Systematics of Scissors Mode in Gd Isotopes from experiment with DANCE Detector

Jiří Kroll
for DANCE collaboration

Faculty of Mathematics and Physics, Charles University, Prague
Outline

- Motivation
- SM observed in \((n,\gamma)\) reaction
- DANCE experiment at LANSCE
- DICEBOX simulations of gamma decay
- Main results
- Conclusions
Scissors mode (SM) in $M_1$ PSF

SM proposed in deformed nuclei by theorists in late 70’s:

Scissors mode (SM) in $M_1$ PSF

SM proposed in deformed nuclei by theorists in late 70’s:


SM experimentally confirmed in high-resolution (e,e’) experiments on rare-earth nuclei

Scissors mode (SM) in $M1$ PSF

SM proposed in deformed nuclei by theorists in late 70’s:


SM experimentally confirmed in high-resolution (e,e’) experiments on rare-earth nuclei


SM for the GS transitions in even-even nuclei studied in detail in the 80’s and 90’s mainly using the ($\gamma,\gamma'$) experiments
SM in Nuclear Resonance Fluorescence technique

\[ I_s = \frac{2J + 1}{2J_0 + 1} \left( \frac{\pi \hbar c}{E_\gamma} \right)^2 \frac{\Gamma_0 \Gamma_f W(\theta)}{\Gamma} \frac{W(\theta)}{4\pi} \]

\[ \Gamma_0 = 8\pi \sum_{XL=1}^{\infty} \frac{(L + 1)}{L[(2L + 1)!!]^2} \left( \frac{E_\gamma}{\hbar c} \right)^{2L+1} \frac{2J_0 + 1}{2J + 1} B(XL, E_\gamma) \uparrow \]

\[ B(E1) \uparrow = 2.866 \times 10^{-3} \frac{\Gamma_0}{E_\gamma^3} \text{[e}^2\text{fm}^2] \]

\[ B(M1) \uparrow = 0.2598 \frac{\Gamma_0}{E_\gamma^3} \text{[}\mu_N^2\text{]} \]

\[ \theta = 127^\circ \quad \theta = 90^\circ \]

\[ W(\theta)_{\text{Dipole}} = \frac{3}{4} (1 + \cos^2(\theta)) \]

\[ W(\theta)_{\text{Quadrupole}} = \frac{5}{4} (1 - 3\cos^2(\theta) + 4\cos^4(\theta)) \]

\[ W(90^\circ) / W(127^\circ) = 0.734 \quad \text{dipole} \]

\[ W(90^\circ) / W(127^\circ) = 2.28 \quad \text{quadrupole} \]
SM in Nuclear Resonance Fluorescence technique

SM proposed in deformed nuclei by theorists in late 70’s:

SM experimentally confirmed in high-resolution (e,e’) experiments on rare-earth nuclei

SM for the GS transitions in even-even nuclei studied in detail in the 80’s and 90’s mainly using the (γ,γ’) experiments

In well-deformed even-even nuclei
$E_{SM} \approx 3$ MeV and $\Sigma B(M1) \approx 3 - 3.5 \mu_N^2$. 
SM in Nuclear Resonance Fluorescence technique

SM proposed in deformed nuclei by theorists in late 70's:

SM experimentally confirmed in high-resolution ($e,e'$) experiments on rare-earth nuclei:

Exploiting data from $(\gamma,\gamma')$ – a sum rule was derived by N. Lo Iudice and A. Richter, Phys. Lett. B 304, 193 (1993).

\[ \sum B(M1)^+ \approx 0.0042 \frac{4NZ}{A^2} E_{SC} A^{5/3} (g_p - g_n)^2 \delta^2 [\mu_N^2] \]
In odd nuclei $\Sigma B(M1,\text{odd}) \approx \frac{1}{3} \Sigma B(M1,e-e)$ from $(\gamma,\gamma') \leftarrow$ problems with high NLD
SM in Oslo method \((^3\text{He}-\text{induced reactions})\)

CACTUS 28 NaI(Tl) 5” x 5”

8 Si charged particle telescopes
SM observed in \((n,\gamma)\) reactions - TSC

**LWR-15 reactor**

- **6 m long neutron guide**
- **HPGe #1** \(\varepsilon_R = 25\%\)
- **HPGe #2** \(\varepsilon_R = 28\%\)
- **Target**
- **\(^{6}\text{Li}_2\text{CO}_3\) (m = 0.88g)**
- **DAQ time: 800 h**

