Spin of resonances and Photon Strength Functions from multi-step γ cascades following the resonance neutron capture in Dy isotopes

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Charles University in Prague

May 17, 2015

Outline

1. Motivation

2. ^{161}Dy(n_{res}, γ) and ^{163}Dy(n_{res}, γ) at DANCE
   - Experimental information at DANCE

3. Results
   - Resonance spin assignment
   - Experimental & Simulated MSC spectra
   - Comparison for ^{162}Dy
   - Comparison for ^{164}Dy

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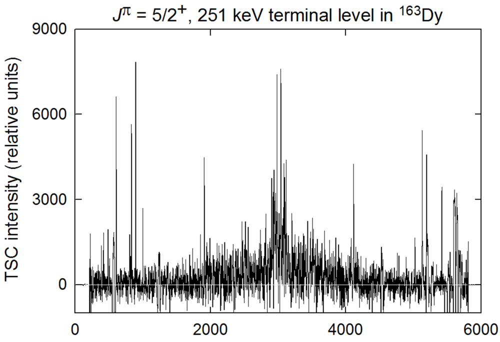
Motivation

Results of TSC experiment in 1995 improved in 2004 with reaction ^{162}Dy(n_{th}, γ)^{163}Dy showed necesity of postulating the scissors mode (SM) with these properties:

- $E_{SM} \approx 3$ MeV, $\Gamma_{SM} \approx 0.6$ MeV, $\sum B(M1) \uparrow = 6.2\mu_N^2$
- above all states up to $\approx$ 4MeV of excitation energy



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Among other results from Oslo the Dy measurements were published in:

- A. Voinov et al., Phys. Rev. C63, 044313 (2001)
- M. Guttormsen et al., Phys. Rev. C68, 064306 (2003)
- H.T. Nyhus et al., Phys. Rev. C85, 014323 (2012)

quoting the parameters of SM resonance:

- ^{162}Dy $\sum B(M1)\uparrow = 6.8(8)\mu_N^2$
- ^{164}Dy $\sum B(M1)\uparrow = 5.4(1.0)\mu_N^2$
- ^{163}Dy Oslo and TSC results were shown compatible

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On the contrary, the result of MSCs from DANCE is that strength of SM in e-e Gd's is 2-4$\times$ lower compared to odd ones...

The questions then arise:

- Is the SM strength in neighbouring e-e and odd nuclei comparable or significantly different?
- Are results from resonance and thermal capture consistent?
- If so, how do they compare to other results - (γ, γ') and Oslo?
- And one evergreen: What happens with SM at higher excitation energies?

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To answer these questions one needs:

- suitable target nuclei

✓ $^{161-163}$Dy all have reasonable cross section and stable well-deformed products

✓ $^{162-164}$Dy products have been measured in Oslo

✓ ^{162}Dy has $S_n = 8.197$ MeV - not that lower than $3 \times E_{SM}$

- suitable aparatus

✓ DANCE at LANL

- beam time

✓ 2013 and 2014

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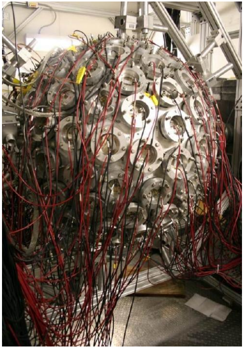
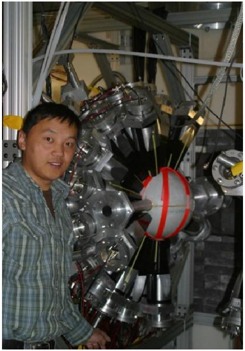
DANCE

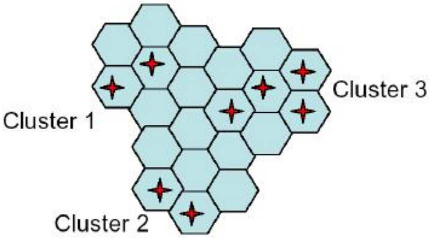
Neutron capture reactions were measured for eV region using **D**etector for **A**dvanced **N**eutron **C**apture **E**xperiments in 2013 with aim to perform resonance spin assignment and study of the photon strength functions models.



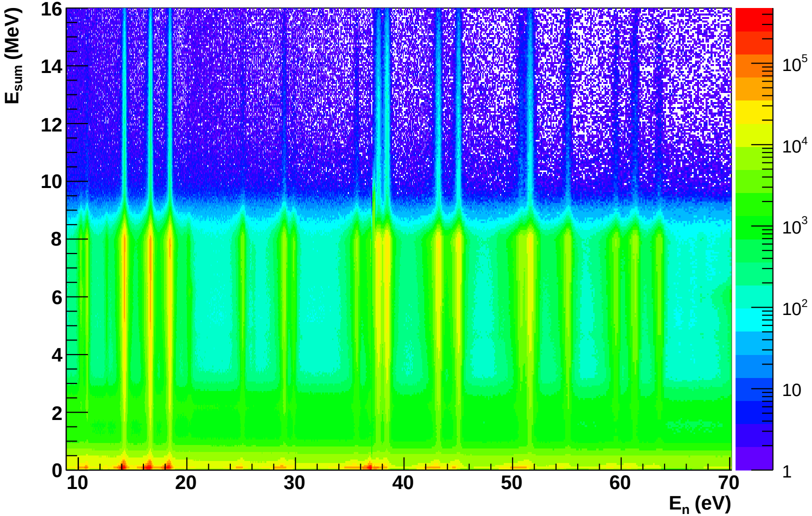


Experimental data reduction

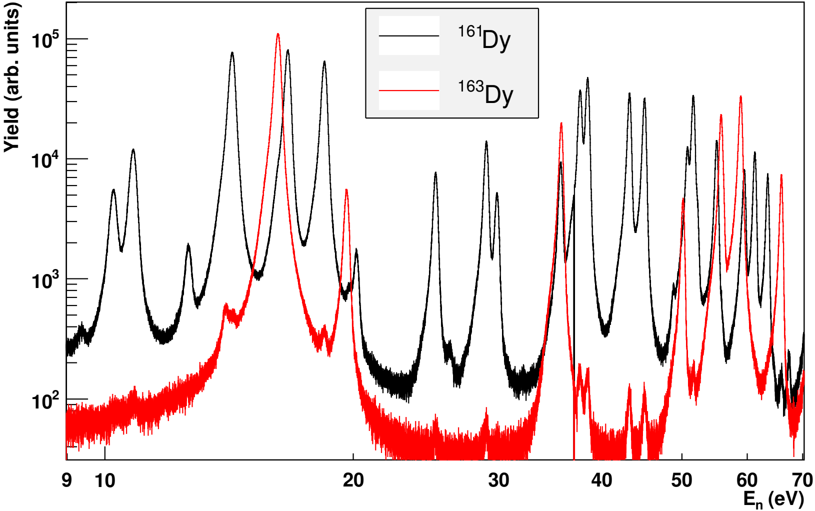
- Signals from BaF_2 crystals falling in preset time window form cascade.
- Signals in adjacent BaF_2 crystals are grouped in clusters $\rightarrow$ cluster multiplicity *m*.
- Many useful 3D histograms are created - E_n vs *m* vs E_{sum} and E_n vs *m* vs E_γ for certain E_{sum} intervals.



