FROM RESEARCH TO INDUSTRY

Isomeric ratio measurements for the radiative neutron capture $^{176}Lu(n,\gamma)$ at DANCE

Oslo 2017

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Introduction

- Interests of the ^{176}Lu nucleus
  - Stable nucleus with a high spin ground state ($J^{\pi}=7^{-}$)
    → population by neutron capture of high spin states ($J^{\pi}=13/2^{-}$ and $J^{\pi}=15/2^{-}$)
  - Astrophysics interests through the s-process of the nucleosynthesis

K. Wisshak et al., Phys. Rev. C ***73****, 015807 (2006)*

- To complete XS and MACS and compare with reaction models

Cross section of ^{176}Lu(n,γ) reaction

- Isomeric ratio interests
  - Strong check of predictions from evaluations
    → Can contribute to improve nuclear reaction models and ingredients

Isomeric cross section ratios in the ^{176}Lu(n,γ) reaction

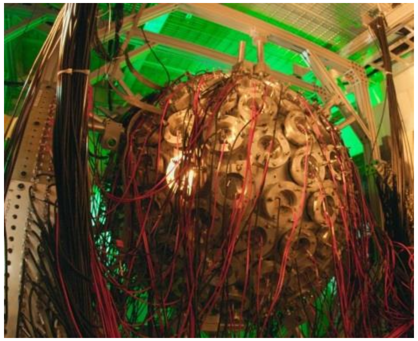
- Knowing resonances and isomeric states, this allows to study feedings and gamma Strength Function (gSF) through gamma spectrum

Gamma strength function in the ^{176}Lu(n,γ) reaction

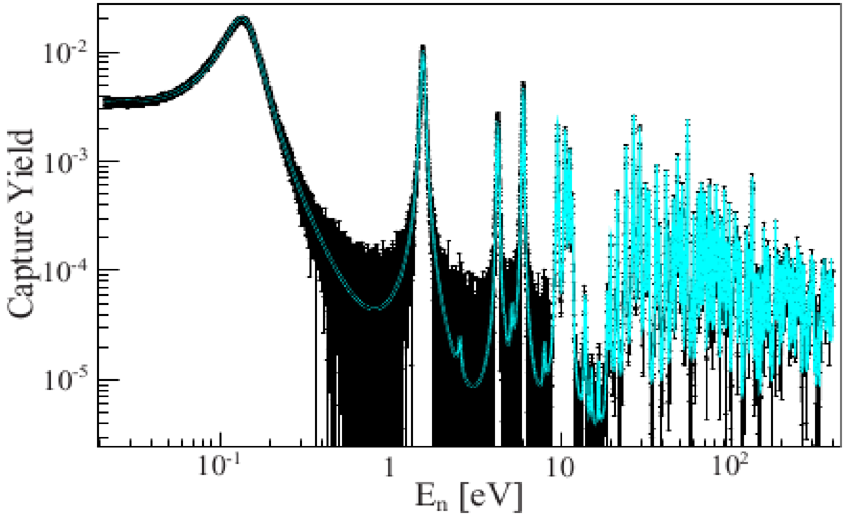
Experimental setup at DANCE

DANCE at Lujan Center (LANL)

Cross section measurements from meV to keV

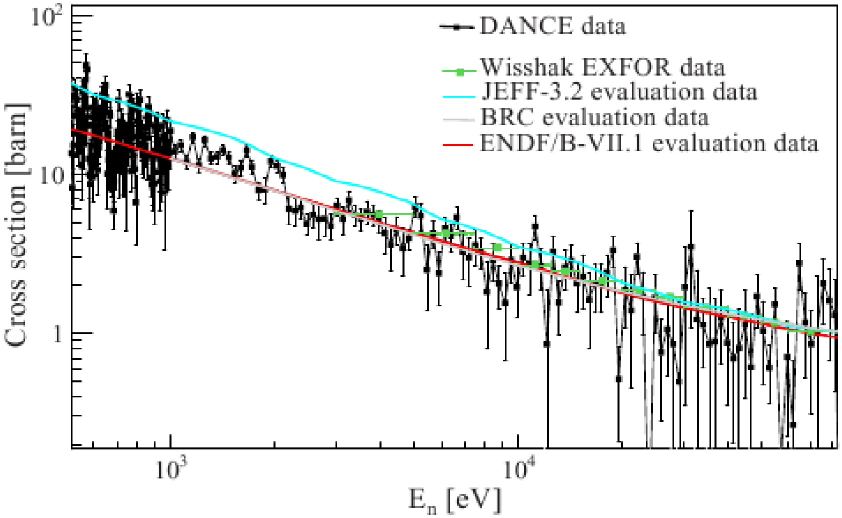


Resonance region



O. Roig et al., Phys. Rev. C ***93****, 034602 (2016)*

keV region



To check more precisely ingredients of models,

- we extract isomeric cross section ratios
- we look at gSF with DANCE as it was done using TSC method

M. Krtička, F. Bečvář, S. Valenta, ^{177}Lu, Charles Univ., Prague (2008-2010)

Isomeric cross section ratio

- Defined here as isomer/total cross section ratio
- Experimentally: need to take into account the detection efficiency

Number of detected isomers

γ cascade detection efficiency

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

Isomer detection efficiency

Number of detected γ cascades

Experimentally determined

Geant4-EVITA simulations

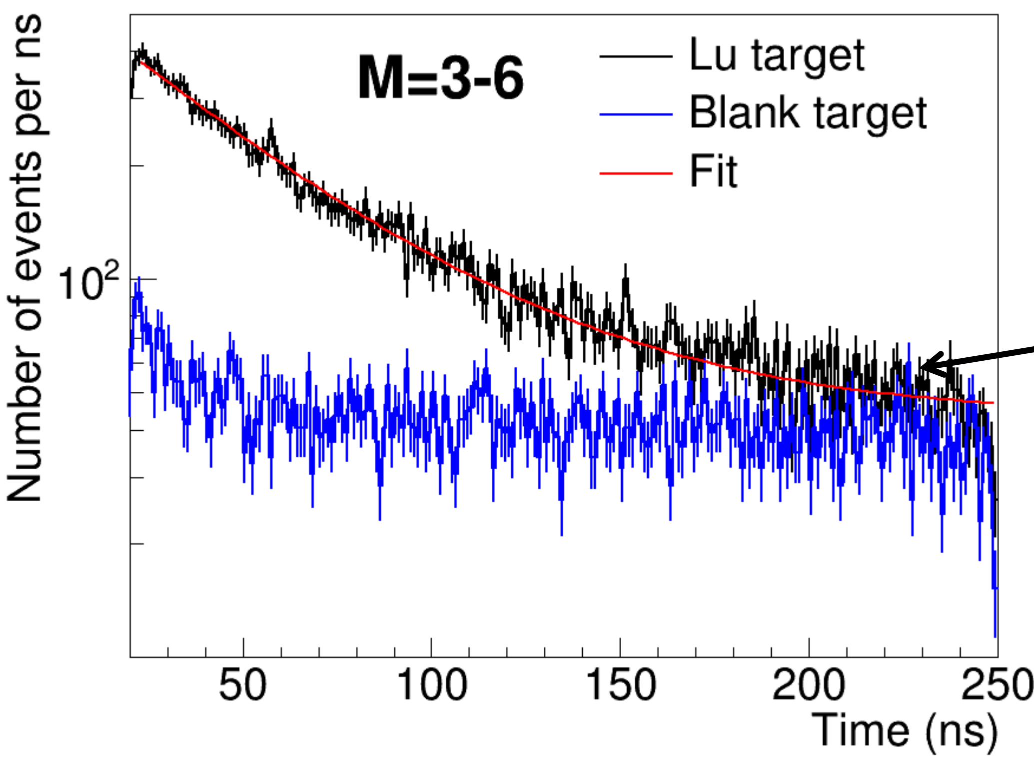
- Isomeric ratio calculated for a wide neutron energy range (8.5 eV up to 100 keV) → all resonances with spins $J^{\pi}=13/2^{-}$ and $15/2^{-}$
- Isomer: defines the final step of the γ cascade

