The two-step (and multiple-step) γ cascade method as a tool for studying γ-ray strength functions

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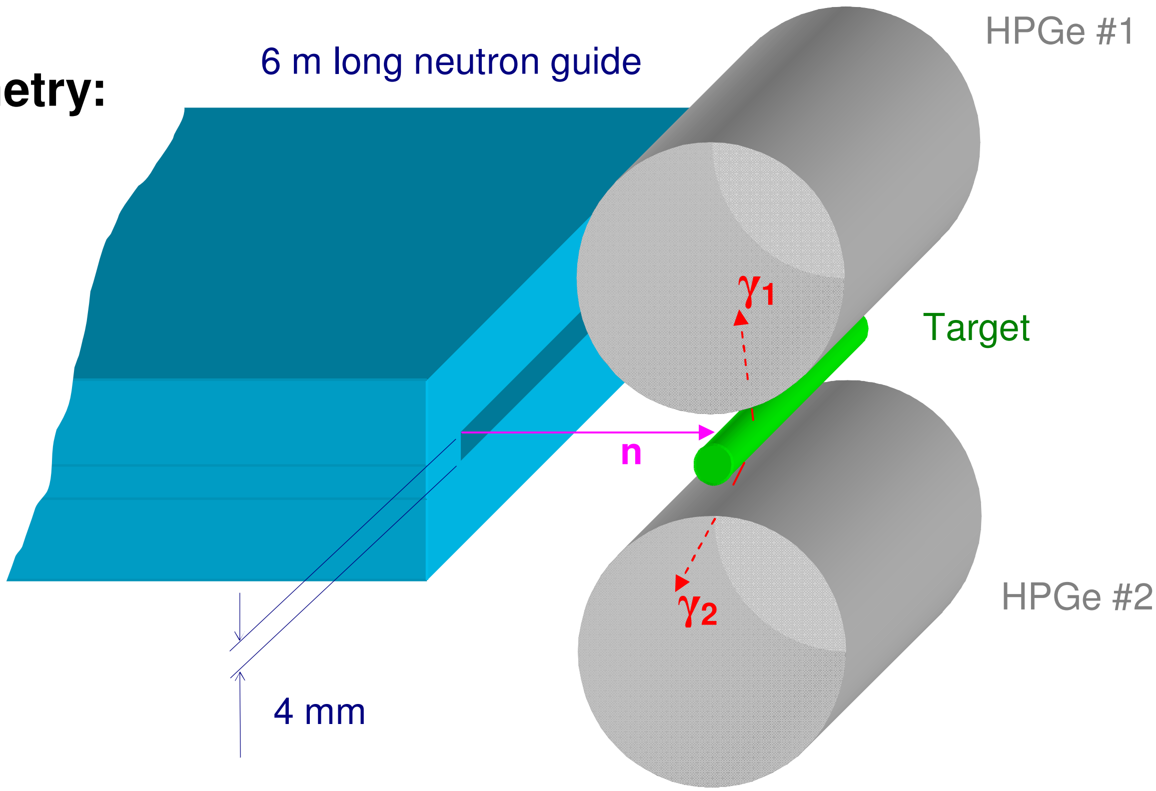
faculty of mathematics and physics

Outline

- The method of two-step γ-cascades following thermal neutron capture (setup at Rez near Prague)
- Two-step (multi-step) γ-cascades following resonance neutron capture (DANCE - LANL)
- Data processing - DICEBOX code
- Examples / Results (Enhancement of PSFs at low energies, Scissors mode)

The method of two-step γ-cascades following TNC

Geometry:



Data acquisition:

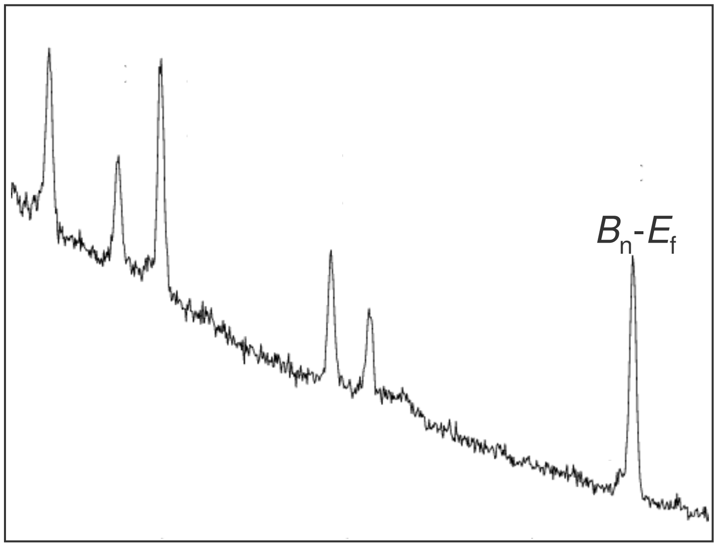
Three-parametric, list-mode

- Energy $E_{\gamma 1}$
- Energy $E_{\gamma 2}$
- Detection-time difference

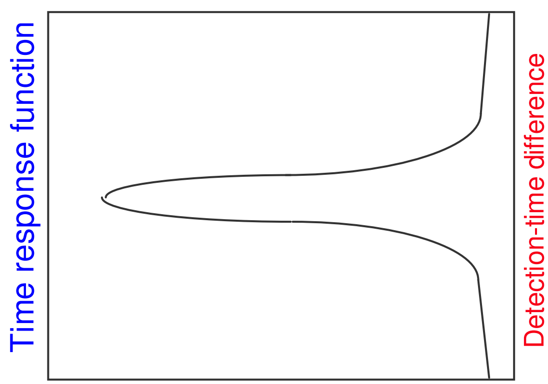

HMOT. 2700 Kg
50 Kg.
CANBERRA

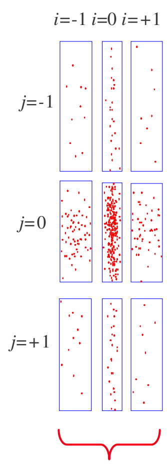
TSC spectra

Spectrum of energy sums

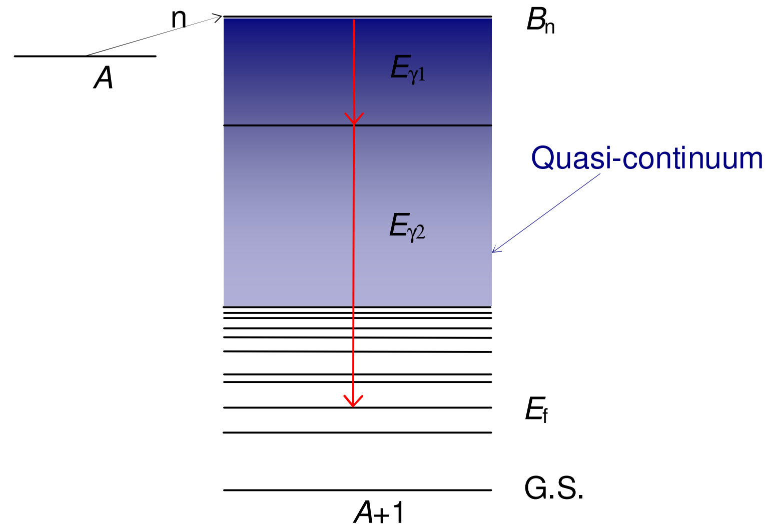


Energy sum $E_{\gamma 1}$+ $E_{\gamma 2}$





List-mode data



Accumulation of the TSC spectrum from, say, detector #1:

The contents of the bin, belonging to the energy $E_{\gamma 1}$, is incremented by

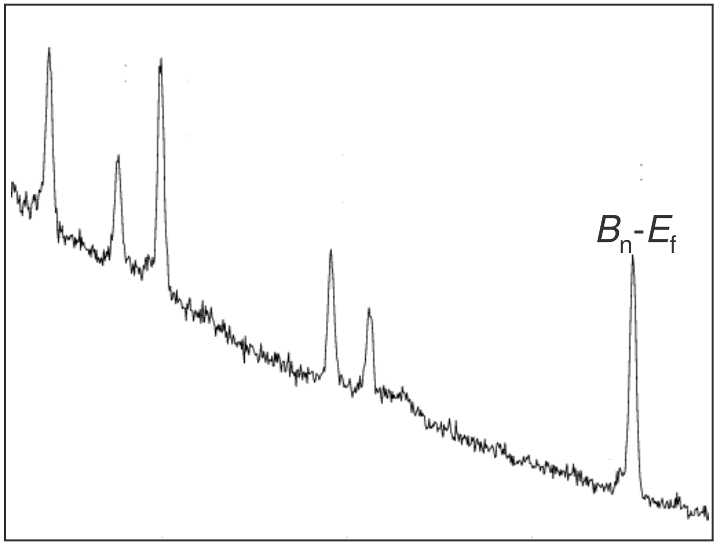
$$q = \alpha_{ij},$$

where α_{ij} is given by the position and the size of the corresponding window in the 2D space "*detection time*"×"*energy sum* $E_{\gamma 1}+E_{\gamma 2}$".

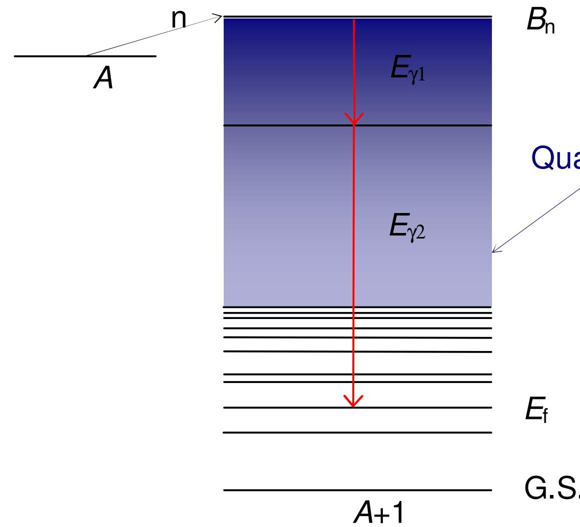
⇒ background-free spectrum

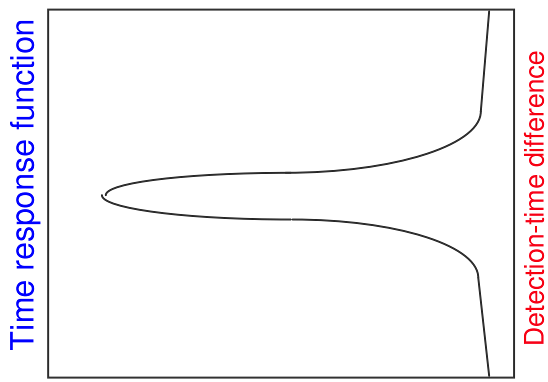
TSC spectra

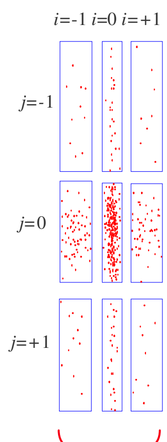
Spectrum of energy sums



Energy sum $E_{\gamma1}$+ $E_{\gamma2}$

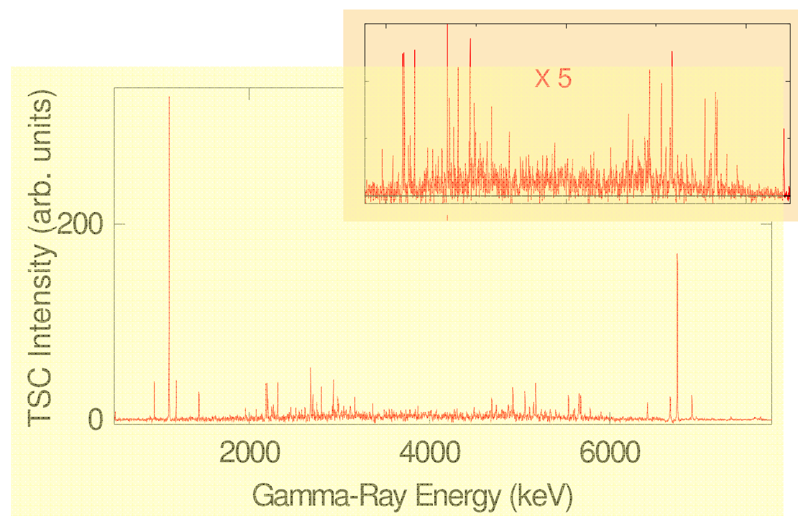




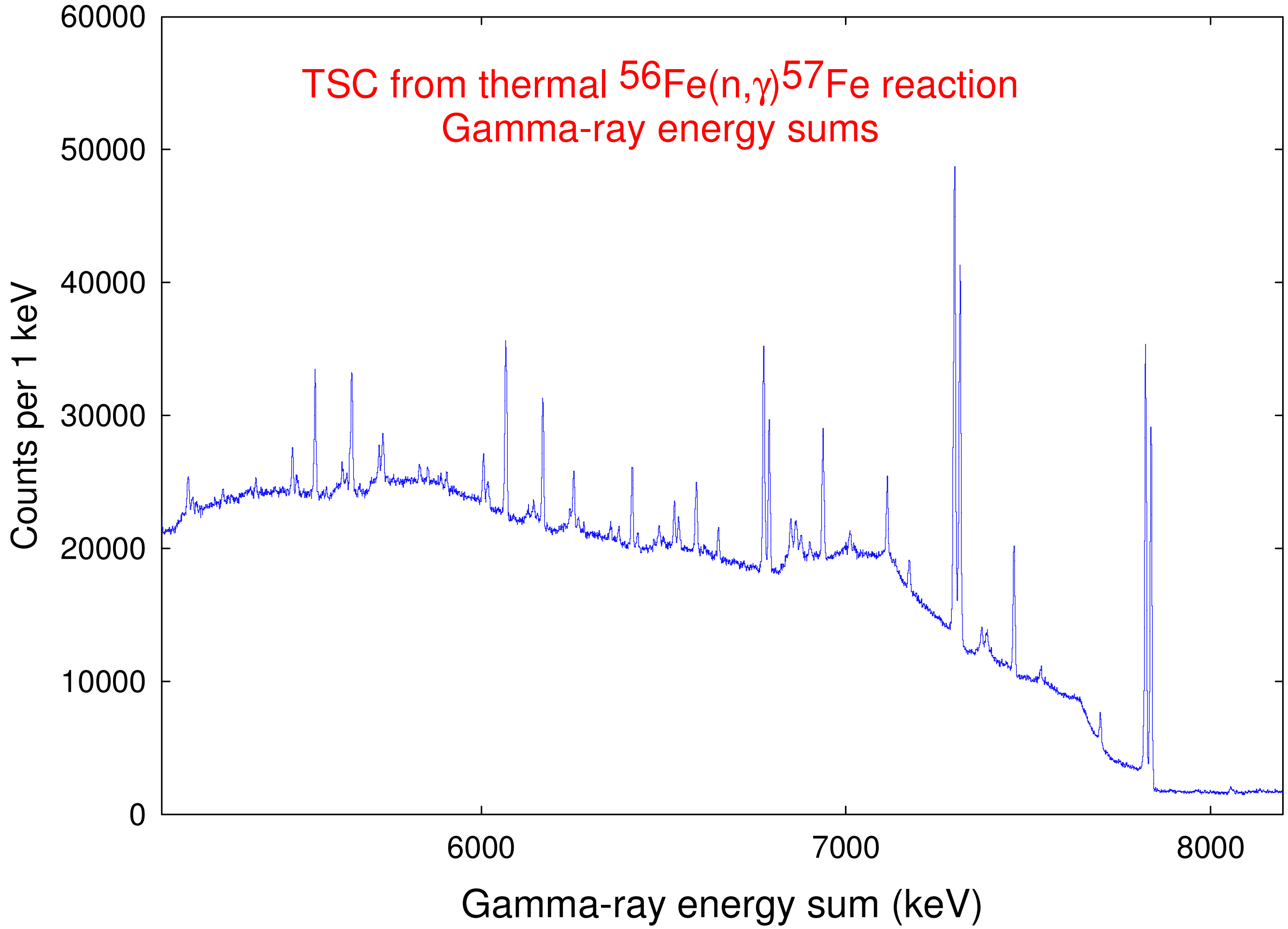


List-mode data

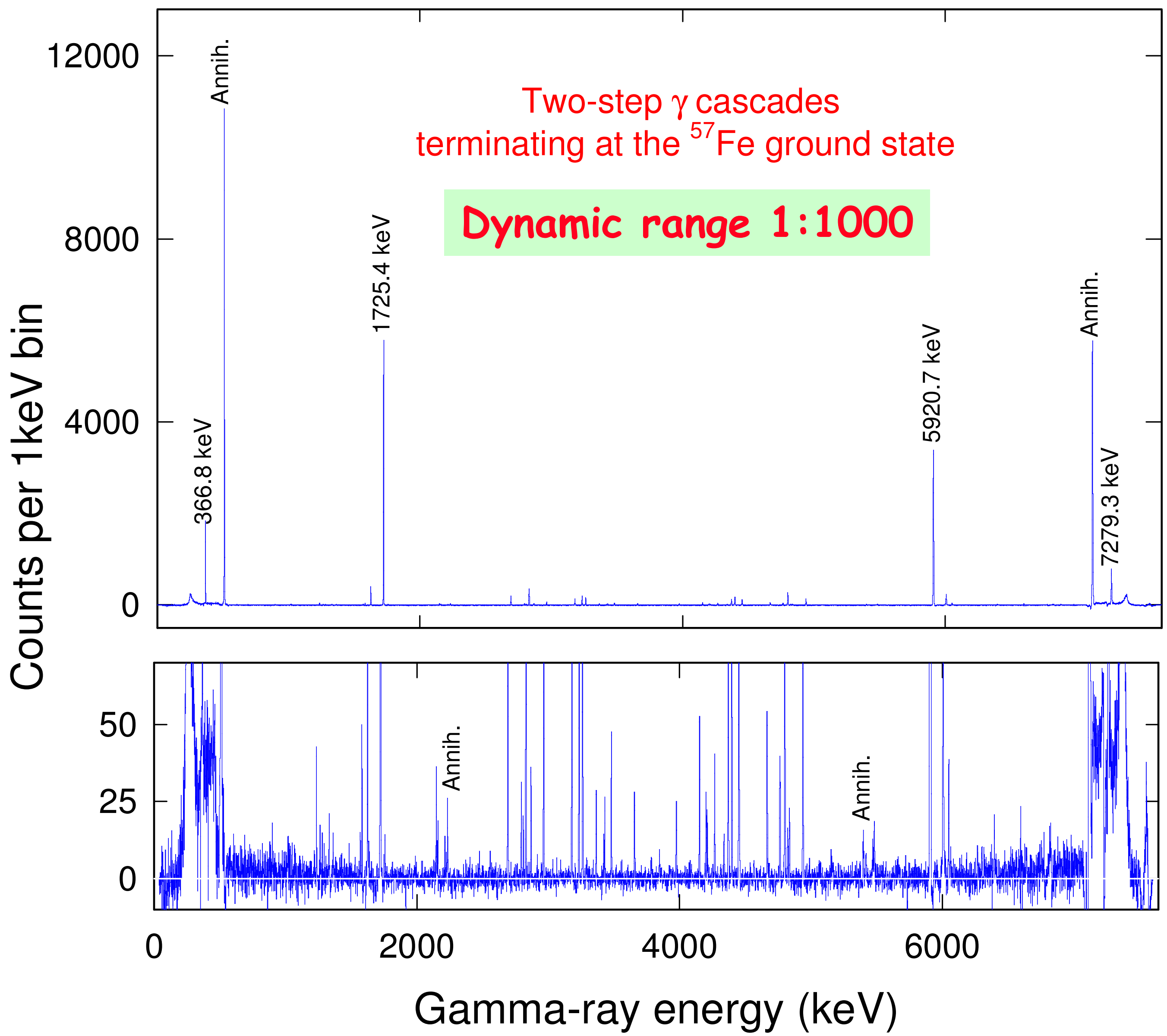
TSC spectrum - taken from **only one** of the detectors



