Radiative deexcitation of ^{177}Lu

Nuclear level density and γ strength function

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Inauguration de la plateforme MOSAIC

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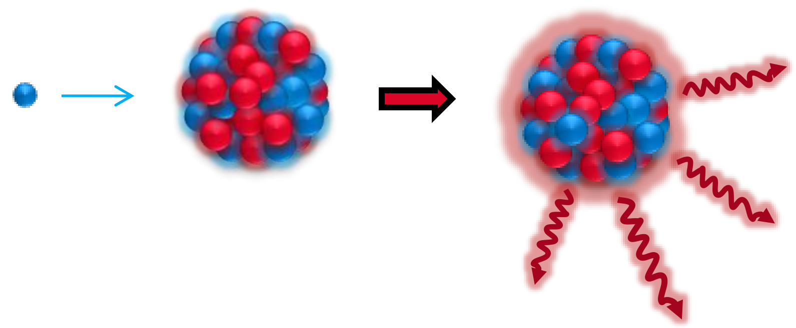
Motivations

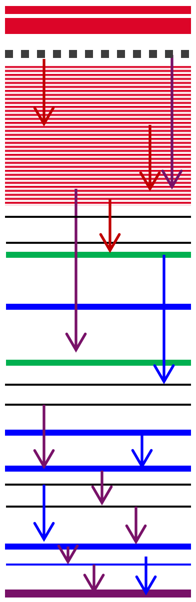
Improve predictability of neutron radiative capture cross sections for neutron-rich nuclei.

Bring constrains to models by determining two essential ingredients:

- γ strength function
- Nuclear level density



Radiative capture (n,γ)



Studied nucleus: ^{177}Lu

^{175}Lu	^{176}Lu	^{177}Lu
97.41 %	2.59 %	
	3.68 h / 3.8 10^{10} y	160.1 d / 6.71 d

Stellar nucleosynthesis, s-process

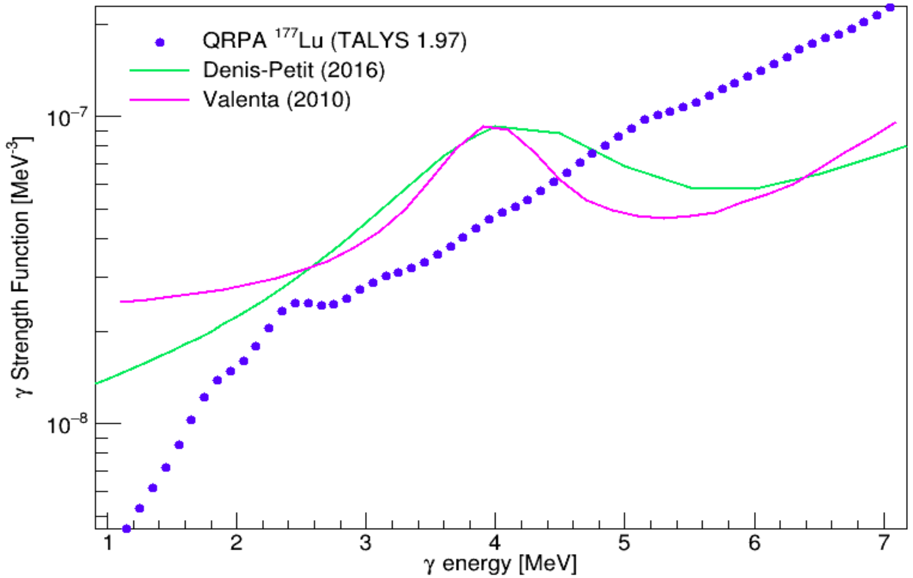
Motivations

Why NLD and γSF for ^{177}Lu?

- ^{176}**Lu target is one of the heaviest naturally odd-odd nucleus (Z=71, N=105)**
- **Previous experiments and theoretical computations:**
  - Various measurements: evidence of a resonance around 4 MeV
  - Weak resonance in γSF based on QRPA computations

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

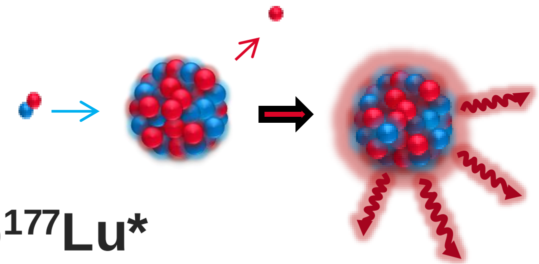
Two-Step γ cascade measurements
S. Valenta, Dipl. thesis, Charles Univ., Prague (2010)



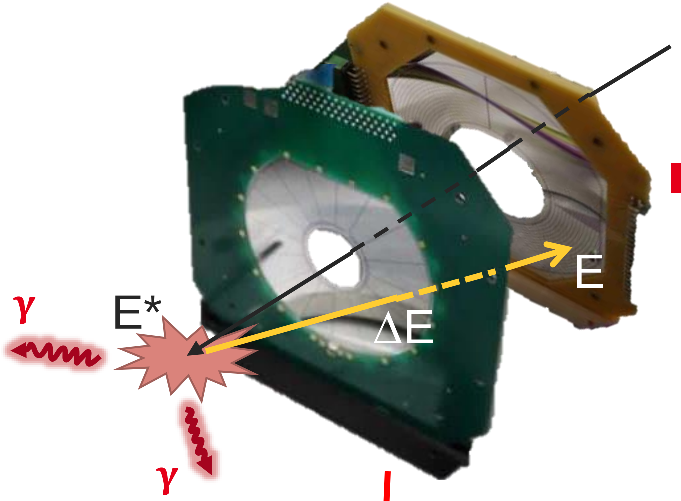
- **Need new precise γSF measurements**
  - Use the Oslo method to extract NLD and γSF,
  - Test the method on isomers of ^{177}Lu,
  - Improve predictability of (n,γ) reactions by improving determination of γSF.

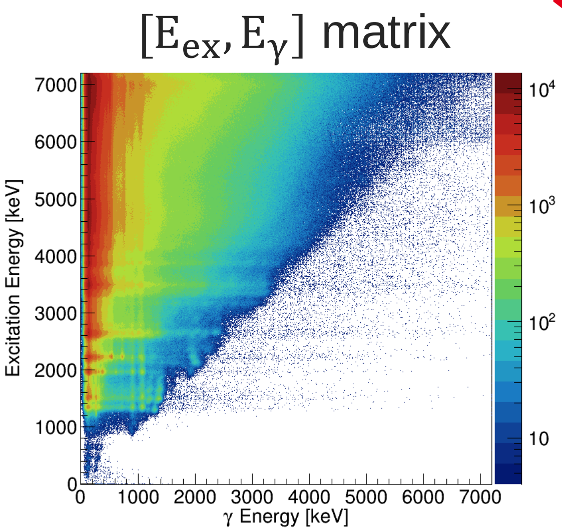
Transfer reaction: $^{176}Lu(d,p)^{177}Lu^*$

Experiment principle: populate ^{177}Lu with a known excitation energy, under neutron emission, and measure the corresponding γ de-excitation.



