Determination of radiative strength functions

OHIO UNIVERSITY 1804

and level density

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Motivation

- Discrete spectroscopy

  Energies of discrete $[2^+, 3^-$, etc.] levels

  Reduced transition matrix elements [B(E2)]

- Continuous spectroscopy

  Level density, spacing

  $$\rho(E)$$

  Radiative strength function

  $$\frac{\mathrm{d}B(XL\uparrow)}{\mathrm{d}E_\gamma} \propto f_{XL}(E_\gamma)$$

Motivation (continued)

- Nuclear structure
  - Level spacing → regularity, chaos
  - Sudden changes in LD → (phase) transitions
  - Resonances in RSF → simple excitation modes
- Applications (Hauser-Feshbach cross sections)
  - Astrophysical reactions
  - Medical isotope production
  - Reactor technology, transmutation of waste, stockpile stewardship, production of rare isotope beams

Level density measurements

- Counting of discrete levels (up to 50/MeV)
- Counting of neutron (proton) resonances (need corrections)
- Evaporation spectra
- Ericson fluctuation
- Fluctuation analysis of giant resonances
- ‘Oslo method’

Level density (theory)

- Path-integral methods
  - Static path+random phase approximation
  - Shell Model Monte Carlo
- Higher moments of the Hamiltonian
- Combinatorial methods

RSF measurements

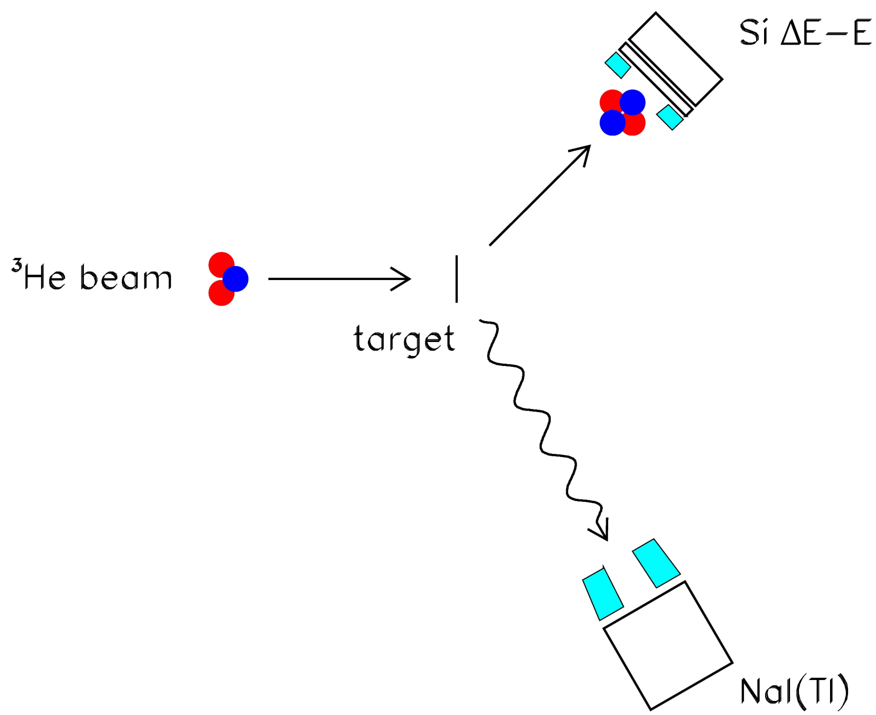
- Photoneutron cross sections and photon scattering
- Primary γ intensities after neutron capture, two-step-cascade intensities
- Total γ spectrum fitting method (hot GDRs)
- ‘Oslo method’

RSF (theory)

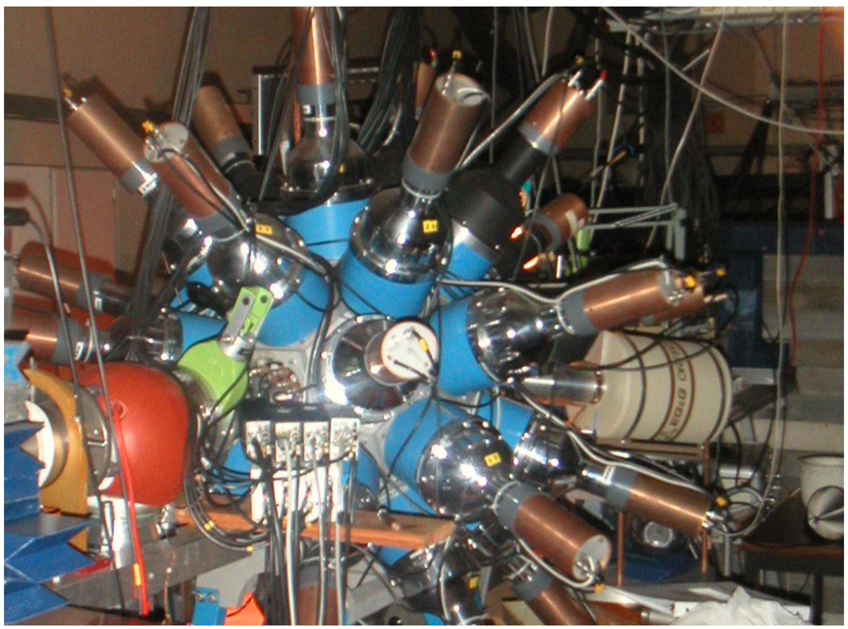
- Nuclear response to simple electromagnetic operators (random phase approximation)
- Giant electric dipole resonance:
  - Shape fluctuation models
  - Collisional damping model
- Other effects
  - Strength fluctuations
  - Superradiance

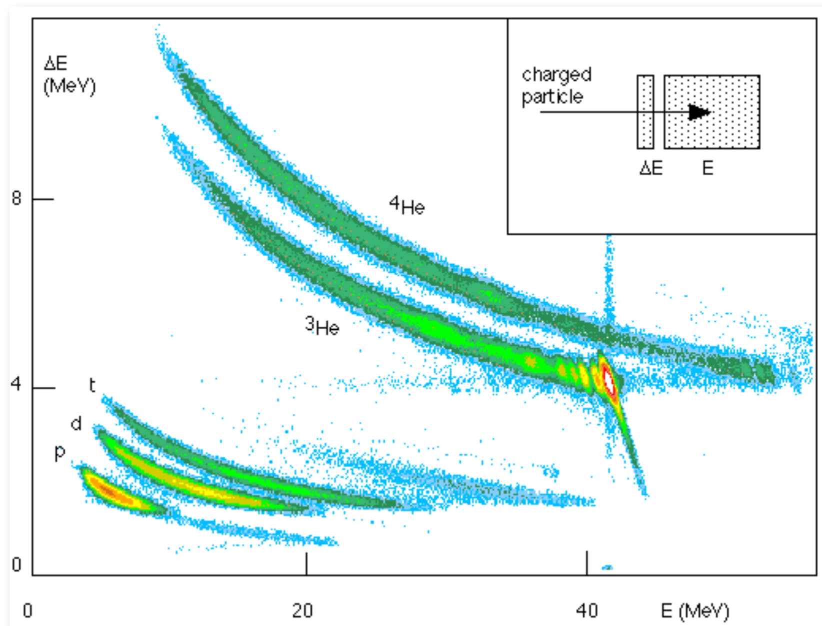
The Oslo method explained

- Excitation-energy indexed total γ spectra from (^{3}He,$\alpha\gamma$) and (^{3}He,^{3}He'γ) reactions at ~40 MeV