**DAQ conditions for the TSCs:**
- energies \(E_{\gamma_1}\) and \(E_{\gamma_2}\)
- time difference

**Neutron shielding:**
- \(^{6}\text{Li}_2\text{CO}_3\)

**Low energy \(\gamma\)-ray shielding:** Lead

\[ E_n = 0.025 \text{ eV} \]

\[ 3.0 \times 10^6 \text{ n cm}^{-2} \text{ s}^{-1} \]
SM observed in \((n,\gamma)\) reactions – TSC


To get TSC spectra for separate final levels, the sum coincidence method was used
SM observed in \((n,\gamma)\) reactions - TSC

Both transitions resonate at the same time.

\[ E_{SR} \approx 3.0 \text{ MeV} \]
\[ \Gamma_{SR} \approx 0.6 \text{ MeV} \]
SM observed in \((n,\gamma)\) reactions – TSC

Both transitions resonate at the same time

\[ E_{SM} \approx 3.0 \text{ MeV} \]
\[ \Gamma_{SM} \approx 0.6 \text{ MeV} \]
SM observed in \((n,\gamma)\) reactions - TSC

SM on the excited states was observed for the first time in TSC experiment with \(^{163}\text{Dy}\)


Simulation assumption:
SM is built only on the states below the energy of 2.5 MeV

Corridors represent the region of residual Porter-Thomas fluctuations.
SM observed in \((n,\gamma)\) reactions - TSC

SM on the excited states was observed for the first time in TSC experiment with \(^{163}\text{Dy}\) (M. Krtička et al., Phys. Rev. Lett. 92, 172501 (2004)).

Simulation assumption:
SM is built on all \(^{163}\text{Dy}\) levels

\begin{align*}
E_{\text{SM}} &= 3.0 \text{ MeV}, \quad \Gamma_{\text{SM}} = 0.6 \text{ MeV} \\
\sum B(M1)^{\uparrow} &\approx 6 \mu_{N}^{2}
\end{align*}

Corridors represent the region of residual Porter-Thomas fluctuations.
SM observed in (n,\(\gamma\)) reactions - TSC

No resonance structure postulated near 3 MeV in PSF

SM in M1 PSF: \(E_{SM} = 2.6\) MeV, \(\Gamma_{SM} = 0.6\) MeV, \(\sigma_{SM} = 1.0\) MeV
SM observed in \((n,\gamma)\) reactions - TSC

SM in \(M1\) PSF only on the GS:
\[ E_{SM} = 2.6 \text{ MeV}, \quad \Gamma_{SM} = 0.6 \text{ MeV} \text{ and } \sigma_{SM} = 1.0 \text{ MeV} \]

SM in \(M1\) PSF:
\[ E_{SM} = 2.6 \text{ MeV}, \quad \Gamma_{SM} = 0.6 \text{ MeV} \text{ and } \sigma_{SM} = 1.0 \text{ MeV} \]
Moderated W target gives “white” neutron spectrum ≈ 14 n’s / proton

Repetition rate 20 Hz

Pulse width ≈ 125 ns

DANCE (Detector for Advanced Neutron Capture Experiments) detector is placed on a 20m long flight path / ≈ 1 cm beam after collimation

Average proton current ≈ 100 μA
DANCE experiment at LANSCE – BaF$_2$ crystals

- **DANCE** consists of 160 BaF2 crystals (fullerene-type structure)
  - total efficiency of detecting a photon from cascade > 90%
  - efficiency for 1 MeV photon ≈ 86%
  - energy resolution: \( \frac{dE}{E} = 1.089 \times 10^{-2} + 0.146/\sqrt{E} \)
    - 1 MeV γ-ray ≈ 16%
    - 6 MeV γ-ray ≈ 7%
  - timing resolution ≈ 2 ns
DANCE experiment at LANSCE - signal

- Data Acquisition System
  - Each crystal is connected to a channel in two different digitizers
  - Acqiris 4-channel DC256 digitizers (500 MHz, 8 bit resolution)

- BaF$_2$ light output consists of
  - Fast component (0.6 ns, 220 nm) – 1 integral / 32pts = 64 ns
  - Slow component (630 ns, 310 nm) – 5 integrals / 100pts = 200 ns

- Data rate reduced to $\approx$ 1 Mbyte/s

- DAQ has $\approx$ 40 ms to read out the digitizers, extract the waveform information and send data to the Midas served