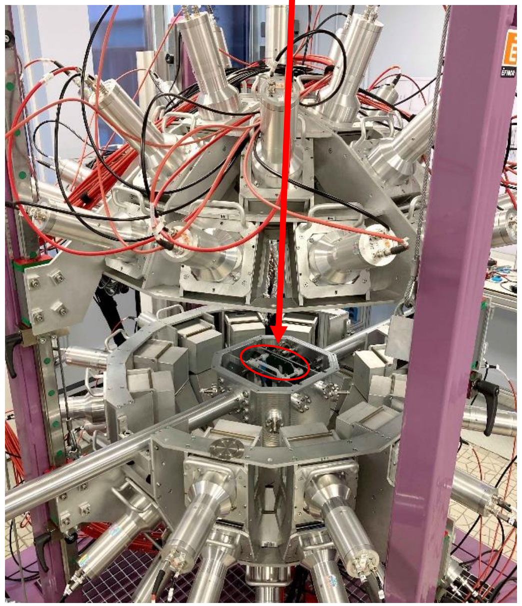
$^{176}Lu(d,p)^{177}Lu^*$



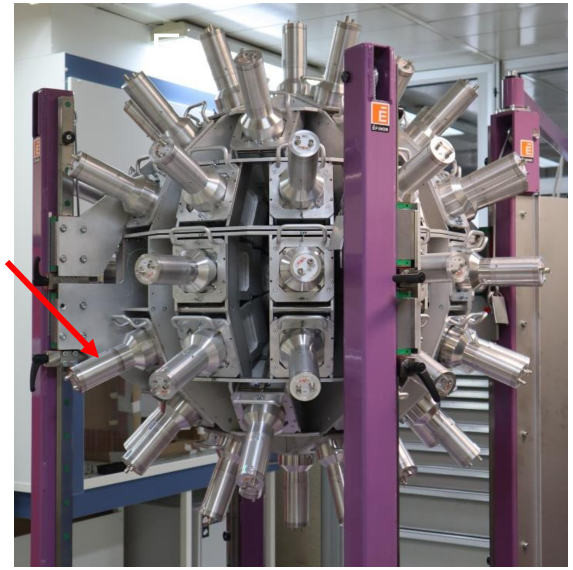


Experiment using **SFγNCS detector**:

- Detection of emitted **protons** (energy, emission angle) to compute excitation energy (2 segmented Si detectors in telescope configuration)
- Detection of **γ cascade in coincidence** with protons (sphere of 60 NaI(Tl) detectors)



NaI detector



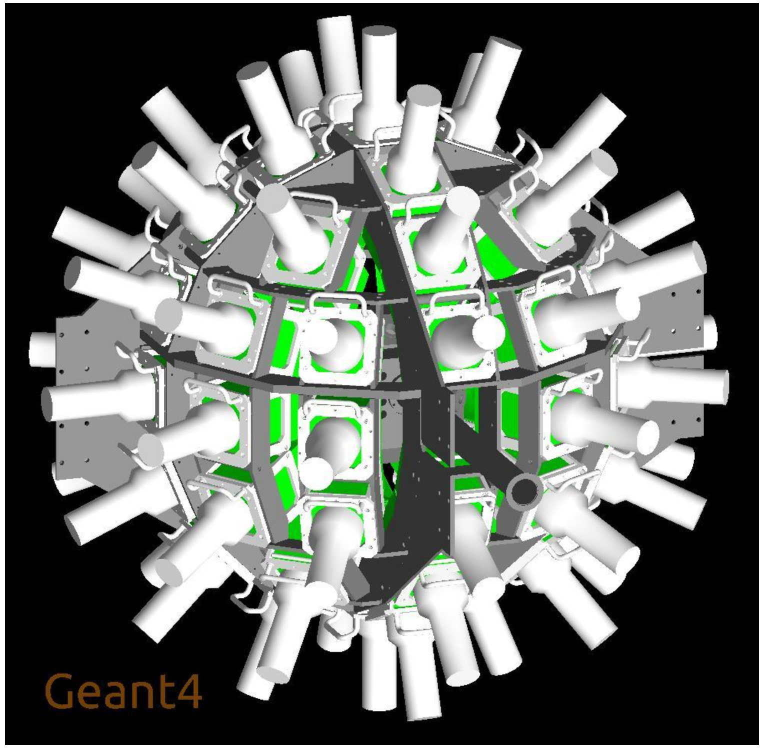
Resolution:

- E_{ex} : σ = 35 keV
- E_{γ} : σ = 20 keV (at 662 keV)
- T_{NaI} : σ = 2 ns

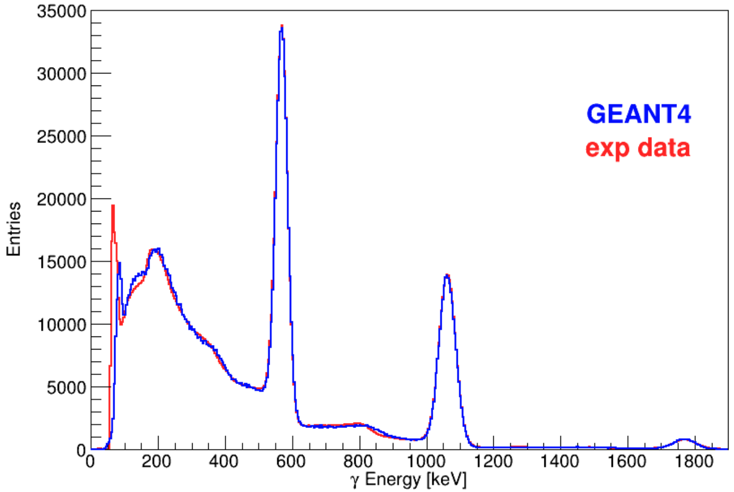
Absolute γ efficiency: ~50 %

Simulations with GEANT4

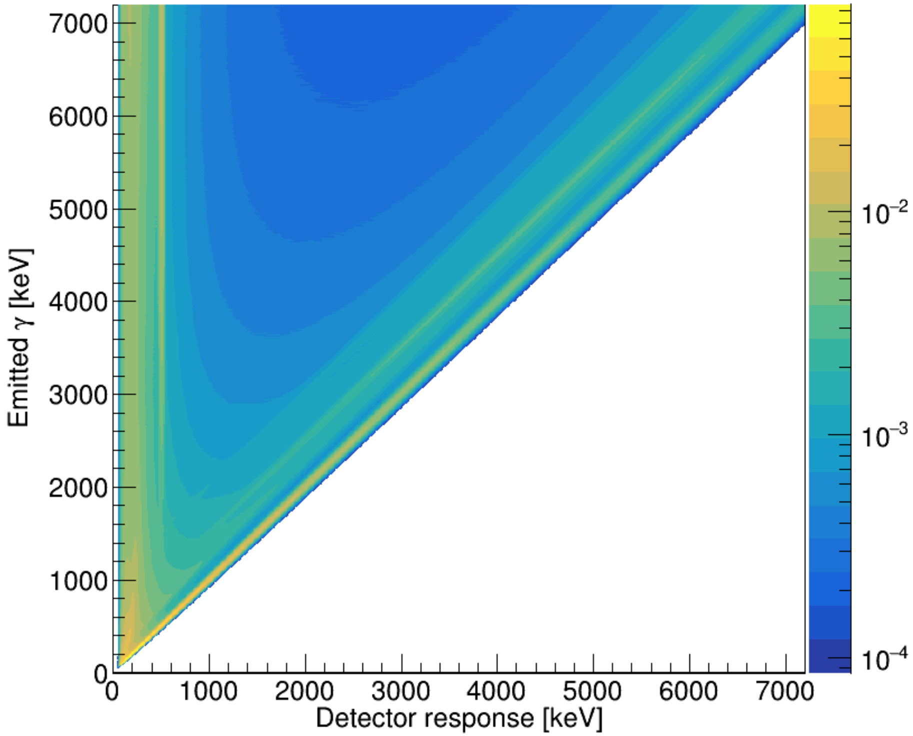
Determining the detector response matrix.
Source and background measurements to adjust simulation on experiment.



