Nuclei studied at the Oslo Cyclotron Laboratory

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3rd Workshop on Level Density and Gamma Strength

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Layout

Introduction to Oslo experiments

$\rightarrow$ extract NLD and RSF simultaneously

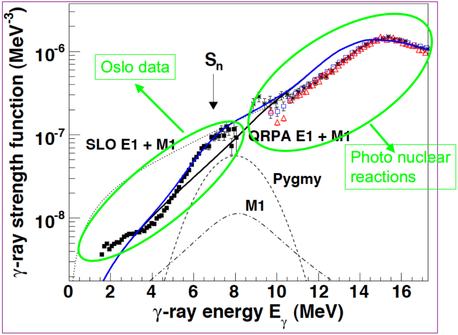
- The functional form is determined from the experimental data alone
- Slope found by normalizing to other experimental data

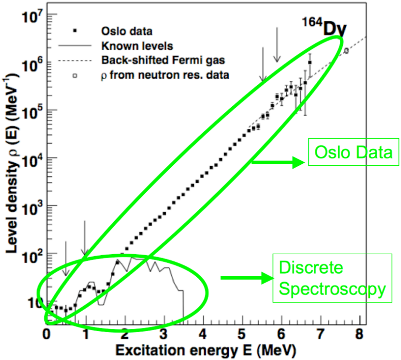
What type of nuclei has been studied?

- Magic nuclei: $^{116-119,121,122}Sn$, $^{205-208}Pb$
- Rare earth isotopes: $^{148,149}Sm$, $^{160-164}Dy$, $^{166,167}Er$, $^{170-172}Yb$
- Lighter nuclei: $^{44,45}Sc$, ^{46}Ti, $^{50,51}V$, $^{56,57}Fe$, $^{93-98}Mo$

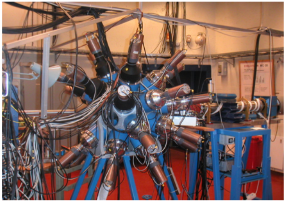
- -Scissor mode
- -Neutron skin oscillation?
- -Upbend

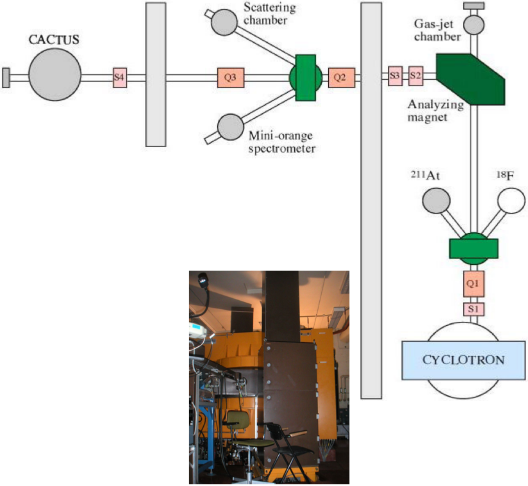
Which energy region?





Experimental setup

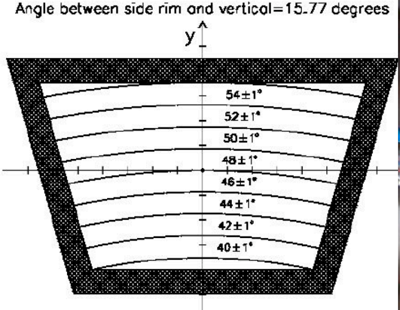


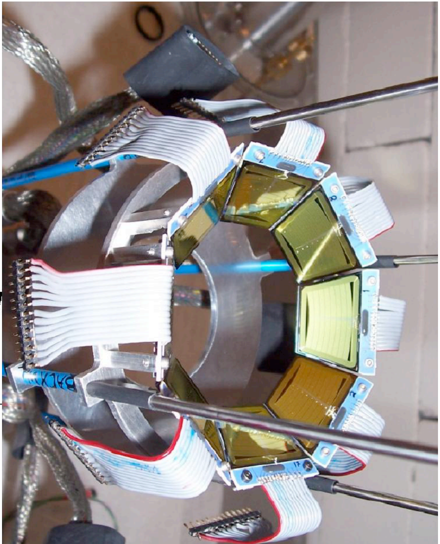


- **Beam**: p, d, ^{3}He, α.
- **Reactions**: (p,p'γ), (^{3}He,^{3}He'γ), (p,dγ), (p,tγ), (^{3}He,$\alpha\gamma$)
- **Target**: $\sim 1 - 2$ mg/cm^2 thick foil of enriched target.