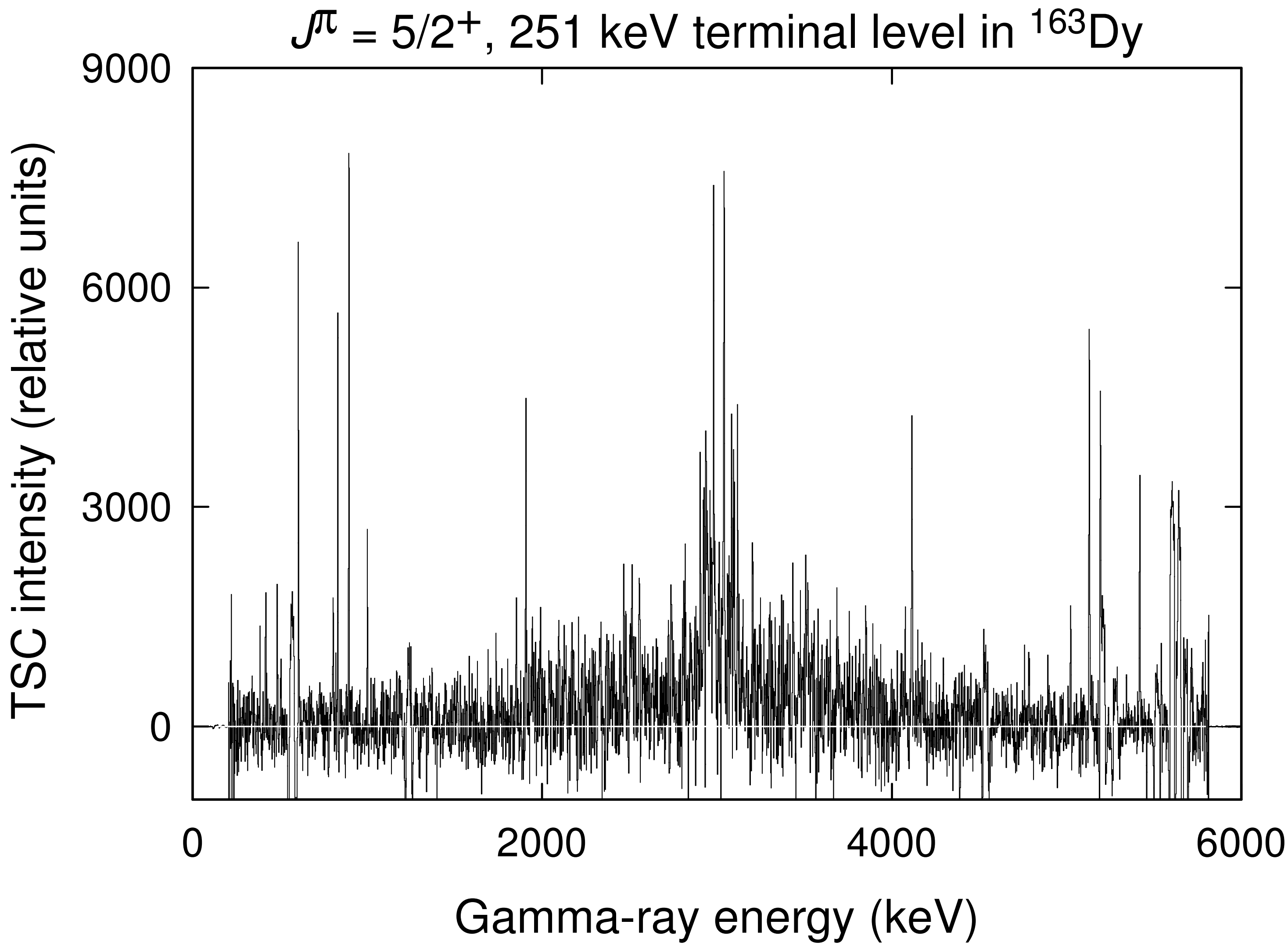
Example of sum-energy spectra (^{57}Fe)



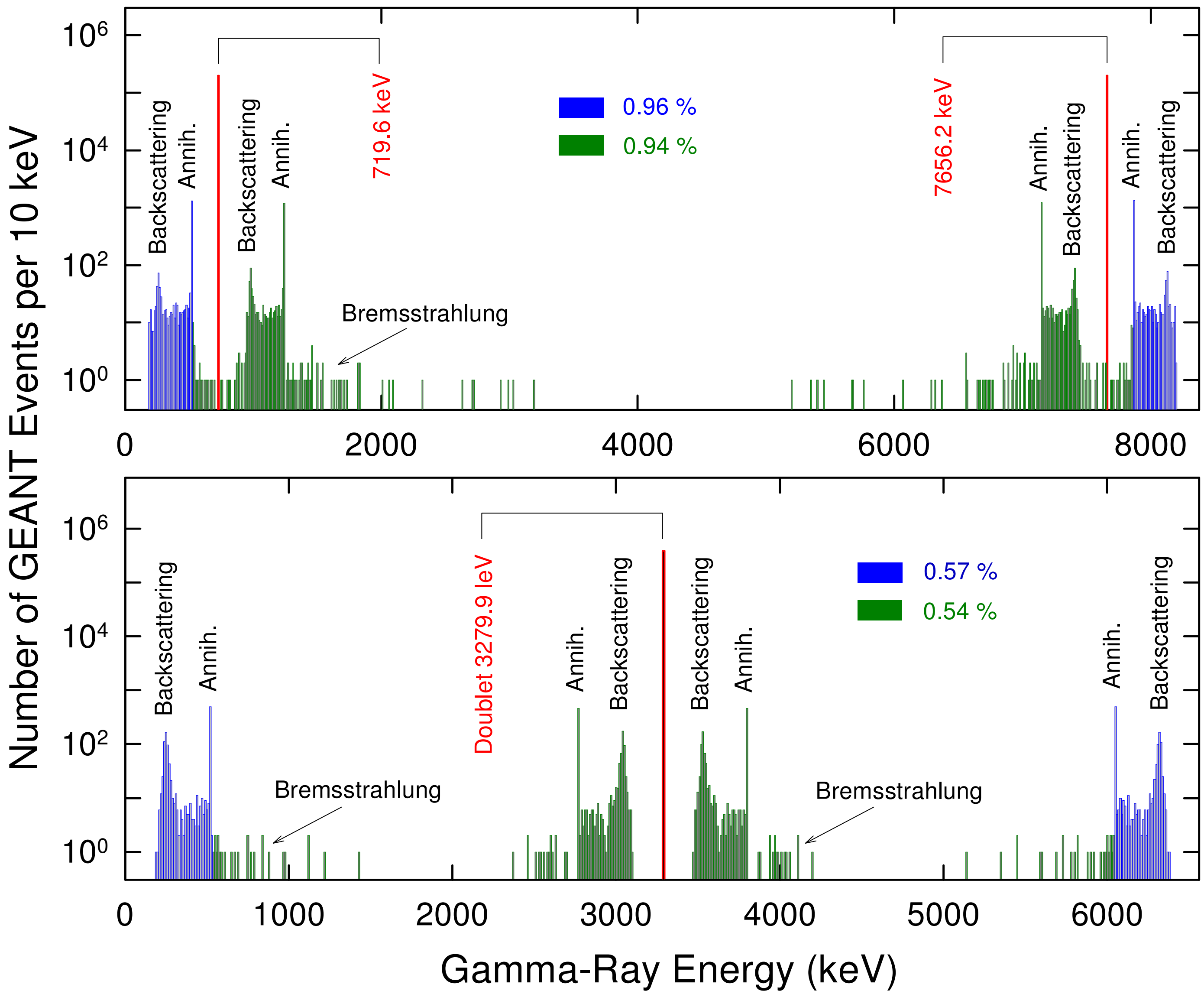
Example of a TSC spectrum



Example of a TSC spectrum



Results of GEANT3 simulations - $^{95}Mo(n,\gamma)^{96}Mo$

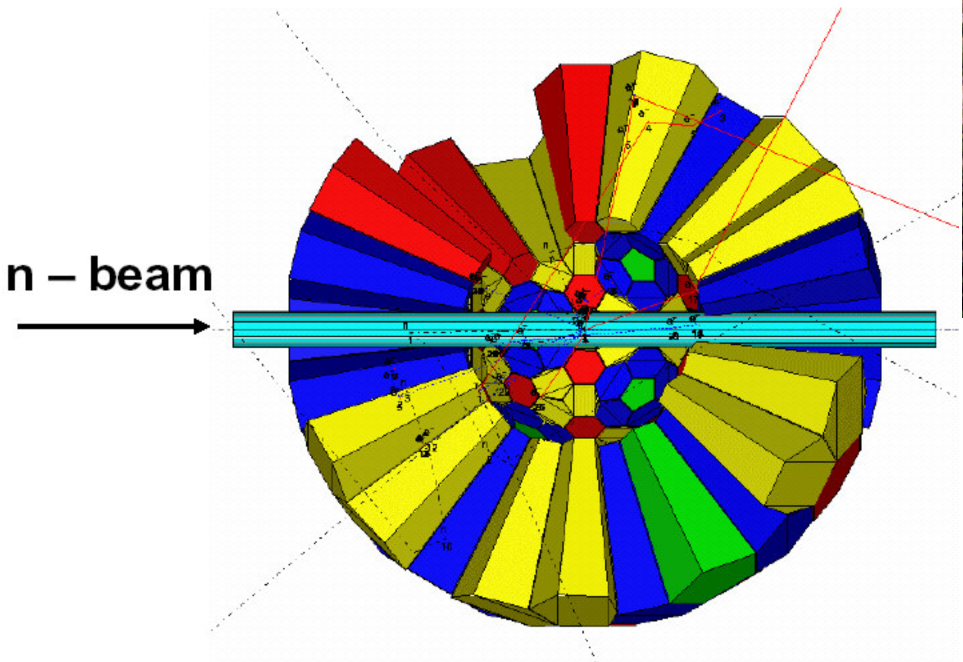


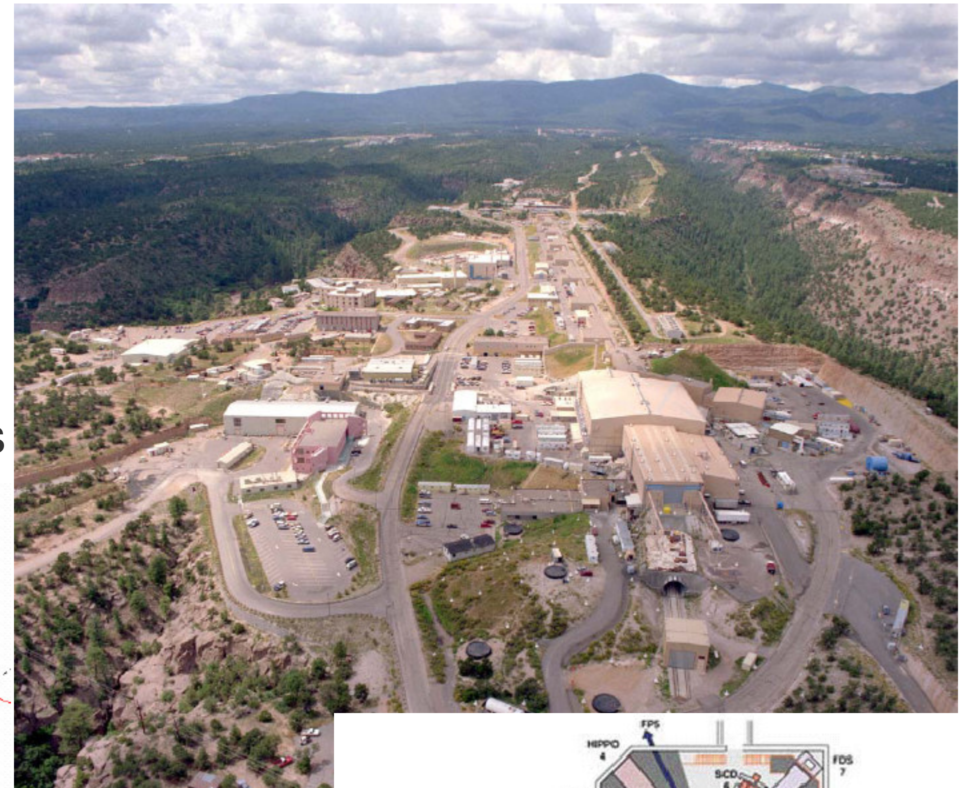
- Two-step (multi-step) γ-cascades following neutron capture with higher energies (in the region of resolved or unresolved resonances)

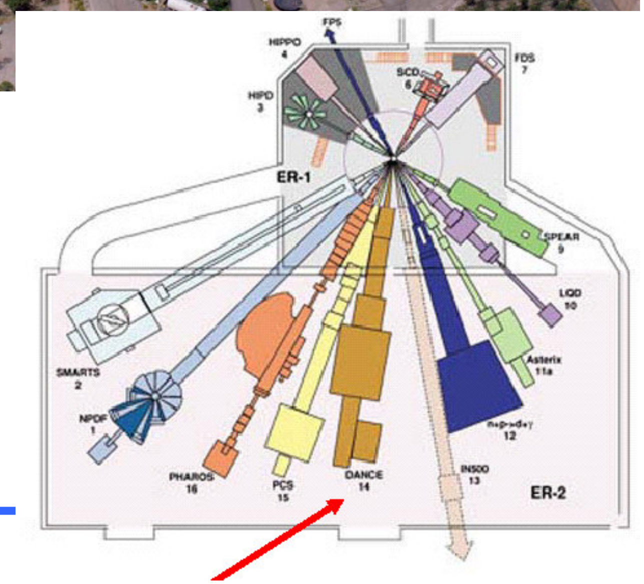
- Measured with BaF_2 detector array (DANCE – LANL, n_TOF)

DANCE @ LANSCE

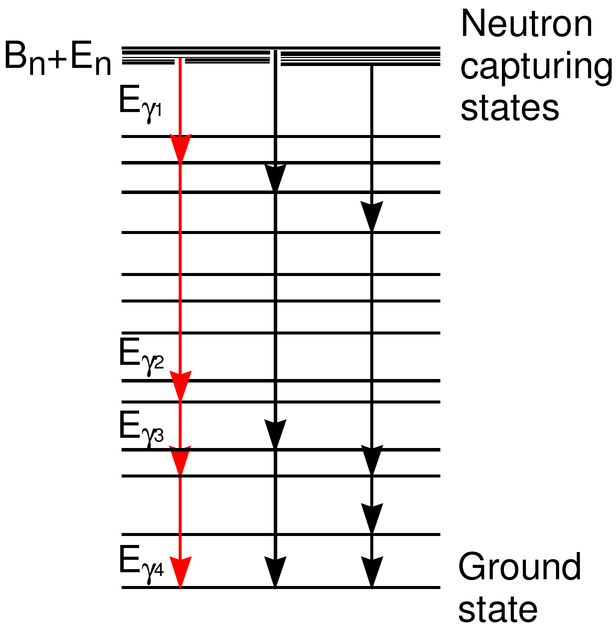
- Moderated W target gives “white” neutron spectrum, ~14 n’s/proton
- DANCE is on a 20 m flight path / ~1 cm @ beam after collimation
- repetition rate 20 Hz
- pulse width ≈ 125 ns
- DANCE consists of 160 BaF_2 crystals

