Scissors Mode of Gd nuclei studied from resonance neutron capture at DANCE

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Outline

- Motivation
- 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:

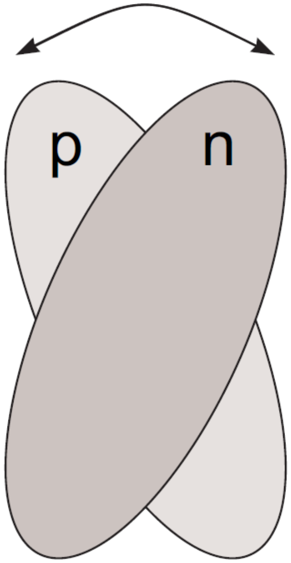
*N. Lo Iudice and F. Palumbo, PRL **53** (1978) 1532*
R. R. Hilton, in Proceedings of the International Conference on Nuclear Structure, Dubna, 1976

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

*D. Bohle at al., Phys. Lett. **B137** (1984) 27*

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 $\Sigma B(M1) \approx 3 - 3.5\ \mu_N^2$.



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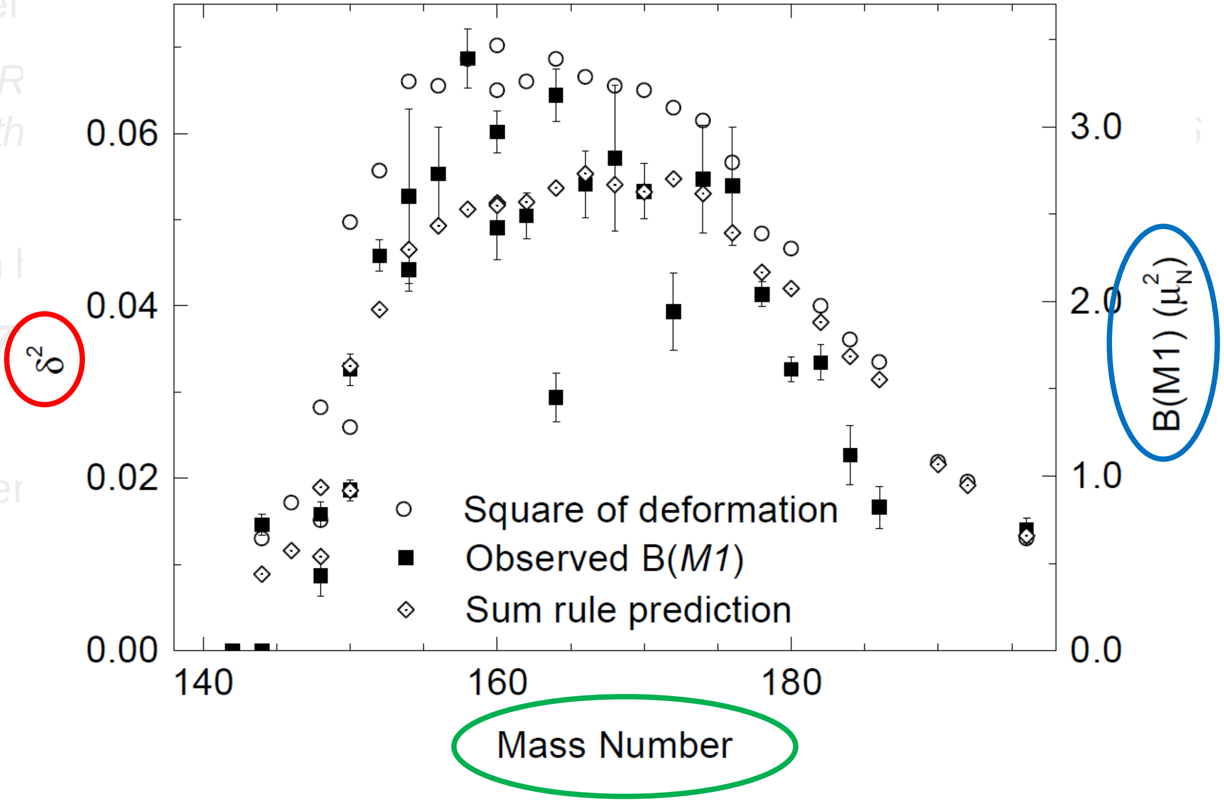
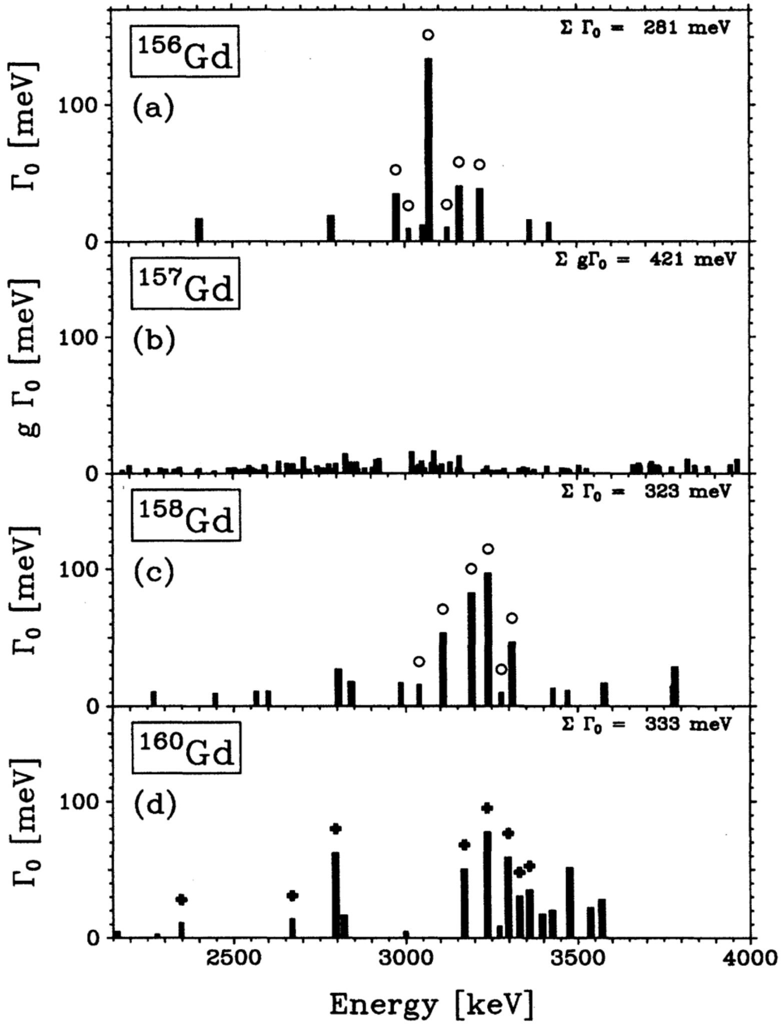
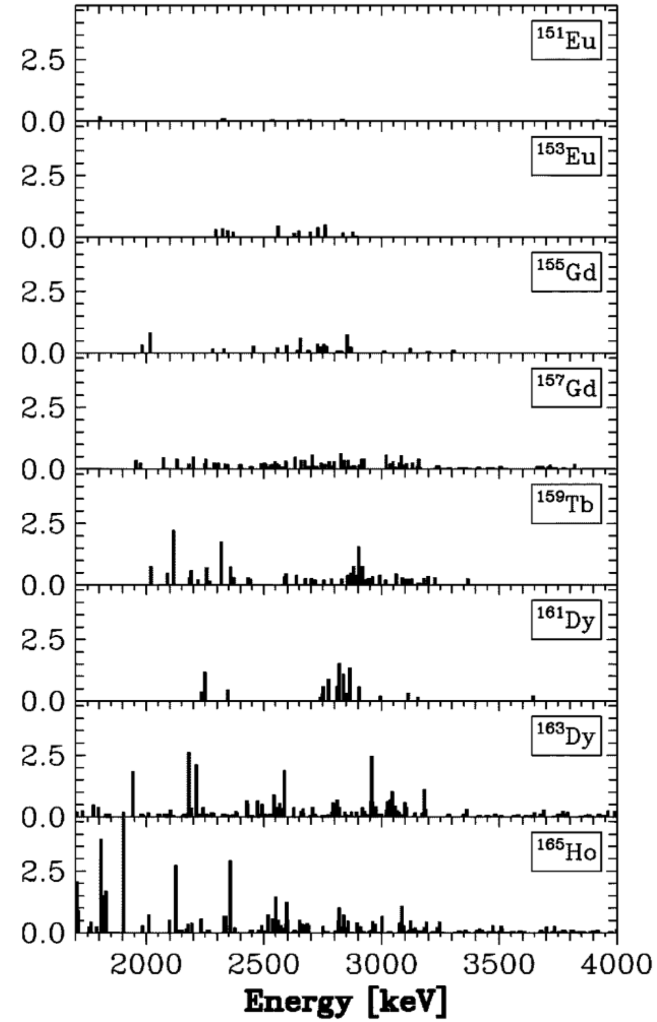


Exploiting data from (γ,γ') – a sum rule was derived by *N. Lo Iudice and A. Richter, Phys. Lett.* ***B304*** *(1993) 193*

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

Scissors mode (SM) in $M1$ PSF



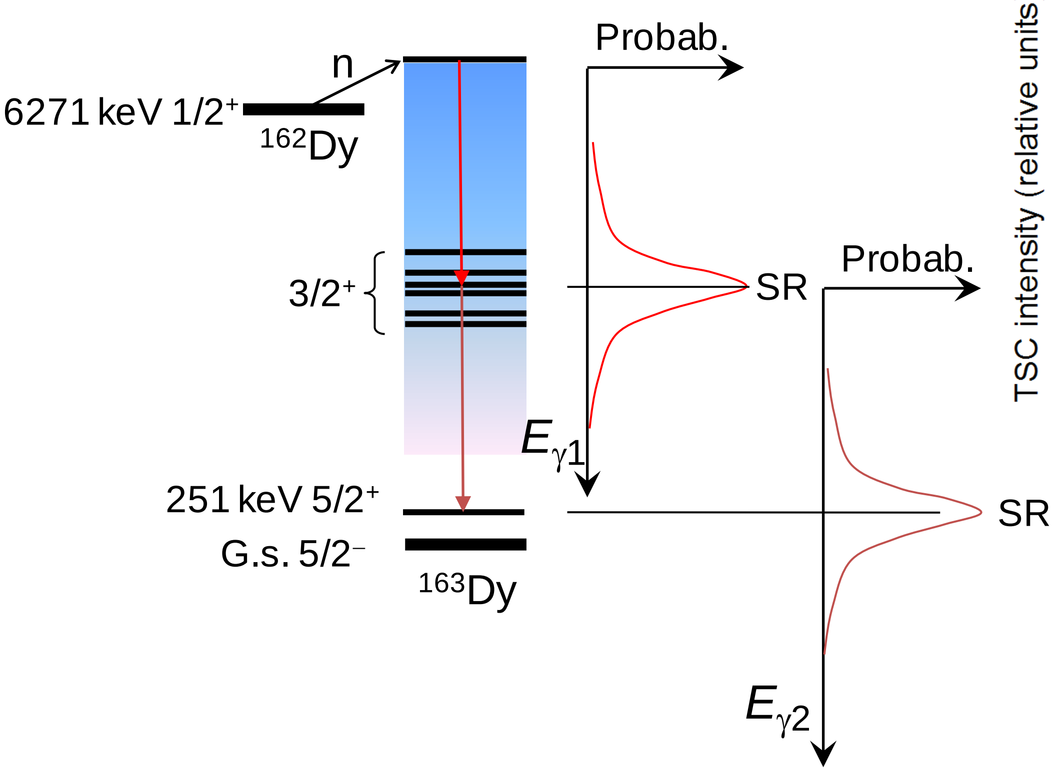


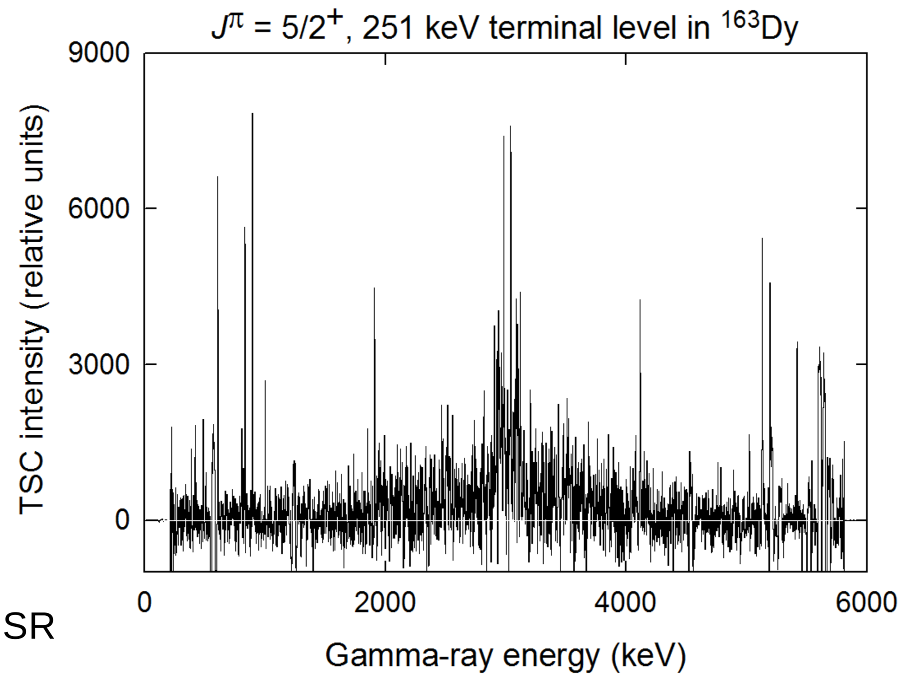
In odd nuclei $\Sigma B(M1,\text{odd}) \approx 1/3\ \Sigma B(M1,\text{e-e})$ from (γ,γ') ← problems with high NLD

Scissors mode in *M*1 PSF observed from (n,γ) reactions

SM on the excited states was observed for the first time in TSC experiment with ^{163}Dy in 1995

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





To get TSC spectra for separate final levels, the sum coincidence method was used

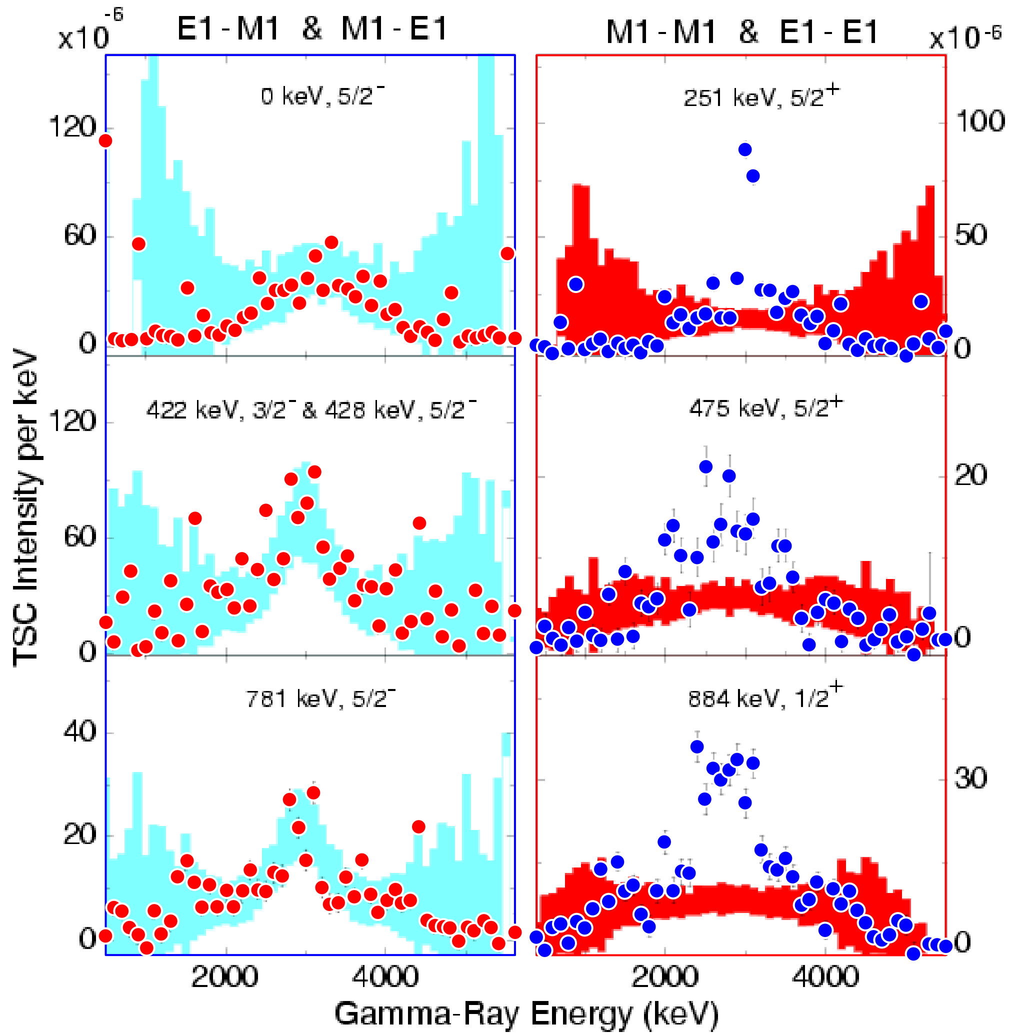
J. Honzátko et al., NIM A376 (1996) 434 .

