Scissors mode in ^{162,164}Dy from (n,γ) reactions

DANCE collaboration

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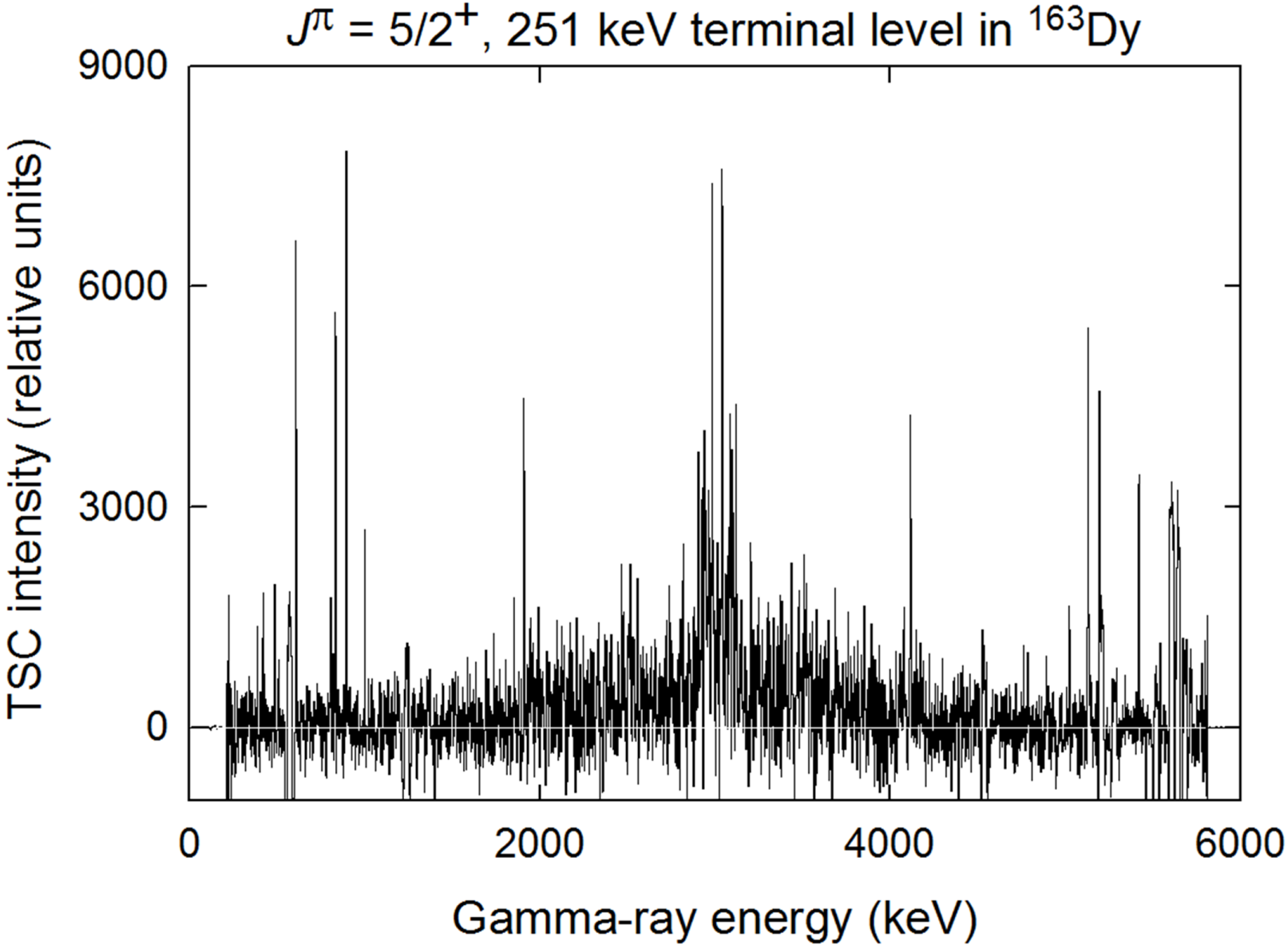
for CGS15 Dresden

Motivation

Results of TSC experiment 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
- follows Brink hypothesis

Motivation


$J^{\pi} = 5/2^{+}$, 251 keV terminal level in ^{163}Dy
TSC intensity (relative units)
9000
6000
3000
0
0
2000
4000
6000
Gamma-ray energy (keV)

Motivation

What happens with SM at higher excitation energies?
How is the SM fragmented?
Are results from resonance and thermal capture consistent?
How do we compare to other results ((γ,γ'),Oslo)?

To answer these questions one needs:

- suitable pair of nuclei $\surd$ ^{161}Dy$(n_{th},\gamma)^{162}$Dy
- suitable aparatus $\surd$ EXOGAM at ILL and DANCE at LANL
- beam time $\surd$

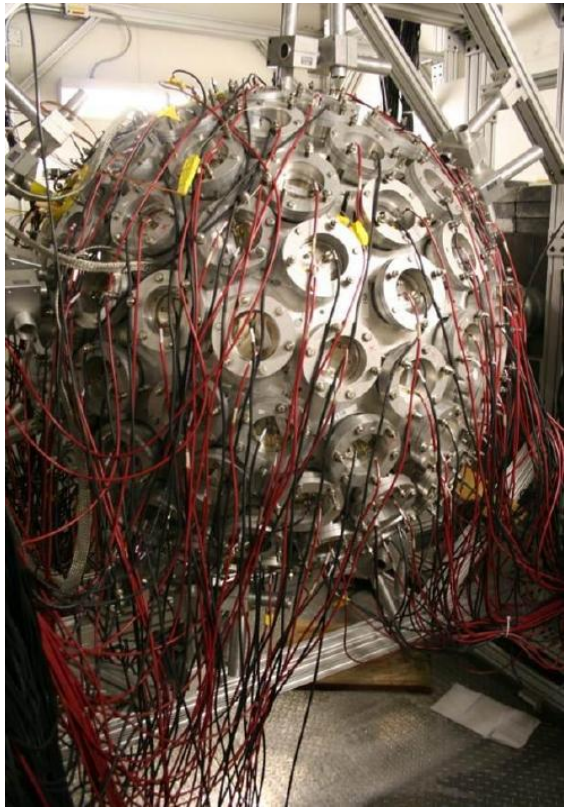
Why ^{161}Dy(n,γ)^{162}Dy?

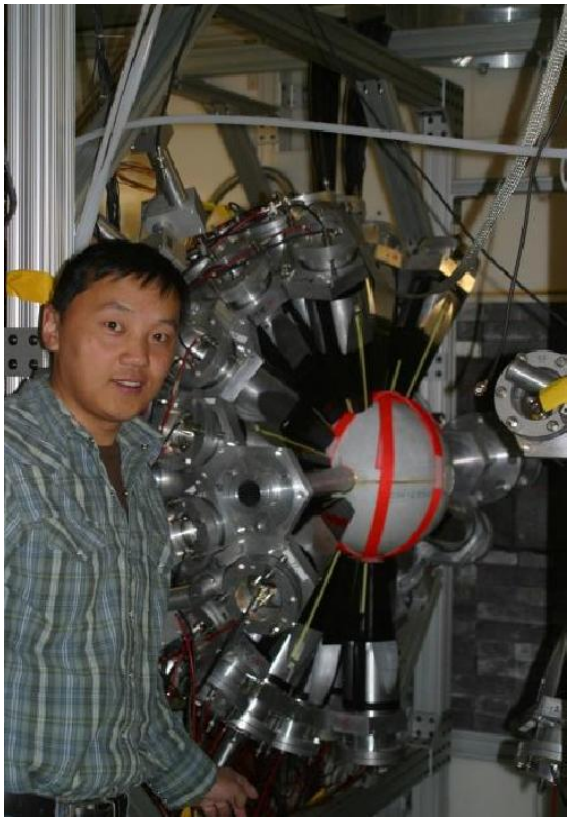
- stable target with reasonable σ and stable well-deformed product
- $S_n = 8.197$ MeV - not that lower than $3 \times E_{SM}$
- suitable spins and parities of levels involved in decay:
  - capturing states $J^\pi = 2, 3^+$
  - low lying states of both parities and spins from 0 to 6
- available target enriched to $> 90\%$

$\Rightarrow$ possible three step cascades M1-M1-M1 (and other combinations)
$\Rightarrow$ possible two step cascades of all combinations

^{161}Dy(n_{res}, γ) and ^{163}Dy(n_{res}, γ) at DANCE

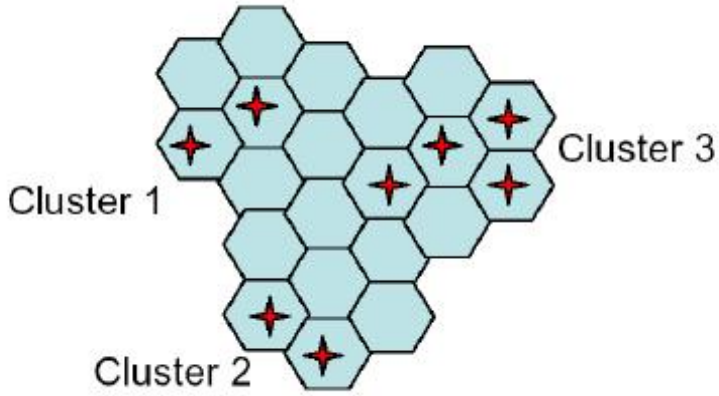
Capture reactions were measured for neutron energies from $\approx$ eV to $\approx$ MeV using **D**etector for **A**dvanced **N**eutron **C**apture **E**xperiments in 2013 with aim to perform resonance spin assignment and
study of the photon strength functions and nuclear level density models.



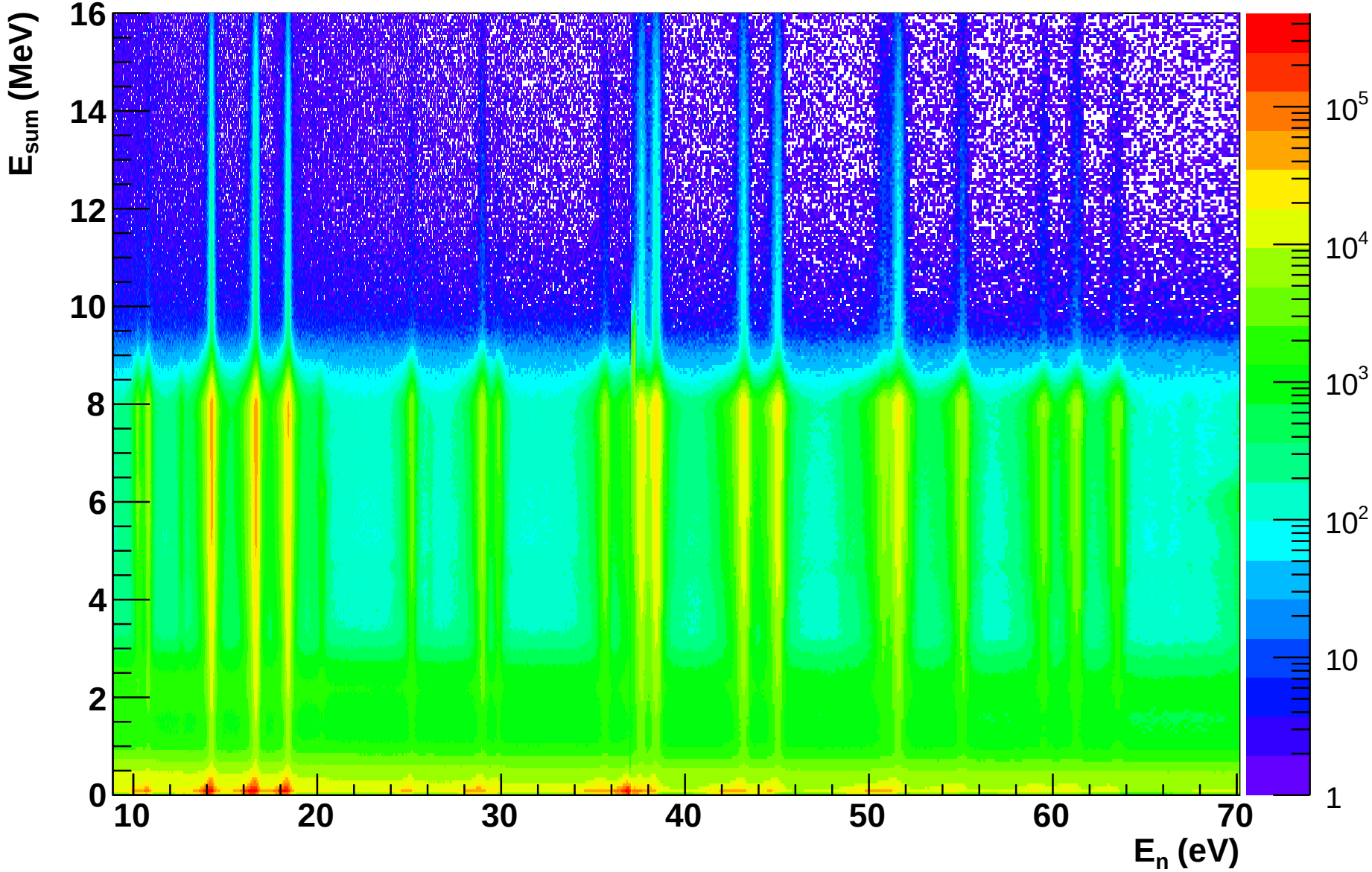


Experimental information at DANCE

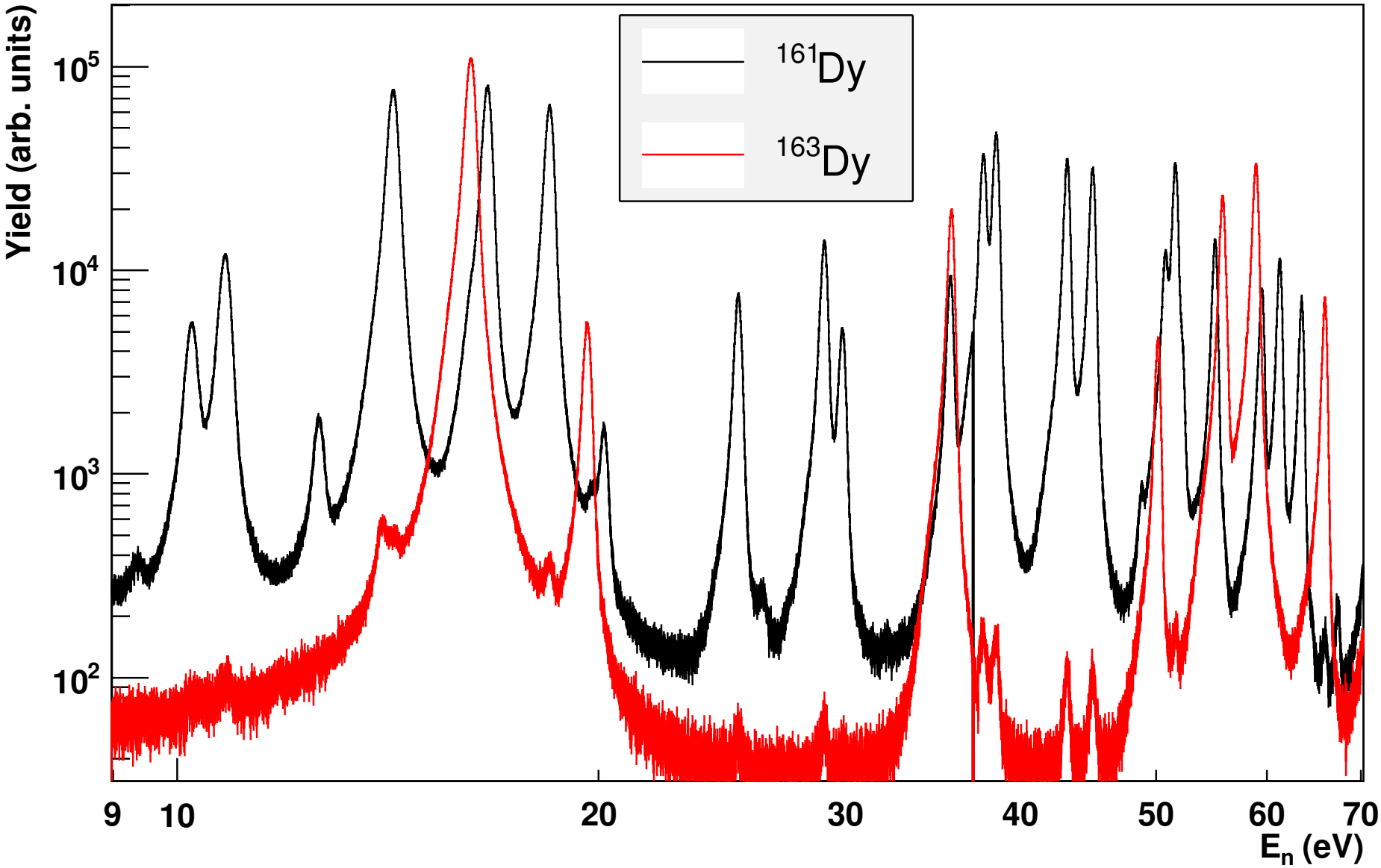
- Signals from BaF_2 crystals falling in preset time window form cascade.
- Signals in adjacent BaF_2 crystals are grouped in clusters $\rightarrow$ cluster multiplicity m.
- Many useful 3D histograms are created - E_n vs m vs E_{sum} and E_n vs m vs E_γ for certain E_{sum} intervals.



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

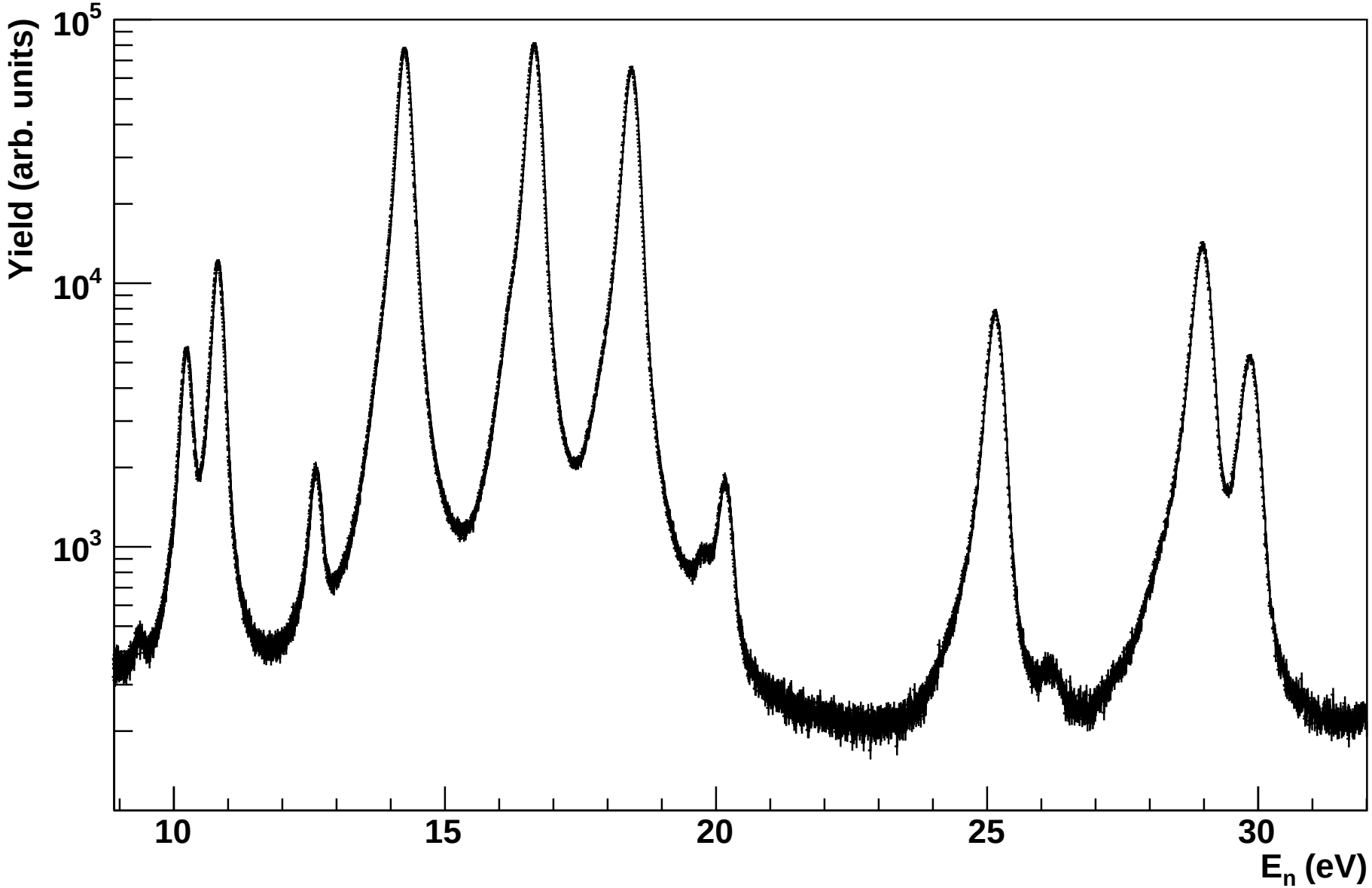
Used method by Bečvář et. al. published in NIM A 647, 73 (2011)
Optimized γ-multiplicity-based spin assignments of s-wave neutron resonances