Experimental setup

- **Detector array**:
  - 28 NaI(Tl) γ-detectors, 5" $\times$ 5", $\epsilon \approx 15\%$ at $E_\gamma = 1.33$ MeV.
  - 64 Si ΔE-E particle telescopes $\Delta\theta \approx 2$.

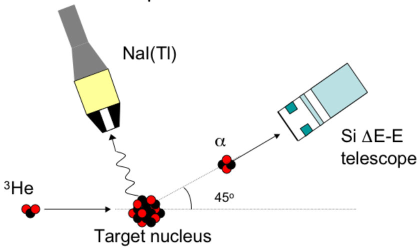


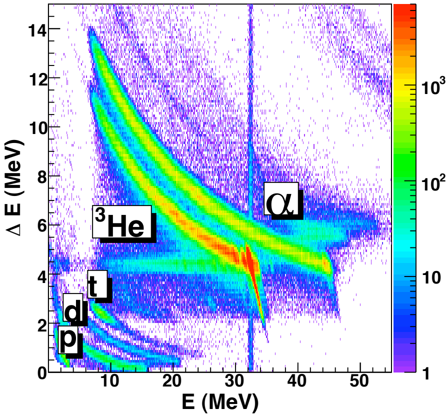


Particle identification

Inelastic scattering ^{164}Dy(^{3}He,^{3}He') ^{164}Dy
Pick-up ^{164}Dy(^{3}He,α) ^{163}Dy

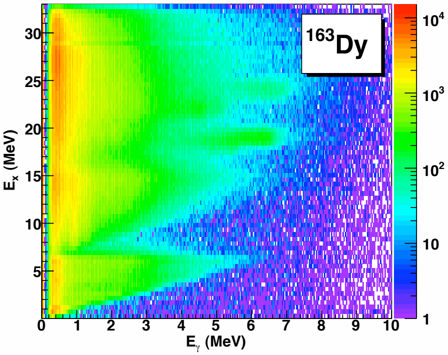
Particle-γ coincidences





Particle-γ-coincidence spectra

From the known Q-values the excitation energy of the nuclei are calculated from the detected ejectile energy by using reaction kinematics.



$\alpha - \gamma$-coincidence matrix, (^{163} Dy).

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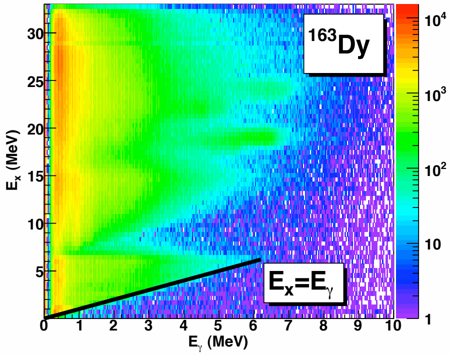

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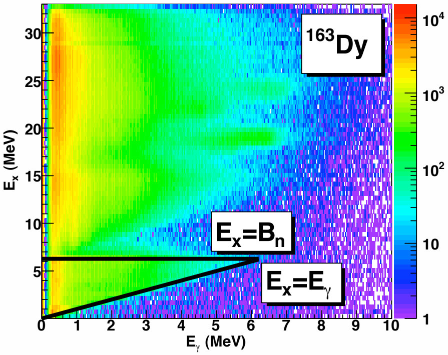

