
# Novel signatures for QPTs from mixed-symmetry states

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U.S. DEPARTMENT OF ENERGY | Office of Science

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# Signatures of quantum phase transitions

The interaction between protons and neutrons is a major driver for nuclear deformation. Most signatures for QPTs, however, are of isoscalar character.

Federman and Pittel, Phys. Rev. C 20, 820 (1979)

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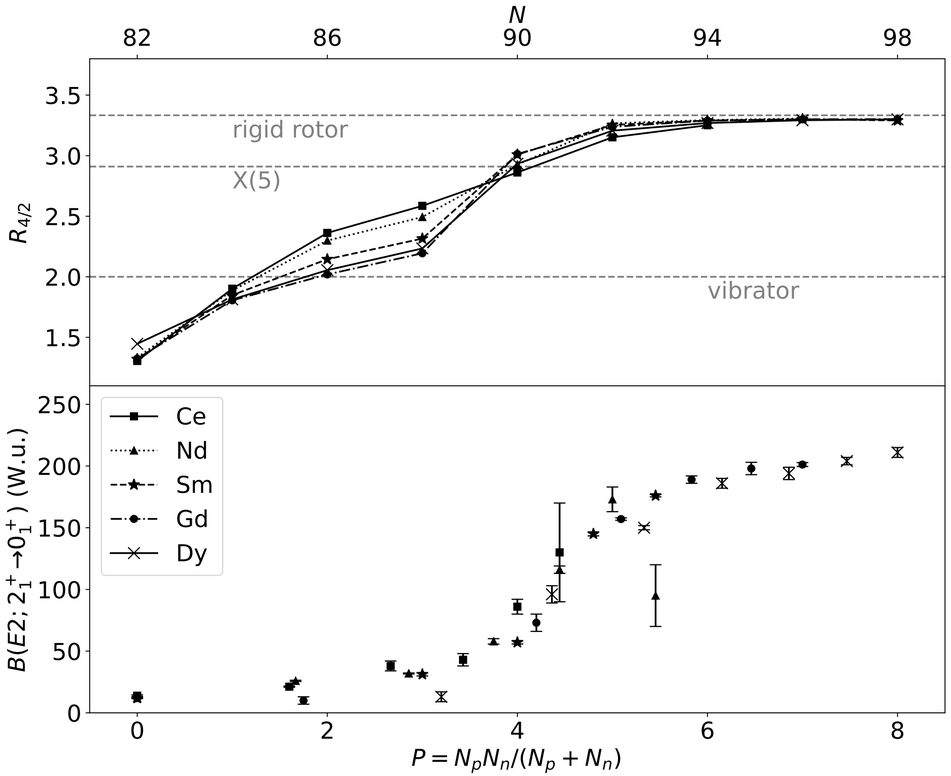


Casten, Phys. Rev. Lett. 58, 658 (1987)

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The interaction between protons and neutrons is a major driver for nuclear deformation. Most signatures for QPTs, however, are of isoscalar character.

Federman and Pittel, Phys. Rev. C 20, 820 (1979)

The most prominent examples for mixed-symmetry states are

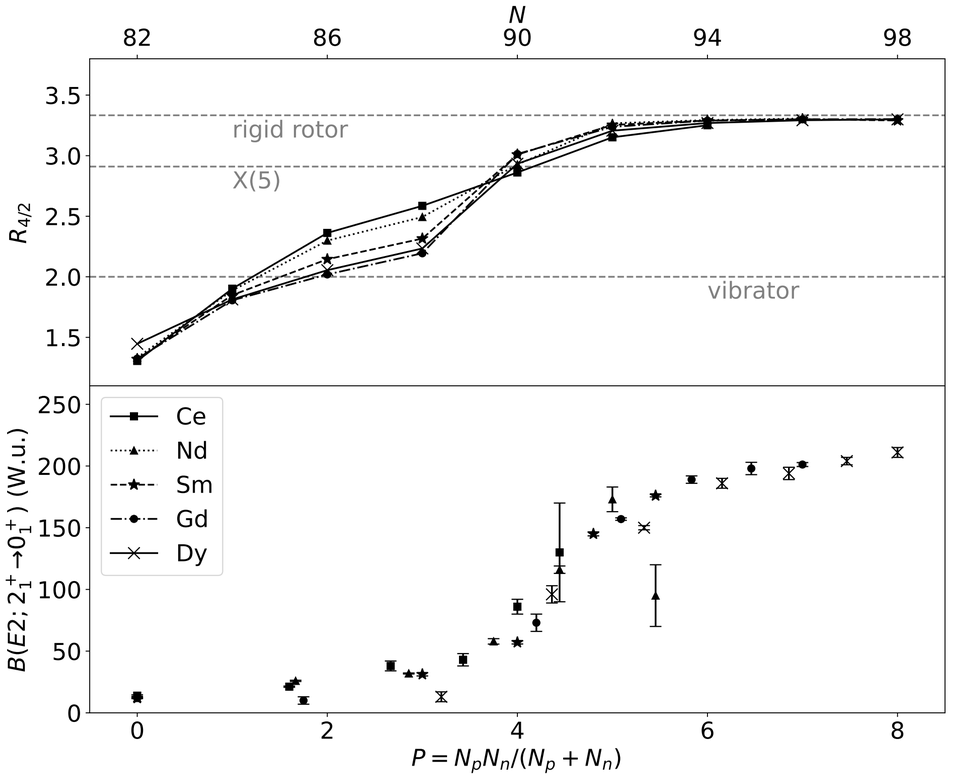
Iachello, Phys. Rev. Lett.53, 1427 (1984)
Dieperink, Prog. Part. Null. Phys. 3, 121 (1983)

- the $2^+_{ms}$ state of vibrational nuclei

Pietralla, Prog. Part. Nucl. Phys. 60, 225 (2008)

- the $1^+_{sc}$ scissors mode of deformed nuclei

Lo Iudice, Phys. Rev. Lett. 41, 1532 (1978)
Bohle, Phys. Rev. Lett. 1378, 27 (1984)
Heyde, Rev. Mod. Phys. 82, 2365 (2010)

