^{169}Tm(n,γ) Cross Section and Statistical γ Decay Properties from DANCE Measurements*

I. Knapová[1], *K. Horčičková*[2], *A. Couture*[1], *C. Fry*[1], *F. Gunsing*[3], *T. Kawano*[1], *K. J. Kelly*[1], *M. Krtička*[2], *E. Leal Cidoncha*[1], *C. J. Prokop*[1], *R. Reifarth*[1], *G. Rusev*[1], *J. L. Ullmann*[1], *S. Valenta*[2]

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[2]Institute of Particle and Nuclear Physics, Charles University, Prague
[3]CEA Irfu, Université Paris-Saclay

Oslo Workshop, May 2026

Funding acknowledgments

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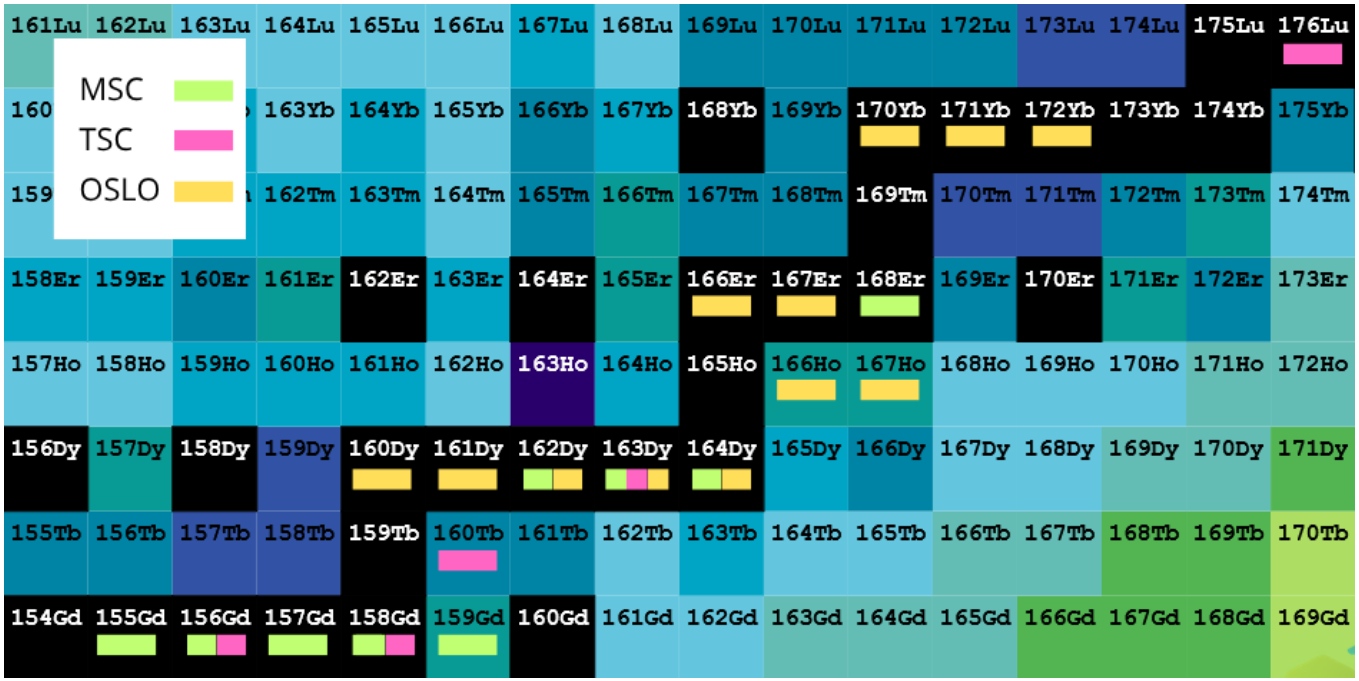
Why Thulium?

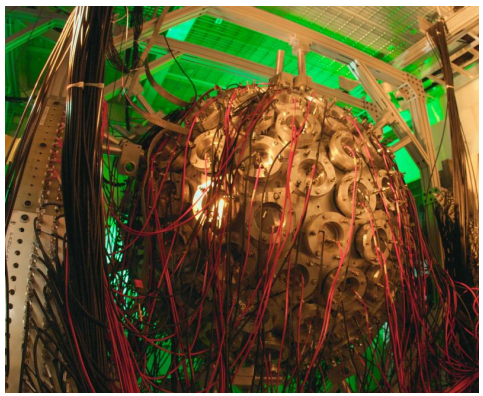
- Thulium - monoisotopic rare-earth element
- diagnostic tool for monitoring neutron flux
- astrophysical interest: nuclei synthesis around $A = 170$
- systematic study of the PSFs and LD in the region



Experiment

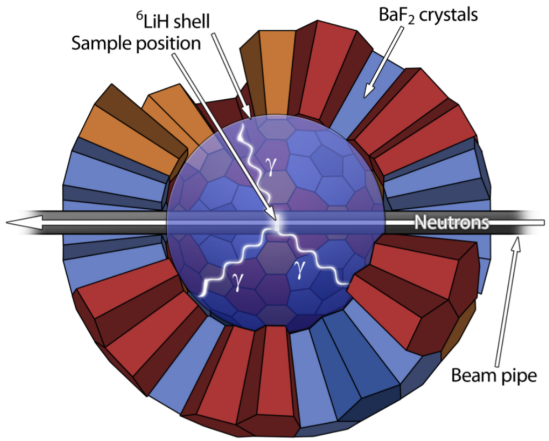
- data from Los Alamos National Laboratory (LANL)

- Detector for Advanced Neutron Capture Experiments (DANCE)



Experiment

- measuring $^{169}\mathrm{Tm}(n,\gamma)$
- neutron resonances: $J^\pi = 0^+, 1^+$
- DANCE:
  - 160 BaF_2 scintillation crystals
  - 20.25 m from the spallation target
  - covers $\approx 3.5\ \pi$ solid angle



cut through DANCE detector

- neutrons produced in a spallation reaction of 800-MeV protons striking a tungsten target
- neutron energies from sub-thermal to units of MeV

Analysis

Two parts of the analysis:

1. Kamila – Photon Strength Functions (PSFs)
   - compound nucleus ^{169}Tm+n
   - coincidence γ-ray spectra
   - collective states impact: scissors mode (SM)

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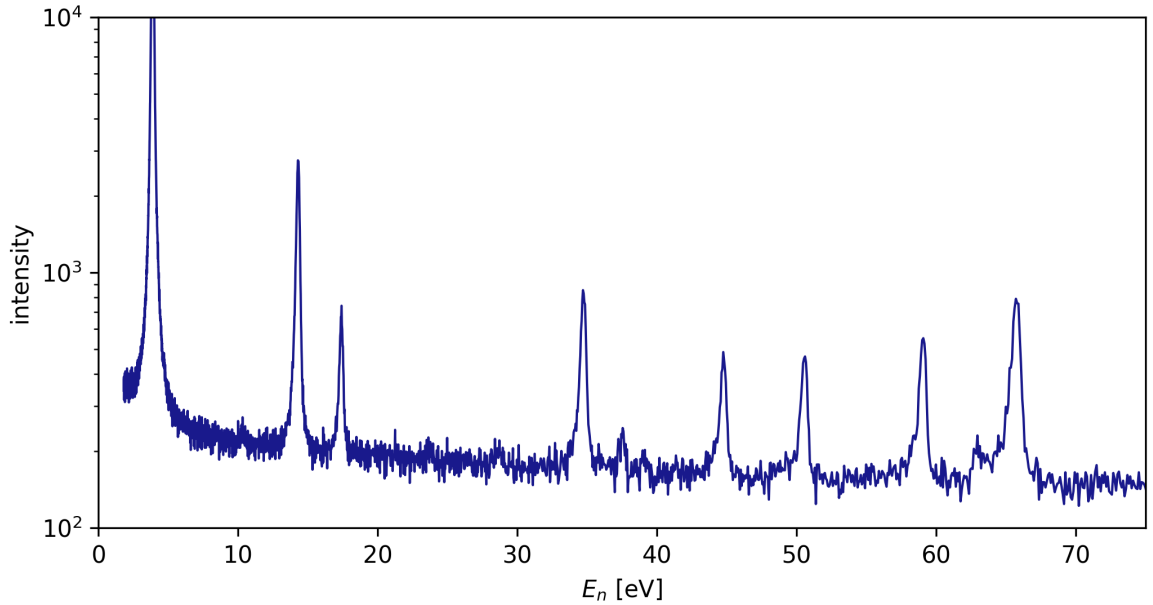

