Statistical Spectroscopy

past, present & future?

Andreas Schiller, Ohio U

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

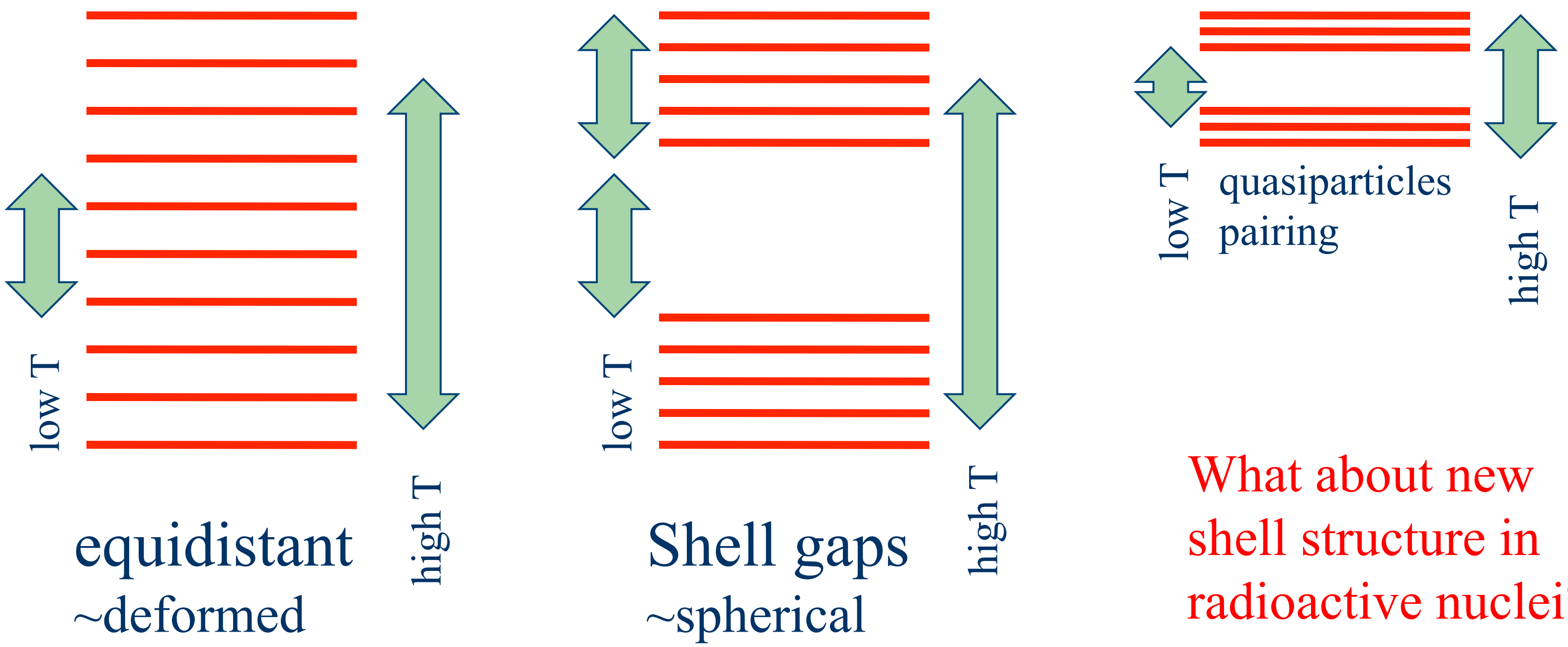
- Counting of discrete levels (up to 100/MeV)
- Counting of neutron (proton) resonances
- Evaporation spectra
- Ericson fluctuation
- Fluctuation analysis of giant resonances
- Excitation-energy indexed gamma spectra

Level density (theory)

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

Structures in level density

- a~g (averaged around Fermi energy)



