

Photon Strength Function Phenomenology

Achievements and open problems

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faculty of mathematics and physics



Outline

- **Genesis of the extreme statistical model for γ decay of nuclear levels, Brink hypothesis, introduction of Photon Strength Function (PSF)**
- **Conventional models for $E1$ and $M1$ PSFs**
- **Comparison between the high-energy (n,γ) and the photonuclear data on TSCs**
- **Testing models for PSF at intermediate γ -ray energies: survey of the results**
- **Evidence for scissors-mode resonances of excited nuclei**
- **Comparison of data from (γ,γ') , $(^3\text{He},^3\text{He}',\gamma)$ and $(^3\text{He},\alpha\gamma)$ reactions**
- **Open problems**
- **Summary**



The *extreme* statistical model of γ decay

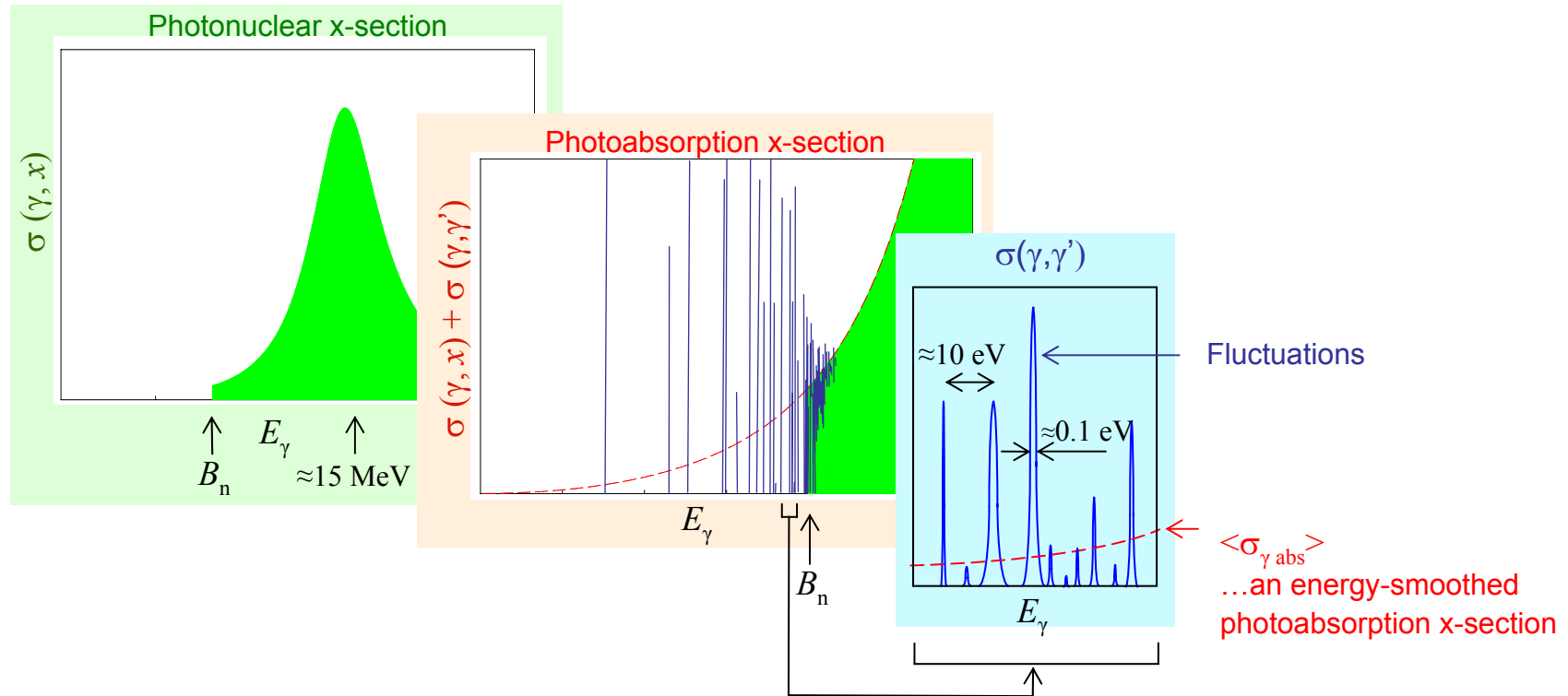
Cornerstones

- *Weisskopf's general notion of the strength function*
- **Fragmentation of strength of GDR and other resonances**
- **Brink hypothesis**
- **Porter-Thomas fluctuations of partial radiation widths**
- **The principle of the detailed balance**
- **Axel-Brink (AB) model in its general formulation**



Fragmentation of the GDR

C. B. Dover, R. H. Lemmer, F. J. W. Hahne, Ann. Phys. (NY). **70**, 458 (1972)



In photoabsorption experiments the presumable Lorentzian shape of the GDR describes even the average strength of the discrete lines below the particle emission threshold



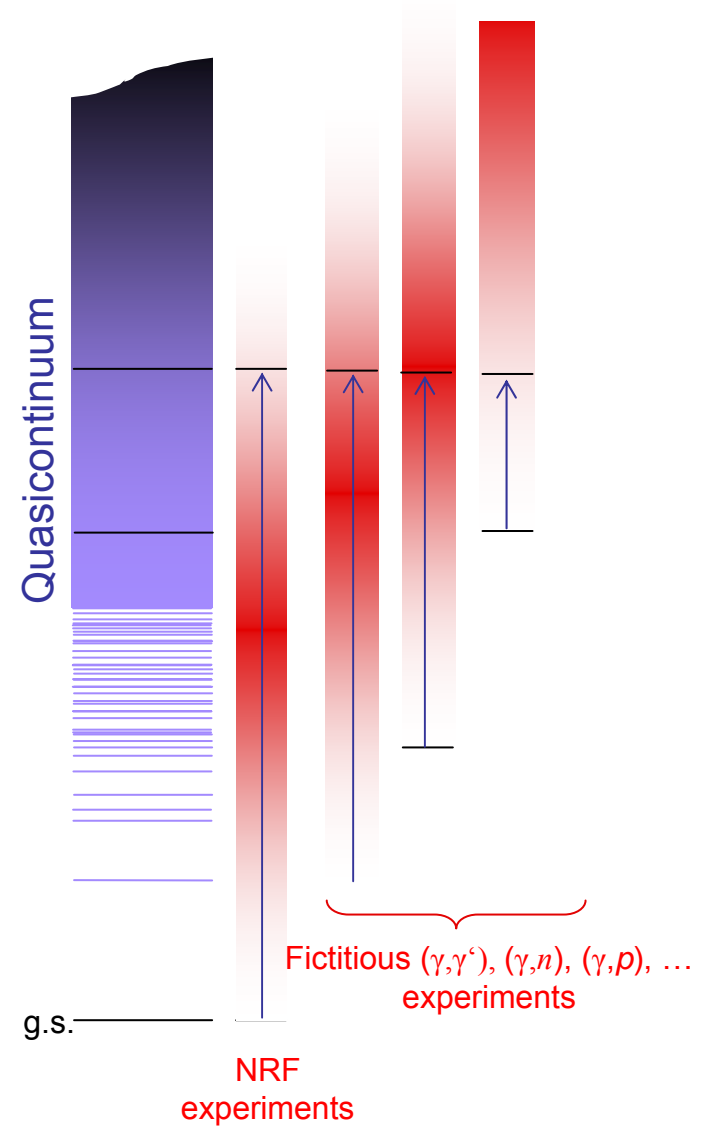
Brink hypothesis

Paraphrased as

“Energy-smoothed photoabsorption cross section

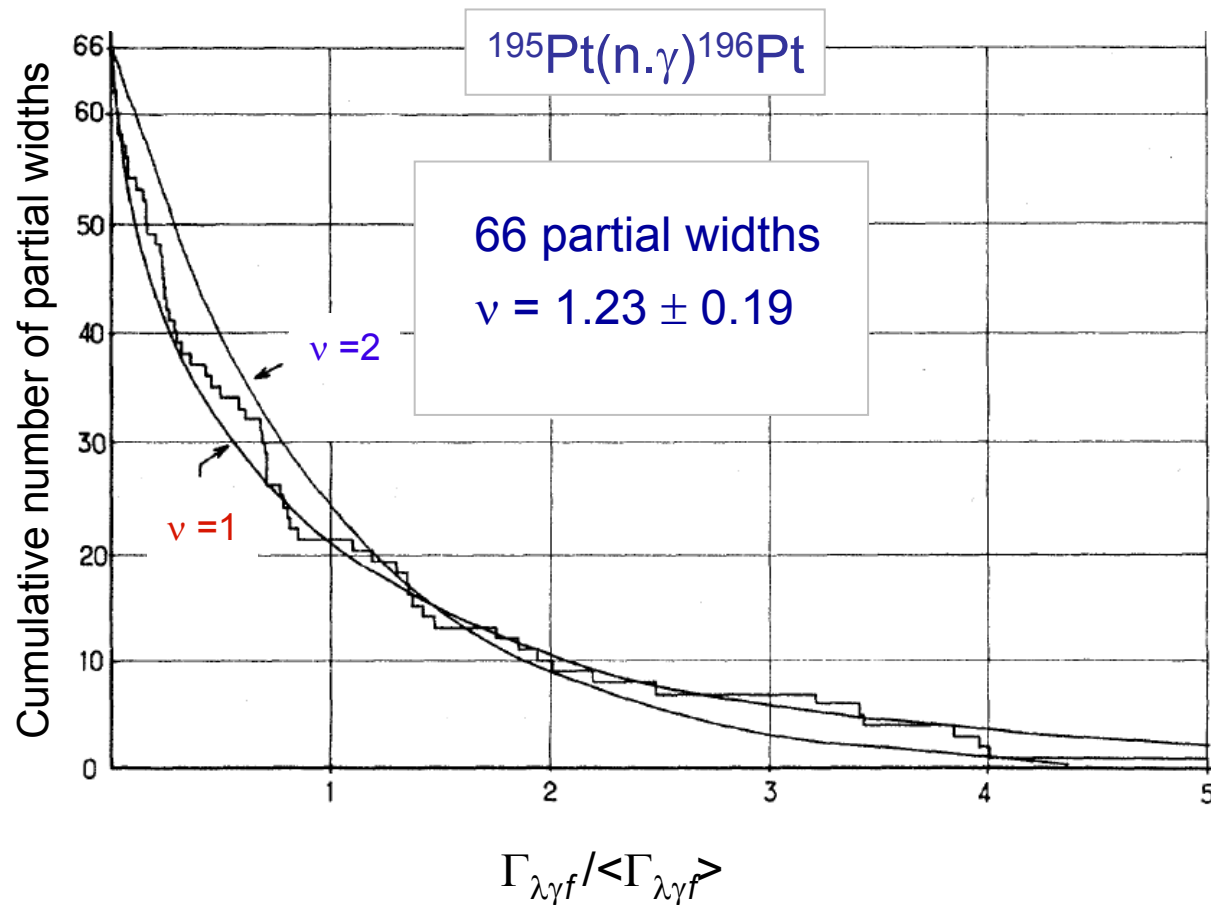
$$\overline{\sigma_{\gamma \text{ abs}}(E_{\gamma})}$$

does not depend on initial excitation energy of a target nucleus”



Validity of Porter-Thomas distribution

H. E. Jackson, *et al.*, PRL **12** (1966) 656



So far, the best test ...



Relation between $\sigma_{\gamma \text{ abs}}$ and $E1$ g.s. transition rates

Peter Axel, Phys. Rev. **126** (1962) 671

- Validity of the principle of the detailed balance
- Ideal fragmentation of the of the $E1$ GDR strength to individual nuclear levels
- J -independence of the expectation value for the ratio

$$\Gamma_{\lambda\gamma 0}^{(J)}/D_J,$$

$\Gamma_{\lambda\gamma 0}^{(J)}$ – partial radiation width for a transition $\lambda \rightarrow 0$ (g.s.)
 D_J – average spacing of initial levels λ with spin J



$$f_{\text{AB}}^{(E1)}(E_{\gamma}) \equiv \frac{\langle \Gamma_{\lambda\gamma 0}^{(J)} \rangle}{E_{\gamma}^3 D_J} = \frac{1}{3(\pi \hbar c)^2} \cdot \frac{\overline{\sigma_{\gamma \text{ abs}}(E_{\gamma})}}{E_{\gamma}}$$

Photon strength function for γ transitions to the g.s. introduced ...



Axel-Brink model (general formulation)

Introduction of Photon Strength Function

Generalization

$$f_{AB}^{(E1)}(E_\gamma) \equiv \frac{\langle \Gamma_{\lambda\gamma 0}^{(J)} \rangle}{E_\gamma^3 D_J} = \frac{1}{3(\pi \hbar c)^2} \cdot \frac{\overline{\sigma_{\gamma \text{ abs}}(E_\gamma)}}{E_\gamma}$$

Photon strength function for γ transitions to the g.s.



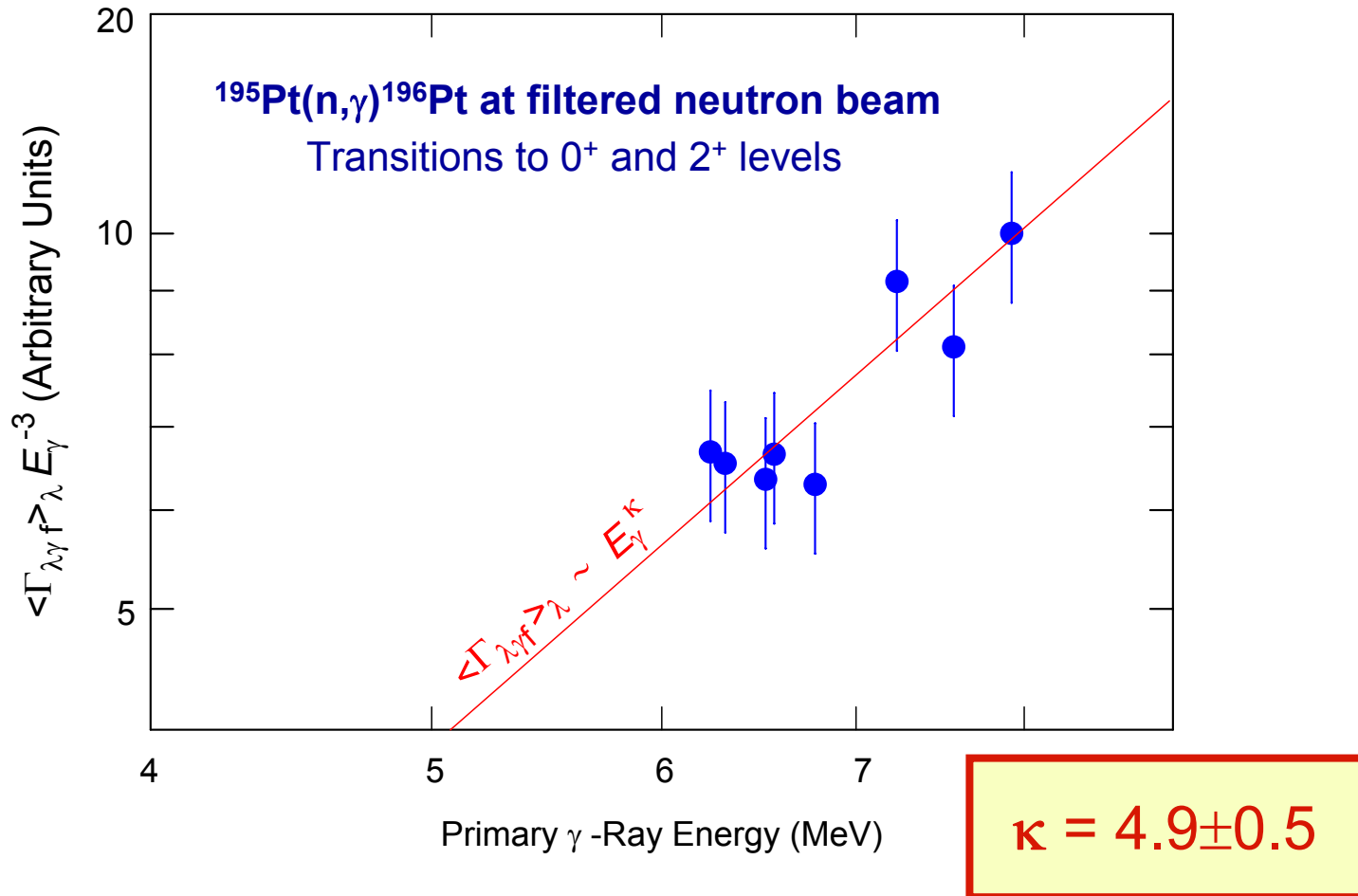
$$f_{AB}^{(E1)}(E_\gamma) \equiv \frac{\langle \Gamma_{\lambda\gamma f}^{(J)} \rangle}{E_\gamma^3 D_J} = \frac{1}{3(\pi \hbar c)^2} \cdot \frac{\overline{\sigma_{\gamma \text{ abs}}(E_\gamma)}}{E_\gamma}$$

Photon strength function for γ transitions to any final level f

Identical

First hint for validity of the Axel-Brink Model

Data of L. M. Bollinger and G. E. Thomas, PRL **25** (1967) 1143



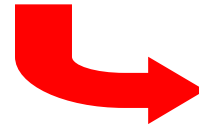
First hint for validity of the Axel-Brink model

L. M. Bollinger and G. E. Thomas, Phys. Rev. Lett. **18** (1967) 1143:

“There is no adequate, theoretically based explanation of the E_γ^5 dependence of the experimental widths, although an idea introduced by Brink and developed by Axel may be relevant.”

