DE LA RECHERCHE À L'INDUSTRIE

La structure nucléaire via la mesure des spectres γ de capture à n_TOF

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Workshop NACRE
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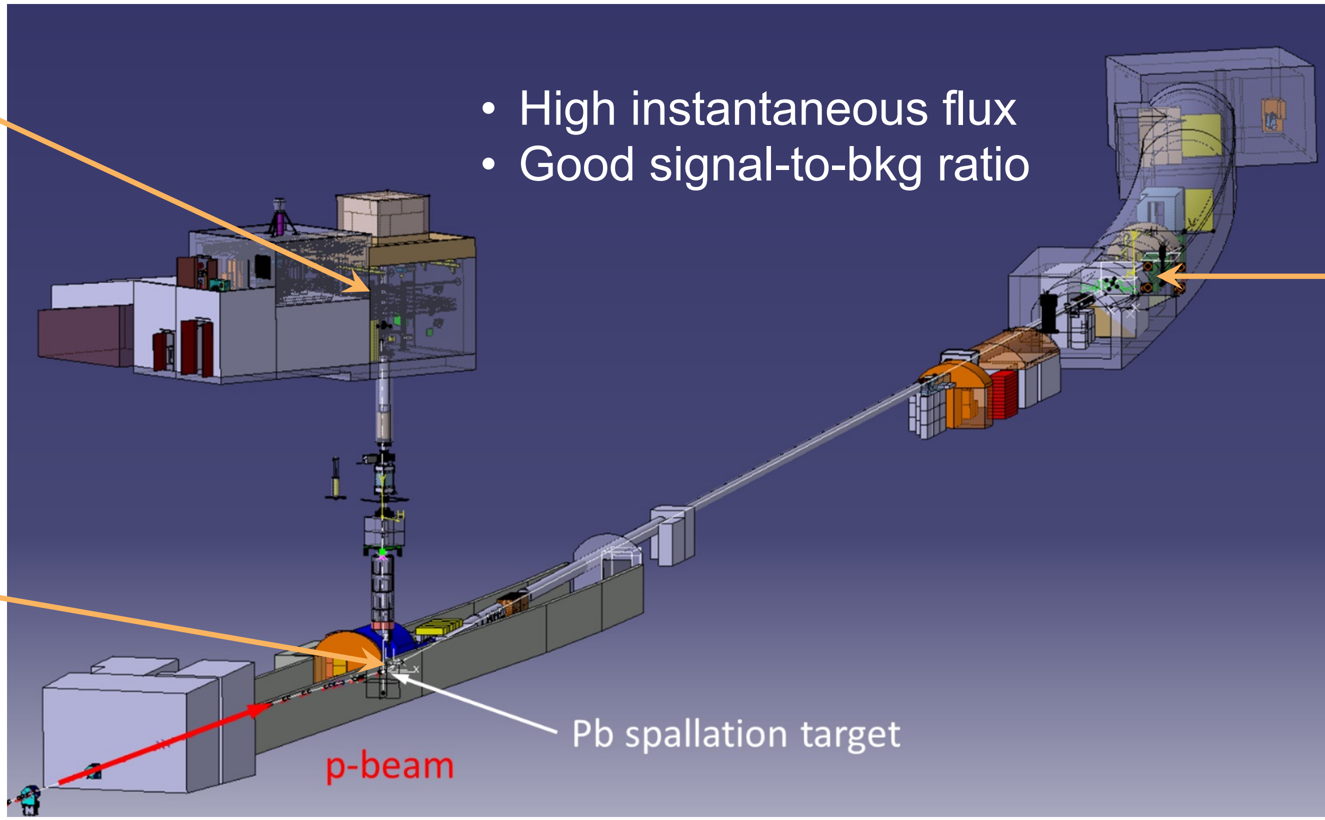
Nuclear Structure from Capture γ-rays

1. n_TOF and TAC
2. Experimental data
3. Modelling and simulations
4. Comparison with data
5. Conclusions

n_TOF facility at CERN

EAR 2
Since 2014
~18 m
~10^7 n/cm^2 (/pulse)
$\Delta E/E$ ~10^{-2} (1keV)

NEAR
(> 2021)
~3 m
~10^8 n/cm^2 (/pulse)



EAR 1
Since 2001
~182 m
~10^5 n/cm^2 (/pulse)
$\Delta E/E$ ~10^{-4} (1keV)

p-beam: 0.8 Hz – 20 GeV/c – 7 ns RMS – 7.10^{12} p/pulse – 2.10^{15} n/pulse (300 n/p)

Nuclear Structure from Capture γ-rays

n_TOF facility at CERN

(n,f) measurements

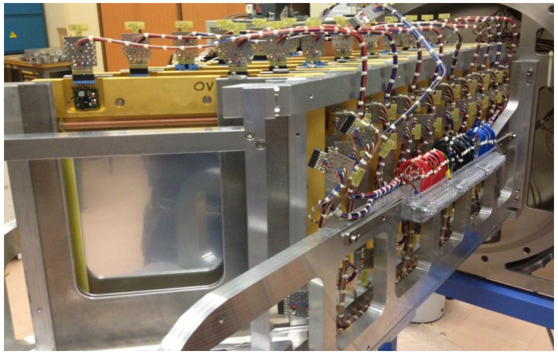
- FIC (Fast Ionization Chamber)
- PPAC (Parallel Plate Avalanche Counters)
- MicroMegas (MicroMesh Gaseous detector)

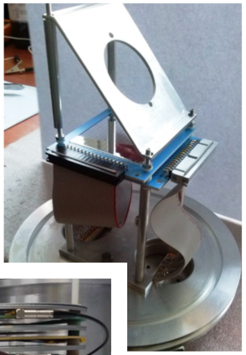
(n,γ) measurements

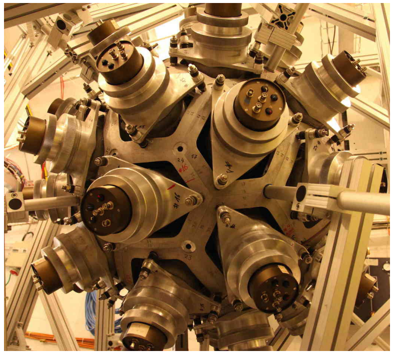
- C_6D_6 scintillators
- TAC (Total Absorption Calorimeter)

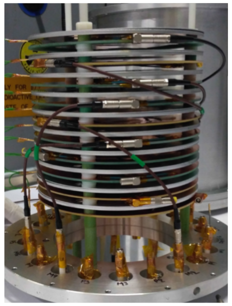
(n,cp) measurements

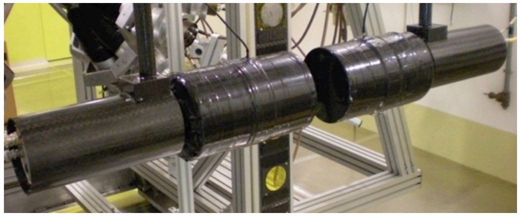
- Si telescope for (n,p) and (n,α)
- MicroMegas for (n,α)





