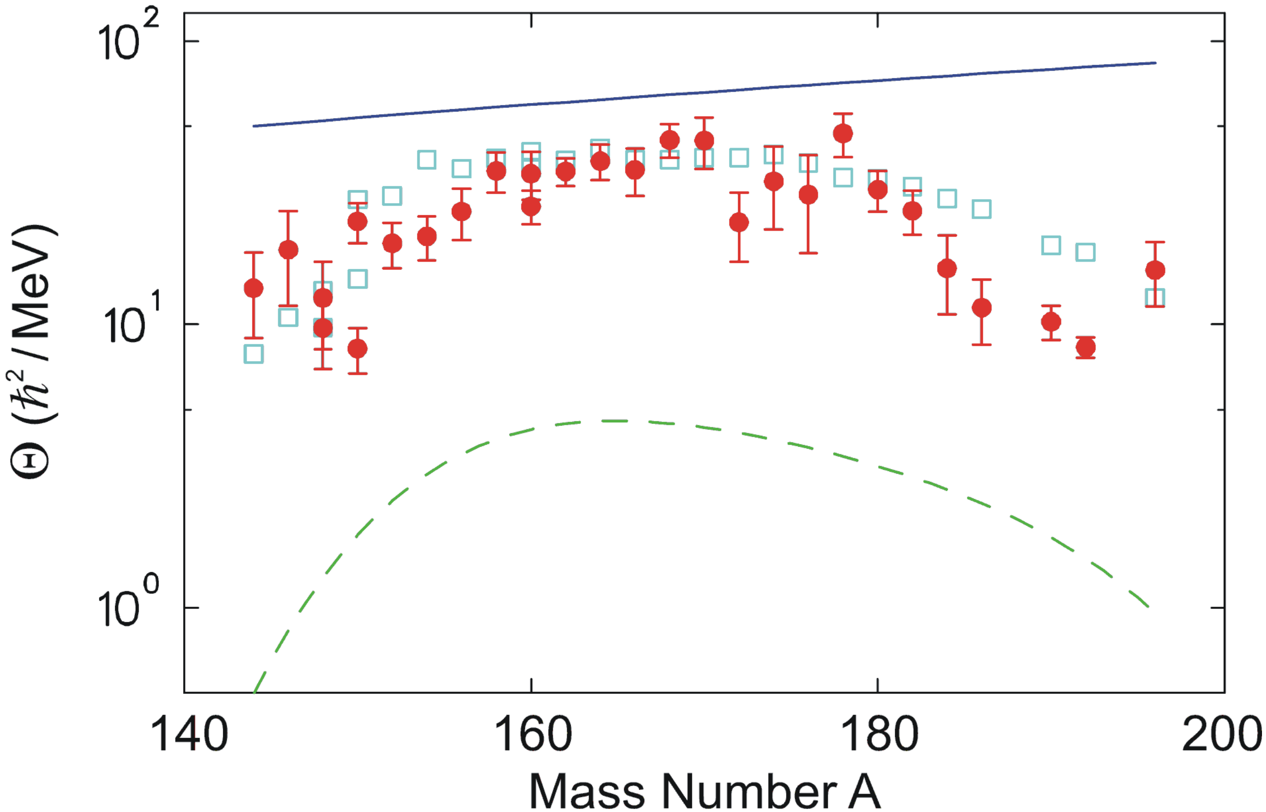
Systematics

F. Pogliano et al., Phys. Rev. C 107, 034605 (2023)



Large uncertainties but scissors mode strength seems to be higher

Moments of Inertia



$\Theta_{M1} = \frac{4\pi S_{-1}}{3g_{IV}^2}$

$\Theta_{gsb} = \frac{3\hbar^2}{E_{2_1^+}}$

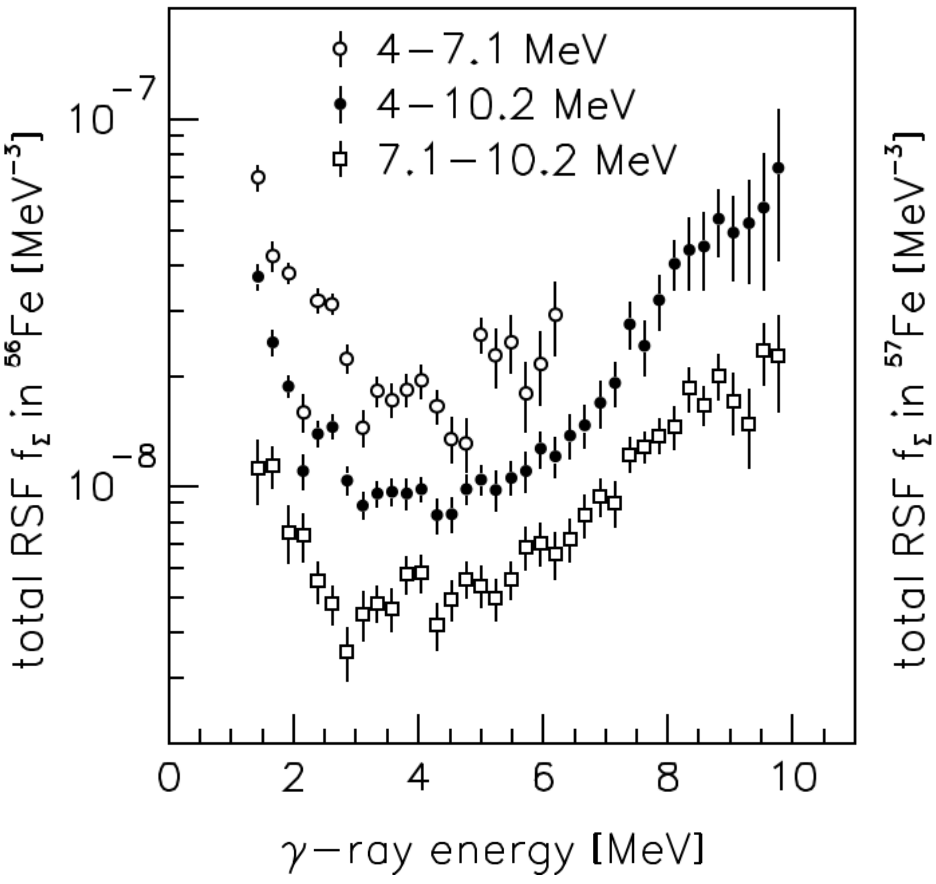
$\Theta_{rig} = \frac{2}{5} MR^2$

$\Theta_{irrot} = \Theta_{rig} \cdot \delta^2$

Increase of MoI with excitation energy towards rotational limit?

The Low-Energy Enhancement (LEE) or Upbend in Oslo Experiments

A. Voinov et al., Phys. Rev. Lett. 93, 142504 (2004)