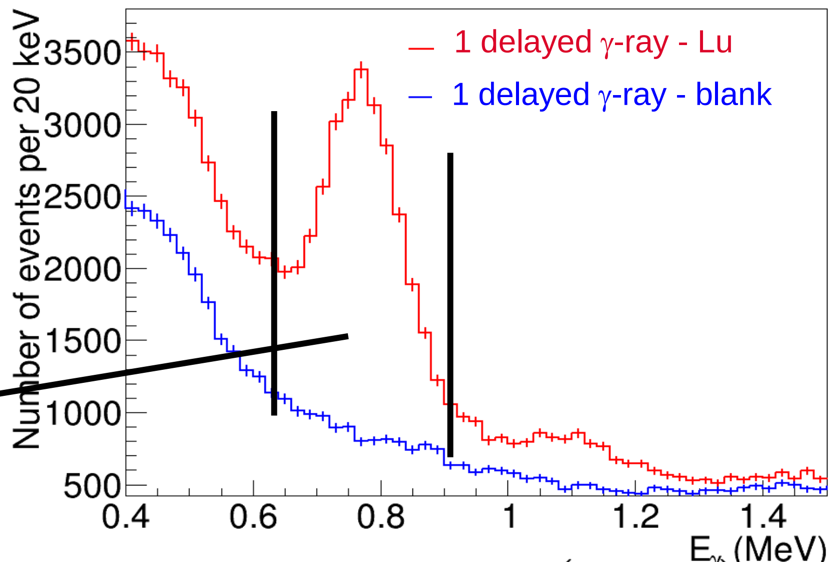
Isomer selections

Time and energy selections

762 keV

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$





Ajustement : $f(t) = A_0 \exp\left(-\ln 2 \frac{t}{T}\right) + B$

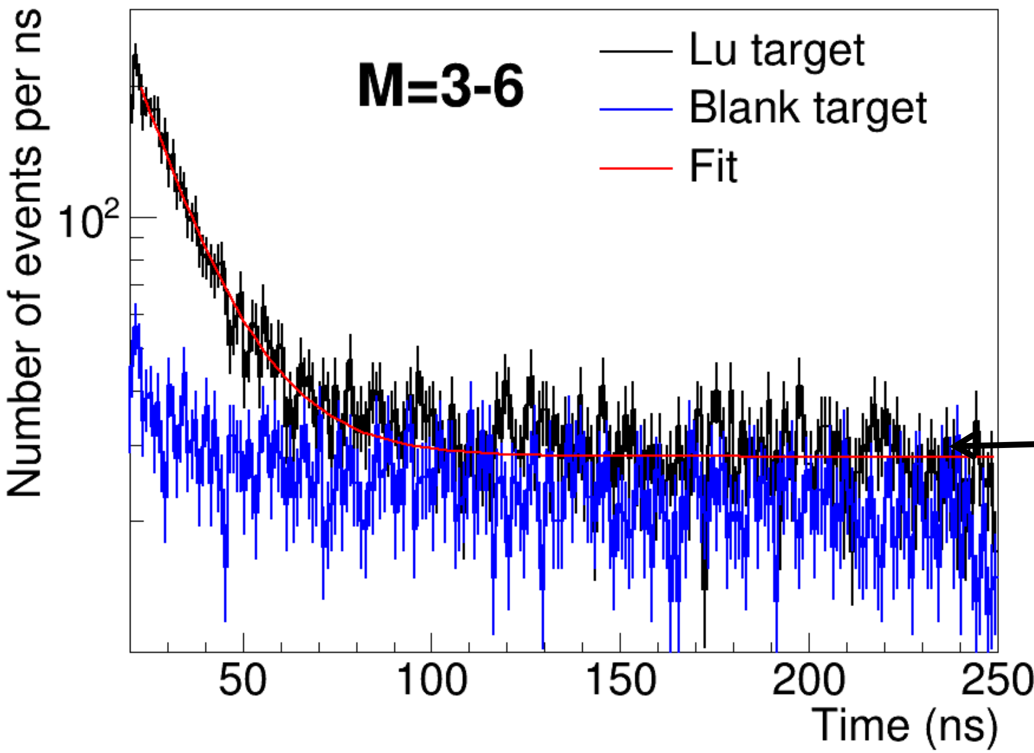
A_0 (cps/ns)	T (ns)	B (cps/ns)
522.8 ± 11.5	35.0 ± 0.9	43.1± 1.3

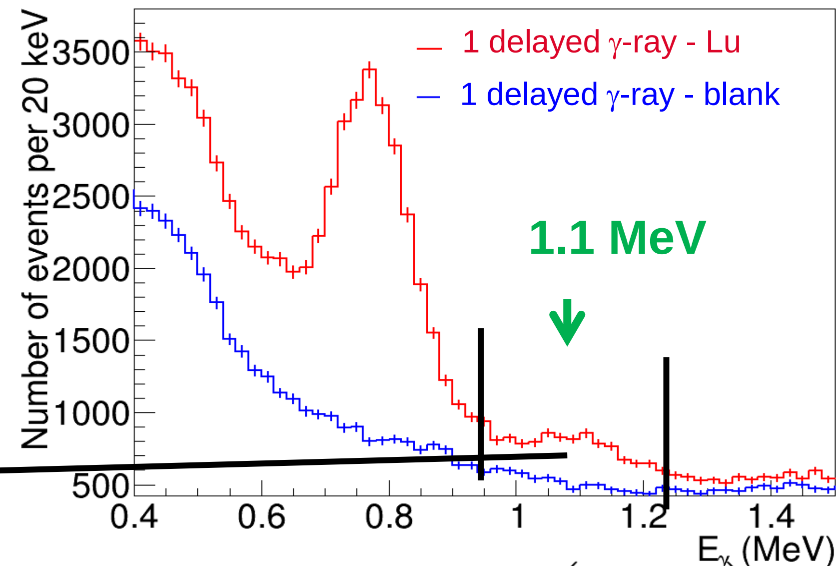
➢ **E_{iso}=761.7 keV, $T_{1/2}$=32.8 ± 2.4 ns, $J^{\pi}=5/2^-$**

Isomer selections

Time and energy selections

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$





Ajustement : $f(t) = A_0 \exp\left(-\ln 2 \frac{t}{T}\right) + B$

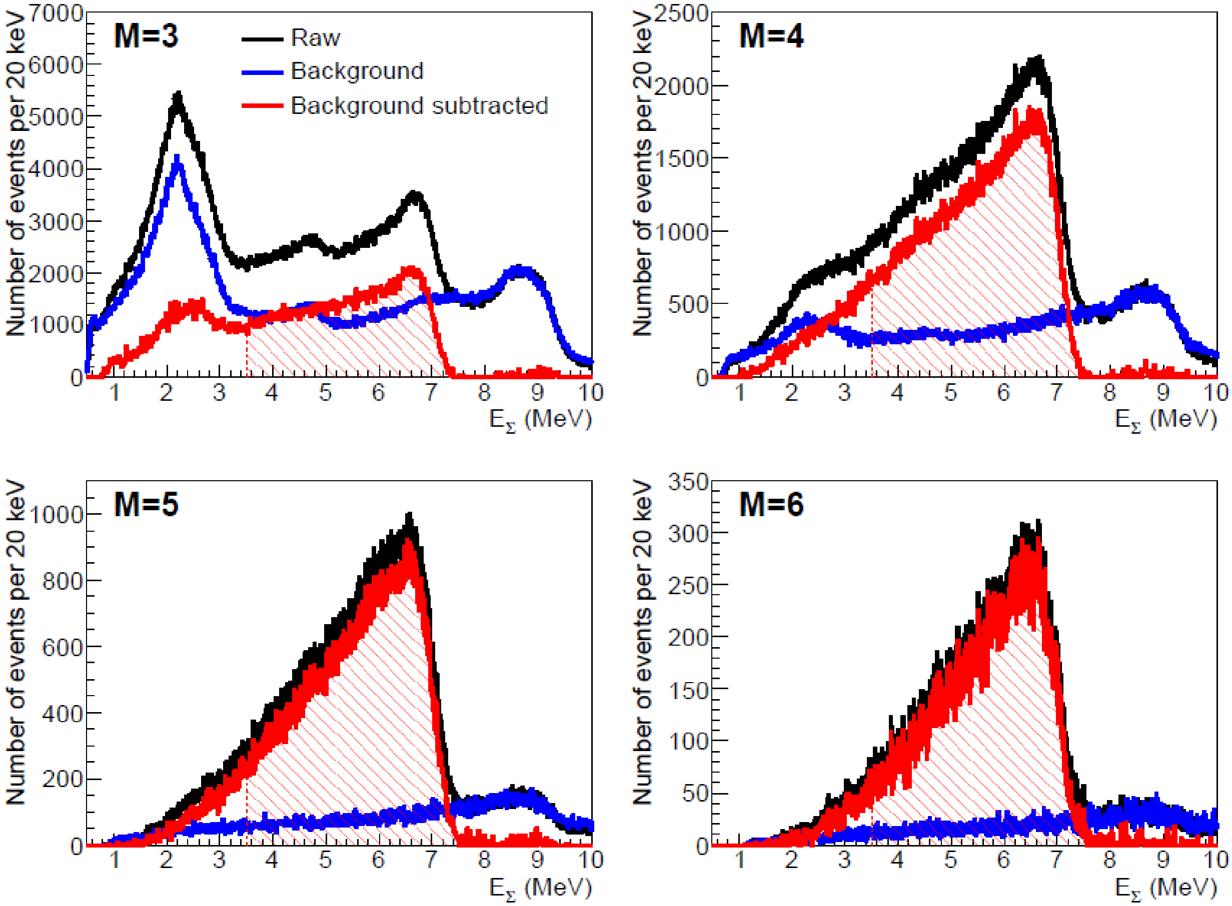
A_0 (cps/ns)	T (ns)	B (cps/ns)
750.3 ± 62.2	10.8 ± 0.5	28.2 ± 0.5

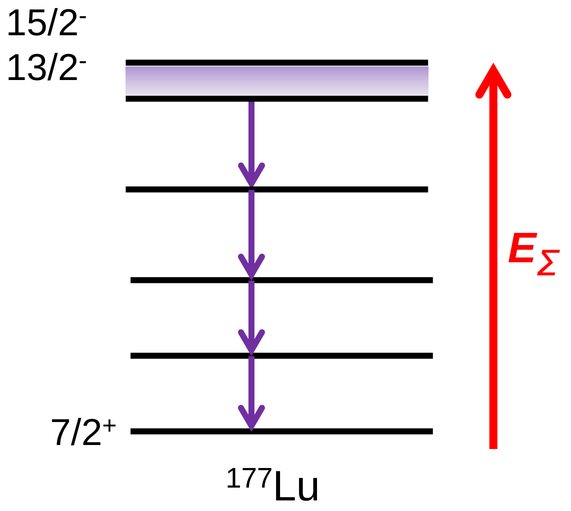
➢ E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ± 1.0 ns, J^{π}=15/2^{+}

Number of detected cascades

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

- Integration of the sum energy spectrum for each multiplicity
  - Background subtraction with the blank target



