Photon Strength Functions and Nuclear Level Densities in Gd Nuclei from Neutron Capture Experiments

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Outline

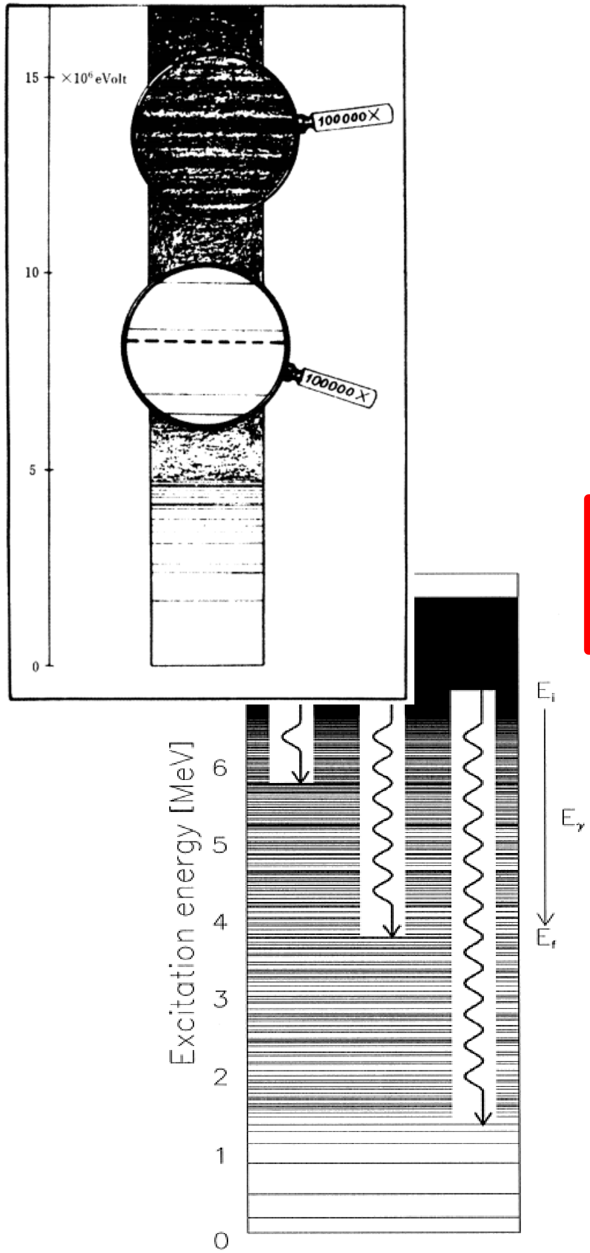
I. DANCE results for $^{153,155\text{-}159}Gd$ products

II. TSC measurement in Řež on $^{155,157}Gd$ targets

III. TSC results

IV. Comparison of TSC and DANCE results

Physical motivation – photon strength functions



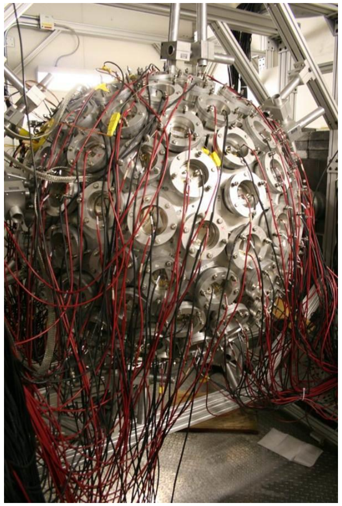
Transitions from/to quasicontinual part of the energy spectrum

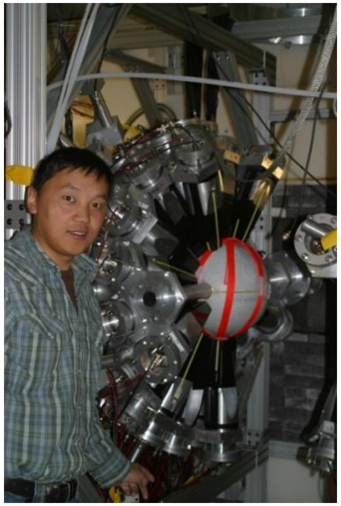
$$\overline{\Gamma}_{XL}\left(J_{\alpha}^{\pi_\alpha} \to \beta\right) = \frac{f_{XL}\left(E_\gamma, J_{\alpha}^{\pi_\alpha} \to E_\beta J_\beta \sigma_\beta\right)(\hbar\omega)^{2L+1}}{\rho\left(E_\beta + E_\gamma, J_{\alpha}^{\pi_\alpha}\right)}$$

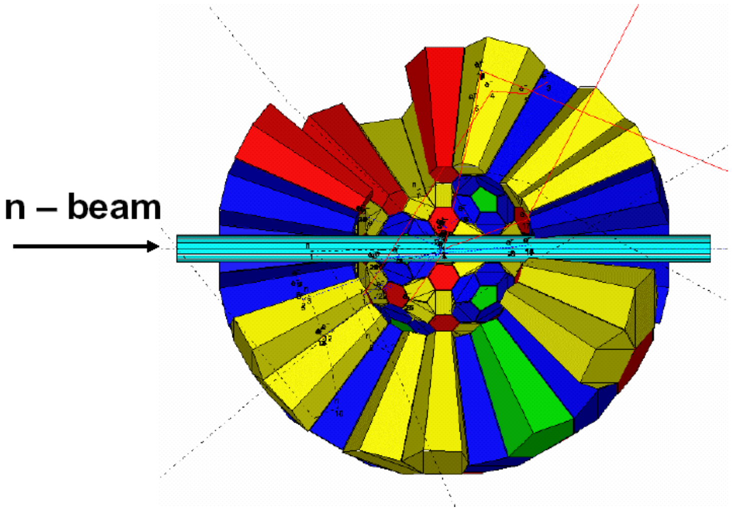
Photon Strength Function **Nuclear Level Density**

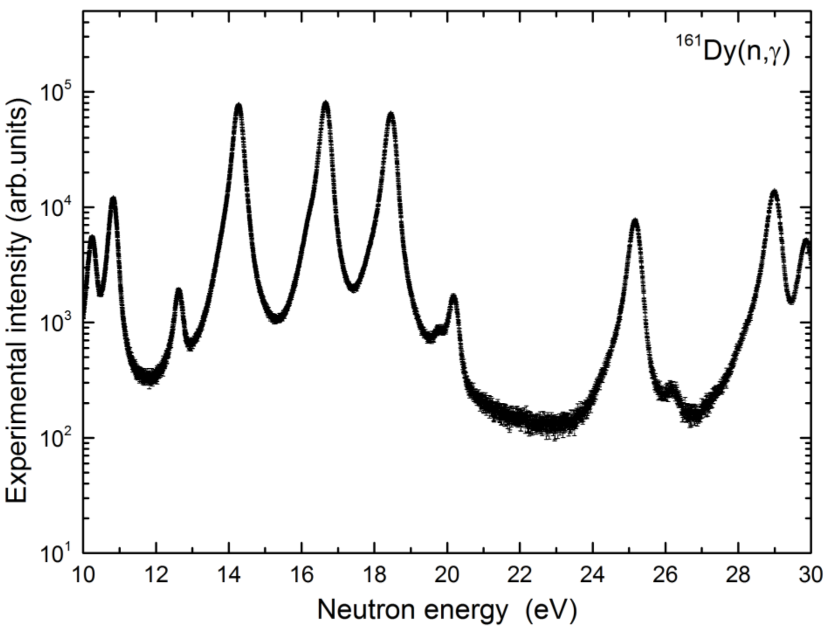
Basic components of nuclear statistical model

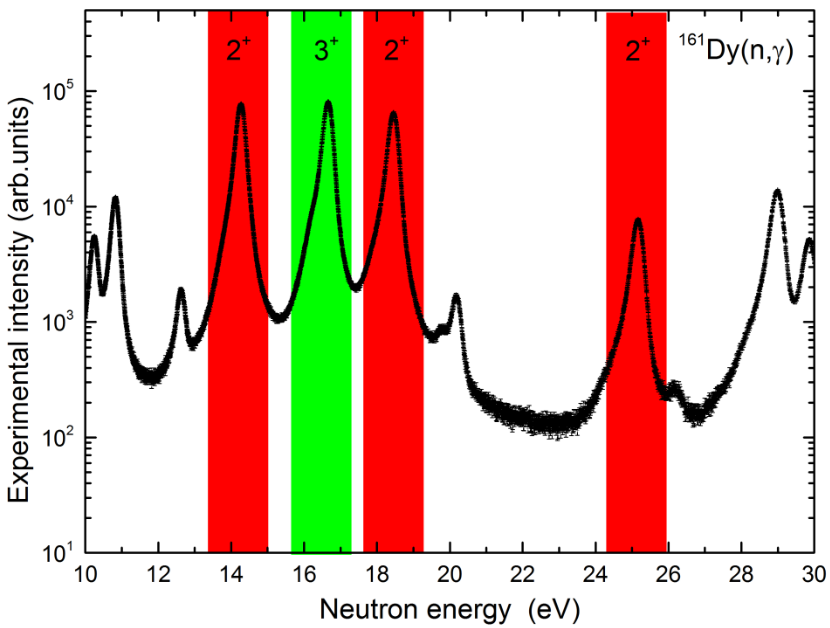
DANCE (n,γ) measurements - data processing



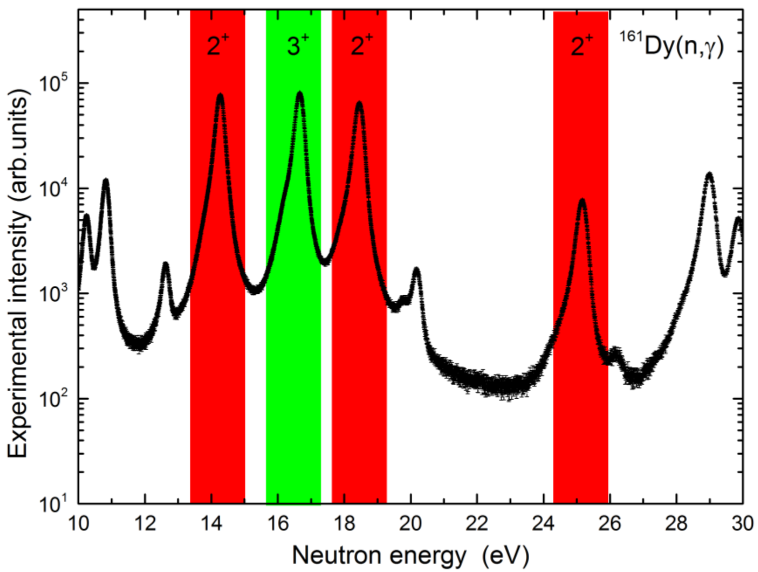


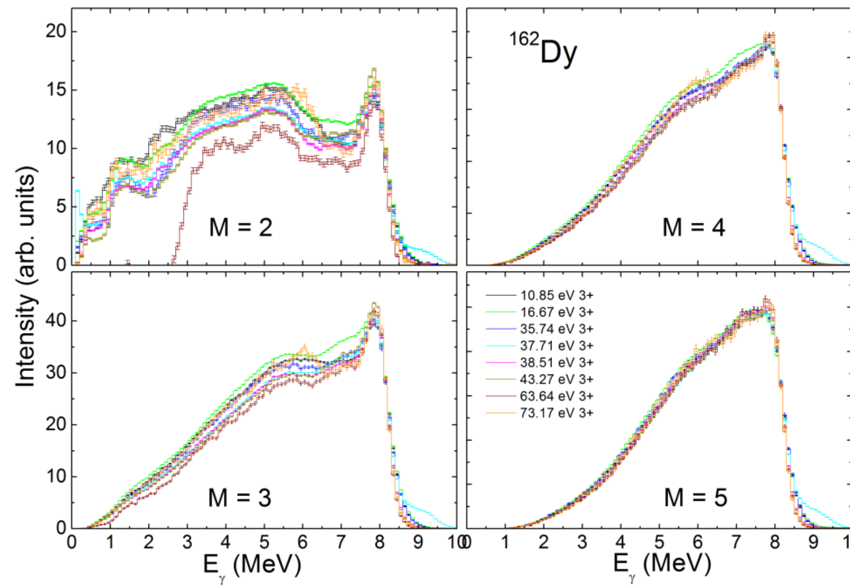


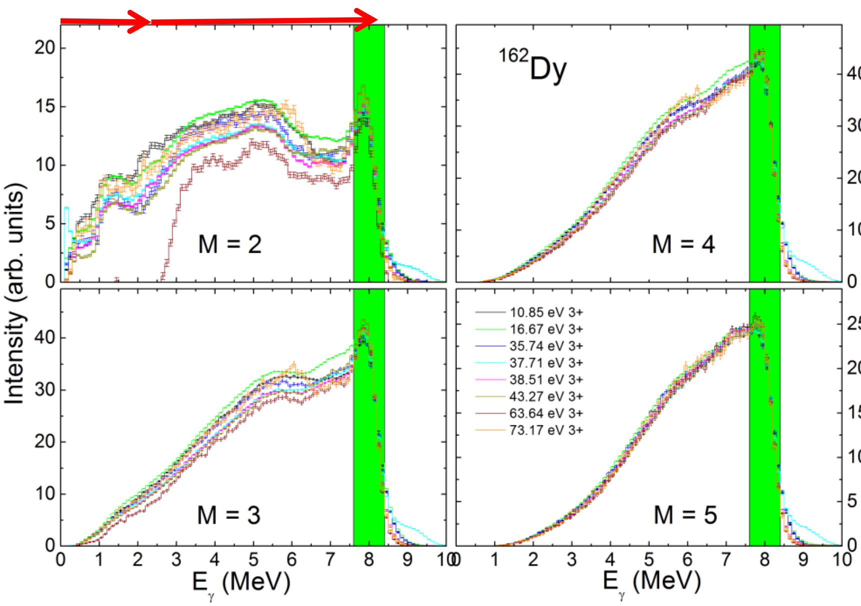




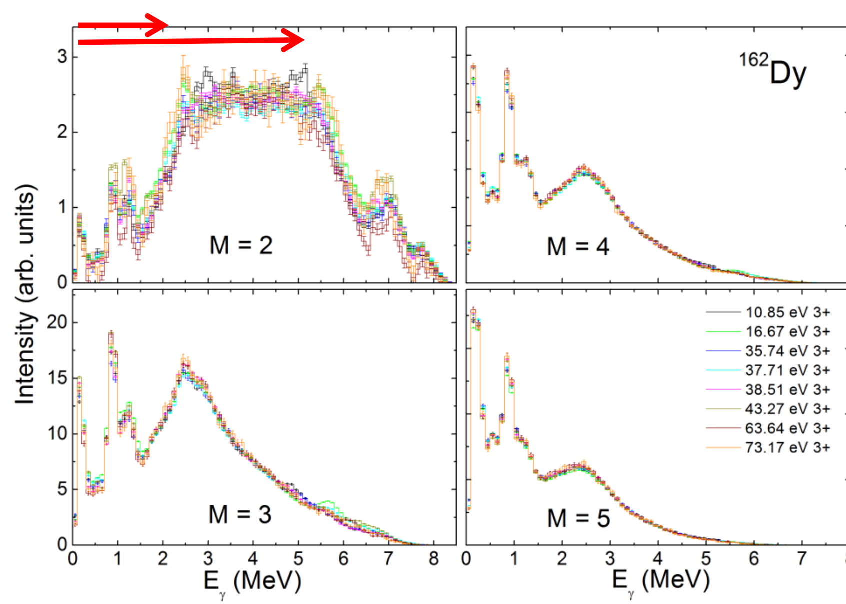
DANCE (n,γ) measurements - data processing