First observed in ^{56,57}Fe, later in many more nuclei

Systematics are unclear!

Strong astrophysical implications

Shell-model results suggest M1

LEE: Relation to the Scissors Mode?

Idea based on shell-model results

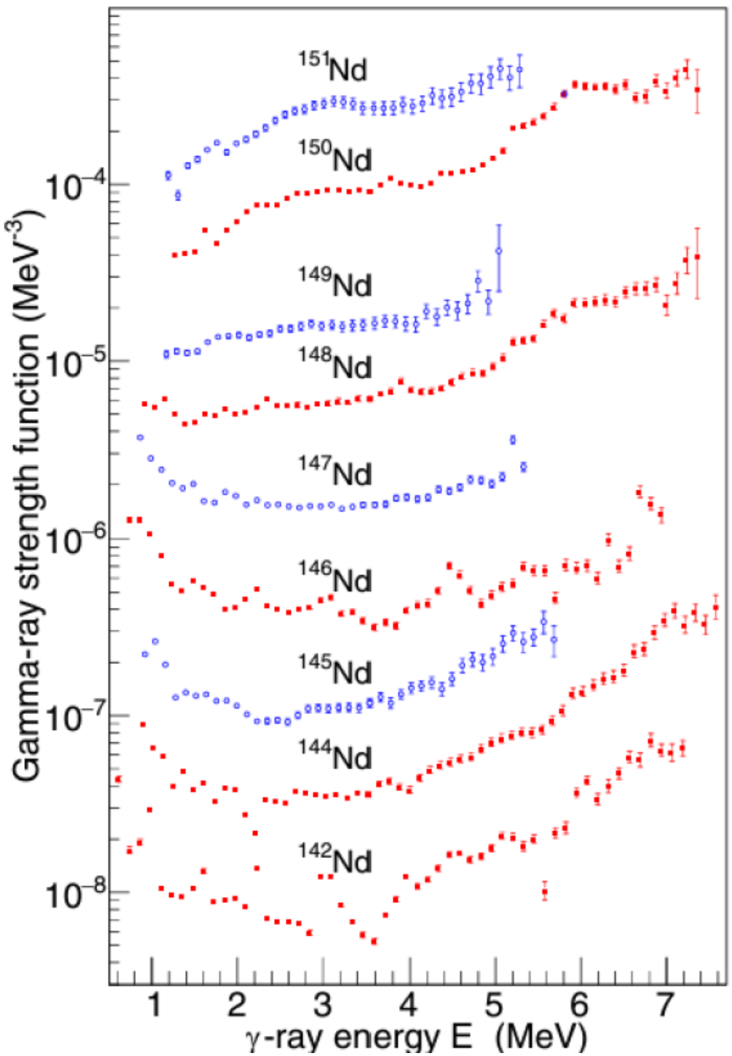
R. Schwengner et al., Phys. Rev. Lett. 118, 092502 (2017)

Orbital strength is shifted from scissors mode in deformed nuclei to LEE in spherical nuclei and the total B(M1) strength is constant

Test case:

Chain of Nd isotopes with transition from spherical to prolate deformed nuclei

M. Guttormsen et al., Phys. Rev. C 106, 034314 (2022)



LEE: Relation to the Scissors Mode?