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

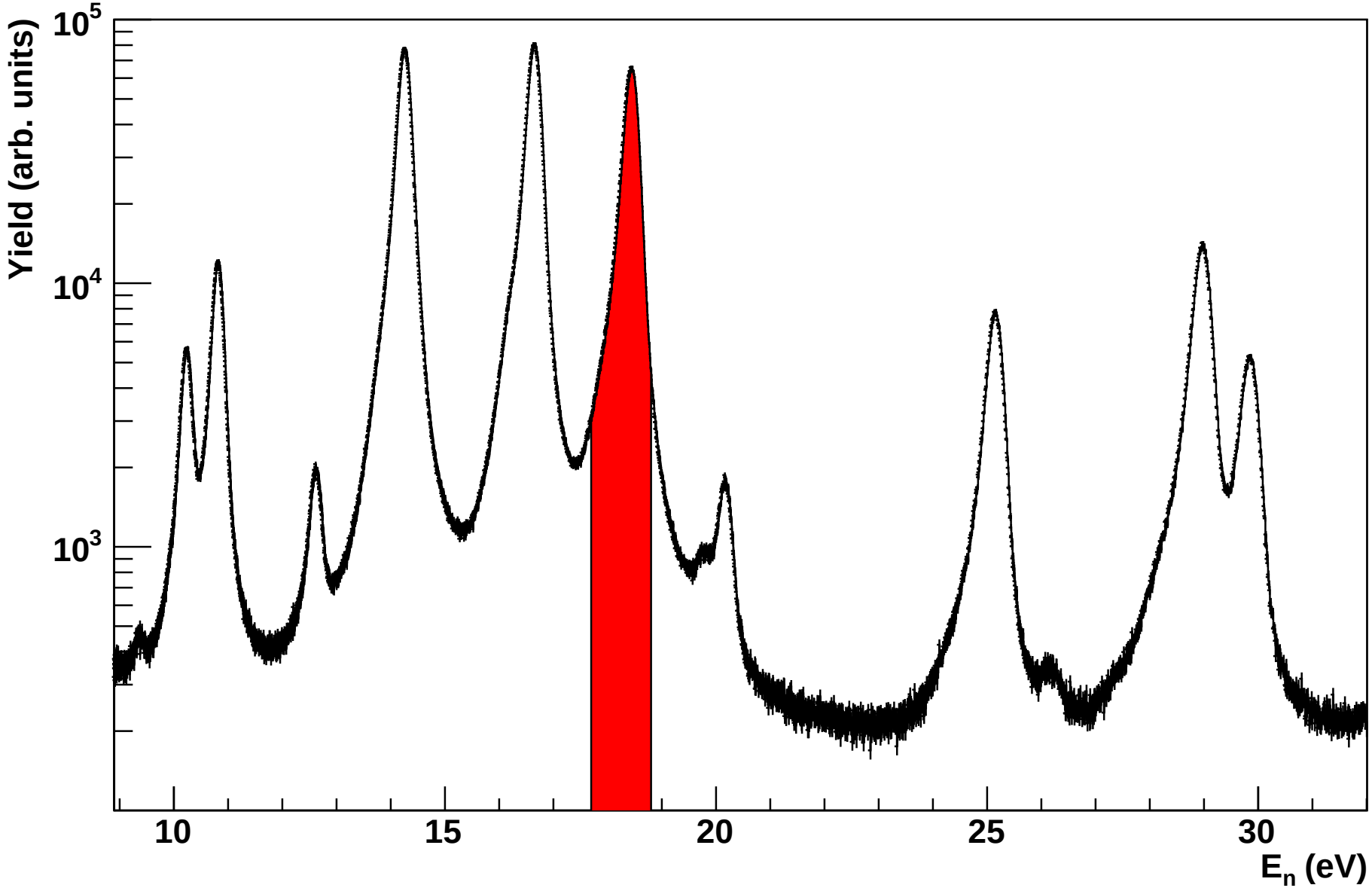
$$Y(E_n) = Y(E_n)_{J=I+\frac{1}{2}} + Y(E_n)_{J=I-\frac{1}{2}} + (Y(E_n)_{\text{background}}),$$

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**.

