

DE LA RECHERCHE À L'INDUSTRIE



STUDY OF THE PHOTON STRENGTH FUNCTION AND LEVEL DENSITY IN THE GAMMA DECAY OF $n+^{234}U$

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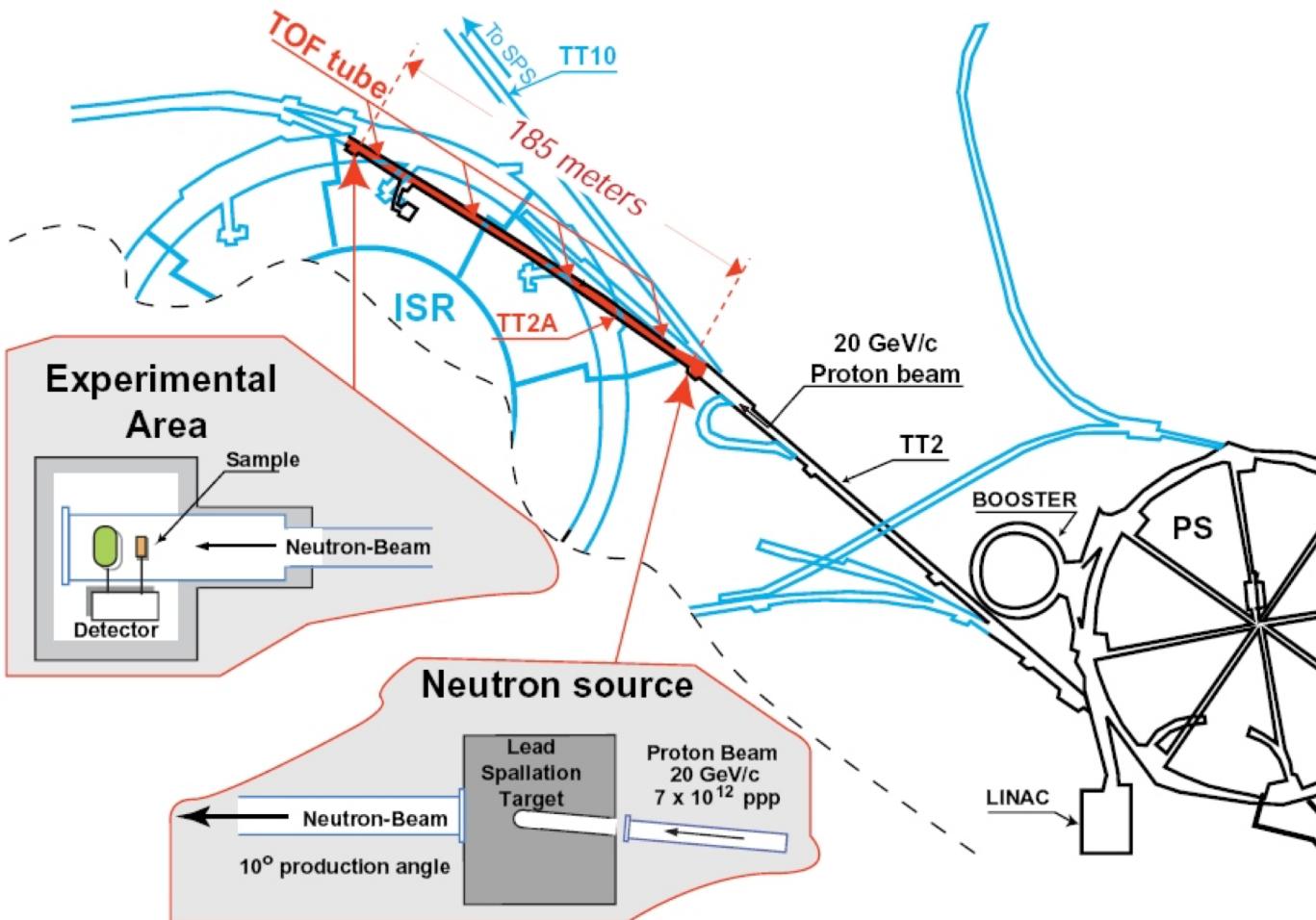
OUTLINE

- Introduction
 - *The n_TOF facility at CERN*
 - *The Total Absorption Calorimeter*
 - *Observables*
- Experimental data
 - *Resonance Spectra*
 - *Deposited Energy Spectra*
 - *Resonances Comparison*
- Simulation
 - *DICEBOXC*
 - *GEANT 4*
- Result: Comparison of simulations and measurements
- Conclusions
- Outlook

Motivation

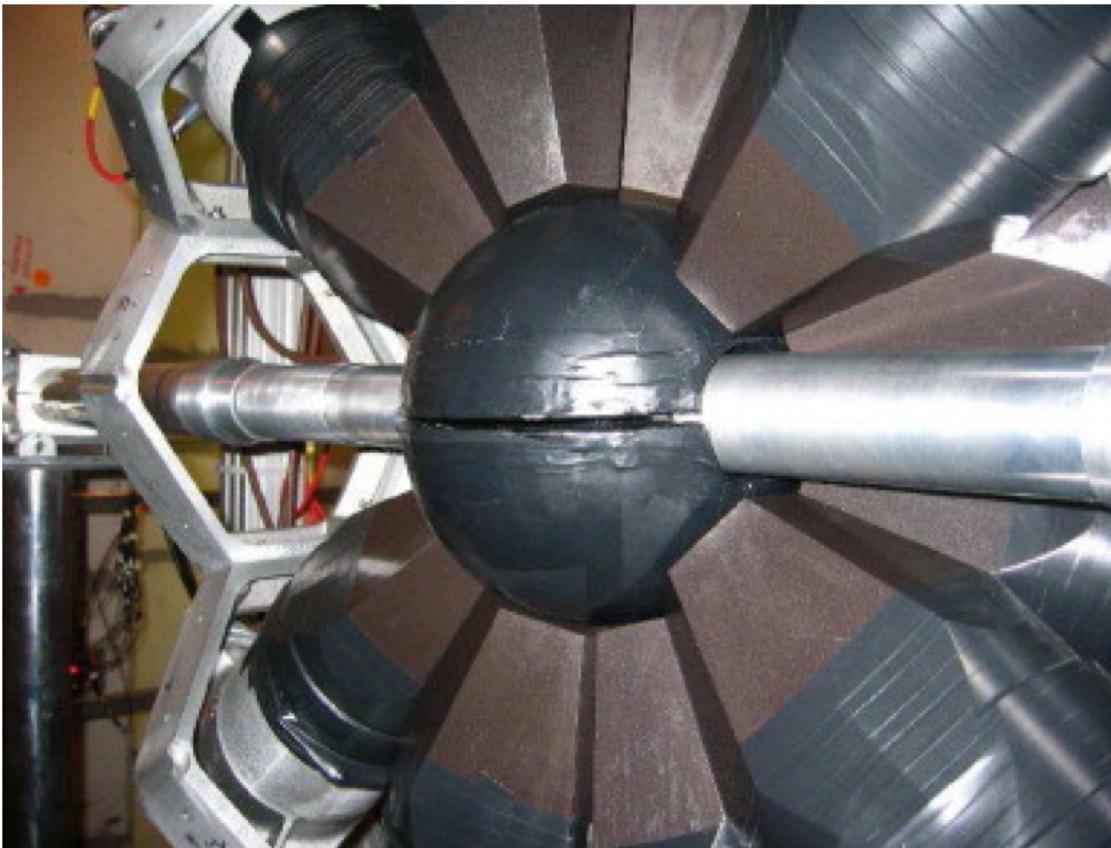
- Photon strength functions and level densities are fundamental to calculate the cross section and to model the γ -decay processes in neutron capture.
- Validating the simulation models and parameters thanks to the data measured with the TAC.
- Applications in nuclear astrophysics and nuclear technologies.

The n_TOF facility at CERN



- The proton beam.
- The spallation target.
- The TOF beam line or neutron tube.
- The experimental area.

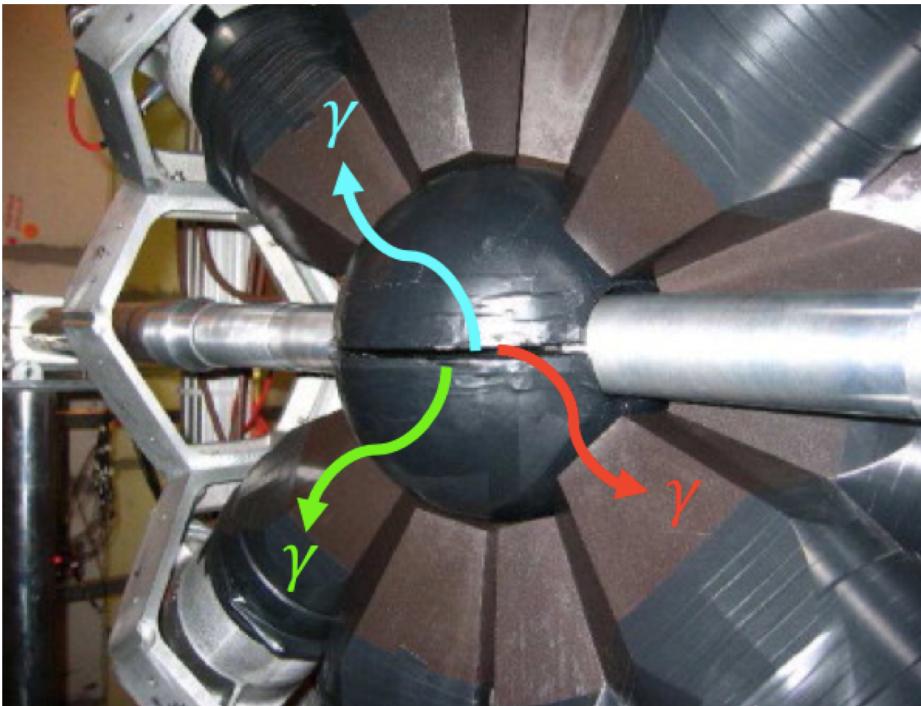
The Total Absorption Calorimeter (TAC)



- 40 BaF₂ crystal to form a detector with 4π solid angle coverage.
- Efficiency of nearly 100% which allows detecting almost all γ -rays emitted from the sample.
- Two layers of neutron absorber materials between the sample and the crystal.

