Do we understand radiative strength functions?

Of validity of the Brink hypothesis at the low-energy tail of GDER from experimental data

Milan Krtička

CHARLES UNIVERSITY PRAGUE

faculty of mathematics and physics

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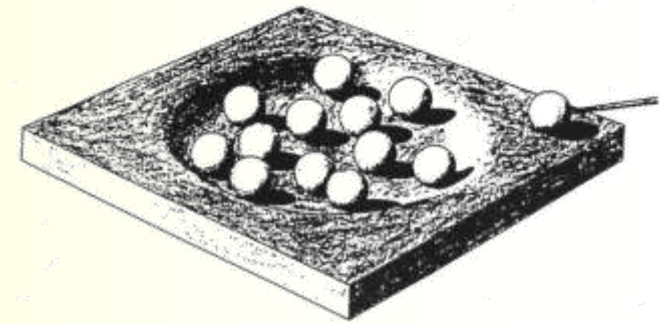
Introduction

Bohr's wooden toy model
of the compound nucleus



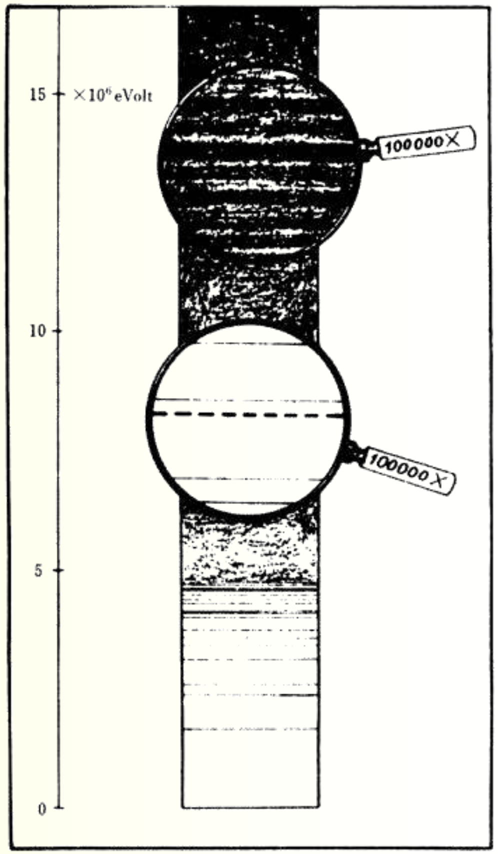
Decay of levels at low excitation energies

- often known experimentally
- described by "structure" effects
- Properties of individual levels can be predicted in models

Decay of levels in the region of high level density

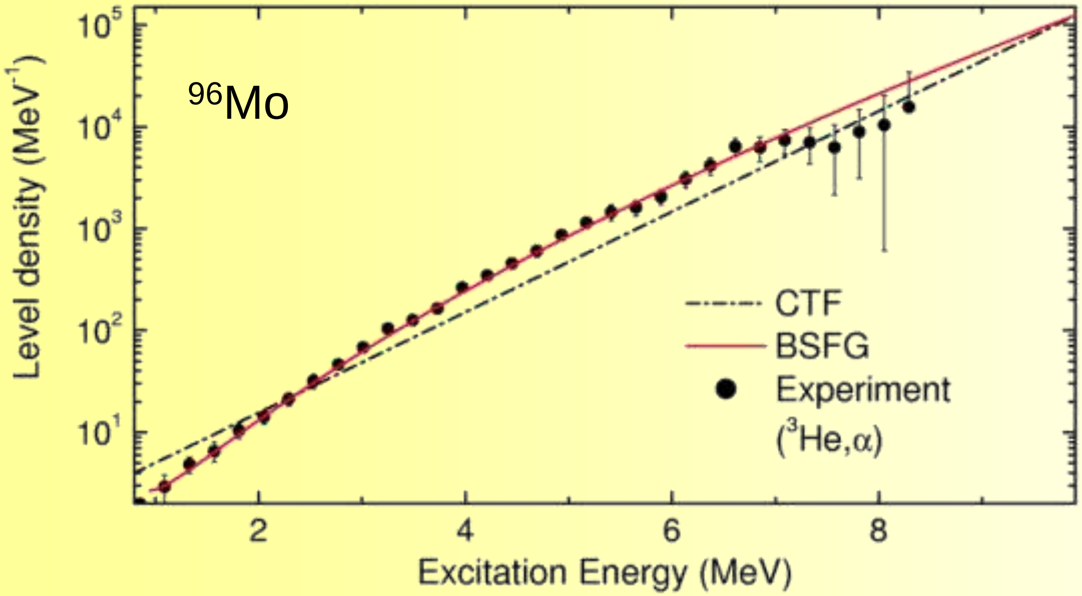
- described by "statistical approach"
- average quantities
  - level density & γ-ray (photon, radiative) strength functions (+ Brink hypothesis)

    (two quantities are needed
    for description of γ decay or γ absorption)
- fluctuation properties
  - Porter-Thomas fluctuations of partial radiation widths

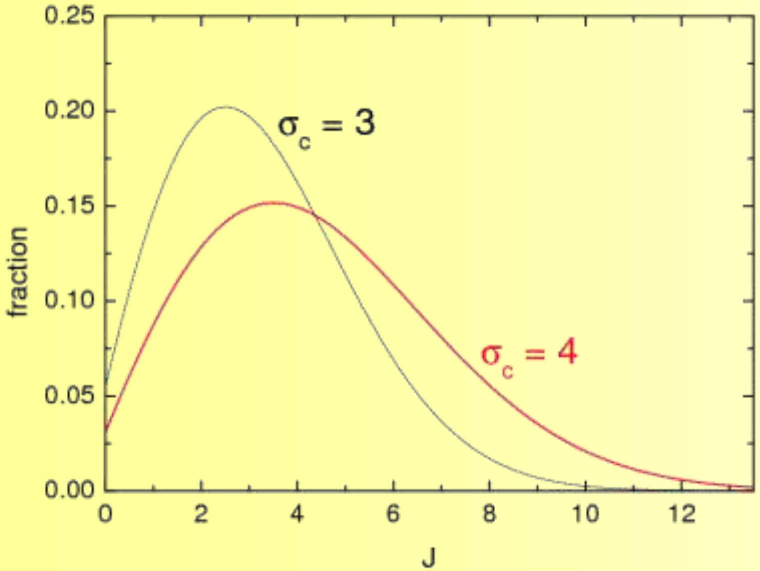


Niels Bohr - Nature (1936)

Nuclear level density



- Experimental information is not very rich:
  - often only low-lying levels and neutron resonances (very restricted spin window) are known



- There are several widely-used models:
  - Back Shifted Fermi Gas (BSFG) model
  - Constant-Temperature (CT) model
  - HFB calculation (Hilaire)

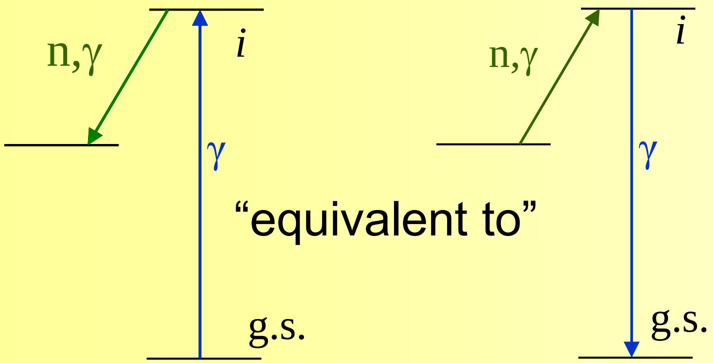
    …
- Problem with spin and parity dependence

$$\rho(J) = \frac{2J+1}{2\sigma_c^2}\ \exp\left(-\frac{(J+1/2)^2}{2\sigma_c^2}\right)$$

Detailed balance principle

- To characterize the strength of transitions one can use different quantities, e.g. partial radiation width or photoabsorption x-section

The principle of the detailed balance:



$$W = \frac{2\pi}{\hbar} \, |M|^2 \, \rho(\text{final states})$$

where “equivalent to” means:

$$|M(i \to \text{g.s.})| = |M(\text{g.s.} \to i)|$$

$$\Gamma^{(XL)}_{i\to\text{g.s.}} = \frac{1}{(\pi\hbar c)^2} \frac{E_\gamma^{2L}}{2L+1} \frac{\sigma^{(XL)}_{\text{g.s.}\to i}}{\rho(E_i, J_i, \pi_i)}$$

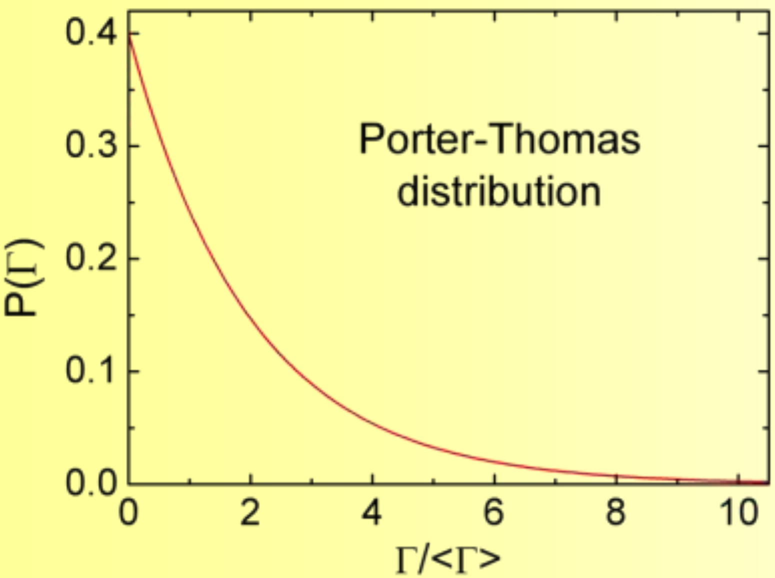
- There exists other “equivalent” quantities:

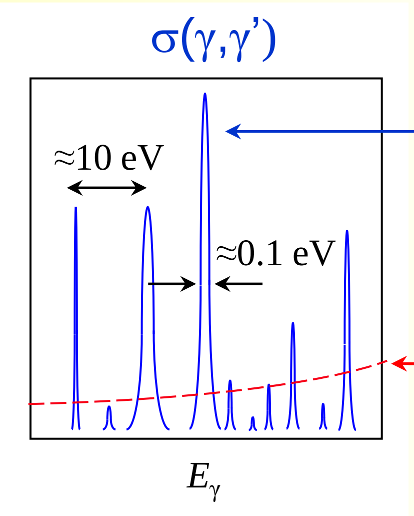
$$\Gamma^{(XL)}_{i\to\text{g.s.}} = \frac{8\pi}{L[(2L+1)!!]^2} \left(\frac{E_\gamma}{\hbar c}\right)^{2L+1} B(XL)\downarrow$$

$$B(XL)\downarrow = \frac{2J_i+1}{2J_{\text{g.s.}}+1} B(XL)\uparrow$$

Fluctuations of radiation widths

- In reality, individual partial radiation widths are expected to strongly fluctuate – according to Porter-Thomas distribution (χ^2 distribution with ν=1)





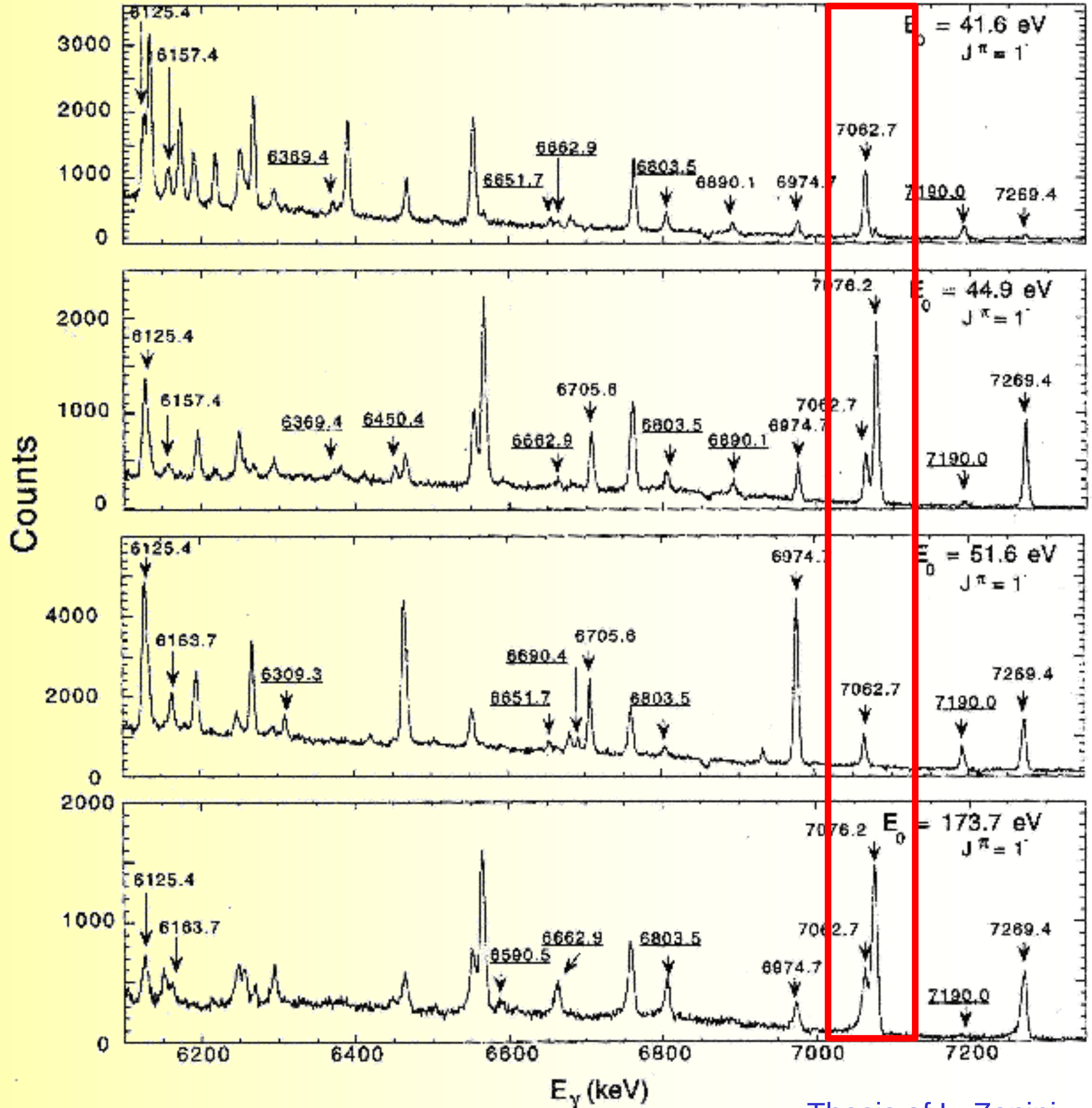
Porter-Thomas fluctuations ($\chi^2_{\nu=1}$ distribution)

$\langle\sigma_{\gamma\ abs}\rangle$
…an energy-smoothed photoabsorption x-section

- Average quantities are (must be) used

- Example:

  Spectra of primary transitions from several 1^- resonances in $^{107}Ag(n,\gamma)$