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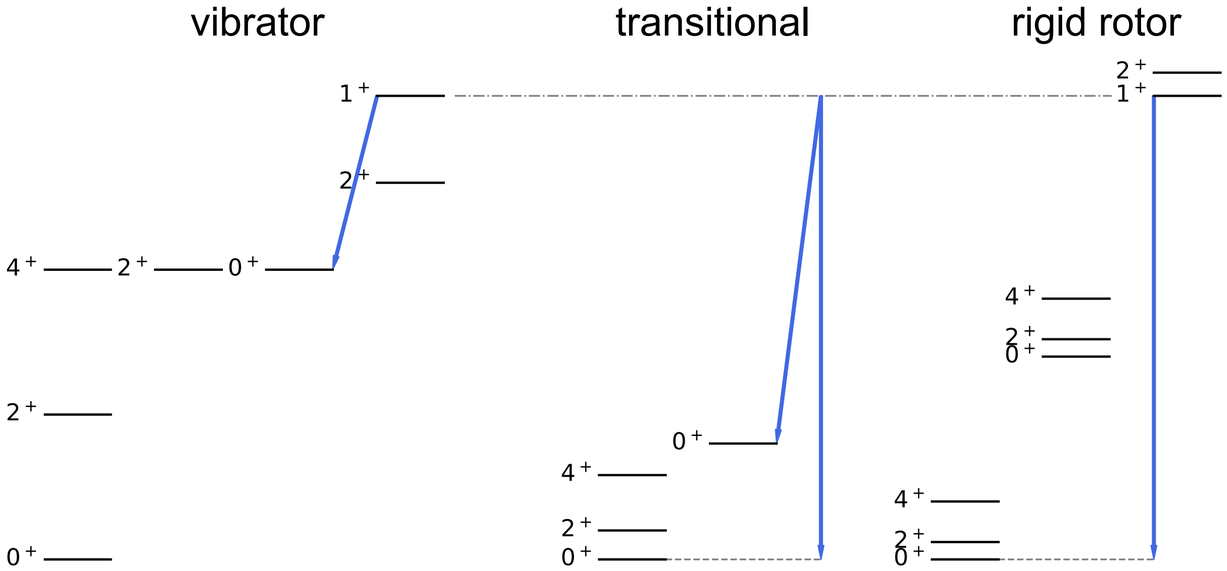
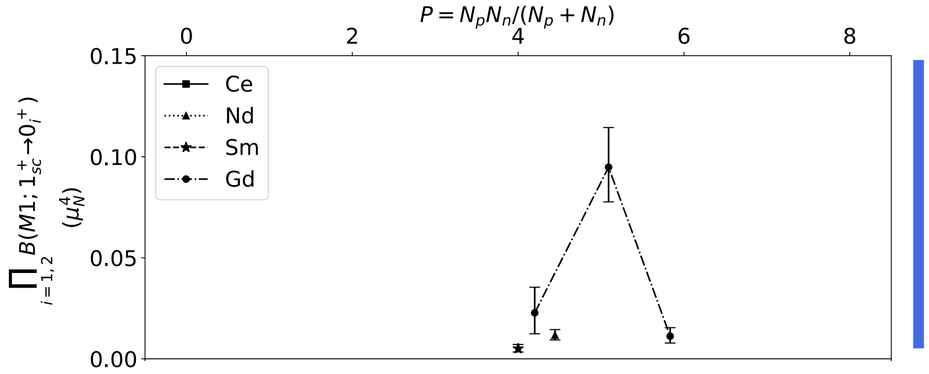
# Scissors mode at the phase transition

The $M1$ decay behavior of the scissors mode has been established as a signature of the $N = 90$ quantum phase transition. Beller, Dissertation, TU Darmstadt (2014)



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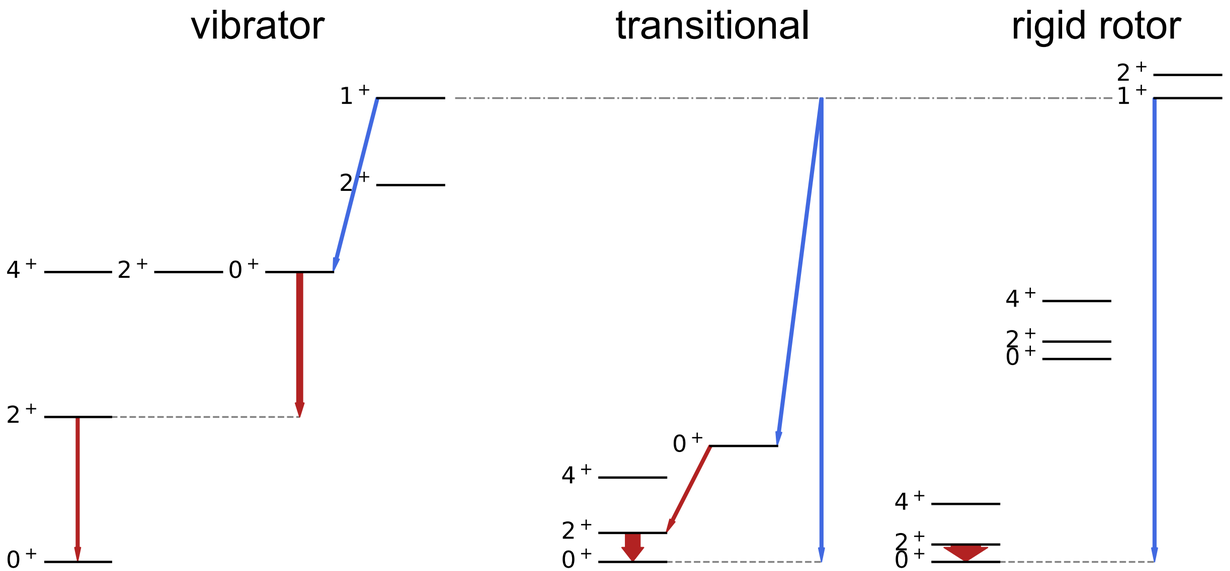
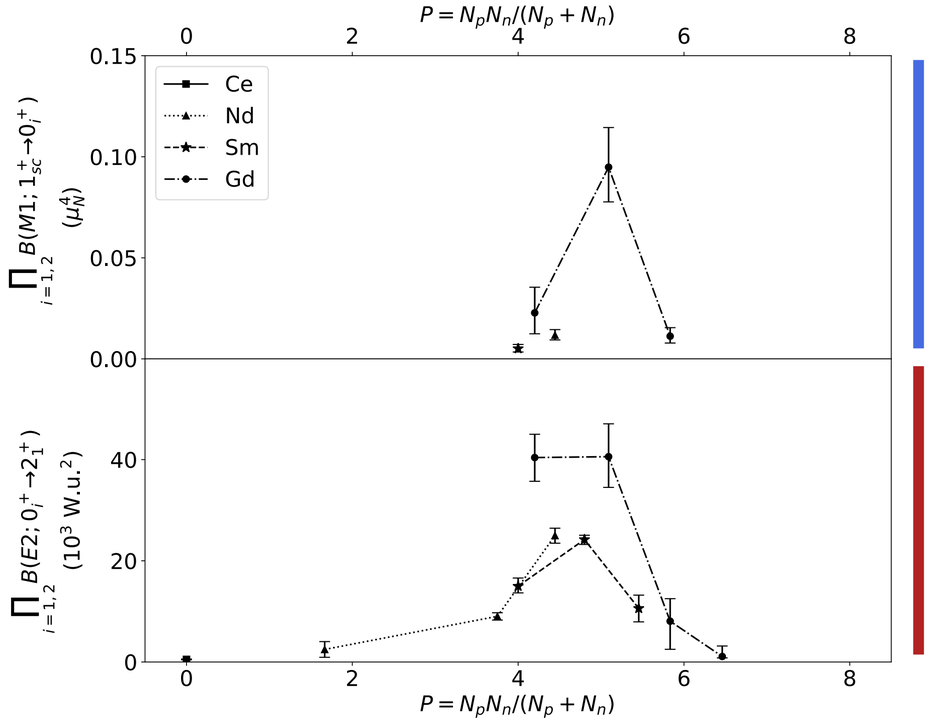