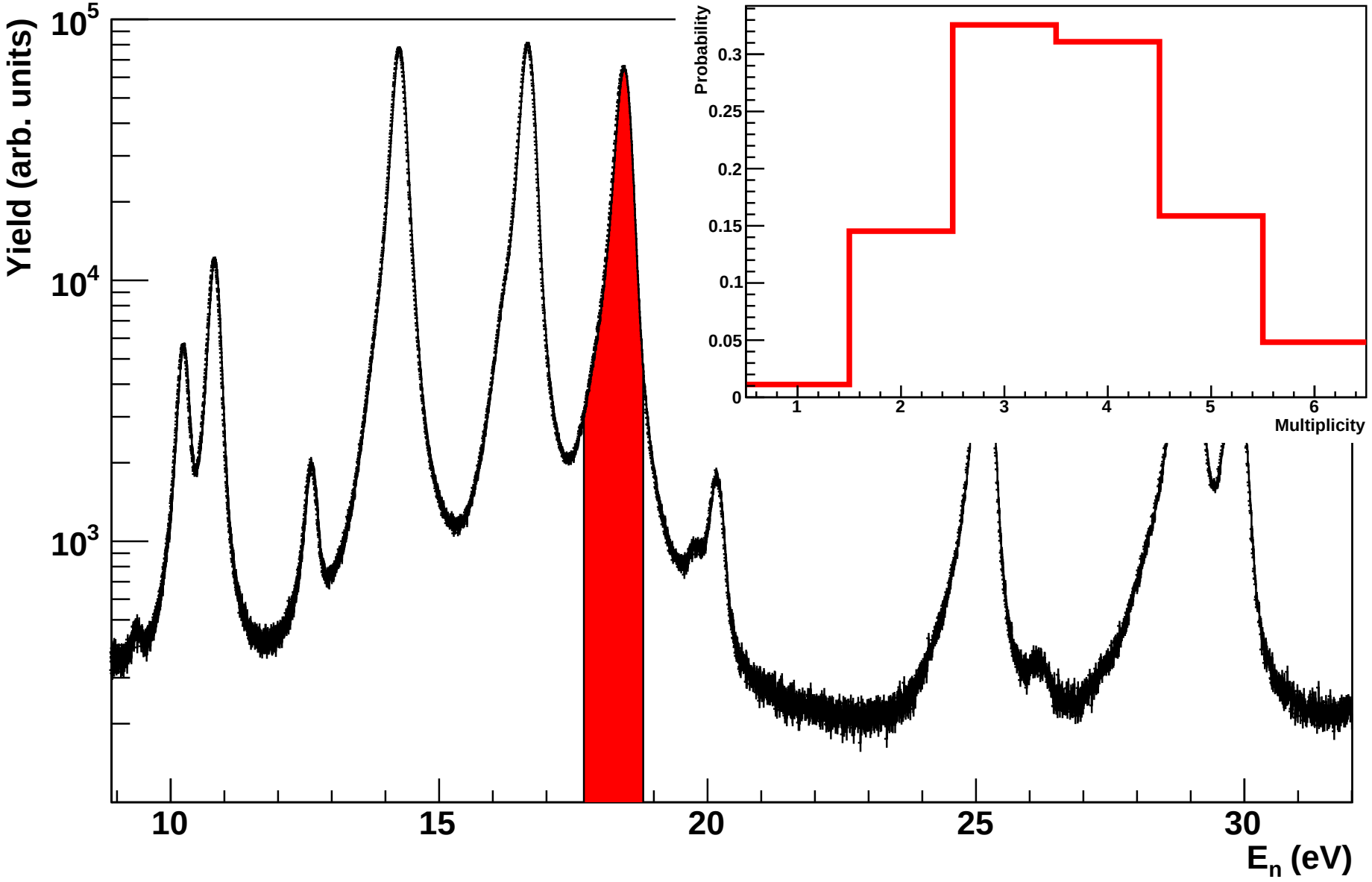
Resonance spin assignment



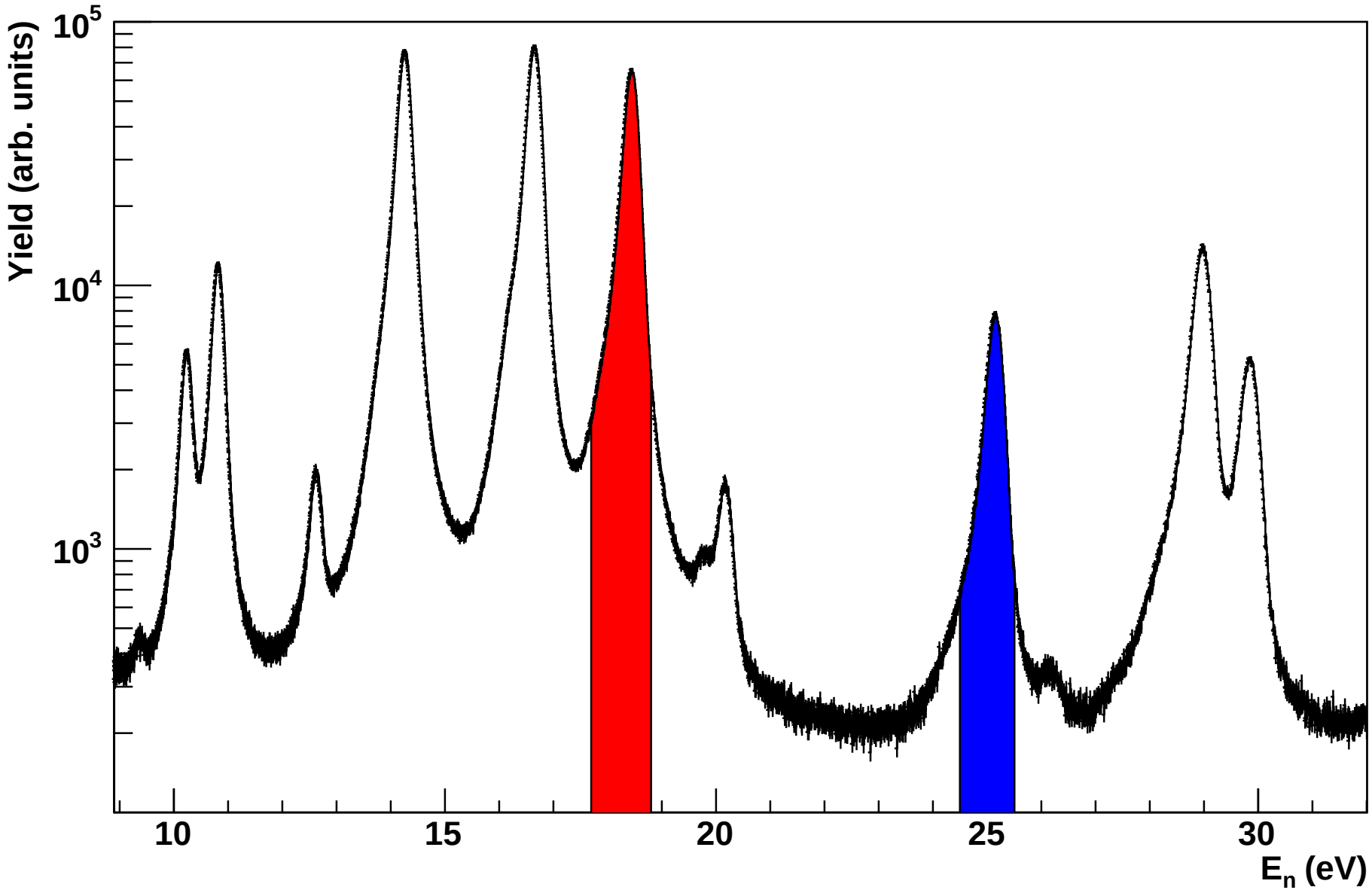
Resonance spin assignment



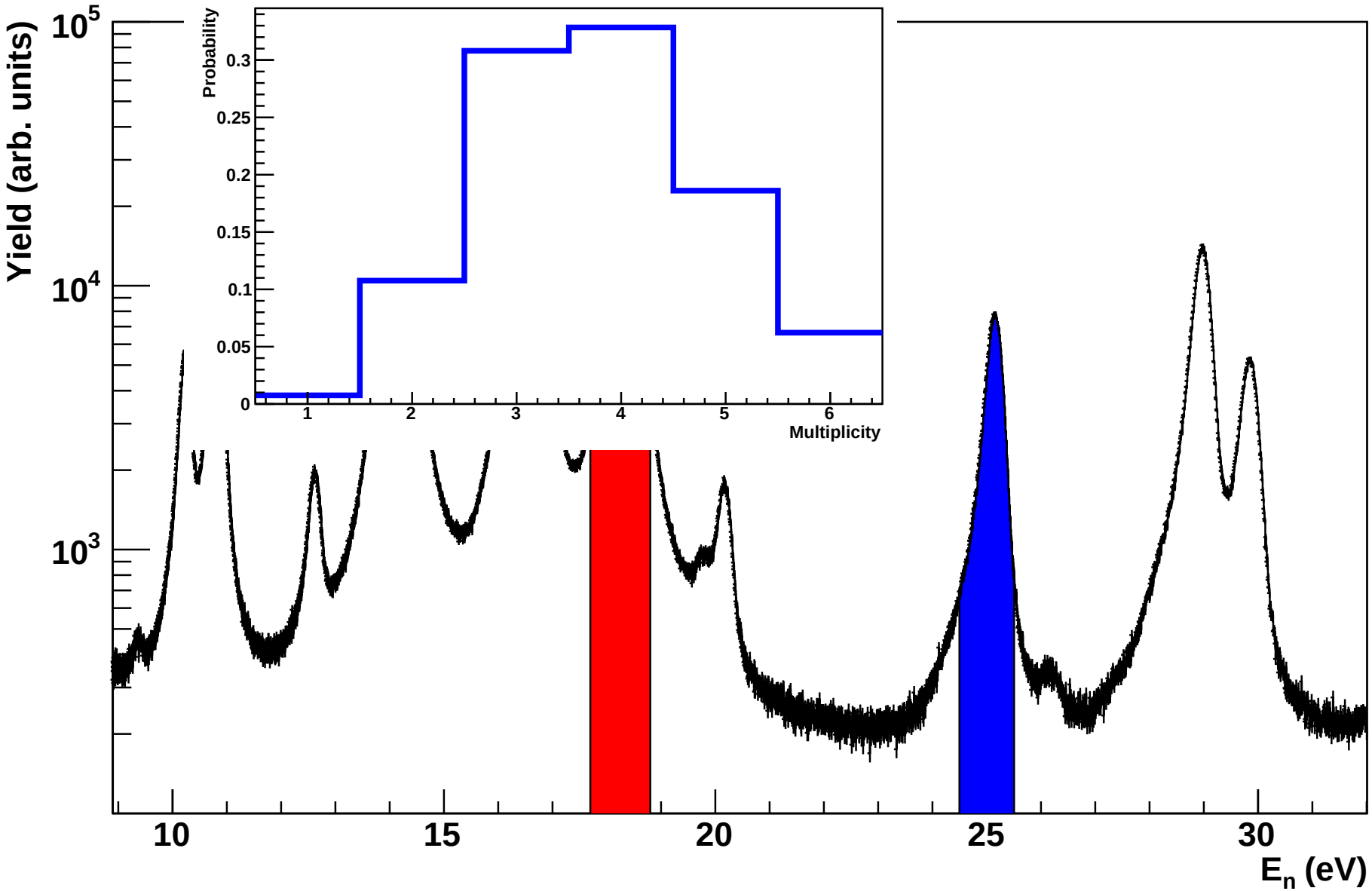
Resonance spin assignment



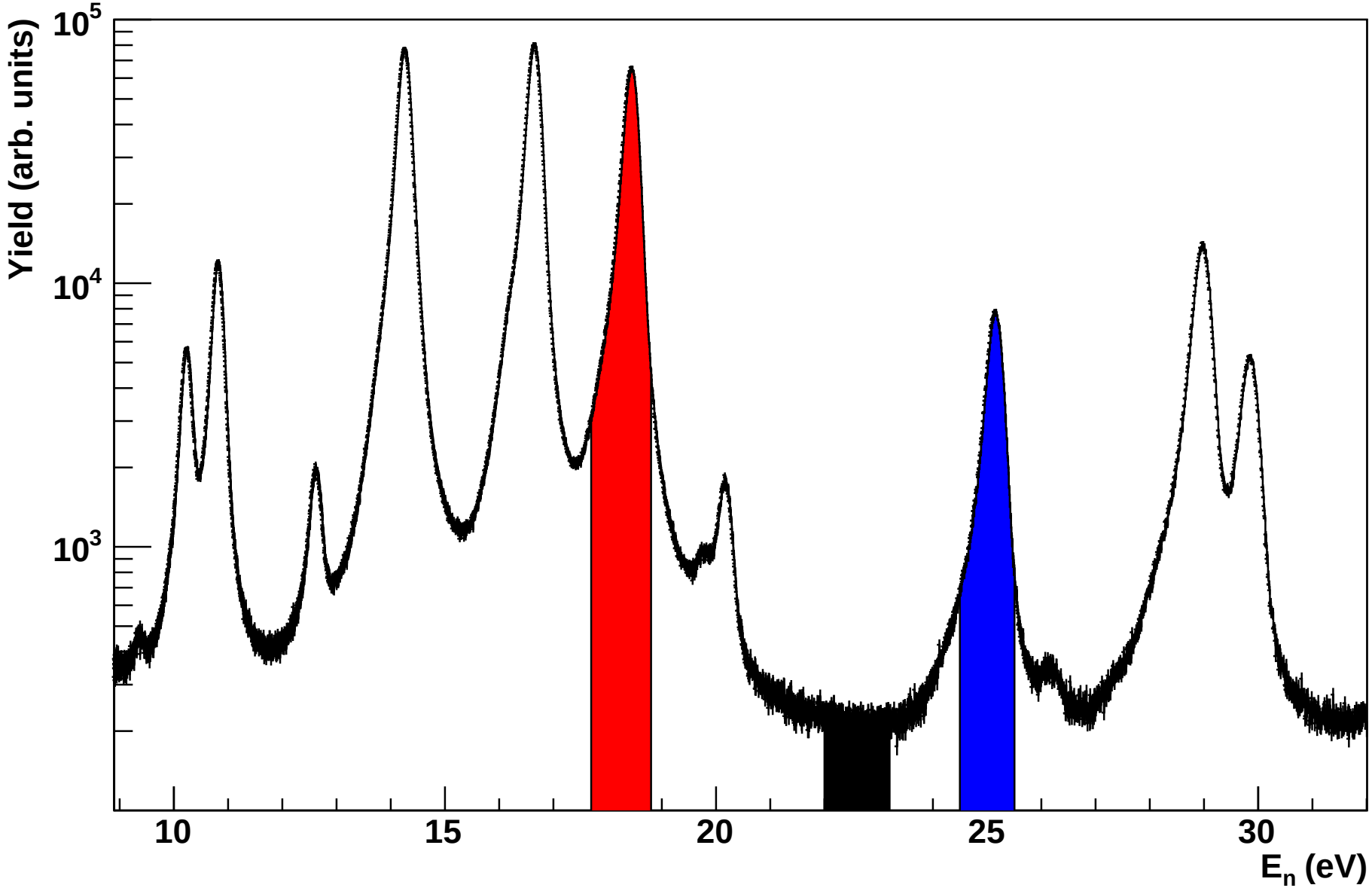
Resonance spin assignment



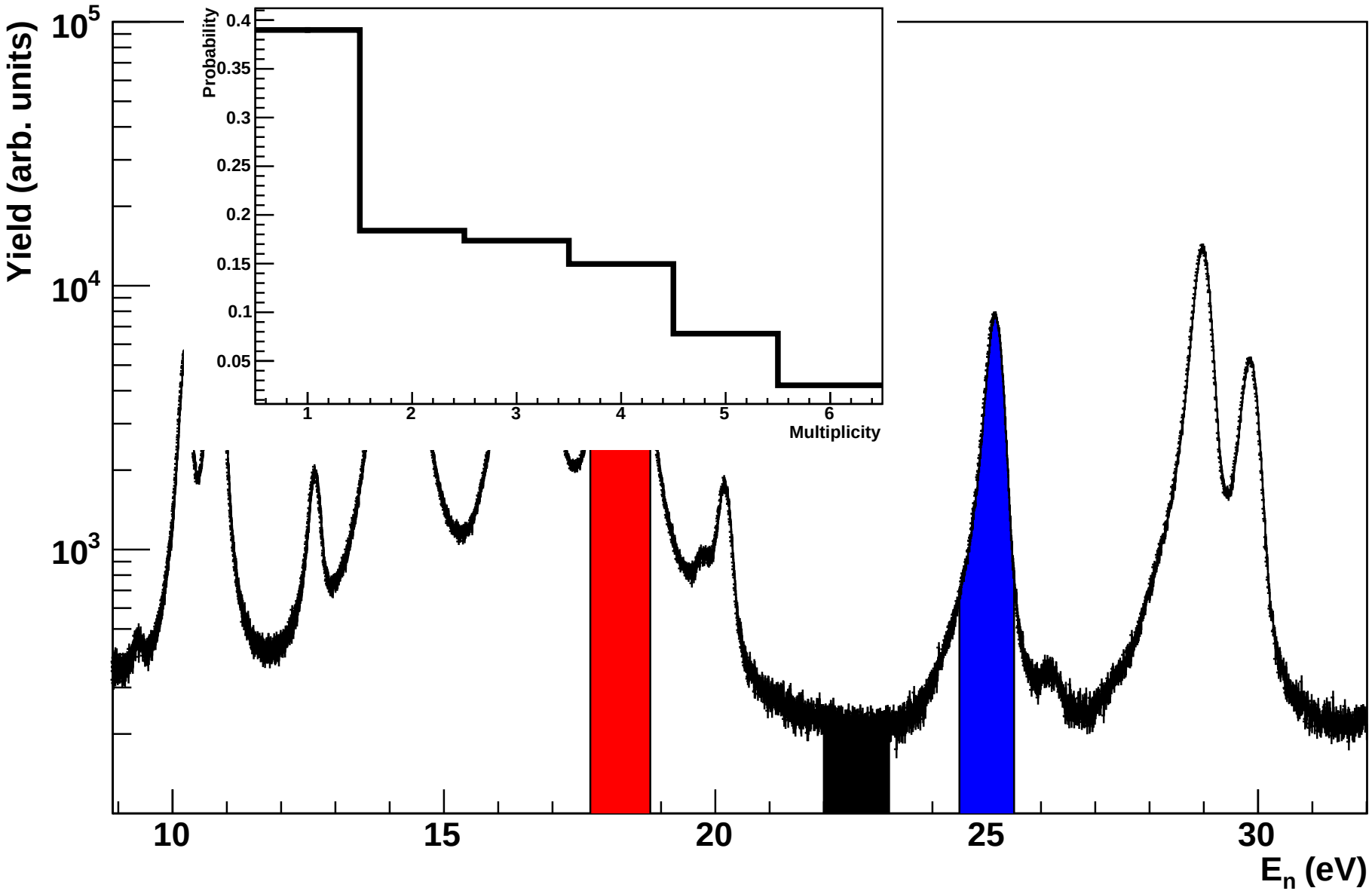
Resonance spin assignment

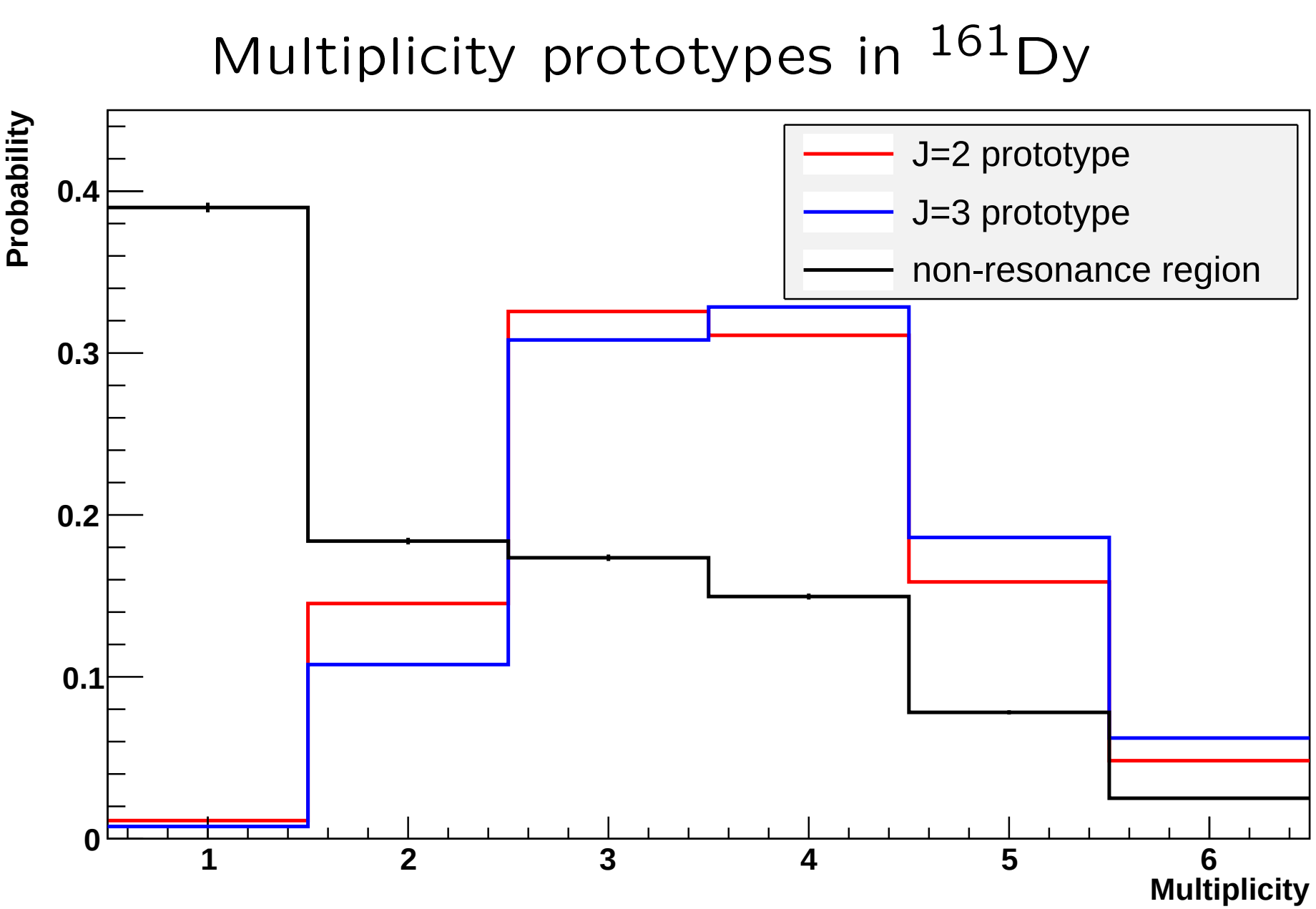


Resonance spin assignment



Resonance spin assignment



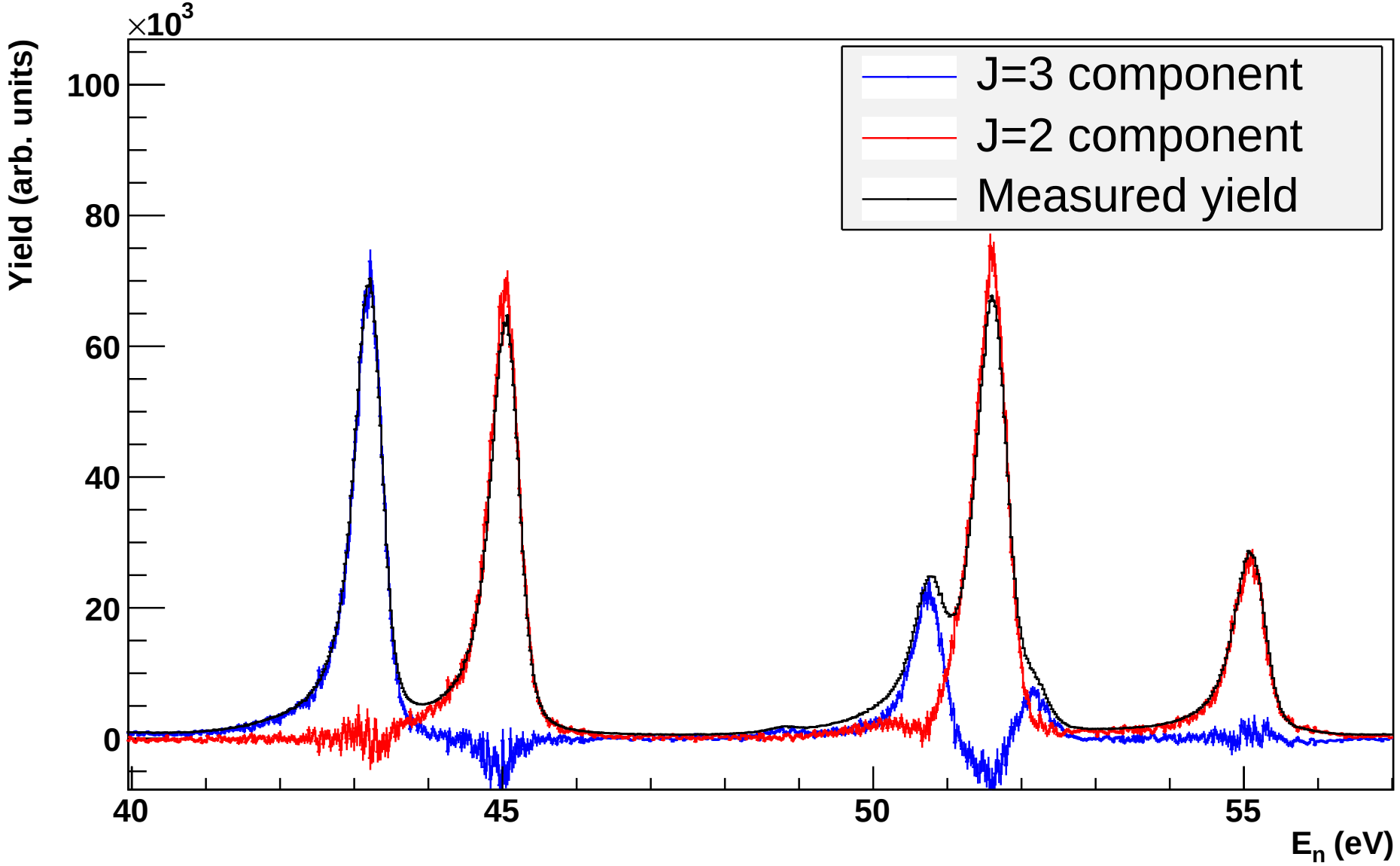

Multiplicity prototypes in ^{161}Dy
Probability
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
Multiplicity
J=2 prototype
J=3 prototype
non-resonance region

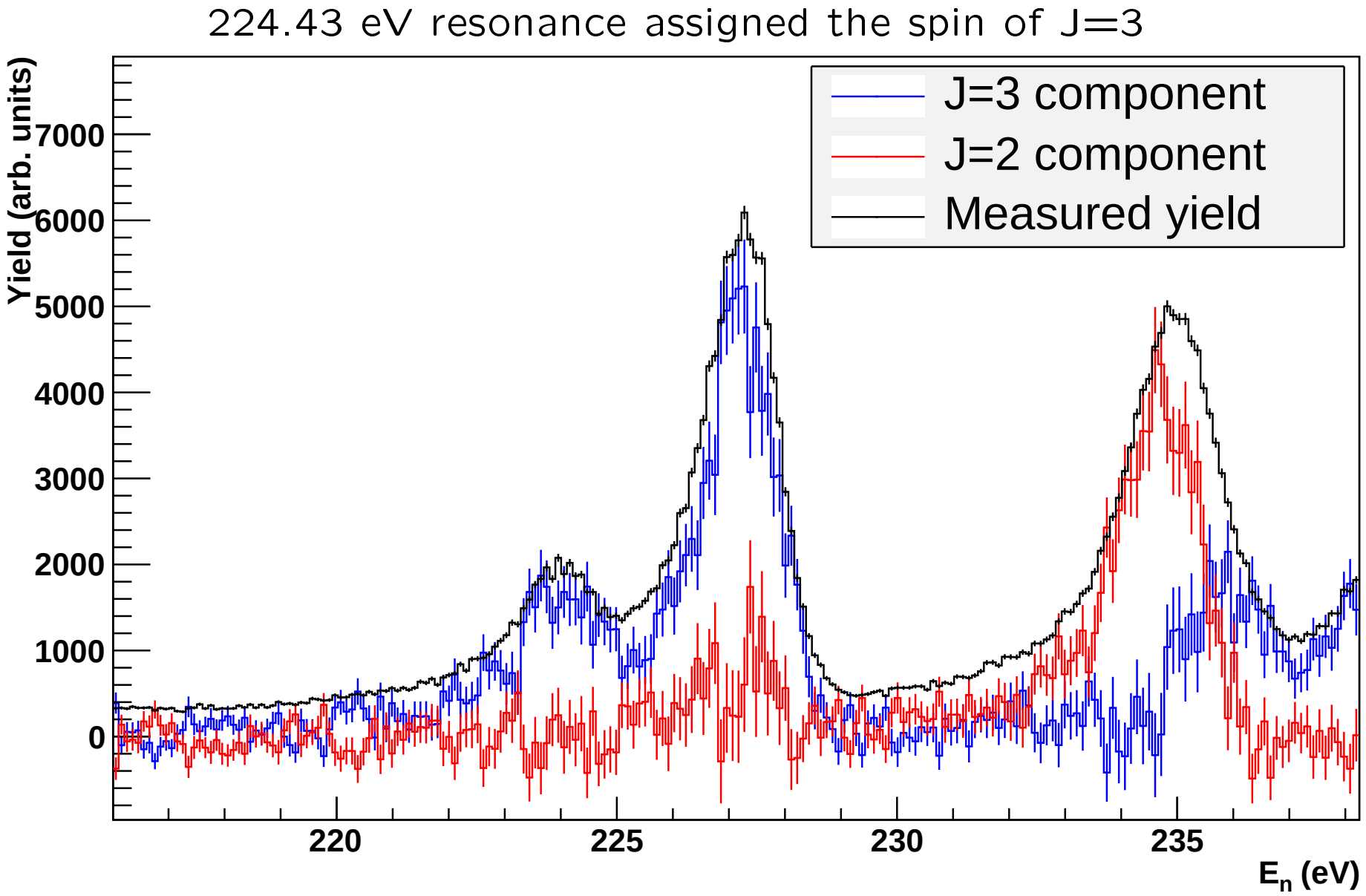
Resonance spin assignment in ^{161}Dy

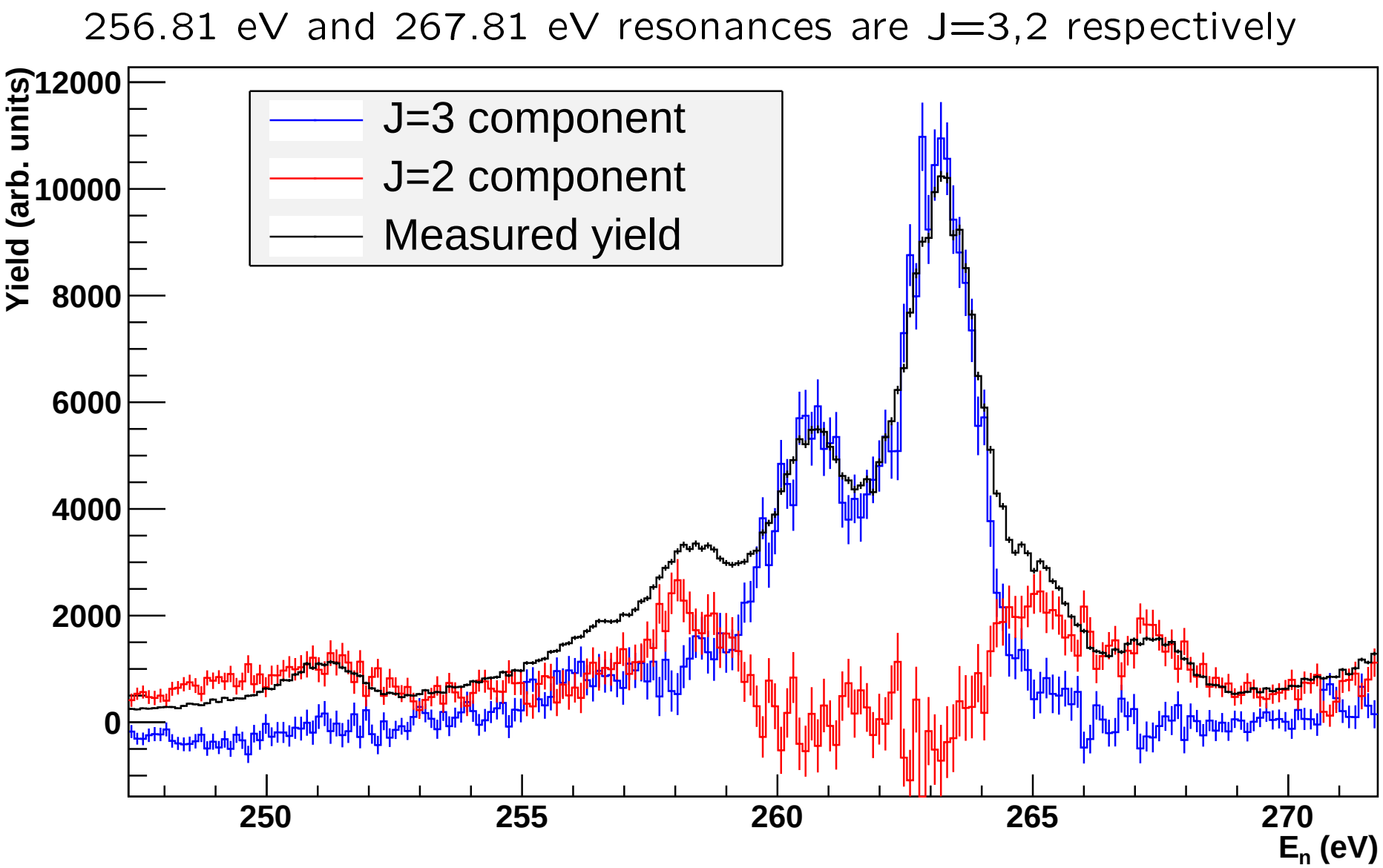
Results obtained for both nuclei.
Works up to ≈ 440 eV in ^{161}Dy and ≈ 950 eV in ^{163}Dy.
Overall good agreement with Atlas of Neutron Resonances by S.F.Mughabghab.
For 114 resonances in ^{161}Dy:

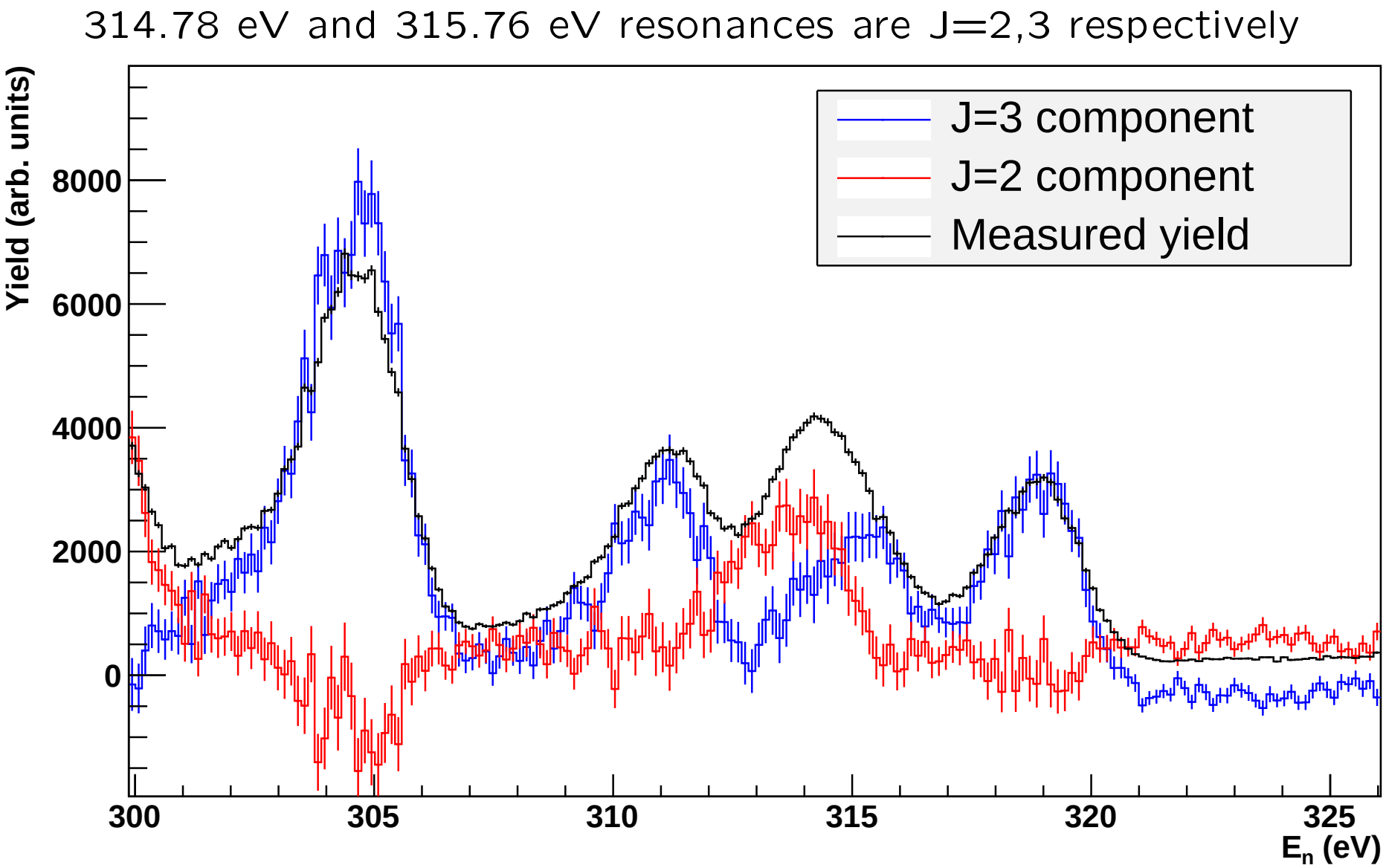
- 24 new assignments - from unknown J to J=2 or J=3
- 1 reassignment - 91.12 eV seems to be J=2 rather than J=3
- several possible close dublets that need futher investigation with help of DICEBOX/GEANT4/SAMMY

Confirmation of spin assignment on a few non-prototype resonances




224.43 eV resonance assigned the spin of J=3
J=3 component
J=2 component
Measured yield
Yield (arb. units)
7000
6000
5000
4000
3000
2000
1000
0
220
225
230
235
E_n (eV)