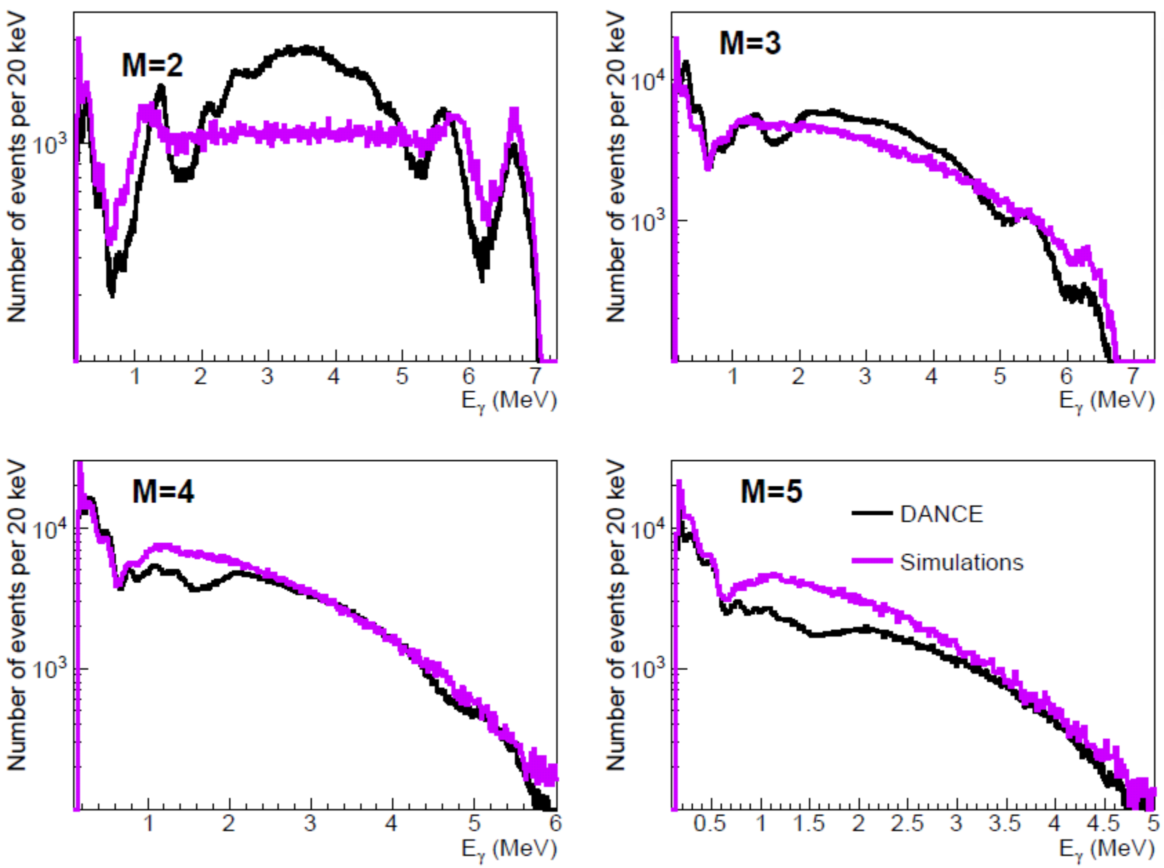


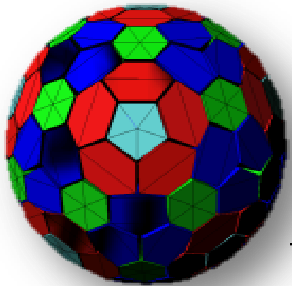
γ-cascade simulations with EVITA

- Comparison between experimental and simulated spectra
  - Initial level selection
    - Selection on neutron energy: $J^{\pi}=13/2^{-}$ resonance at 0.14 eV
    - Selection on sum energy

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

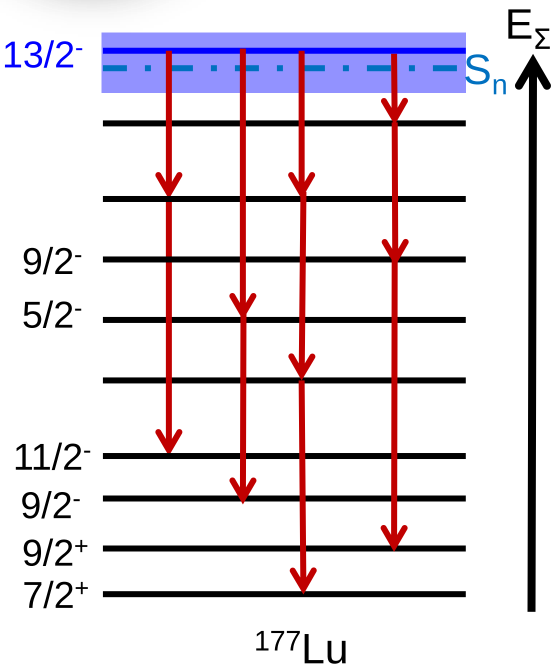
*M. Jandel et al., NIM B, **261**, 1117 (2007)*





B. Morillon (2010)

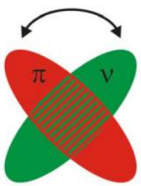
EVITA: a Monte-Carlo code based Hauser-Feshbach formalism with inputs from TALYS code

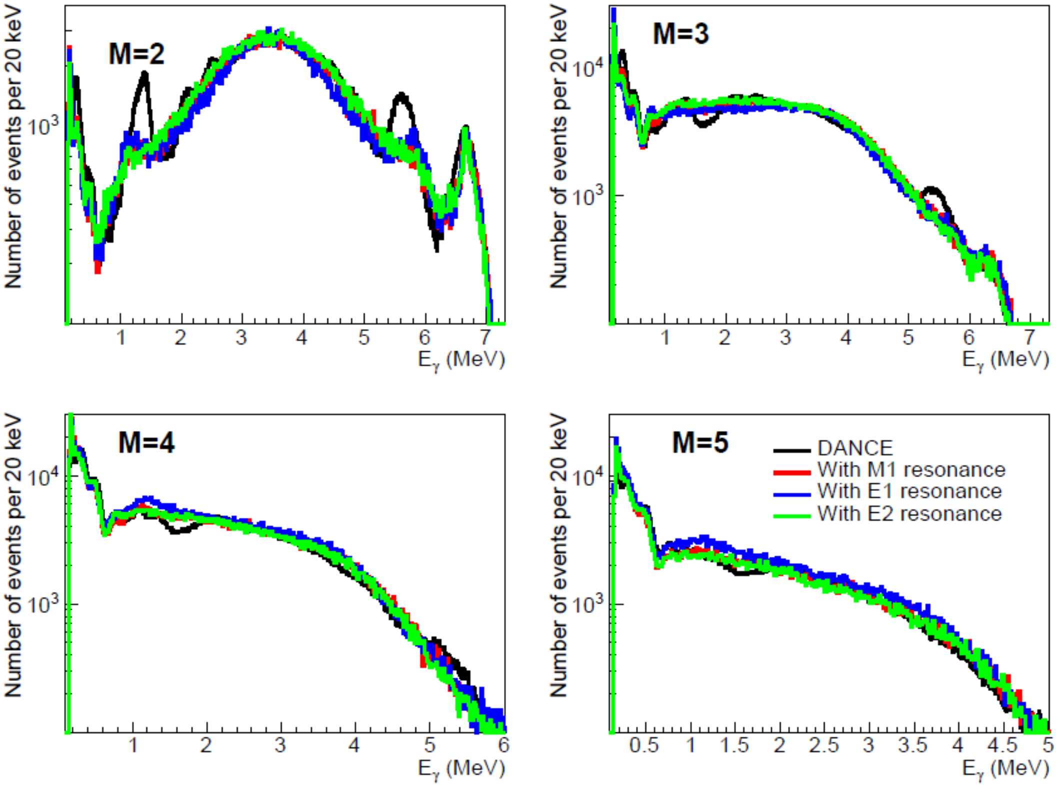


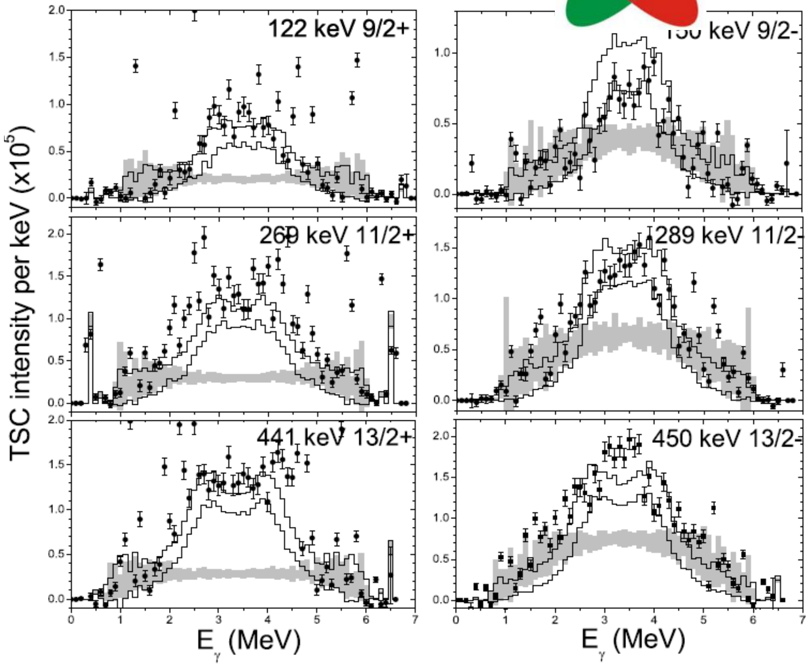
➢ **Experimental γ-ray spectra are not reproduced**

Photon strength functions

- Addition of a low-energy resonance in the PSF (M1 scissor mode ?)