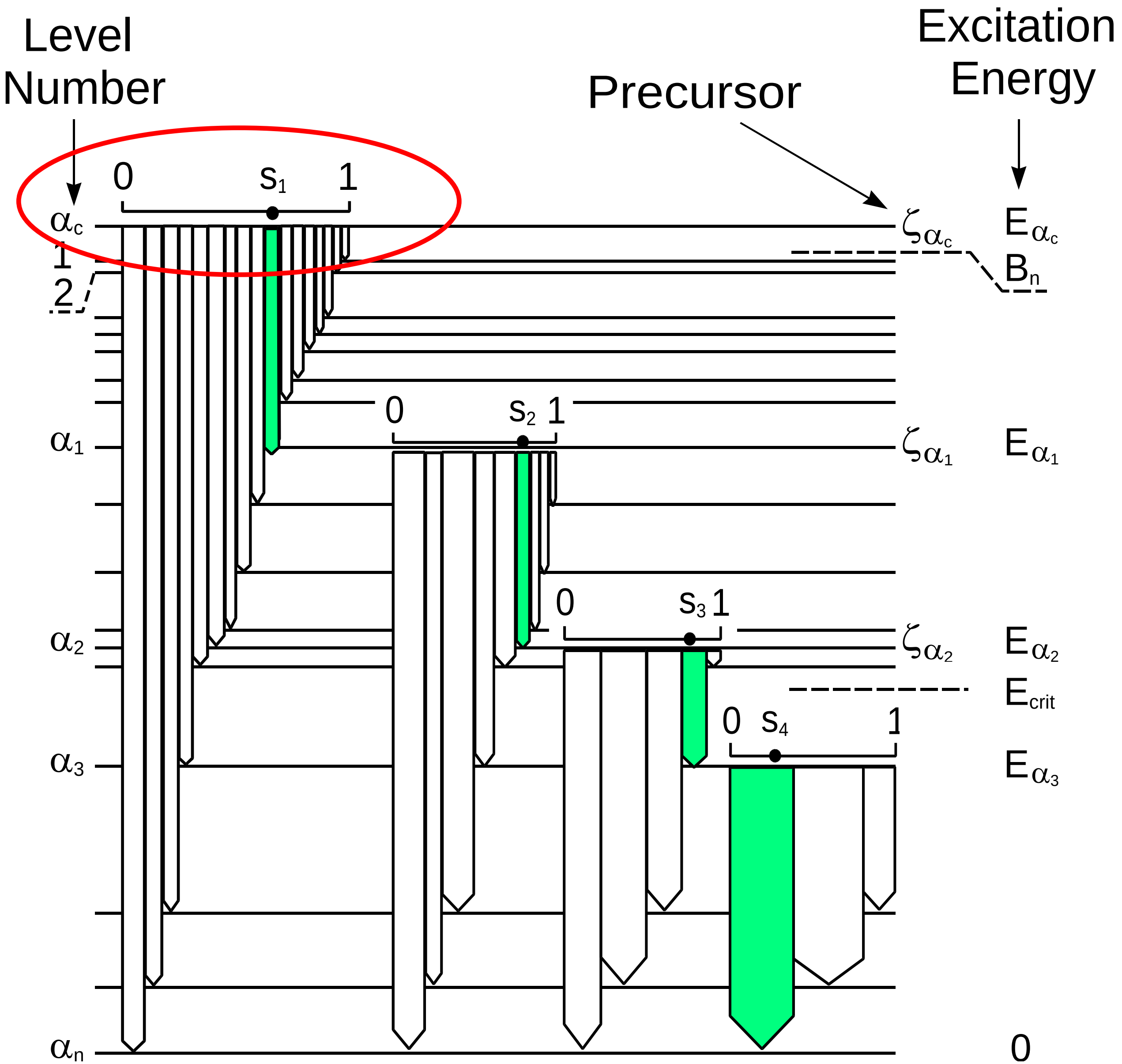


Q-value range at full-energy peak



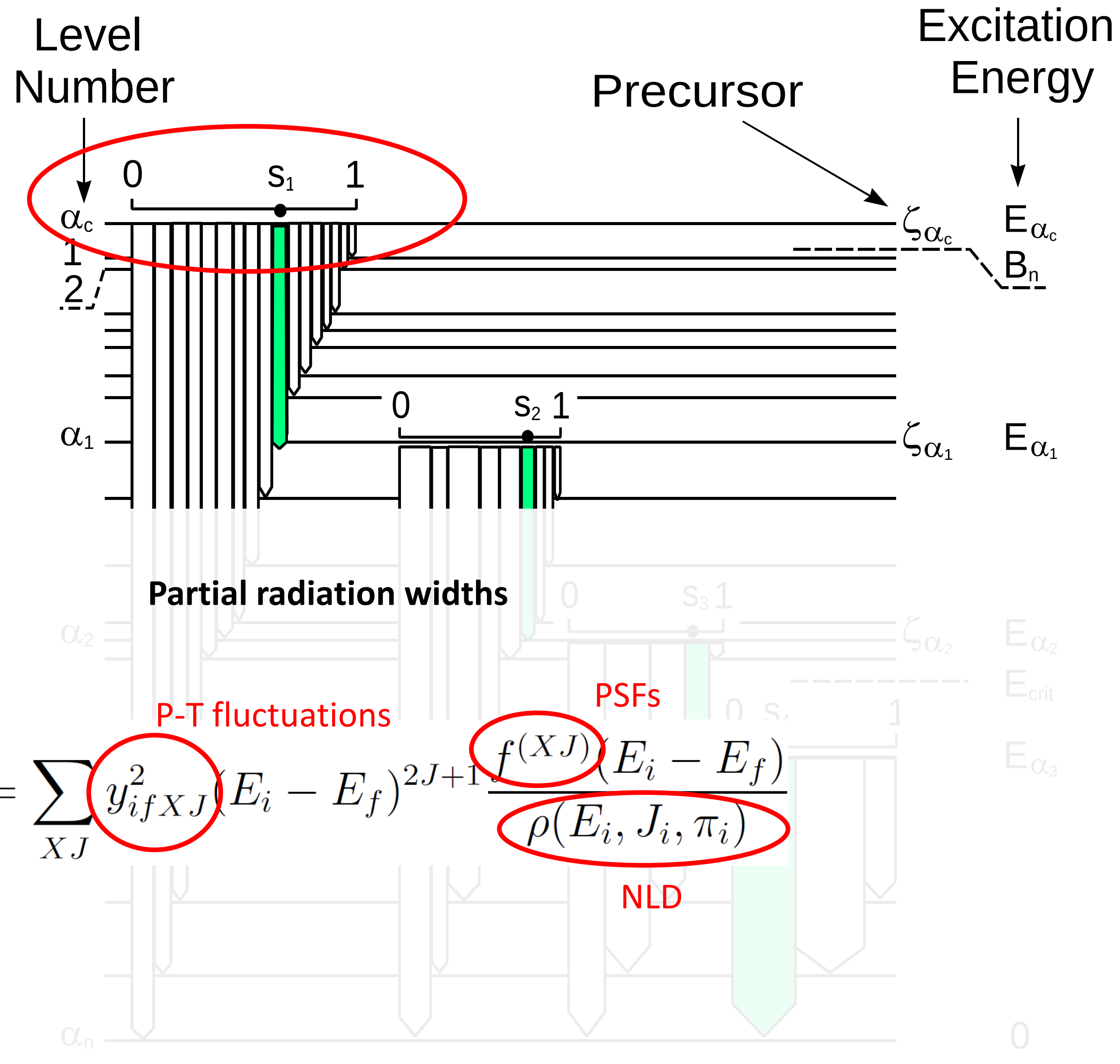
Multi-step cascade spectra

DANCE (n,γ) measurements – DICEBOX simulation



F. Bečvář, Nucl. Instr. Meth. A **417**, 434 (1998).

DANCE (n,γ) measurements – DICEBOX simulation



Partial radiation widths

P-T fluctuations

PSFs

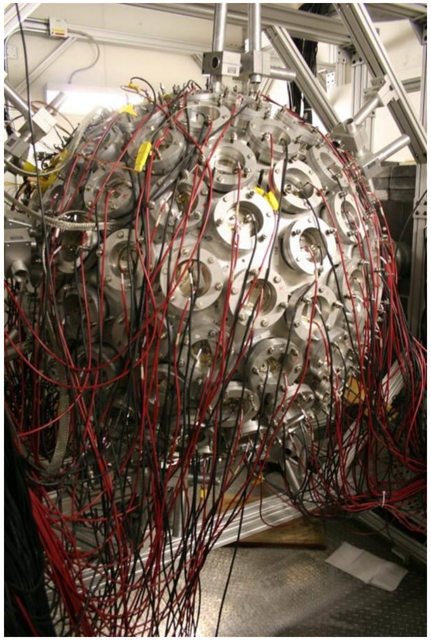
$$\Gamma_{i\gamma f} = \sum_{XJ} y^2_{ifXJ} (E_i - E_f)^{2J+1} \frac{f^{(XJ)}(E_i - E_f)}{\rho(E_i, J_i, \pi_i)}$$

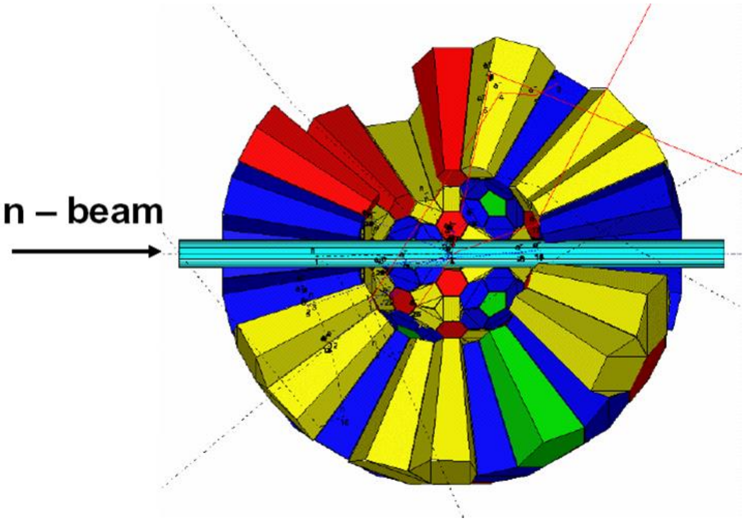
NLD

F. Bečvář, Nucl. Instr. Meth. A **417**, 434 (1998).

DANCE (n,γ) measurements – Geant4 simulation

- 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.

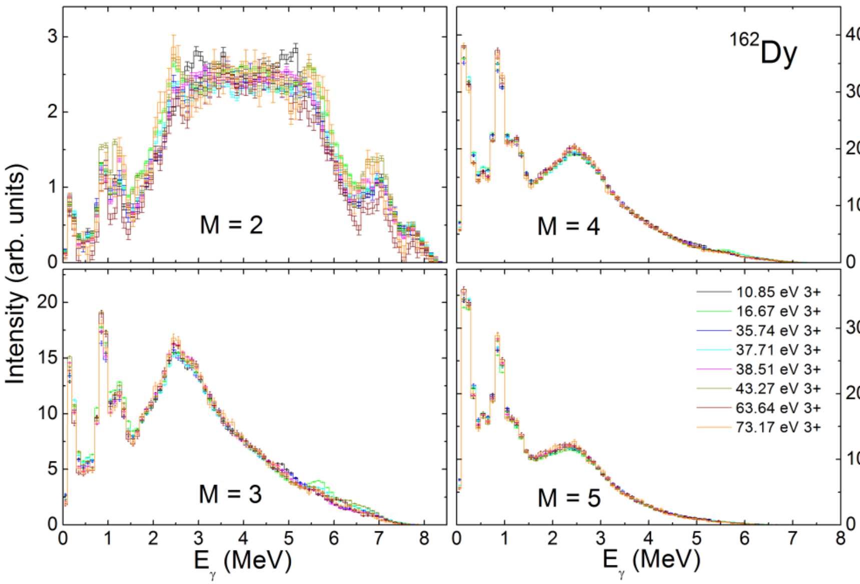




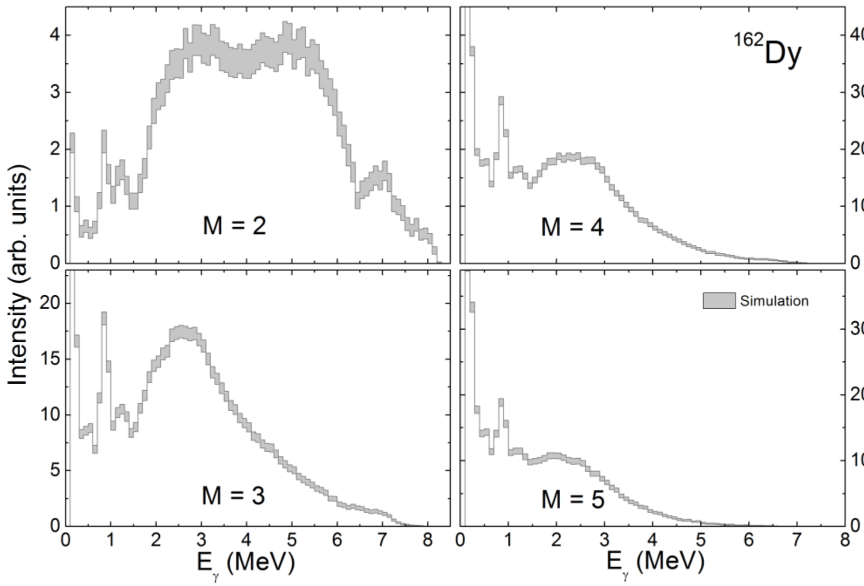
M. Jandel *el al.*, Nucl. Instr. Meth. B **261**, 1117 (2007).