Basics of data processing

Each event is characterized by

1. neutron energy
2. detected multiplicity
3. deposited γ energies

$\rightarrow$ event-by-event sorting into various spectra

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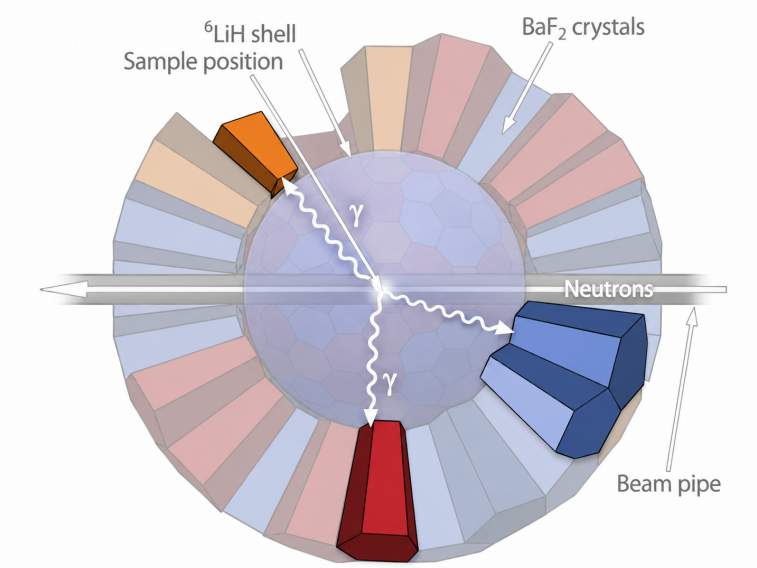

- neutron energies by the time-of-flight (TOF) method
- all signals detected within a preset coincidence window of 10 ns $\rightarrow$ one event
- all *neighboring* signals[a] form a cluster
- number of clusters: detected multiplicity M

[a] one γ ray may deposit energy in several detectors $\rightarrow$ clusterization

Multi-Step γ-ray Cascade spectra

MSC spectra are created from events

- with total deposited energy in narrow interval around $S_n = 6.592\,\text{MeV}$ (energy released in neutron capture)
- corresponding to strong, well-separated resonances
- sorted by multiplicity M ($\leftarrow$ good estimate of # of γ-rays)

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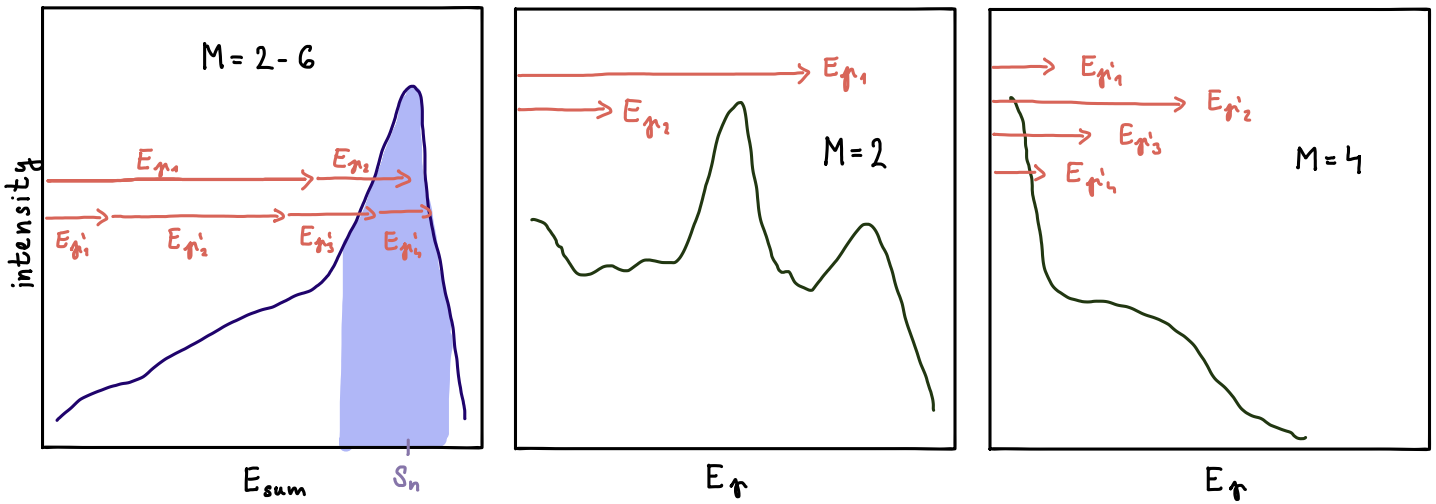
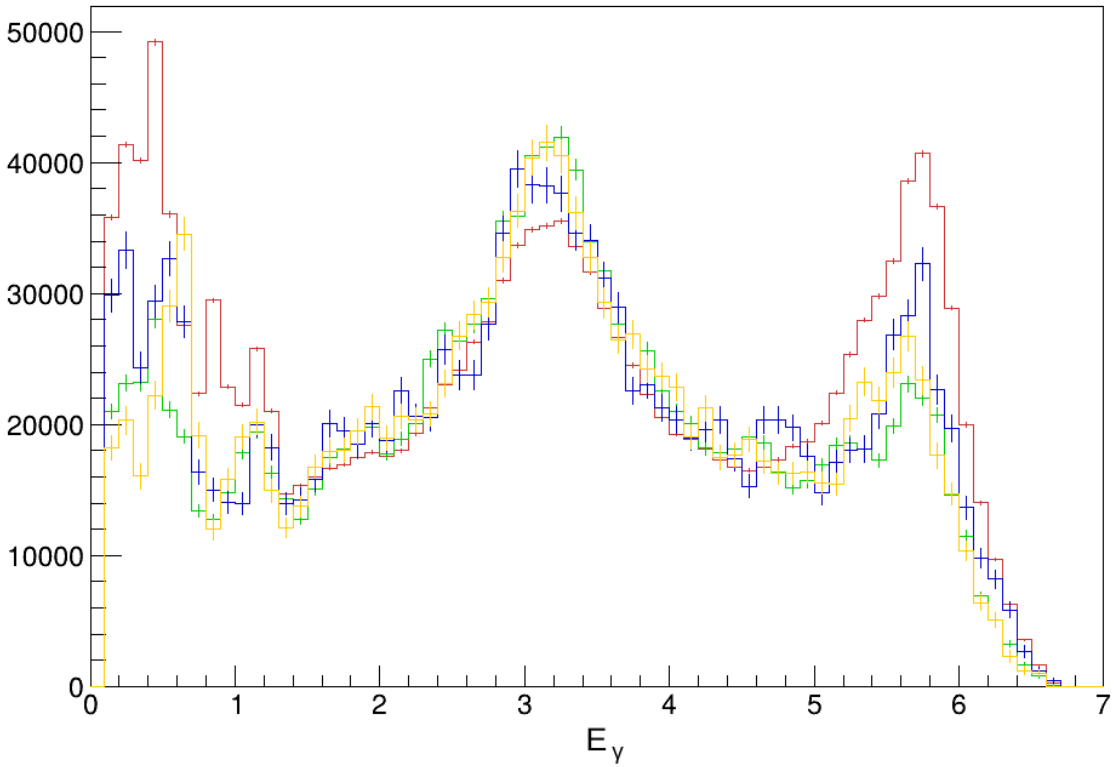
MSC spectra are distribution of E_γ for each M



19 $J^\pi = 1^+$ and **6** $J^\pi = 0^+$ resonances $\rightarrow$ average spectra for each spin group

MSC spectra

- Porter-Thomas fluctuations $\Rightarrow$ spectra from individual resonances slightly different, but show similar features
- between spin groups statistically significant differences but again similar features



MSC spectra of few 1^+ resonances, $M = 2$

Simulations

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2. GEANT4 simulation[2,3] of the detector response
3. compare spectra, assess compatibility, rinse and repeat

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Models from literature

The following are available for odd-odd compound:

- PSF parameters from Oslo analysis ^{166}Ho[1]
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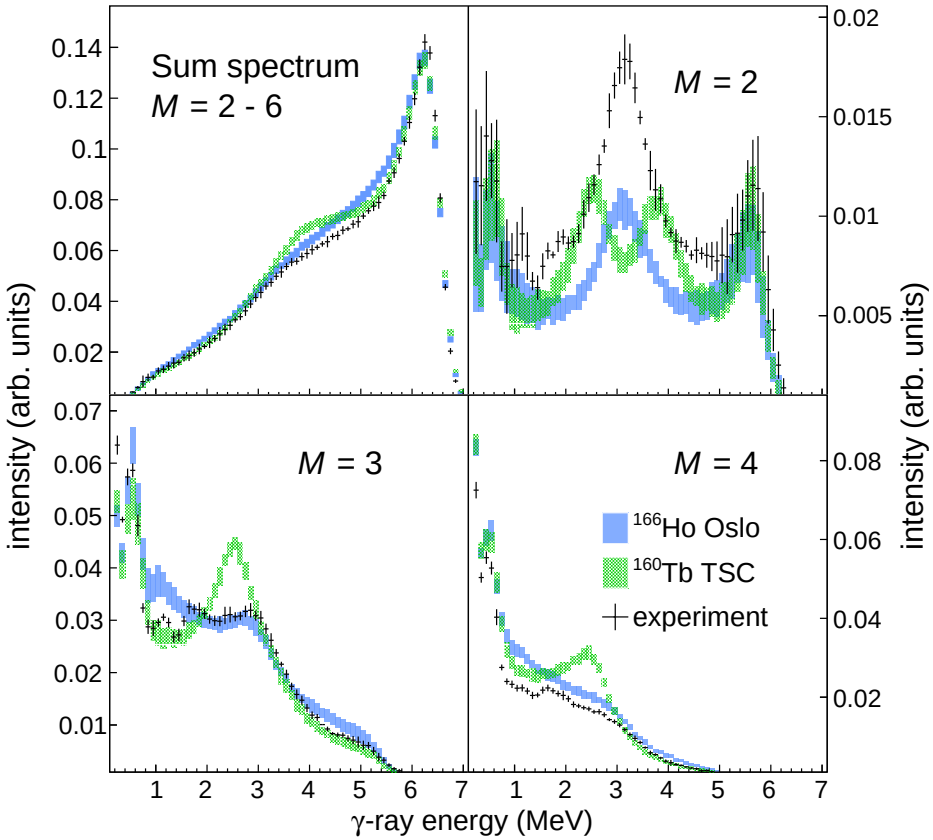
- global calculations from IAEA PSFs database: D1M-QRPA, SMLO

→ unsatisfactory description



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- SM energy at about 3.3 MeV (surely in 3.0-3.5 MeV)
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Level Density conclusions:

- BSFG model preferred w.r.t. CT or microscopical HFB
- no indication of parity asymmetry or other fine effects

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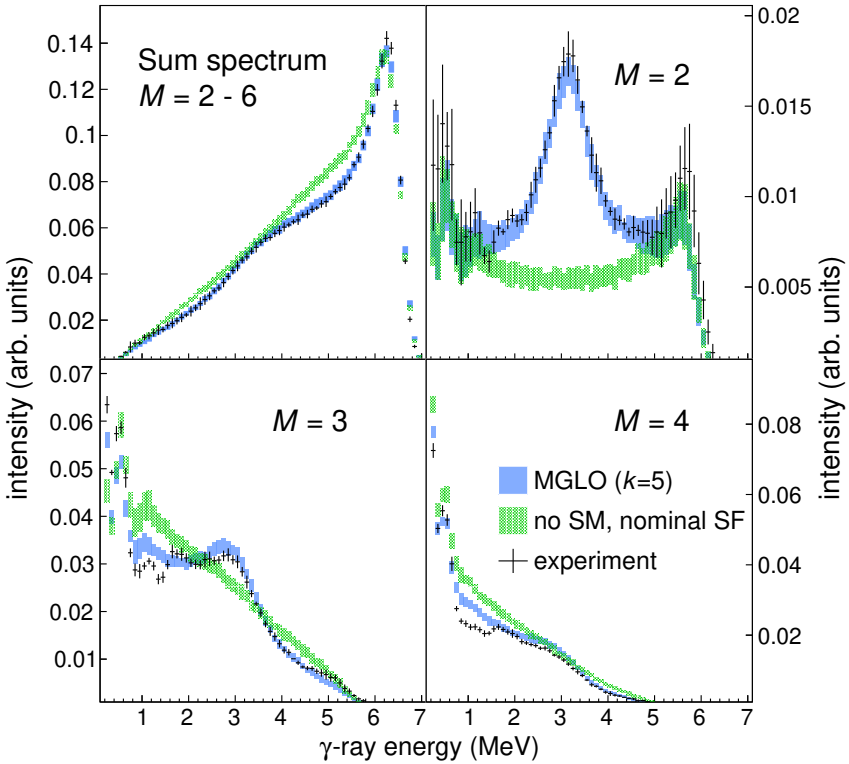

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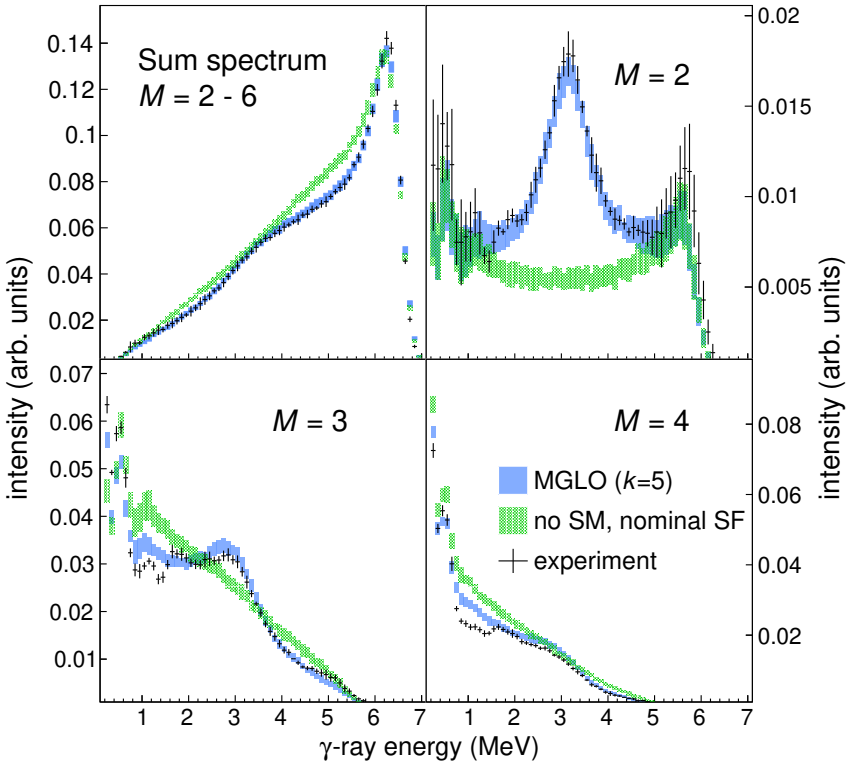
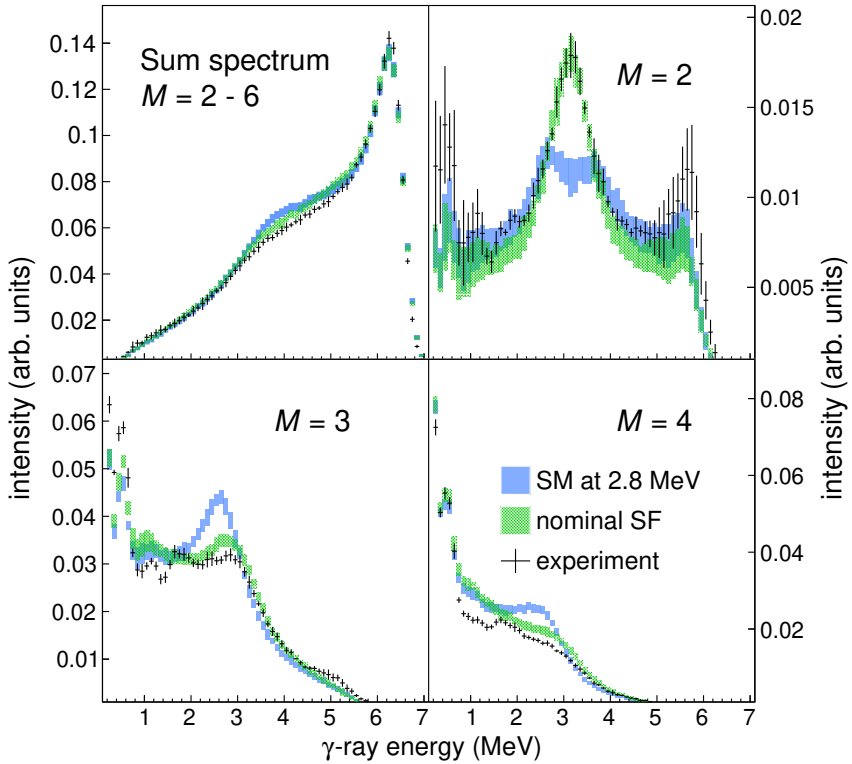
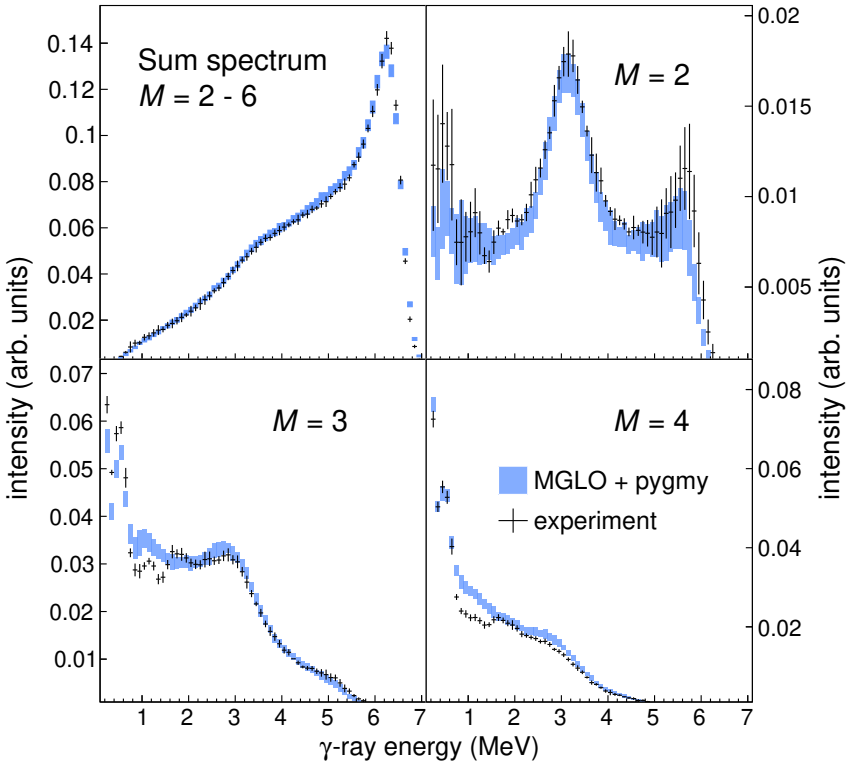
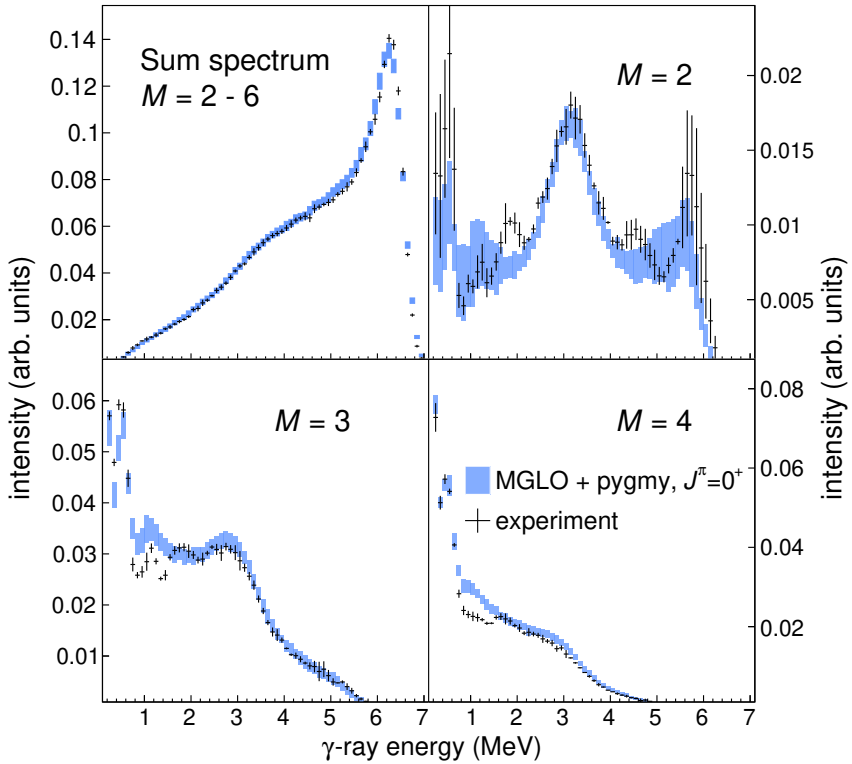




