Scissors mode resonances built on excited levels in Gd nuclei studied from resonance neutron capture

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Outline

- Scissors mode
- 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:

N. Lo Iudice and F. Palumbo, PRL 53 (1978) 1532

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

In well-deformed nuclei

$E_{SM} \approx 3$ MeV and $\Sigma B(M1) \approx 3 - 3.5 \mu_N^2$
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Exploiting data from ($\gamma,\gamma'$) it was derived a phenomenological sum rule by N. Lo Iudice and A. Richter, Phys. Lett. B304 (1993) 193

$$\sum B(M1) \uparrow \approx 0.0042 \frac{4NZA}{A^2} E_{SC} A^{5/3} (g_p - g_n)^2 \delta^2 \left[ \mu_N^2 \right]$$
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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

In well-deformed nuclei

\[ E_{\text{SM}} \approx 3 \text{ MeV} \text{ and } \Sigma B(M_1) \approx 3 - 3.5 \mu_N^2 \]

In odd nuclei \( \Sigma B(M_1,\text{odd}) \approx 1/3 \Sigma B(M_1,\text{e-e}) \) from \((\gamma,\gamma')\) ← problems with high Level Density
Scissors mode (SM) in $M1$ PSF (2)

SM on the excited states was observed for the first time in TSC experiment with $^{163}$Dy

*M. Krťčka at al., PRL 92 (2004) 172501*
Scissors mode (SM) in $M1$ PSF (2)

SM on the excited states was observed for the first time in TSC experiment with $^{163}$Dy

M. Krtička et al., PRL 92 (2004) 172501

Corridors predicted by simulations reflect fluctuations involved in the decay (mainly Porter-Thomas fluctuations)

Simulation assumption: Entire absence of the SM
Scissors mode (SM) in $M1$ PSF (2)

SM on the excited states was observed for the first time in TSC experiment with $^{163}$Dy

M. Krtička et al., PRL 92 (2004) 172501

Simulation assumption:
SM is built only on the states below the energy of 2.5 MeV
Scissors mode (SM) in $M1$ PSF (2)

SM on the excited states was observed for the first time in TSC experiment with $^{163}$Dy

M. Krtička at al., PRL 92 (2004) 172501

- $TT_f = +$
- $TT_f = -$

DICEBOX Simulations

Simulation assumption:
SM is built on all $^{163}$Dy levels
Scissors mode (SM) in $M_1$ PSF (2)

SM on the excited states was observed for the first time in TSC experiment with $^{163}$Dy.

$E_{SM} = 3.0$ MeV, $\Gamma_{SM} = 0.6$ MeV and $\Sigma B(M1)^{\uparrow} \approx 6 \, \mu_N^2$

Similar results are observed also in Oslo in $(^3$He, $x \gamma)$ reactions.

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M. Krtíčka at al., PRL 92 (2004) 172501
DANCE experiment at LANSCE

- Moderated W target gives “white” neutron spectrum ≈ 14 n’s / proton
- Repetition rate 20 Hz
- Pulse width ≈ 125 ns
- DANCE detector is placed on a 20m long flight path / ≈ 1 cm beam after collimation
- DANCE consists of 160 BaF$_2$ crystals
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 some information about the Photon Strength Functions (PSFs)
DANCE experiment at LANSCE (2)

- **TOF method** → neutron capture at strong isolated resonances
- The background for these strong resonances is very small or removable
DANCE experiment – data processing

Sum spectra for different multiplicities

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

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

Sum spectra for different multiplicities

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

Clusters:
- Cluster 1
- Cluster 2
- Cluster 3

Intensity (arb. units) vs. $E_\gamma$ (MeV)
DANCE experiment – data processing (2)

What do we really compare with the outputs of simulations?

Experimental MSC spectra

Sum spectra for different multiplicities
Simulations of gamma decay – DICEBOX (1)

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.
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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

$$\rho(E_i, J_i, \pi_i)$$
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Simulations of gamma decay – LD

Tested models of LD (total)

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

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

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

$$
\Gamma_{\gamma f} = \sum_{XJ} y^2_{iJ} \langle XJ \rangle^2 (E_i - E_f)^{2J+1} \frac{f(XJ) (E_i - E_f)}{\rho(E_i, J_i, \pi_i)}
$$
Simulations of gamma decay – PSFs

Tested models of PSFs: SLO, KMF and EGLO

$^{156}\text{Gd}$

Gamma-ray energy (MeV) vs. PSF ($\times 10^7$ MeV$^3$)

