Radiative strength functions in deformed nuclei (^{162,4}Dy, ^{168}Er) and population of $K^{\pi}=4^{+}$ isomeric state in ^{168}Er from resonance neutron capture

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faculty of mathematics and physics

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Outline

- Experiment and data processing
- Results
  - Radiative Strength Functions and "unexpected" fluctuations properties of ^{162,4}Dy spectra
    PhD thesis of Standa Valenta
  - Radiative Strength Functions and "very high" population of the isomeric state in ^{168}Er
    Diploma thesis of Ingrid Knapová

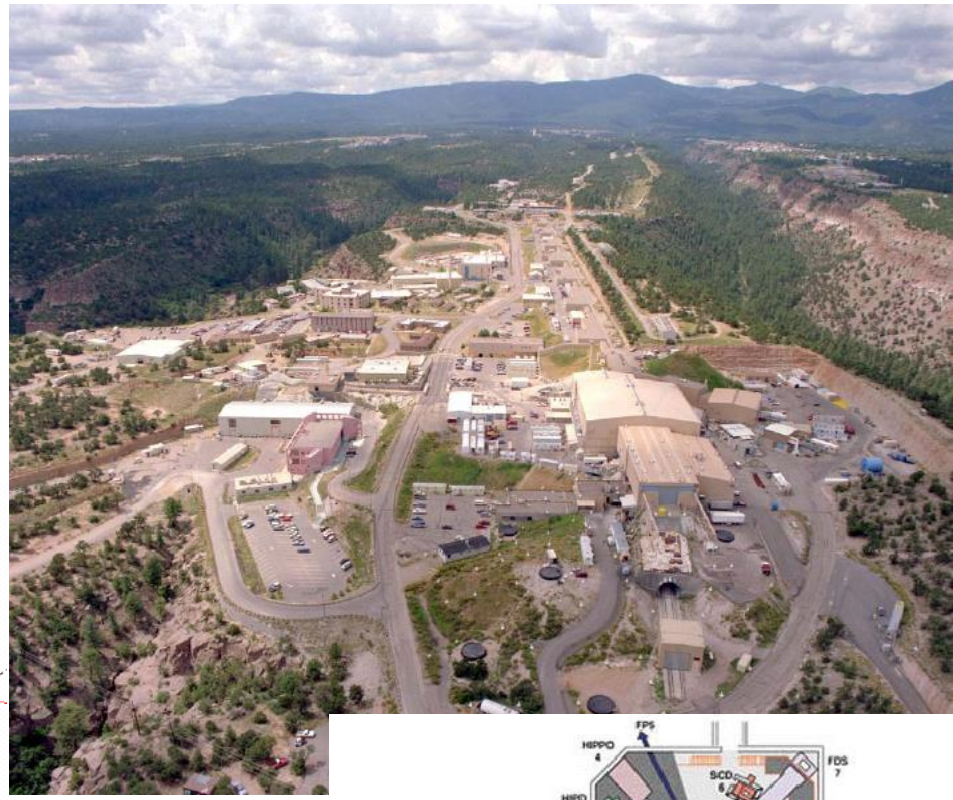
Other collaborators:
LANL: R.F. Casten, A.J. Couture, J.L. Ullmann, B. Baramsai

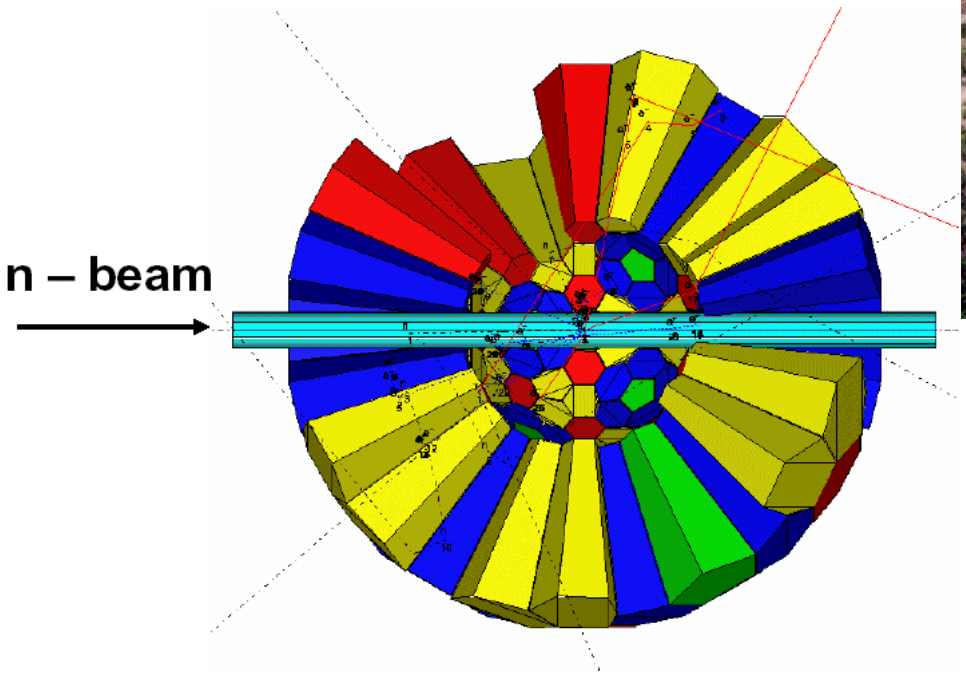
Prague: F. Becvar

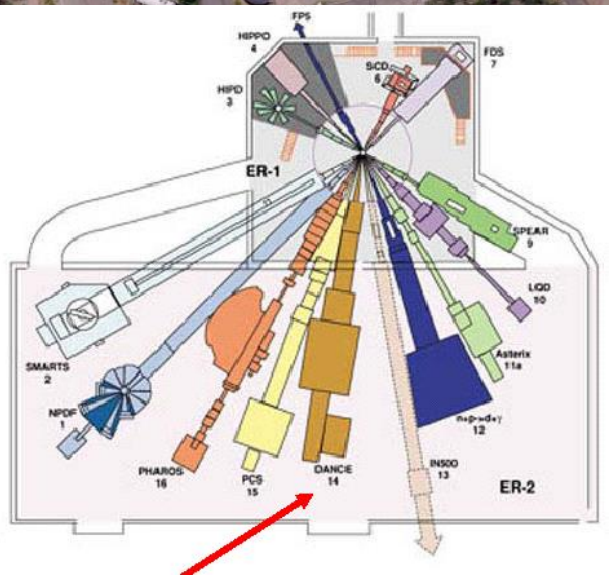
NCSU: G.E. Mitchell

Experiment - 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





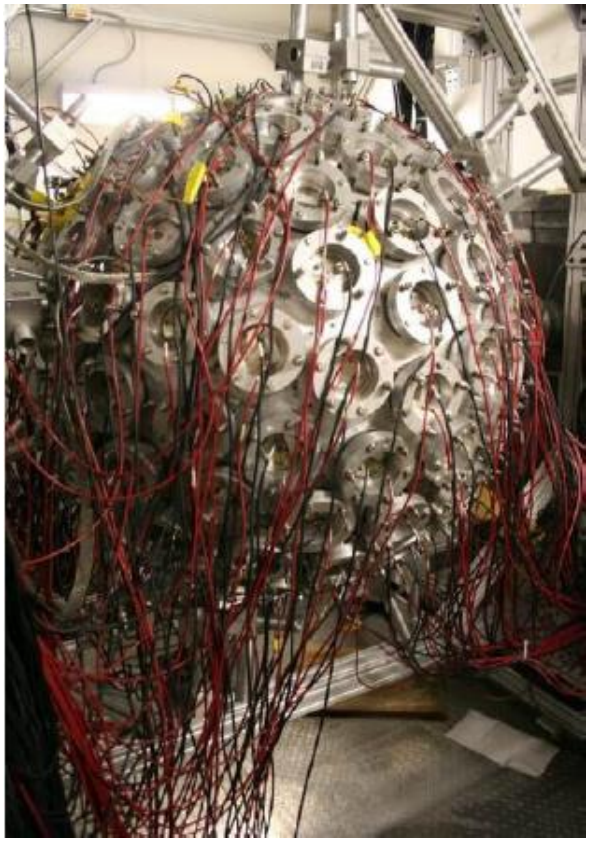


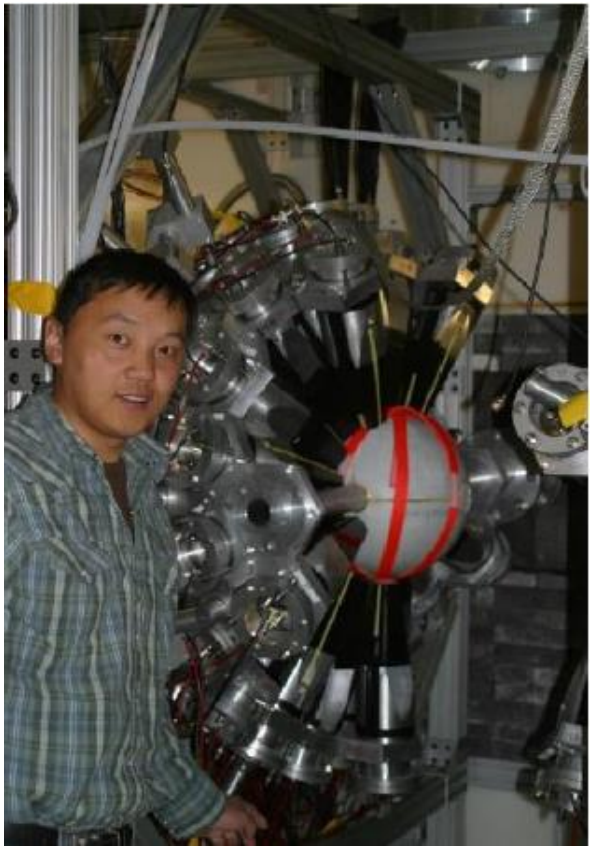
see also talks of J. Ullmann, O. Roig, and N. Bazhazhina

Experiment

- Radiative neutron capture measured for sub keV region using Detector for Advanced Neutron Capture Experiments (DANCE)

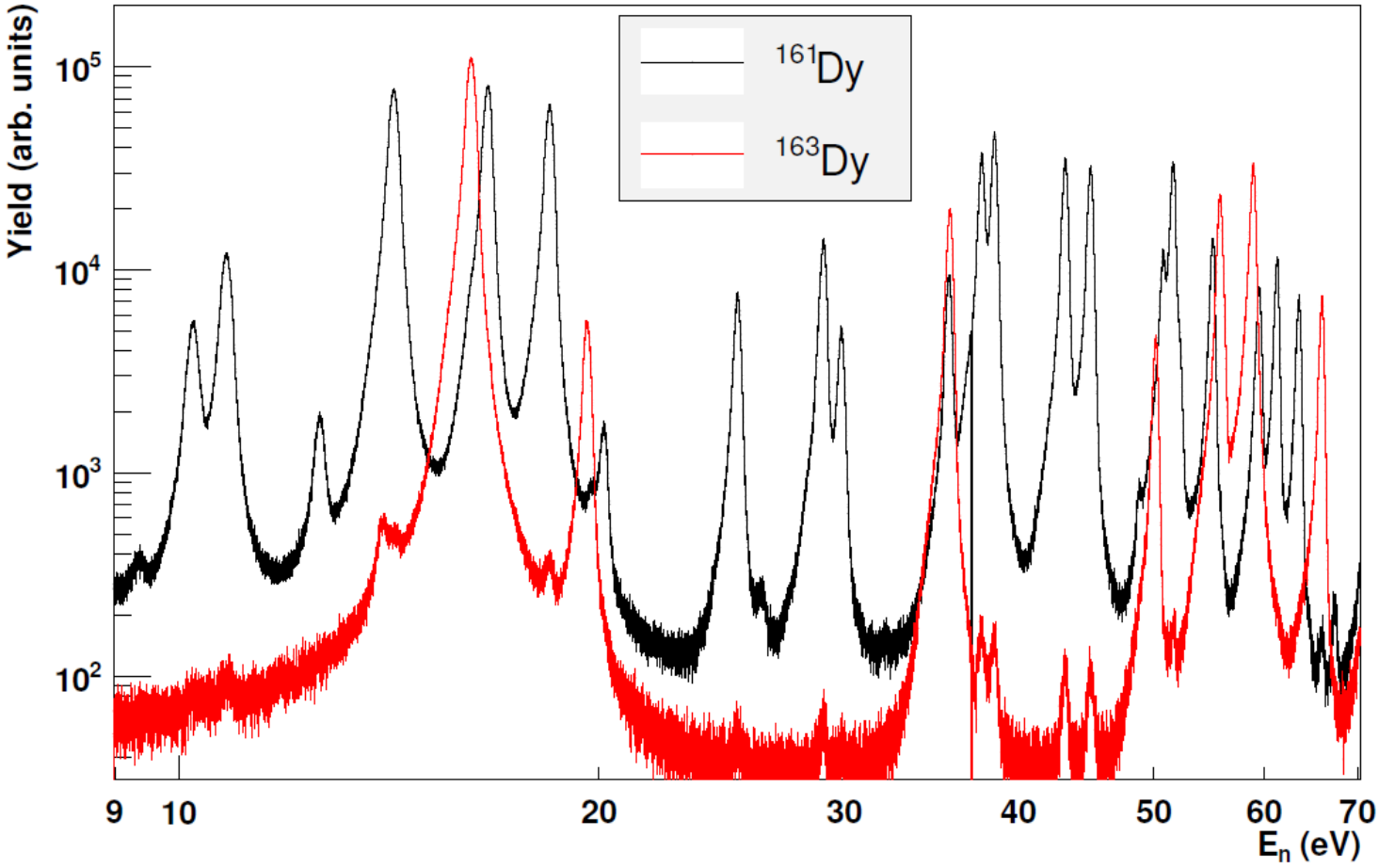
  with aim to study RSF (and perform resonance spin assignment)