![TIME LINE FOR ONE BEAM SPILL](image)
DANCE experiment at LANSCE - calibration

- Primary energy calibration ($^{88}\text{Y}$, $^{60}\text{Co}$, $^{22}\text{Na}$)
- Gain for each crystal updated run-by-run by the $\alpha$-particles from Ra isotopes present in BaF$_2$ crystals
- Signal from $\alpha$-particles is easily identified
DANCE experiment at LANSCE - calibration

- Primary energy calibration ($^{88}$Y, $^{60}$Co, $^{22}$Na)
- Gain for each crystal updated run-by-run by the $\alpha$-particles from Ra isotopes present in BaF$_2$ crystals
- Signal from $\alpha$-particles is easily identified
Primary energy calibration ($^{88}$Y, $^{60}$Co, $^{22}$Na)

Gain for each crystal updated run-by-run by the $\alpha$-particles from Ra isotopes present in BaF$_2$ crystals

Signal from $\alpha$-particles is easily identified
With a DANCE detector we have measured stable Gd isotopes

$^{153}\text{Gd}, \; ^{155}\text{Gd}, \; ^{156}\text{Gd}, \; ^{157}\text{Gd}, \; ^{158}\text{Gd}, \; ^{159}\text{Gd}$

mainly to get information about the Photon Strength Functions (PSFs)
• **TOF method** → we are interested only in the strong and well-isolated resonances

• The background for these strong resonances is small and can be subtracted
DANCE experiment – data processing

Sum-energy spectra for different multiplicities

- \( J = 1 \) (100.2 eV)
- \( J = 2 \) (48.8 eV)

Multiplicities:
- \( M = 2 \)
- \( M = 3 \)
- \( M > 4 \)
DANCE experiment – data processing

Experimental MSC spectra

Sum-energy spectra for different multiplicities
1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data
Simulations of gamma decay – DICEBOX

1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an a priori known level density

$$\rho(E_i, J_i, \pi_i)$$

Level density
Simulations of gamma decay – NLD


1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an a priori known level density.

$$\rho(E_i, J_i, \pi_i)$$ Level density

3. Partial radiation widths $\Gamma_{if}$ for transitions between initial (i) and final (f) levels are generated according to the formula:

$$\Gamma_{i\gamma f} = \sum_{XJ} g_{iXJ}^2 (E_i - E_f)^{2J+1} \frac{f^{(XJ)}(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}$$
1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an a priori known level density:

$$\rho(E_i, J_i, \pi_i)$$

Level density

3. Partial radiation widths $\Gamma_{i\gamma f}$ for transitions between initial (i) and final (f) levels are generated according to the formula:

$$\Gamma_{i\gamma f} = \sum_{XJ} y_{XJ}^2 f_{XJ} (E_i - E_f)^{2J+1} \frac{\rho(XJ)(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}$$

PSFs
Simulations of gamma decay – PSFs

The energy of the SM is $3.0 \text{ MeV}$, damping width is $1.0 \text{ MeV}$ and the strength $S_{B_{\text{tot}}(\text{SM})} \uparrow \approx 7.46 \mu_N^2$.

Simulations of gamma decay – DICEBOX

1. Below a **critical energy** $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an *a priori* known level density

\[ \rho(E_i, J_i, \pi_i) \]

**Level density**

3. **Partial radiation widths** $\Gamma_{i\gamma f}$ for transitions between initial (i) and final (f) levels are generated according to the formula:

\[
\Gamma_{i\gamma f} = \sum_{XJ} g_{ij}^2 f_{XJ} (E_i - E_f)^{2J+1} \frac{f(XJ)(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}
\]

**PSFs**
Simulations of gamma decay – DICEBOX

1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an a priori known level density

$$\rho(E_i, J_i, \pi_i)$$ Level density

3. Partial radiation widths $\Gamma_{\gamma f}$ for transitions between initial (i) and final (f) levels are generated according to the formula:

$$\Gamma_{\gamma f} = \sum_{XJ} y_{i,f,XJ}^2 (E_i - E_f)^{2J+1} \frac{f(x,J)(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}$$

P-T fluctuations

PSFs
Simulations of gamma decay – DICEBOX

1. Below a critical energy $E_{\text{crit}}$ the energies $E$, spins $J$, parities $\pi$ and the decay properties of all levels are taken from known data.

2. Above the critical energy $E_{\text{crit}}$ the energies $E$, spins $J$ and parities $\pi$ of levels are obtained by random discretization of an a priori known level density $\rho(E_i, J_i, \pi_i)$.