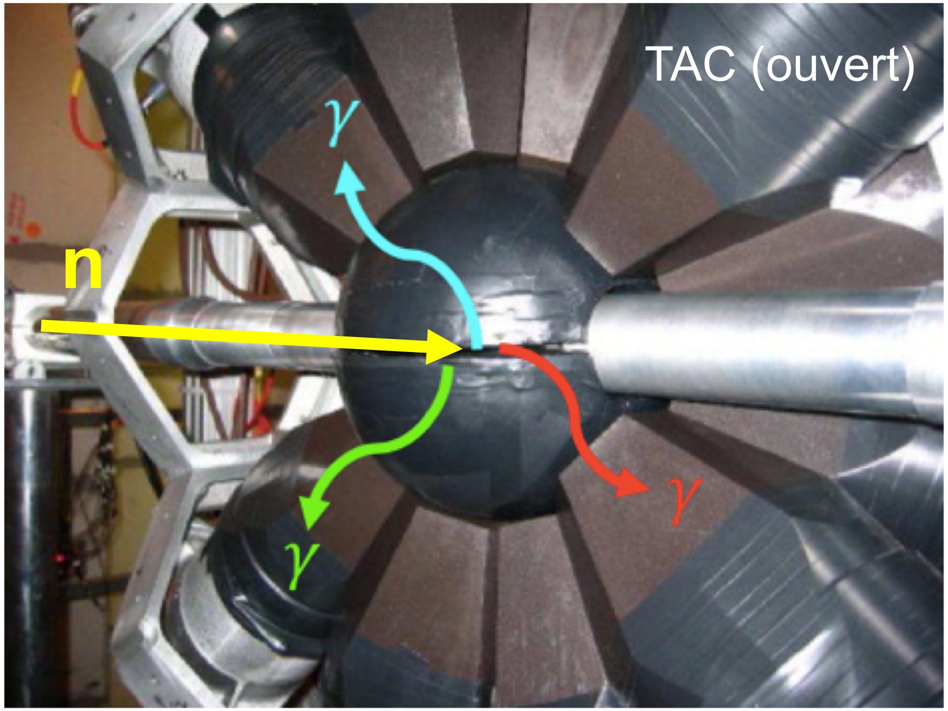






n_TOF Total Absorption Calorimeter (TAC)

Detection of γ-rays in a 4π segmented BaF_2 calorimeter (40 crystals)



$$E_{Sum} = E_1 + E_2 + E_3 = S_n + E_n$$
$$m_{cr} = 3$$

- E_{Sum} is the total energy deposited in the TAC
- m_{cr} is the number of crystals detecting a gamma from the same cascade
- E_n is the incident neutron energy, deduced from the time-of-flight

1. n_TOF and TAC
2. **Experimental data**
3. Modelling and simulations
4. Comparison with data
5. Conclusions

Measurements with the n_TOF TAC

Five capture measurements on uranium isotopes

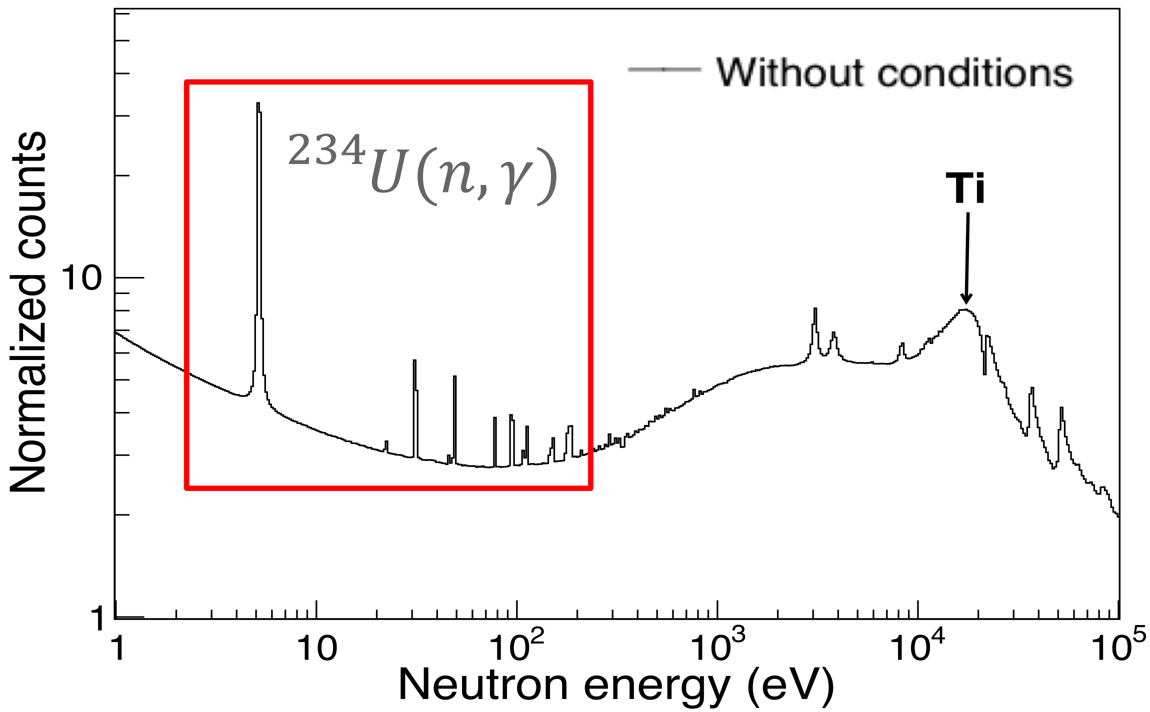
- U-233 – M. Bacak et al., ND 2019, EPJ Conf. 239 (2020) 01043
- U-234 – W. Dridi, PhD Thesis, Université d'Evry Val d'Essonne, 2006
- U-235 – J. Balibrea et al., Phys. Rev. C 102 (2020) 044615
- U-236 – M.J. Vermeulen, PhD Thesis, University of York, 2015
- U-238 – T. Wright et al., Phys. Rev. C 96 (2017) 064601

The results presented here are for non-fissile isotopes: n + U-234,236,238

More details in the PhD Thesis of J. Moreno-Soto (Université Paris-Saclay, 2020) or the corresponding publication: Phys. Rev. C 105 (2022) 024618