Scissors mode in $M1$ PSF observed from (n,γ) reactions

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*

π_f = +
π_f = -
DICEBOX Simulations



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.

Scissors mode in *M*1 PSF observed from (n,γ) reactions

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

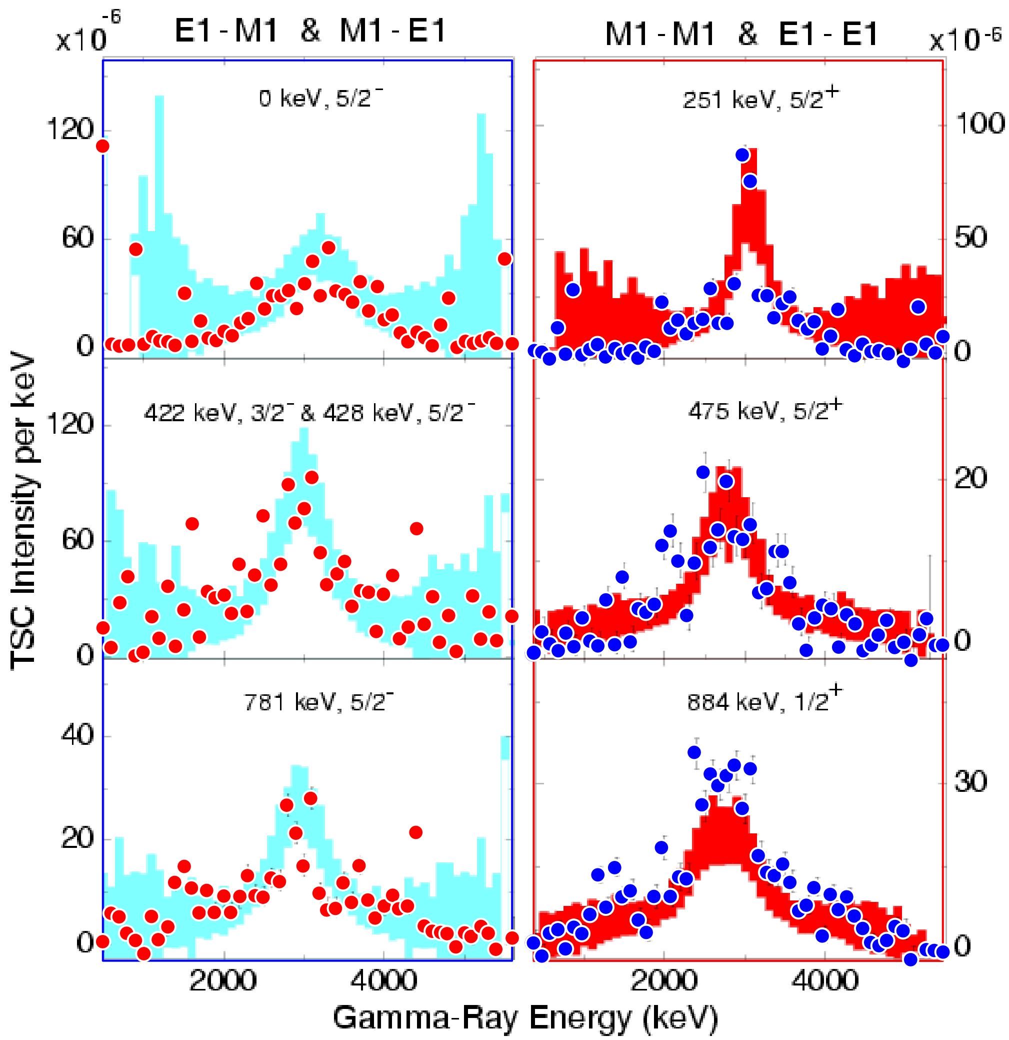
*M. Krtička at al., PRL **92** (2004) 172501*

π_f = + (red), π_f = - (cyan) } DICEBOX Simulations

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

Simulation assumption:

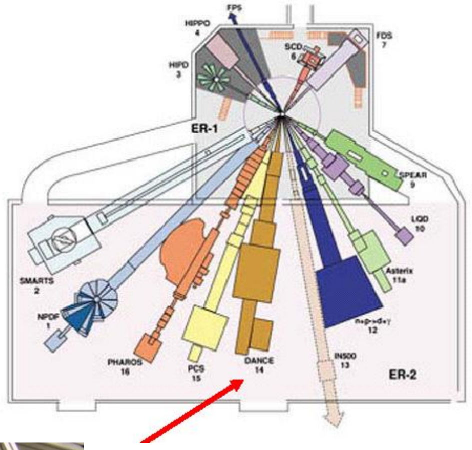
SM is built on all ^{163}Dy levels

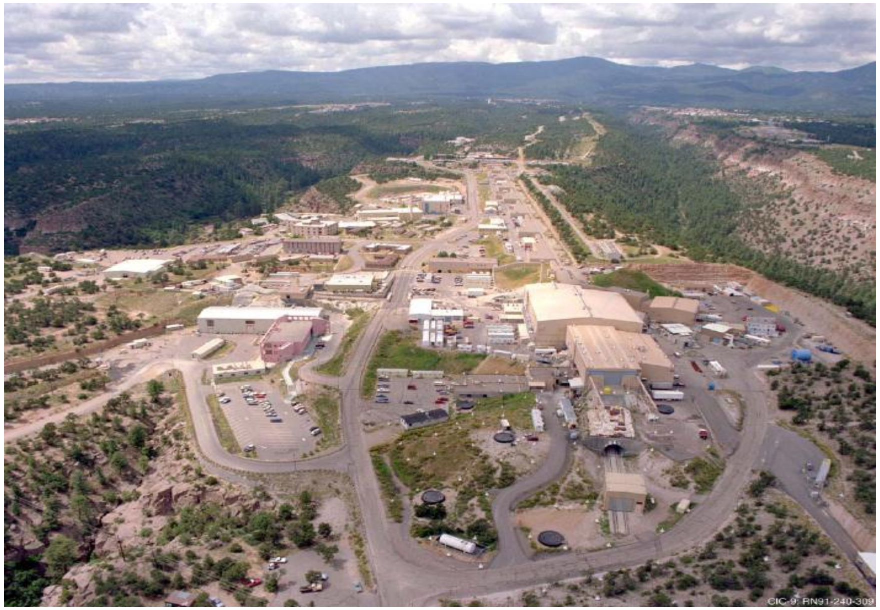


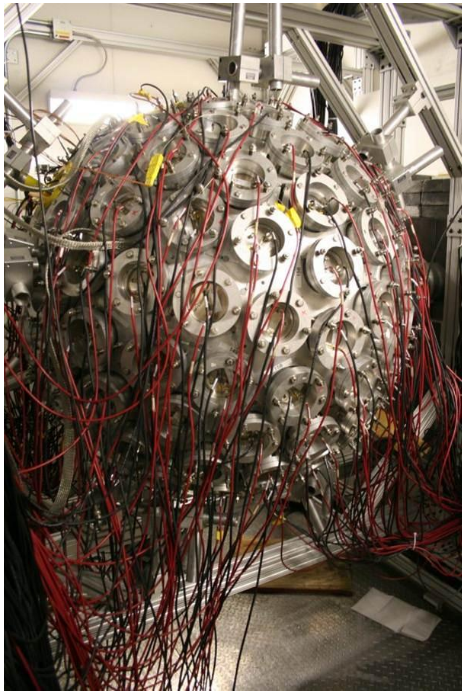
Corridors represent the region of residual Porter-Thomas fluctuations.

DANCE experiment at LANSCE

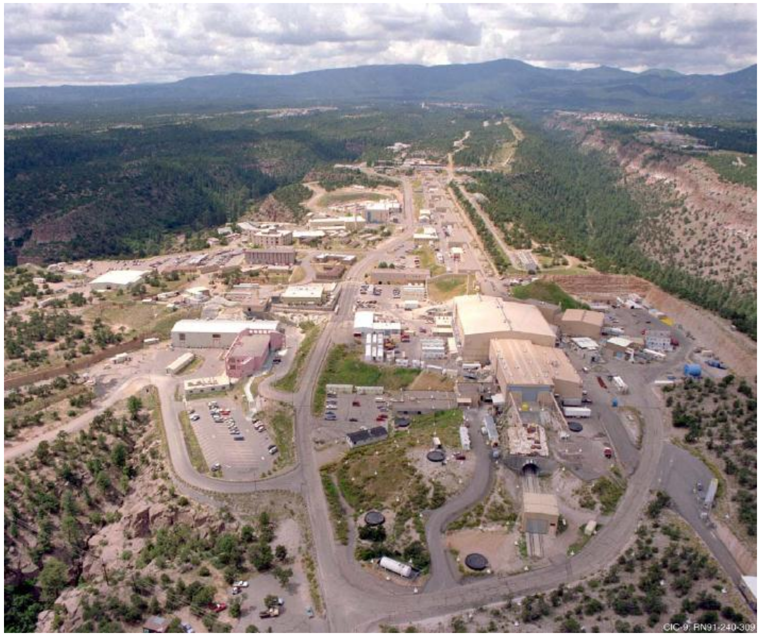
- Moderated W target gives “white” neutron spectrum ≈ 14 n’s / proton
- Repetition rate 20 Hz
- Pulse width ≈ 125 ns
- DANCE detector is placed on a 20m long flight path / ≈ 1 cm beam after collimation
- DANCE consists of 160 BaF_2 crystals







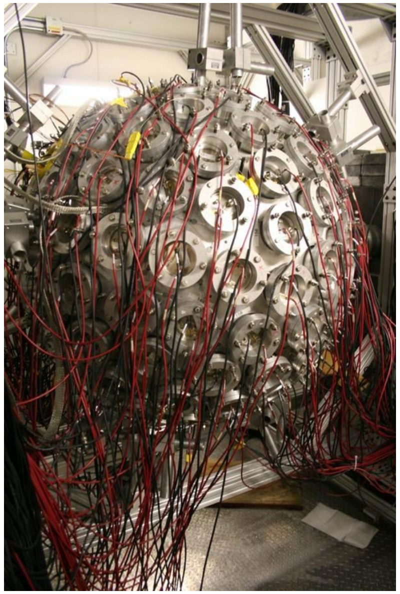
DANCE experiment at LANSCE

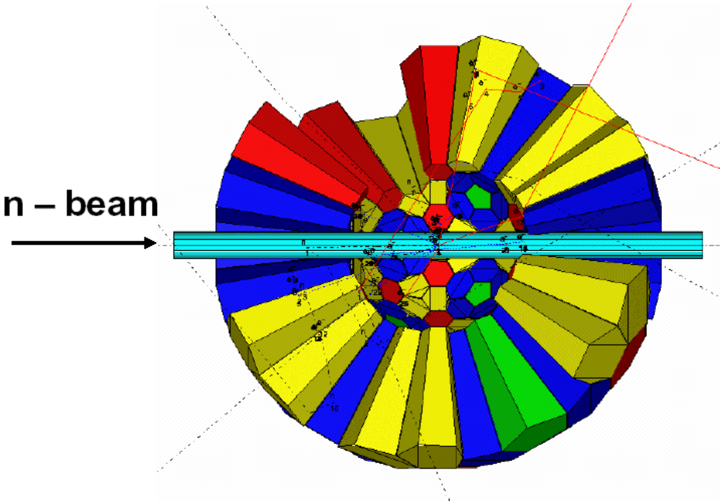


With a DANCE detector we have measured stable Gd isotopes

^{153}Gd, ^{155}Gd, ^{156}Gd, ^{157}Gd, ^{158}Gd, ^{159}Gd

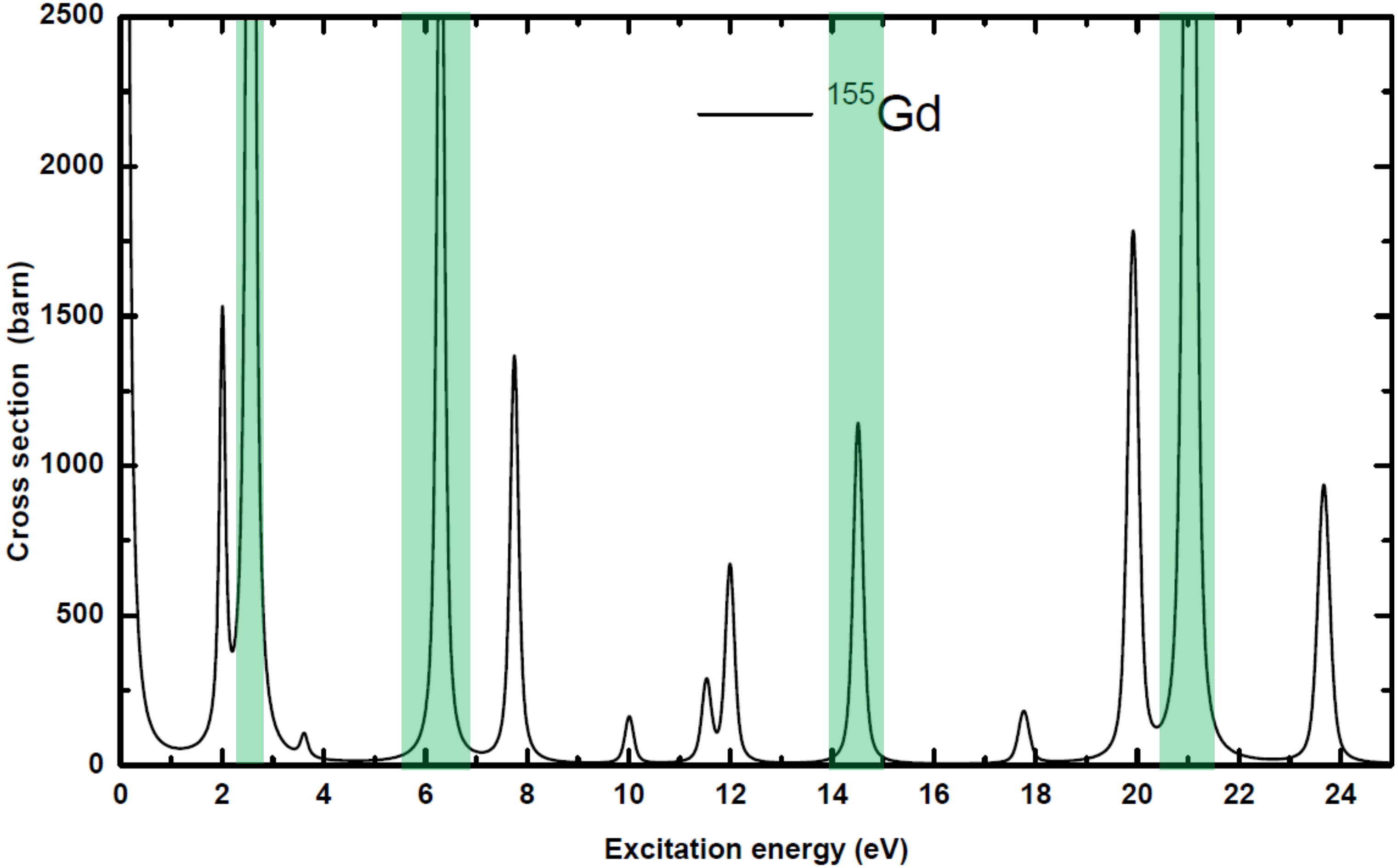
mainly to get information about the Photon Strength Functions (PSFs)