3. Partial radiation widths $\Gamma_{i\gamma f}$ for transitions between initial (i) and final (f) levels are generated according to the formula:

$$\Gamma_{i\gamma f} = \sum_{XJ} y_{i f X J}^2 (E_i - E_f)^{2J+1} \frac{f(XJ)(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}$$

P-T fluctuations

4. Partial radiation widths $\Gamma_{i\gamma f}$ for different initial and/or final levels are statistically independent.
Simulations of gamma decay – DICEBOX

Nuclear Realization:

10^6 energy levels

10^{12} \Gamma_{i\gamma f}

System of precursors

Level Number

Precursor

Excitation Energy

P-T fluctuations

The outputs of DICEBOX simulations are transformed to the form of Geant4 input.

Simulations of detector response include the exact geometry and chemical composition (regular and irregular pentagonal and hexagonal BaF$_2$ crystals), all shielding, aluminium beamline, radioactive target holder, etc.
Comparison of experimental MSC spectra with simulations

- To get information on PSFs and LD we compare experimental data with outputs of simulations.

Experimental MSC spectra for five different resonances with $J^\pi = \frac{1}{2}^+$

Simulated MSC spectra produced by DICEBOX and Geant4 (grey corridors are consequence of Porter-Thomas fluctuations)
Simulation assumptions:

**E1**: MGLO ($k_0 = 4.0$, $E_{\gamma 0} = 4.5$ MeV)

**M1**: SP + SF

**E2**: SP

**NLD**: BSFG

---

Simulation assumptions:

**E1**: MGLO ($k_0 = 4.0$, $E_{\gamma 0} = 4.5$ MeV)

**M1**: SP + SF + SM

**E2**: SP

**NLD**: BSFG

$E_{SM}=3.0$ MeV, $\Gamma_{SM}=1.0$ MeV,

$\Sigma B_{tot}(SM)\uparrow = 7.46 \, \mu_N^2$
Comparison of experimental MSC spectra with simulations

Simulation assumptions:

\( E_1 \): MGLO \((k_0 = 4.0, E_{\gamma 0} = 4.5 \text{ MeV}) + \text{SR} \\
\( M_1 \): SP + SF \\
\( E_2 \): SP \\
\( \text{NLD} \): BSFG

\( E_{\text{SR}} = 3.0 \text{ MeV}, \Gamma_{\text{SR}} = 1.0 \text{ MeV}, \sigma_{\text{SM}} = 0.7 \text{ mb} \)

\( E_{\text{SM}} = 3.0 \text{ MeV}, \Gamma_{\text{SM}} = 1.0 \text{ MeV}, \Sigma B_{\text{tot}}(\text{SM}) \uparrow = 7.46 \mu_N^2 \)
Comparison of experimental MSC spectra with simulations

Simulation assumptions:

$E_1$ : MGLO ($k_0 = 4.0$, $E_{\gamma_0} = 4.5$ MeV) + SR
$M_1$ : SP + SF + SM (below 3 MeV)
$E_2$ : SP
$NLD$ : BSFG

$E_{SM} = 3.0$ MeV, $\Gamma_{SM} = 1.0$ MeV,
$\Sigma B_{tot}(SM)^\uparrow = 7.46 \mu_N^2$

$E_{SM} = 3.0$ MeV, $\Gamma_{SM} = 1.0$ MeV,
$\Sigma B_{tot}(SM)^\uparrow = 7.46 \mu_N^2$
\[ \Sigma B(M1, 2.7-3.7) \uparrow \text{ in even nuclei} \]

\[ \sum B_{\text{NRF}}(M1) \uparrow (\mu_N^2) \]


\(^{148}\text{Sm} \) [red] S. Siem et al., PRC 65, 044314 (2002);
\(^{160,162}\text{Dy} \) [red] M. Guttormsen et al., PRC 68, 064306 (2003);
\(^{164}\text{Dy} \) [red] H.T. Nyhus et al., PRC 81, 024325 (2010);
\(^{166}\text{Er} \) [red] E. Melby et al., PRC 63, 044309 (2001);
\(^{172}\text{Yb} \) [red] A. Voinov et al., PRC 63, 044313 (2001);
\(^{158}\text{Gd} \) [blue] A. Chyzh et al., PRC 84, 014306 (2011);
\(^{156}\text{Gd} \) [blue] B. Baramsai et al., PRC 87, 044609 (2013).
$\Sigma B(M1, 2.7-3.7)^\uparrow$ in odd / odd-odd nuclei


$^{149}$Sm [red] S. Siem et al., PRC 65, 044314 (2002); $^{161}$Dy [red] M. Guttormsen et al., PRC 68, 064306 (2003);