For Lorentzian E1 GDR and a typical heavy nucleus:

$$\frac{d}{dE_\gamma} \ln f_{AB}^{(E1)}(E_\gamma) \approx 2 \quad \text{at} \quad E_\gamma \approx 7 \text{ MeV} \quad \text{for a typical heavy nucleus}$$



$$\langle \Gamma_{\lambda\gamma f} \rangle_\lambda \propto E_\gamma^5$$

Generalization of E1 PSF seemed true:

$$f_{AB}^{(E1)}(E_\gamma) \equiv \frac{\langle \Gamma_{\lambda\gamma f}^{(J)} \rangle}{E_\gamma^3 D_J} = \frac{1}{3(\pi \hbar c)^2} \cdot \frac{\overline{\sigma_{\gamma \text{ abs}}(E_\gamma)}}{E_\gamma}$$

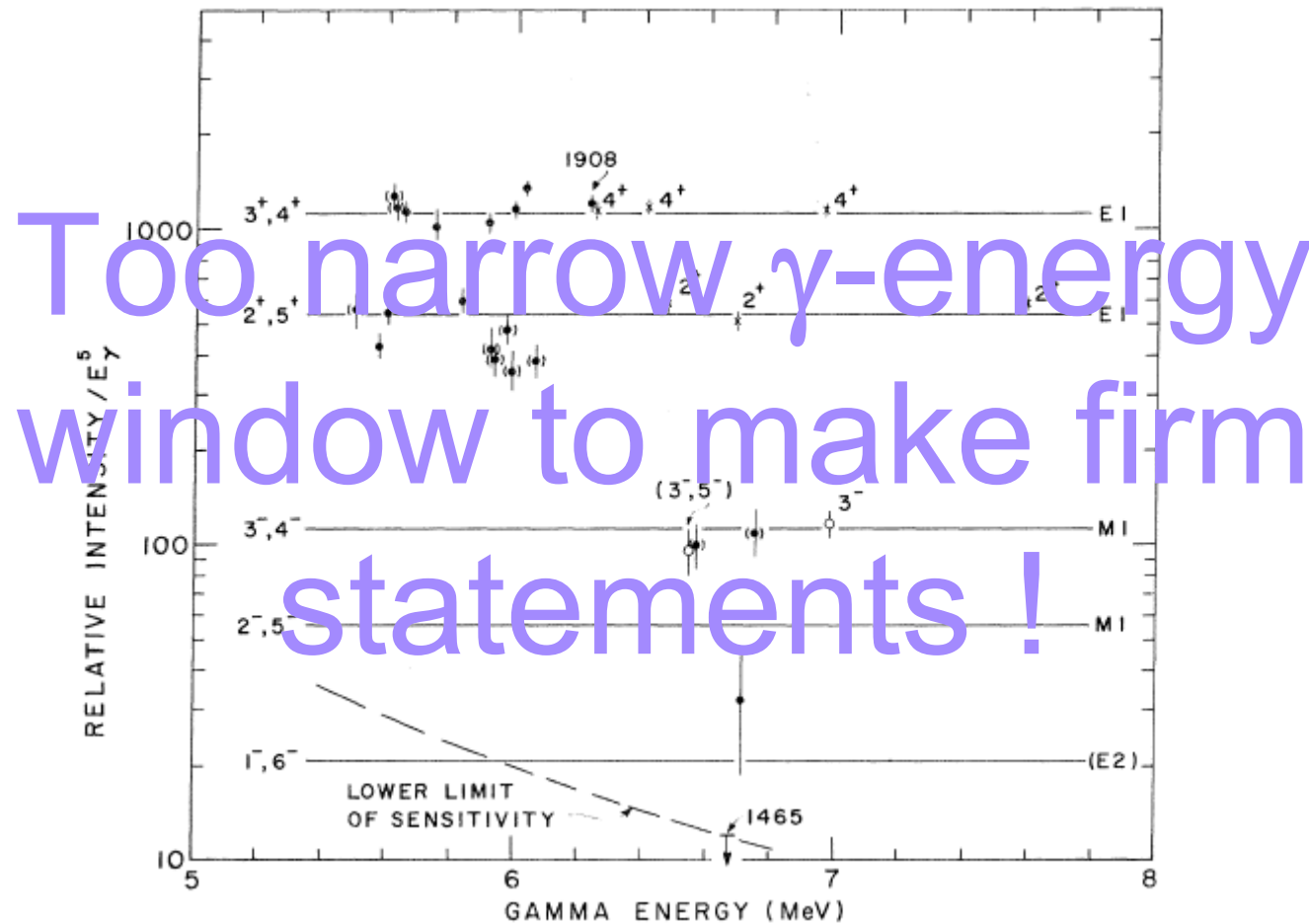
... the birth of the extreme statistical model for γ decay of nuclear levels



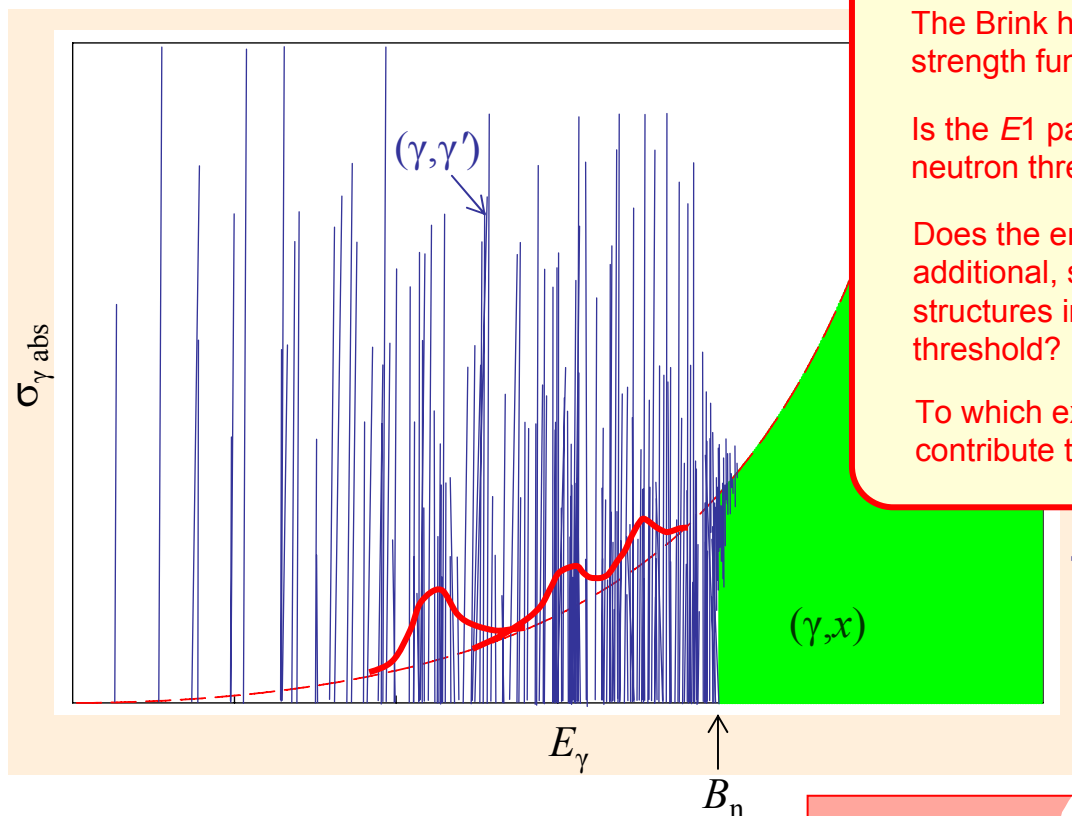
Evidence for validity of AB model: taken for granted

ARC data from $^{149}\text{Sm}(n,\gamma)^{150}\text{Sm}$ reaction

D. Buss and R. K. Smither, PRC 2 (1970) 1513



Photon strength functions: problems



The Brink hypothesis and the paradigm of the photon strength function: do they hold?

Is the $E1$ part of $\langle \sigma_{\gamma \text{ abs}}(E_{\gamma}) \rangle$ for energies near and below neutron threshold an extrapolation of a Lorentzian GDR?

Does the energy dependence of $\langle \sigma_{\gamma \text{ abs}}(E_{\gamma}) \rangle$ display additional, statistically significant resonance-like structures in the region near or below the neutron threshold?

To which extent the other multipolarities (M1, E2, ...) contribute to photoabsorption cross section $\langle \sigma_{\gamma \text{ abs}}(E_{\gamma}) \rangle$?

The main obstacles in studying PSFs:

- strong Porter-Thomas fluctuations of partial rad. widths
- limited knowledge of other quantities (level densities, ...)

(γ, x) – g.s. only

(n, γ) at isolated neutron resonances, ARC

(γ, γ') – NRF, g.s. only

(n, γ) – two-step & n -step cascades
 $(^3\text{He}, ^3\text{He}'\gamma)$, $(^3\text{He}, \alpha\gamma)$

$(p, p'\gamma)$ at small angles of scattering



Models used for E1 PSF

1. Axel-Brink model:

$$f_{\text{AB}}^{(E1)}(E_\gamma) = \frac{1}{3(\pi\hbar c)^2} \frac{\sigma_G \Gamma_G^2 E_\gamma}{(E_\gamma^2 + E_G^2)^2 + E_\gamma^2 \Gamma_G^2}$$

2. Model of Kadenskij, Markushev and Furman:

$$f_{\text{KMF}}^{(E1)}(E_\gamma, T_f) = \frac{1}{3(\pi\hbar c)^2} \underbrace{\left(\frac{1 + 2f'_1/3}{1 + 2f'_0} \right)^{1/2}}_{\text{Landau-Migdal parameters}} \frac{\sigma_G E_G \tilde{\Gamma}_G(E_\gamma, T_f)}{(E_\gamma^2 + E_G^2)^2}$$

Landau-Migdal parameters

$$\tilde{\Gamma}_G(E_\gamma, T_f) = \frac{\Gamma_G}{E_G^2} (E_\gamma^2 + 4\pi^2 T_f^2)$$

The damping width due to strongly interacting quasiparticles

Kadenskij, Markushev, Furman (1982)

... energy and temperature dependence

- An approximation for low γ -ray energies
- Not justified for deformed nuclei
- At $T > 0$ it gives a non-zero limit for $E_\gamma \rightarrow 0$
- Diverges for $E_\gamma \rightarrow E_G$



Models used for E1 PSF

3. Model GLO:

$$f_{\text{GLO}}^{(E1)}(E_\gamma, T_f) = \frac{1}{3(\pi\hbar c)^2} \frac{\sigma_G \tilde{\Gamma}_G^2 E_\gamma}{(E_\gamma^2 + E_G^2)^2 + E_\gamma^2 \tilde{\Gamma}_G^2} + f_{\text{KMF}}^{(E1)}(0, T_f)$$

$$\tilde{\Gamma}_G(E_\gamma, T_f) = \frac{\Gamma_G}{E_G^2} (E_\gamma^2 + 4\pi^2 T_f^2)$$

R. E. Chrien, Dubna Report No. D3, 4, 17-86-747 (1987)

Divergence for $E_\gamma \rightarrow E_G$ removed

4. Semi-empirical model EGLO:

$$f_{\text{EGLO}}^{(E1)}(E_\gamma, T_f) = \frac{1}{3(\pi\hbar c)^2} \frac{\sigma_G \tilde{\tilde{\Gamma}}_G^2 E_\gamma}{(E_\gamma^2 + E_G^2)^2 + E_\gamma^2 \tilde{\tilde{\Gamma}}_G^2} + f_{\text{KMF}}^{(E1)}(0, T_f)$$

$$\tilde{\tilde{\Gamma}}_G(E_\gamma, T_f) = \left[k_0 + \frac{E_\gamma - E_{\gamma 0}}{E_G - E_{\gamma 0}} (1 - k_0) \right] \frac{\Gamma_G}{E_G^2} (E_\gamma^2 + 4\pi^2 T_f^2)$$

k_0 , $E_{\gamma 0}$ adjustable parameters

J. Kopecky, M. Uhl and R. E. Chrien, PRC 47 (1993) 312

A good description for spherical, transitional and deformed nuclei achieved at energies $E_\gamma > 6$ MeV



Models for $M1$ PSF

1. The single-particle model

A constant PSF

2. The spin-flip model

Analogous to AB model for $E1$ PSF

Parameters deduced from the $(p,p'\gamma)$ data

3. The scissors-resonance temperature-independent model

Photon strength assumed not to depend on nuclear temperature

$$f^{(M1,SR)}(E_\gamma) = \frac{16\pi}{27(\hbar c)^3} \frac{E_0}{\arctan(2E_0/\Gamma_{SR})} \frac{\Gamma_{SR} E_\gamma}{(E_\gamma^2 + E_{SR}^2)^2 + E_\gamma^2 \Gamma_{SR}^2} \sum B(M1)\uparrow$$