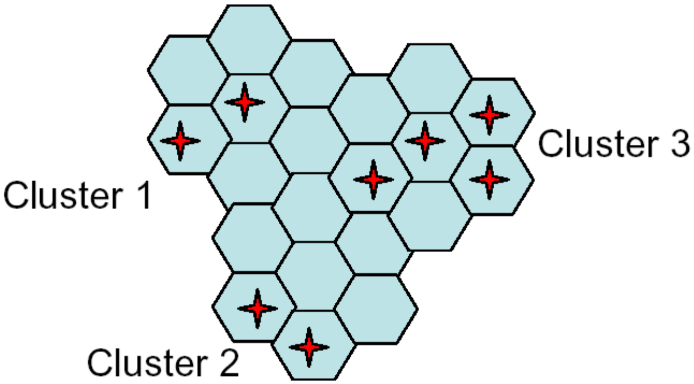


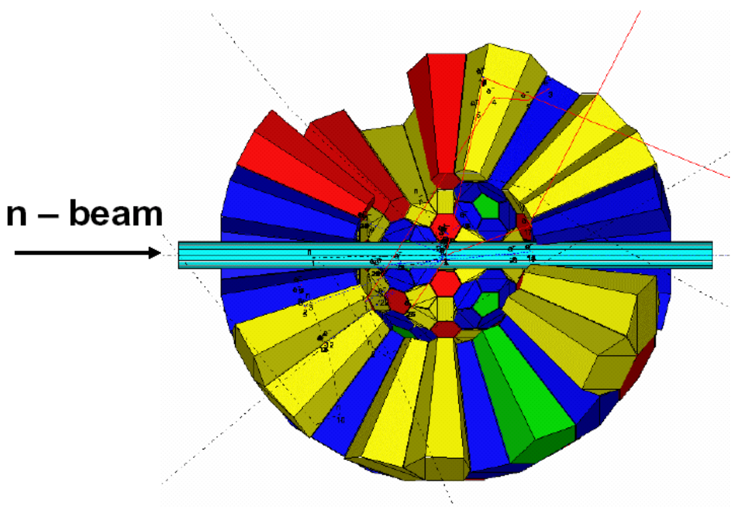
DANCE experiment at LANSCE

- **TOF method** → neutron capture at strong isolated resonances
- The background for these strong resonances is very small (can be subtracted)

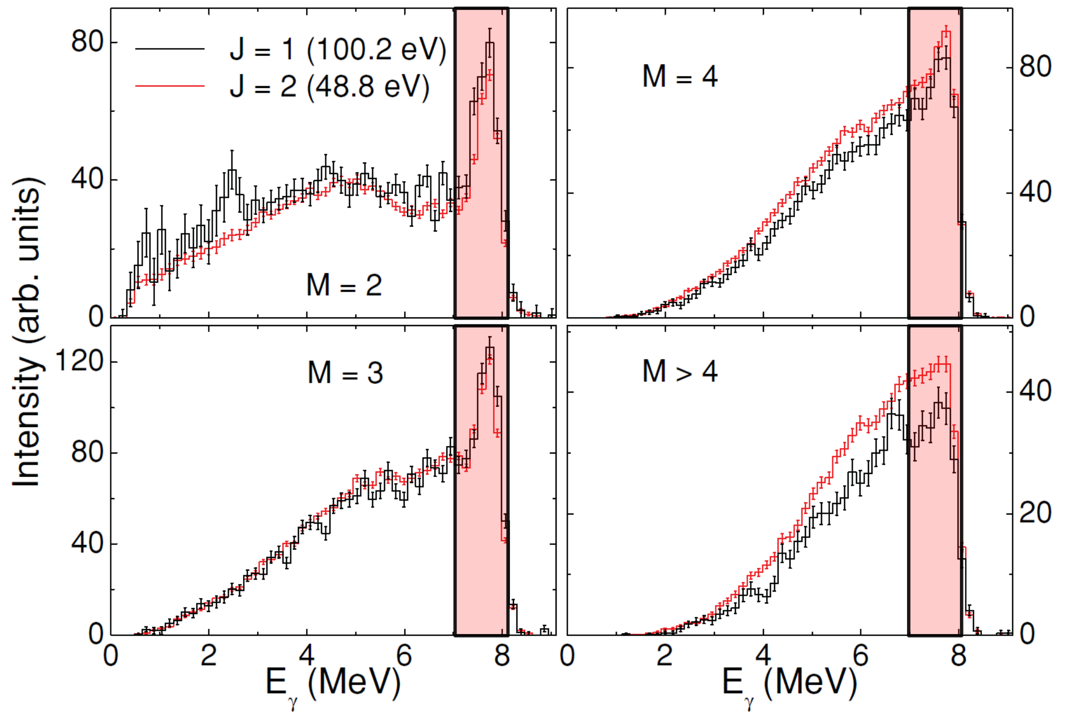


DANCE experiment – data processing





Sum spectra for different multiplicities

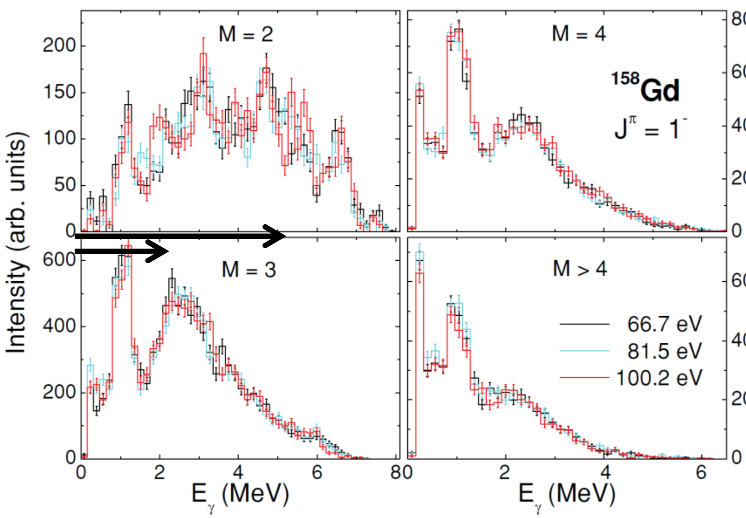


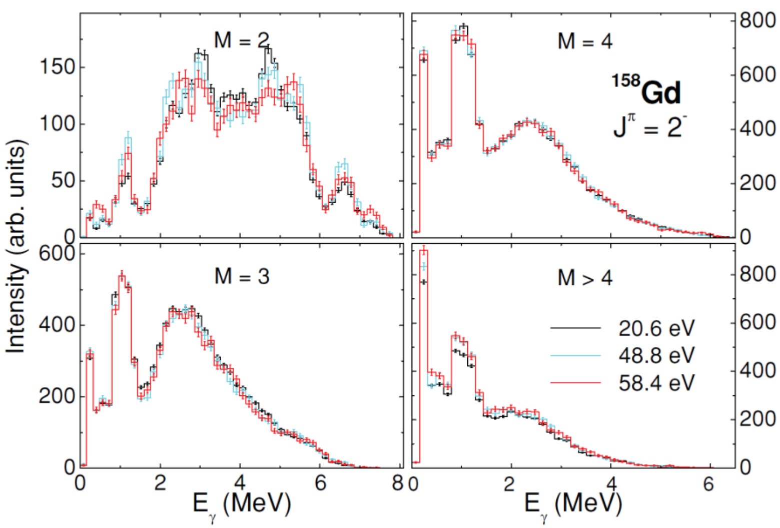
*M. Heil et al., NIM Phys. Res. A **459**, 229 (2001).*
*R. Reifarth et al., NIM Phys. Res. A **531**, 530 (2004).*

DANCE experiment – data processing

What do we really compare with the outputs of simulations?

Experimental MSC spectra





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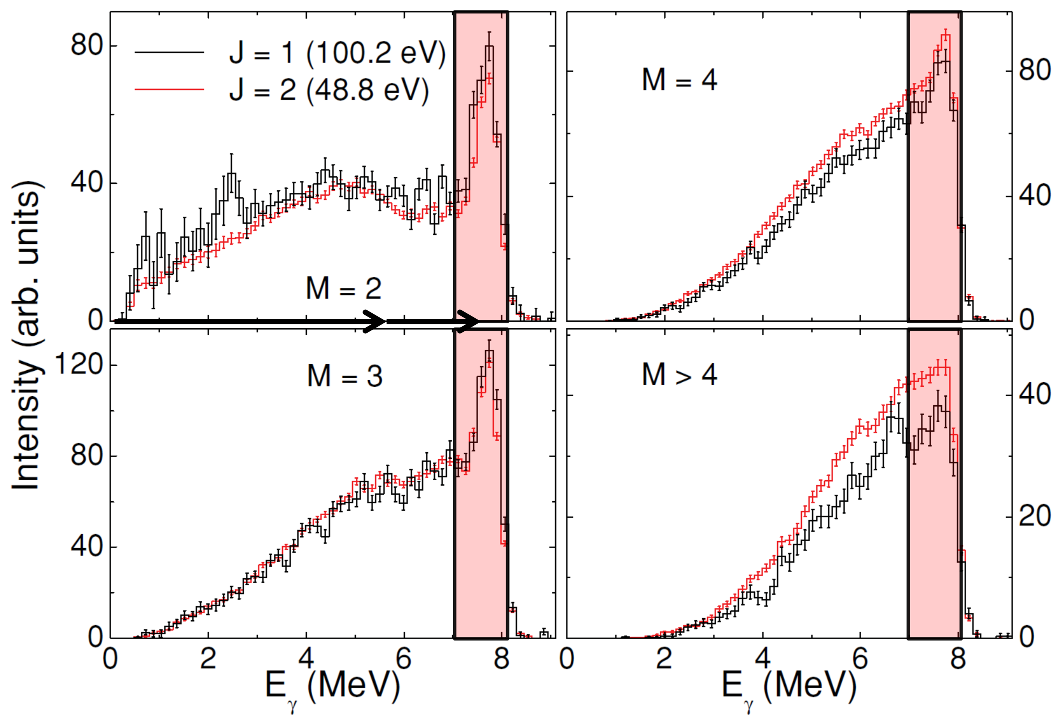

Simulations of gamma decay – DICEBOX

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

Simulations of gamma decay – DICEBOX

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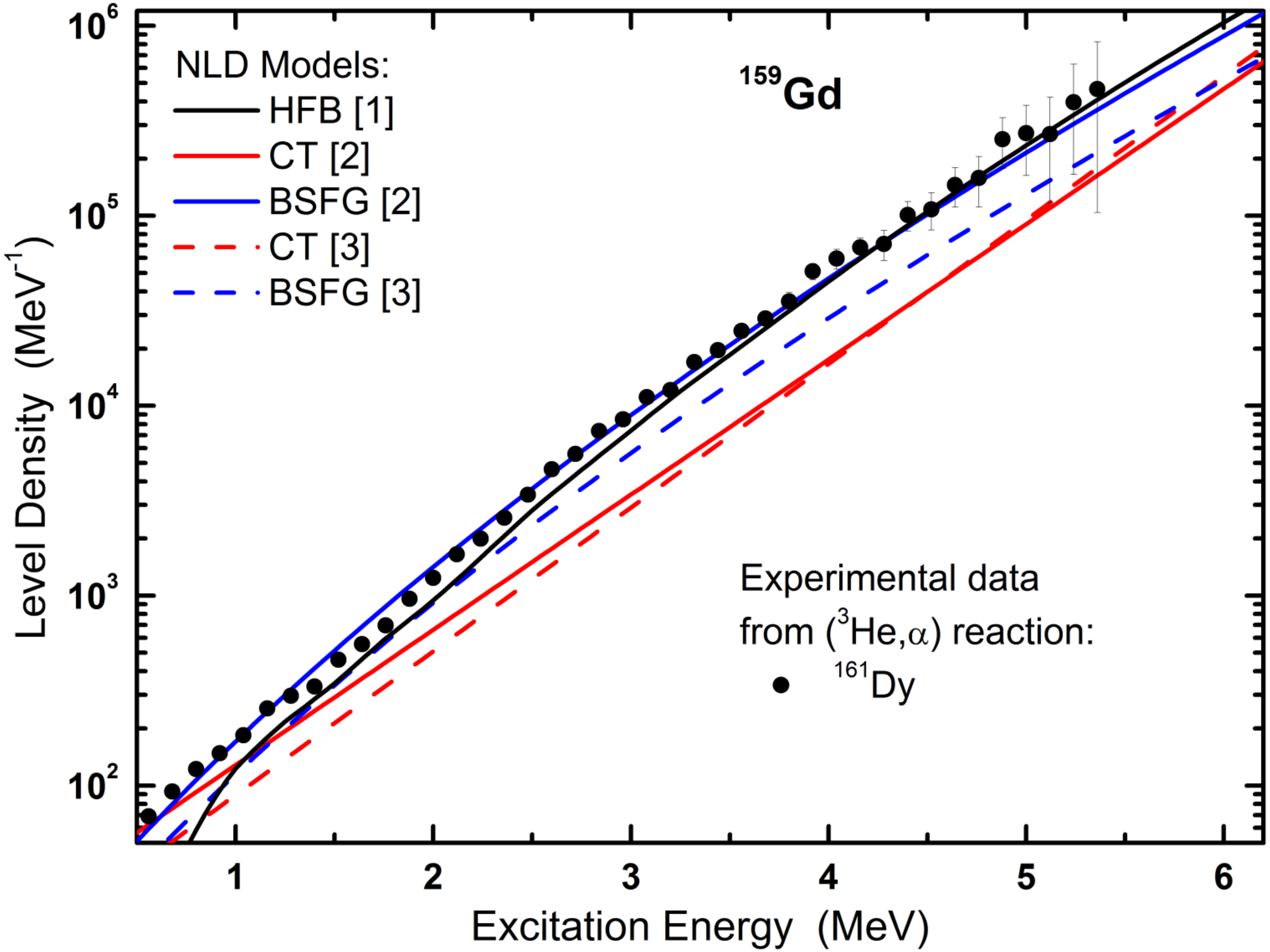
2. Above the critical energy E_{crit} the energies *E*, spins *J* and parities π of levels are obtained by random discretization of an *a priory* known level density

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

Level density

Simulations of gamma decay – NLD



[1] R. Capote *et al*., Nucl. Data Sheets **110**, 3107 (2009).
[2] T. von Egidy and D. Bucurescu, Phys. Rev. **C72**, 044311 (2005).
[3] T. von Egidy and D. Bucurescu, Phys. Rev. **C80**, 054310 (2009).

