# Nuclear level density and gamma strength function of $^{64}$Ni: preliminary results

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# CONTENTS

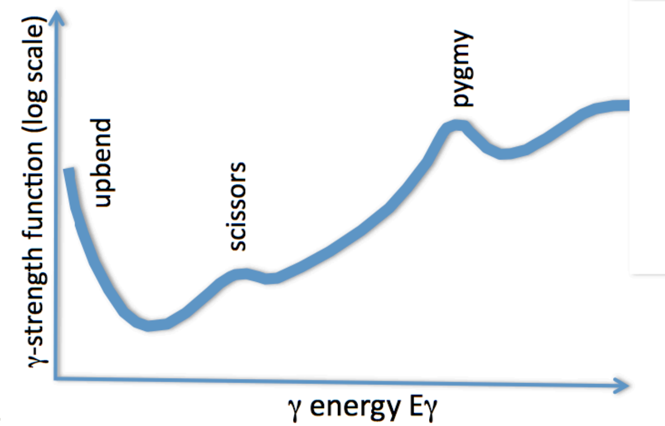
# INTRODUCTION

***Use of the Oslo method to extract the nuclear level density and the gamma strength function of $^{64}$Ni. Analysis and comparison with the results for neighbouring nuclei.***

Applications:

- Calculation of cross-sections
  → Nuclear **ASTROPHYSICS**:
  **Neutron capture** cross-sections
  Stellar nucleosynthesis

- Structures:
  - Breaking of nucleon pairs (l.d)
  - Gamma resonances (g.s)



# INTRODUCTION: Why $^{64}$Ni?

- Good candidates to have gamma resonances:
  - M1 spin-flip resonances in $^{58,60,62}$Ni (6-11 MeV) [1]
  - Pygmy resonance in $^{68}$Ni at 9.5 MeV. [2]

**Low-energy enhancement** of $^{60}$Ni (below 3 MeV)

- Suggested M1 character for 60Ni. [3]
- Theoretical mechanism to explain the upbend based on E1 type transitions [4]. Shell-model calculations give a strong low-energy M1 component in the $\gamma$-strength function [5,6]

→ If also present in heavier, more neutron rich nuclei, this upbend could lead to modifications of the $(n, \gamma)$ rates →impact the s-process abundances and possibly the r-process yields. [7]


→ [1]Djalali et al., Systematic of the excitation of M1 resonances in medium heavy nuclei, Nucl. Phys. A388, 1 (1982).

→ [2] D. M. Rossi et al., Phys. Rev. Lett. 111, 242503 (2013)

→ [3] A. Voinov, *et a.*, Phys. Rev. C 81, 024319 (2010).

→ [4] E. Litvinova and N. Belov, Phys. Rev. C 88, 031302 (R) (2013).

→ [5] R. Schwengner, S. Frauendorf, and A. C. Larsen, Phys. Rev. Lett. 111, 232504 (2013).

→ [6] B. Alex Brown, and A. C. Larsen, Phys. Rev. Lett. 113. 252502 (2014)

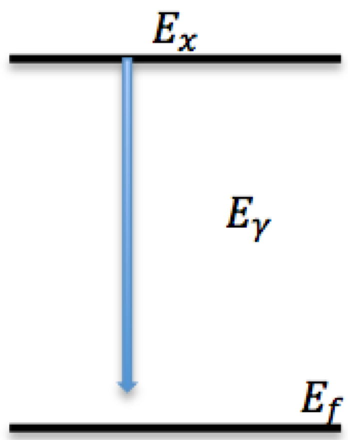
→ [7] C. Lederer, C. Massimi, S. Altstadt, *et al.*, Phys. Rev. Lett. 110, 022501 (2013).