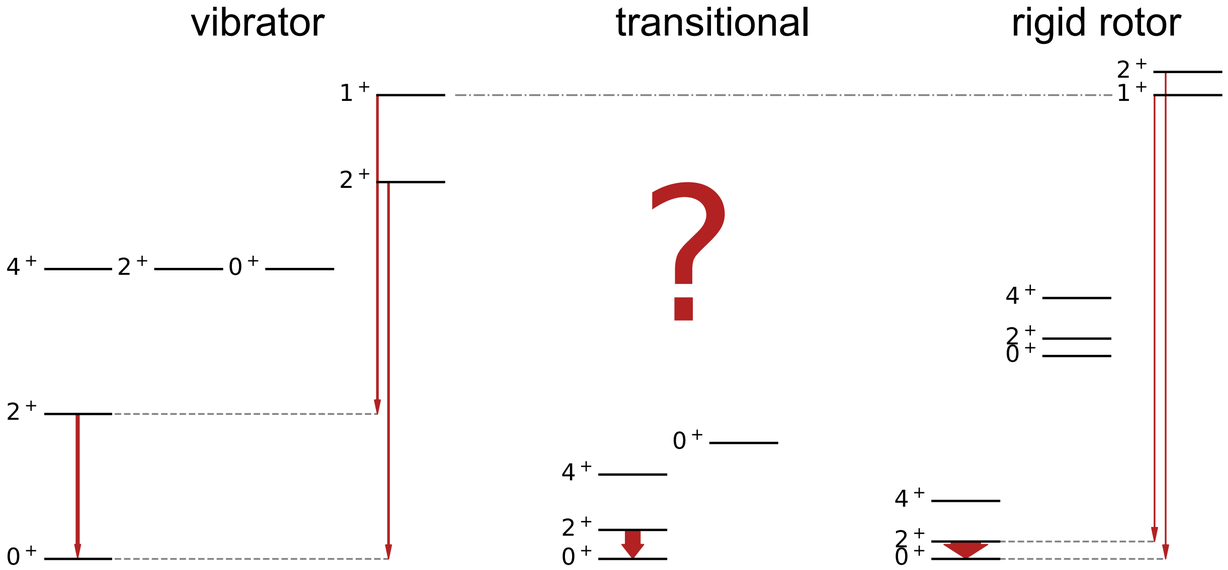




Link to $E2$ transition strengths: Beller, Dissertation, TU Darmstadt (2014)

$$\prod_{i\in\{1,2\}} B(M1; 0_i^+ \to 1_{sc}^+) \propto \prod_{i\in\{1,2\}} B(E2; 0_i^+ \to 2_1^+)$$

# Novel signatures from mixed-symmetry states

Based on the known $M1$ decay behavior of the scissors mode new signatures based on mixed-symmetry states can be conceived.



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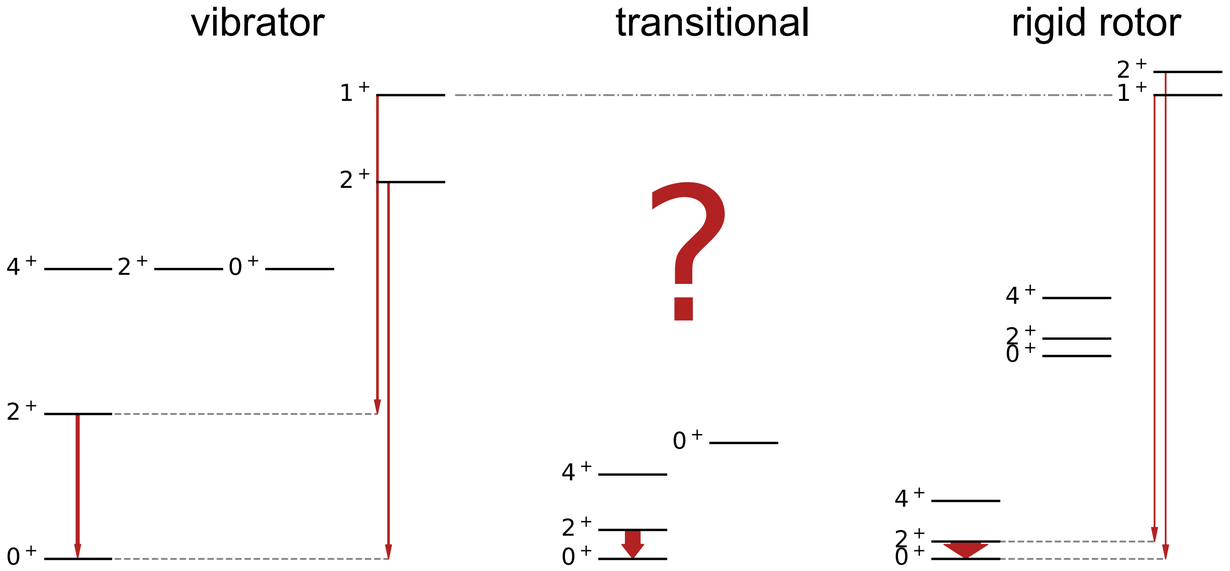



Potential new signatures:

- $[E(2^+_{\text{ms}}) - E(1^+_{\text{sc}})]/E(2^+_{\text{ms}})$

  Li, Phys. Rev. C 71, 044318 (2005)

