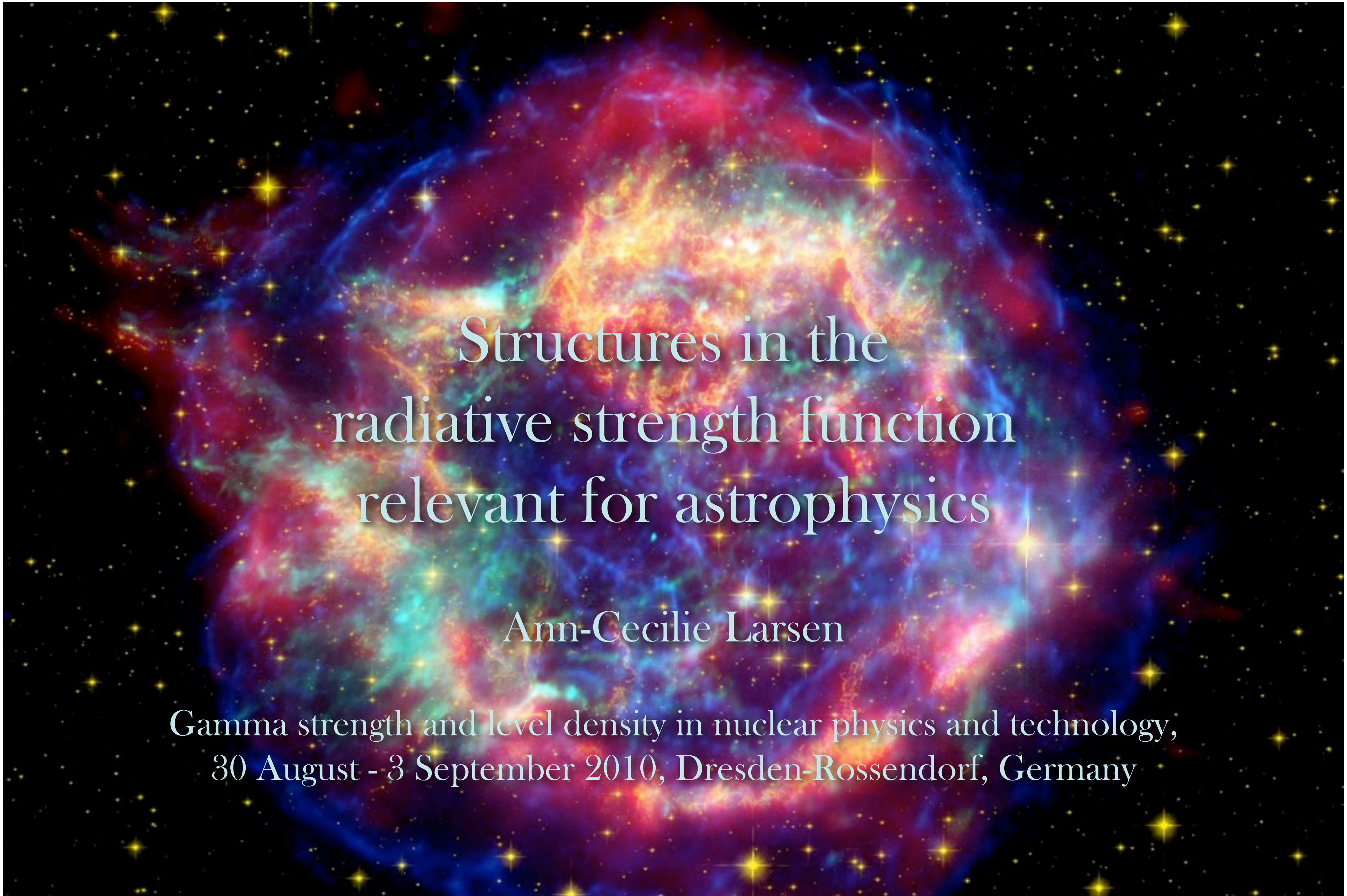


Structures in the radiative strength function relevant for astrophysics

Ann-Cecilie Larsen

Gamma strength and level density in nuclear physics and technology,
30 August - 3 September 2010, Dresden-Rossendorf, Germany

DEPARTMENT OF PHYSICS
UNIVERSITY OF OSLO

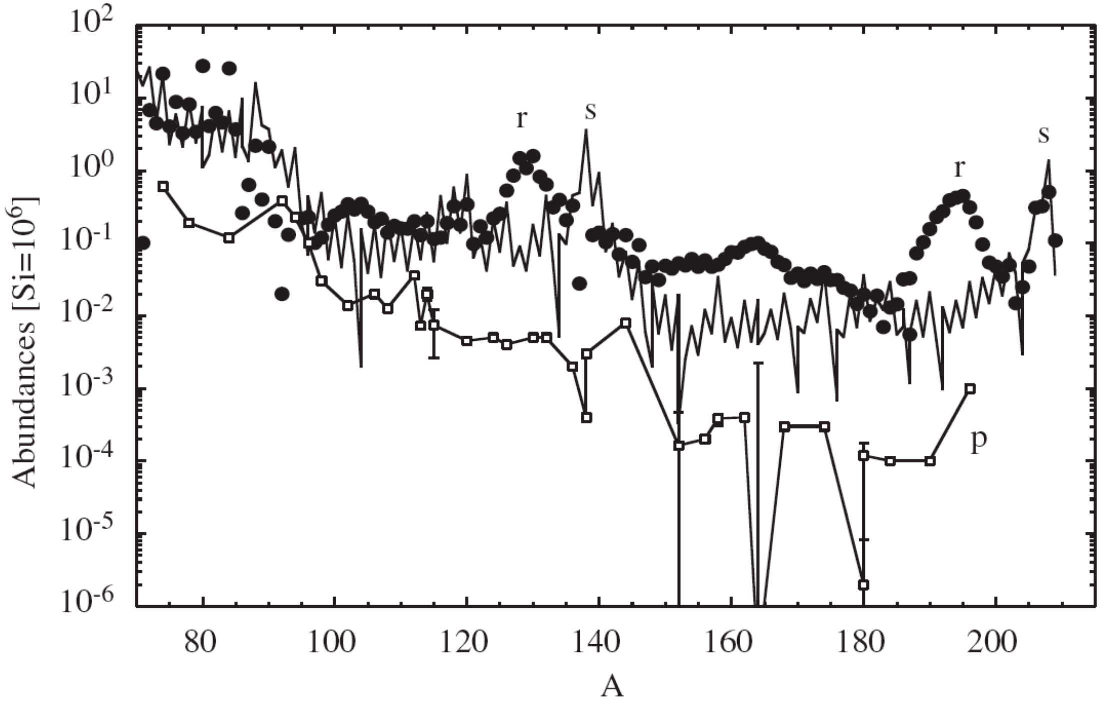
OCL
Oslo Cyclotron Laboratory

SAFE
Senter for Akseleratorbasert
Forskning og Energifysikk

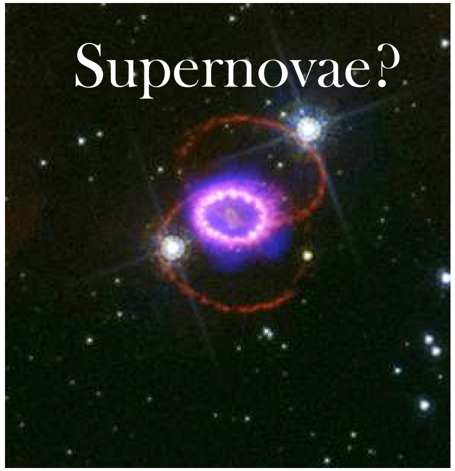
Outline

- Motivation
- Experiments @ OCL
- Tin isotopes - *E*1 pygmy dipole resonance
- Light and medium-mass nuclei - low-energy enhancement
- Summary & outlook

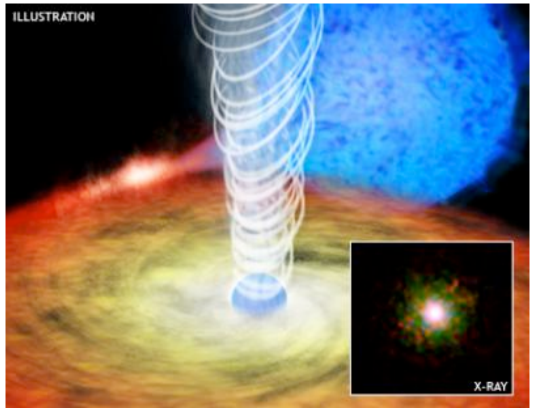
A tough nut to crack



[M. Arnould *et al.,* Phys. Rep. 450, 97 (2007)]



Neutron star mergers?



Maxwellian-averaged reaction rates

$$N_A \langle \sigma v \rangle (T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu(E) E \exp\left[-\frac{(E + E_x^\mu)}{kT}\right] dE$$

Optical model potentials

Level densities

Radiative strength functions

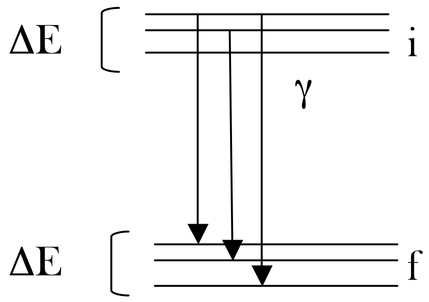
$$G(T) = \sum_\mu (2I^\mu + 1)/(2I^0 + 1) \exp(-E_x^\mu / kT)$$

N_A: Avogadro's number; m: reduced mass of initial system; E: relative energy of projectile/target; I^μ, E_x^μ: spin/excitation energy of excited states μ; σ^μ: reaction cross section.

In large network calculations:
≈ 2000 nuclei, ≈20 000 cross sections

Radiative (γ-ray, photon) strength functions

- A measure on the average, nuclear electromagnetic response determined by the nuclear structure and the available degrees of freedom
- Directly related to partial decay widths and reduced transition probabilities
- Fruitful concept in the quasi-continuum/continuum region
- For dipole radiation: $f(E_\gamma) = \tau(E_\gamma)/(2\pi E_\gamma^3)$



... but how well do we know this quantity?