The experimental setup





The Oslo method explained (II)

- Unfolding

$$\text{folded}(E_x, E_\gamma) = \sum_{E'_\gamma} \text{response}(E_\gamma, E'_\gamma) \cdot \text{unfolded}(E_x, E'_\gamma)$$

- First generation

$$\text{total}(E_x, E_\gamma) = \sum_{E'_\gamma} \text{first}(E_x, E'_\gamma) \cdot [\delta_{E_\gamma, E'_\gamma} + \text{total}(E_x - E'_\gamma, E_\gamma)]$$

- Factorization (Brink-Axel)

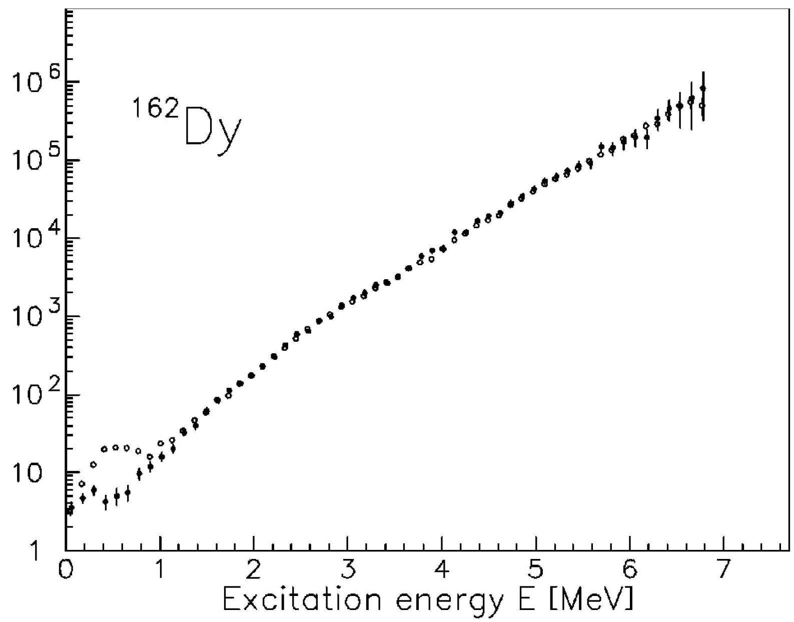
$$\Gamma(E_x, E_\gamma) \propto \rho(E_x - E_\gamma) \cdot f(E_\gamma) \cdot E_\gamma^3$$

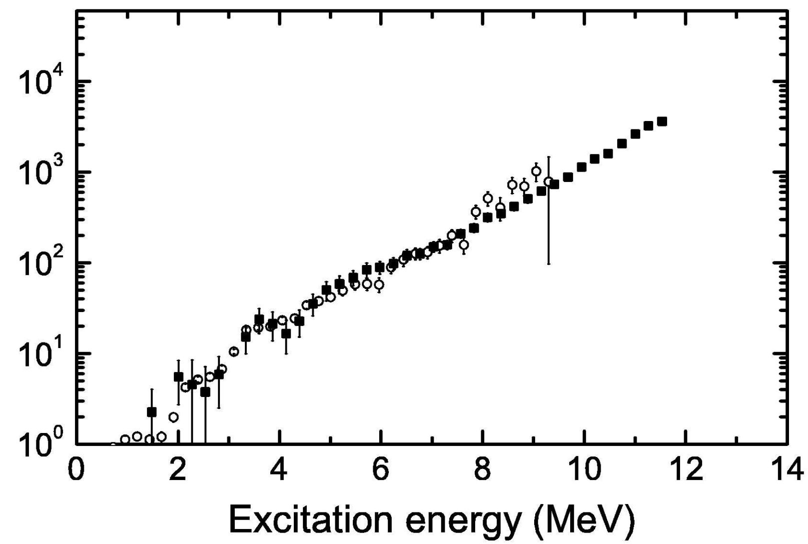
More details about the Oslo method

- First-generation method requires normalization of spectra (multiplicity/singles)
- Factorization requires *a priori* knowledge of
  - level density at two energies (counting of discrete levels, resonance spacing) and
  - total radiative strength function at one energy (total average radiative widths of neutron resonances)

Test of results (level densities)

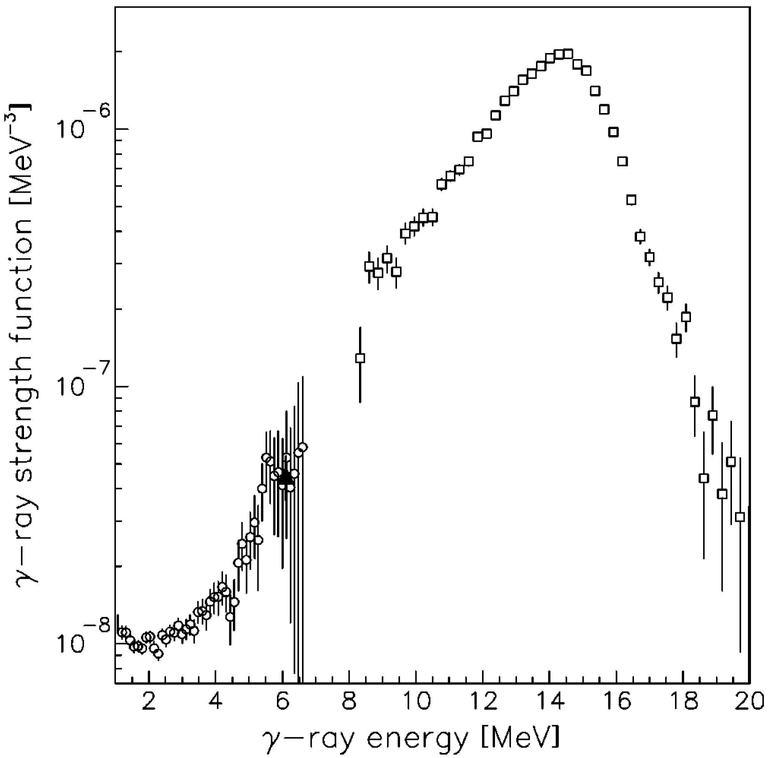
- ^{162}Dy only Oslo method
- ^{56}Fe Oslo ↔ evaporation



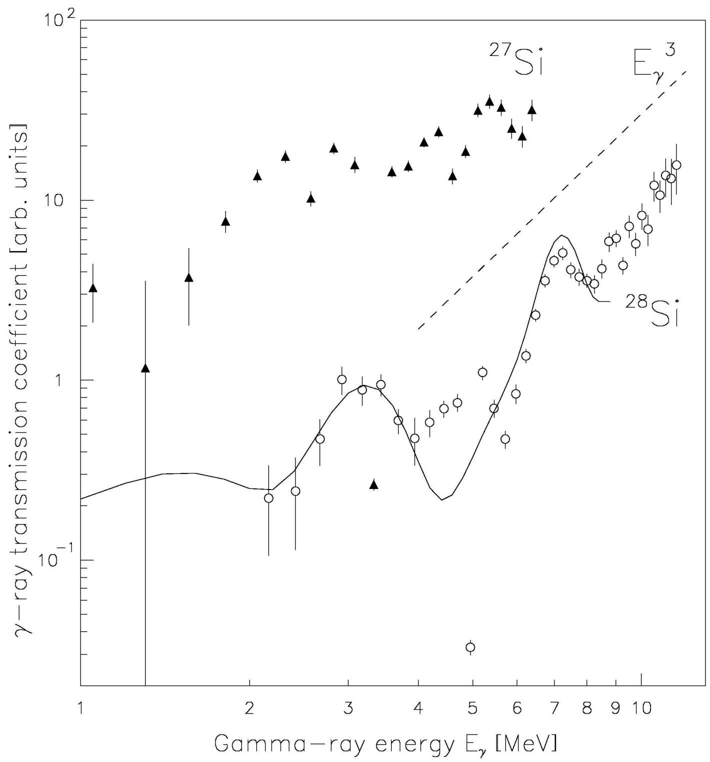


Test of results (RSF)