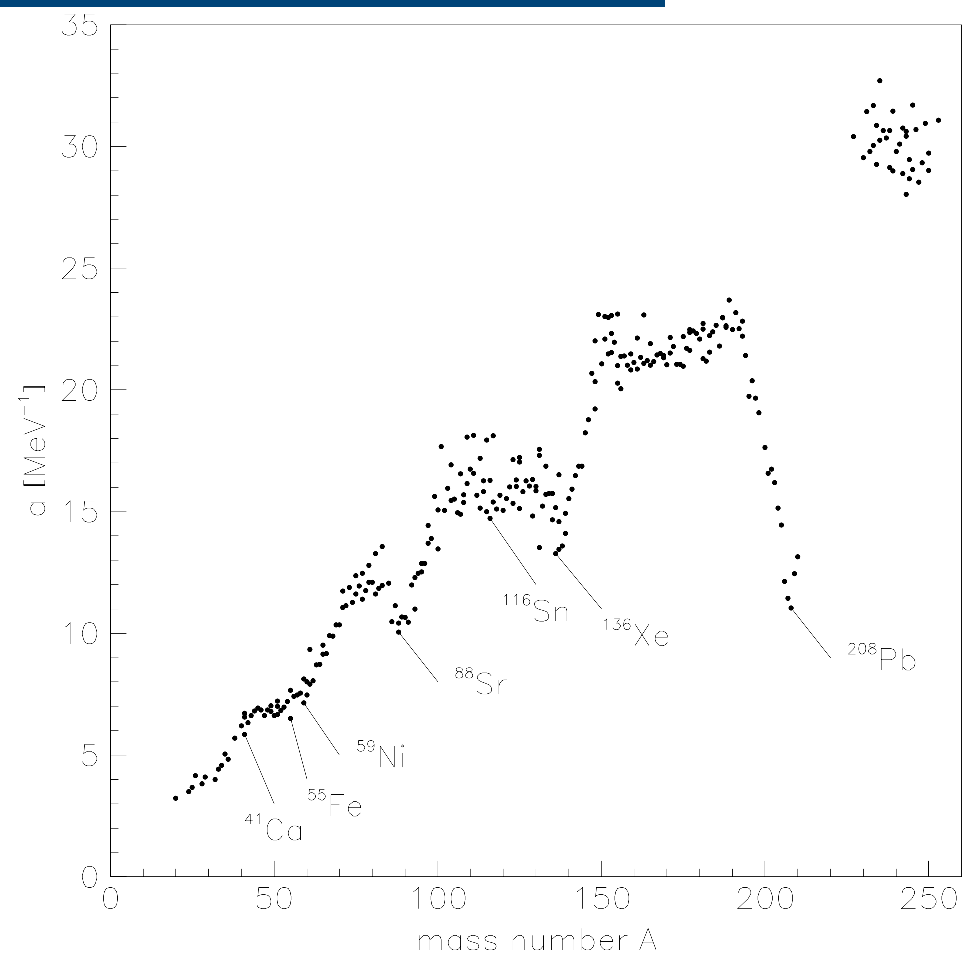
What about new shell structure in radioactive nuclei?

Shell structure of level density

• a from neutron resonance spacings ~7 MeV

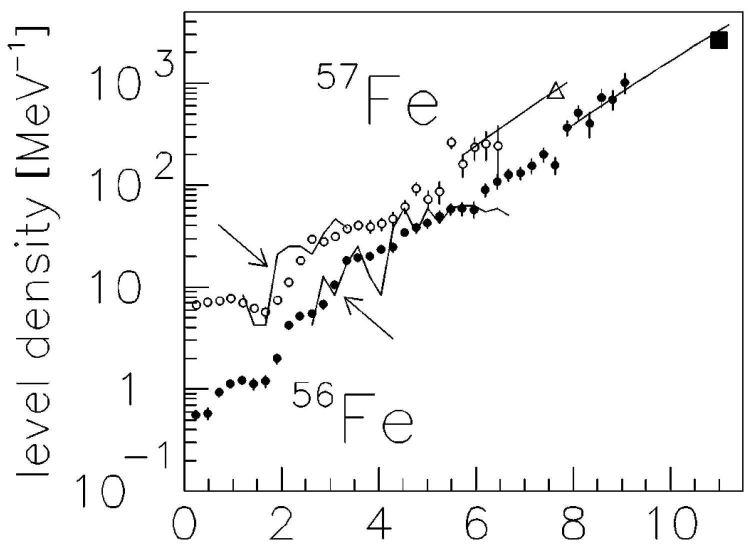
• averaging at intermediate T (low for shell gaps, high for pairing)