*F. Bečvář et al., EPJ WOC, **93**, 01054 (2015)*
S. Valenta, Diploma thesis, Charles Univ., Prague (2010)

Resonance parameters :

- E=4.25 MeV
- Γ=2 MeV
- σ=3.75 mb

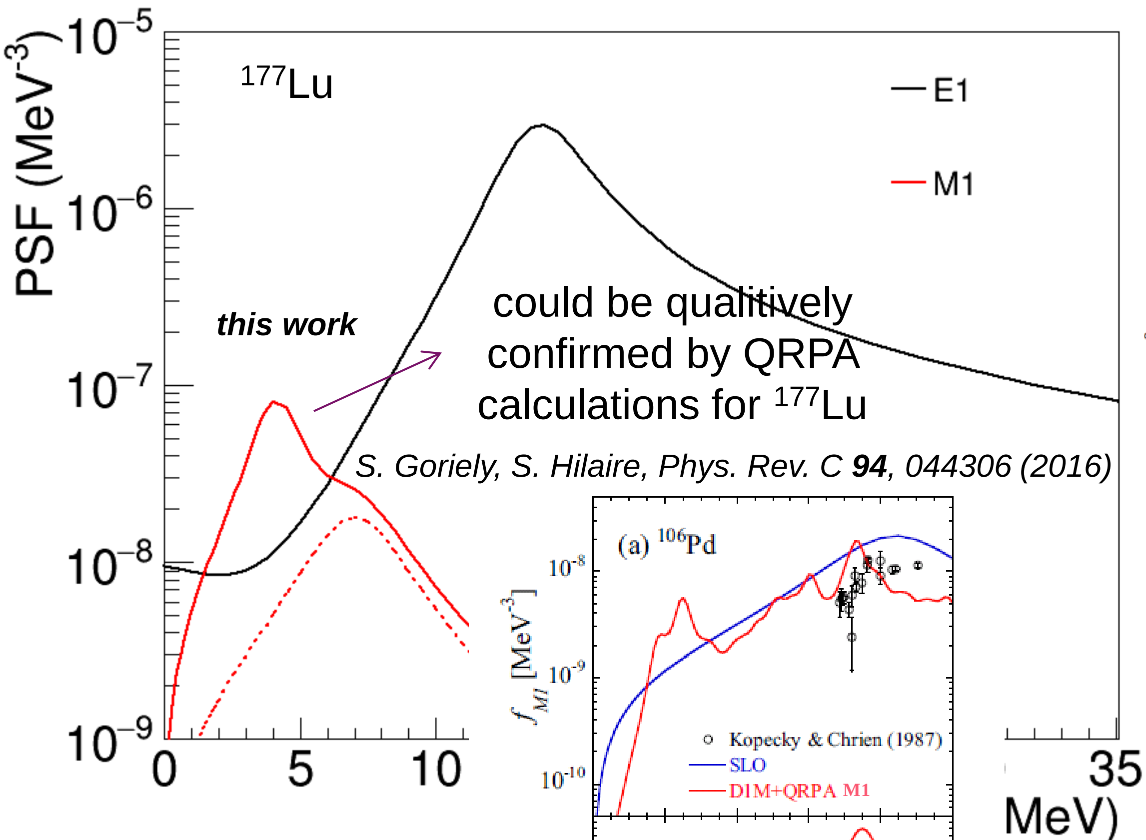
M1 resonance parameters :

- E=4.0 MeV
- Γ=1.0 MeV
- σ=2 mb

- **γ-ray spectra are now better reproduced**
- **EM nature of the resonance not determined with our data**

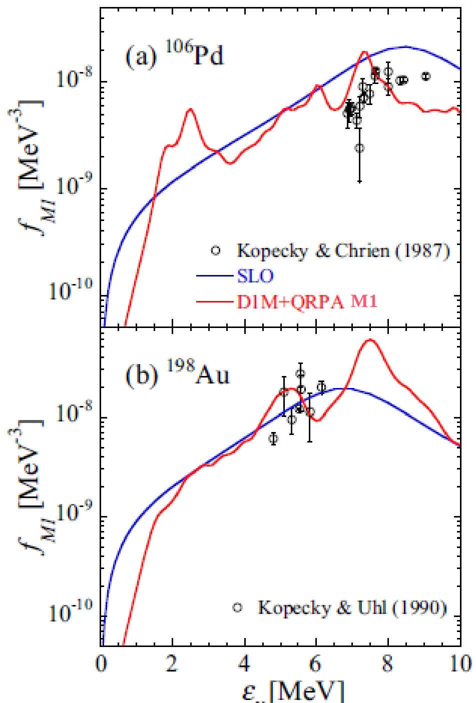
Also for ^{152,154,156,158}Gd : *J. Kroll, Phys. Rev. C **88** 034317 (2013)*

Photon strength functions



could be qualitively confirmed by QRPA calculations for ^{177}Lu

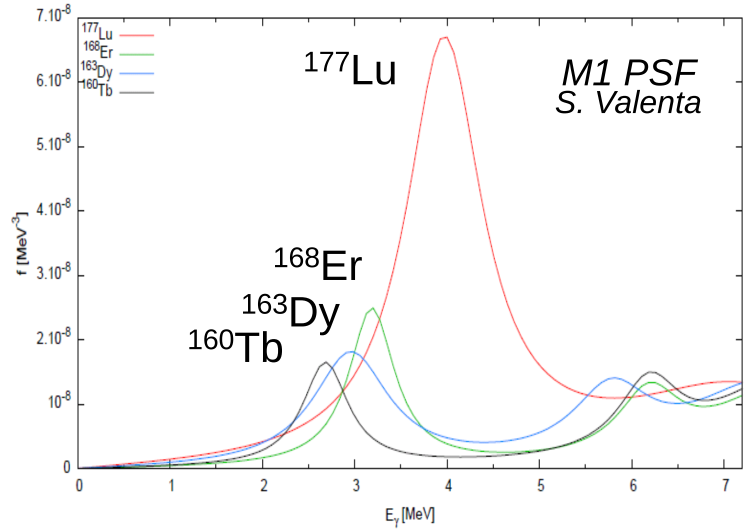
S. Goriely, S. Hilaire, Phys. Rev. C ***94****, 044306 (2016)*



Resonance parameters

- E=4.25 MeV
- Γ=2 MeV
- σ=3.75 mb

confirmation of previous results



F. Bečvář et al., EPJ WOC, ***93****, 01054 (2015)*

S. Valenta, Dipl.thesis, Charles Univ., Prague (2010)

M1 resonance parameters :

- E=4.0 MeV
- Γ=1.0 MeV
- σ=2 mb

See talks of S. Goriely, S. Hilaire and M. Krtička

Also for ^{152,154,156,158}Gd : *J. Kroll, Phys. Rev. C* ***88*** *034317 (2013)*

Impact on the (n,γ) cross section

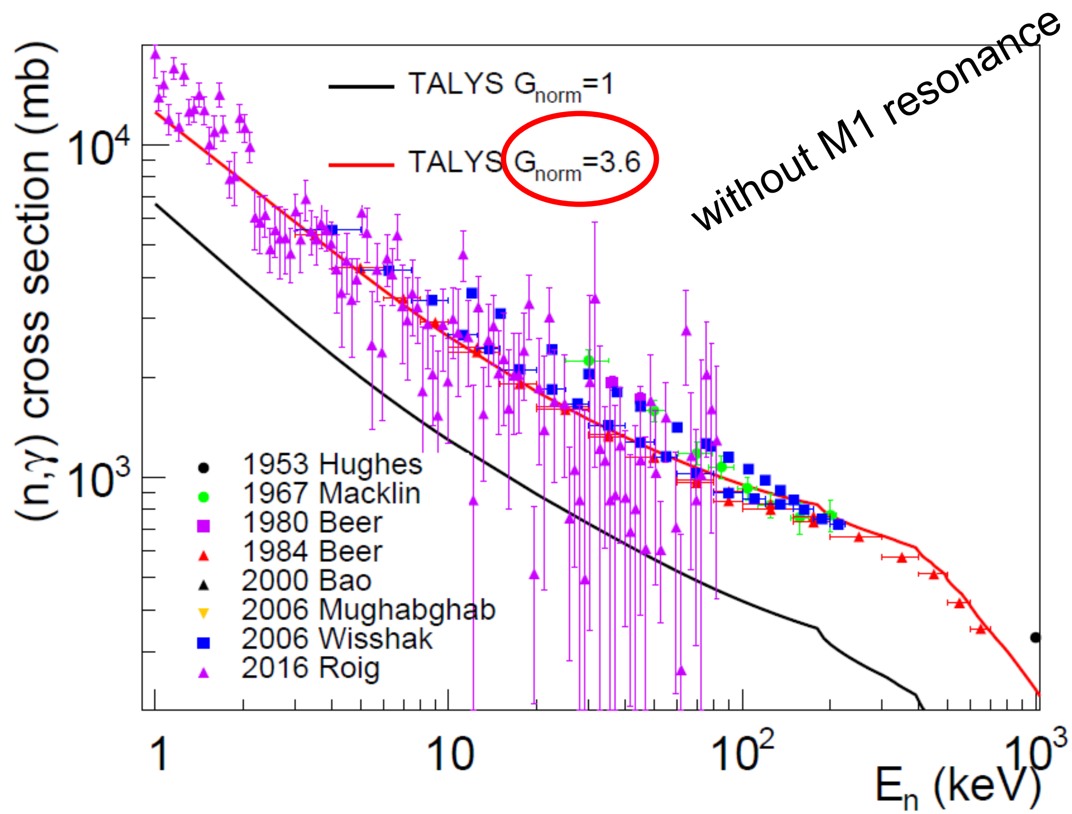
- PSF are renormalize to reproduce the experimental data

Level density

$$\frac{2\pi\Gamma_\gamma}{D_0} = G_{norm}\sum_J\sum_\Pi\sum_{X\ell}\sum_{I'=|J-\ell|}^{J+\ell}\sum_{\Pi'}\int_0^{S_n} dE_\gamma\, T_{X\ell}(E_\gamma)\,\rho(S_n-E_\gamma,I',\Pi')\,f(X,\Pi',\ell)$$