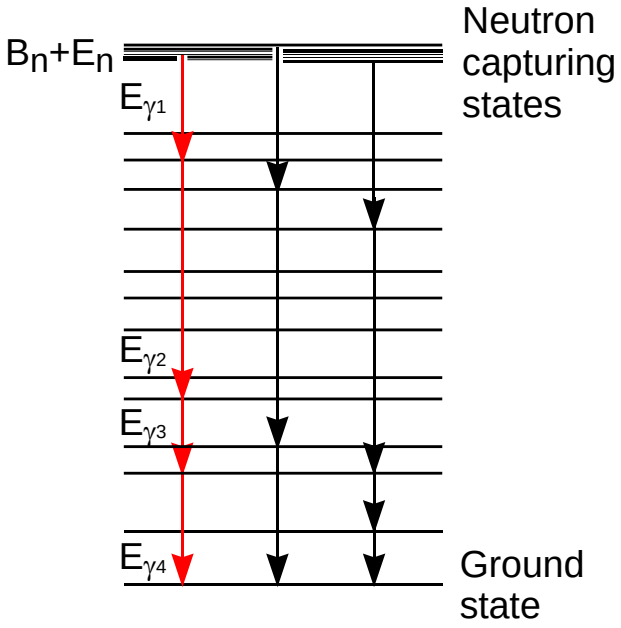
ToF spectra

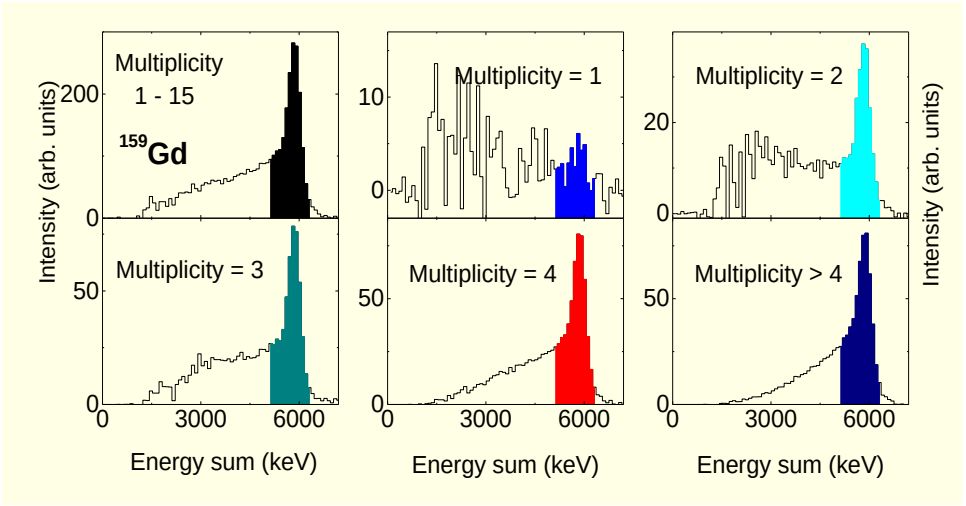
Spectra can be obtained from several neutron resonances

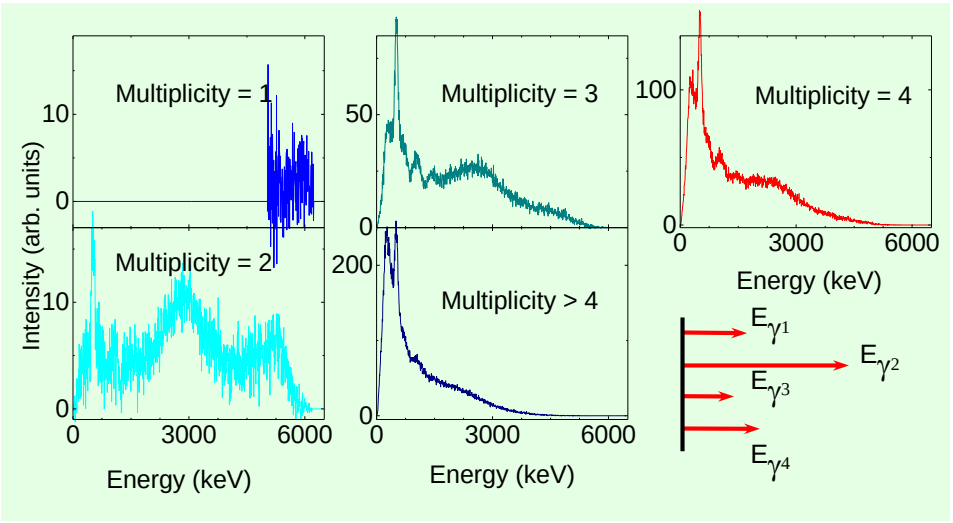


(Narrow) gate on Esum near Sn applied – 800 keV wide cuts

Spectra of our interest

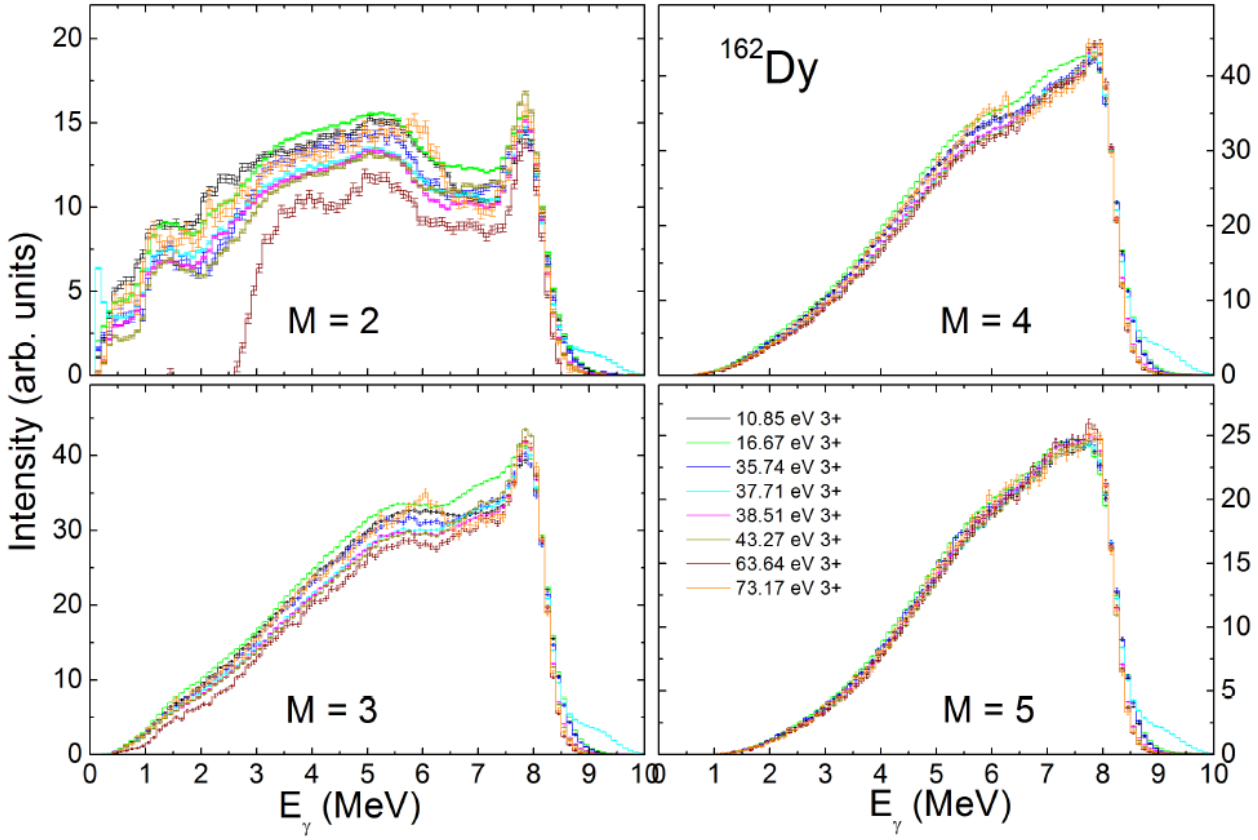




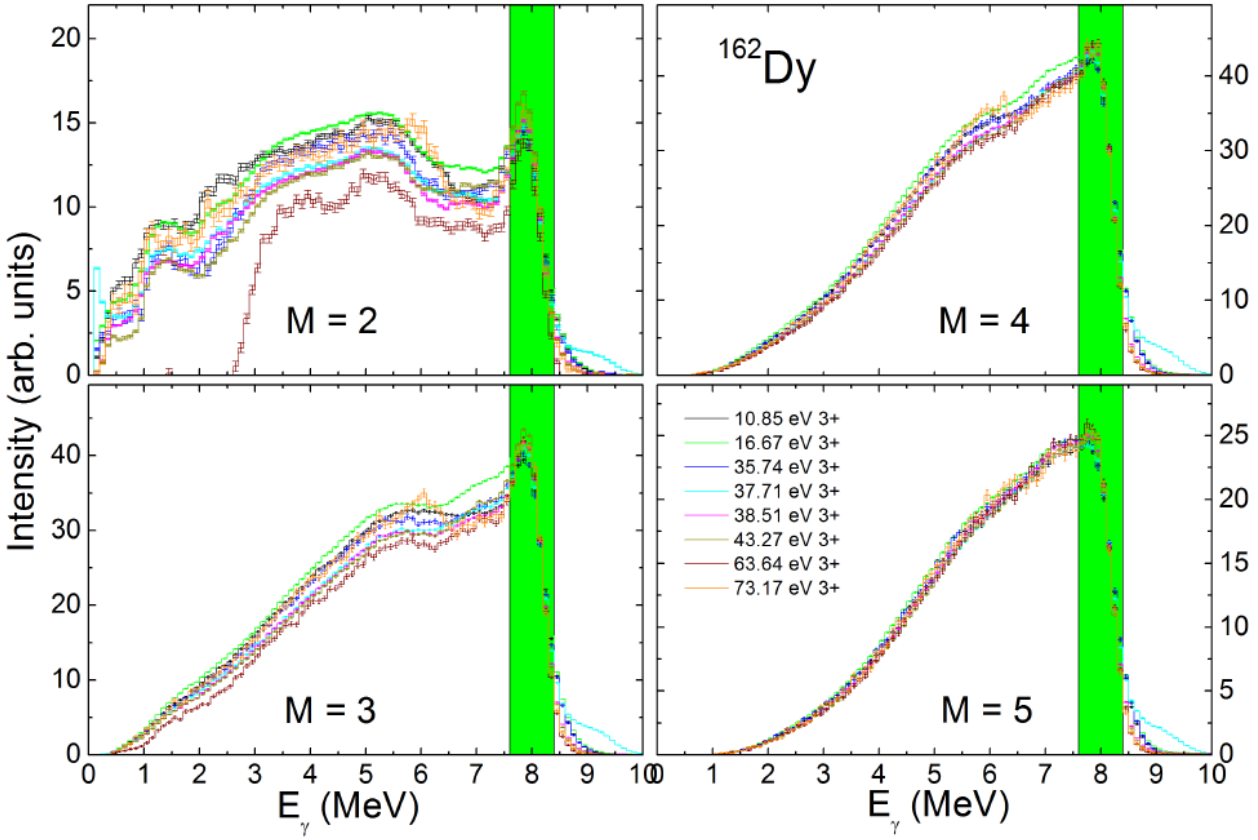


Verification of possible validity of various RSF and NLD models
based on comparison of observables – sum-energy and MSC spectra with predictions of simulations based on statistical model of nucleus