Take the E_n vs *m* vs E_{sum} and do sum of all *m*



Take the previous and gate on $E_{sum} \approx S_n$



Resonance spin assignment

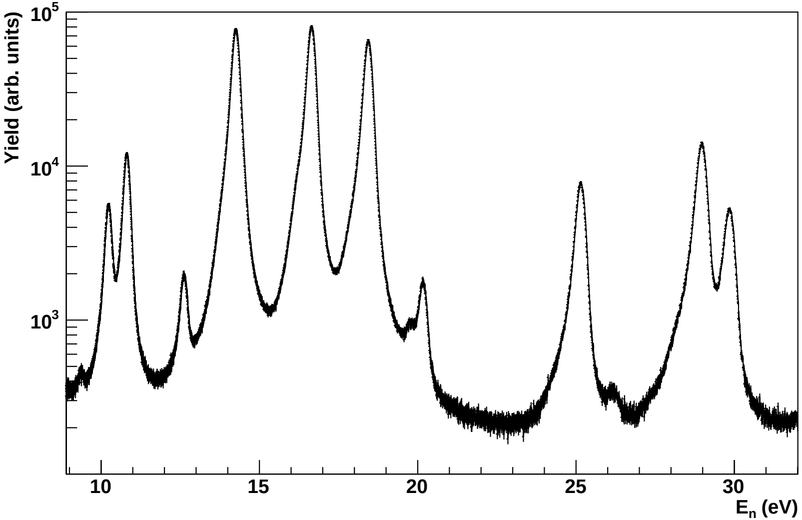
Used method by Bečvář et. al. published in NIM A 647, 73 (2011) *Optimized γ-multiplicity-based spin assignments of s-wave neutron resonances*

Yield (as a function of E_n) is assumed in form:

$$Y(E_n) = Y(E_n)_{J=I+\frac{1}{2}} + Y(E_n)_{J=I-\frac{1}{2}} + (Y(E_n)_{\mathrm{background}}),$$

where the partial yields are obtained bin-by-bin by least square fit of **multiplicity** vector $\vec{m}$ in given bin using so-called multiplicity **prototypes**.

Optimized γ-multiplicity-based spin assignment



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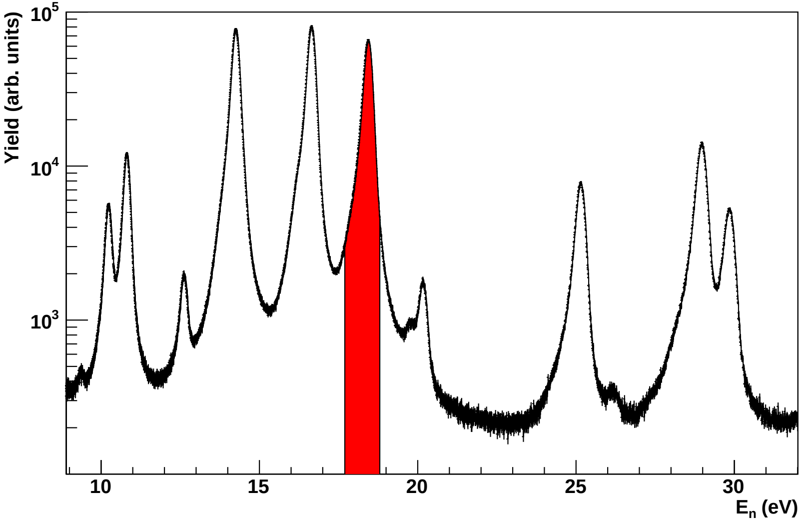

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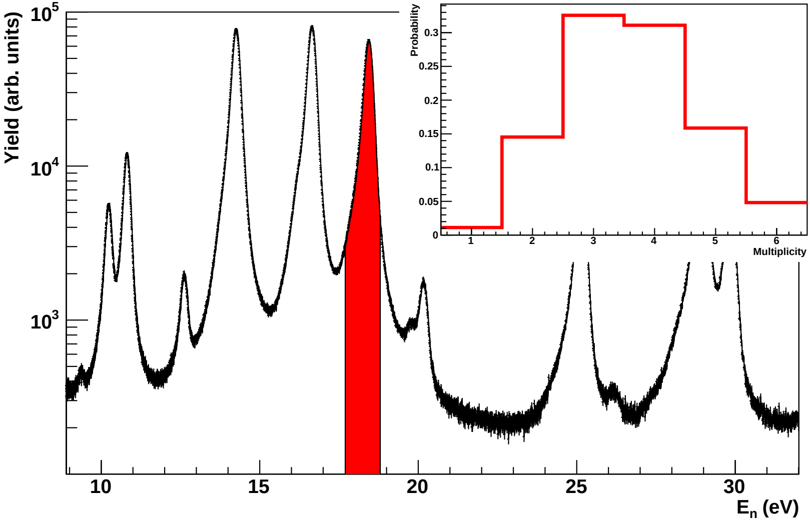

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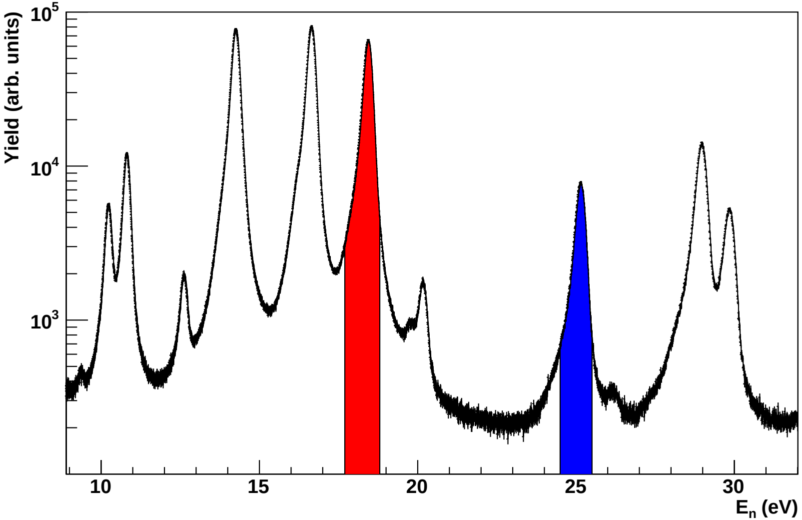

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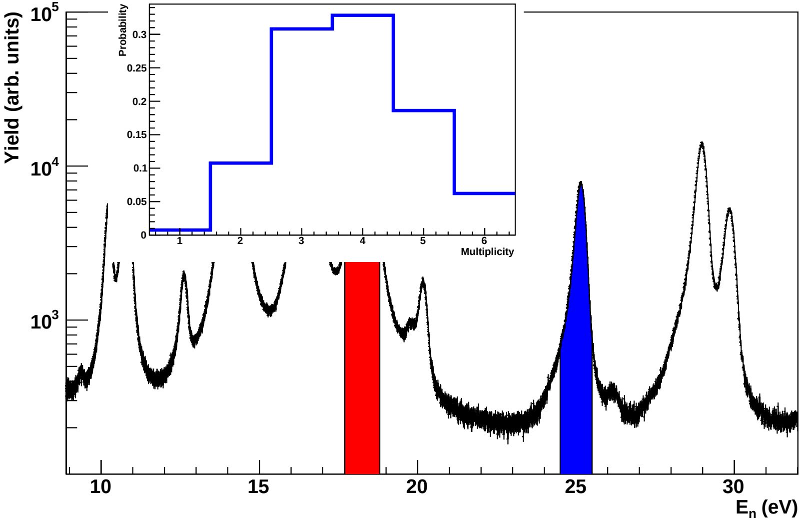