# INTRODUCTION: NUCLEAR GAMMA DECAY IN THE QUASI-CONTINUUM

- Probability:

$$P(E_x^{'}, E_\gamma) \propto \rho(E_f) \cdot \tau(E_\gamma)$$

- Gamma tranmission coefficient: $\tau(E_\gamma)$




- Where :

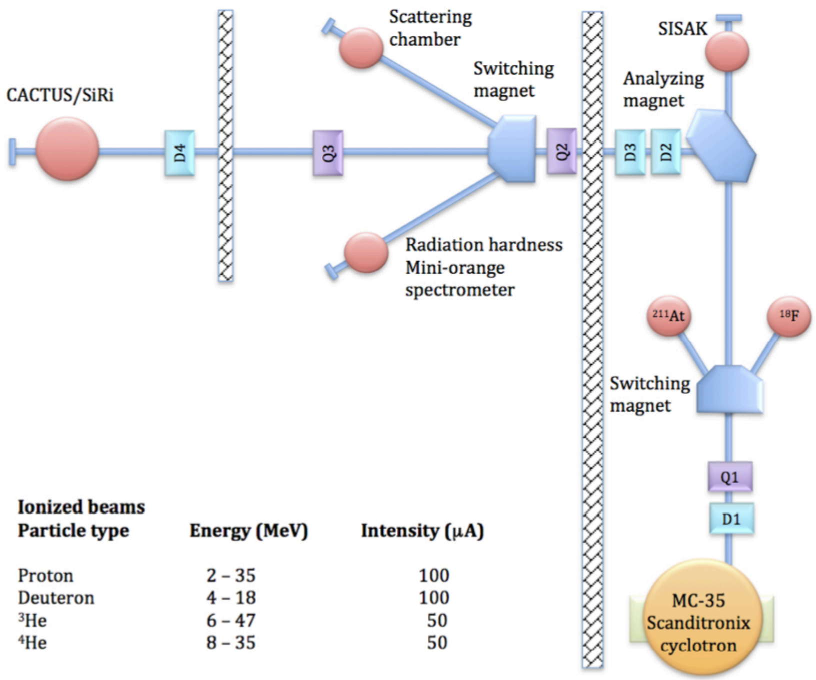
$$f_L(E_\gamma) = \frac{\tau(E_\gamma)}{2\pi E_\gamma^{2L+1}}$$

- Main contribution: L=1
- Result: $P(E, E_\gamma) \propto \rho(E_f) 2\pi E_\gamma^3 f(E_\gamma)$

# EXPERIMENTAL METHOD

Oslo Cyclotron Laboratory (OCL), 5 days.

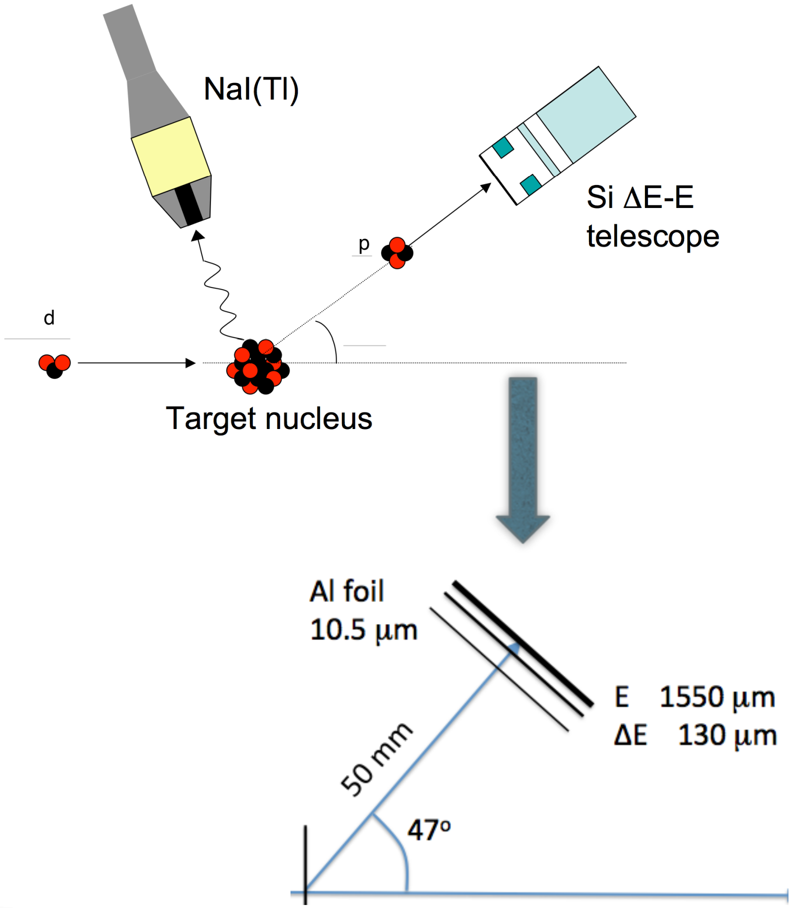
- $^{64}$Ni target ( 99% purity, 1mg/cm2 thickness)
- Backward angles
- 16 MeV proton beam →study the $^{64}$Ni(p,p')$^{64}$Ni reaction.