- $B(E2; 2^+_{\text{ms}} \rightarrow 0^+_1)B(E2; 2^+_1 \rightarrow 0^+_1)$

- $B(E2; 1^+_{\text{sc}} \rightarrow 2^+_1)B(E2; 2^+_1 \rightarrow 0^+_1)$

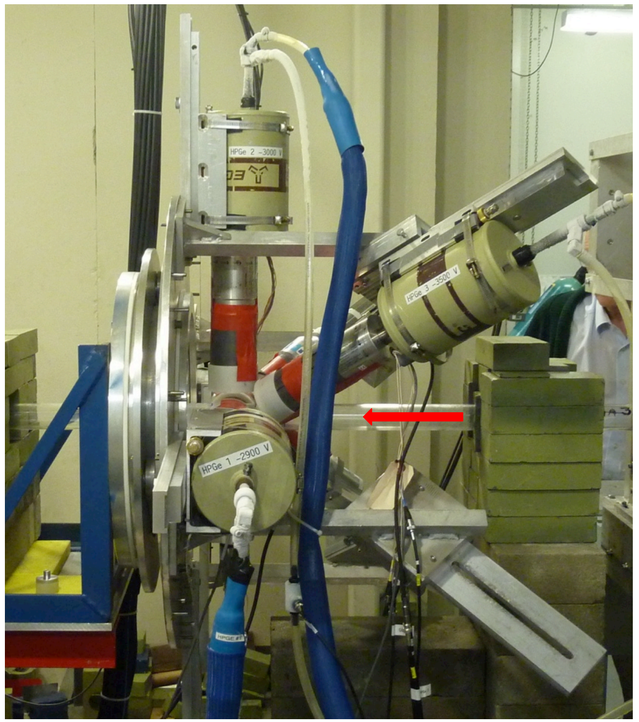
  Beck, Phys. Rev. Lett. 118, 212502 (2017)

→ Investigate the scissors mode's $E2$ properties across the $N = 90$ QPT!

# NRF experiments at HI$\gamma$S

Nuclear resonance fluorescence experiments off $^{154,156}$Gd and $^{162,164}$Dy were performed at the High Intensity $\gamma$-ray Source using the $\gamma^3$ setup.

Weller, Prog. Part. Nucl. Phys. 62, 257 (2009)




Löher, Nucl. Instr. Meth. Phys. Res. A 723, 136 (2013)

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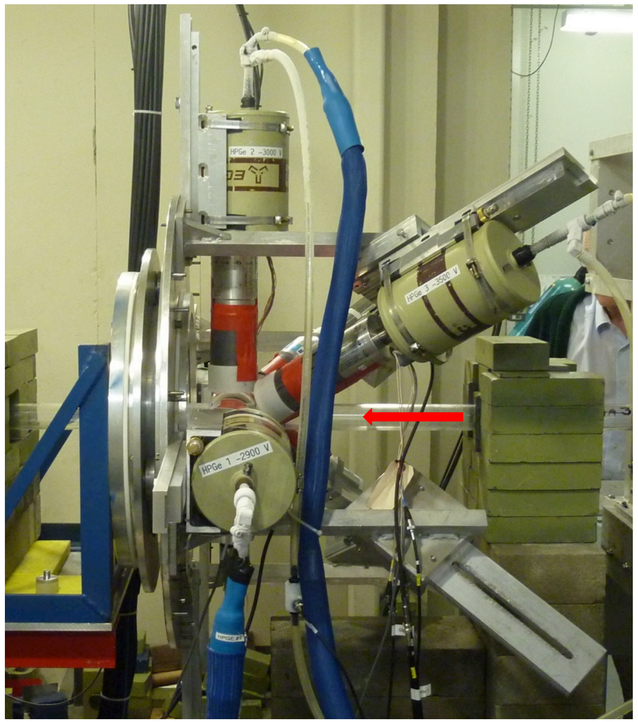

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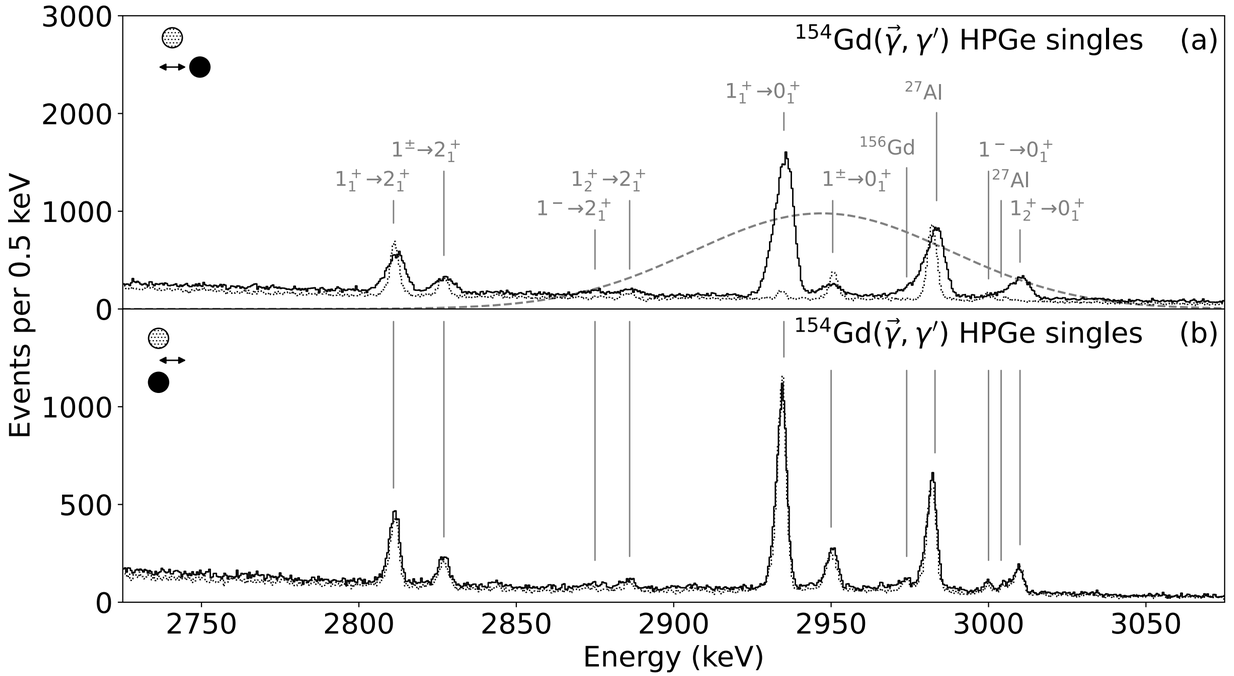


