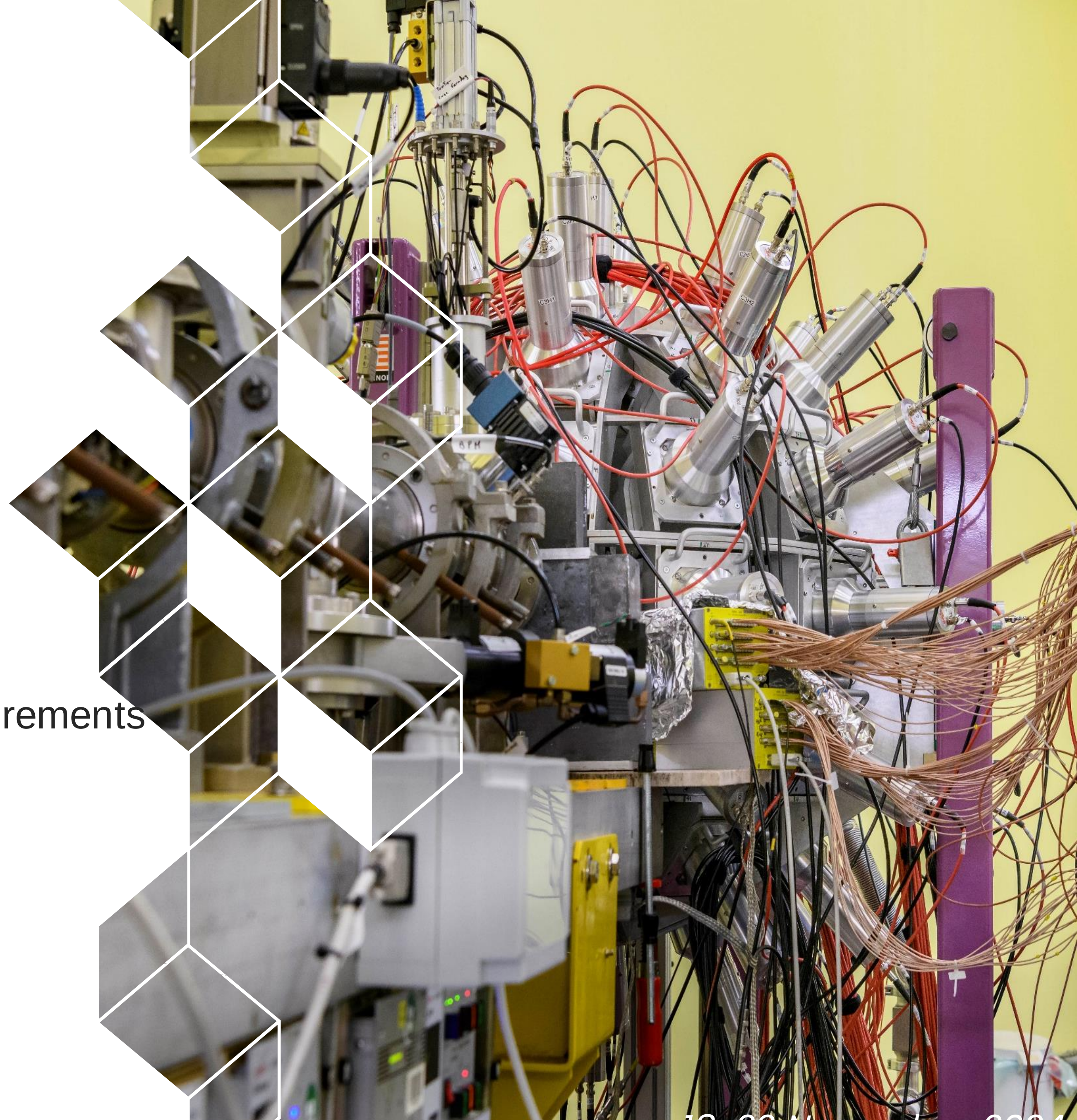
The SFγNCS detector versus nuclear properties

An experimental setup for γ strength function measurements

Chloé Fougères, Laurent Gaudefroy, Vincent Méot,
Mathilde Pottier (PhD), **Olivier Roig**

CEA, DAM, DIF, 91297 Arpajon, France
Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France



18-22 November 2024

ESNT: Nuclear excitations and multipole resonance

Outlines

1. **Context**
2. **What we measure and how**
3. **What we deduce**
4. **How we interpret**

Discussions / Questions at any time !

Context

The goal is to improve the predictability of the neutron radiative capture cross section calculations

- ✓ the inclusion of microscopic models **helps** to reproduce radiative capture cross-sections on instable isotopes

  *A. Ebran et al. , Phys. Rev. C **98**, 014327 (2020)*

- ✓ and the inclusion of precise M1 Scissor Resonance (SR) **gives** a better agreement between (n,γ) cross-section measurements and predictions

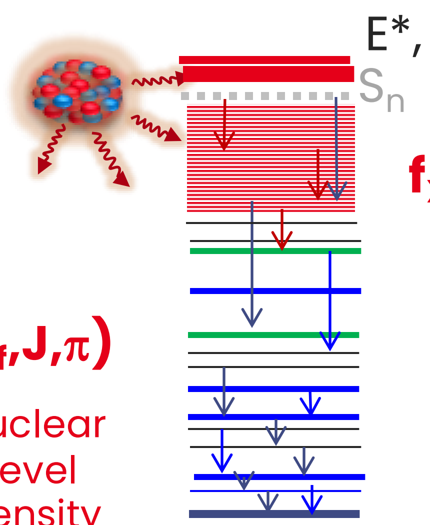
  *S.Goriely et al. , Phys. Rev. C **98**, 014327 (2018)*

Here, it is a focus on **the OSLO method to extract the ingredients of interest: gSF and NLD**

through the first measurements using the new **SFyNCS detector from CEA,DAM in Bruyères-le-Châtel**

Which observables we measure and how

What we want to know:
how are emitted g-rays by a nucleus formed by neutron capture, excited at high energy S_n+E_n



$f_{XL}(E_\gamma,J,\pi)$

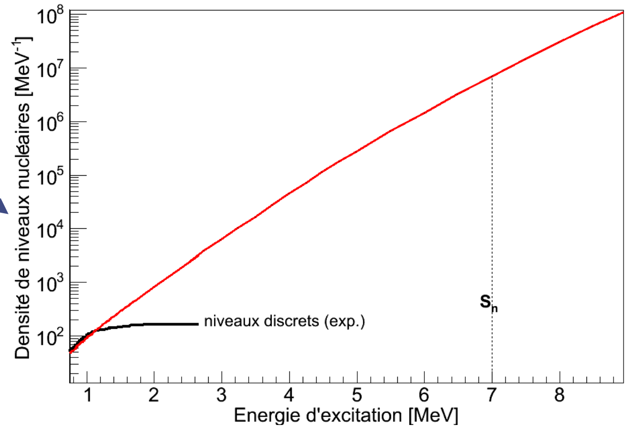
gamma strength function

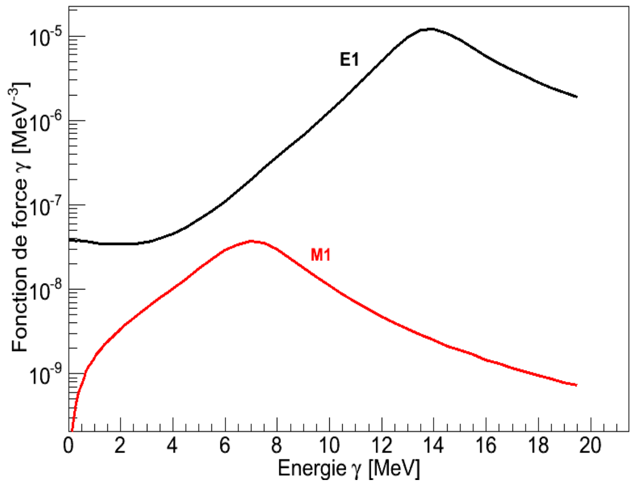
$\rho(E_f,J,\pi)$

nuclear level density

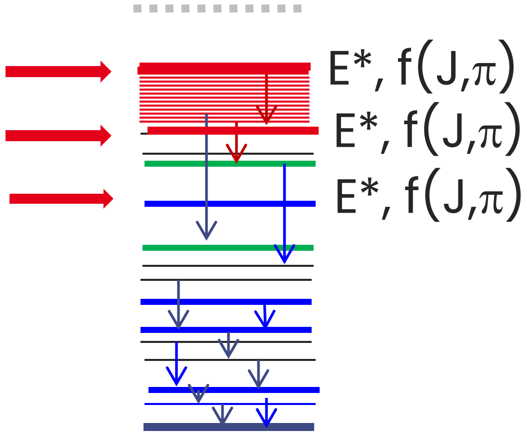
What we need to obtain:
Nuclear level density for all excitation energies and γ strength function for all γ-rays energies

(+ OMP)





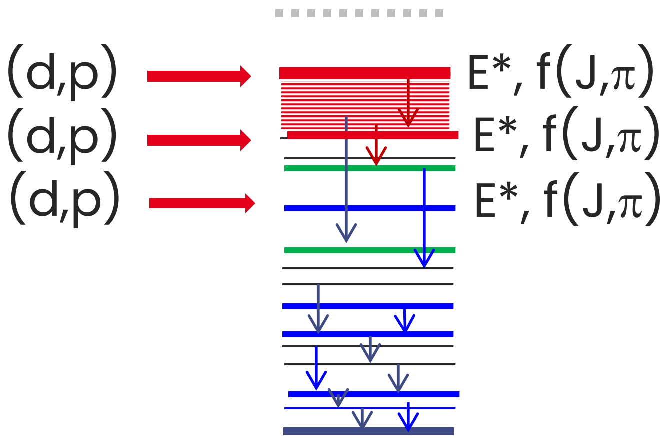
What we can do:
To probe at all excitation energies the γ-rays decay of the nucleus