Thesis of L. Zanini

Photon (γ-ray) Strength Functions

- Average quantities are used
- One of them is "experimental" PSF (RSF, γSF)

- describe "average probability of decay"

$$f^{(XL)} = \frac{1}{(\pi\hbar c)^2}\frac{\overline{\sigma}_{\text{tot}}^{(XL)}(\beta \to \alpha)}{(2L+1)E_\gamma^{2L-1}}$$

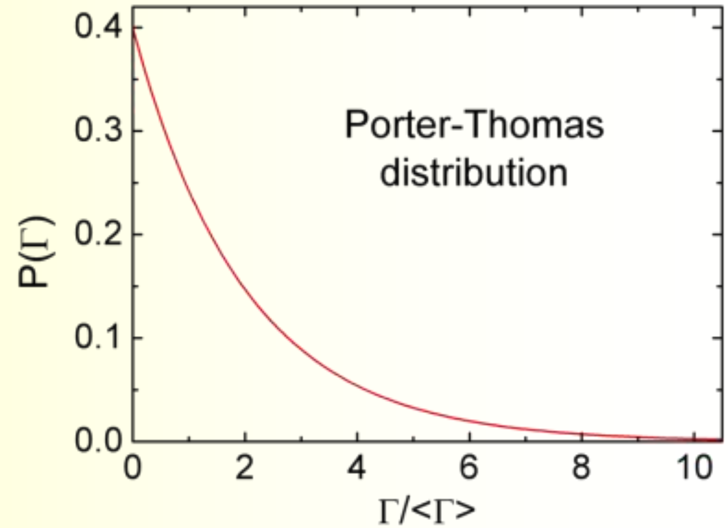
α

β

$$\overline{\Gamma}_{\alpha\gamma\beta}^{(XL)} = \frac{f^{(XL)}E_\gamma^{2L+1}}{\rho(E_\alpha, J_\alpha, \pi_\alpha)}$$

$$[f^{(XL)}] = \text{MeV}^{-(2L+1)}$$

$$\int\limits_\Delta f^{(XL)} dE_\gamma = \text{const} \times \sum_\Delta B(XL)\uparrow$$



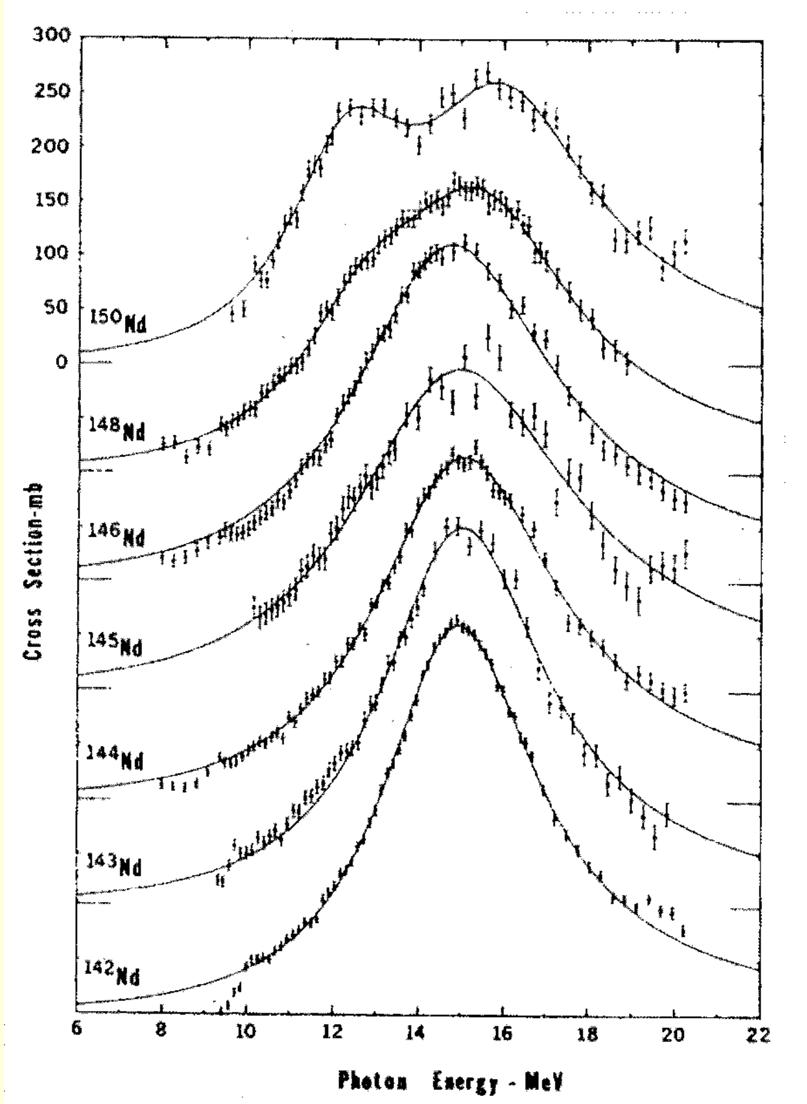
Giant Dipole Electric Resonance

- classical electrodynamics (response of a charged mass-point with damping to the external electric field in the long-wave approximation) $\Rightarrow$ the collective mode in E1 PSF should be described by Lorentzian shape

$$f_{\mathrm{BA}}^{(E1)}(E_\gamma) = \frac{1}{3(\pi\hbar c)^2} C_\Sigma \frac{E_\gamma \Gamma_G}{\left(E_\gamma^2 - E_G^2\right)^2 + E_\gamma^2 \Gamma_G^2}$$

$$C_\Sigma = \sigma_G \Gamma_G$$

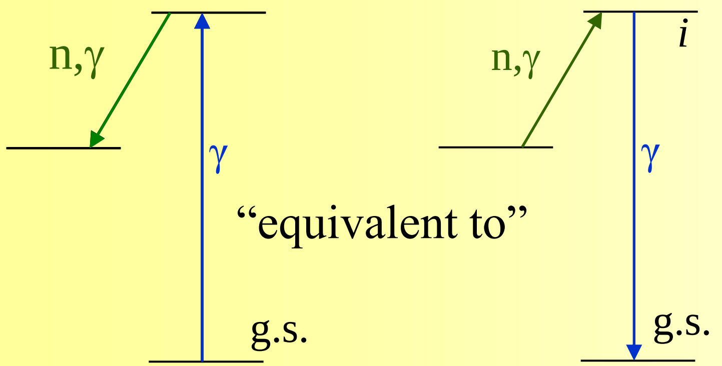
- measured in (γ,xn) experiments in many nuclei (above neutron separation energy)
- experiment does not distinguish multipolarity, dominance of E1 assumed



B.L. Berman, S.C. Fultz, Rev. Mod. Phys. 47 (1975) 713

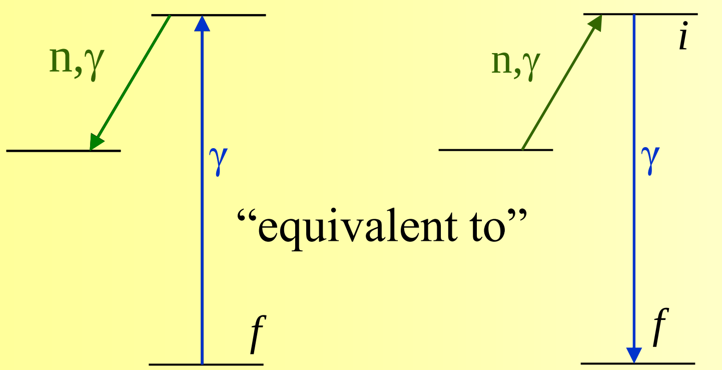
Brink hypothesis

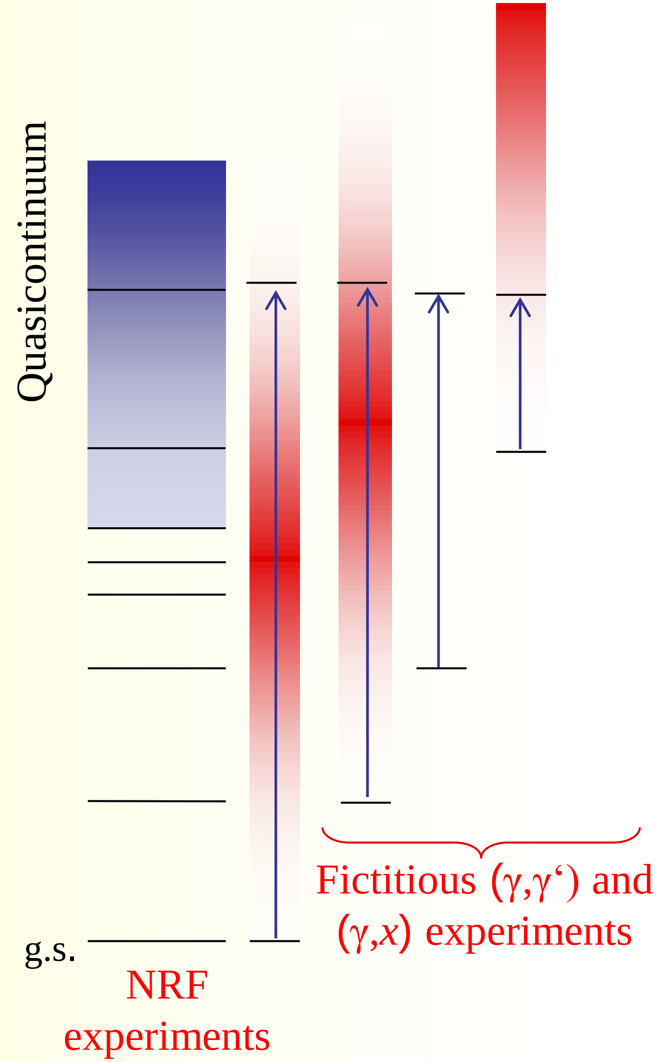
A target in photonuclear/photoabsorption experiment is in the <u>ground state</u>



Identical !

<u>Brink hypothesis</u>:
generalization "g.s." → "*f*"





Photoexcitation pattern of an <u>excited</u> target nucleus

Brink hypothesis

- The energy dependence of the photoeffect is independent of the detailed structure of the initial state
- Suggested for E1 transitions on the tail of the GDER
- Usually generalized: any “collective” excitation mode built on excited states have the same properties as those built on the ground state

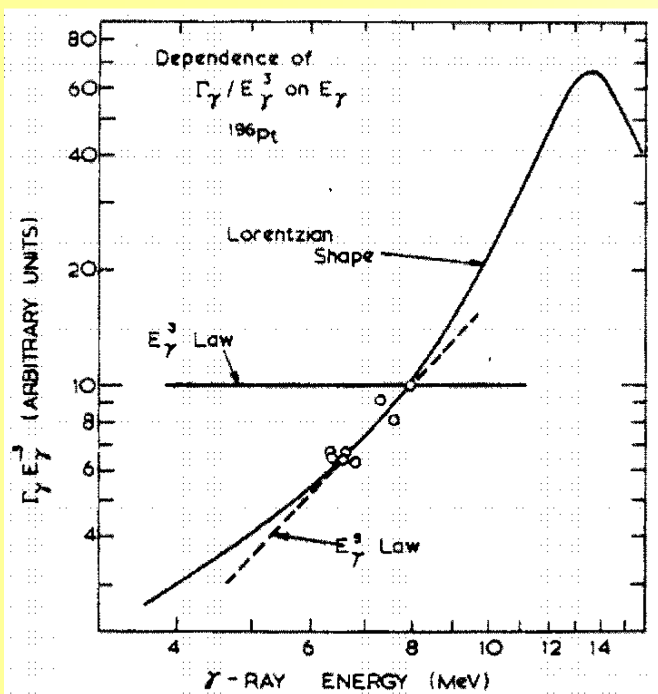
- Quantities which PSFs can dependent on:
  - type of transitions (E1, M1, E2, …) ✓
  - γ-ray energy ✓
  - microscopic properties of the level (T,J^{π}) **?**
    No dependence $\Rightarrow$ Brink hypothesis

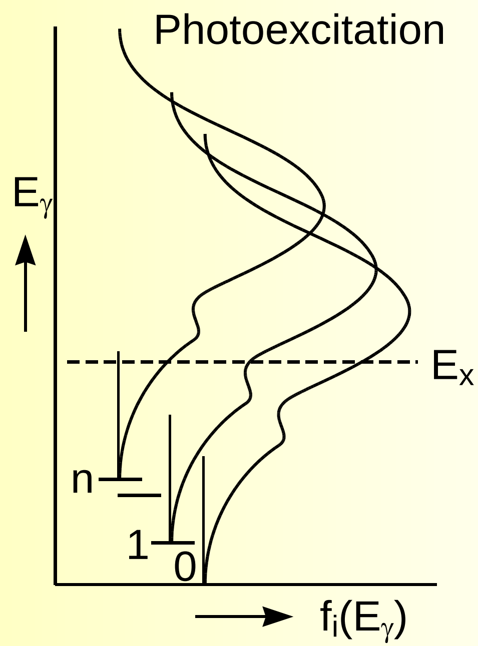
  - not applicable at the lowest excitation energies (surely not below pairing gap)

Brink hypothesis

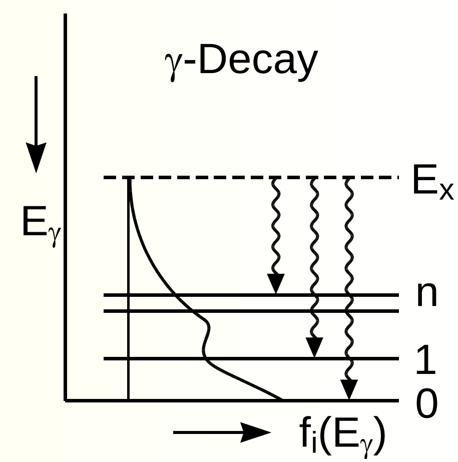
Validity of the hypothesis?