Simulated SFγNCS detector

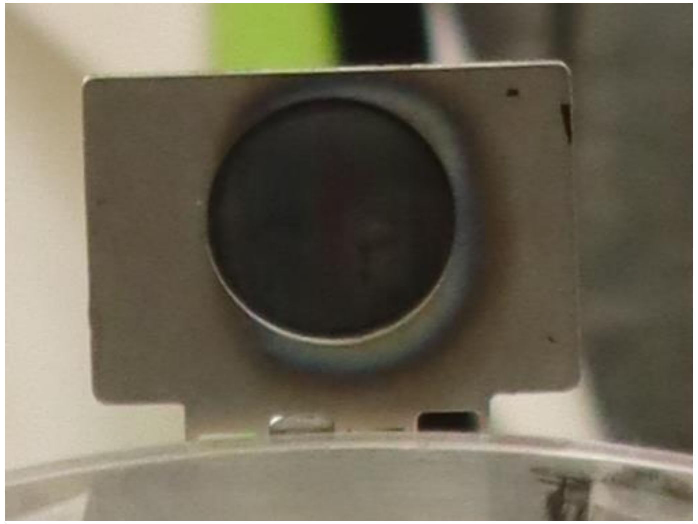


^{207}Bi source



Response matrix

Target and beam



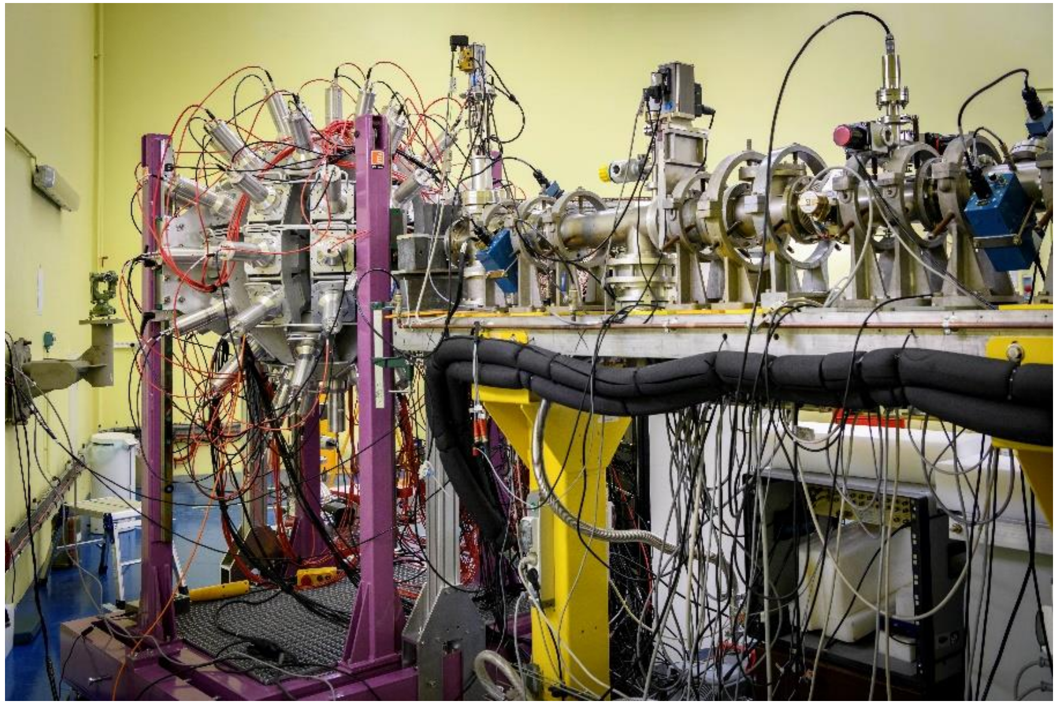
^{176}Lu target

Target made at SIDONIE isotopes separator in Orsay
Isotopic enrichment from natural: **2.59 % to 99.9 % of ^{176}Lu**.

Details:

- 243 µg/cm^2 (2 weeks of beam)
- Carbon backing, 100 µg/cm^2
- Diameter: 12 mm

Experiment in June 2023
Deuteron beam with an intensity of a few nA and 12 MeV energy with NENUPHAR accelerator at CEA (130 h)