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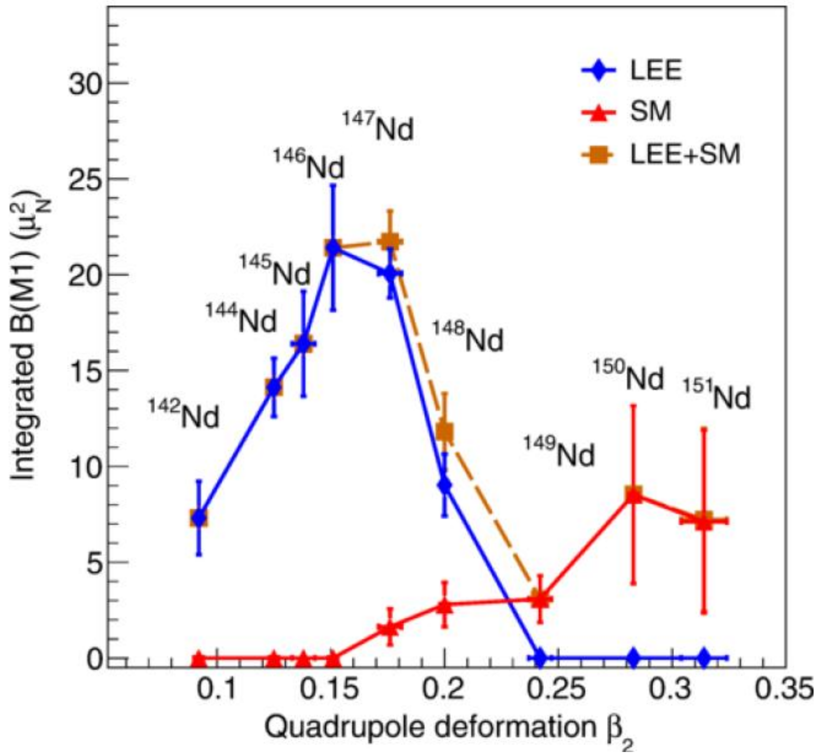
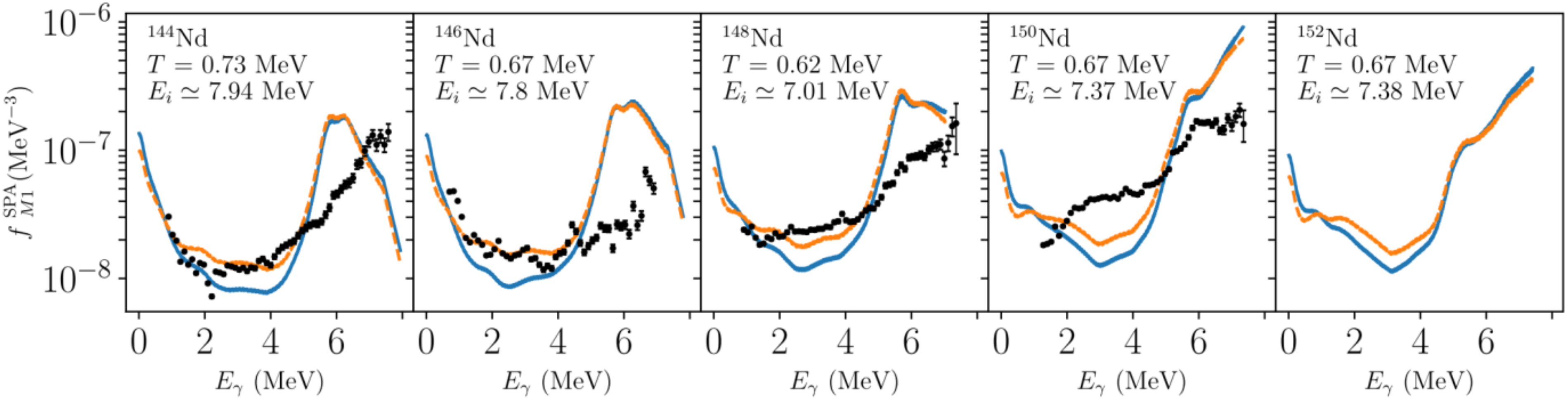
M. Guttormsen et al. Phys. Rev. C 106, 034314 (2022)