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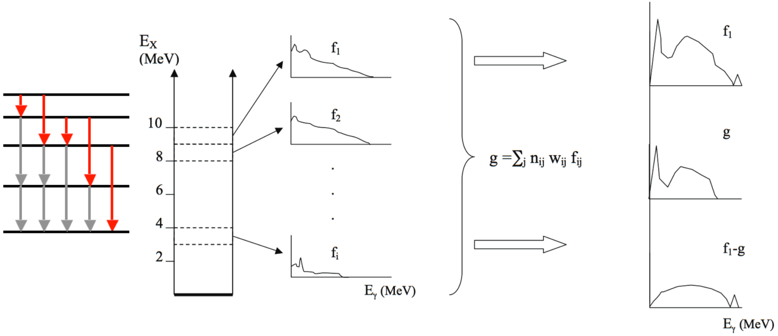
A short introduction to the Oslo method

- Unfold the γ-ray spectra.
- Isolate the first (primary) gamma ray from each γ-decay cascade.



Brink-Axel's hypothesis

Excitation modes built on excited states have the same properties as those built on the ground state.

$\rightarrow \mathcal{T}(E_\gamma)$ independent of excitation energy.

Factorization according to Fermis Golden rule

$$\mathbf{P}(\mathbf{E_i}, \mathbf{E}_\gamma) \propto \mathcal{T}(\mathbf{E}_\gamma)\rho(\mathbf{E_i} - \mathbf{E}_\gamma), \quad \text{where} \quad \mathbf{E_f} = \mathbf{E_i} - \mathbf{E}_\gamma \tag{1}$$

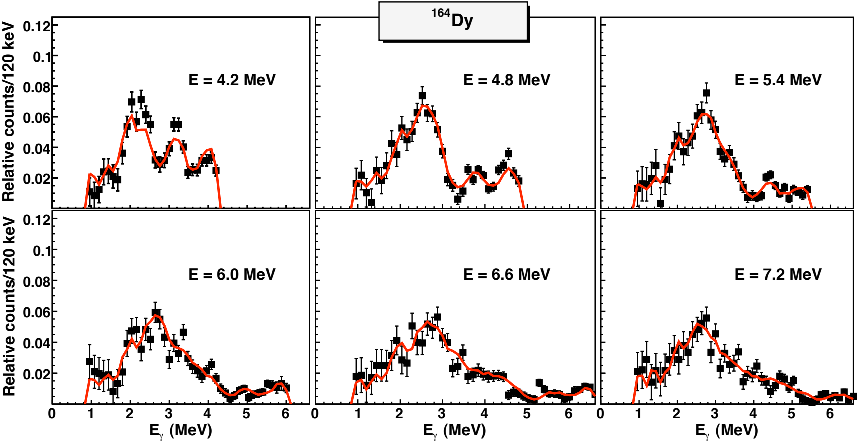
Least-squares method obtain $\rightarrow \mathcal{T}(E_\gamma)$ and $\rho(E_i - E_\gamma)$

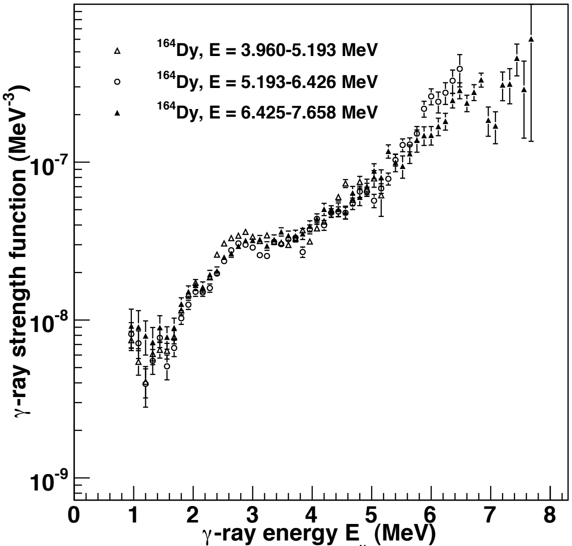
$$\widetilde{\rho}(E_i - E_\gamma) = A \exp[\alpha(E_i - E_\gamma)]\, \rho(E_i - E_\gamma) \tag{2}$$

and

$$\widetilde{\mathcal{T}}(E_\gamma) = B \exp(\alpha\, E_\gamma)\, \mathcal{T}(E_\gamma), \tag{3}$$