Which observables we measure and how

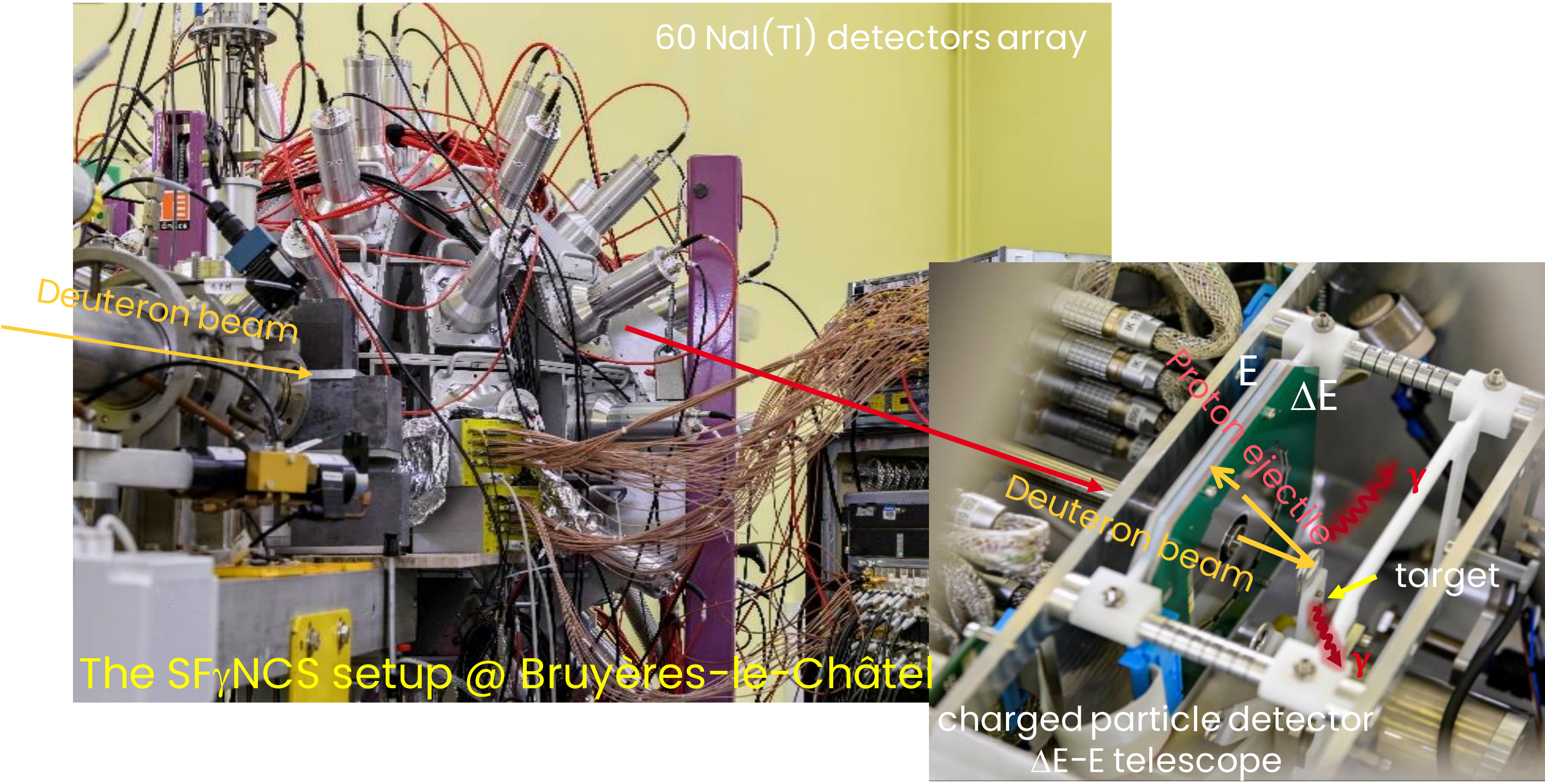
What we do

Excitation by (d,p) reaction
at several



How we measure

(d,p) reaction on a target at the center of
gamma array with a charged particle detector

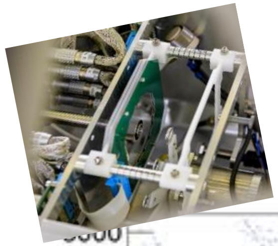


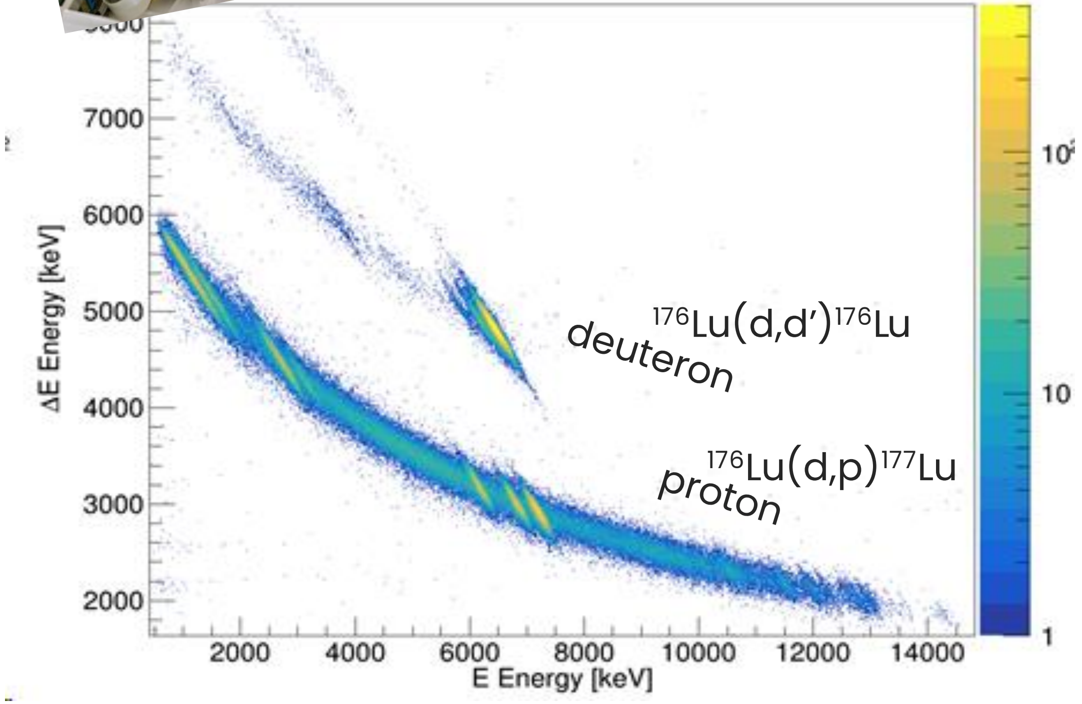
O. Roig, M. Pottier, V. Méot, L. Gaudefroy et al, Nucl. Instr. Meth. A, to be submitted (2024)

Which observables we measure and how

What we obtain

Identification of the formed nucleus, the energy and the angle of the proton ejectile, the excitation energy of the formed nucleus





Measuring DE (lost energy) and E (residual energy)

We select the proton line

→ (d,p) reaction thus the studied excited nucleus

We can measure the proton energy

→ E_{proton} = DE+E+corrections

Measuring the angle of proton ejectile (# ring hit)

We measure the excitation energy of the studied nucleus

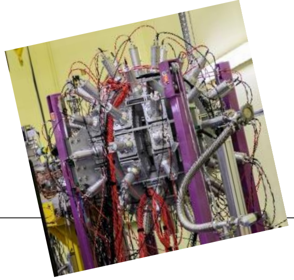
→ $E^* = f(\theta, A_{beam}, A_{target}, E_{beam}, E_{proton})$

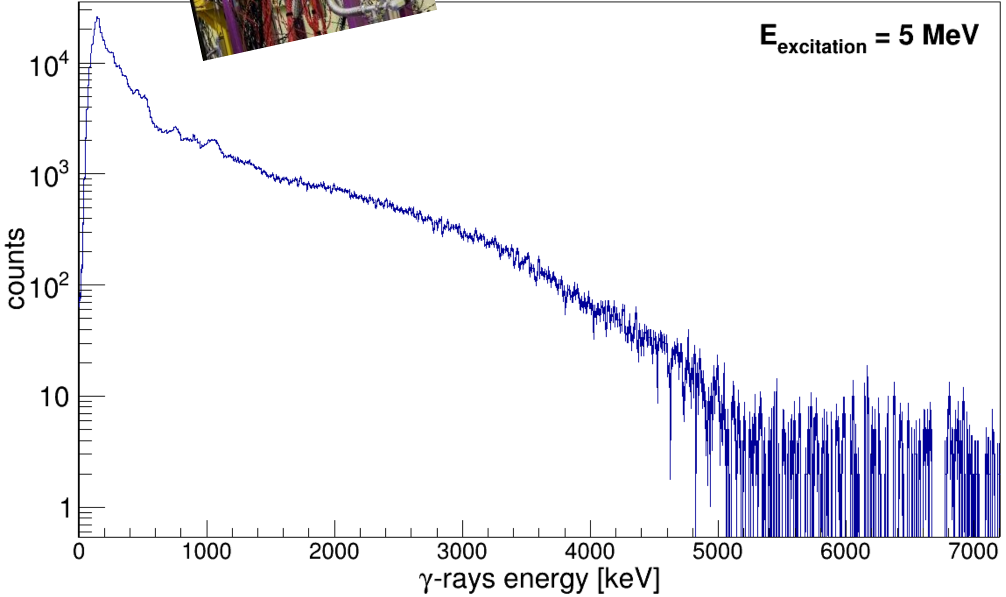
And the ***start time T_0 of the event***