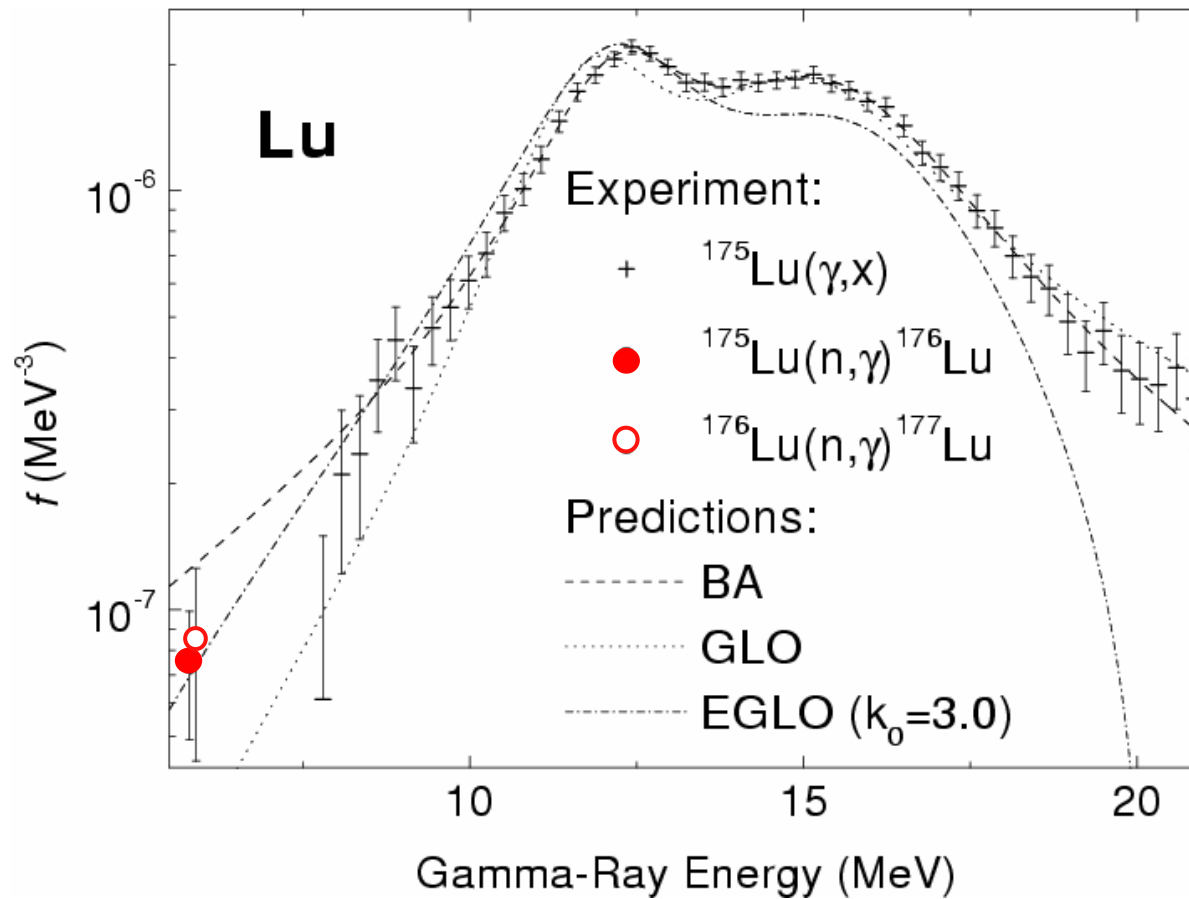
$$E_0 = \sqrt{E_{SR}^2 - \Gamma_{SR}^2/4}$$

F. B., *et al.*, PRC **52** (1995) 1278

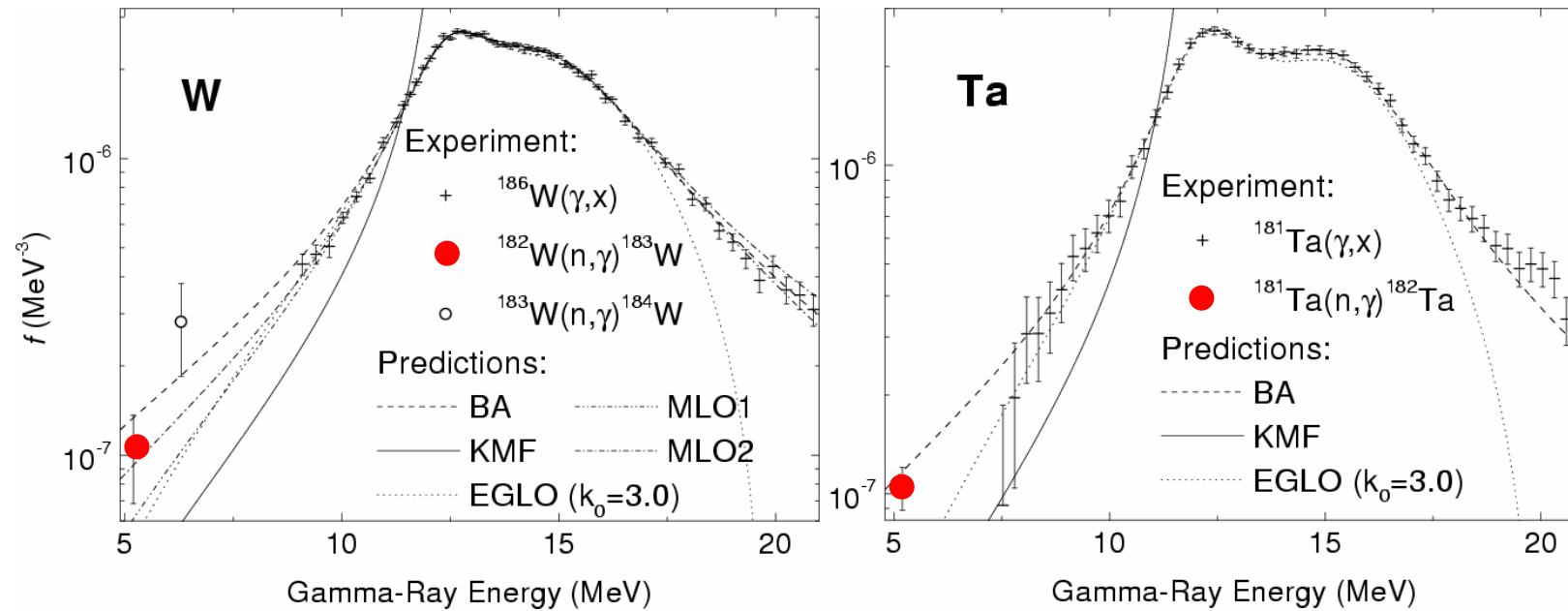
It was believed for long time that the $E1$ strength dominated $M1$...



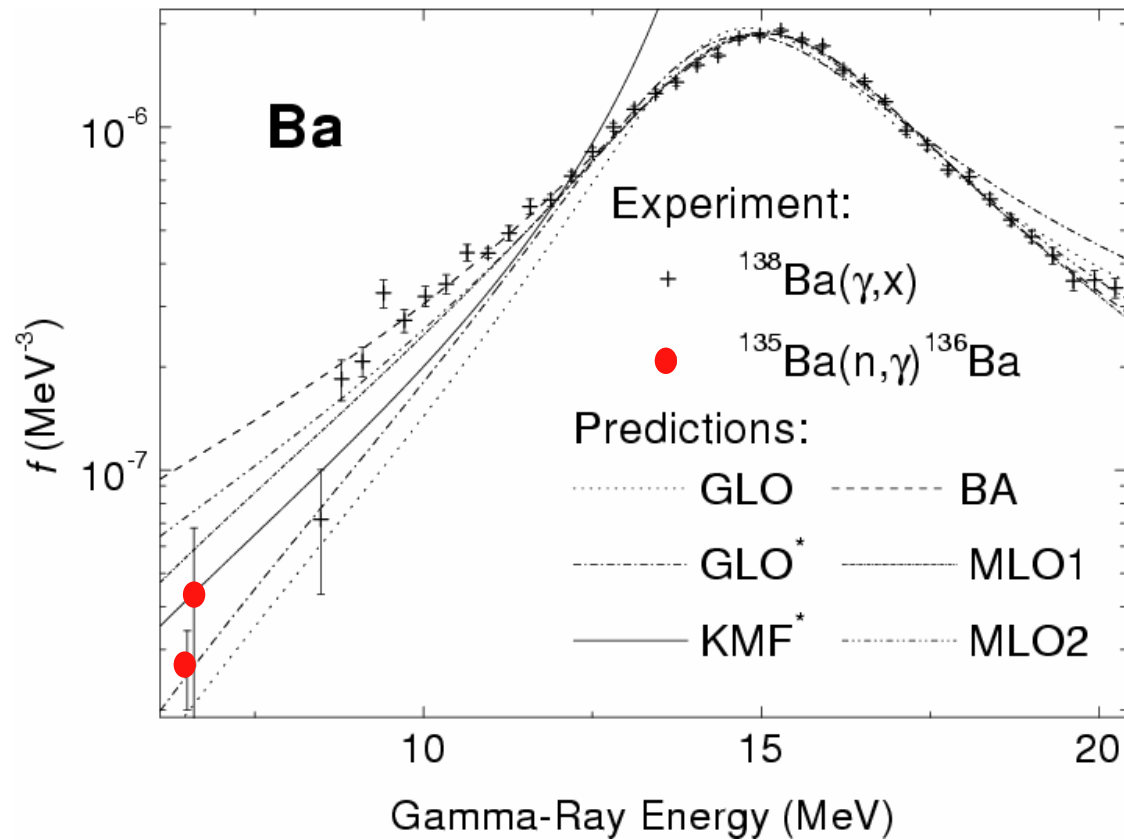
Comparison between photonuclear and primary (n,γ) data



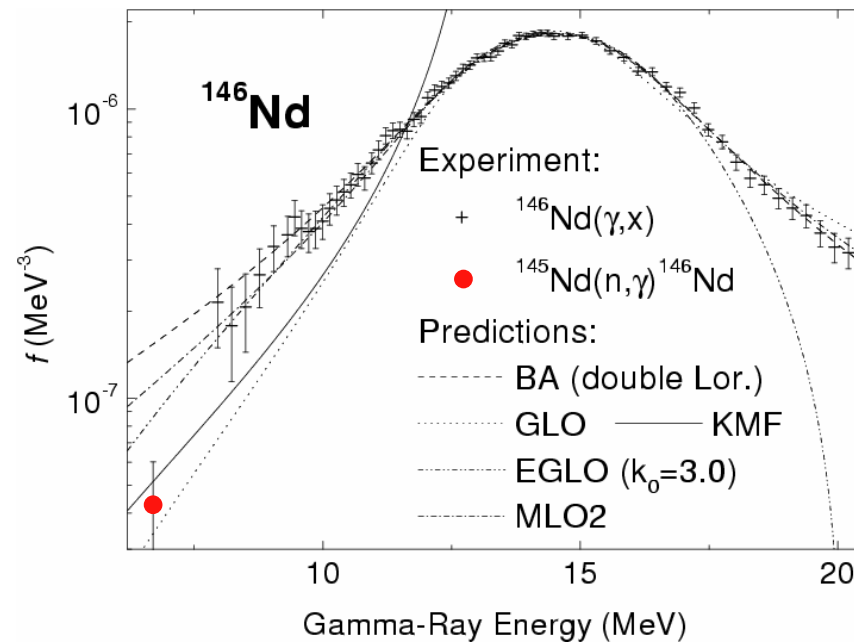
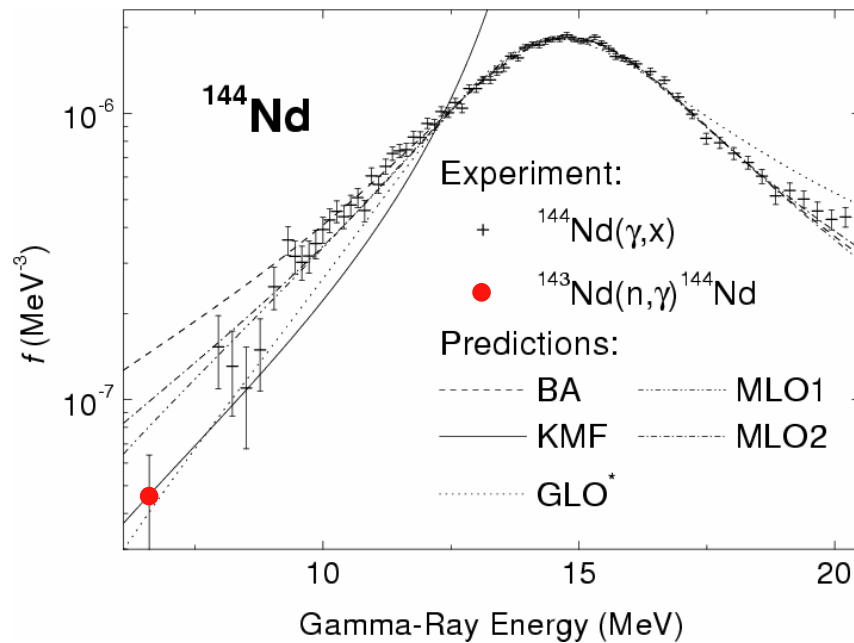
Comparison between photonuclear and primary (n,γ) data



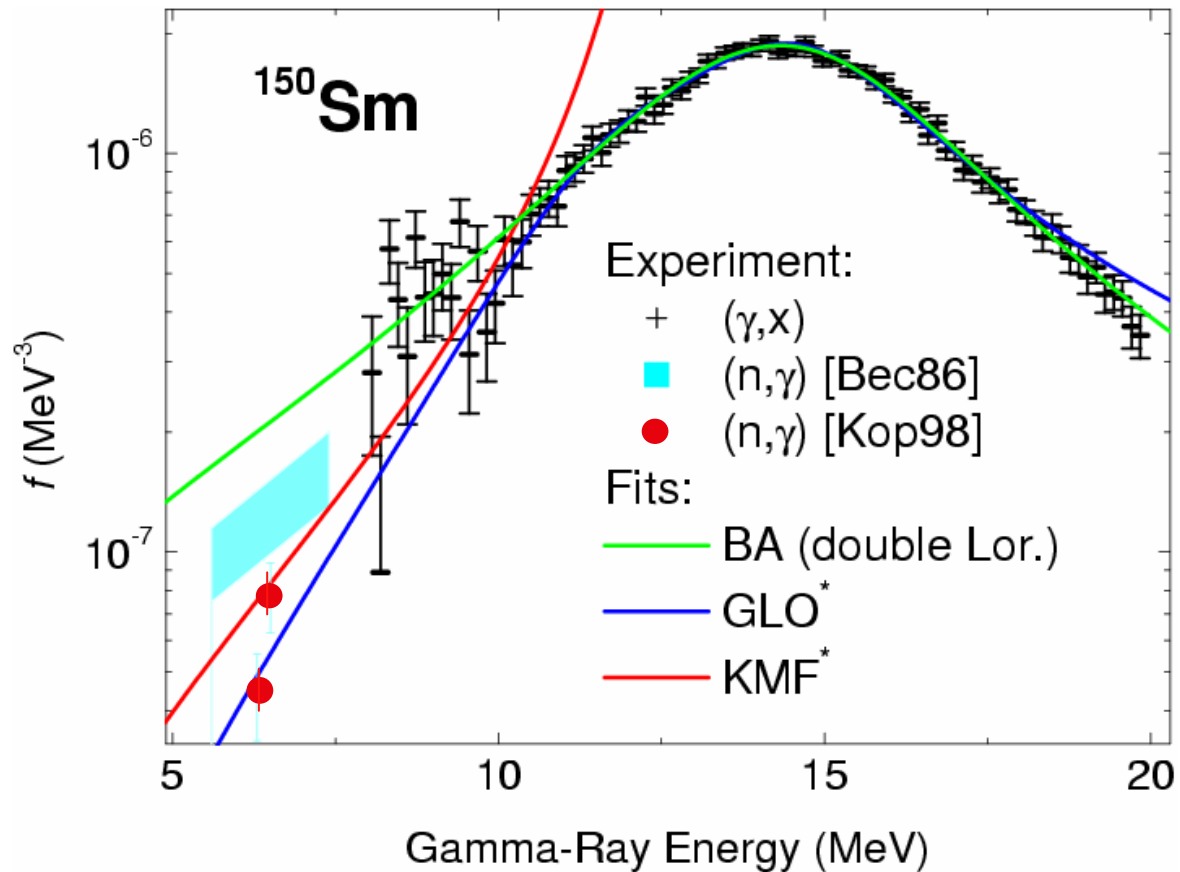
Comparison between photonuclear and primary (n,γ) data