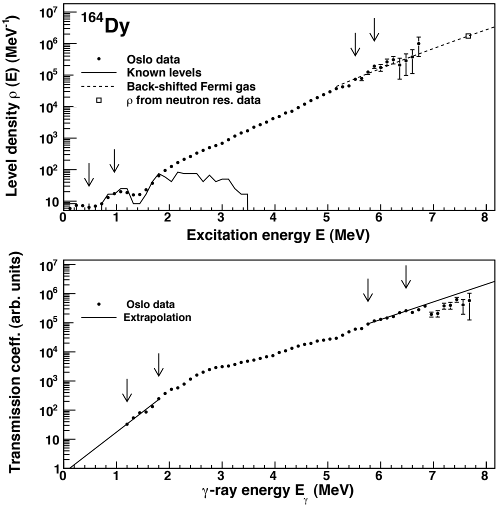
Does it work?


164Dy
E = 4.2 MeV
E = 4.8 MeV
E = 5.4 MeV
E = 6.0 MeV
E = 6.6 MeV
E = 7.2 MeV
Relative counts/120 keV
Relative counts/120 keV
0.12
0.1
0.08
0.06
0.04
0.02
0.12
0.1
0.08
0.06
0.04
0.02
0 1 2 3 4 5 6
0 1 2 3 4 5 6
0 1 2 3 4 5 6
Eγ (MeV)
Eγ (MeV)
Eγ (MeV)



- Strength function extracted for 3 sets of initial excitation energies
- Striking similarity ⇒ indicates no strong temperature dependence in the strength function

Normalizing $\mathcal{T}(E_\gamma)$ and $\rho(E_i - E_\gamma)$



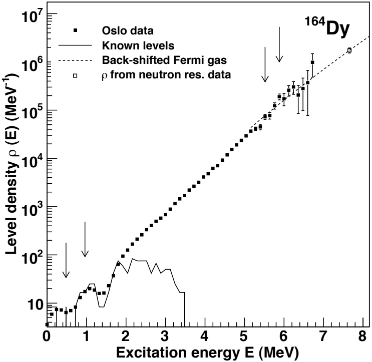
$\rho(E_i - E_\gamma)$:

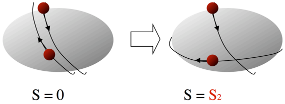
- Known levels at low energy
- Neutron resonance data → extrapolated by the BS Fermi-gas model

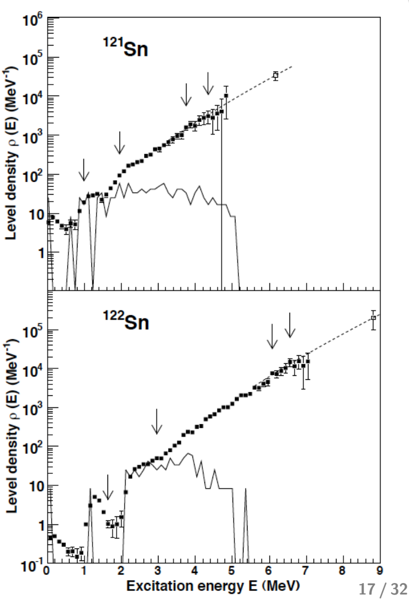
$\mathcal{T}(E_\gamma)$:

- Calculated from average total radiative width $< \Gamma_\gamma >$

H. K. Toft et. al., PRC 83, 044320 (2011)→







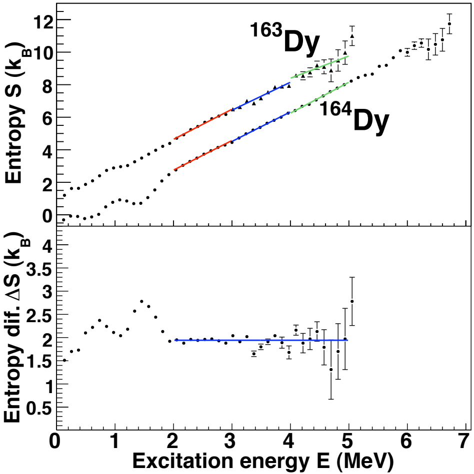
Microcanonical ensemble

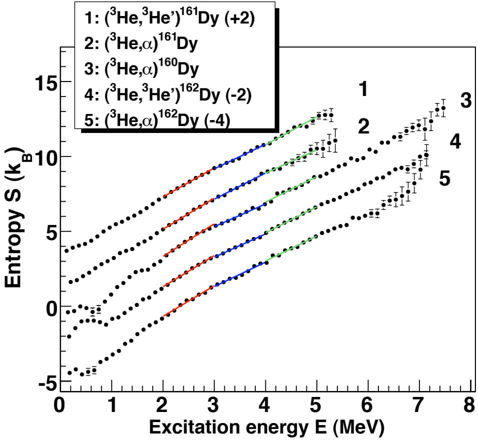
Entropy

$$S(E) = \ln \rho(E) + S_0$$

Temperature

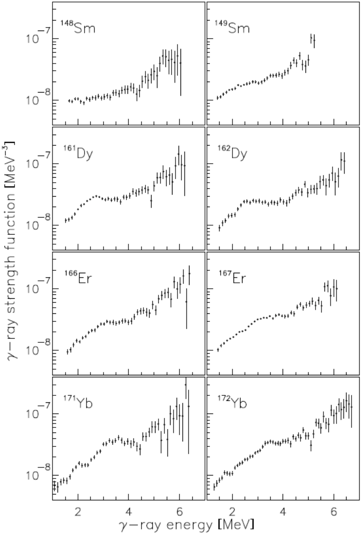
$$T = \left(\frac{\delta S}{\delta E}\right)_V^{-1}$$



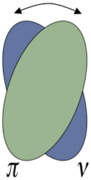


- 2-3 MeV:
  T=0.51(2) MeV
- 3-4 MeV:
  T=0.60(2) MeV
- 4-5 MeV:
  T=0.57(3) MeV

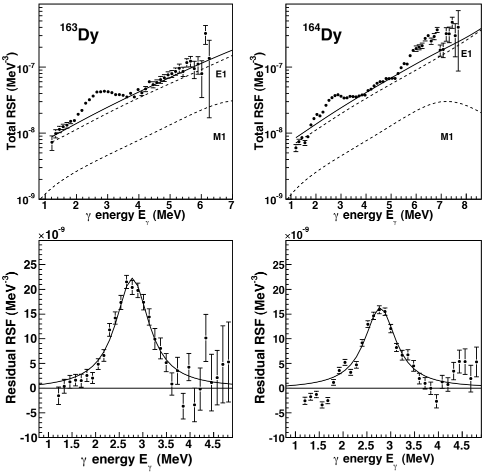
Scissor mode



- An excitation mode that can be built on every excited state.
- When it decays to the state it is built on it emits a ~ 3 MeV γ.

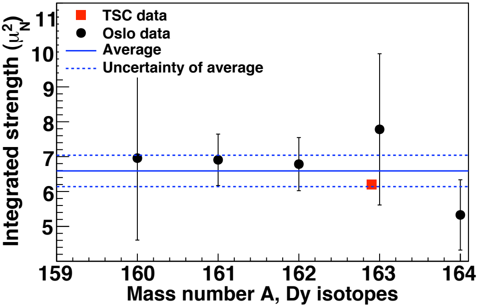


Scissor mode



- The width of the resonance seems to vary slightly for different nuclei.
- The total integrated strength is about the same. Average value of 6.6(4) μ_N^2