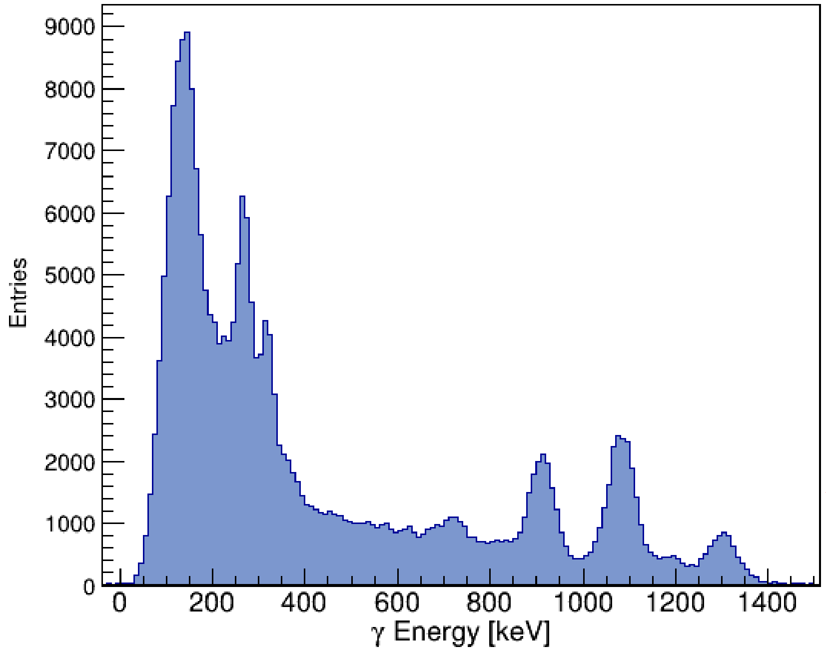


SFγNCS detector on beamline

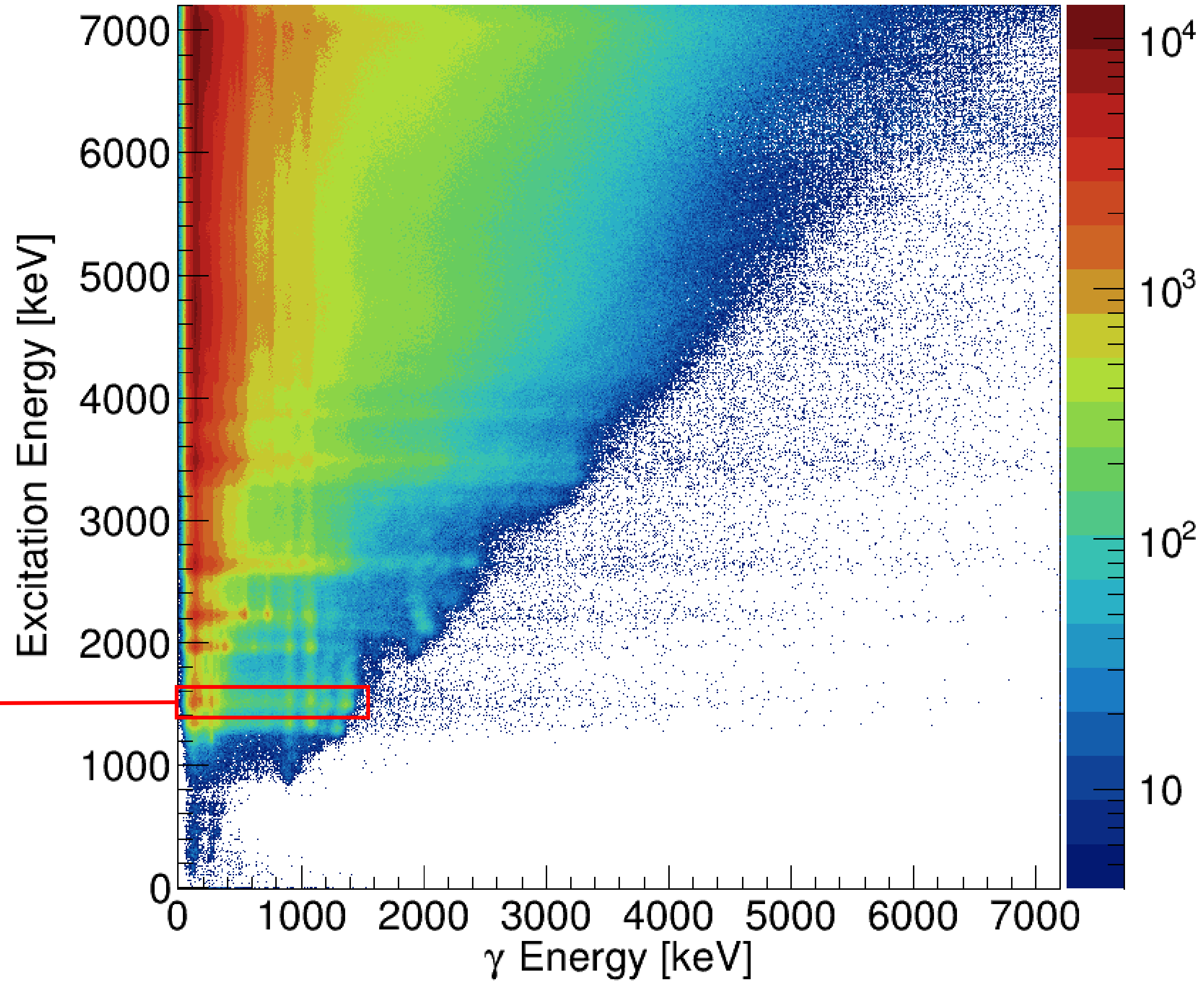
Excitation energy - γ energy matrix

γ spectrum available for each excitation energy range.
1.2 10^8 entries

γ spectrum projection for excitation energy between 1290 keV and 1390 keV

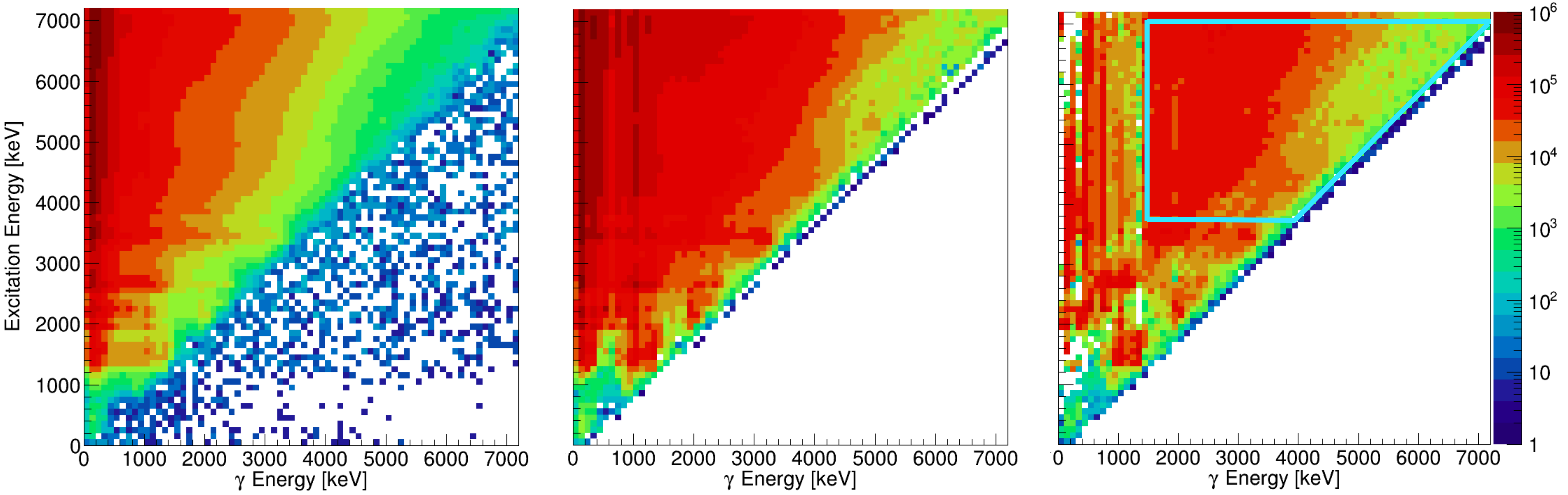


^{177}Lu, matrix with background substraction



γ spectra unfolding and primary γ extraction

The measured γ spectra are unfolded to get the emitted spectra (unfolding methods[1][2]).
Primary γ matrix is extracted from unfolded matrix[3].



Raw matrix | Unfolded matrix | Primary γ matrix

Region where Oslo method is applied

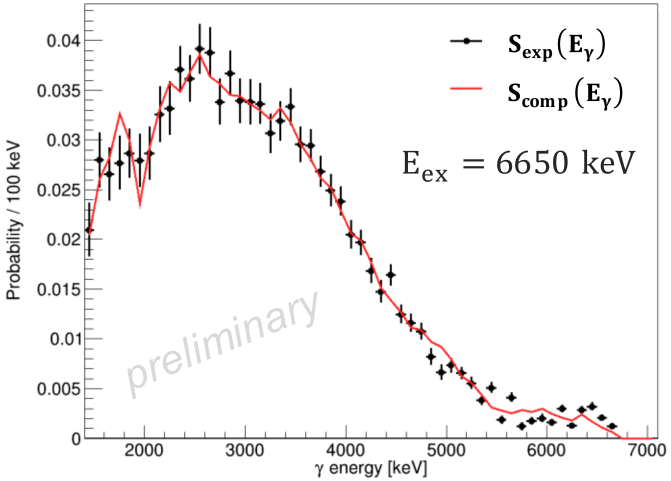
[1] R. Gold, ANL 6984 (1964).
[2] M. Guttormsen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 374, 371 (1996).
[3] M. Guttormsen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 255, 518 (1987).

Nuclear level density and γ strength function

Oslo method[1]

Brink-Axel hypothesis: γ strength function is independant of the energies, spins and parities of initial and final levels, it depends only on the γ energy.