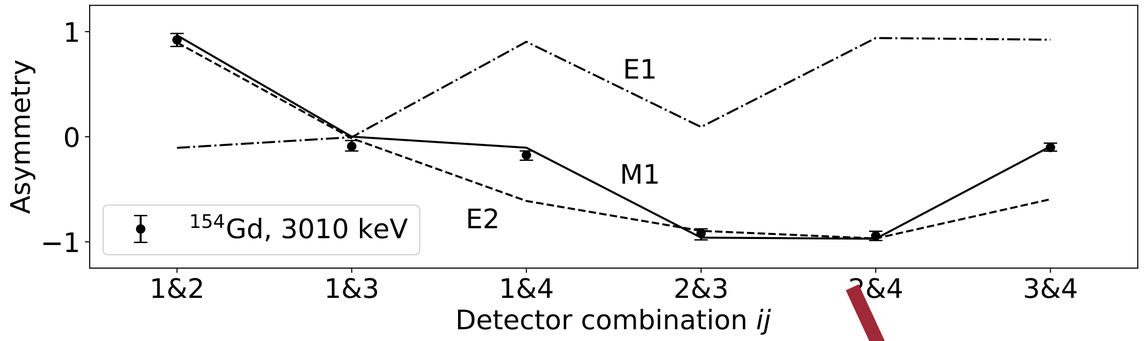

$\vartheta = 90°$

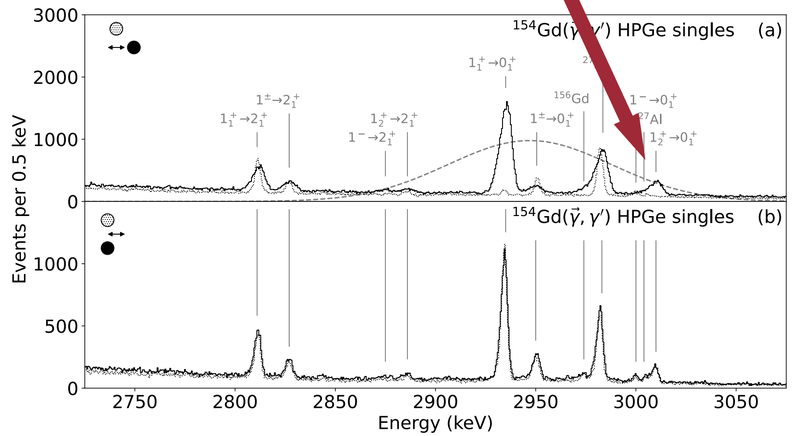
$\vartheta = 135°$

# Determination of multipole mixing ratios

## Angular momentum and parity quantum numbers

Pietralla, Phys. Rev. Lett. 88, 012502 (2002)



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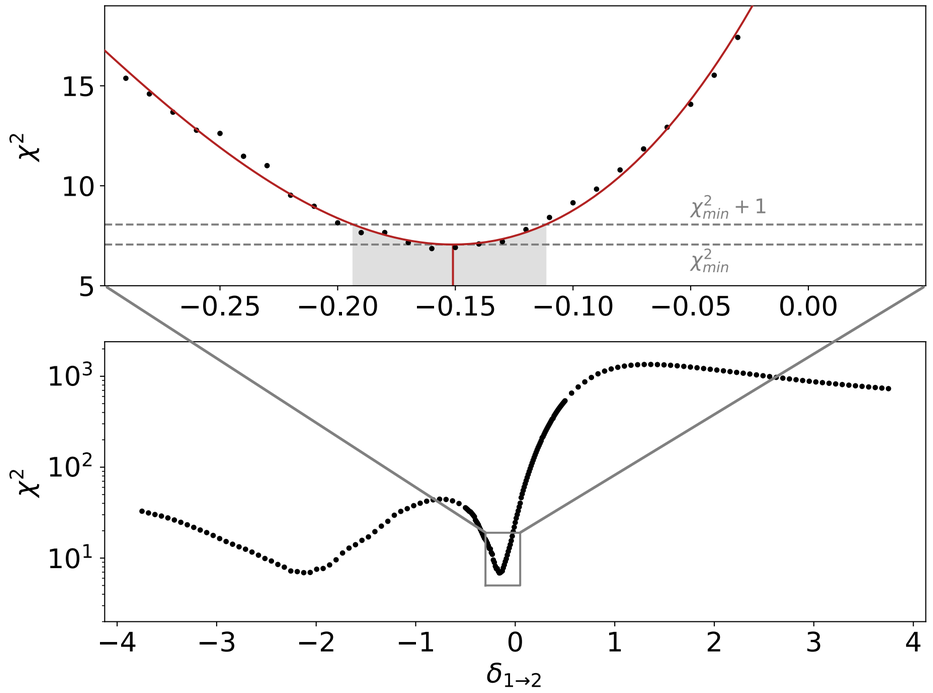
Rusev, Phys. Rev. C 79, 047601 (2009)




$$\delta_{1\to2} = \frac{\langle 2_1^+ \| T(E2) \| 1_{sc}^+ \rangle}{\langle 2_1^+ \| T(M1) \| 1_{sc}^+ \rangle}$$

$$B(E2; 1_{sc}^+ \to 2_1^+)$$

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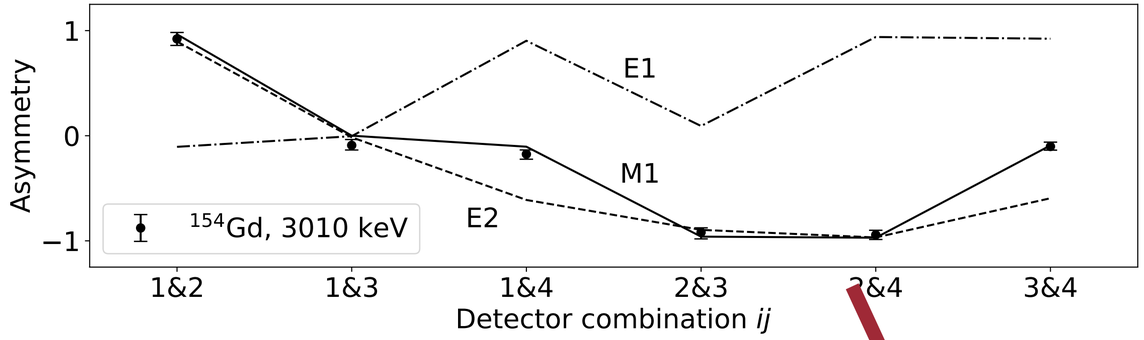
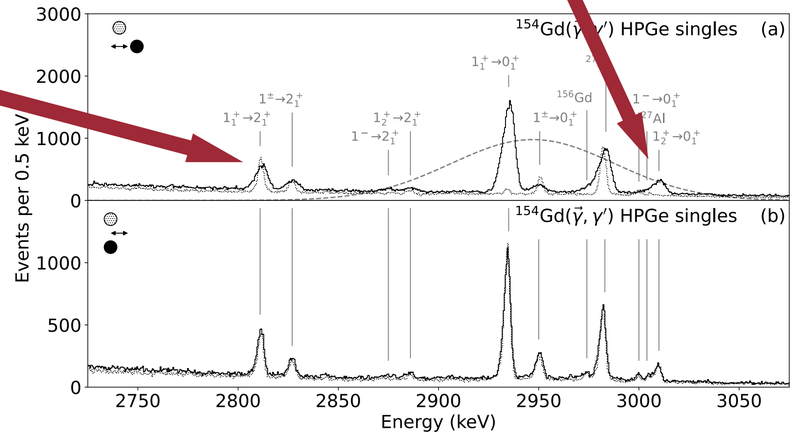