Scissor mode



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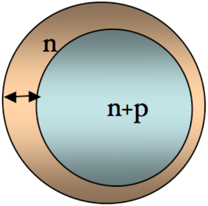
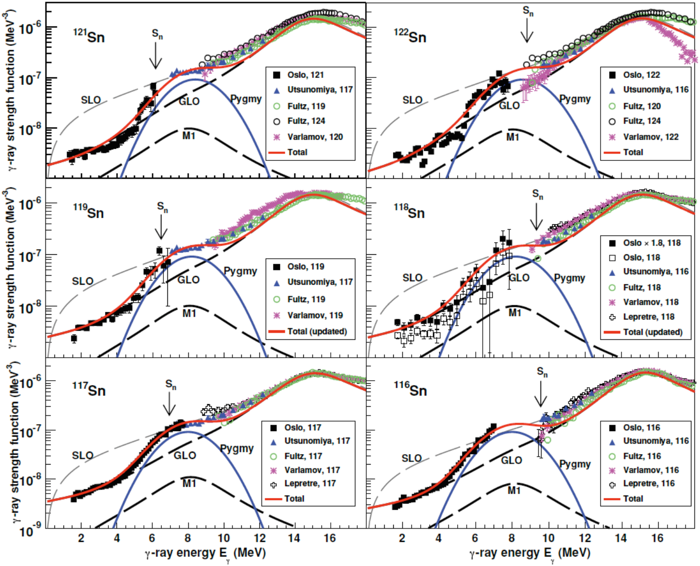
Enhanced strength in *Sn* nuclei

- Enhanced strength in the energy region $4 < E_\gamma < 11$ MeV.
- The electromagnetic character is not established, but $E1$ character established in exotic $^{129-133}Sn$ isotopes.
- Might stem enhanced GMDR or from $E1$ *neutron skin oscillation*.

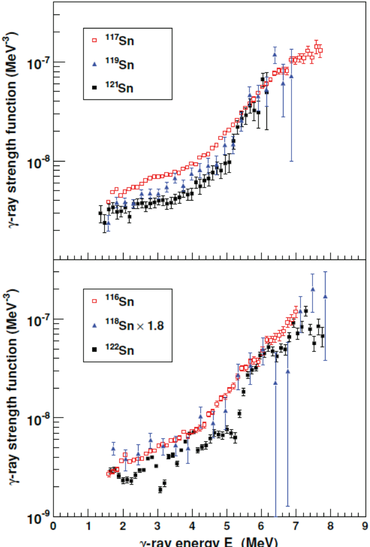




H. K. Toft et. al., PRC 83, 044320 (2011) Not clear how to model the resonances

- Red line: Total strength → GLO for GEDR, SLO for GMDR, Gausian dist. for pygmy
- SLO failes for GEDR in low γ-region

H. K. Toft et. al., PRC 83, 044320 (2011)



How do the strength function depend on N?

- Tail of resonance decreases in strength as N increas.
- Log-slope change occurs for higher E_γ in ^{121,122}Sn than for ^{116,117}Sn ($\approx$ 4.5 MeV for ^{116}Sn, $\approx$ 5.2 MeV for ^{122}Sn)
- Centroids increas with N $\rightarrow$ 8.0(1) MeV for ^{116,117}Sn 8.2(1) MeV for ^{118,119}Sn 8.4(1) MeV for ^{121}Sn 8.6(2) MeV for ^{122}Sn

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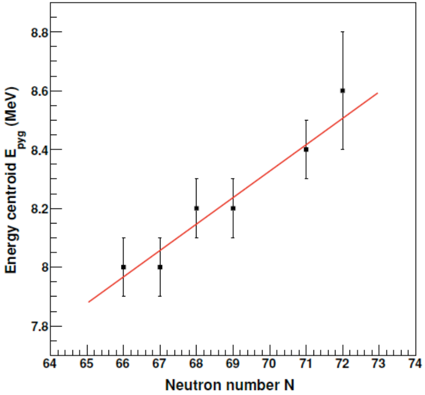
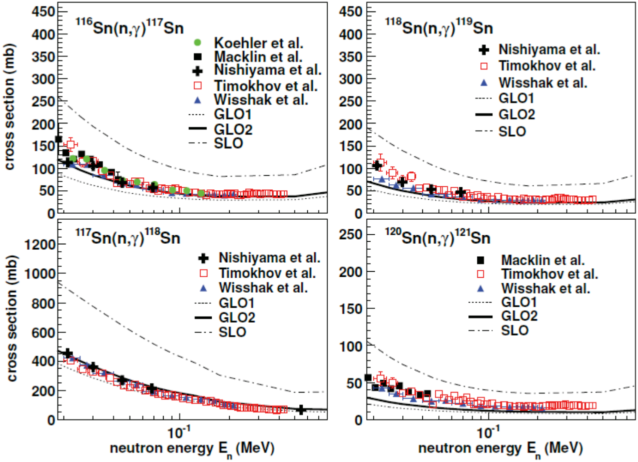