n_TOF data – Time-of-Flight spectrum

Main data for $\sigma(E_n)$, which was the initial goal of the measurements



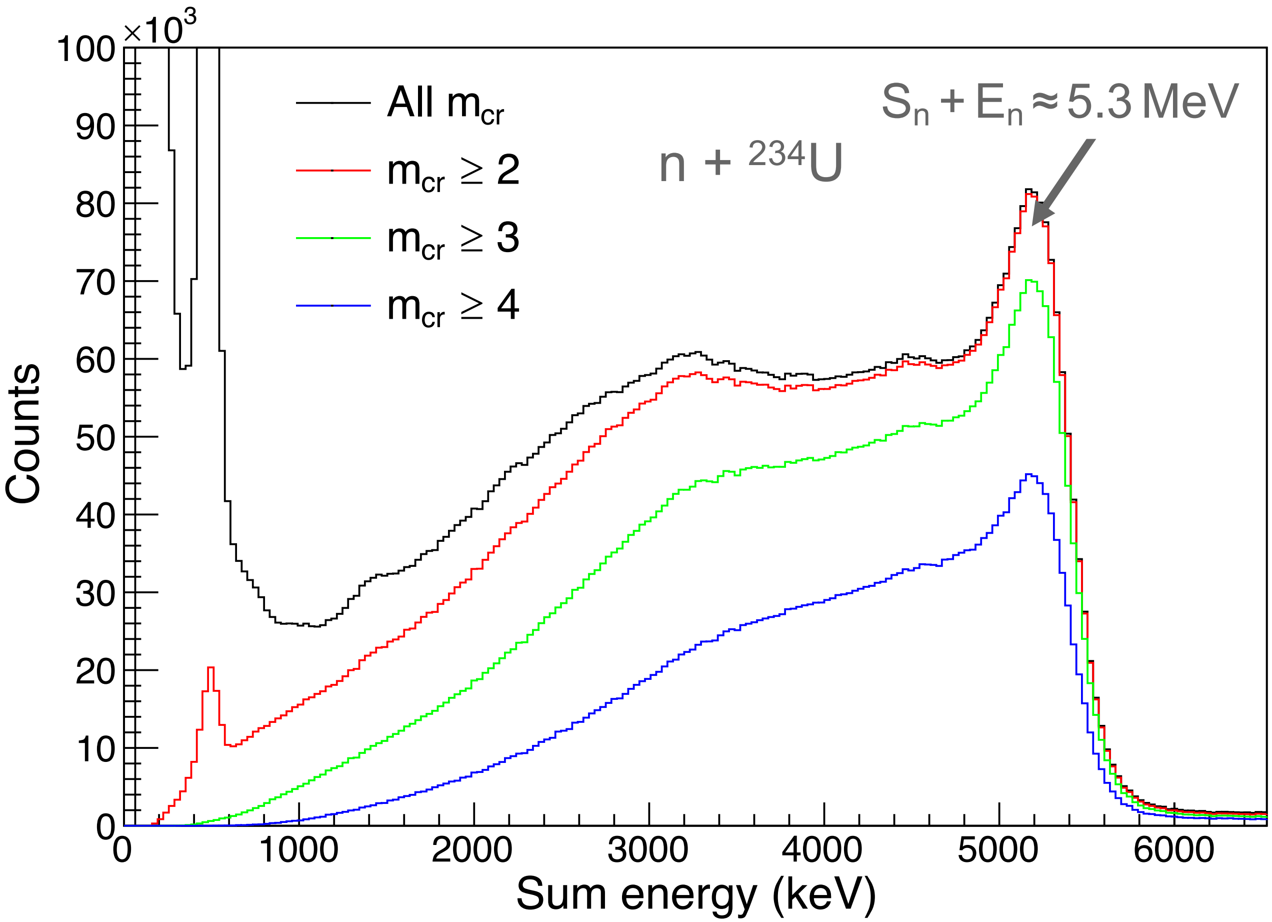
Example for n + ^{234}U system

- 120 resolved levels ($E^* > S_n$)
- Level energy, spin, parity
- Level widths Γ_n, Γ_γ, Γ_f

See, e.g., JEFF-3.3 or Mughabghab's Atlas of Neutron Resonances

n_TOF data – Sum energy (E_{Sum}) spectra

Key data to improve S/B and to correct for cuts (discarded counts)

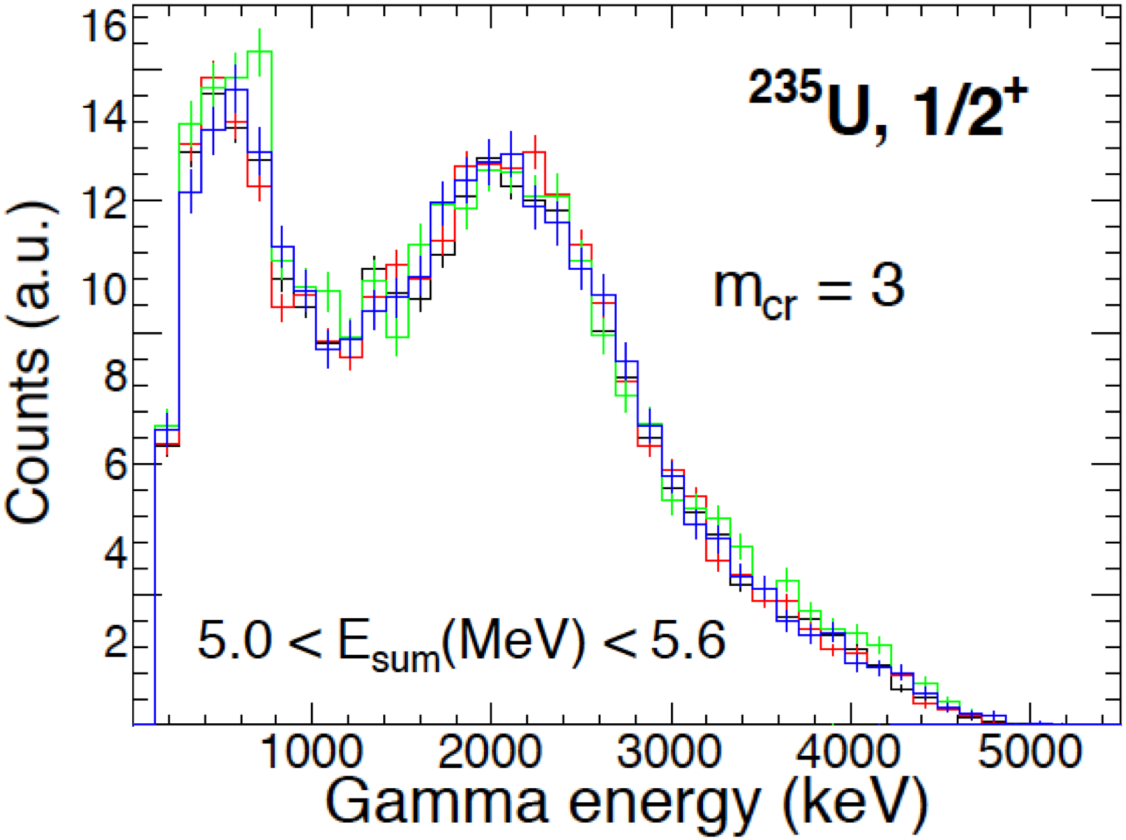


Most of the background can be rejected by a criteria on the crystal multiplicity $m_{cr} \geq 2$

Optimisation of the S/B ratio requires another criteria: $E_{Sum} \approx 5.3$ MeV ($5.0 < E_{sum}$ (MeV) < 5.6)

n_TOF data – Multi-Step-Cascade (MSC) spectrum

Key data for (low-resolution) spectroscopy of nuclear structure



Energy distribution of the γ-rays for a three-step cascade (m_{cr} = 3), e.g.,

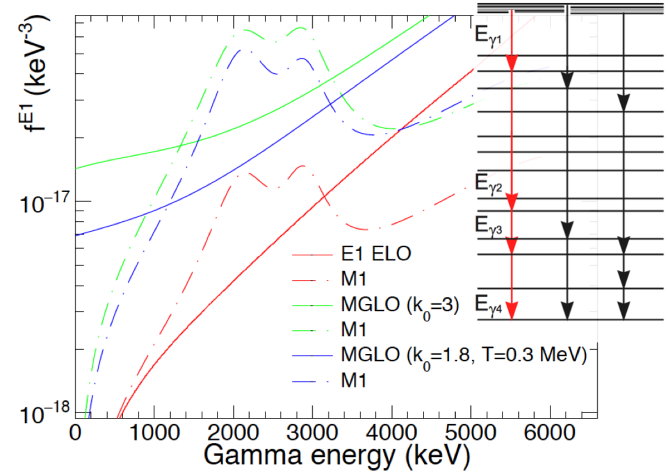
- $E_{\gamma 1}$ ~600 keV
- $E_{\gamma 2}$ ~2000 keV
- $E_{\gamma 3}$ ~2400 keV

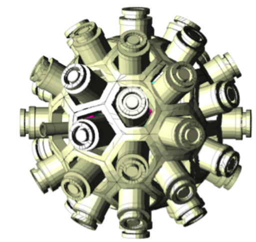
Nuclear Structure from Capture γ-rays

Modelling and Simulations

Geant4 simulations coupled to a model of the electromagnetic (EM) deexcitation cascade in radiative capture

➠ Test of state-of-the-art codes (Dicebox, Fifrelin), models (of PSF, LD), and parameters (RIPL, ENSDF)