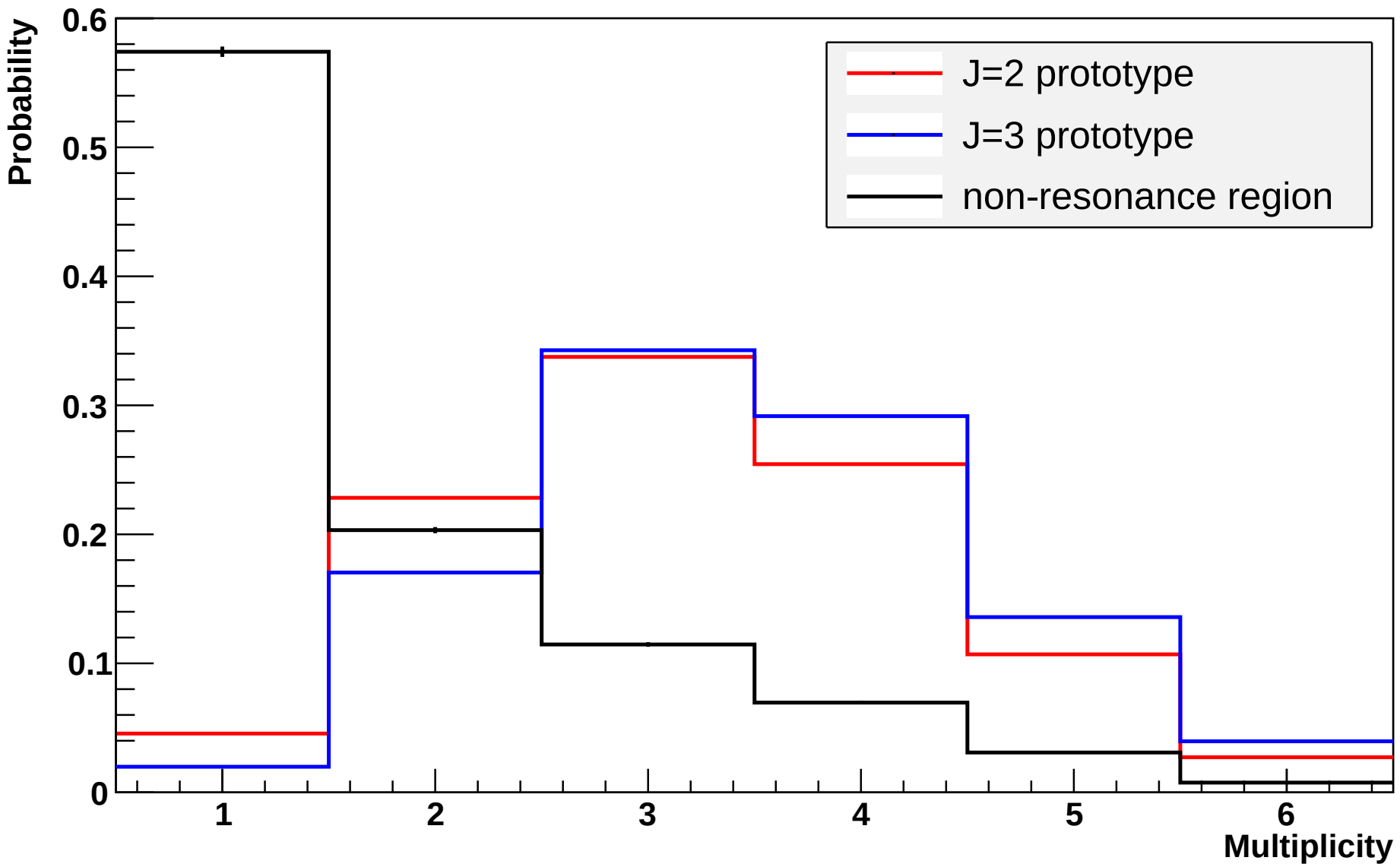

256.81 eV and 267.81 eV resonances are J=3,2 respectively
J=3 component
J=2 component
Measured yield
Yield (arb. units)
12000
10000
8000
6000
4000
2000
0
250
255
260
265
270
E_n (eV)


314.78 eV and 315.76 eV resonances are J=2,3 respectively
J=3 component
J=2 component
Measured yield
Yield (arb. units)
8000
6000
4000
2000
0
300
305
310
315
320
325
E_n (eV)

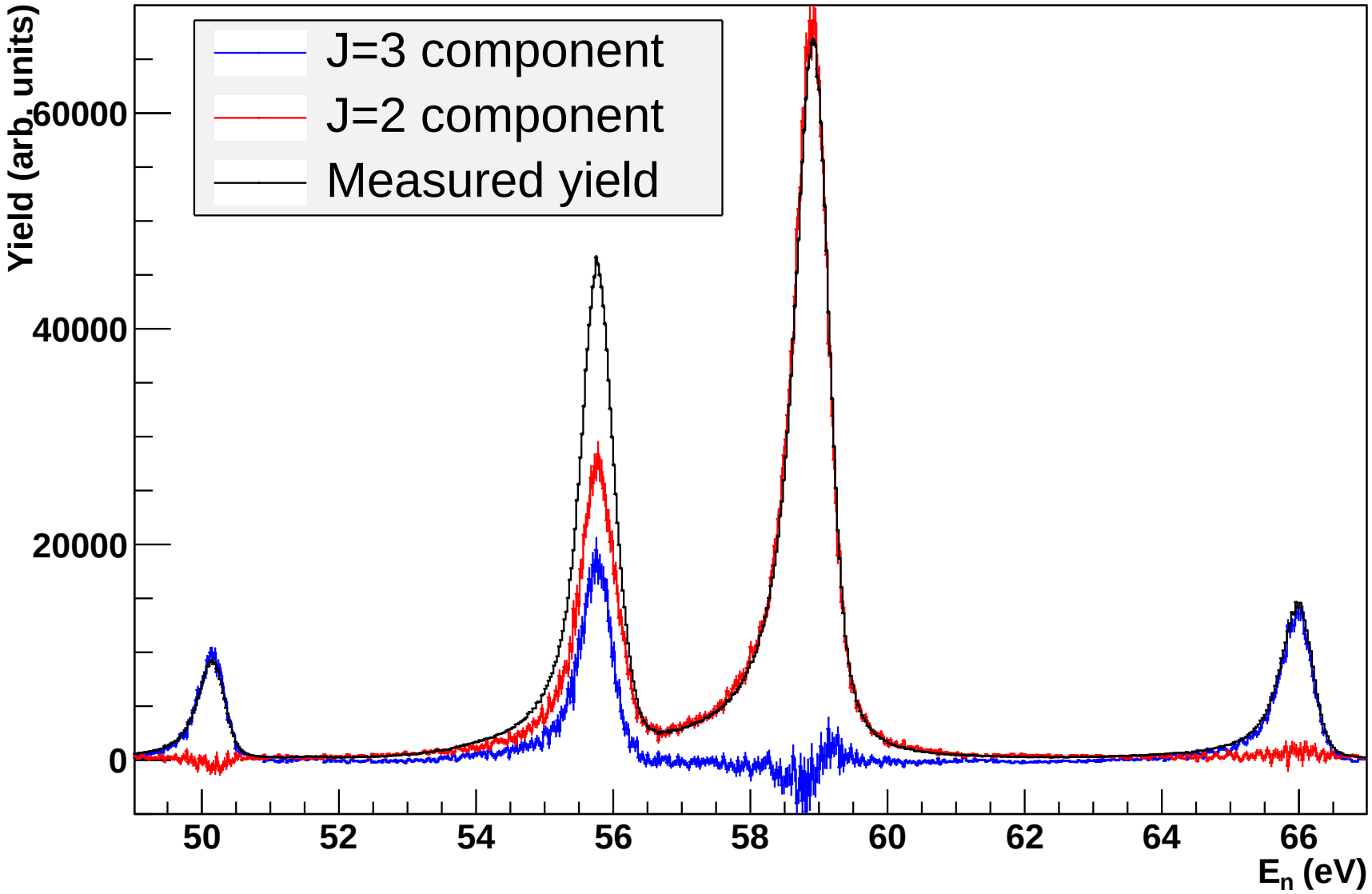
Resonance spin assignment in ^{163}Dy

Overall good agreement with Atlas of Neutron Resonances by S.F.Mughabghab.
For 102 resonances in ^{163}Dy:

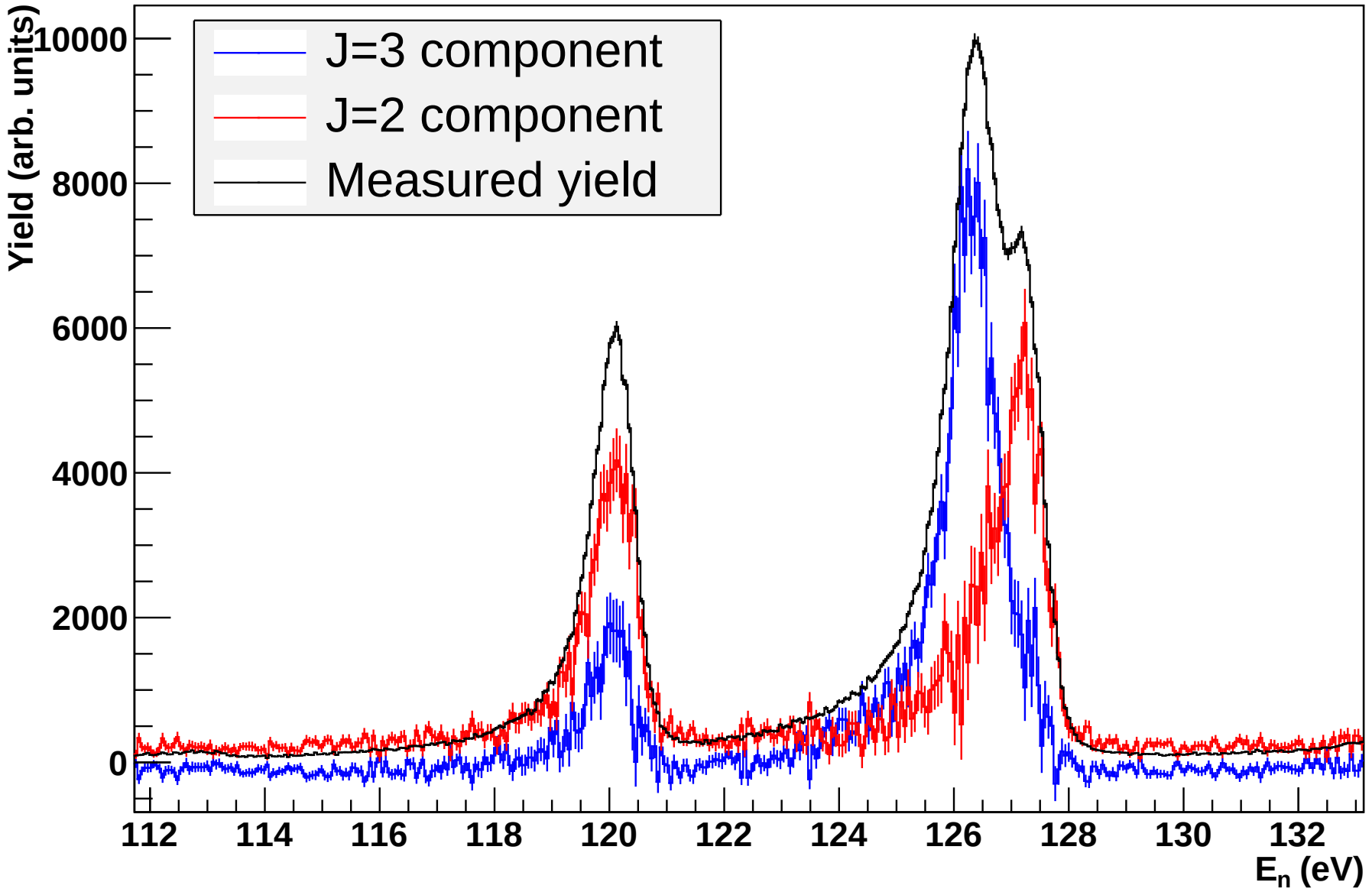
- 5 new assignments - from unknown J to J=2 or J=3
- 6 reassignments - from J=2 to J=3 and vice versa
- several possible close dublets that need futher investigation with help of DICEBOX/GEANT4/SAMMY
- several weak resonances remain inconclusive due to low statistics


Multiplicity prototypes in ^{163}Dy
Probability
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
Multiplicity
J=2 prototype
J=3 prototype
non-resonance region

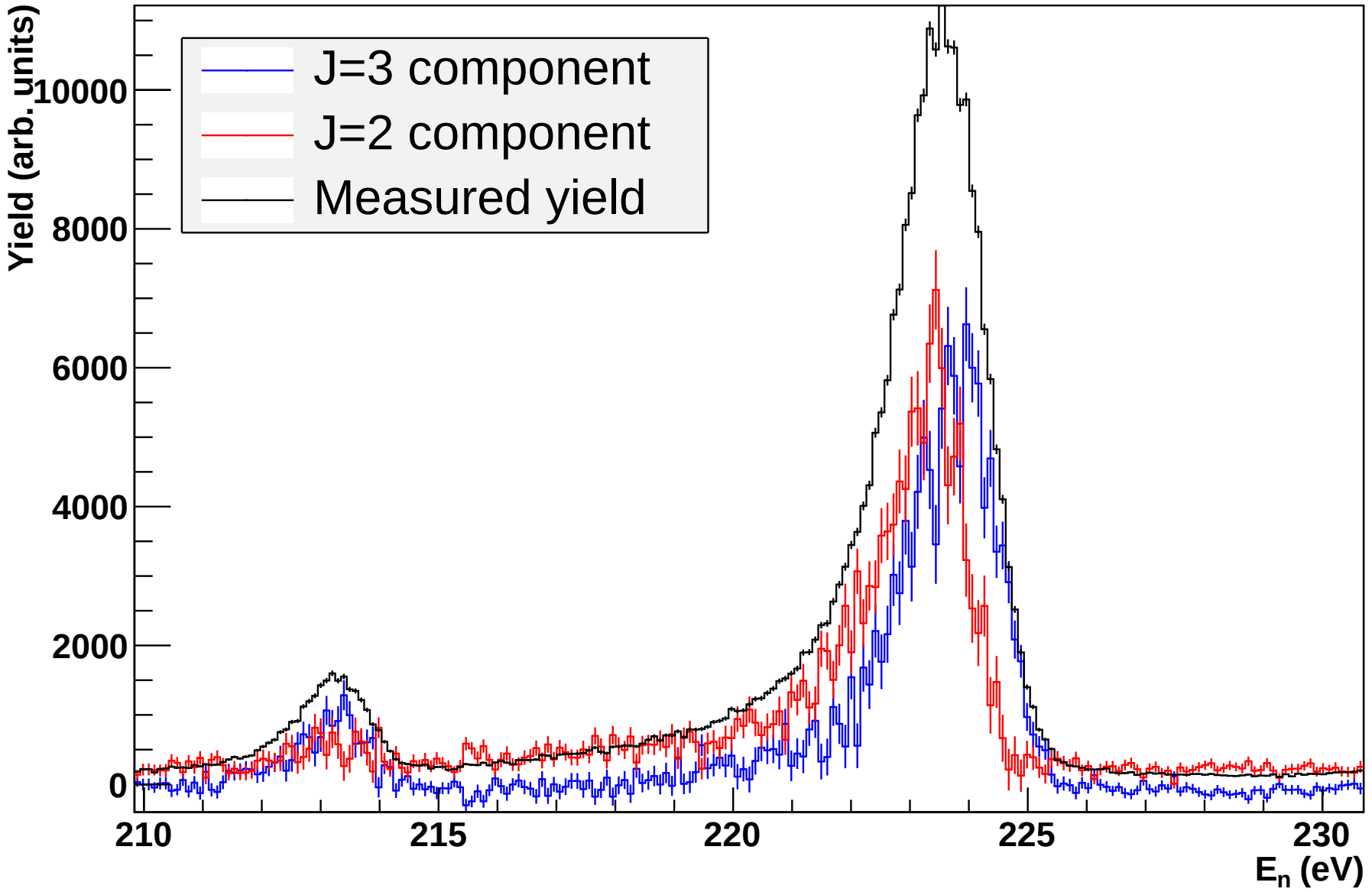
Confirmation of spin assignment on few non-prototype resonances (and possible appearance of close dublet)