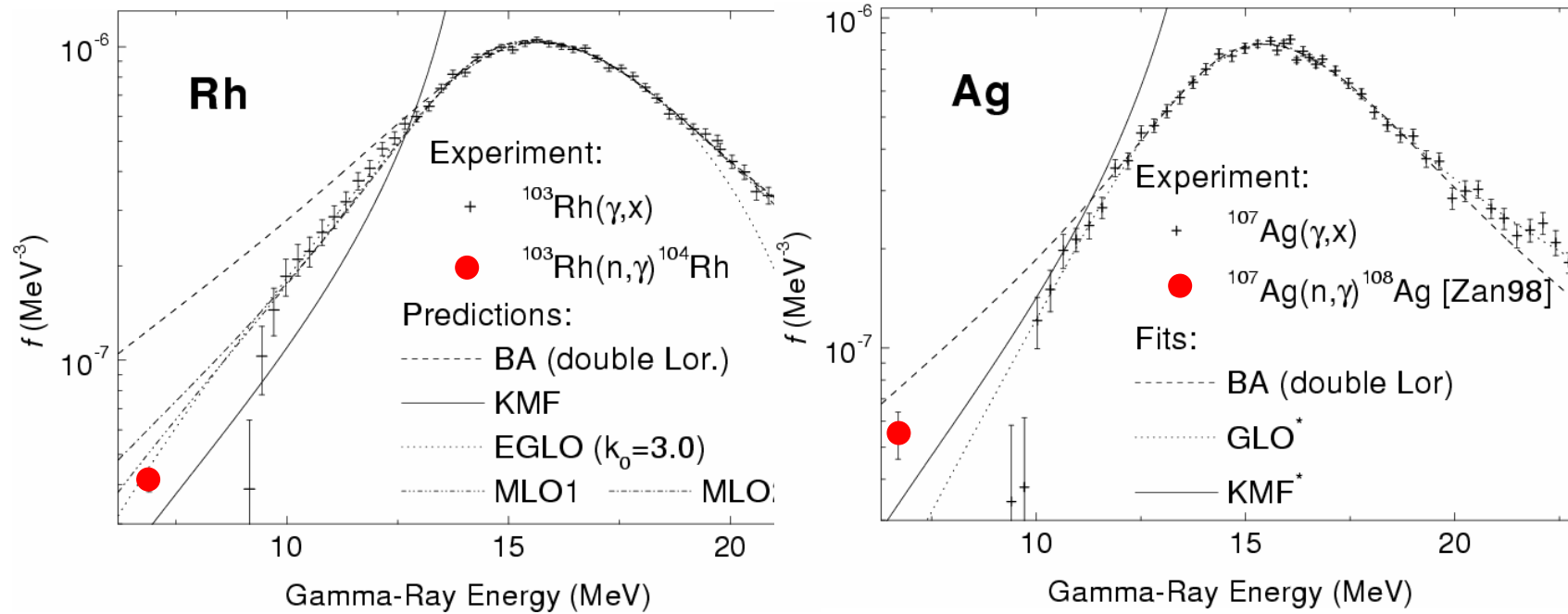
Comparison between photonuclear and primary (n,γ) data



Comparison between photonuclear and primary (n,γ) data



Comparison between photonuclear and primary (n,γ) data



Accounted for by
triaxiality ?

Comparison between photonuclear and (n, γ) data

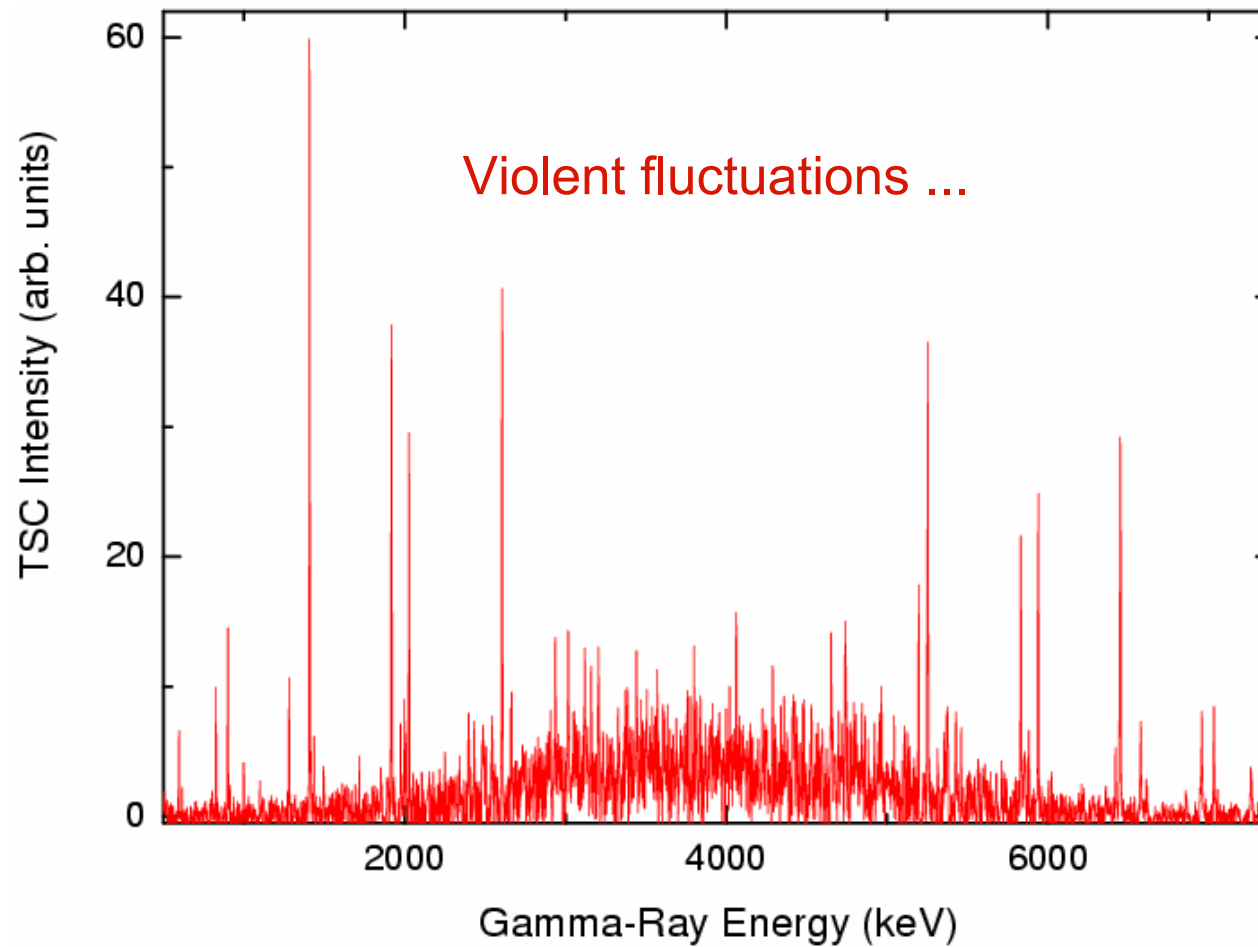
Conclusions from primary γ -ray data

- PSFs for deformed rare-earth nuclei in γ -ray energy region of 6-8 MeV are in reasonable accordance with predictions of the Axel-Brink model
- PSFs of spherical and transitional nuclei in the same γ -ray energy region are appreciably lower compared to predictions of this model

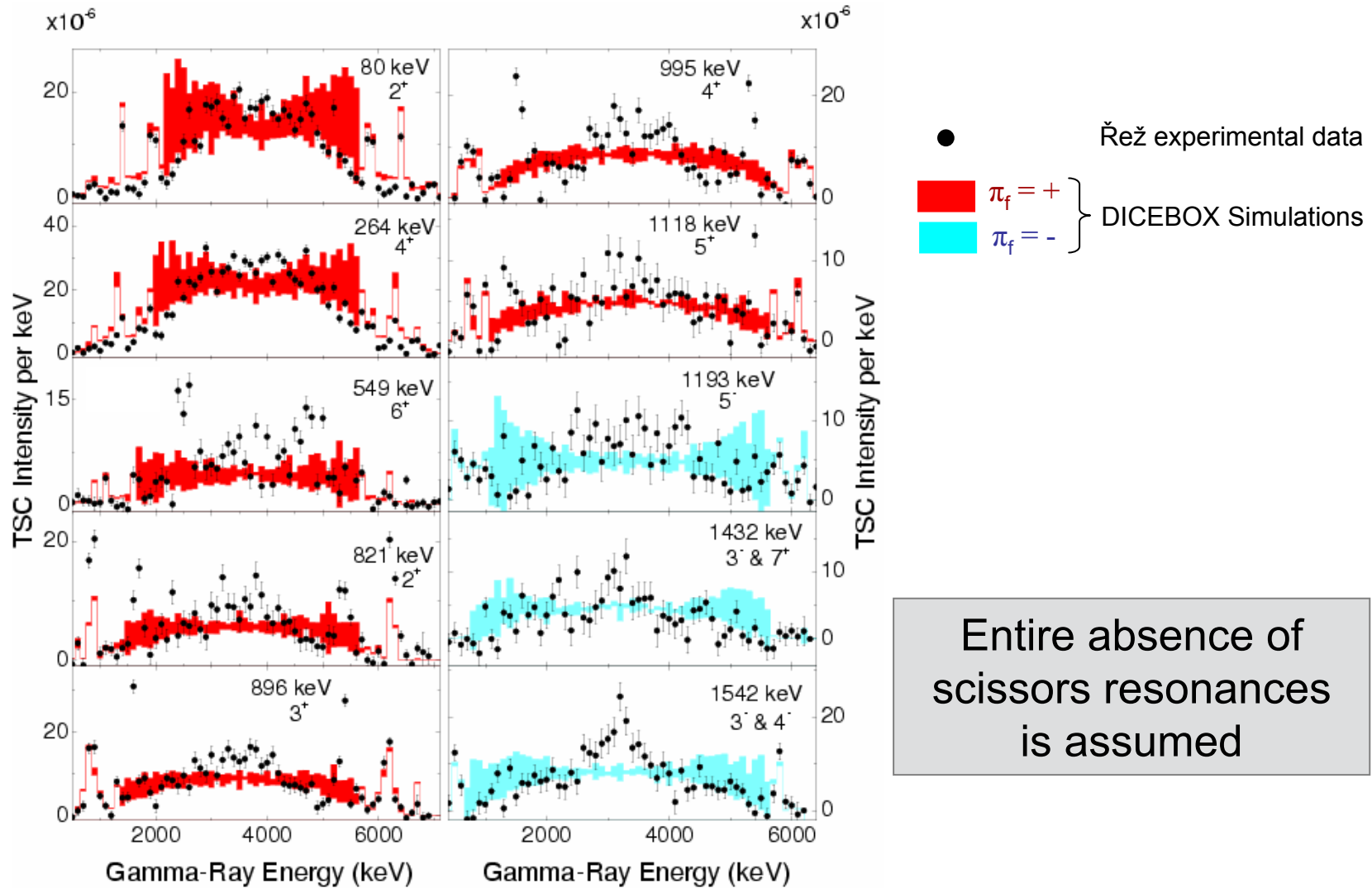


Two-step γ cascades: the $^{167}\text{Er}(n,\gamma)^{168}\text{Er}$ reaction

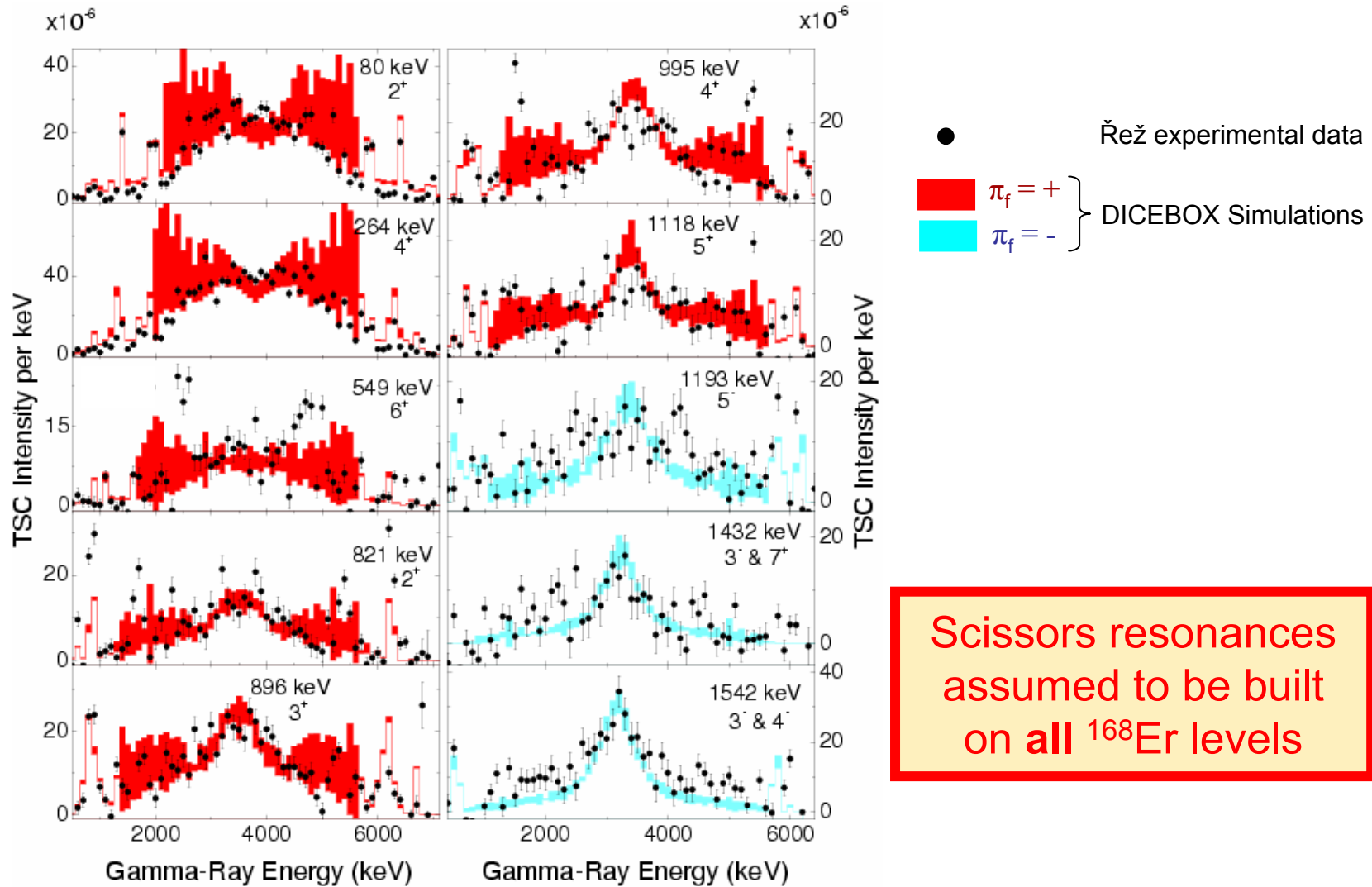
TSCs terminating at the $J^\pi = 4^+$, 264 keV level in ^{168}Er