γ transmission coefficient → PSF

Measured on neutron resonances



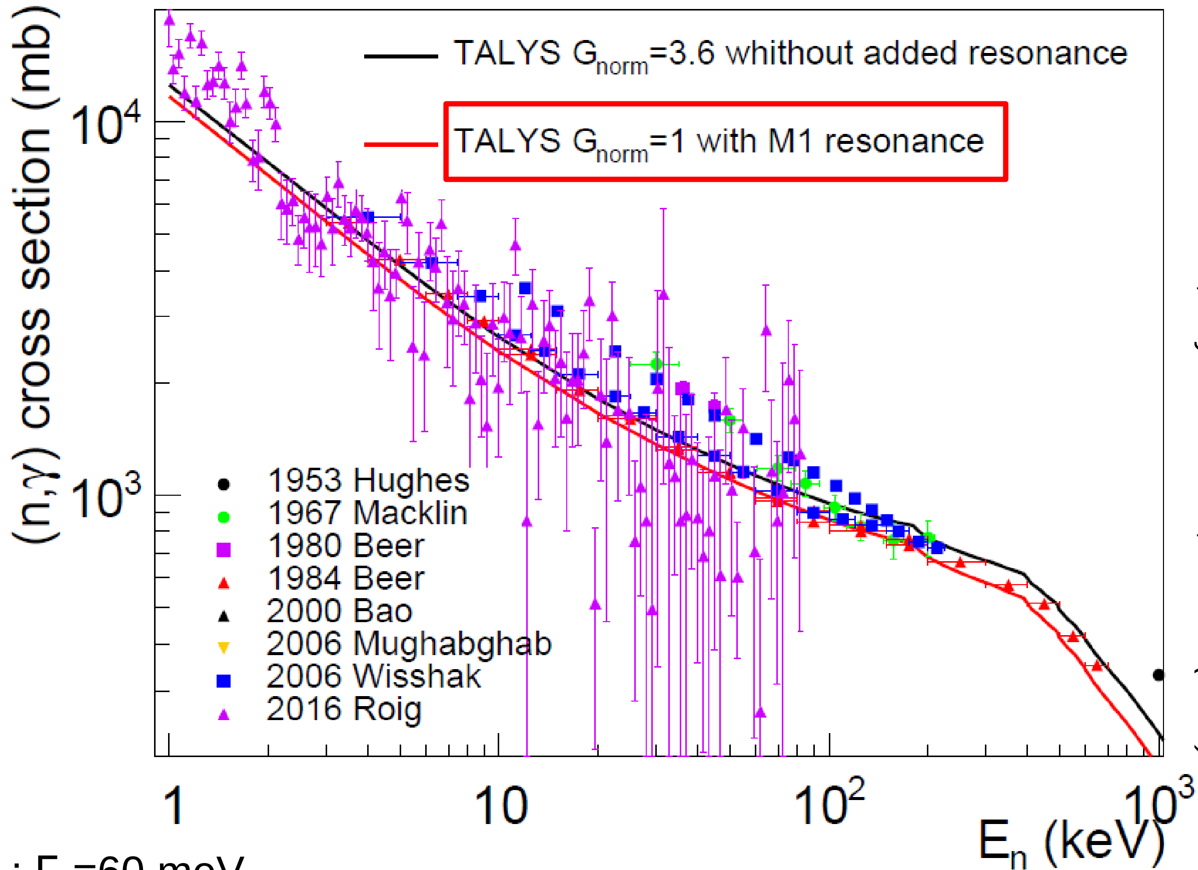
TALYS: Γ_γ=20 meV (G_{norm}=1)
Γ_γ=77 meV (G_{norm}=3.6)

Experimentally: $\langle\Gamma_\gamma\rangle$=65.8 ± 0.2 meV

O. Roig et al., Phys. Rev. C ***93****, 034602 (2016)*

Impact on the (n,γ) cross section

- With the low-energy resonance → renormalization not required



D. Denis-Petit et al., Phys. Rev. C ***94****, 054612 (2016)*

TALYS with M1 resonance : Γ_γ=60 meV

Experimentally: $\langle\Gamma_\gamma\rangle$=65.8 ± 0.2 meV

O. Roig et al., Phys. Rev. C ***93****, 034602 (2016)*

Seen also by J. Ullmann for ^{238}U, Phys. Rev. C ***89,*** *034603 (2014)*

Isomeric ratios

Comparisons between experiment and calculations

- Experimental results *D. Denis-Petit et al., Phys. Rev. C **94**, 054612 (2016)*

Isomer	Experimental R_{iso} (%)
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	10.5 ± 0.6
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	4.8 ± 0.6

- Calculations with TALYS for the different added resonances

	Calculated R_{iso} (%) for the added resonances			
Isomer	**Ø**	**M1**	**E1**	**E2**
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	4.1	5.7	5.0	6.4
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	2.6	2.0	2.0	1.6

➢ **Discrepancies between experimental and calculated values**

Isomeric ratios for different level density models

- Isomeric ratios from phenomenological level density models
  - Back-shifted Fermi gas

Isomer	Calculated R_{iso} (%) Ø	M1	E1	E2	Exp R_{iso} (%)
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	4.9	4.6	4.3	5.0	10.5 ± 0.6
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	2.3	1.9	1.9	1.4	4.8 ± 0.6

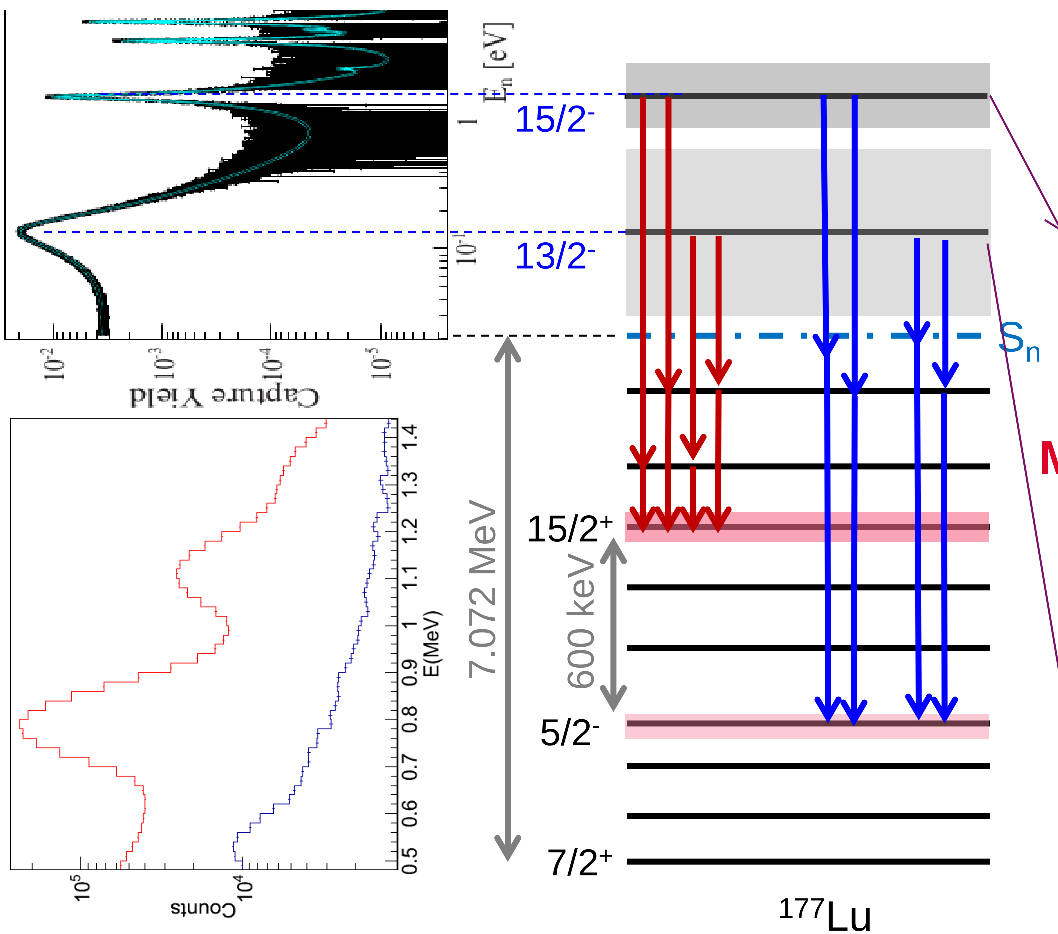
- Isomeric ratios from microscopic level density models
  - HFB with combinational method

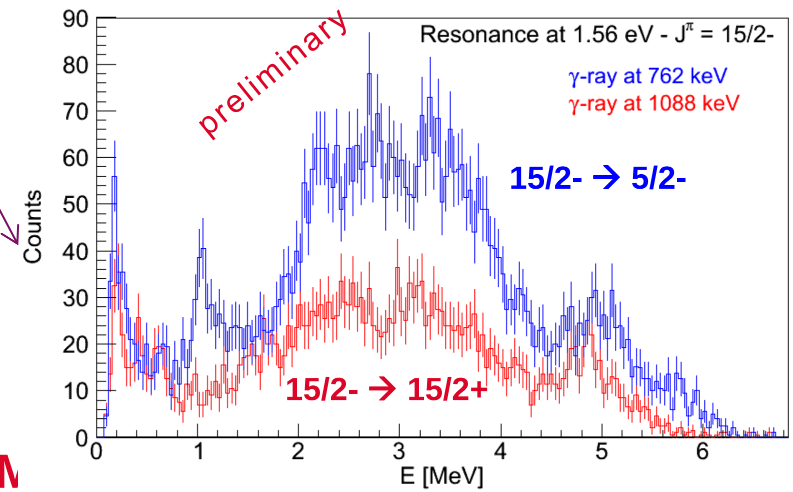
Isomer	Calculated R_{iso} (%) Ø	M1	E1	E2	Exp R_{iso} (%)
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	3.9	5.3	4.4	5.9	10.5 ± 0.6
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	2.4	1.7	1.7	1.3	4.8 ± 0.6