Shift from LEE to scissors mode as function of deformation
Total B(M1) strength not constant

Recent Theoretical Work

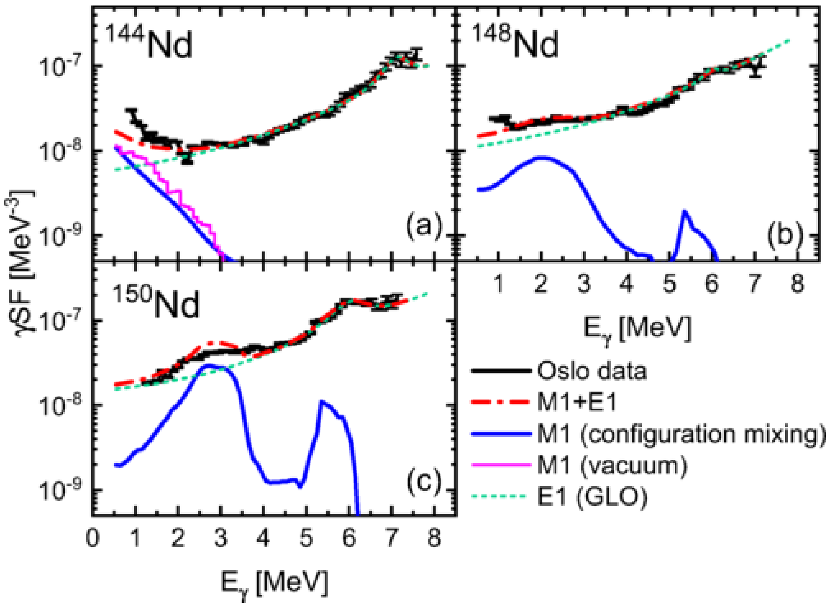
A. Mercenne et al., Phys. Rev. C 110, 054313 (2024)

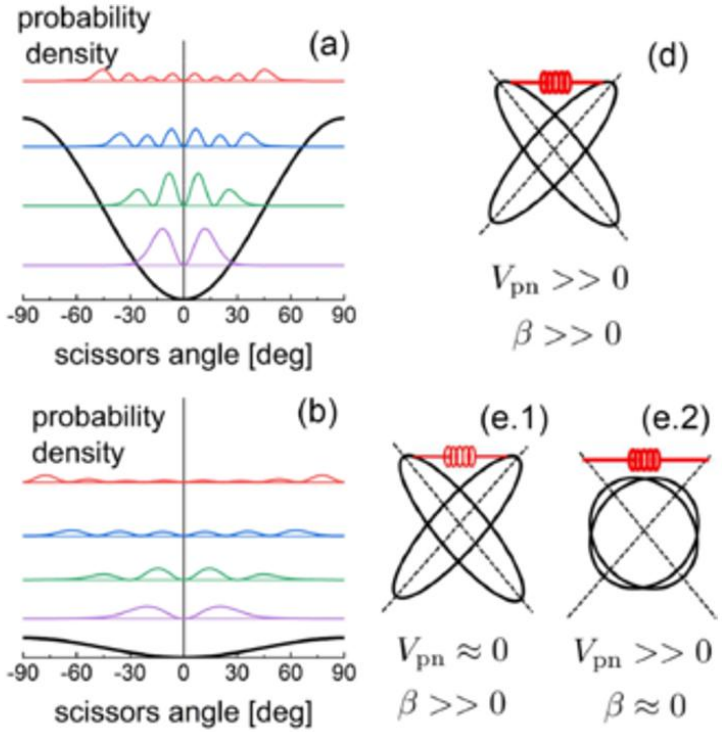


Calculations with shell-model Monte Carlo (SMMC) method
LEE aproximately independent of deformation

Recent Theoretical Work

F.-Q. Chen et al. Phys. Rev. Lett. 134, 082502 (2025)





Proton-neutron projected shell model

Consistent with shift between scissors mode and LEE as function of deformation

LEE interpreted as “quasifree” scissors mode rotation

Thank you for your attention

M1 Operator

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$$\hat{O}(M1) = \left[\sum_{k=1}^{Z} \left(g_l{}^{\pi} \mathbf{l}_k + g_s{}^{\pi} \mathbf{s}_k \right) + \sum_{k=Z+1}^{A} \left(g_l{}^{\nu} \mathbf{l}_k + g_s{}^{\nu} \mathbf{s}_k \right) \right] \mu_N$$