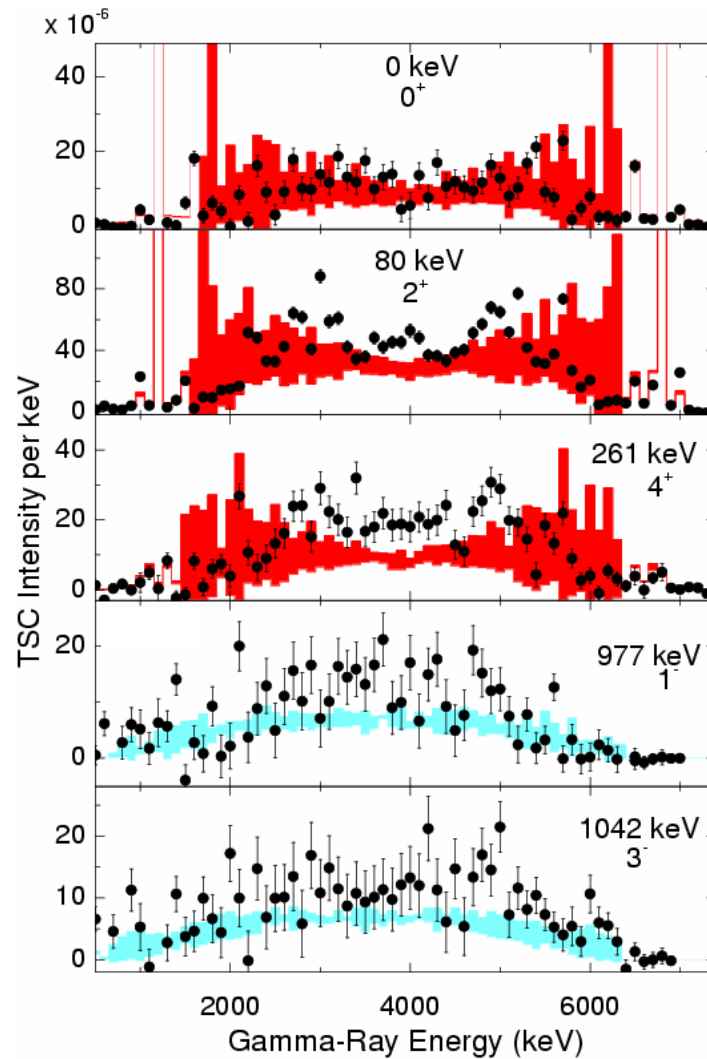
TSCs in the $^{167}\text{Er}(n,\gamma)^{168}\text{Er}$ reaction



TSCs in the $^{167}\text{Er}(n,\gamma)^{168}\text{Er}$ reaction



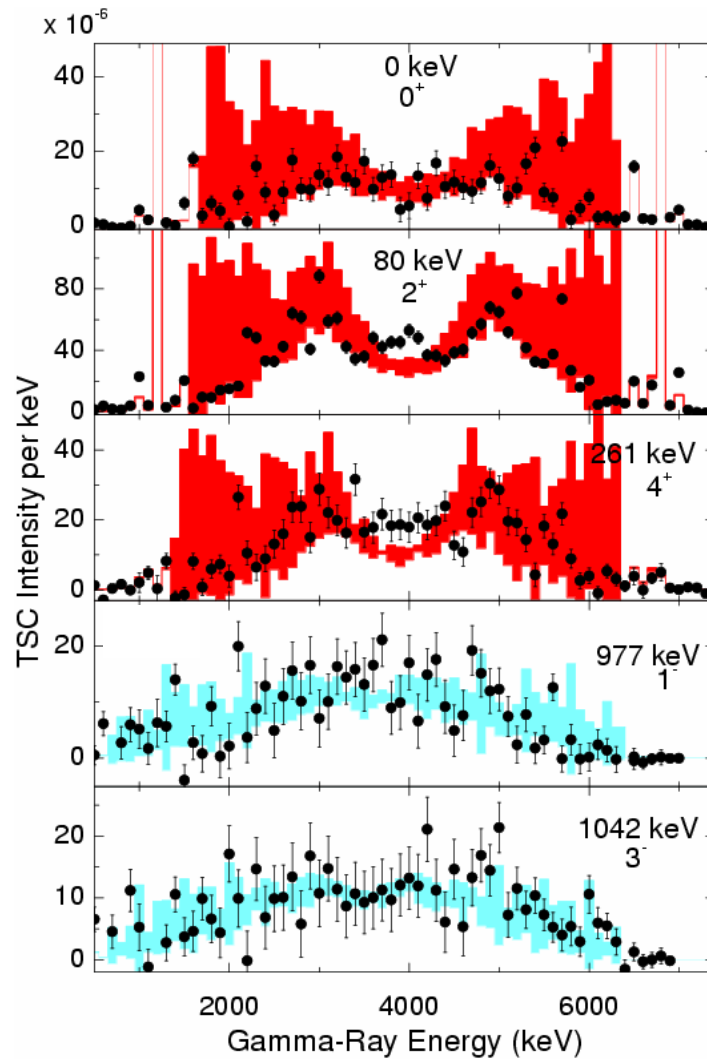
TSCs in the $^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$ reaction



● Řež experimental data
■ $\pi_f = +$
■ $\pi_f = -$ } DICEBOX Simulations

Entire absence of
scissors resonances
is assumed

TSCs in the $^{157}\text{Gd}(n,\gamma)^{158}\text{Gd}$ reaction

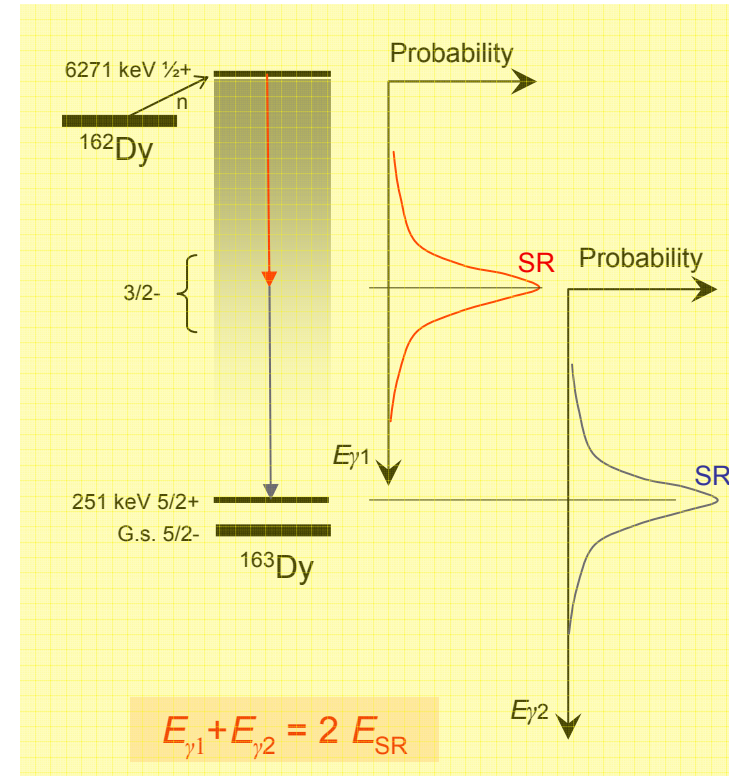
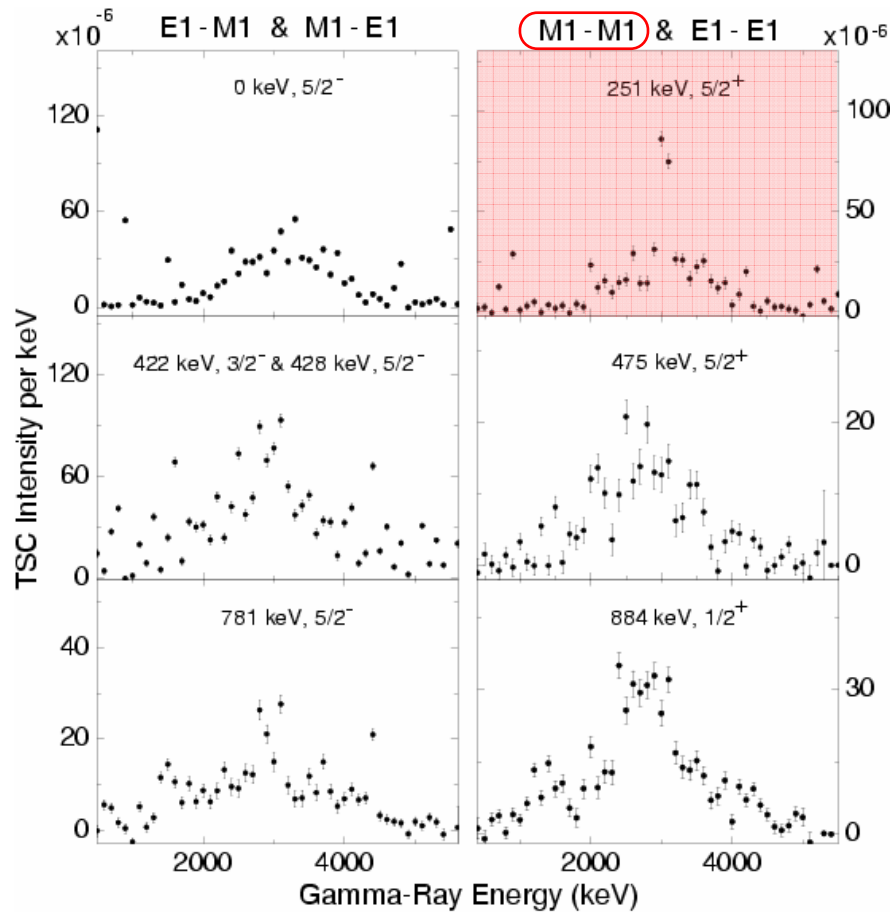


● Řež experimental data
■ $\pi_f = +$
■ $\pi_f = -$ } DICEBOX Simulations

Scissors resonances
assumed to be built
on all ^{158}Gd levels

TSCs in the $^{162}\text{Dy}(n,\gamma)^{163}\text{Dy}$ reaction

M. Krticka et. al, PRL **92** (2004) 172501

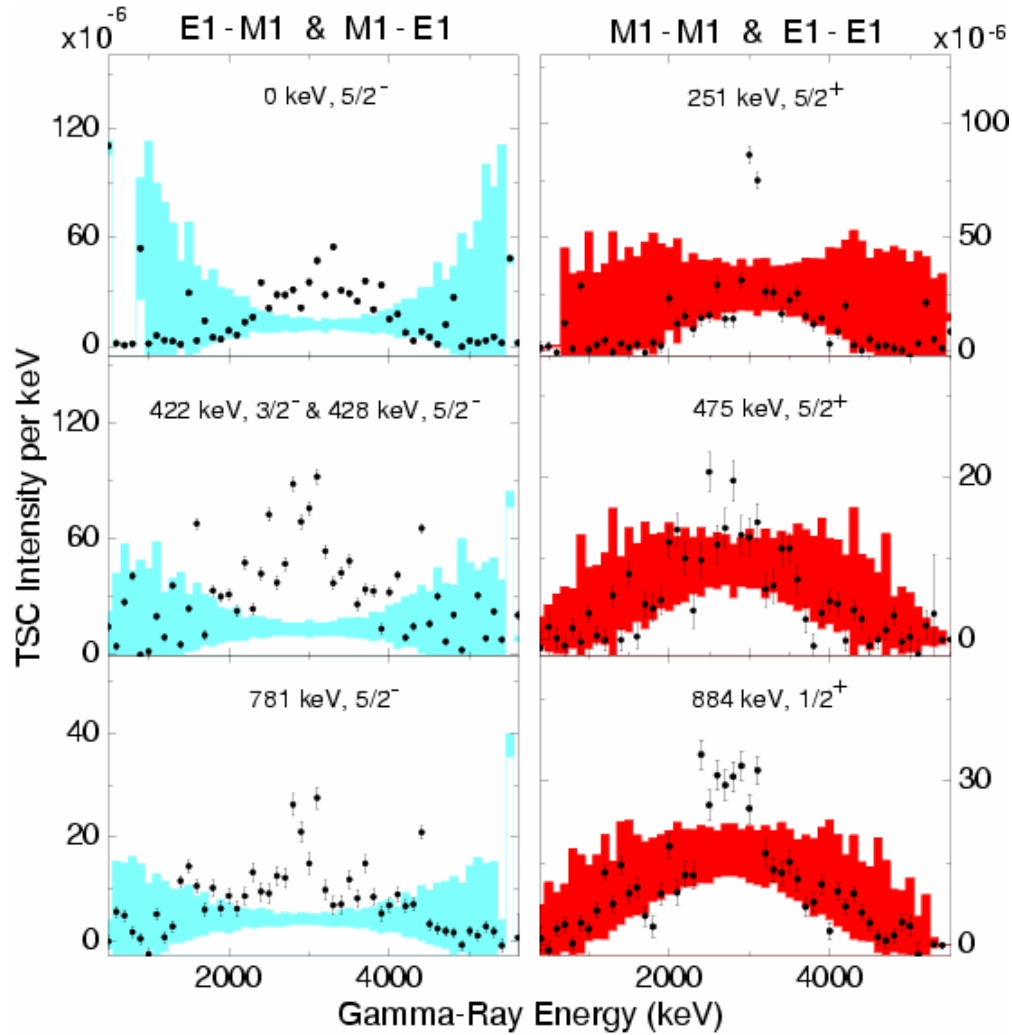


Sharpening the peak at the midpoint
of the TSC spectrum

**A unique possibility of a sensitive test for presence of SRs
for the 251 keV final level
built on the levels in the quasicontinuum**



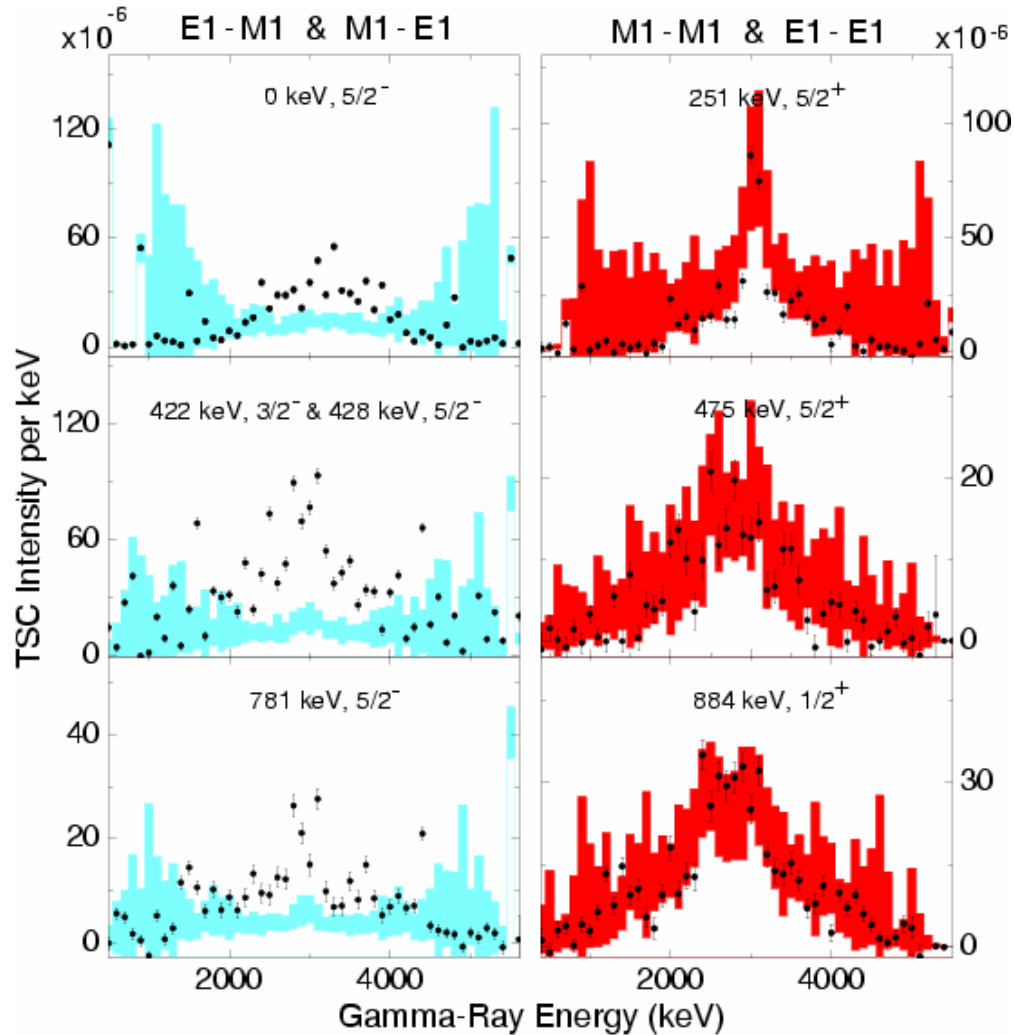
TSCs in the $^{162}\text{Dy}(n,\gamma)^{163}\text{Dy}$ reaction