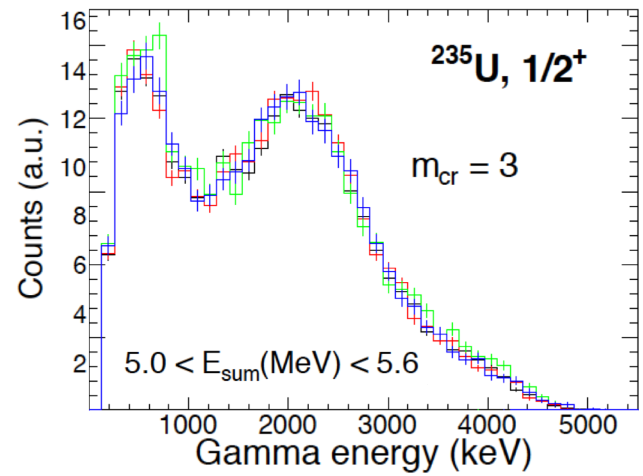


Modelling

- PSF, LD
- EM cascade
- G4 simulation

Consistent modelling of the uranium isotopic chain (U-234,236,238) that best reproduce all n_TOF γ-ray spectra

➠ Global validation of low-energy models and parameters (RIPL/ENSDF, LD, PSF…)



n_TOF data

- γ-ray spectra
- γ-ray multiplicity

Model Parameters

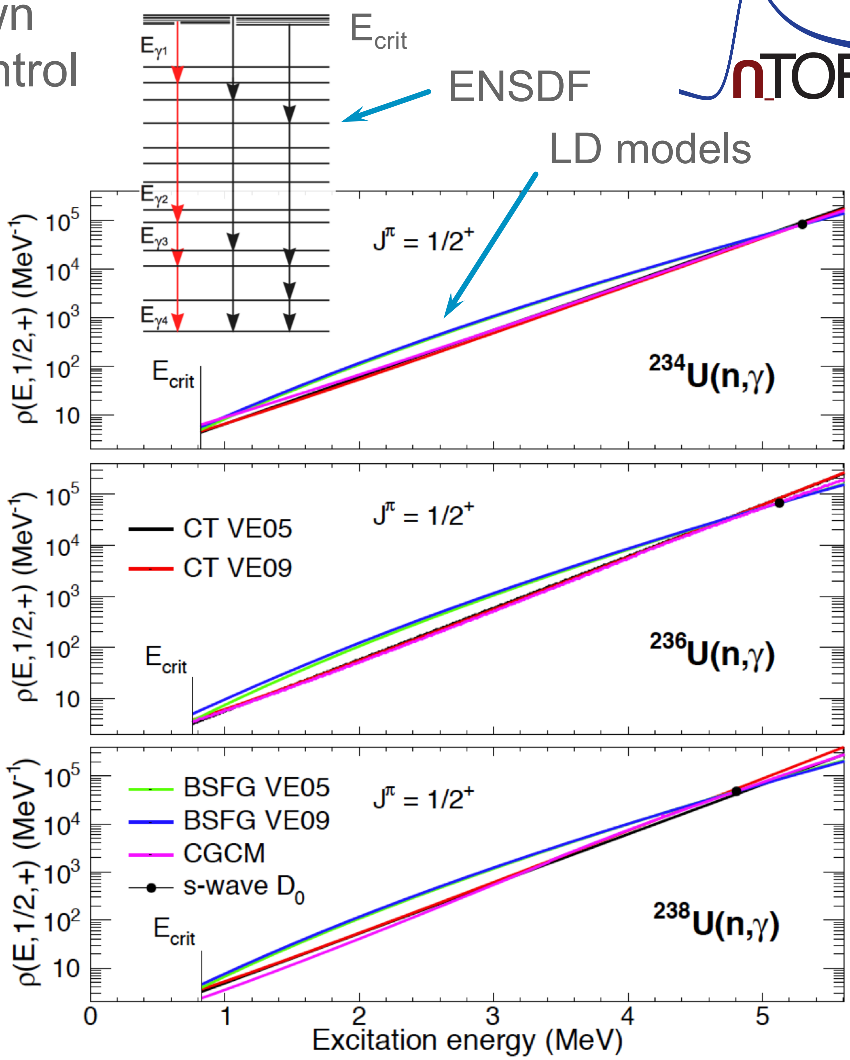
- ✔ (rel.) well-known
- ✔ (rel.) under control
- ✔ (rel.) uncertain

EM cascade (incl. internal conversion)

- Well-known discrete levels and transitions below E_{crit} (ENSDF) ✔
- Conversion electrons (BrIcc) ✔
- Level density (LD) beyond discrete levels (various models tested) ✔
- PSF for E1 ✔ and M1 ✔ transitions (various models tested)

Full simulation of the TAC response

- Geometry, materials
- BaF_2 resolution
- Dead time



Nuclear Structure from Capture γ-rays

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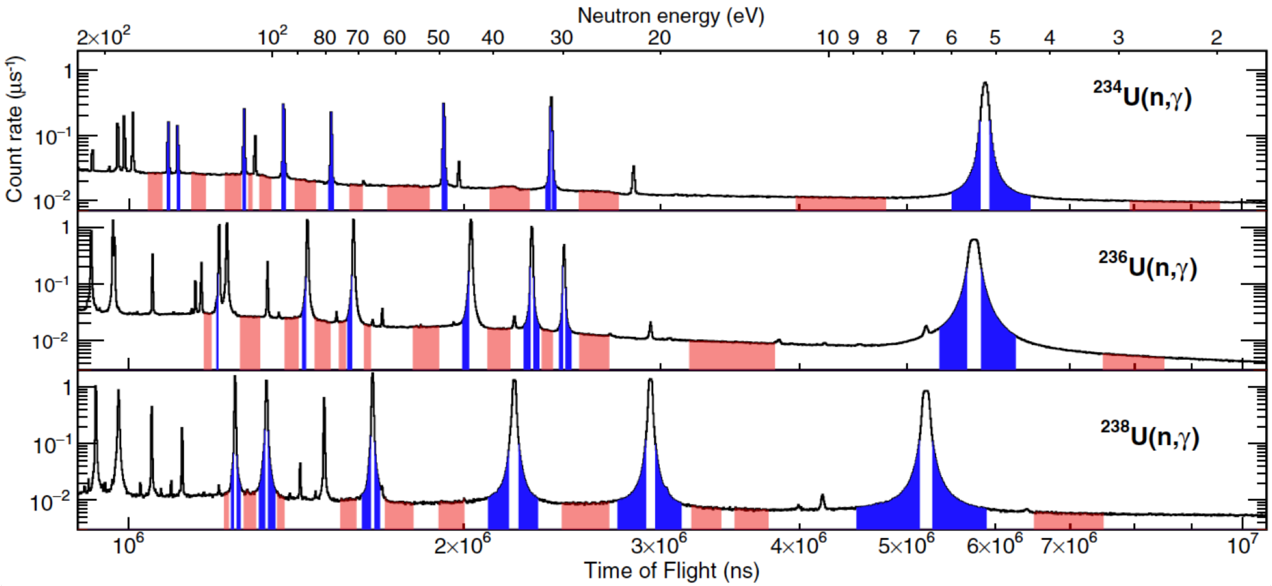
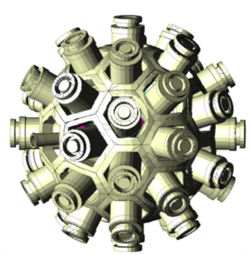


- TOF windows for studying the γ-ray spectra in/outside the resonances (blue/red)
- The dead time effects are under control in the wings where the count rate is below ~0.1 count/μs ✔