Sum-energy spectra

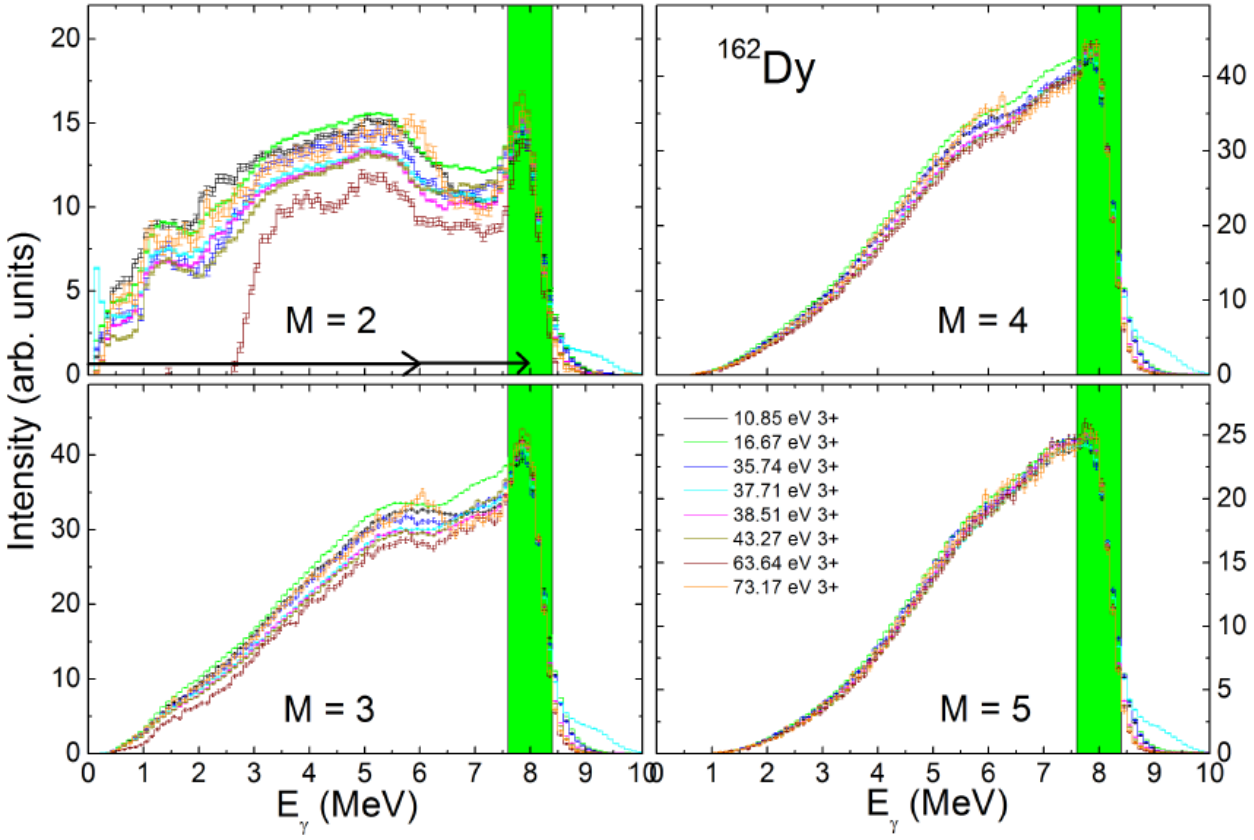


Sum-energy spectra

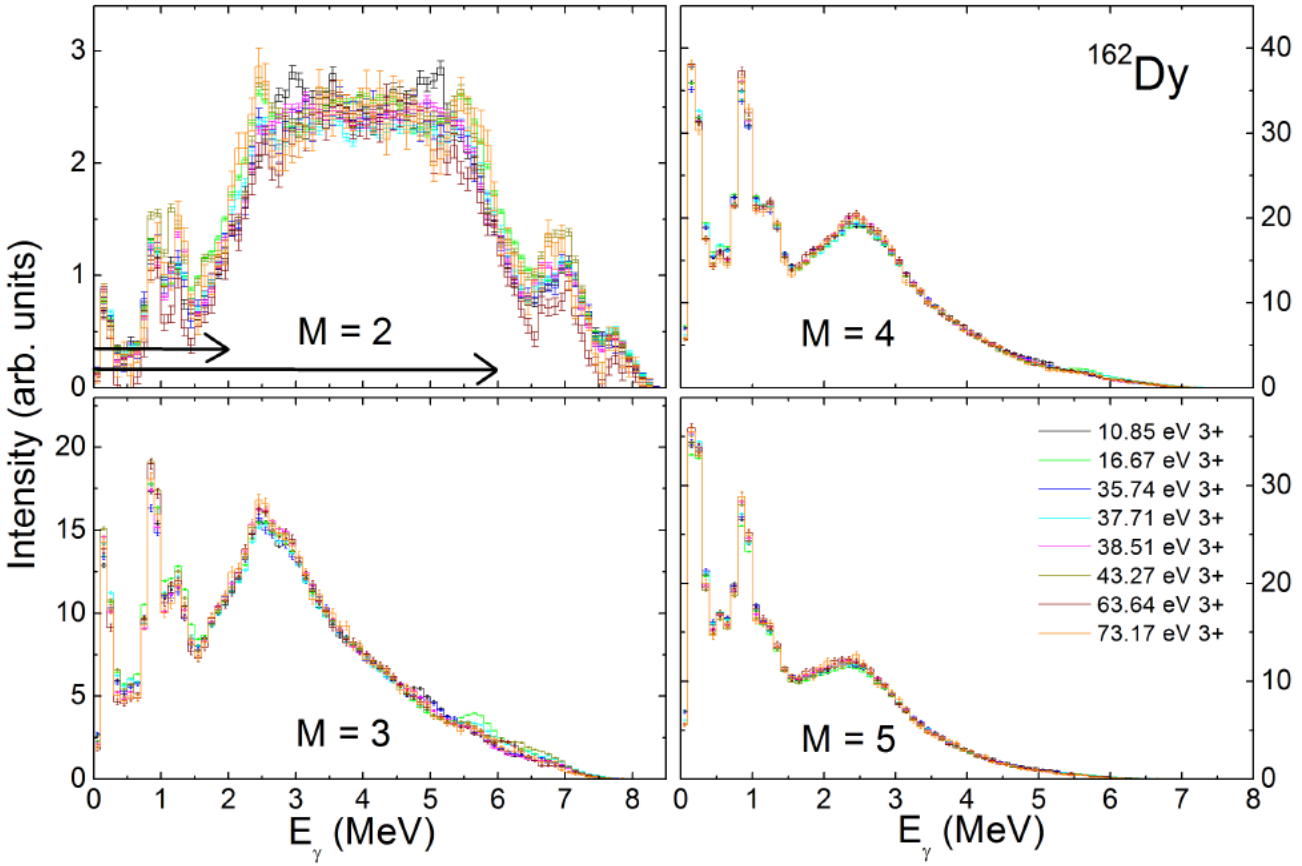


Normalization to the same number of events in M=2-7 in sum-energy peak (highlighted area)

Sum-energy spectra



MSC spectra



Spectra obtained for “many” well-isolated resonances

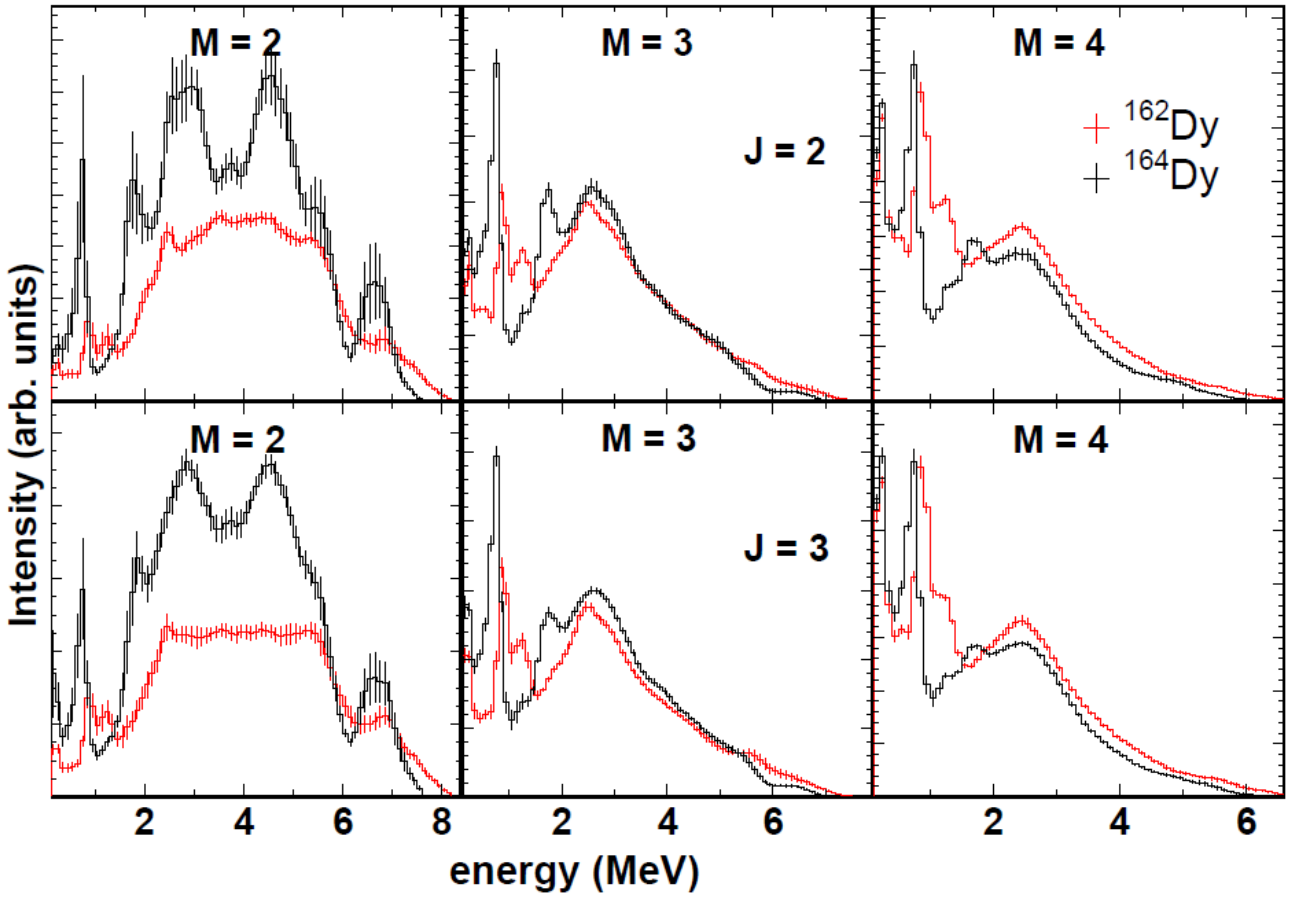
^{161}Dy(n,γ): 25x $J^\pi = 2^+$, 22x $J^\pi = 3^+$

^{163}Dy(n,γ): 14x $J^\pi = 2^-$, 26x $J^\pi = 3^-$

At least some checks of fluctuation properties become possible

“Average” MSC spectra

Distribution of resonances - mean and variance – can be obtained by different approaches (**simple averaging**, weighted averaging, estimate of distribution parameters from Maximum-likelihood method)



Different resonance parities:

positive in 162Dy (S_n = 8.2 MeV),

negative in 164Dy (S_n = 7.65 MeV)

Data processing

- Experimental spectra come from a complicated interplay between radiative strength functions (RSFs) and level density (LD)
- Complicated detector response to each cascade

$\Rightarrow$ Comparison of predictions based on statistical model simulations with experimental counterparts

- Cascades generated using statistical model of γ decay (using DICEBOX code)
- Detector response (GEANT4) applied to each γ cascade