Entire absence of SRs is assumed



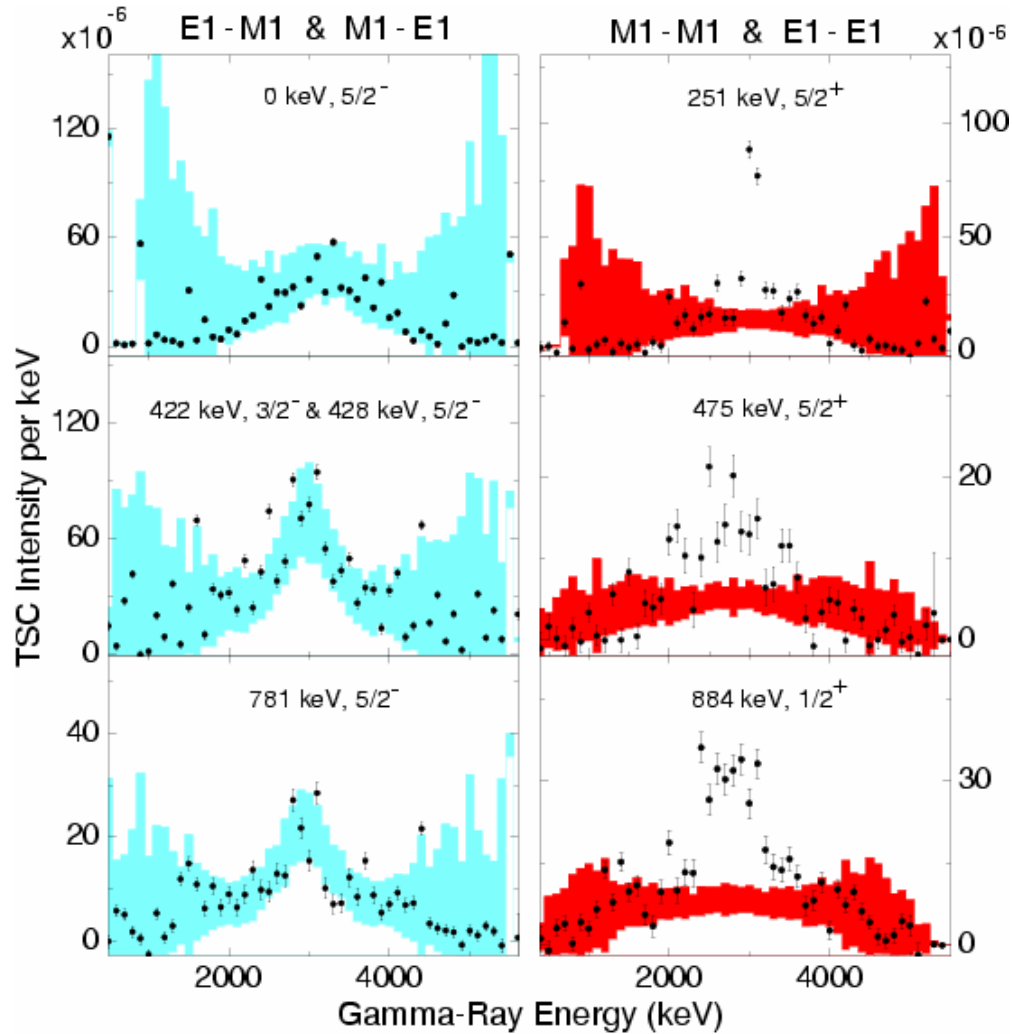
TSCs in the $^{162}\text{Dy}(n,\gamma)^{163}\text{Dy}$ reaction



A “pygmy E1 resonance”
with energy of 3 MeV
assumed to be built on
all levels



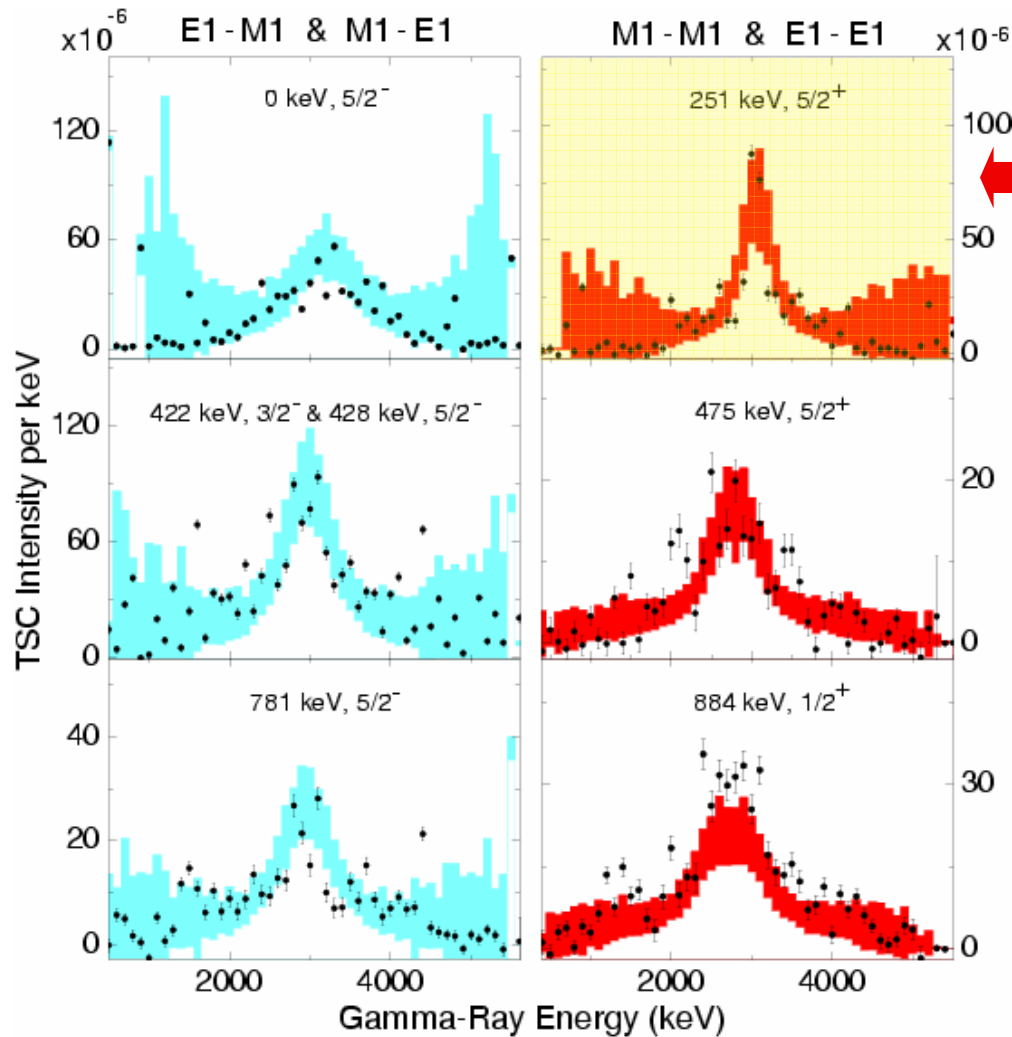
TSCs in the $^{162}\text{Dy}(n,\gamma)^{163}\text{Dy}$ reaction



SRs assumed to be built only on all levels below 2.5 MeV



TSCs in the $^{162}\text{Dy}(n,\gamma)^{163}\text{Dy}$ reaction



Sharpening the 3 MeV peak well reproduced

plus

a quantitative agreement between the predicted and simulated TSC spectra

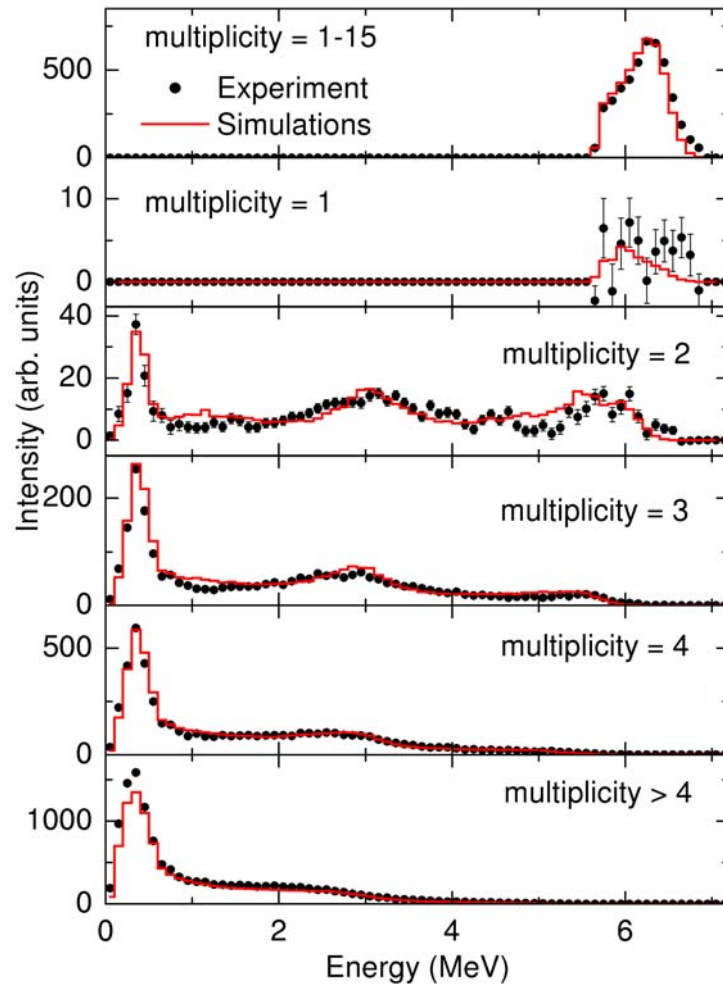
Scissors resonances assumed to be built on all ^{163}Dy levels



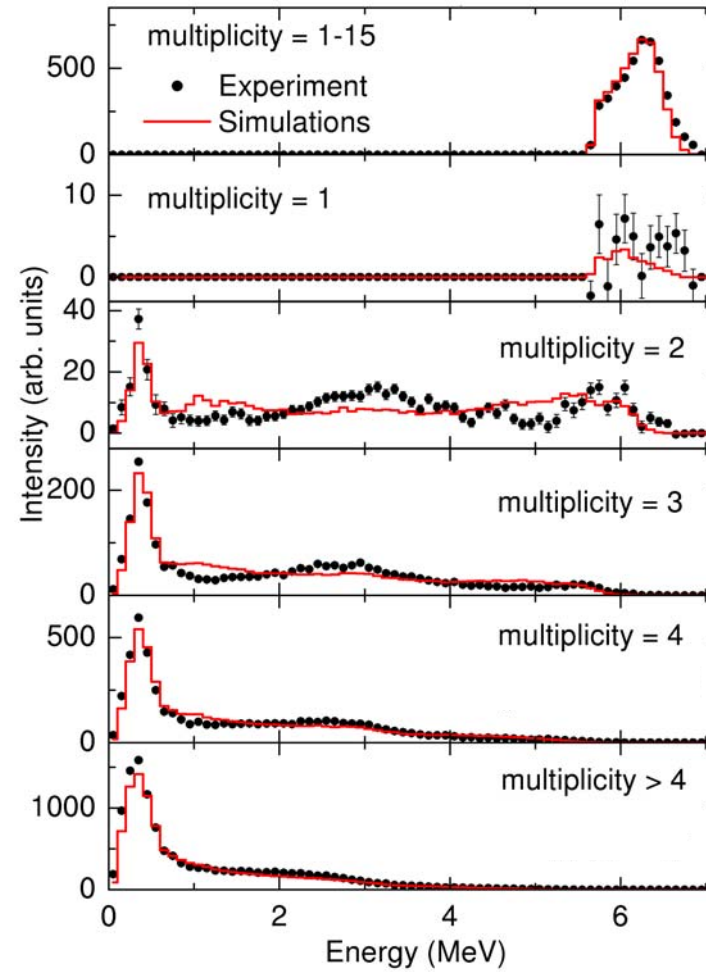
n -step cascades following the capture of keV neutrons in ^{162}Dy