Full simulation of the TAC response

- Geometry, materials ✔
- BaF_2 resolution ✔
- Dead time ✔



Nuclear Structure from Capture γ-rays

Model Parameters

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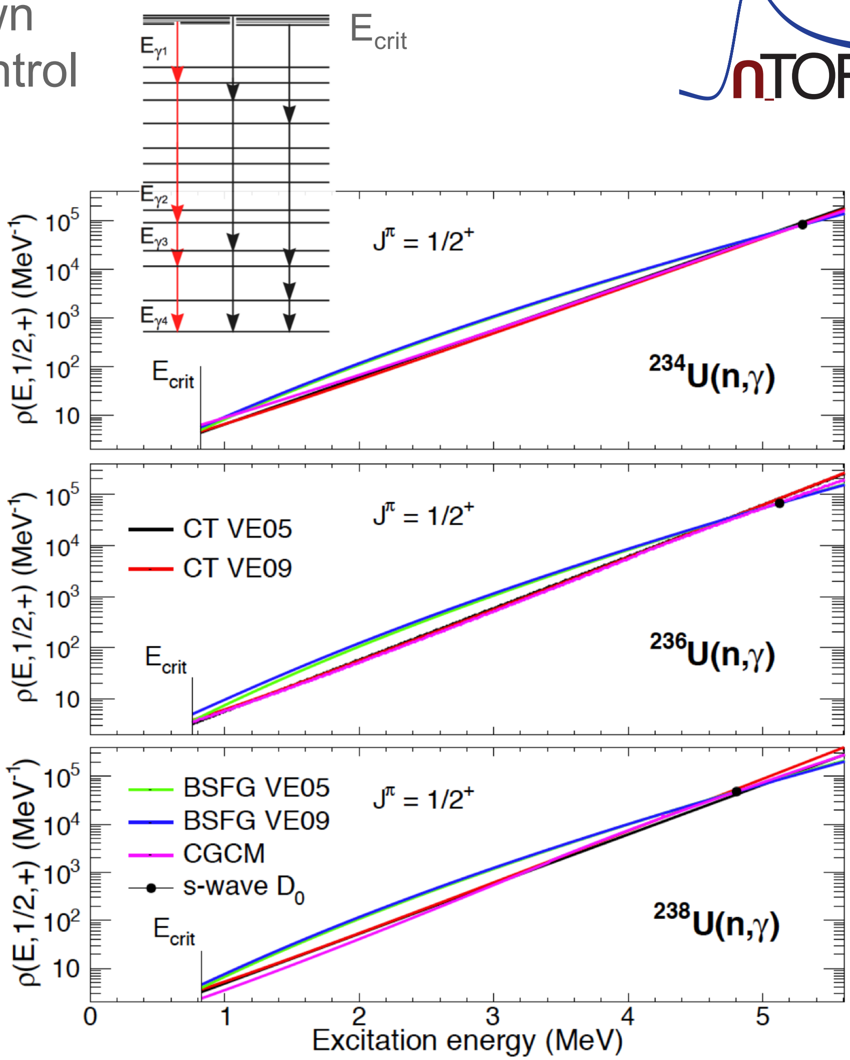
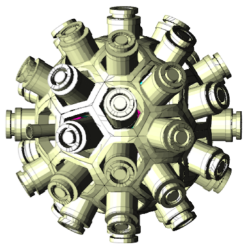
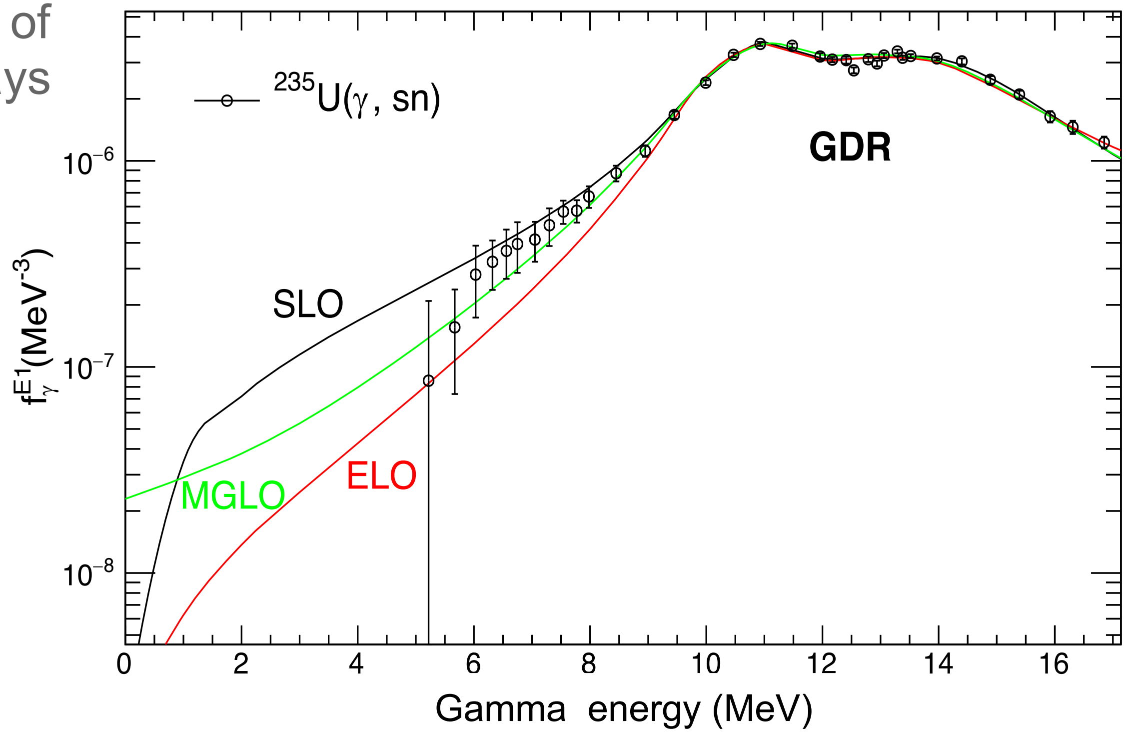




Focus on the Photon Strength Function (PSF)