Which observables we measure and how

What we obtain

γ-rays energies of the studied nucleus decay





event by event in coincidence with DE-E telescope

for each E*

Measuring E_γ

We obtain γ-rays spectrum for each excitation energy

Measuring E_γ by detector

We can obtain γ-rays angular correlations

We can obtain multiplicity distribution of γ-rays

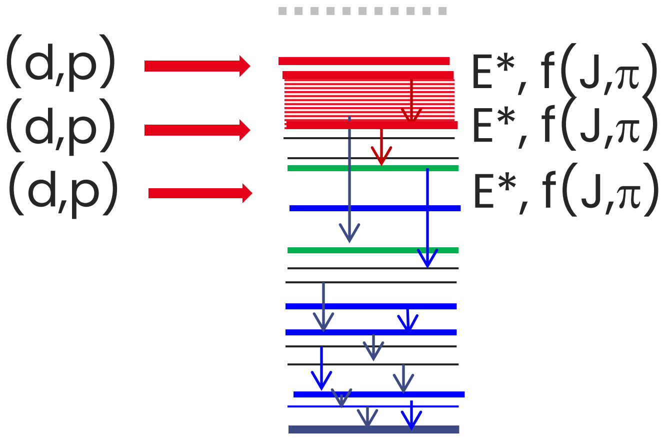
under investigation

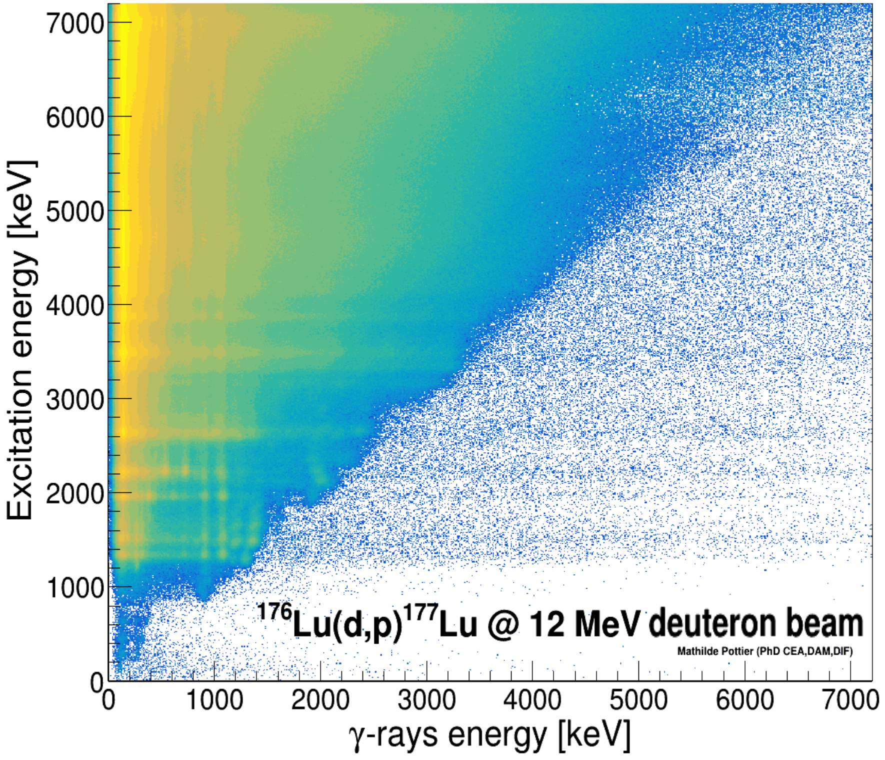
And the ***stop time T_γ for each γ-ray of the event***

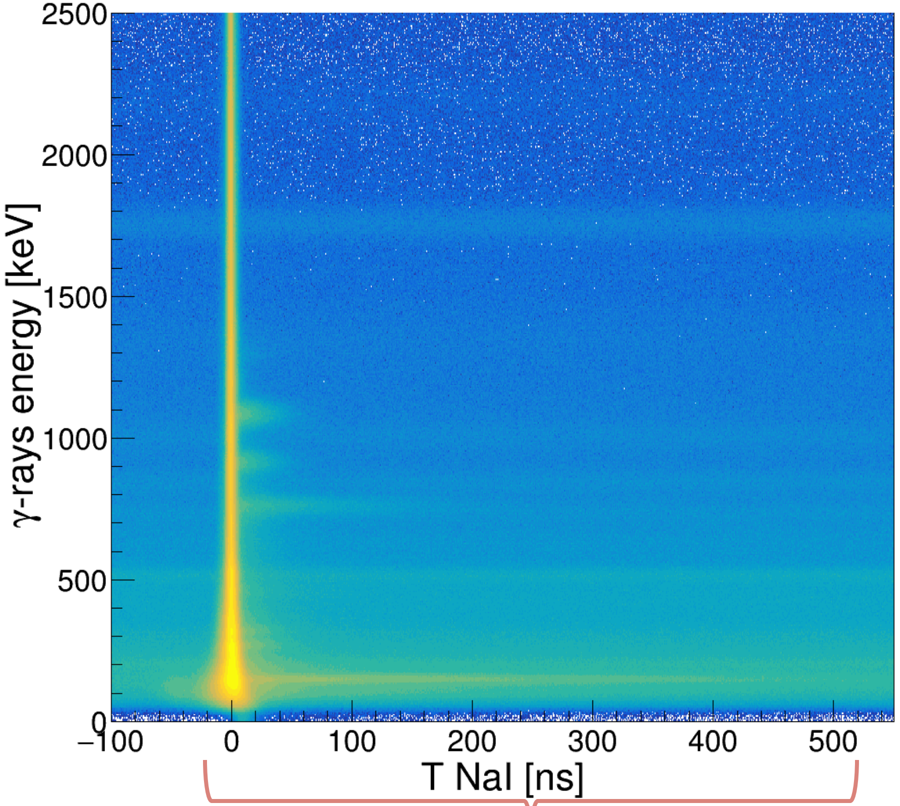
Which observables we measure and how

What we do

Excitation by (d,p) reaction







All γ−cascades

Experimental input for the Oslo method

P(E*, E$_{\text{detected γ-rays}}$) matrix

prompt γ−rays

delayed γ−rays

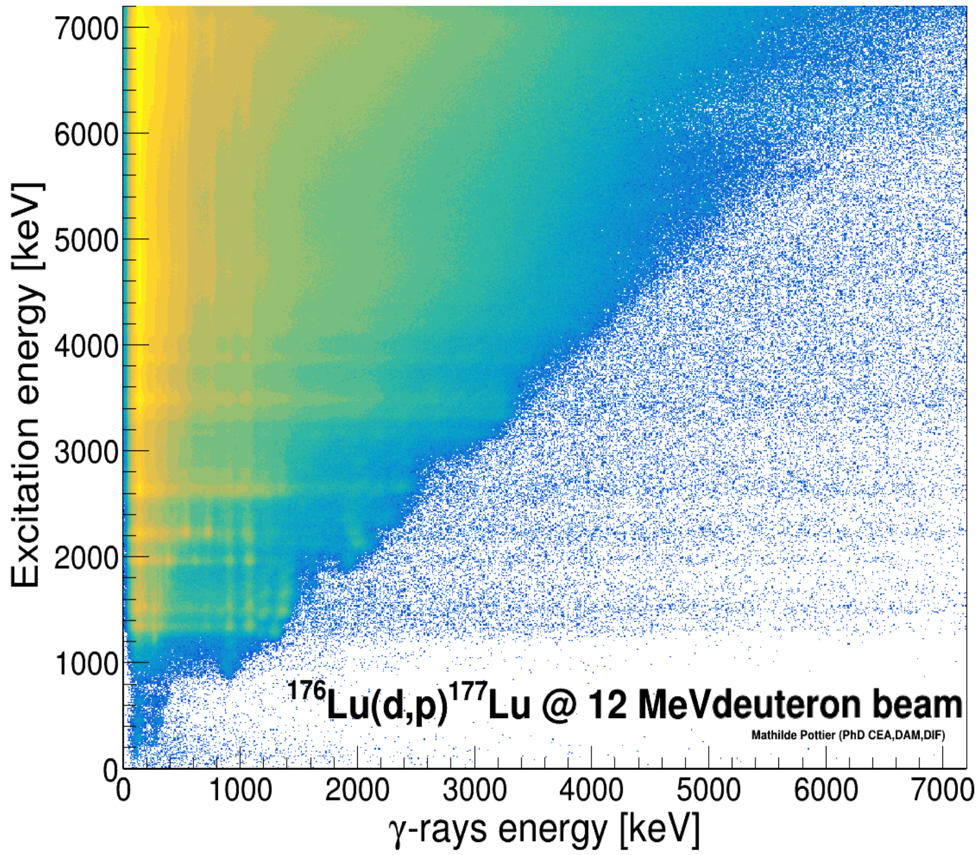
by products

discrete levels :branching ratio at each E*

half-life, isomeric ratio

Which observables we measure and how

Experience



$P(E^*, E_{detected\ \gamma\text{-}rays})$

Calculations

To compare at this level, we need :