- ^{148}Sm

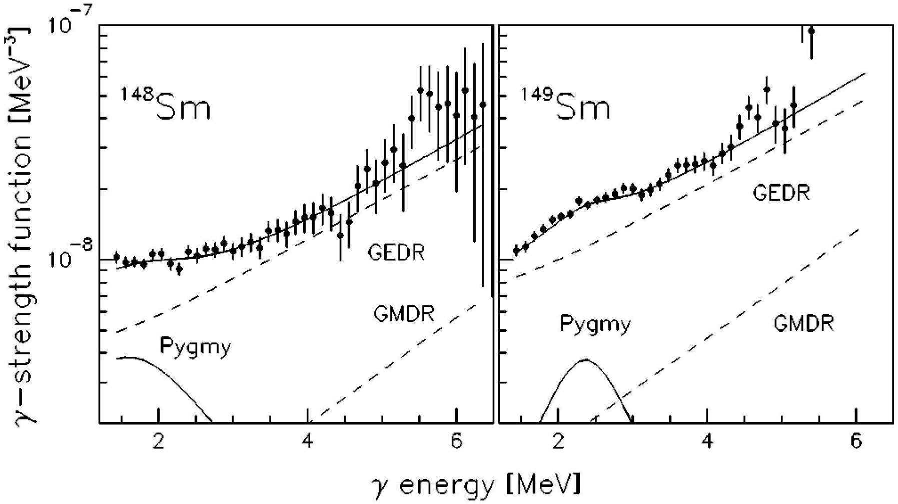


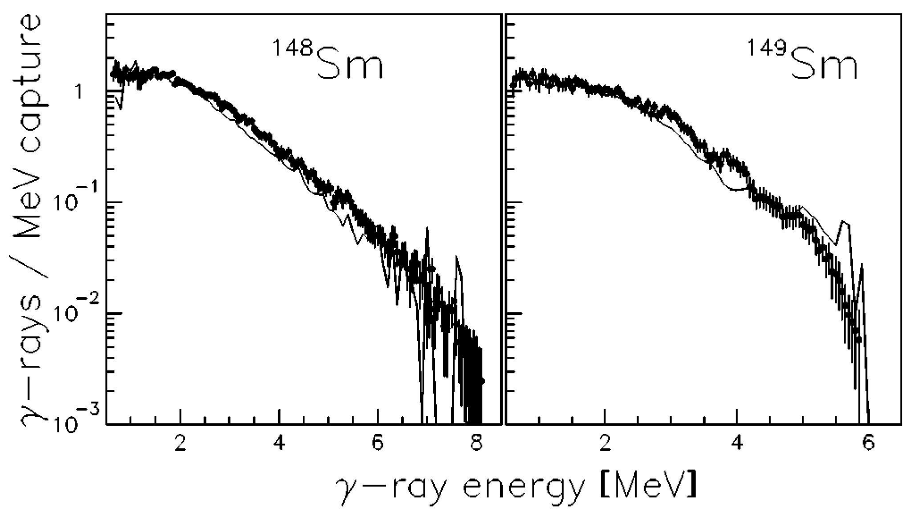
- ^{28}Si



Further tests and comparisons

- ^{148,149}Sm





Highlights of results so far

Level density

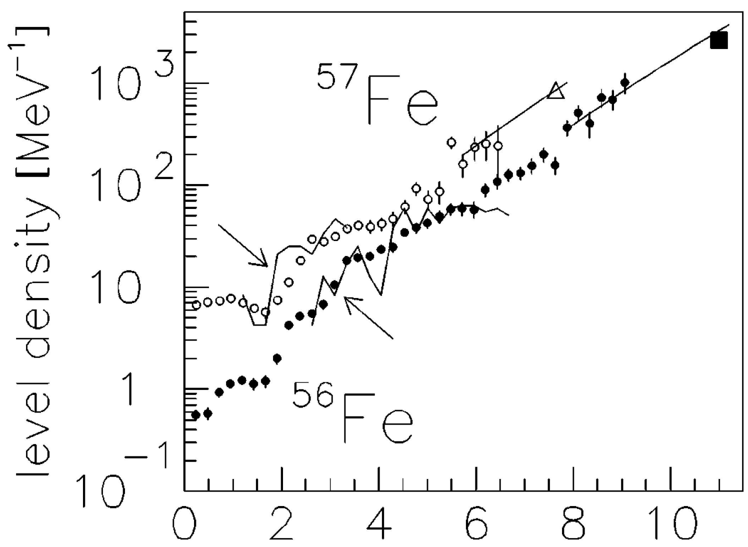
- Steps in level density correspond to successive breaking of Cooper pairs
- S-shape of canonical heat capacity curve
- Thermodynamical phase transition

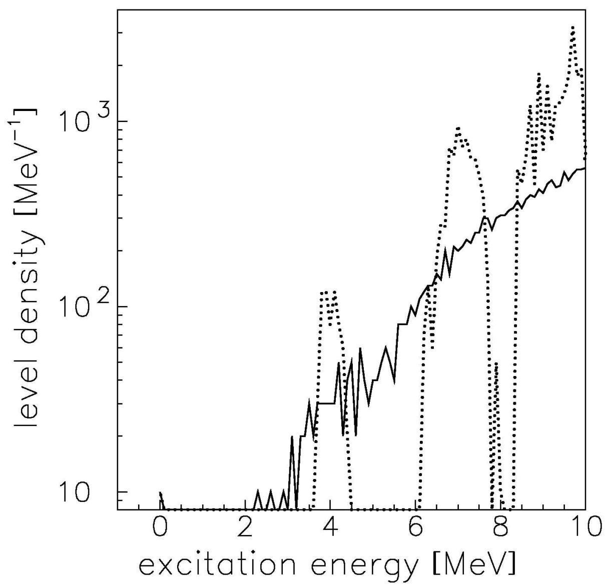
Radiative strength function

- Presence of a 6.5 μ_N^2 resonance at ~3 MeV in deformed rare earth nuclei
- Low energy enhancement of radiative strength function below 2.5 MeV in Mo and Fe
- Pygmy resonance in stable Sn isotopes