DANCE (n,γ) measurements – comparison

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



Experimental MSC spectra for several neutron resonances with $J^{\pi} = 3^{+}$

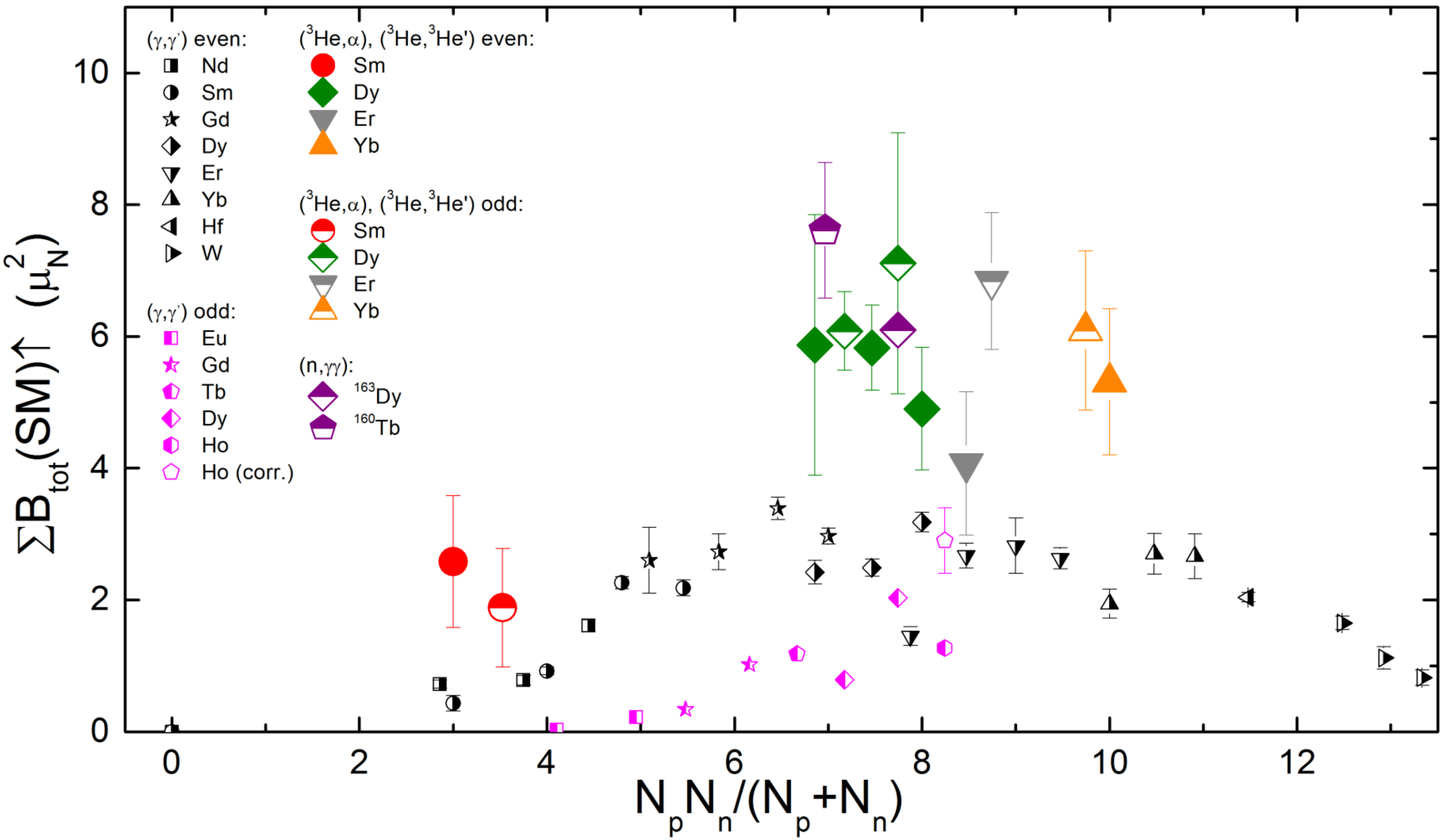


Simulated MSC spectra produced by DICEBOX and Geant4
(grey corridors are consequence of Porter-Thomas fluctuations)

DANCE (n,γ) measurements – comparison

Isot.	*E*1	*M*1: f_{M1} = SM+SP+SF	*E*2: f_{E2} =const	NLD
^{153}Gd	MGLO (k_0 = 2, Eg_0 = 4.5 MeV)		3E-11 MeV^{-5}	BSFG
^{155}Gd	MGLO (k_0 = 3, Eg_0 = 4.5 MeV)		3E-11 MeV^{-5}	BSFG
^{156}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	?	5E-11 MeV^{-5}	BSFG
^{157}Gd	MGLO (k_0 = 3, Eg_0 = 4.5 MeV)		5E-11 MeV^{-5}	BSFG
^{158}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)		5E-11 MeV^{-5}	BSFG
^{159}Gd	MGLO (k_0 = 4-5, Eg_0 = 4.5 MeV)		5E-11 MeV^{-5}	BSFG

Scissors Mode strength – Summary



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

NRF data odd [magenta] A. Nord *et al.,* Phys. Rev. C **67,** 034307 (2003).

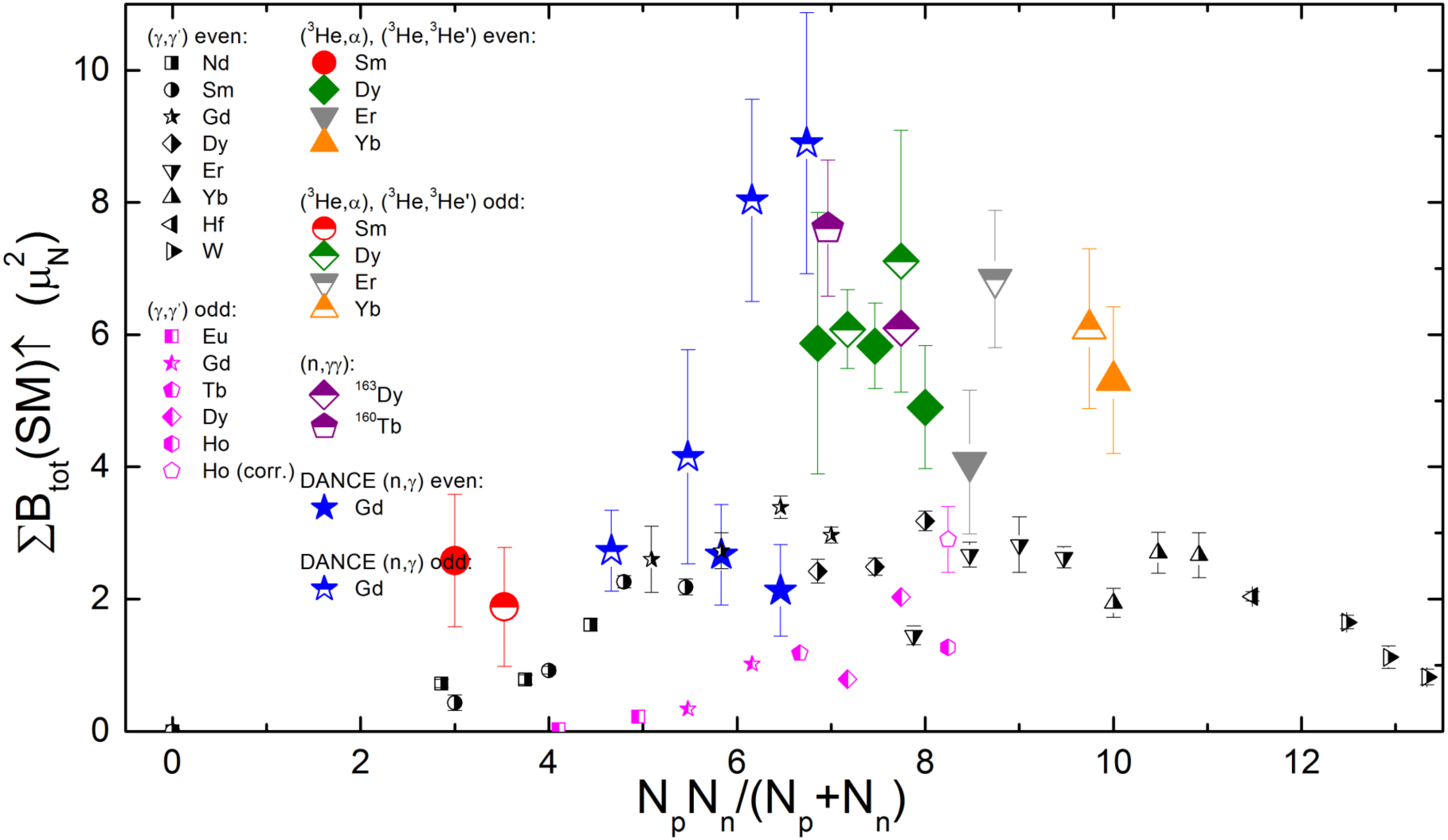
^{148,149}Sm [red] S. Siem *et al.*, PRC **65**, 044314 (2002); **^{160,161,162}Dy** [red] M. Guttormsen *et al.,* PRC **68**, 064306 (2003);

^{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);

^{171,172}Yb [red] A. Voinov *et al.*, PRC **63**, 044313 (2001);

^{163}Dy [purple] M. Krtička *et al.* PRL 92, 175501 (2004); **^{160}Tb** [purple] J. Kroll *et al.*, Int. Jour. Mod. Phys. E, V. 20, N. 2, 526 (2011).

Scissors Mode strength – Summary



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^{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);

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^{163}Dy [purple] M. Krtička *et al.* PRL 92, 175501 (2004); **^{160}Tb** [purple] J. Kroll *et al.*, Int. Jour. Mod. Phys. E, V. 20, N. 2, 526 (2011).

^{158}Gd [blue] A. Chyzh *et al.*, PRC **84**, 014306 (2011); **^{156}Gd** [blue] B. Baramsai *et al.*, submitted to PRC.

^{153,155,157,159}Gd [blue] J. Kroll *et al.*, PRC **88**, 034317 (2013); J. Kroll *et al.,* EPJ Web of Conferences 21, 04005 (2012); J. Kroll *et al.,* Physica Scripta T **154**, 014009 (2013).

DANCE (n,γ) measurements – comparison

Isot.	*E*1	*M*1: f_{M1} = SM+SP+SF		*E*2: f_{E2} = c	NLD
^{153}Gd	MGLO (k_0 = 2, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.0 MeV $\Sigma B(SM)\uparrow$ = 2.1-3.4 μ_N^2	0.5-2.0 (10^{-9} MeV^{-3})	3E-11 MeV^{-5}	BSFG
^{155}Gd	MGLO (k_0 = 3, Eg_0 = 4.5 MeV)	E_{SM} = 2.5-2.7 MeV $\Sigma B(SM)\uparrow$ = 2.5-5.8 μ_N^2	2.0-2.5	3E-11 MeV^{-5}	BSFG
^{156}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.7-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.9-3.5 μ_N^2	2.0-4.0	5E-11 MeV^{-5}	BSFG
^{157}Gd	MGLO (k_0 = 3, Eg_0 = 4.5 MeV)	E_{SM} = 3.0-3.1 MeV $\Sigma B(SM)\uparrow$ = 6.5-9.6 μ_N^2	0-1.0	5E-11 MeV^{-5}	BSFG
^{158}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.4-2.8 μ_N^2	1.0-2.5	5E-11 MeV^{-5}	BSFG
^{159}Gd	MGLO (k_0 = 4-5, Eg_0 = 4.5 MeV)	E_{SM} = 2.9-3.1 MeV $\Sigma B(SM)\uparrow$ = 6.9-10.9 μ_N^2	0-2.0	5E-11 MeV^{-5}	BSFG

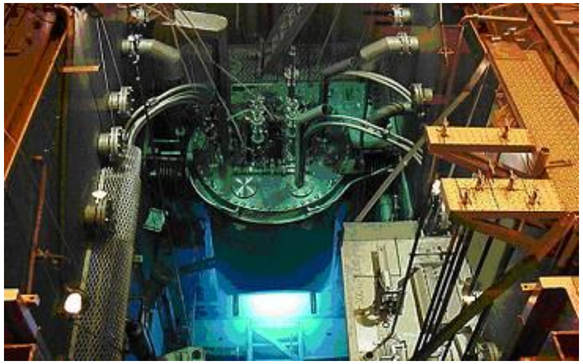
TSC measurement

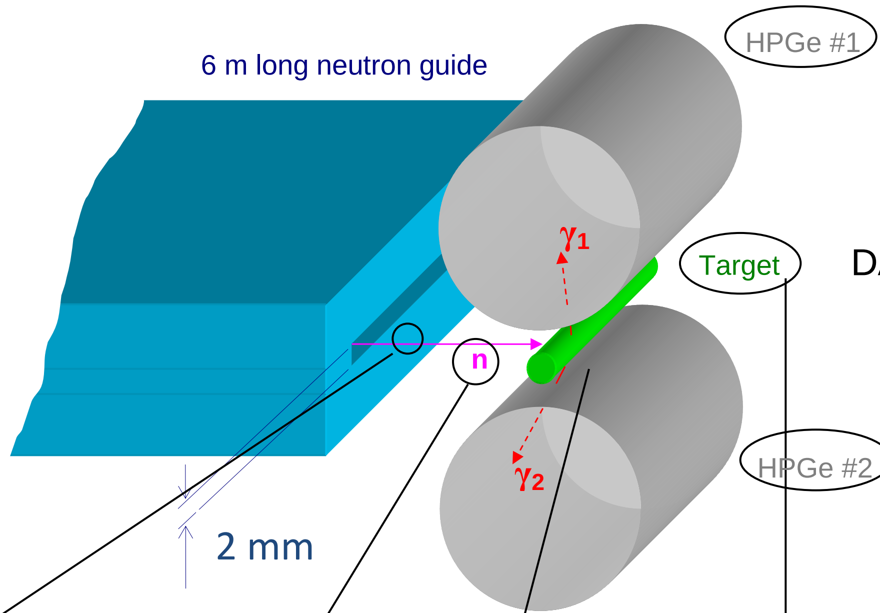
How to verify the DANCE results:

- DANCE measurement on the isotopes directly comparable with the Oslo data – ^{161,163}Dy, ^{162}Dy
  talk of S. Valenta
- Independent experimental technique for Gd isotopes – Two-Step Cascade measurement at Řež