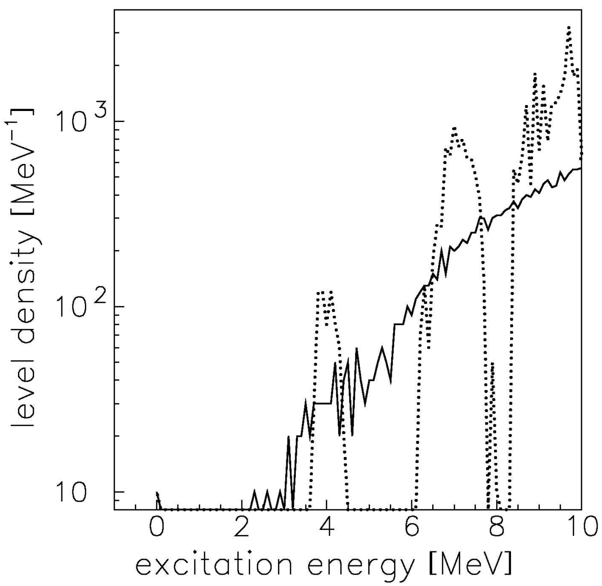
• mostly stable targets



Pairing and level densities

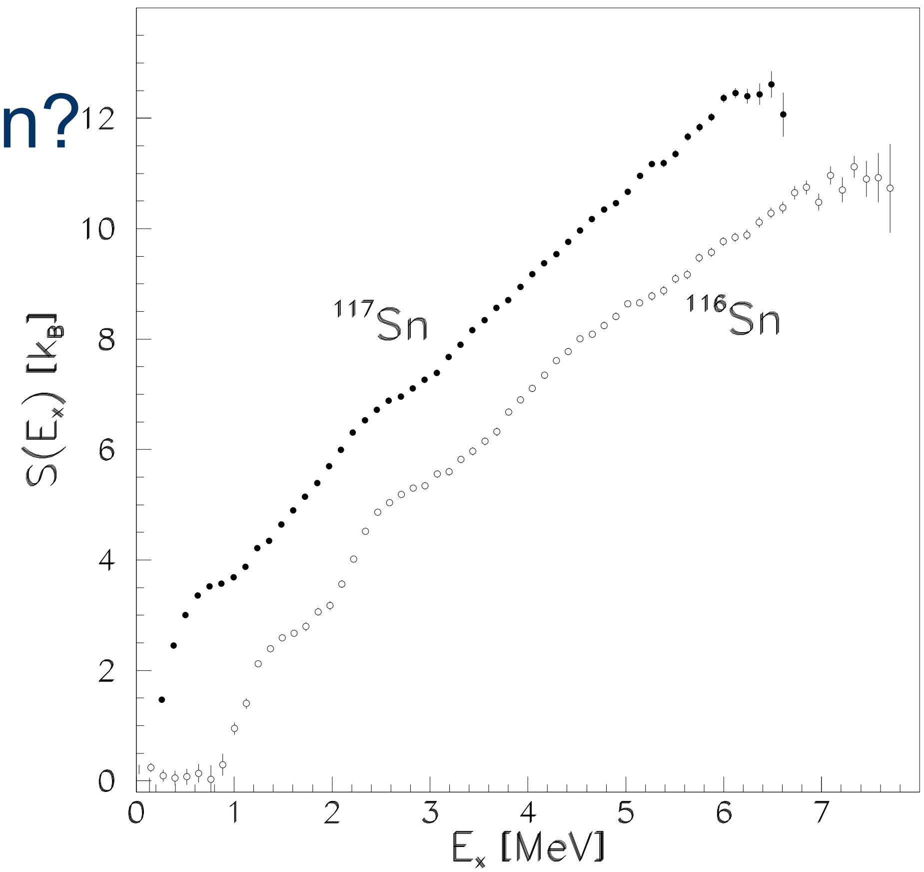
- Steps in level density correspond to breaking of successive Cooper pairs