Step in level densities

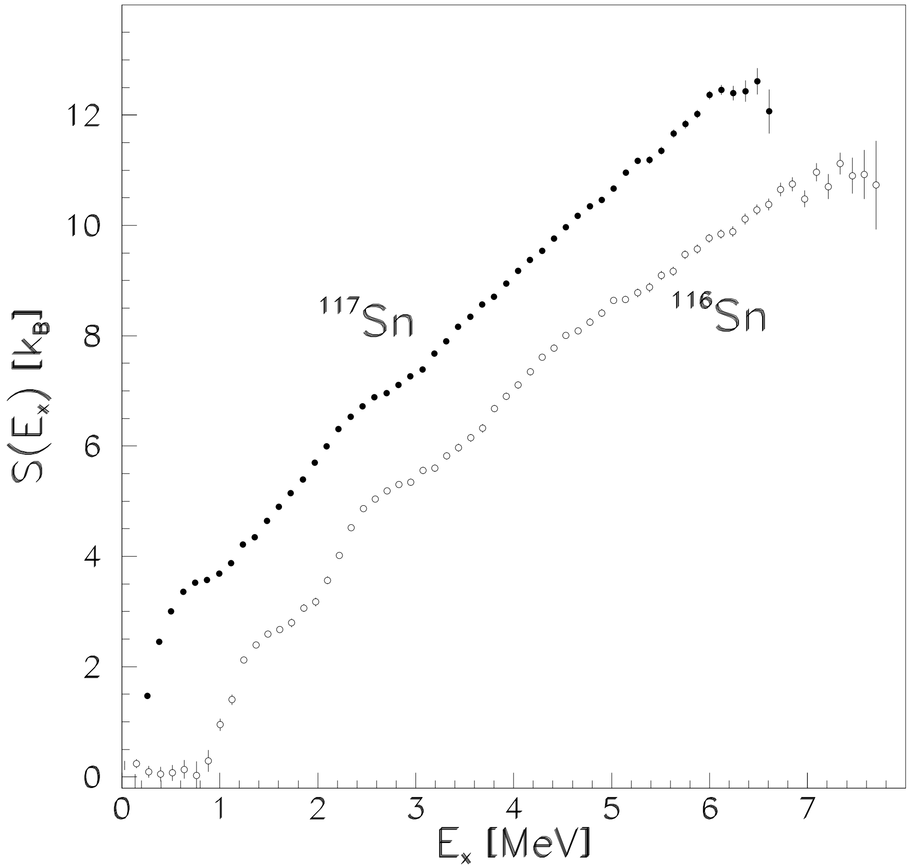
- Steps in level density correspond to breaking of successive Cooper pairs





The best staircase: ^{116}Sn

- $^{117}Sn + {}^{3}He$



Level density → thermodynamics

- Microcanonical

  Requires energy bins ΔE over which ρ(E) behaves

$$S(E) \propto \rho(E)$$

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

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

- Canonical

  Formalism for fixed T, not E

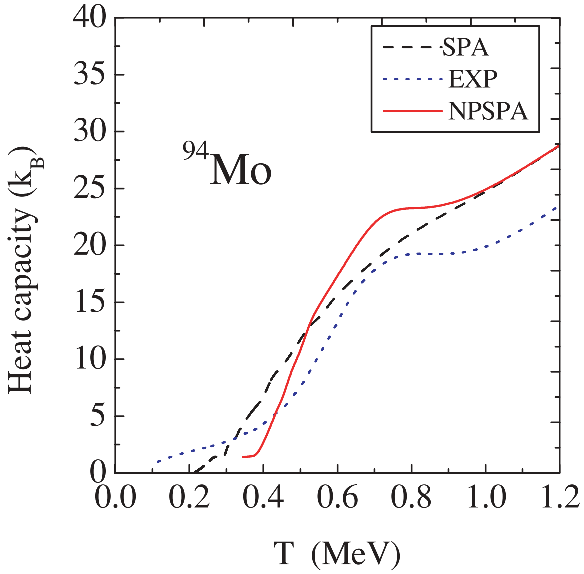
$$S(T) = \frac{\partial}{\partial T} \left[T \cdot \ln Z(T) \right]$$

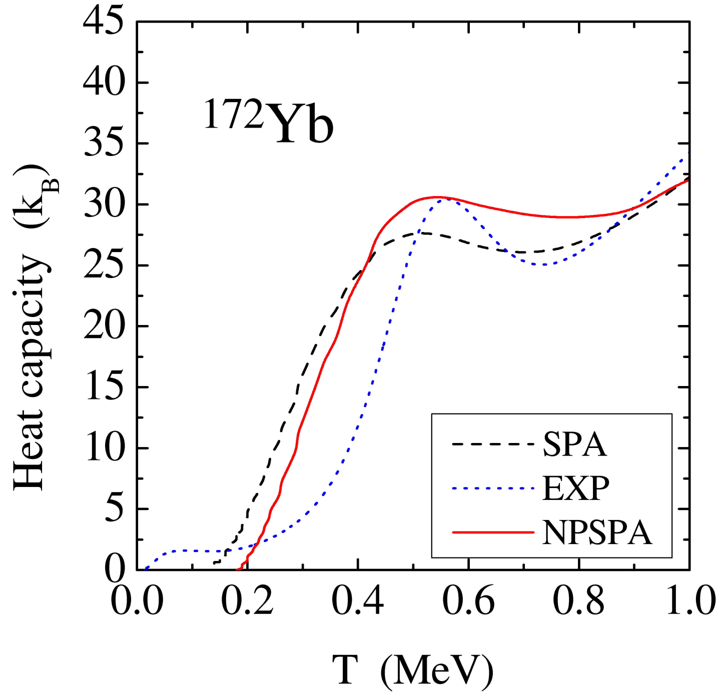
$$E(T) = T^2 \frac{\partial}{\partial T} \ln Z(T)$$

$$C_V(T) = \frac{\partial}{\partial T} E(T)$$

S-shaped heat capacity

- S-shape instead of discontinuity in $C_V(T)$ curve
- Phase transition in a finite system
- Many calculations
  - SPA
  - SMMC



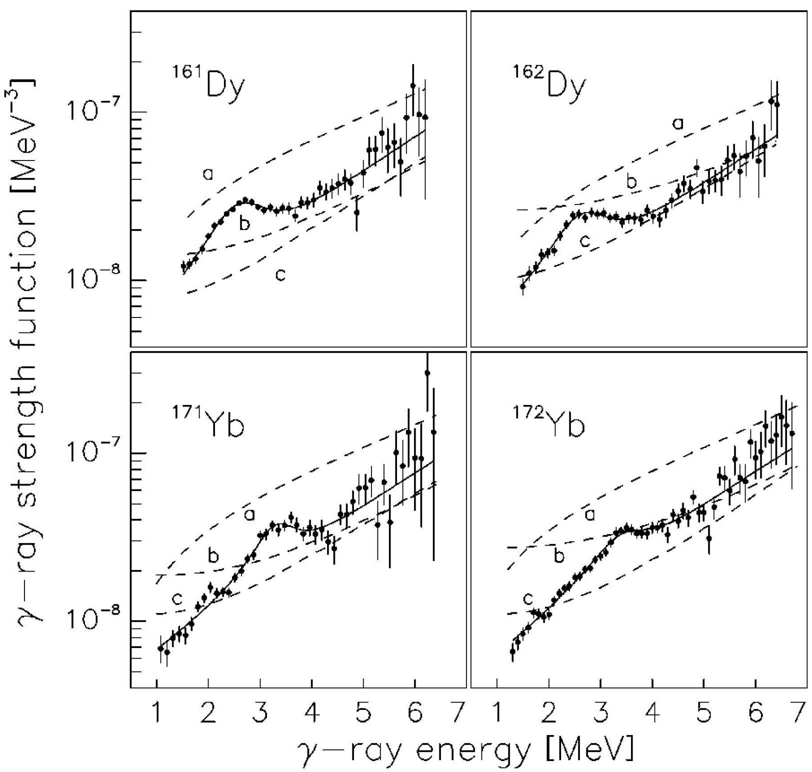


More thermodynamics

- Investigation of microcanonical caloric curve
- Single-particle entropy (odd-even difference)
- Zeros of complex-T partition function
- Linearized Helmholtz free energy
- Geometric definition of ‘mesoscopic’ caloric curve from temperature-energy probability distributions
- Thermodynamic language in finite systems?