$^{163}$Dy [red] H.T. Nyhus et al., PRC 81, 024325 (2010); $^{167}$Er [red] E. Melby et al., PRC 63, 044309 (2001);


$\Sigma B(M1, 2.7-3.7) \uparrow$ all data together


$^{148,149}$Sm [red] S. Siem et al., PRC 65, 044314 (2002); $^{160,161,162}$Dy [red] M. Gutormsen et al., PRC 68, 064306 (2003);

$^{163,164}$Dy [red] H.T. Nyhus et al., PRC 81, 024325 (2010); $^{166,167}$Er [red] E. Melby et al., PRC 63, 044309 (2001);

$^{163,164}$Yb [red] A. Voinov et al., PRC 63, 044313 (2001);


$\Sigma B_{\text{tot}}(\text{SM}) \uparrow$ all data together


$^{148,149}_{\text{Sm}}$ [red] S. Siem et al., PRC 65, 044314 (2002); $^{160,161,162}_{\text{Dy}}$ [red] M. Guttormsen et al., PRC 68, 064306 (2003);

$^{163,164}_{\text{Dy}}$ [red] H.T. Nyhus et al., PRC 81, 024325 (2010); $^{166,167}_{\text{Er}}$ [red] E. Melby et al., PRC 63, 044309 (2001);

$^{163}_{\text{Yb}}$ [red] A. Voinov et al., PRC 63, 044313 (2001);


$\Sigma B_{\text{tot}}(\text{SM}) \uparrow$ all data together


$^{148,149}\text{Sm}$ [red] S. Siem et al., PRC 65, 044314 (2002); $^{160,161,162}\text{Dy}$ [red] M. Guttormsen et al., PRC 68, 064306 (2003);
$^{163,164}\text{Dy}$ [red] H.T. Nyhus et al., PRC 81, 024325 (2010); $^{166,167}\text{Er}$ [red] E. Melby et al., PRC 63, 044309 (2001);
$^{160}\text{Tb}$ [red] A. Voinov et al., PRC 63, 044313 (2001);
$^{158}\text{Gd}$ [blue] A. Chyzh et al., PRC 84, 014306 (2011); $^{156}\text{Gd}$ [blue] B. Baramsai et al., PRC 87, 044609 (2013).

Conclusions

- *M1 SM* plays an important role in gamma deexcitation of studied Gd isotopes.

- *M1 SM* is observed above the accessible excited states in all studied Gd nuclei.

- Values of $\Sigma B(M1,2.7-3.7)^\uparrow$ obtained for $^{156,158}$Gd are slightly below the results of $(\gamma,\gamma')$ experiments.

- We have gotten new results for $\Sigma B(M1)^\uparrow$ present in odd rare-earth isotopes $^{153,155,157,159}$Gd.

- Odd-even asymmetry of $\Sigma B(M1)^\uparrow$ in $^{156,158}$Gd and $^{157,159}$Gd is in disagreement with the Oslo data for Dy isotopes.
DANCE collaboration

U. Agvaanluvsan¹, B. Baramsai², J.A. Becker³, F. Bečvář⁴, T.A. Bredeweg⁵, A. Chyzh²,³, A. Couture⁵,
D. Dashdorj²,³, R.C. Haight⁵, M. Jandel⁵, A.L. Keksis⁵, J. Kroll⁴, M. Krčička⁴, G.E. Mitchell²,
J.M. O’Donnell⁵, W. Parker³, R.S. Rundberg⁵, J. L. Ullmann⁵, S. Valenta⁴, D.J. Vieira⁵, C.L. Walker²,
J.B. Wilhelmy⁵, J.M. Wouters⁵ and C.Y. Wu³

¹ MonAme Scientific Research Center, P.O.Box 24-603, Ulaanbaatar, Mongolia
² North Carolina State University, Raleigh, North Carolina 27695, USA, and Triangle Universities Nuclear Laboratory,
   Durham, North Carolina 27708, USA
³ Lawrence Livermore National Laboratory, Livermore, California 94551, USA
⁴ Charles University in Prague, Faculty of Mathematics and Physics, V Holešovičkách 2, CZ-180 00 Prague 8, Czech
   Republic
⁵ Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

Prague group

F. Bečvář, M. Krčička, J. Kroll and S. Valenta

Charles University in Prague, Faculty of Mathematics and Physics, V Holešovičkách 2, CZ-180 00 Prague 8, Czech
   Republic