Simulation of γ cascades - DICEBOX

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

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

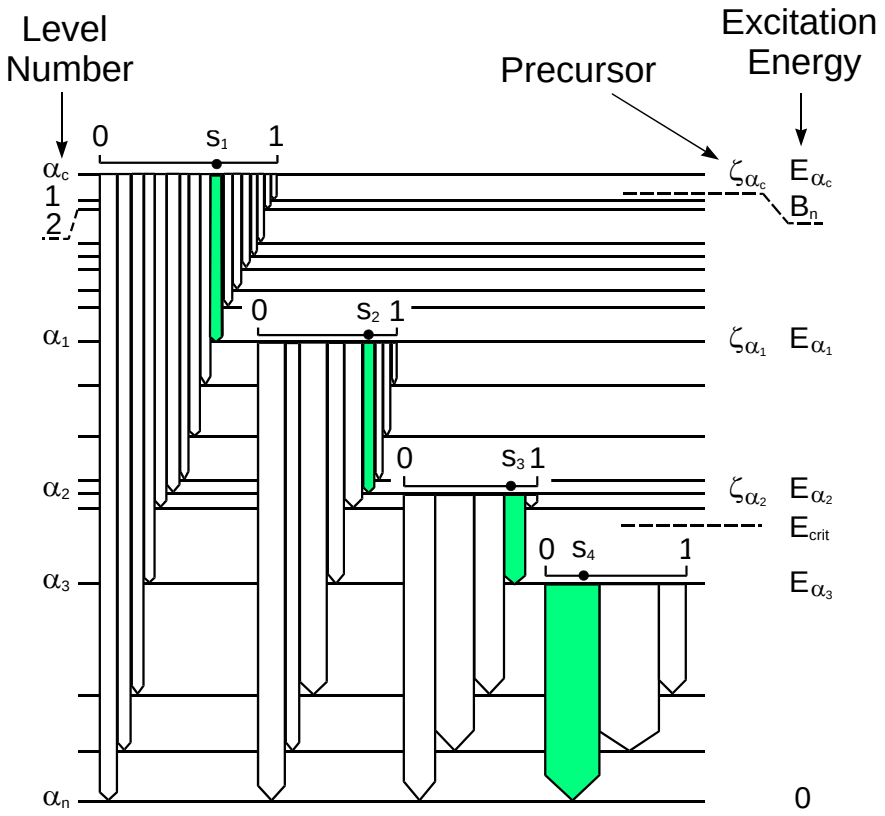
  where $f^{(XL)}$ and ρ are also *a priori* known
- Selection rules governing the γ decay are fully observed
- Any pair of partial radiation widths $\Gamma_{i\gamma f}^{(XL)}$ is statistically uncorrelated

DICEBOX – Statistical decay simulations

Modelling of the decay:

- "nuclear realization" (10^6 levels $\Rightarrow$ 10^{12} $\Gamma_{\lambda\gamma f}$)
  "precursors" are introduced
- comparable quantities (shapes of spectra, multiplicity, population of low-lying levels, shapes of TSC spektra) are „integral" quantities
- 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 features of DICEBOX - fluctuations

- Infinite number of artificial nuclei (nuclear realizations) can be obtained for the same set of level density and RSFs models – nuclear realizations differ in exact number of levels and intensities of transitions between each pair of them
  $\Rightarrow$ leads to different predictions from different nuclear realizations
- DICEBOX allows us to treat predictions from different nuclear realizations, i.e. expected fluctuations
- The size of fluctuations depends on the (observable) quantity and nucleus

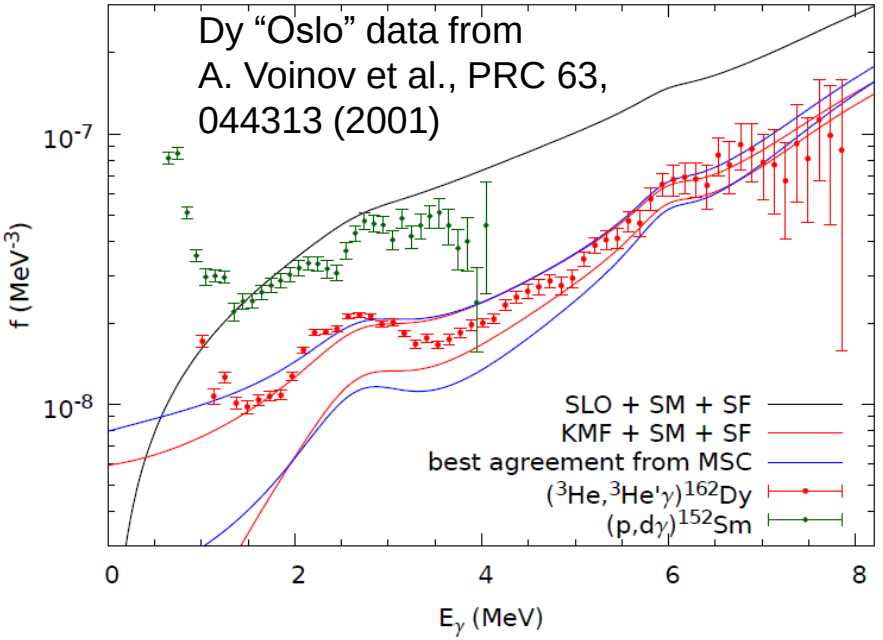
- Majority of results (sum-energy and MSC spectra) insensitive to absolute values of RSFs but only to energy dependence of RSFs and their “composition” (E1, M1)

Analysis of Dy data

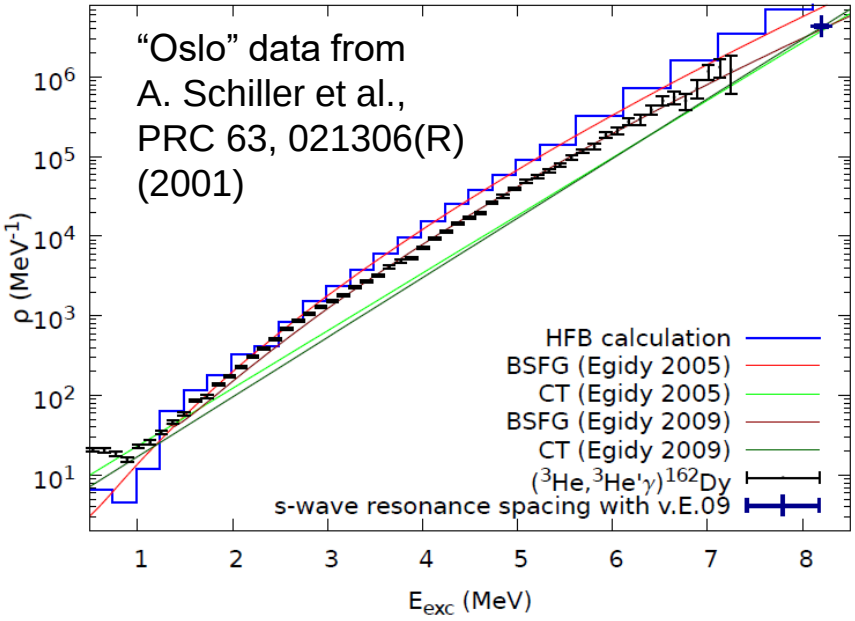
Dy – first nuclei in RE region, with data from NRF, Oslo and DANCE

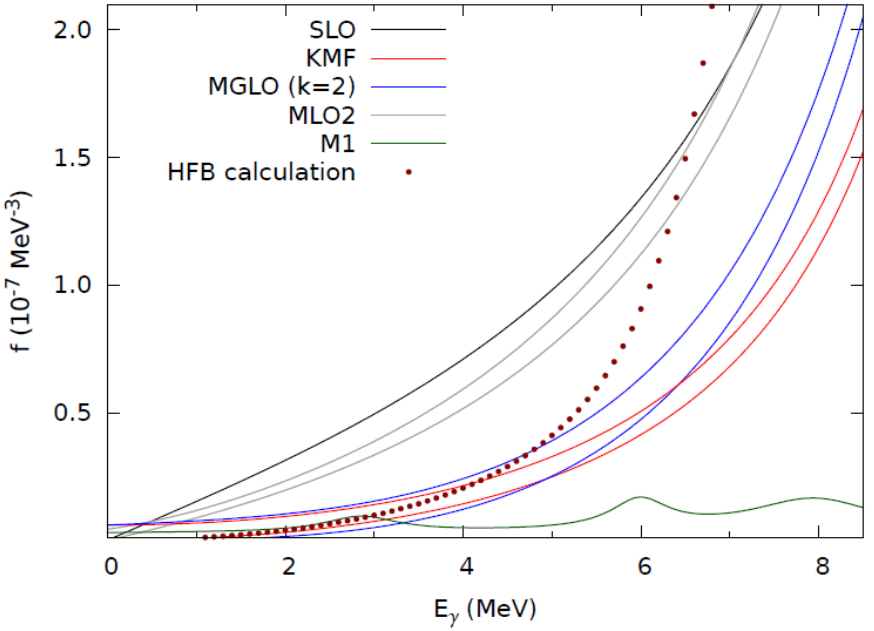
Many different RSF and LD models tested in simulations

- LD – BSFG and CTF
- RSF – all models listed in RIPL-3 + some additional models



Sm data from A. Simon et al., PRC 93, 034303 (2016)





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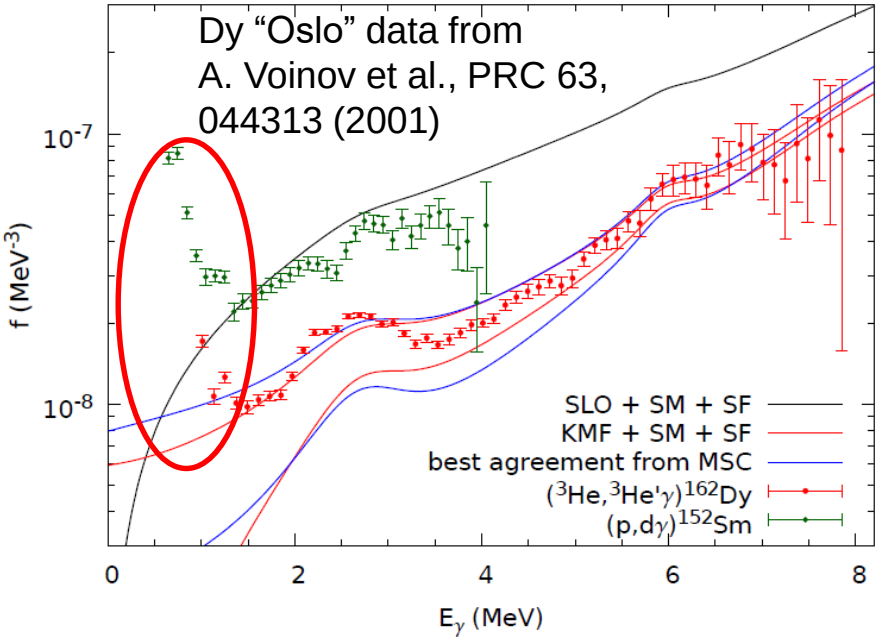