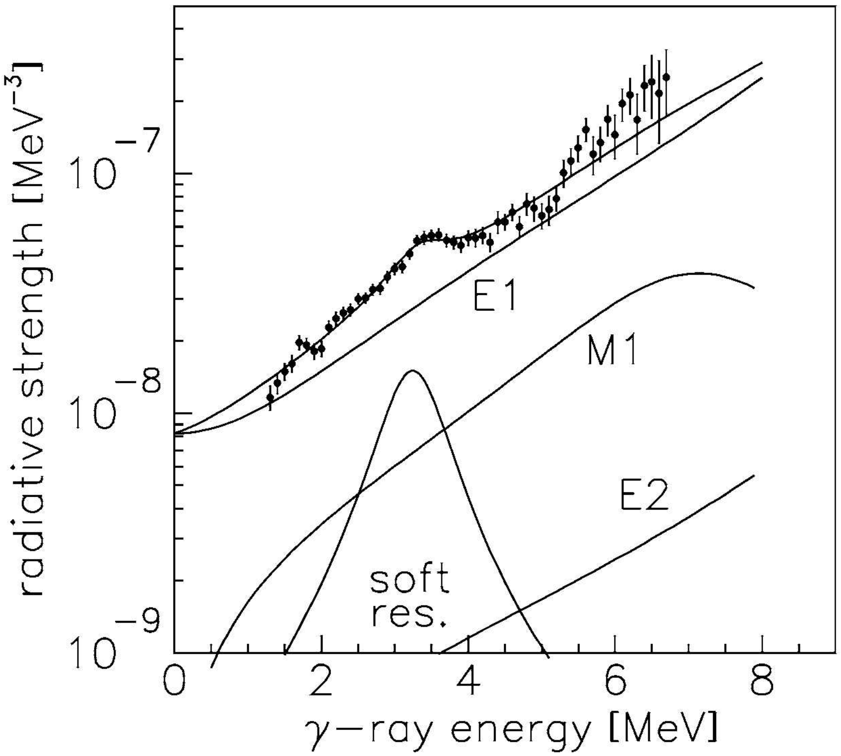
Results for the RSF

- Low-energy resonance in deformed rare-earth nuclei

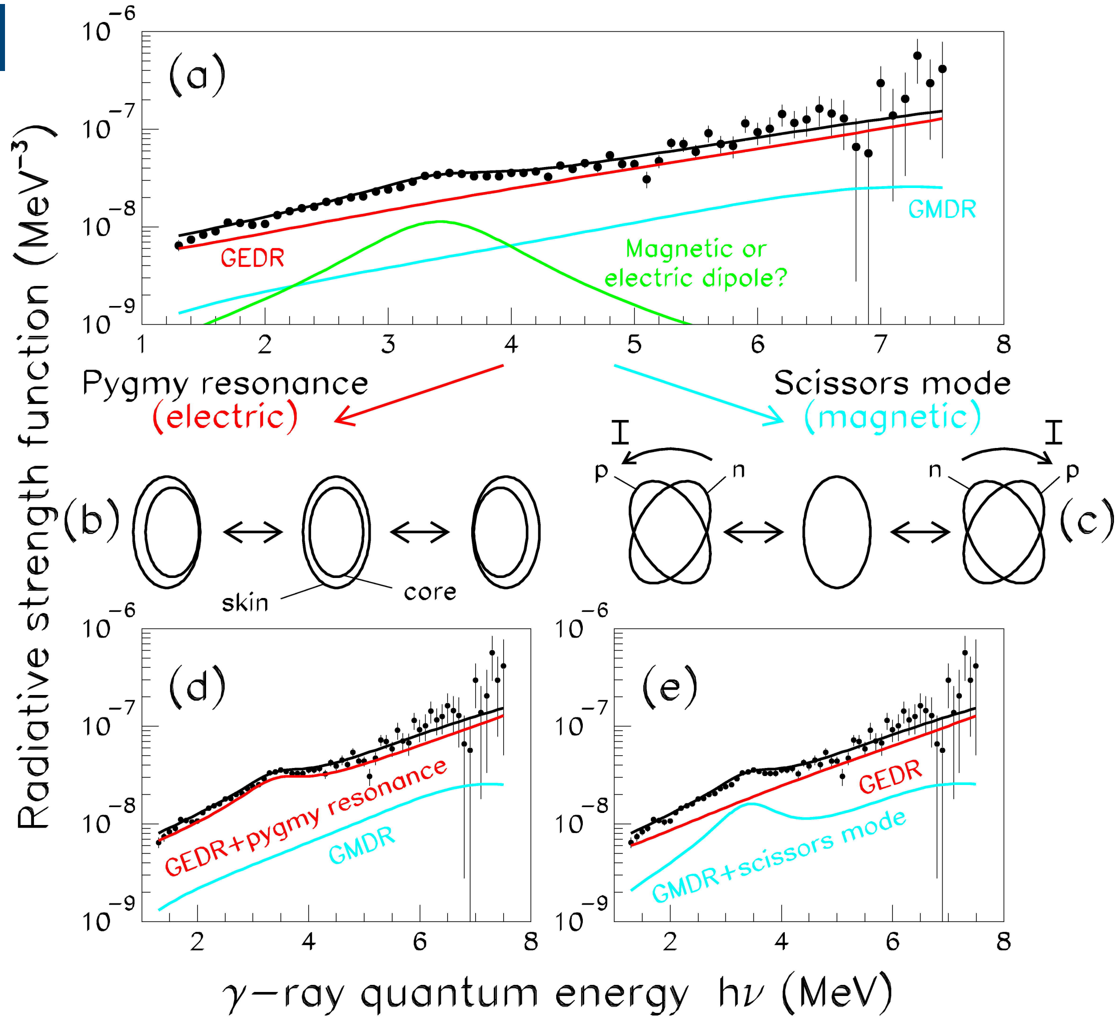


A closer look at the ^{172}Yb RSF

- Separation of RSF into four components
  - KMF E1
  - M1 spin-flip
  - E2 GQR
  - Soft dipole