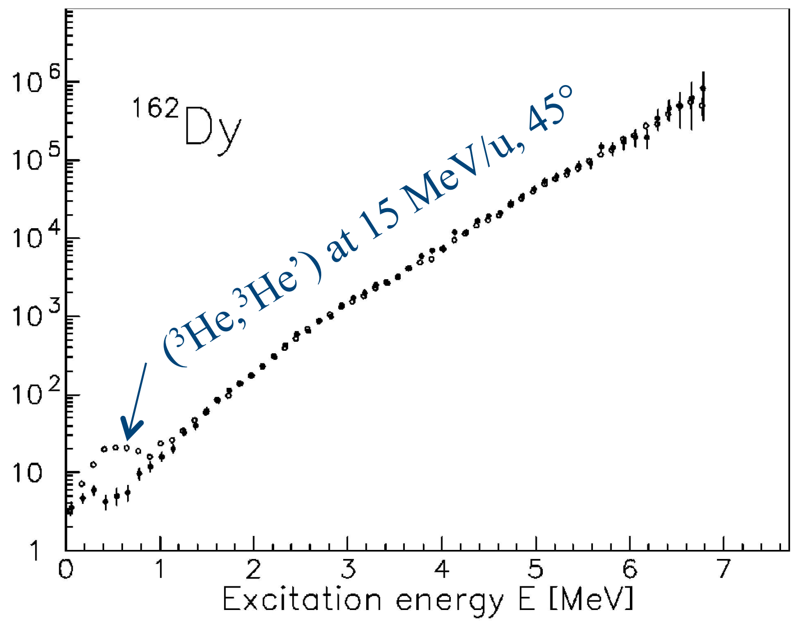
The best staircase: ^{116}Sn

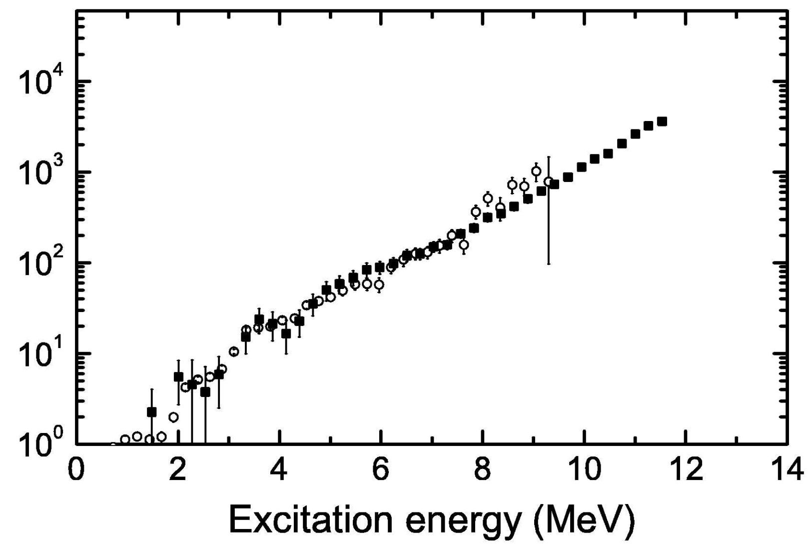
- $^{117}Sn + ^{3}He$
- spin distribution?



Comparison between experiments

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





Level density and rare isotopes

- Manifestation of new gaps in shell structure
- Low separation energy, wide continuum levels
- Need for experimental data
  - Evaporation spectra (integral/spectral method)
  - Excitation-energy indexed gamma spectra (need normalization)
- Spin and parity distribution in stable isotopes

Strength function measurements

- Photoneutron cross sections and photon absorption/scattering (real/virtual photons)
- Primary γ intensities after neutron capture, two-step-cascade intensities
- Total γ spectrum fitting method (hot GDRs)
- Excitation-energy indexed gamma spectra

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

Structures in strength functions

- Dominated by giant resonances
- GDR: 1ħω and 2ħω cross shell excitations

  shape of GDR determined mostly by deformation

- GMR: transitions between spin-orbit partners

  connected to GT strength function, single/double humped?