Consistency for both resonance spins





Best description

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- SM at 3.3 MeV, width 1.0 MeV, strength 6(1) μ_N^2
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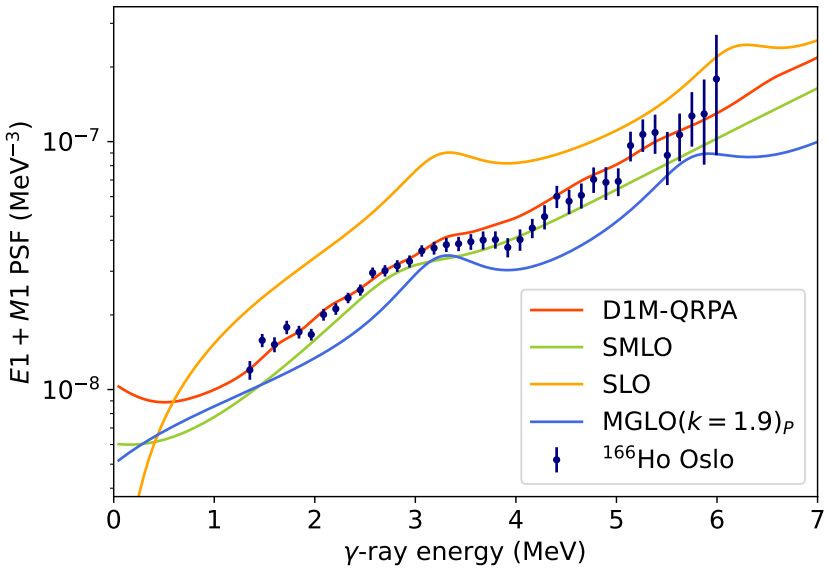

- other $E1$ PSFs giving acceptable description: KMF, SLO

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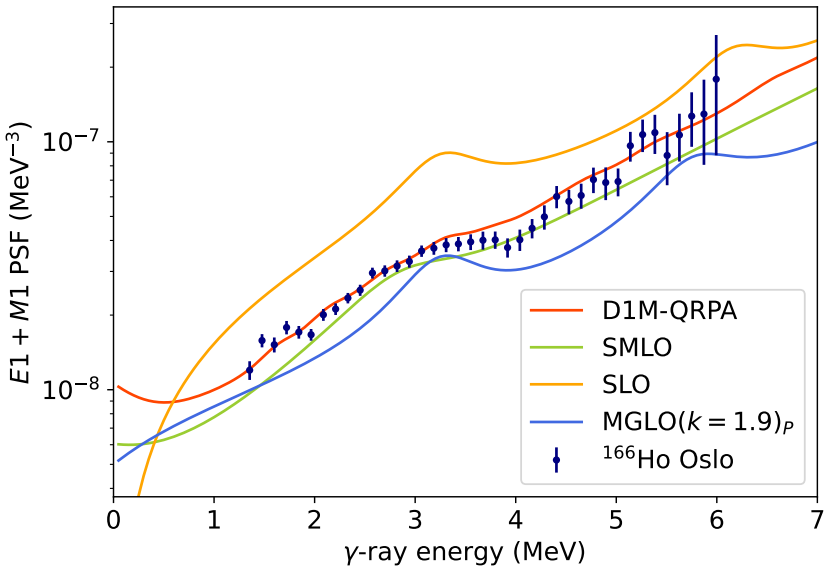
Total radiative width

- MSC are not sensitive to the absolute scale of PSFs, total radiative width $\overline{\Gamma}_\gamma$ is the only quantity which is sensitive
- value from the literature ENDF/B-VII.0: $\overline{\Gamma}_\gamma = 86\,\text{meV}$
- MGLO $E1$ PSF parametrized to reproduce this value



model comb.	$\overline{\Gamma}_\gamma$ (meV) $J^\pi = 0^+$	$J^\pi = 1^+$
SLO	231(5)	
MGLO(k=1.9)$_P$	92(2)	
KMF	90.5(15)	
D1M-QRPA	37.2(35)	175(5)
SMLO	30.9(26)	146(4)

Cross-section

Measured for energies between 1.8 eV to 0.97 MeV using 2 samples (thin and thick) with $n = 6.9 \times 10^{-6}$ and 1.7×10^{-4} atoms/b.