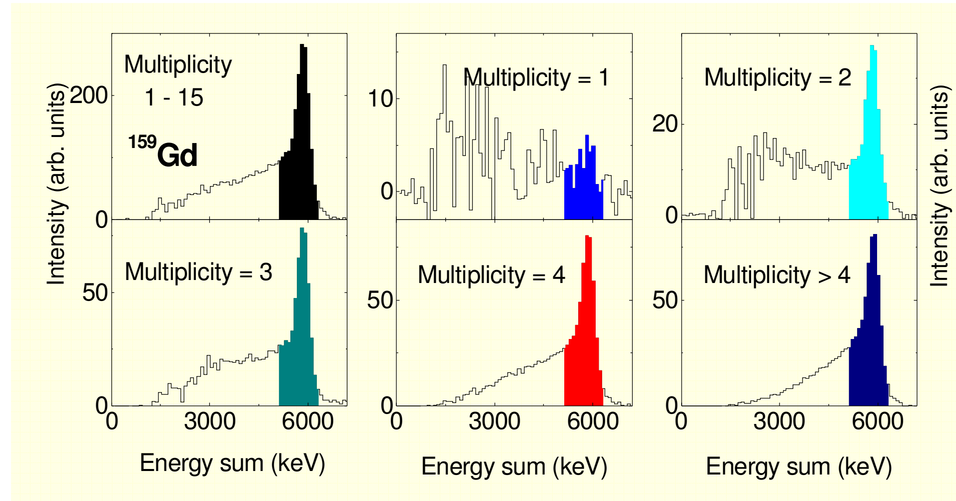


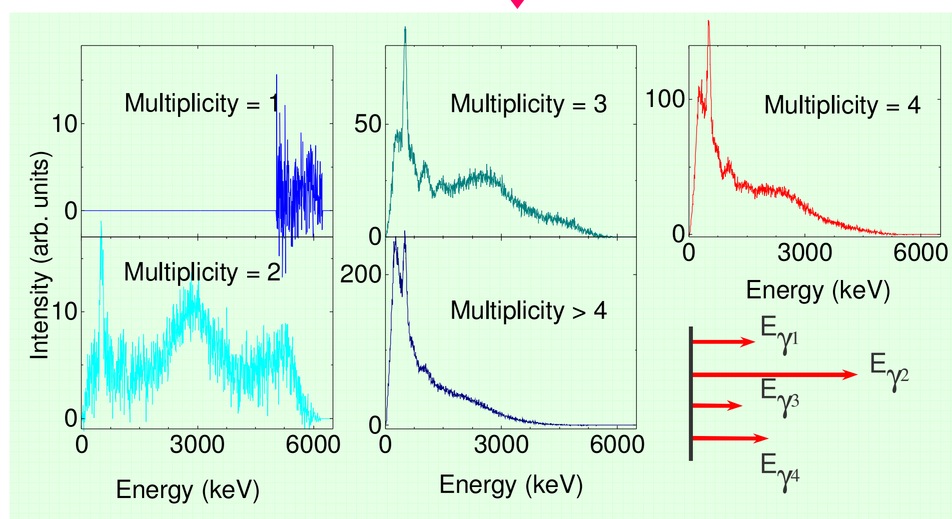




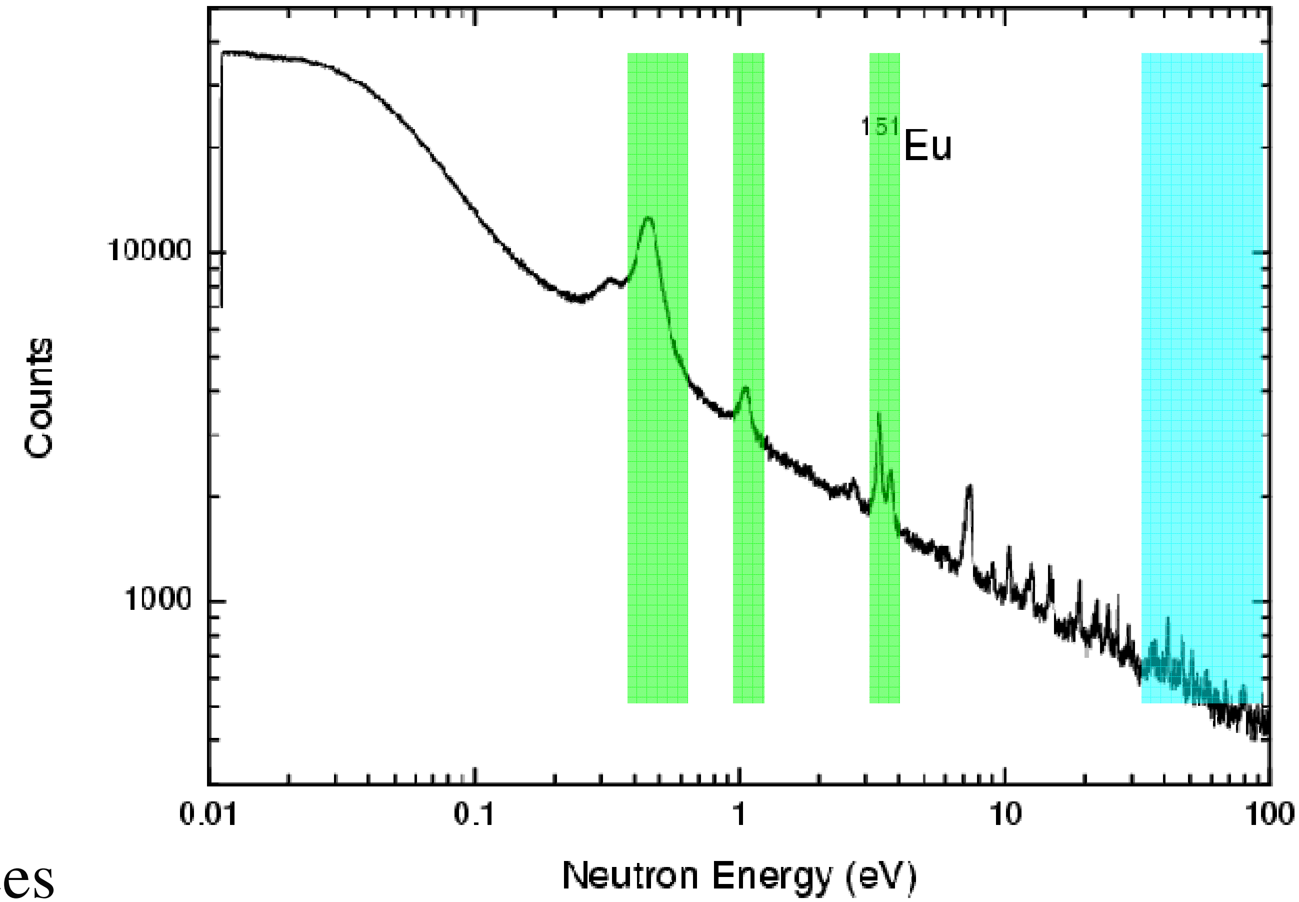
What can be checked?







What can be checked?

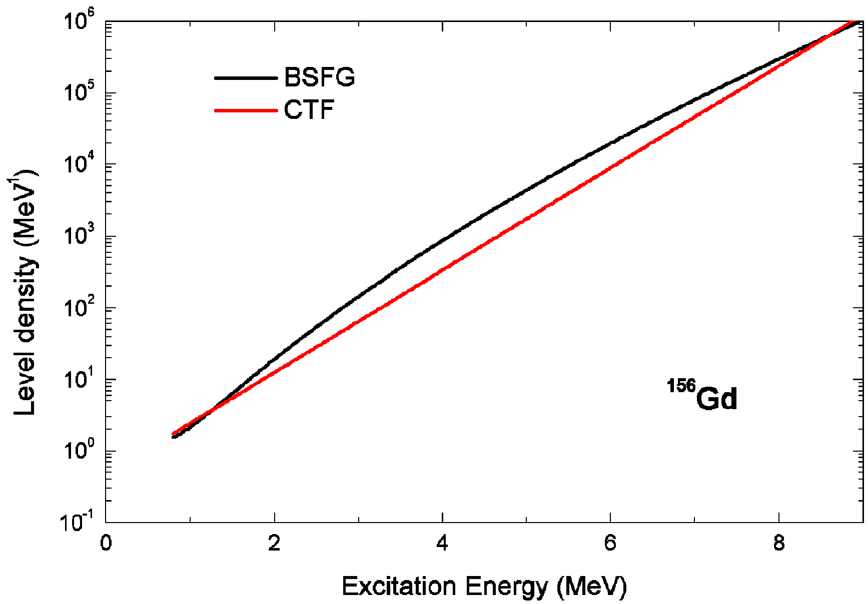


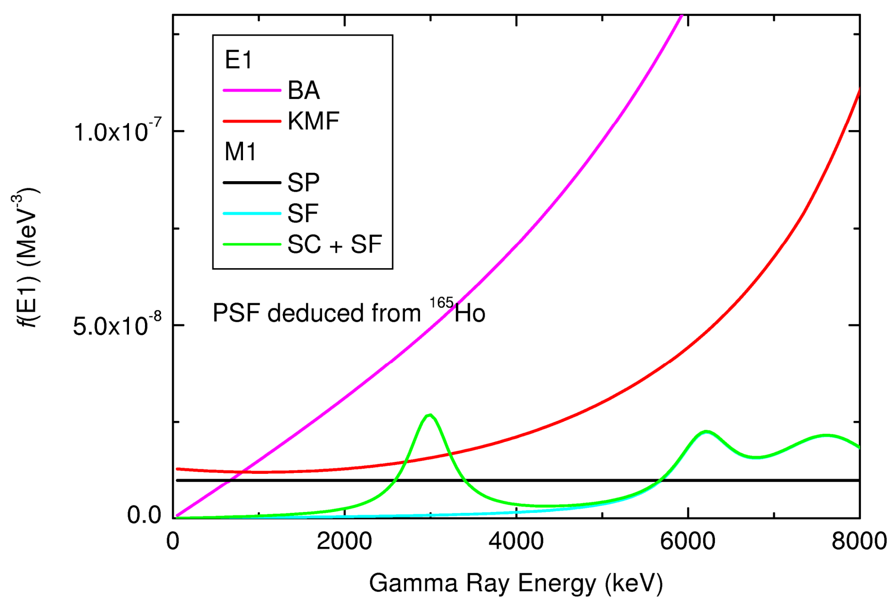
We can gate on

- strong resonances
  (spectra from different resonance spins
  can be compared)
- unresolved region

How to process data from these experiments?

- Result of interplay of level density and γ-ray SF





- Comparison with predictions from decay governed by different level density formulas and γ-ray strength functions
- Code DICEBOX is used for making these simulations
  - Simulates gamma decay of a compound nucleus within extreme statistical model

Simulation of γ cascades - DICEBOX algorithm

Main assumptions:

- For nuclear levels below certain "critical energy" spin, parity and decay properties are known from experiments
- Energies, spins and parities of the remaining levels are assumed to be a random discretization of an *a priori* known level-density formula
- A partial radiation width $\Gamma_{i\gamma f}^{(XL)}$, characterizing a decay of a level *i* to a level *f*, is a random realization of a chi-square-distributed quantity the expectation value of which is equal to

$$f^{(XL)}(E_\gamma)\, E_\gamma^{2L+1}/\rho(E_i),$$

where $f^{(XL)}$ and ρ are also *a priori* known

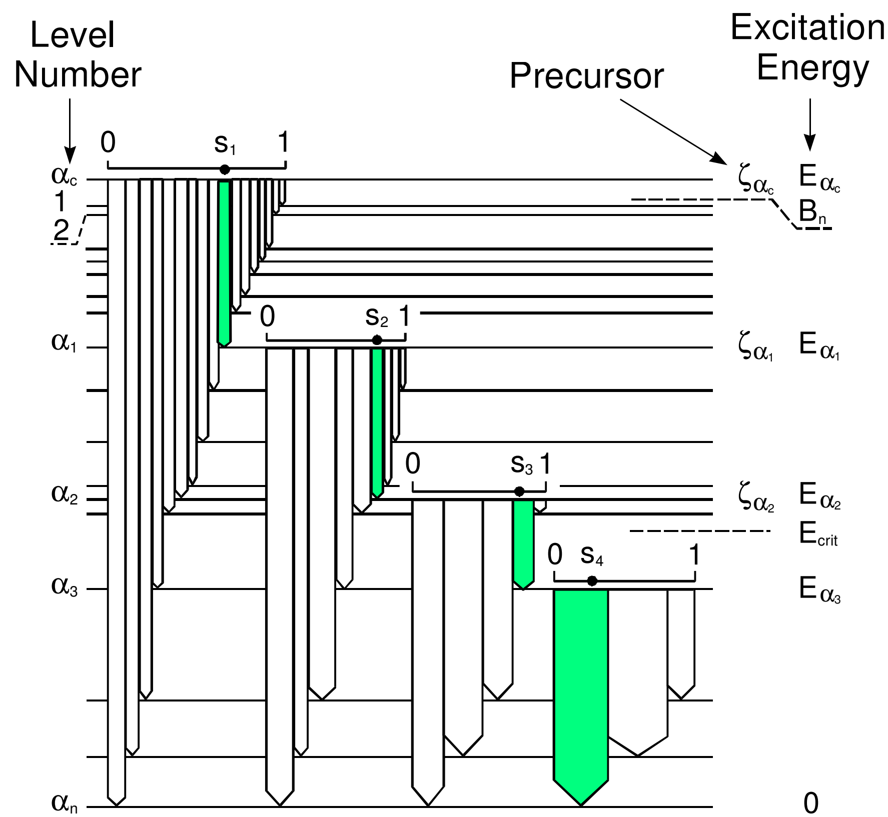
- Selection rules governing the γ decay are taken into account
- Any pair of partial radiation widths $\Gamma_{i\gamma f}^{(XL)}$ is statistically uncorrelated

Modelling within ESM

Simulation of the decay:

- "nuclear realization" (10^6 levels $\Rightarrow 10^{12}\ \Gamma_{\lambda\gamma f}$) $\Rightarrow$ "precursors" are introduced
- fluctuations originating from nuclear realizations cannot be suppressed

Deterministic character of random number generators is exploited



Outcomes from modelling are compared with experimental data

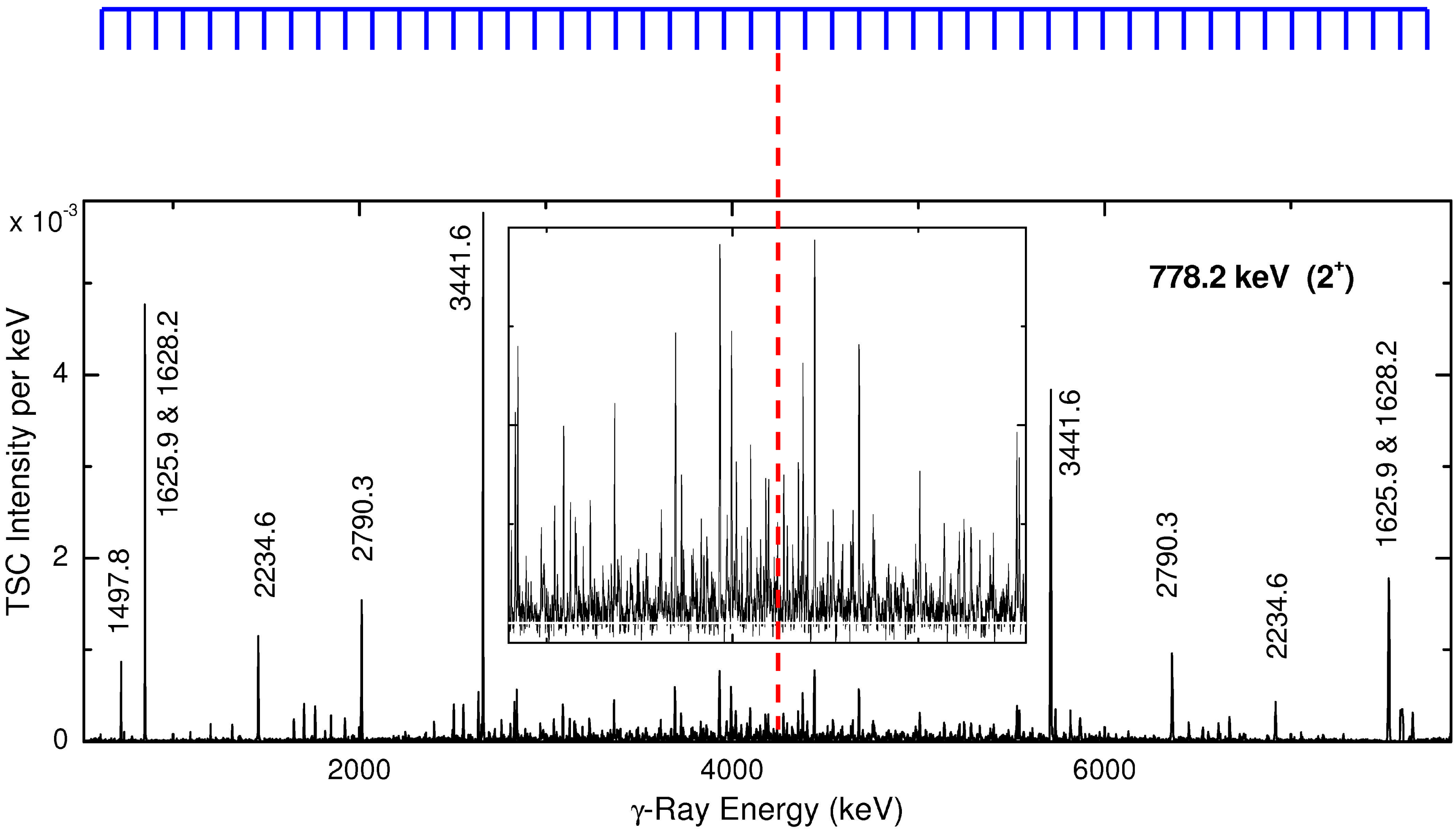
Main feature of DICEBOX

- There exists infinite number of artificial nuclei (nuclear realizations), obtained with the same set of level density and γ-ray SFs models that differ in exact number of levels and intensities of transitions between each pair of them
  ⇒ leads to different predictions from different nuclear realizations
- DICEBOX allows to treat predictions from different nuclear realizations
- The size of fluctuations from different nuclear realizations depend on the (observable) quantity - in our case intensity of TSC cascades - and nucleus

- Due to fluctuations only “integral” quantities can be compared
- In principle, simulation of detector response must be applied
  (very simple in the TSC setup, GEANT simulations for DANCE)