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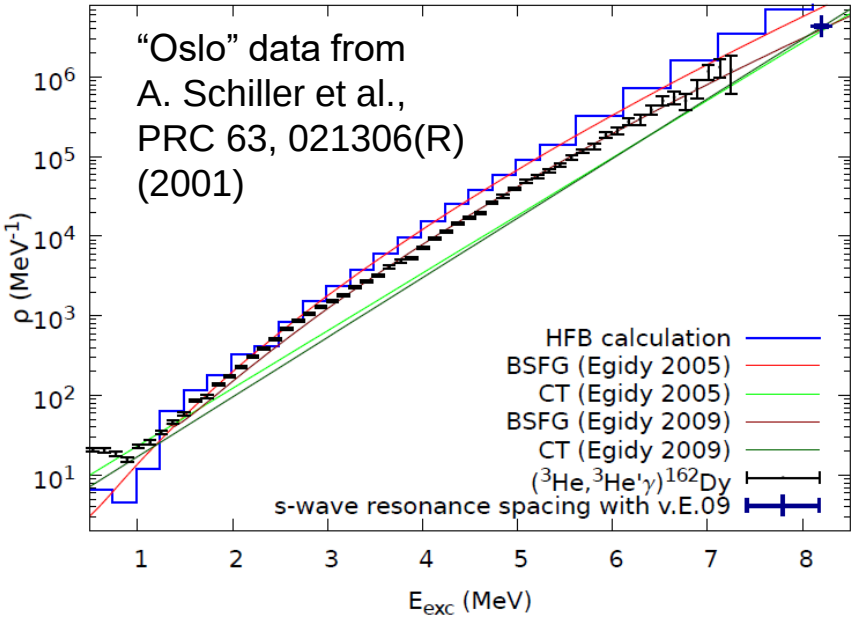
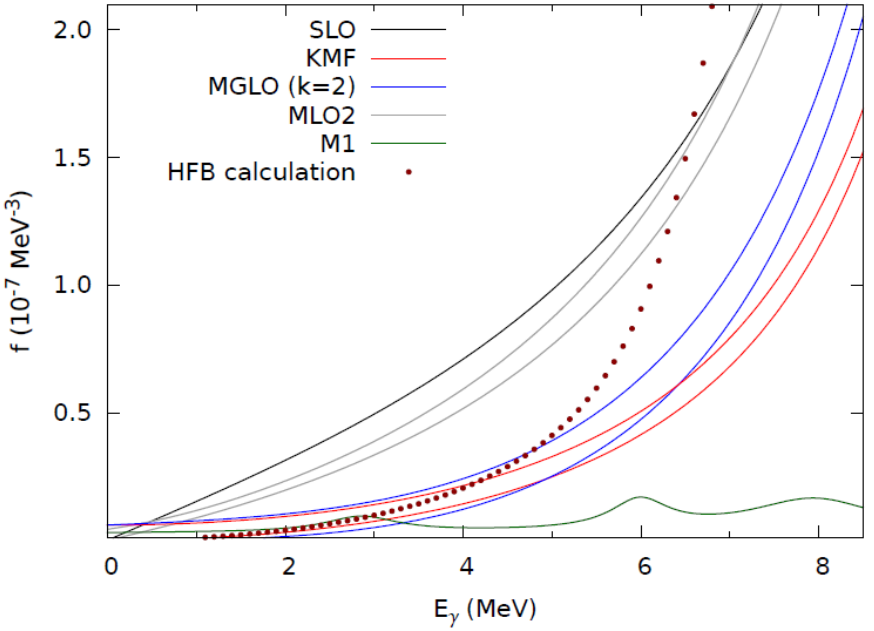




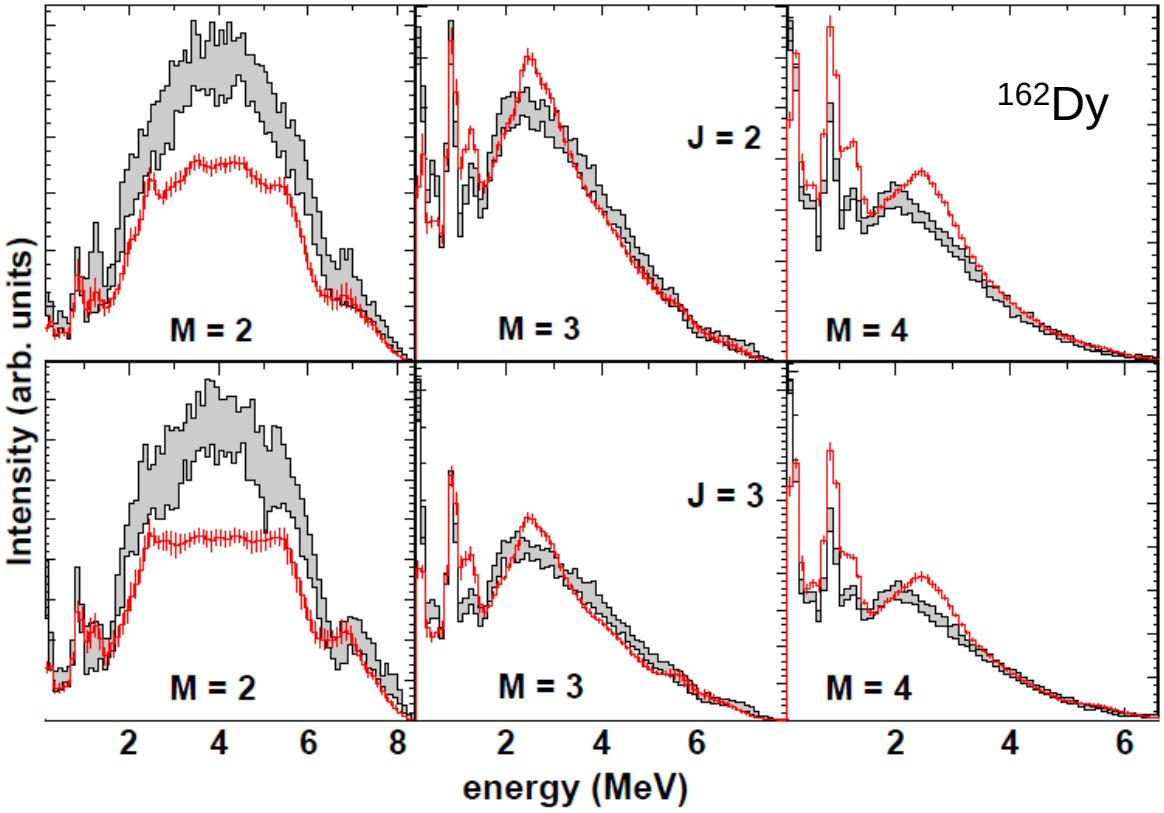
Results - Dy

- Two different spins
- Different parity of resonances (^{162}Dy x ^{164}Dy)

- Validity of many models can be rejected

Results - Dy

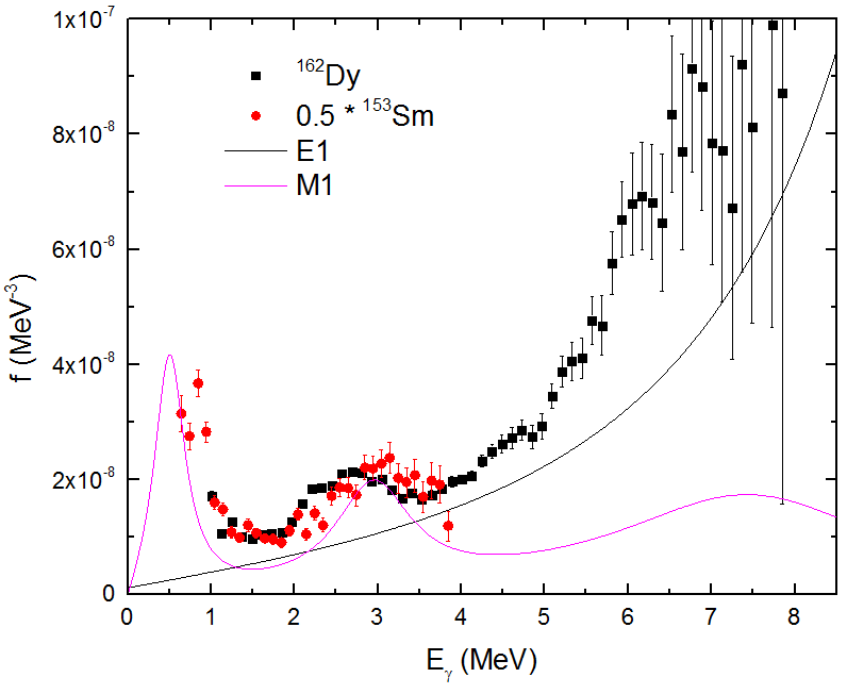
- Resonance near 3 MeV has to be postulated also for primary transitions and has to be of M1 character (scissors mode)
- E1 character of the resonance structure not consistent with data; E_{SM} = 2.8-3.0 MeV, Γ_{SM} = 1.0-1.4 MeV

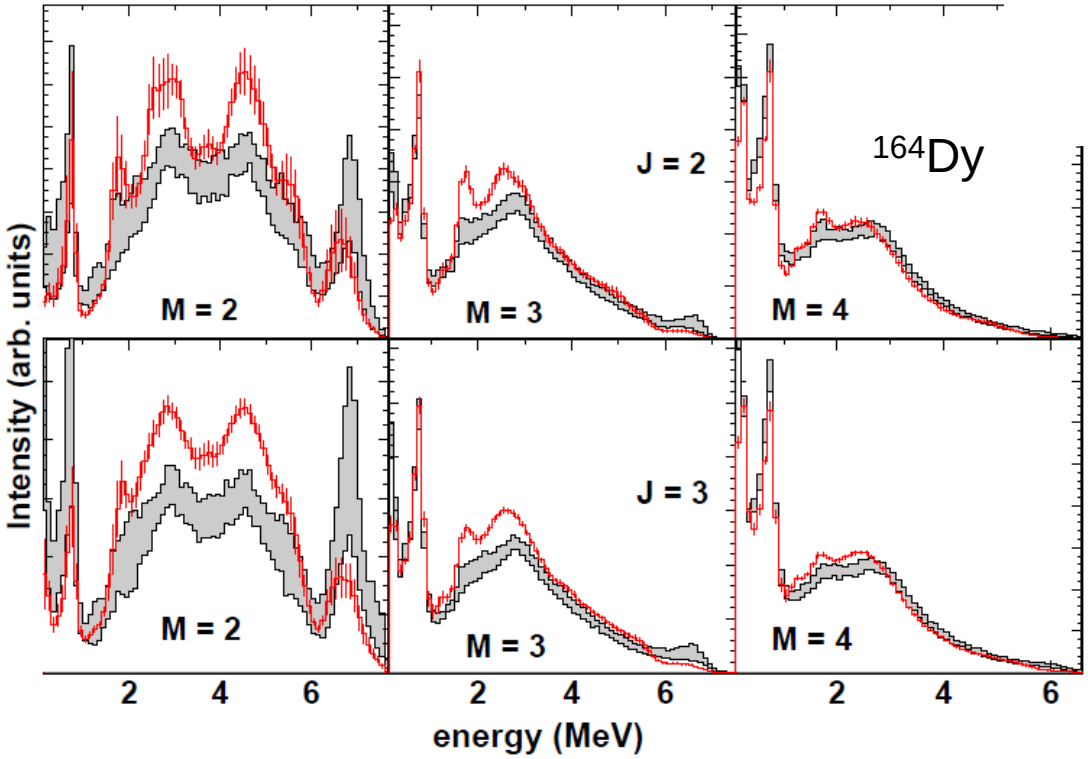


No scissors mode assumed

Results - Dy

- A low-energy RSF enhancement was tested
- “Very conservative low-energy enhancement” describing data from ^{152,154}Sm(p,dγ) is unable to reproduce spectra



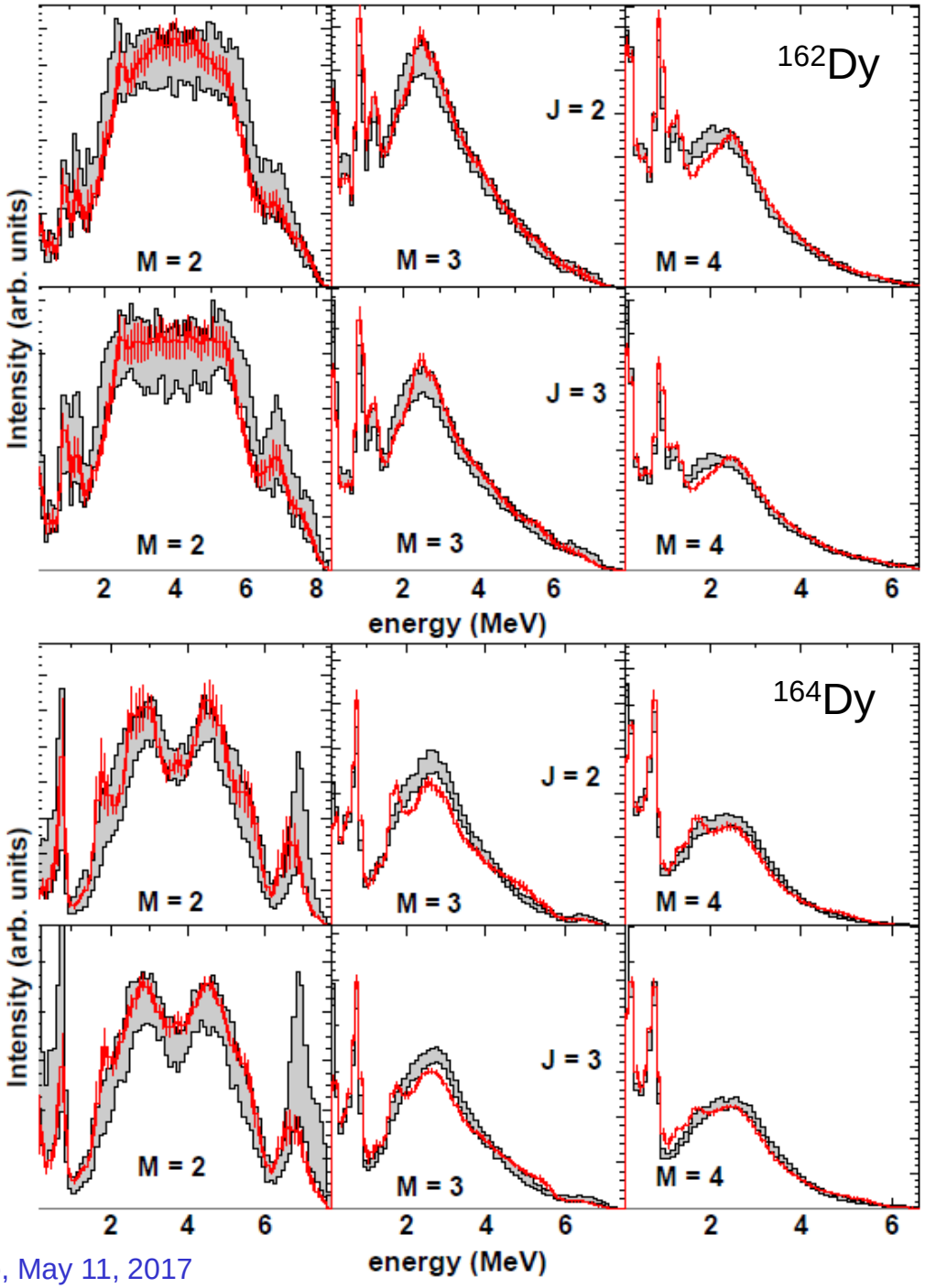


Dy data: A. Voinov et al., PRC 63, 044313 (2001)