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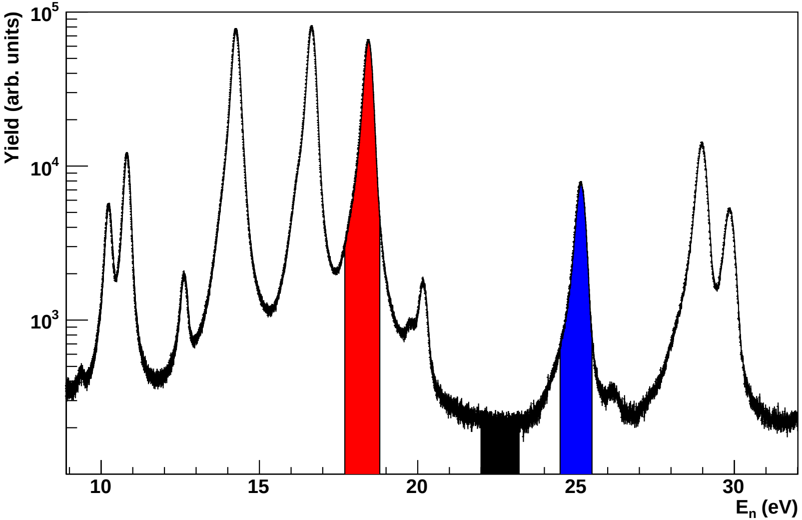

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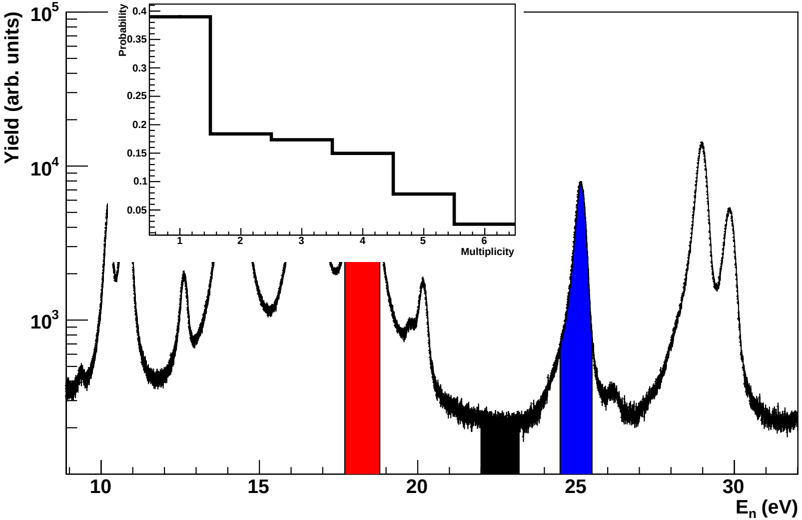
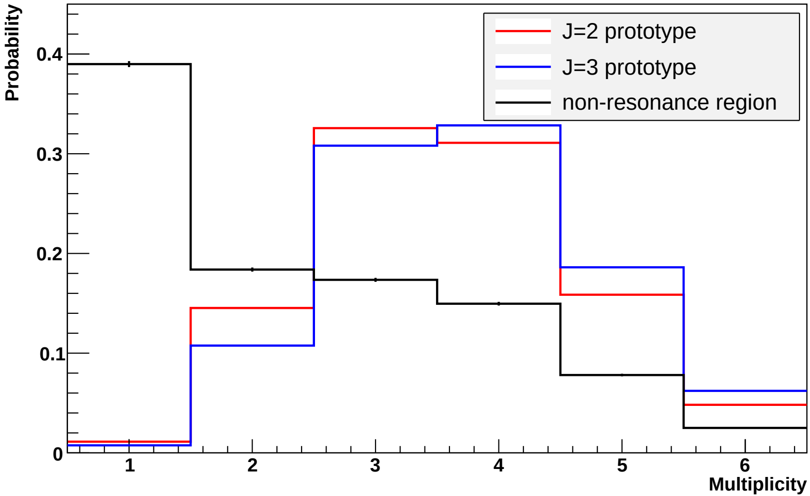
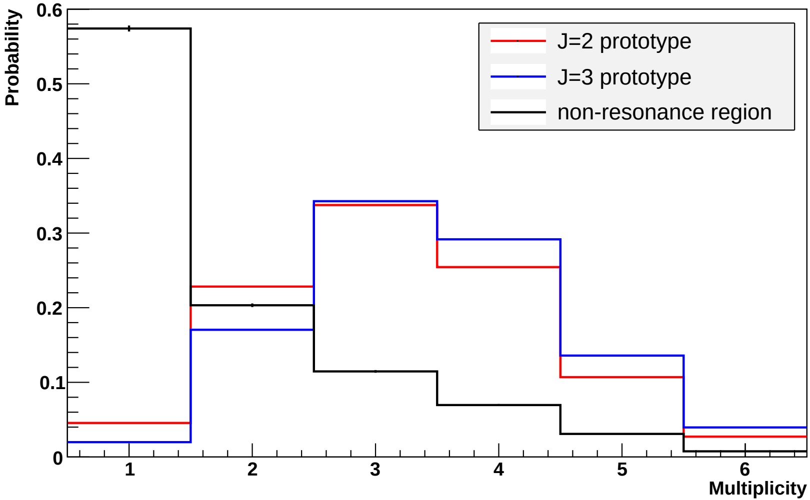


Multiplicity prototypes in ^{161}Dy



Multiplicity prototypes in ^{163}Dy

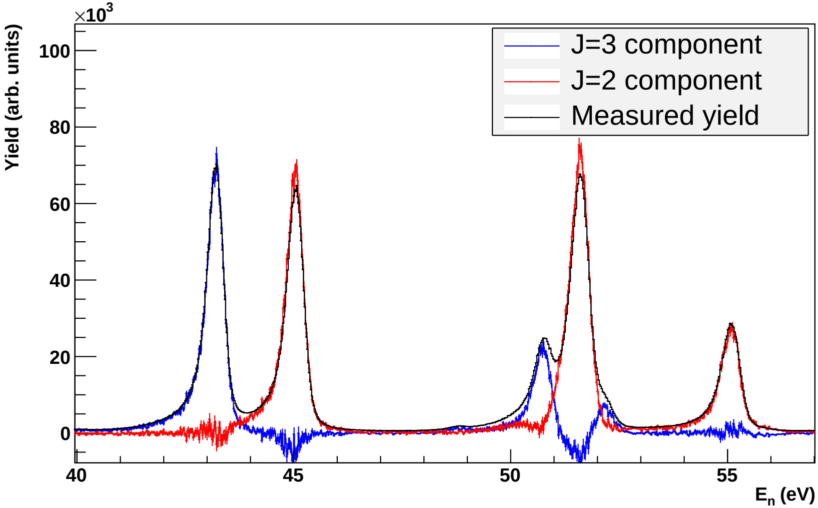


Results for resonance spins in ^{161}Dy

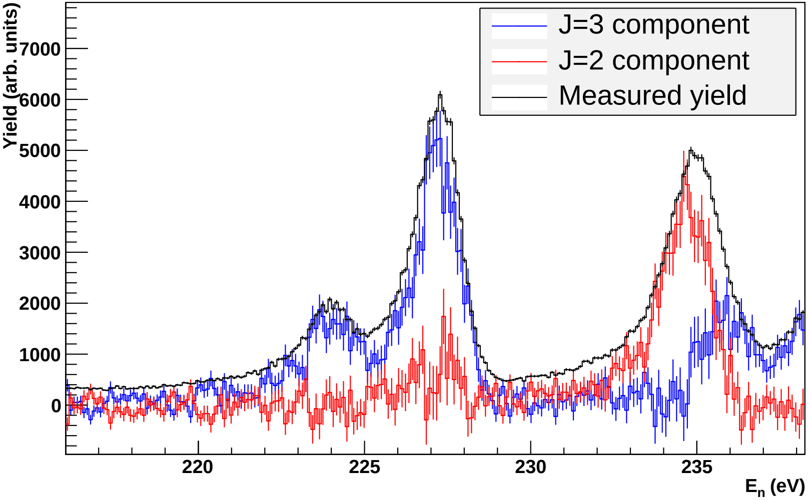
Works up to $\approx$ 440 eV.
Overall good agreement with Atlas of N. Res. by S.F.Mughabghab.
For 114 resonances in ^{161}Dy:

- 24 new assignments - from unknown J to J=2 or J=3
- 1 reassignment - 91.12 eV seems to be J=2 rather than J=3
- several possible close dublets that need futher investigation with help of DICEBOX/GEANT4/SAMMY
- testing the set within RMT prediction using Δ_3 statistics confirm complete set below 125 eV that is 47 resonances
- $D^{\mathrm{ours}} = 2.65(8)$ eV compared to $D^{\mathrm{Mugh}} = 2.14(15)$ eV and $D^{\mathrm{Oslo}} = 2.4(2)$ eV

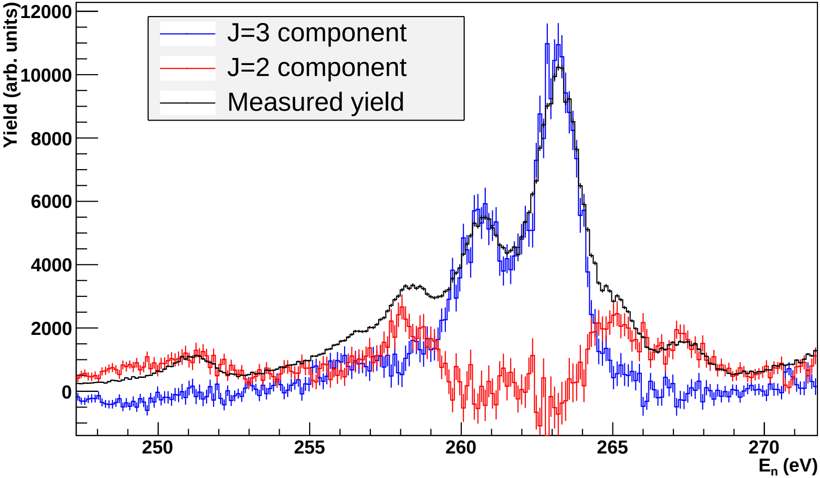
Confirmation of spin on a few non-prototype resonances



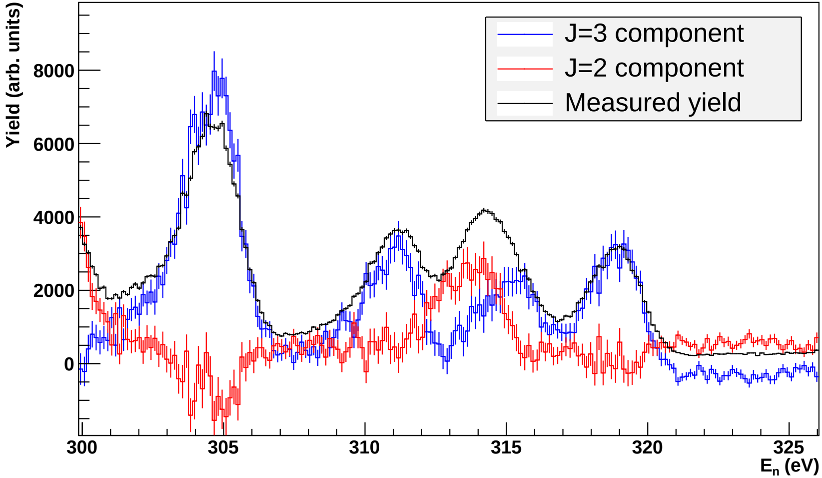
224.43 eV resonance assigned the spin of J=3



256.81 eV and 267.81 eV resonances are J=3,2 respectively



314.78 eV and 315.76 eV resonances are J=2,3 respectively

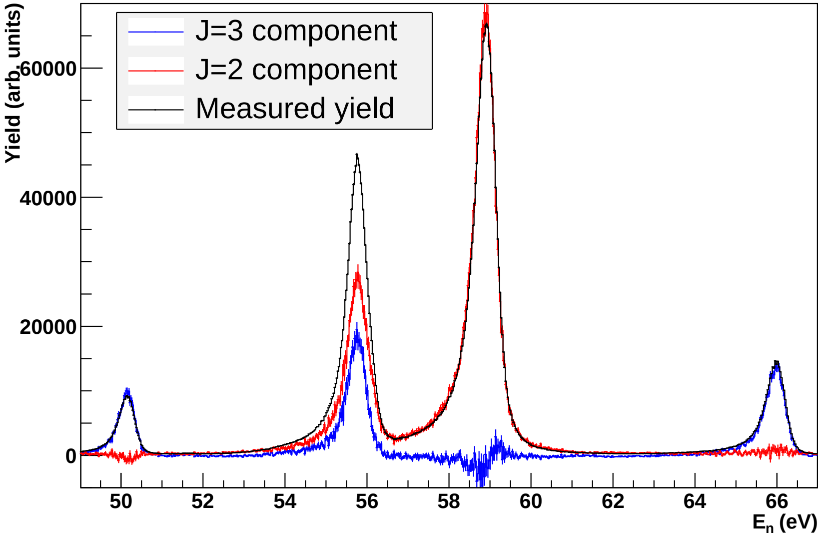


Results for resonance spins in ^{163}Dy

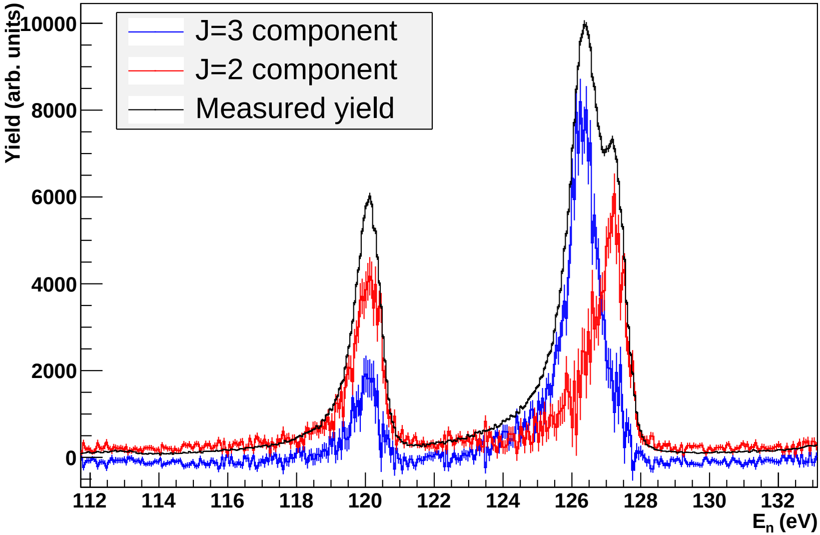
Works up to $\approx$ 950 eV.
Overall good agreement with Atlas of N. Res. by S.F.Mughabghab.
For 102 resonances in ^{163}Dy:

- 5 new assignments - from unknown J to J=2 or J=3
- 6 reassignments - from J=2 to J=3 and vice versa
- several possible close dublets that need futher investigation with help of DICEBOX/GEANT4/SAMMY
- several weak resonances remain inconclusive due to low statistics
- testing the set within RMT prediction using Δ_3 statistics raises questions rather than giving answers
- threshold sensitivity test for non-observation of weak resonances will be carried out