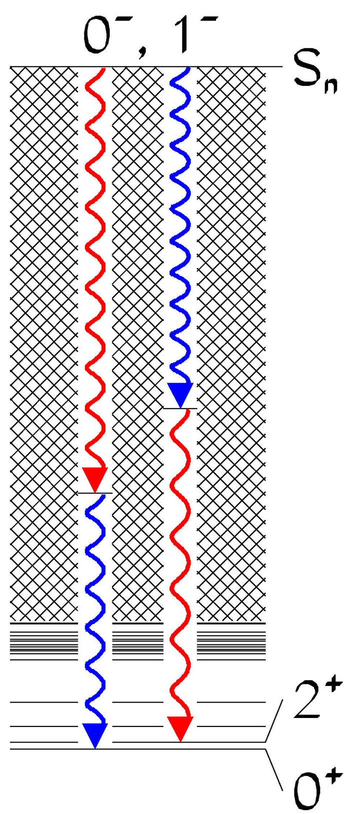


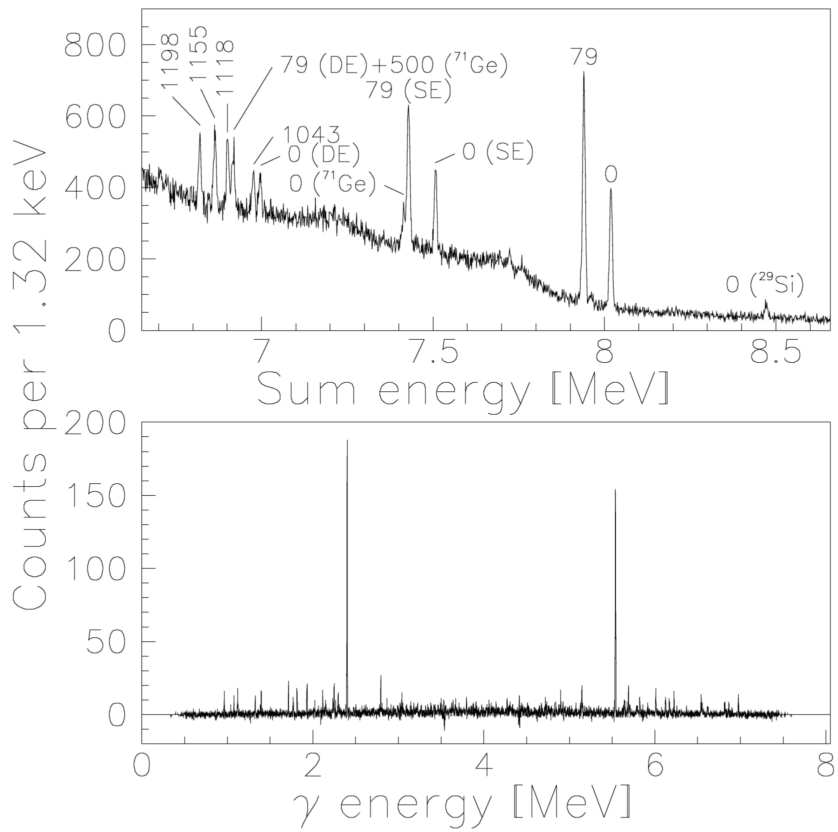
Is the soft resonance E1 or M1?



Two-step-cascade method

- Neutron s-capture
  - Parity of initial state
- Two steps to g.s.
  - Parity of final state





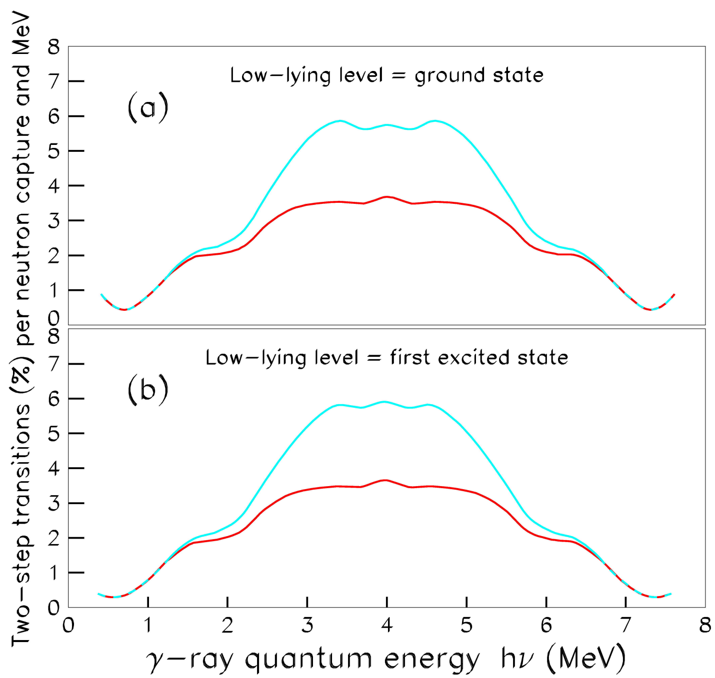
Two-step-cascade method (II)

- Sum of RSFs known

$$f(E1) + f(M1) = f_{\exp}$$

$$\Pi_i = \Pi_f : \quad I \propto f(E1)^2 + f(M1)^2$$

$$\Pi_i \neq \Pi_f : \quad I \propto 2 \cdot f(E1) \cdot f(M1)$$



$$E1: \quad 90\% f(E1) + 10\% f(M1) \Rightarrow I \propto 18\% [f_{\exp}]^2$$

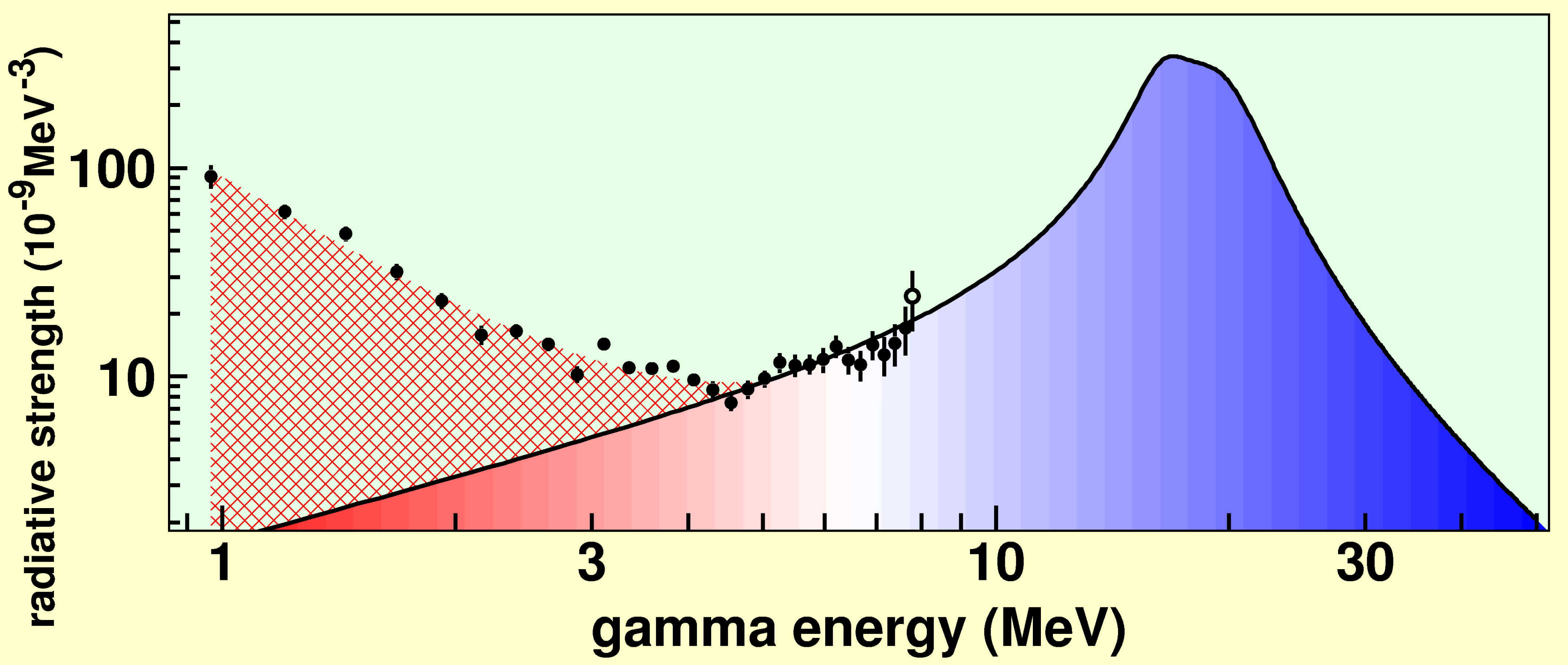
$$M1: \quad 50\% f(E1) + 50\% f(M1) \Rightarrow I \propto 50\% [f_{\exp}]^2$$