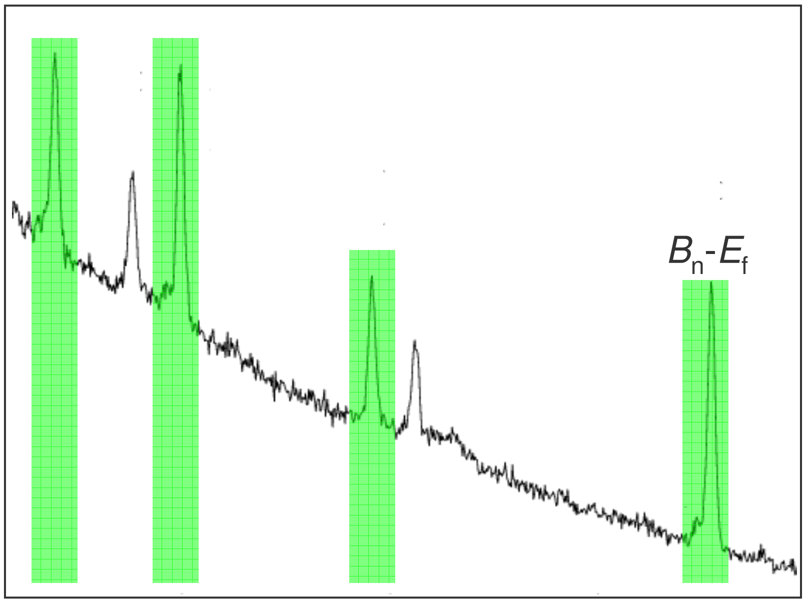
Example of a TSC spectrum

Wide-bin TSC spectra

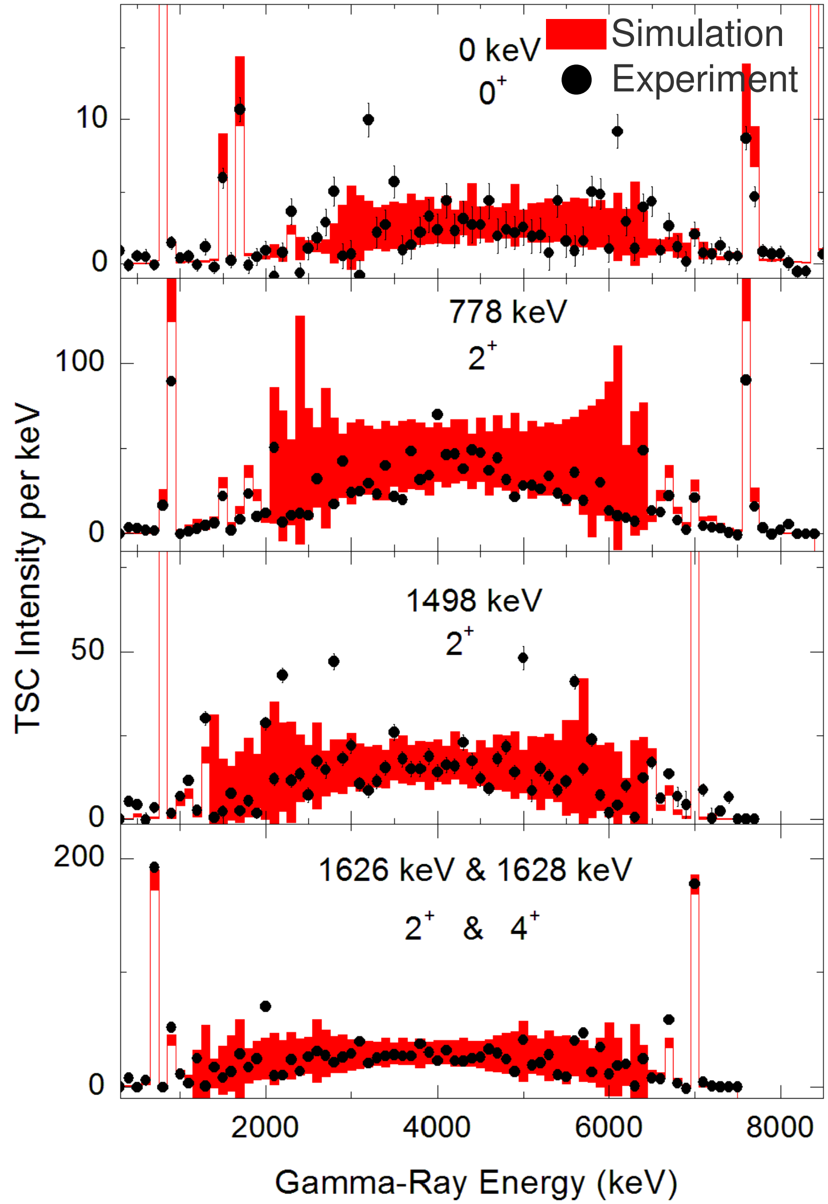


Examples of spectra

Spectrum of energy sums



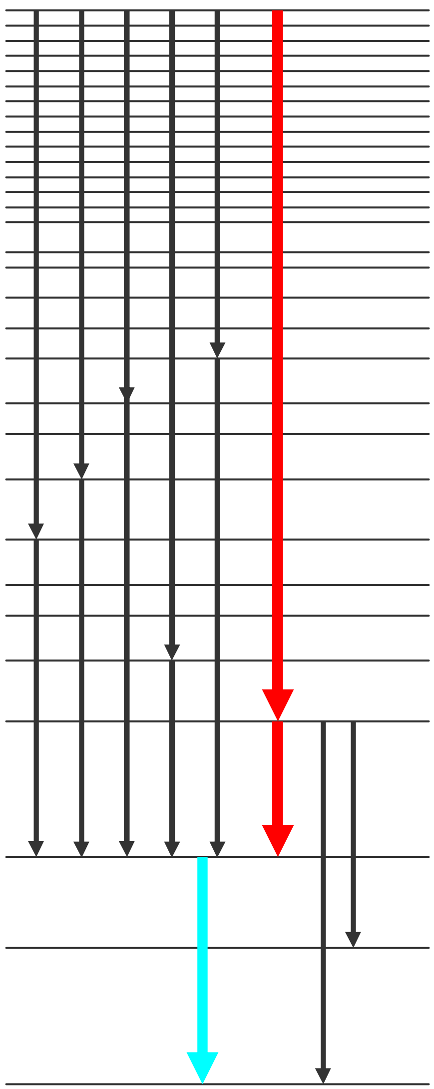
Energy sum $E_{\gamma 1}+E_{\gamma 2}$



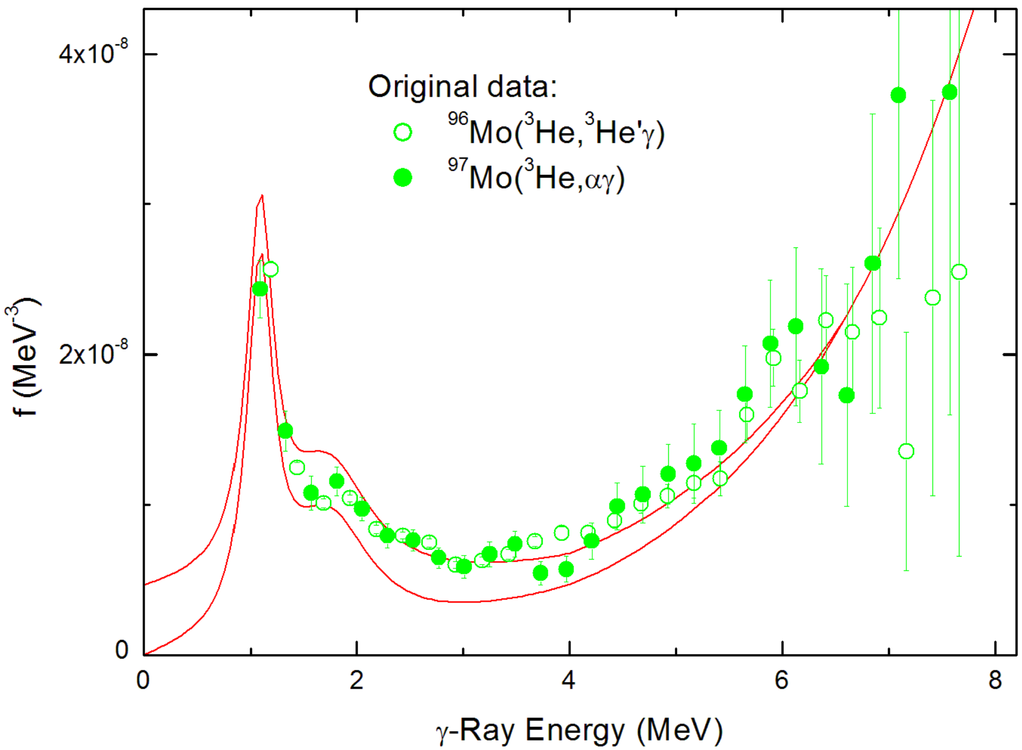
Normalization of experimental spectra

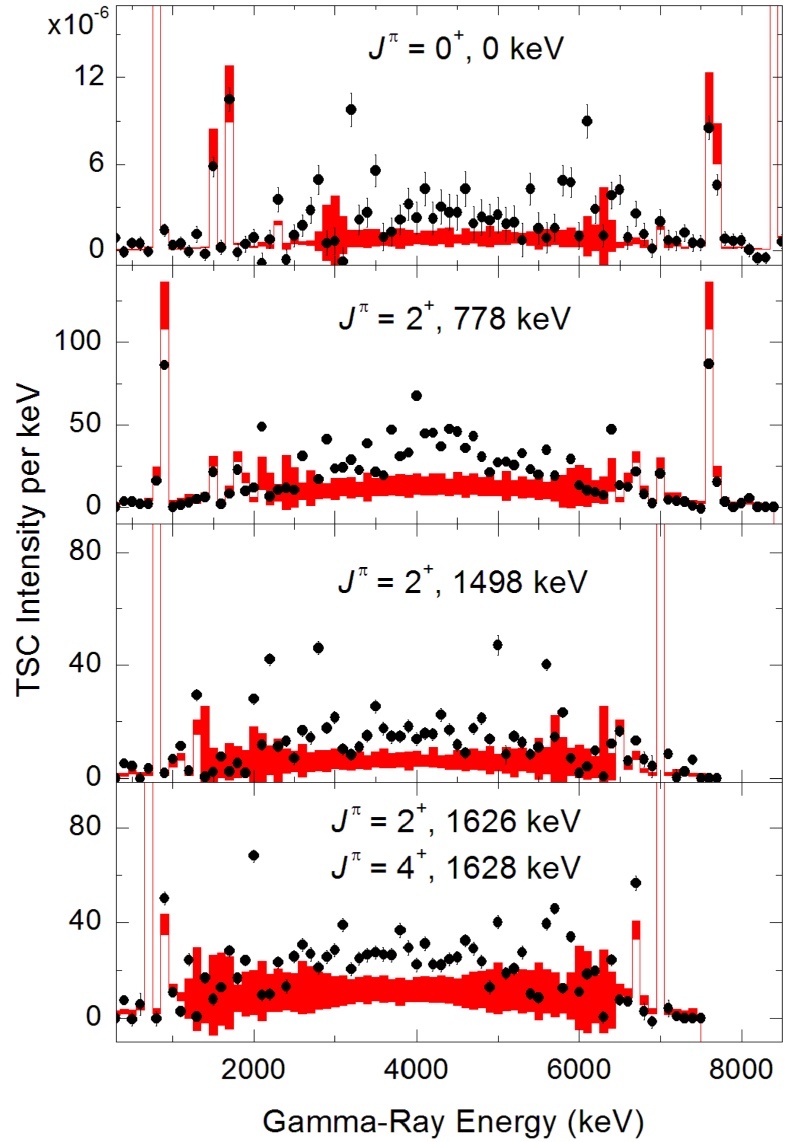
- Knowing intensity of one γ-ray cascade ⇒ simulated/experimental TSC intensities to all final levels can be normalized

- Corrections to angular correlation and vetoing must be done



Enhanced PSF at low energies - ^{96}Mo





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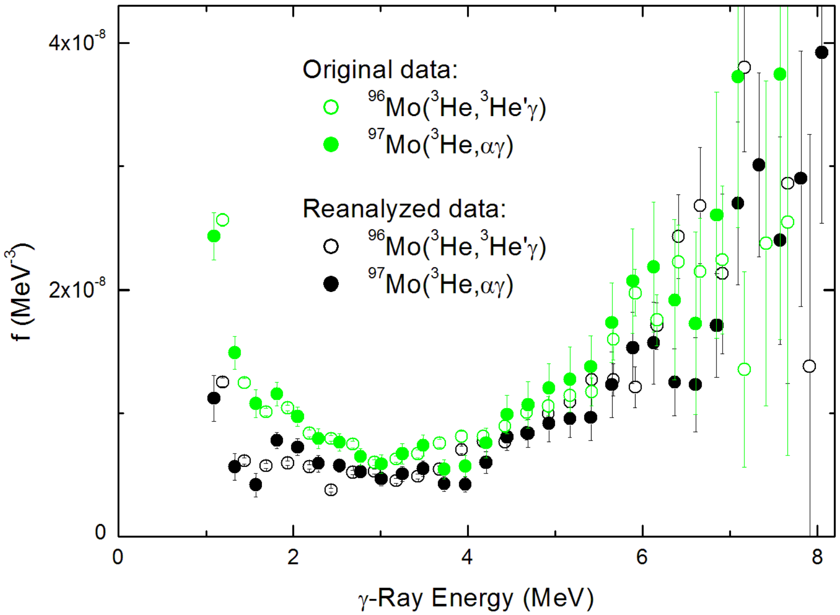