- at least approximately - from primaries in (n,γ) reaction and “hot” nuclei
- some weak signs of temperature (excitation energy) dependence in hot nuclei
- valid probably not only for GDER but also for M1 scissors mode



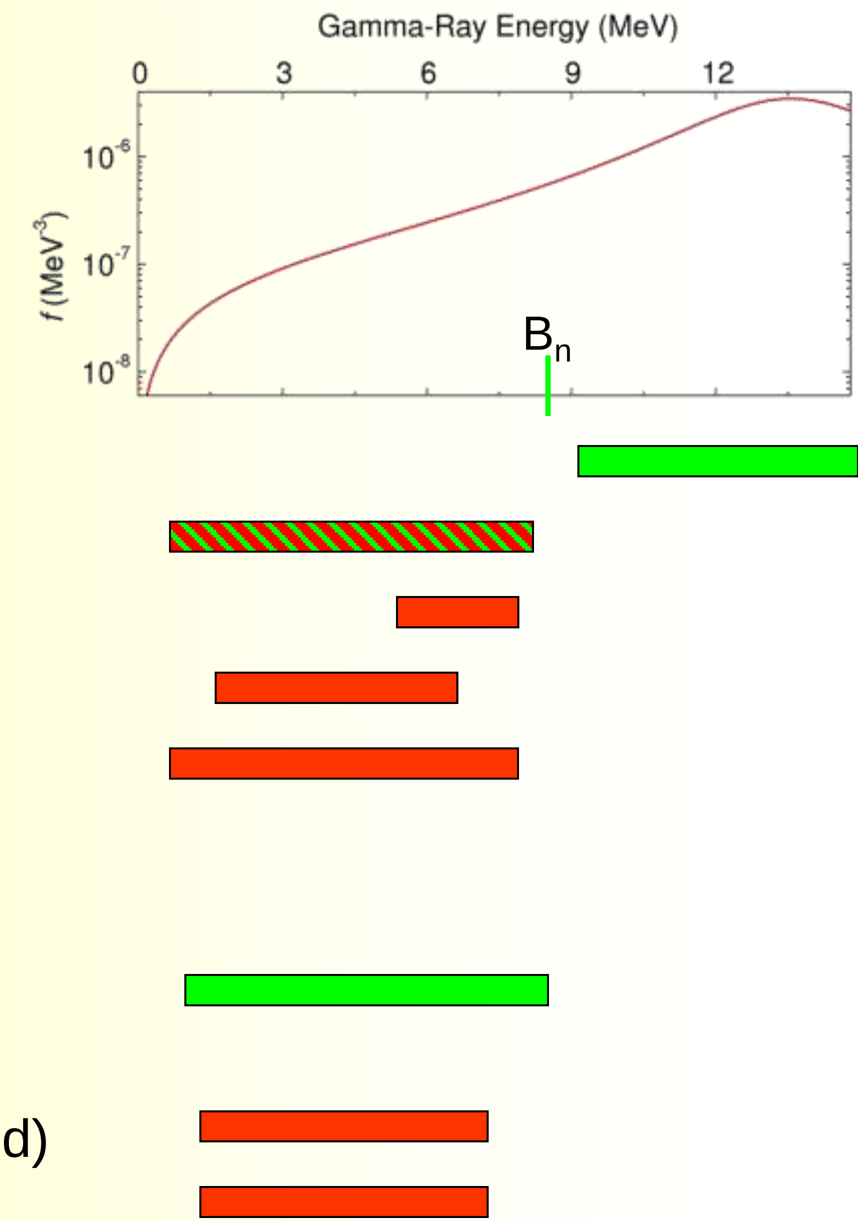


$f_0(E_\gamma) = f_1(E_\gamma) = f_n(E_\gamma) = f(E_\gamma)$



Where could we learn about PSFs from?

(at low-energy GDER tail, nuclei near the valley of stability)

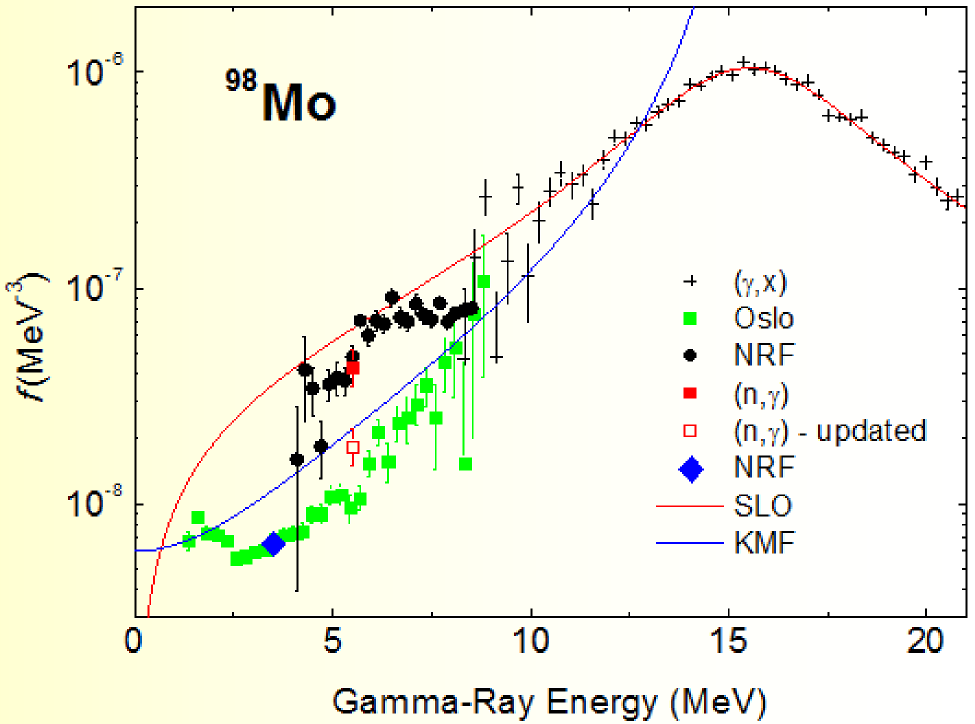


- photoexcitation techniques
  - (γ,particle)
  - NRF experiments
- primaries from (n,γ) reaction
- two-step cascades spectra - (n,γ)
- spectrum fitting method
  - singles spectra
  - coincidence spectra
- inelastic scattering of charged particles (e,e'), (p,p'), (α,α') …
- sequential extraction (Oslo, ^{3}He-induced)
- particle - γ - γ coincidence
- …

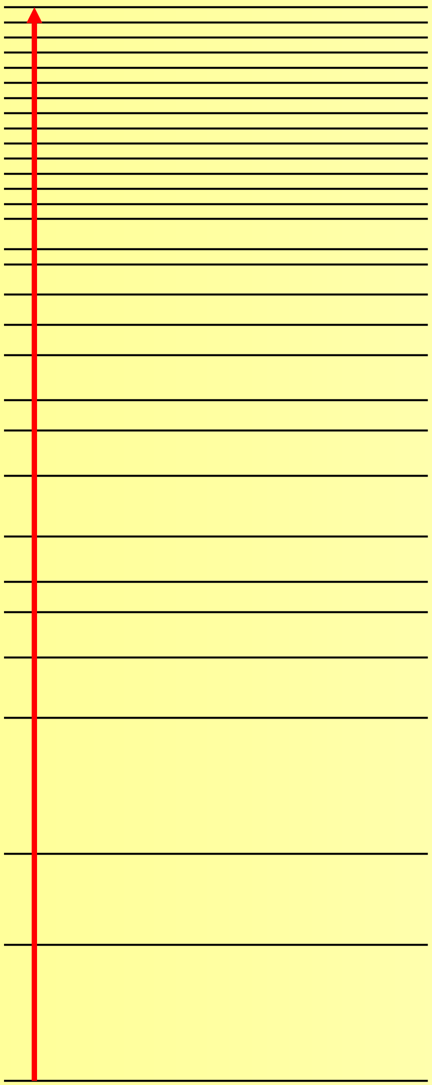
“Experimental” PSFs below S_n

Many problems:

- Inconsistency of PSFs derived from different experiments (difference in PSF shape from NRF and “decay” probing experiments,…)
- Exact shape of E1 at low energy tail of GDER
- Dependence of low-energy GDER tail on excitation energy (temperature)
- Contribution of M1 strength
- Existence of additional resonance structure (pygmy dipole resonance, low-energy upbend,…)
- …



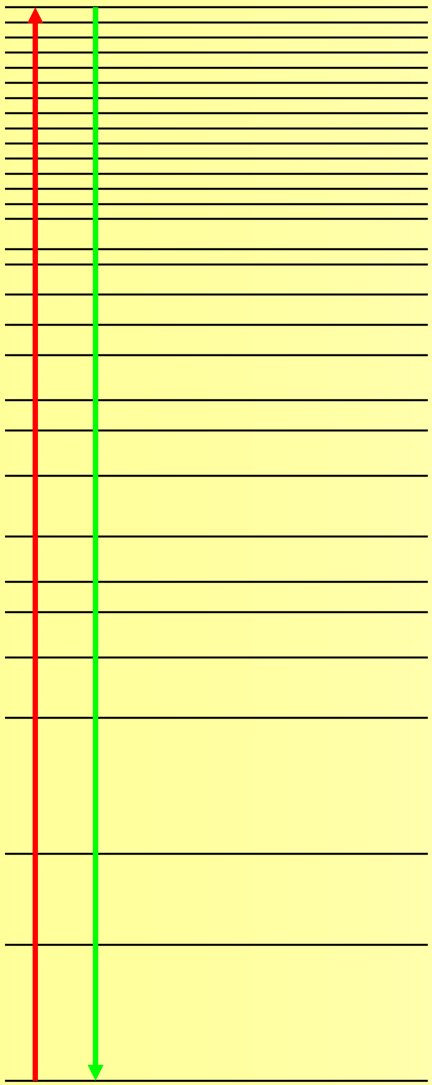
^{142}Nd(γ,γ') @ HIγS

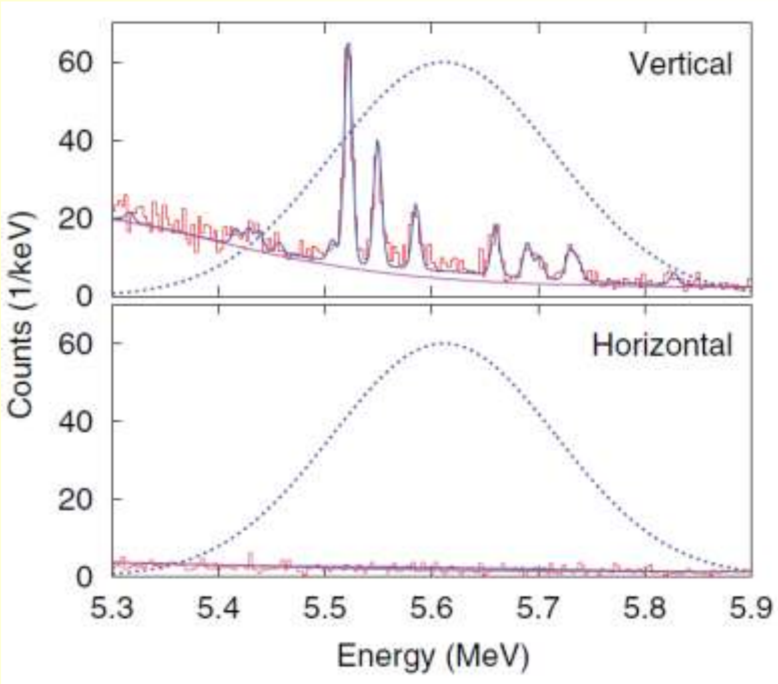


G.S. (0+)

C.T. Angell et al., PRC 86, 051302(R) (2012)

$^{142}Nd(\gamma,\gamma')$ @ HIγS

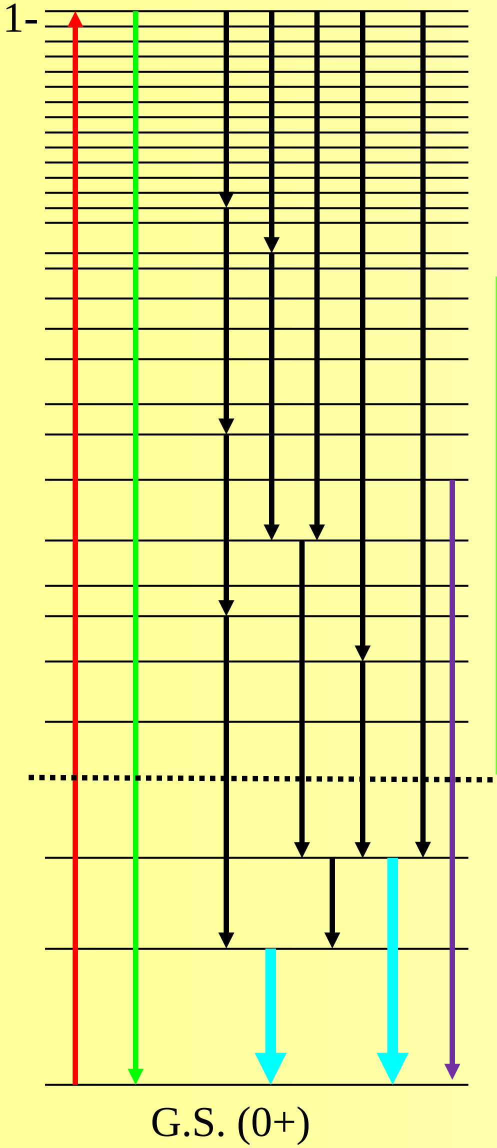




- "Monoenergetic photon beam"
- Linear polarization allows separate E1 from M1 (γ,γ) contribution – only E1 (vertical) observed

C.T. Angell et al., PRC 86, 051302(R) (2012)

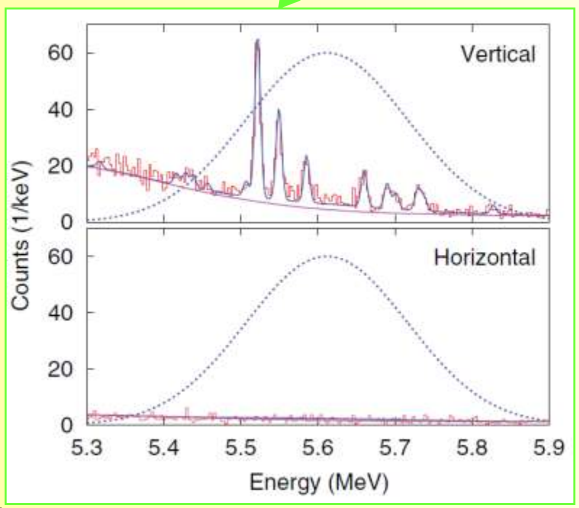
^{142}Nd(γ,γ') @ HIγS



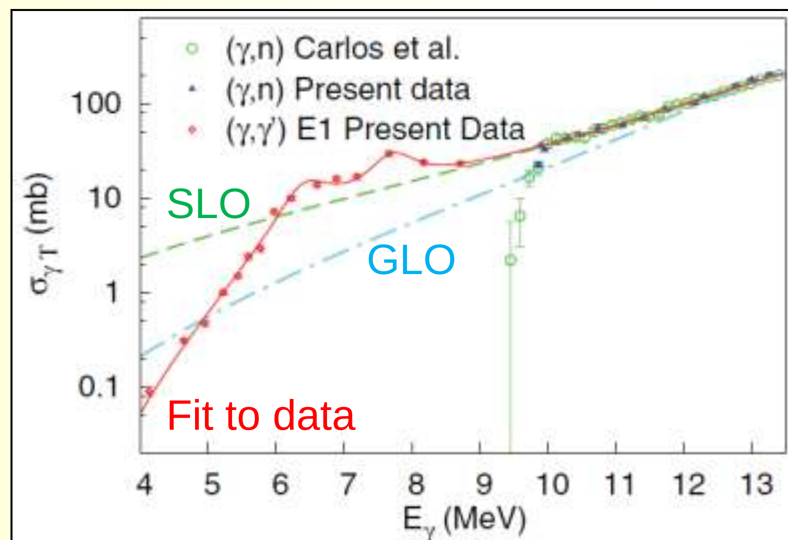
Total cross section given by

$$\sigma_{\gamma T} = \sigma_{\gamma\gamma} + \sigma_{\gamma LL} + \sigma_{\gamma cont}$$

Negligible at low excitation energies, several per cent in PDR region – must be corrected from "simulations"