TSC measurement – experimental setup

LWR-15 reactor





ε_R = 25%

DAQ time: 300 h

ε_R = 28%

3.0 x 10^6 n cm^{-2} s^{-1}

E_n = 0.025 eV

Natural Gd target

$\sigma_{th}(^{157}Gd)/\sigma_{th}(^{155}Gd) = 4.1$

Abund. ^{157}Gd 15.7%, ^{155}Gd 14.8%

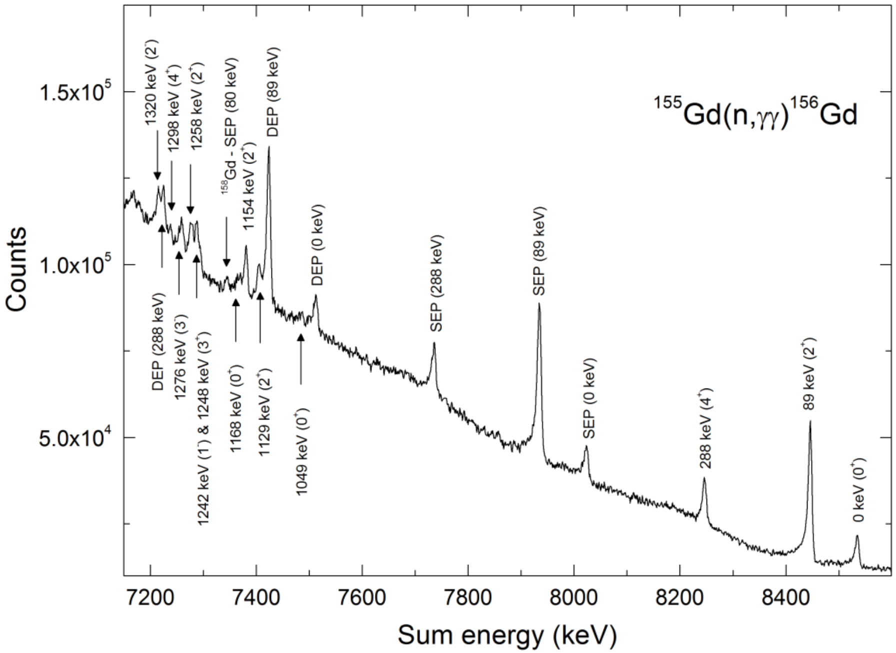
DAQ conditions for the TSCs:

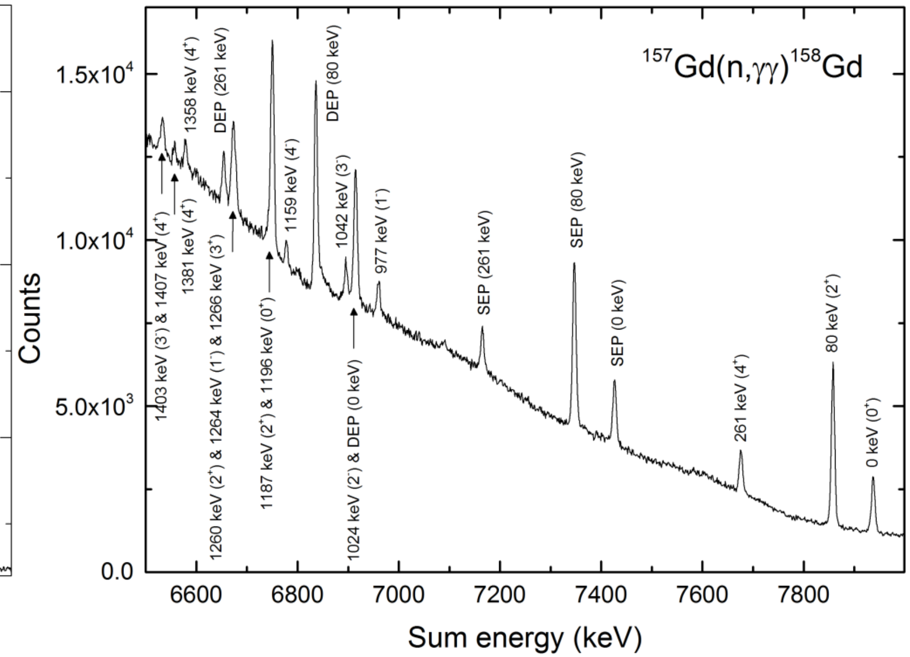
- energies $E_{\gamma 1}$ and $E_{\gamma 2}$
- time difference

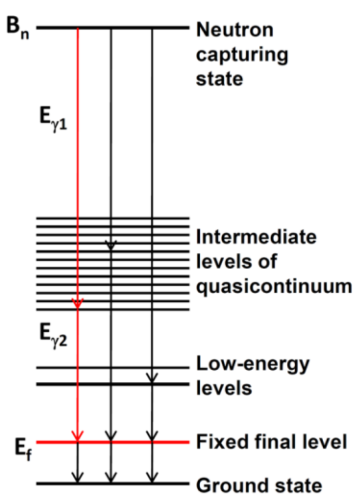
Neutron shielding: $^6Li_2CO_3$

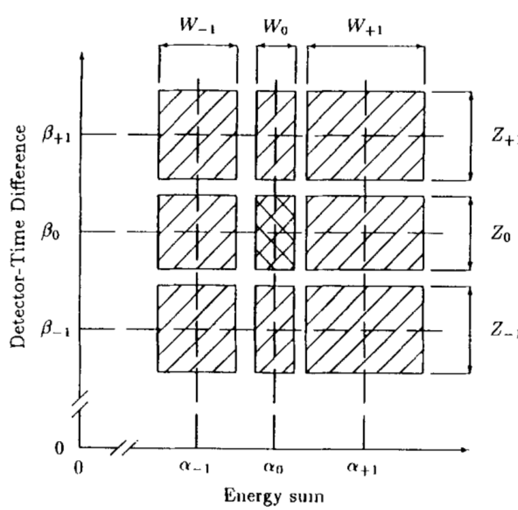
Low energy γ-ray shielding: Lead

TSC measurement – experimental setup





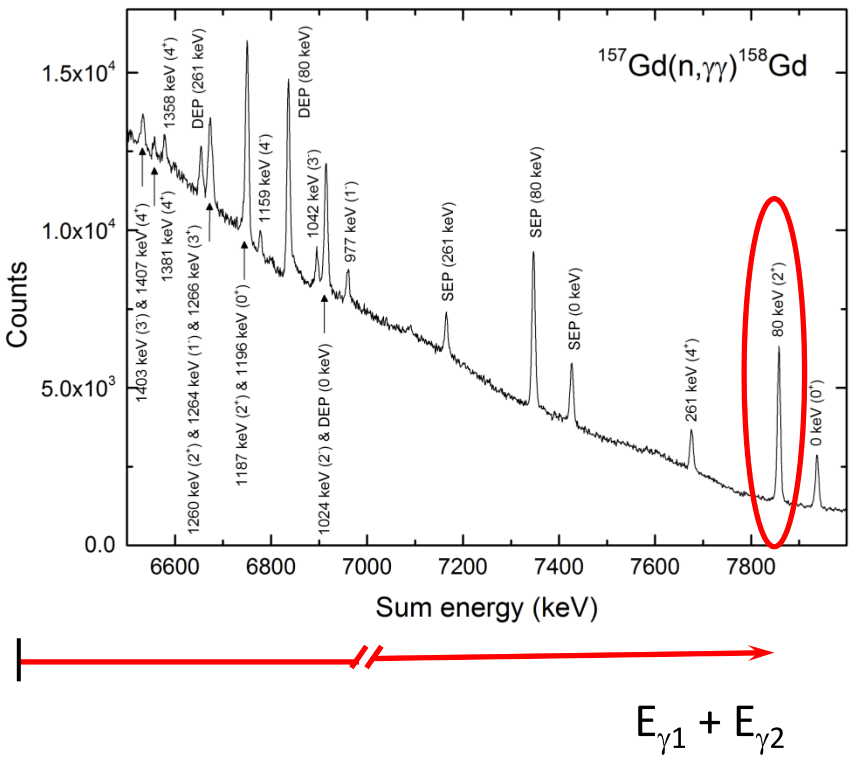


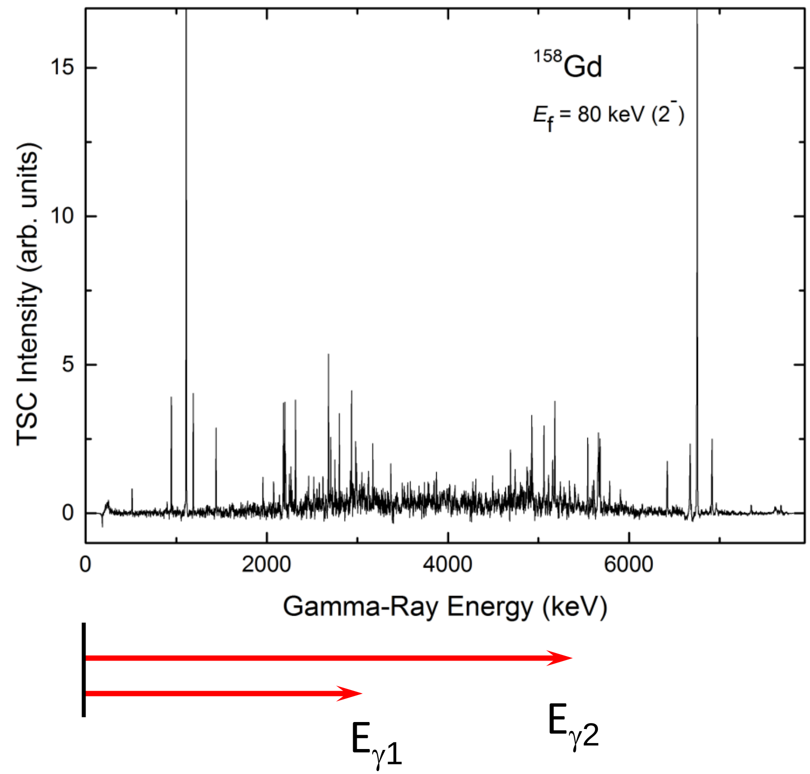


From information about $\boldsymbol{E_{\gamma1}}$ and $\boldsymbol{E_{\gamma2}}$ and **detection time difference**, one can retrieve virtually background-free TSC spectra.

J. Honzatko *et al.*, Nucl. Instr. Meth. A 376, 434 (1996).

TSC measurement – experimental setup



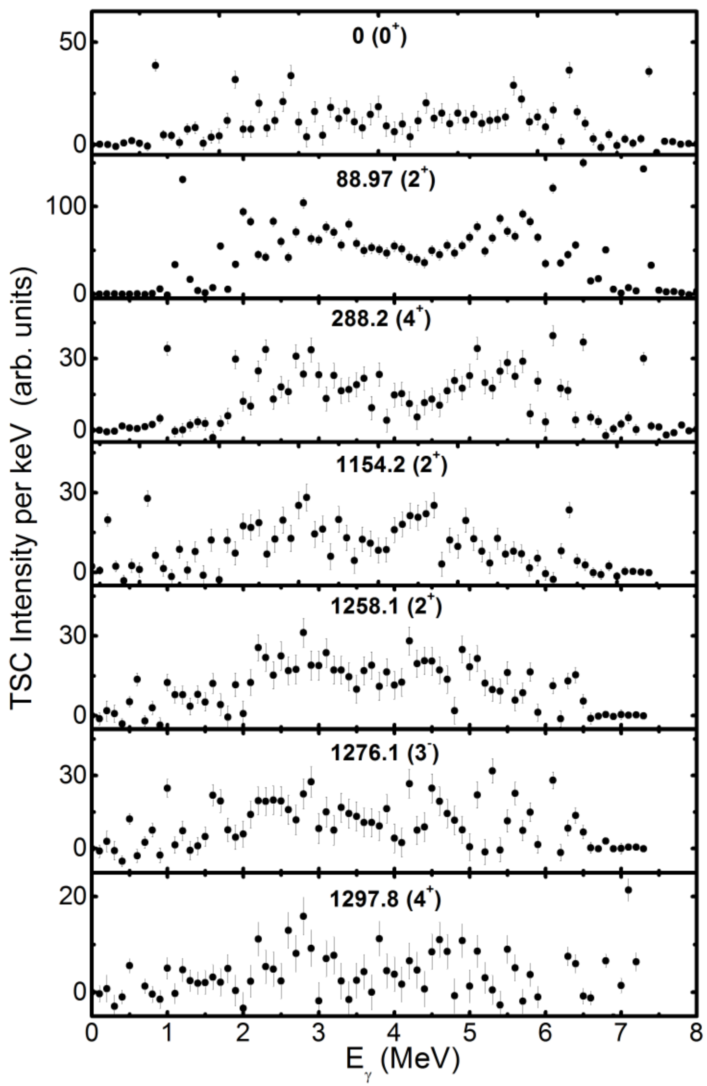


From information about $\boldsymbol{E_{\gamma 1}}$ and $\boldsymbol{E_{\gamma 2}}$ and **detection time difference**, one can retrieve virtually background-free TSC spectra.

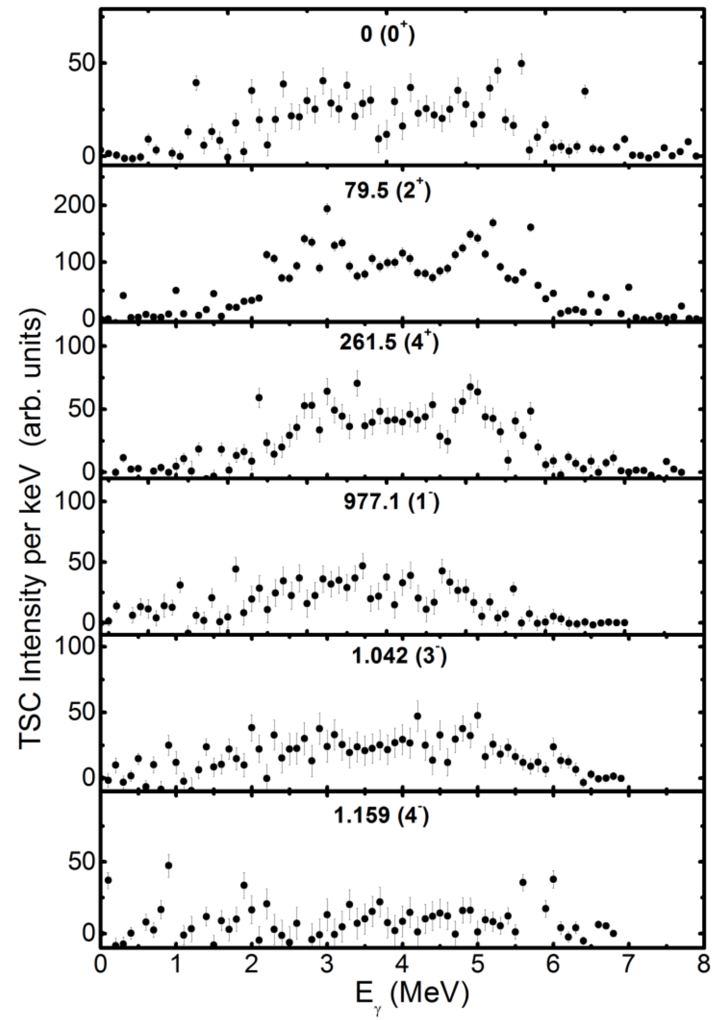
J. Honzatko *et al.*, Nucl. Instr. Meth. A 376, 434 (1996).