Hard facts

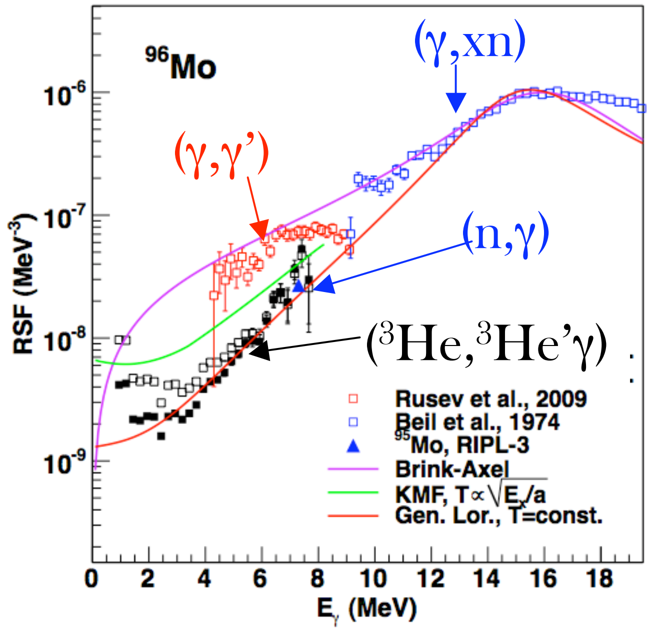
Experiments:

- Above S_n: (γ,n), (γ,p), (γ,xn), (γ,2n), …
- Below S_n: (γ,γ'), (e,e'), (n,γ), (n,2γ), (α,α'γ), (p,p'γ), (^{3}He,αγ), …

… but discrepancies between the measurements do occur

Theories/models:

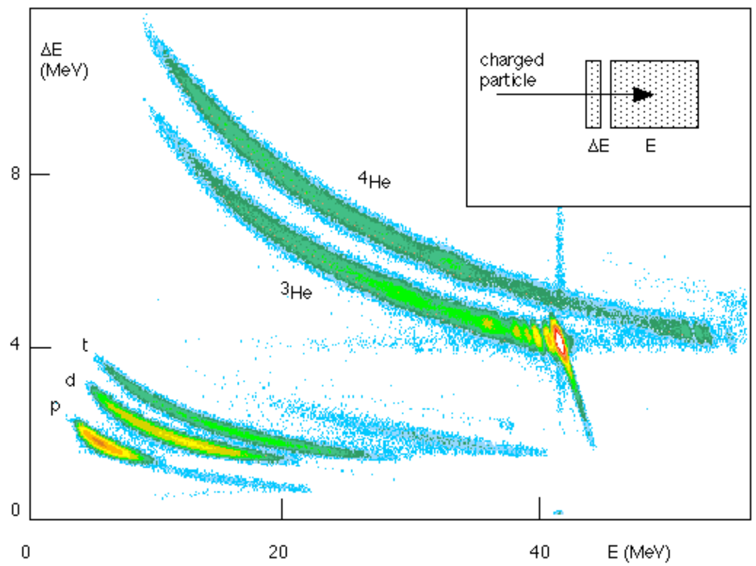
- Brink-Axel (Standard Lorentzian)
- Kadmenskij, Markushev and Furman
- Generalized Lorentzian
- Modified Lorentzian
- Random-phase approximation
- Quasi-particle phonon model
- …

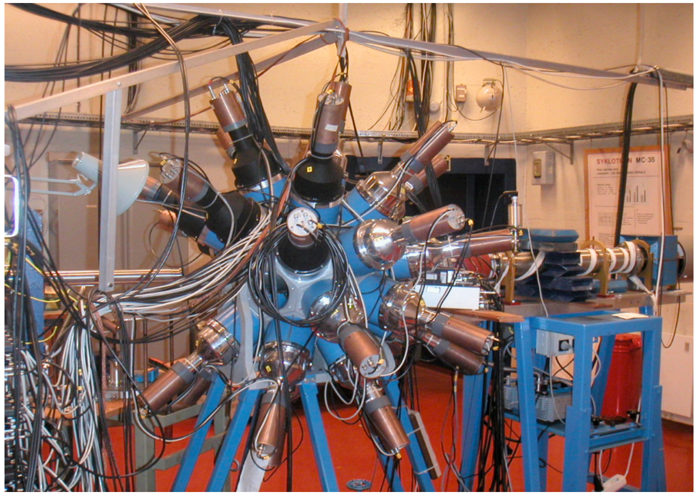


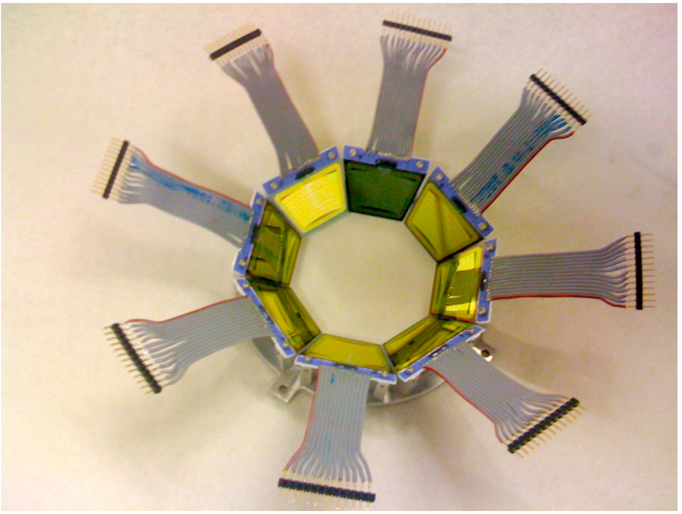
… but no universal description for all mass regions and phenomena

Experiments @ OCL

- Beams: p, d, ^{3}He, α
- Reactions: (p,p'γ), (^{3}He,^{3}He'γ), (p,dγ), (p,tγ), (^{3}He,αγ)
- CACTUS: 28 5" x 5" NaI(Tl), ε≈15% @ E_γ=1.33 MeV
- SiRi (new): 64 Si ΔE-E particle telescopes, Δθ≈2°