$$S(E_\gamma, E^*) \propto F(E_\gamma) * \rho(E^* - E_\gamma)$$



Primary γ spectra: computed and experimental

Nuclear level density and γ strength function

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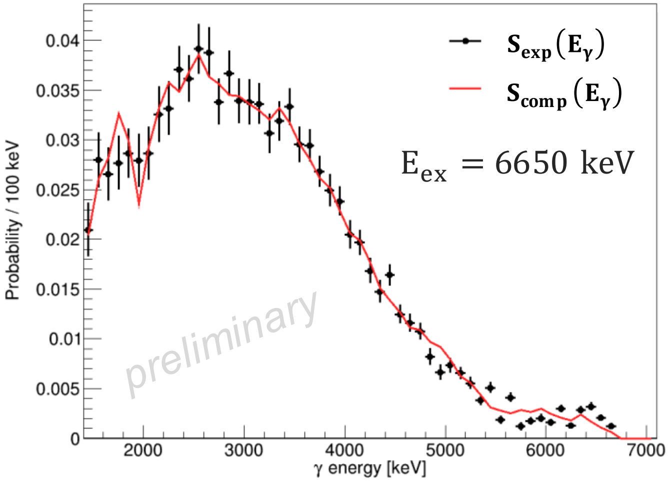
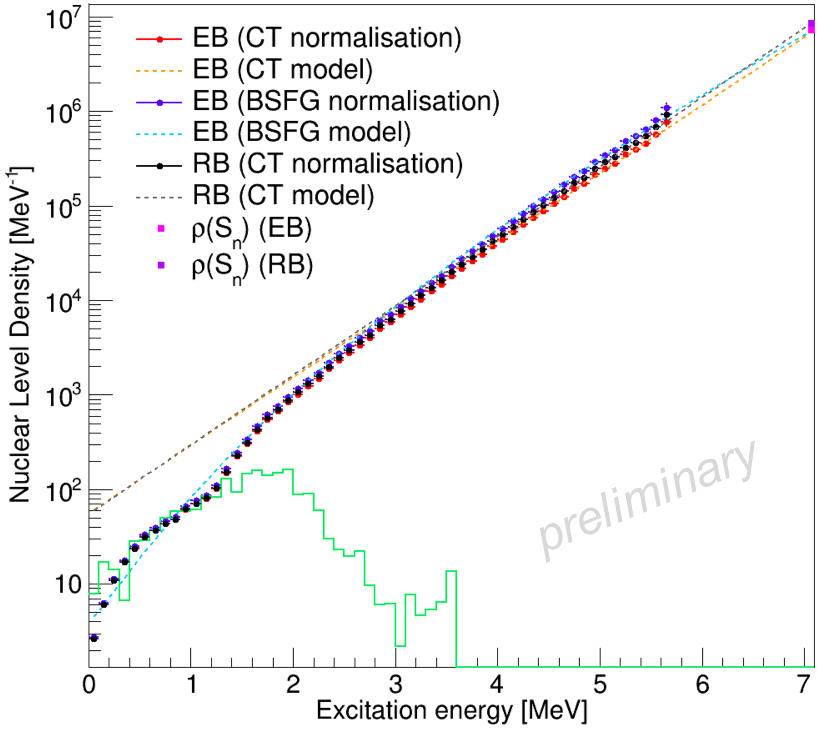
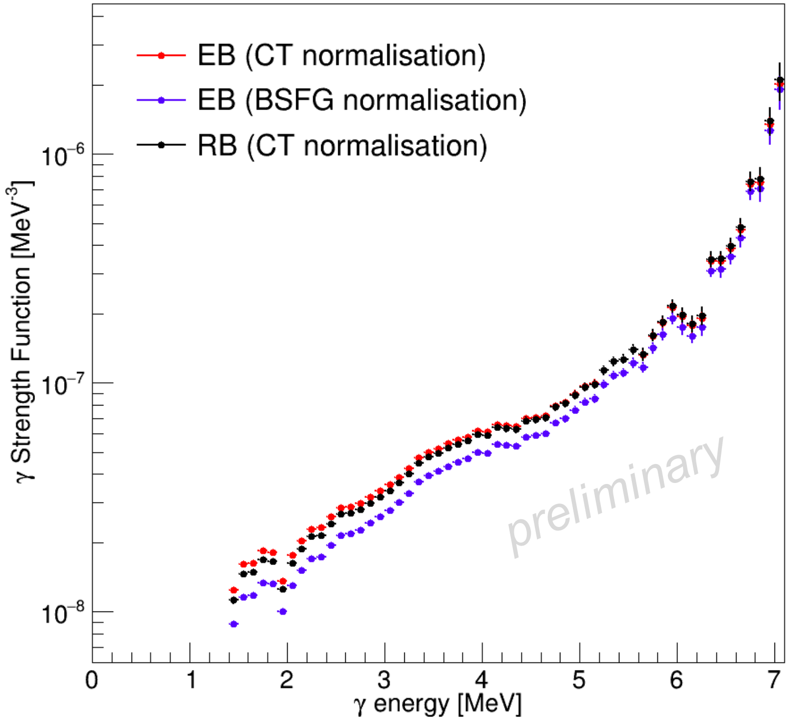


Primary γ spectra: computed and experimental





Parameters for normalisation

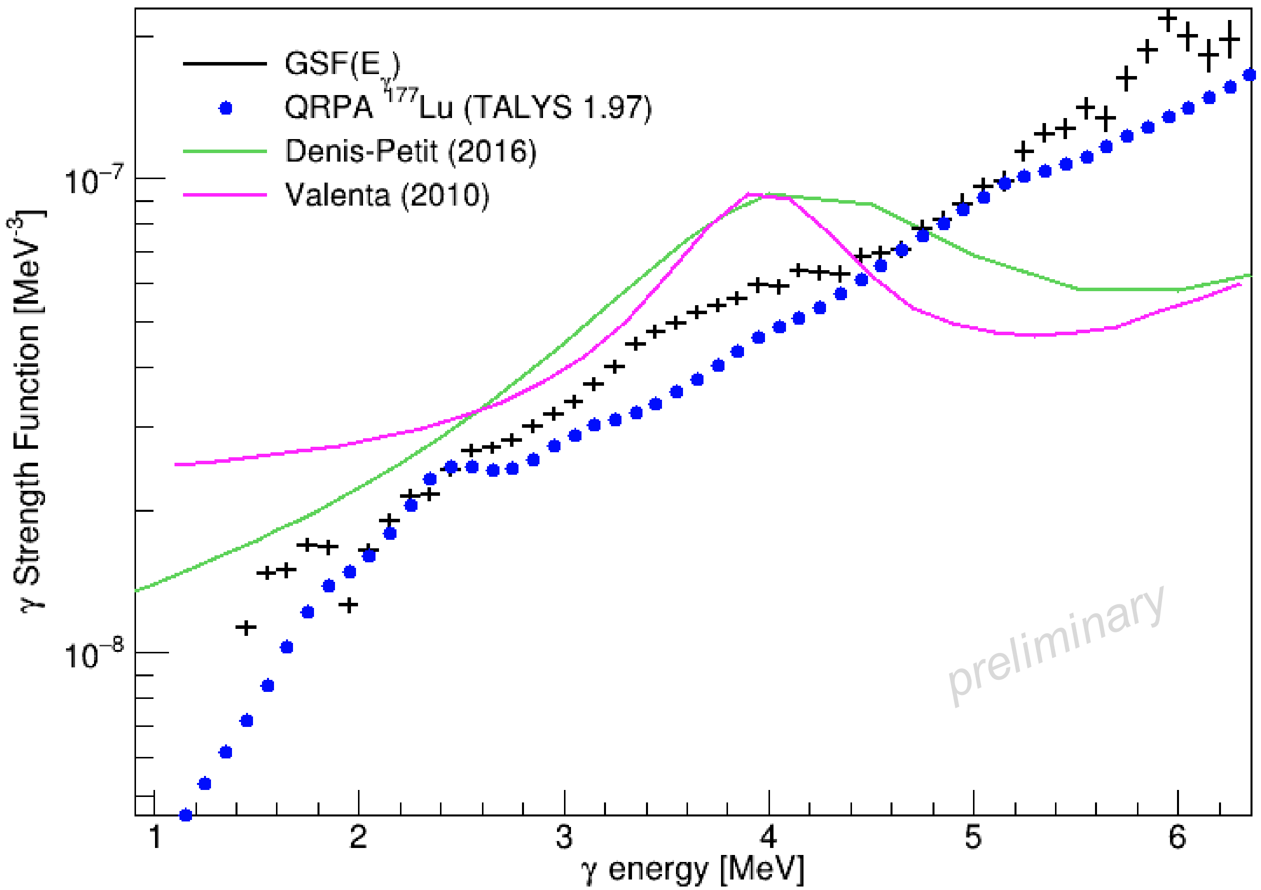
- D_0 = 1.45 (6) eV[2]
- $\langle\Gamma_\gamma\rangle$ = 66 (1) meV[2]
- CT/BSFG model extrapolation
- Known levels (NUDAT)

Spin cutoff models

- EB[3] (empirical) : $\sigma(S_n) = 4.88$
- RB[4] (rigid-body) : $\sigma(S_n) = 7.38$

[1] A. Schiller *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A 447, 498 (2000).
[2] O. Roig *et al.*, Phys. Rev. C 93, 034602 (2016).
[3] T. von Egidy and D. Bucurescu, Phys. Rev. C 80, 054310 (2009)
[4] T. von Egidy and D. Bucurescu, Phys. Rev. C 73, 049901 (2006)

γ strength function



Previous works, adjustement on experimental spectra of simulated γ spectra with a γ cascade code + γSF models for E1, M1:

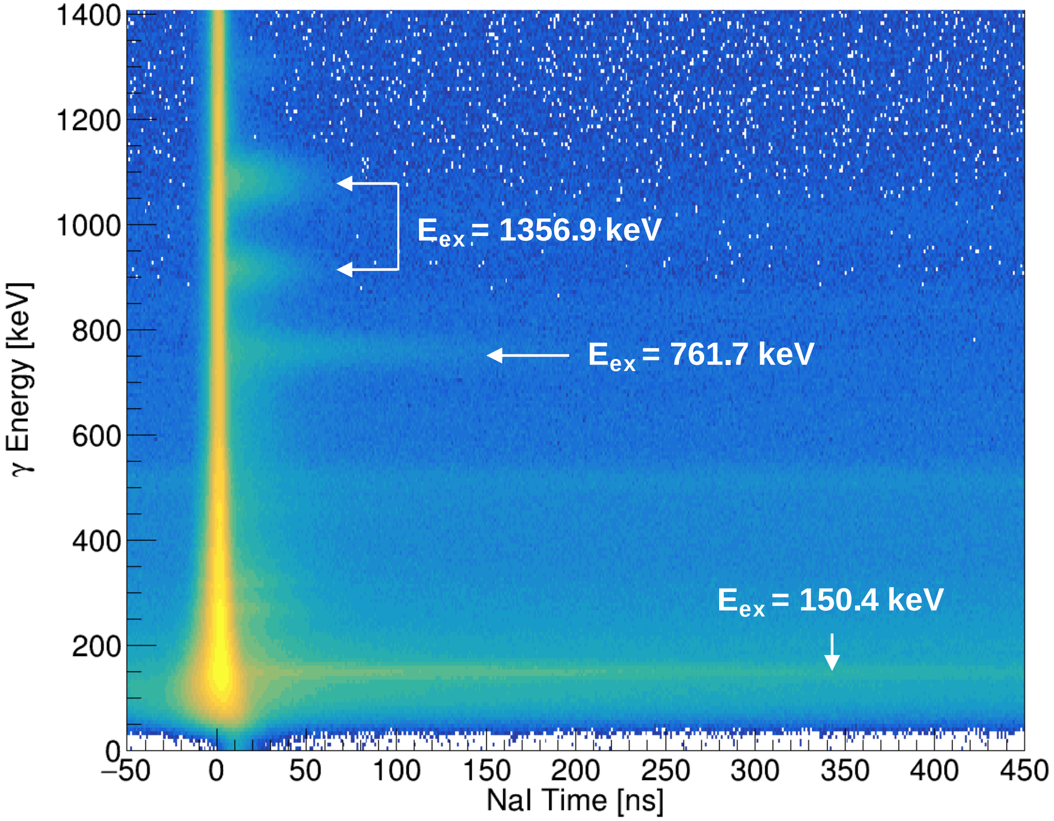
- Denis-Petit[1]: EVITA + EGLO + SLO
- Valenta[2]: DICEBOX + KMF + SF

Need this γSF to reproduce spectra.

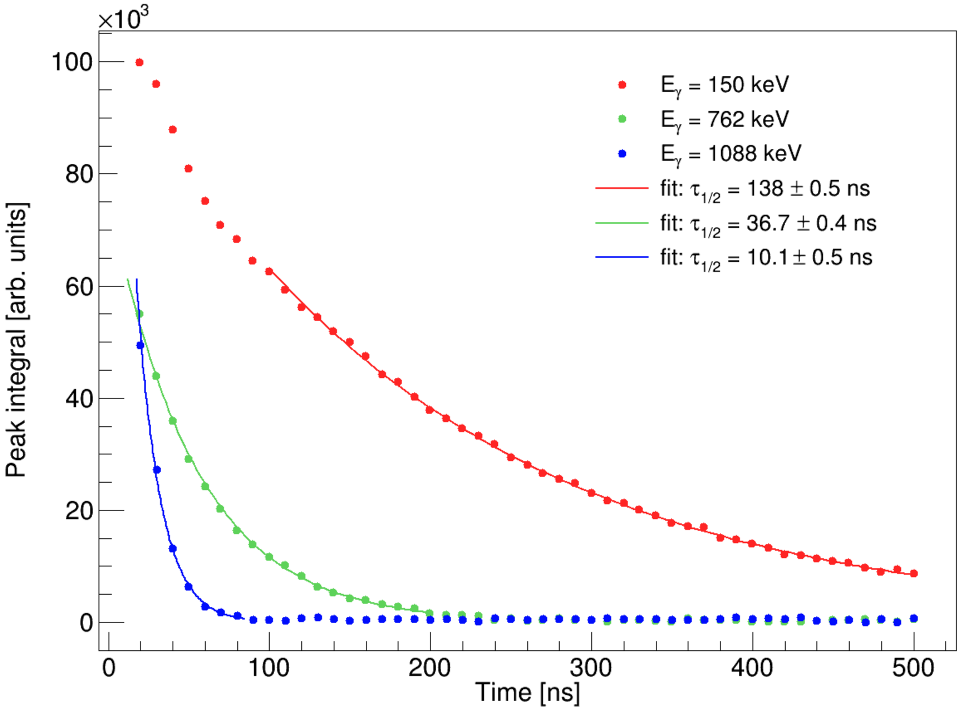
Follows the general shape of γSF based on QRPA computations.
Resonance around 4 MeV as in previous works but with less strength.

[1] D. Denis-Petit *et al*., Phys. Rev. C 94, 054612 (2016).
[2] S. Valenta, Dipl. thesis, Charles Univ., Prague (2010).

Isomers identification in ^{177}Lu



γ energy versus NaI time
Time until 500 ns



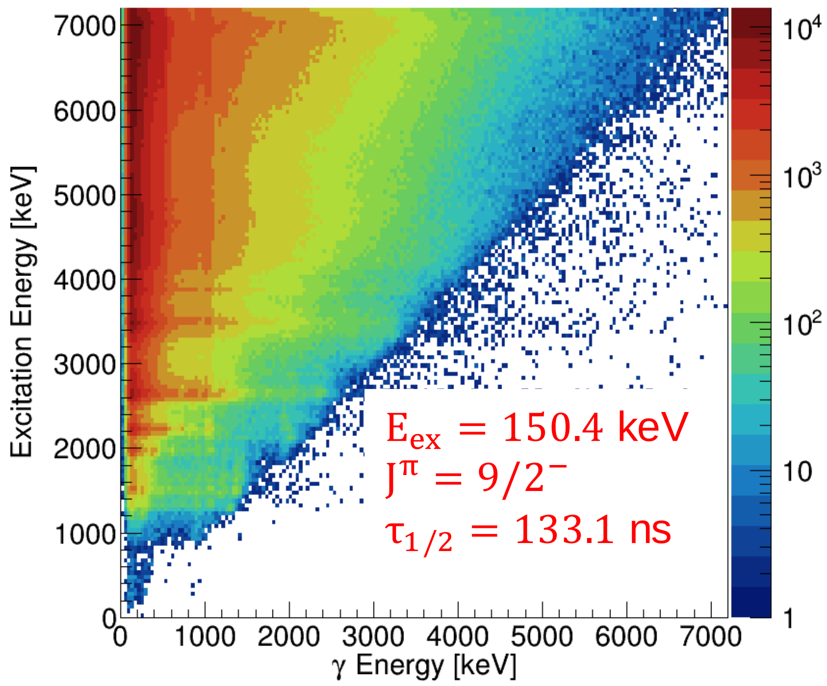
Peak integral versus NaI time

3 isomeric levels identified (NUDAT)