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Level density

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

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

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PSFs

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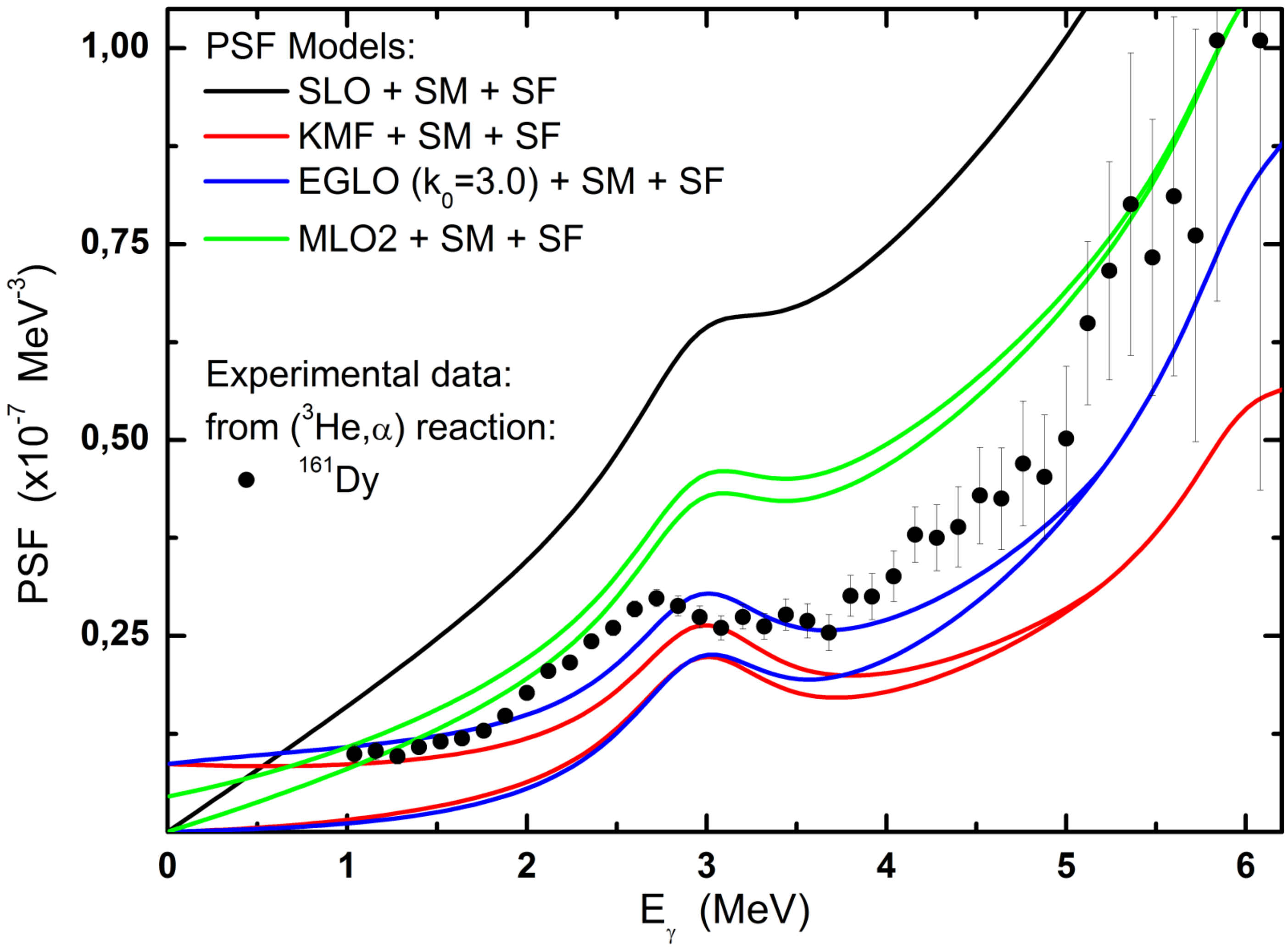
Simulations of gamma decay – PSFs



The energy of the SM is 3.0 MeV, damping width is 1.0 MeV and the strength $\Sigma B(M1, 2.7\text{-}3.7)\uparrow \approx 3.39\ \mu_N^{2}$.

Simulations of gamma decay – DICEBOX

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P-T fluctuations

PSFs

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Level density

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P-T fluctuations

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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 leves

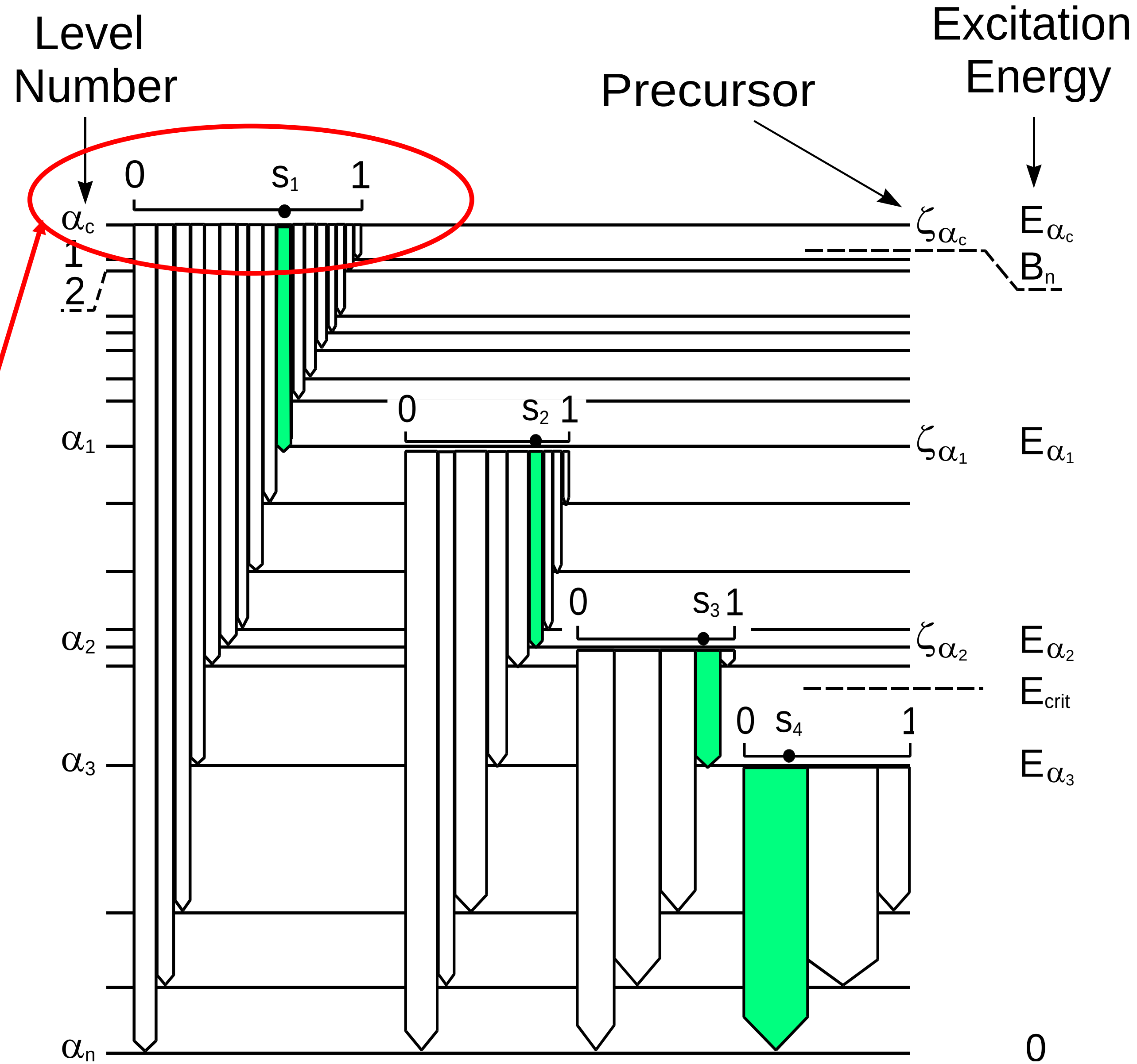
$10^{12}\ \Gamma_{i\gamma f}$

System of precursors

P-T fluctuations

$$P(x)dx = \frac{1}{\sqrt{2\pi x}} e^{-x/2} \mathrm{d}x$$

$$x = \Gamma_{i\gamma f}/\overline{\Gamma}$$

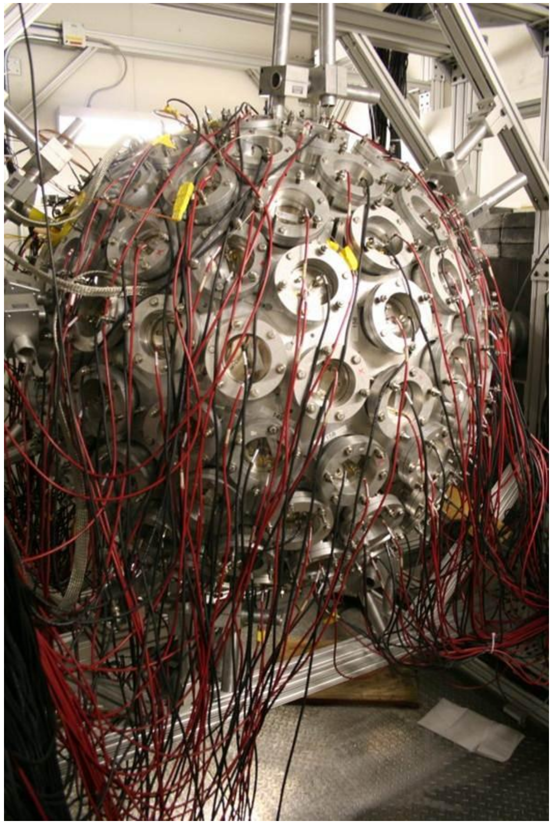


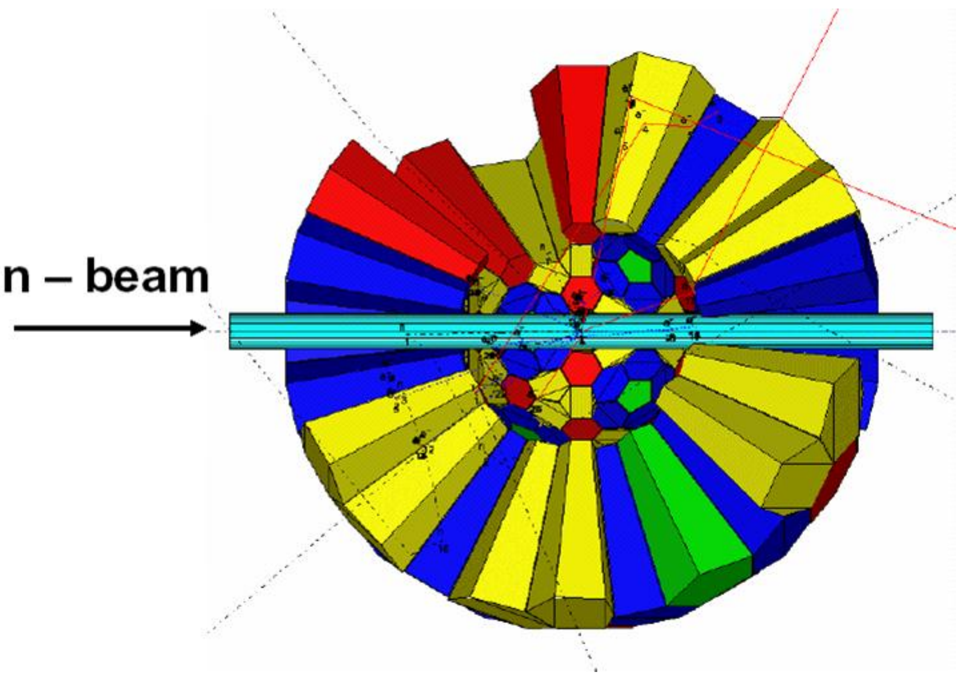
F. Bečvář, NIM A417 (1998) 434

Detector response – Geant4

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

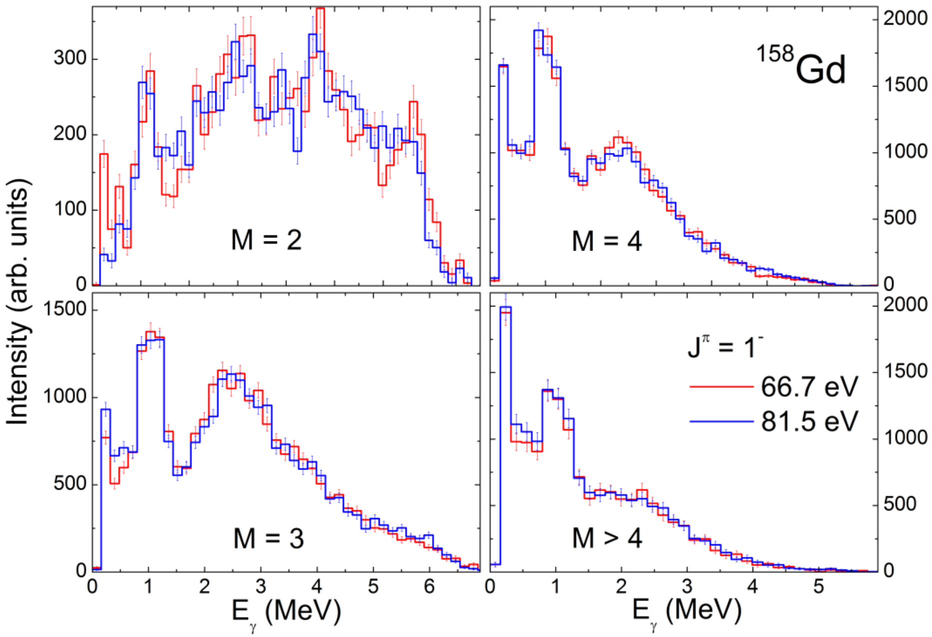
- Simulations of detector response include the exact geometry and chemical composition (regular and irregular pentagonal and hexagonal BaF_2 crystals), all shielding, aluminium beamline, radioactive target holder, etc.