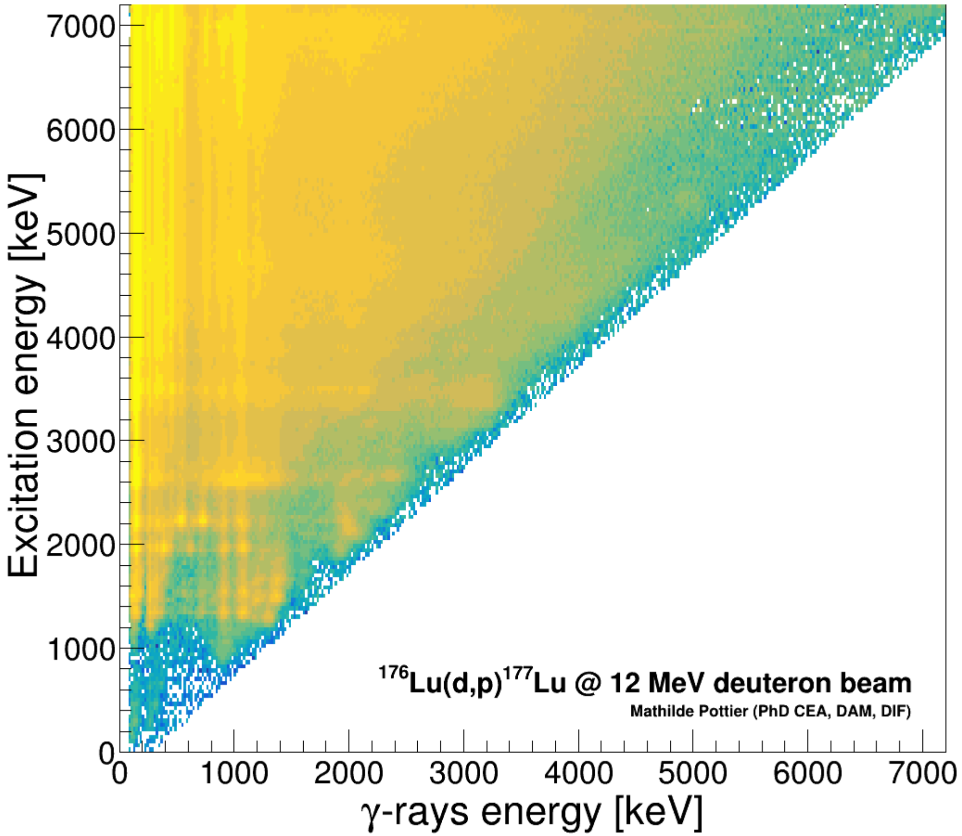
- **spin distribution**
- **to simulate the gamma cascade** codes with inputs
  - **NLD**
  - **gSF**
  - Nuclear structure, …
- **to fold with the detector response** from GEANT4 code

γ –cascade codes
DICEBOX
FIFRELIN
DEGA / CASGAM

under investigation
MCMC technic – **20 parameters**

What we deduce from measurements and how

First step : unfolding techniques **From $P(E^*, E_{detected\ \gamma\text{-rays}})$ matrix to $P(E^*, E_{emitted\ \gamma\text{-rays}})$**



$P(E^*, E_{emitted\ \gamma\text{-rays}})$

Method Gold or Guttormsen technics

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

$$X = Eemitted = DY = DE_{detected}$$

- Itération

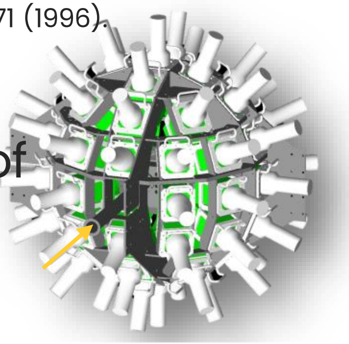
$$D_{ii}^{(m+1)} = \frac{x_i^{(m)}}{y_i^{(m)}}$$

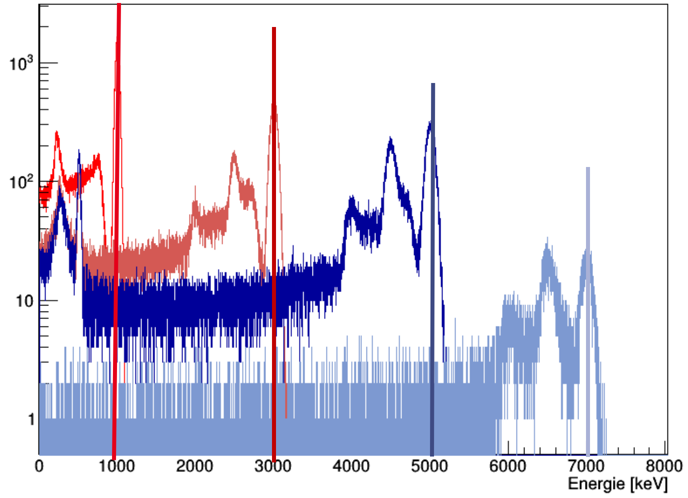
$$X^{(m+1)} = D^{(m+1)}Y$$

$$Y^{(m+1)} = AX^{(m+1)}$$

$$X^{(n)}$$

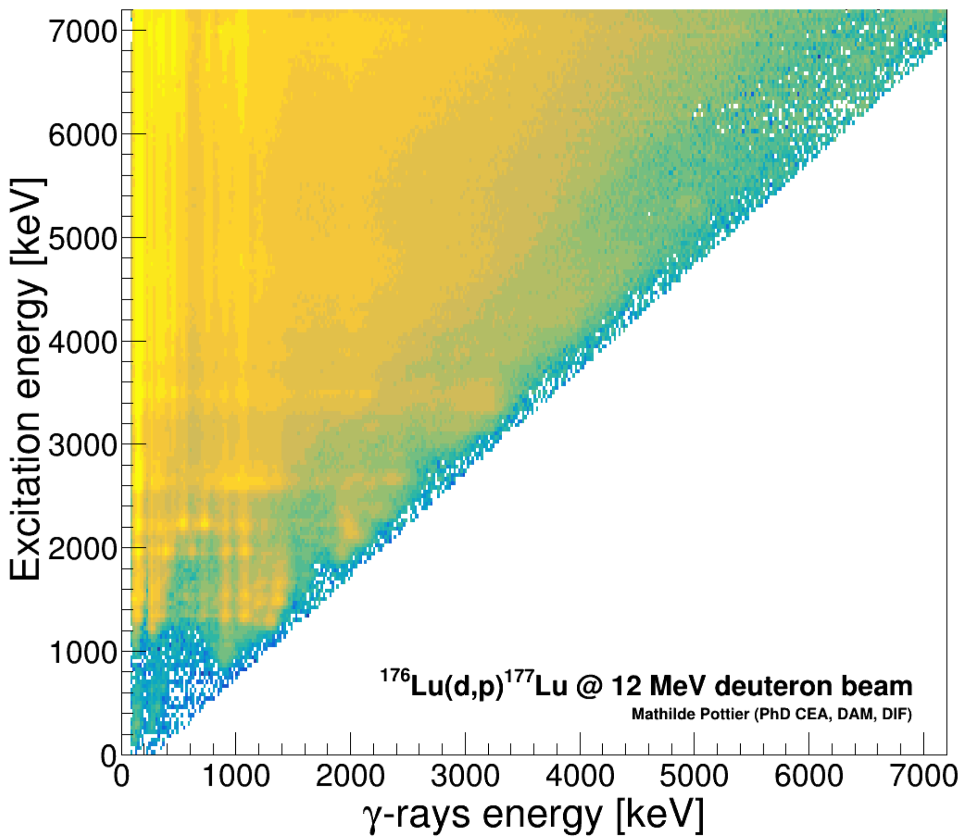
GEANT4 simulation of detector response A





What we deduce from measurements and how

Experience



$P(E^*, E_{detected\ \gamma\text{-rays}})$

Calculations

To compare at this level, we need :

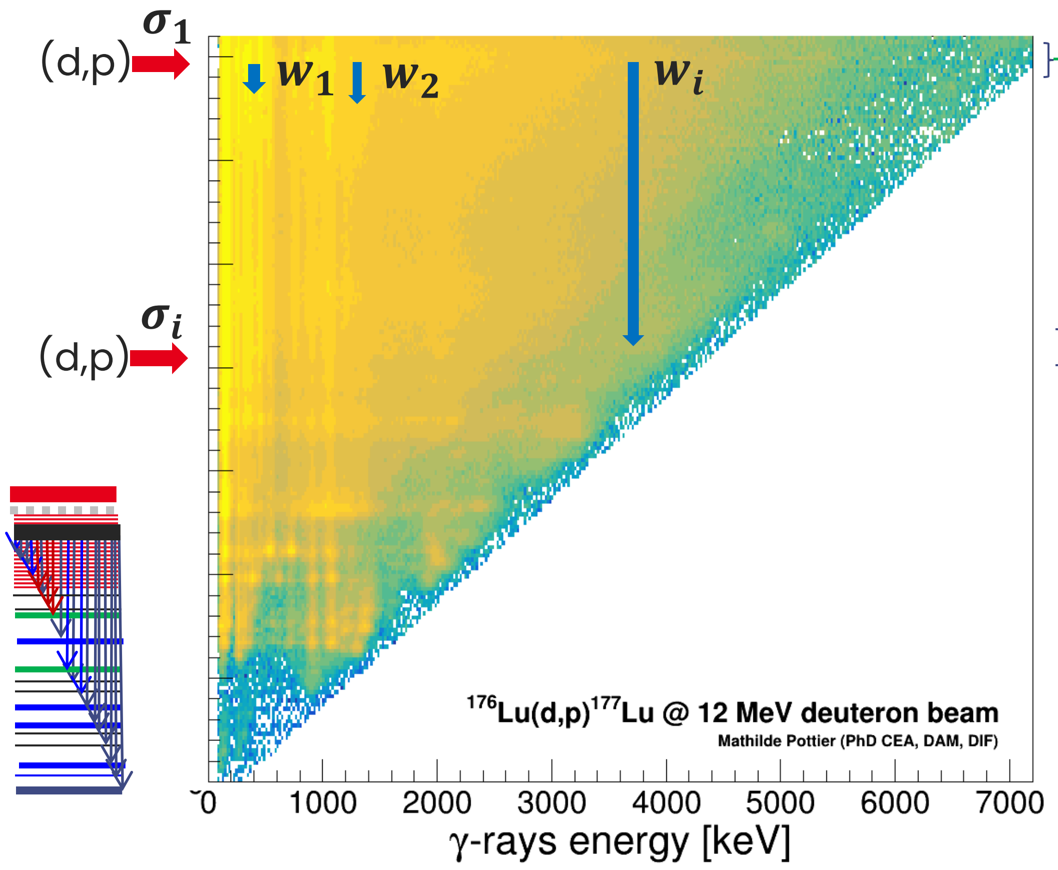
- **spin distribution**
- **To simulate the gamma cascade** codes with inputs
  - **NLD**
  - **gSF**
  - Nuclear structure, …

γ –cascade codes
DICEBOX
FIFRELIN
DEGA / CASGAM

under investigation
MCMC technic – **20 parameters**
only one step less !