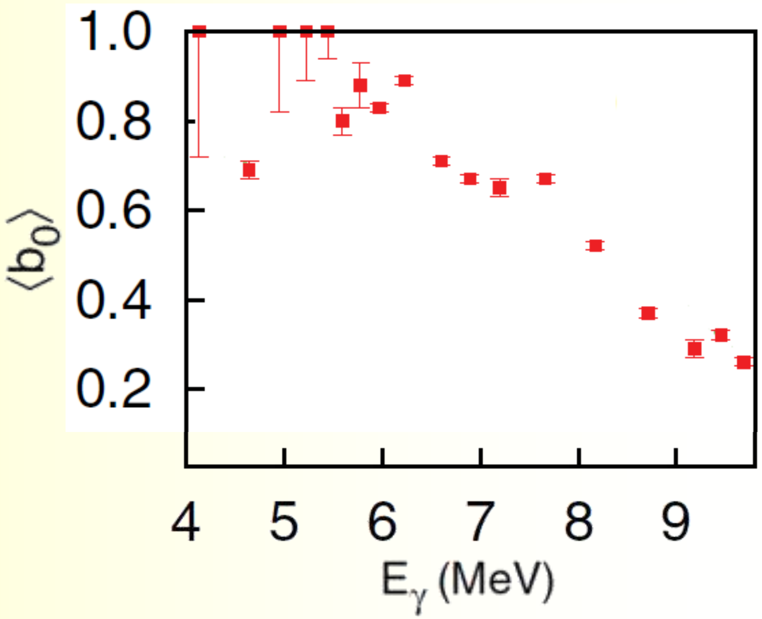


^{142}Nd:
seven 2^{+} levels below 3.5 MeV; almost all intensity goes via the first excited state



^{142}Nd(γ,γ') @ HIγS

- In addition to total cross section we can look at "GS branching" $\langle b_0 \rangle = \sigma_{\gamma\gamma} / \sigma_{\gamma T}$ or $\langle b_0 \rangle = \sigma_{\gamma\gamma} / \sigma_{\gamma LL}$



C.T. Angell et al., PRC 86, 051302(R) (2012)

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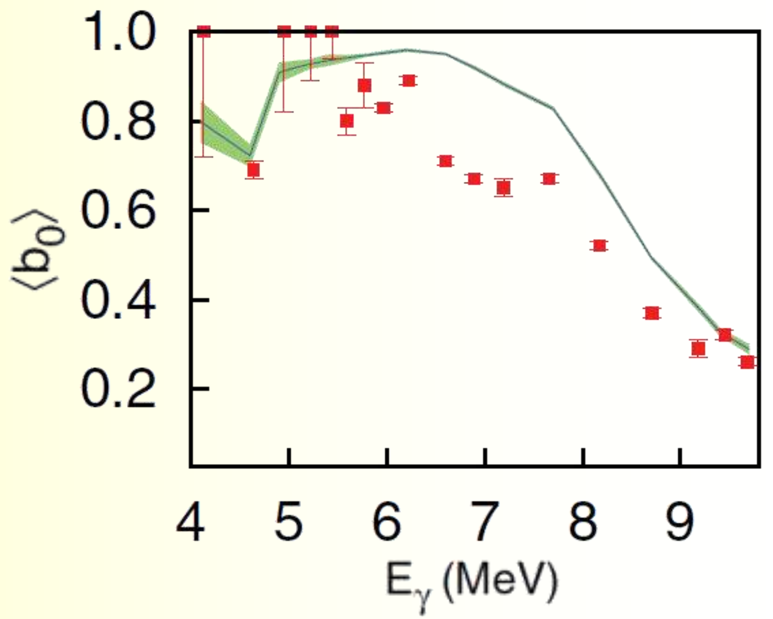
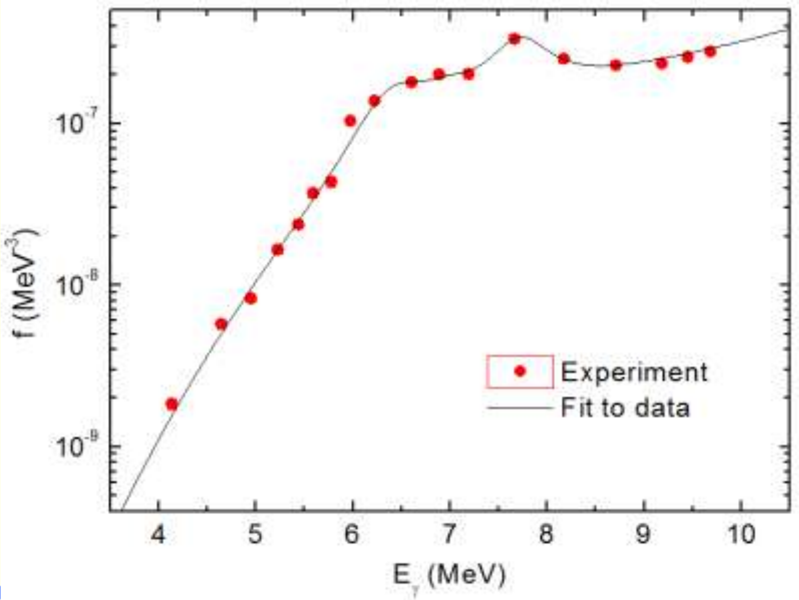
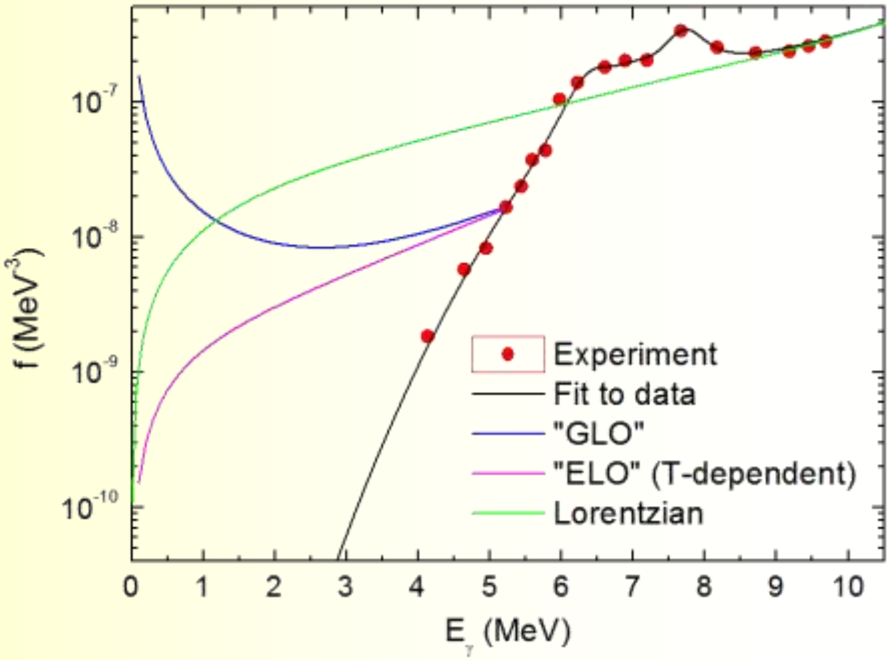
- Experimental values of $\langle b_0 \rangle$ can be compared with results of simulations assuming the validity of the statistical model (DICEBOX code)
- Extrapolation of PSFs down to low γ energies is needed





C.T. Angell et al., PRC 86, 051302(R) (2012)

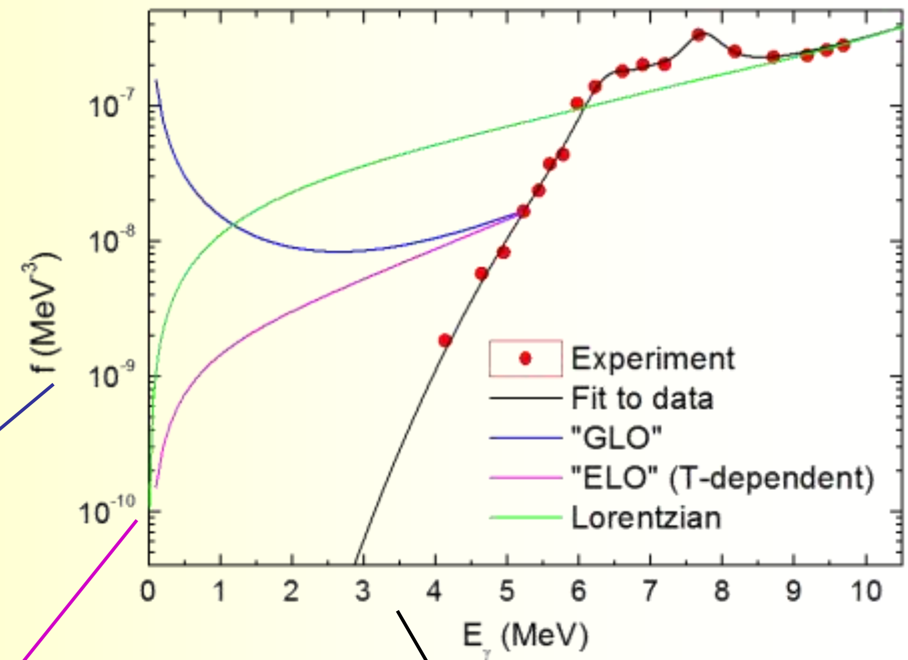
^{142}Nd(γ,γ') @ HIγS

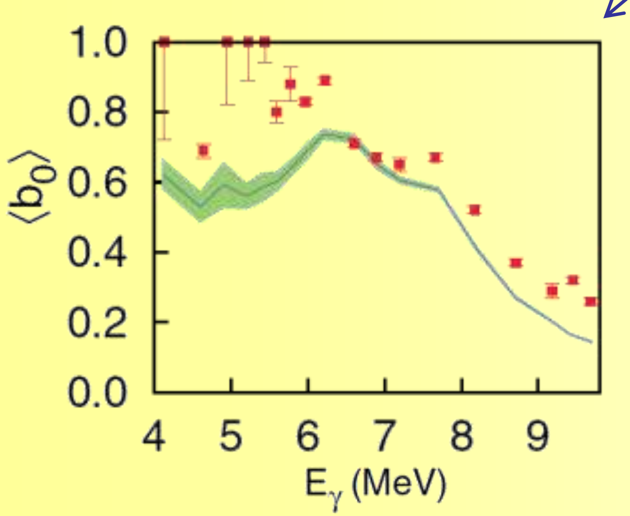


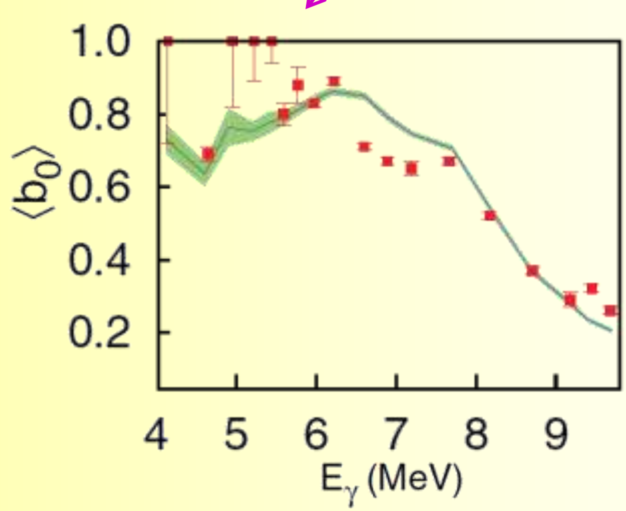
$\langle b_0 \rangle = \sigma_{\gamma\gamma} / \sigma_{\gamma LL}$

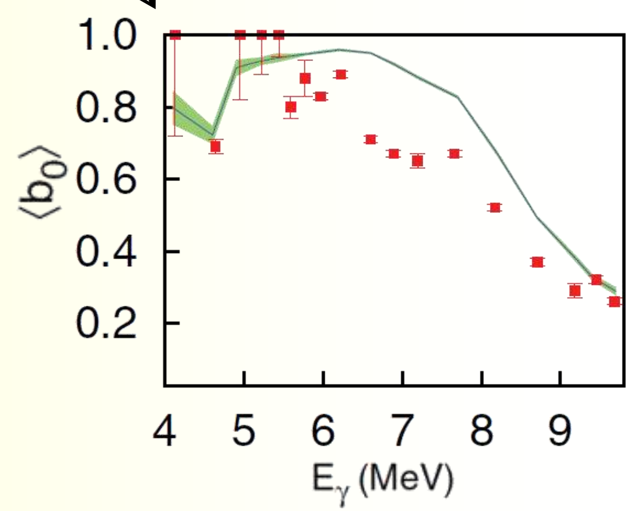
^{142}Nd(γ,γ') @ HIγS

- None of tested models is able to reproduce $<b_0>$ at all energies
- Problem with the shape of $<b_0>$, especially at 6-8 MeV
  $\Rightarrow$ assumptions in simulations are not correct
- Virually no influence of NLD, many PSFs models tested $\Rightarrow$ problem with Brink hypothesis
  (at least for PDR region)



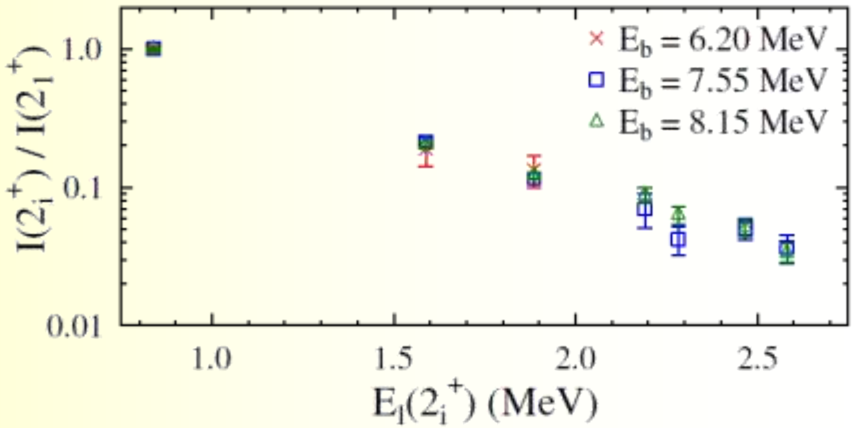


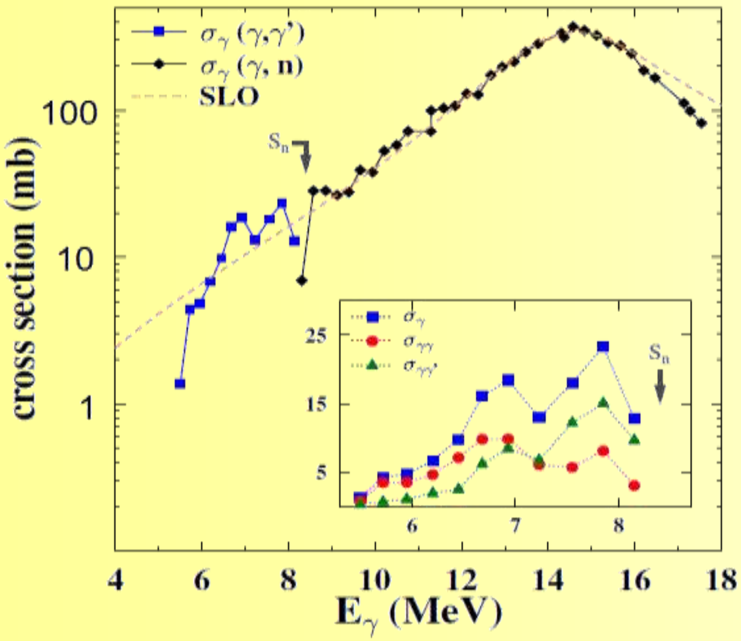


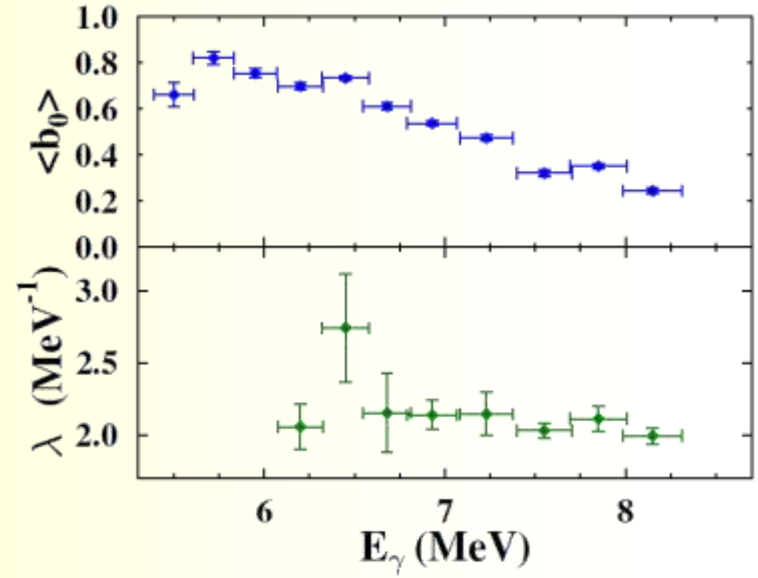


$^{130}Te(\gamma,\gamma')$ @ HIγS – preliminary results

- Additional observable to $\sigma_{\gamma T}$ ($\sigma_{\gamma LL}$) and $\langle b_0 \rangle$ checked
- Observed population I of several 2^+ states shows a log decrease with excitation energy E
- Assuming that $I \sim \exp(-\lambda.E)$, parameter λ can be checked with results from simulations