Sm data: A. Simon et al., PRC 93, 034303 (2016)

Results - Dy

- Good agreement obtained with models “similar but not exactly the same” as Oslo models
- It is difficult to reproduce both isotopes with exactly the same RSF model – especially taking into account total radiation width

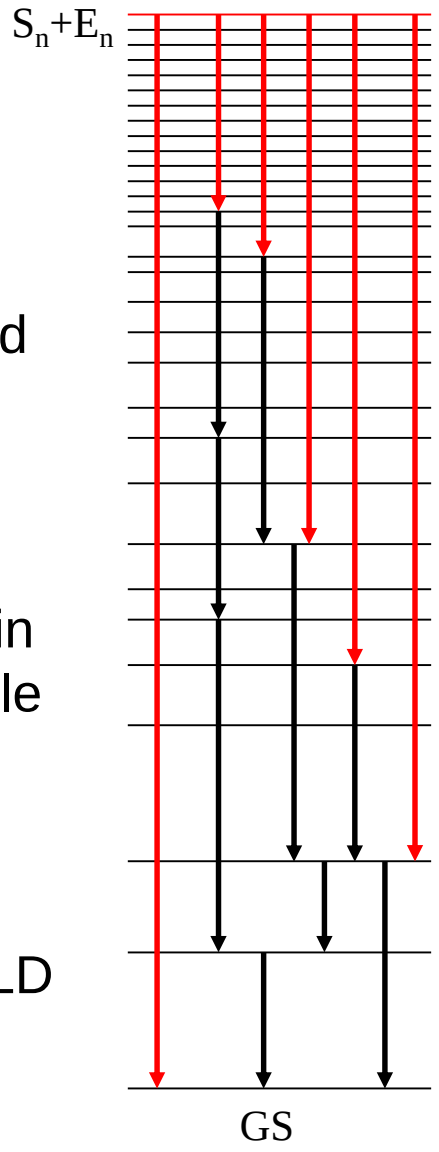


Expected fluctuations

- Different “sources” of fluctuations in simulations

- In a real nucleus, the fluctuations come only from intensities of primary transitions – all levels below neutron resonances and secondary intensities are fixed
- Unfortunately, we do not know which realization of the decay scheme is realized in nature

- So far, simulations made with different level schemes in each simulated artificial nucleus – CPU time reasonable
- Is such an approach correct?
- For Dy nuclei we have made for the first time (time-consuming) tests for fixed levels below capturing state and intensities of secondary transitions (for two RSF+LD combinations)

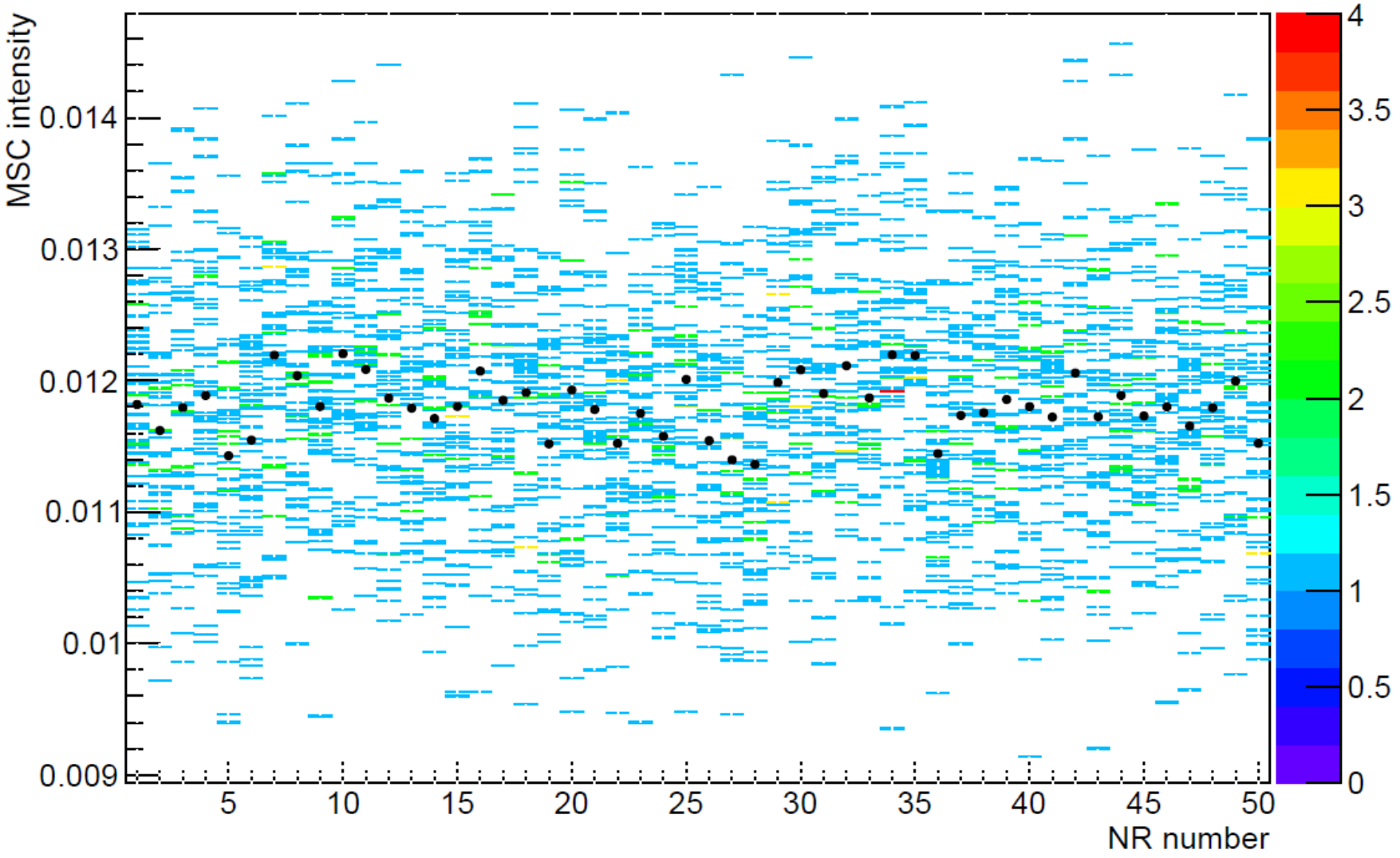


Findings related to widths of distribution

Results from simulations

- For chosen combination of RSFs and LD, fluctuations due to primary transitions do not strongly depend on actual choice of the level scheme – we can reasonably well separate fluctuations due to (i) “unknown level scheme” and (ii) “fluctuation of primary intensities”
- For all bins via region of “high level density” the fluctuations of type (ii) are higher than that of type (i), usually dominantly – perfect justification of the comparison used in all previous RE nuclei

Different fluctuation sources



50 different nuclear resonances (NR) in a bin in MSC M=2 spectrum
For each, 50 different realizations of primaries simulated

Findings related to widths of distribution

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- Results can strongly depend on the isotope (mass, LD)
  but should be similar in nuclei in the same mass range (similar LD)

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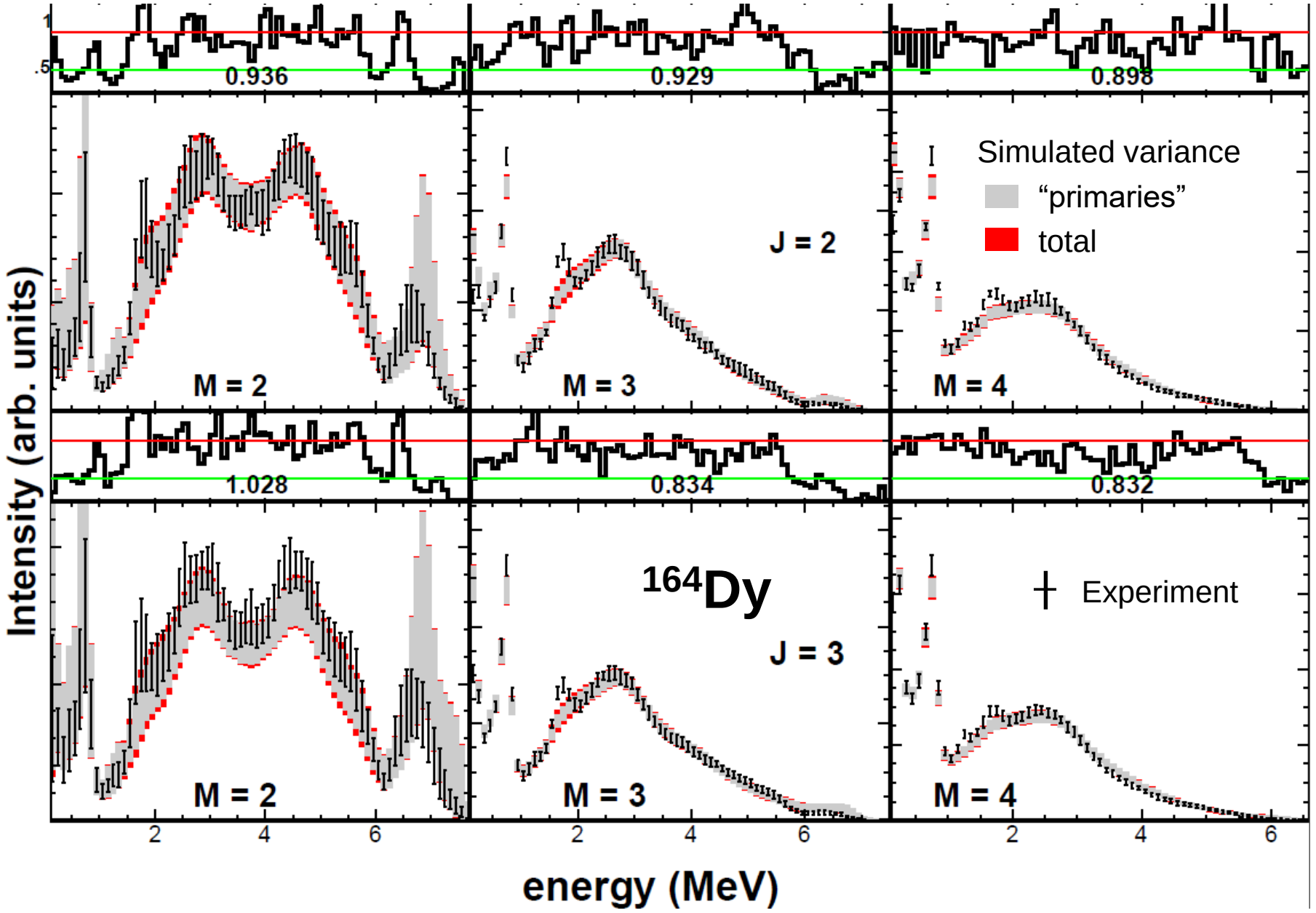
Comparison between experiment and simulations