Observables

- The cascade events are reconstructed by taking γ -rays detected in the BaF₂ detectors in a time coincidence window. You can get:



- The resonance spectrum given by the neutron energy, E_n , calculated by the time of flight.
- The crystal multiplicity distribution, m_{cr} , given by the number of hit crystals in each cascade event.
- The multi-step cascade spectra and the total deposited energy spectra for each cascade event, E_{Sum} .

$$E_{Sum} = E_1 + E_2 + E_3 \sim S_n + E_n$$

$$m_{cr} = 3$$

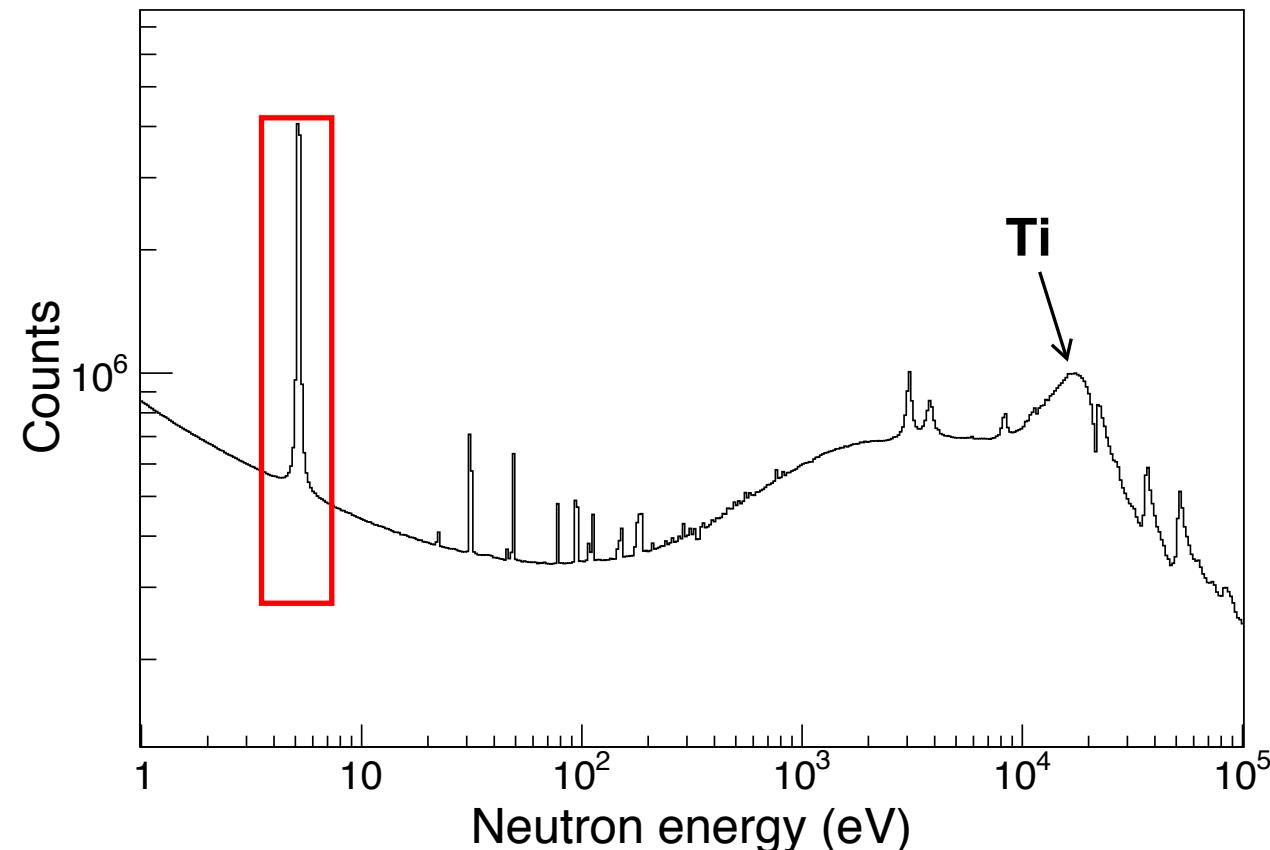
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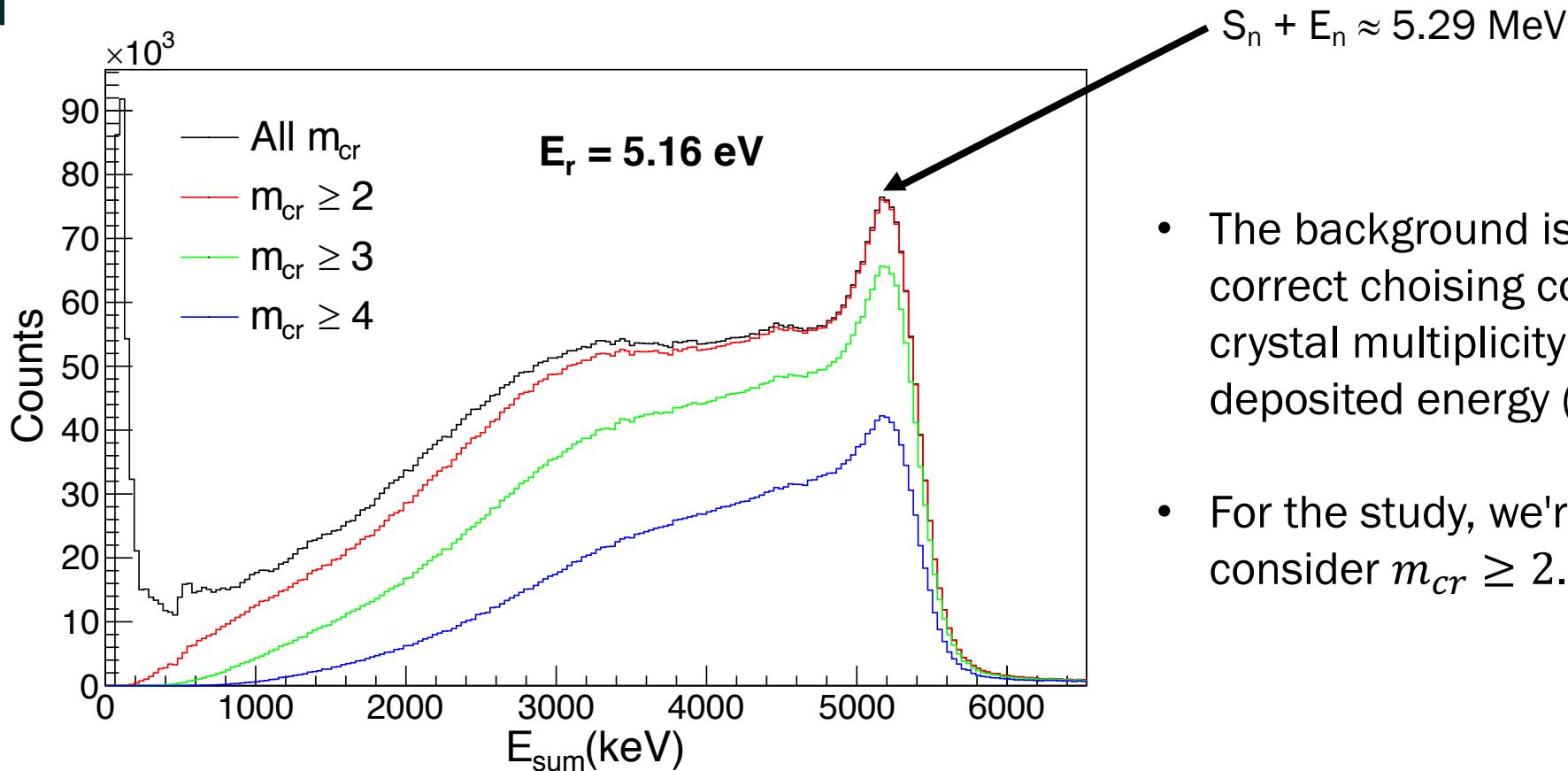
[1] W.Dridi, PhD (Universite d'Evry Val d'Essonne Ecole Docotorale Sitevry, 2006)

Resonance Spectra

- We will focus the analysis in the first resonance which is located at an energy of 5.16 eV for the neutron.