- SLO
- KMF
- EGLO (2.0,4.5)
- EGLO (4.0,4.5)
Simulations of gamma decay – PSFs

The energy of the SM is 3.0 MeV, damping width is 1.0 MeV and the strength $\Sigma B(M1, 2.7-3.7) \uparrow \approx 1.4 \, \mu_N^2$ (green) and $\Sigma B(M1, 2.7-3.7) \uparrow \approx 1.6 \, \mu_N^2$ (pink).
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:

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

PSFs
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:

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

Level density

P-T fluctuations

PSFs
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:

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

4. Partial radiation widths $\Gamma_{i\gamma f}$ for different initial and/or final levels are statistically independent.
Simulations of gamma decay – DICEBOX (5)

Nuclear Realization:

10^6 energy levels

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

System of precursors

Level Number

\begin{align*}
\text{Level} & \text{Number} \\
0 & s_1 \\
1 & s_2 \\
2 & s_3 \\
\end{align*}

Precursor

Excitation Energy

\begin{align*}
\zeta_{\alpha_1} & \quad E_{\alpha_1} \\
\zeta_{\alpha_2} & \quad E_{\alpha_2} \\
\zeta_{\alpha_c} & \quad E_{\alpha_c} \\
\zeta_{\alpha_3} & \quad E_{\alpha_3} \\
\end{align*}

P-T fluctuations

\[ P(x)dx = \frac{1}{\sqrt{2\pi}x} e^{-x^2/2} dx \]

\[ x = \Gamma_{i\gamma f}/\Gamma \]
The outputs of DICEBOX simulations are transformed to the form of Geant 4 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.
To obtain the information about the PSFs and LD we have to compare the experimental data with the outputs of simulations.

Experimental MSC spectra for two different resonances

Simulated MSC spectra produced by DICEBOX and Geant4 (grey corridors are produced mainly by the P-T fluctuations)
Results (1)

Simulation assumption:

KMF + SP + SP + BSFG(1)

KMF + SF + SP + SP + BSFG(1)
Results (2)

Simulation assumption:
KMF + SM + SF + SP + SP + BSFG(1)

SM postulated only above the GS

SM parametrazation:

\[ E_{SM} = 3.0 \text{ MeV}, \ \Gamma_{SM} = 1.0 \text{ MeV}, \]
\[ \sigma_{SM} = 0.2 \text{ mb} \]
Simulation assumption:

KMF + **SM** + SF + SP + SP + BSFG(1)

SM parametrazation:

\[ E_{SM} = 3.0 \text{ MeV}, \ \Gamma_{SM} = 1.0 \text{ MeV}, \ \sigma_{SM} = 0.2 \text{ mb} \]
Results (4)

Simulation assumption:
KMF + SM + SF + SP + SP + BSFG(1)

SM parametrazation:

\[ E_{SM} = 3.0 \text{ MeV}, \quad \Gamma_{SM} = 1.0 \text{ MeV}, \quad \sigma_{SM} = 0.2 \text{ mb} \]
Our results on $^{158}$Gd were published in PRC 84 (2011) 014306

DANCE result for SM in $^{158}$Gd: $E_{SM} = 3.0(1)$ MeV, $\Gamma_{SM} = 1.0(2)$ MeV, $\Sigma B(M1,2.7-3.7) < 1.5 \mu_N^2$


$(\gamma,\gamma')$ exp. results for SM in $^{158}$Gd: $\Sigma B(M1,2.7-3.7) = 3.71(59) \mu_N^2$
Our results on $^{158}$Gd were published in PRC 84 (2011) 014306

DANCE result for SM in $^{158}$Gd: $E_{\text{SM}} = 3.0$ MeV, $\Gamma_{\text{SM}} = 1.0$ MeV, $\Sigma B(M1, 2.7-3.7) < 1.5 \mu_N^2$

($\gamma, \gamma'$) exp. results for SM in $^{158}$Gd: $\Sigma B(M1, 2.7-3.7) = 3.71(59) \mu_N^2$

Comparison of DANCE data for $^{158}$Gd with the results from Oslo ($^3$He, $\alpha$) exp. on $^{160}$Dy, $^{162}$Dy and experiments with the reaction $^{160}$Gd($\gamma$,n)
We are processing data from DANCE experiment on $^{156}$Gd

Preliminary results for $^{156}$Gd: $E_{\text{SM}} = 3.0$ MeV, $\Gamma_{\text{SM}} = 1.0$ MeV, $\Sigma B(M1, 2.7-3.7) < 2.0 \, \mu_N^2$

($\gamma, \gamma'$) exp. results for SM in $^{156}$Gd: $\Sigma B(M1, 2.7-3.7) = 2.73(27) \, \mu_N^2$
We are processing also data from **DANCE experiment on** $^{153}\text{Gd}$, $^{155}\text{Gd}$, $^{157}\text{Gd}$, $^{159}\text{Gd}$
Comparison of very preliminary results obtained for $^{153}\text{Gd}$ and $^{159}\text{Gd}$
Results (8)