- Results are rather puzzling

Comparison of distributions



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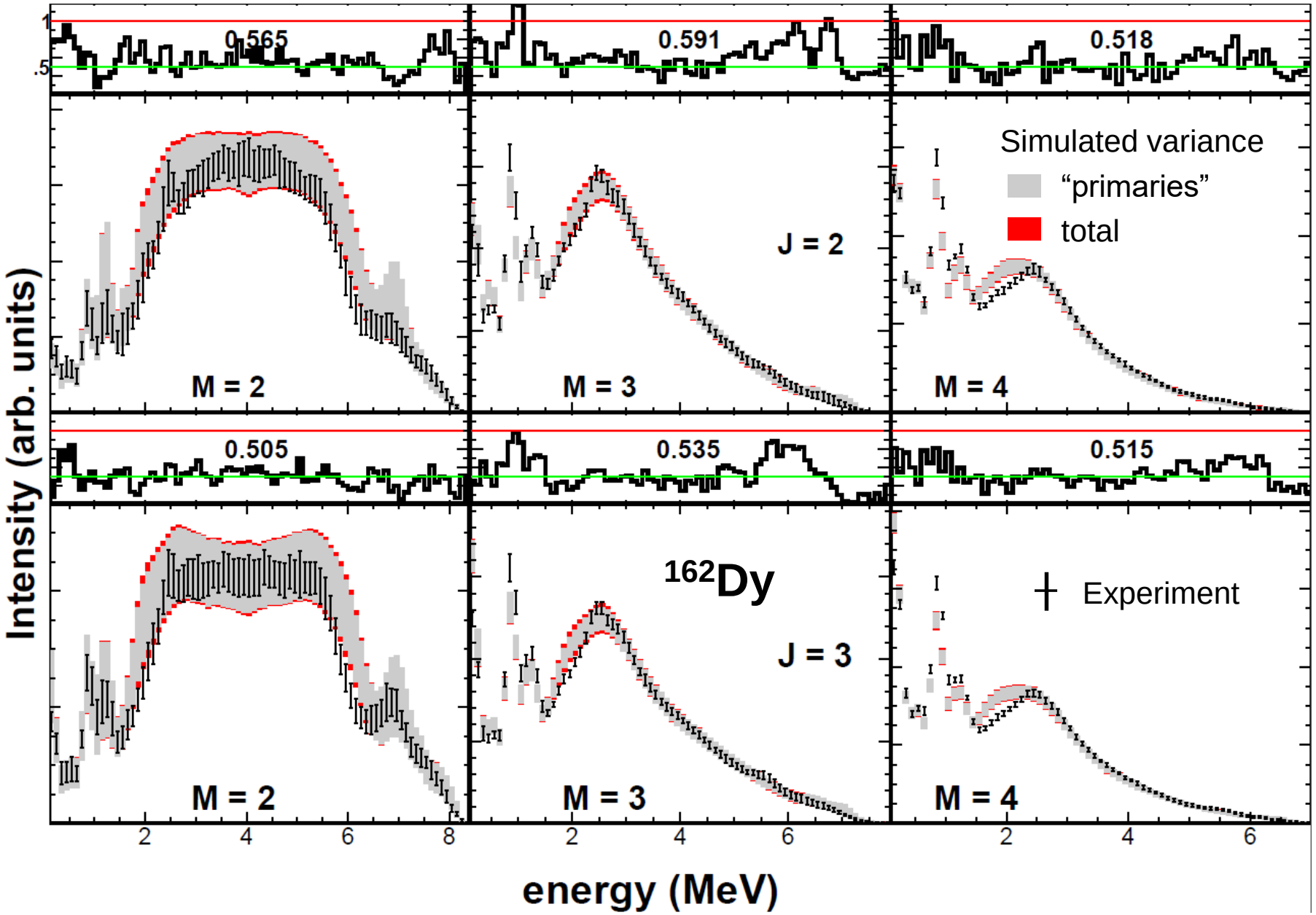
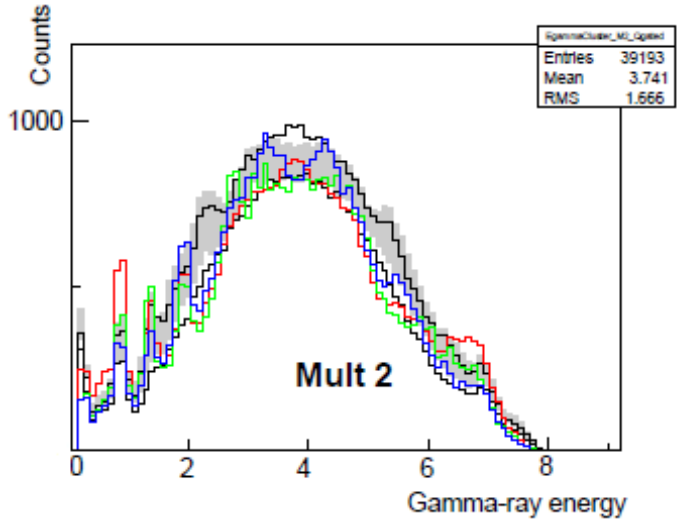
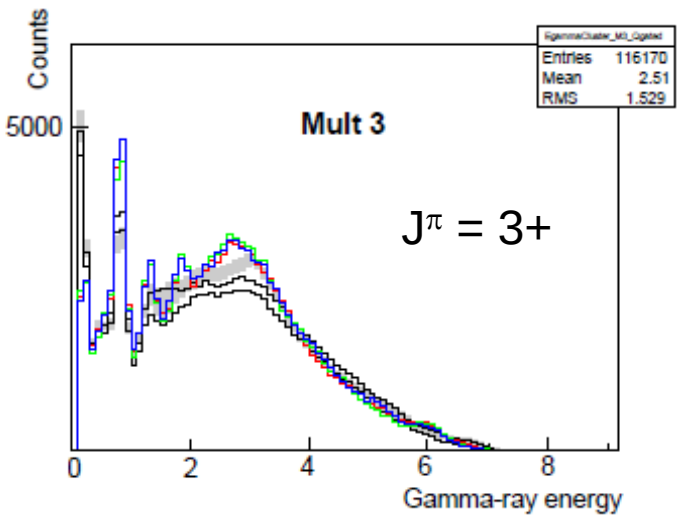


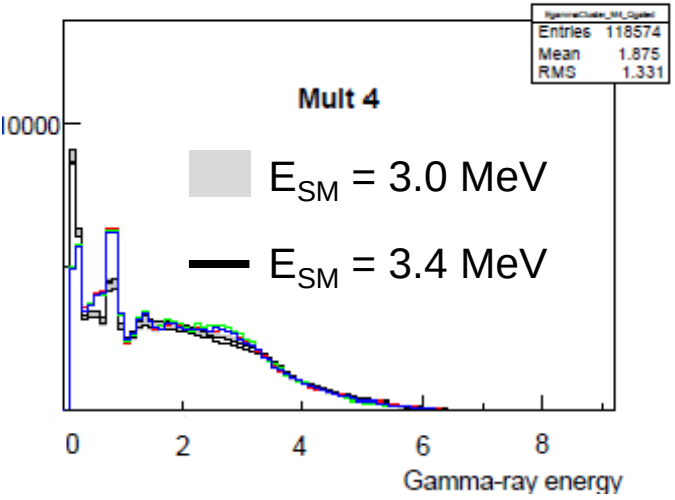
^{168}Er – very preliminary results

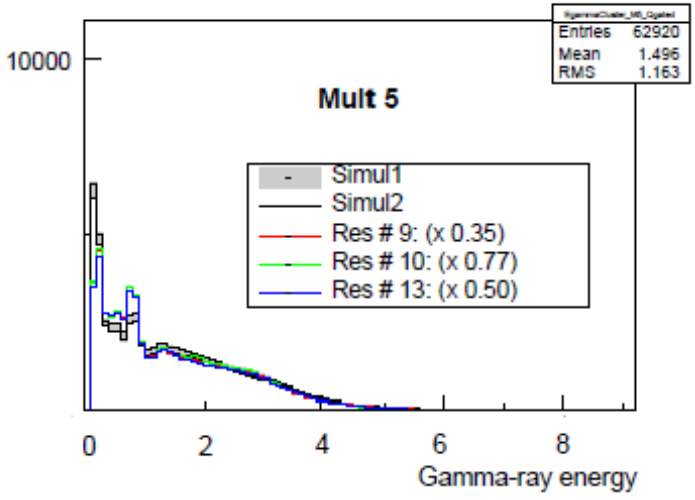
^{168}Er results – MSC spectra

- MSC spectra are well reproduced with similar model combinations as Dy (and Gd) spectra, i.e. with the scissors mode, BSFG LD model,…