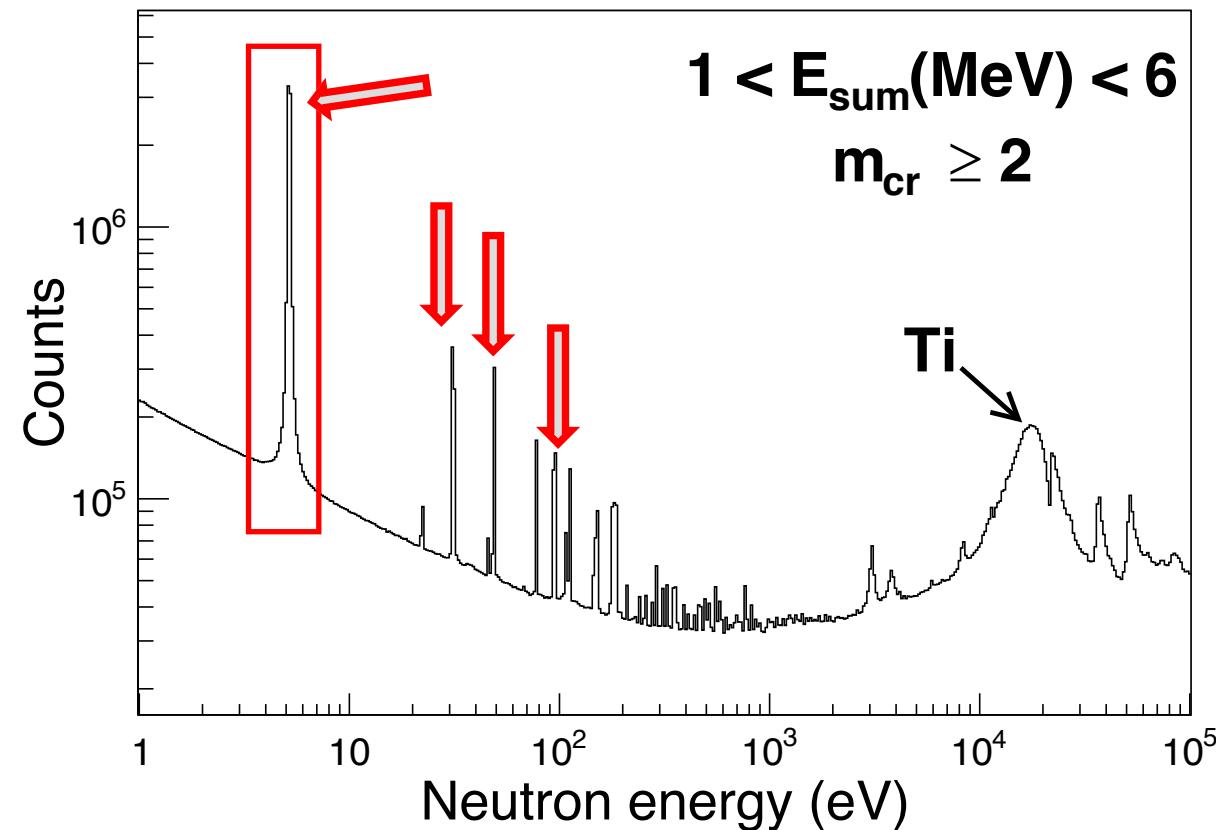


Deposited Energy Spectra



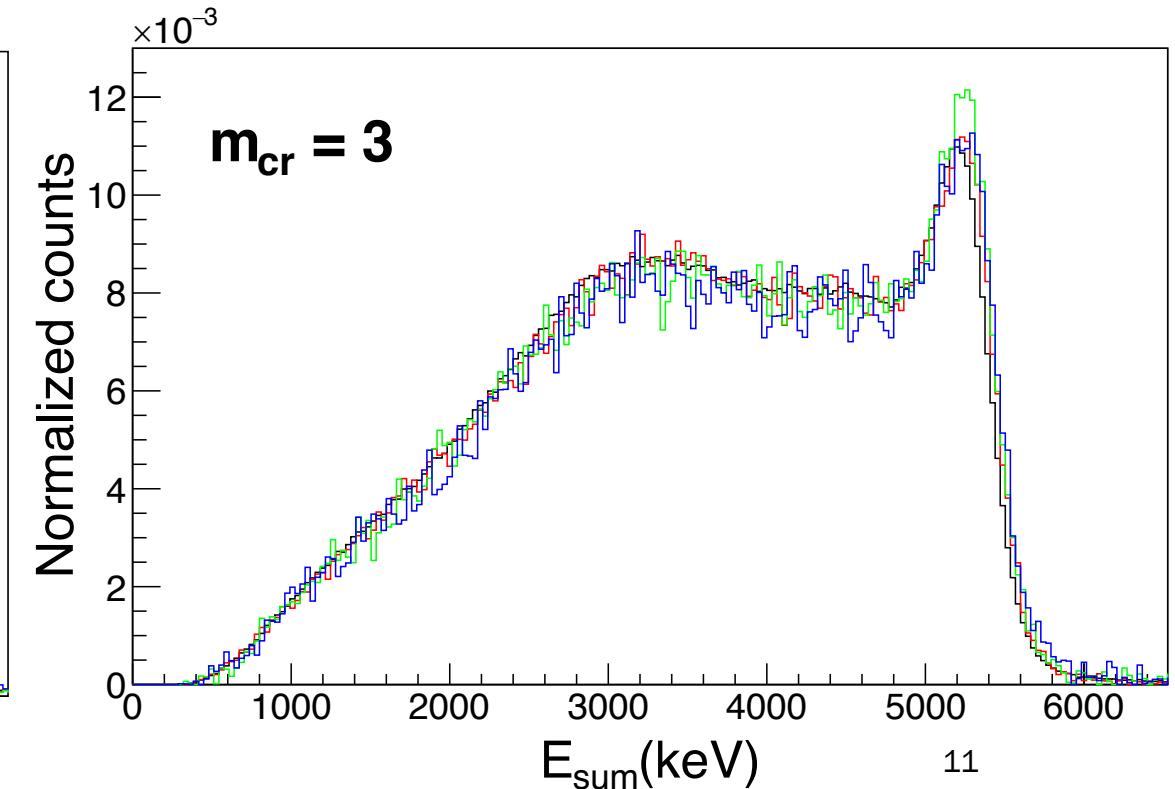
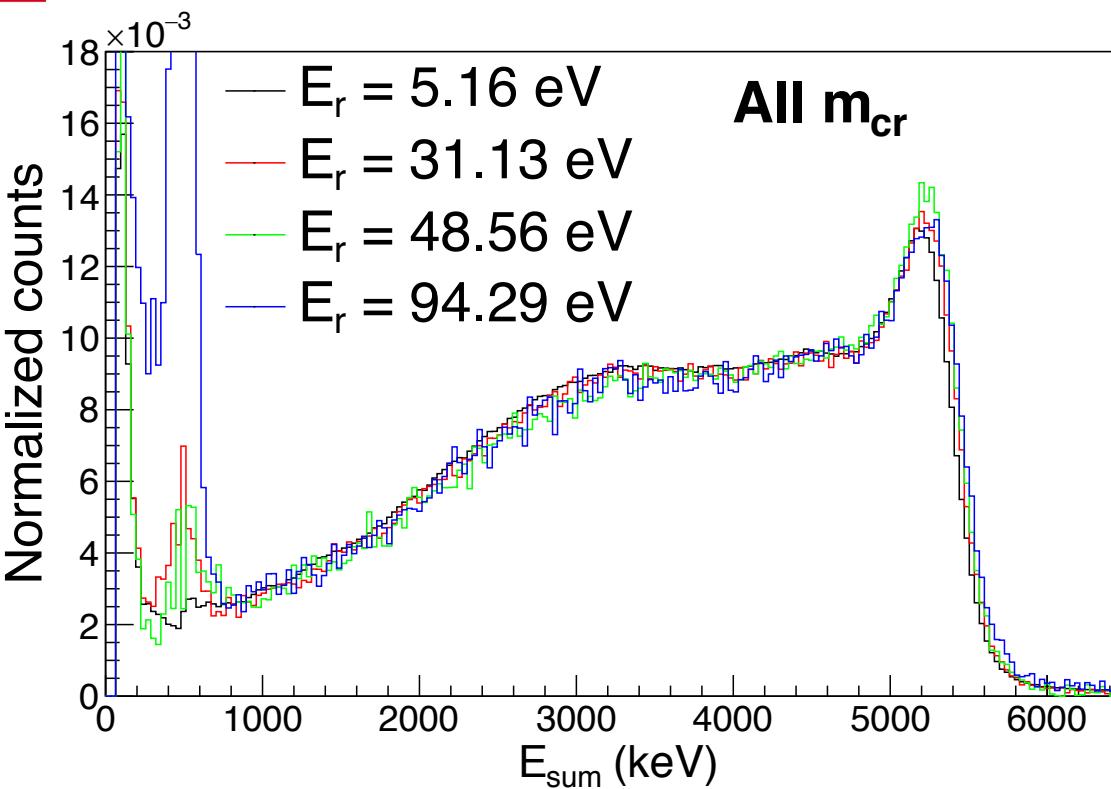
Resonance Spectra

- To determine if the analysis performed on the first resonance is representative of other ones with the same spin and parity, four resonances of ^{234}U are compared.