What we deduce from measurements and how

Second step: extraction of primary g-rays



Method *M. Guttormsen et al., Nucl. Instr. Meth. A 255, 518 (1987)*

normalisation of f_i to f_1

$$n_{1i} = \frac{\sigma_1}{\sigma_i} = \frac{A(f_1)}{\langle M_1 \rangle} \times \frac{\langle M_i \rangle}{A(f_i)} \quad with \ \langle M_i \rangle = \frac{E_i^*}{\langle E_i \rangle}$$

primary γ-rays spectrum

$$h_1 = f_1 - \sum_i n_{1i} w_i f_i$$

first (bin) unfolded γ-rays spectrum

probability to feed i from 1

i^{th} (bin) unfolded γ-rays spectrum

iterative to find w_i

$E_{primary\ \gamma\text{-rays}} \equiv h \equiv w_i$ ➡ **$P(E^*, E_{primary\ \gamma\text{-rays}})$**

$P(E^*, E_{emitted\ \gamma\text{-rays}})$

A. C. Larsen et al., Phys. Rev. C 83, 034315 (2011)
J. E. Midtbø et al., Comp. Phys. Com. 262, 107795 (2021)

What we deduce from measurements and how

Second step: extraction of primary γ-rays

Hypothesis

1. "γ decay from any excited state **is independent of its formation**." => "populated by the decay of higher-lying states as directly by the (d, p) reaction" is considered as similar.

2. "In the quasicontinuum, we … apply statistical considerations so we only require that in a **given excitation energy bin** all levels with the same spin-parity are populated approximately equally (instead of specific states)."

3. "the populated spin distribution should be approximately **constant as a function of the excitation energy**."

If not, possible corrections

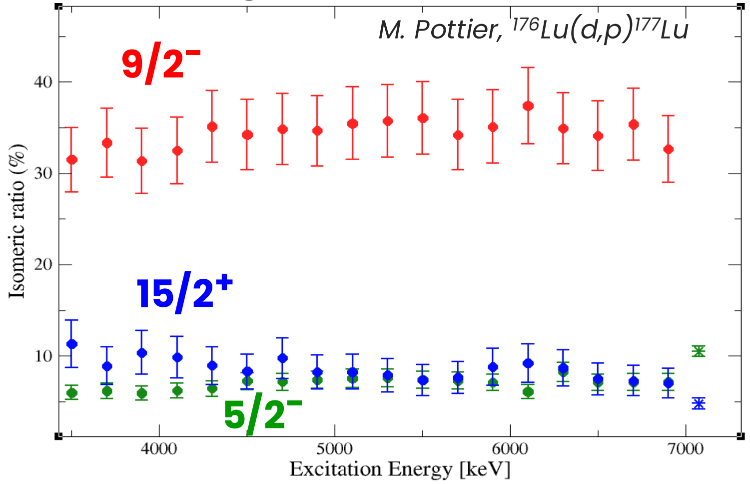
F. Zeiser et al., Phys. Rev. 100, 024305 (2019)

Argumentation / Discussion

It is reasonable to say:
in this region of high level density,

- nucleus is like a compound nucleus
- reaction time << states lifetimes
- nucleus has thermalized before decay

Feeding of isomers constant vs E*

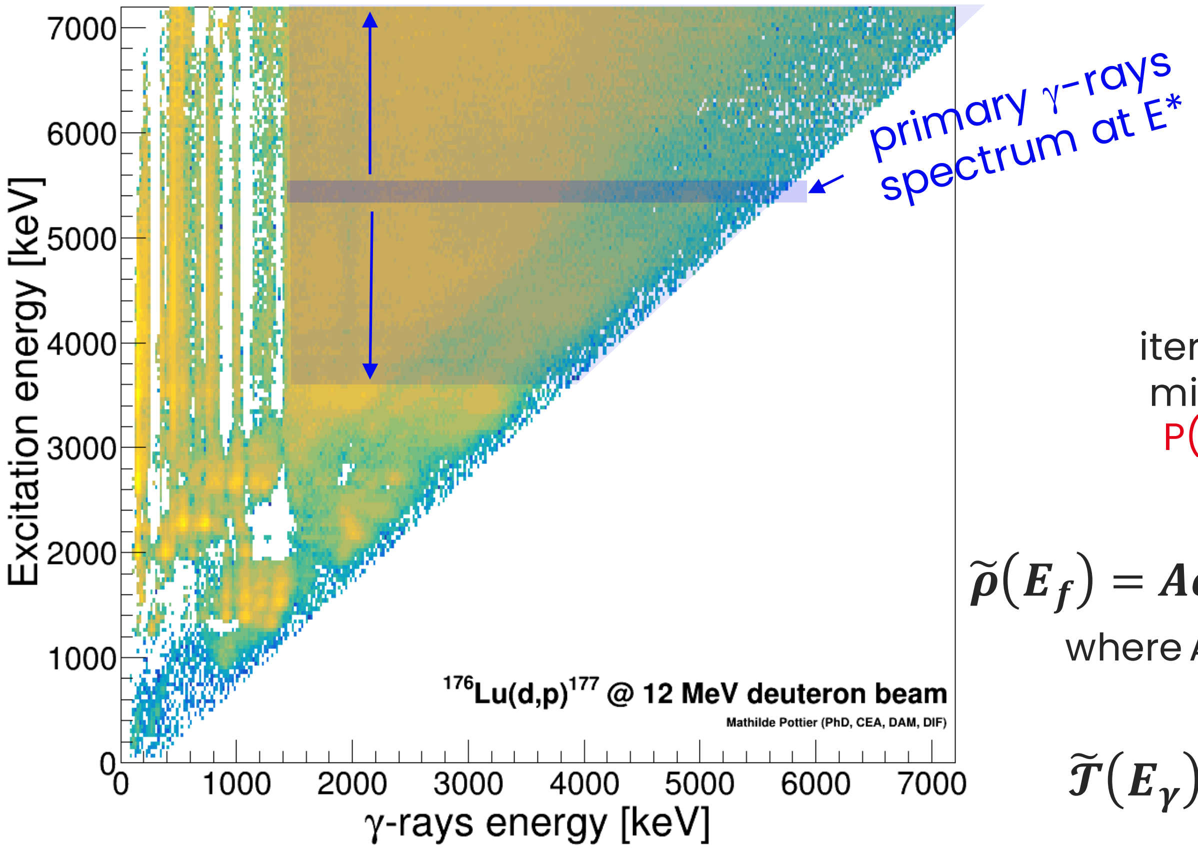


A. C. Larsen et al., Phys. Rev. C 83, 034315 (2011)

What we deduce from measurements and how

Last step: extraction of γSF and NLD

Method *A. Schiller et al., Nucl. Instr. Meth. A 447, 498 (2000)*
A. C. Larsen et al., Phys. Rev. C 83, 034315 (2011)

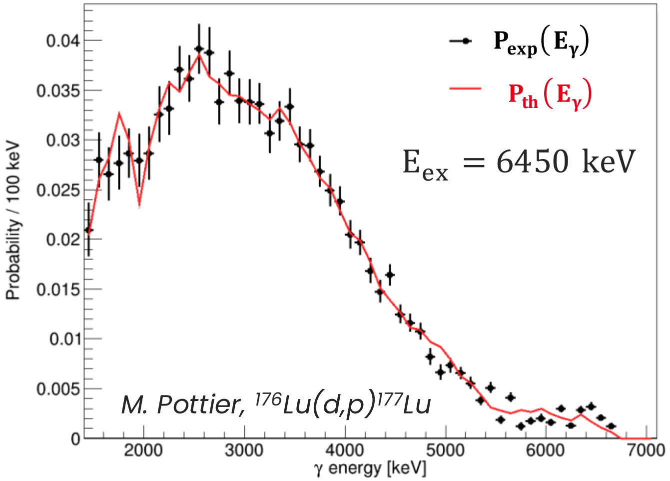


$P(E^*, E_{\text{primary }\gamma\text{-rays}})$

$$P(E^*, E_\gamma) \propto \rho(E_f)\mathcal{T}(E_\gamma)$$

$$P_{th}(E^*, E_\gamma) = \frac{\rho(E - E_\gamma)\mathcal{T}(E_\gamma)}{\sum_{E_\gamma = E_\gamma^{min}}^{E} \rho(E - E_\gamma)\mathcal{T}(E_\gamma)}$$

iterative method with χ^2 minimization between $P(E^*, E_\gamma)$ and $P_{th}(E^*, E_\gamma)$



$$\tilde{\rho}(E_f) = A\exp(\alpha(E - E_\gamma))\,\rho(E - E_\gamma)$$

where A et α normalized on discrete levels and at S_n (D_0)