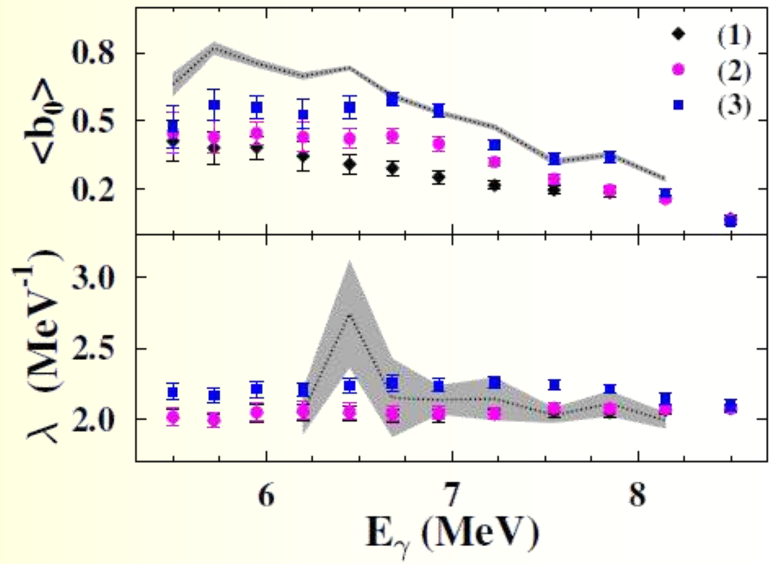


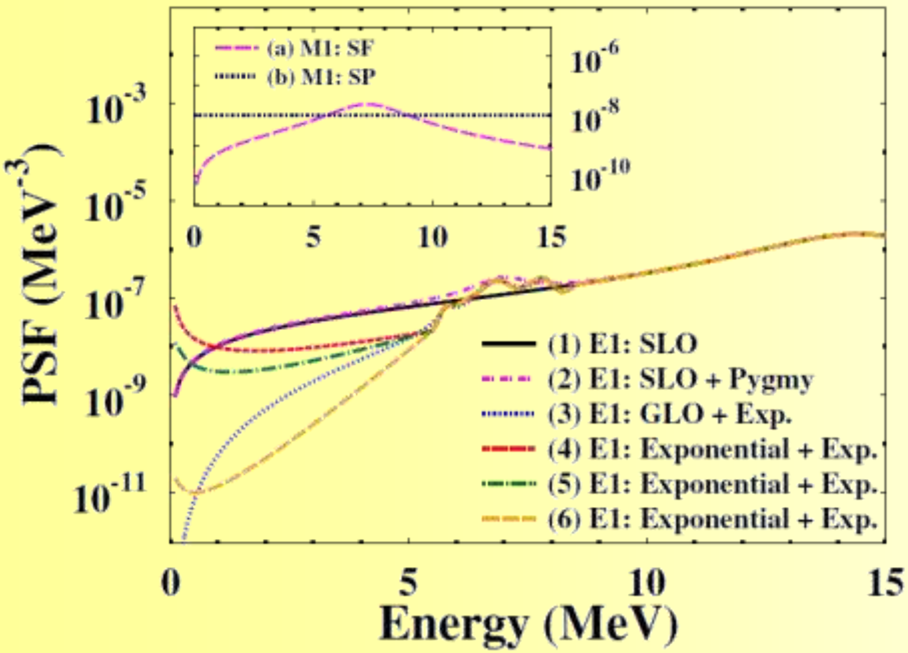


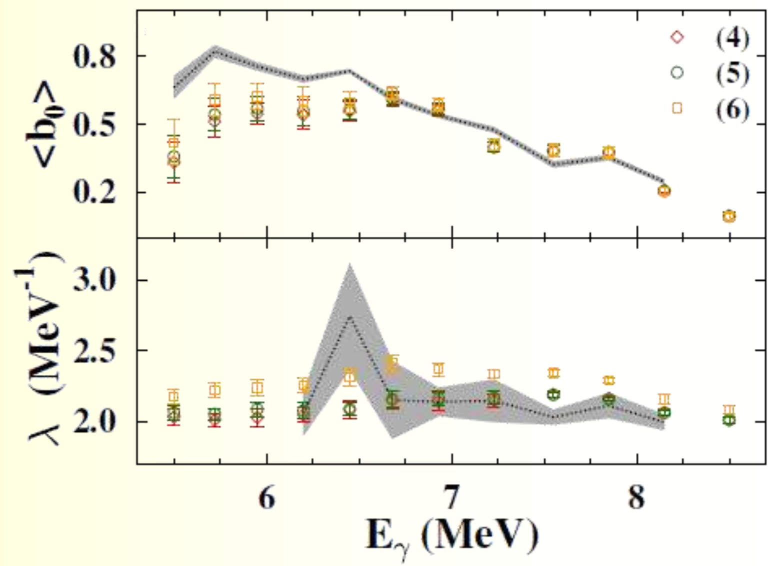
J. Isaak, D. Savran,…, to be submitted to PRC/PRL

^{130}Te(γ,γ') @ HIγS – preliminary results

- Several PSFs models tested
- Shape of <b_0> is not that problematic as in ^{142}Nd – PSF from PDR region seem to have no problem with the Brink hypothesis
- But it is extremely difficult to achieve simultaneous reproduction of <b_0> and λ at all energies, especially for E < 6.5 MeV







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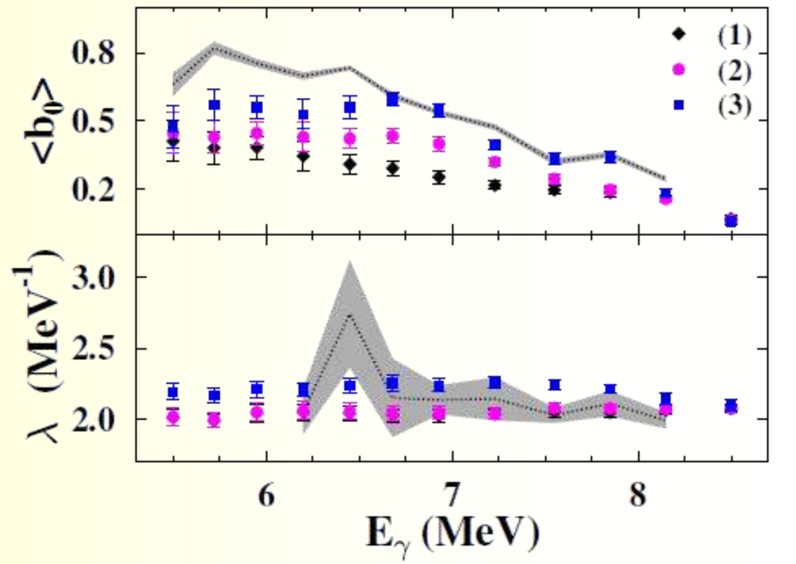
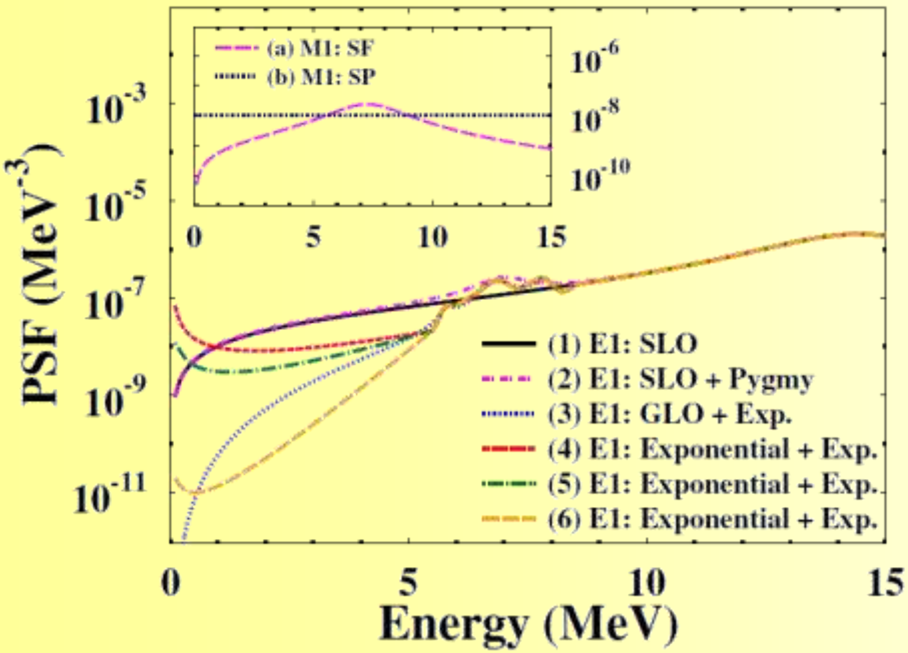


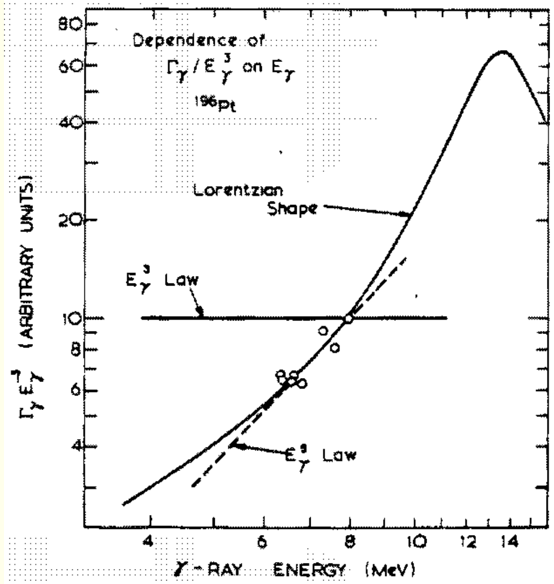


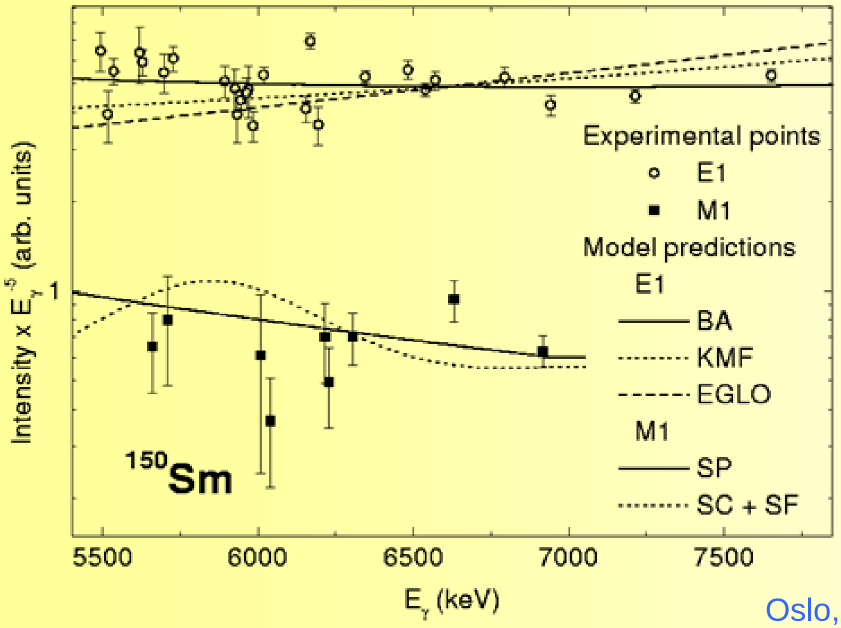
- Estimate of influence of "non-statistical" effects (below 6.5 MeV)

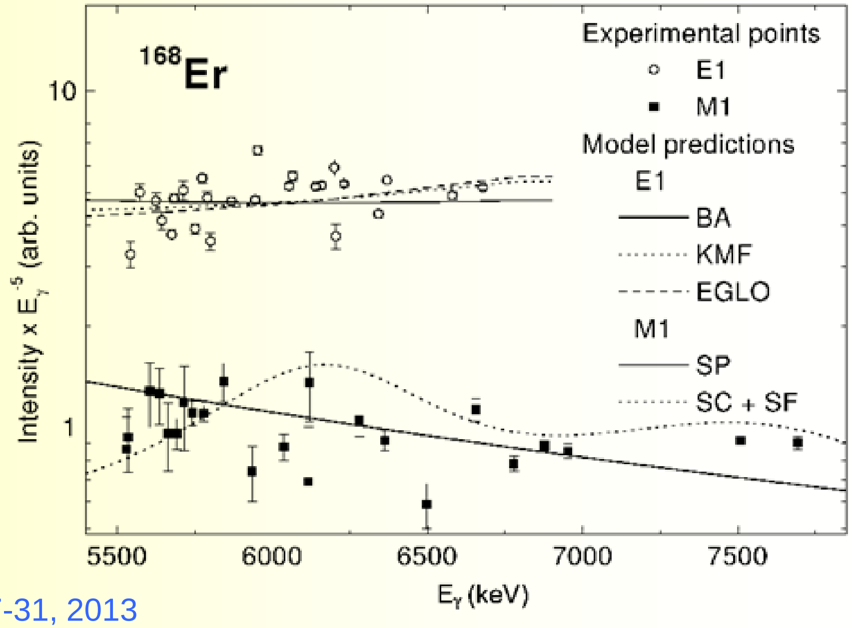
$$\frac{\sigma^{gs}}{\sigma_\gamma} = \frac{\langle b_0 \rangle - \langle b_0 \rangle^{stat}}{1 - \langle b_0 \rangle^{stat}} \sim 0.5$$