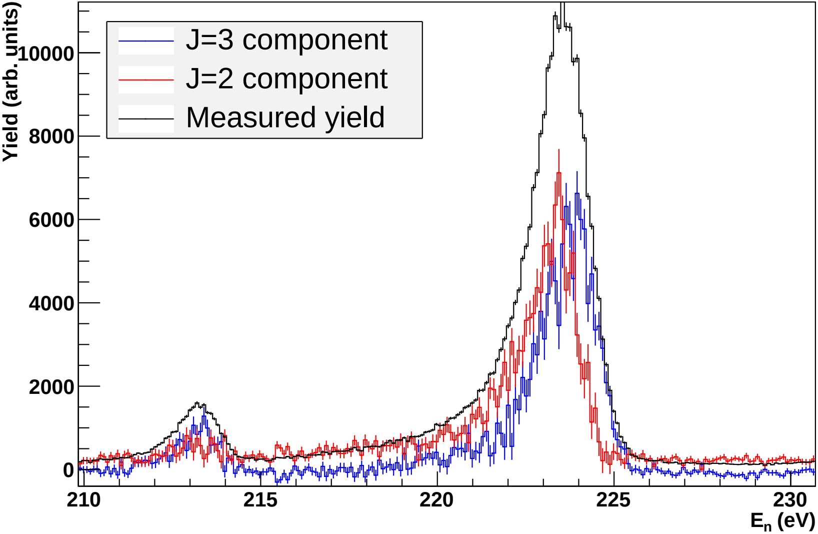
Confirmation of spin on a few non-prototype resonances



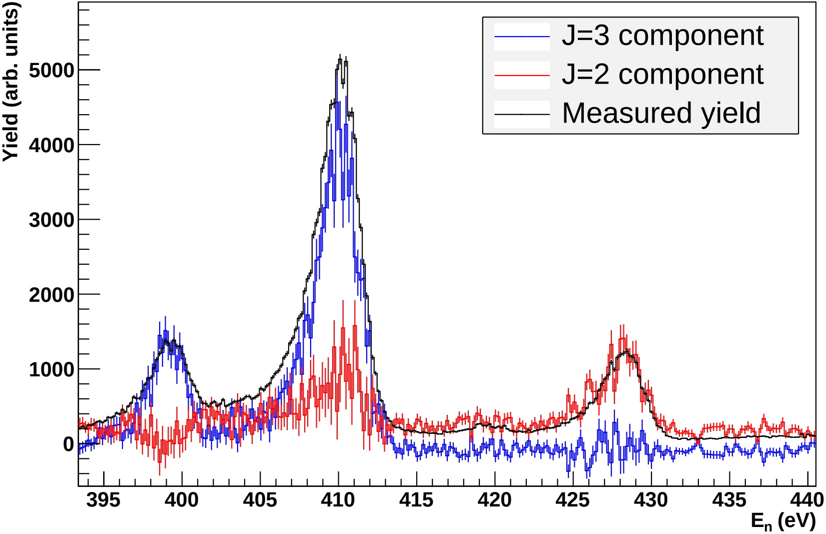
127.46 eV is J=2 not J=3, possible dublet at ≈ 120.33 eV



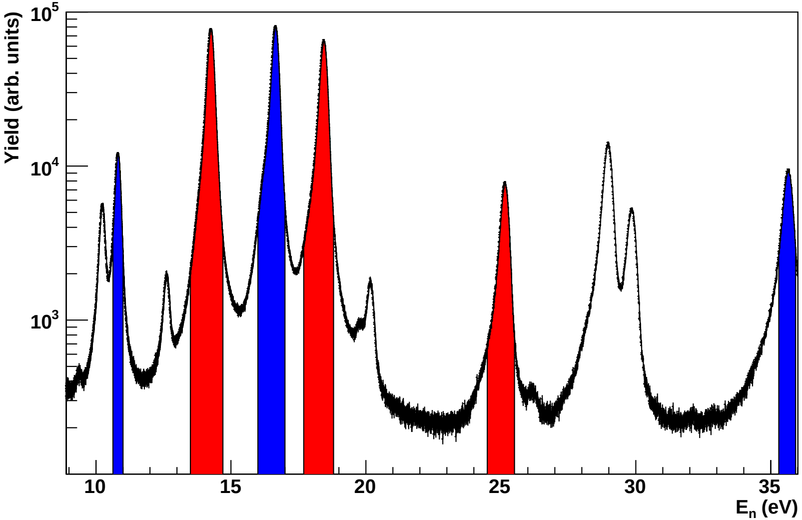
224.15 eV is not single J=2 resonance but dublet



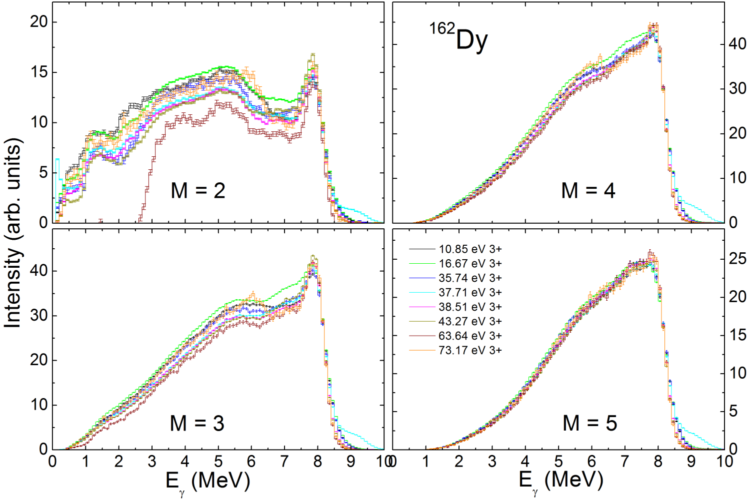
411.08 eV is J=3 rather than J=2



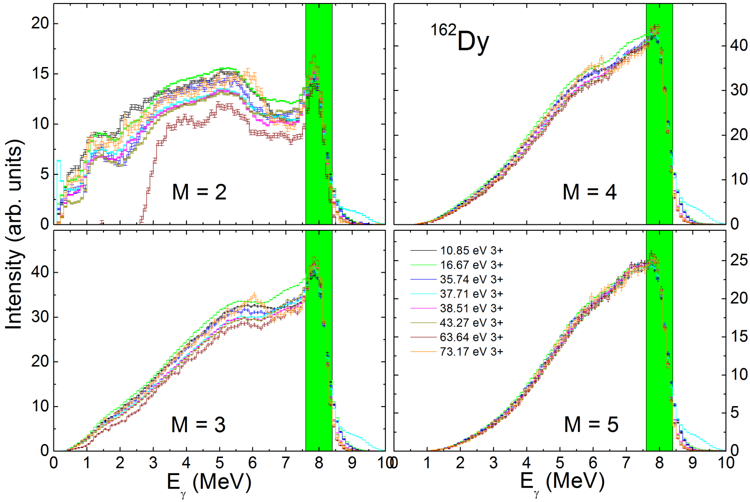
Strong resonances with firm spin assignment