The PSF characterizes the ability of the nucleus to absorb or emit γ-rays

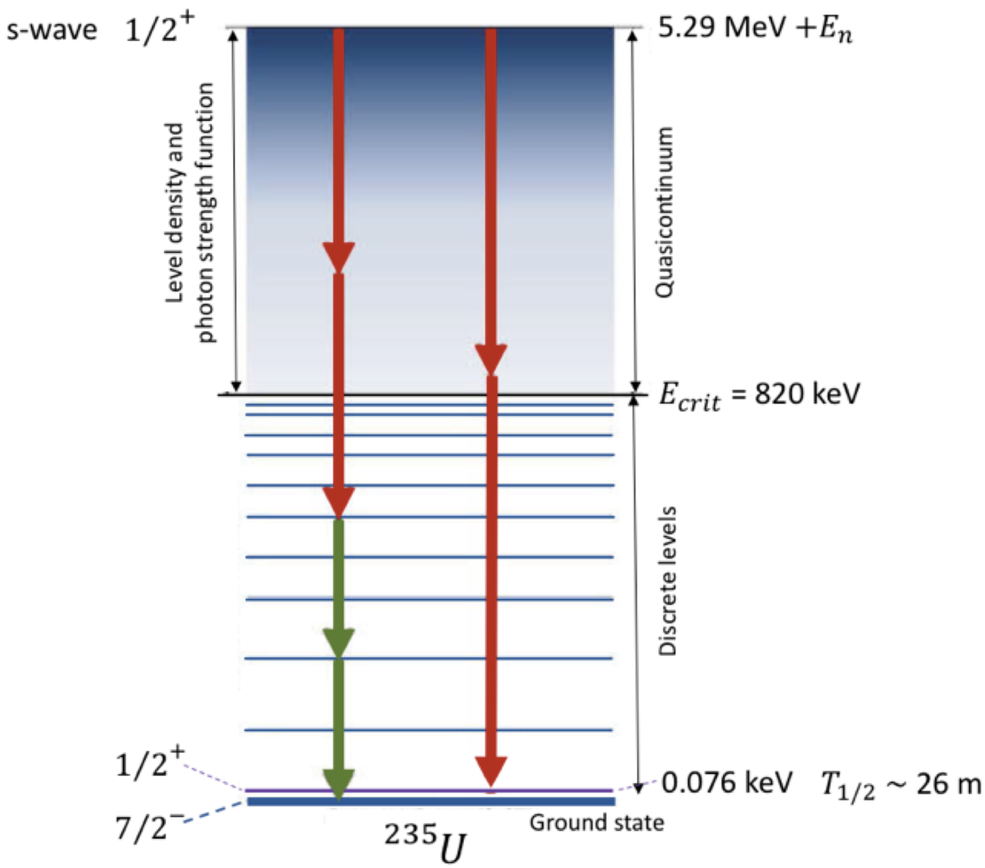
- Many photoneutron xs measurements in the GDR region (E_γ ~10-16 MeV)
- Few and contradictory experimental data at lower energy ($E_\gamma < S_n$~5 MeV)



The PSF is essential for modelling the EM cascade from one level to another

PSF and LD are difficult to disentangle

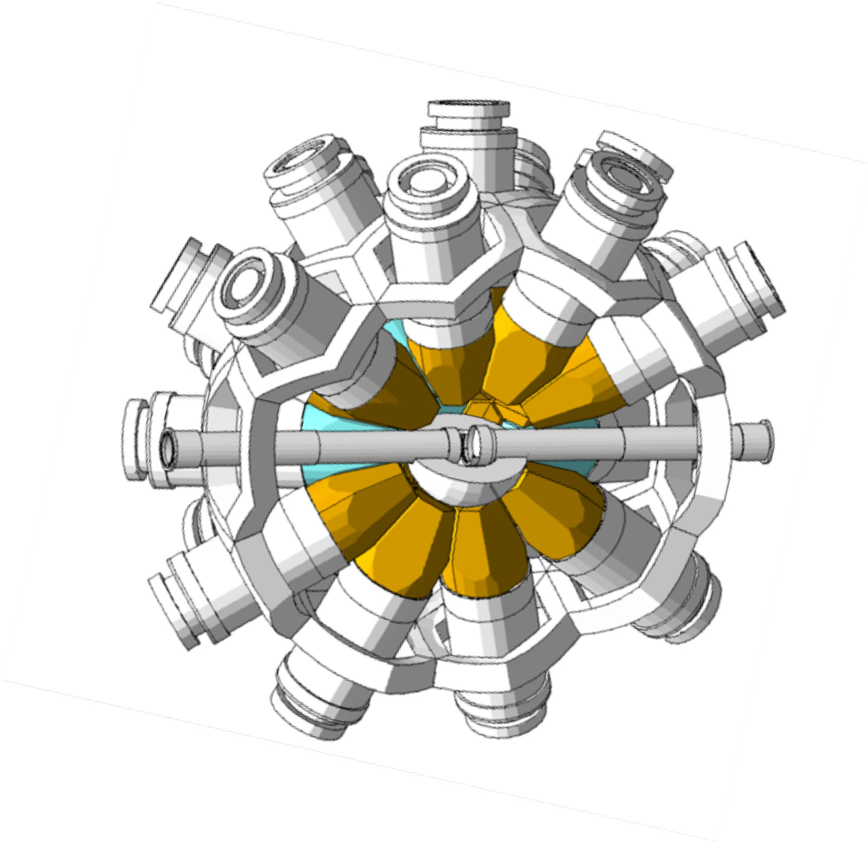
Monte-Carlo simulation of the EM cascade (with DICEBOX)

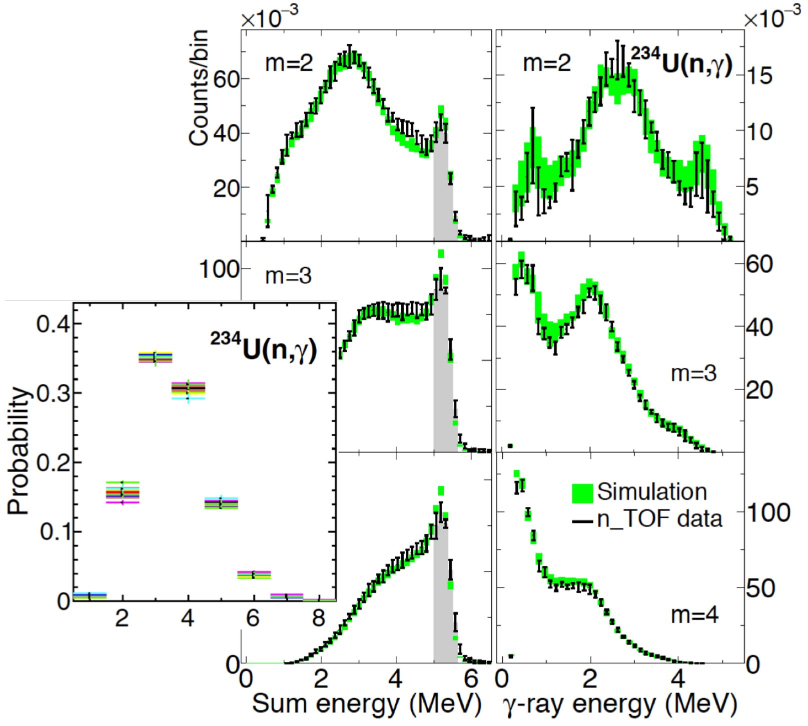


- Initial level E^* (~5.3 MeV), J^π (1/2+) and $\Gamma_{\gamma,i}$
- Down to E_{crit} : Additional levels and probability transitions sampled from LD and PSF models
- Below E_{crit} : Experimental levels and transitions
- Final level is the ground state or a metastable state