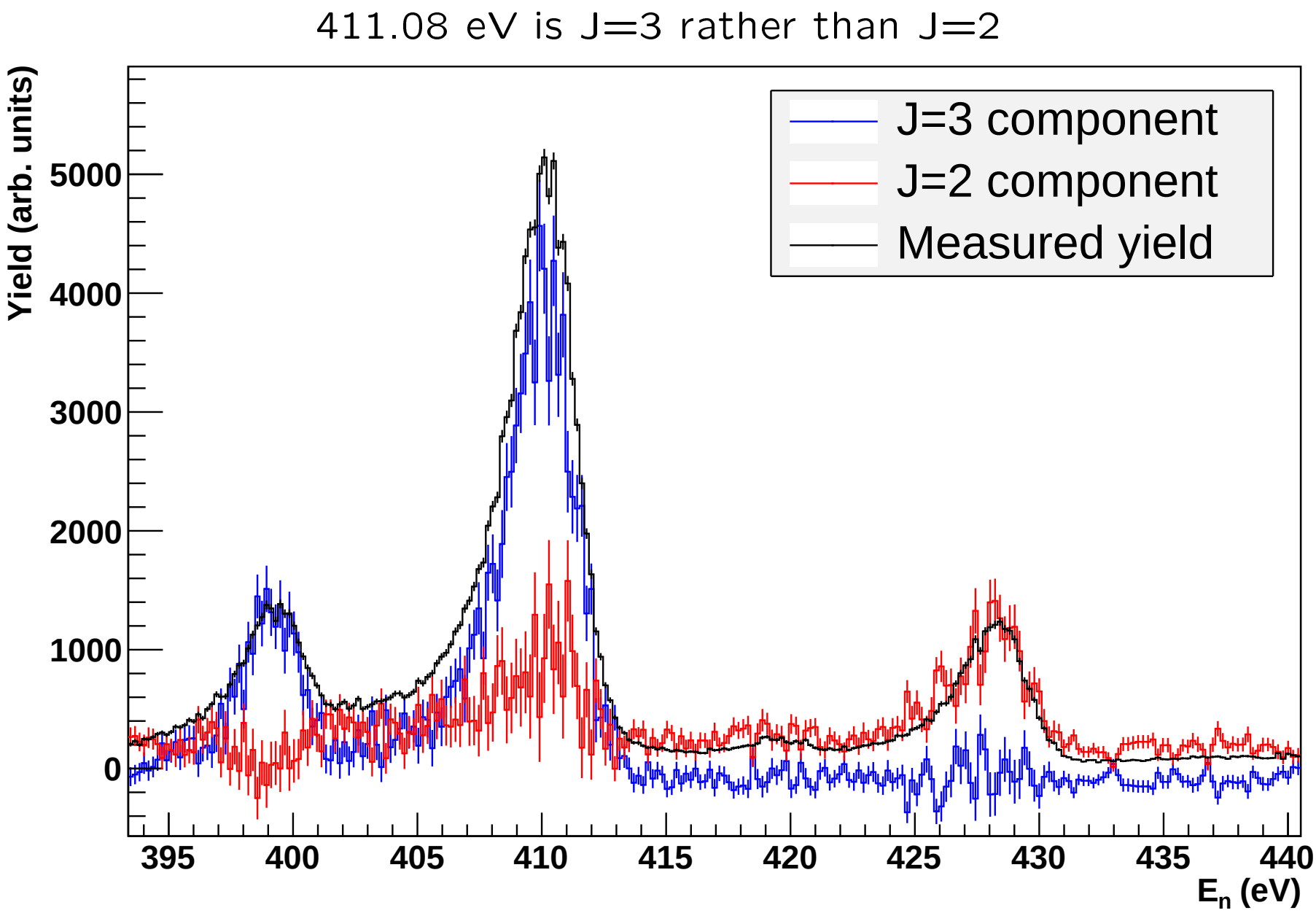


127.46 eV is J=2 rather than J=3, possible dublet at ≈ 120.33 eV

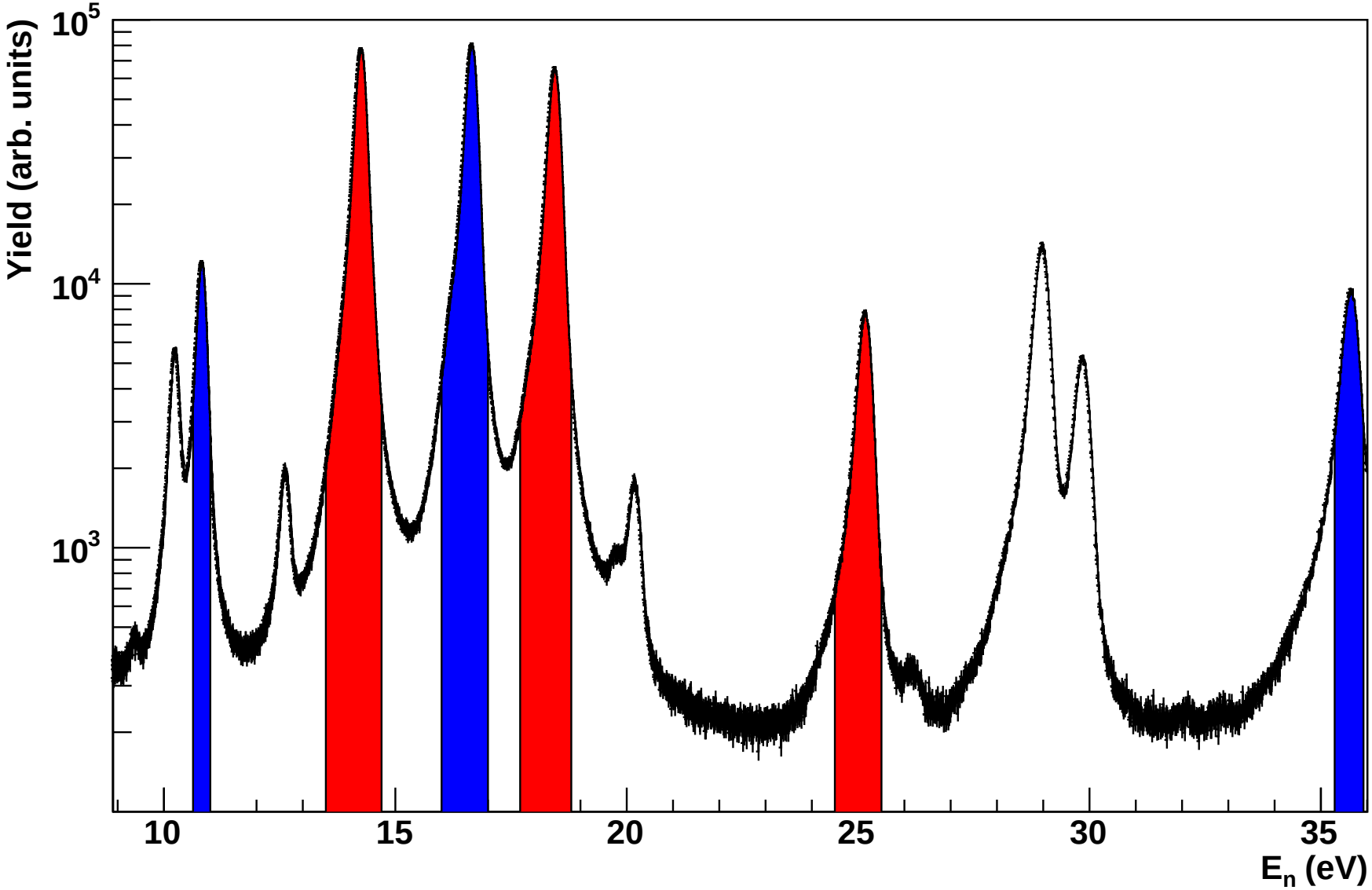


224.15 eV is not single J=2 resonance but dublet with different spins

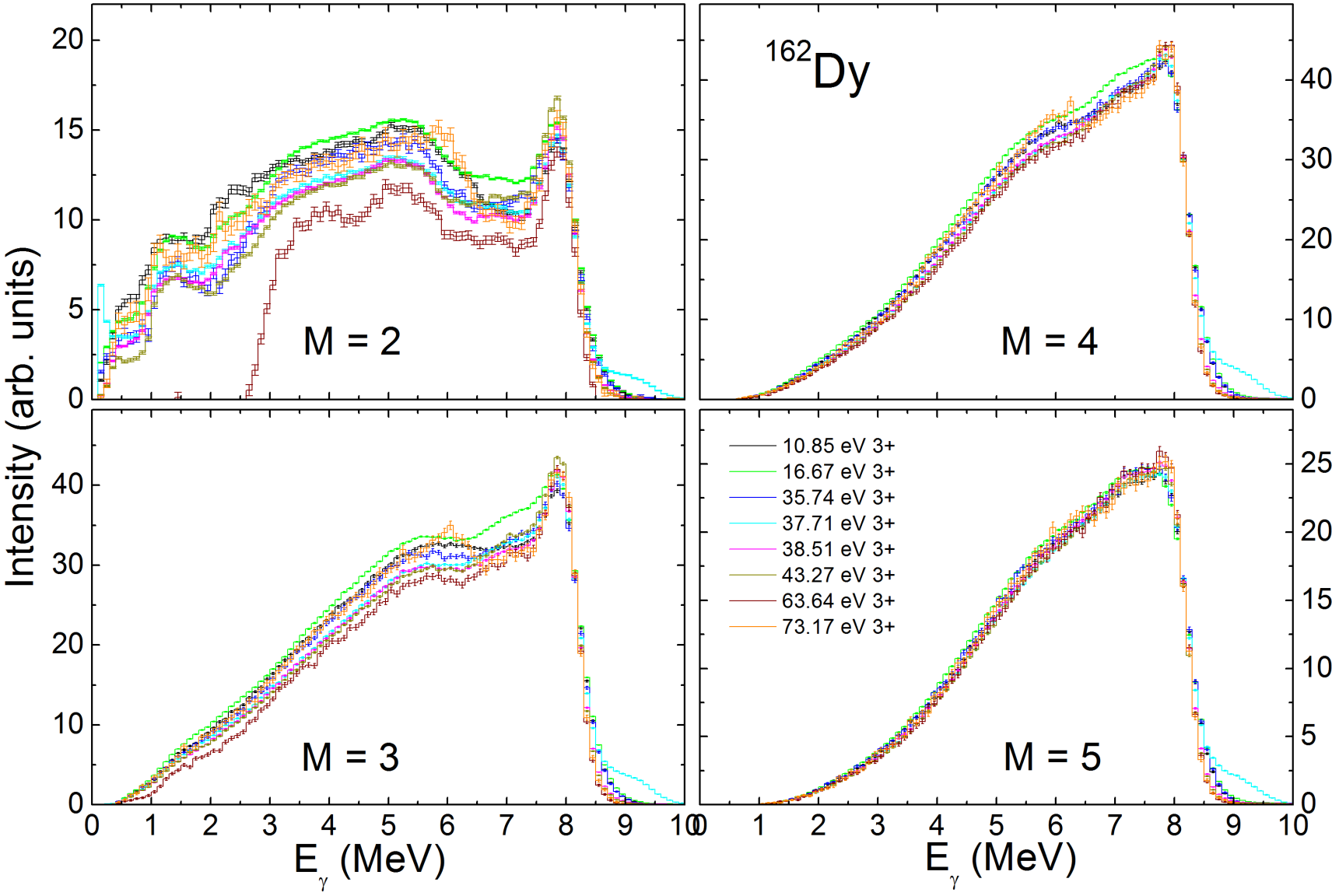



411.08 eV is J=3 rather than J=2
J=3 component
J=2 component
Measured yield
Yield (arb. units)
5000
4000
3000
2000
1000
0
395
400
405
410
415
420
425
430
435
440
E_n (eV)

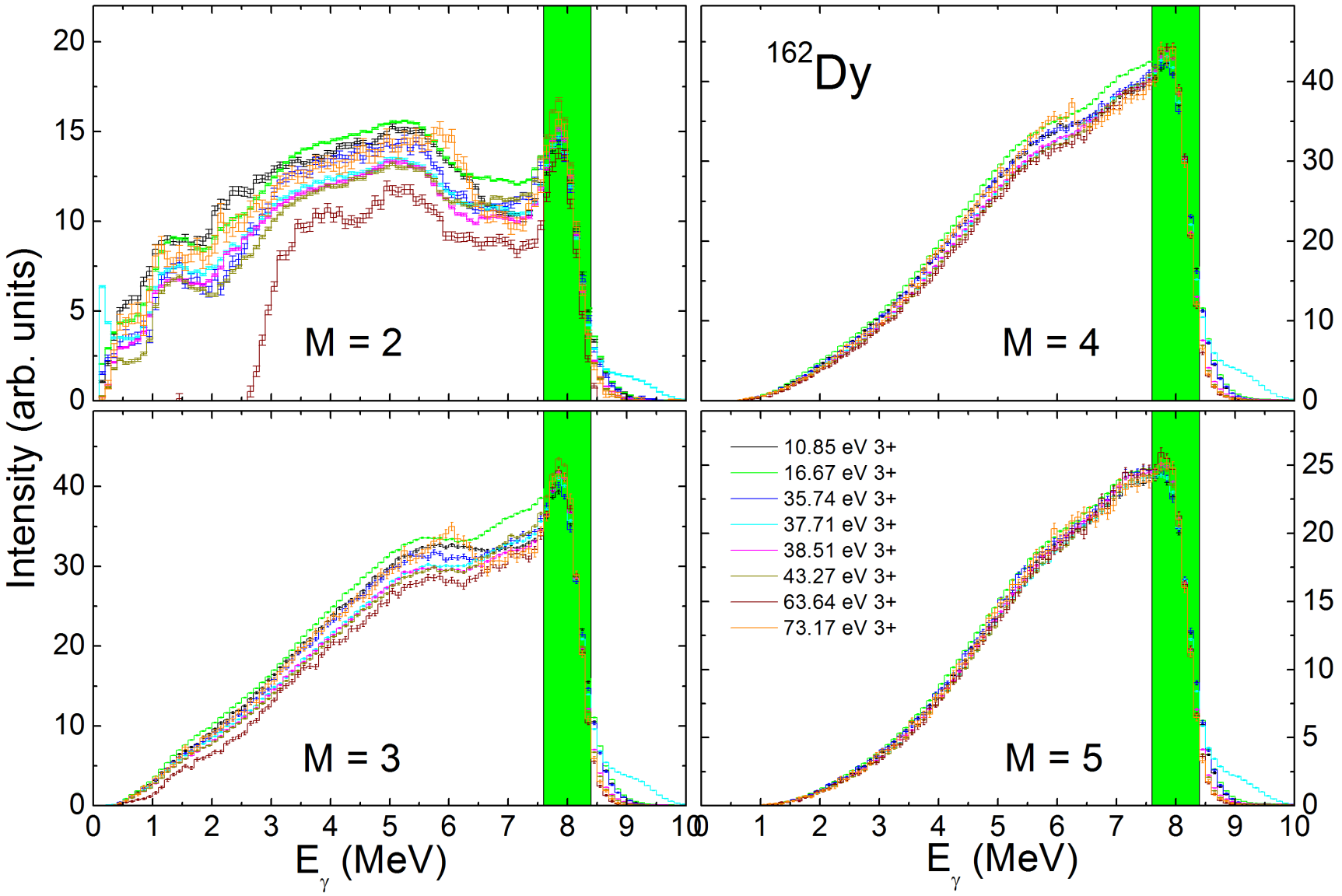
Search for the photon strength functions - experimental MSC spectra



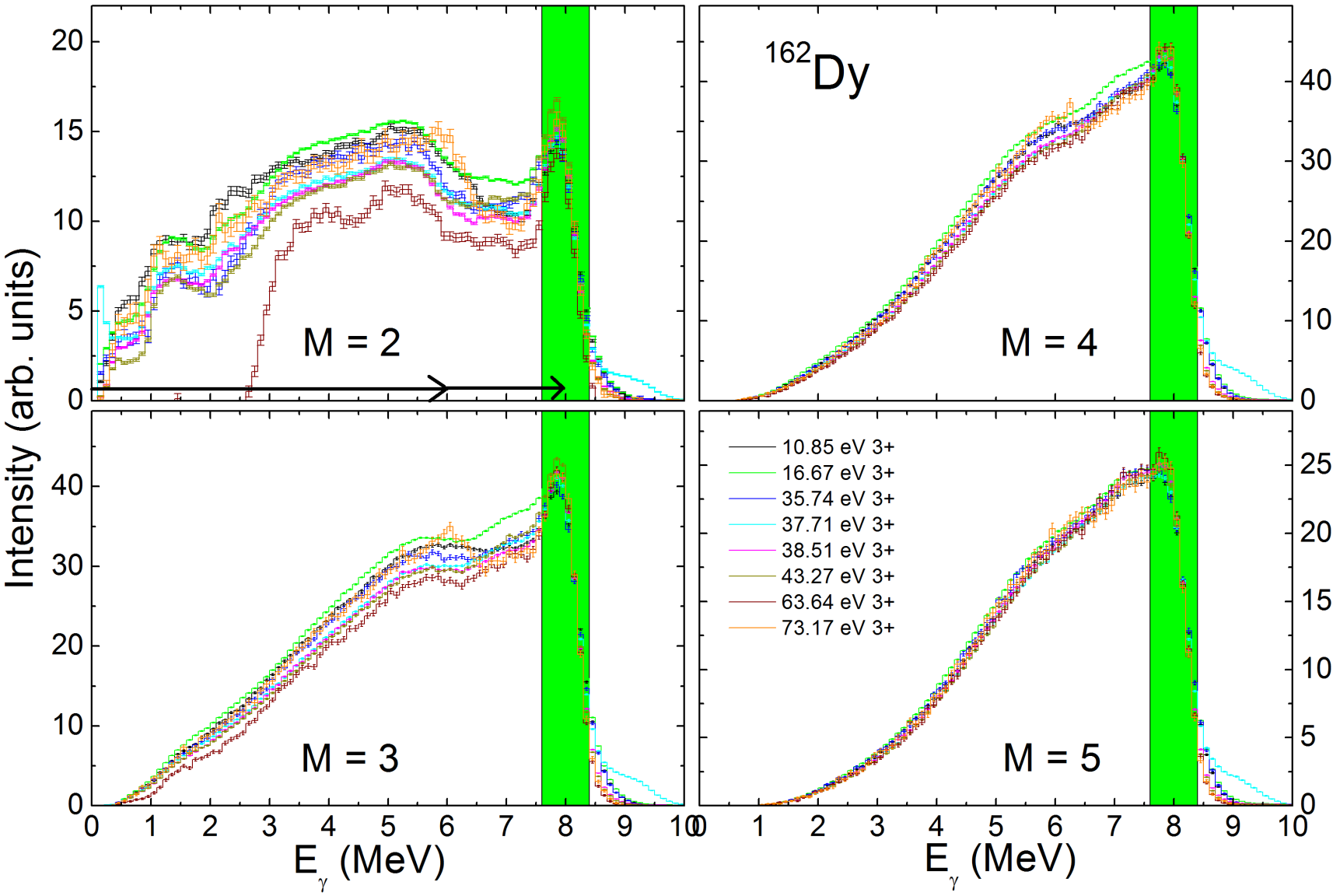
Search for the photon strength functions - experimental MSC spectra



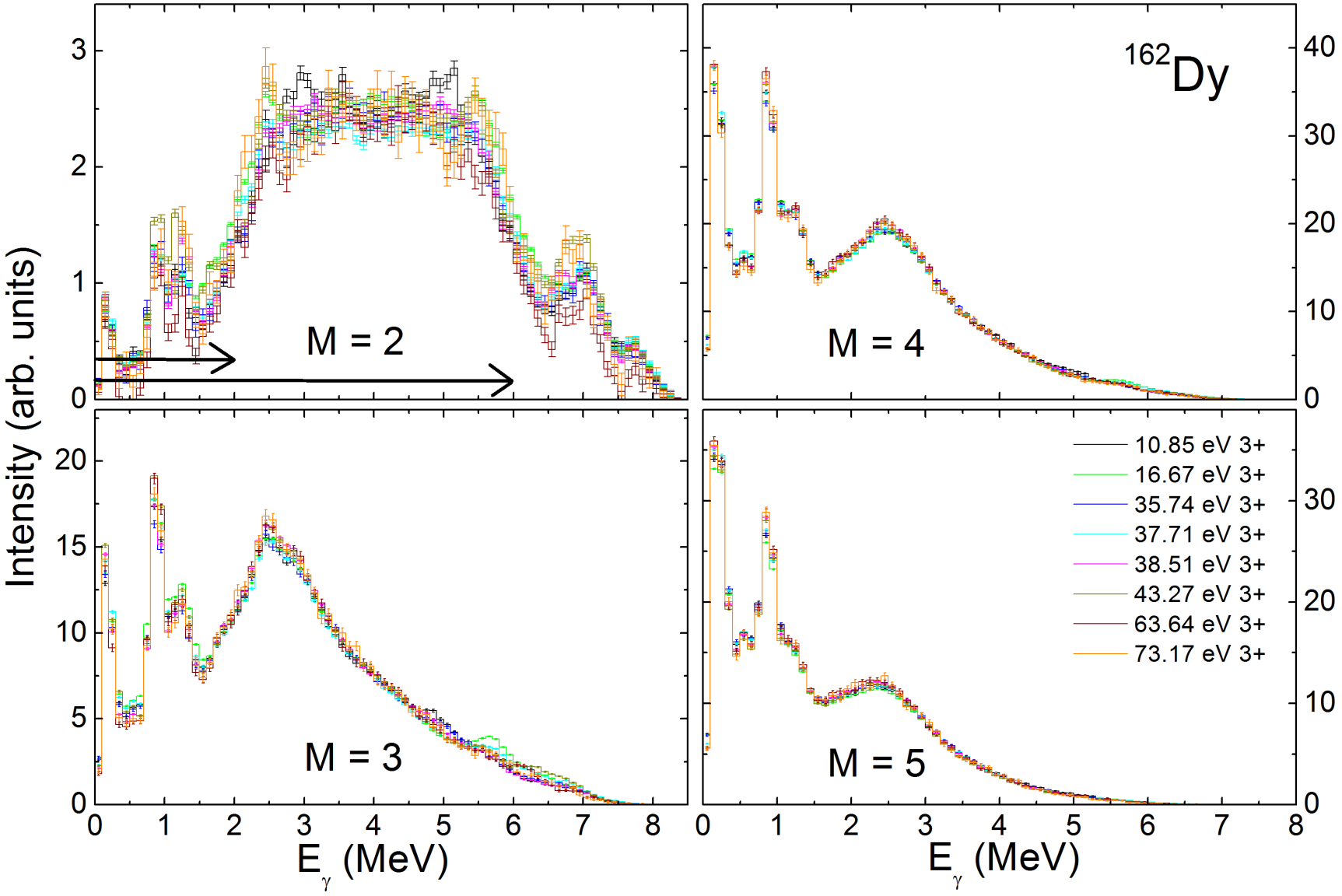
Search for the photon strength functions - experimental MSC spectra



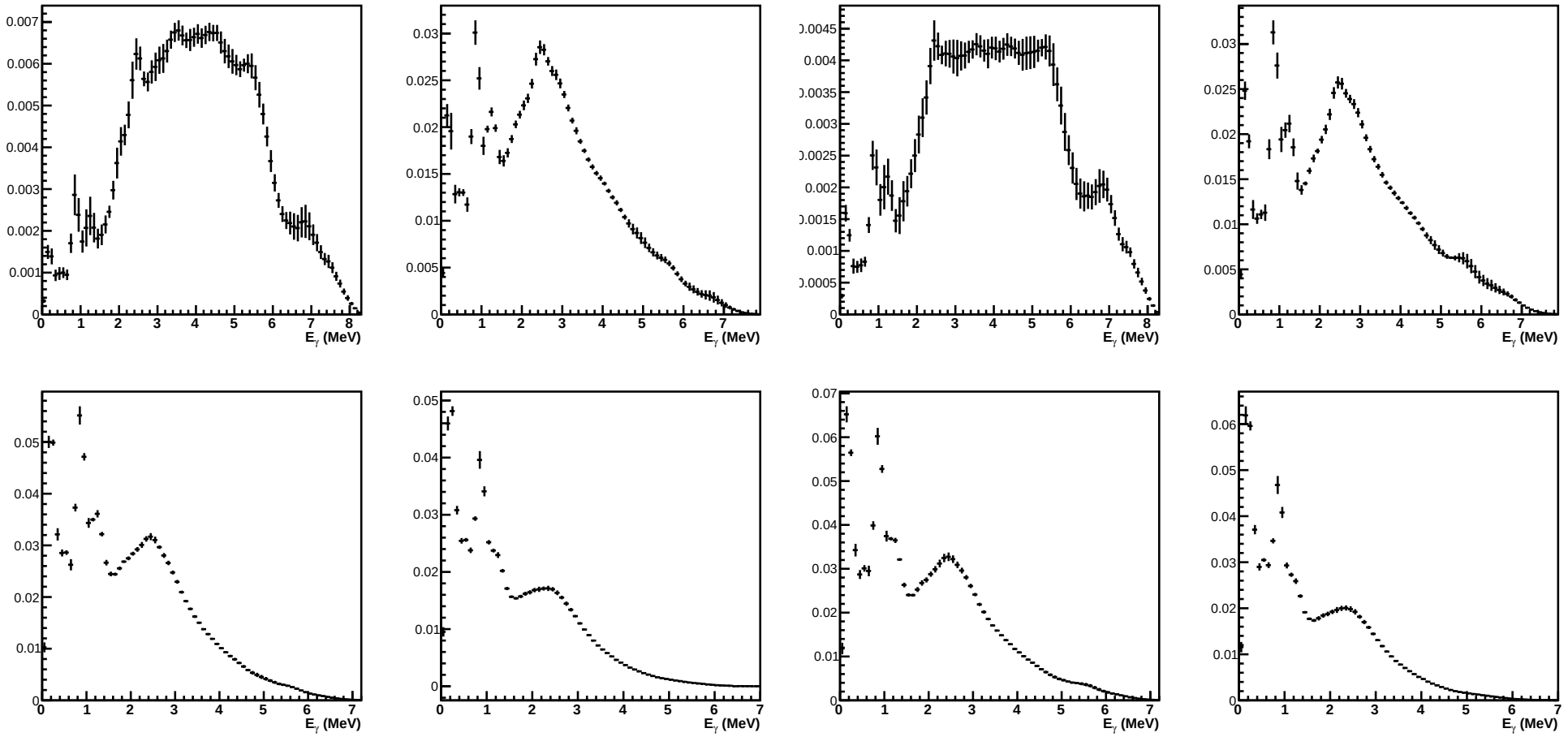
Search for the photon strength functions - experimental MSC spectra



Search for the photon strength functions - experimental MSC spectra



Search for the photon strength functions - experimental MSC spectra



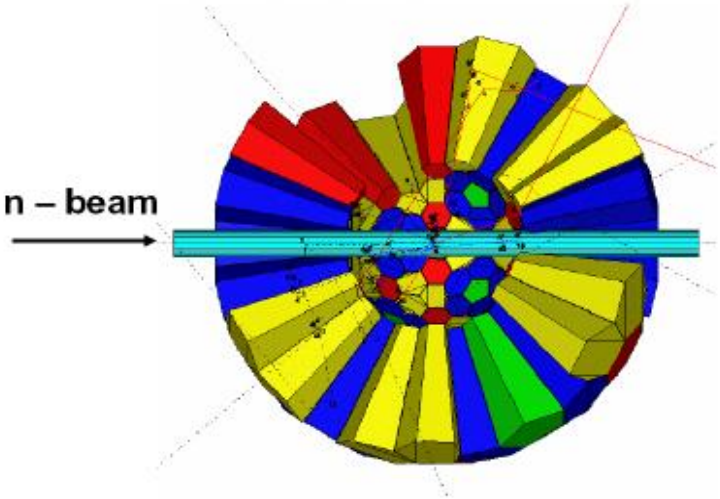
Mean spectra created from 25 and 22 resonances of spin 2 and 3 respectively.