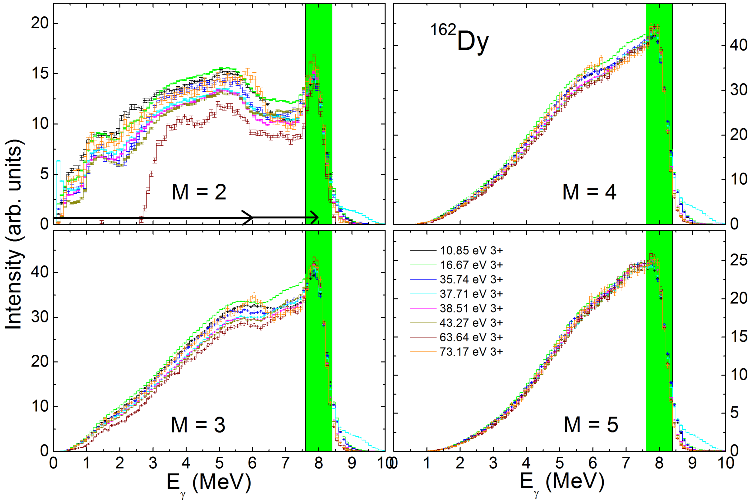
Spectra of energy sums



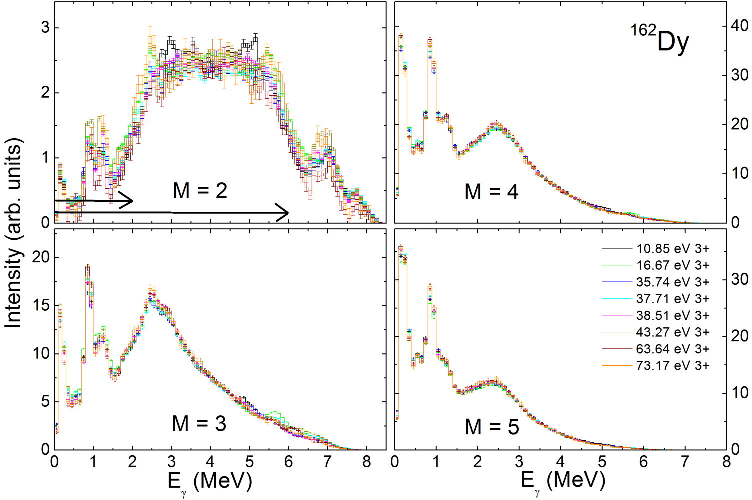
Take only the fully detected cascades



Take the energies forming the cascades

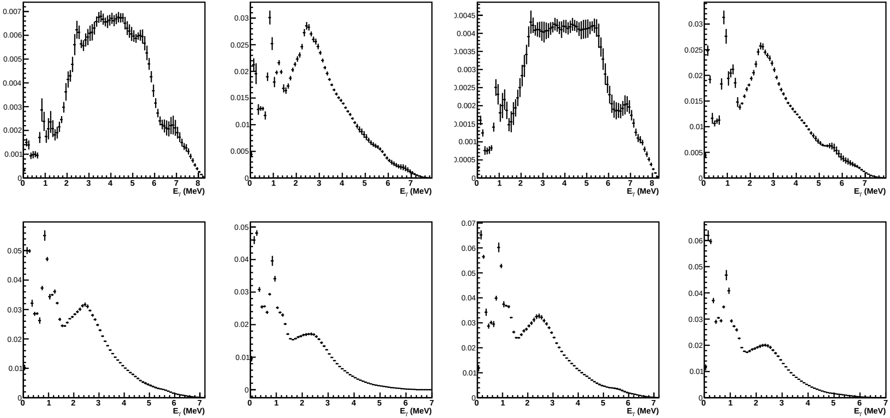


Experimental multi-step γ cascades (MSC) spectra



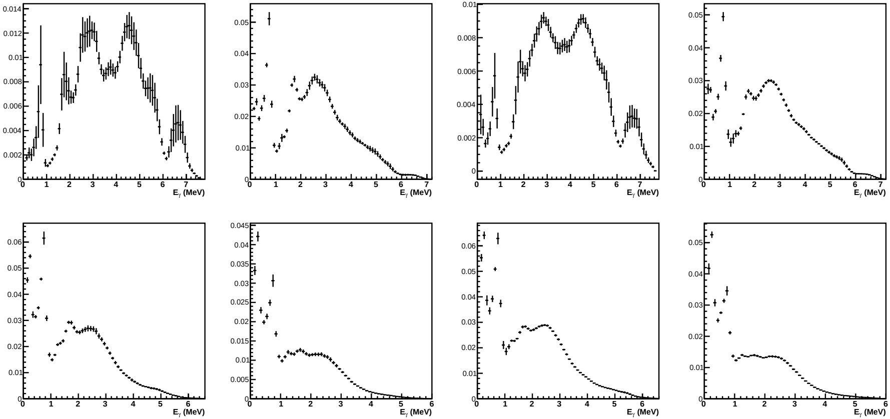
Experimental MSC spectra for ^{162}Dy

Mean spectra from 24 and 21 resonances of spin 2 and 3.



Experimental MSC spectra for ^{164}Dy

Mean spectra from 13 and 25 resonances of spin 2 and 3.



Monte Carlo generation of MSC spectra

Cascades from DICEBOX simulation

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

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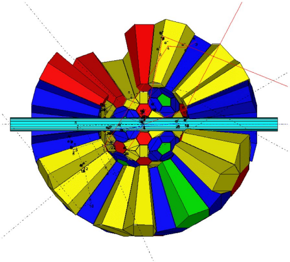
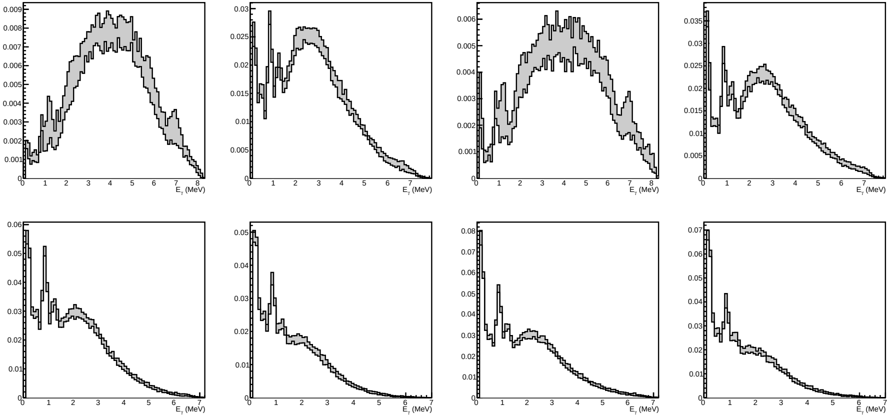
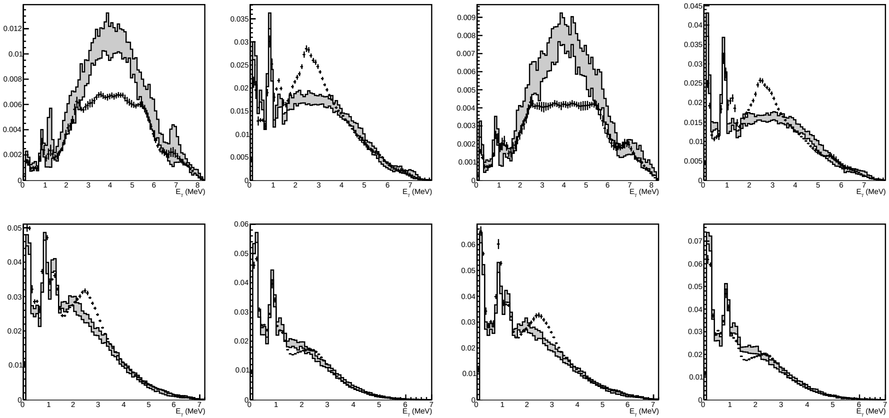
are fed to GEANT4 detector response of DANCE