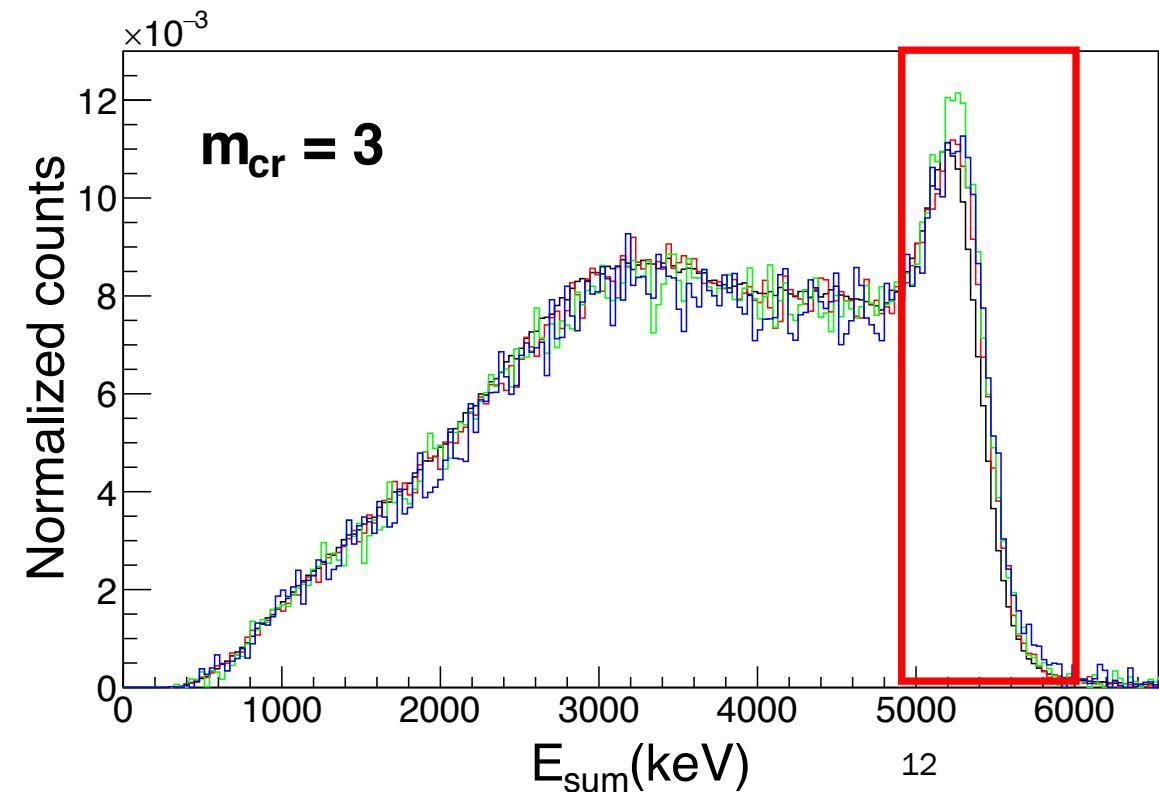
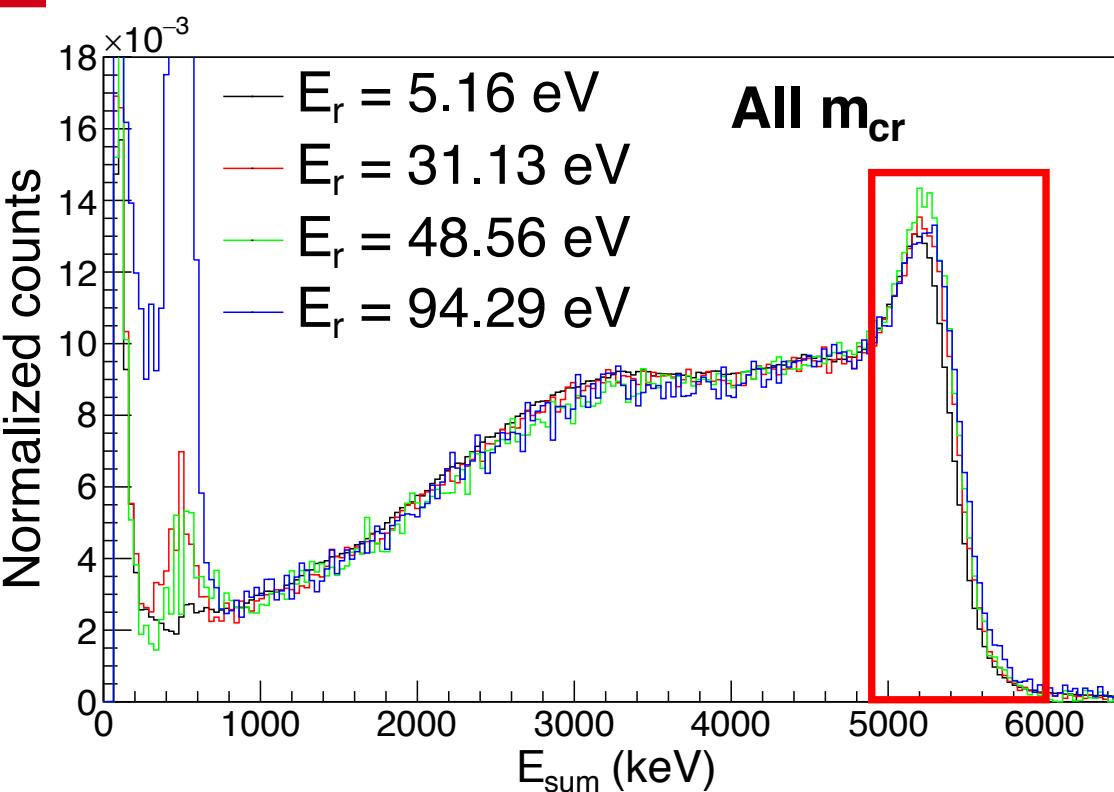
Resonance comparison, E_{sum} .

$E_r(eV)$	ℓ	J	Γ_n (mb)	Γ_γ (mb)	Γ_f (mb)
5.16	0	1/2	3.92	30	0.018
31.13	0	1/2	7.2	26	0.0086
48.56	0	1/2	8.73	26	0
94.29	0	1/2	41.7	26	0.0335



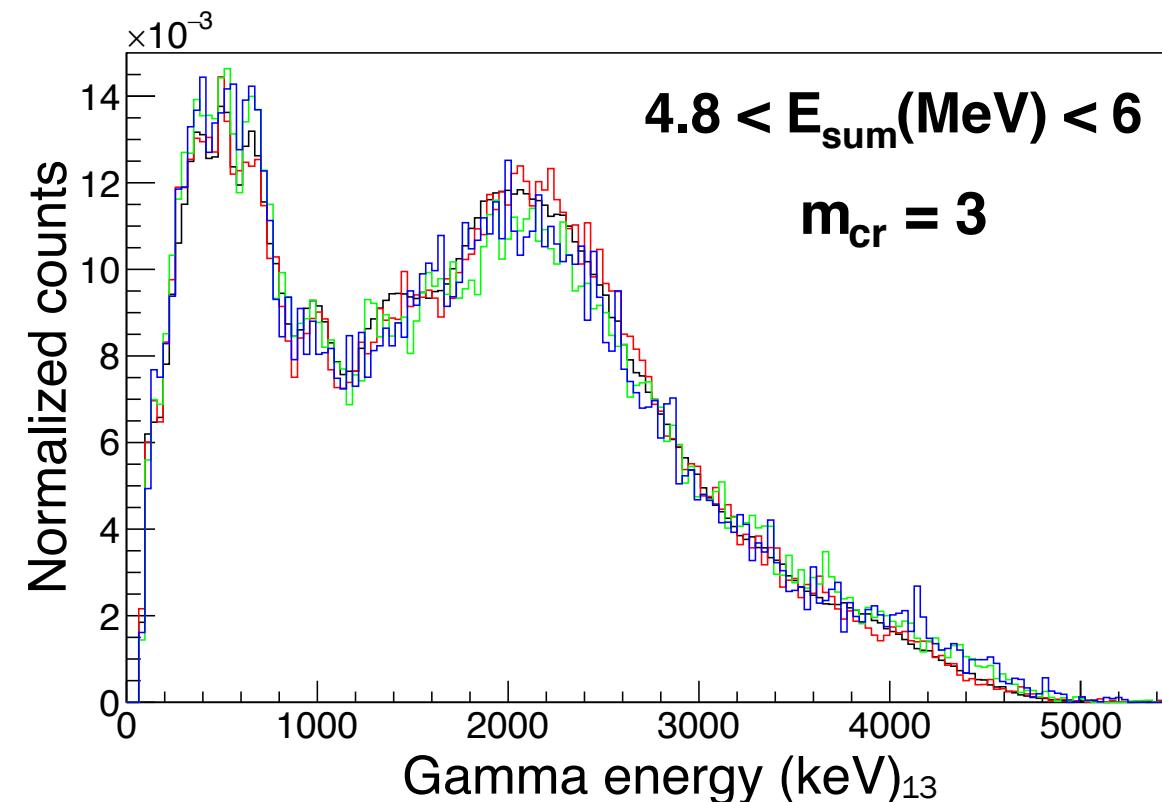
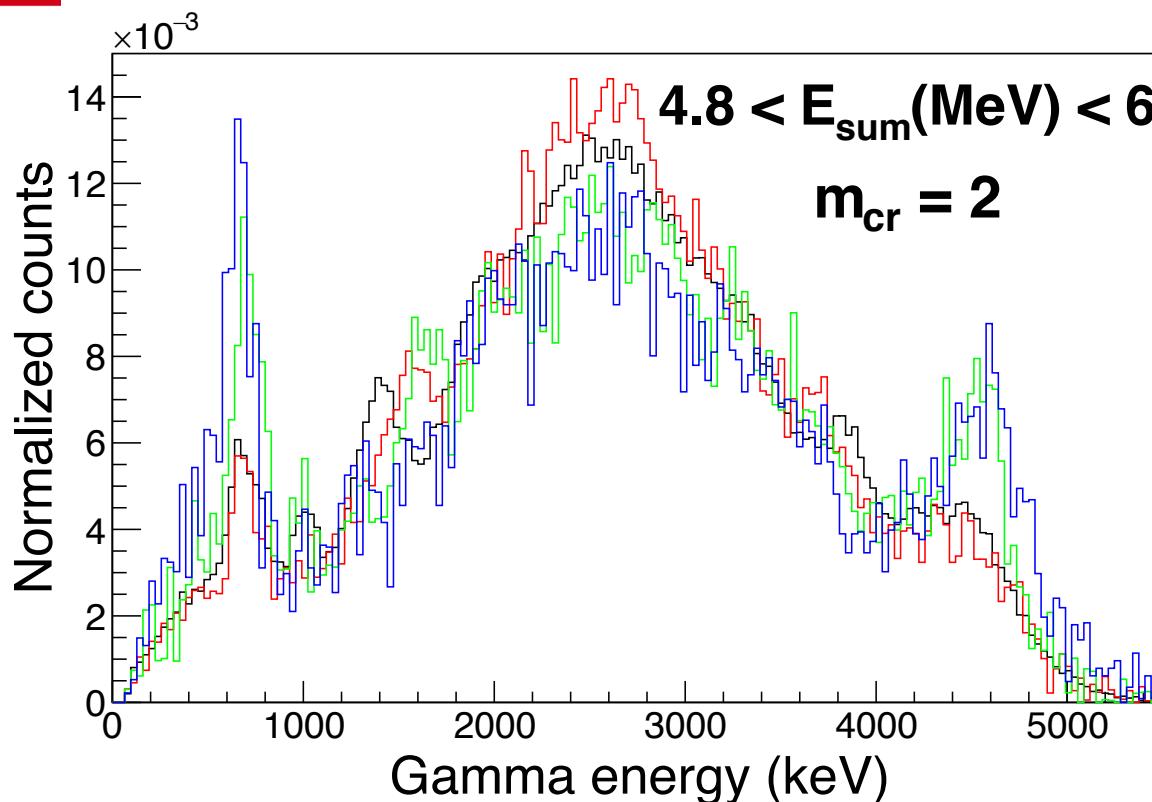
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Resonance comparison, E_γ .