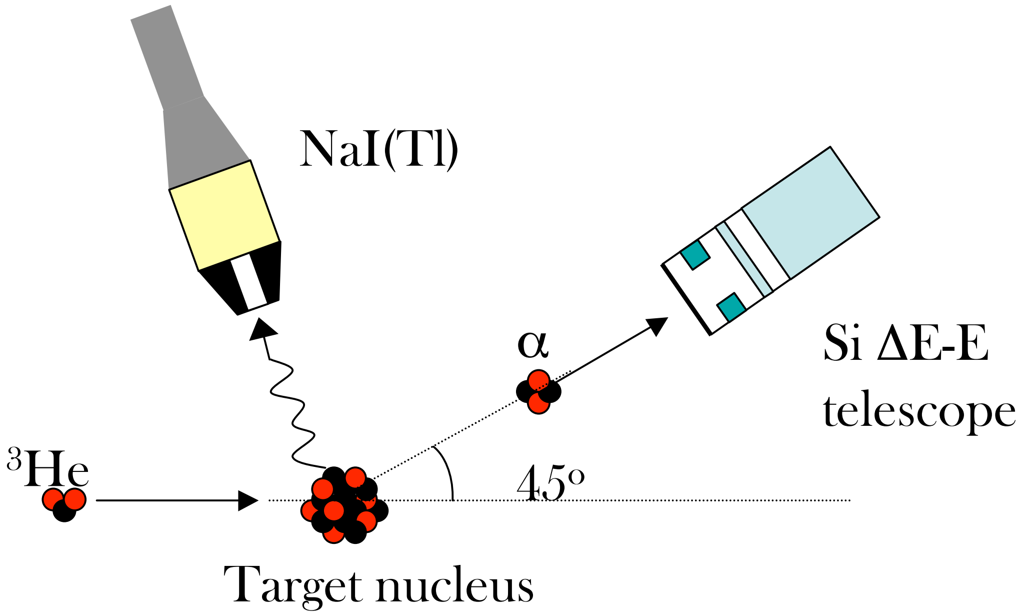


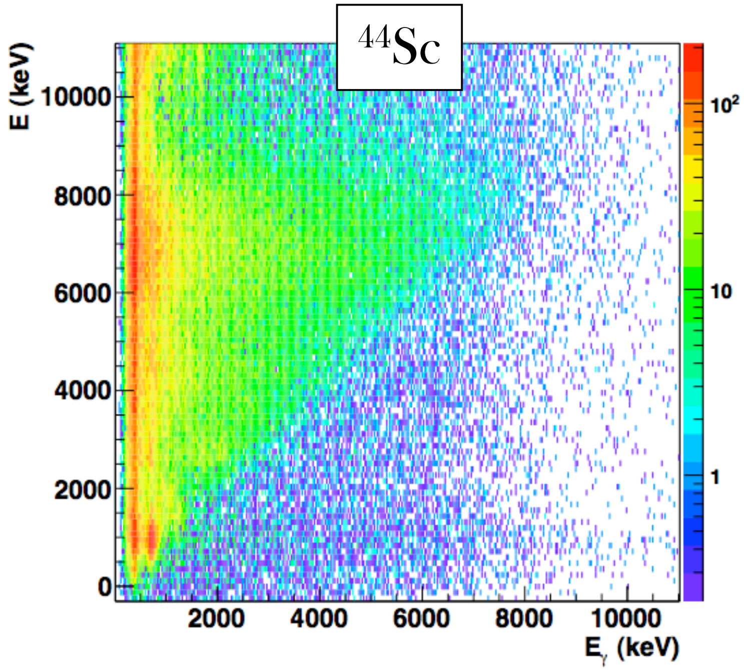




Experimental technique

- Particle-γ coincidences → E_x-tagged γ-ray spectra

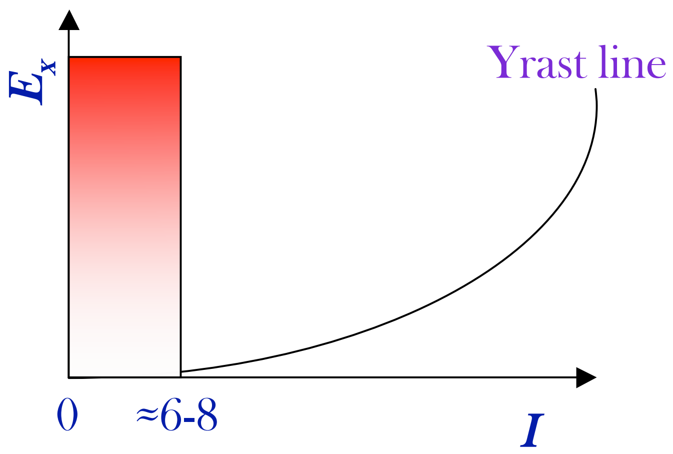


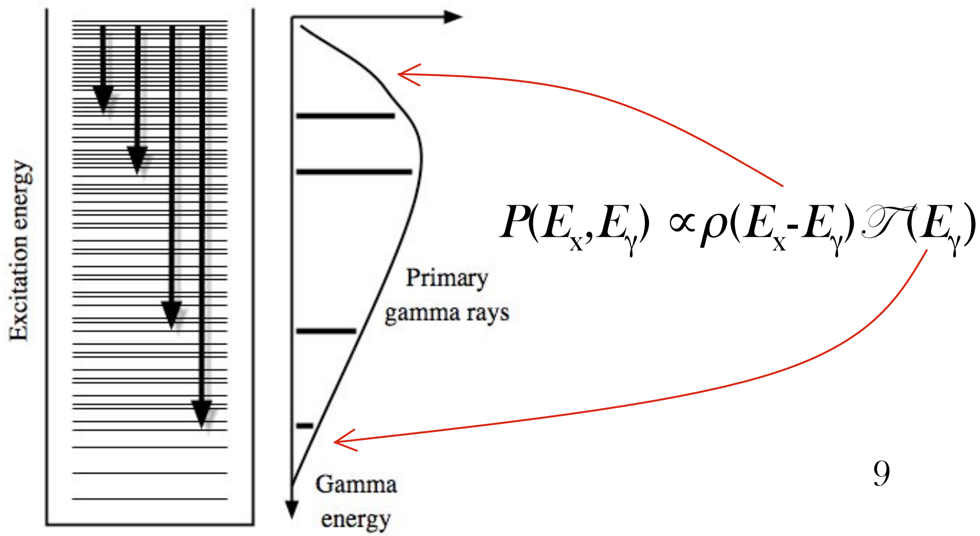


S_n=9700 keV
S_p=6696.3 keV

The Oslo method in a 

- Deconvolution (unfolding) of γ-ray spectra
  [M. Guttormsen *et al.*, NIM A **374**, 371 (1996)]
- Separate primary (first-generation) γ rays
  [M. Guttormsen *et al.*, NIM A **255**, 518 (1987)]
- Extract level density and γ-ray strength function from the primary γ-ray spectra
  [A. Schiller *et al.*, NIM A **447**, 498 (2000)]





$$P(E_x,E_\gamma) \propto \rho(E_x-E_\gamma)\mathcal{T}(E_\gamma)$$

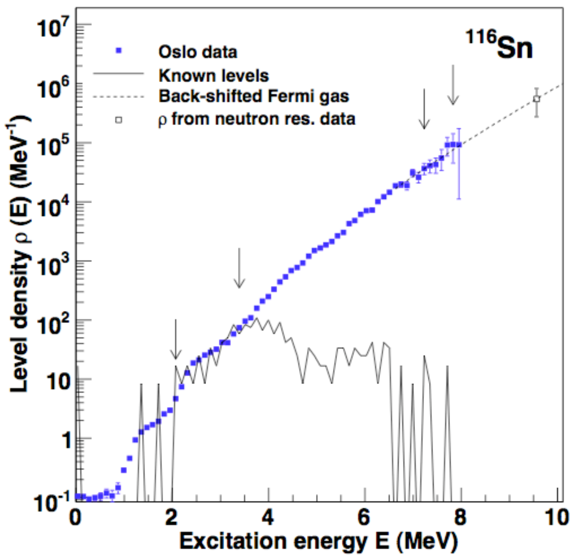
Normalization

$$\rho(E_x\text{-}E_\gamma) = A\rho'(E_x\text{-}E_\gamma)\ \exp[\alpha(E_x\text{-}E_\gamma)]$$

$$\mathcal{T}(E_\gamma) = B\,\mathcal{T}'(E_\gamma)\ \exp[\alpha(E_\gamma)]$$

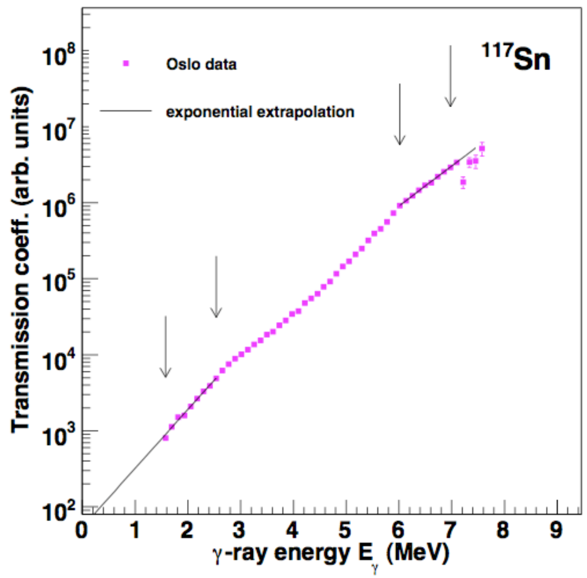
[A. Schiller *et al.*, NIM A **447**, 498 (2000)]

A, α: discrete levels + *D*

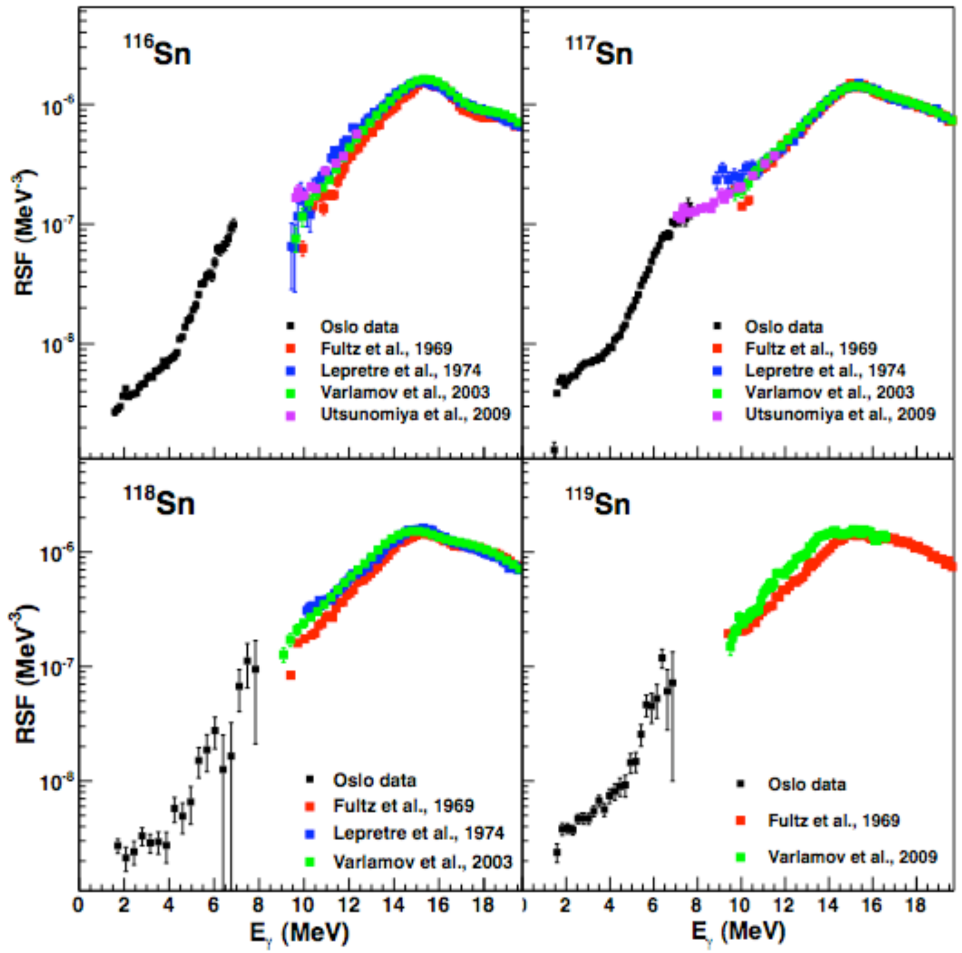


Assuming $g(E_x, I)$ and $\rho_+ = \rho_-$

B: average, total rad. width $\langle\Gamma_\gamma\rangle$

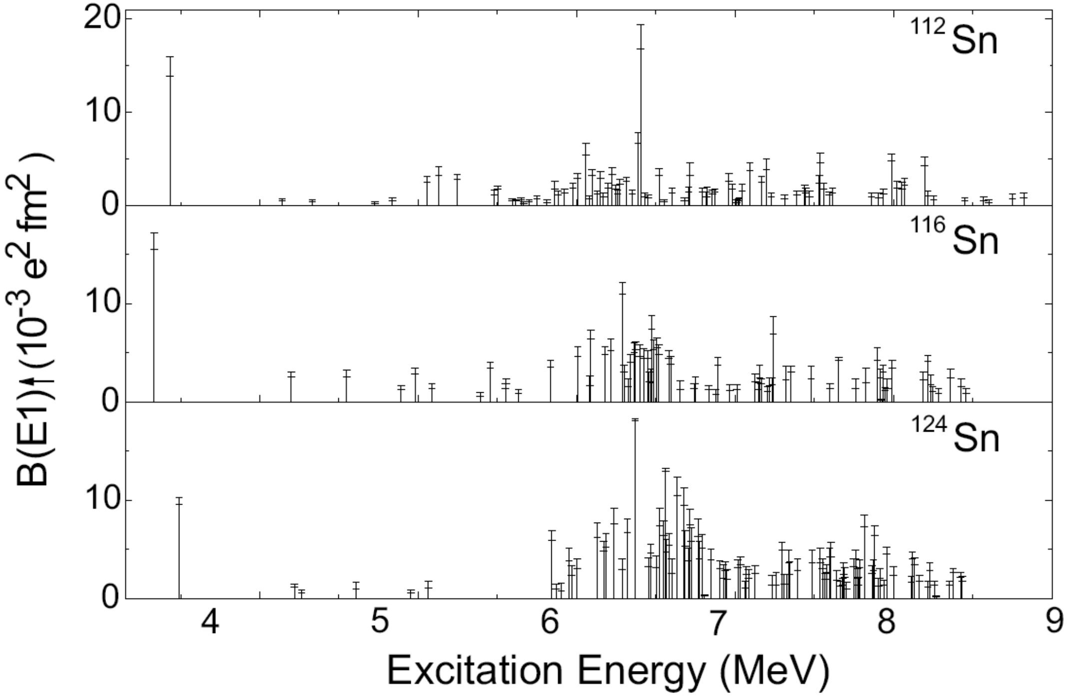


Experimental results - tin isotopes



[U. Agvaanluvsan *et al.,* PRL **102**, 162504 (2009) and H. K. Toft *et al.,* PRC **81**, 064311 (2010)]