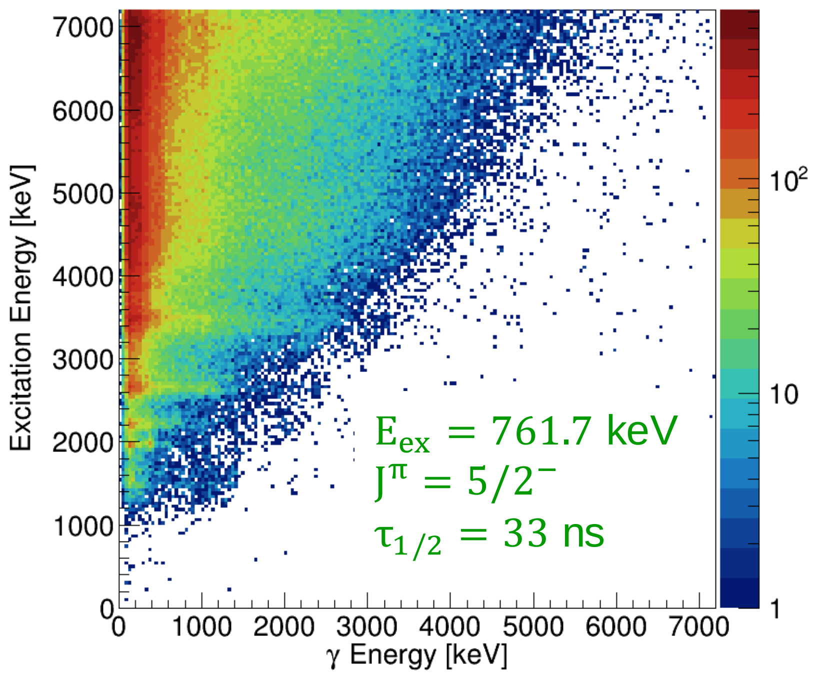
- 150.4 keV, $\tau_{1/2} = 133 \pm 2.4$ ns
- 761.7 keV, $\tau_{1/2} = 33 \pm 2$ ns
- 1356.9 keV, $\tau_{1/2} = 10.8 \pm 0.5$ ns

➡ Build $[E_{ex} - E_\gamma]$ matrix gated by isomeric levels.

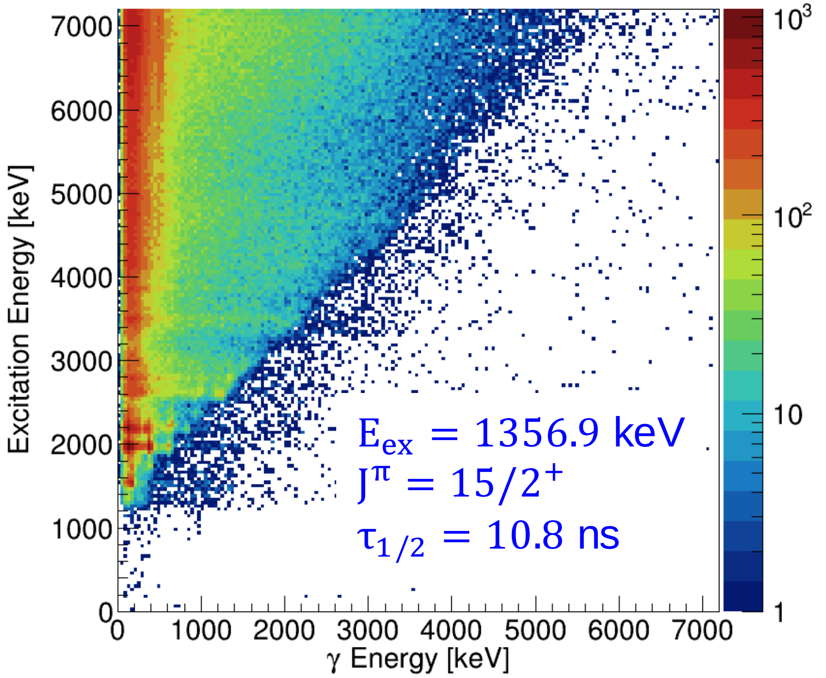
$[E_{ex} - E_{\gamma}]$ matrix gated by isomeric levels



8.1 10^{6} entries



4.7 10^{5} entries



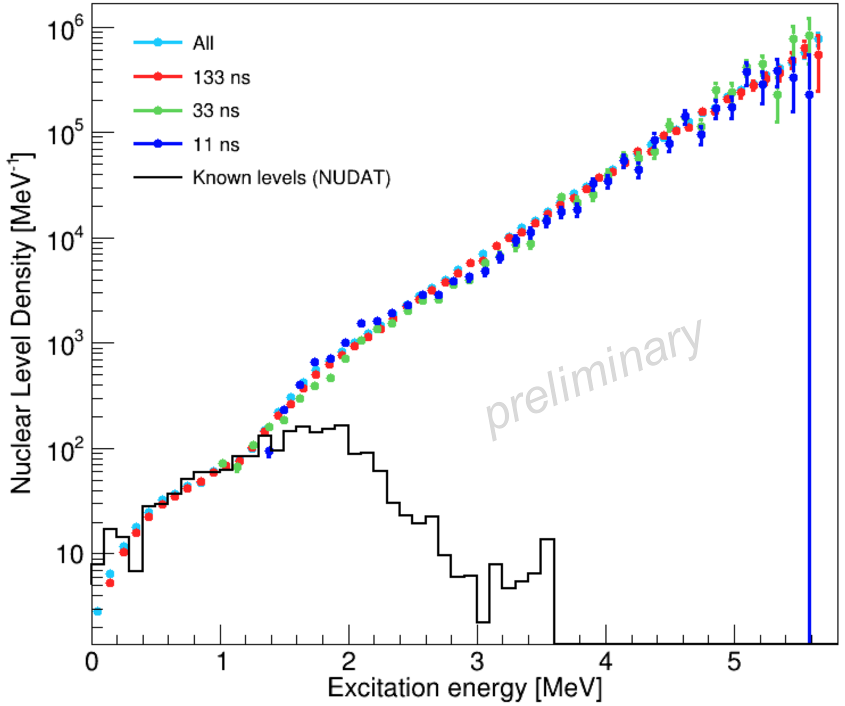
4.7 10^{5} entries

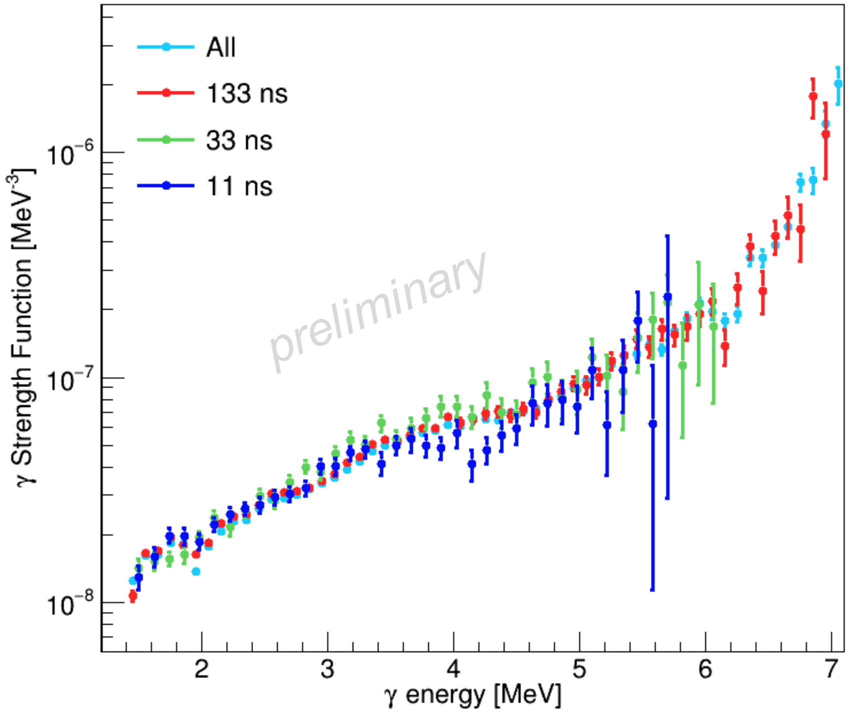
γ strength function for isomeric levels → Should be identical to γ strength function for all γ cascades according to Brink-Axel hypothesis

Isomers

$E_{ex} = 150.4$ keV, $J^{\pi} = 9/2^{-}$, $\tau_{1/2} = 133.1$ ns
$E_{ex} = 761.7$ keV, $J^{\pi} = 5/2^{-}$, $\tau_{1/2} = 33$ ns
$E_{ex} = 1356.9$ keV, $J^{\pi} = 15/2^{+}$, $\tau_{1/2} = 10.8$ ns

Levels at 761.7 and 1356.9 keV have lower statistics.
Normalisation with discrete levels is tricky.