$E_r(eV)$	ℓ	J	Γ_n (mb)	Γ_γ (mb)	Γ_f (mb)
5.16	0	1/2	3.92	30	0.018
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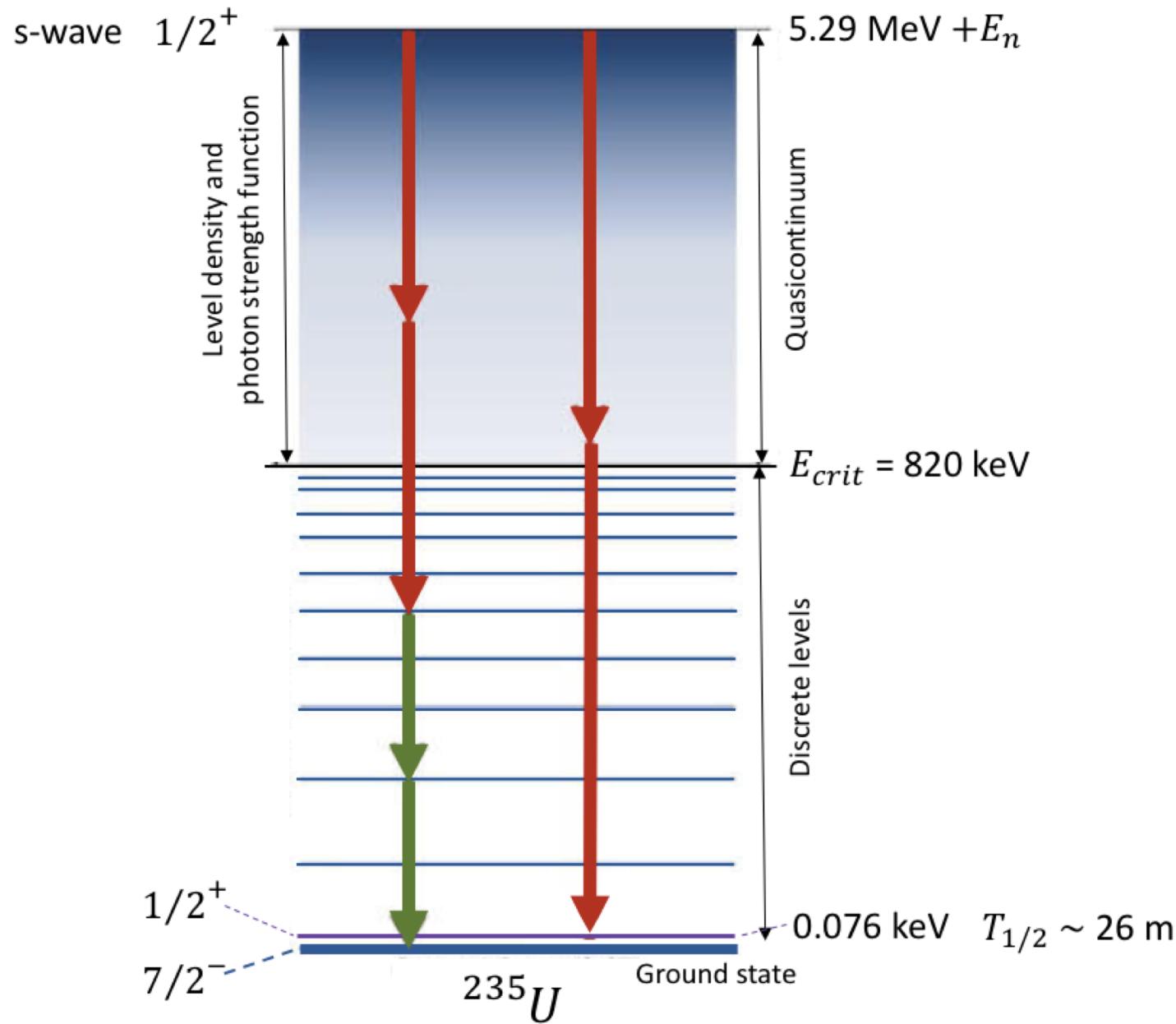
DICEBOXC

- DICEBOXC is a C++ code based on the idea developed by F. Bečvář [1].
[1] F. Bečvář, NIMA 417 (1998) 434
- The average partial radiation width for transitions between two levels following a random choice from Porter Thomas distribution is given by

$$\langle \Gamma_{a\gamma b} \rangle = \frac{E_\gamma^{2L+1} f^{X,L}(E_\gamma)}{\rho(E_a, J_a, \pi_a)} \quad X = E, M$$

Where ρ is the level density, $f^{X,L}$ is the photon strength function (PSF).

- DICEBOXC simulates sets of levels produced from a level density formula $\rho(E_a, J_a, \pi_a)$ and sets of random partial radiation widths, known as nuclear realizations.



- Initial level has given E , J^π , and $\Gamma_{\gamma,i}$.
- Generate levels according to level density model.
- Associate random number seed to each level to assure identical pdf for decay.
- Transitions according to level density and photon strength function.
- “Known” levels and transitions up to “critical energy”.

DICEBOXC Features

- Most current models for level densities and gamma strength functions, both analytical parametrized models and numerical interpolation files.
- Internal conversion hard-coded using Hager-Seltzer and Dragoun et al. tables.
- Levels and transitions from ENSDF format translated to simple textfile for further adjustments (level exclusion, spin-parity refinements).
- User input file with keyword-value structure

Level Density (LD)

- The level density is calculated as the product of three factors

$$\rho(E, J, \pi) = \rho_\pi(E, \pi) \times \rho_J(E, J) \times \rho_E(E)$$

Each component is characterized by a model with parameters.

- Parity distribution:

$$\rho_\pi(E, \pi) = 1/2$$

- Spin distribution: $\rho_J(E, J) = \exp\left(-\frac{J^2}{2\sigma_c^2}\right) - \exp\left(-\frac{(J+1)^2}{2\sigma_c^2}\right) \approx \frac{2J+1}{2\sigma_c^2} \cdot \exp\left(-\frac{\left(J+\frac{1}{2}\right)^2}{2\sigma_c^2}\right)$

where $\sigma_c(E)$ is the spin cutoff and varies from one model to another.

■ Total level density:

- Constant temperature (CT):

$$\rho_E(E) = \frac{1}{T} \exp\left(\frac{E-E_0}{T}\right) \quad \sigma_c(E) = \text{constant}$$

- Back-Shifted Fermi Gas (BSFG):

$$\rho_E(E) = \frac{\exp(2\sqrt{a(E-E_1)})}{12\sqrt{2}\sigma_c a^{1/4}(E-E_1)^{5/4}} \quad \sigma_c(E) = \text{energy dependent}$$

- Back-Shifted Fermi Gas Modified (BSFGM). $\sigma_c(E)$ = related to moment of inertia

- BSFG – RIPL-3 $\sigma_c(E)$ = energy dependent $a(E)$ = energy dependent

- Tabulated microscopic level density calculated within the Hartree-Fock-BCS model (HFB)

Photon Strength Function (PSF)

- Single Particle strength function (SP): $f_{XL}(E_\gamma) = \text{Constant}$
- Standard Brink-Axel Lorentzian model with fixed width (SLO).

$$f_{XL}(E_\gamma) = \sum \frac{\sigma_0 \Gamma_G}{(2L+1)(\pi\hbar c)^2} \frac{E_\gamma \Gamma_G}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_G^2}$$

- Standard Lorentzians with energy-dependent damping width (XLO).

$$\Gamma_T = \Gamma_G \frac{E_\gamma^2 + 4\pi^2 T^2}{E_G^2}$$

- Kadmenskii, Markushev and Furman model (KMF)

$$f_{XL}(E_\gamma) = \sum \frac{\sigma_0 \Gamma_G}{(2L+1)(\pi\hbar c)^2} \frac{0.7 \times E_G \Gamma_T}{(E_\gamma^2 - E_G^2)^2}$$

- Generalized Lorentzian model (GLO)