➢ **No strong impact of the levels density models on the isomeric ratios**

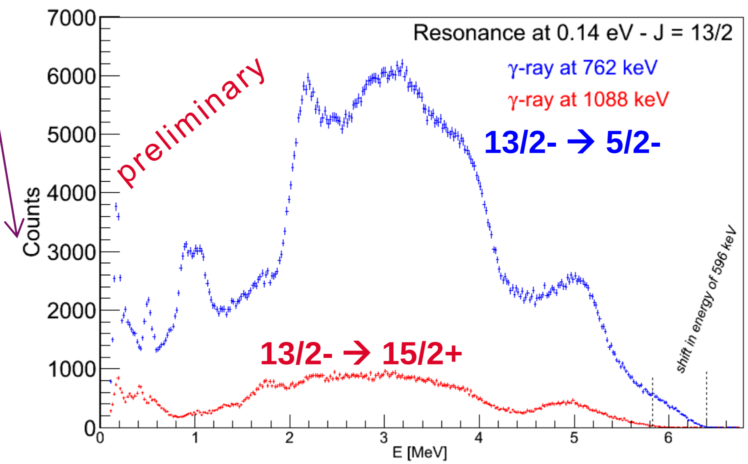
➢ **Still discrepancies between experimental and calculated values**

More precise studies of gSF and isomers feeding





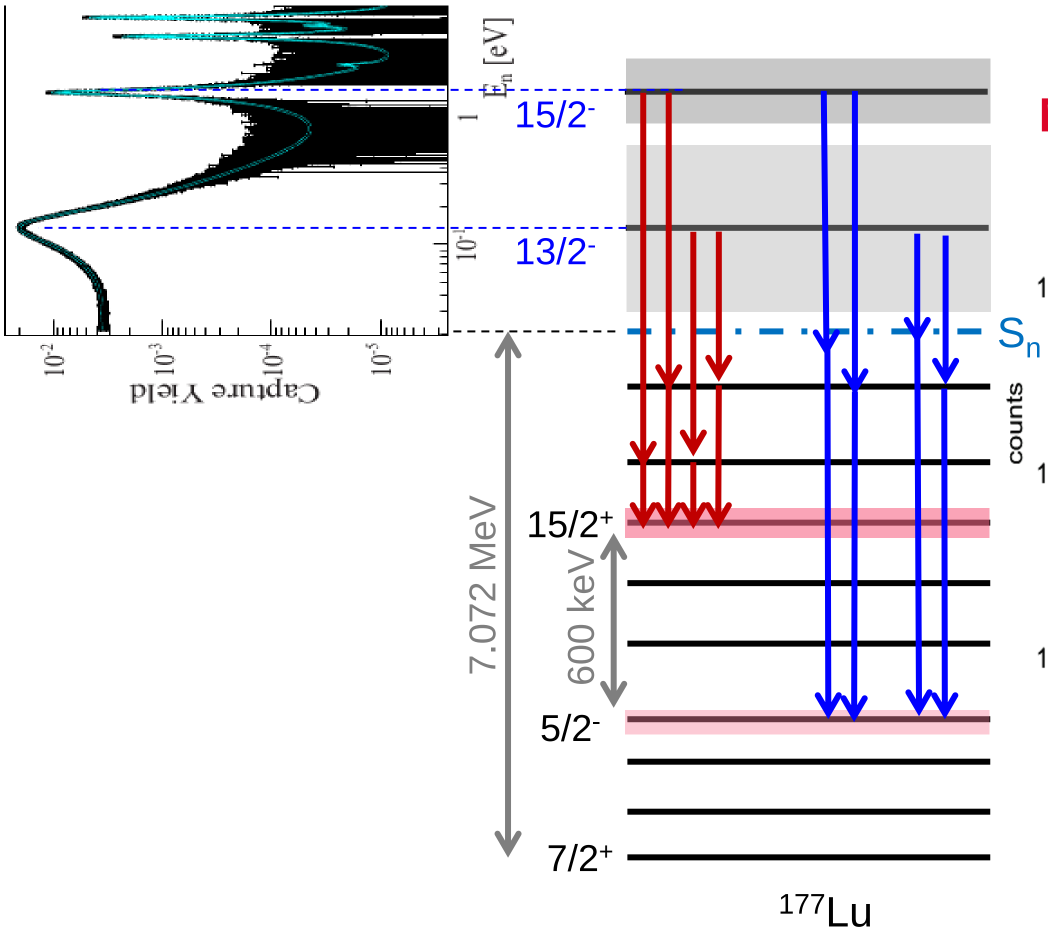
$$E_\Sigma \in [S_n - E_{iso} - e, S_n - E_{iso} + e]$$



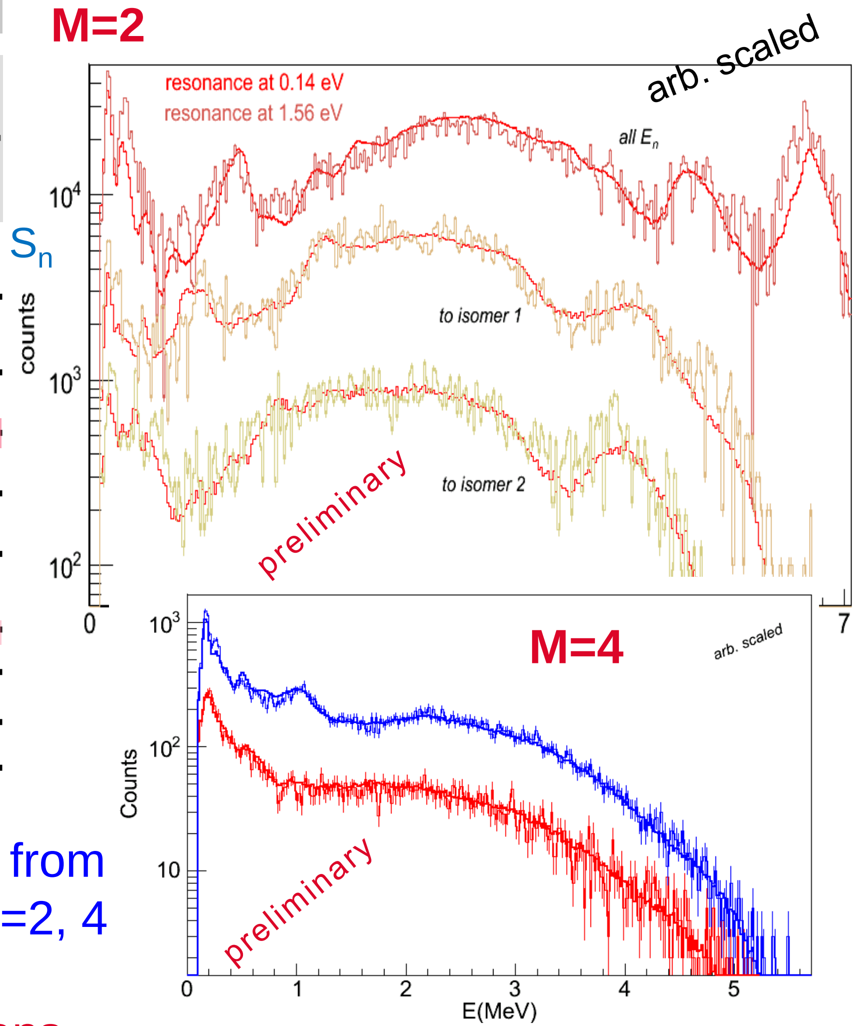
Significant difference between isomers feeding

- Gamma spectrum with M=2
- Intensity

More precise studies of gSF and isomers feeding



$E_\Sigma \in [S_n-E_{iso}-e, S_n-E_{iso}+e]$



No significant difference between γ–cascades from the 2 resonances for gamma spectrum with M=2, 4

except intensities of feeding

➡ to be interpreteded with the help of simulations

Conclusion and perspectives

- Conclusions
  - Isomeric ratios determined for two isomers with **different spins**
  - Discrepancies between experimental and calculated values: factor ~2-3
  - Addition of a resonance in the PSF to reproduce the data
  - Electromagnetic nature of this resonance cannot be determined with the DANCE data

New measurements of ^{177}Lu levels scheme and TSC at FIPPS (ILL) in Autumn 2017

- Perspectives
  - Need to improve the data used in the evaluations: isomer feeding
  - QRPA calculations are in progress to assess the PSF and the nature of the needed resonance
  - Calculations with other reaction codes (DICEBOX,…)
  - Analysis of DANCE measurements for **different neutron resonances** in progress
    - ➢γ cascade well defined to compare with Hauser Feshbach calculations in progress
    - ➢Could address the K mixing issue

Thank you for your attention

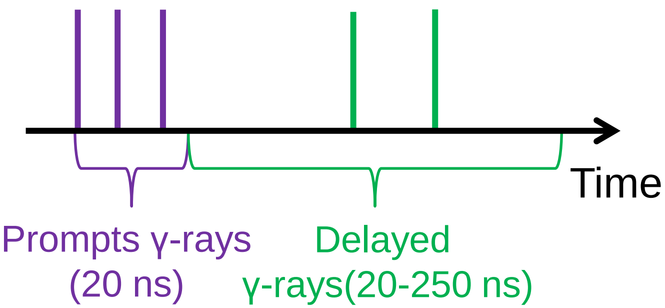
Commissariat à l'énergie atomique et aux énergies alternatives