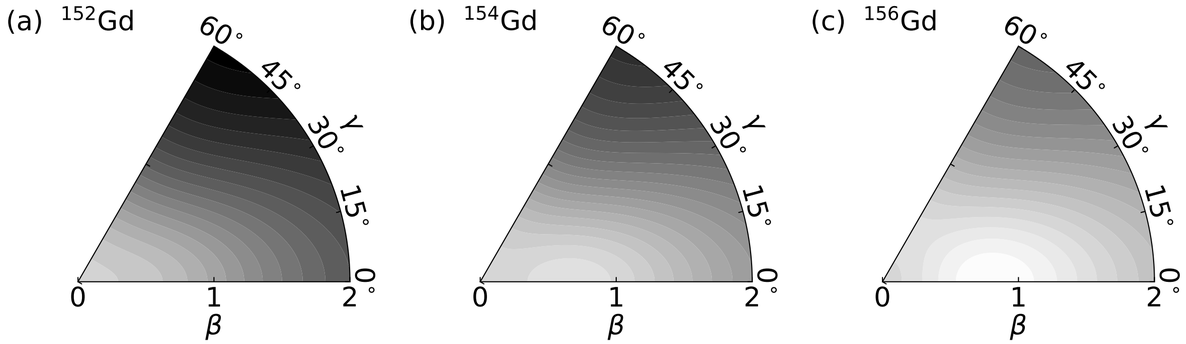
# Description in the Interacting Boson Model-2

Use the newly determined $F$-vector $E2$ transition strengths for an improved description of mixed-symmetry states in the framework of the IBM-2.

Iachello und Arima, The Interacting Boson Model (1987)

Start from available IBM-1 parameter sets and employ an iterative procedure.

McCutchan, Phys. Rev. C 69, 064306 (2004)
McCutchan, Phys. Rev. C 74, 057302 (2006)




Extend to the description to IBM-2 using the $F$-spin symmetric Hamiltonian

$$H = \epsilon(n_{d_\pi} + n_{d_\nu}) + \kappa(Q^\chi_\pi + Q^\chi_\nu) \cdot (Q^\chi_\pi - Q^\chi_\nu) + M(\xi_1, \xi_2, \xi_3)$$

and the extended consistent-$Q$ formalism.

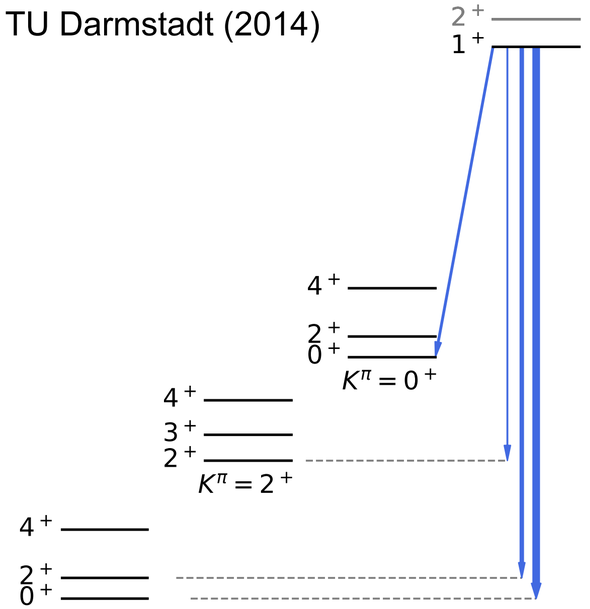
# Description in the Interacting Boson Model-2

| Observable | Experiment | IBM | | Unit |
|---|---|---|---|---|
| | | $\xi_1 = \xi_2 = \xi_3$ | $\xi_1 = \xi_3, \xi_2$ | |
| $E(0_1^+)$ | 0.000 | 0.000 | 0.000 | MeV |
| $E(2_1^+)$ | 0.089 | 0.089 | 0.089 | MeV |
| $E(4_1^+)$ | 0.288 | 0.288 | 0.288 | MeV |
| $E(6_1^+)$ | 0.585 | 0.591 | 0.591 | MeV |
| $E(0_\beta^+)$ | 1.049 | 1.036 | 1.036 | MeV |
| $E(2_\gamma^+)$ | 1.154 | 1.133 | 1.133 | MeV |
| $E(0_3^+)$ | 1.168 | 1.836 | 1.836 | MeV |
| $\overline{E}(1_{sc}^+)$ | 3.060[a] | 3.060 | 3.060 | MeV |
| $\overline{E}(2_{sc}^+)$ | | 3.086 | 2.523 | MeV |
| $B(E2; 2_1^+ \to 0_1^+)$ | 189(3) | 189 | 189 | W.u. |
| $B(E2; 4_1^+ \to 2_1^+)$ | 264(4) | 269 | 269 | W.u. |
| $B(E2; 6_1^+ \to 4_1^+)$ | 295(8) | 293 | 292 | W.u. |
| $B(E2; 0_\beta^+ \to 2_1^+)$ | $8^{+4}_{-7}$ | 11.9 | 11.9 | W.u. |
| $B(E2; 2_\gamma^+ \to 0_1^+)$ | 4.68(16) | 1.581 | 1.581 | W.u. |
| $B(E2; 1_{sc}^+ \to 2_1^+)$ | 0.093(66)[b] | 0.113 | 0.094 | W.u. |
| $B(E2; 2_{sc}^+ \to 0_1^+)$ | | 0.049 | 0.019 | W.u. |
| $\mu(2_1^+)$ | 0.774(8)[c] | 0.774 | 0.774 | $\mu_N$ |
| $B(M1; 1_{sc}^+ \to 0_1^+)$ | 1.02(9)[a] | 1.020 | 1.020 | $\mu_N^2$ |
| $B(M1; 1_{sc}^+ \to 2_1^+)$ | 0.51(6)[a] | 0.619 | 0.614 | $\mu_N^2$ |
| $B(M1; 1_{sc}^+ \to 0_\beta^+)$ | 0.013(4)[a] | 0.134 | 0.013 | $\mu_N^2$ |
| $B(M1; 2_{sc}^+ \to 2_1^+)$ | | 1.608 | 0.410 | $\mu_N^2$ |

# Determination of Majorana parameters

The $M1$ decay properties of the scissors mode cannot necessarily be used alone for the determination of the parameters of the Majorana operator.