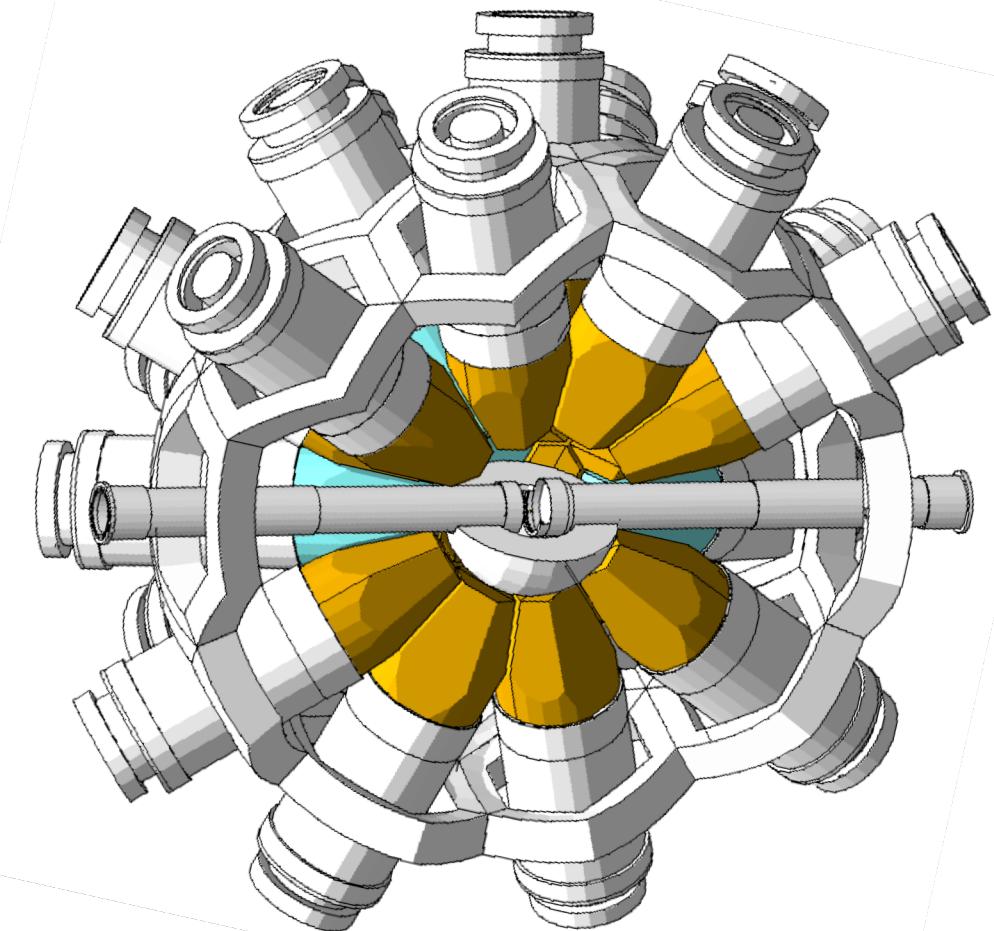
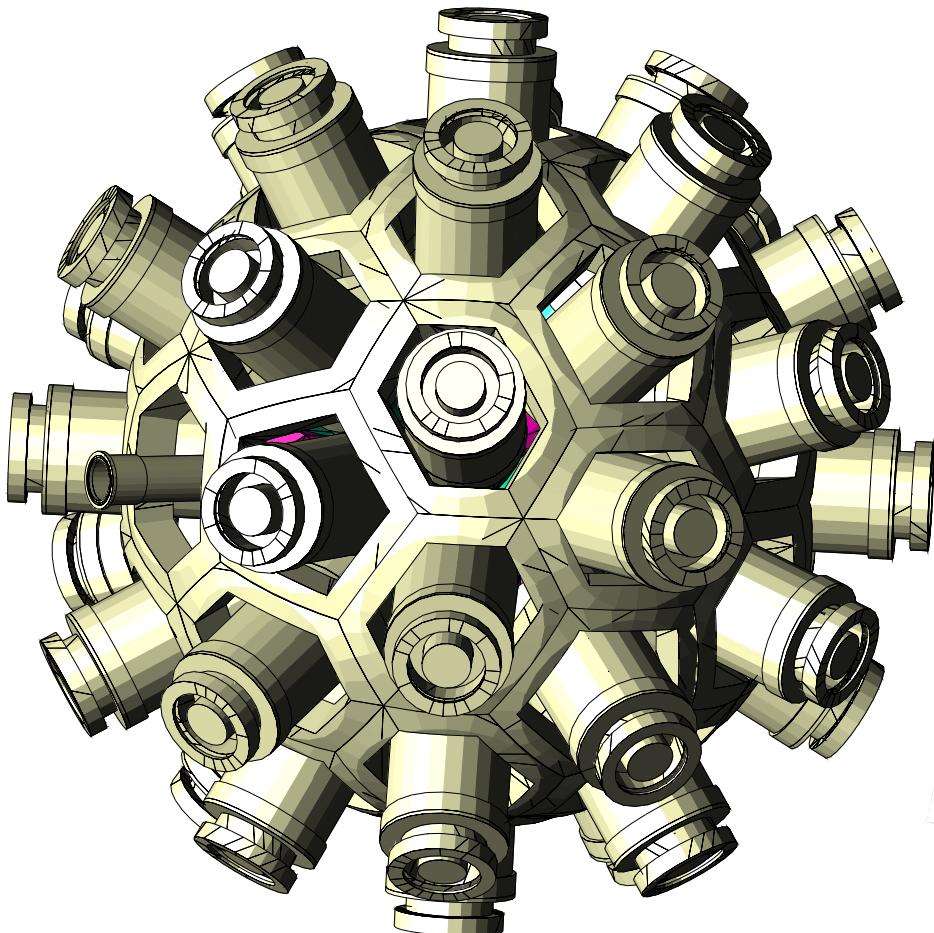
$$f_{XL}(E_\gamma) = \sum \frac{\sigma_0 \Gamma_G}{(2L+1)(\pi\hbar c)^2} \left(\frac{0.7 \times \Gamma_G 4\pi^2 T^2}{E_G^5} + \frac{E_\gamma \Gamma_T}{(E_\gamma^2 - E_G^2)^2 + E_\gamma^2 \Gamma_T^2} \right)$$

- Enhanced Generalized Lorentzian model (EGLO)

$$\Gamma_T = \left[\kappa_0 + (1 - \kappa_0) \frac{E_\gamma - E_0}{E_G - E_0} \right] \Gamma_G \frac{E_\gamma^2 + 4\pi^2 T^2}{E_G^2}$$

- Tabulated microscopic photon strength function calculated according to Hartree Fock QRPA theory (HFQRPA).

TAC Simulation: GEANT 4



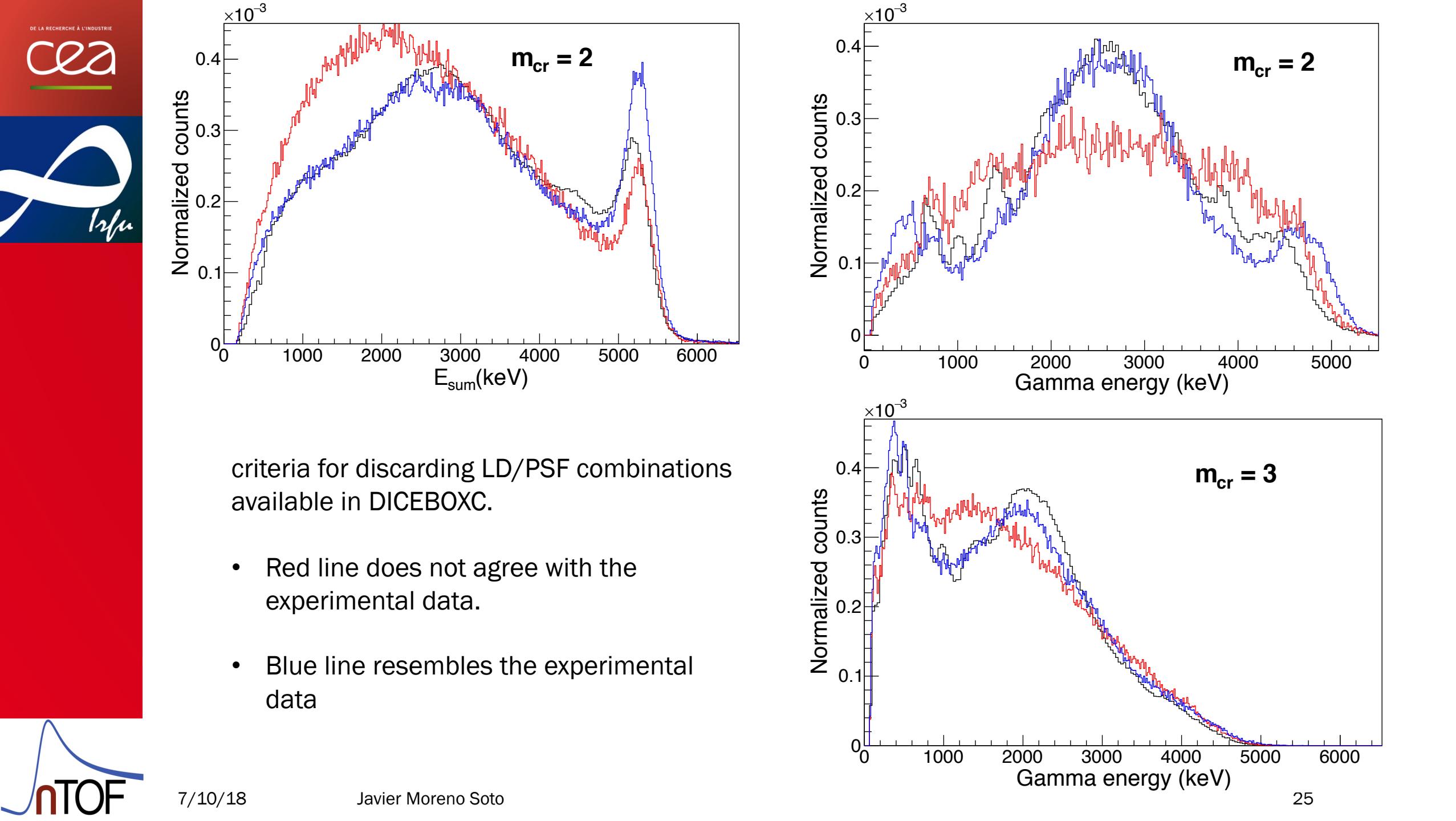
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Results : Comparison of simulations and measurements

- DICEBOXC offers various combinations of LD and PSF for the E1 transitions which are checked and compared with the experimental data

LD\PSF	SLO	XLO	GLO	KMF	EGLO	HFB
CT	X	X	X	X	X	X
BSFG	X	X	X	X	X	X
BSFGM I_{rigid}	X	X	X	X	X	X
BSFGM $0.5I_{\text{rigid}}$	X	X	X	X	X	X
BSFG RIPL-3	X	X	X	X	X	X
HFB	X	X	X	X	X	X



Results : Comparison of simulations and measurements

- In black combinations whose behavior agrees with the experimental data. In red combinations do not reproduce the experimental data.