$E_n = 90\text{-}100\text{ keV}$

SRs built on **all** ^{163}Dy levels

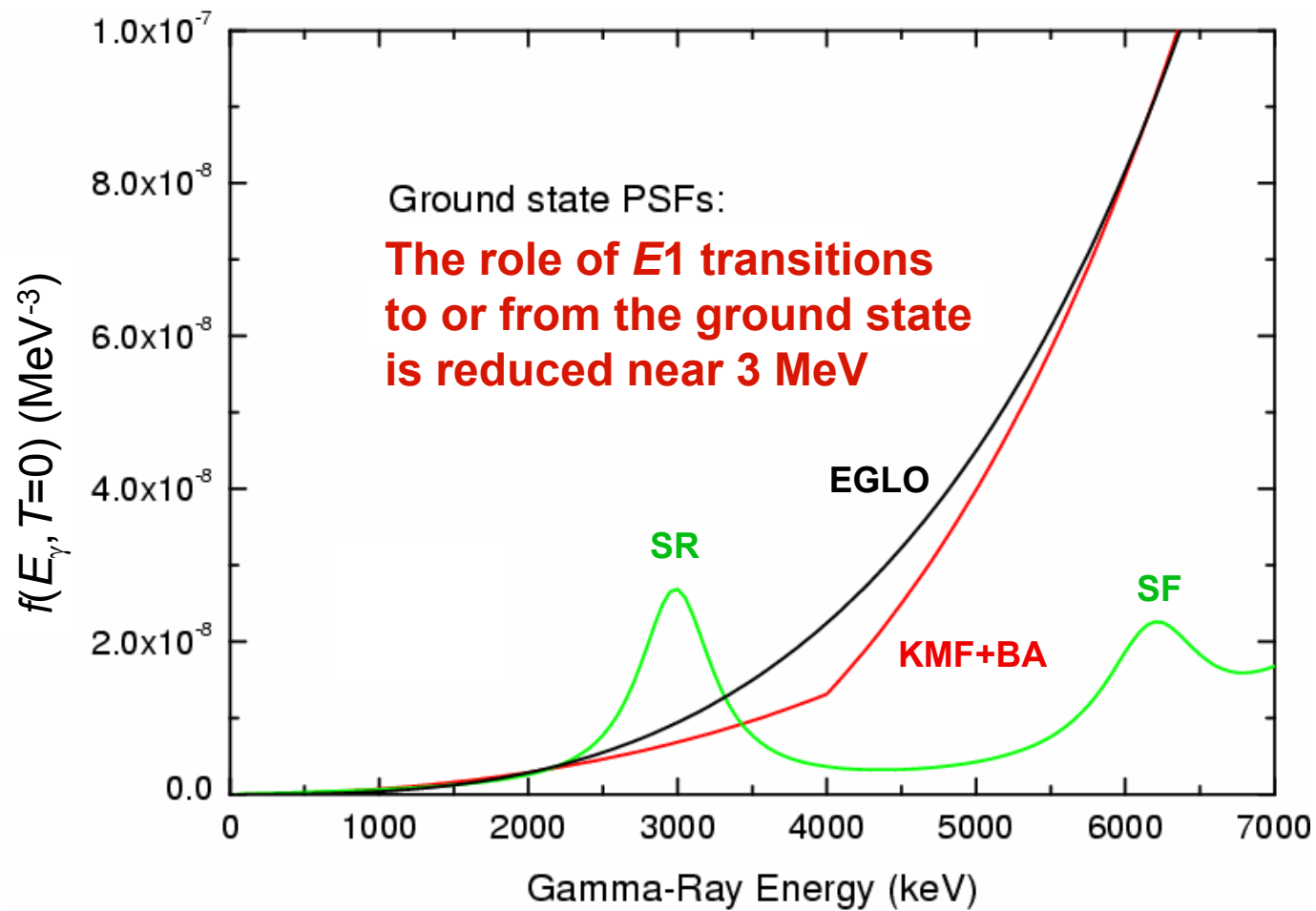


...only on levels with $E_f < 2.5\text{ MeV}$



^{163}Dy : optimum models for photon strength functions

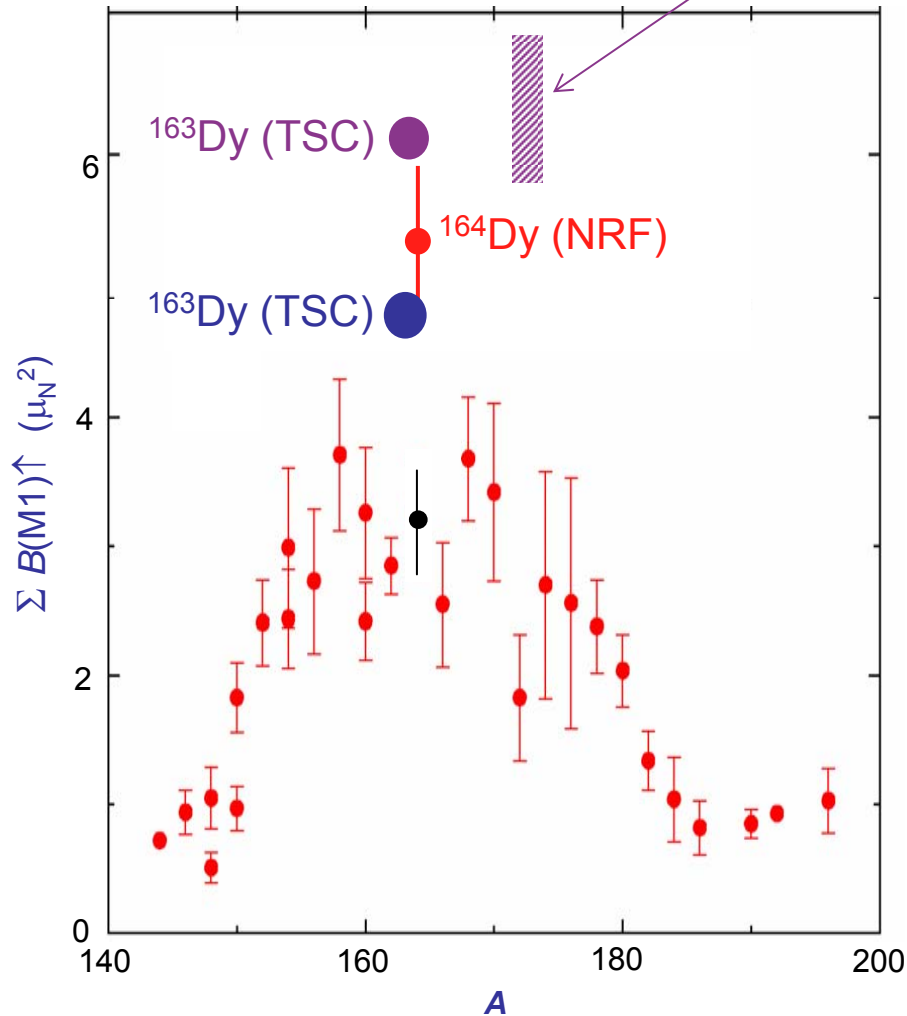
Photon strength functions plotted refer to the γ transitions to the ground state of ^{163}Dy



Comparison between the TSC and NRF data

I. NRF data for 29 even-even nuclei

Theory of E. Lipparini and S. Stringari, Phys. Rep. 175 (1989) 103



Redrawn from J. Enders *et al.*, PRC 59 R1851 (1999)

- Summing interval for $\Sigma B(M1)\uparrow$: **2.5 - 4.0 MeV**
- Summing interval for $\Sigma B(M1)\uparrow$: **2.7- 3.7 MeV**
- Summing interval for $\Sigma B(M1)\uparrow$: **2.5 - 4.0 MeV**
- deduced from data in original paper
of J. Margraf *et al.*, PRC 52, 2429 (1995)
- Value from TSCs in ^{163}Dy ;
summing interval for $\Sigma B(M1)\uparrow$: **2.5 - 4.0 MeV**
- Value from TSCs in ^{163}Dy :
total sum $\Sigma B(M1)\uparrow$



Scissors-mode strength $\Sigma B(M1)\uparrow$:

A considerable loss due to a finite summing energy interval

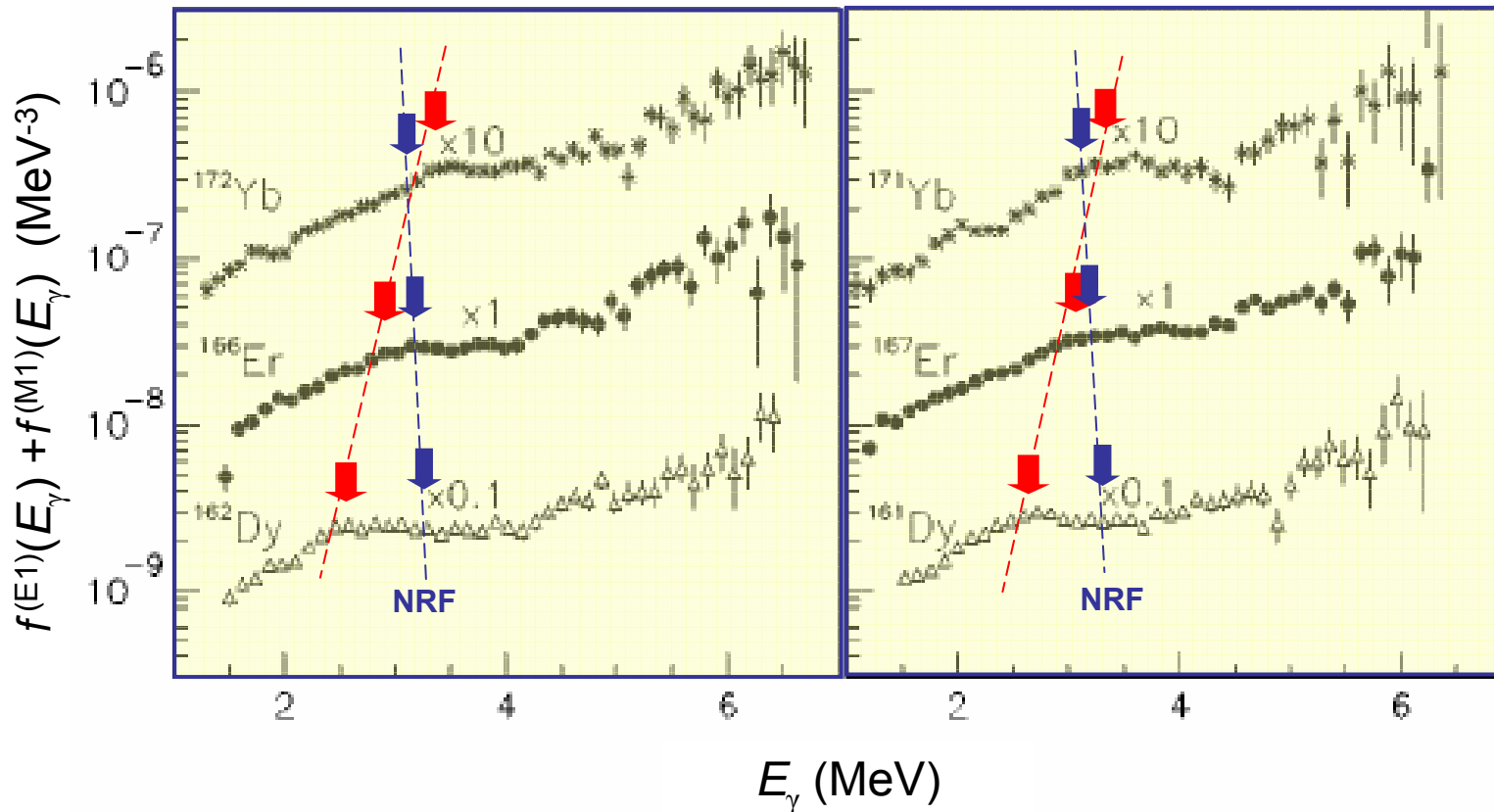
The data from TSCs in odd ^{163}Dy agree well with the NRF data at least for even-even ^{164}Dy ...



A 3 MeV resonance seen from ($^3\text{He},\alpha$) reactions in deformed nuclei

Oslo method

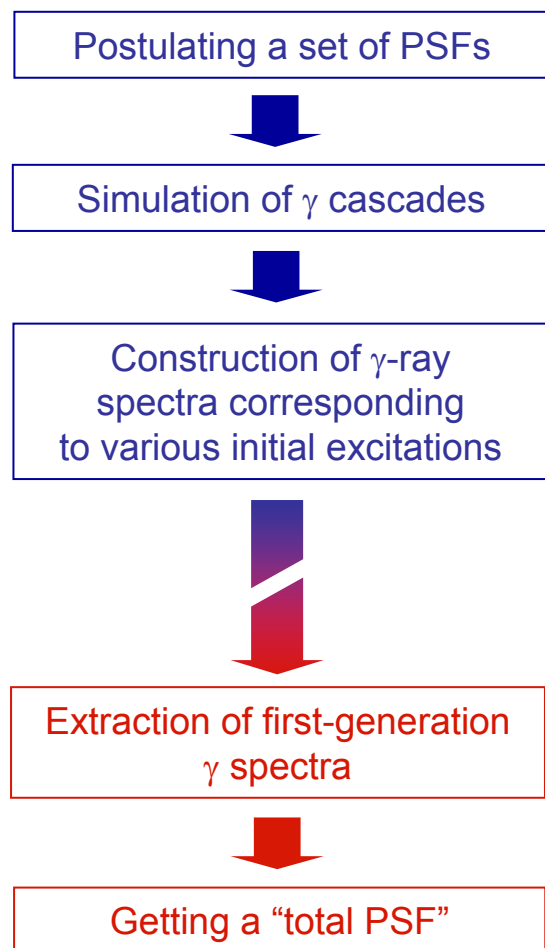
Data taken from a paper of E. Melby *et al.*, PRC **63** (2001) 044309



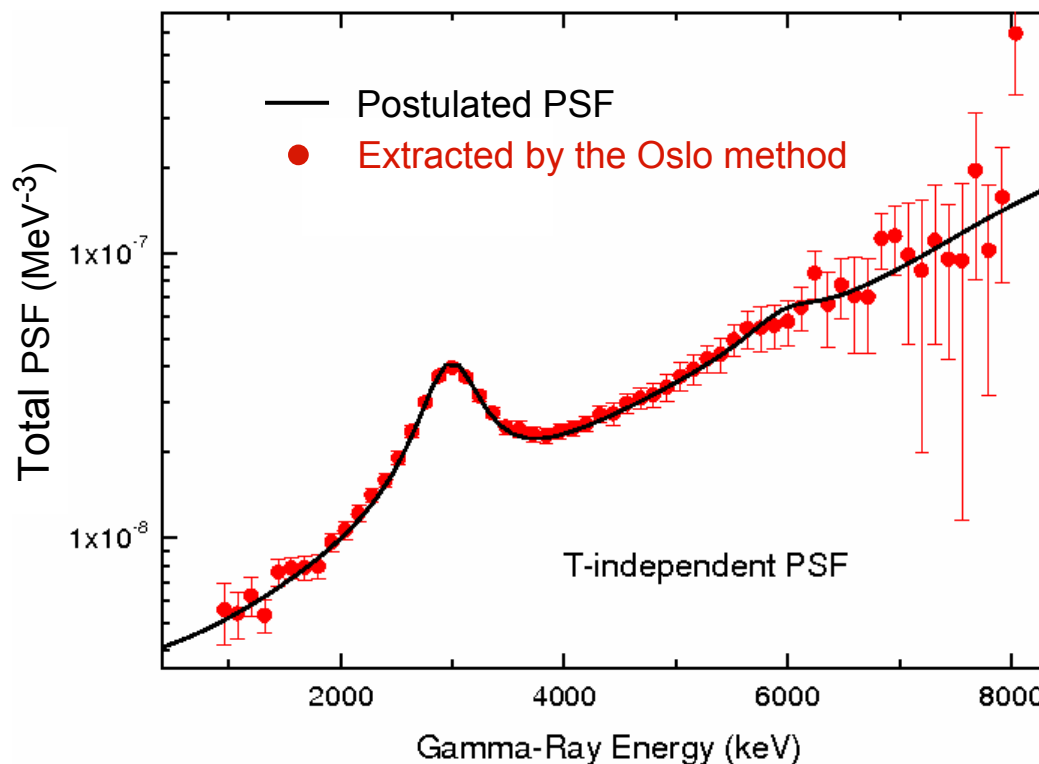
- The resonance energy increases with A
- It is too wide