$g_l{}^{\pi} = 1$ $\quad$ $g_l{}^{\nu} = 0$

$g_s{}^{\pi} = 5.586$ $\quad$ $g_s{}^{\nu} = -3.826$

$$= \left[\sum_{k=1}^{A} \left\{ \left(g_l{}^{IS} \mathbf{l}_k + g_s{}^{IS} \frac{\sigma_k}{2} \right) + \left(g_l{}^{IV} \boxed{\mathbf{l}_k} + g_s{}^{IV} \frac{\sigma_k}{2} \right) \tau_z(k) \right\} \right] \mu_N$$

rewrite as

$\vec{L}_\pi - \vec{L}_\nu$

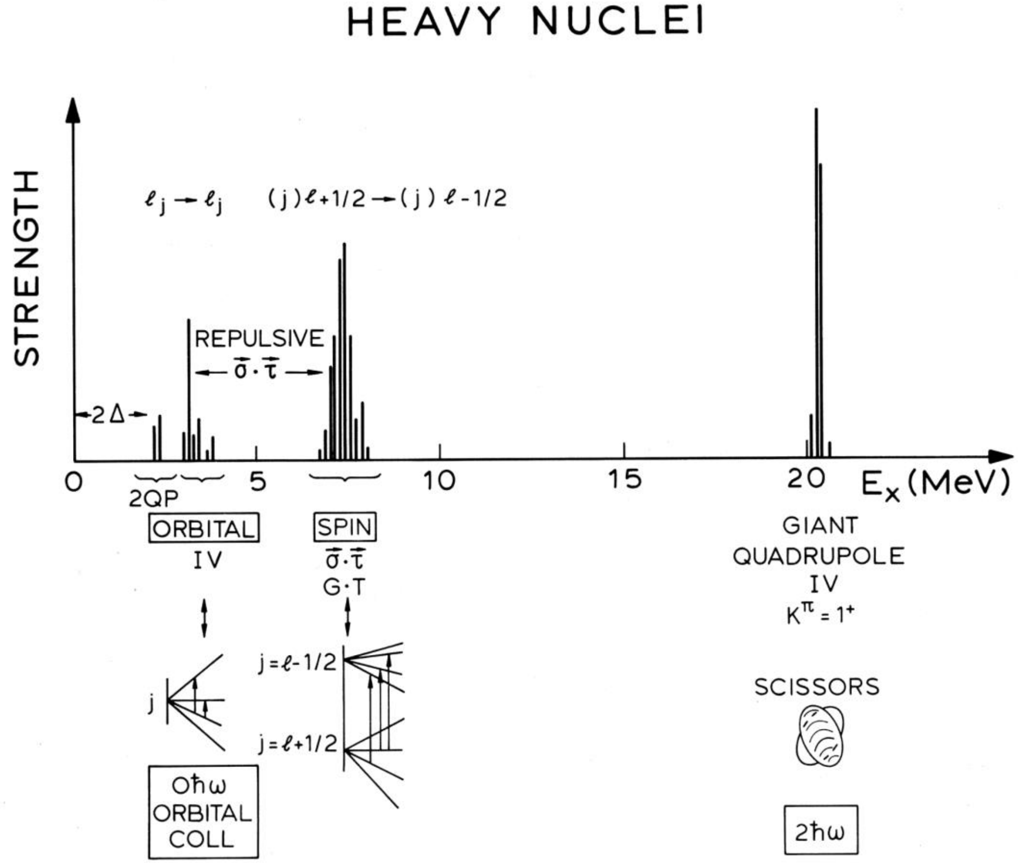
rotation generator

$g_l^{IS} = 0.5$ $\quad$ $g_l^{IV} = 0.5$

$g_s^{IS} = 0.880$ $\quad$ $g_s^{IV} = 4.706$ large

M1 Response in Heavy Nuclei

K. Heyde et al., Rev. Mod. Phys. 82, 2375 (2010)



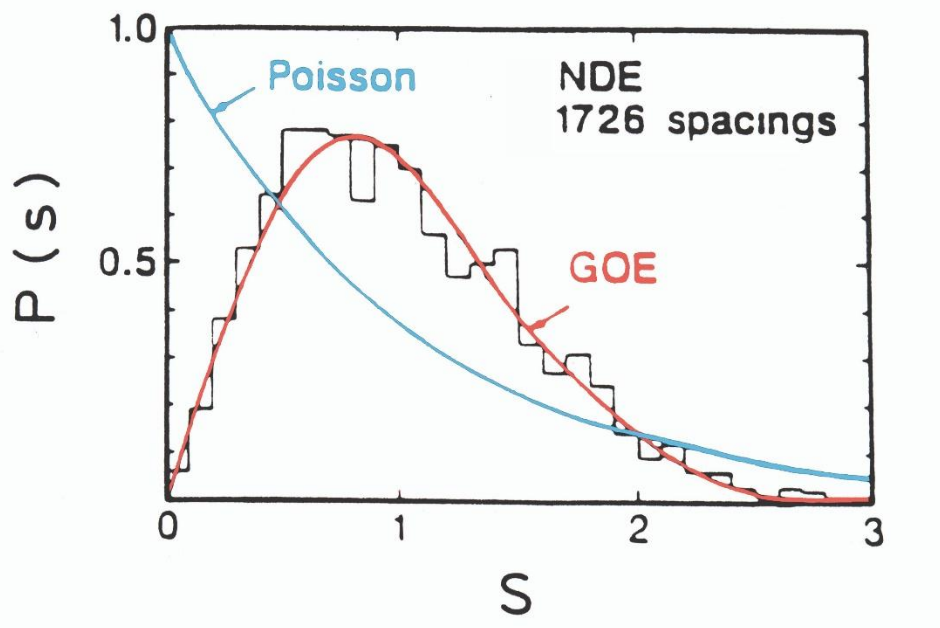
only for deformed

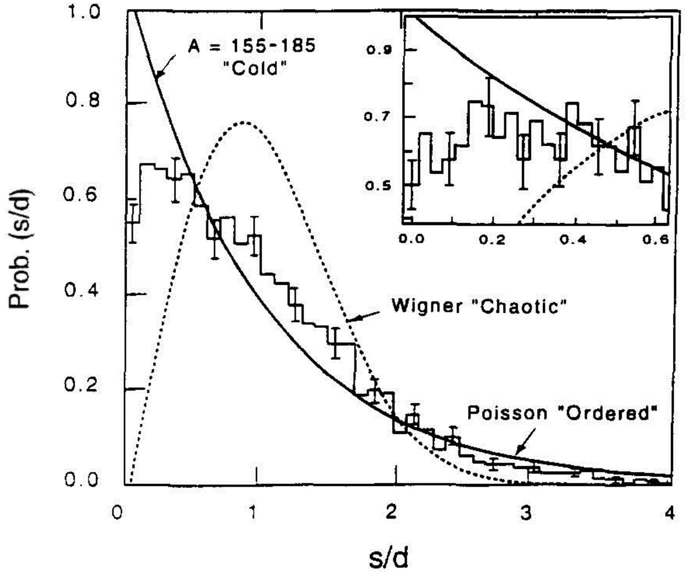
only for deformed

Level Statistics

R.U. Haq, A. Pandey, O. Bohigas,
Phys. Rev. Lett. 48, 1086 (1982).

J.D. Garrett et al.,
Phys. Lett. B 392, 24 (1997)