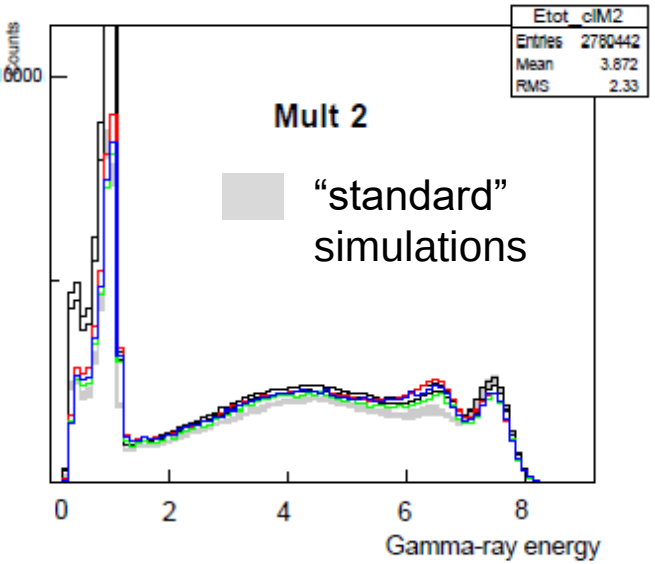


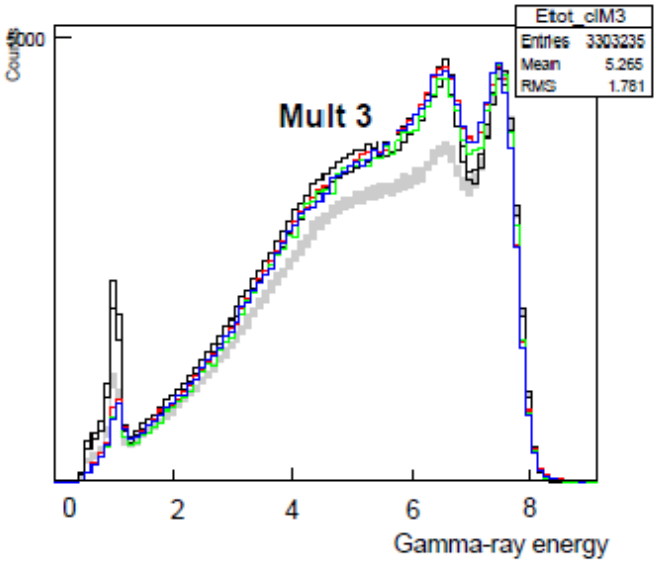


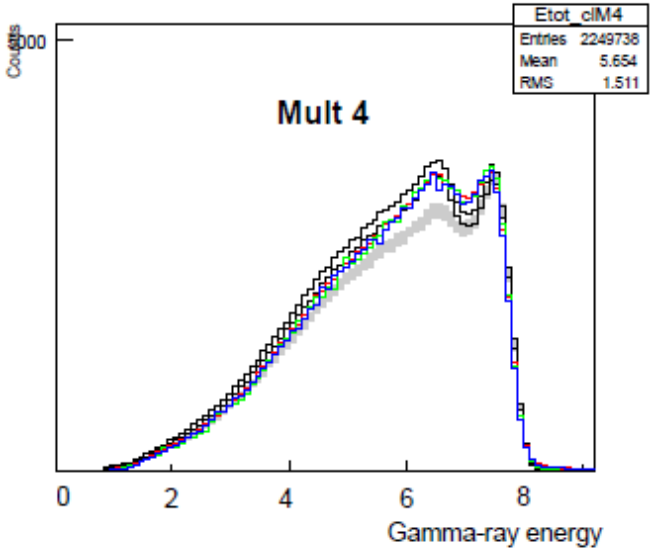
… no surprise

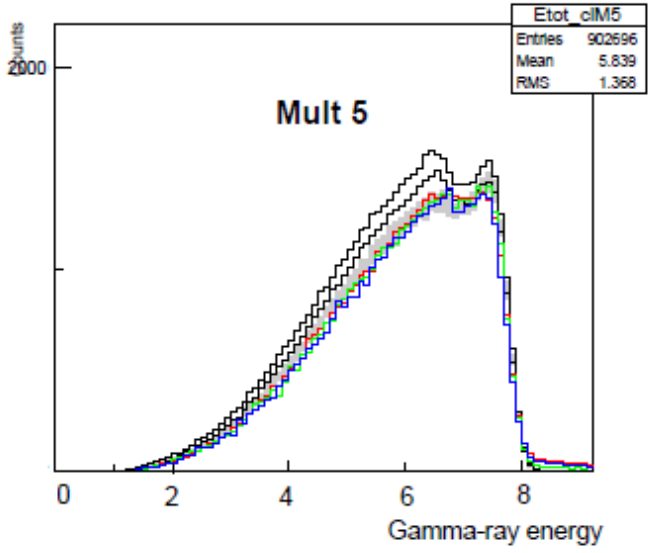
^{168}Er results – Sum-energy spectra

spectra for 20 ns coincidence window









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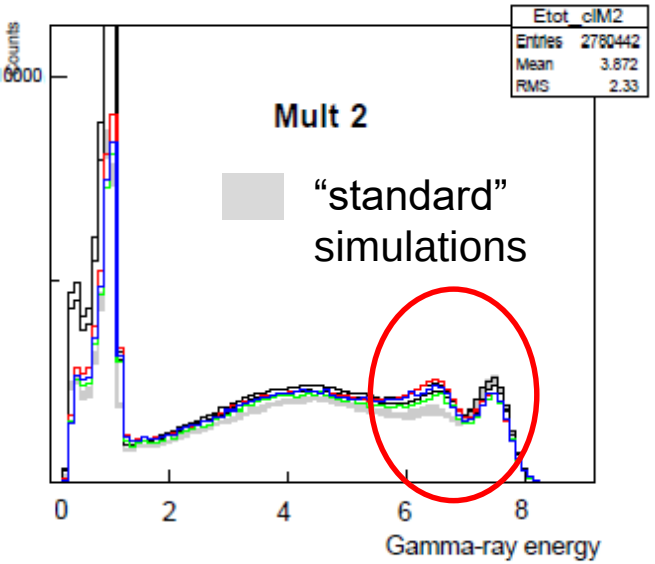

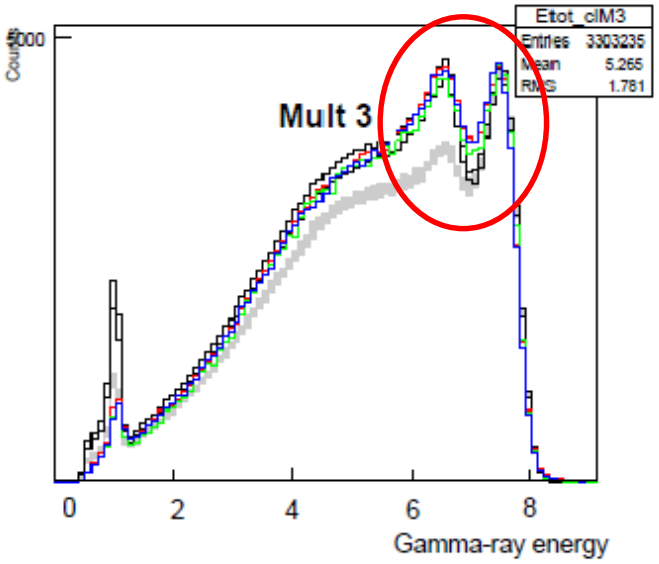

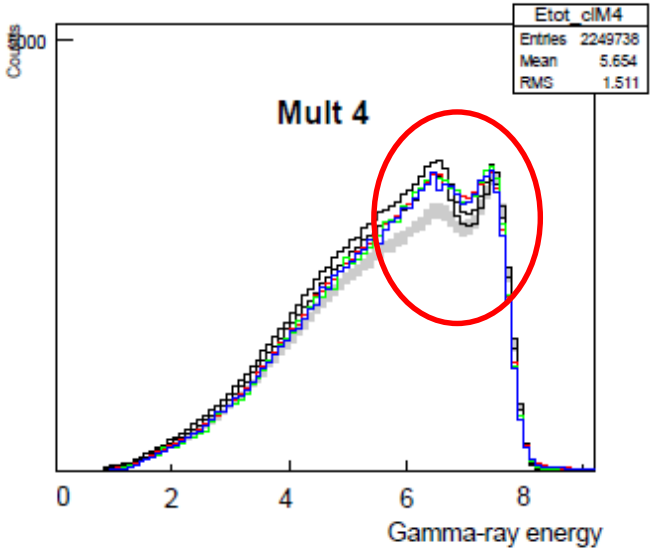

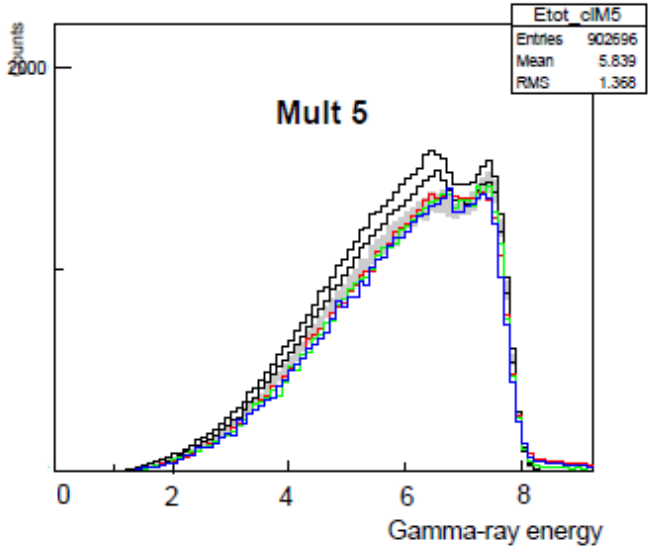

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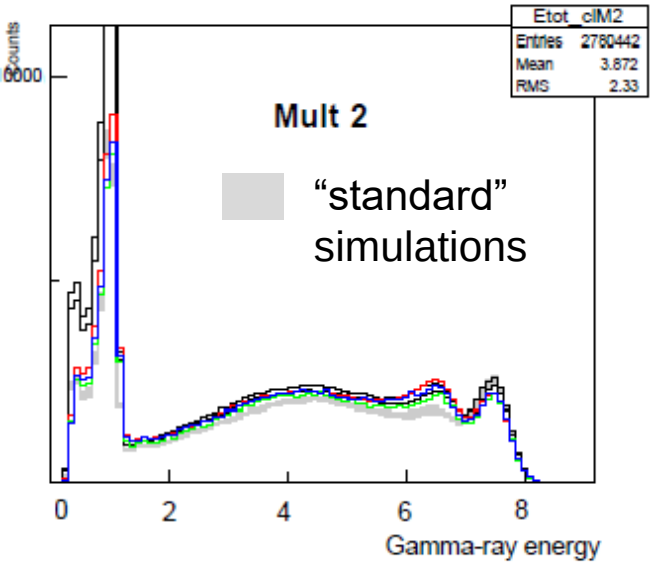

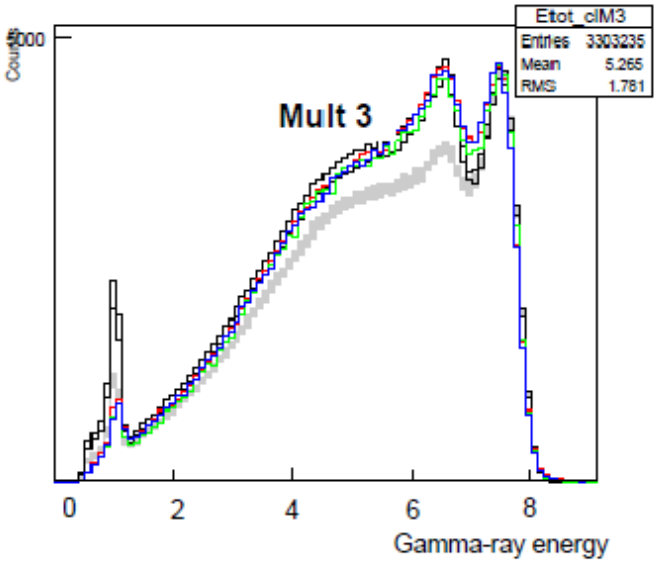

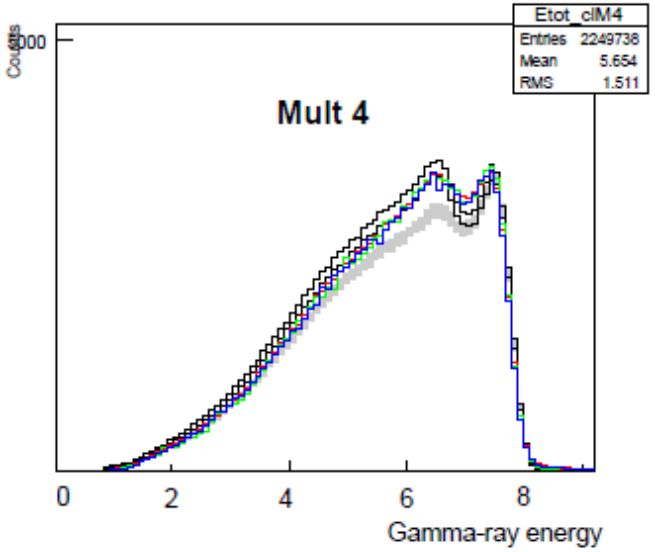

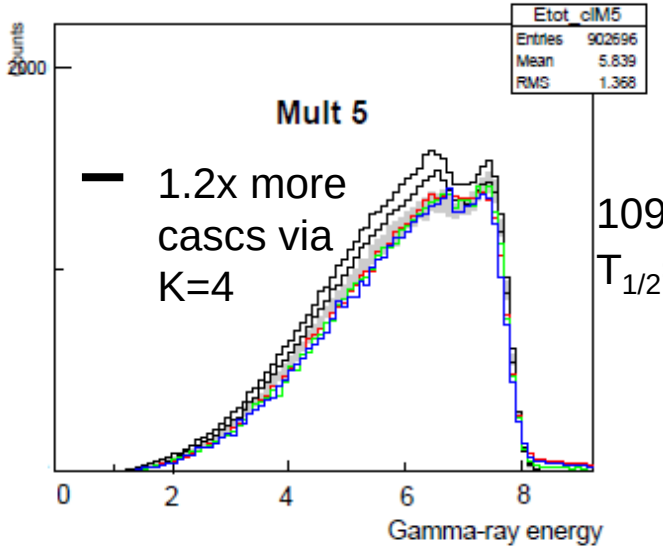

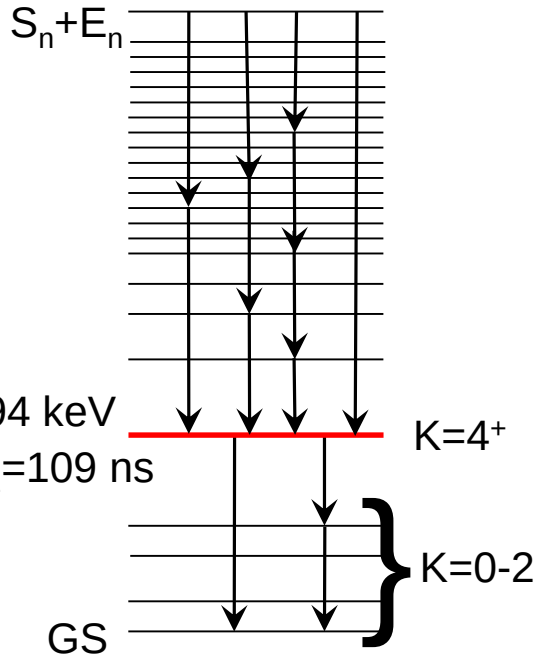

Summary

- Problems with fluctuations in Dy
- Problems with population of the isomeric state in ^{168}Er

  problems with populations of isomeric states observed also in other deformed nuclei ^{177}Lu, ^{236}U @ DANCE,
  ^{180}Hf isotope from measurement in unresolved resonance region at Karlsruhe - K. Wisshak et al., PRC73, 045807 (2006)

Possible explanation?

We can only speculate

- influence of level density (spin cut-off)
- influence of quantum number K in these nuclei
- …

Thank you very much for your attention!