Validation testing of the Oslo method



RESULTS



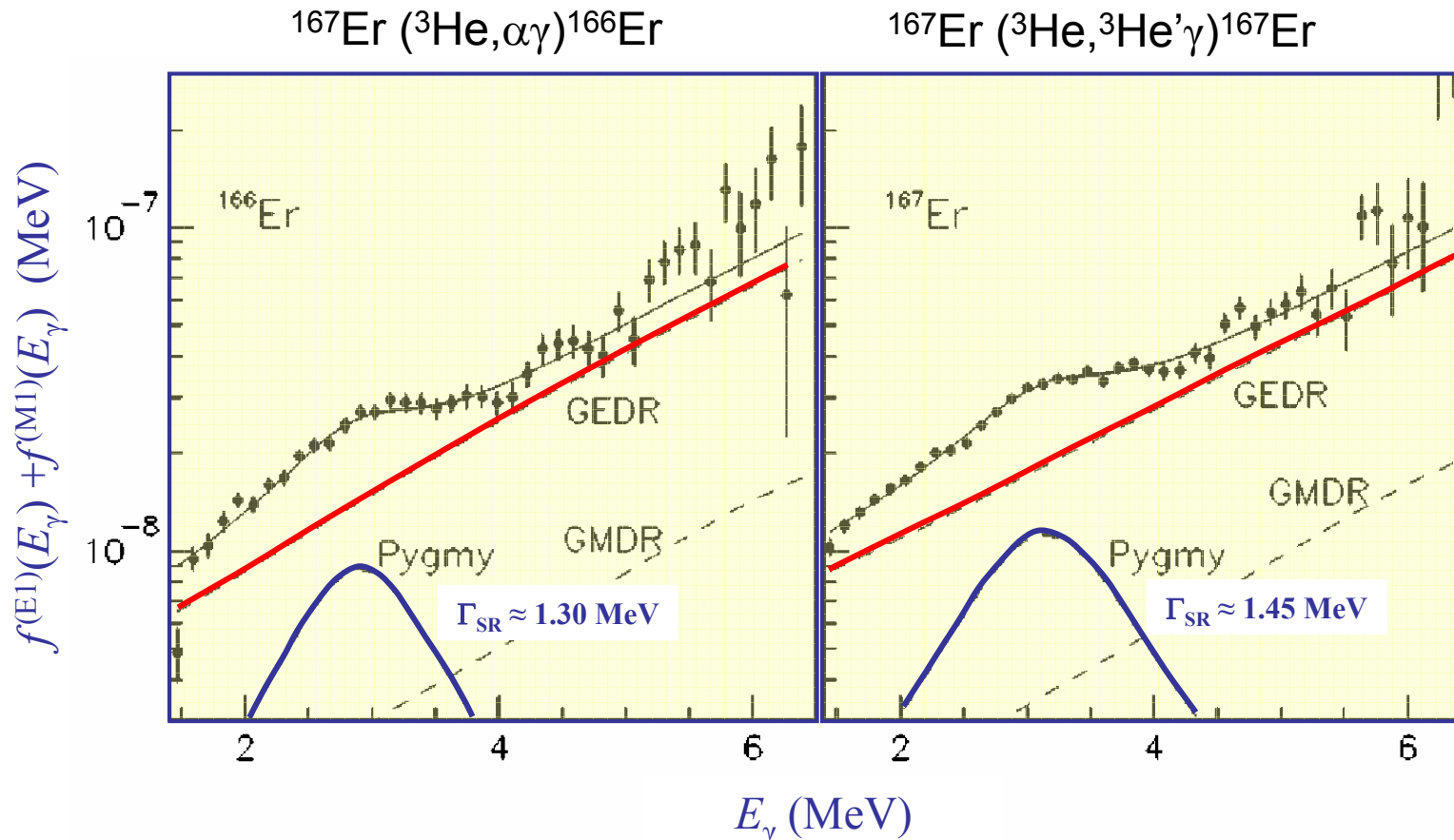
The Oslo data treatment should not distort the shape of SR's

Reaction mechanism involved?



A 3 MeV resonance seen from ($^3\text{He},\alpha\gamma$) and ($^3\text{He},^3\text{He}'\gamma$) reactions

E. Melby *et al.*, PRC 63 (2001) 044309

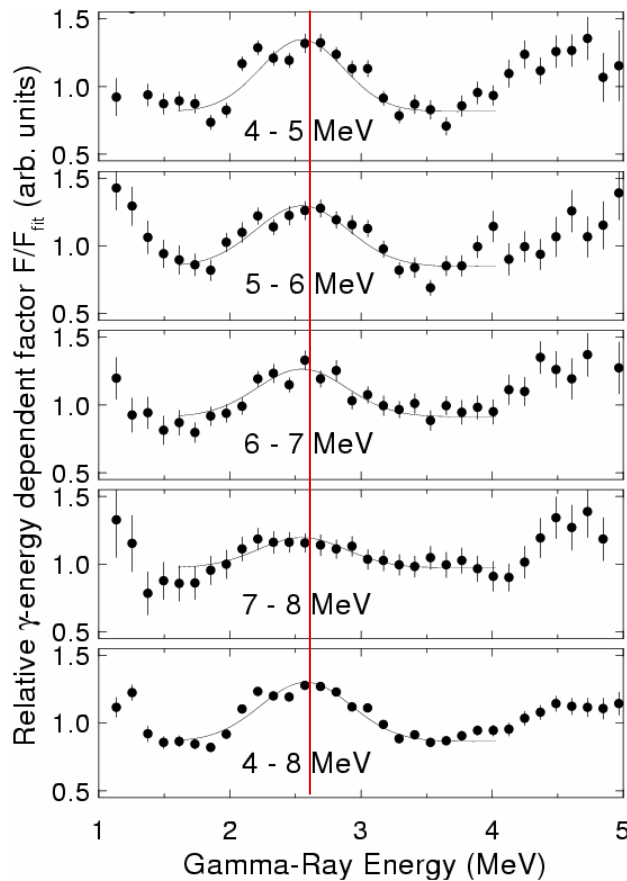


Contradictions with the NRF and TSC data:

- (1) the strength of the 3 MeV resonance too small compared to the E1 strength at 3 MeV
- (2) this resonance is wider by a factor of two or more – **smearing due to a shift of E_{SR} with E_{exc} ?**



The 3 MeV resonance-like structure in the $^{172}\text{Yb}(^3\text{He},^3\text{He}'\gamma)^{172}\text{Yb}$ data



It does not seem to be the case:

- the position of the 3 MeV peak is remarkably stable with changing the initial excitation

Data taken from A. Schiller *et al.*, Physics of Atomic Nuclei 62 (2001) 1186



A comparison between the ($^3\text{He},\alpha$) and NRF data on $E1$ and $M1$ strength of ^{166}Er and ^{168}Er

Reaction	γ -ray energy interval	$\int f^{(M1)}(E_\gamma) dE_\gamma / \int f^{(E1)}(E_\gamma) dE_\gamma$
$^{168}\text{Er}(\gamma,\gamma')^{168}\text{Er}$	2.5-4.0 MeV	1.84 ^{a)}

^{a)} Data from linear γ -ray polarization measurements (sets of 46 $M1$ transitions and 30 $E1$ transitions);
H. Maser *et al.*, PRC **53** (1996) 2749.

Effects of a temperature- or E_{exc} - dependent
 $E1$ photon strength function?



A comparison between the NRF **E1** data for *g.s. transitions* with predictions of AB and KMF models

	$\sum_i \Gamma_{i\gamma_0}$ (meV)	
	¹⁵⁸ Gd (2.8–3.6 MeV)	¹⁶⁸ Er (2.7–3.7 MeV)
NRF data	65–200 ^{a,c)}	220–250 ^{b,c)}
AB model	1500±200 ^{d)}	2000±400 ^{d)}
KMF model	250±200 ^{d)}	330±120 ^{d)}

^{a)} H. H. Pitz, *et al.*, NPA **492** (1989) 411.

^{b)} Data from linear γ -ray polarization measurements (sets of 46 *M1* transitions and 30 *E1* transitions); H. Maser *et al.*, PRC **53** (1996) 2749.

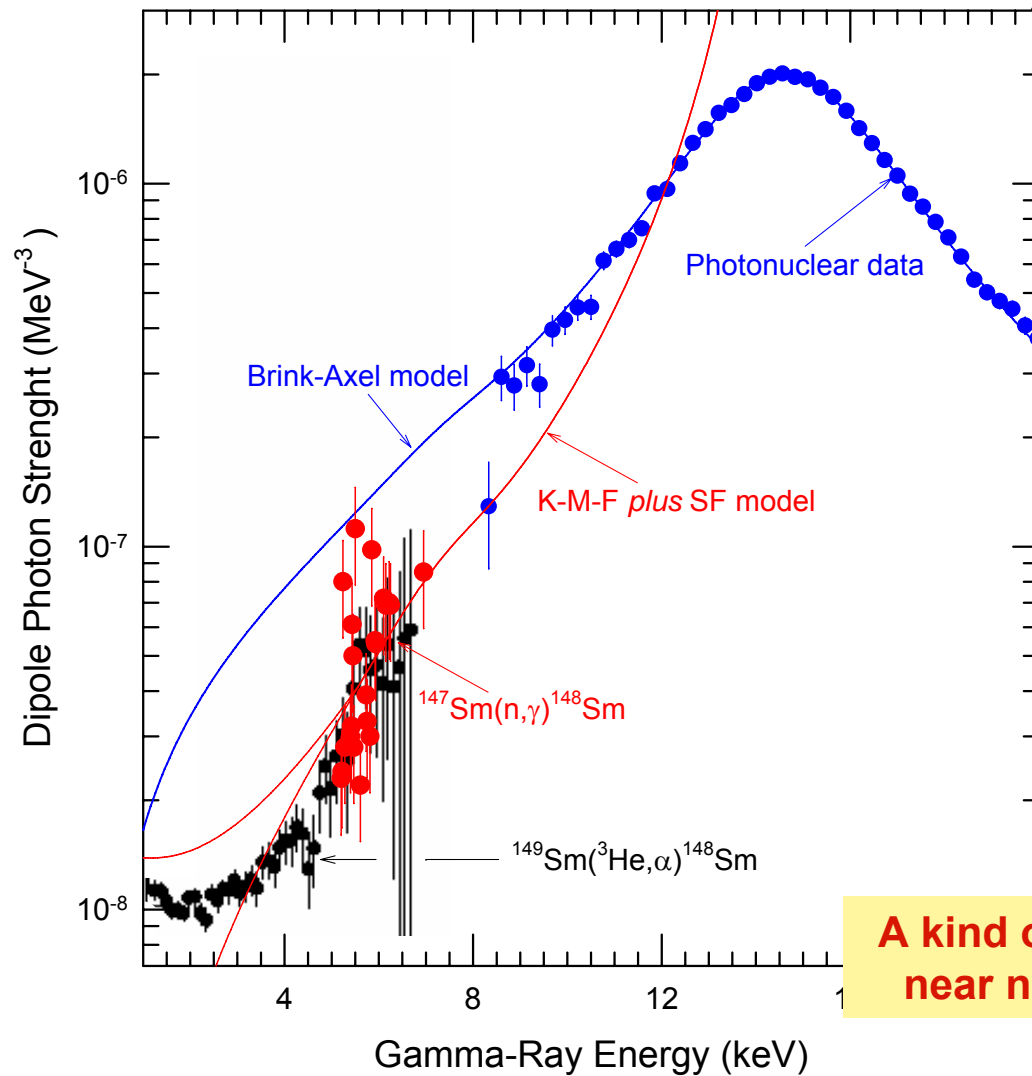
^{c)} Estimated uncertainty due to the threshold for observation of weak γ lines.

^{d)} Porter-Thomas uncertainties shown.

For *g.s.* transitions near 3 MeV
the Axel-Brink model does not hold



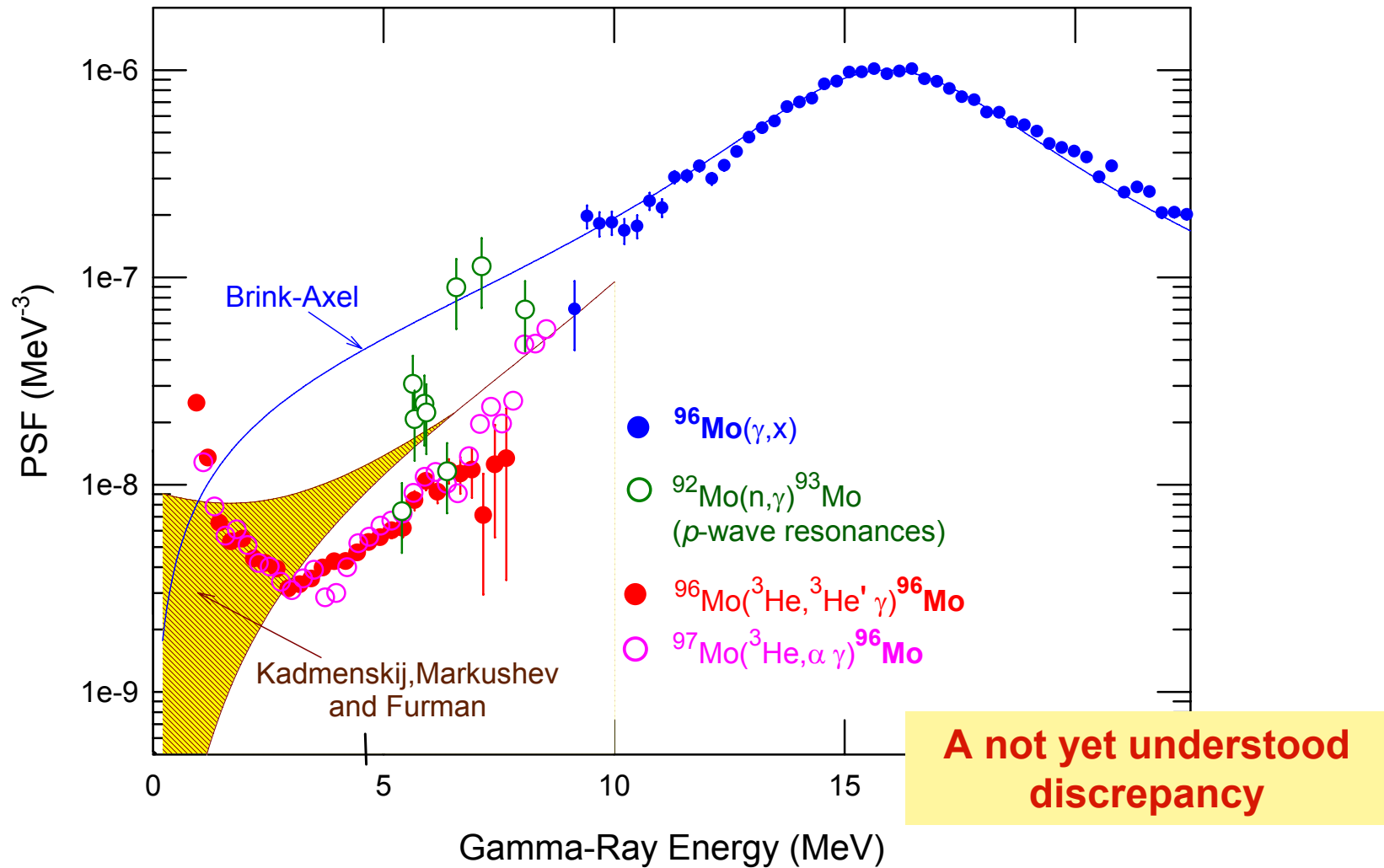
... primary (n, γ) data and secondary data from ^3He -induced γ -emission



A kind of “phase transition“ near neutron threshold?



Photon strength functions of ^{96}Mo



SUMMARY

A deficit of photon strength in spherical and transitional nuclei at γ -ray energies of 6-8 MeV

$E1$ NRF data for well deformed nuclei display the deficit of photon strength compared to predictions of the AB model at 3 MeV

The method of two-step cascades and the “ γ -calorimetric method” proved to be efficient tools for studying PSFs at intermediate γ -ray energies of 2 - 4 MeV

Strong evidence for scissors-like vibrations of *excited* deformed nuclei

The scissors $M1$ mode *per se* displays, indeed, resonance-like behavior

Very large values of the reduced $B(M1)_{\uparrow}$ strength found
- a deeper revision of the NRF data at energies near 3 MeV needed

Many issues are to be settled





Thank you!