GEANT4 simulations + post processing

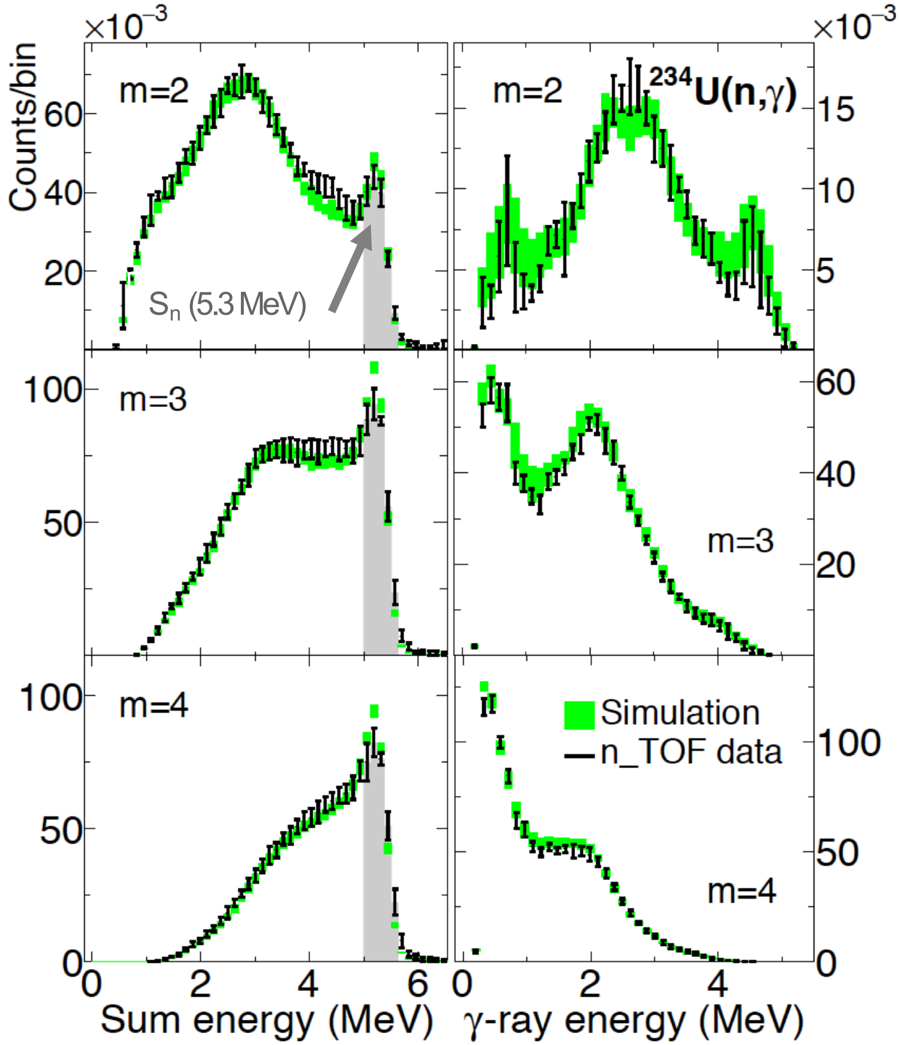
Monte-Carlo transport & detection of photons in the experimental set-up





Nuclear Structure from Capture γ-rays

Comparison with data for Sum-energy and MSC spectra



- Comparison of the data and simulations after fine-tuning of models parameters
- Consistent analysis of n+U-234, n+U-236 and n+U-238 systems
- Unique set of PSF parameters for the three uranium isotopes

More in J. Moreno-Soto, S. Valenta, et al., Constraints on the dipole photon strength for the odd uranium isotopes, PRC 105 (2022) 024618

Additional constraint from the total radiative widths Γ_γ

TABLE III. Total radiative widths Γ_γ of s-wave resonances obtained with different model combinations. The combinations labeled MGLO(k) consisted of the CT NLD model [50] and the MGLO $E1$ PSF model with a constant temperature of $T = 0.3$ MeV unless specified otherwise. Values for more model combinations can be found in the Supplemental Material [35].

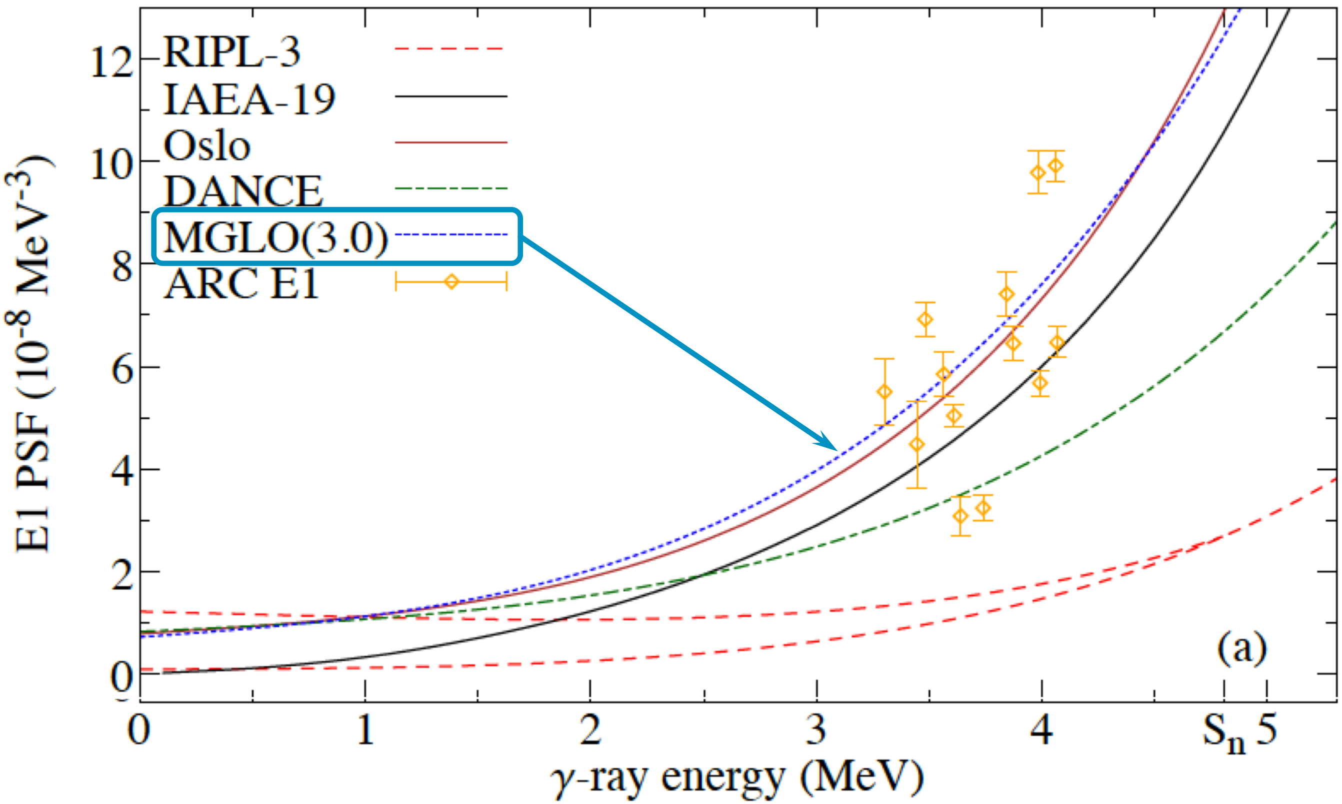
Model combination	Γ_γ (meV)		
PSF-LD	^{234}U(n,γ)	^{236}U(n,γ)	^{238}U(n,γ)
RIPL-3	16.1(2)	12.9(2)	9.5(2)
IAEA-19	29.4(6)	19.3(5)	13.9(5)
Oslo	19.9(4)	20.4(6)	18.6(8)
DANCE	22.0(5)	17.2(4)	15.9(6)
MGLO(1.8)	25.4(7)	20.1(5)	15.9(6)
MGLO(2.5)	30.5(10)	23.9(7)	18.8(7)
MGLO(3.0)	39.0(12)	30.9(9)	24.3(9)
MGLO($k, T(E)$)	26.7(7)[a]	24.5(6)[b]	19.2(7)[c]
Mughabghab's atlas [58]	25.3(10)	23.4(8)	23.36(31)
Mughabghab's atlas [51]	36.7(7)	23.4(8)	22.9(4)
JEFF-3.3 [5,59]	26.0	23.0	22.5
ENDF/B-VIII.0 [4]	26.0	19.5	22.5

- Total radiative widths Γ_γ provide additional constraints on PSF (and LD)
- Fair agreement (with different k-values) between MGLO(k) model and evaluated Γ_γ (the k-values compensate for differences in LD)

More in J. Moreno-Soto, S. Valenta, et al., Constraints on the dipole photon strength for the odd uranium isotopes, PRC 105 (2022) 024618