LD\PSF	SLO	XLO	GLO	EGLO	KMF	HFB
CT	X	X	X	X	X	X
BSFG	X	X	X	X	X	X
BSFGM I_{rigid}	X	X	X	X	X	X
BSFGM $0.5I_{rigid}$	X	X	X	X	X	X
BSFG RIPL-3	X	X	X	X	X	X
HFB	X	X	X	X	X	X

- Parameters for the E1 transition are from RIPL-3 database [1] while for M1 transition the parameters come from the reference [2]. Finally, the E2 transition parameters are based on theory [3]

[1] R. Capote, et al., Nuclear Data Sheets 110 , 3107 (2009), special Issue on Nuclear Reaction Data

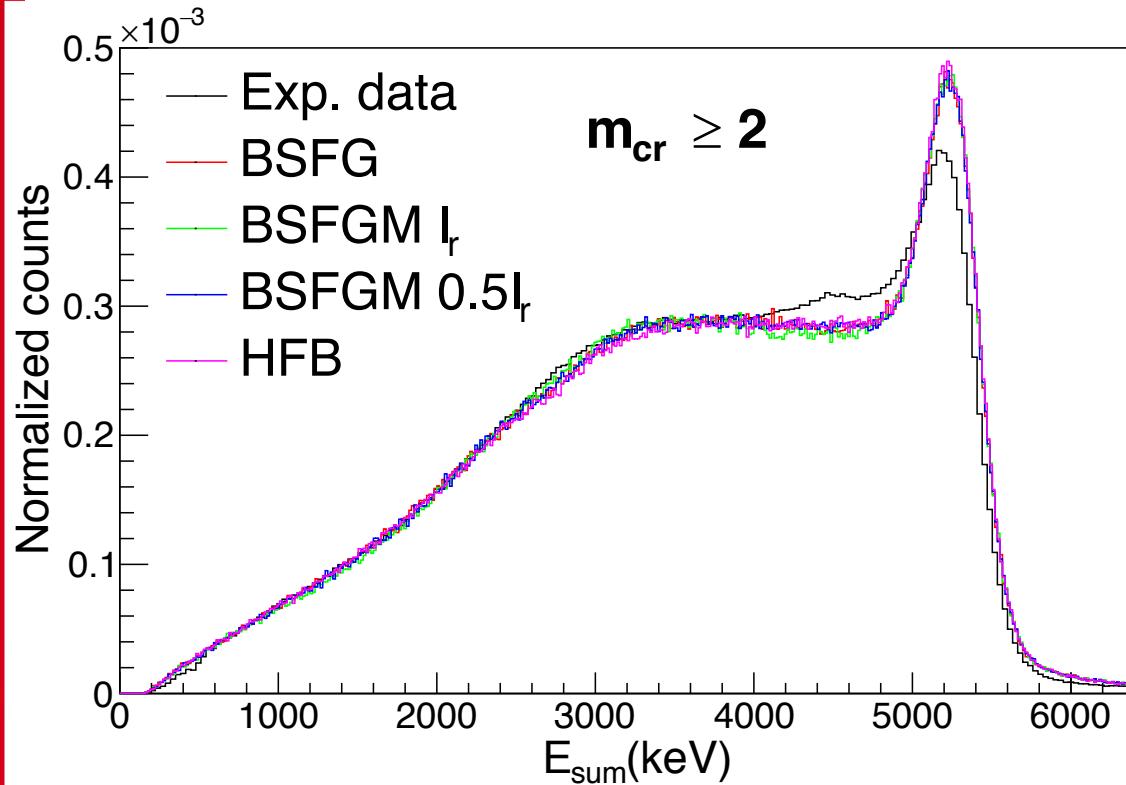
[2] J.L. Ullmann, et al., Phys. Rev. C 96 , 024627 (2017)

[3] Int. Atomic Energy Agency, Handbook for Calculations of Nuclear Reaction Data Reference. Input Parameter Library, IAEA-TECDOC-1034 (Vienna, 1998)

Transition	E_1 (MeV)	Γ_1 (MeV)	σ_1 (mb)	E_2 (MeV)	Γ_2 (MeV)	σ_2 (mb)	E_3 (MeV)	Γ_3 (MeV)	σ_3 (mb)
E1 (EGLO)	11.11	1.12	243.3	13.41	4.98	426			
M1 (SLO)	2.15	0.80	0.45	2.90	0.60	0.40	6.61	4.00	7.00
E2 (SLO)	10.21	1.175	1.7						

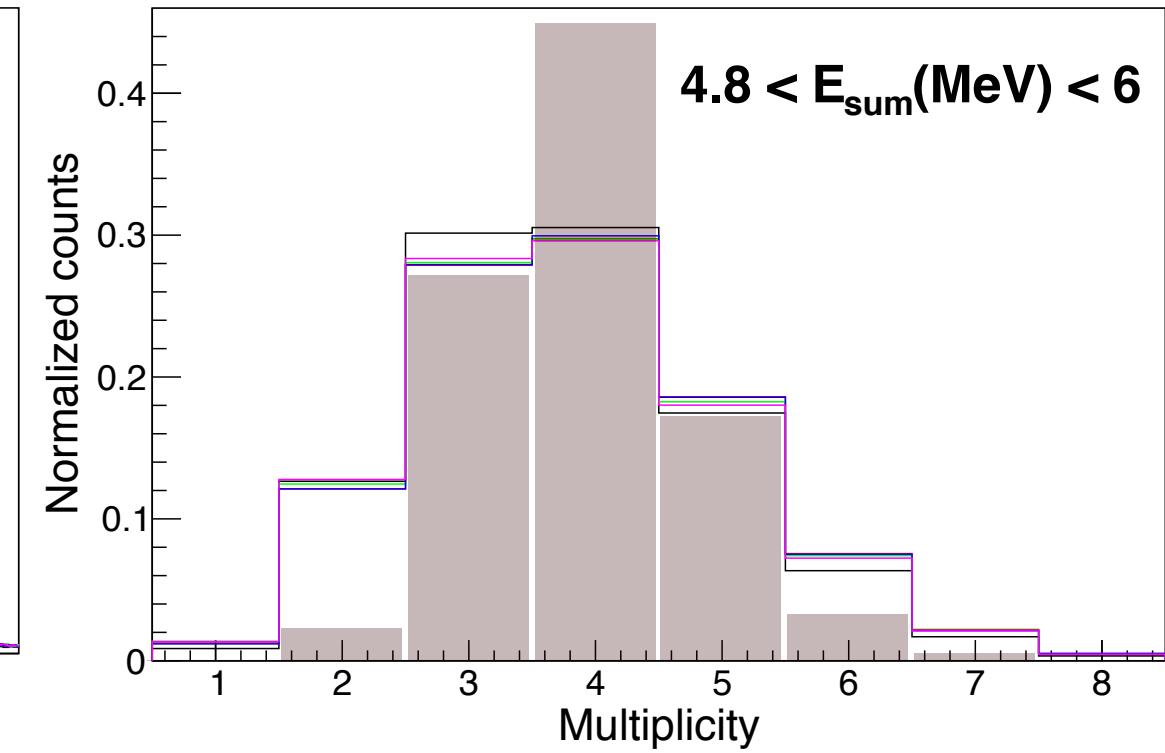
Total deposited energy spectra and multiplicity distribution

PSF → EGLO



Exp. data $\begin{cases} \text{Mean value} = 3.78 \\ \text{Standard deviation} = 1.21 \end{cases}$

Simulation $\begin{cases} \text{Mean value} = 3.83 \\ \text{Standard deviation} = 1.28 \end{cases}$