Brink hypothesis and (n,γ) data

- Intensities of primary transitions from “average resonance capture” indicated a reasonable validity of Brink hypothesis
  (a scatter of points seems to be explainable with Porter-Thomas fluctuations – simulations needed)







Brink hypothesis and (n,γ) data

- Several tests have been made with "spectral-fitting method" (and analysis of TSC spectra) using DICEBOX
- Brink hypothesis can be violated in any way in simulations

- No definitive conclusion about temperature (excitation energy) dependence of E1 transitions can be made
  - in Gd isotopes, T-independent PSF (KMF) requires T ≈ 0.3 MeV in a very good agreement with Oslo data on Dy
- Brink hypothesis seems to be a very good approximation for M1 scissors mode

- Fluctuation of points TSC spectra in ^{96}Mo are in a reasonable agreement with simulations based on Porter-fluctuations – no "structure" effects needed for excitation above about 2.5 MeV

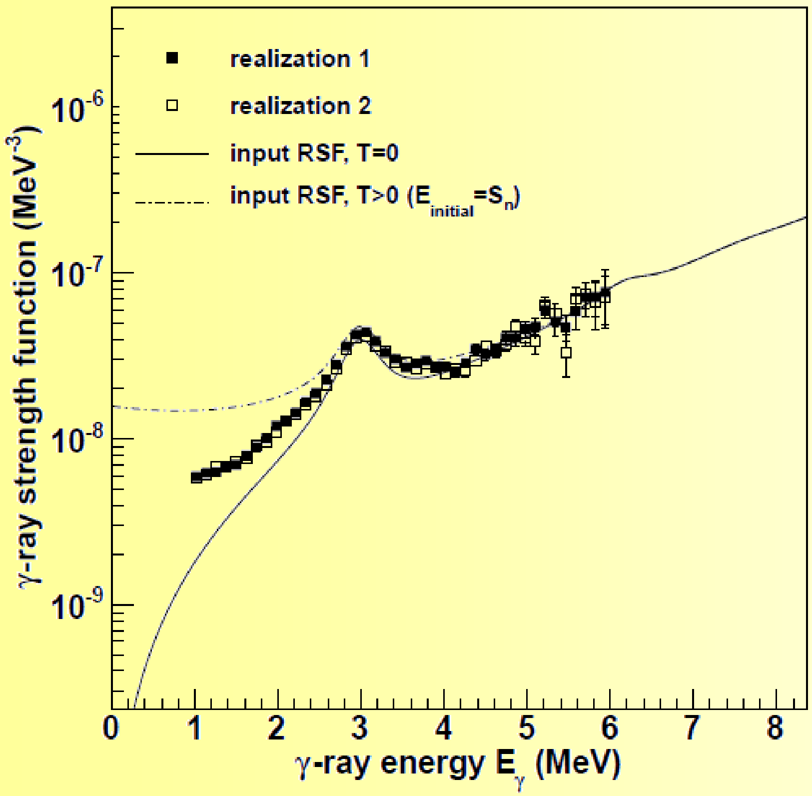
Brink hypothesis and Oslo method

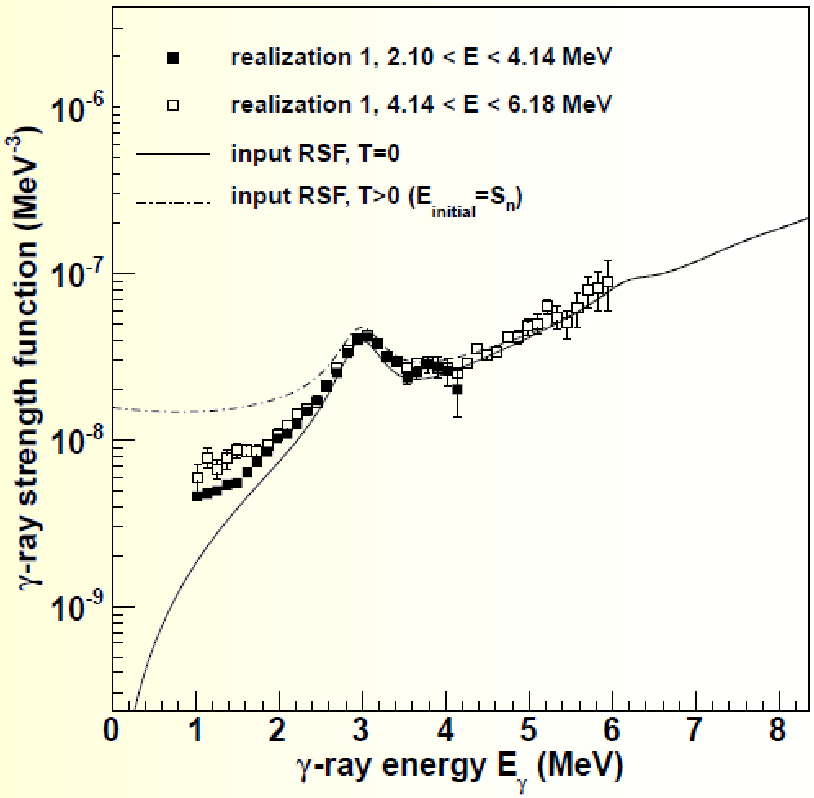
- Spectra of primaries are extracted from measured spectra (unfolding of detector response)
- Iterative procedure applied to spectra of primaries - two functions can be obtained
  - one dependent only on excitation energy (level density)
  - the other one only on γ-ray energy (transmission coefficient/PSF)
  - Brink hypothesis is an important part of the method

- What does happen if the PSF depends on excitation energy?

Brink hypothesis and Oslo method

A.C. Larssen et al., PRC 83, 034315 (2011)

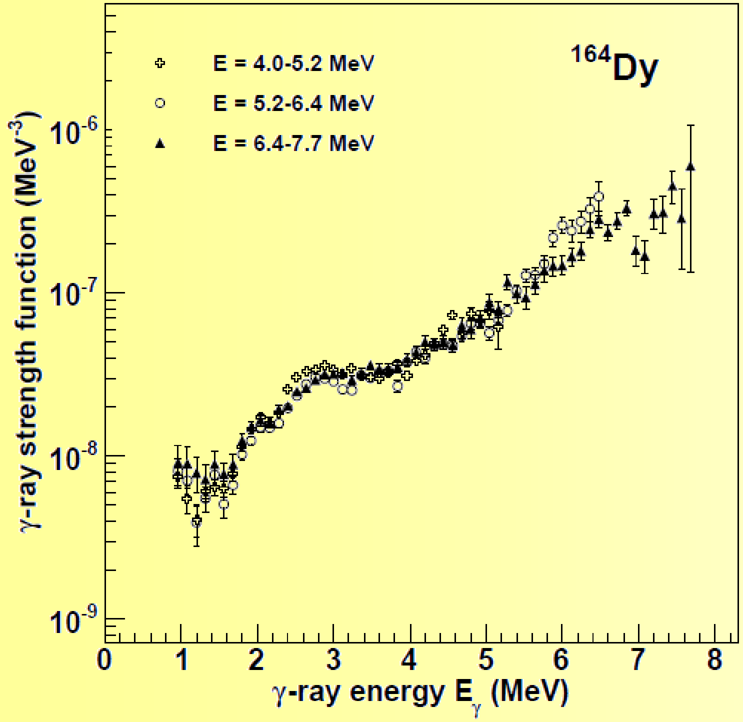


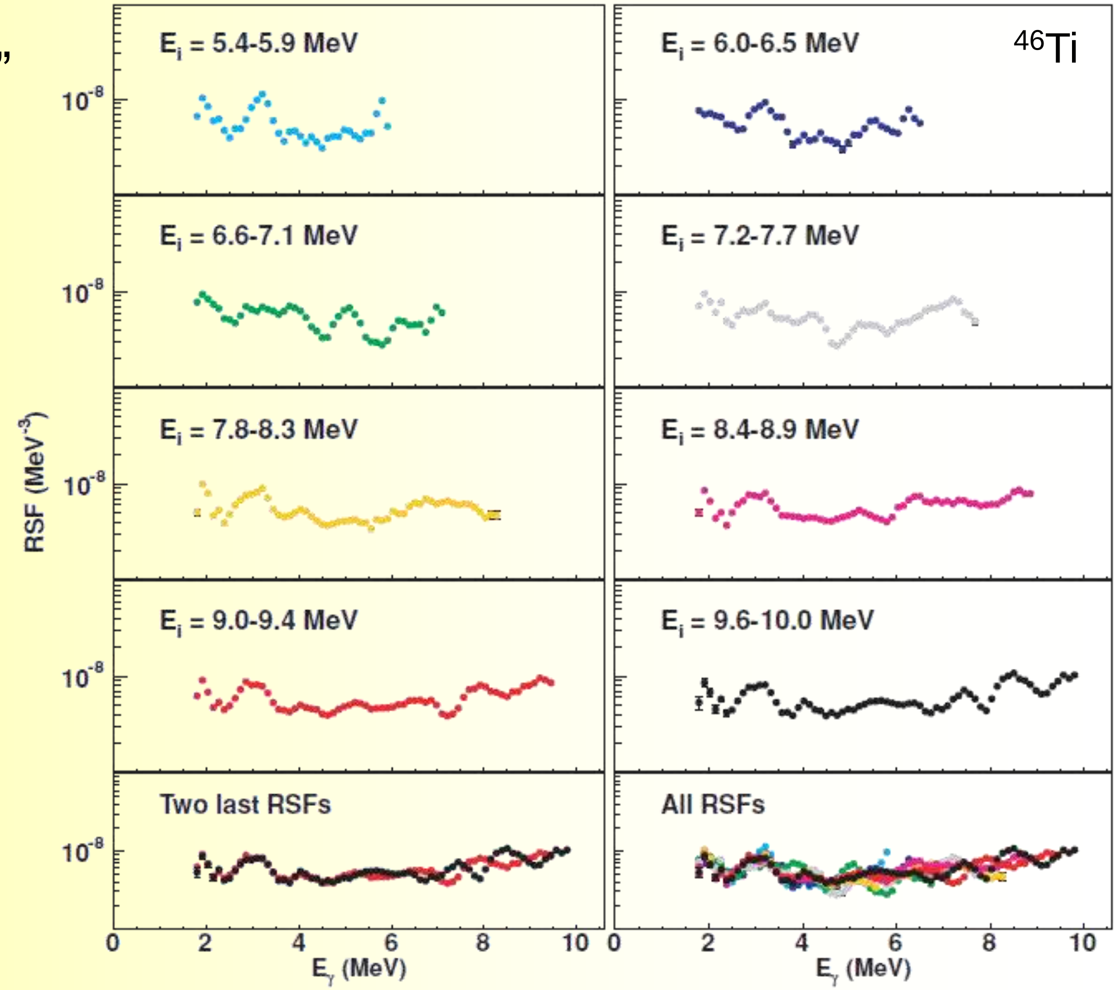


- A test using simulated spectra of "artificial" ^{163}Dy using T-dependent PSF (GLO)
- Shown PSF correspond to $T_f = 0$ and $T_f = \sqrt{(S_n - E_\gamma)}$

Brink hypothesis and Oslo method

Experimental spectra indicate PSF "reasonably independent" of excitation energy
(if averaging is sufficient and PSF concept can be used)



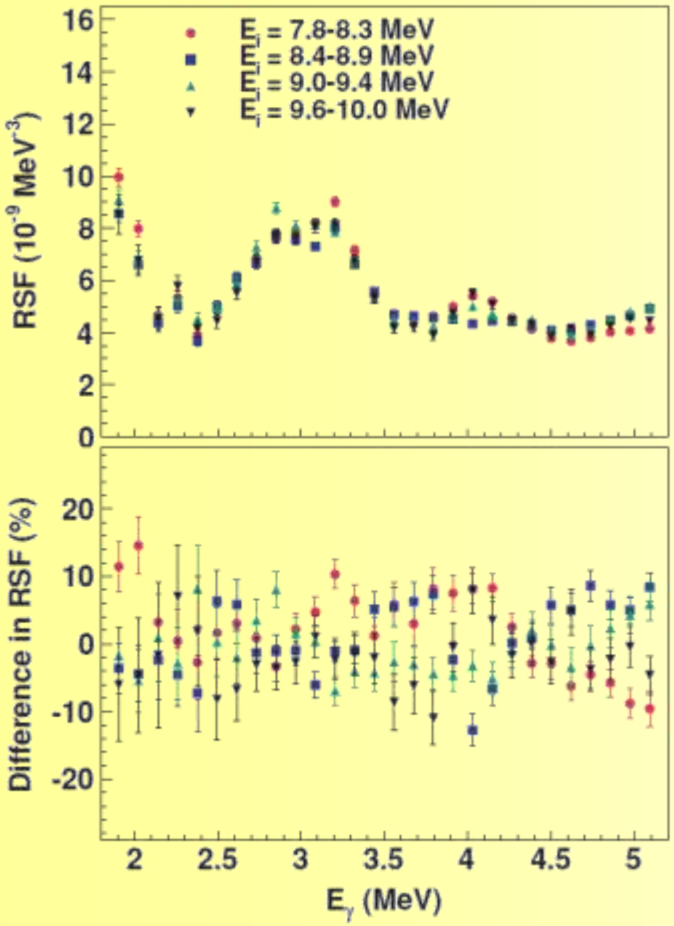


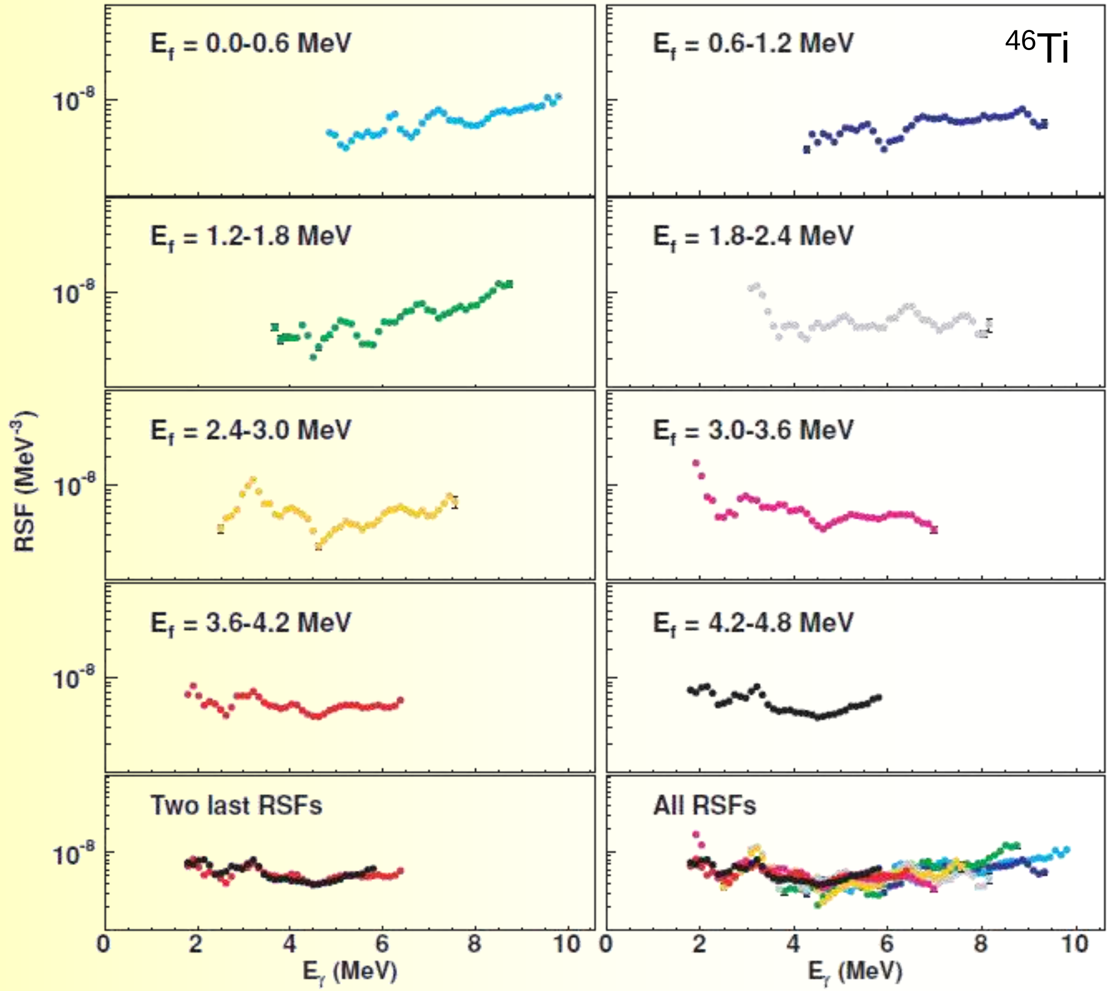
A.C. Larssen et al., PRC 83, 034315 (2011)