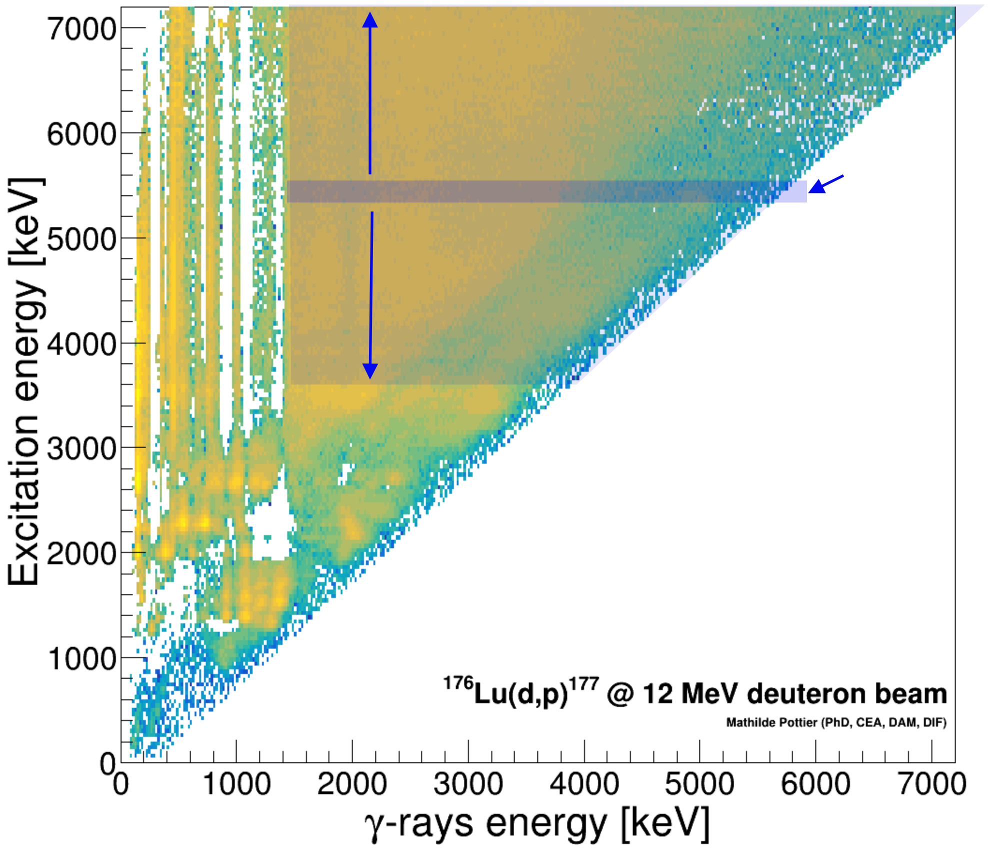
$$\tilde{\mathcal{T}}(E_\gamma) = B\exp(\alpha E_\gamma)\mathcal{T}(E_\gamma)$$

γSF

$$f_{XL}(E_\gamma) = \frac{2\pi E_\gamma^{(2L+1)}}{\widetilde{\mathcal{T}_{XL}}(E_\gamma)}$$

What we deduce from measurements and how

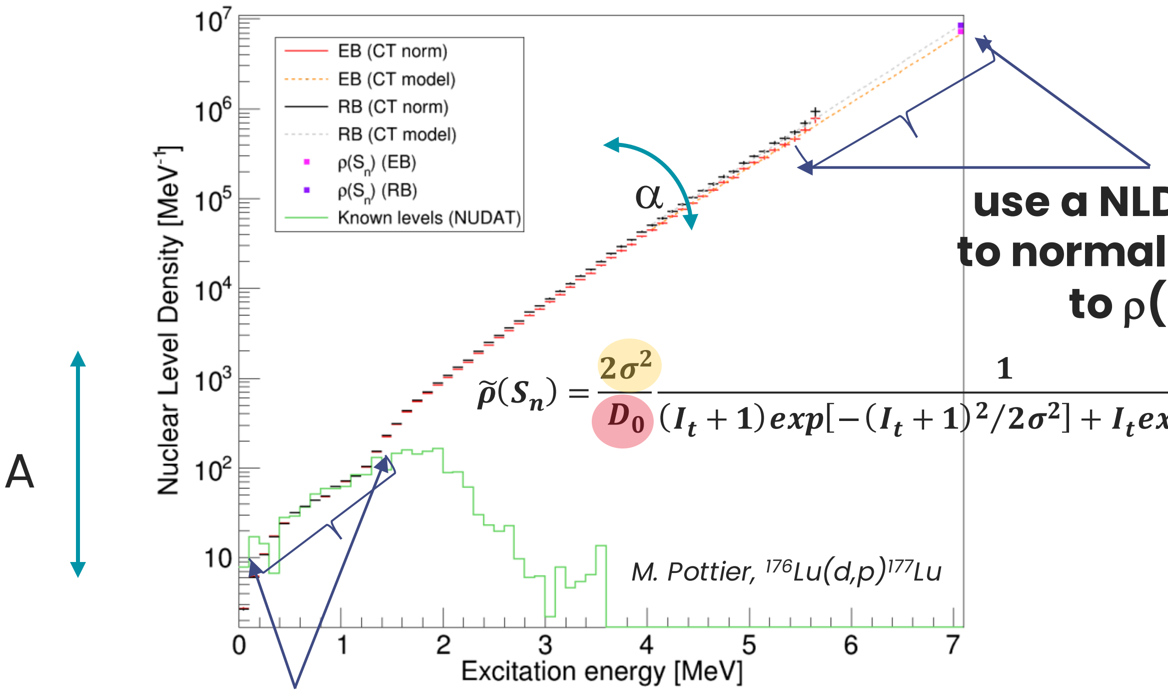
Last step: extraction of γSF and NLD



$P(E^*, E_{primary\ \gamma\text{-rays}})$

$$\tilde{\rho}(E_f) = A exp(\alpha(E - E_\gamma))\ \rho(E - E_\gamma)$$

where A et α normalized on discrete levels and at S_n (D_0)



$$\tilde{\rho}(S_n) = \frac{2\sigma^2}{D_0} \frac{1}{(I_t+1)exp[-(I_t+1)^2/2\sigma^2] + I_t exp[-I_t^2/2\sigma^2]}$$

use a NLD model to normalize data to ρ(S_n)

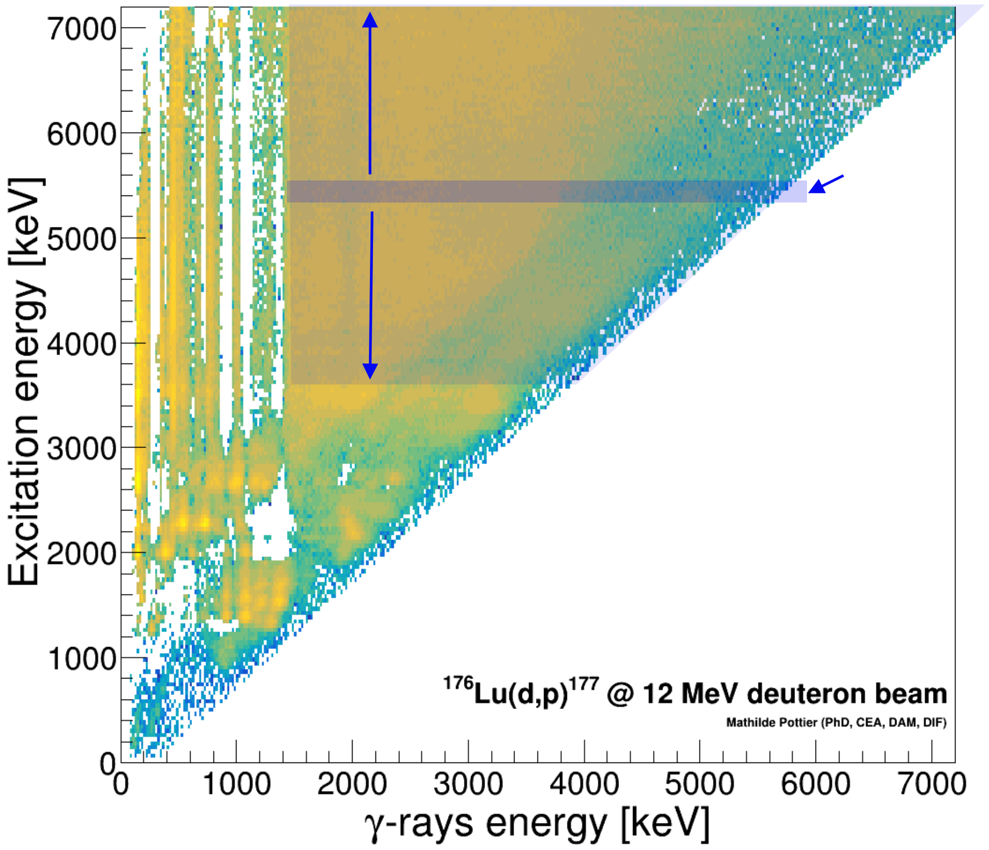
use existant data to normalize data at low energies

sys. *T. von Egidy and D. Bucurescu, Phys. Rev. C 80, 054310 (2009)*

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

What we deduce from measurements and how

Last step: extraction of γSF and NLD



$P(E^*, E_{primary\ \gamma\text{-}rays})$

$$\widetilde{\mathcal{T}}(E_\gamma) = B\exp(\alpha E_\gamma)\mathcal{T}(E_\gamma)$$

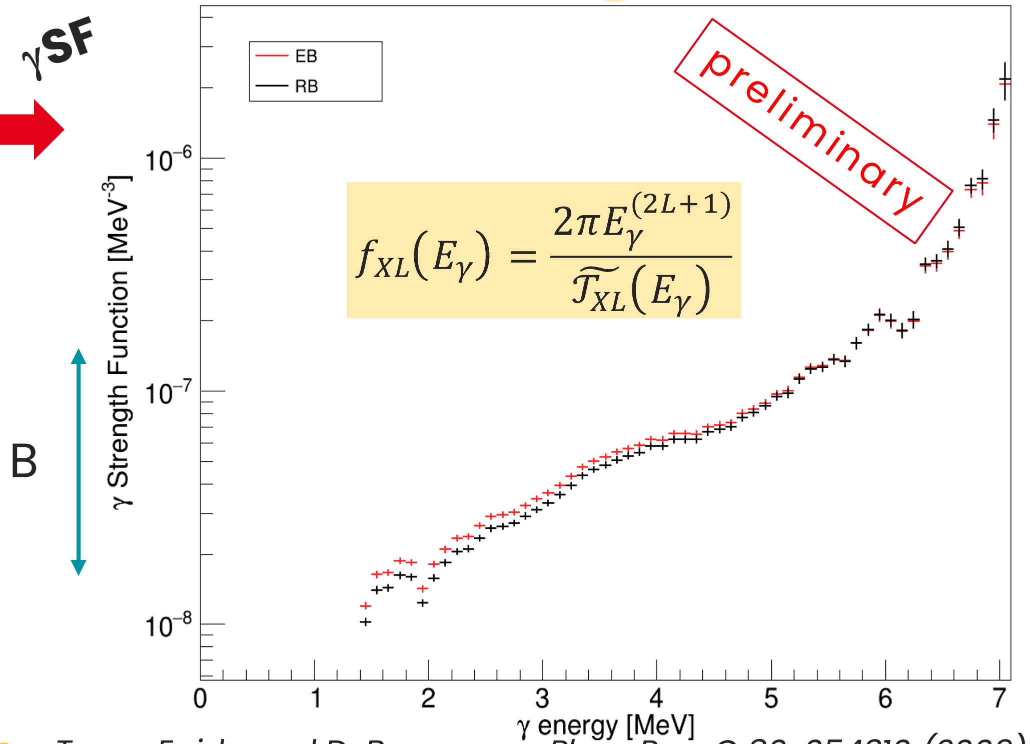
where B normalized on Γ_γ and α comes from NLD norm.