TSC measurement – experimental TSC spectra

$^{155}Gd(n,\gamma\gamma)^{156}Gd$



$^{157}Gd(n,\gamma\gamma)^{158}Gd$



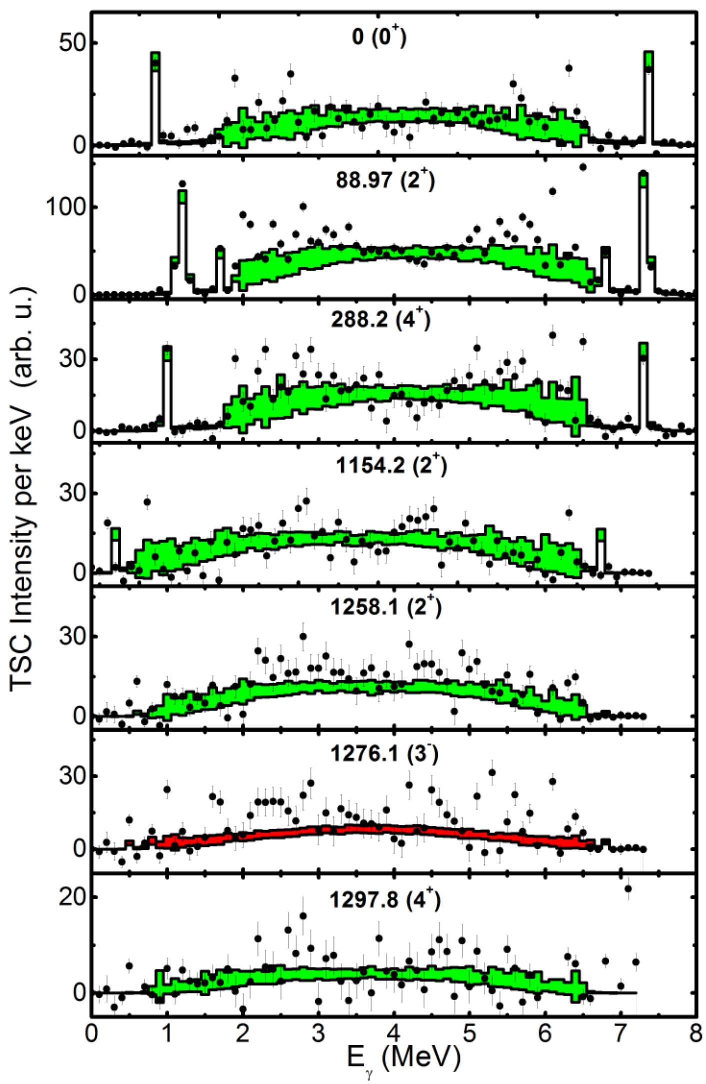
TSC measurement – M1 single-particle

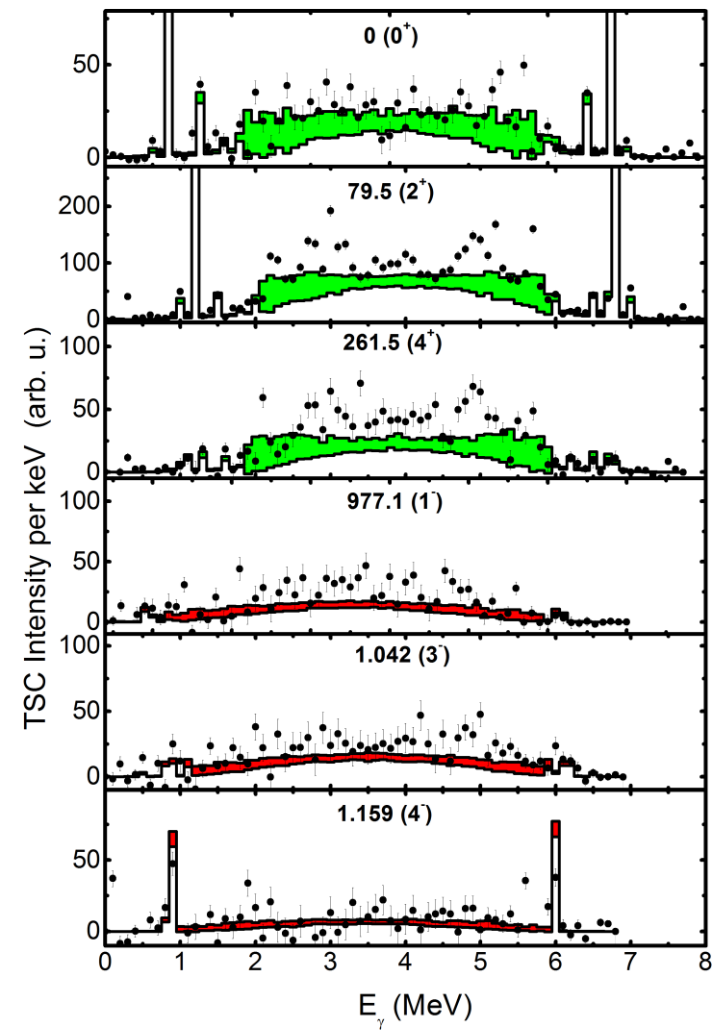
^{155}Gd(n,$\gamma\gamma$)^{156}Gd

Dicebox input

^{157}Gd(n,$\gamma\gamma$)^{158}Gd

E1: MGLO (k_0 = 3.0, $E_{\gamma 0}$ = 4.5 MeV)
M1: SP = $1.58\times10^{-9}\ A^{0.47\pm0.21}$
NLD: BSFG



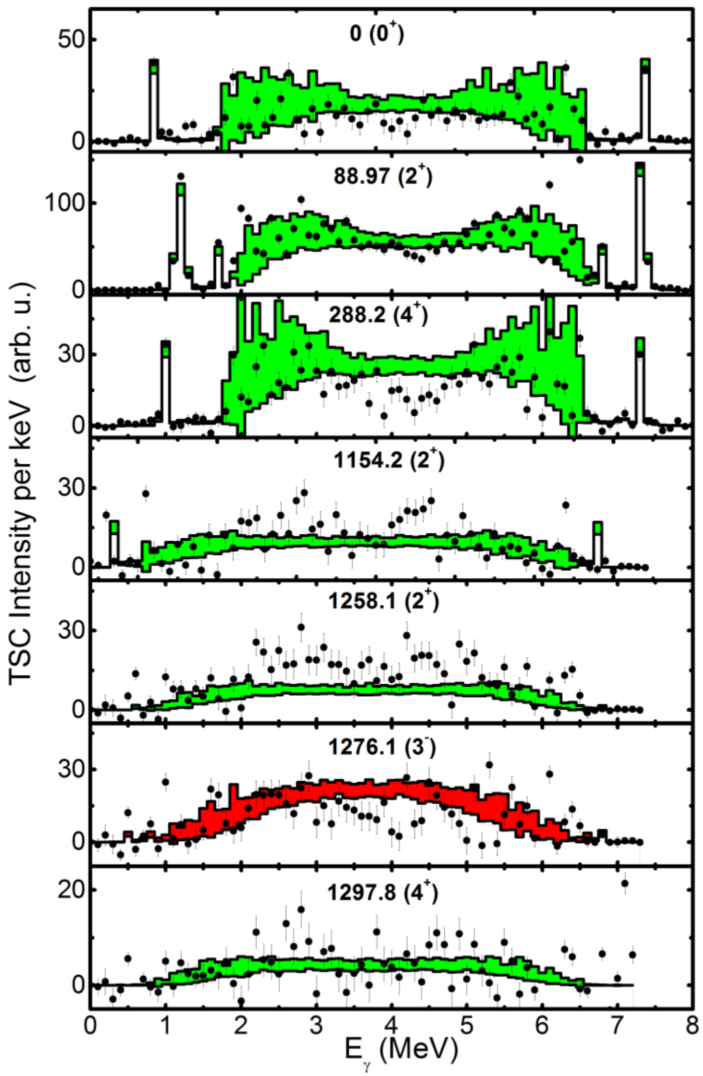


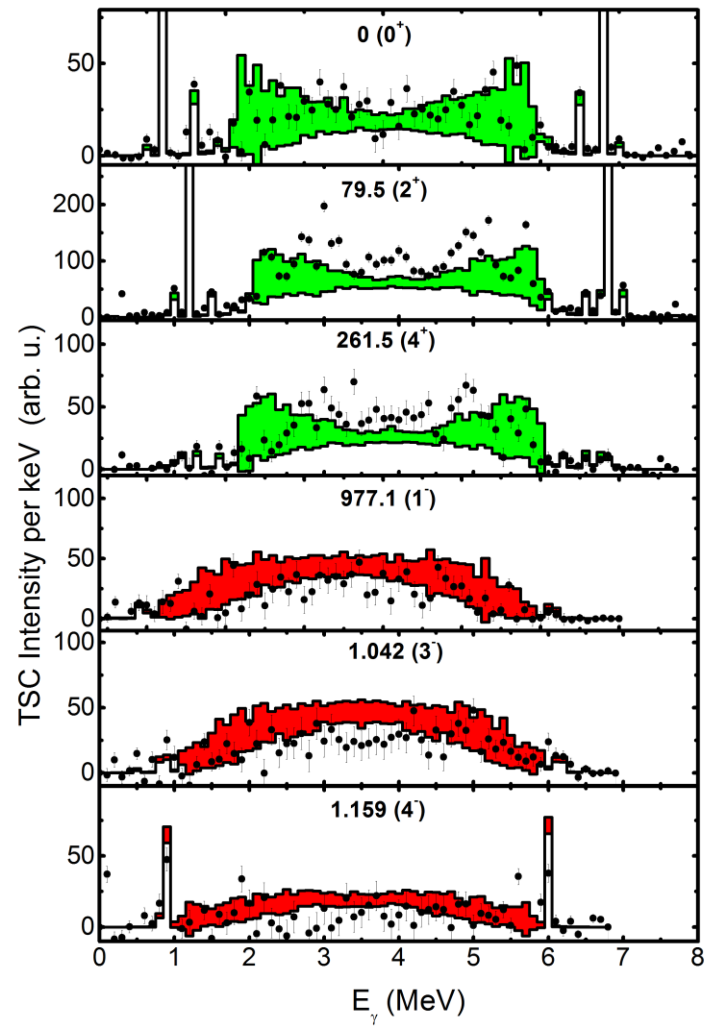
TSC measurement – M1 spin-flip

$^{155}Gd(n,\gamma\gamma)^{156}Gd$ | **Dicebox input** | $^{157}Gd(n,\gamma\gamma)^{158}Gd$

E1: MGLO (k_0 = 3.0, $E_{\gamma 0}$ = 4.5 MeV)
M1: SF
NLD: BSFG

$E_{SF,1}$ = 6 MeV, $\Gamma_{SF,1}$ = 0.8 MeV, $\sigma_{SF,1}$ = 0.7 mb
$E_{SF,2}$ = 8 MeV, $\Gamma_{SF,2}$ = 1.8 MeV, $\sigma_{SF,2}$ = 1.1 mb





TSC measurement – M1 scissors mode + SP + SF

$^{155}Gd(n,\gamma\gamma)^{156}Gd$

SP = 2e-9 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.20 mb

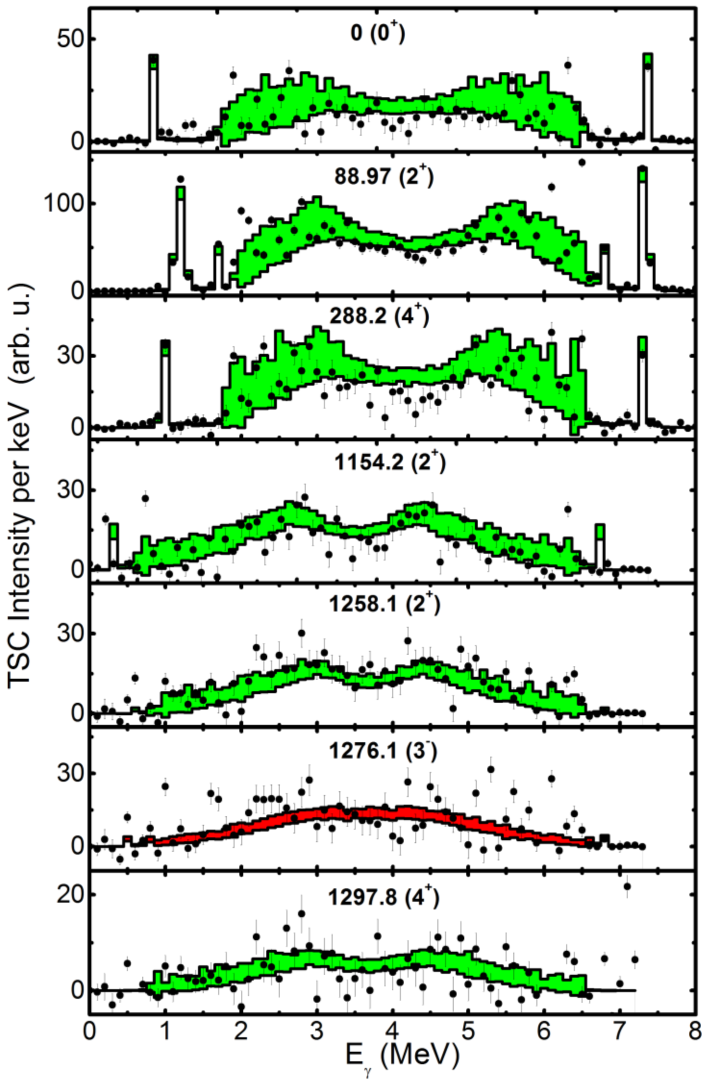
Dicebox input

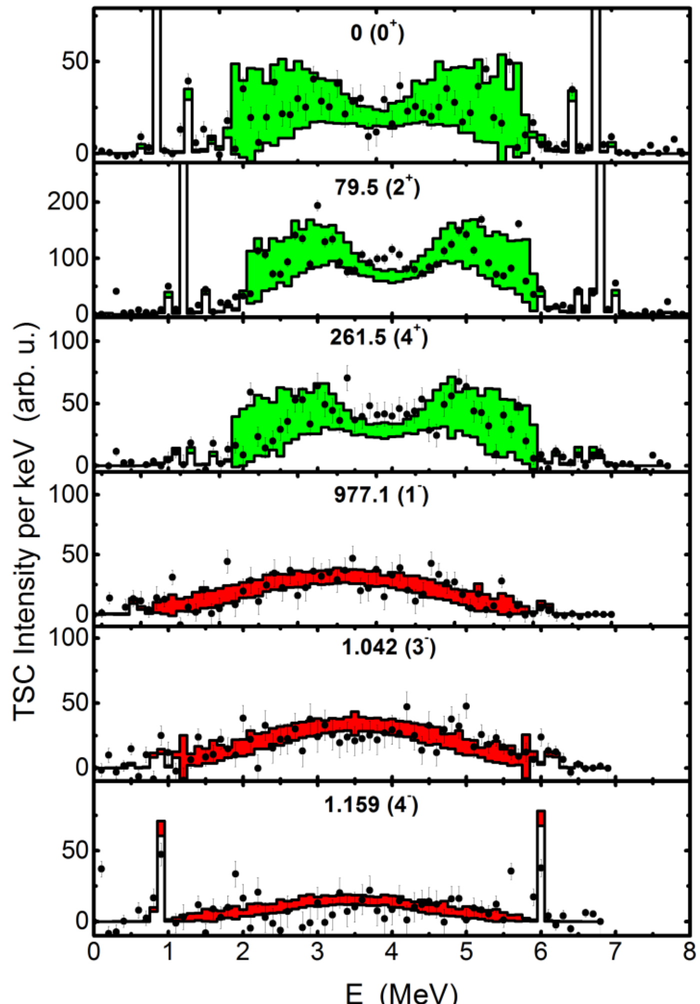
E1: MGLO (k_0 = 3.0, $E_{\gamma 0}$ = 4.5 MeV)
M1: SM + SF + SP
NLD: BSFG