Search for the photon strength functions - simulated MSC spectra

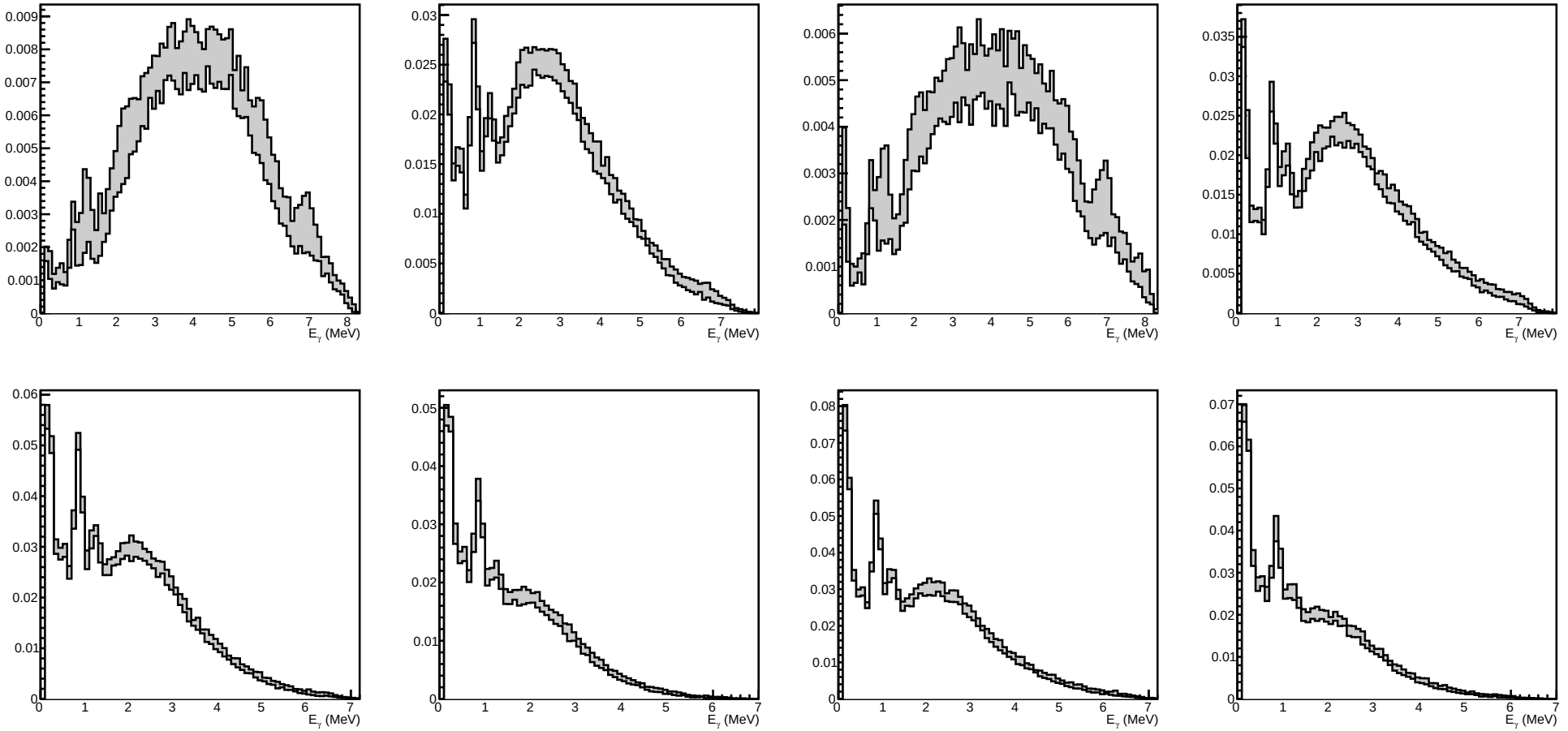
Cascades from DICEBOX simulation

$$\Gamma_{\alpha\gamma\beta} = \sum_{X,L} y^2_{\alpha\beta XL} \left(E_\alpha - E_\beta\right)^{2L+1} \frac{f_{XL}\left(E_\alpha - E_\beta\right)}{\rho\left(E_\alpha, J_\alpha, \pi_\alpha\right)}$$

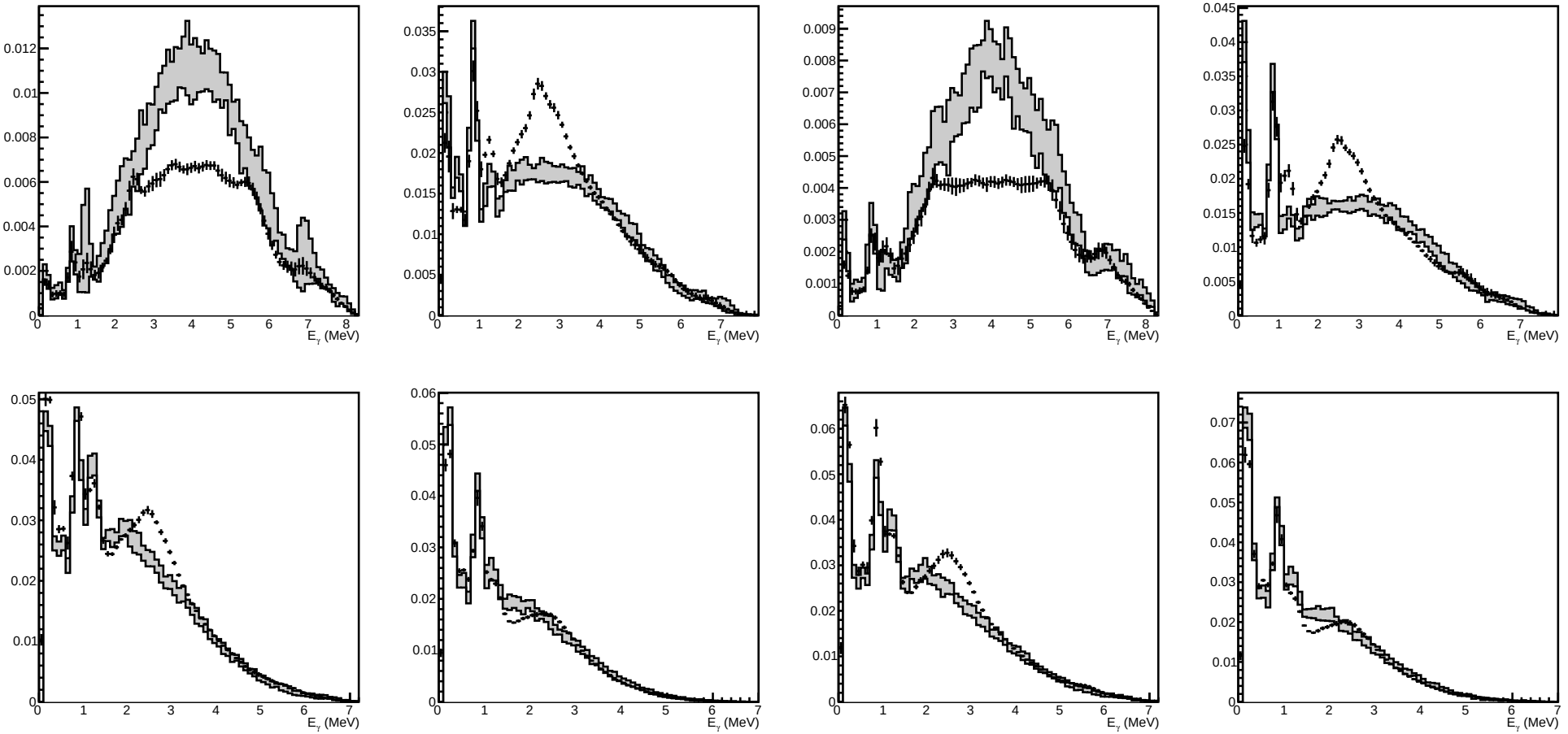
are fed to GEANT4 detector response



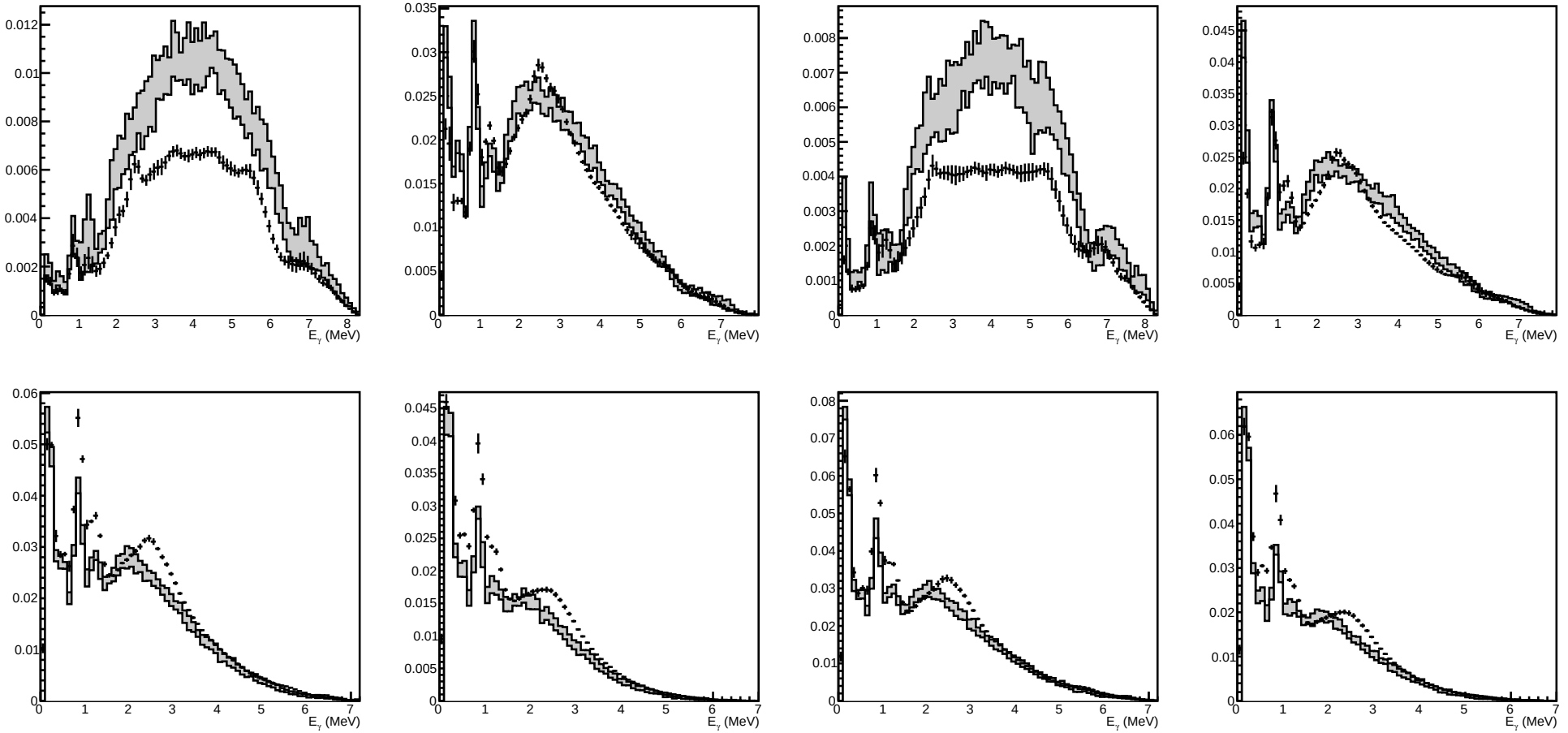
Search for the photon strength functions - simulated MSC spectra



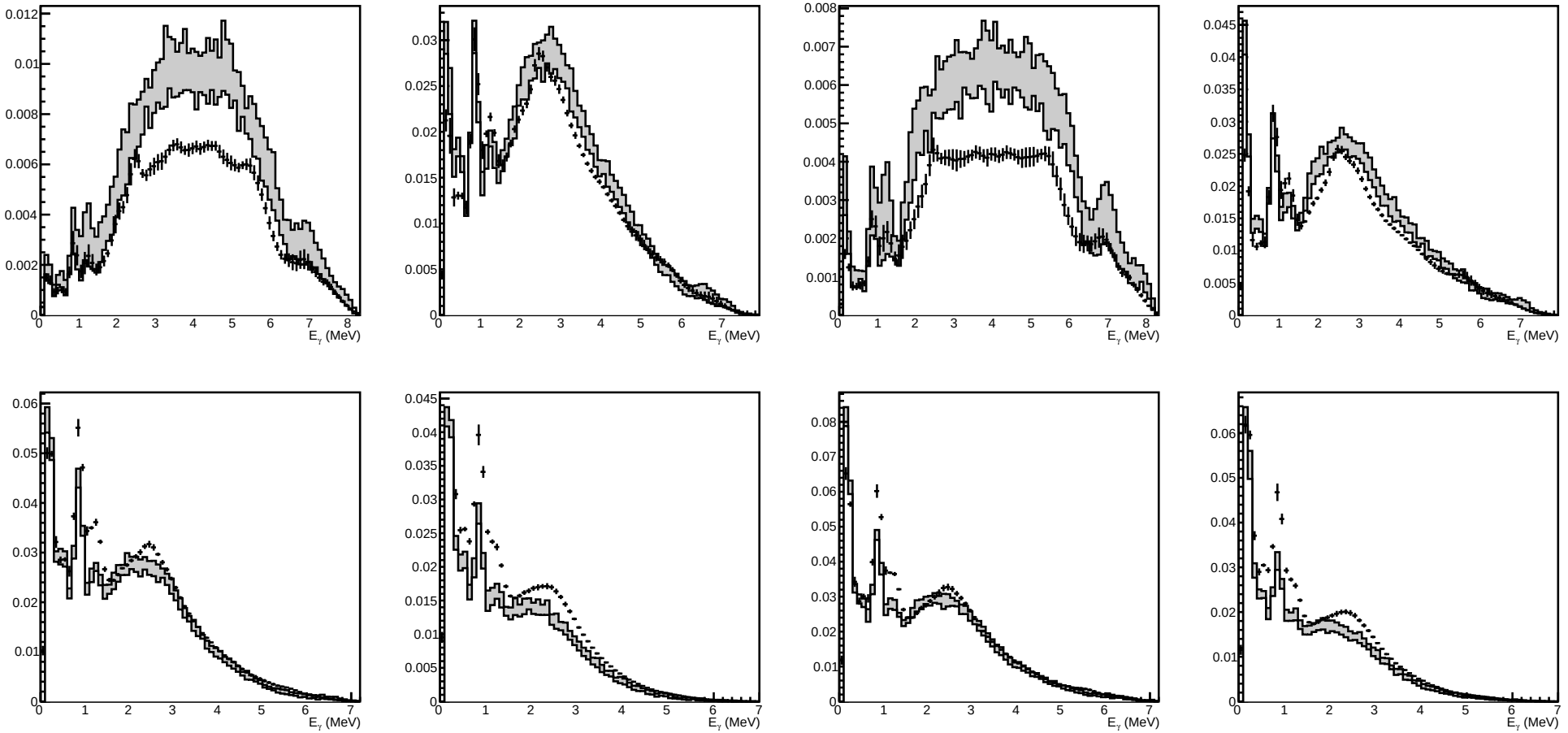
Search for the photon strength functions - SLO in E1 and Spin-Flip in M1



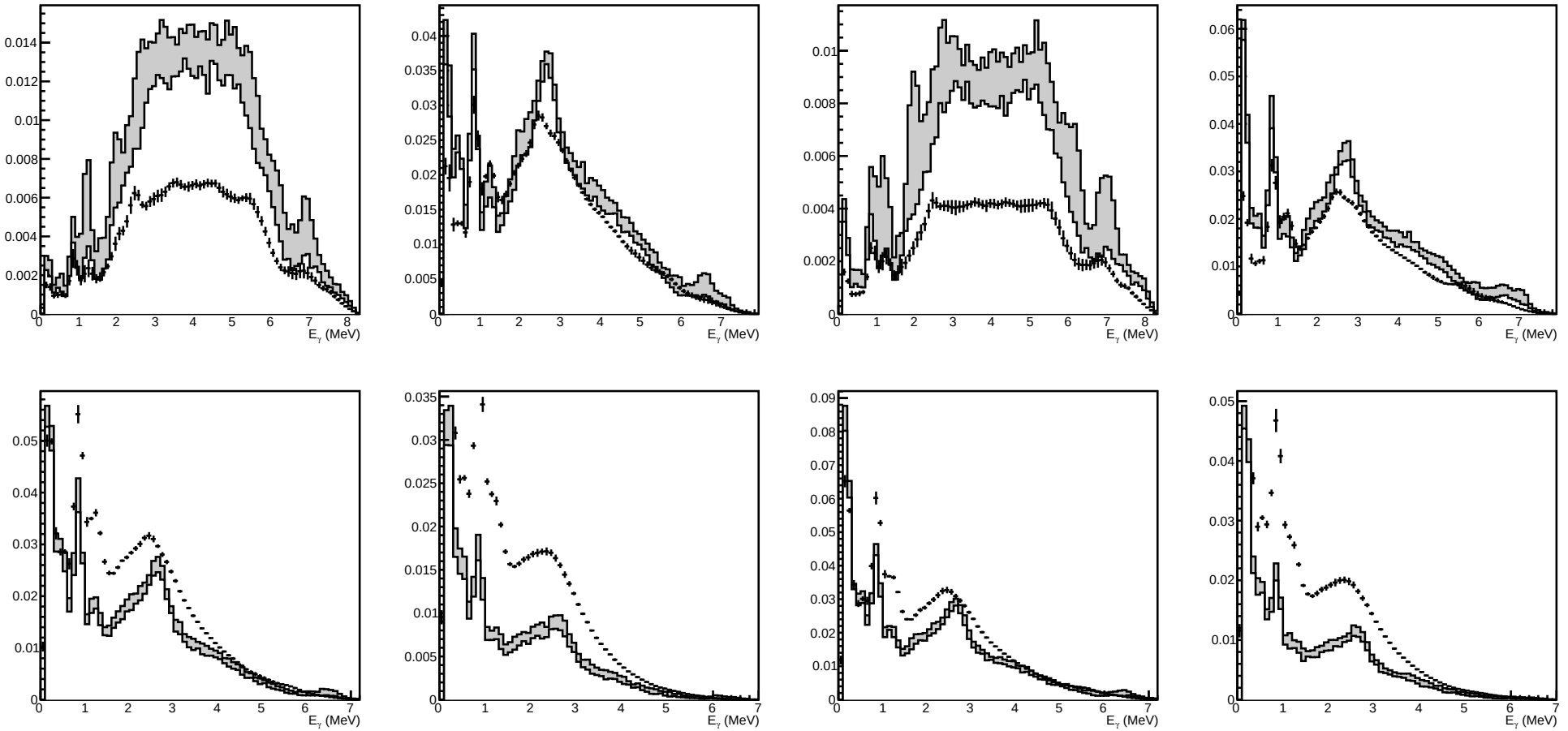
Search for the photon strength functions - KMF in E1 and Spin-Flip in M1



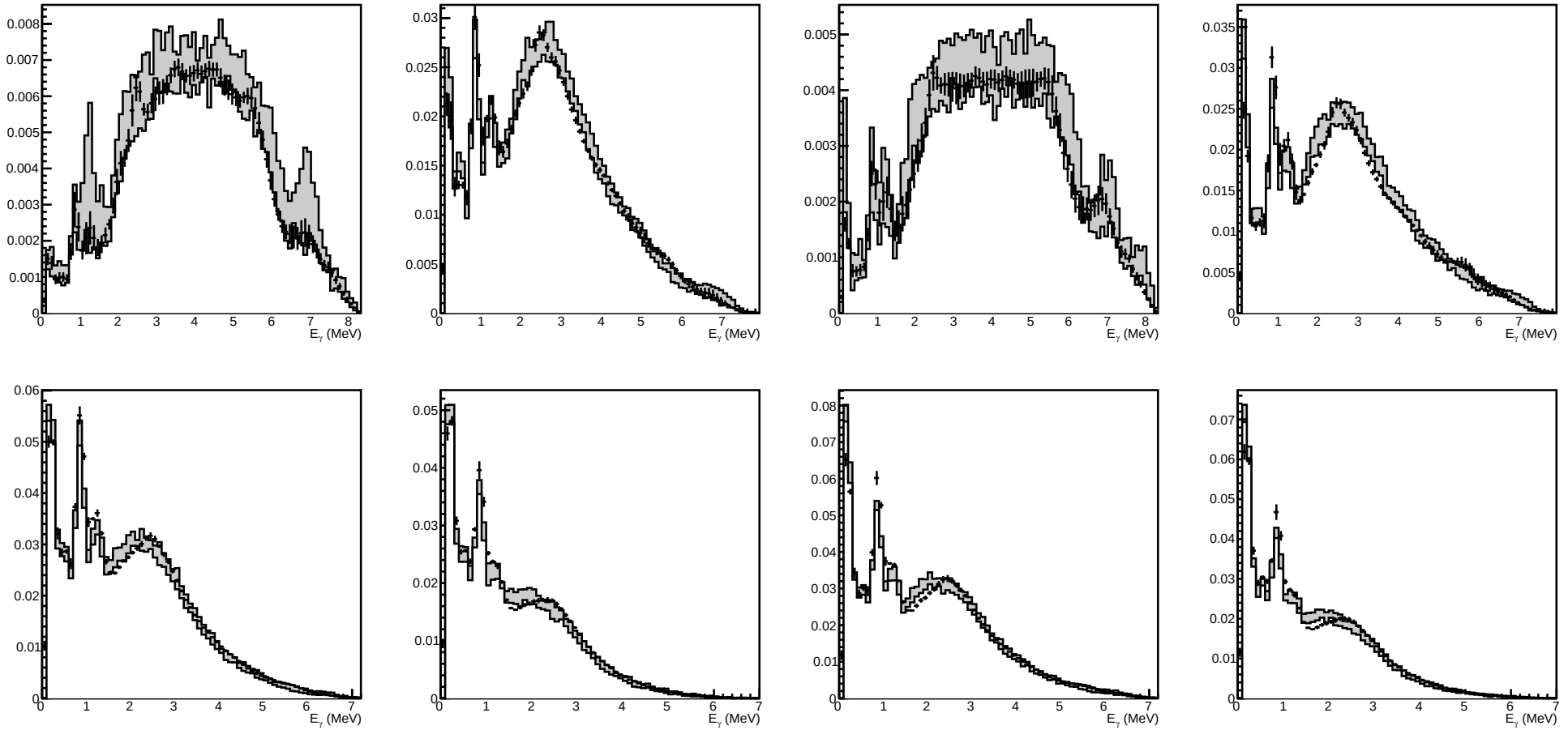
Search for the photon strength functions - Best PSFs from ^{158}Gd at DANCE



Search for the photon strength functions - Oslo results with SM resonance in M1 PSF