$$\langle\Gamma_\gamma(S_n, I_t \pm 1/2)\rangle = \frac{BD_0}{2\pi}\int_{E_\gamma=0}^{S_n} dE_\gamma \mathcal{T}(E_\gamma) \times \rho(S_n - E_\gamma)\sum_{J=-1}^{1} g(S_n - E_\gamma, I_t \pm 1/2 + J)$$

use an exponential to extrapolate $\mathcal{T}$ to 0

$$g(E, I) = \frac{2I+1}{2\sigma^2}\exp[-(I+1/2)^2/(2\sigma^2)]$$

γSF



$$f_{XL}(E_\gamma) = \frac{2\pi E_\gamma^{(2L+1)}}{\widetilde{\mathcal{T}}_{XL}(E_\gamma)}$$

sys. *T. von Egidy and D. Bucurescu, Phys. Rev. C 80, 054310 (2009)*

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

What we deduce from measurements and how

Last step: extraction of γSF and NLD

Method *A. Schiller et al., Nucl. Instr. Meth. A 447, 498 (2000)*
A. C. Larsen et al., Phys. Rev. C 83, 034315 (2011)

Hypothesis

1. "The γ-ray transmission coefficient $\mathcal{T}$ **is assumed to be independent of excitation energy"** : generalized Brink hypothesis

$$P(E^*, E_\gamma) \propto \rho(E_f)\mathcal{T}(E_\gamma) \leftarrow \mathcal{T}(E_\gamma, E^*)$$

Important issue

2. Spin distribution in $\tilde{\rho}(S_n)$ and $\langle \Gamma_\gamma(S_n, I_t \pm 1/2) \rangle$
Mismatch between populated spin reached by the reaction and intrinsic NLD.

3. Parity distribution : equal for heavy nuclei
Asymmetry can change the $\tilde{\rho}(S_n)$ and favors M1 transitions

to be included in error bars

Thèse de D.M. Brink, Oxford Univ. (1955)
P. Axel, Phys. Rev. 126, 671 (1962)

Argumentation / Discussion

Is it valid ?

- not at high temperature/high spins
- where is the limit ?
- below 10 MeV, no clear experimental evidence to invalidate this hypothesis

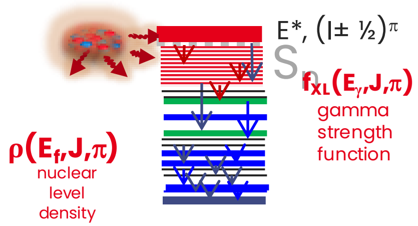
Corrections needed ?

- Microscopic calculation can help ?
- This could strongly affect gSF, need to make assumptions and include them to error bars ?

A. C. Larsen et al., Phys. Rev. C 83, 034315 (2011)

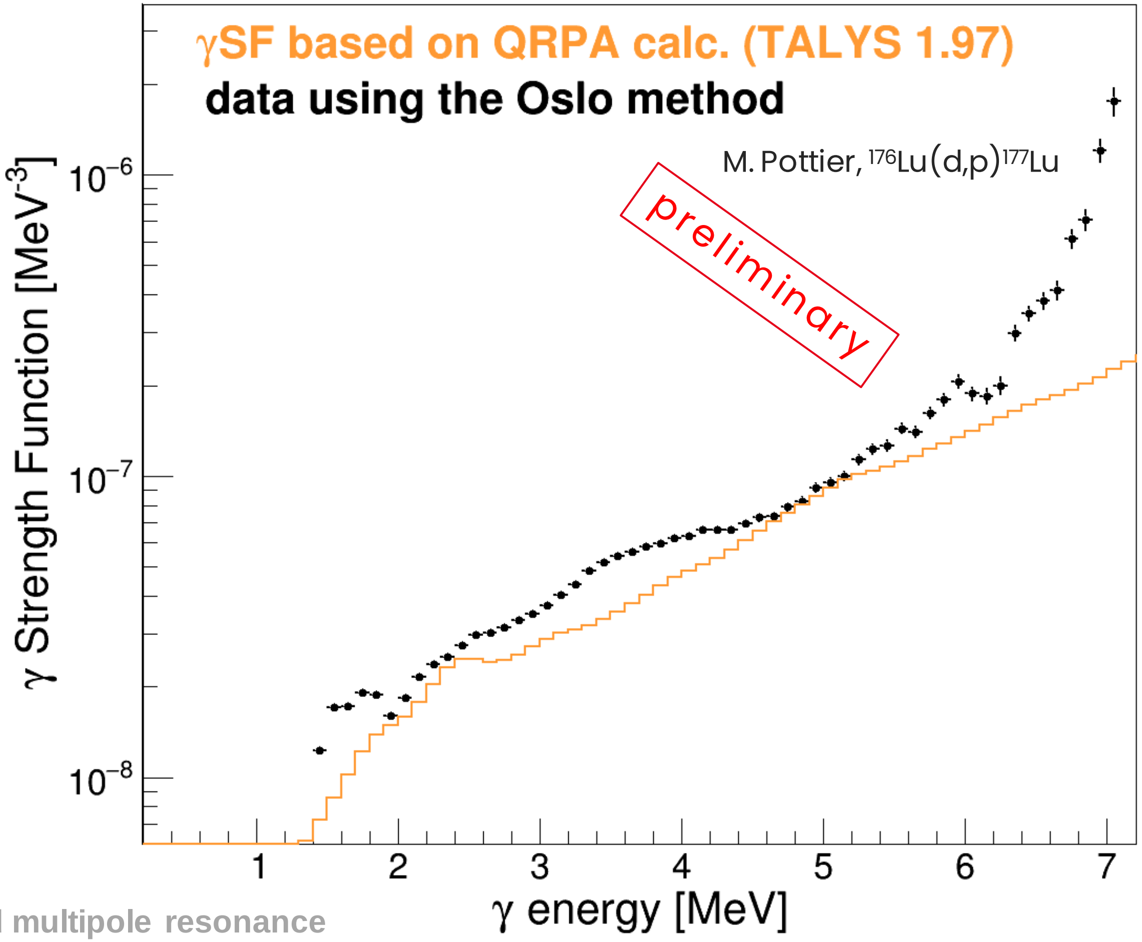
What we deduce from measurements and how

Experience



Calculations

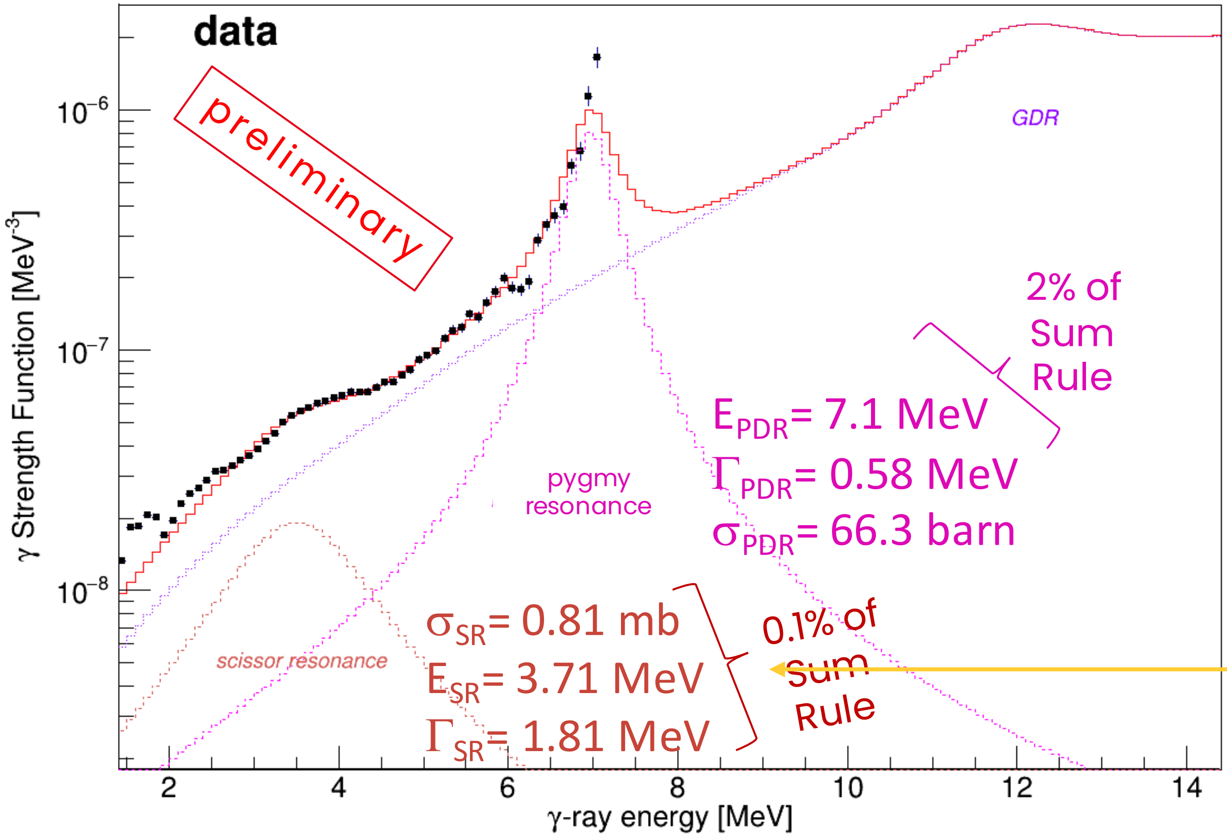
To compare at this level, phenomenological or microscopic models can be directly used