$E_{SF,1}$ = 6 MeV, $\Gamma_{SF,1}$ = 0.8 MeV, $\sigma_{SF,1}$ = 0.7 mb
$E_{SF,2}$ = 8 MeV, $\Gamma_{SF,2}$ = 1.8 MeV, $\sigma_{SF,2}$ = 1.1 mb

$^{157}Gd(n,\gamma\gamma)^{158}Gd$

SP = 0 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.25 mb





TSC - M1 scissors mode (above GS) + SP + SF

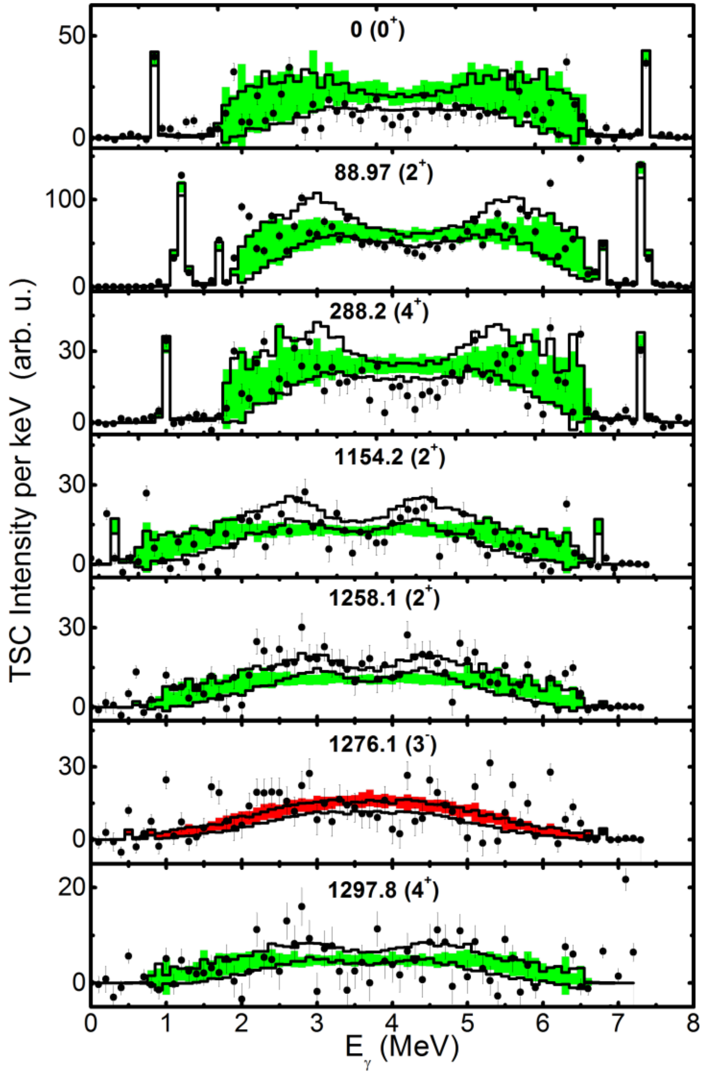
Dicebox input

E1: MGLO (k_0 = 3.0, $E_{\gamma 0}$ = 4.5 MeV)
M1: SM + SF + SP
NLD: BSFG

$E_{SF,1}$ = 6 MeV, $\Gamma_{SF,1}$ = 0.8 MeV, $\sigma_{SF,1}$ = 0.7 mb
$E_{SF,2}$ = 8 MeV, $\Gamma_{SF,2}$ = 1.8 MeV, $\sigma_{SF,2}$ = 1.1 mb

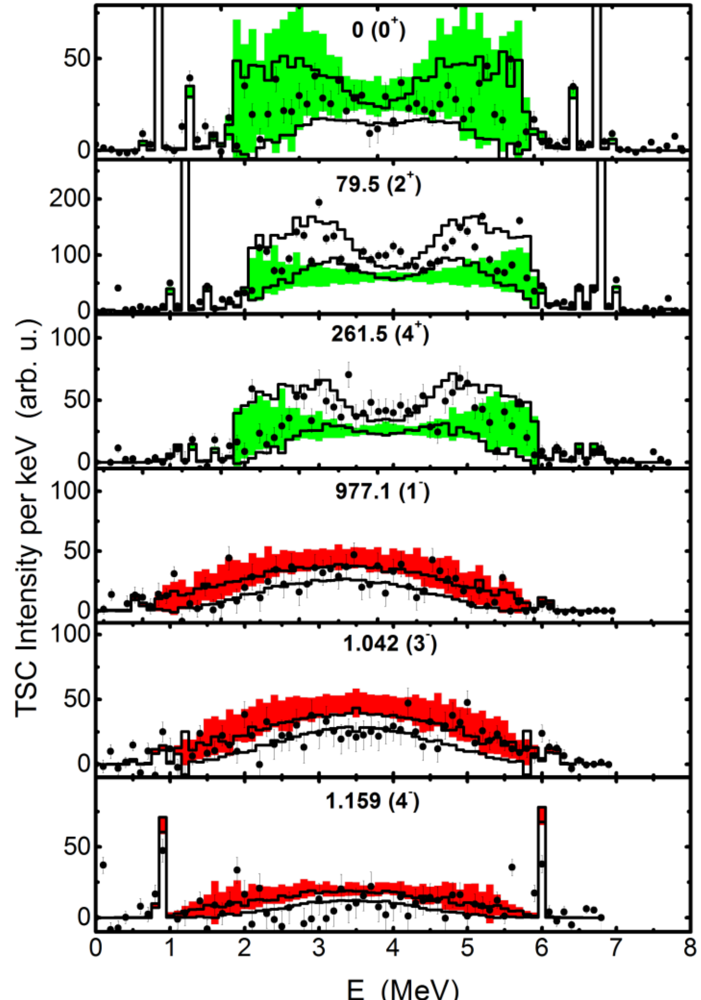
^{155}Gd(n,γγ)^{156}Gd

SP = 2e-9 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.20 mb

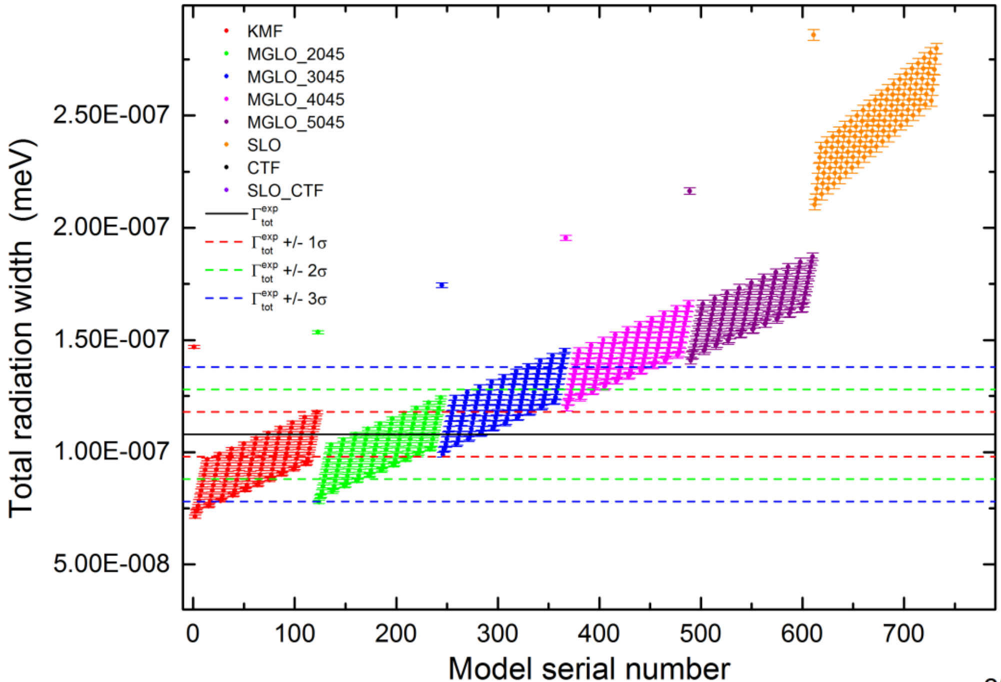


^{157}Gd(n,γγ)^{158}Gd

SP = 0 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.25 mb

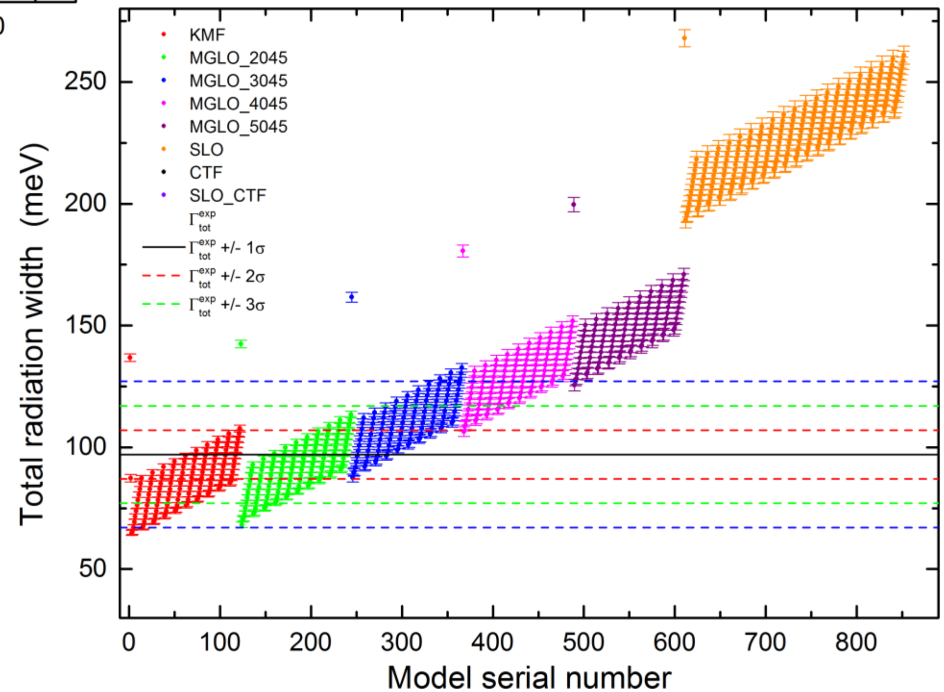


TSC – Total Radiation Width



$^{155}Gd(n,\gamma\gamma)^{156}Gd$

$^{157}Gd(n,\gamma\gamma)^{158}Gd$



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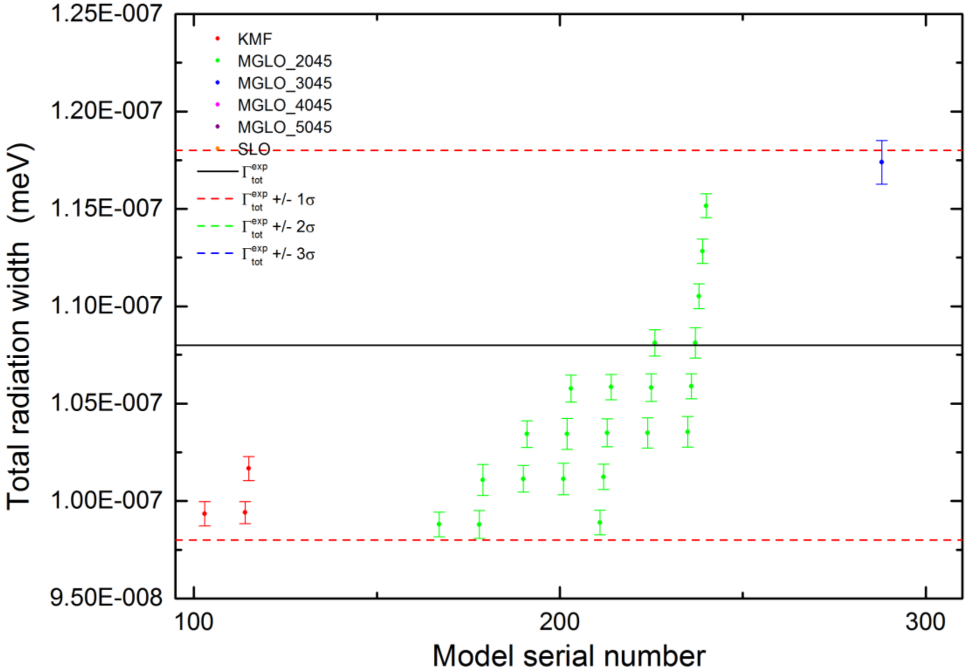

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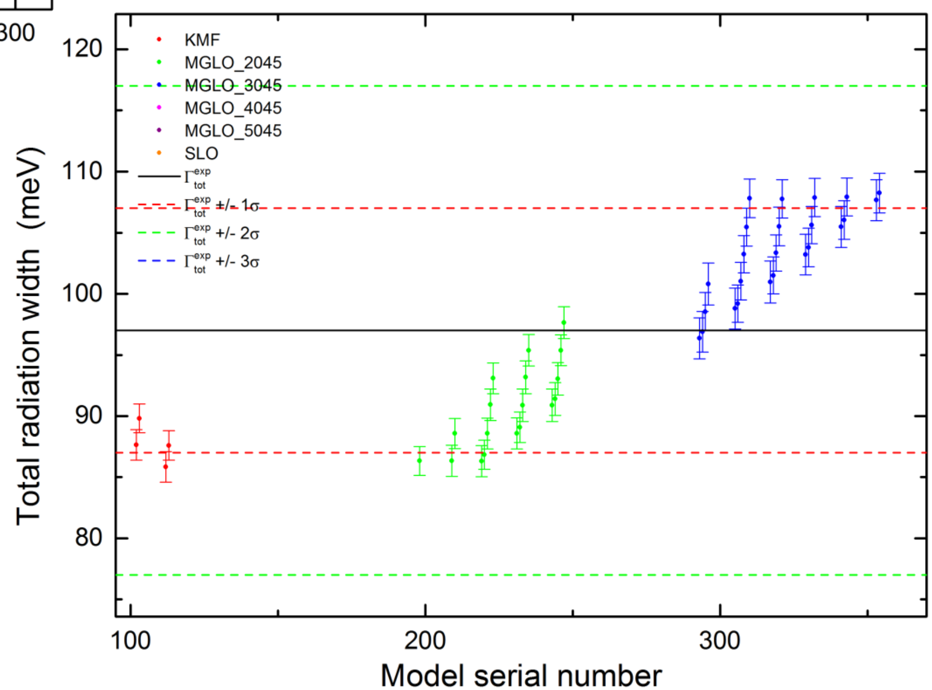