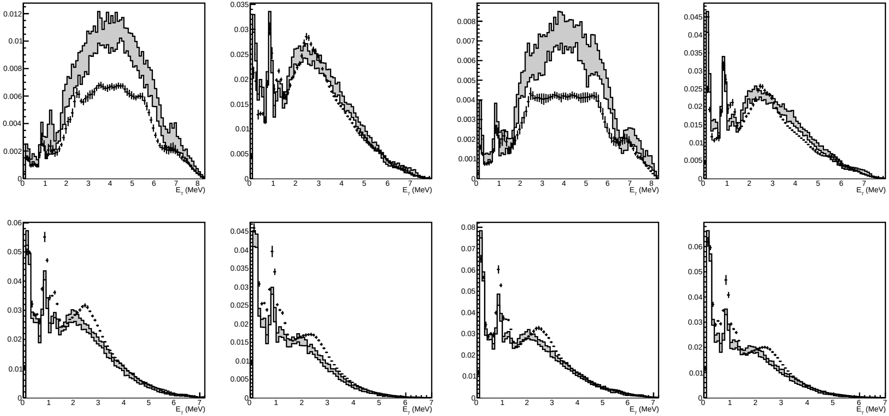
Simulated MSC spectra



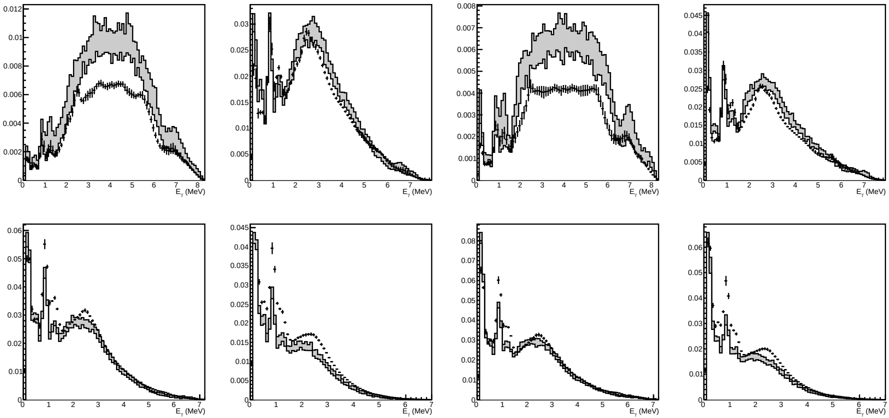
SLO in E1 and Spin-Flip in M1



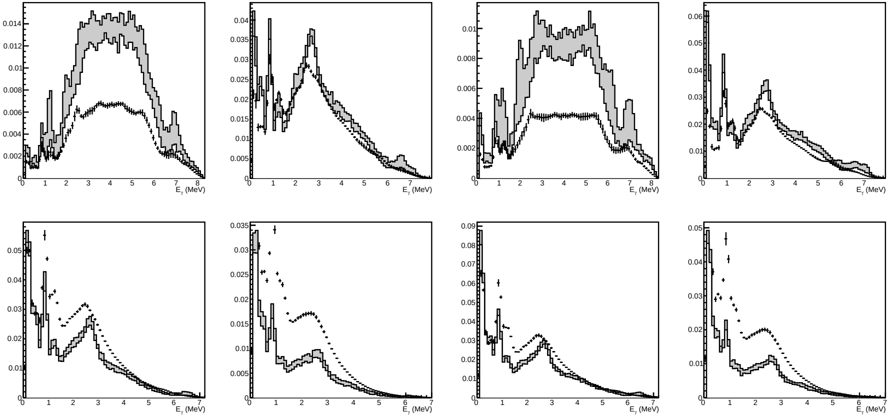
KMF in E1 and Spin-Flip in M1



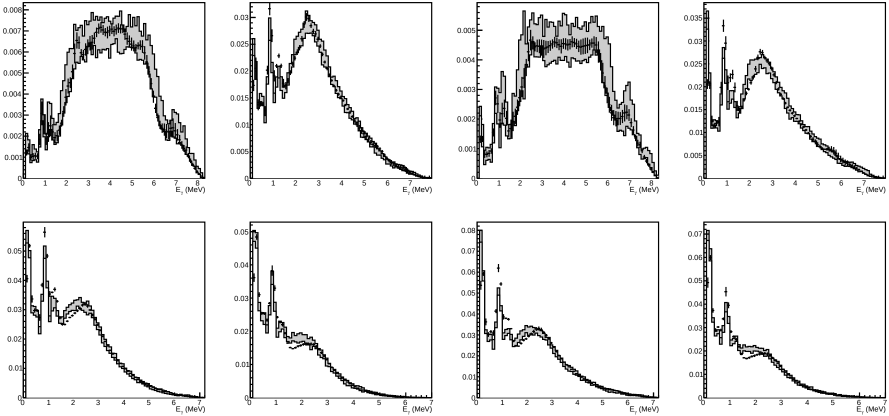
Best PSFs from ^{158}Gd at DANCE



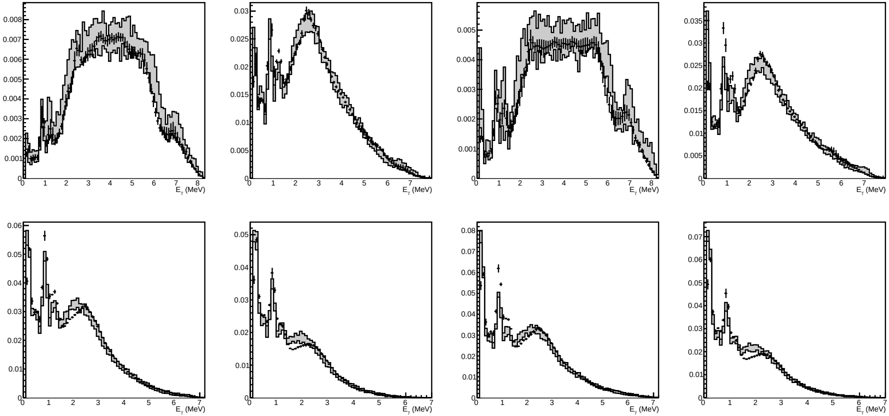
PSFs from M. Guttormsen et al., PRC68, 2003



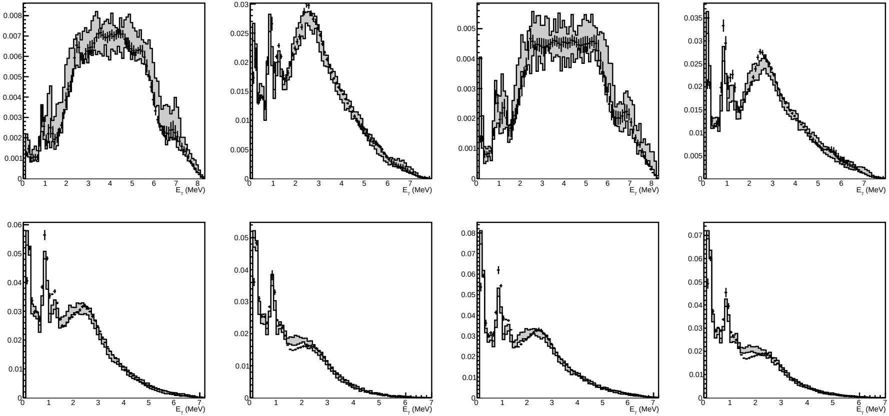
KMF in E1, SM and constant term in M1 adjusted



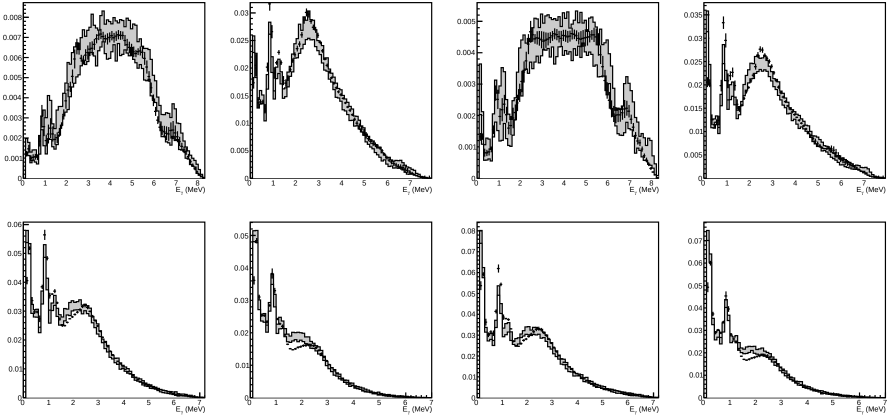
MGLO (k=2) in E1, SM and constant term in M1 adjusted