Total deposited energy spectra

PSF → EGLO

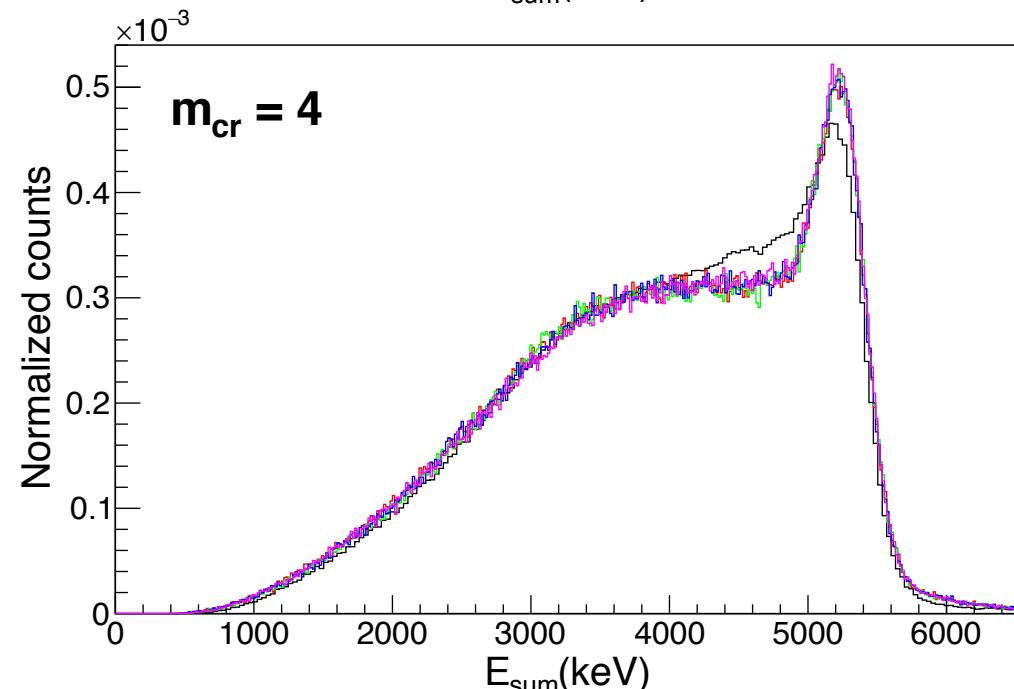
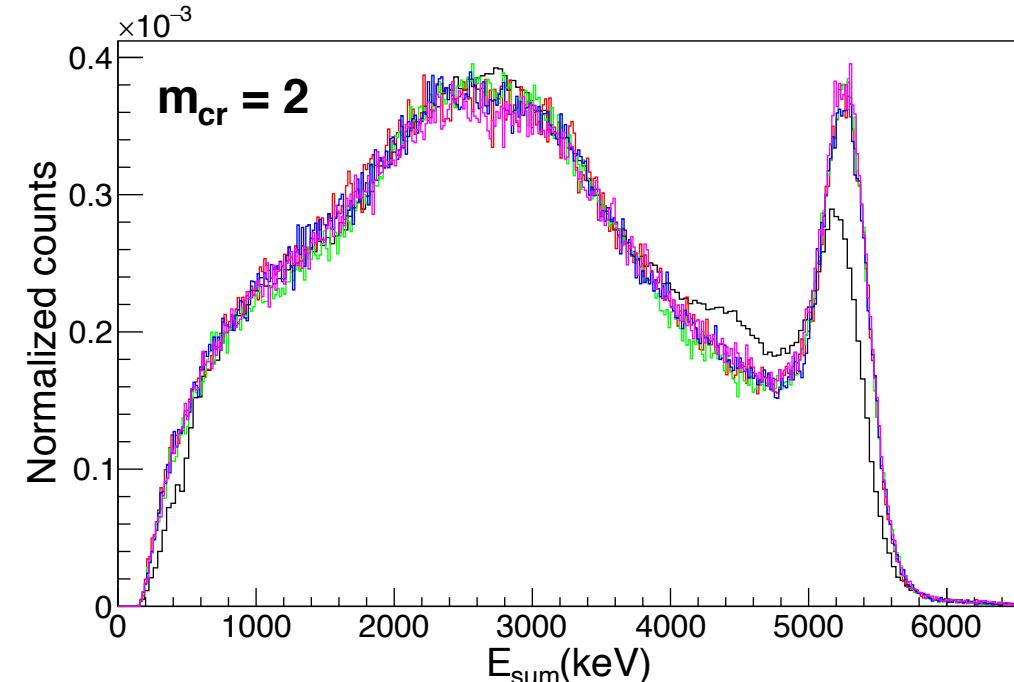
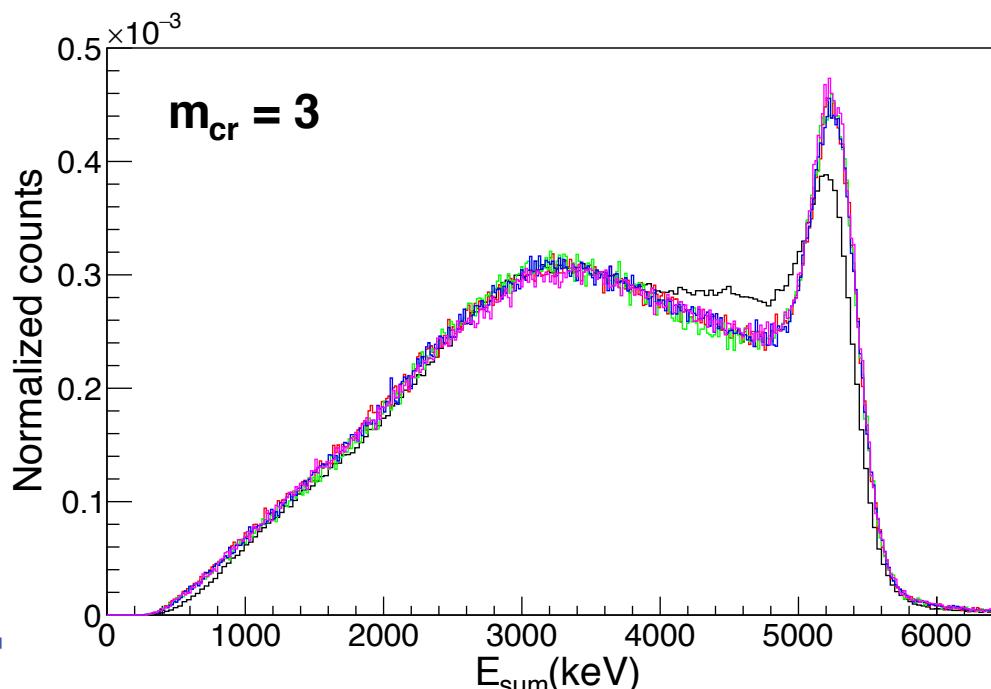
— Exp. data

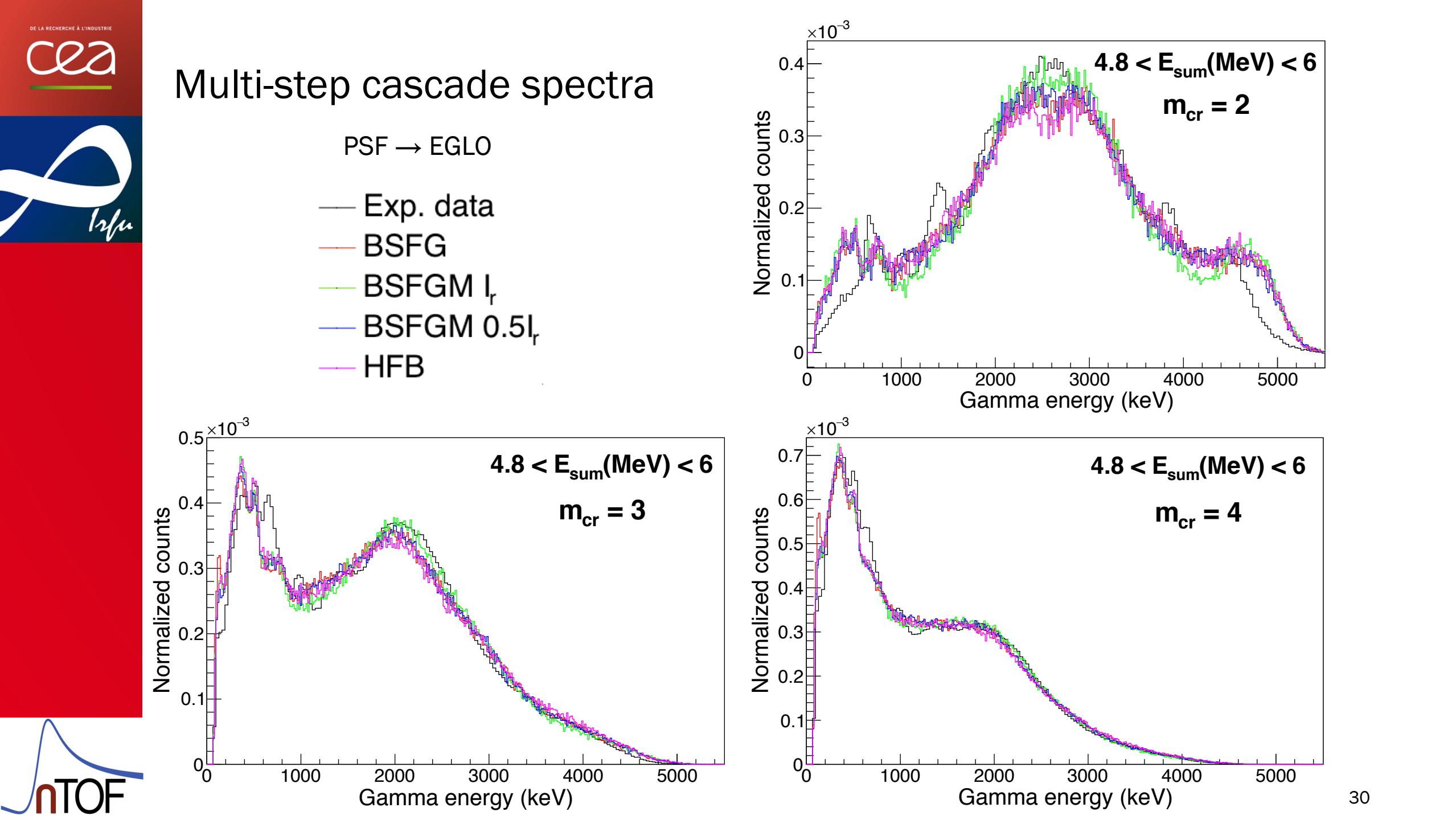
— BSFG

— BSFGM I_r

— BSFGM $0.5I_r$

— HFB





Conclusion

- The best combinations are XLO, GLO and EGLO for the photon strength function and BSFG, BSFGM and HFB for the level density. Overall, these models reproduce the experimental data, but further improvements are possible.
- In the total deposited energy E_{sum} spectra the simulations show a greater number of counts at the sum peak with respect to the experimental data and a dip between 4 MeV and 5 MeV.
- In the multi-step cascade spectra for $m_{cr} = 3$ simulations miss the peak at 658 keV but agree with the shape of experimental data. The biggest difference is produced in the $m_{cr} = 2$ spectra. However, it was seen that for $m_{cr} = 2$ further investigations are necessary.

Outlook

- continue studying the system $n + ^{234}U$: study effect of the primary intensities, try other models for M1 PDF, study sensitivity of the parameters, etc.
- Similar study for system $n + ^{238}U$.
- Comparison with other simulation codes as FIFRELIN.