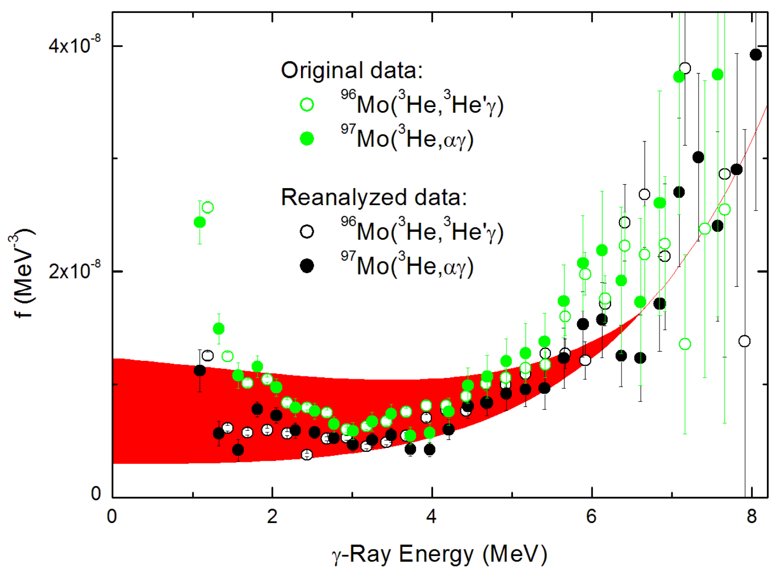

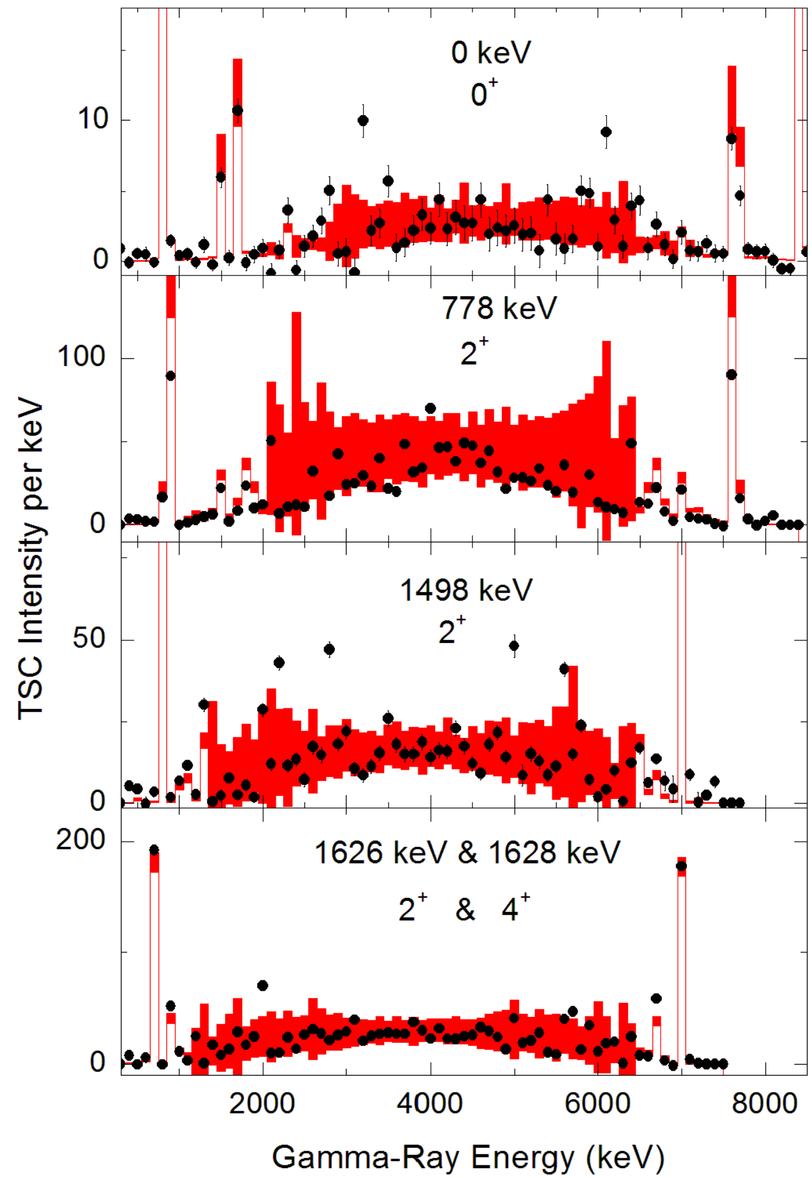

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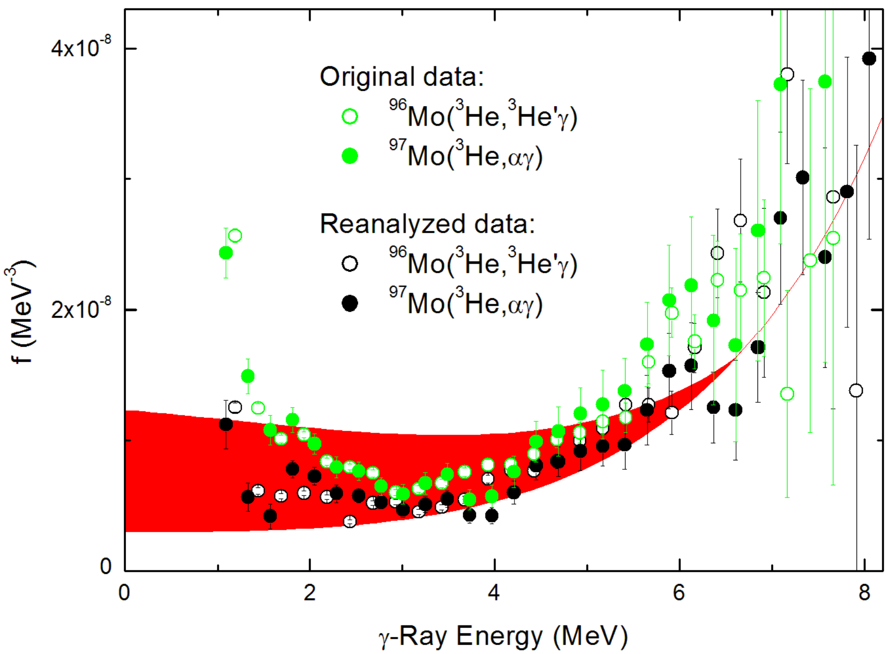
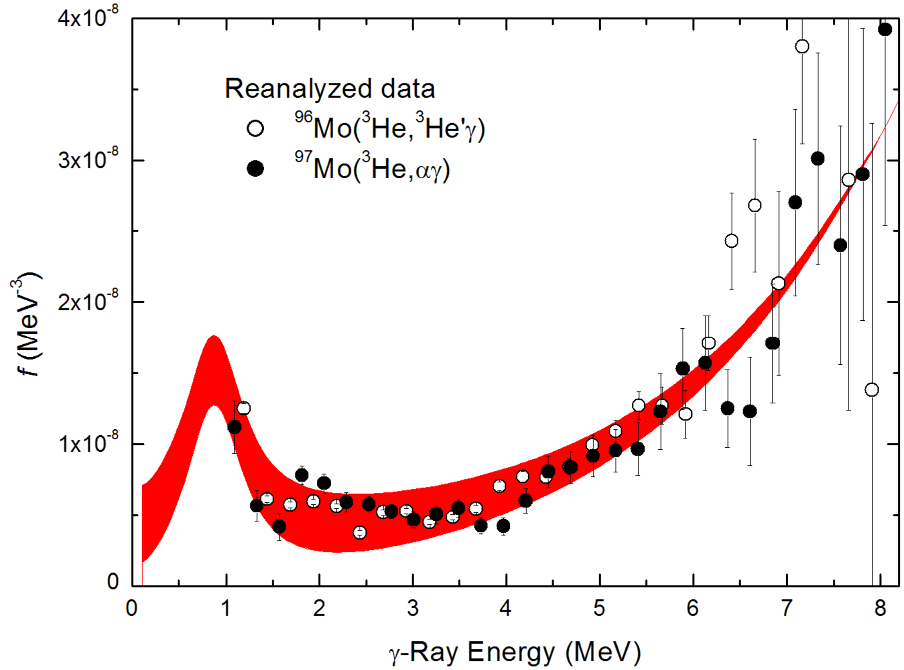


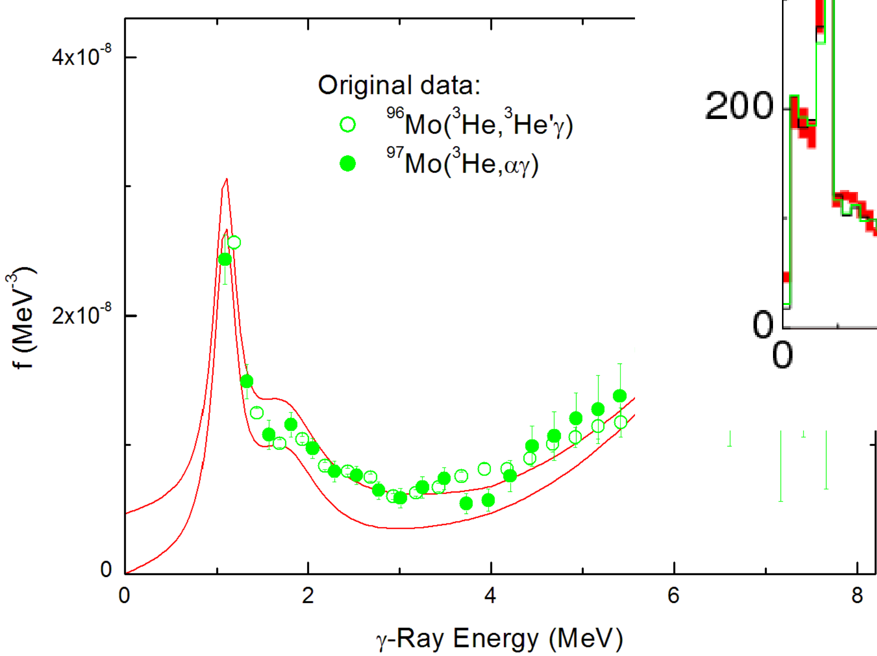


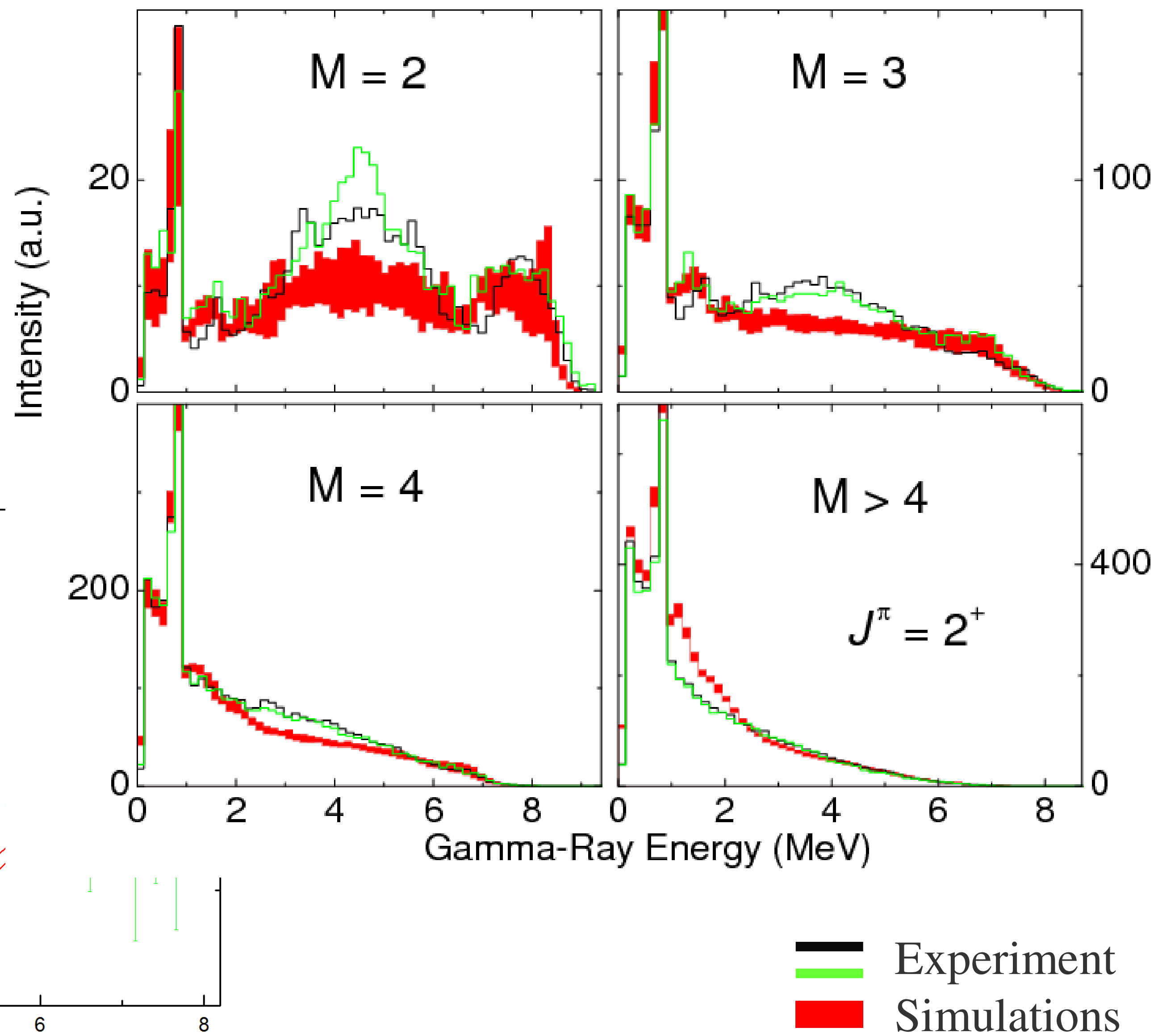
Pictures with comparison similar but correct statistical analysis excludes also this model at 99.8 % confidence level

Krticka et al., PRC 77 054319 (2008)

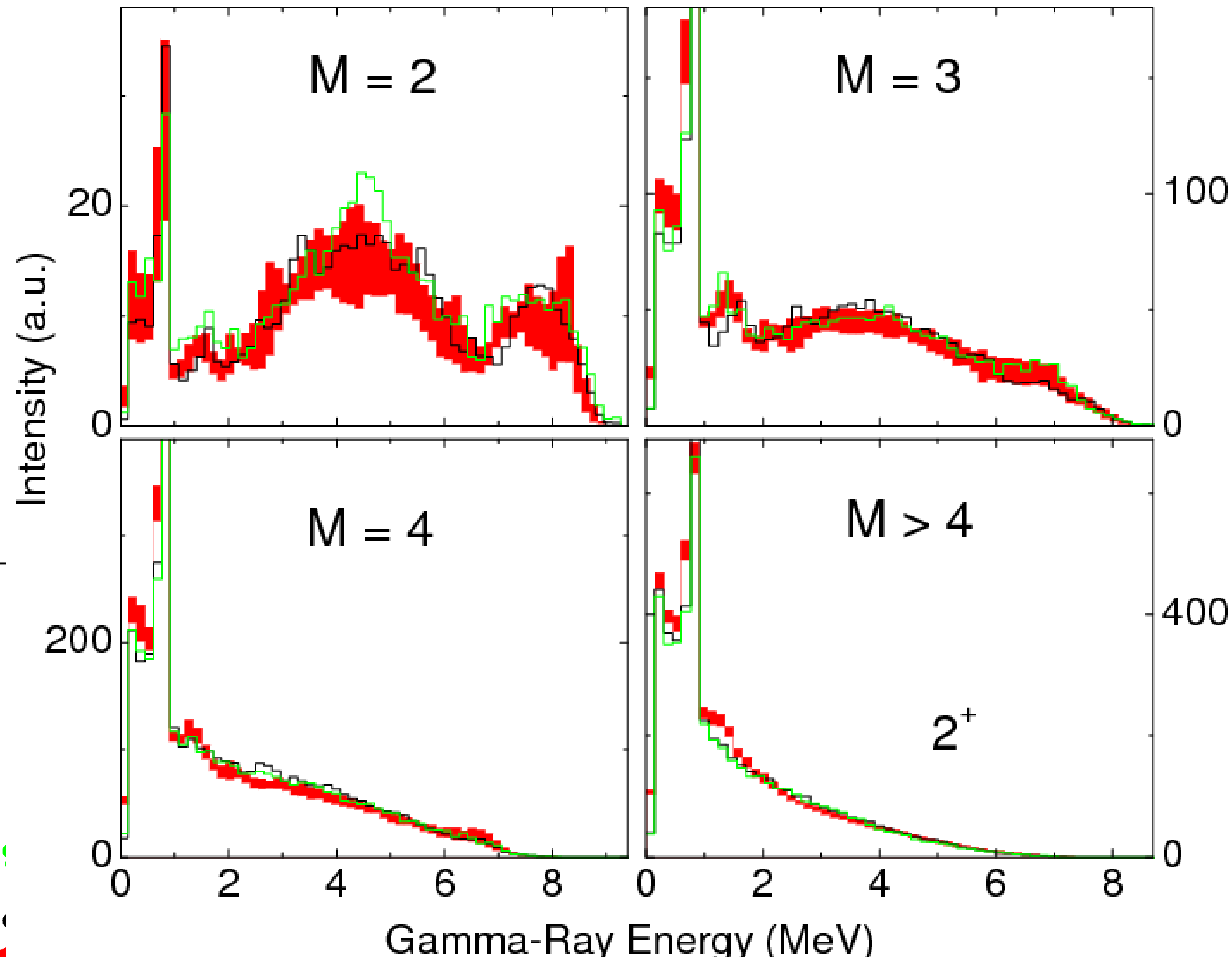
⇒ the enhancement is very weak if any analysis of data from DANCE confirm this