- Scissors mode

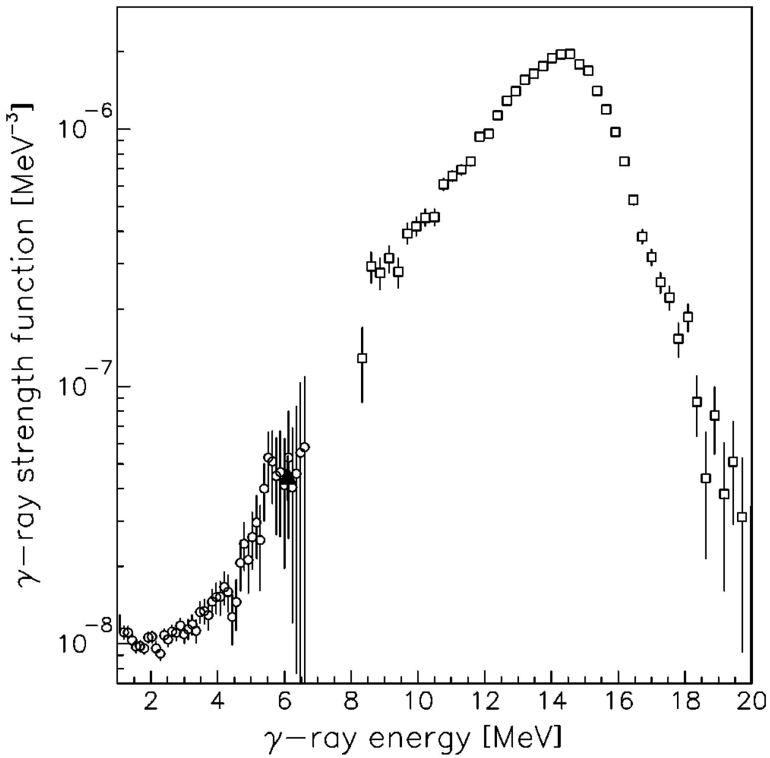
  single/double humped, strength temperature dependent?

Change of shell structure gives largest B(E1) value in ^{11}Be

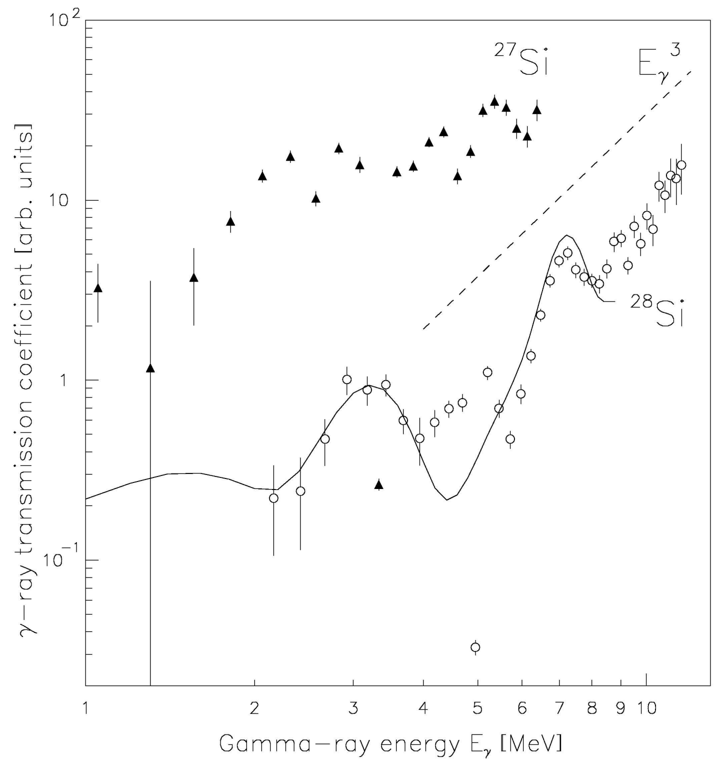
Spin-orbit force ~ $\hat{l} \cdot \hat{s} \; \frac{\mathrm{d}V(r)}{\mathrm{d}r}$