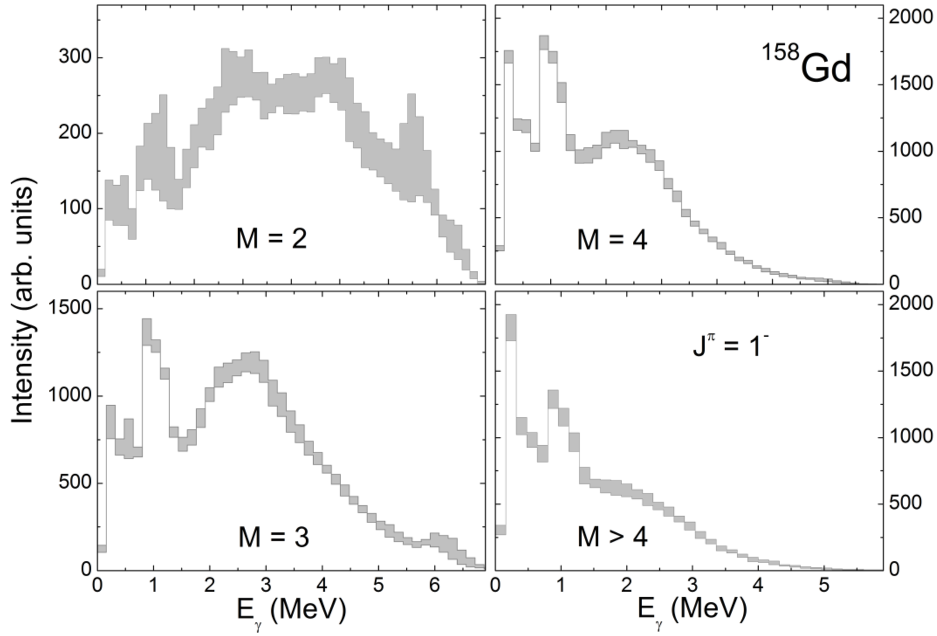


Comparison of experimental data with the outputs of simulations

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

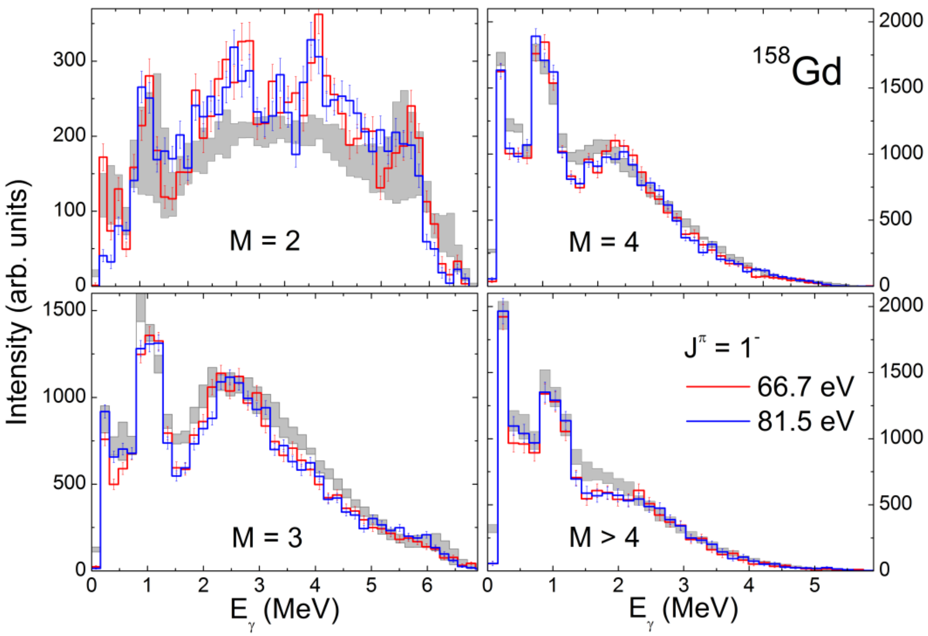


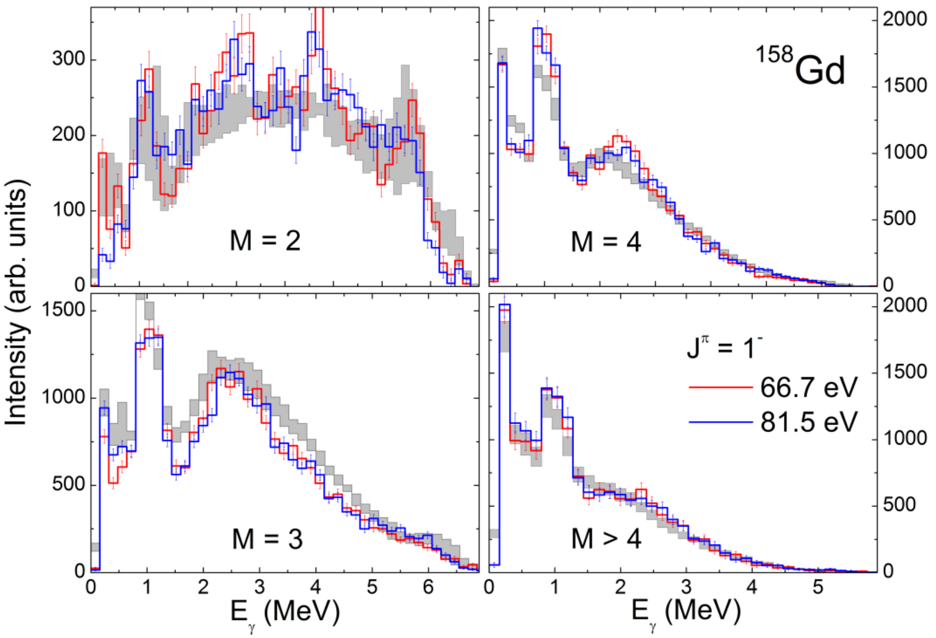
Experimental MSC spectra for two different resonances with $J^{\pi} = 1^{-}$



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

SM in even nuclei





Simulation assumption:

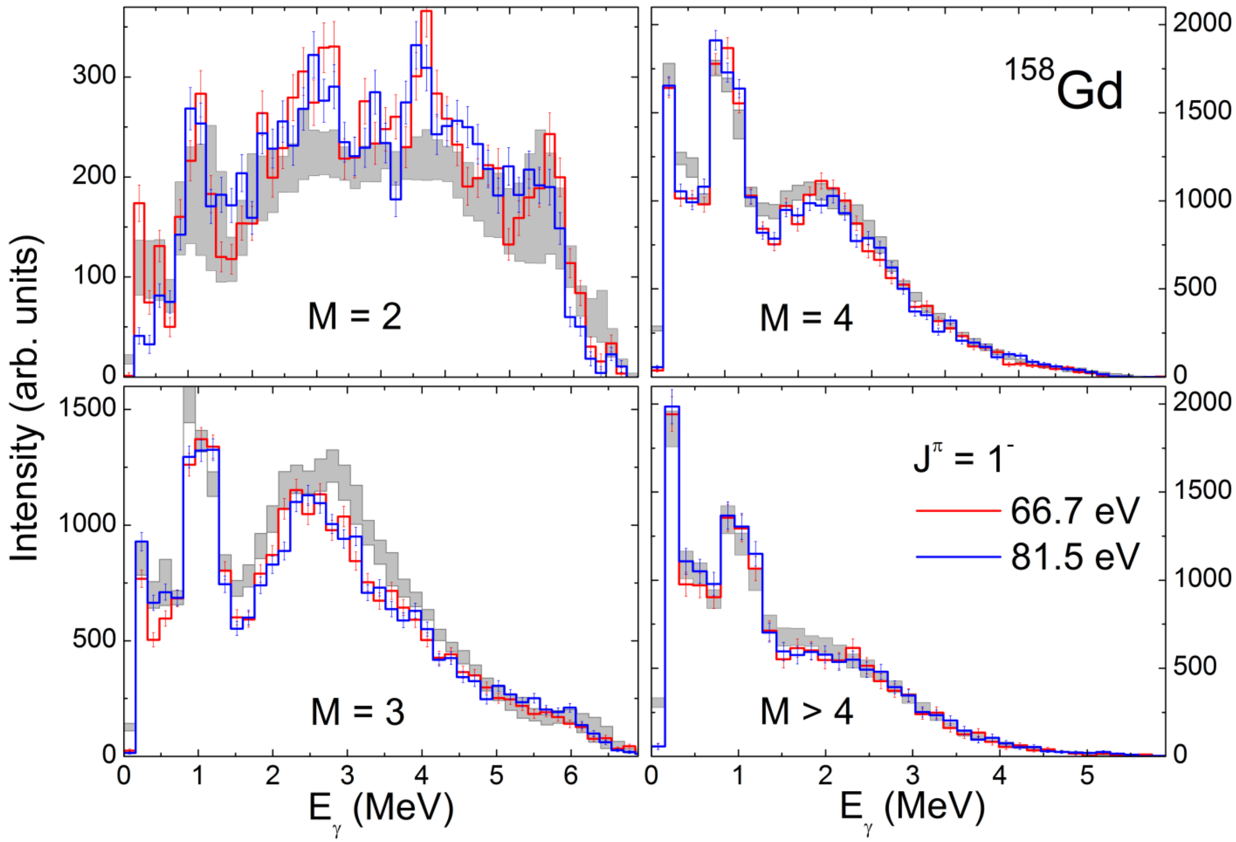
KMF + **SP** + SP + BSFG(1)

***E*1** ***M*1** ***E*2** **LD**

Simulation assumption:

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

SM in even nuclei



Simulation assumption:

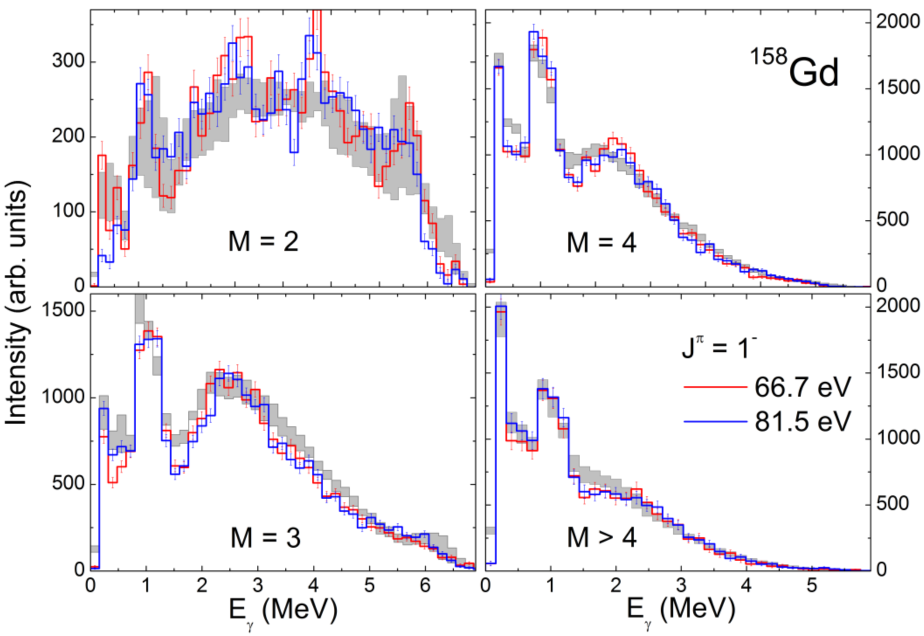
KMF + RS **+ SF + SP** + SP + BSFG(1)

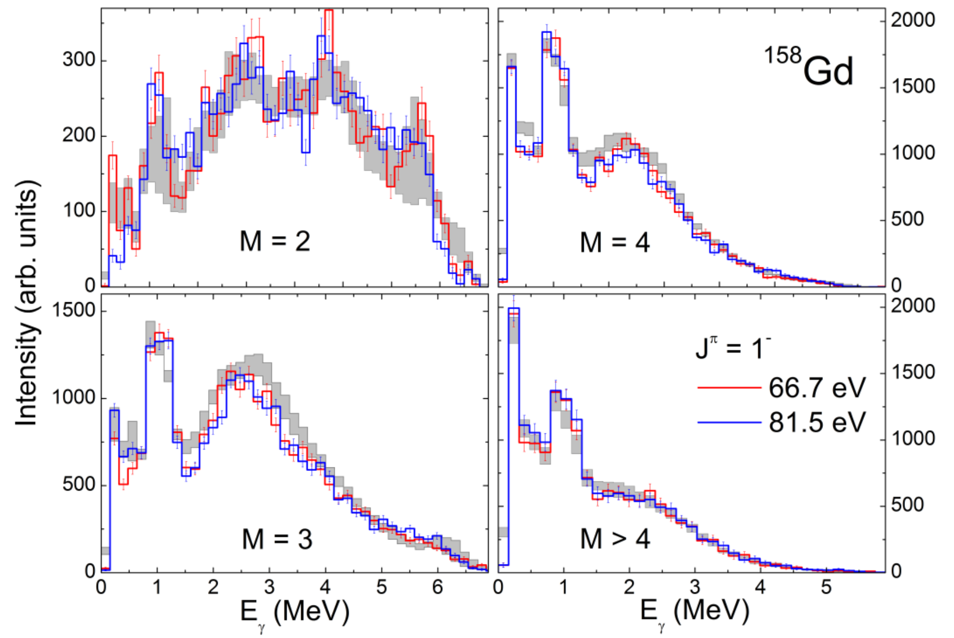
RS parametrization:

E_{RS} = 3.0 MeV, Γ_{RS} = 1.0 MeV,

$\Sigma B(E1,\mathrm{RS}) \approx 2.0\ \mu_N^2$

SM in even nuclei





^{158}Gd simulation assumption:

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

E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM postulated only on the GS

^{158}Gd simulation assumption:

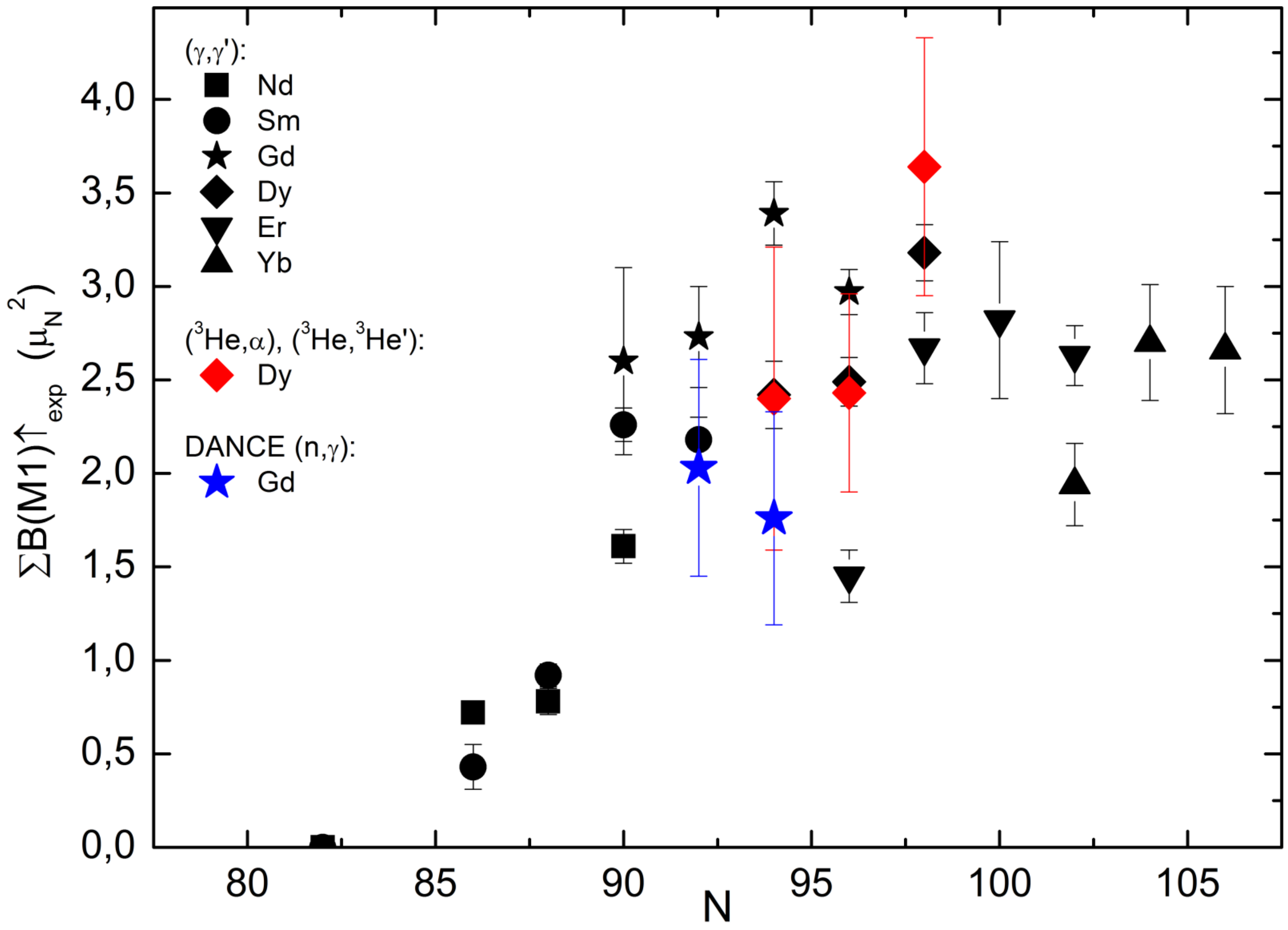
KMF + **SM + SF + SP** + SP + BSFG(1)

E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built on all levels

ΣB(*M1*,2.7-3.7)↑ in even nuclei



NRF data [black] *U. Kneissl et al., Prog. Part. Nucl. Phys.* ***37*** *349 (1996).*

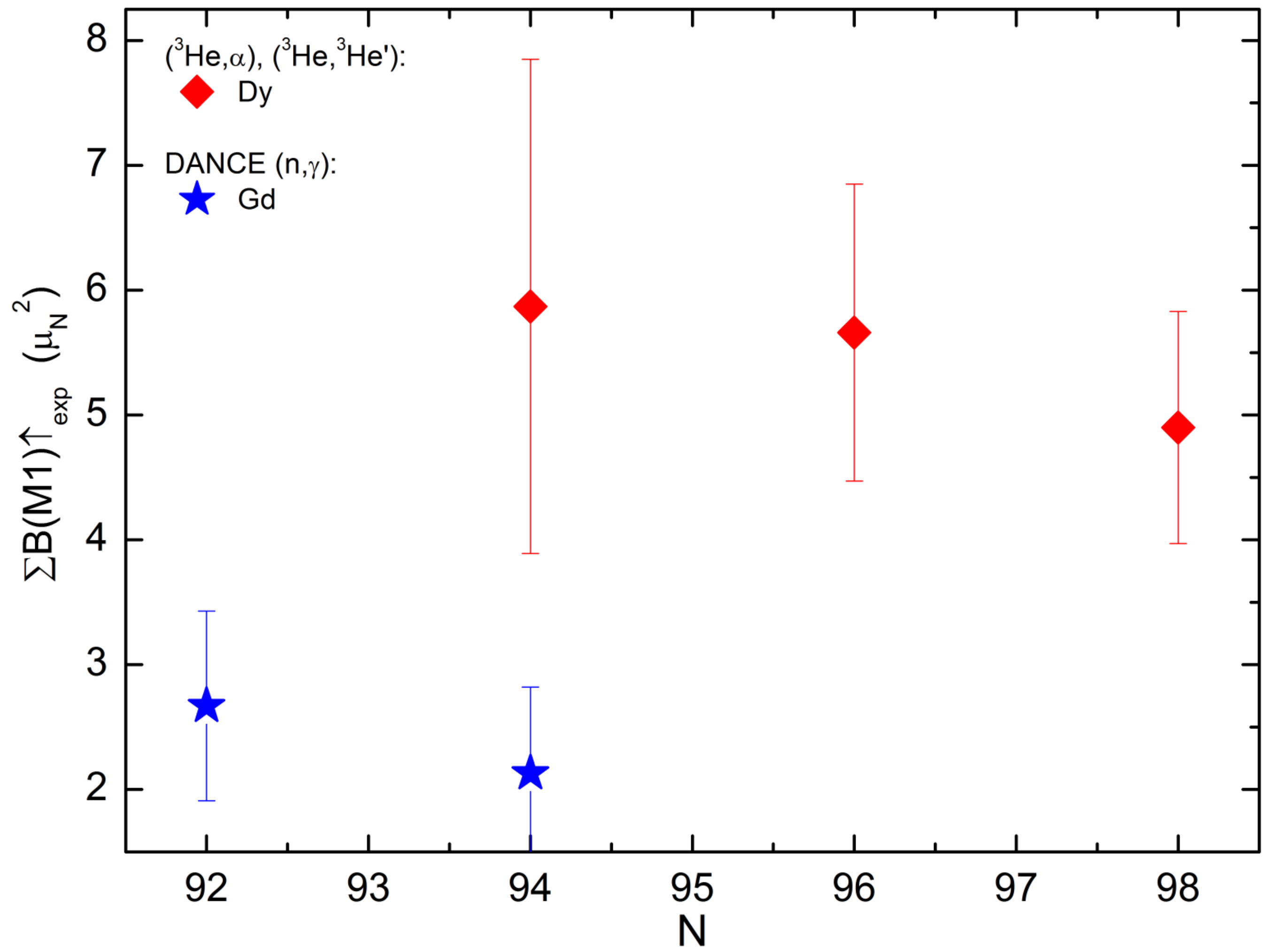
^{160,162}Dy [red] *M. Guttormsen et al., PRC* ***68****, 064306 (2003).*

^{164}Dy [red] *H.T. Nyhus et al., PRC* ***81****, 024325 (2010).*

^{158}Gd [blue] *A. Chyzh et al., PRC* ***84****, 014306 (2011).*

^{156}Gd [blue] *B. Baramsai et al., submitted to PRC.*

ΣB(*M1*,SM)↑ in even nuclei



^{160,162}Dy [red] *M. Guttormsen et al., PRC **68**, 064306 (2003).*
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^{158}Gd [blue] *A. Chyzh et al., PRC **84**, 014306 (2011).*
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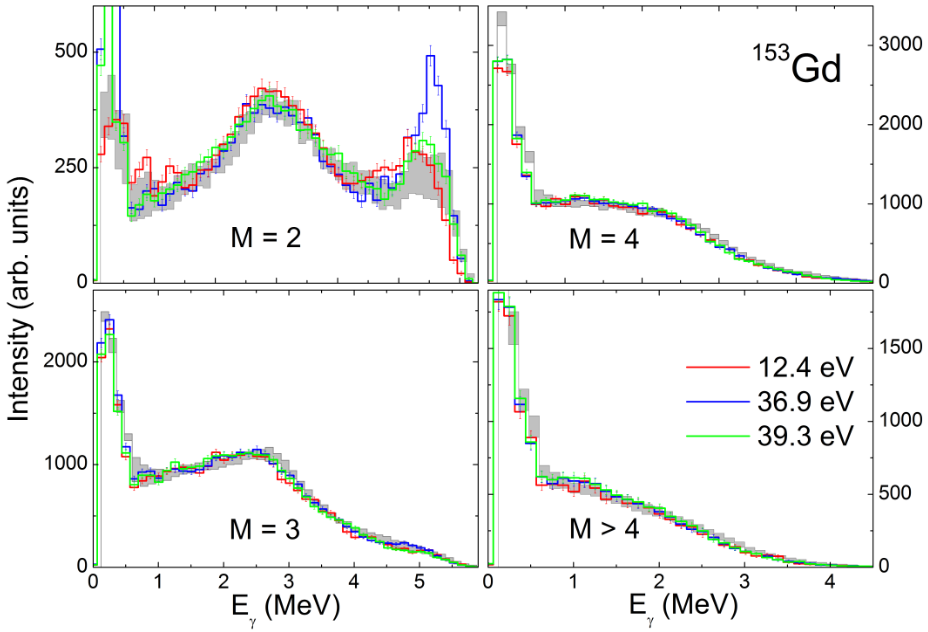
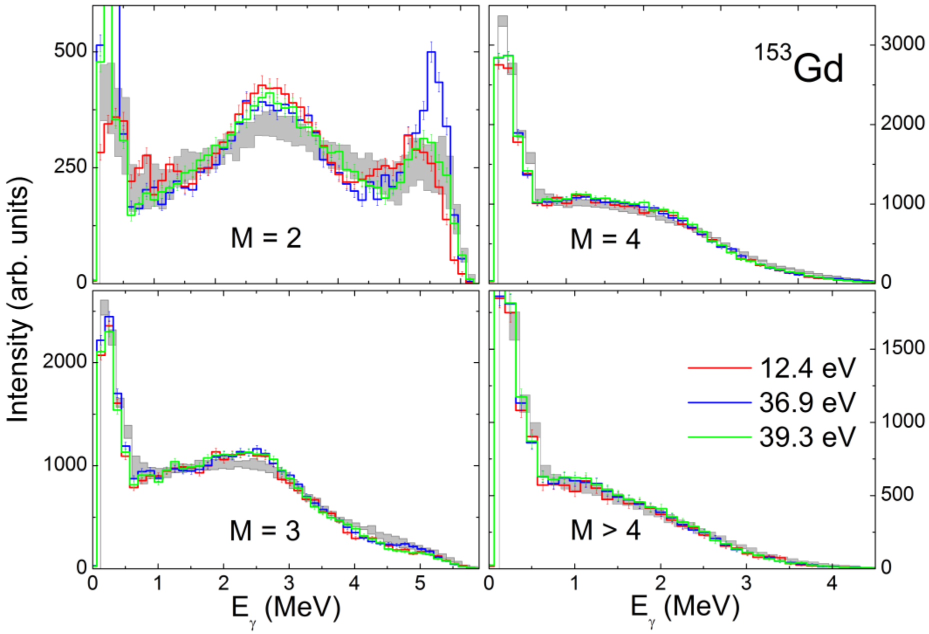
^{153}Gd results

Comparison of preliminary results obtained for ^{153}Gd





^{153}Gd simulation assumption:

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

E_{SM} = 2.9 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built on all levels

^{153}Gd simulation assumption:

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

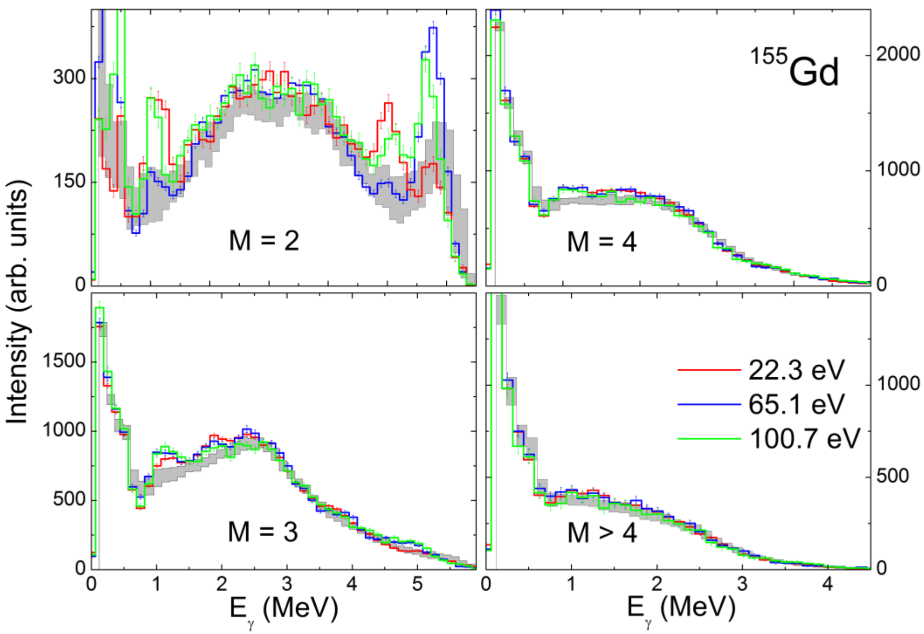
E_{SM} = 2.9 MeV, Γ_{SM} = 1.0 MeV,

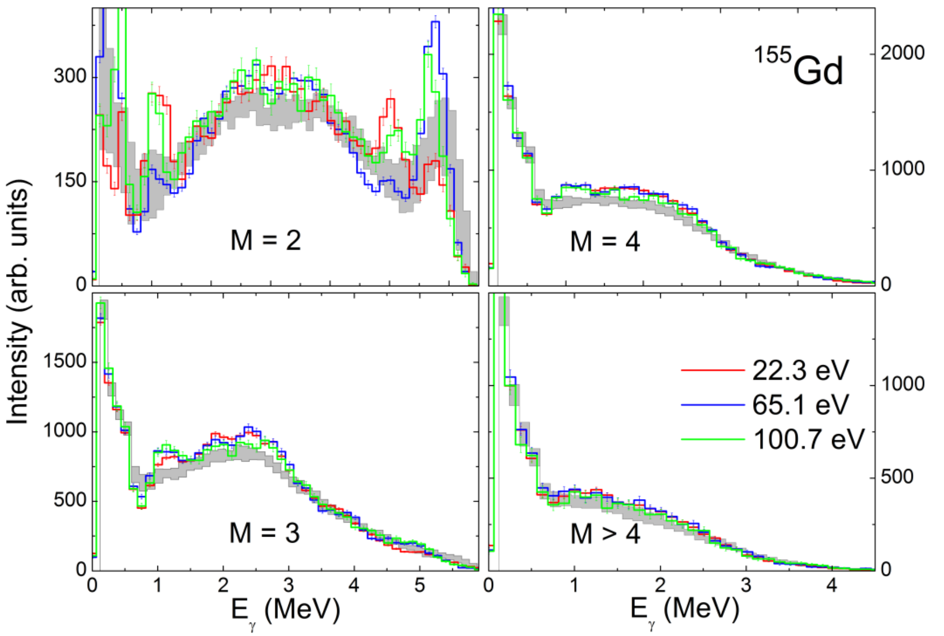
$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built only on the levels below 2.5 MeV

^{155}Gd results

Comparison of preliminary results obtained for ^{155}Gd





^{155}Gd simulation assumption:

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

E_{SM} = 2.7 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built on all levels

^{155}Gd simulation assumption:

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

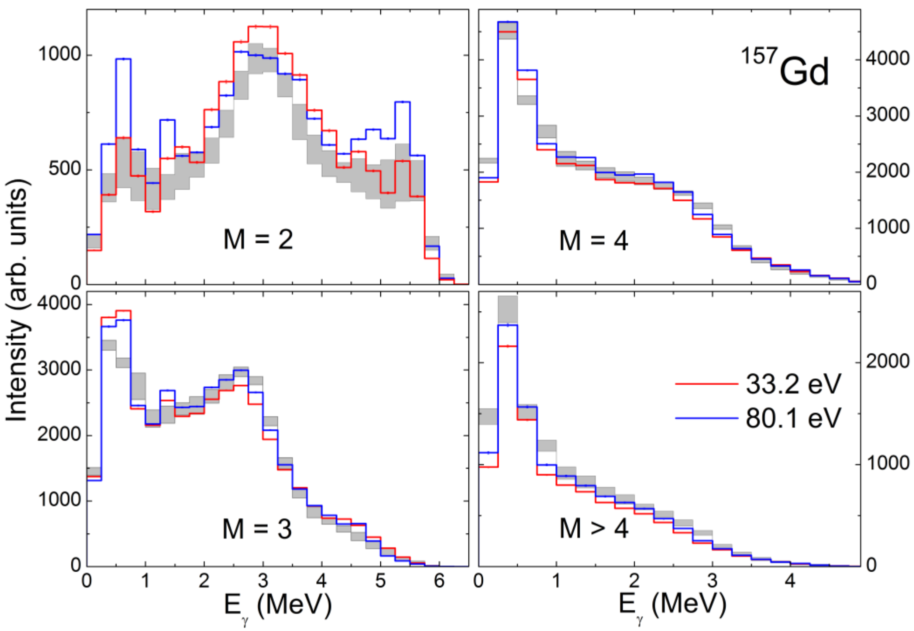
E_{SM} = 2.7 MeV, Γ_{SM} = 1.0 MeV,

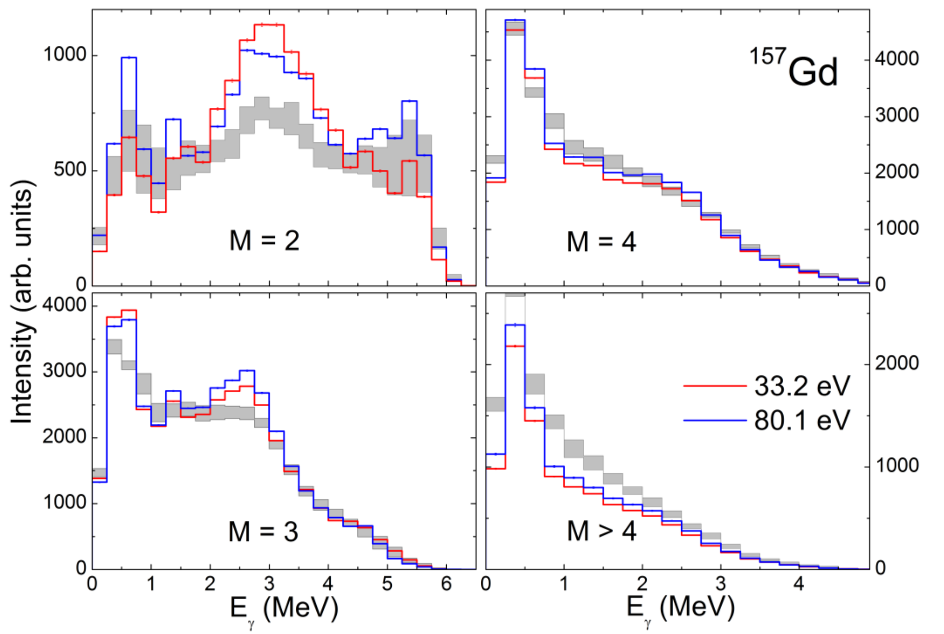
$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built only on the levels below 2.5 MeV

^{157}Gd results

Comparison of preliminary results obtained for ^{157}Gd





^{157}Gd simulation assumption:

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

E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 6.0\ \mu_N^2$

SM built on all levels

^{157}Gd simulation assumption:

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

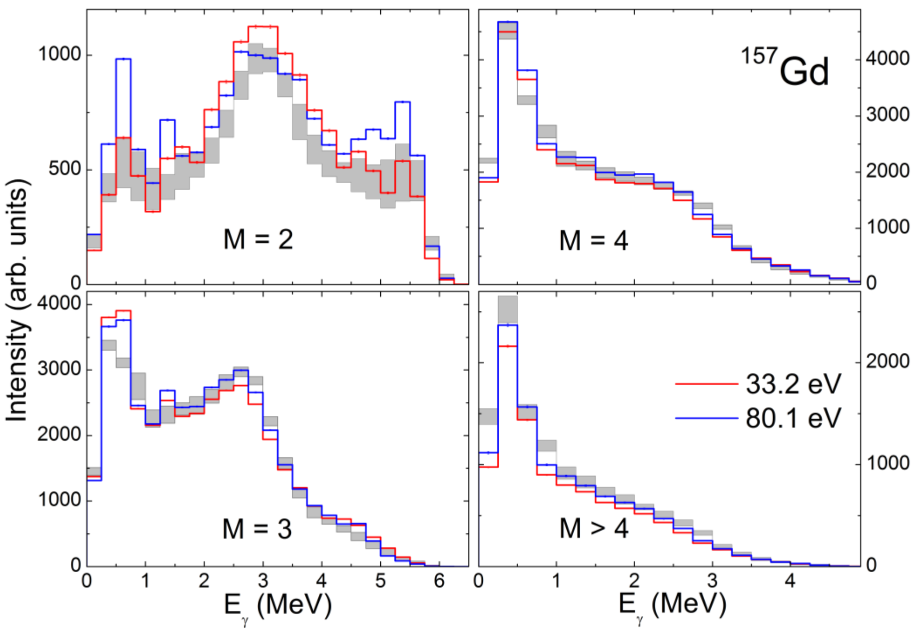
E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

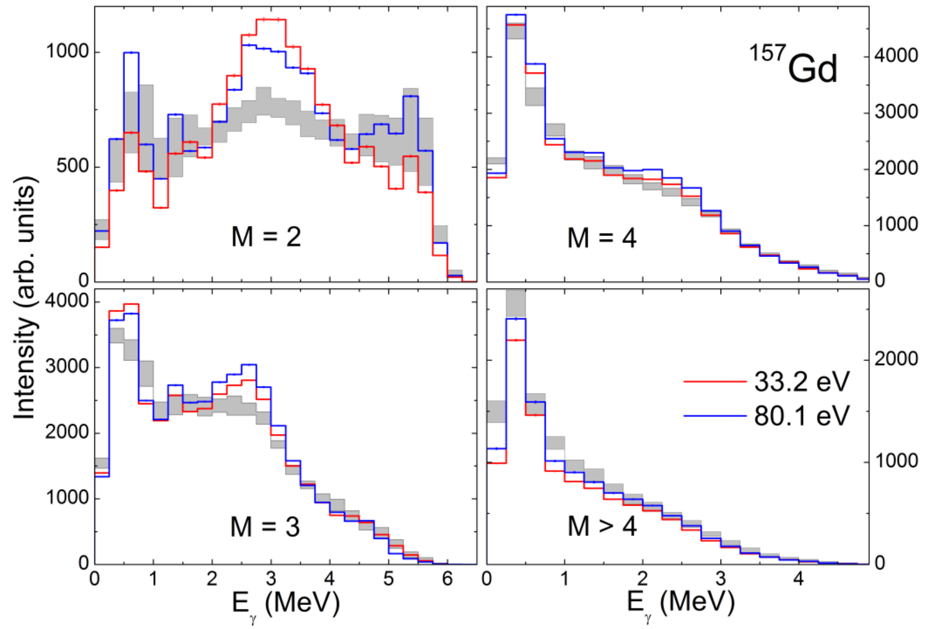
$\Sigma B(M1,SM) \approx 2.0\ \mu_N^2$

SM built on all levels

^{157}Gd results

Comparison of preliminary results obtained for ^{157}Gd





^{157}Gd simulation assumption:

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

E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

$\Sigma B(M1,SM) \approx 6.0\ \mu_N^2$

SM built on all levels

^{157}Gd simulation assumption:

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

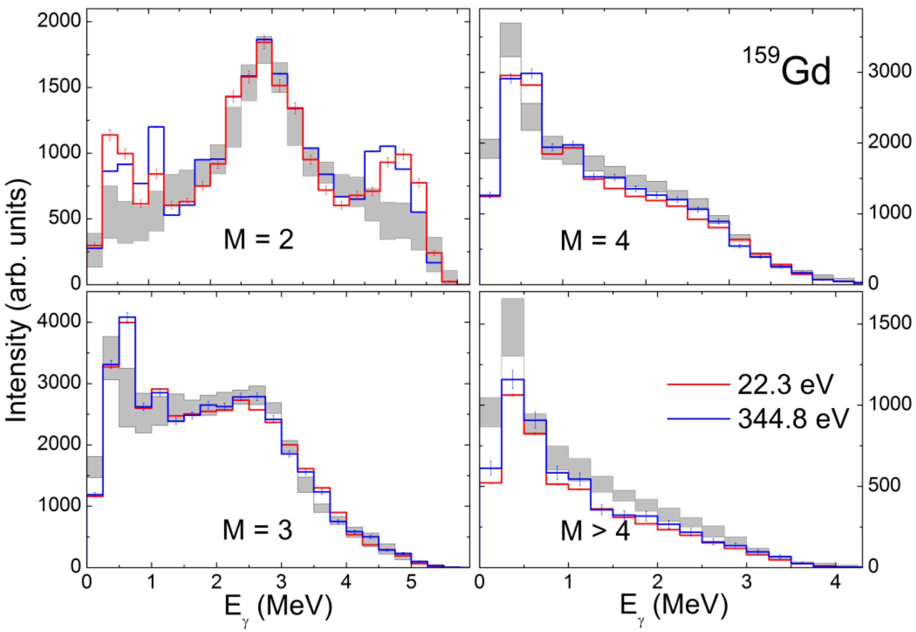
E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

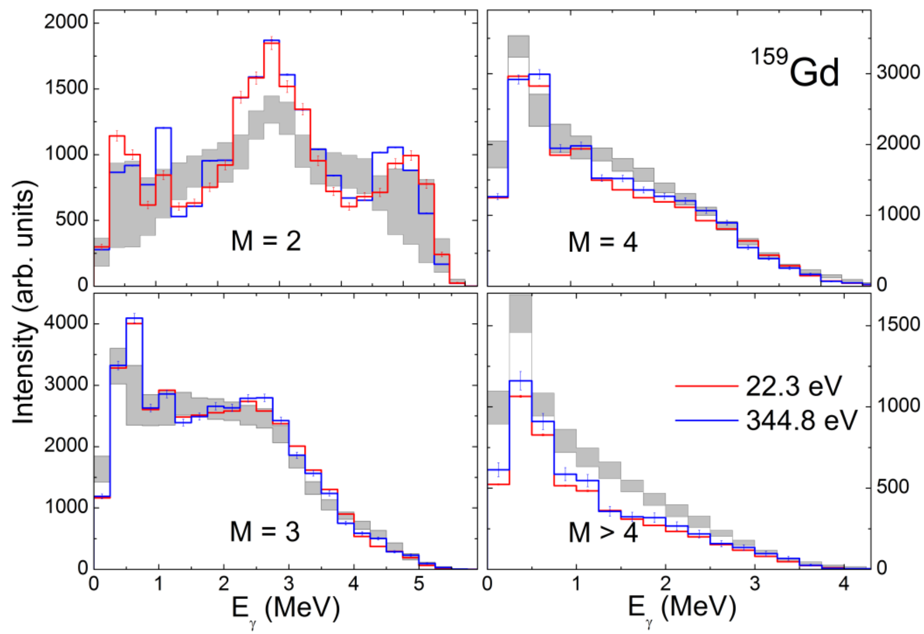
$\Sigma B(M1,SM) \approx 6.0\ \mu_N^2$

SM built only on the levels below 2.5 MeV

^{159}Gd results

Comparison of preliminary results obtained for ^{159}Gd





^{159}Gd simulation assumption:

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

E_{SM} = 3.0 MeV, Γ_{SM} = 0.9 MeV,

ΣB(*M*1,SM) ≈ 5.0 μ_N^2

SM built on all levels

^{159}Gd simulation assumption:

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

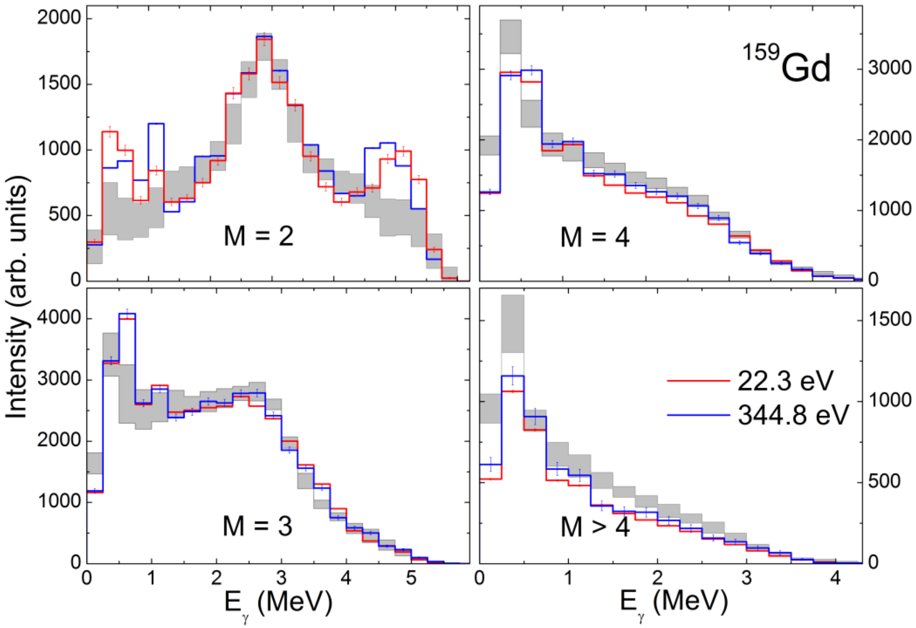
E_{SM} = 3.0 MeV, Γ_{SM} = 1.0 MeV,

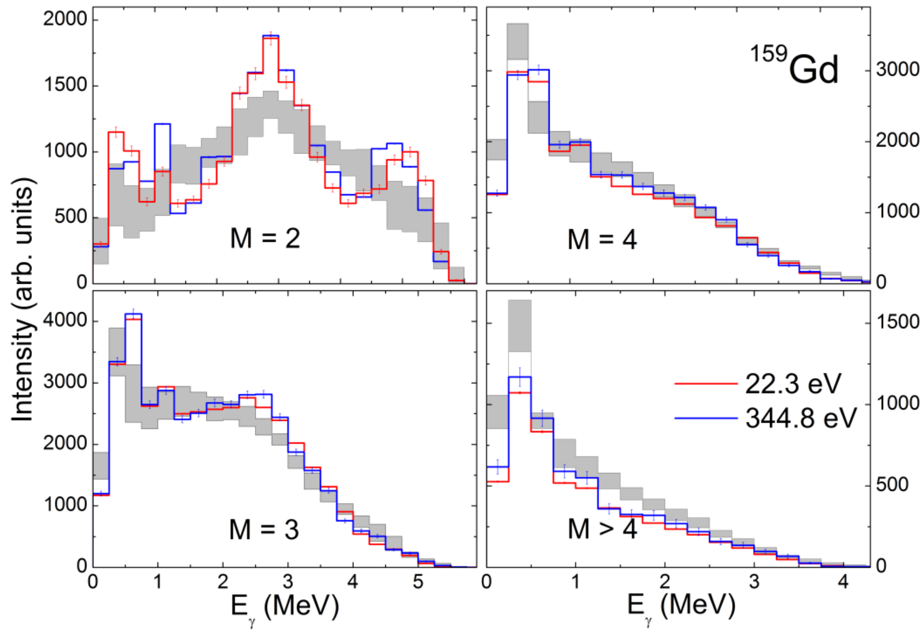
ΣB(*M*1,SM) ≈ 2.0 μ_N^2

SM built on all levels

^{159}Gd results

Comparison of preliminary results obtained for ^{159}Gd





^{159}Gd simulation assumption:

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

E_{SM} = 3.0 MeV, Γ_{SM} = 0.9 MeV,

$\Sigma B(M1,\mathrm{SM}) \approx 5.0\ \mu_N^2$

SM built on all levels

^{159}Gd simulation assumption:

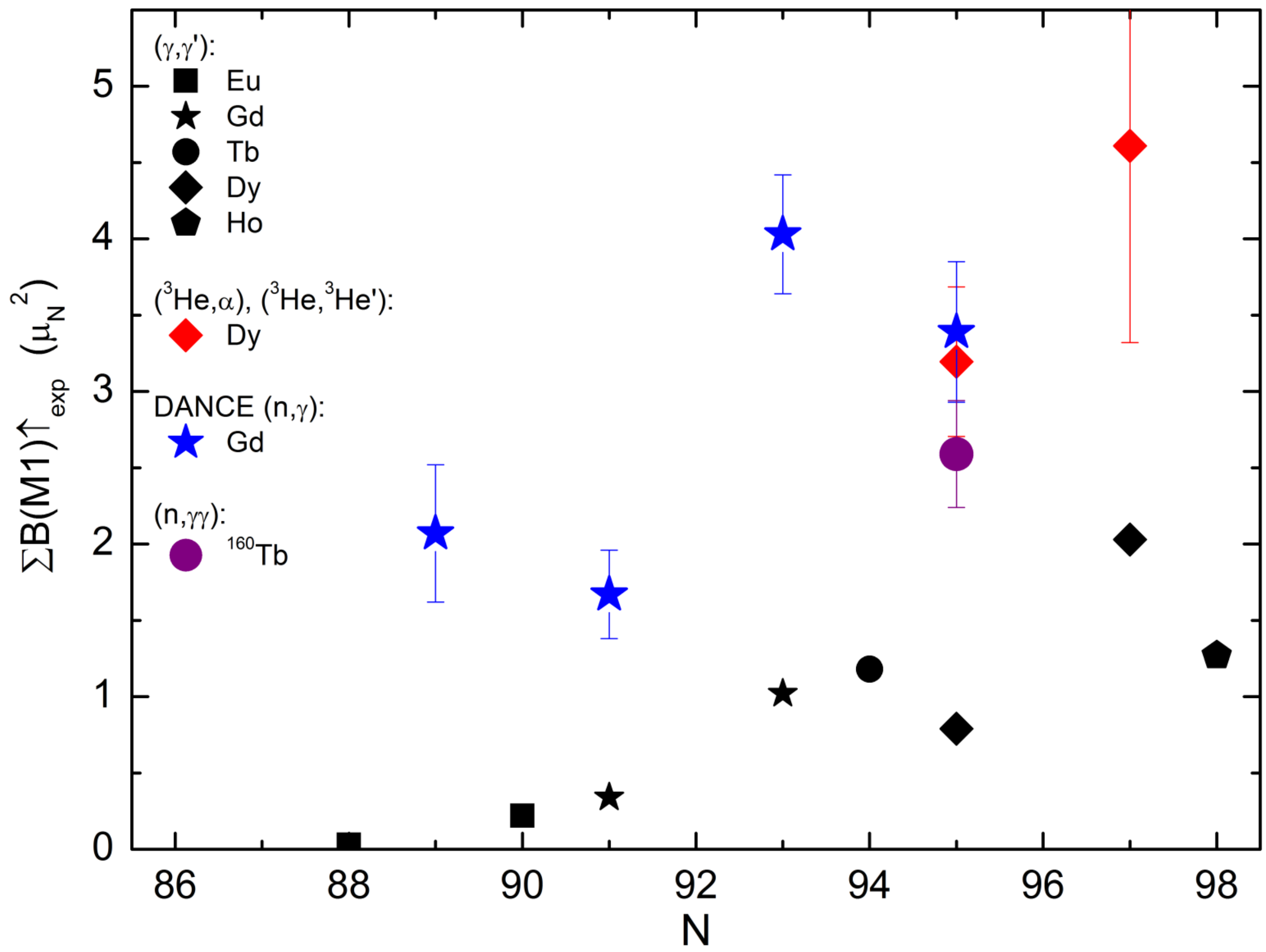
KMF + **SM + SF +SP** + SP + BSFG(1)

E_{SM} = 3.0 MeV, Γ_{SM} = 0.9 MeV,

$\Sigma B(M1,\mathrm{SM}) \approx 5.0\ \mu_N^2$

SM built only on the levels below 2.5 MeV

ΣB(*M1*,2.7-3.7)↑ in odd nuclei



NRF data [black] *A. Nord et al., PRC **67**, 034307 (2003).*

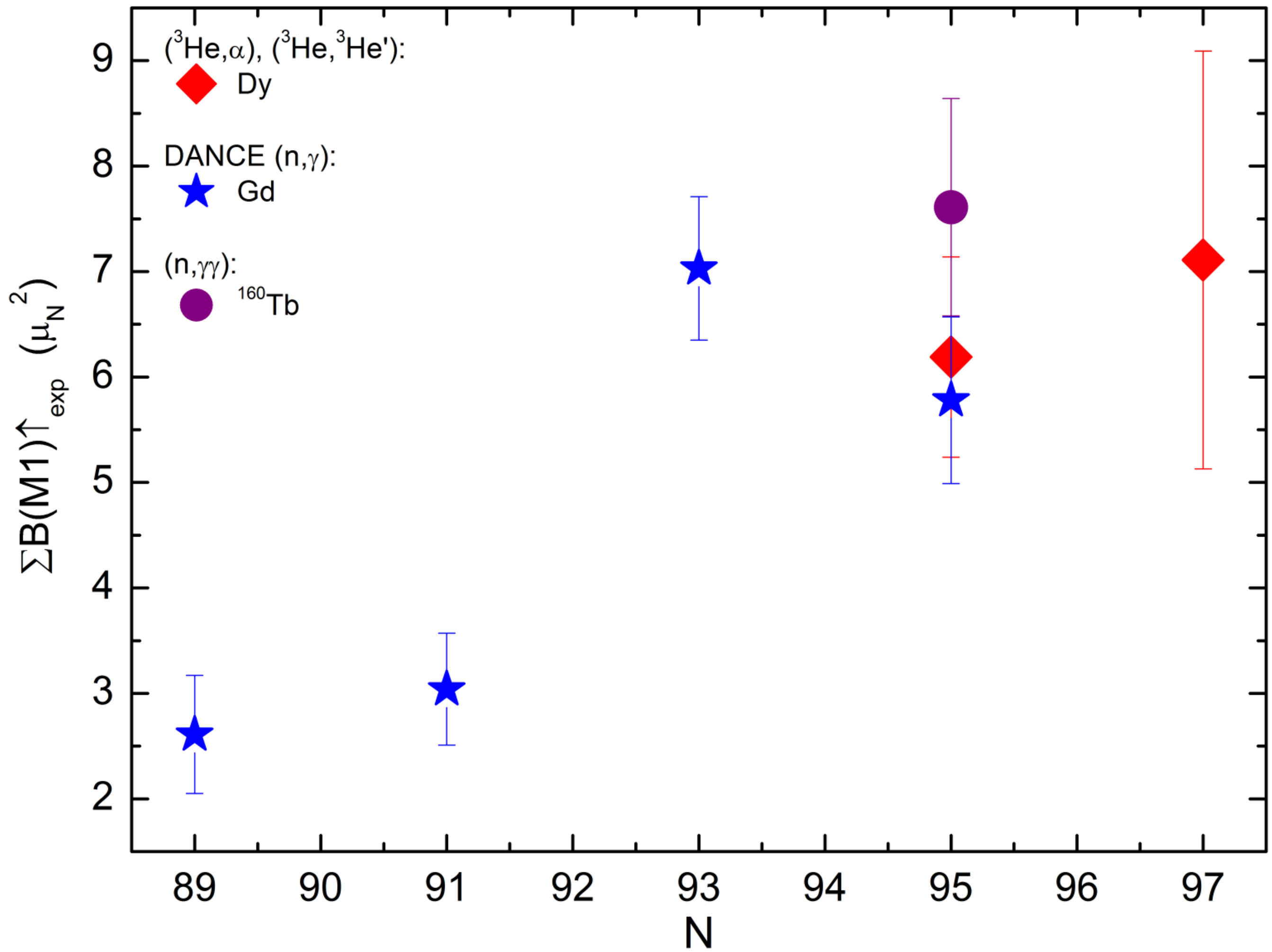
^{161}Dy [red] *M. Guttormsen et al., PRC **68**, 064306 (2003).*

^{163}Dy [red] *H.T. Nyhus et al., PRC **81**, 024325 (2010).*

^{153,155,157,159}Gd [blue] Preliminary results

^{160}Tb [purple] *J. Kroll et al., Int. Jour. of Mod. Physics E, Vol. **20**, No. 2 (2011) 526 – 531.*

ΣB(*M1*,SM)↑ in odd nuclei



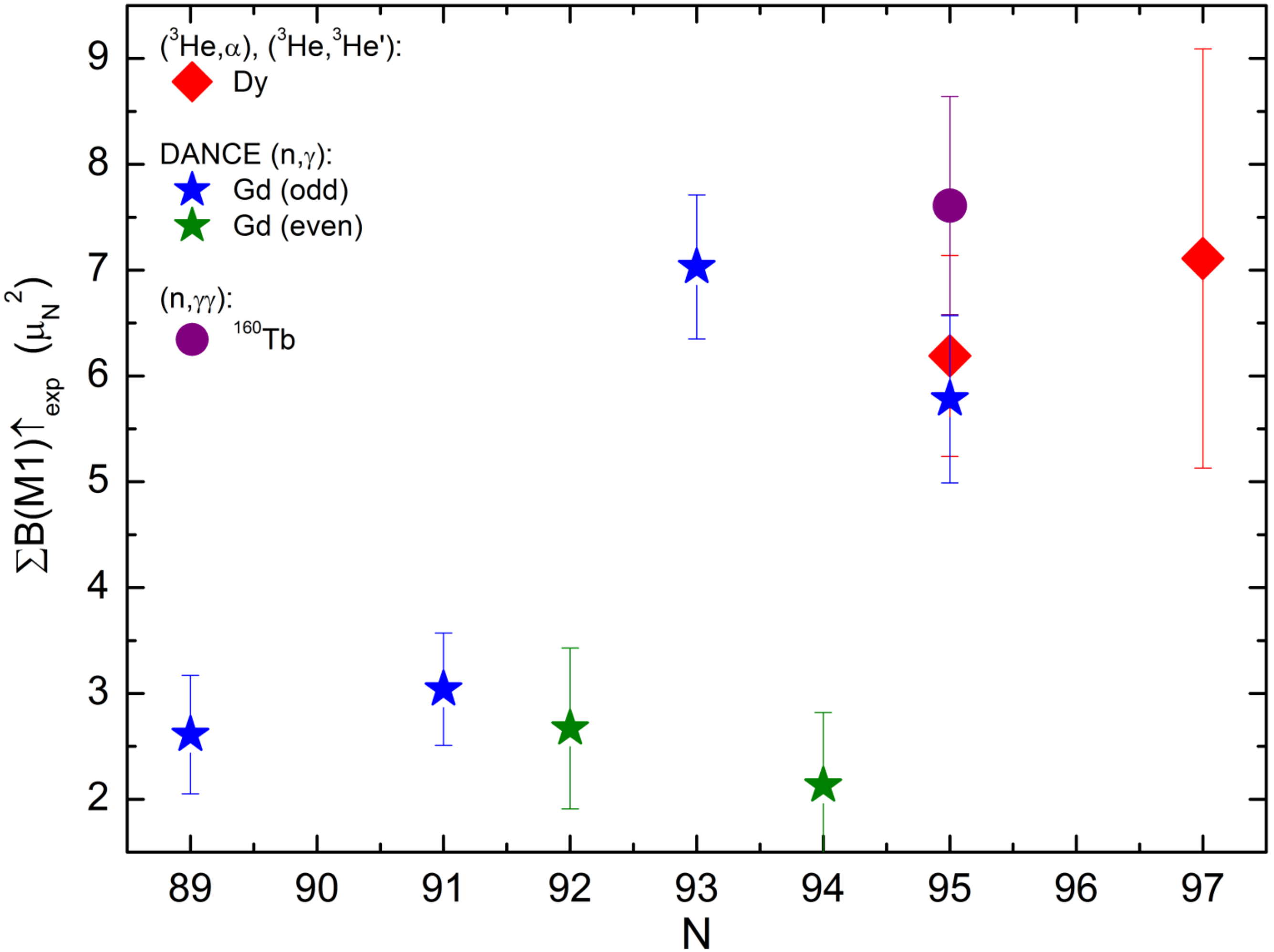
^{161}Dy [red] *M. Guttormsen et al., PRC* ***68****, 064306 (2003).*

^{163}Dy [red] *H.T. Nyhus et al., PRC* ***81****, 024325 (2010).*

^{153,155,157,159}Gd [blue] Preliminary results

^{160}Tb [purple] *J. Kroll et al., Int. Jour. of Mod. Physics E, Vol.* ***20****, No. 2 (2011) 526 – 531.*

ΣB(*M1*,SM)↑ in odd nuclei



^{161}Dy [red] *M. Guttormsen et al., PRC **68**, 064306 (2003).*
^{163}Dy [red] *H.T. Nyhus et al., PRC **81**, 024325 (2010).*
^{153,155,157,159}Gd [blue] Preliminary results
^{158}Gd [green] *A. Chyzh et al., PRC **84**, 014306 (2011).*
^{156}Gd [green] *B. Baramsai et al., submitted to PRC.*
^{160}Tb [purple] *J. Kroll et al., Int. Jour. of Mod. Physics E, Vol. **20**, No. 2 (2011) 526 – 531.*

Conclusions

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

- Values of ΣB(*M*1,2.7-3.7)↑ obtained for ^{156,158}Gd are slightly below the results of (γ,γ') experiments. Significant part of the observed strength corresponds to the non-resonant structure present in *M*1 PSF.

- We have received new results for ΣB(*M*1) present in odd rare-earth isotopes ^{153,155,157,159}Gd.

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

- Difference between ΣB(*M*1) in ^{156,158}Gd and ^{157,159}Gd.

DANCE collaboration

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