Comparison of very preliminary results obtained for $^{153}$Gd and $^{159}$Gd

$^{159}$Gd
Simulation assumption:
KMF + SP + SP + BSFG(1)

$^{159}$Gd
Simulation assumption:
KMF + SF + SP + SP + BSFG(1)
Simulation assumption:

\[KMF + SM + SF + SP + SP + BSFG(1)\]

153Gd

\[E_{SM} = 2.9 \text{ MeV}, \quad \Gamma_{SM} = 1.0 \text{ MeV}, \quad \sigma_{SM} = 0.2 \text{ mb}\]

SM built on all 153Gd levels

159Gd

\[E_{SM} = 3.0 \text{ MeV}, \quad \Gamma_{SM} = 0.9 \text{ MeV}, \quad \sigma_{SM} = 0.2 \text{ mb}\]

SM built on all 159Gd levels

Results (9)

Comparison of very preliminary results obtained for 153Gd and 159Gd
Comparison of very preliminary results obtained for $^{153}\text{Gd}$ and $^{159}\text{Gd}$

**$^{153}\text{Gd}$**

Simulation assumption:

\[ \text{KMF + SM + SF + SP + BSFG(1)} \]

\[ E_{SM} = 2.9 \text{ MeV}, \; \Gamma_{SM} = 1.0 \text{ MeV}, \; \sigma_{SM} = 0.2 \text{ mb} \]

SM built on all $^{153}\text{Gd}$ levels

**$^{159}\text{Gd}$**

Simulation assumption:

\[ \text{KMF + SM + SF + SP + BSFG(1)} \]

\[ E_{SM} = 3.0 \text{ MeV}, \; \Gamma_{SM} = 0.9 \text{ MeV}, \; \sigma_{SM} = 0.5 \text{ mb} \]

SM built on all $^{159}\text{Gd}$ levels
Results (9)

Comparison of very preliminary results obtained for $^{153}$Gd and $^{159}$Gd

$^{153}$Gd

Simulation assumption:
KMF + SM + SF + SP + BSFG(1)

$E_{SM} = 2.9$ MeV, $\Sigma B(M1,2.7-3.7) \approx 1.5 \mu_N^2$

SM built on all $^{153}$Gd levels

$^{159}$Gd

Simulation assumption:
KMF + SM + SF + SP + BSFG(1)

$E_{SM} = 3.0$ MeV, $\Sigma B(M1,2.7-3.7) \approx 3.5 \mu_N^2$

SM built on all $^{159}$Gd levels
Comparison of very preliminary results obtained for $^{153}$Gd and $^{159}$Gd

$^{153}$Gd Simulation assumption:

KMF + SM + SF + SP + BSFG(1)

$E_{SM} = 2.9$ MeV, $\Gamma_{SM} = 1.0$ MeV, $\sigma_{SM} = 0.2$ mb

SM only above the GS

$^{159}$Gd Simulation assumption:

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$E_{SM} = 3.0$ MeV, $\Gamma_{SM} = 0.9$ MeV, $\sigma_{SM} = 0.5$ mb

SM only above the GS
Comparison of very preliminary results obtained for $^{153}\text{Gd}$ and $^{159}\text{Gd}$

**$^{153}\text{Gd}$**

Simulation assumption:

KMF + SM + SF + SP + SP + BSFG(1)

$E_{\text{SM}} = 2.9$ MeV, $\Gamma_{\text{SM}} = 1.0$ MeV, $\sigma_{\text{SM}} = 0.2$ mb

**$^{159}\text{Gd}$**

Simulation assumption:

KMF + SM + SF + SP + SP + BSFG(1)

$E_{\text{SM}} = 3.0$ MeV, $\Gamma_{\text{SM}} = 0.9$ MeV, $\sigma_{\text{SM}} = 0.5$ mb
Conclusions

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

- In case of $^{158}$Gd we have obtained $\Sigma B(M1, 2.7-3.7) < 1.5 \mu_N^2$. This value is in disagreement with the NRF experiments.

- SM resonances are built not only on the GS but also on excited levels in all studied Gd isotopes.

- The $E1$ origin of the resonance-like structures in the MSC spectra of studied Gd isotopes is unambiguously excluded.

- Difference between $\Sigma B(M1)$ in $^{156,158}$Gd and $^{157,159}$Gd may be the illustration of the odd nucleon effect to the nuclear deformation.
DANCE collaboration

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Thank you for your attention!