Is there a linear relation between pygmy centroid and N?

$$E_{\mathrm{pyg}} = 2.0(16) + 0.090(23)N$$

Nuclear cross sections

H. K. Toft et. al., PRC 83, 044320 (2011)



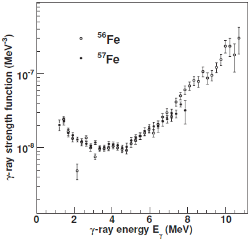
Cross sections for $^{117-119,121}$Sn calculated using the reaction code TALYS

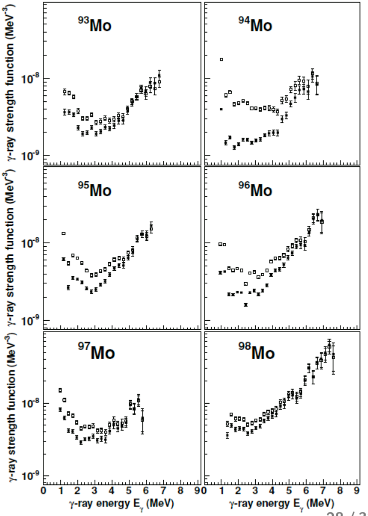
- GLO1 → without pygmy
- GLO2 → with pygmy

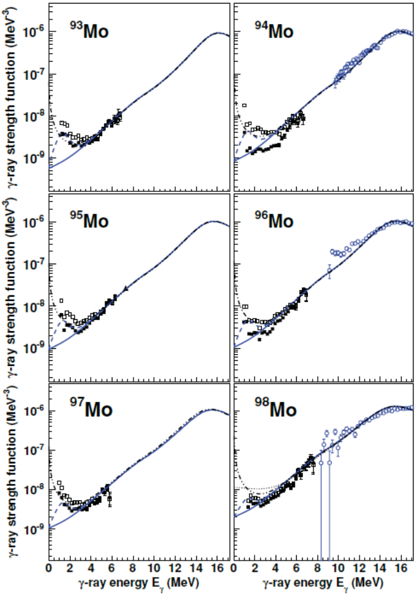
Upbend

- An unexpected strongly enhanced strength function at $E_\gamma < 3$ MeV.
- Seen in Mo isotopes ($Z = 42$), but not in Sn isotopes ($Z = 50$), $\rightarrow$ will it be present in Cd ($Z = 48$) and Pd ($Z = 46$)?

A. C. Larsen and S. Goriely, PRC 82, 014318 (2010) $\rightarrow$
E. Algin et. al., PRC 78, 054321 (2008) $\downarrow$







A. C. Larsen and S. Goriely, PRC 82, 014318 (2010)

- No proper theoretical description of the upbend structure
- 3 fits to the experimental data:
  *Blue solid line=GLO with constant temp.
  $T_f = 0.3$ MeV
  *Blue dashed line=GLO + an low lying resonance represented by a SLO
  *Dash-dotted line=Modyfied the energy dependent width of the GLO model.

Summary

- **With the Oslo method one can simultaneously extract the level density and RSF.**
- **Important quantities that give rich information about nuclear structure $\rightarrow$ resonances, splitting of Cooper pairs...**
- **Results extracted at the OCL have astrophysical consequences.**