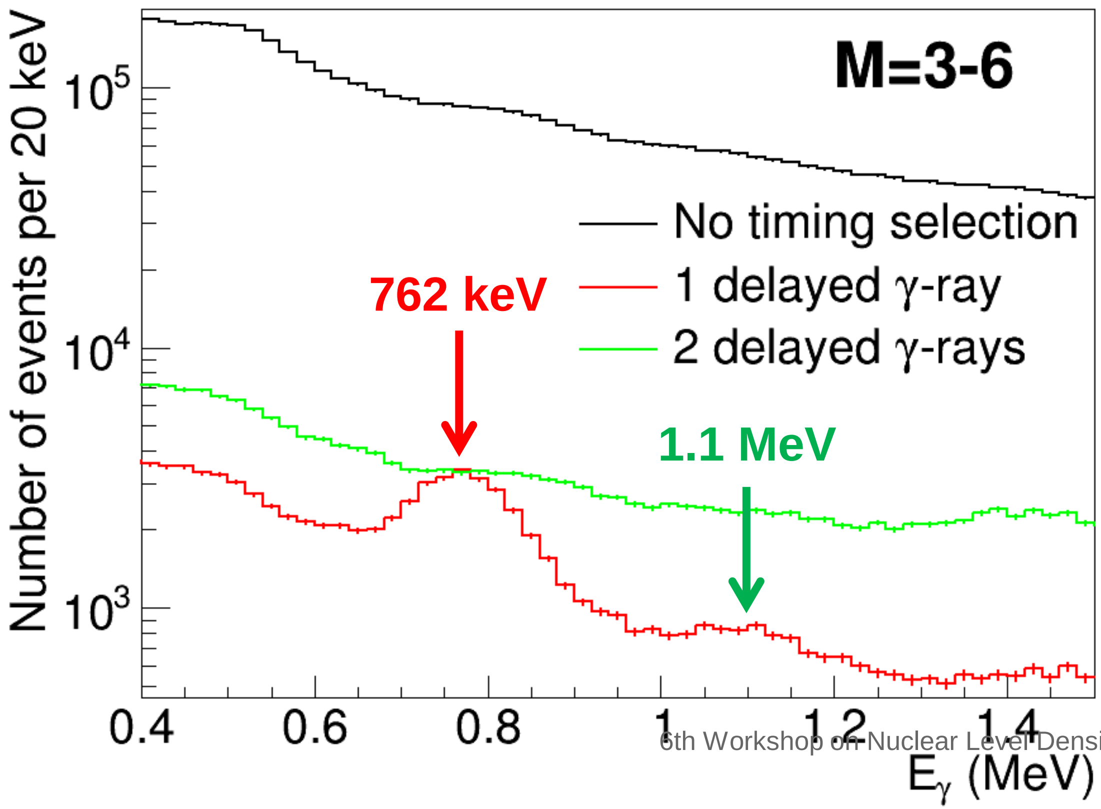
Isomer selections

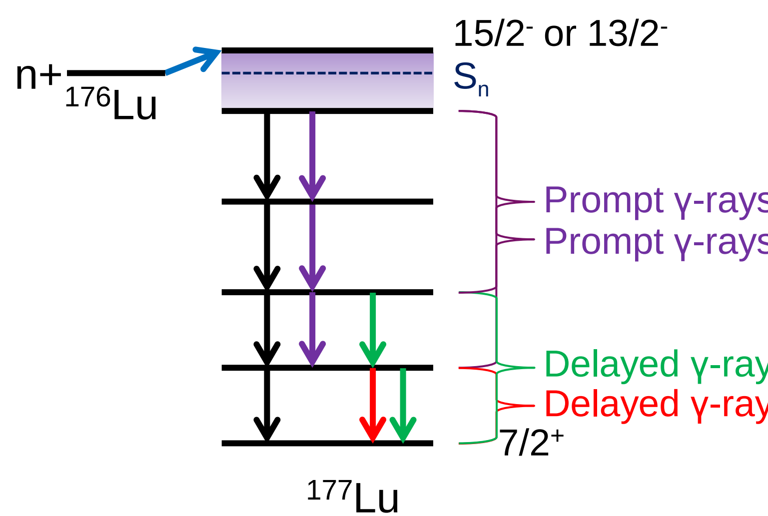
Timing selection on cluster events

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

- For a given cluster multiplicity:
  - Prompt γ-cascade defined in the first 20 ns
  - Delayed γ-rays are in the 20-250 ns range







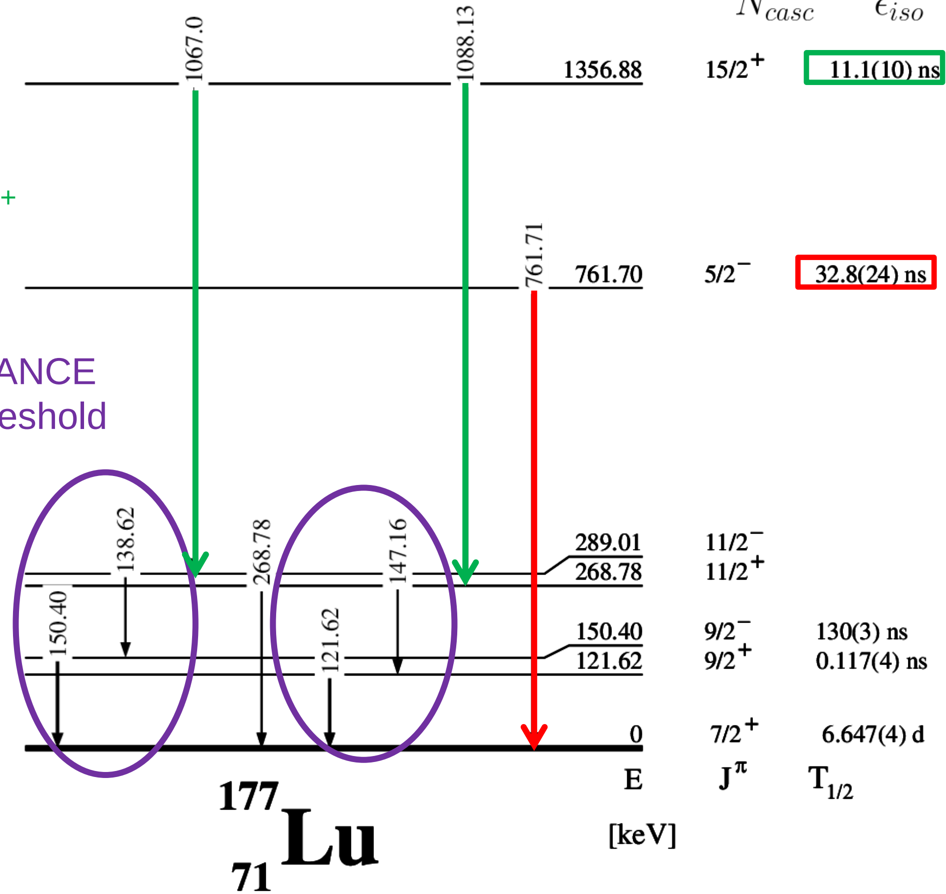
Isomer selections

Events with only one delayed γ-ray

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

- Two isomers highlighted :
  - E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns, $J^{\pi}=5/2^-$
  - E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns, $J^{\pi}=15/2^+$

Below the DANCE detection threshold



E_{iso}=761.7 keV :

$$N_{iso} = \frac{A_0\,T}{\ln 2}\,\frac{1}{I_{\gamma}(761.7)}$$

E_{iso}=1356.9 keV :

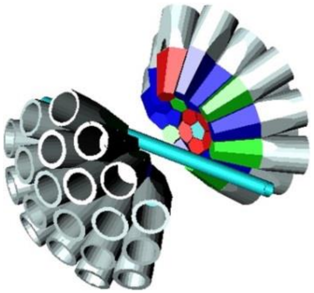
$$N_{iso} = \frac{A_0\,T}{\ln 2}\,\frac{1}{I_{\gamma}(1088.1)(1 - I_{\gamma}(168.8)) + I_{\gamma}(1067.0)}$$

Detection efficiencies

- Detection efficiencies obtained with Geant4 simulation of DANCE

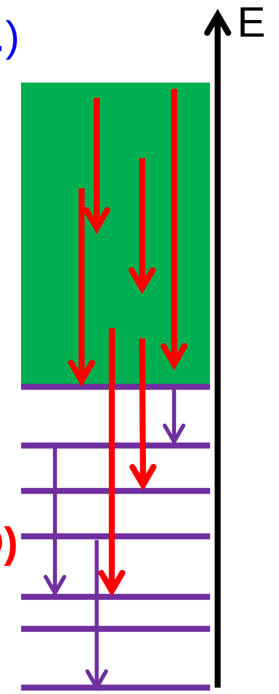
  *M. Jandel et al., NIM B, **261**, 1117 (2007)*