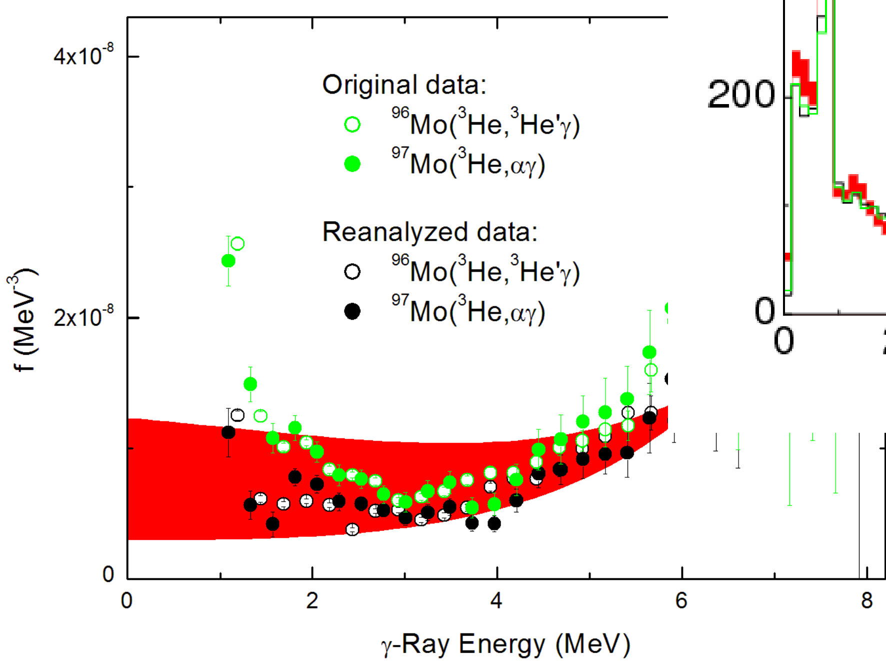
Enhanced PSF at low energies - ^{96}Mo





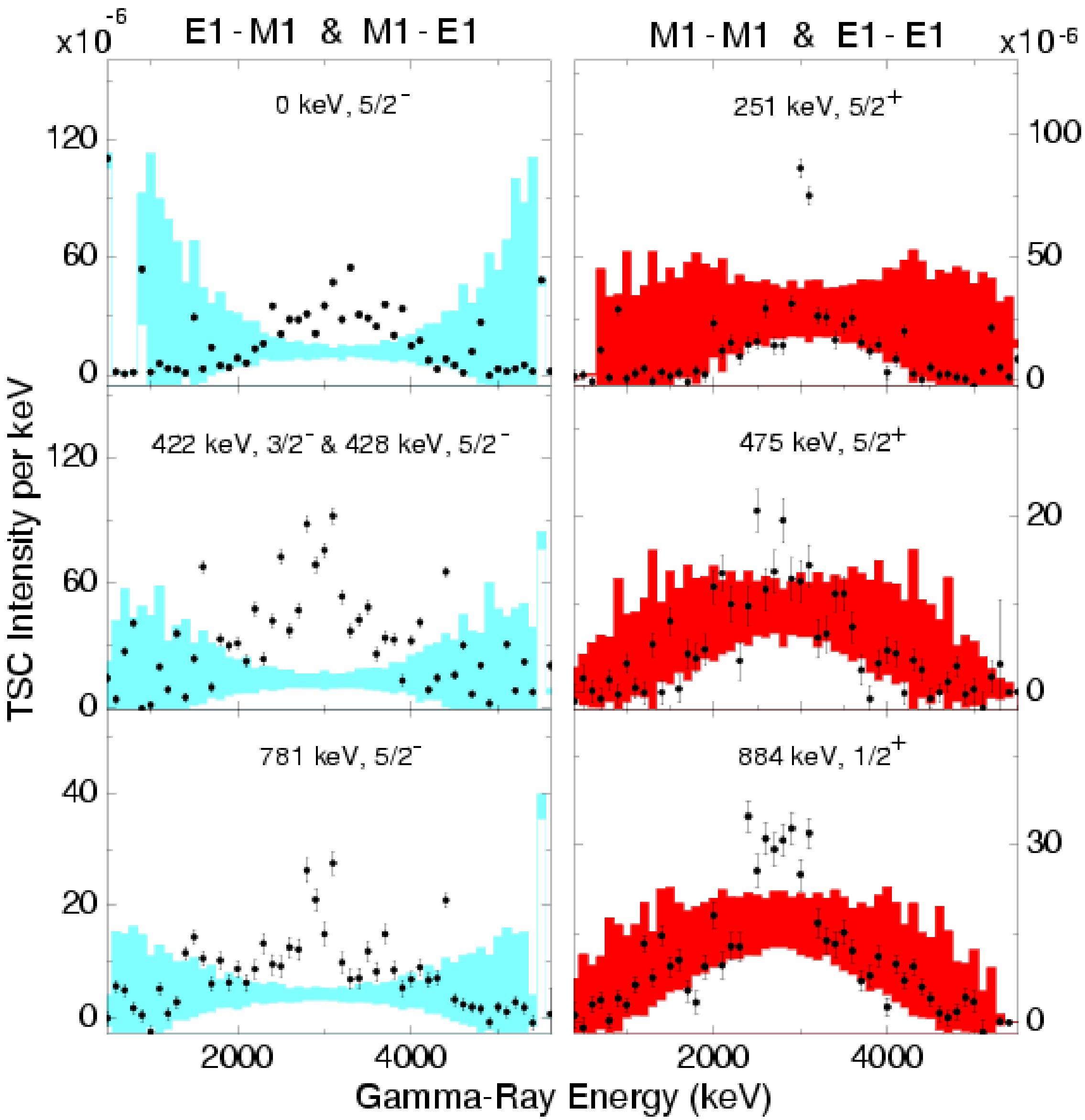
Enhanced PSF at low energies - ^{96}Mo

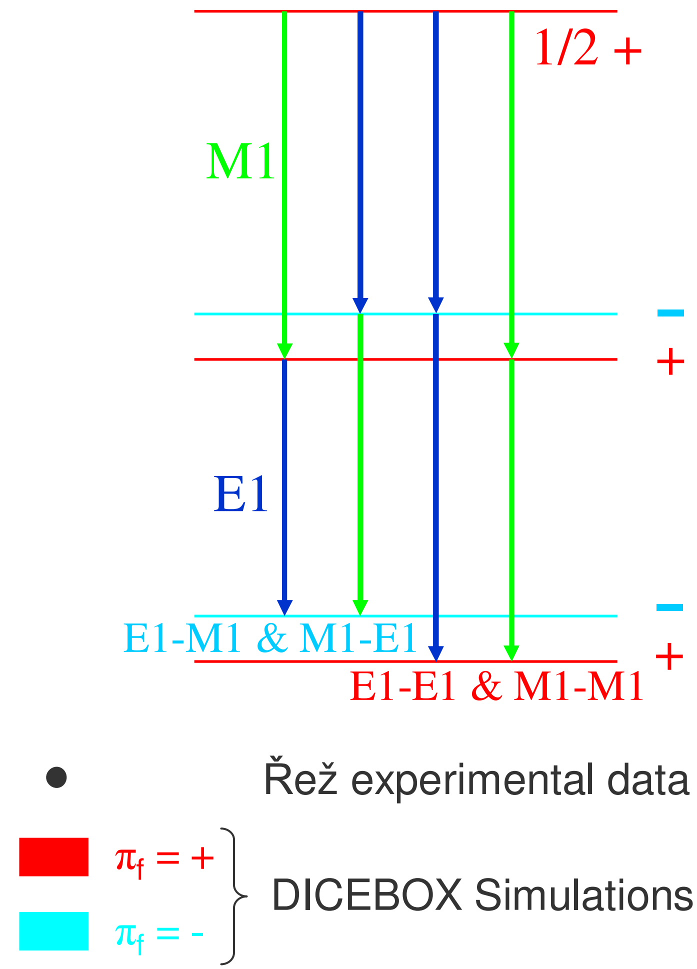




S. Sheets et al., Phys. Rev. C **79**, 024301 (2009)

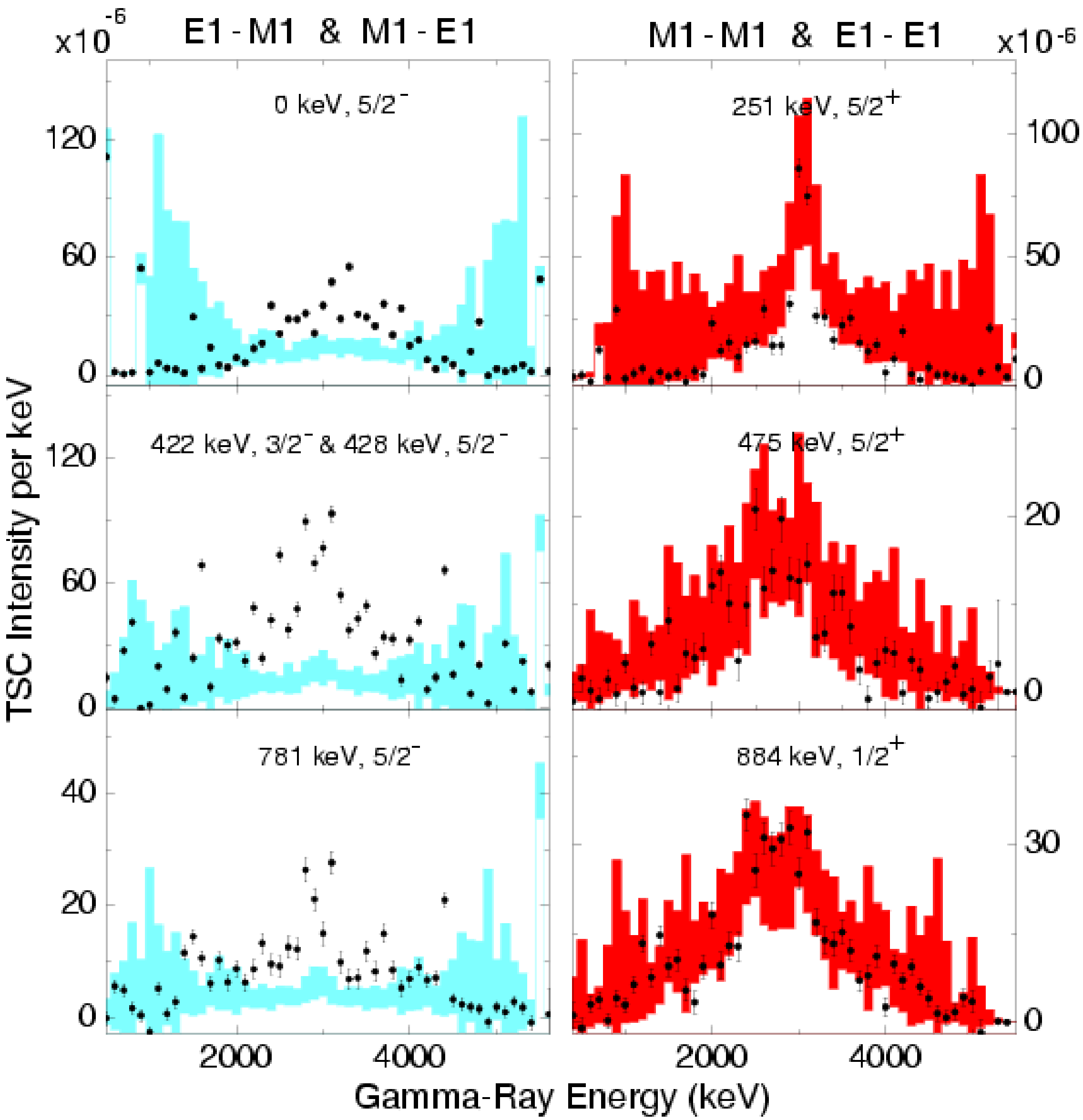
TSCs in the ^{162}Dy(n,γ)^{163}Dy reaction – deformed nuclei





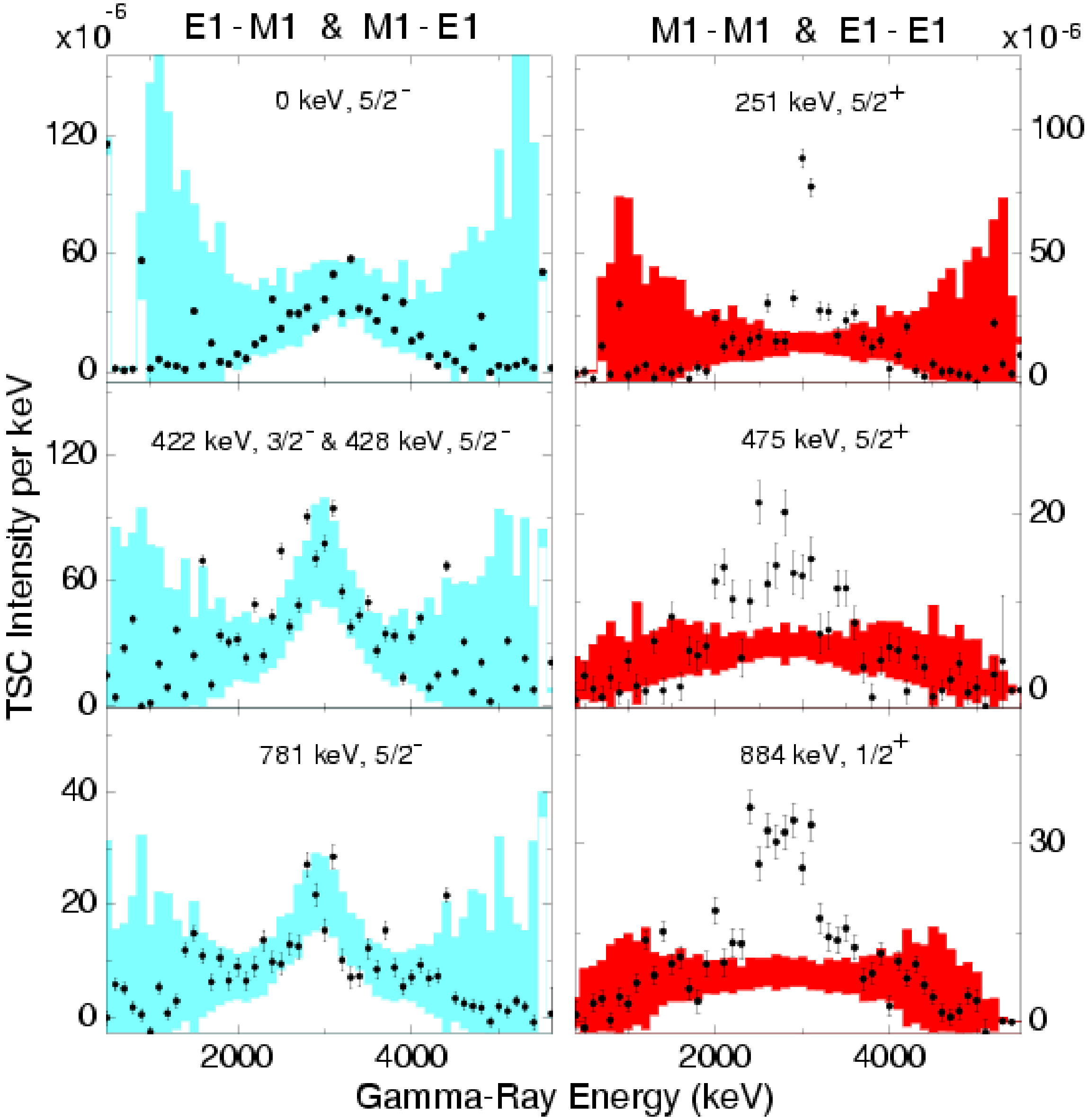
Entire absence of SRs is assumed

TSCs in the $^{162}Dy(n,\gamma)^{163}Dy$ reaction



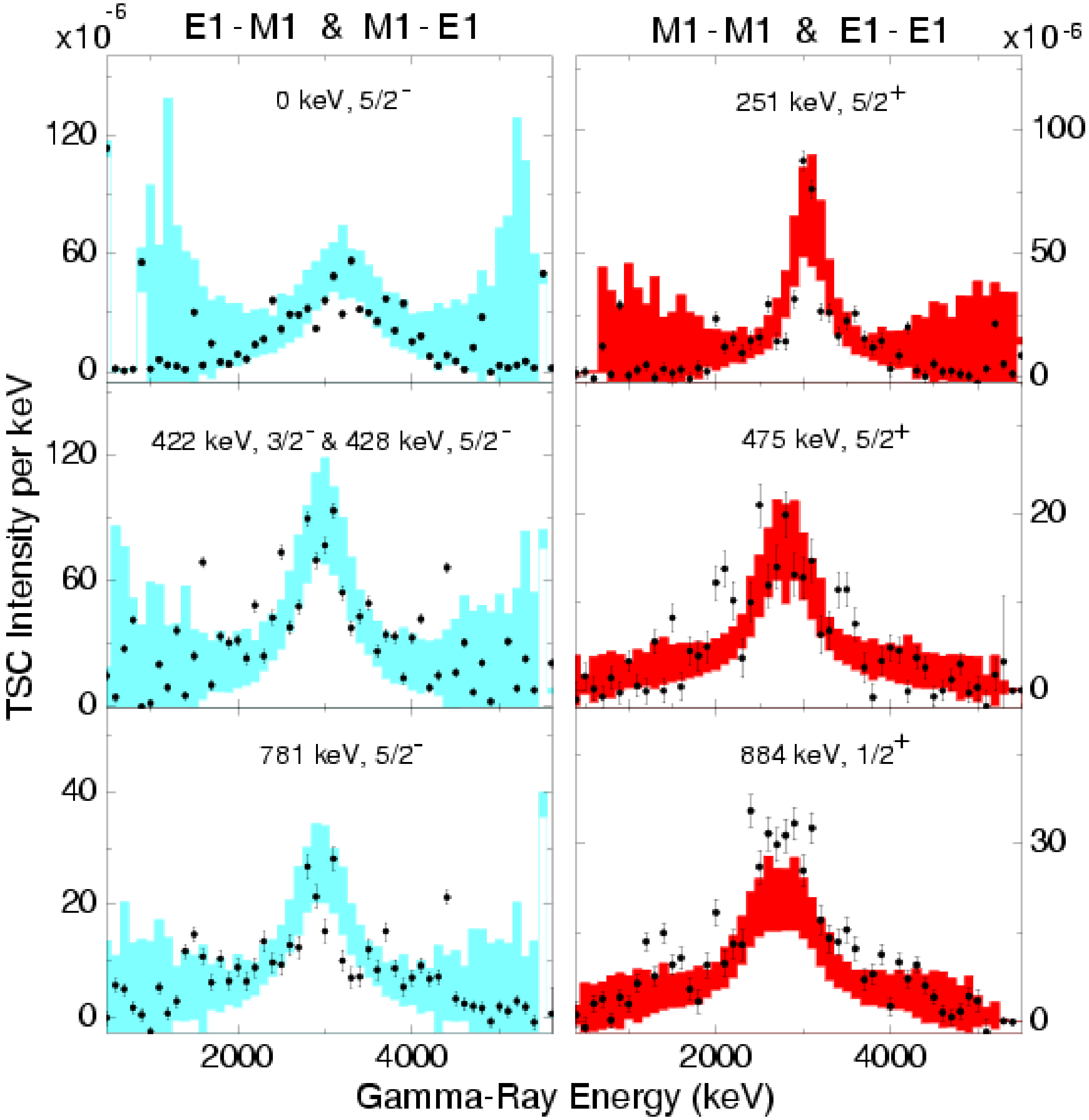
A "pygmy E1 resonance" with energy of 3 MeV assumed to be built on **all** levels