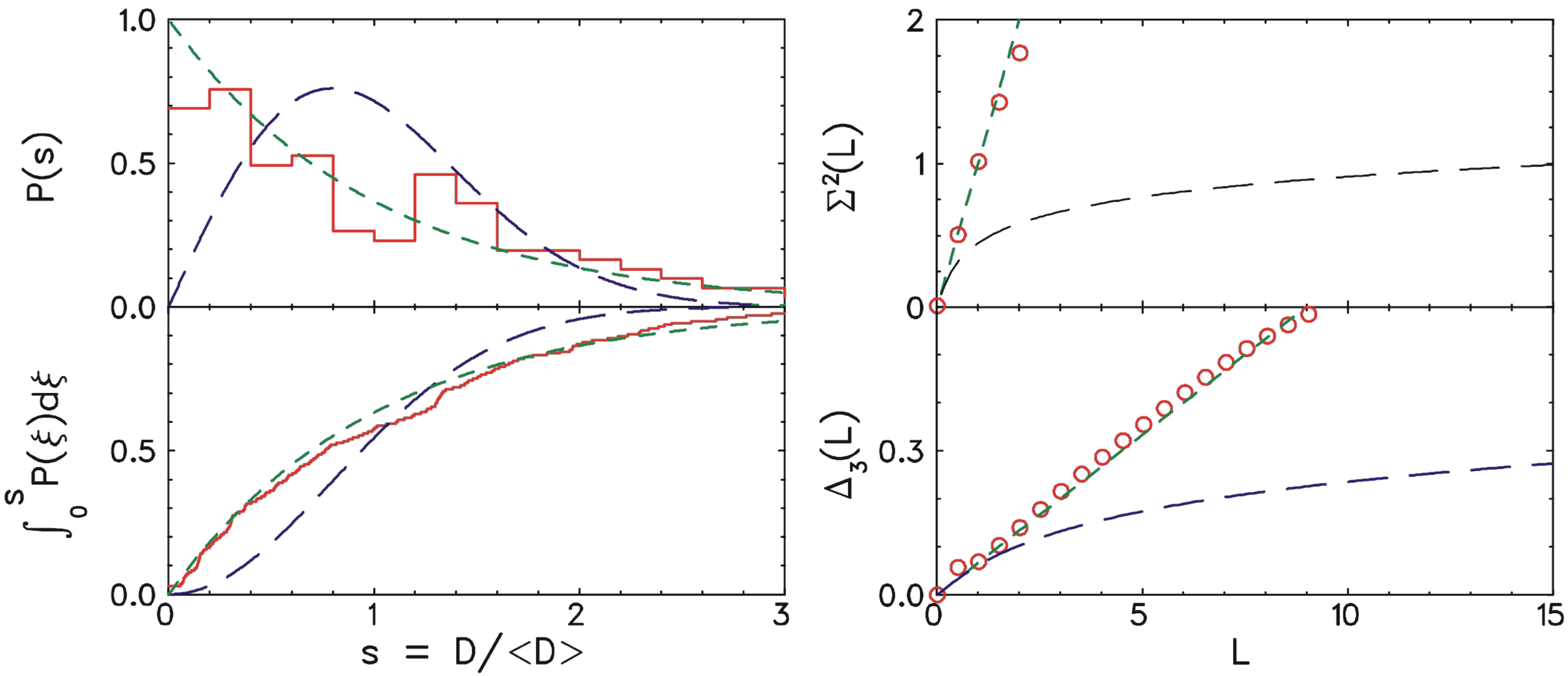
Neutron capture s-wave resonances

Yrast transitions in deformed nuclei

Level Spacing Distribution of Scissors Mode

J. Enders et al., Phys. Lett. B 486, 273 (2000)