*E*1 pygmy resonance in Sn (I)



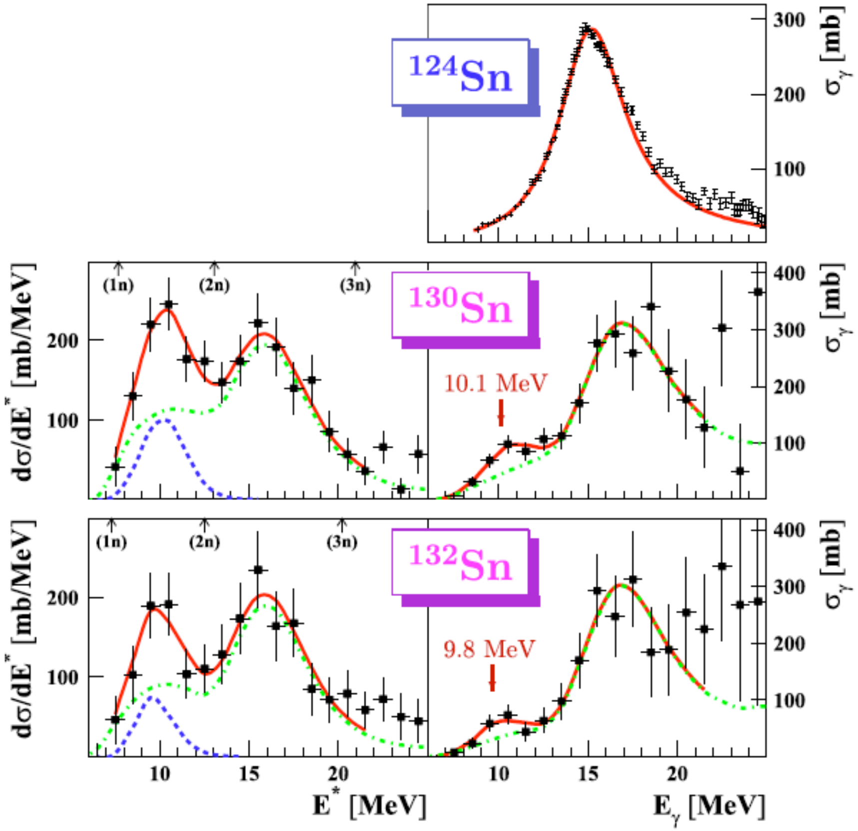
(γ,γ')

[^{112}Sn: Özel *et al.,* NPA 788, 385c (2007)

^{116,124}Sn: Govaert *et al.,* PRC **57**, 2229 (1998)]

≈0.4 - 0.6% of TRK sum rule

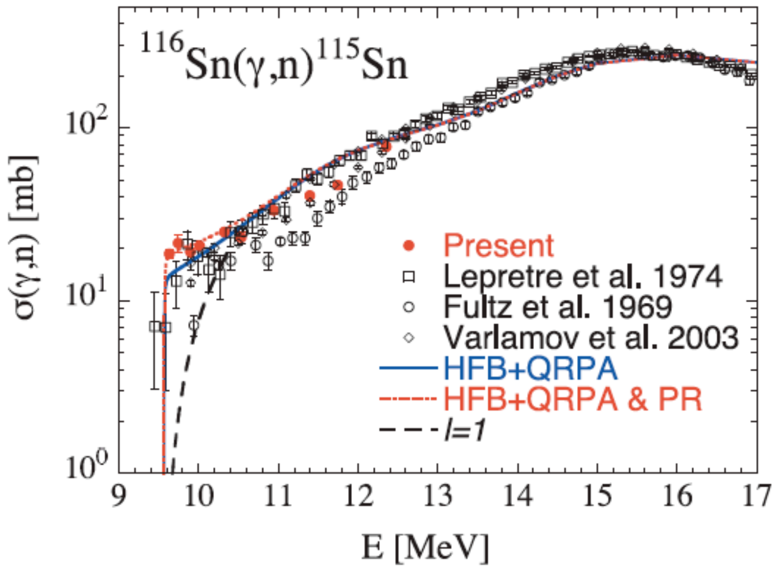
*E*1 pygmy resonance in Sn (II)

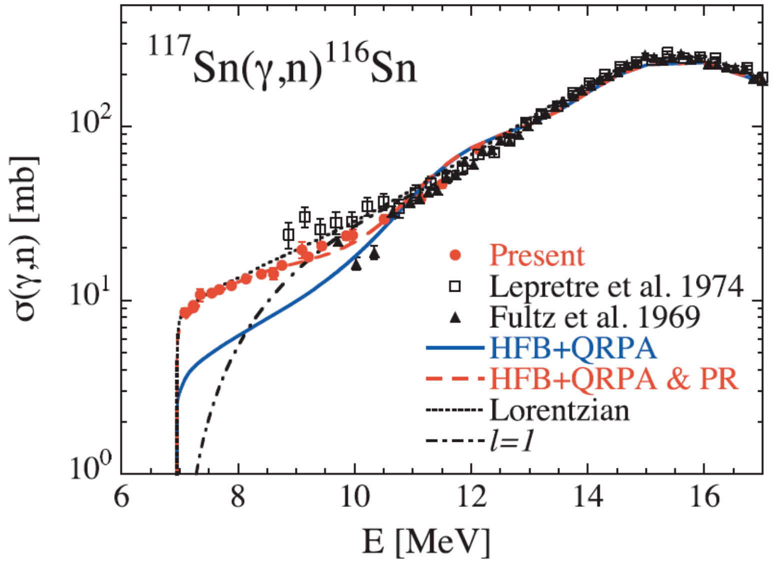


Coulomb dissociation [Adrich *et al.,* PRL **95**, 132501(2005)]

≈4 - 7% of TRK sum rule

*E*1 pygmy resonance in Sn (III)



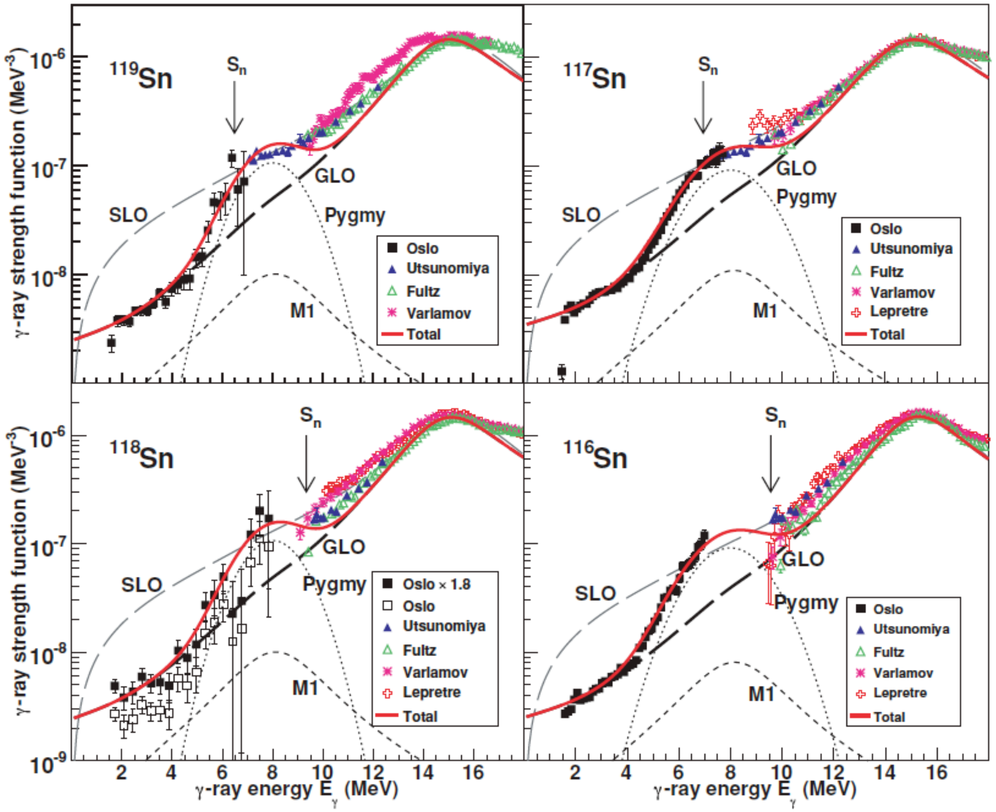


(γ,n) [Utsunomiya *et al.*, PRC 80, 055806 (2009)]

≈1% of TRK sum rule

E1 pygmy resonance in Sn (IV)

E.m. character
(and multipolarity)
not determined



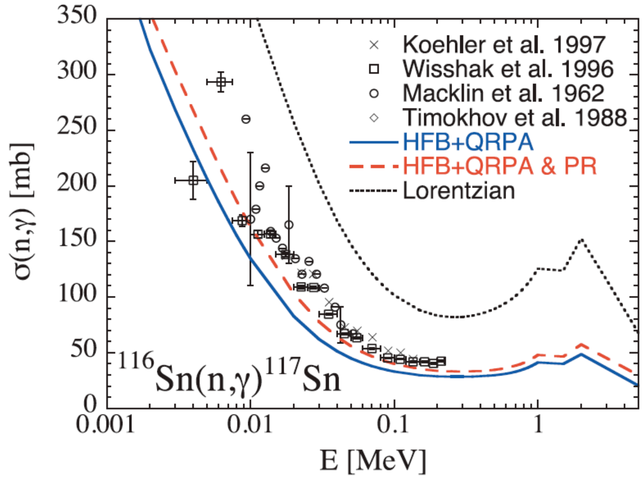
(^{3}He,^{3}He'γ) and (^{3}He,αγ)

[Agvaanluvsan *et al.*, PRL **102**, 162504 (2009); Toft *et al.*, PRC **81**, 064311 (2010)]