DANCE vs TSC results for ^{156}Gd and ^{158}Gd

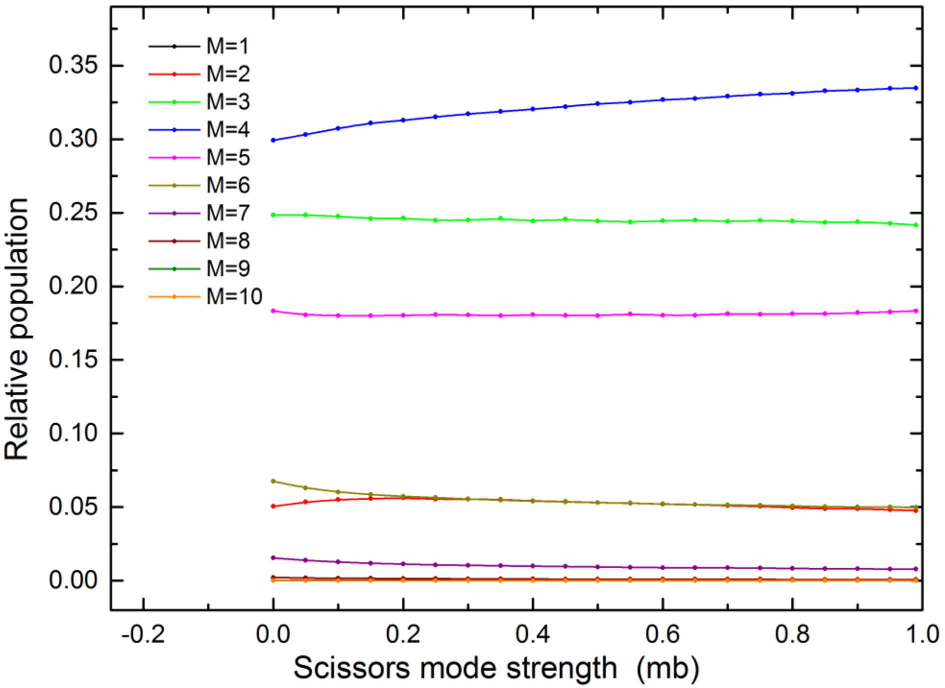
Isot.	*E*1	*M*1: f_{M1} = SM+SP+SF		*E*2: f_{E2} = c	NLD
		DANCE			
^{156}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.7-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.9-3.5 μ_N^2	2.0-4.0 (10^{-9} MeV^{-3})	5E-11 MeV^{-5}	BSFG
^{158}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.4-2.8 μ_N^2	1.0-2.5	5E-11 MeV^{-5}	BSFG
		TSC			
^{156}Gd	KMF, MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.0 MeV $\Sigma B(SM)\uparrow$ = **2.49(76)** μ_N^2	0.5-3.0	5E-11 MeV^{-5}	BSFG
^{158}Gd	KMF, MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.9-3.2 MeV $\Sigma B(SM)\uparrow$ = **2.10(85)** μ_N^2	0.0-2.0	5E-11 MeV^{-5}	BSFG

DANCE vs TSC results for ^{156}Gd and ^{158}Gd

Isot.	*E*1	*M*1: f_{M1} = SM+SP+SF		*E*2: f_{E2} = c	NLD
DANCE					
^{156}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.7-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.9-3.5 μ_N^2	2.0-4.0 (10^{-9} MeV^{-3})	5E-11 MeV^{-5}	BSFG
^{158}Gd	MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.1 MeV $\Sigma B(SM)\uparrow$ = 1.4-2.8 μ_N^2	1.0-2.5	5E-11 MeV^{-5}	BSFG
TSC					
^{156}Gd	KMF, MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.8-3.0 MeV $\Sigma B(SM)\uparrow$ = **2.49(76)** μ_N^2	0.5-3.0	5E-11 MeV^{-5}	BSFG
^{158}Gd	KMF, MGLO (k_0 = 2-3, Eg_0 = 4.5 MeV)	E_{SM} = 2.9-3.2 MeV $\Sigma B(SM)\uparrow$ = **2.10(85)** μ_N^2	0.0-2.0	5E-11 MeV^{-5}	BSFG