Nuclear level density and γ strength function of isomers are consistent with those of all levels.

Conclusion

- First extraction of NLD and γSF of ^{177}Lu with Oslo method:
  - general shape like γSF based on QRPA computations,
  - resonance around 4 MeV with less strength than the one deduced by previous works.

- Extraction of NLD and γSF for isomers of ^{177}Lu:
  - consistent with those of all levels.

- International communications:
  - 9th Workshop on Nuclear Level Density and Gamma Strength (Oslo, Norway),
  - International Symposium on Nuclear Science (Sofia, Bulgaria),
  - PhyNuBE (Oléron, France).

Outlook

- Extract nuclear level density and γ strength function of ^{177}Lu with an alternative method, **Monte-Carlo Markov chain**:
  - ➢ random generation of parameters describing NLD, γSF and initial spin distribution,
  - ➢ comparison of experimental observables (γ spectra, γ multiplicities, isomeric ratios…) and calculated observables at each iteration,
  - ➢ probability distribution of each parameter,
  - ➢ construction of probability distribution of NLD, γSF and initial spin distribution.
  - → Tests with simulated data have been achieved.
  - → First calculations on data runned on super computer last week and will be analyzed very soon.

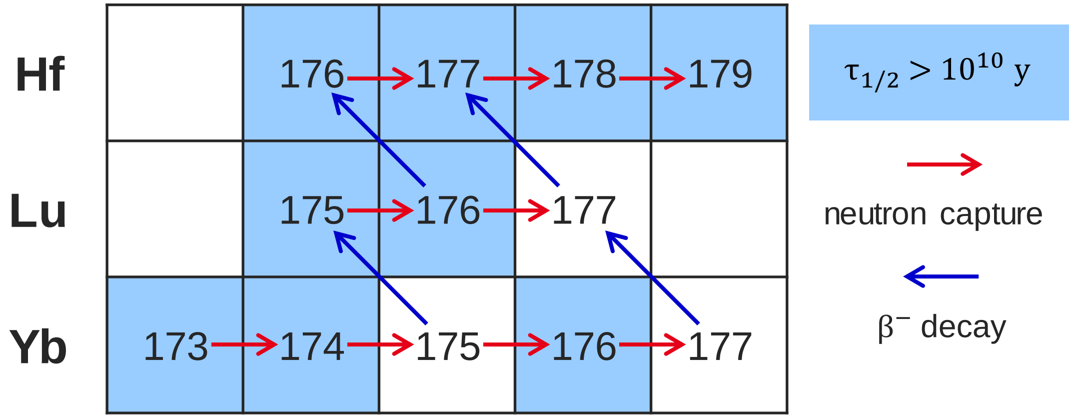
- Use γ-cascade codes to test NLD and γSF found and to reproduce:
  - ➢ experimental spectra,
  - ➢ isomeric ratios.

- Compute (n,γ) cross-section.

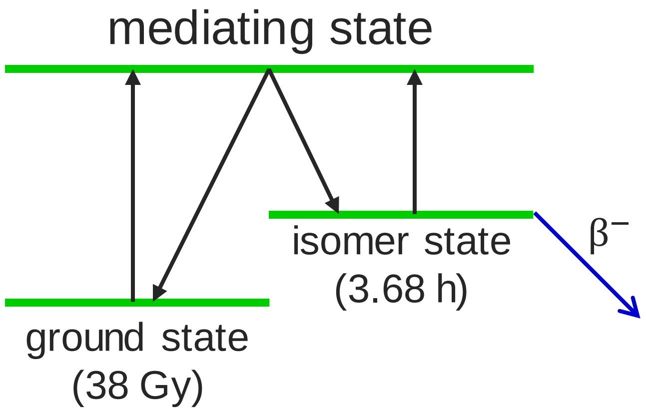
Thank you for your attention

Thesis motivations

Interesting astrophysical properties



s-process in Lu region



Thermal coupling between ^{176g}Lu and ^{176m}Lu

Stellar nucleosynthesis

- ^{176}Lu is s-process only
- short-lived isomer (3.68 h), β^- decay
- thermal coupling between ^{176g}Lu and ^{176m}Lu

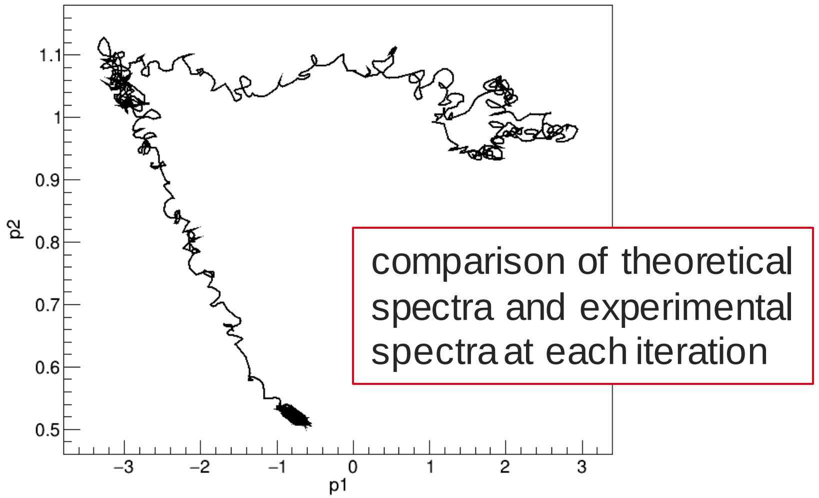
➡ ^{176}Lu as a s-process thermometer

➡ Need ^{176}Lu abundances: cross sections (neutron capture…)

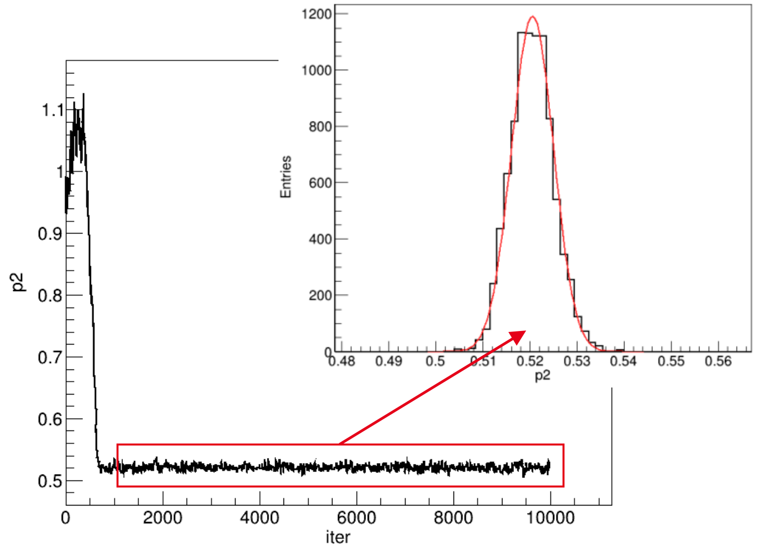
M. Heil *et al.*, ApJ, 673, 434 (2008).

Monte-Carlo Markov chain

- Extract nuclear level density and γ strength function of ^{177}Lu with a different method: **Monte-Carlo Markov chain**



random generation of parameters describing NLD and γSF



after convergence: probability distribution of each parameter

→ Construction of probability distribution of nuclear level density and γ strength function