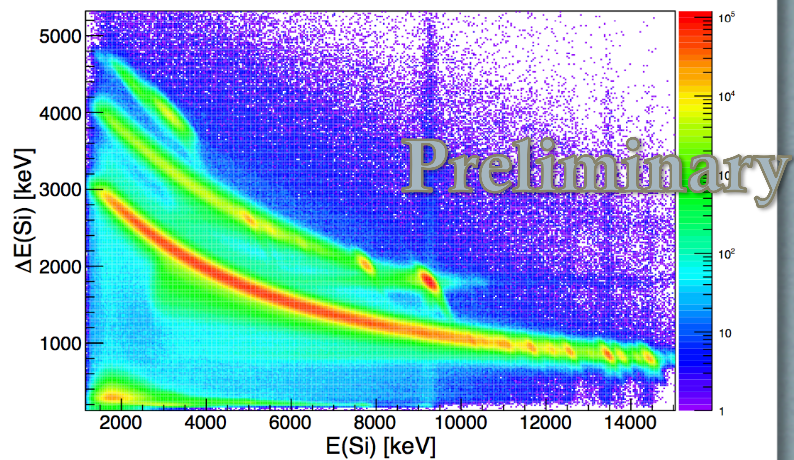



**Ionized beams**

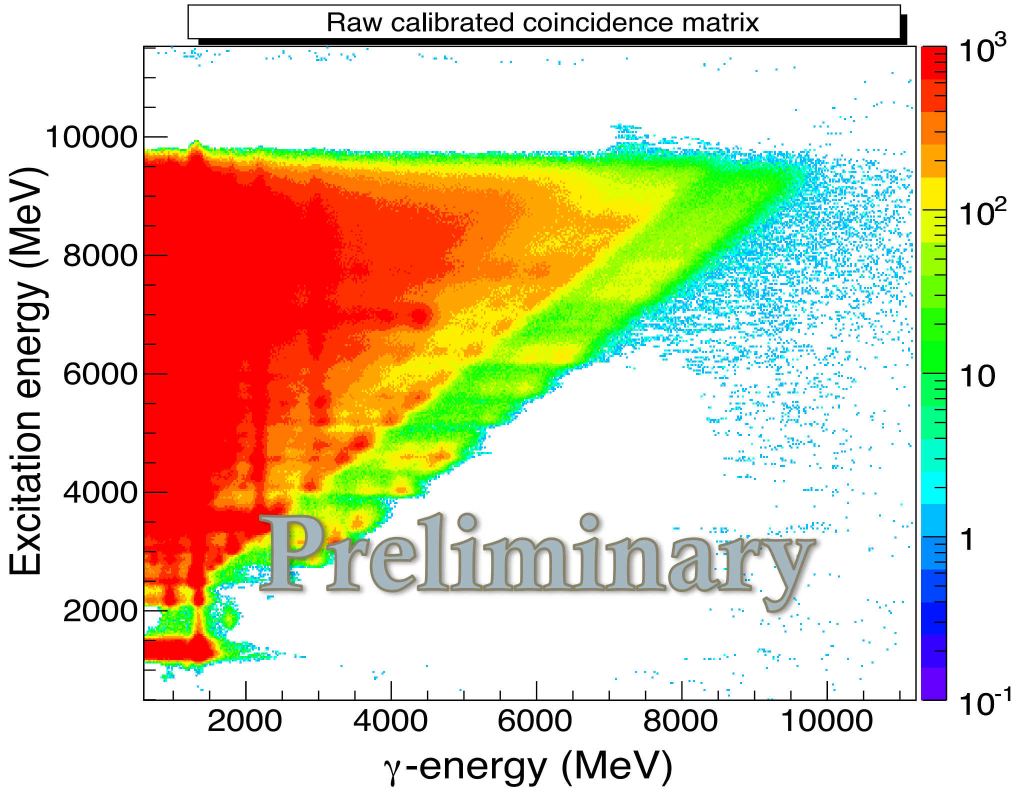
| **Particle type** | **Energy (MeV)** | **Intensity (μA)** |
|---|---|---|
| Proton | 2 – 35 | 100 |
| Deuteron | 4 – 18 | 100 |
| $^{3}$He | 6 – 47 | 50 |
| $^{4}$He | 8 – 35 | 50 |