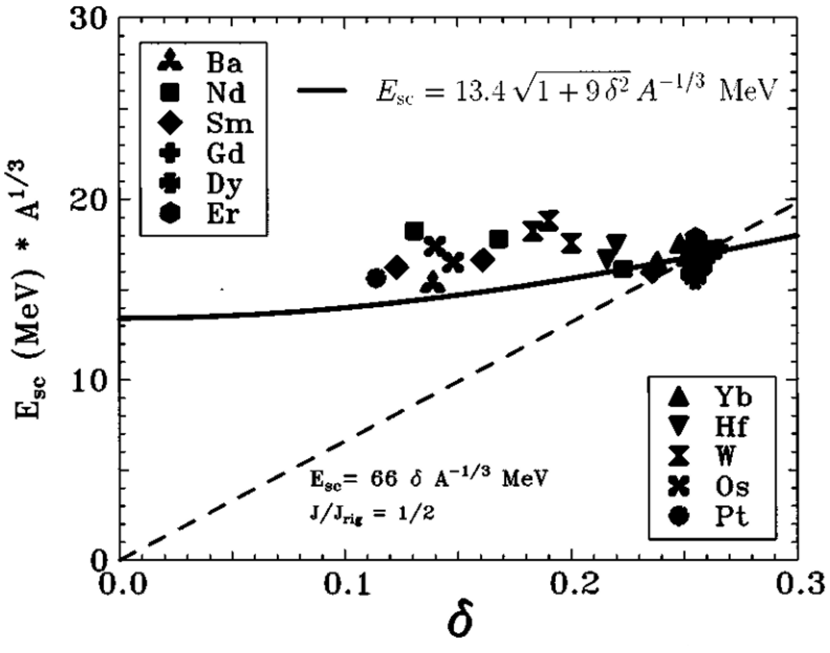
Nuclear data ensemble: 152 $J^{\pi} = 1^{+}$ states from 13 nuclei



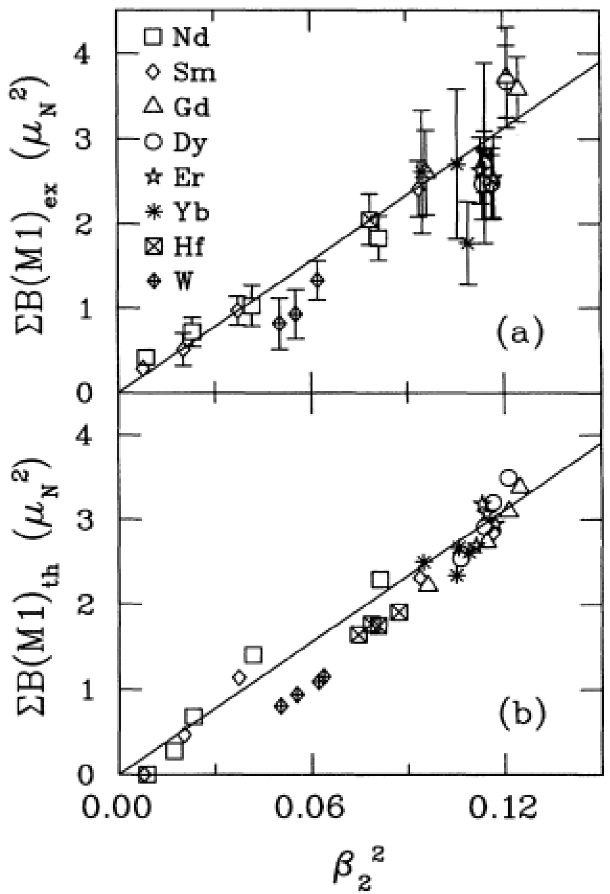
- Proof of a simple collective excitation