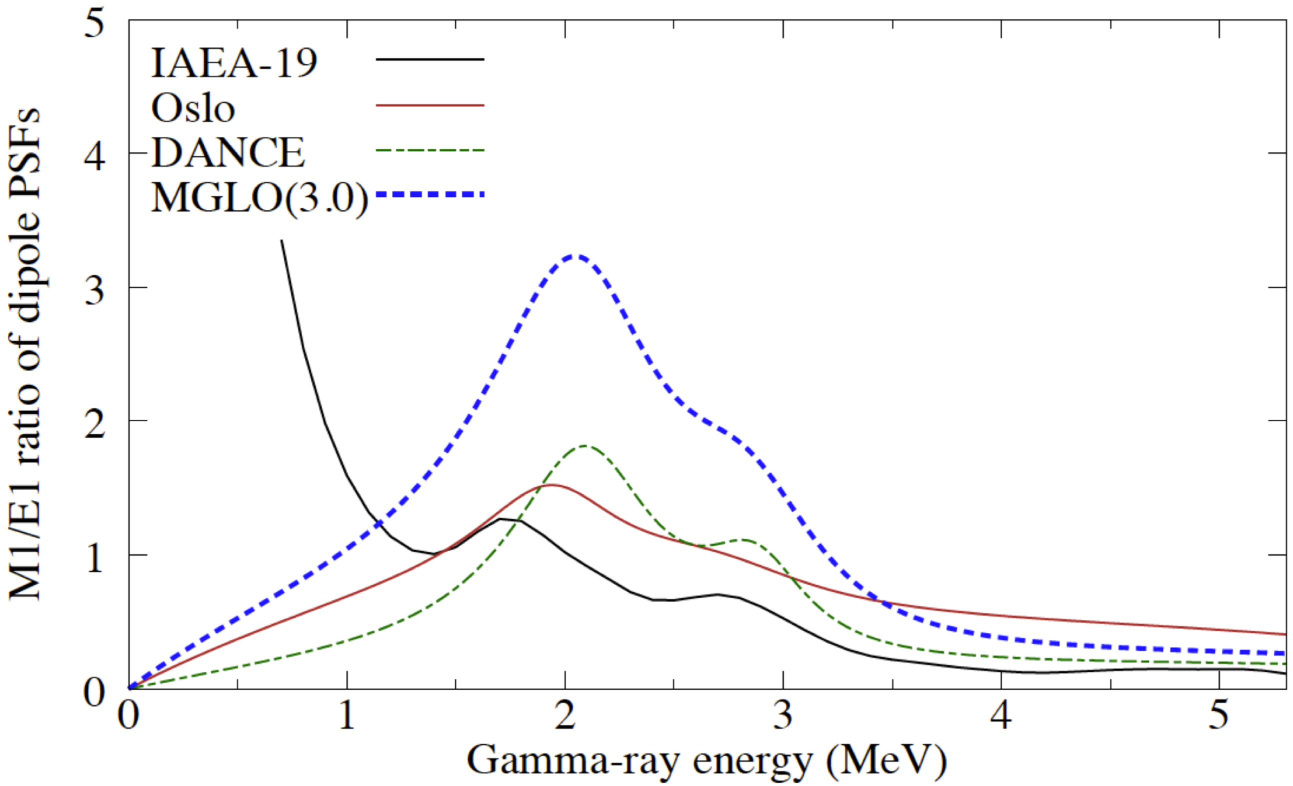
Comparison of E1 PSF

The MGLO model with n_TOF parameters is also consistent with E1 values extracted by Kopecky et al. from U-239 average resonance capture (ARC) data



Comparison of M1/E1 PSF

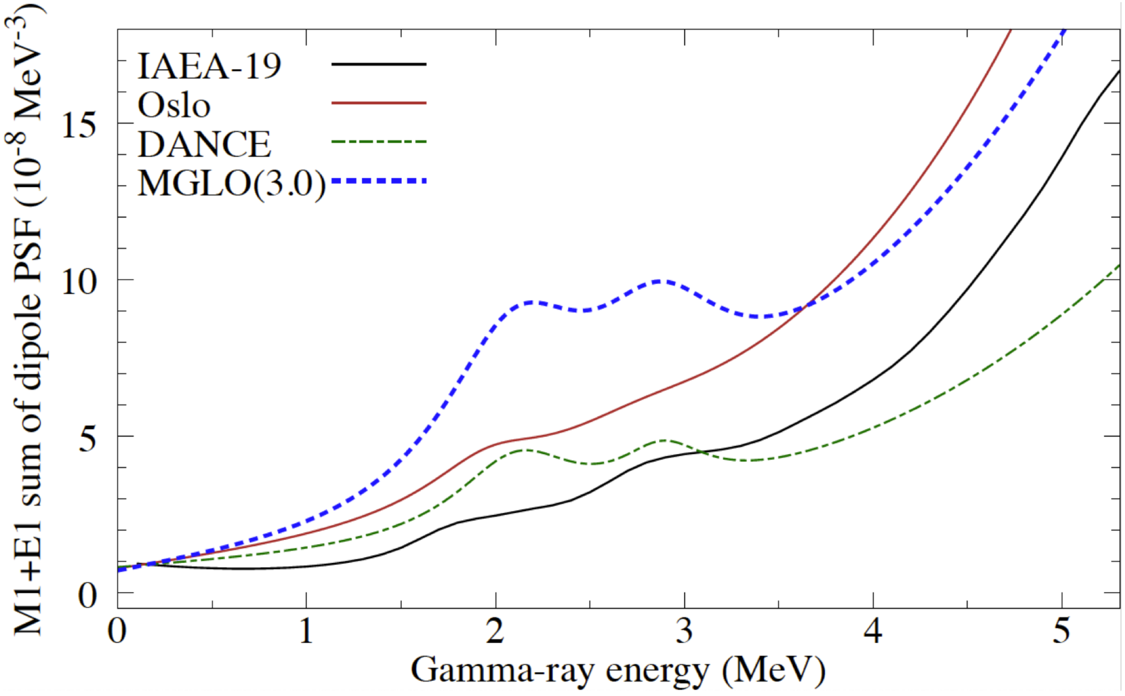
M1/E1 PSF ratio below S_n is key to reproduce γ-ray spectra



The n_TOF simulation with MGLO(3.0) shows the need for a larger M1/E1 ratio at low γ-ray energy (below S_n)

Nuclear Structure from Capture γ-rays

Comparison of dipole (M1+E1) PSF



- Confirmation of the scissors mode peaks at 2 and 3 MeV in the M1 PSF
- Large contribution of the scissors mode is needed to reproduce n_TOF spectra

More in J. Moreno-Soto, S. Valenta, et al., Constraints on the dipole photon strength for the odd uranium isotopes, PRC 105 (2022) 024618

Conclusions

n_TOF

- n_TOF measurements of capture xs using the 4π segmented TAC have been used for low-resolution spectroscopy purpose
- A consistent modelling of the γ-ray sum-energy and MSC spectra, γ-ray multiplicity and total radiative width (Γ_γ) was achieved for non-fissile uranium systems (n + U-234,236,238)
- The simulations depend on various nuclear structure database (RIPL, ENSDF, BrIcc…), which should be under control in order to infer trends on the relatively less known parameters (M1 PSF in this case)
- This study confirms the need for a relatively strong M1 contribution in the PSF of uranium isotopes at low γ-ray energy (E_γ ~ 1 to 4 MeV)

More details in the PhD Thesis of J. Moreno-Soto (Université Paris-Saclay, 2020) or the corresponding publication: Phys. Rev. C 105 (2022) 024618

Thank you for your attention!

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