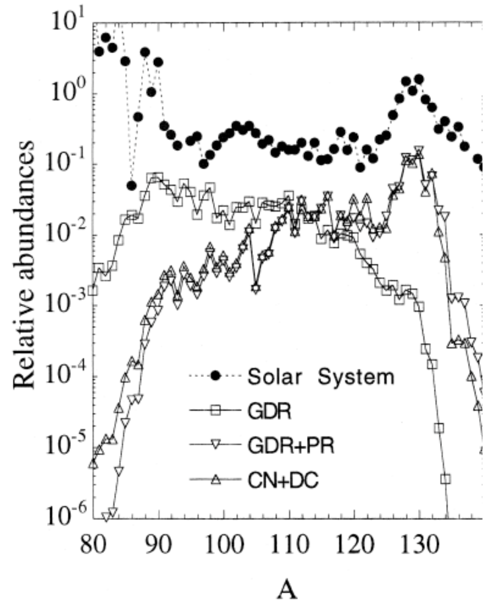
≈ 2% of TRK sum rule (assuming E1)

Effects of the pygmy resonance

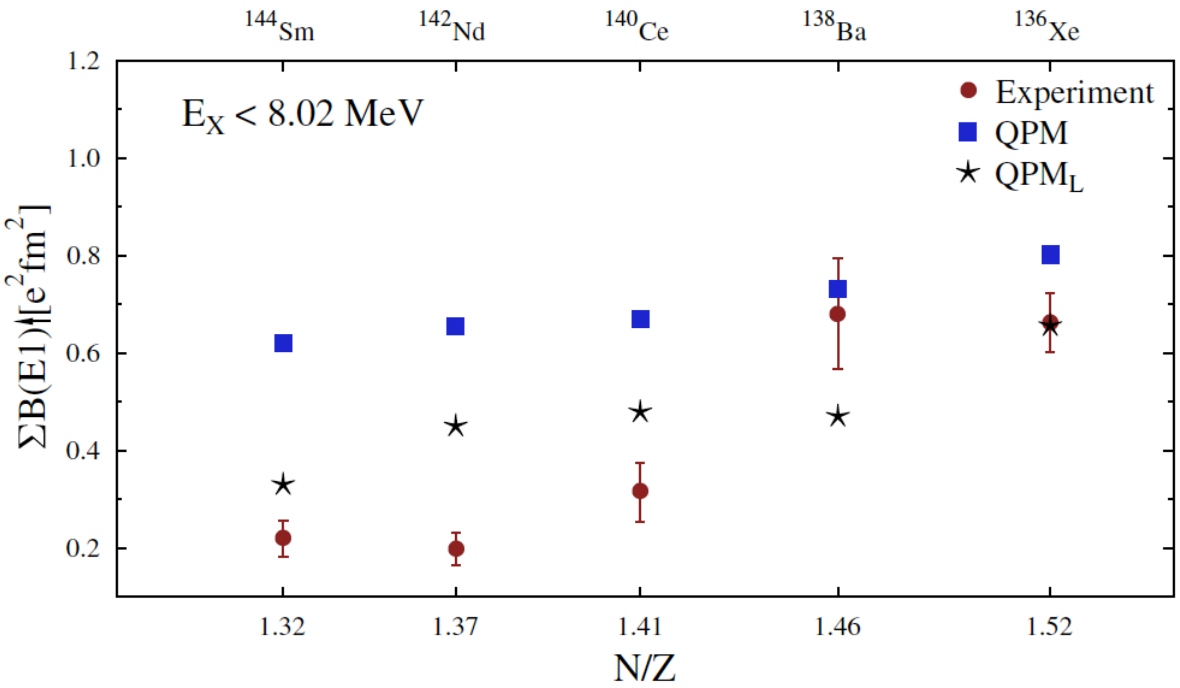
Neutron-capture cross section
[Utsunomiya *et al.*,
PRC 80, 055806 (2009)]



Very simplistic
r-abundance distributions,
$T = 10^9$ K, $N_n = 10^{20}$ /cm^3
(no (n,γ)-(γ,n) equilibrium)
[Goriely, PLB 436, 10 (1998)]



Dependence on neutron number?

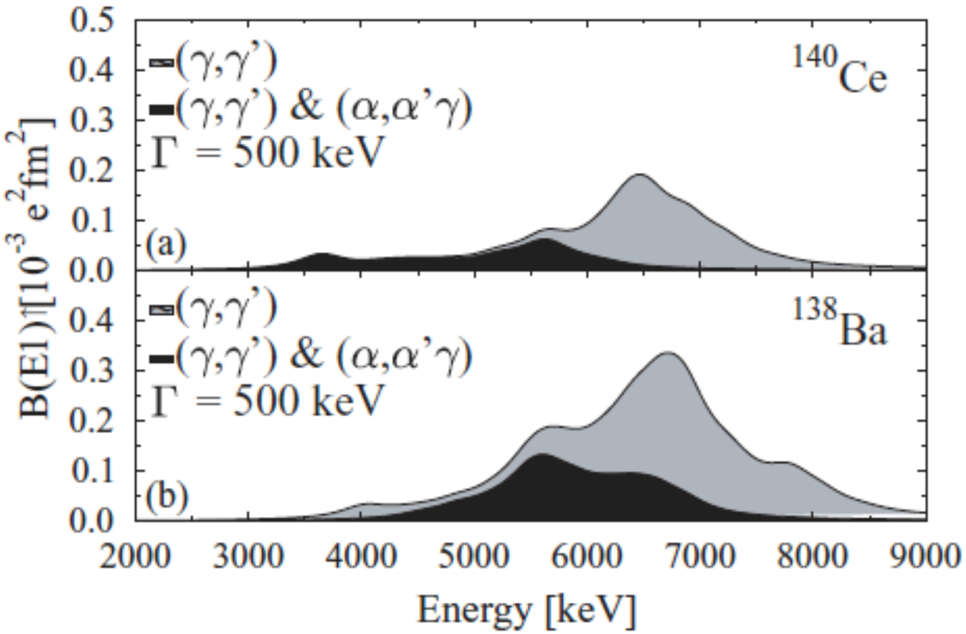


QPM: full quasi-particle phonon model calculation

QPM_L: including only states above the experimental sensitivity limit

[Savran *et al.*, PRL 100, 232501 (2008)]

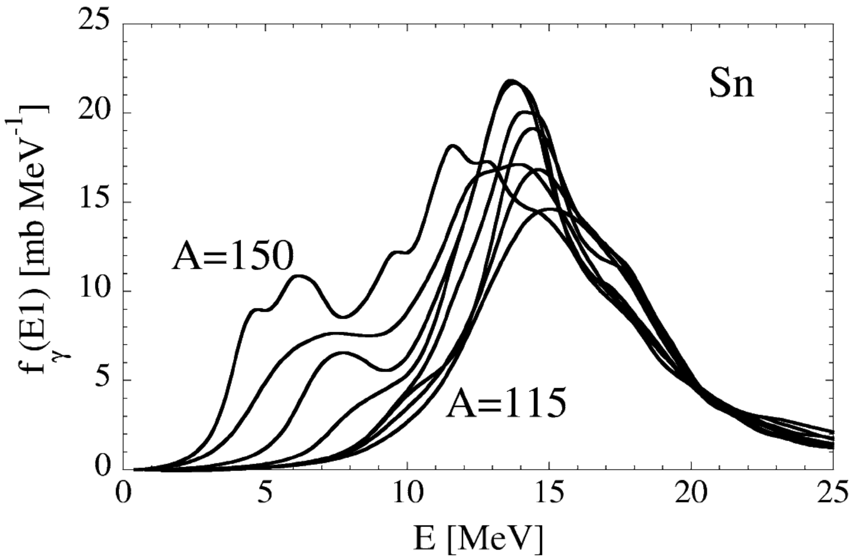
Isoscalar/isovector components?



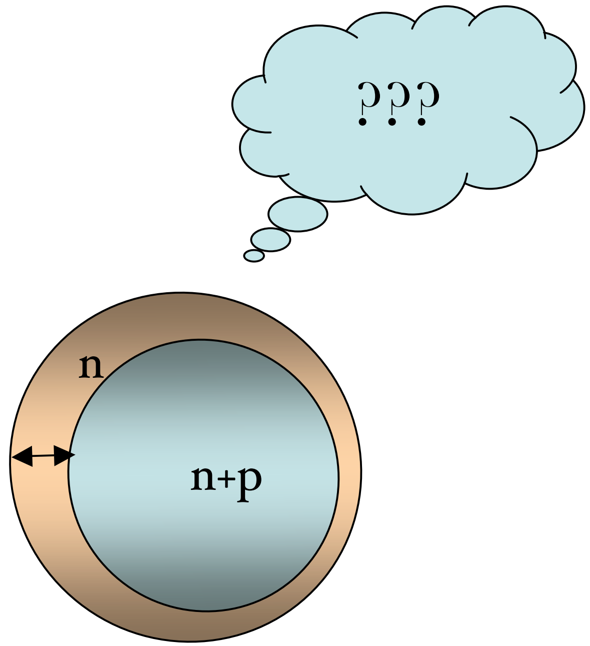
[Endres *et al.,* PRC 80, 034302 (2009)]

Collective or single-particle?

- Neutron skin?