# PARTICLE-GAMMA COINCIDENCES



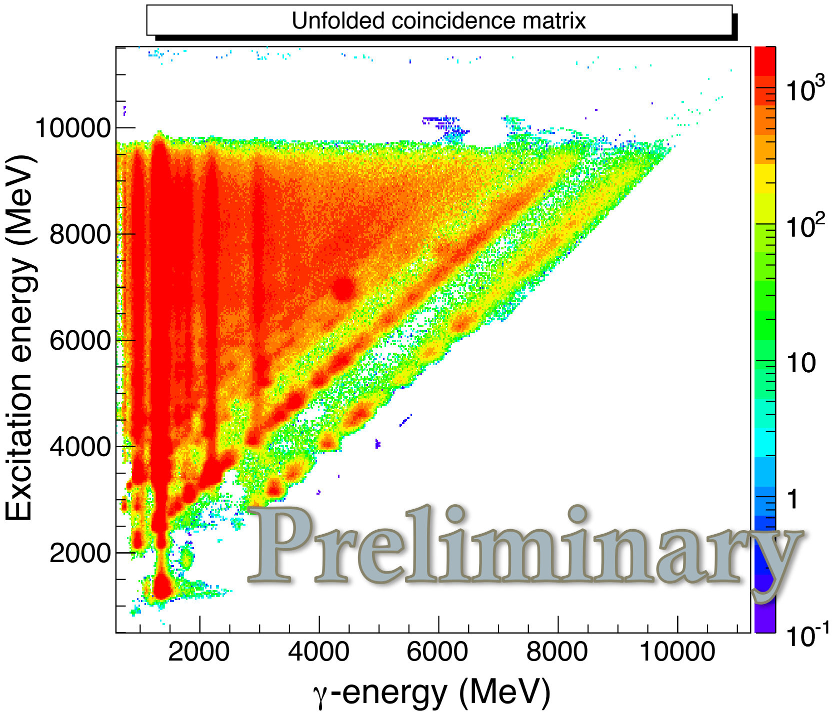
# PARTICLE-GAMMA COINCIDENCE MATRIX. Ex. for $^{64}$Ni



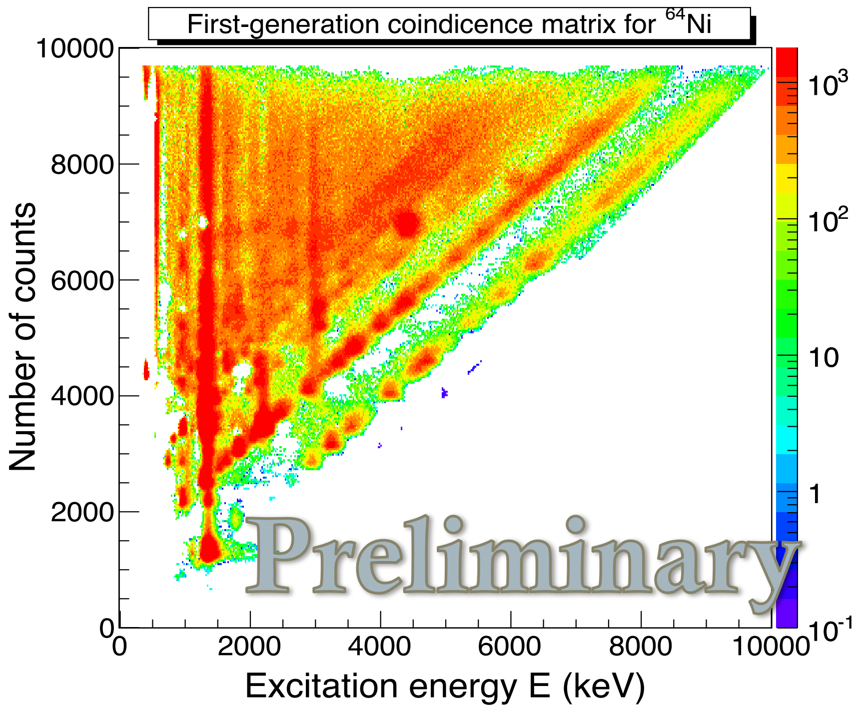

$$P(E_x, E_\gamma) \propto \tau(E_\gamma) \cdot \rho(E_\gamma, E_x)$$

# THE OSLO METHOD

- Unfolding: correct from the response of the dectectors: $f = \mathbf{R}u$




- Extraction of the first-generation gamma-rays:



# EXTRACTION OF THE NUCLEAR LEVEL DENSITY AND THE GAMMA STRENGTH FUNCTION

- Step 1: select data on the matrix, region of statistical decay.
- Minimize:

$$\chi^2 = \frac{1}{N_{\text{free}}} \sum_{E_x=E_{x,\min}}^{E_{x,\max}} \sum_{E_\gamma=E_{\gamma,\min}}^{E_x} \left( \frac{P_{\text{th}}(E_x, E_\gamma) - P(E_x, E_\gamma)}{\Delta P(E_x, E_\gamma)} \right) \qquad \sum_{E_\gamma=E_{\gamma min}}^{E_x} P(E_x, E_\gamma) = 1$$

- The solutions depend on three parameters:

$$\rho'(E_x - E_\gamma) = A\rho(E_x - E_\gamma)e^{\alpha(E_x - E_\gamma)} \ ,$$

$$\tau'(E_\gamma) = B\tau(E_\gamma)e^{\alpha E_\gamma} \ .$$

- To **normalize** these functions: we rely on experimental data.

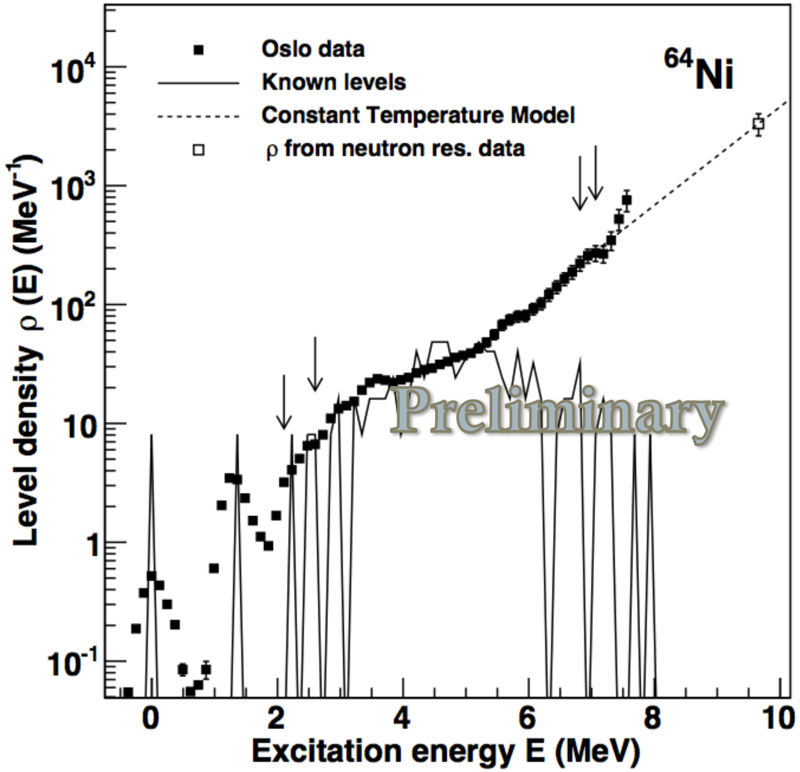
# NORMALIZATION: NUCLEAR LEVEL DENSITY OF $^{64}$Ni

- **At low excitation** energies→ discrete energy levels.
- Usually $\rho$ (Bn) is obtained from neutron-resonance experiments (average spacing for s-wave D0). In this case, no D0 is available and $\rho$ (Bn) is estimated from systematics.
- The Constant Temperature Model is used for interpolation:

$$\rho = \frac{1}{T}\exp\frac{E_x - E_0}{T}$$

→ We observe:

- Good agreement with low-excitation energy states: both the ground state and the first excited 2+ state at 1.345 MeV are clearly seen.
- Saturation of known energy levels at excitation energies above ≈3-4 MeV
- CTM above ≈5.3 MeV.