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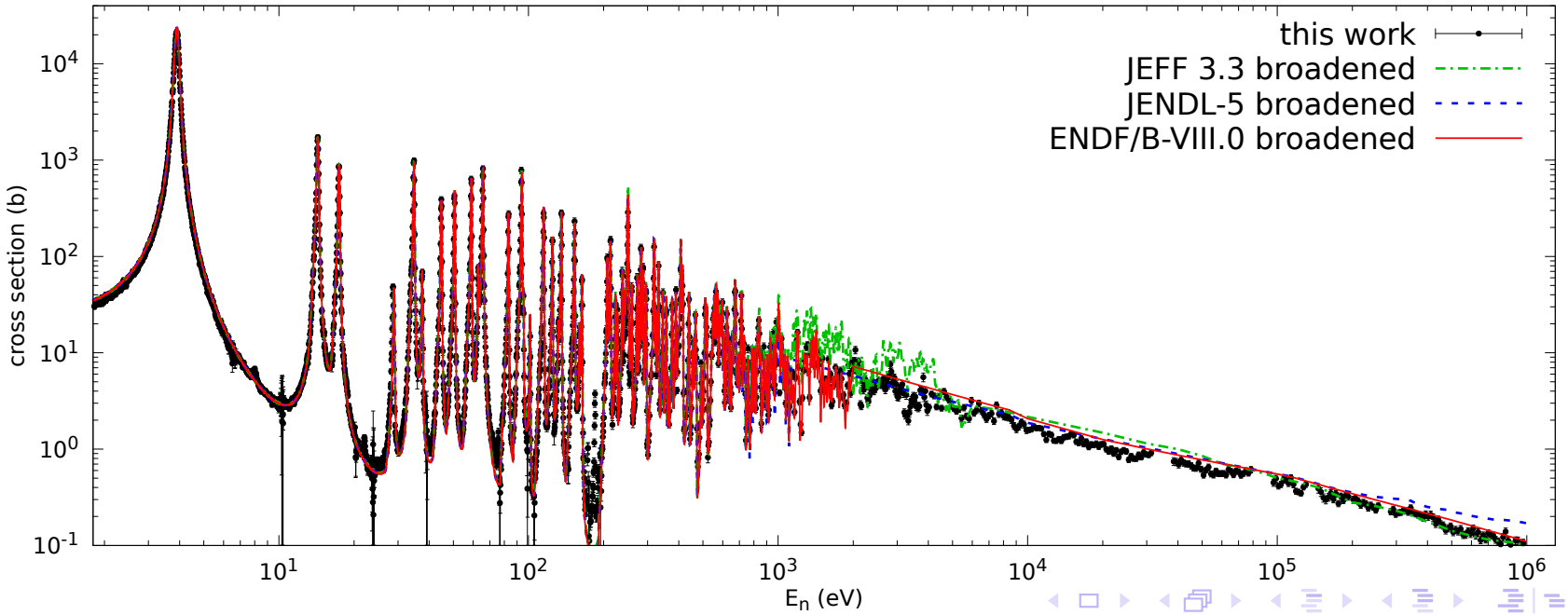
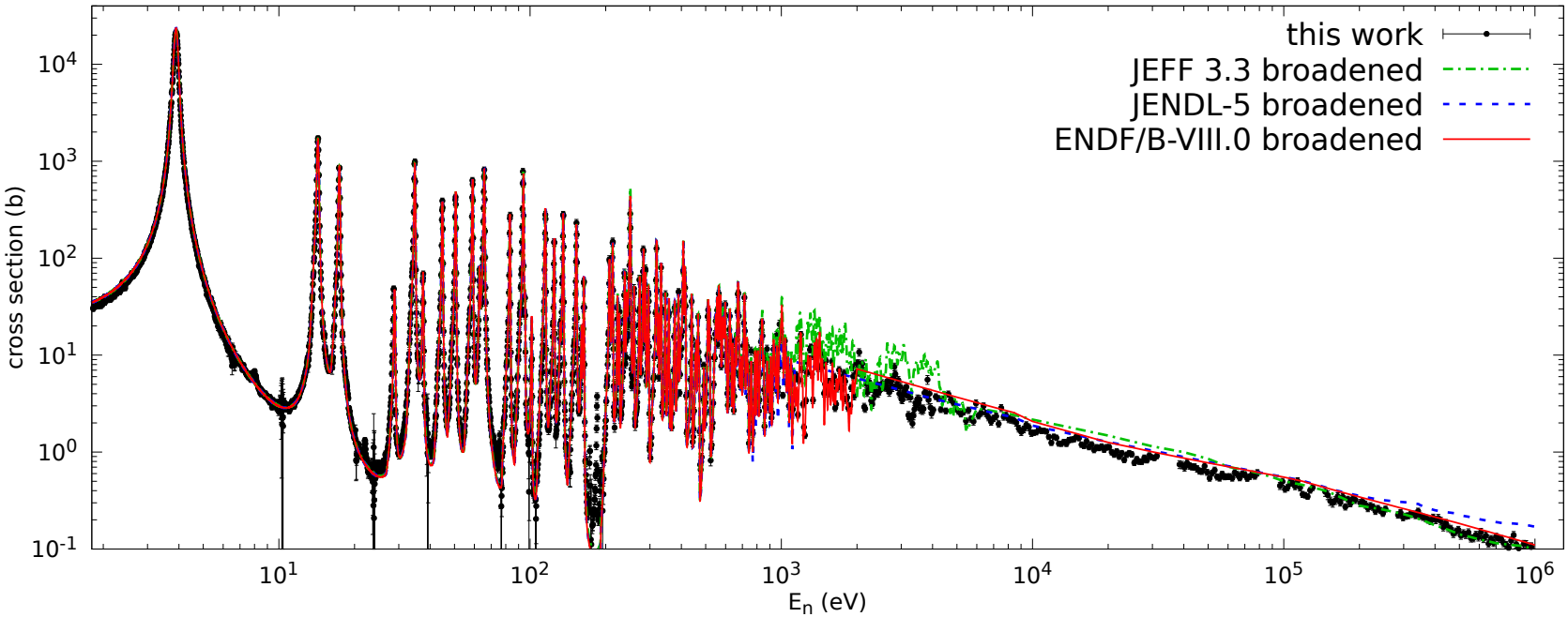


Comparison with evaluations



- up to ≈ 700 keV all almost identical, good description
- in RRR above 1 keV ENDF/B-VIII.0 agrees best
- in URR largest discrepancy between 10 and 100 keV
- above 100 keV JEFF 3.3 consistent, ENDF/B-VIII.0 slightly and JENDL-5 considerably higher

New resonances

- altogether eight new resonances
- energy and $g\Gamma_n$ estimation by SAMMY fit with $\Gamma_\gamma = 86\,\text{meV}$ (average Γ_γ from ENDF/B-VIII.0)

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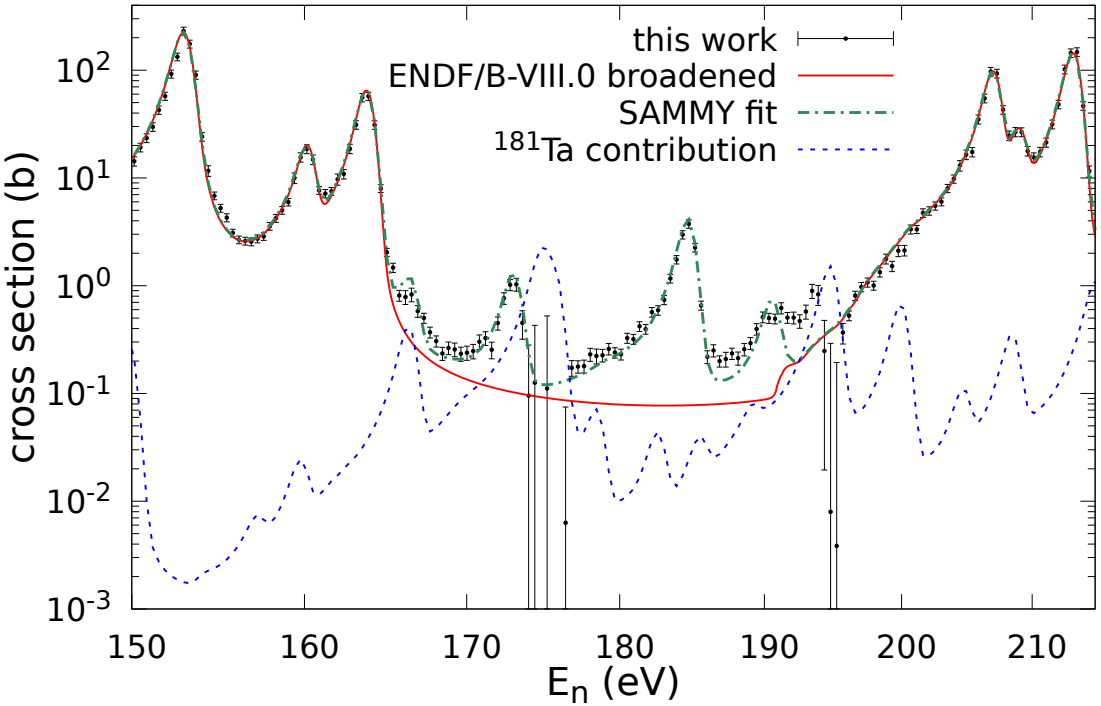
E_R (eV)	$g\Gamma_n$ (meV)
8.037(6)	0.00072(4)
22.03(1)	0.00141(6)
71.85(2)	0.0136(7)
75.57(2)	0.0199(8)
166.46(4)	0.055(8)
173.07(5)	0.086(12)
184.69(2)	0.316(8)
190.61(4)	0.056(3)



new resonance structures at $E_n = 170 - 200\,\text{eV}$

Astrophysical implications

- Maxwellian-averaged capture cross-section (MACS)

$$\sigma_{MACS}(k_B T) = \frac{2}{\sqrt{\pi}} \left(\frac{\mu}{k_B T} \right)^2 \int_0^\infty \sigma(E_n) E_n e^{-\frac{E_n}{k_B T}} d(E_n)$$