Beller, Phys. Rev. Lett. 111, 172501 (2013)
Beller, Dissertation, TU Darmstadt (2014)



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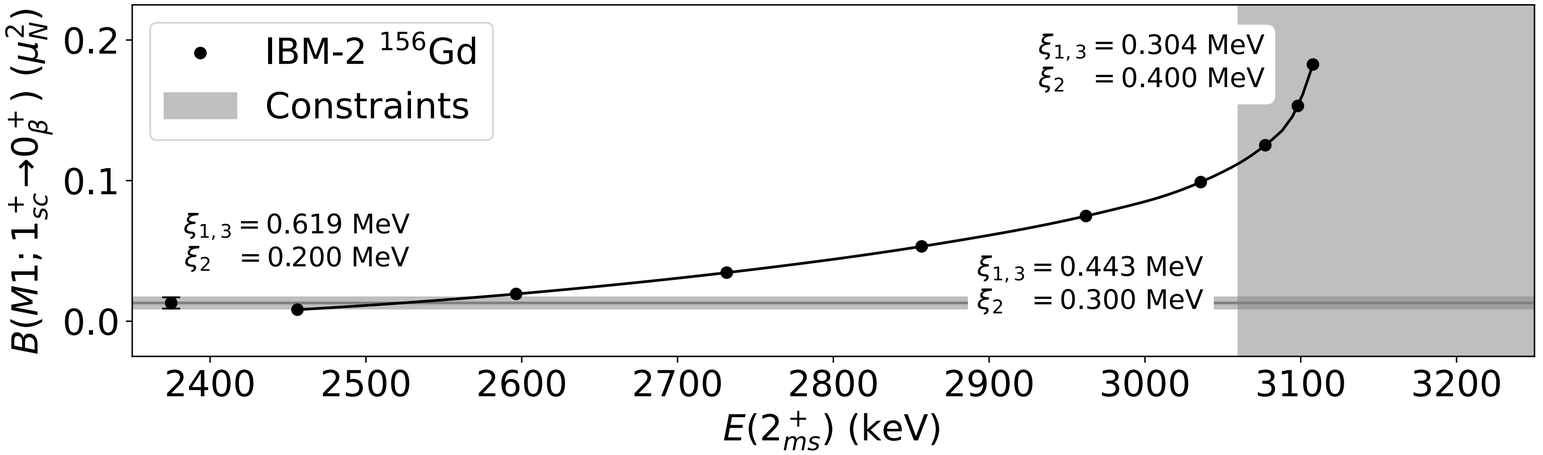


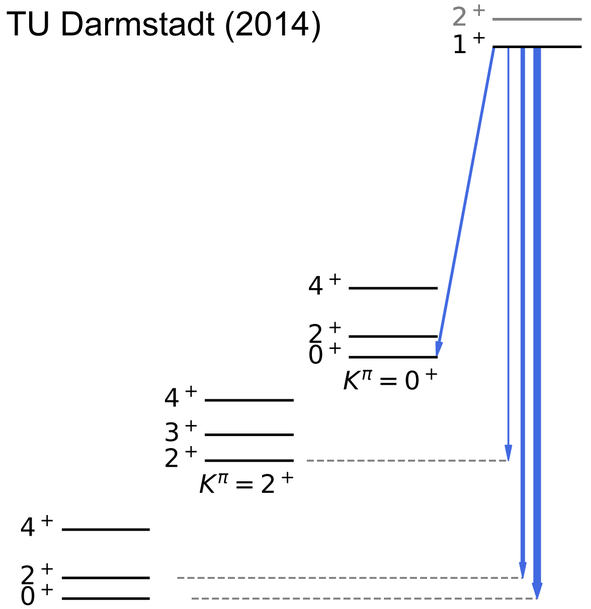

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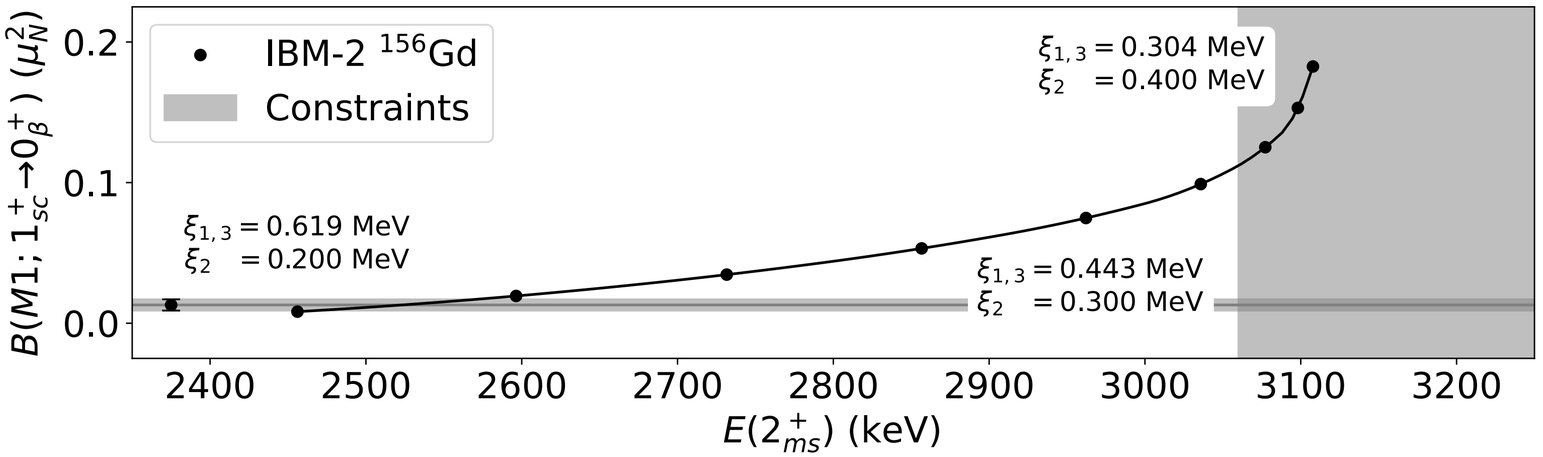
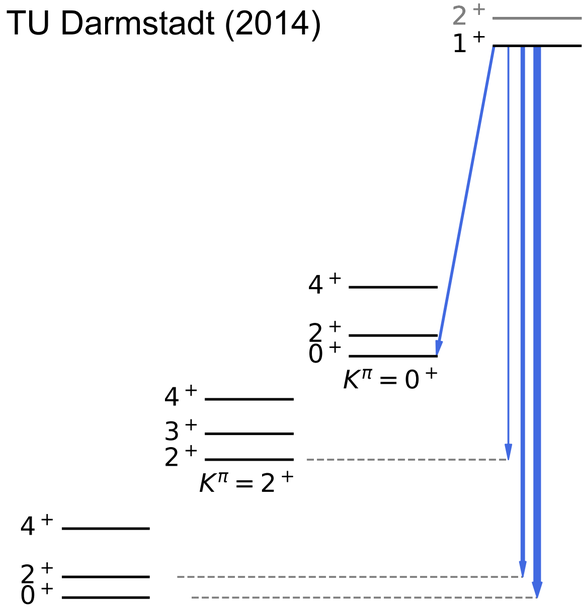