Understanding the Systematics

N. Pietralla et al.,
Phys. Rev. C 58, 184 (1998)

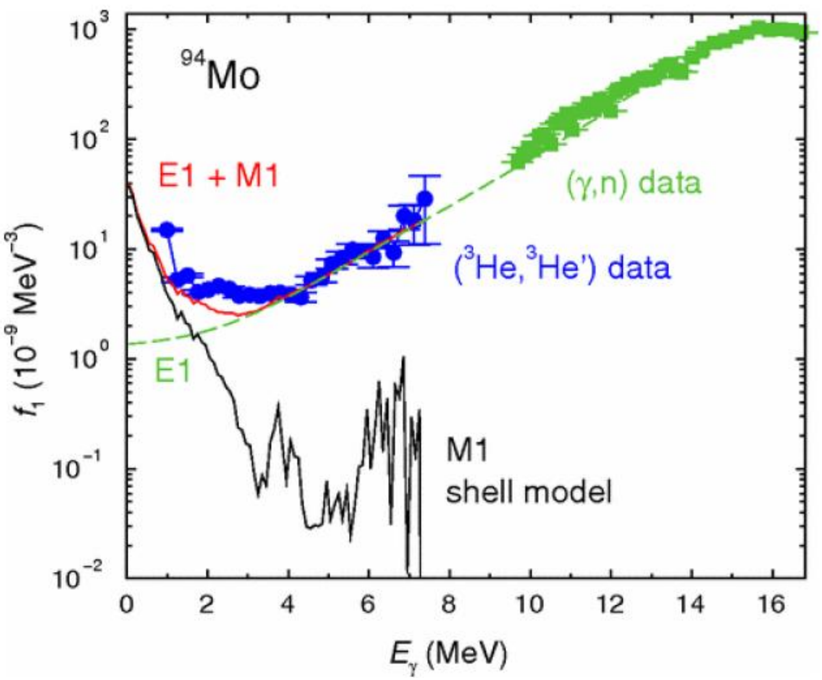


P. von Neumann-Cosel et al.,
Phys. Rev. Lett. 75, 4178 (1995)

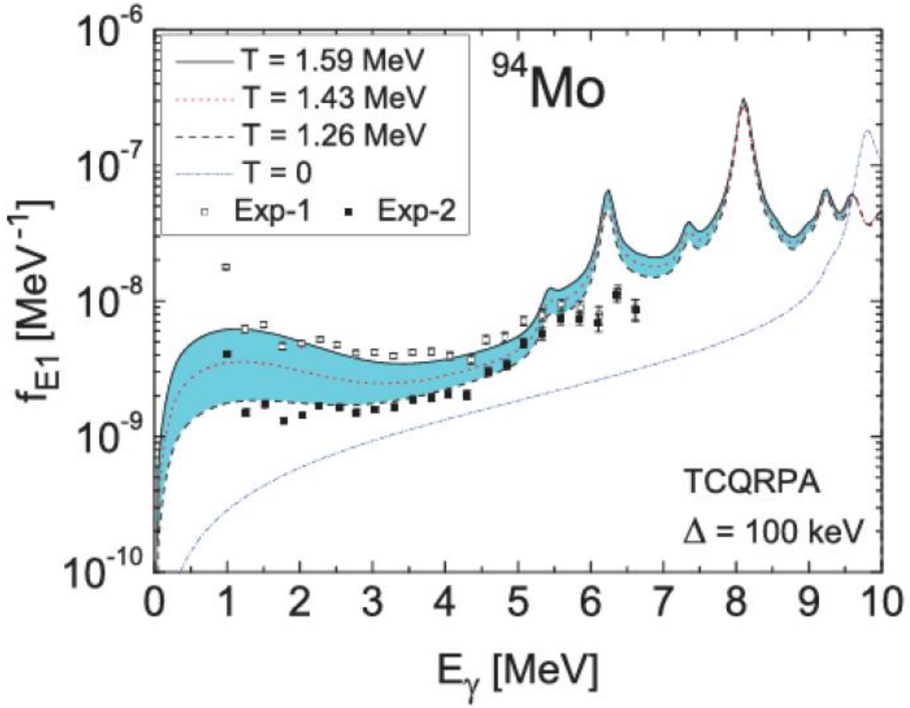


LEE: E1 or M1?

R. Schwengner et al., Phys. Rev. Lett. 111, 232504 (2013)



E. Litvinova and N. Belov, Phys. Rev. C 88, 031302(R) (2013)



Shell model calculations consistent with M1, but no E1 results
Finite tempretatur QRPA sees E1 enhancement around 1 MeV