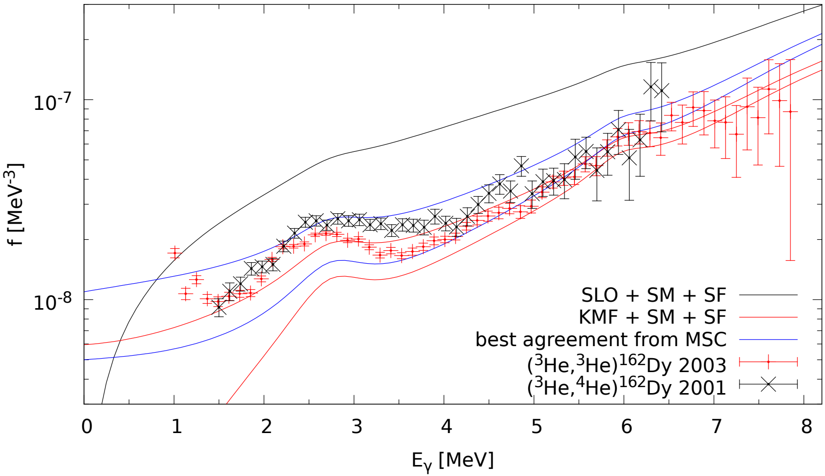
MGLO (k=2) in E1, SM and constant term in M1 adjusted



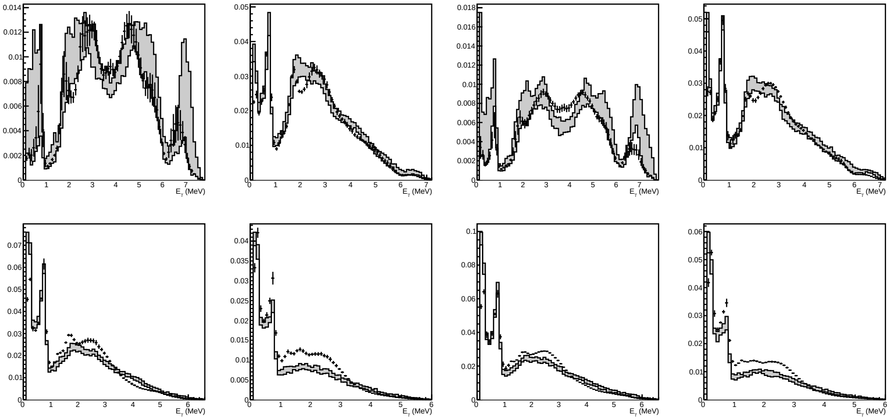
MGLO (k=3) in E1, SM and constant term in M1 adjusted



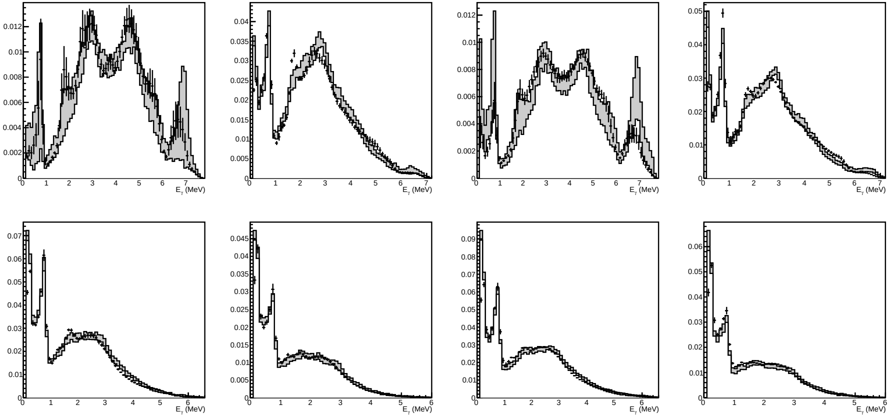
Photon Strength Functions in ^{162}Dy



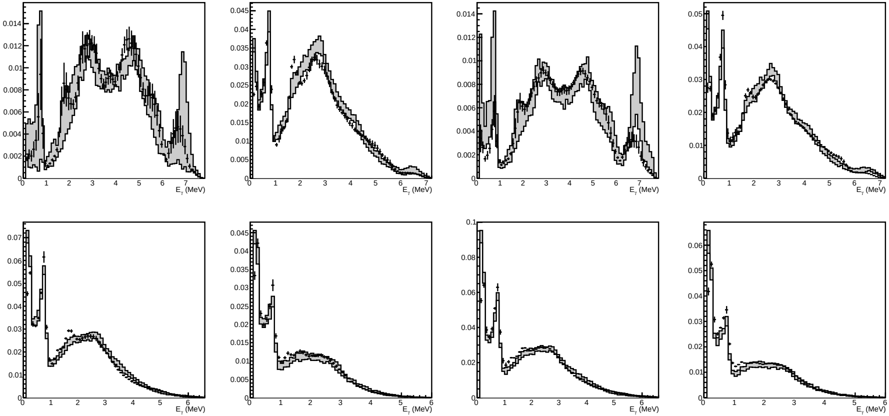
PSFs from H.T. Nyhus et al., PRC85, 2012



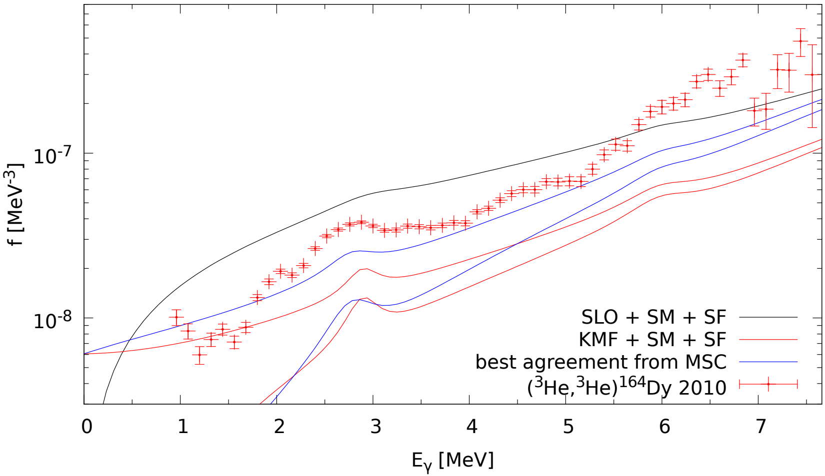
KMF in E1, SM and constant term in M1 adjusted



MGLO (k=3) in E1, SM and constant term in M1 adjusted



Photon Strength Functions in ^{164}Dy



Conclusions

- MSC spectra for both nuclei are incredibly sensitive to M1/E1 balance at "low" E_γ
- Best agreement for ^{162}Dy - E1 in form of MGLO ($k_0 = 2$)
  - $E_{SM} = 2.8$ MeV in good agreement with Oslo $\approx 2.7(1)$ MeV
  - $\sum B(M1) \uparrow = 2.7(4)\mu_N^2$ vs Oslo $6.8(8)\mu_N^2$
  - constant term $f_{M1} = 2.5(5) \times 10^{-9}$MeV^{-3}
- Best agreement **so far** for ^{164}Dy - E1 MGLO ($k_0 = 3$)
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  - $\sum B(M1) \uparrow = 1.4(3)\mu_N^2$ vs Oslo $5.4(1.0)\mu_N^2$
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