# GAMMA STRENGTH FUNCTION

**GDR**: oscillation of proton vs neutron clouds (12-15 MeV). **Use data on $^{60}$Ni [7] and $^{66}$Zn [8]** from photo-neutron cross-sections. Possible since:

→Similar deformation

→In that case the GDR strength varies slowly within isotopic chains and similar Z/A nuclei.

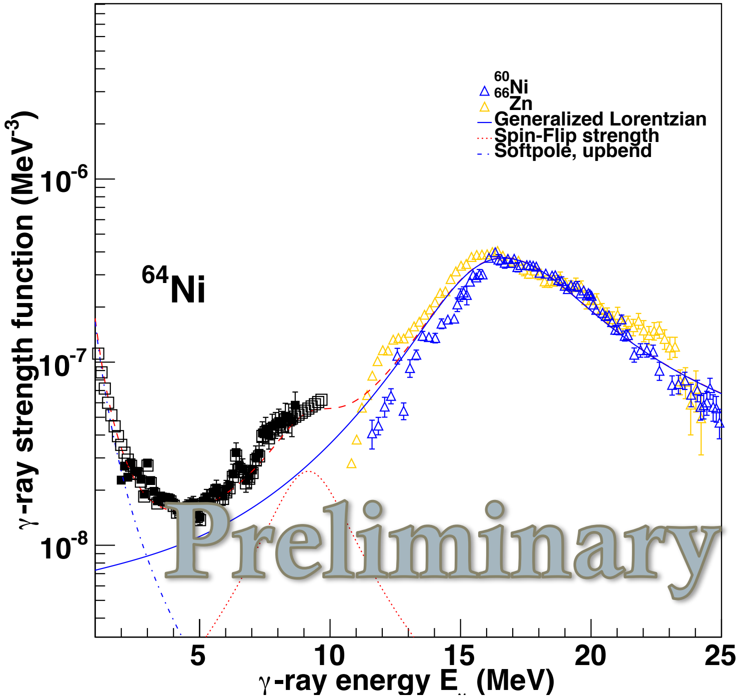
Use of a **Generalized Lorentzian** model for deformed nuclei (two components).

$$f_{E1}^{GLO}(E_\gamma) = \theta \cdot \sigma_r \Gamma_r \left[ \frac{E_\gamma \Gamma_K(E_\gamma, T)}{(E_\gamma^2 - E_r^2)^2 + E_\gamma^2 \Gamma_K^2(E_\gamma, T)} + 0.7 \cdot \frac{\Gamma_K(0,T)}{E_r^3} \right] ,$$

with

$$\Gamma_K(E_\gamma, T) = \frac{\Gamma_r}{E_r^2}(E_\gamma^2 + 4\pi^2 T^2) ,$$

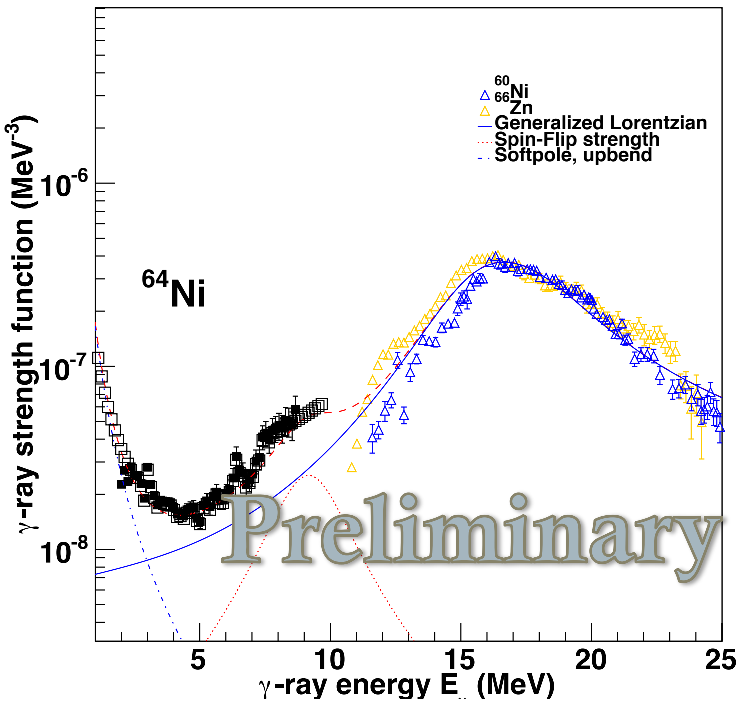
$$\theta = (3\pi^2\hbar^2c^2)^{-1} = 8.674 \cdot 10^{-8}\,\mathrm{mb}^{-1}\mathrm{MeV}^{-2}$$