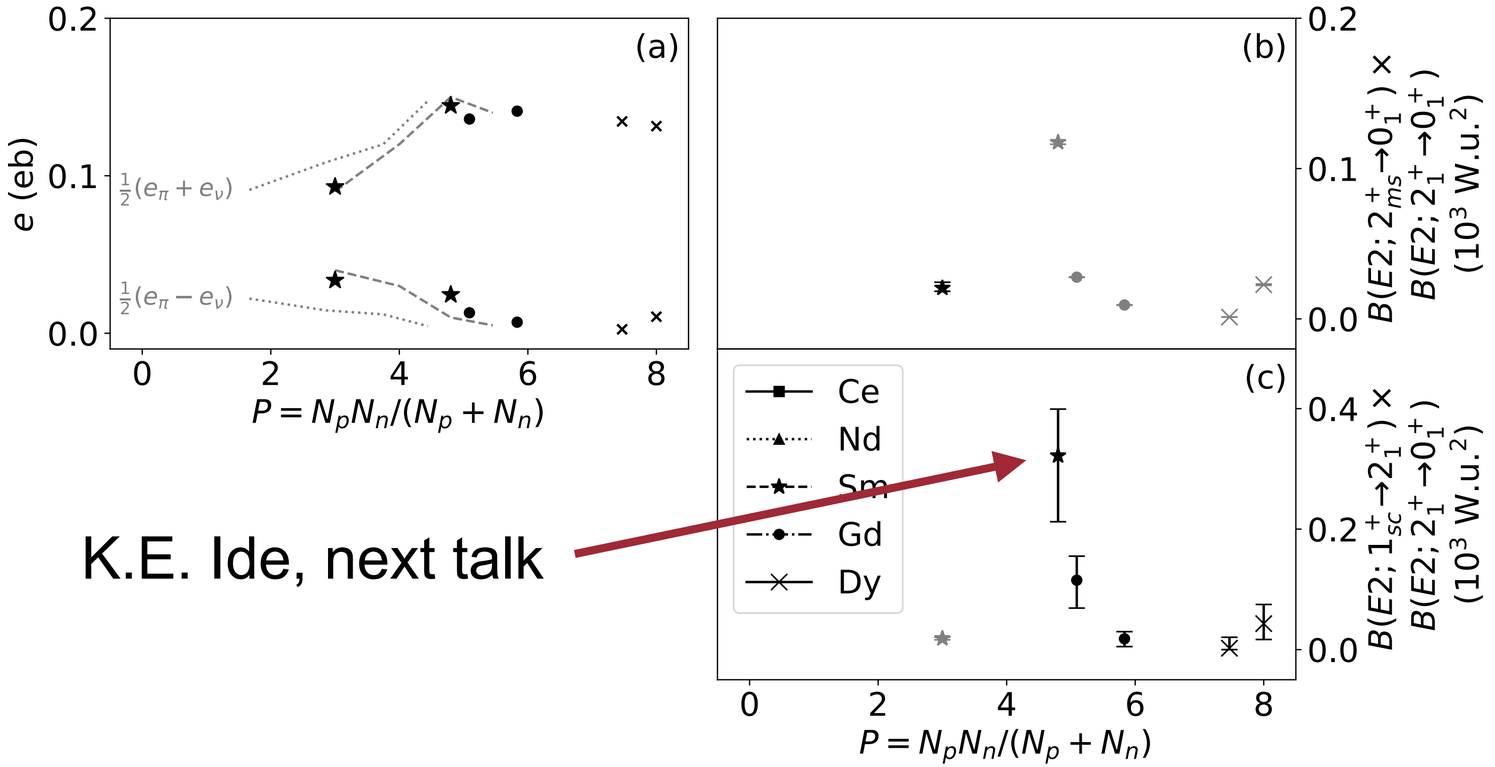

→ Investigate the scissors mode's rotational band!

Is the $0^+_2$ state really the $0^+_\beta$ state? Garrett, J. Phys. G 27, R1 (2001)

# Signatures of quantum phase transitions

With the measured $\Delta F = 1$ $E2$ transition strengths local values for the quadrupole boson charges $e_\pi$ and $e_\nu$ can be determined.

Beck, Phys. Rev. Lett. 118, 212502 (2017)
Ide, Phys. Rev. C 103, 054302 (2021)




K.E. Ide, next talk

$$B(E2; 1^+_{\text{sc}} \to 2^+_1) \propto (e_\nu - e_\pi)^2$$

$$B(E2; 2^+_{\text{ms}} \to 0^+_1) \propto (e_\nu - e_\pi)^2$$

van Isacker, Ann. Phys. 171, 253 (1986)

# Conclusion and learning points

The products of $\Delta F = 0$ and $\Delta F = 1$ $E2$ are promising candidates for novel QPT signatures based on mixed-symmetry states.

→ Need experimental data on $1^+_{\text{sc}}$ and $2^+_{\text{ms}}$ states in the same nucleus!

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Fragmentation of scissors mode constitutes a major challenge:

- What is the underlying mechanism?
- Which influence do potential microscopic influences have?

→ Investigate individual states of the same nucleus!

→ Switch to a microscopic description!


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