[Goriely & Khan, NPA 706, 217 (2002)]

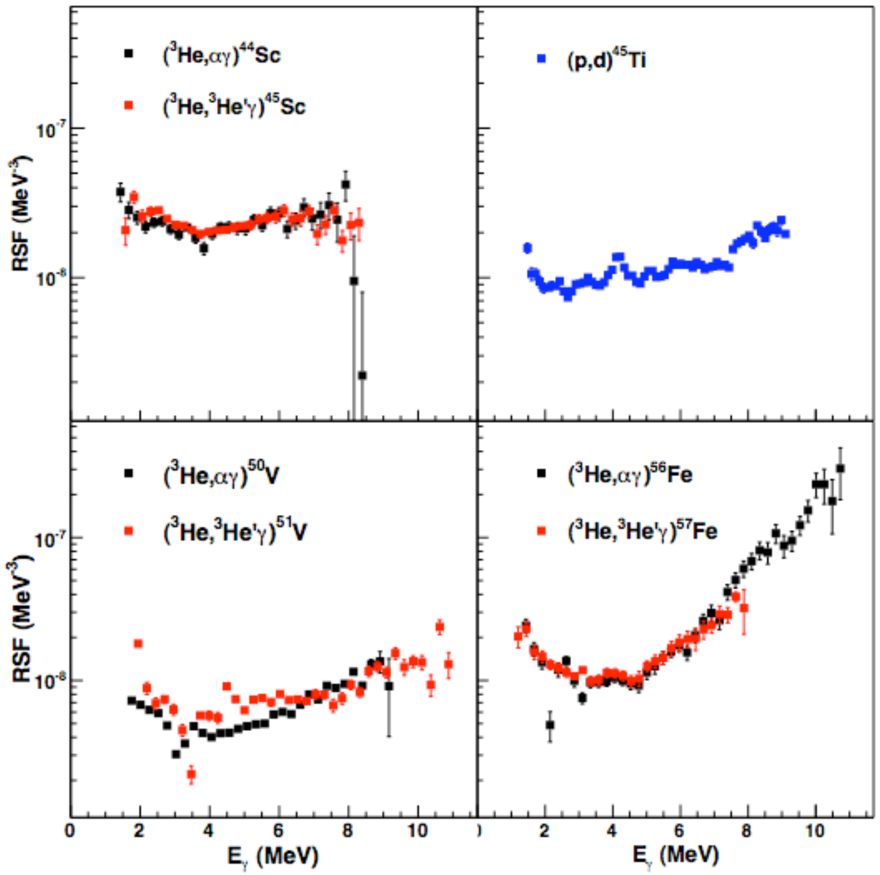


See [Paar *et al.,* Rep. Prog. Phys. 70, 691 (2007)]

Light and medium-mass nuclei

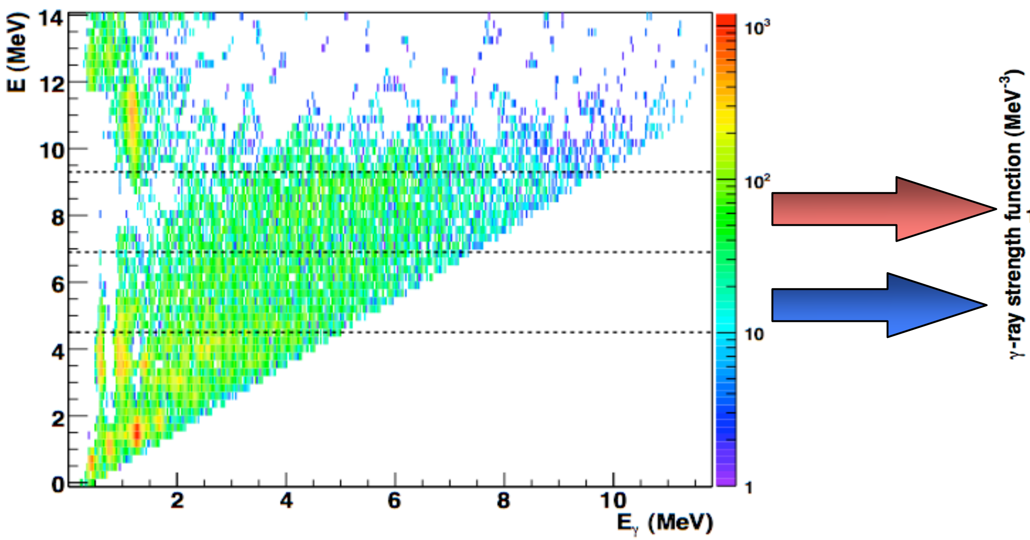
- Increase in the γ-ray strength function at low γ-ray energies

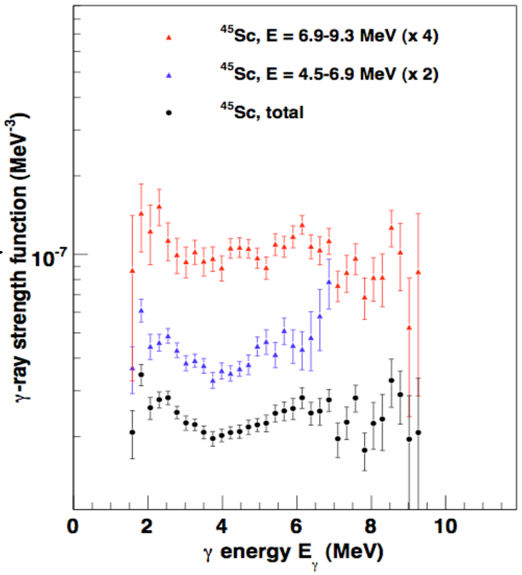
^{56,57}Fe [Voinov *et al.,* PRL 93, 142504 (2004); renormalized: Algin *et al.*, PRC 78, 054321 (2008)]
$^{93\text{-}98}$Mo [Guttormsen *et al.,* PRC 71, 044307 (2005)]
^{50,51}V [Larsen *et al.,* PRC 73, 064301 (2006)]
^{44,45}Sc [Larsen *et al.,* PRC 76, 044303 (2007)]
Maybe in ^{45}Ti [Syed *et al.,* PRC 80, 044309 (2009)]



... but *not* seen for nuclei with $A \geq 116$ (^{116}Sn)

Does the upbend depend on excitation energy?





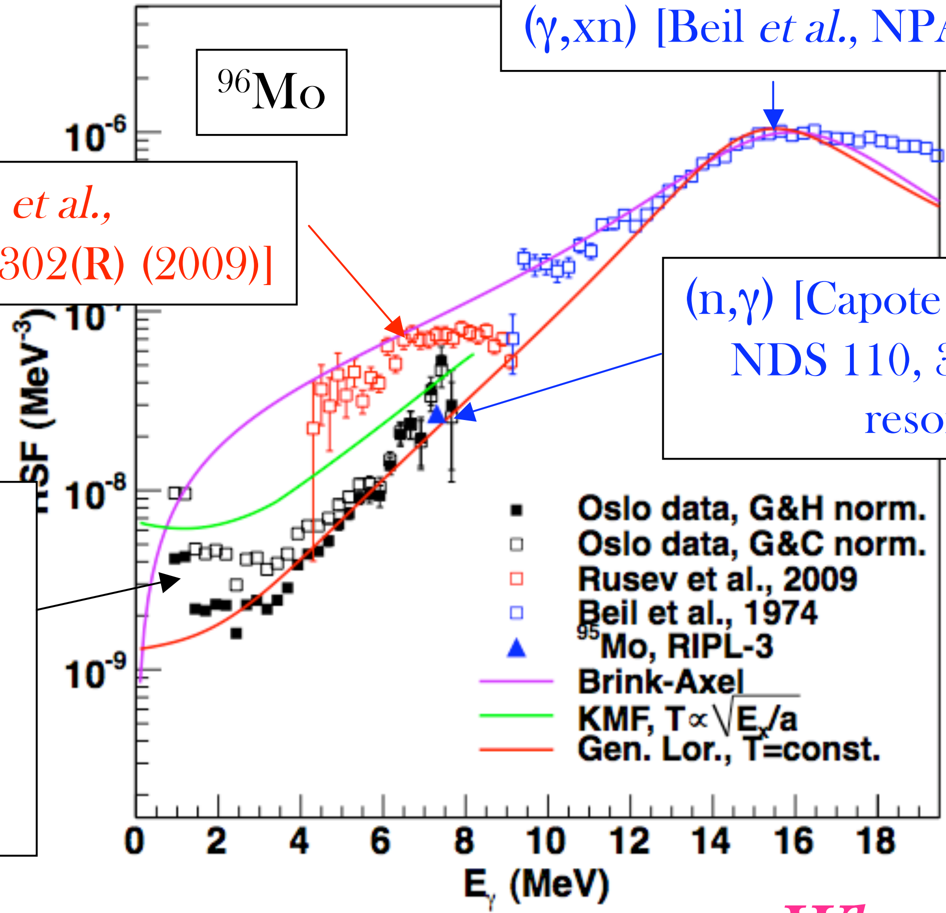
... So far, no evidence for any (strong) E_x dependence

Other experiments (low-energy γ's)

- ^{56}Fe(n,2γ)^{57}Fe: Voinov *et al.,* PRL 93, 142504 (2004) → upbend structure seems to be present. Assignment of e.m. character not possible
- ^{95}Mo(n,2γ)^{96}Mo: Krticka *et al.*, PRC 77, 054319 (2008) → no sign of the upbend
- ^{95}Mo(n,γ)^{96}Mo: Sheets *et al.,* PRC 79, 024301 (2009) → a weak upbend cannot be ruled out
- ^{59}Co(p,2γ)^{60}Ni: Voinov *et al.,* PRC 81, 024319 (2010) → a rather strong upbend of $M1$ character is seen - but is probably due to secondary transitions below $E_x \approx 4$ MeV (only positive-parity states)

... The challenge is to measure the low-energy transitions
in the quasi-continuum

Experimental discrepancies, Mo



(γ,xn) [Beil *et al.*, NPA227, 427 (1974)]

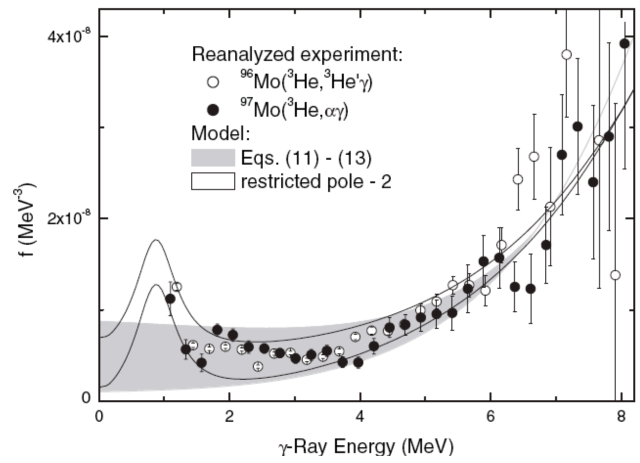
(γ,γ') [Rusev *et al.*, PRC 79, 061302(R) (2009)]

(n,γ) [Capote *et al.*, RIPL-3 compilation, NDS 110, 3107 (2009); coordinator resonances: Ignatyuk]

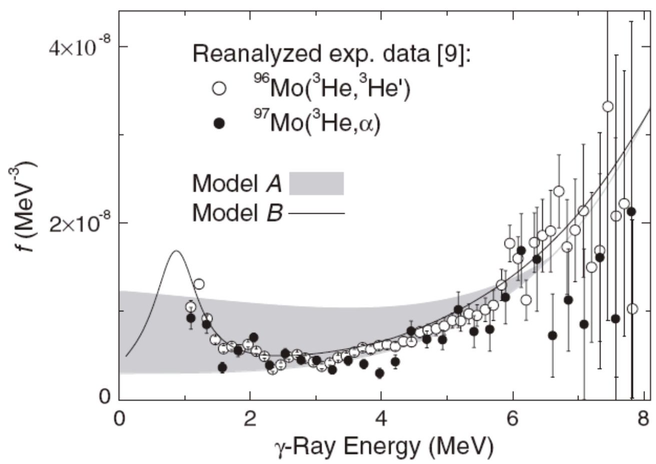
(^{3}He,^{3}He'γ) [Guttormsen *et al.*, PRC 71, 044307 (2005); Larsen & Goriely, PRC 82, 014318 (2010)]

Why so different?