Comparison of experiments

- ^{148}Sm

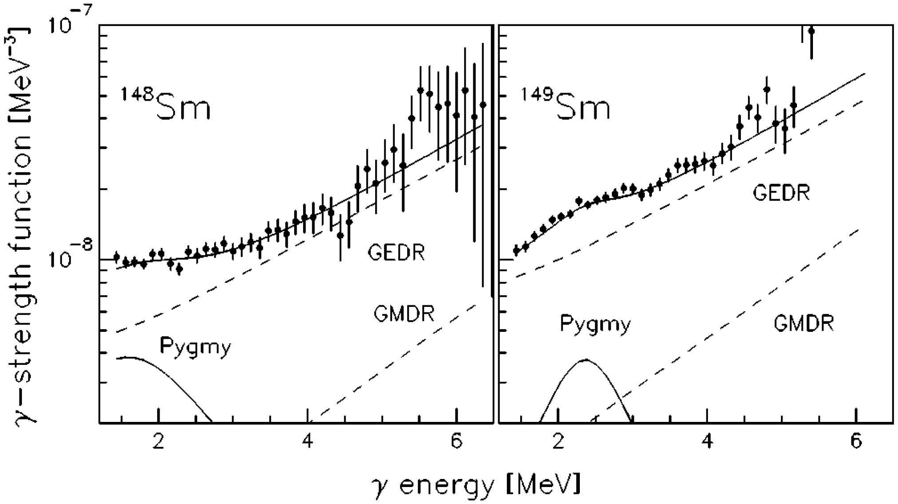


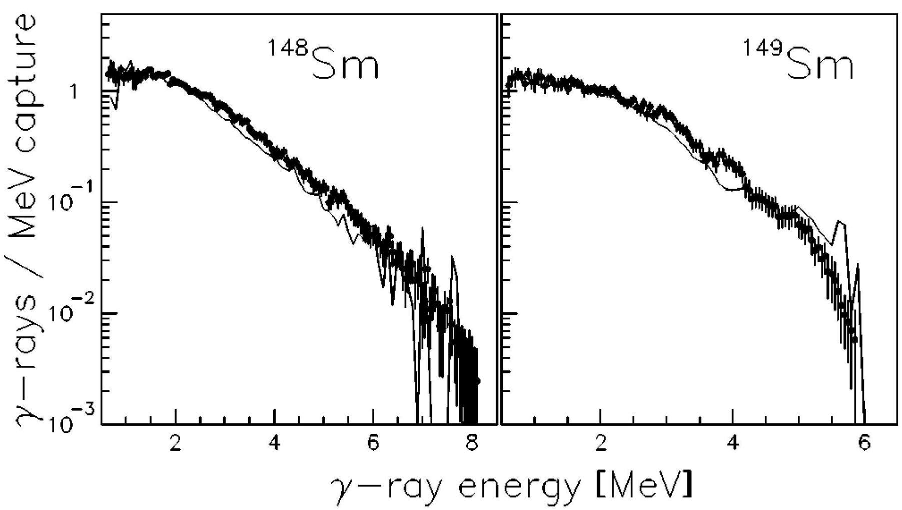
- ^{28}Si



Further tests and comparisons

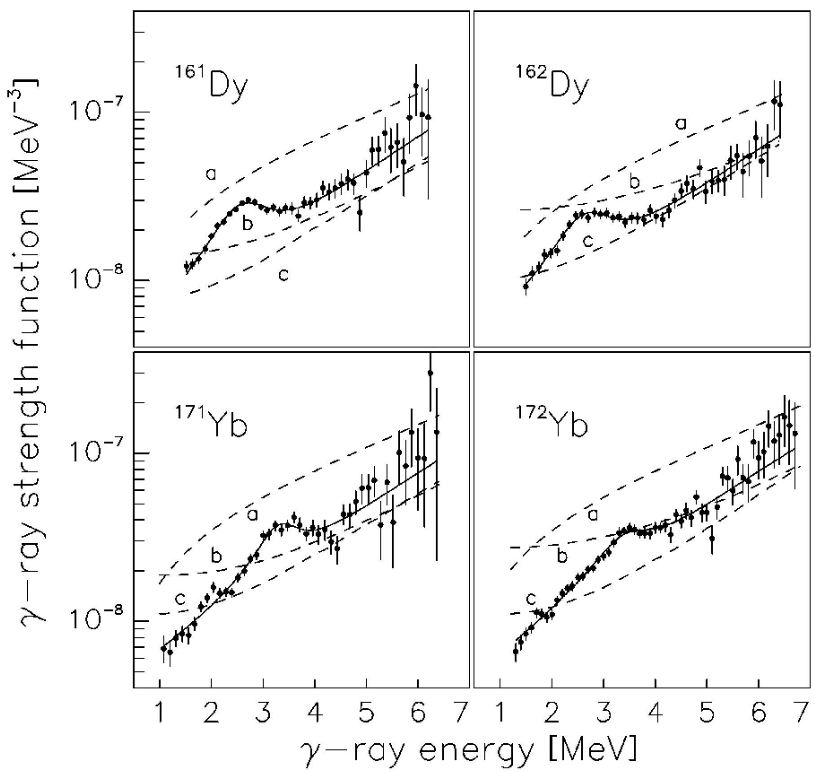