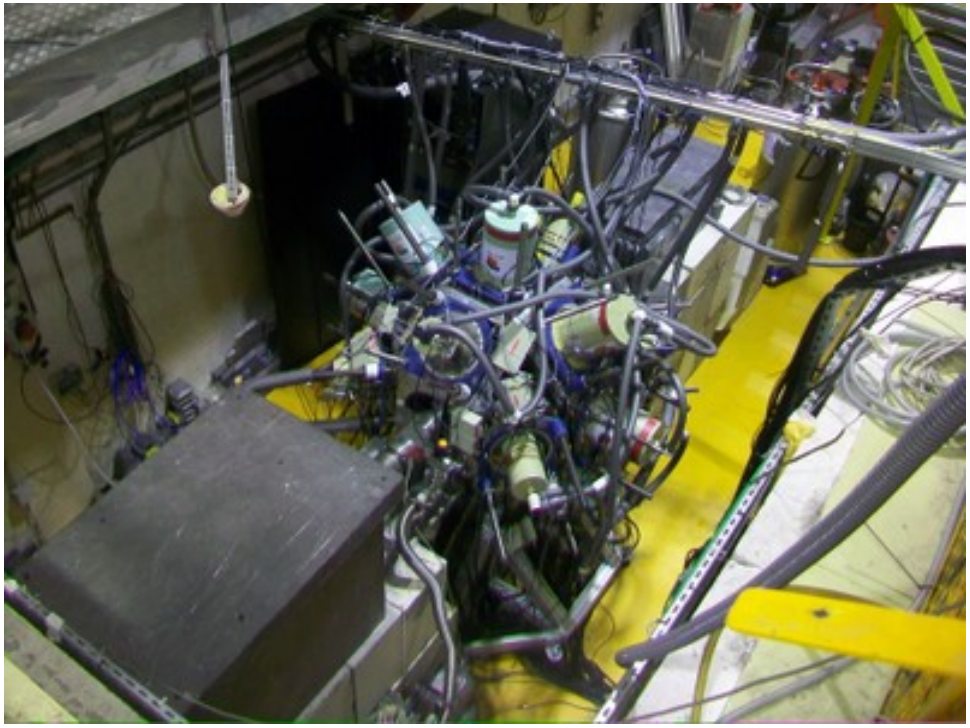


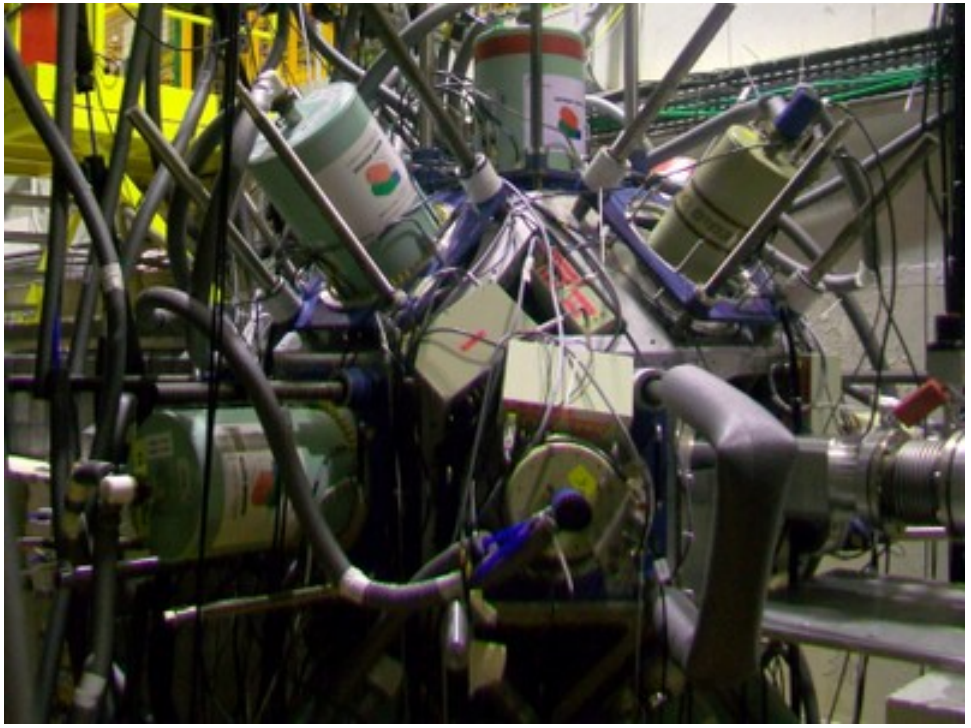
Search for the photon strength functions - Best agreement found so far



EXOGAM at ILL = EXILL Campaign

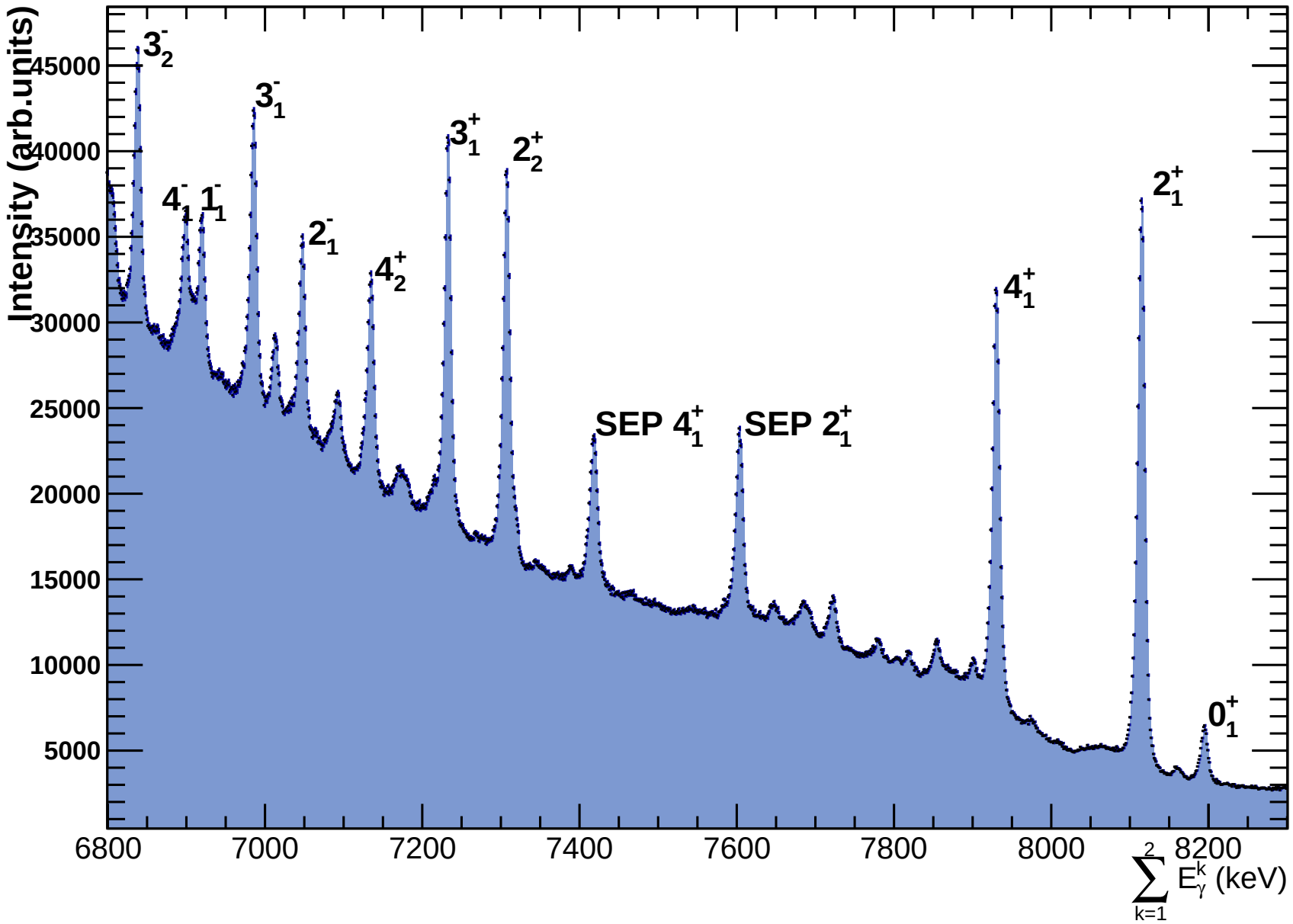
EXOGAM was borrowed to ILL for 2 reactor cycles during 2012-2013.

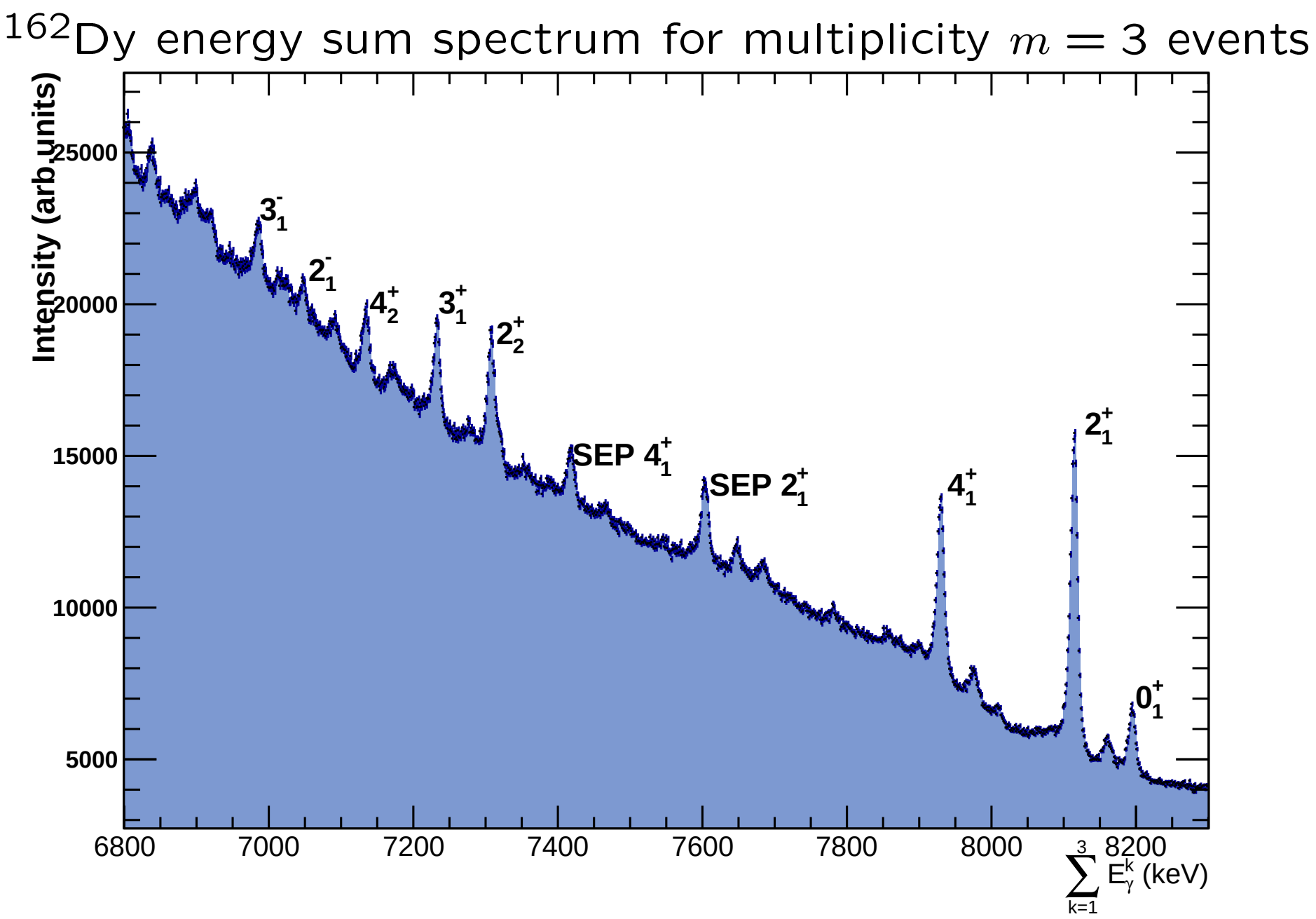


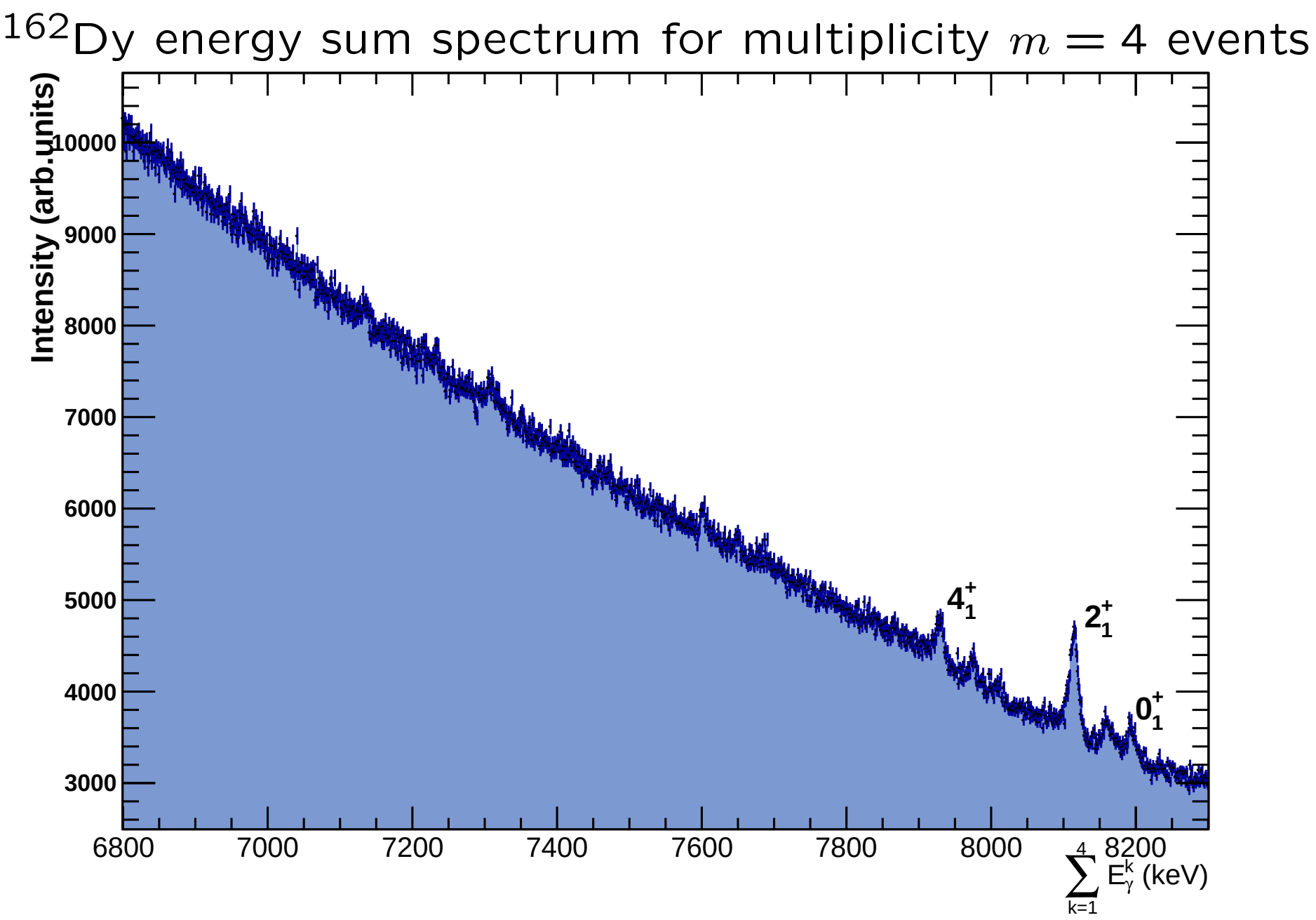


Our experiment was granted 2.5 days of data taking (list mode, several TB) in the end of first cycle in December 2012.

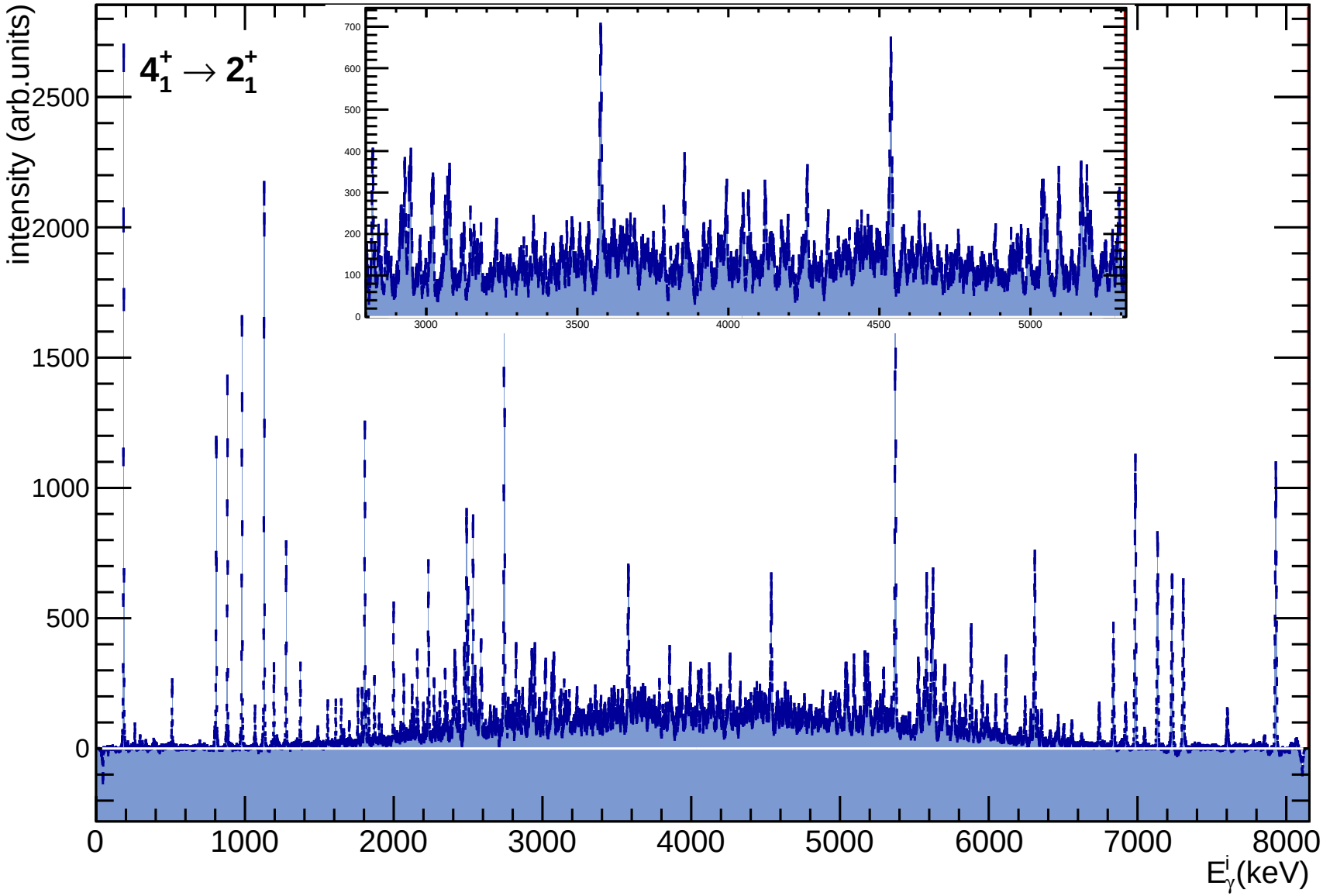
^{162}Dy energy sum spectrum for multiplicity $m = 2$ events



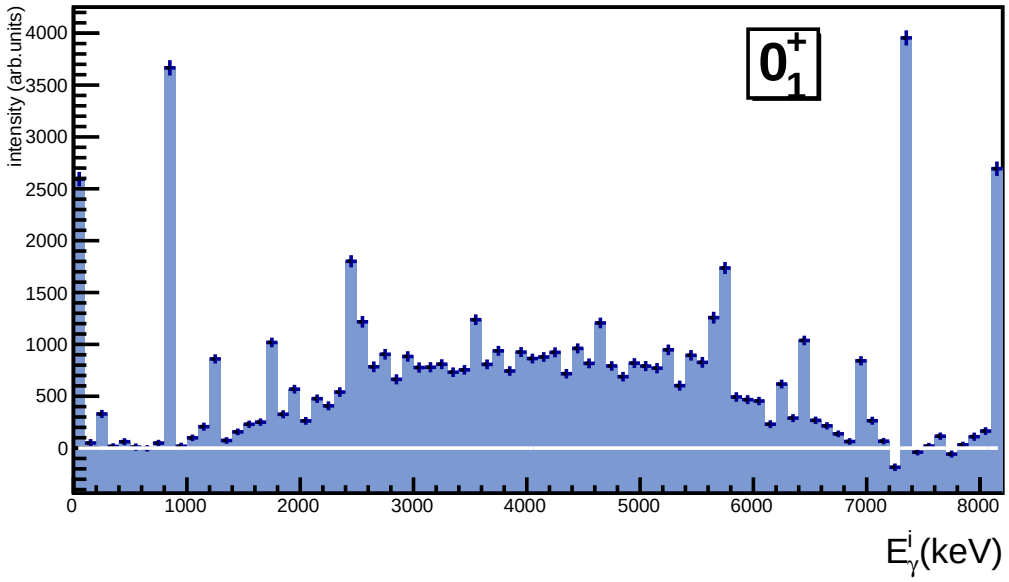

^{162}Dy energy sum spectrum for multiplicity $m = 3$ events
Intensity (arb. units)
25000
20000
15000
10000
5000
6800
7000
7200
7400
7600
7800
8000
8200
$\sum_{k=1}^{3} E_\gamma^k$ (keV)
3_1^-
2_1^-
4_2^+
3_1^+
2_2^+
SEP 4_1^+
SEP 2_1^+
4_1^+
2_1^+
0_1^+