Results from experiment

- TSC intensities to four levels investigated
  - Two positive parity final states
  - Two negative parity final states
- All TSC intensities can be described by
  - Oslo level density
  - Oslo radiative strength function (+ decomposition)
  - M1 multipolarity of soft resonance
- Strength of resonance: $B(M1\uparrow)=6.5\mu_N^2$

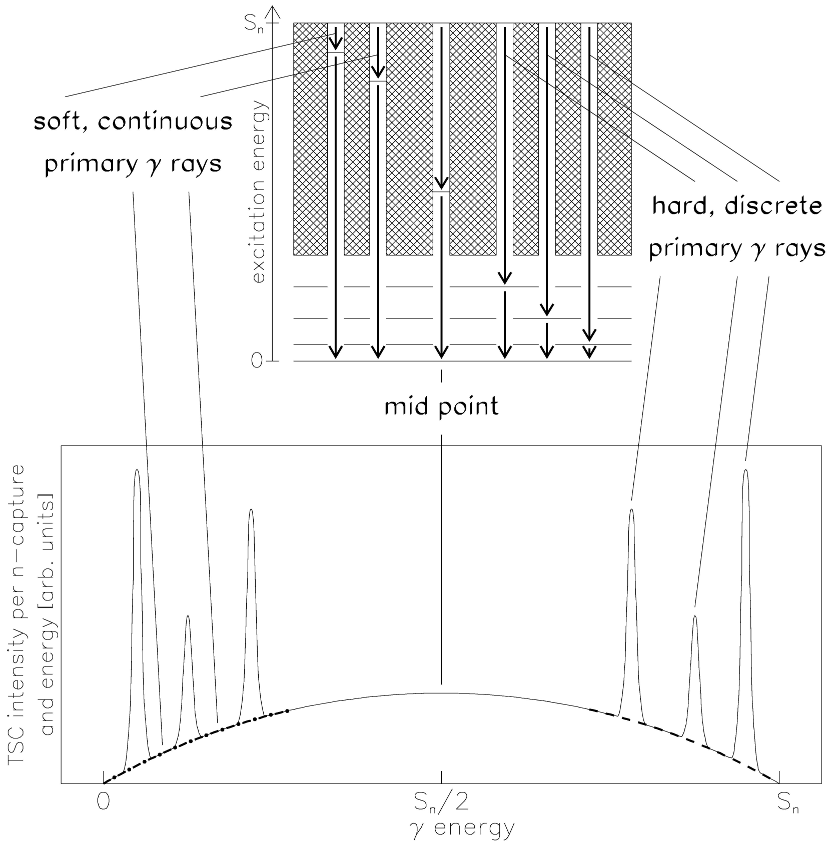
An unexpected discovery

- Soft transitions between warm states in Fe



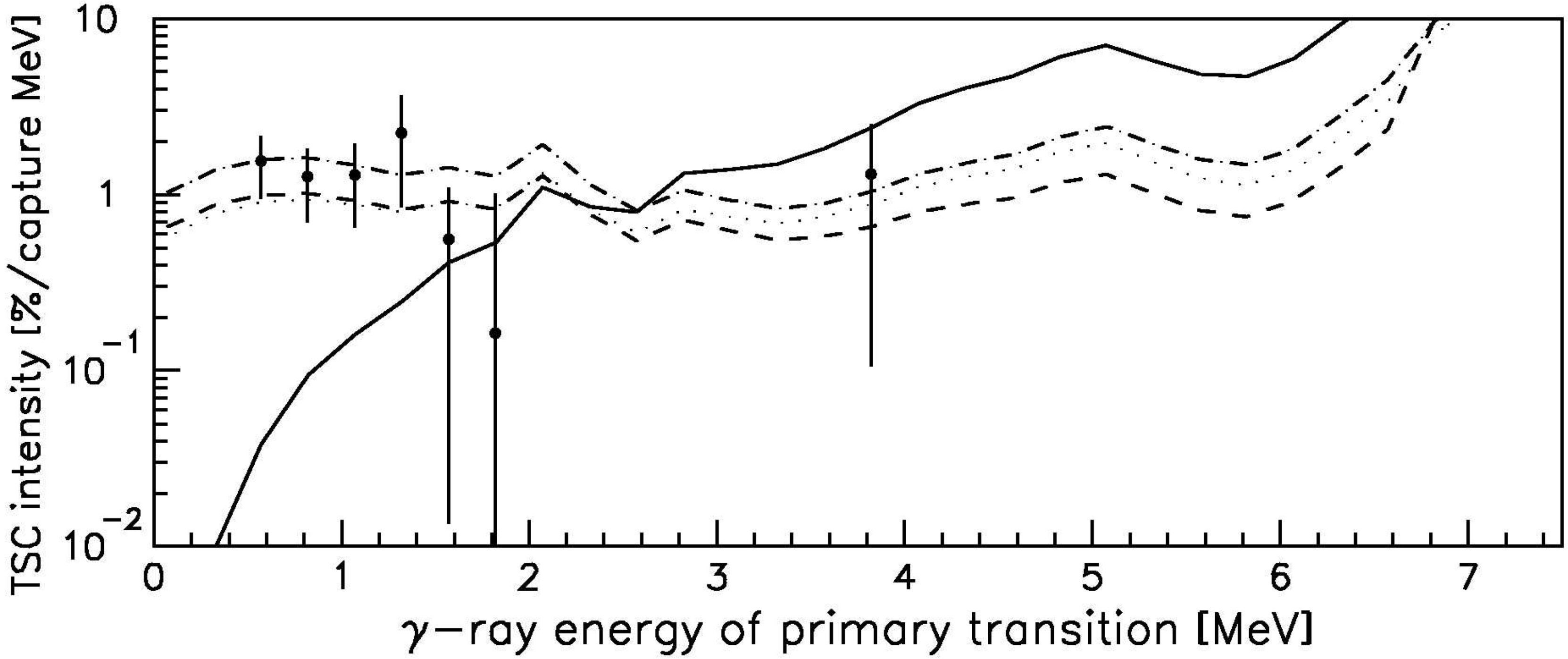
Confirmation with the TSC method

- Extraction of soft primary transitions

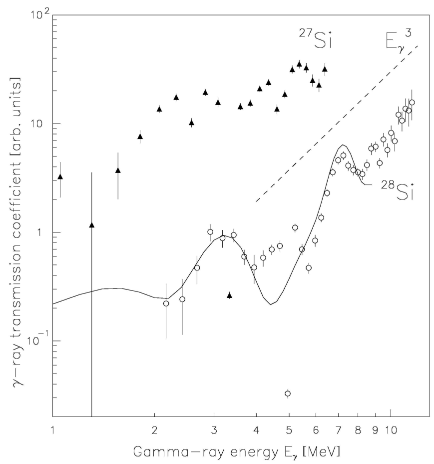


Experimental result

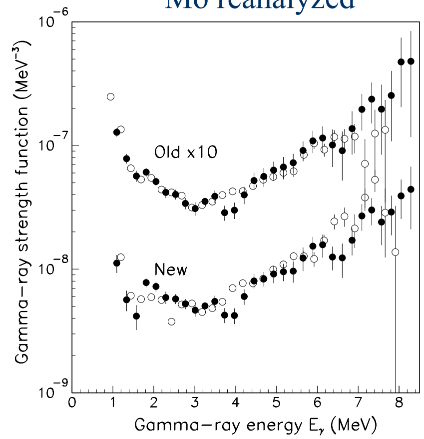
- Description of TSC intensities with Oslo results