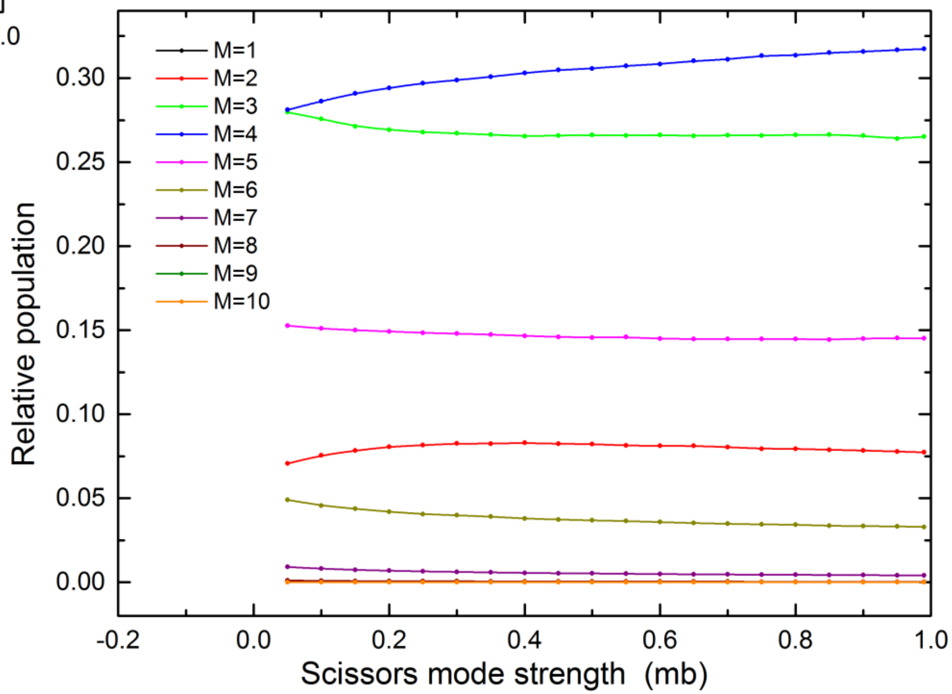
Lower limit of the SM strength

Comments on the TSC method

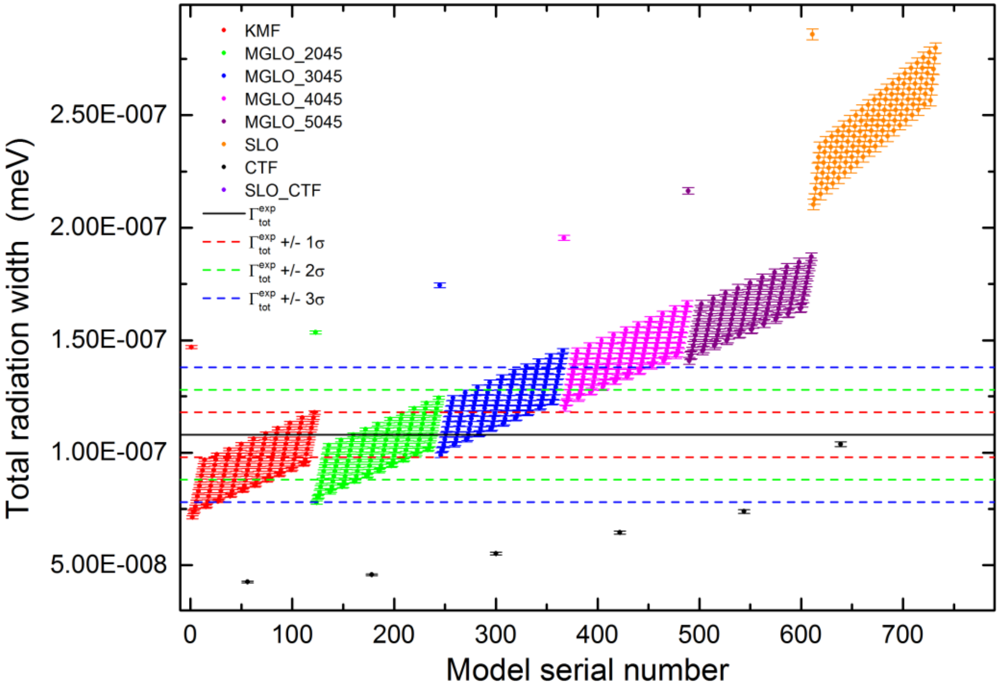


$^{155}\mathrm{Gd}(n,\gamma\gamma)^{156}\mathrm{Gd}$

$^{157}\mathrm{Gd}(n,\gamma\gamma)^{158}\mathrm{Gd}$

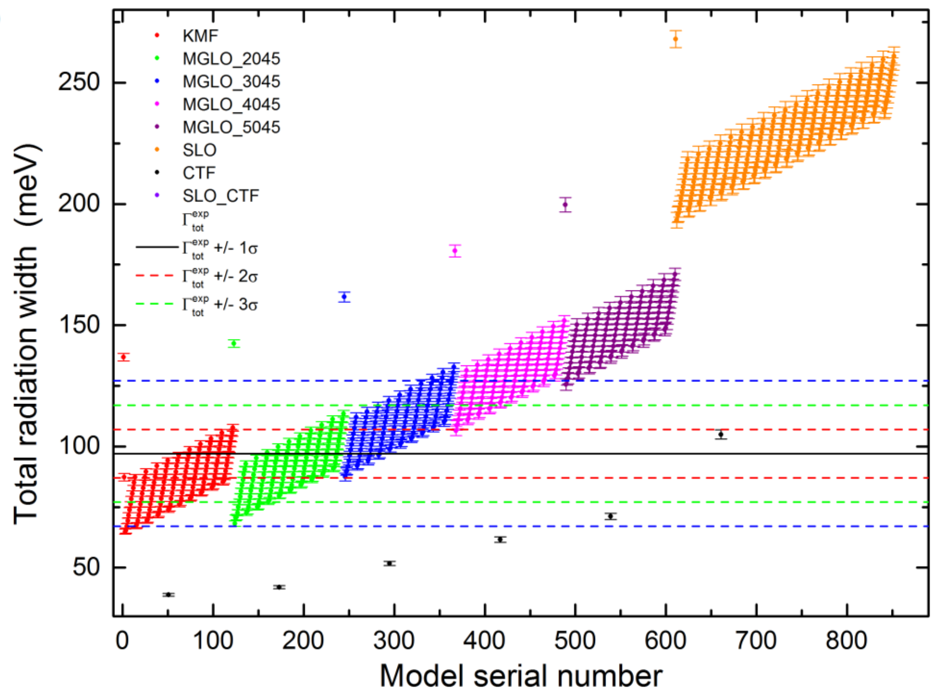


Comments on the TSC method

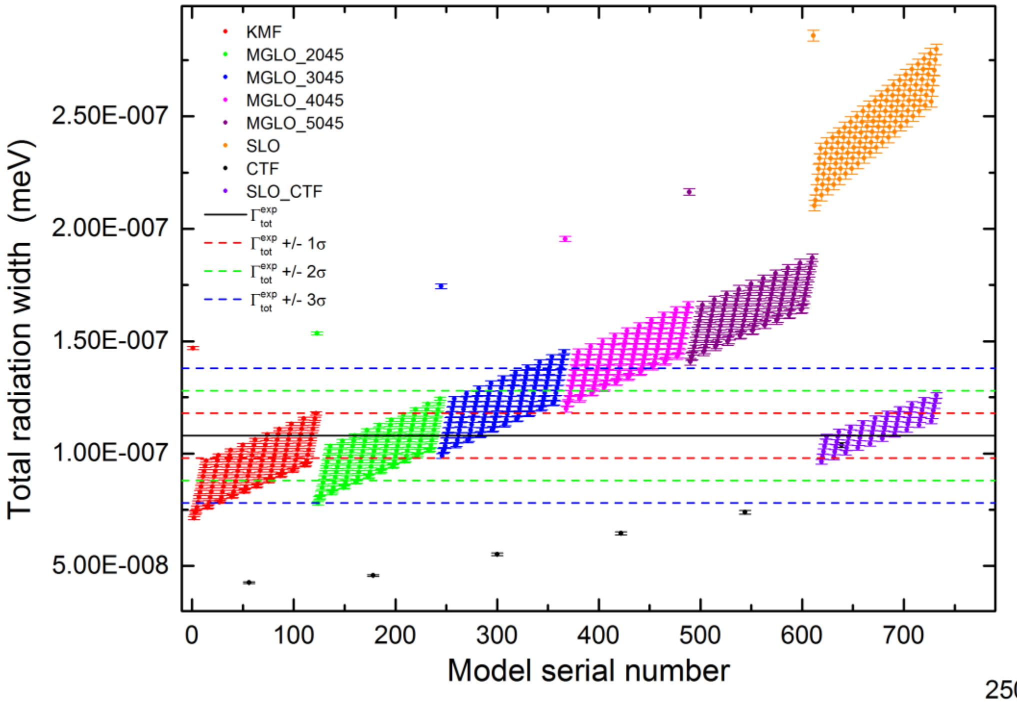


$^{155}Gd(n,\gamma\gamma)^{156}Gd$

$^{157}Gd(n,\gamma\gamma)^{158}Gd$

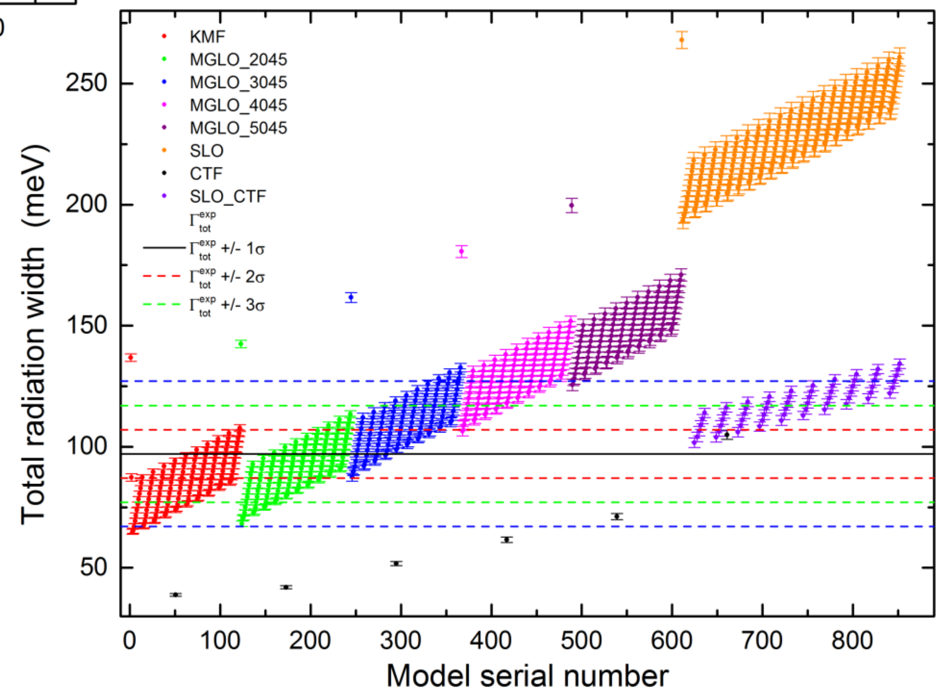


Comments on the TSC method



$^{155}Gd(n,\gamma\gamma)^{156}Gd$

$^{157}Gd(n,\gamma\gamma)^{158}Gd$



TSC – SLO + CT NLD + stronger SM

^{155}Gd(n,$\gamma\gamma$)^{156}Gd

SP = 5e-9 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.70 mb

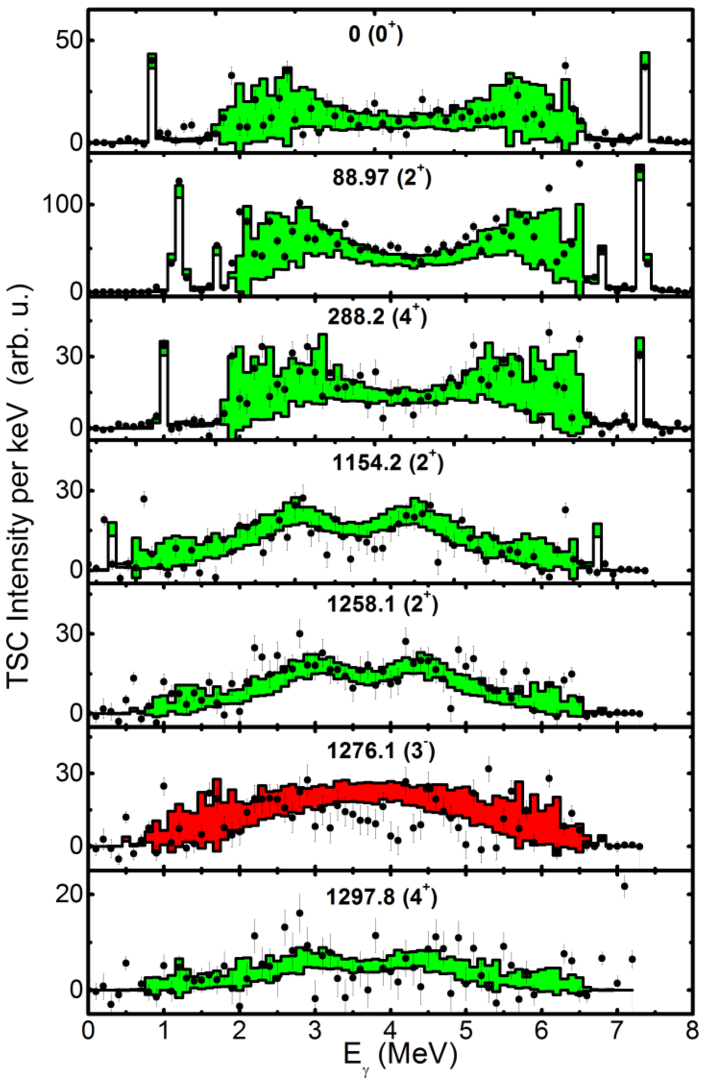
E1: SLO
M1: SM + SF + SP
NLD: BSFG

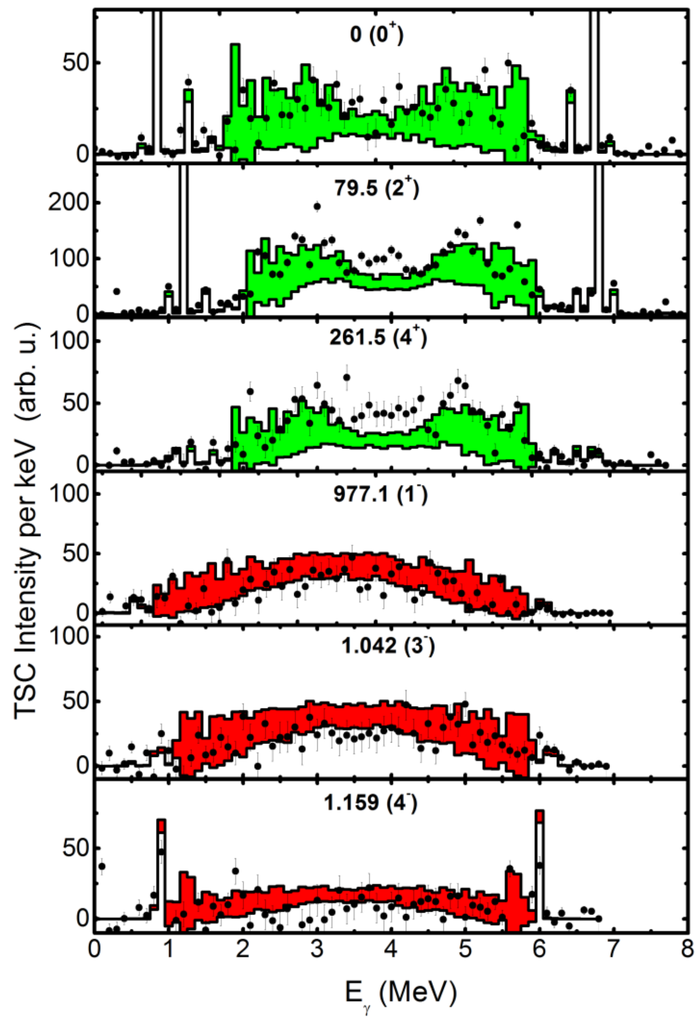
Dicebox input

$E_{SF,1}$ = 6 MeV, $\Gamma_{SF,1}$ = 0.8 MeV, $\sigma_{SF,1}$ = 0.7 mb
$E_{SF,2}$ = 8 MeV, $\Gamma_{SF,2}$ = 1.8 MeV, $\sigma_{SF,2}$ = 1.1 mb

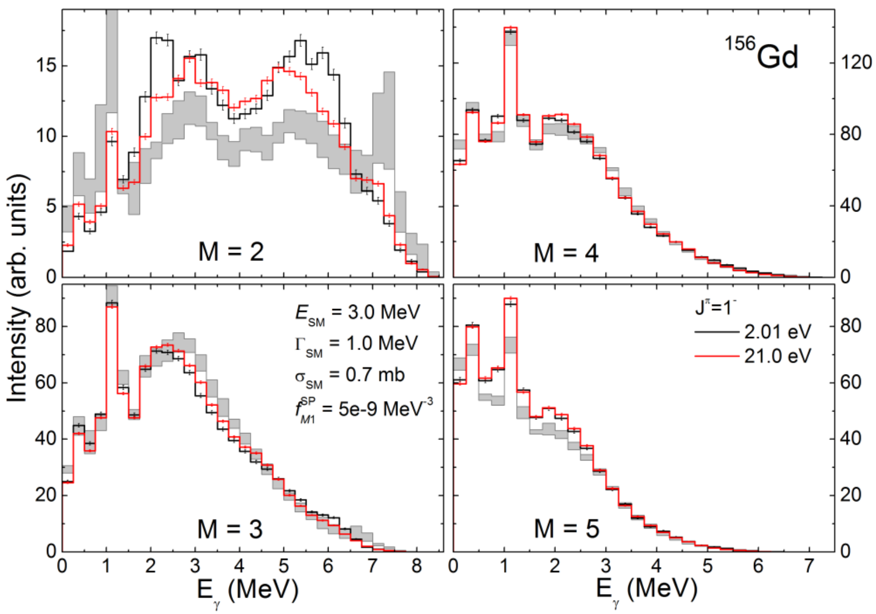
^{157}Gd(n,$\gamma\gamma$)^{158}Gd

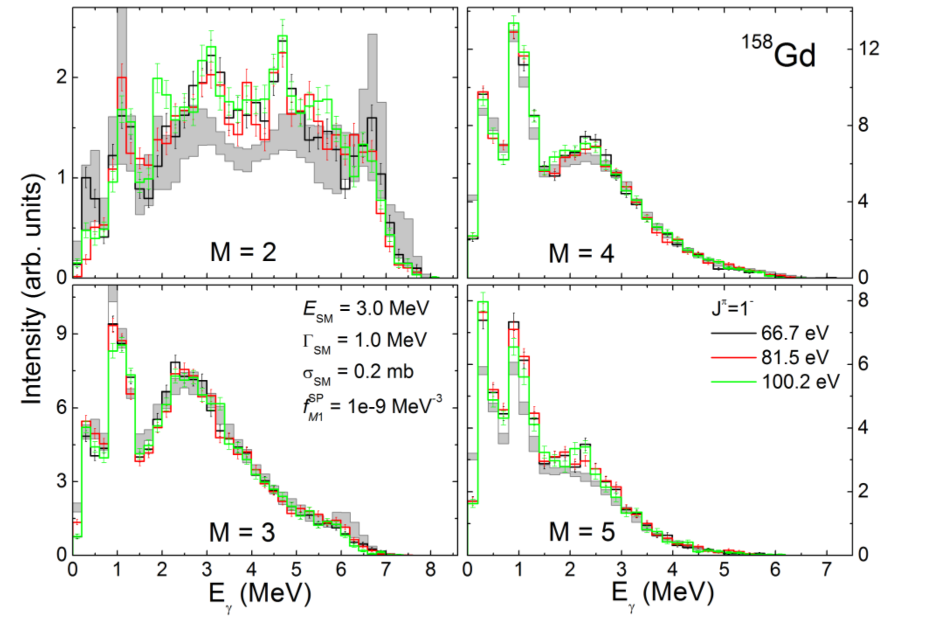
SP = 5e-9 MeV^{-3}
E_{SM} = 3.0 MeV
Γ_{SM} = 1.0 MeV
σ_{SM} = 0.70 mb

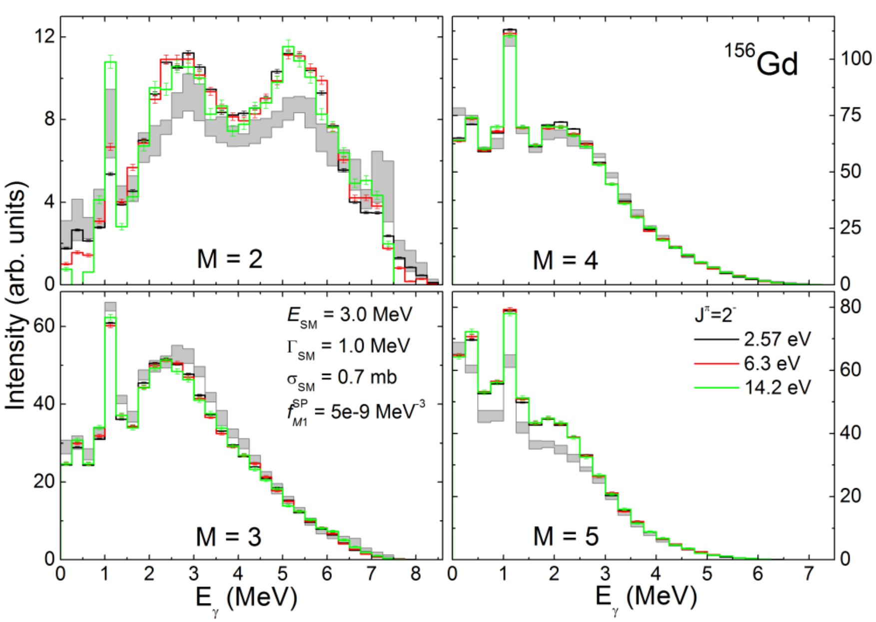


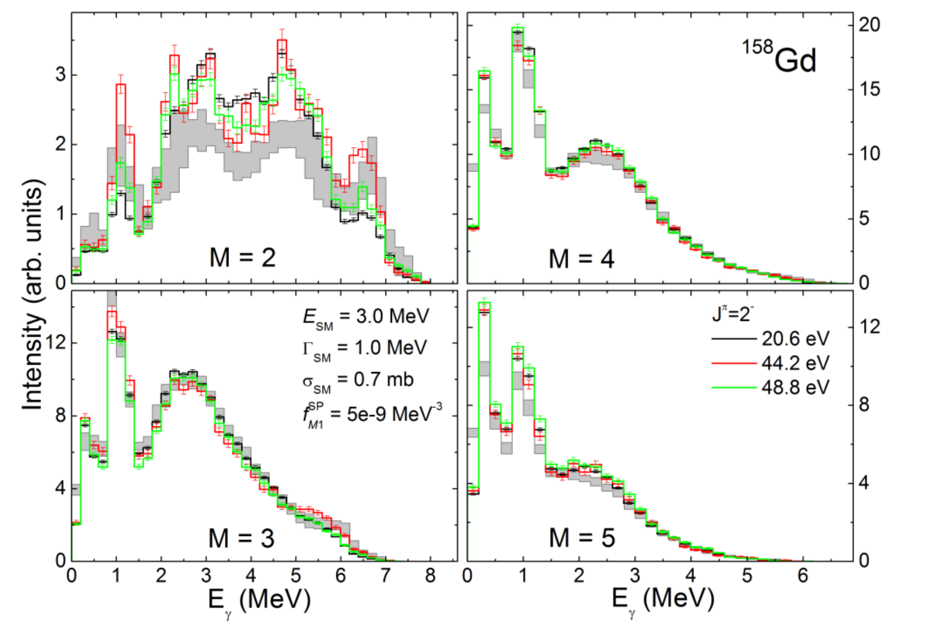


DANCE – SLO + CT NLD + stronger SM









Conclusions

- $^{155}Gd(n,\gamma\gamma)^{156}Gd$ and $^{157}Gd(n,\gamma\gamma)^{158}Gd$ TSC reactions with thermal neutrons were measured at Řež
- the statistical properties were analyzed using the DICEBOX code
- DANCE models of PSFs and NLD reproduce TSC data
- weak scissors mode reproduces TSC data in ^{156}Gd and ^{158}Gd products
- scissors mode must be postulated on excited states
- TSC method has its specific properties – multiplicity two:
  - only lower limits of the SM strength were obtained
  - SLO + CT NLD combination for ^{156}Gd cannot be completely excluded