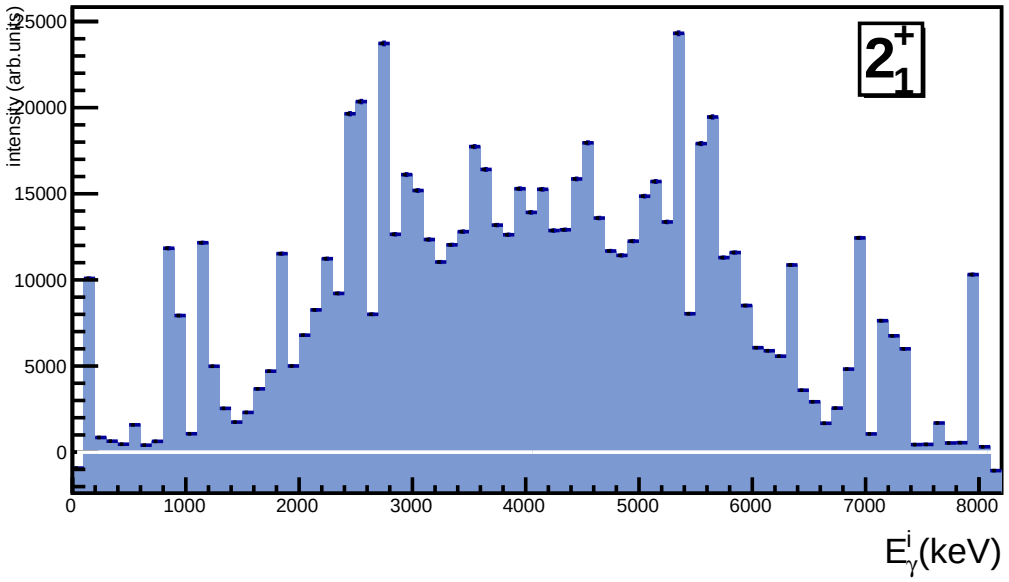

^{162}Dy energy sum spectrum for multiplicity $m = 4$ events
Intensity (arb.units)
10000
9000
8000
7000
6000
5000
4000
3000
6800
7000
7200
7400
7600
7800
8000
8200
4_1^+
2_1^+
0_1^+
$\sum_{k=1}^{4} E_\gamma^k$ (keV)

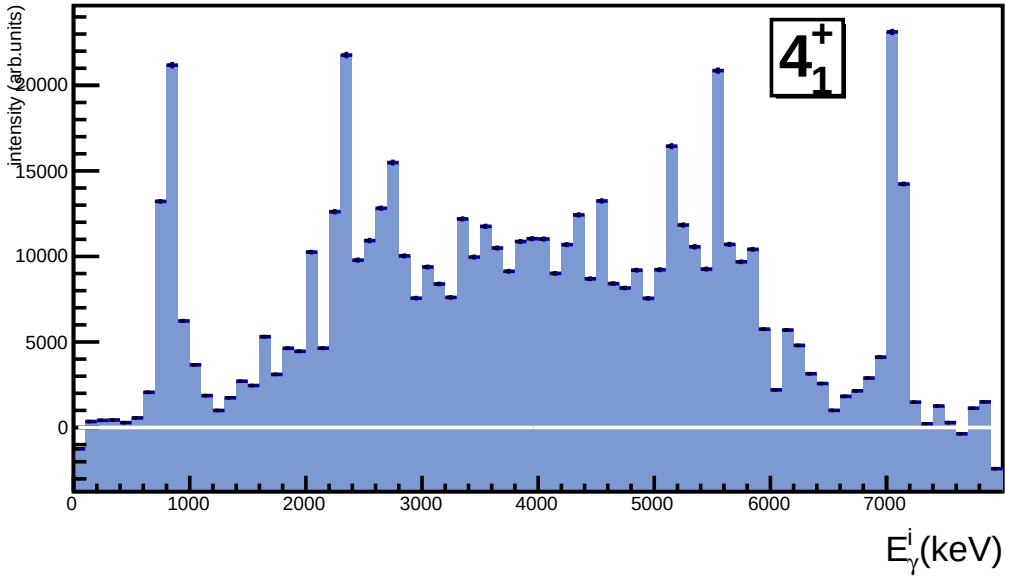
^{162}Dy TSC spectrum for 2_1^+ state

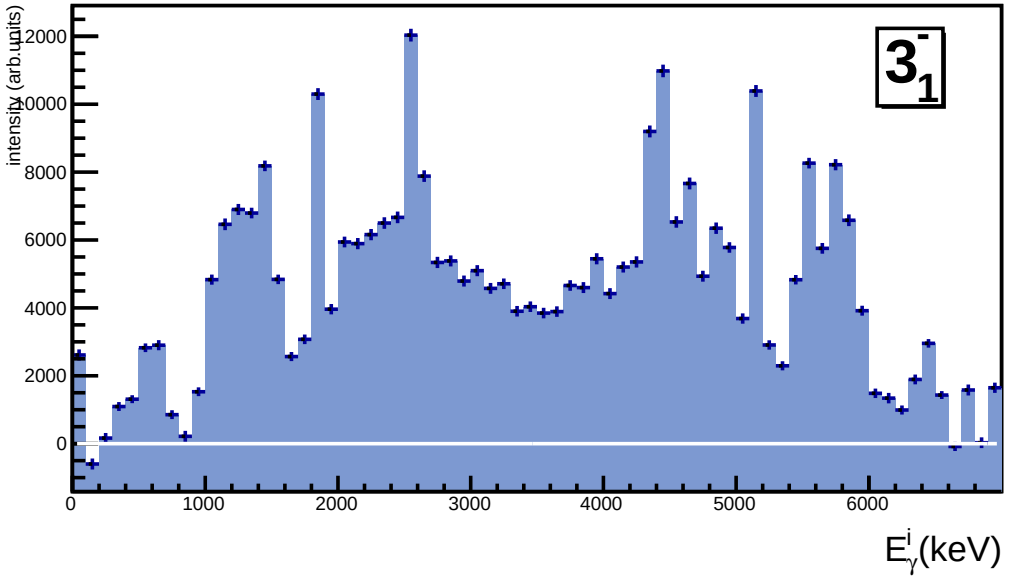


^{162}Dy binned TSC spectra

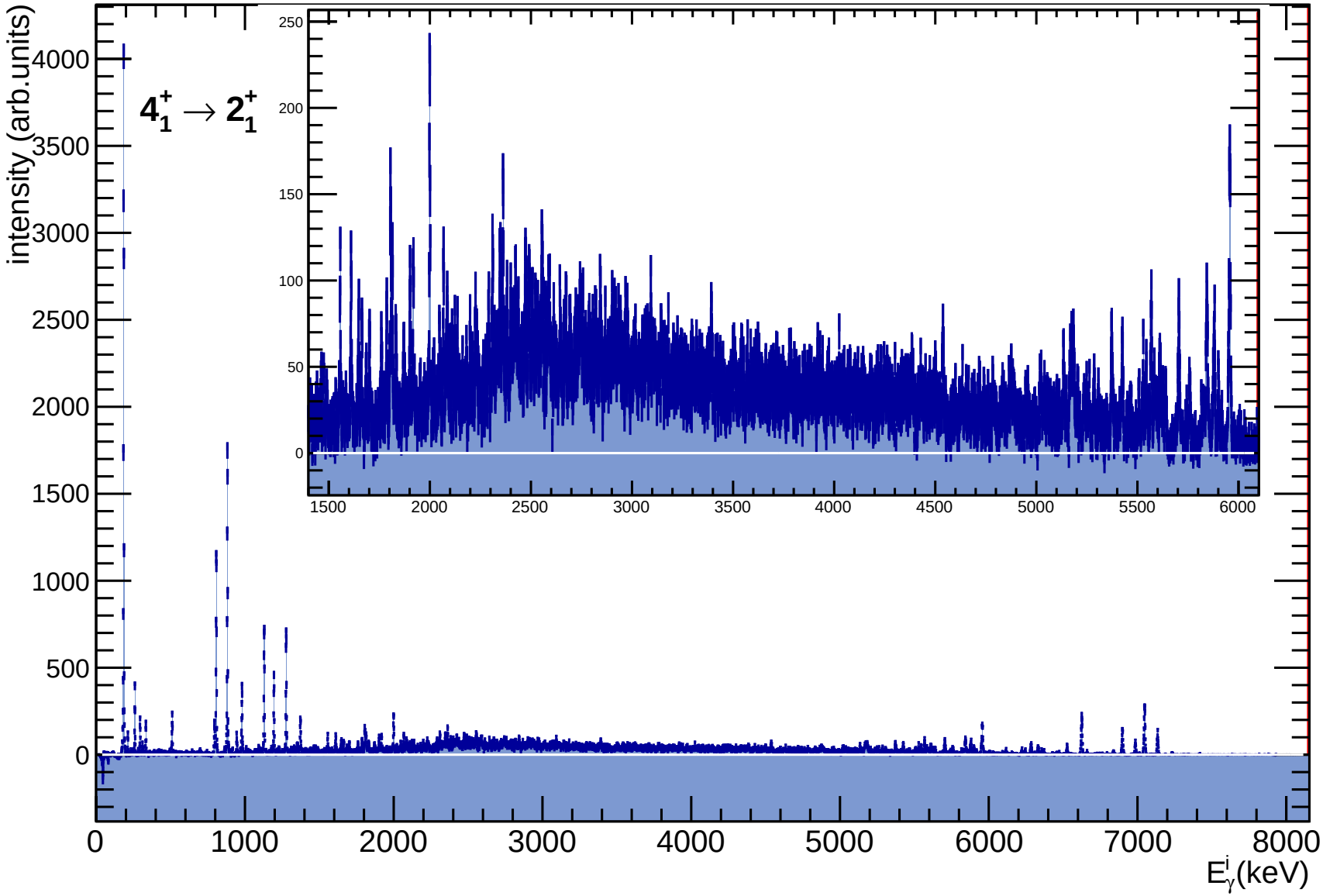




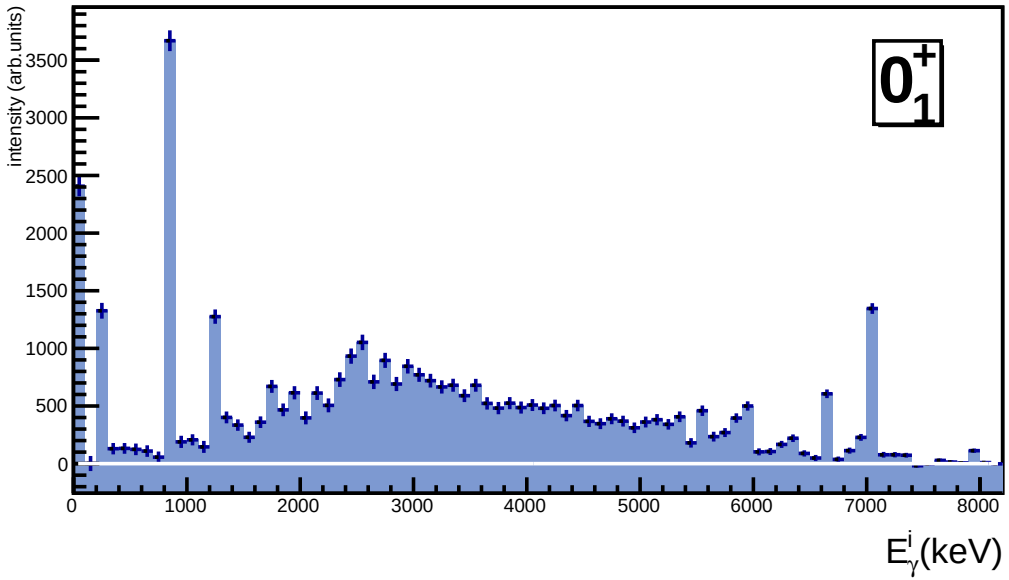


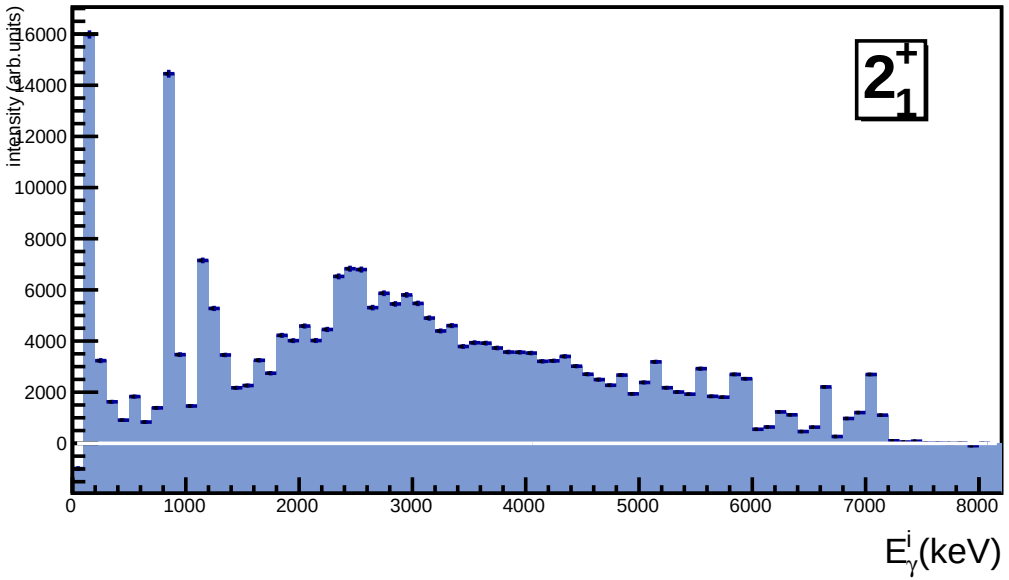


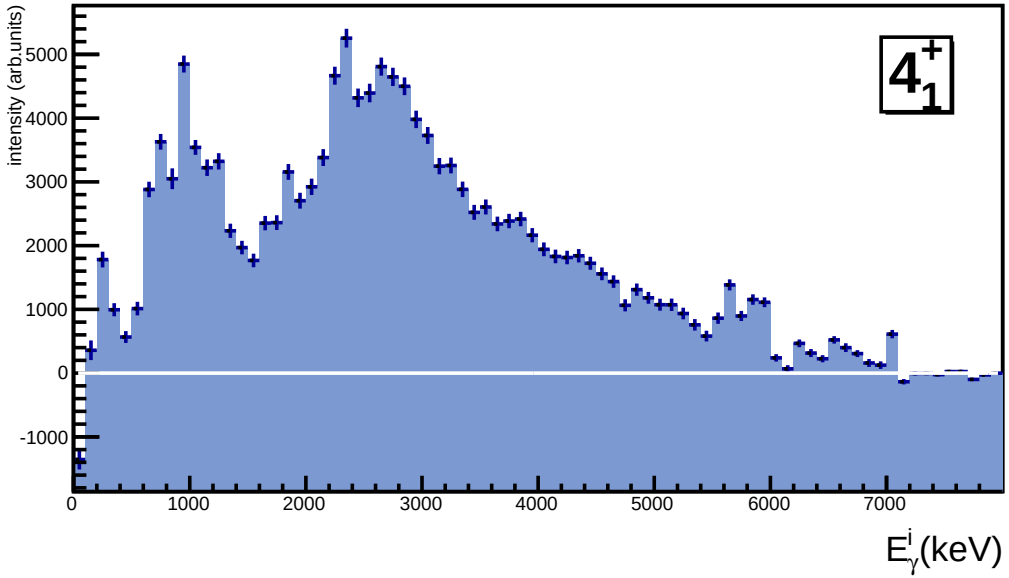
^{162}Dy 3SC spectrum for 2_1^+ state

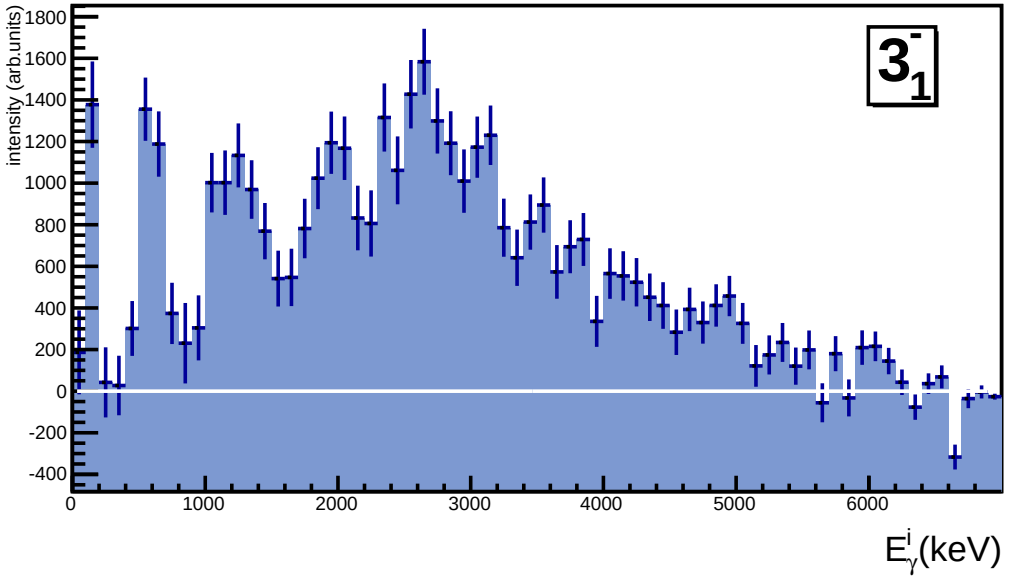


^{162}Dy binned 3SC spectra



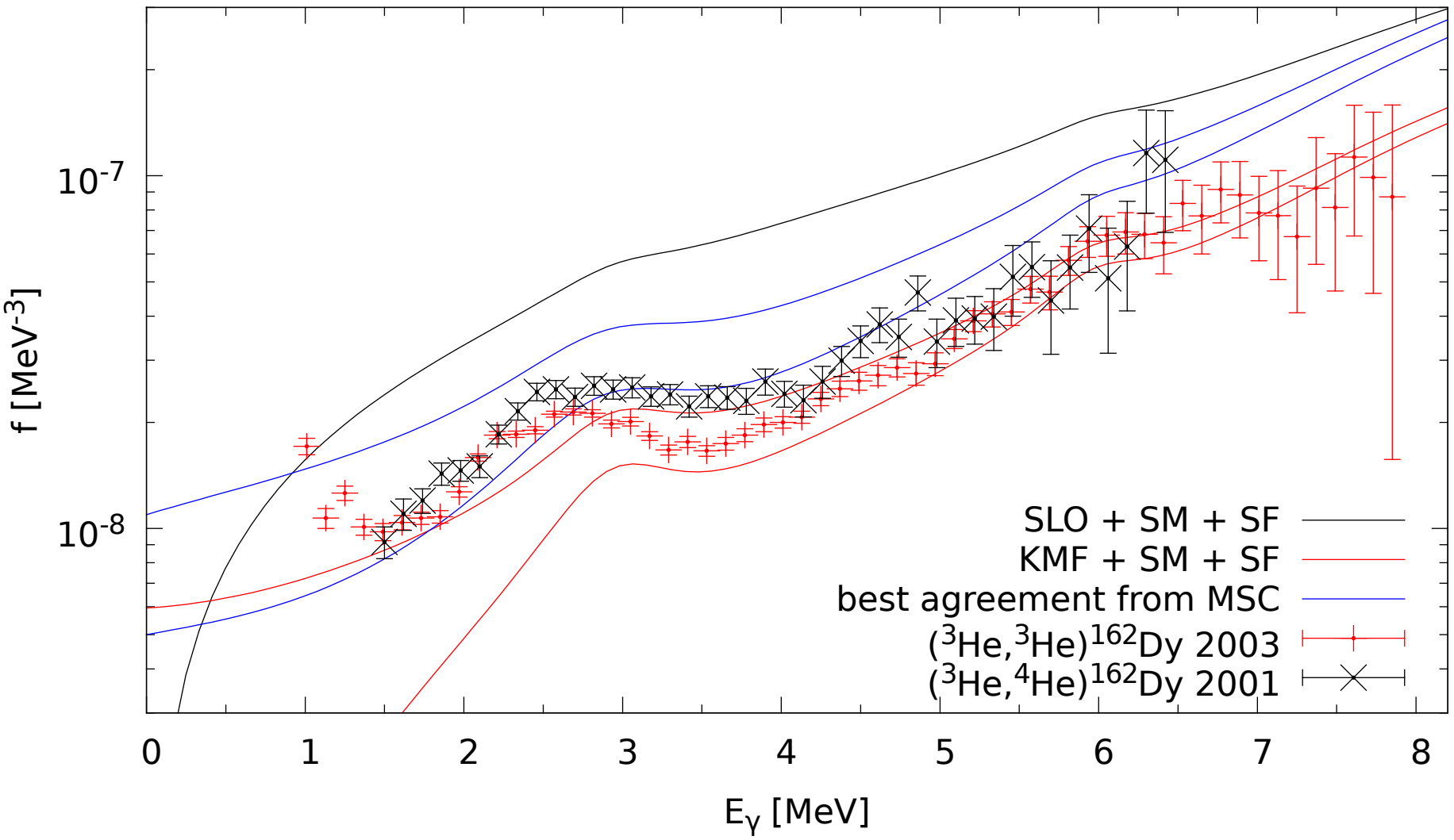






Conclusions

- both DANCE and EXILL delivered high quality data
- MSC spectra for ^{161}Dy are incredibly sensitive to M1/E1 balance at "low" E_γ
- Best agreement found so far - E1 in form of MGLO ($k_0 = 3$) with M1 SM at 3 MeV with strength $\sum B(M1) \uparrow = 5.8\mu_N^2$ and constant term $f_{\mathrm{M1}} = 5 \times 10^{-9}\mathrm{MeV}^{-3}$
- SM is built on all accessible states and follows Brink hypothesis


PSFs in 162Dy
f [MeV-3]
10-7
10-8
0
1
2
3
4
5
6
7
8
Eγ [MeV]
SLO + SM + SF
KMF + SM + SF
best agreement from MSC
(3He,3He)162Dy 2003
(3He,4He)162Dy 2001