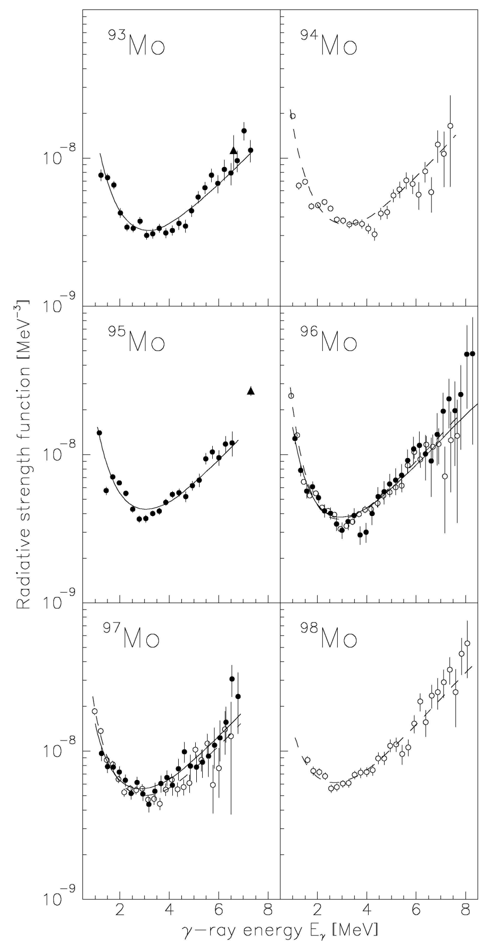


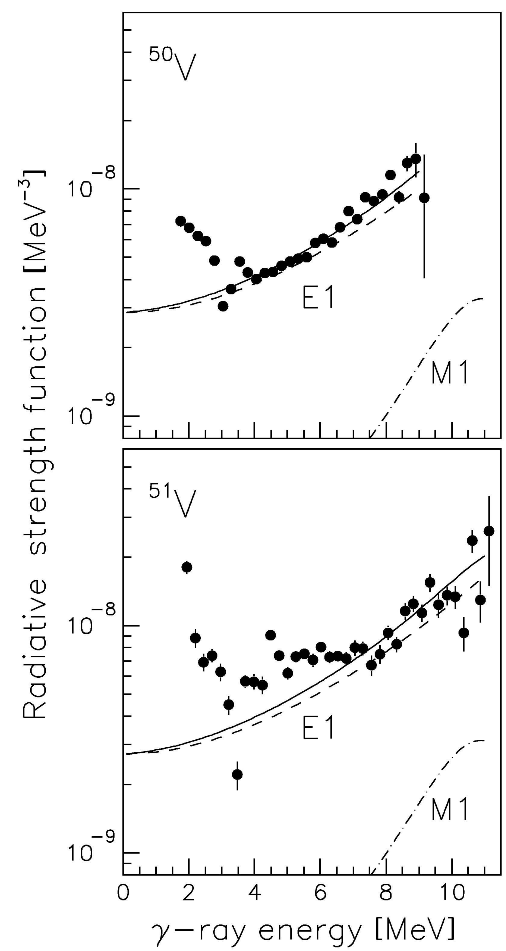
Low-energy RSF enhancement



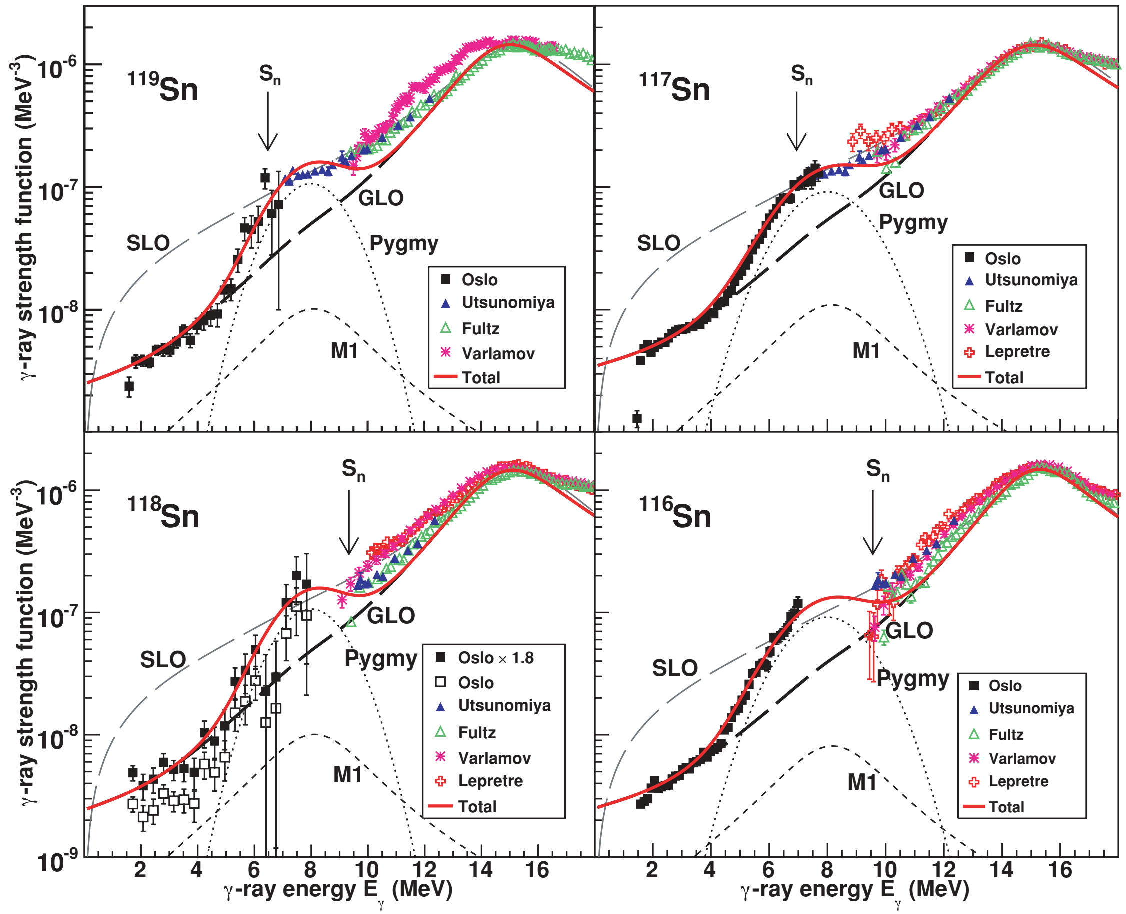
^{96}Mo reanalyzed







Pygmy resonance in Sn isotopes



Conclusion on the Oslo method

- Level densities
  - Good agreement with evaporation spectra
  - Fine structure → Cooper pair breaking
  - Thermodynamics → Pairing phase transition
- Radiative strength functions
  - Good agreement with GDR, primary γ intensities
  - Soft M1 resonance, low-energy enhancement
  - Excellent description of capture γ spectra (total+TSC)
  - Need comparison with (γ, γ') results

Conclusion

- Statistical spectroscopy is a useful tool to investigate nuclear structure, complementary to discrete spectroscopy
- Oslo method a success, good agreement with other methods
  - Evaporation spectra
  - TSC, total cascade spectra, photoneutron σs
  - Need good comparison with (γ,γ') results
- New physics results
  - Pairing phase transition (phase transitions in finite systems)
  - 6.5 μ_N^2 M1 resonance at 3 MeV in deformed rare-earth nuclei
  - Low-energy RSF enhancement in Mo, Fe, V, Sc
  - Pygmy resonance in stable Sn isotopes
  - Establishment of TSC method following p capture (not discussed)

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