M. Guttormsen et al., PRC 83, 014312 (2011)

Brink hypothesis and Oslo method

Concept of PSF seems to be valid even in “light” nuclei from “low” excitation energy

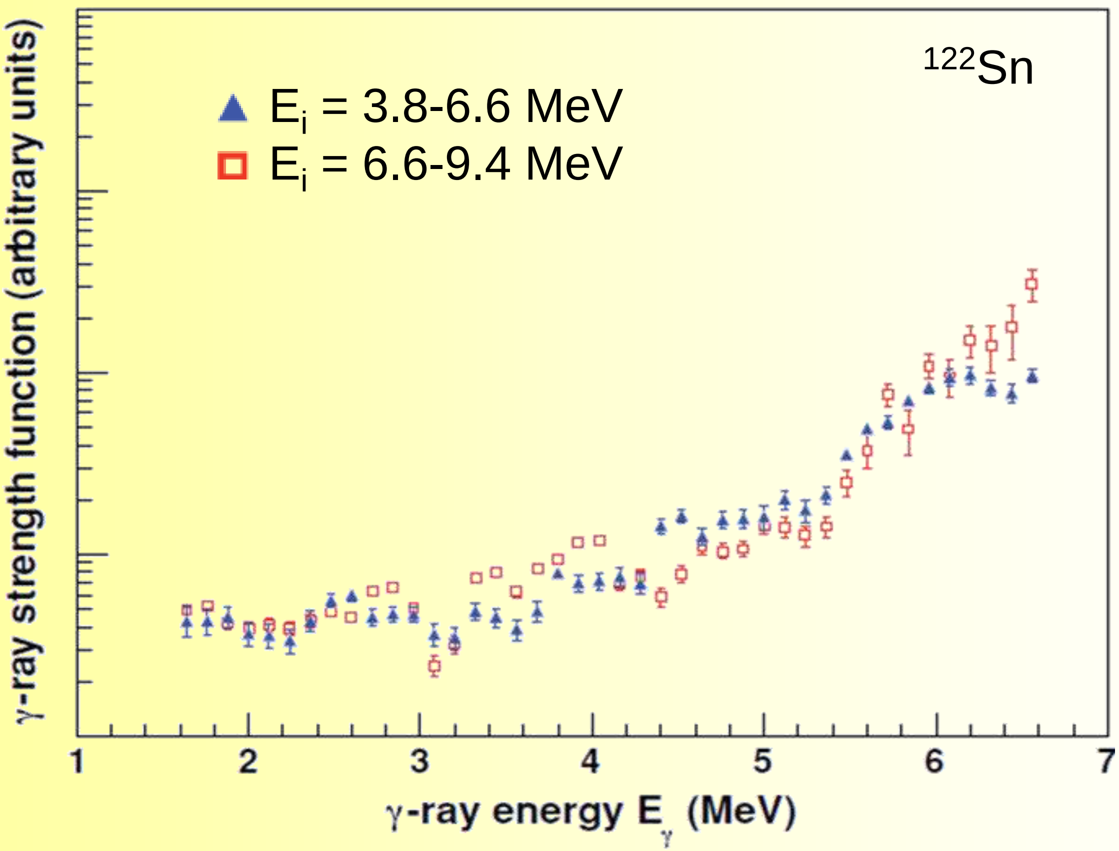




M. Guttormsen et al., PRC 83, 014312 (2011)

Brink hypothesis and Oslo method

Or are there some problems?

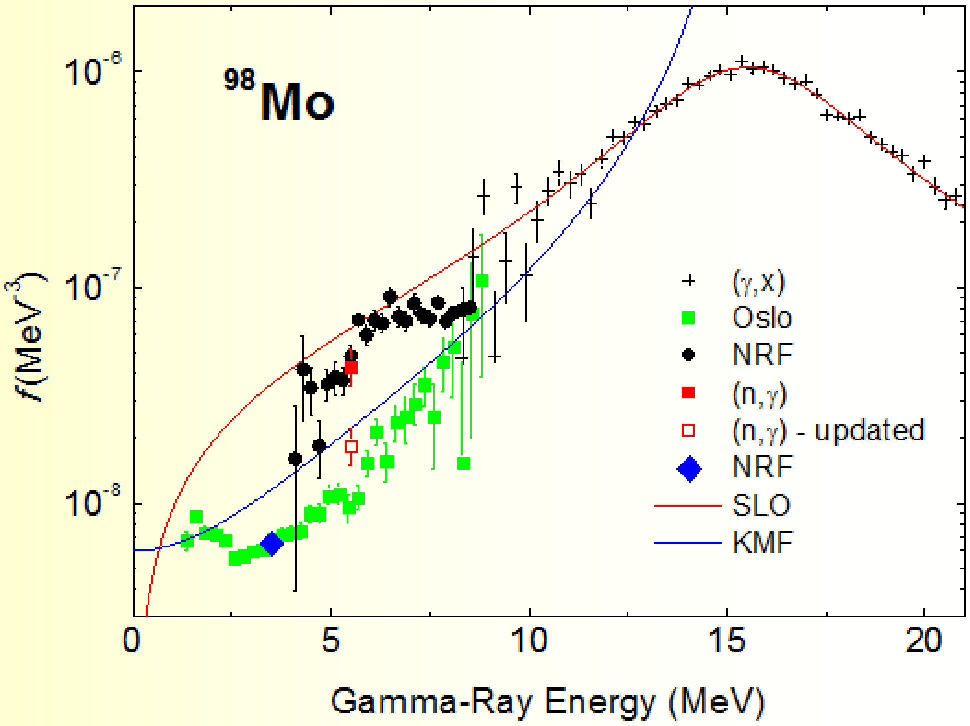


H.K. Toft et al., PRC 83, 044320 (2011)

Main conclusions

about validity of the Brink hypothesis at the low-energy tail of GDER from experimental data

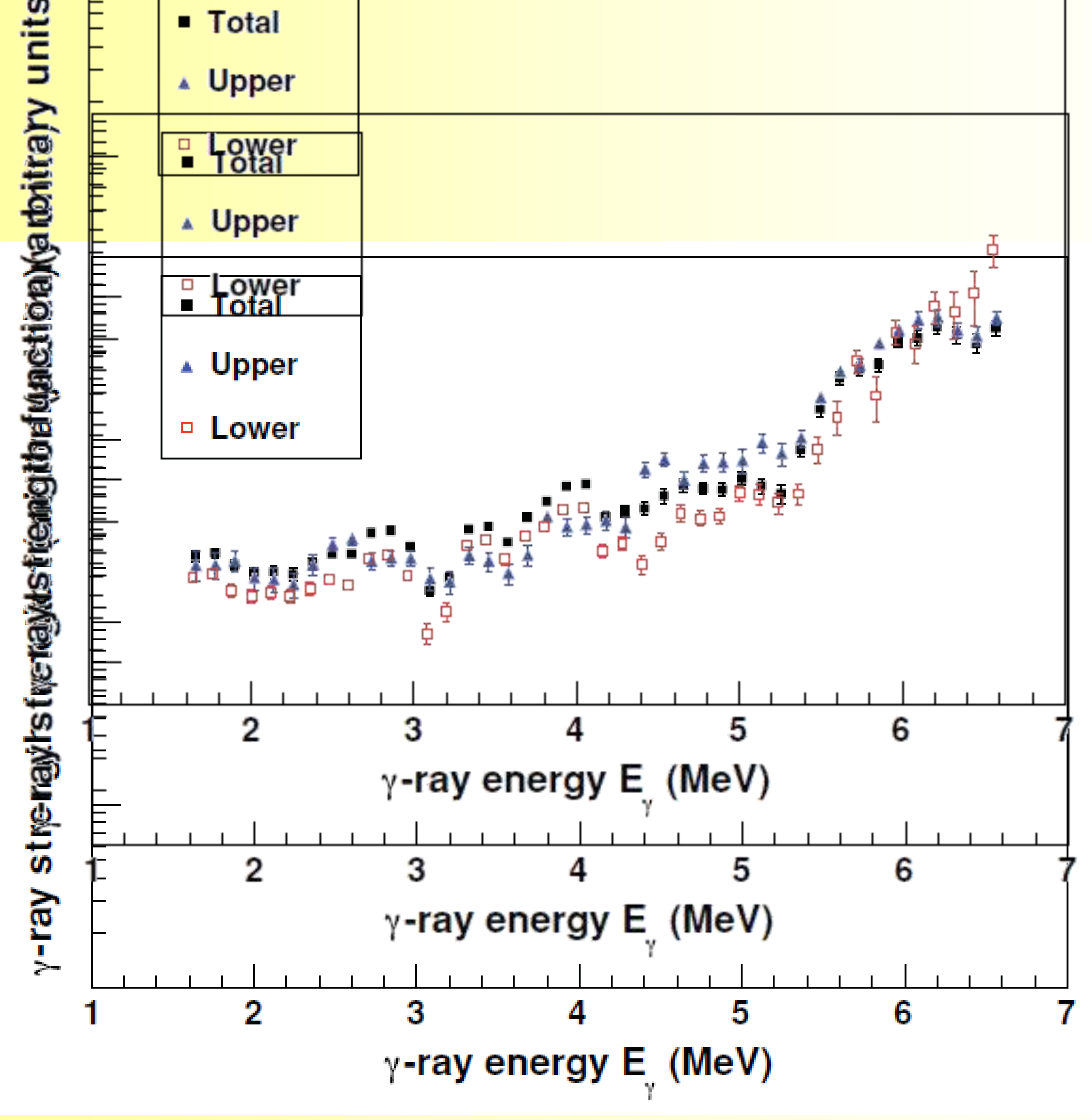
- NRF data suggest that the hypothesis is violated up to energies of several MeV and that PDR might not follow the hypothesis
- Oslo data indicate that Brink hypothesis is a reasonably good concept
- (n,γ) data are inconclusive for E1, require the validity of the hypothesis for M1 scissors mode

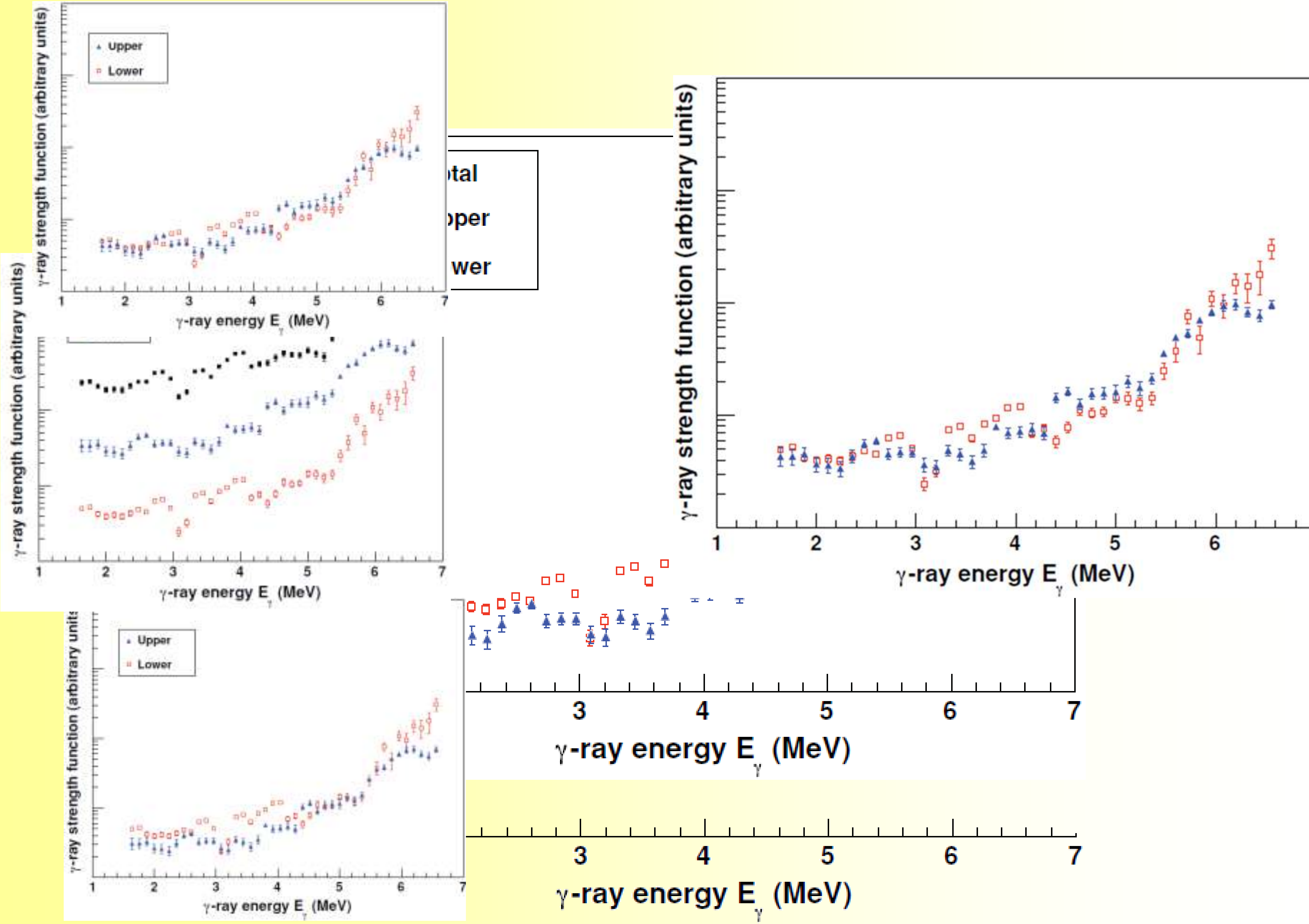


Many thanks to:

- F. Becvar, J. Kroll, S. Valenta from Prague
- G.E. Mitchell, B. Baramsai from NCSU
- C.T. Angell, and HIγS staff
- J. Isaak, D. Savran, … at GSI
- A.C. Larssen, M. Guttormsen, … in Oslo
- J. Ullmann, … at DANCE in Los Alamos

  …


γ-ray strength function (arbitrary units)
Total
Upper
Lower
1
2
3
4
5
6
7
γ-ray energy E_γ (MeV)


Upper
Lower
γ-ray strength function (arbitrary units)
γ-ray energy E_γ (MeV)
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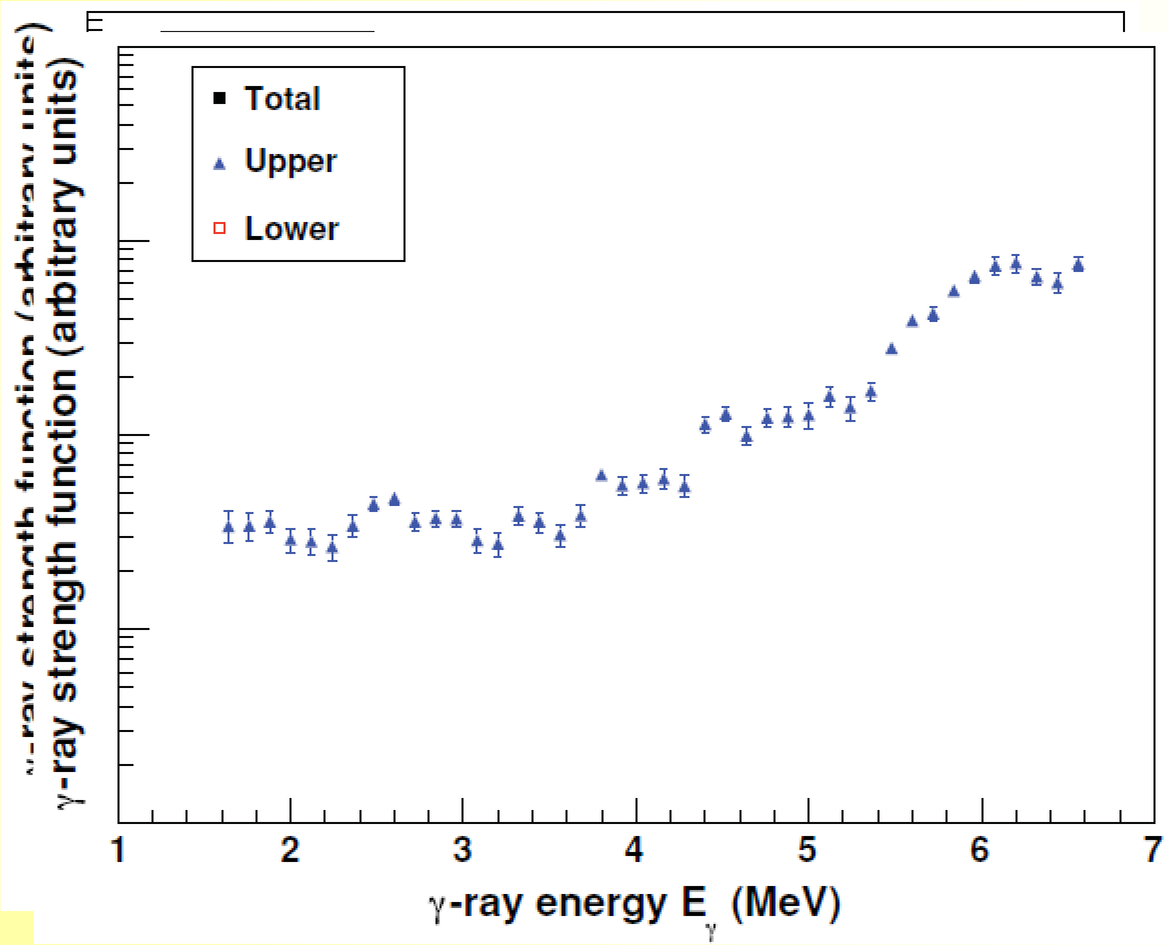
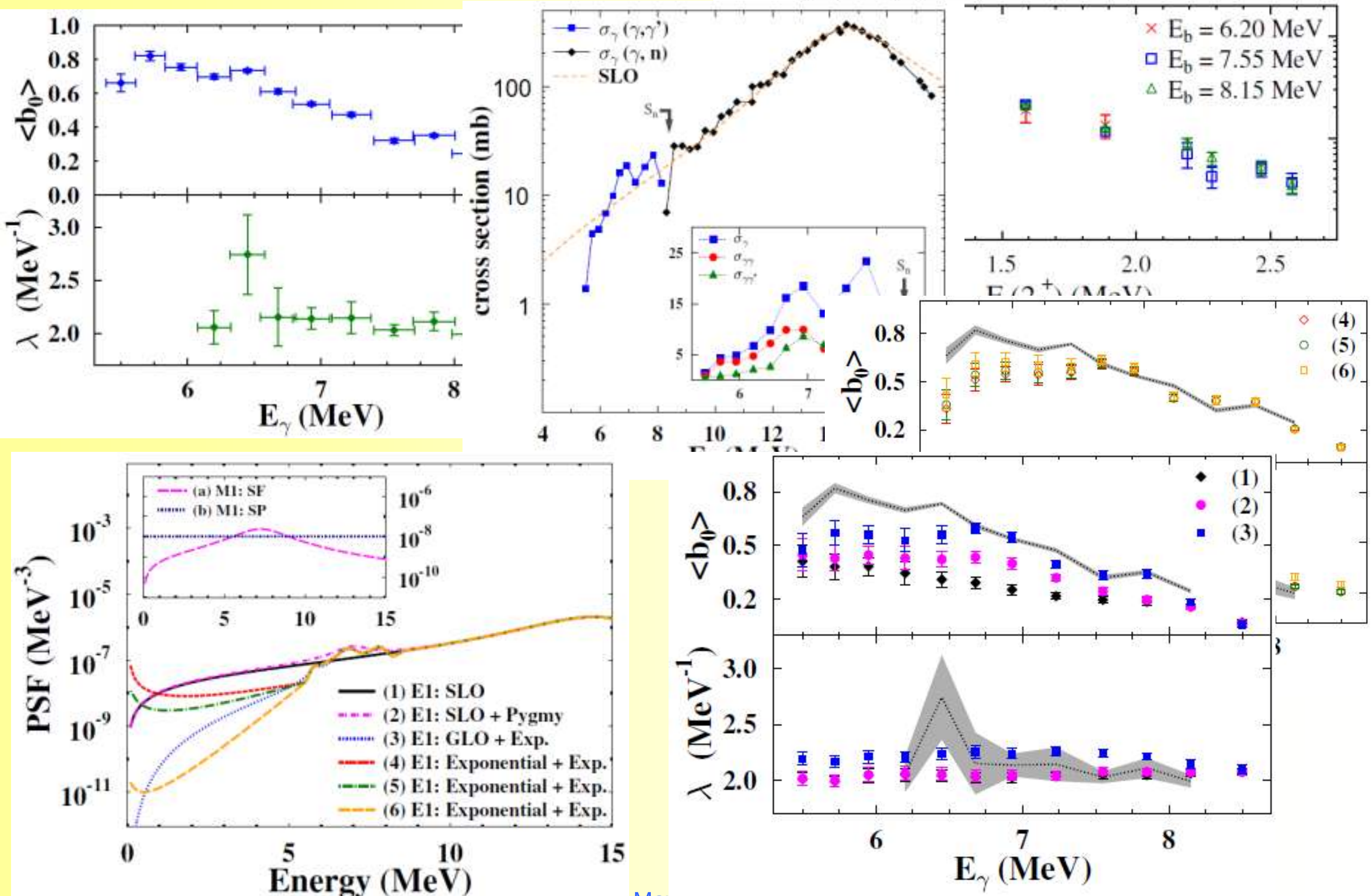
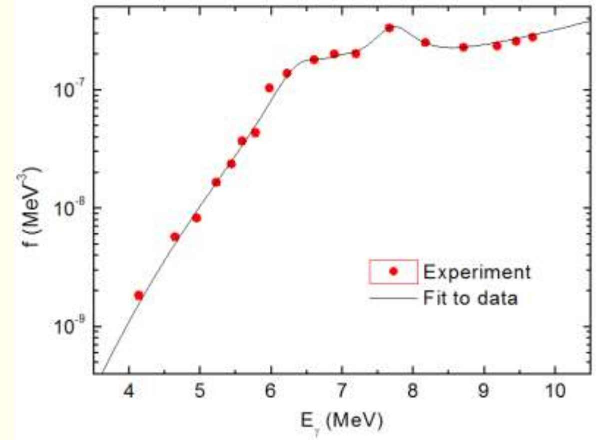
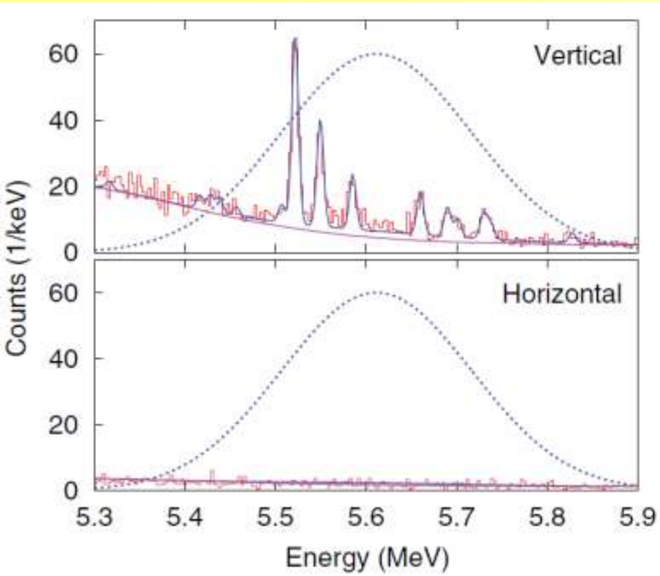
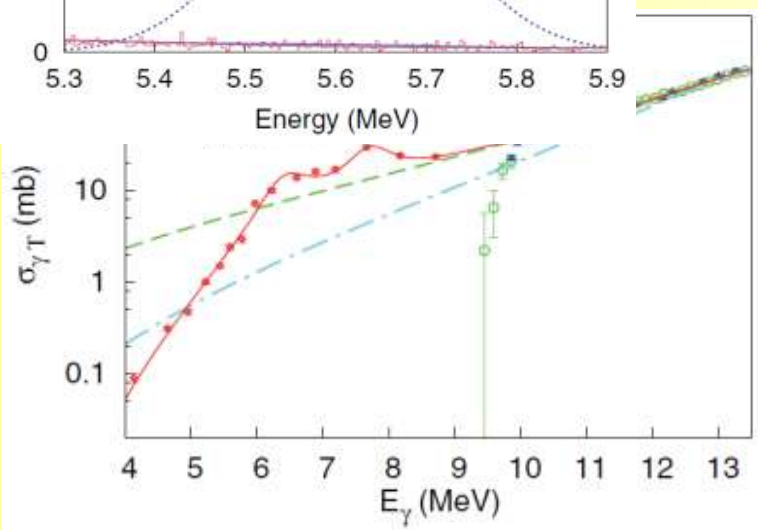

Total
Upper
Lower
γ-ray strength function (arbitrary units)
1
2
3
4
5
6
7
γ-ray energy E_γ (MeV)

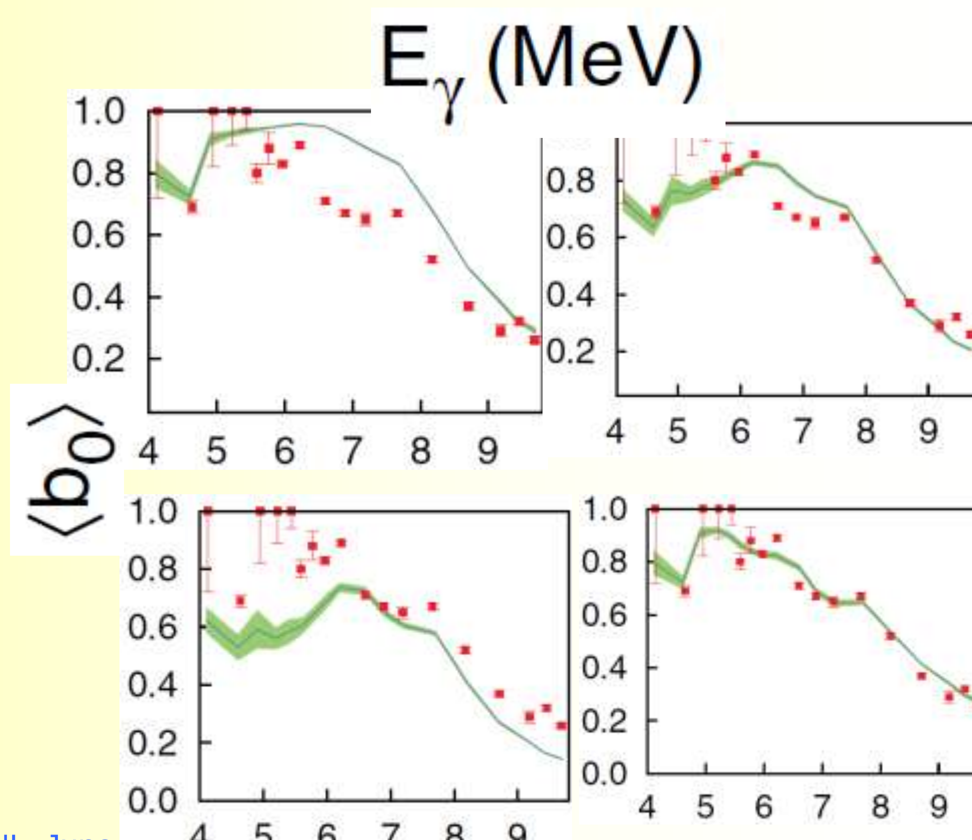
$^{130}Te(\gamma,\gamma')$ @ HIγS – preliminary results




f (MeV^{-3})
E$_\gamma$ (MeV)
Experiment
Fit to data

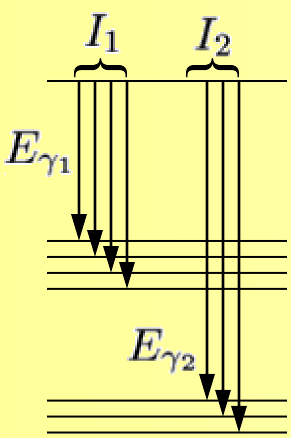

Vertical
Horizontal
Counts (1/keV)
Energy (MeV)


$\sigma_\gamma T$ (mb)
E$_\gamma$ (MeV)


E$_\gamma$ (MeV)
$\langle b_0 \rangle$

Photon strength functions

- give the average probability of photon emission from or photoexcitation of “highly-excited” states (in absolute units)
- are needed in all cases where one deals with γ decay/photoexcitation



$$\frac{I_1}{I_2} = \frac{f(E_{\gamma_1})\,\rho(E_1)\,E_{\gamma_1}^{2L+1}}{f(E_{\gamma_2})\,\rho(E_2)\,E_{\gamma_2}^{2L+1}}$$