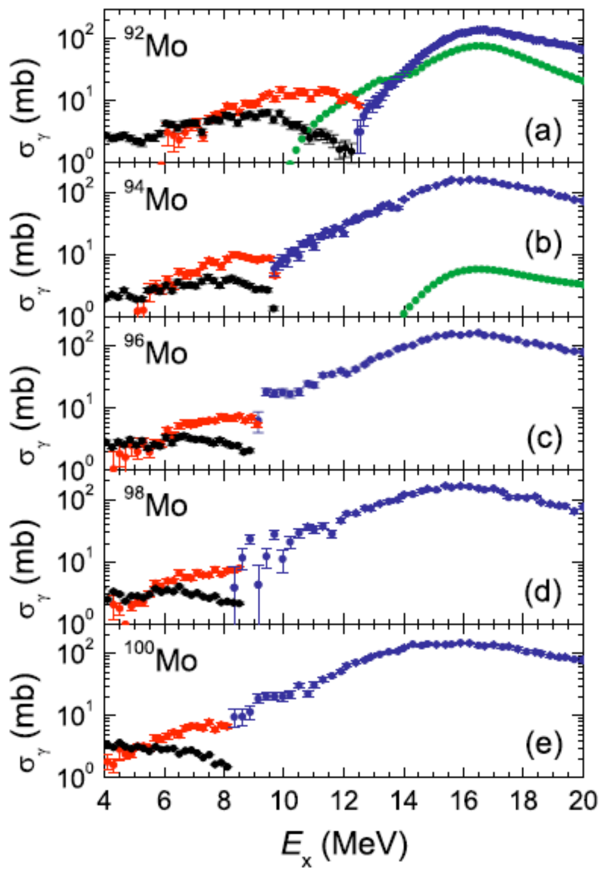
Shape of the RSF, Mo



(n,2γ) [Krticka *et al.,* PRC 77, 054319 (2008)]



(n,γ) [Sheets *et al.,* PRC 79, 024301 (2009)]

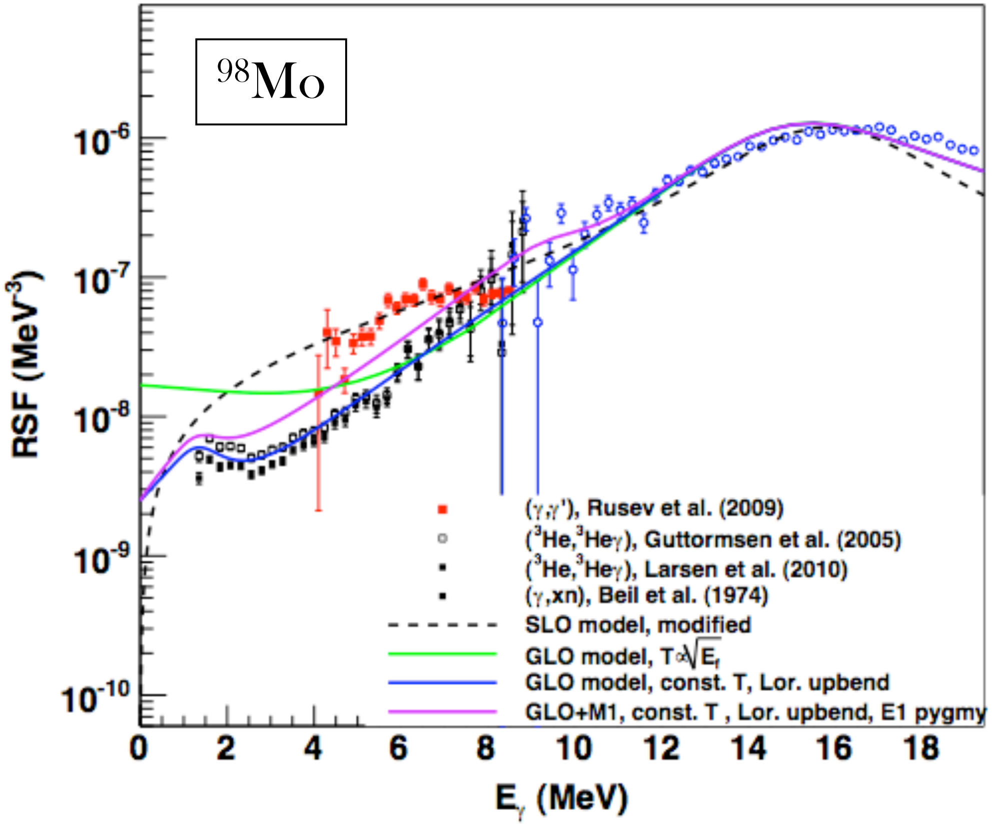


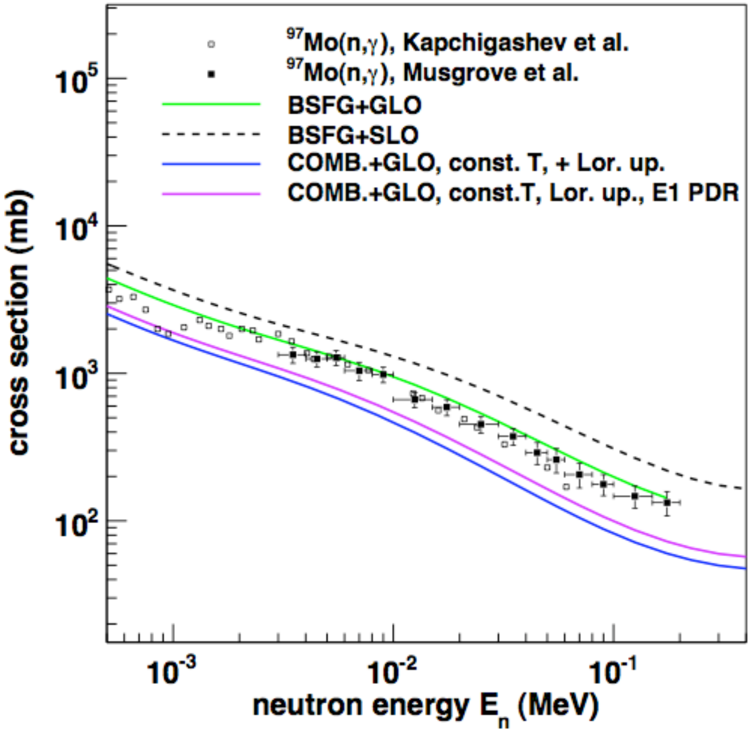
(γ,γ') [Rusev *et al.,*
PRC 79, 061302(R) (2009)]

PRELIMINARY!!!

And even more…

Calculations with the TALYS code
[A. Koning *et al.*] http://www.talys.eu/



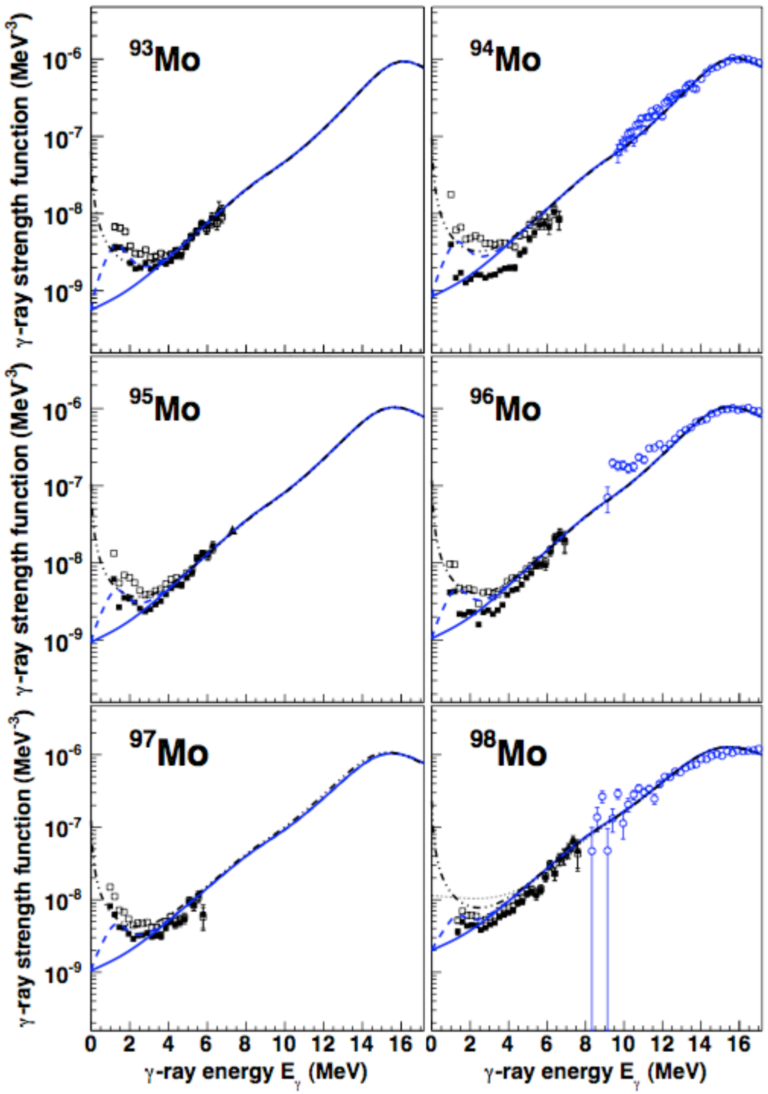


Best agreement with (n,γ): green; best agreement with $\langle\Gamma_\gamma\rangle$: blue