How we can interpret

Experience

Hypothetical interpretation
- E1 or M1 nature
- Resonances presence



2% of Sum Rule

E_{PDR}= 7.1 MeV
Γ_{PDR}= 0.58 MeV
σ_{PDR}= 66.3 barn

σ_{SR}= 0.81 mb
E_{SR}= 3.71 MeV
Γ_{SR}= 1.81 MeV

0.1% of Sum Rule

Calculations

To compare at this level to systematic studies

$$E_{sc} = 66\ \delta A^{-1/3}\ \text{MeV}$$

N. Pietralla et al., Phys. Rev. C ***58****, 184 (1998)*

→ σ_{SR}= 0.27 mb, E_{SR}= 3.5 MeV

$$\sigma_{sc} = 10^{-2}|\beta_2|A^{9/10}\ \text{mb}$$
$$E_{sc} = 5 \times A^{-1/10}\ \text{MeV}$$
$$\Gamma_{sc} = 1.5\ \text{MeV}$$

S.Goriely et al., SMLO, Phys. Rev. C ***99****, 014303 (2019)*

→ σ_{SR}= 0.32 mb, E_{SR}= 2.98 MeV, Γ_{SR}= 1.5 MeV

σ_{SR} × 2.5
E_{SR} ≡
Γ_{SR} × 1.2

→ **Two SRs ?**

What if it is a E2 resonance ?

How we interpret

Example of ^{181}Ta

Z=73
N=108

Argumentation / Discussion

Coherence between similar nuclei ?

PHYSICAL REVIEW C **99**, 054330 (2019)

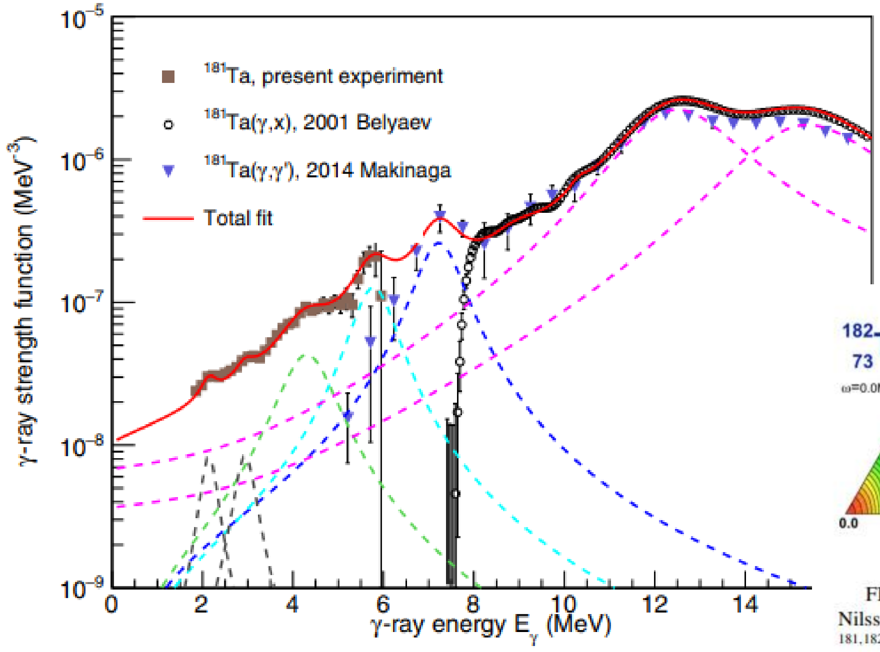


FIG. 8. ^{181}Ta data from the 15 MeV ^{181}Ta$(d,d')^{181}$Ta, ^{181}Ta(γ,γ') [53], and ^{181}Ta(γ,X) [62] reactions. Various resonances were identified (see text for details) and contribute to the total fit (red line) that best matches the experimental data.

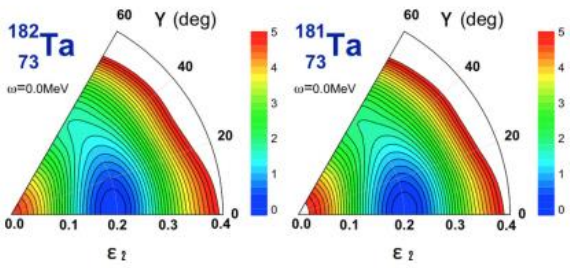
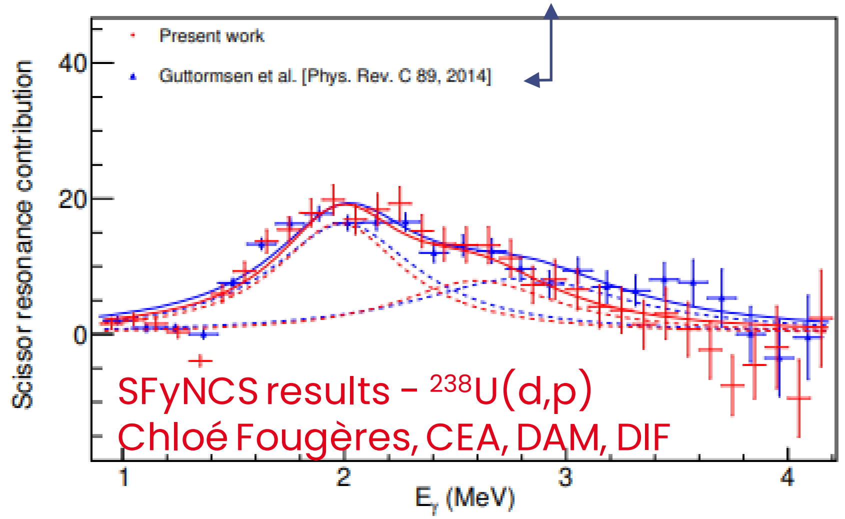


FIG. 9. Potential energy surface calculations with the cranking Nilsson model plus shell correction method for the ground states of ^{181,182}Ta, see text for details.

SR splitting → triaxiality ?

^{164}Dy and ^{174}Yb, N. Lo Iudice et al., Phys. Lett. B 161, 18 (1985)

SR splitting → microscopic calc. can reproduce without triaxiality ? as in actinides *A.A. Kuliev et al., Eur. Phys. J. A 43, 313 (2010)*



SR splitting → deformation

O. Roig, M. Pottier, V. Méot, L. Gaudefroy et al, Nucl. Instr. Meth. A, submitted (2024)

How we interpret

Argumentation / Discussion

Coherence between experiments

Example of ^{181}Ta

Z=73
N=108

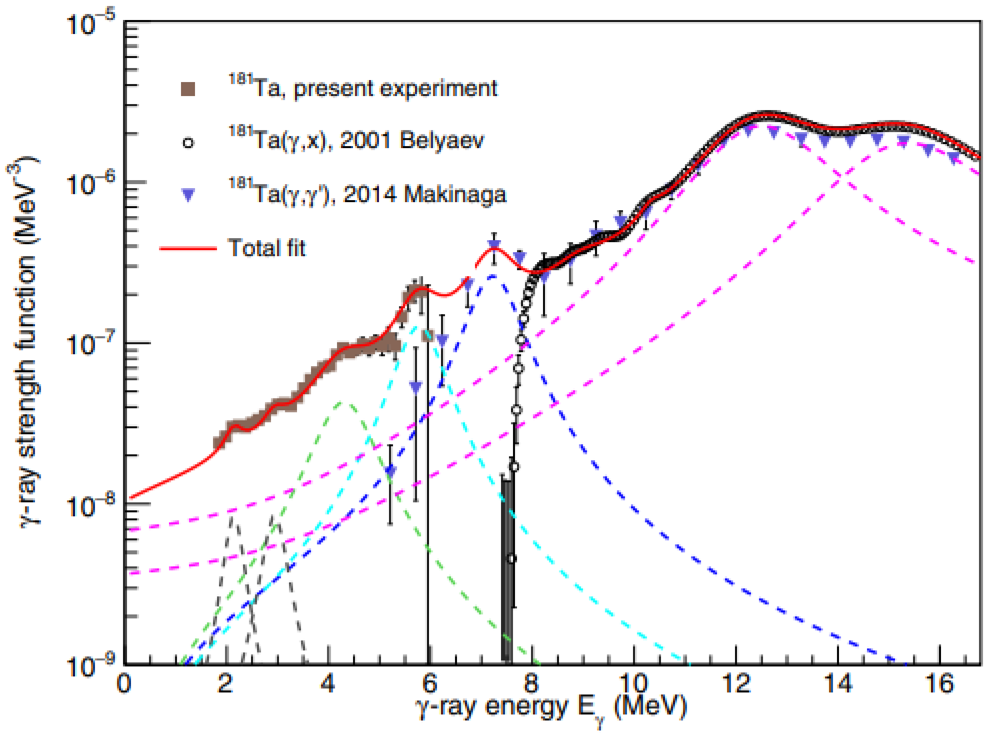
- By finding the same values from different experiments:
  It seems to be the case for ^{181}Ta:
  $(\gamma,\gamma')_{NRF}$ and $(d,d')_{Oslo}$

and detailed balance principle ?

- By reproducing the observables from one to other:
  we are looking at this between our DANCE and SFyNCS experiments on ^{176}Lu $(n,\gamma)_{RC}$ and $(d,p)_{Oslo}$

- …. By performing completely new experiments involving vortex photons

PHYSICAL REVIEW C **99**, 054330 (2019)



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- Thanks for your questions, comments, discussions !