- direct impact on astrophysical nucleosynthesis reaction rates

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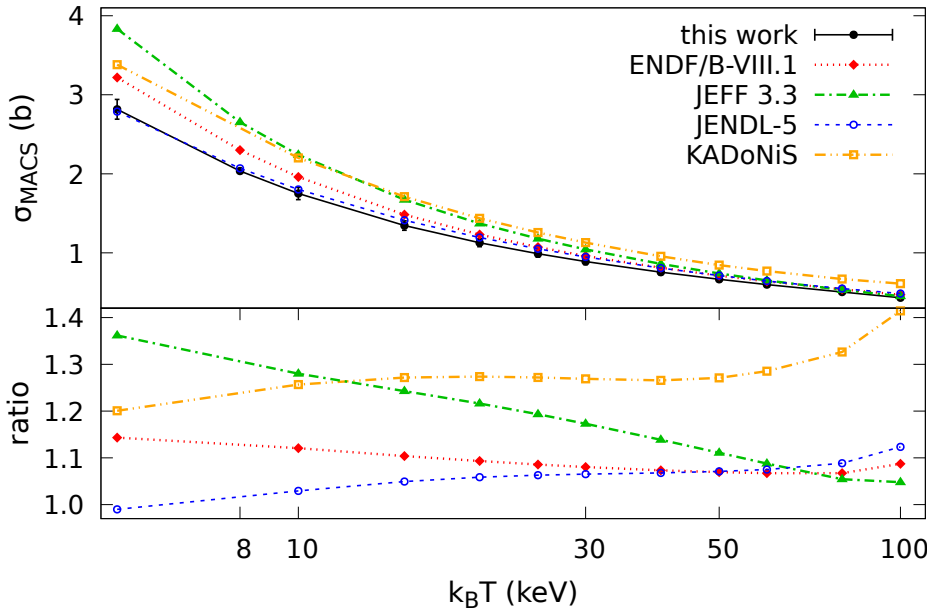
s-process simulation network with NETZ[1]:

- ^{169}Tm abundance increase by 26 %
- changes of the abundances of elements heavier than ^{169}Tm are in the order of 0.2 %

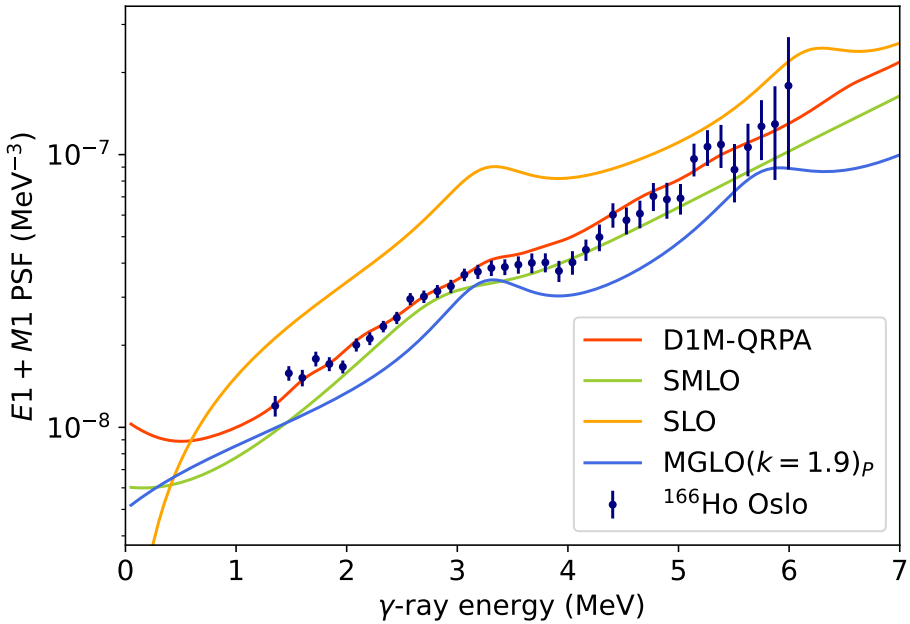


MACS numerically integrated for $k_B T = 5 - 100$ keV

[1] M. Weigand et al. In: *Phys. Rev. C* 92 (2015), p. 045810

Conclusions

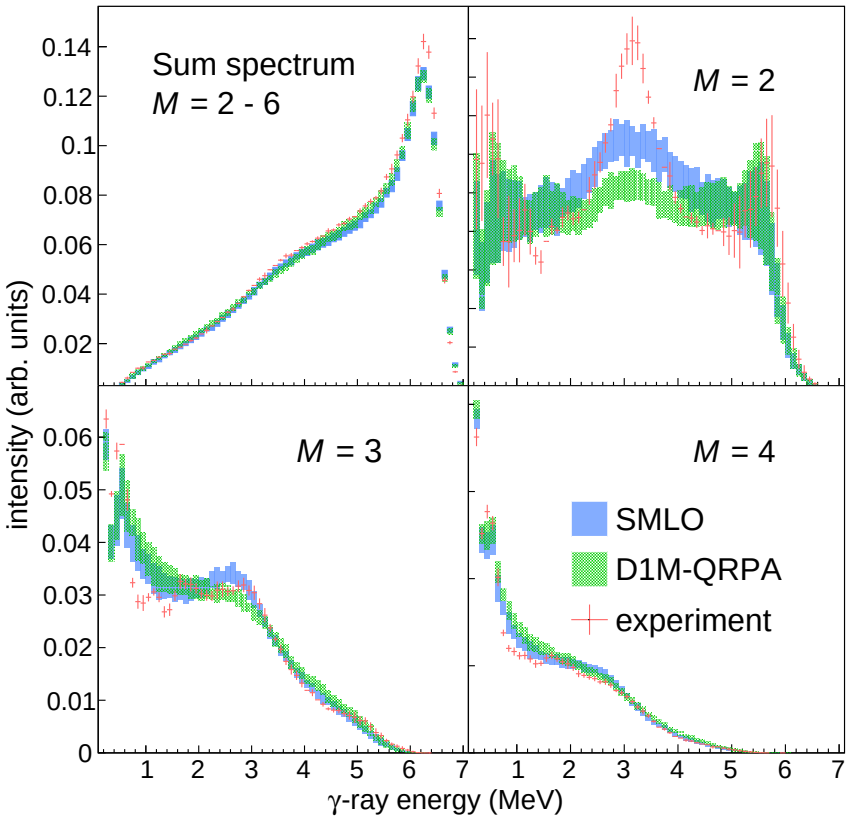
- disagreement of experimental data and previously proposed PSF models
- most successful $E1$ PSF model: MGLO
- necessary to include: SM, SF, and Pygmy
- BSFG level density model preferred



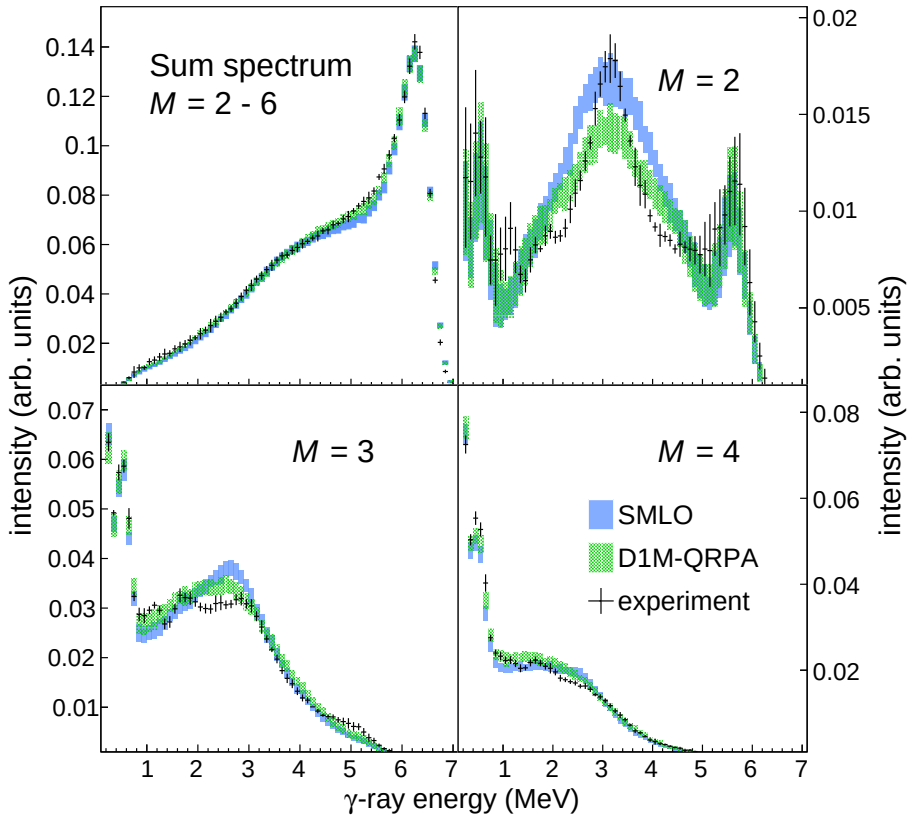
- cross-section measured from 1.8 eV to 0.97 MeV