Modeling the upbend

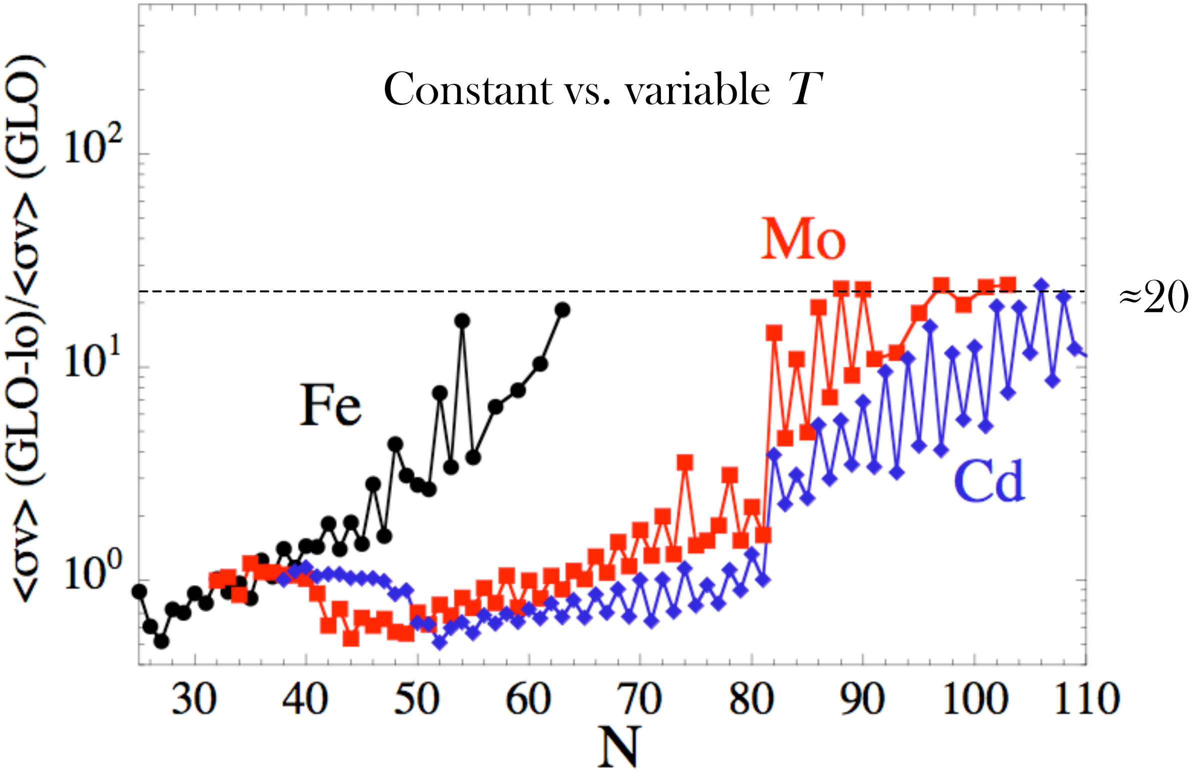
Modified *T*-dependent width
in the GLO model,
or added small Lorentzian resonance.
Note: keeping *T* const. in accordance
with the Brink hypothesis

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



Impact on n-capture rates? (I)

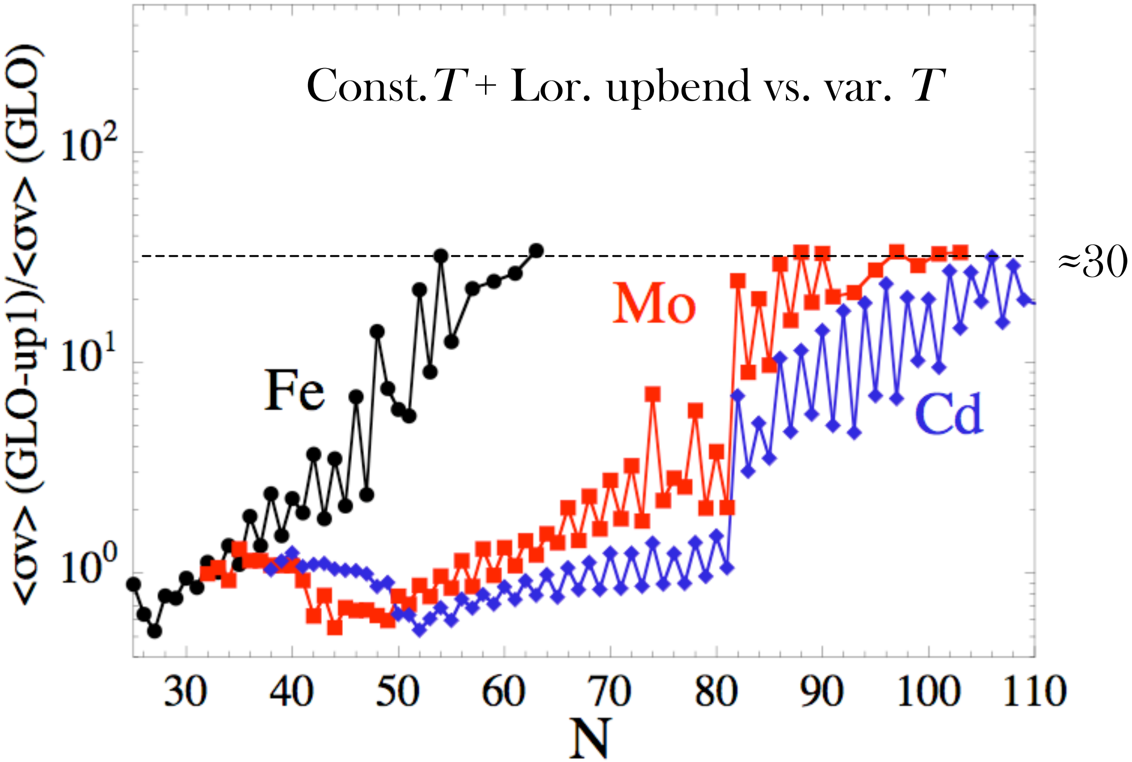
Calculations with the TALYS code
[A. Koning *et al.*] http://www.talys.eu/



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

Impact on n-capture rates? (II)

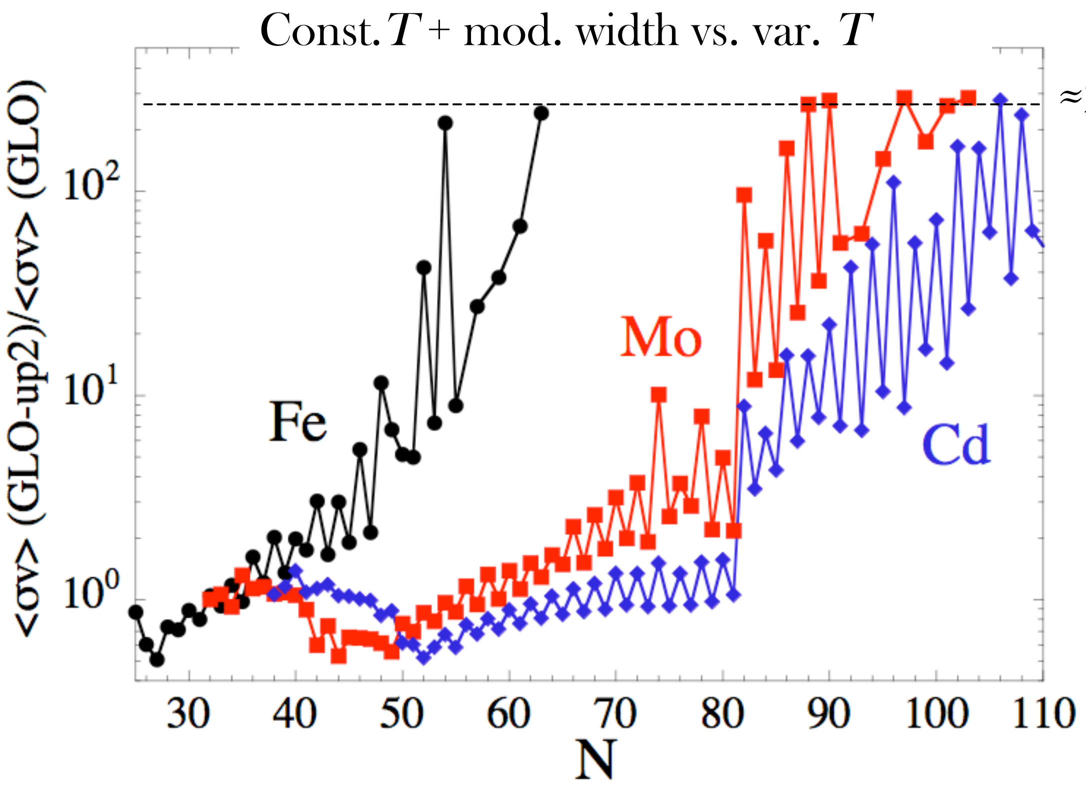
Calculations with the TALYS code
[A. Koning *et al.*] http://www.talys.eu/



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

Impact on n-capture rates? (III)

Calculations with the TALYS code
[A. Koning *et al.*] http://www.talys.eu/



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

Summary & outlook

- The radiative strength function is a very important quantity, but still rather poorly known below S_n
- The Oslo method enables extraction of the functional form of the RSF
- *E*1 pygmy in Sn isotopes – possibly due to neutron skin oscillations
- Upbend structure in some light & medium-mass nuclei – potentially large impact on n-capture rates
- Ongoing analysis on ^{44,46}Ti, ^{59,60}Ni, $^{90\text{-}92}$Zr, ^{105,106,111,112}Cd, and ^{121,122}Sn
- Replacement of the NaI's with BrilLanCe ($LaBr_3$)?

Many open questions in a vast and intriguing field!

You are all very welcome to the

3rd Workshop on Level Density and Gamma Strength, Oslo, May 23 – 27, 2011

Many thanks to the collaborators!

- The Oslo group: A. Bürger, A. Görgen, M. Guttormsen (the big boss), T. W. Hagen, P. Mansouri, H. T. Nyhus, T. Renstrøm, S. J. Rose, I.-E. Ruud, S. Siem, N. U. H. Syed, H. K. Toft, G. M. Tveten, and K. Wikan
- Stephane Goriely, Université Libre de Bruxelles
- Andreas Schiller and Alexander Voinov, Ohio University
- Lee Bernstein, Livermore National Lab
- Undraa Agvaanluvsan, Stanford University/MonAme Scientific Research Center
- Gary Mitchell, North Carolina State University/Triangle Universities Nuclear Laboratory
- Emel Algin, Eskisehir Osmangazi University
- Tom Lönnroth, Åbo Akademi

... and many thanks to you for your patience and attention!