TSCs in the $^{162}Dy(n,\gamma)^{163}Dy$ reaction



SRs assumed to be built only on all levels below 2.5 MeV

TSCs in the ^{162}Dy(n,γ)^{163}Dy reaction



Scissors resonances assumed to be built on **all** ^{163}Dy levels

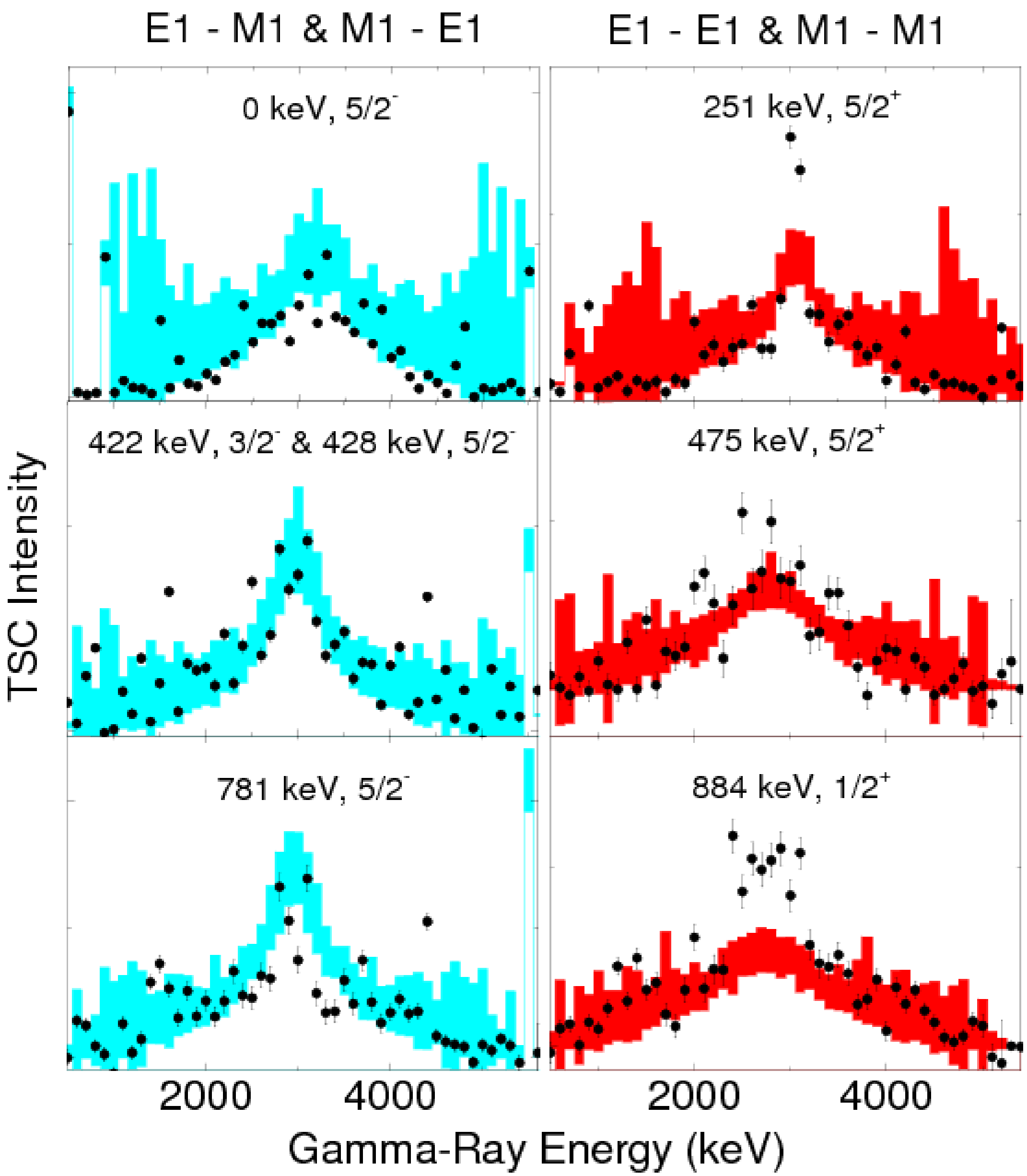
$E = 3.0$ MeV

$\Gamma = 0.6$ MeV

$\Sigma B \approx 6.2\ \mu_N^2$

M. Krticka et al.
Phys. Rev. Lett. **92** (2004) 172501

TSCs in the $^{162}Dy(n,\gamma)^{163}Dy$ reaction



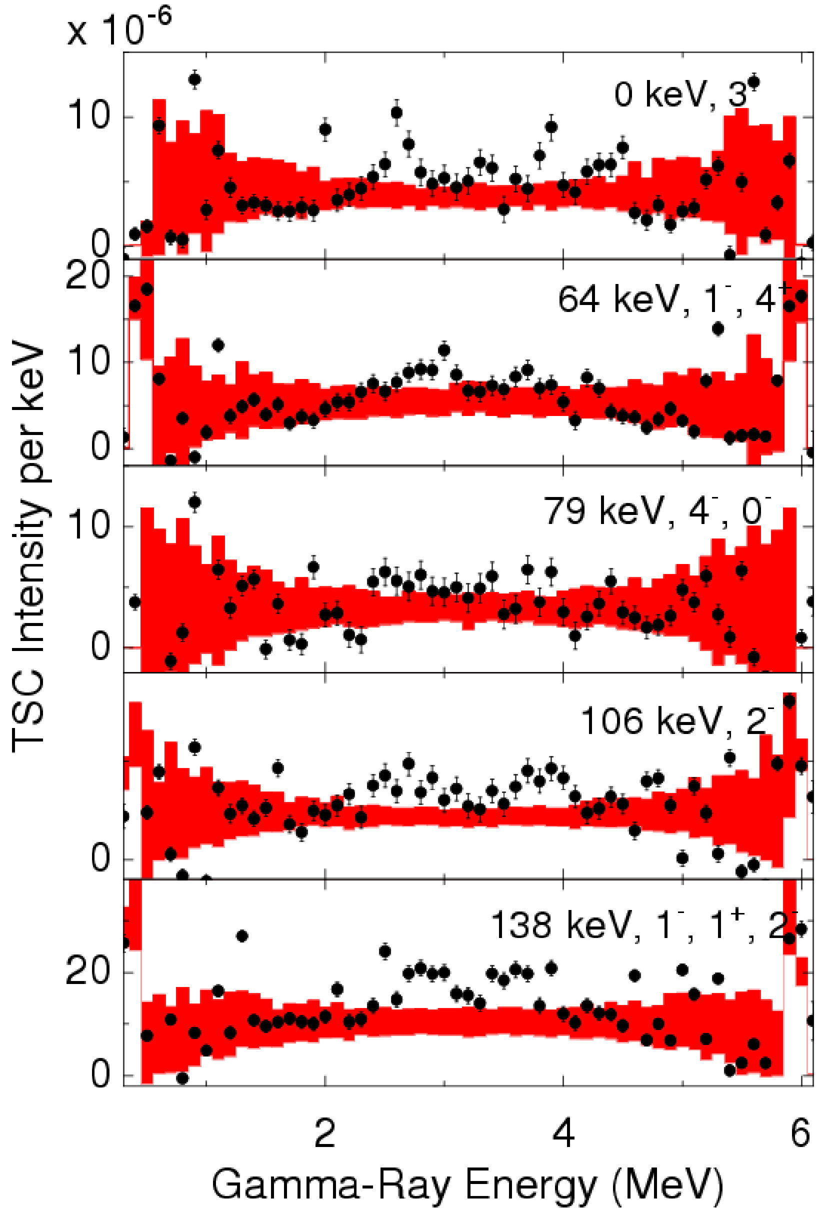
Scissors resonances assumed to be built on **all** ^{163}Dy levels

$E = 3.0$ MeV

$\Gamma = 0.6$ MeV

$\Sigma B \approx 3.0\ \mu_N^2$

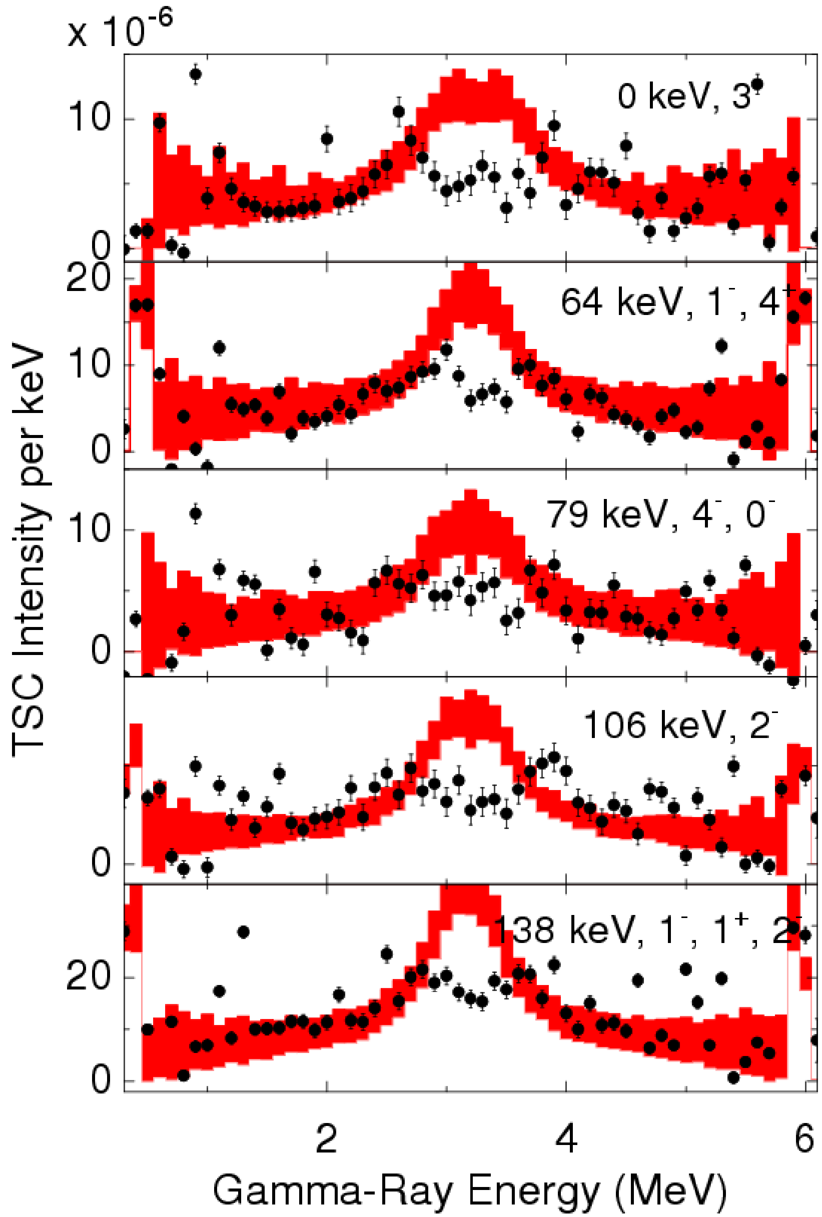
TSCs in the ^{159}Tb(n,γ)^{160}Tb reaction



Preliminary results

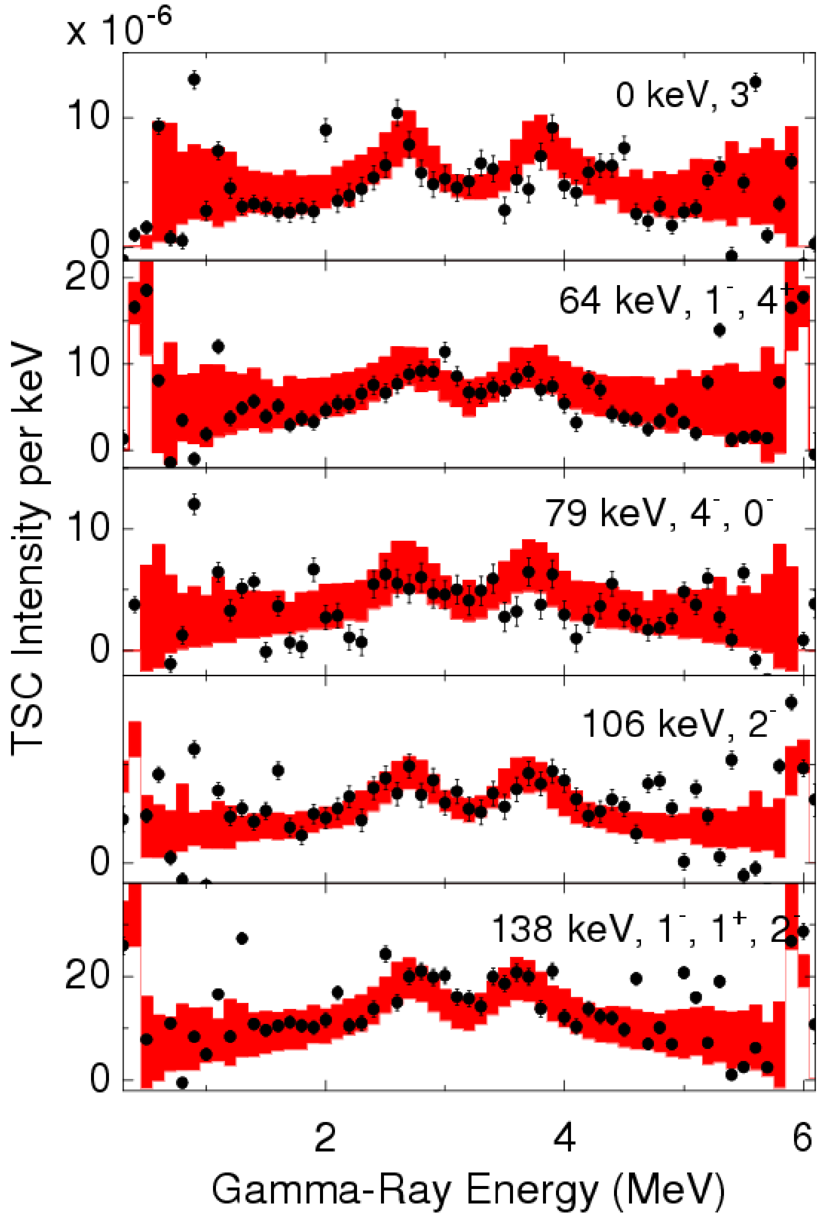
Entire absence of SRs is assumed

TSCs in the ^{159}Tb(n,γ)^{160}Tb reaction



Scissors mode with
E = 3.0 MeV

TSCs in the $^{159}Tb(n,\gamma)^{160}Tb$ reaction



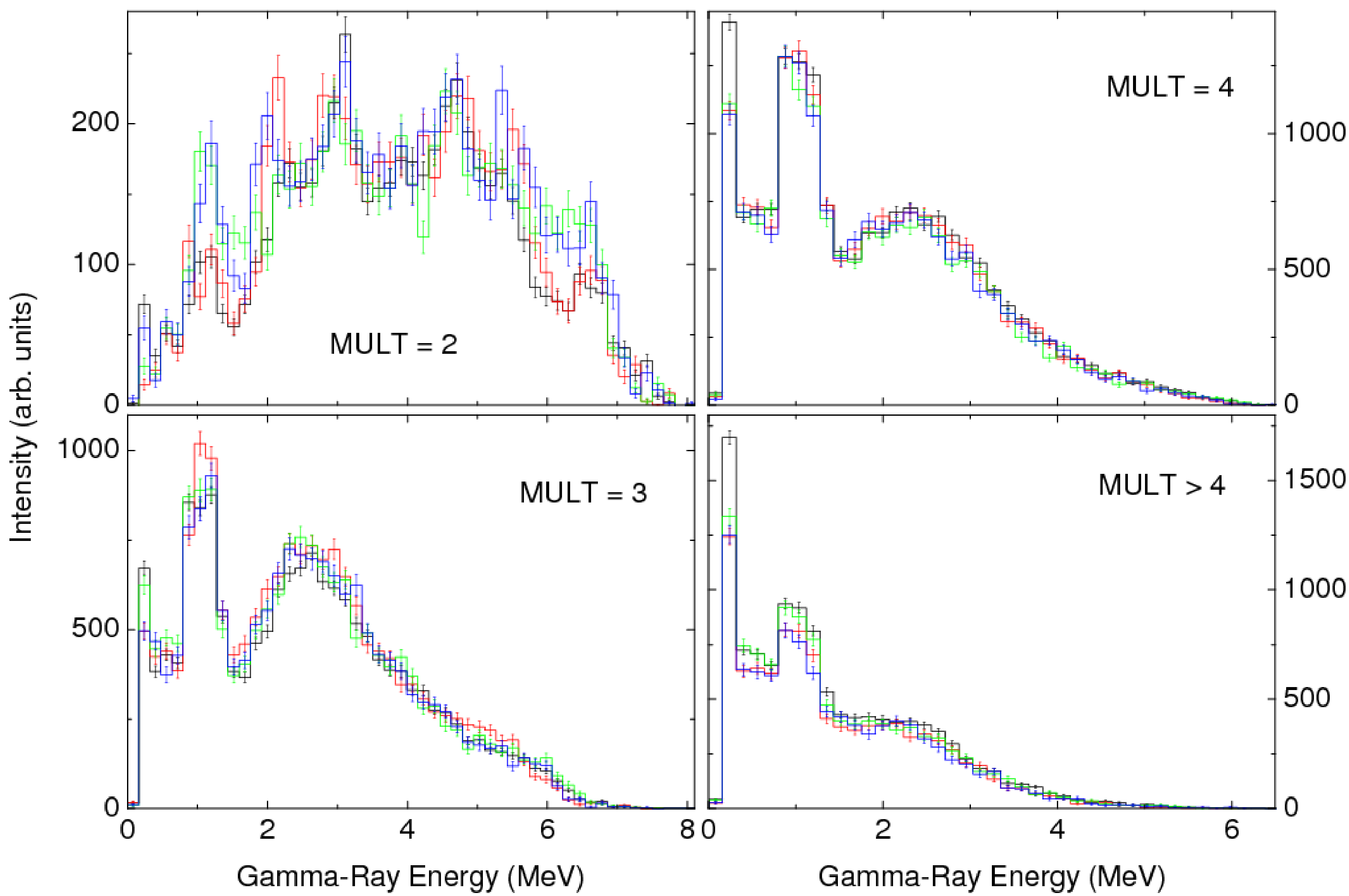
Scissors mode with
E = 2.7 MeV
$\Sigma B \approx 3\ \mu_N^2$