back-up

BSFG LD model

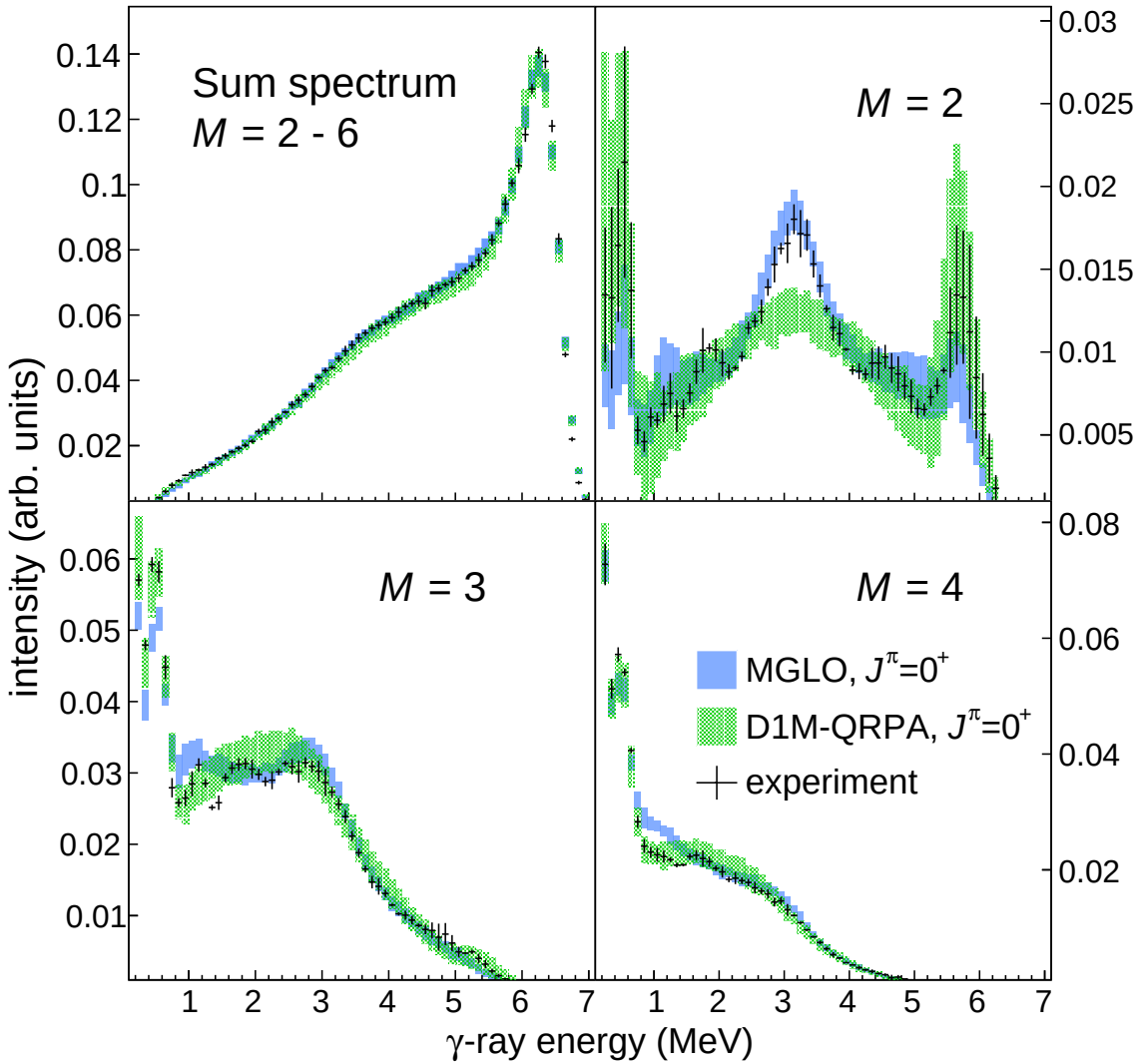


HFB microscopic LD model



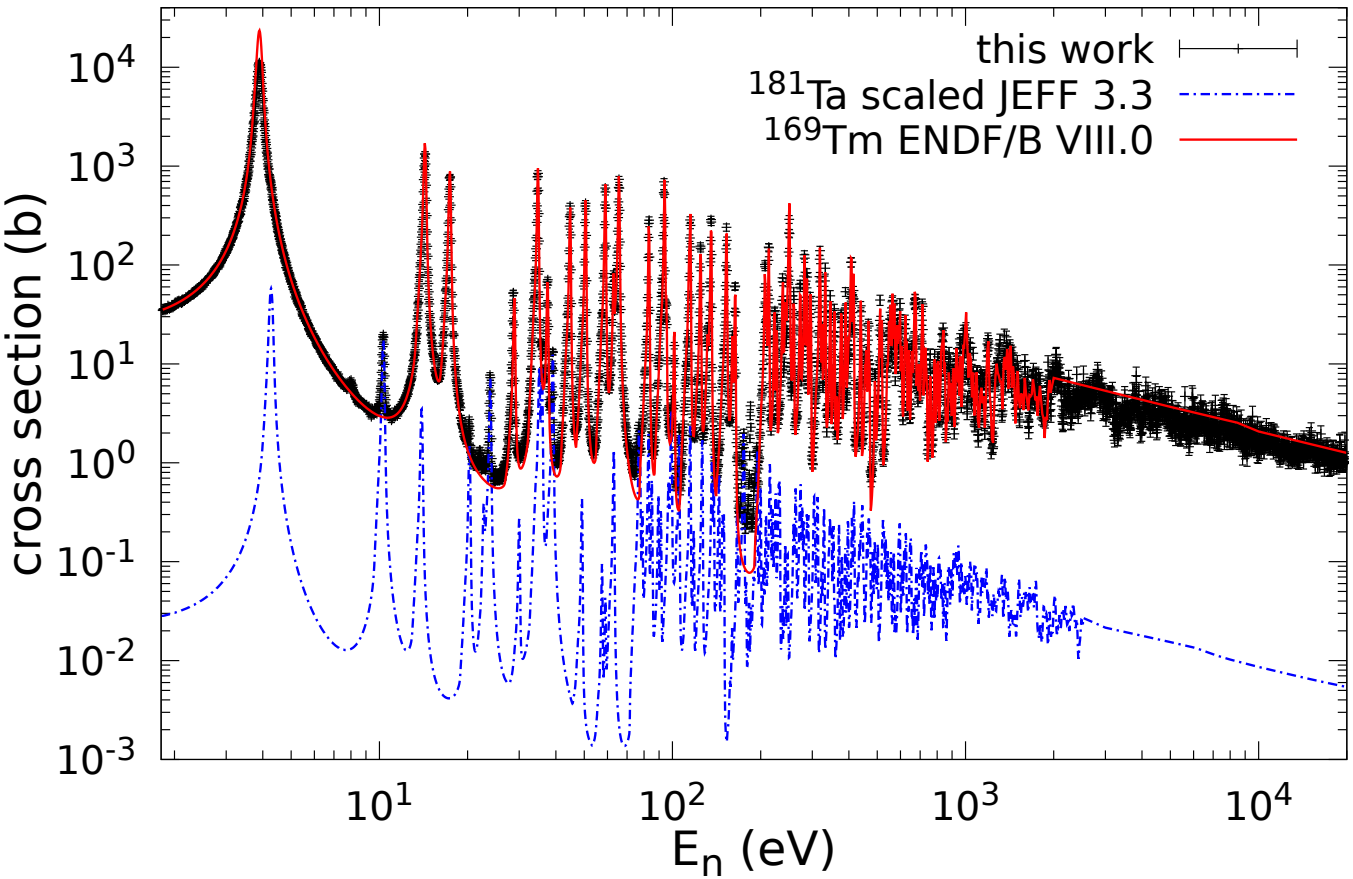
Back-up

D1M-QRPA $J^{\pi} = 0^{+}$



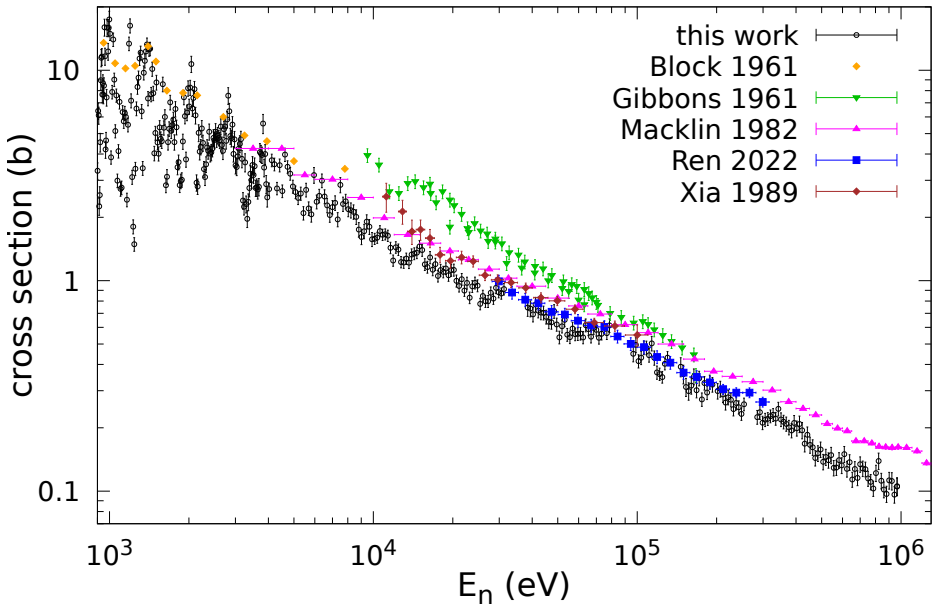
Back-up

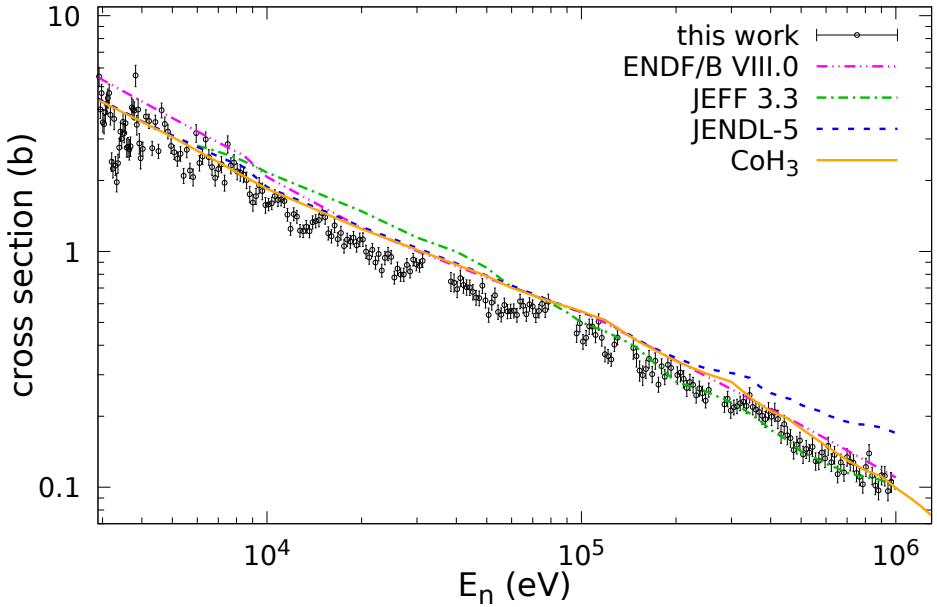
^{181}Ta impurity



Back-up

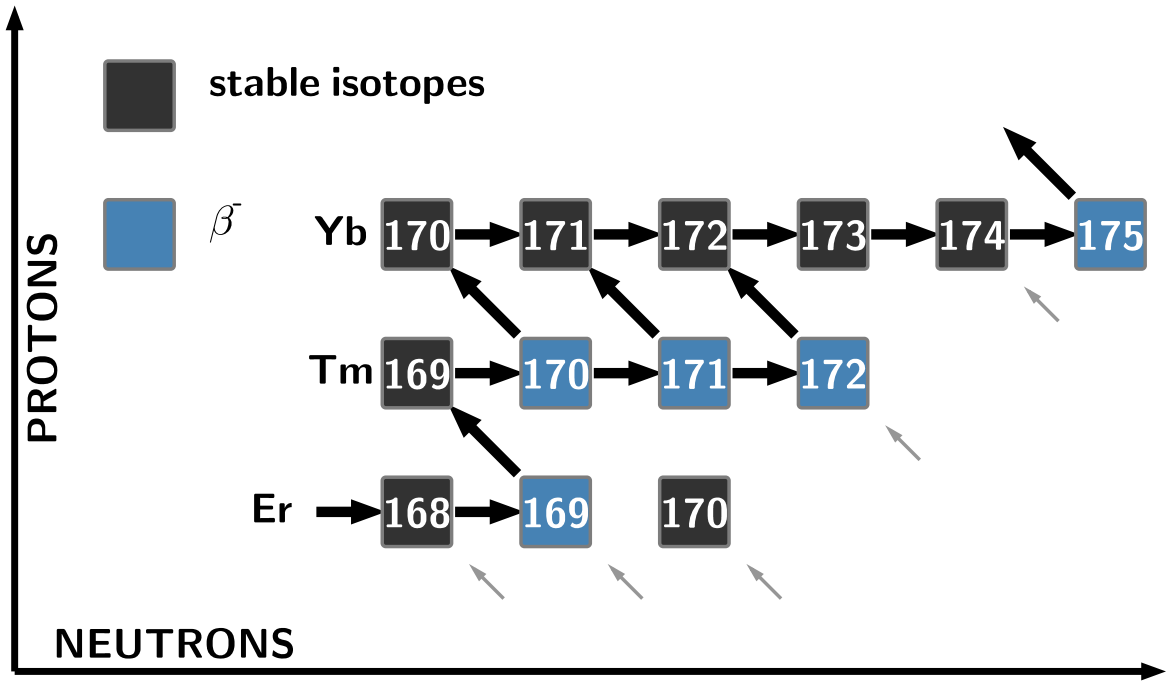
URR


this work
Block 1961
Gibbons 1961
Macklin 1982
Ren 2022
Xia 1989
cross section (b)
10
1
0.1
10^3
10^4
10^5
10^6
E_n (eV)


this work
ENDF/B VIII.0
JEFF 3.3
JENDL-5
CoH_3
cross section (b)
10
1
0.1
10^4
10^5
10^6
E_n (eV)

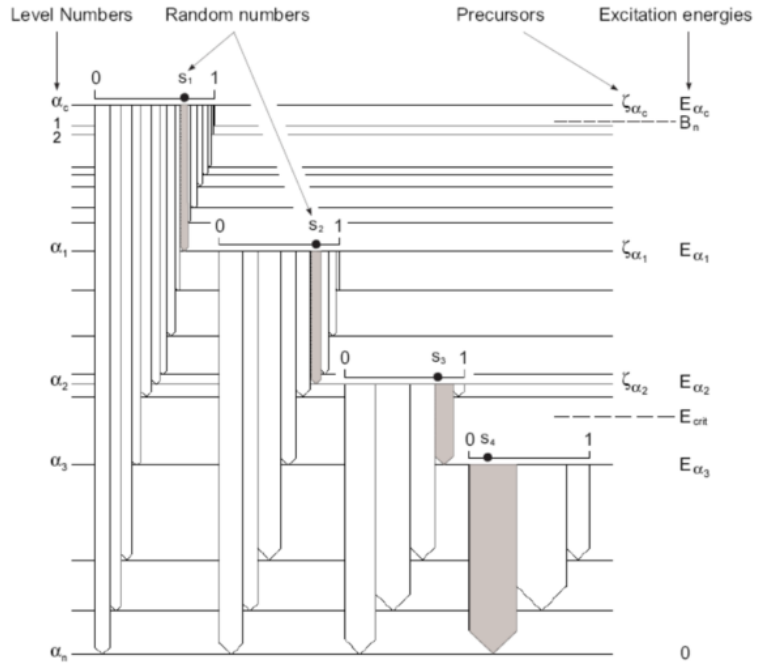
Back-up

s-process



Back-up – simulations of γ cascades

- various PSF and LD model parameters as input
- validity of the statistical model of γ decay above $E_{\mathrm{crit}} = 960\,\mathrm{keV}$
- individual radiative width properties:
  - statistically independent
  - follow the Porter-Thomas (PT) distribution
- impact of PT fluctuations - 20 different artificial nuclei
- within each artificial nucleus 10^5 cascades



- below E_{crit}: decay scheme from ENSDF[1]

[1] C. M. Baglin et al. In: *Nucl. Data Sheets* 153 (2018), pp. 1–494

Back-up

correlation matrix for simulated MSC spectra