- [7] S. C. Fultz, Physical Review, Part C, Nuclear Physics, Vol.10, p.608 (1974).
- [8] A. M. Goryachev, Voprosy Teoreticheskoy i Yadernoy Fiziki, Vol.1982, Issue.8, p.121 (1982)

# GAMMA STRENGTH FUNCTION OF $^{64}$Ni




- **At 9.3 MeV :**

→If it is of E1 character, it could be a **pygmy** mode:

- Often described as a neutron skin oscillation vs N≅ Z core.
- Seen in $^{68}$Ni at 9.5 MeV.

→If it is of M1 character: possible spin-flip resonance.

→ **Fitted to a Standard Lorentian (SLO).**

- **Below 3 MeV:** Data suggest a **low-energy enhancement or upbend!** (seen in $^{60}$Ni, suggested by the $^{59}$Ni data).

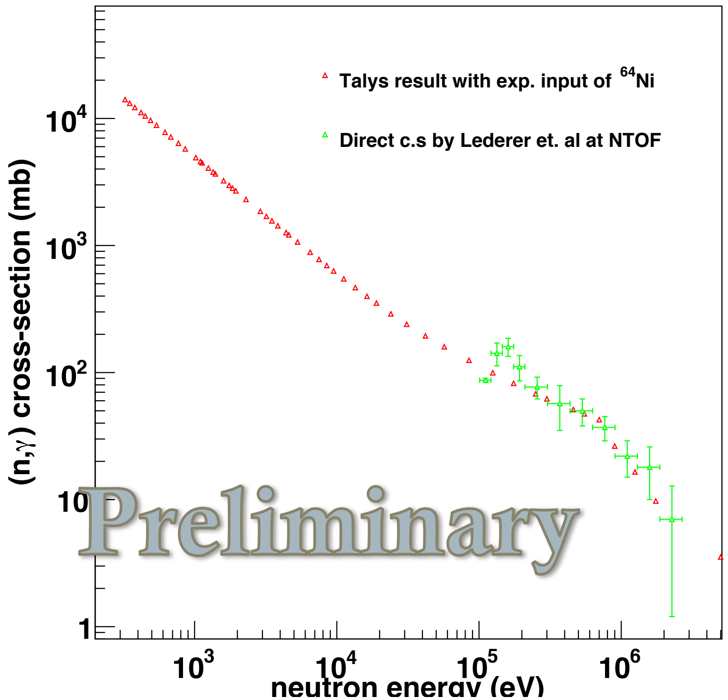
$$f^{upb} = \theta A e^{-bE_\gamma}$$

# TALYS SIMULATION

- The resulting nuclear level density and gamma strength function of 64Ni were then used as input for the program talys and used to calculate the (n,gamma) cross section on 63Ni.

- The calulated cross-section was then compared by experimental data from Lederer et. al.

- The normalization was then checked and the resonace parameters were adjust until a good agreement with the available experimental data was obtained.



# CONCLUSIONS AND OUTLOOK

- **Level density of $^{64}$Ni,** well described by the **CTM** above 5.3 MeV, good agreement with energy levels at lo Ex..
- Resonance-like structure in the gamma strength function at **9.3 MeV (68Ni at 9.5MeV)**
- Data suggest a **low-energy enhancement**. Its introduction leads to a good reproduction of the experimental (n,g) c.s on $^{63}$Ni.
- Very good reproduction of the 63Ni(n,gamma) cross-section.
- Effect of upbend on neutron-capture cross sections in different isotopes and how it evolves for neutron – rich nuclei.
- Very interesting to determine **whether the structures are of M1 or E1 character.**
- Future experiments: study of results for $^{66,67}$Ni from experiment at HIE-ISOLDE.(2016).

# Thank you for your attention!