Very similar results
also for
E = 3.5 MeV
$\Sigma B \approx 2\text{-}7\ \mu_N^2$

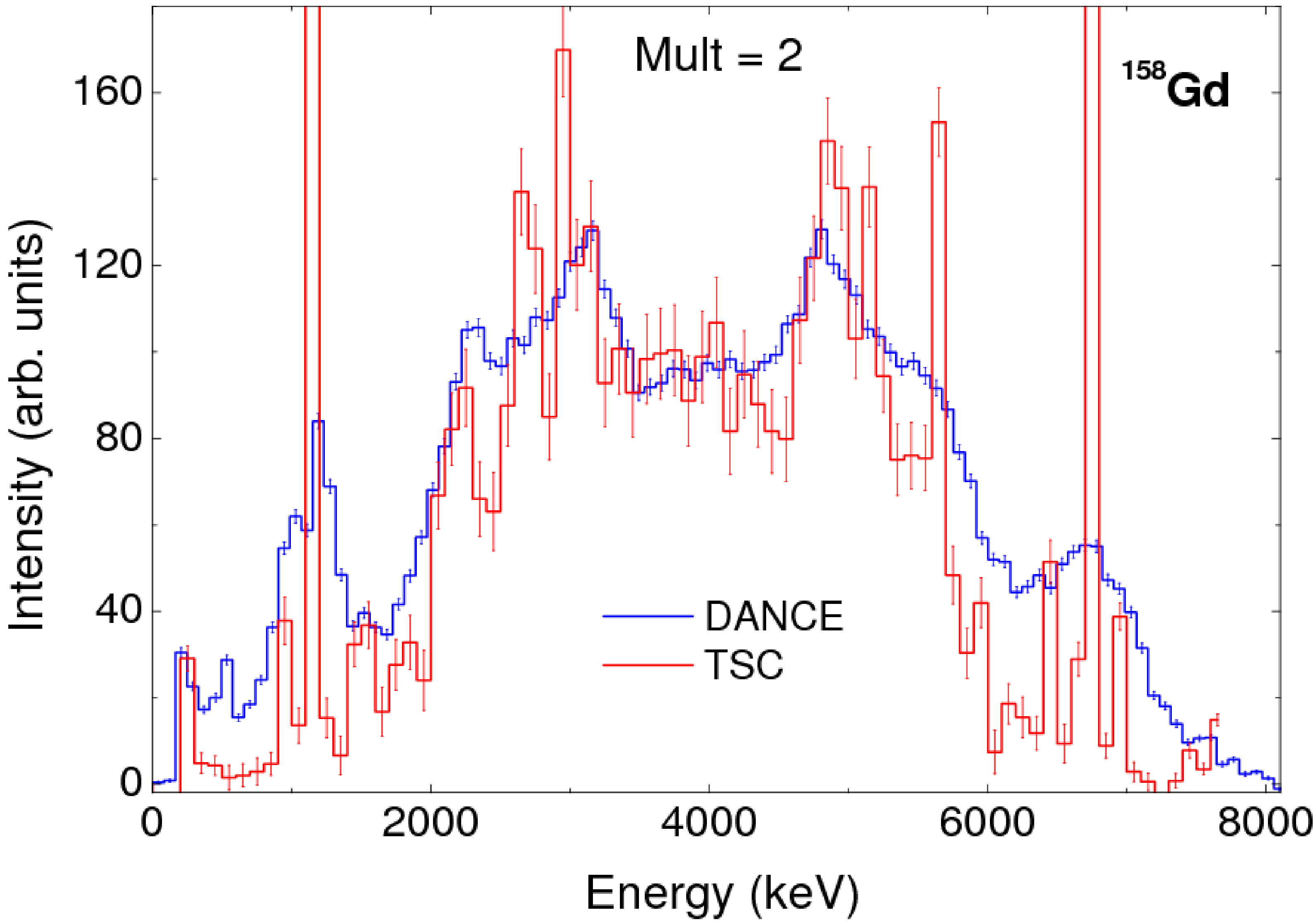
J. Kroll, *diploma thesis,* Prague 2009

^{157}Gd(n,γ)^{158}Gd reaction – deformed nuclei

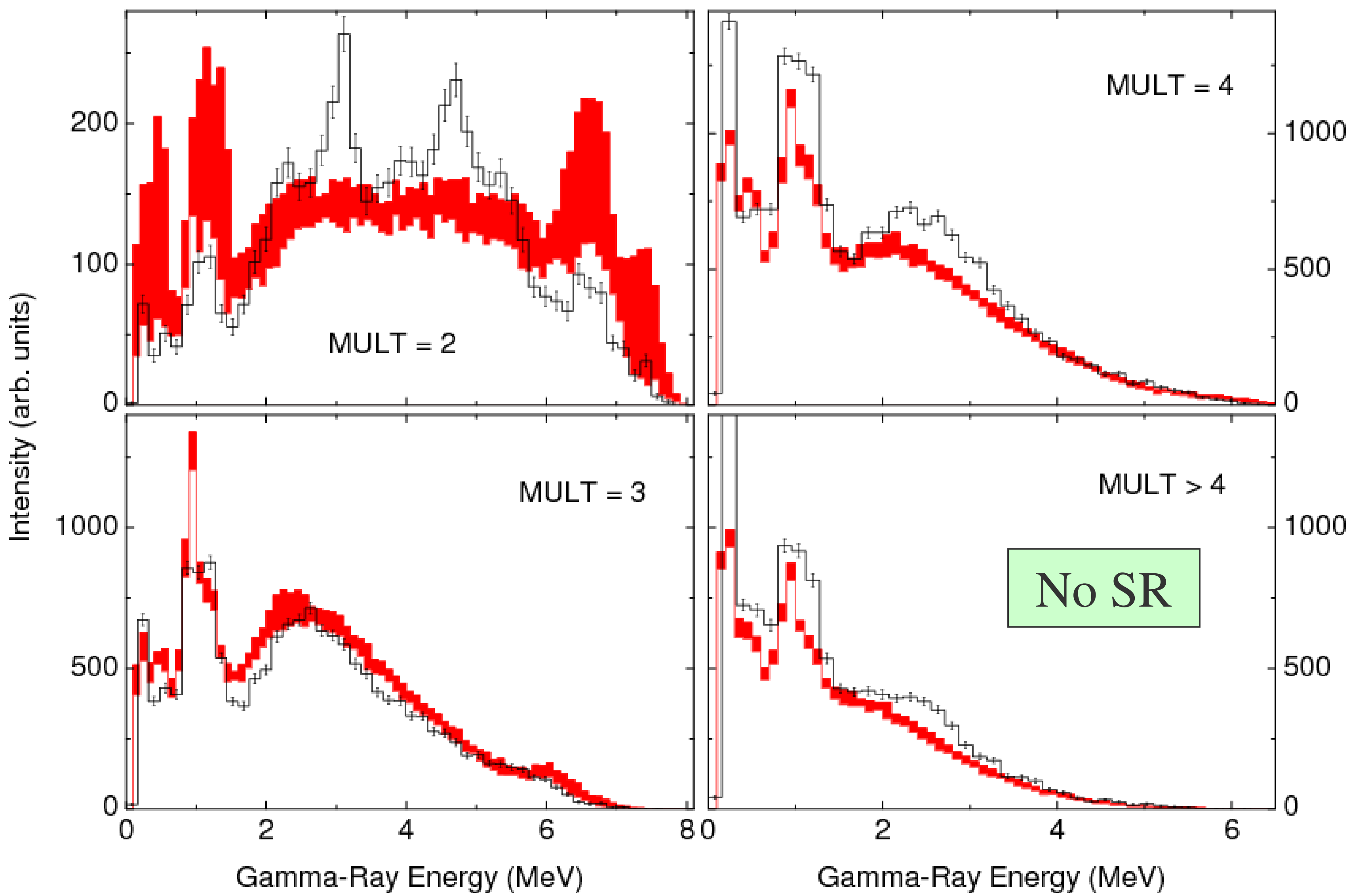
Experimental spectra



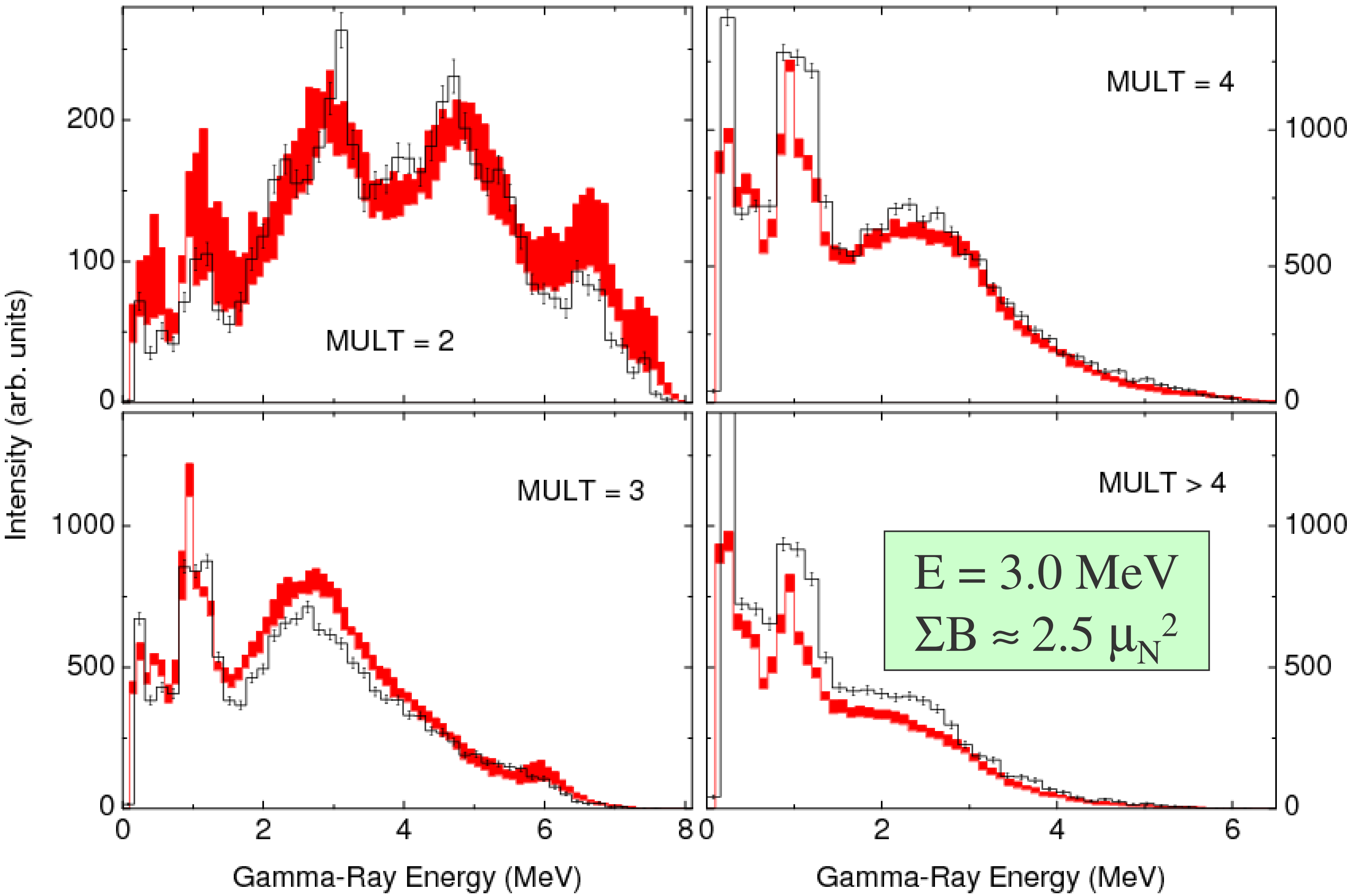
Experiment: TSC vs. DANCE



$^{157}Gd(n,\gamma)^{158}Gd$ reaction – deformed nuclei

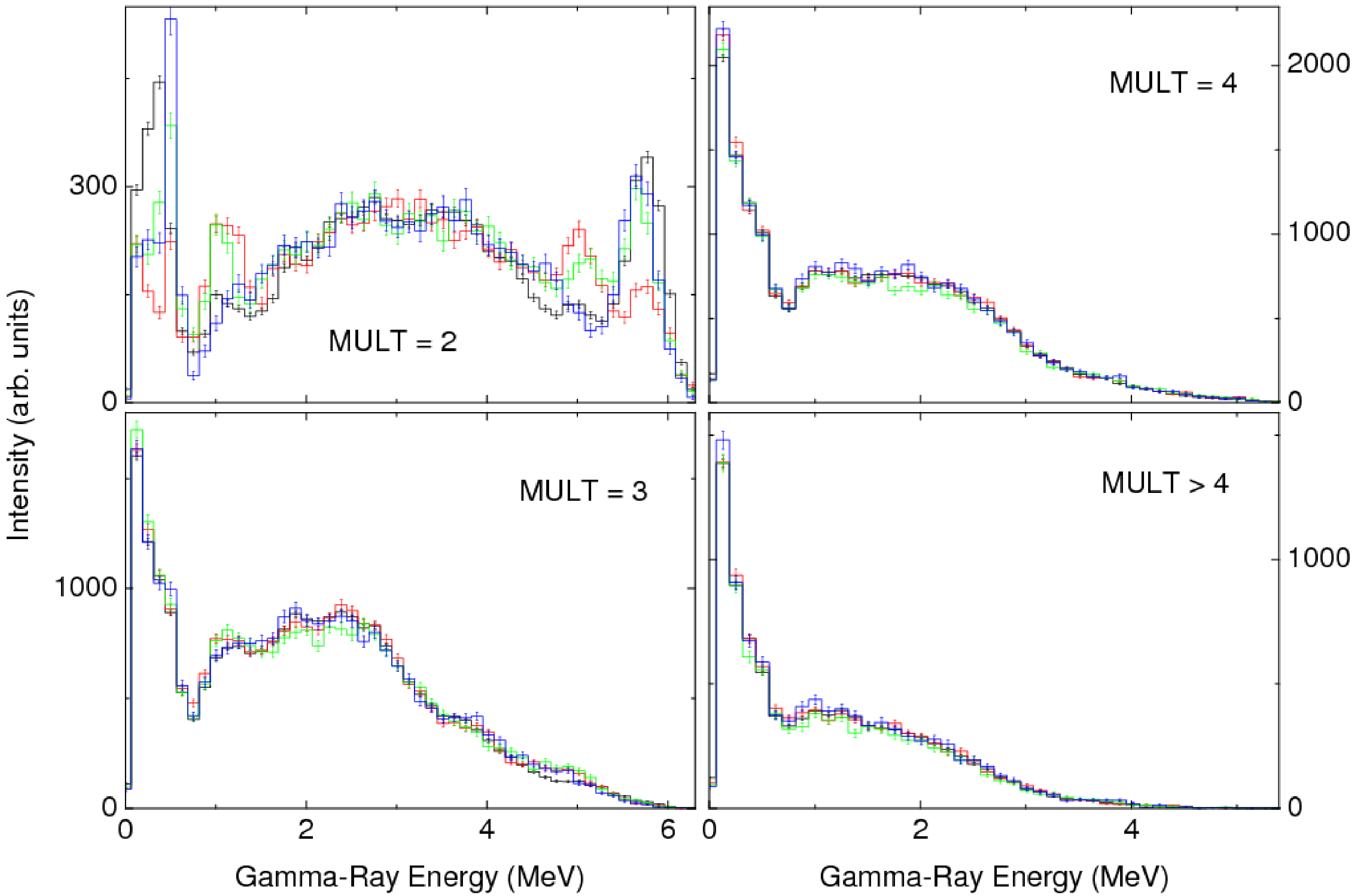


$^{157}Gd(n,\gamma)^{158}Gd$ reaction

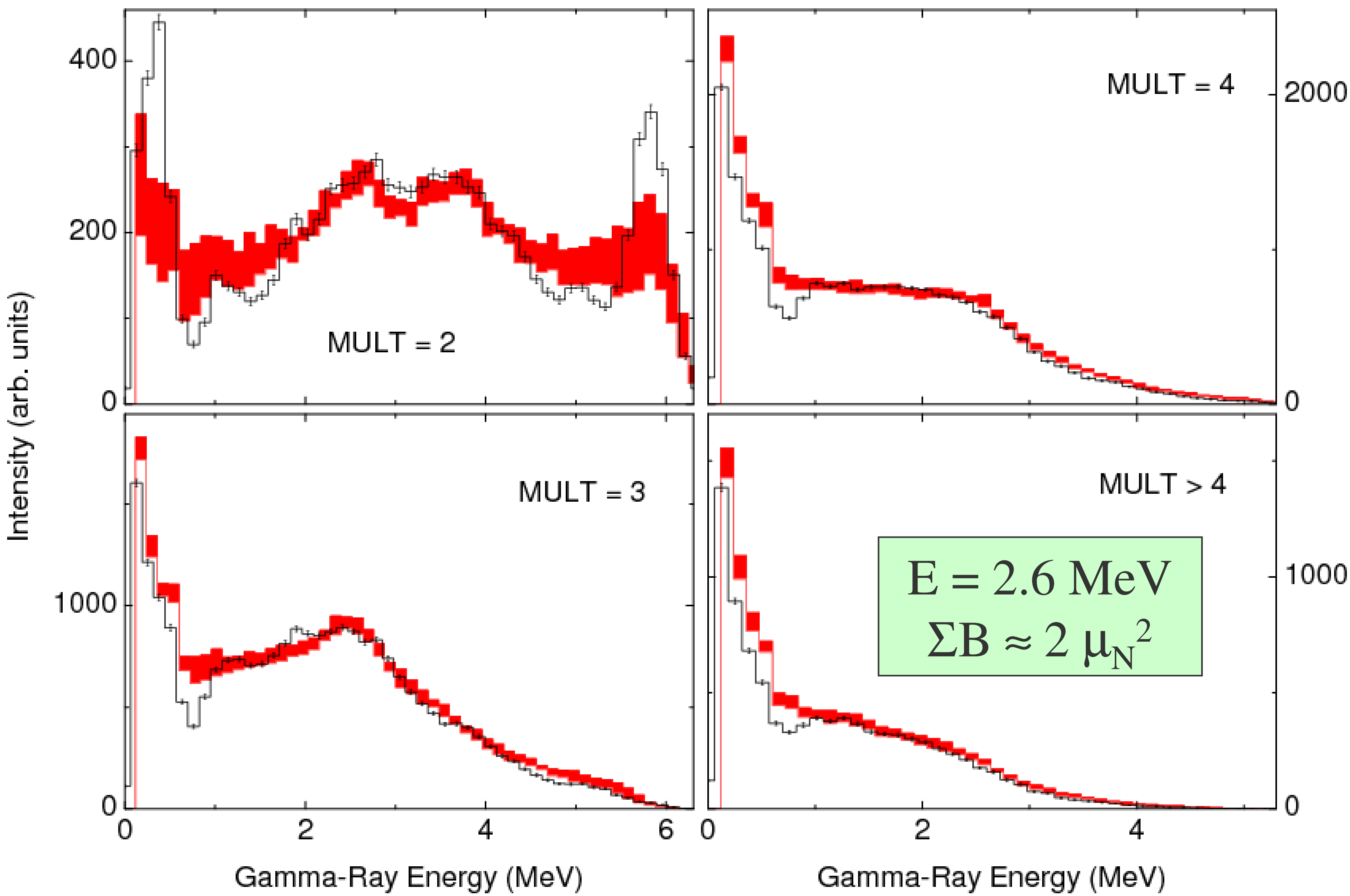


$^{154}Gd(n,\gamma)^{155}Gd$ reaction

Experimental spectra



$^{154}Gd(n,\gamma)^{155}Gd$ reaction



Conclusions

- Two-step and multi-step γ cascade methods are very powerful tools for studying γ-ray SF

- Spectra from presented experiments cannot be processed without simulations – DICEBOX code allows to keep inherent uncertainties due to statistical character of the decay under control

TSC meausurements

Prague - F. Bečvář, M. Krtička, J. Kroll

Řež - I. Tomandl

DANCE

LANL - T.A. Bredeweg, R. Haight, J.M. O'Donnell,
R.S. Rundberg, J.L Uhlmann, D. Vieira, J.M. Wouters,
J.B. Wilhelmy, A. Chyzh, B. Baramsai

LLNL - U. Angvaanluvsan, J.A. Becker, W. Parker, C.Y. Wu,
D. Dashdorj

NCSU - G.E. Mitchell

Prague - F. Bečvář, M. Krtička

Dubna - E.I.Sharapov


Thank you
for your attention