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

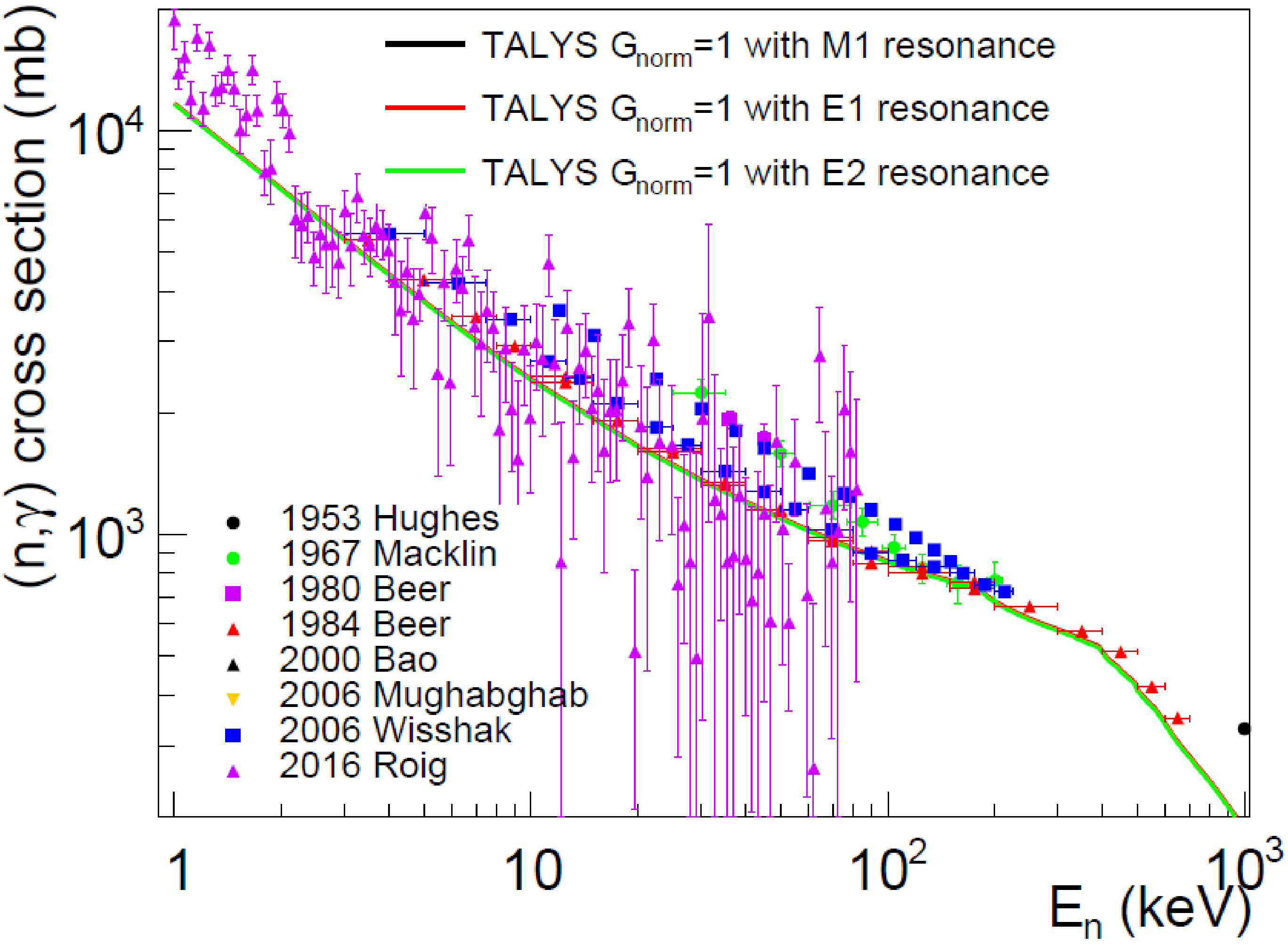


- Simulations of the γ-cascade with the Monte Carlo EVITA code
  - Developped by B. Morillon et al. from CEA/DAM/DIF
  - Based on Hauser-Feshbach formalism
  - Uses somes TALYS outputs

- Parameters of the EVITA and TALYS calculations
  - Optical potential → **Deformed OP developped at CEA** (P. Romain *et al.*)
    - Describe the neutron-nucleus interaction
  - Experimental level scheme → **80 discrete levels (1.5 MeV)**
    - Isomer feeding
    - Discrete transitions
  - Nuclear level density model → **Gilbert & Cameron**
    - Describe the level scheme above a chosen excitation energy
    - Choice of the last discrete level important
  - Photon strength functions → **RIPL-3 systematics (E1:GLO, Other:SLO)**
    - γ de-excitation of the compound nucleus
    - One PSF for each multpolarity: E1,M1,E2,…
    - Linked to the reduced transition probabilities



Impact on the (n,γ) cross section



Isomer detection efficiencies

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

- Cascade detection efficiency ε_{casc} :
  - Simulations of the total energy spectra and the EVITA result

$$\epsilon_{casc} = \frac{\sum_{M=3}^{6} \text{Number cascades detected by DANCE in the Q gate (3.5-7.5 MeV)}}{\sum_{M\geq 1} \text{Number of } \gamma\text{-cascades in the EVITA result}}$$

- Impact of the added resonance on the detection efficiencies

ε_{casc} (%) for the added resonances		
M1	**E1**	**E2**
54.8	56.0	54.0

54.9 ± 1.1 %

➢ **Cascade detection efficiencies weakly sensitive to the γ-cascade**

Isomer detection efficiencies

$$R_{iso} = \frac{N_{iso}}{N_{casc}} \times \frac{\epsilon_{casc}}{\epsilon_{iso}}$$

- Isomer detection efficiency ε_{iso} :
  - Simulations of the γ-ray spectra and the EVITA result

$$\epsilon_{iso} = \frac{\sum_{M=3}^{6} \text{number of γ-rays from the isomer detected by DANCE}}{\sum_{M\geq 1} \text{number γ-rays from the isomer in the EVITA result}}$$

- Impact of the added resonance on the detection efficiencies

	ε_{iso} (%) for the added resonances		
Isomer	**M1**	**E1**	**E2**
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	31.9	31.2	32.0
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	38.1	38.5	37.4

31.7 ± 0.5 %

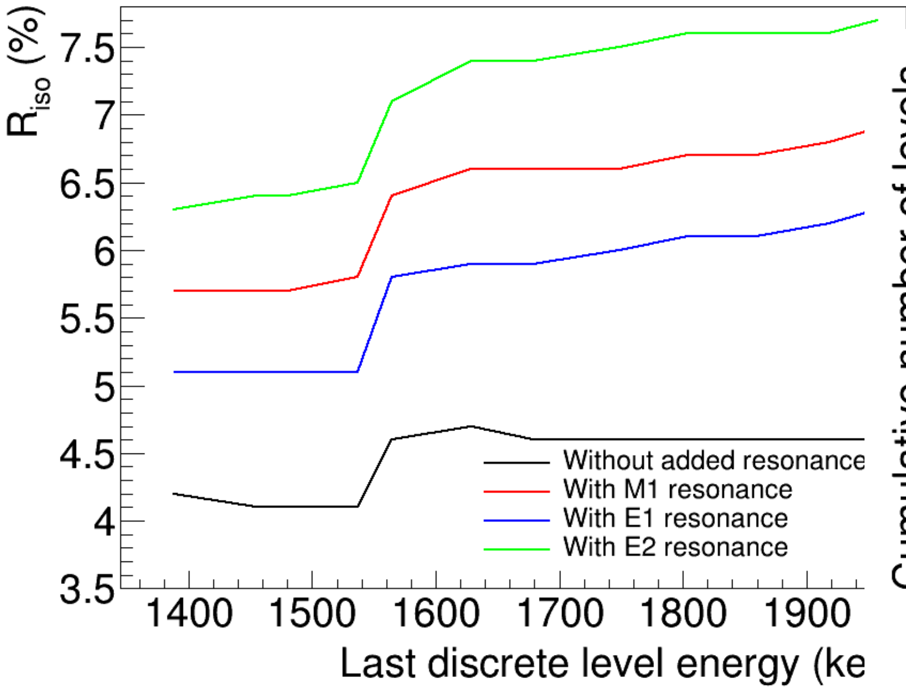
38.0 ± 0.6 %

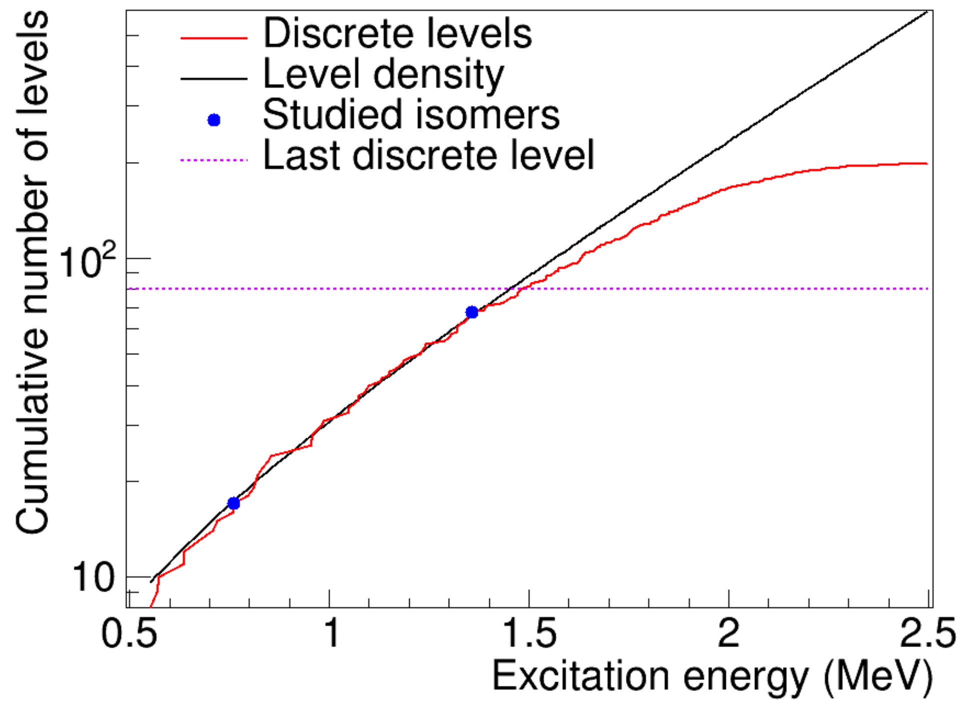
➢ **Isomer detection efficiencies also weakly sensitive to the γ-cascade**

Isomeric ratios as a function of the last discrete level

- Choice of the last discrete level important: link between the level scheme and the level density model

Isomer	Experimental R_{iso} (%)
E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns	10.5 ± 0.6
E_{iso}=1356.9 keV, $T_{1/2}$=11.1 ns	4.8 ± 0.6





E_{iso}=761.7 keV, $T_{1/2}$=32.8 ns

- **Strong impact on the isomeric ratio but still large discrepancies**
- **Need to improve the level scheme ?**