- ^{148,149}Sm



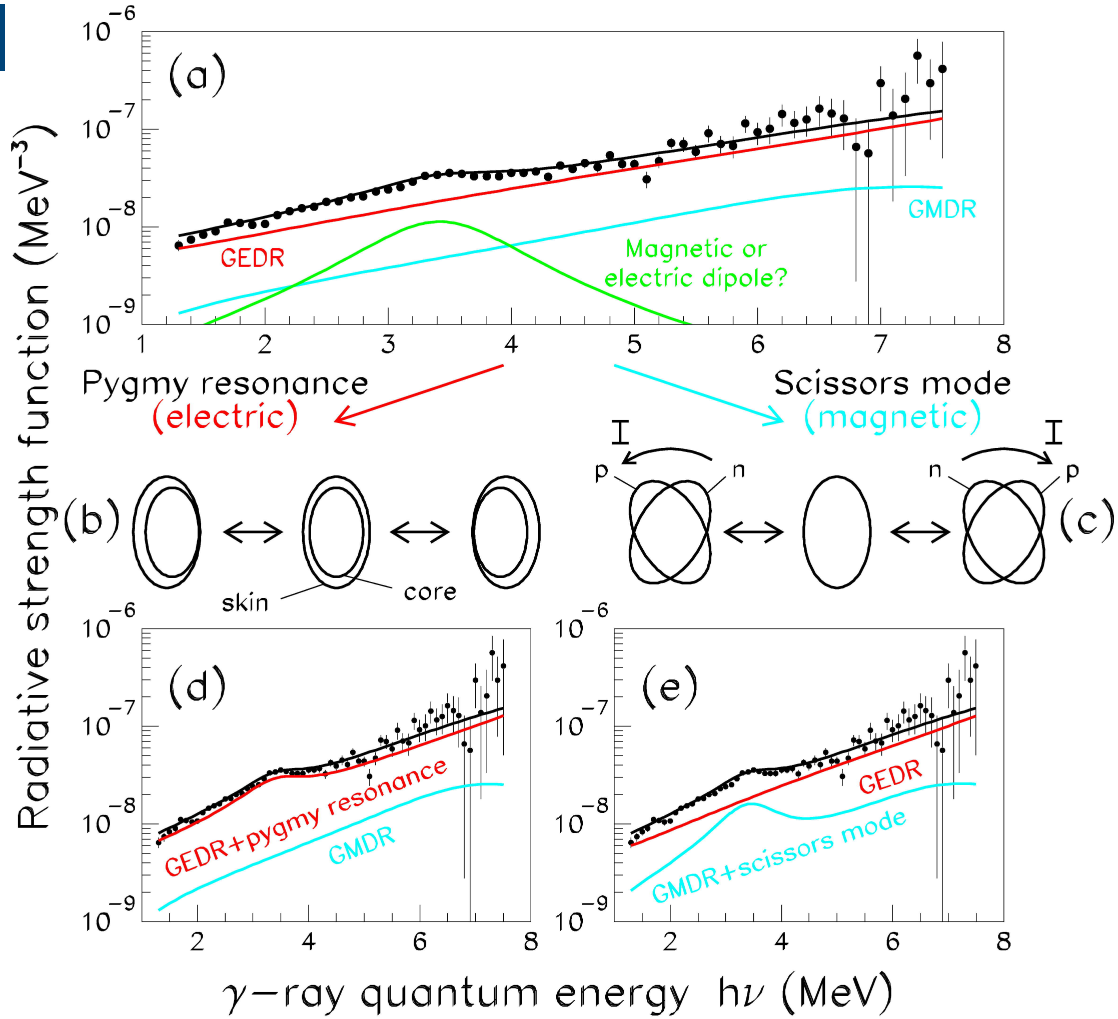


Results for the RSF

- Scissors mode in deformed rare-earth nuclei
  - large strength
  - mostly one humped

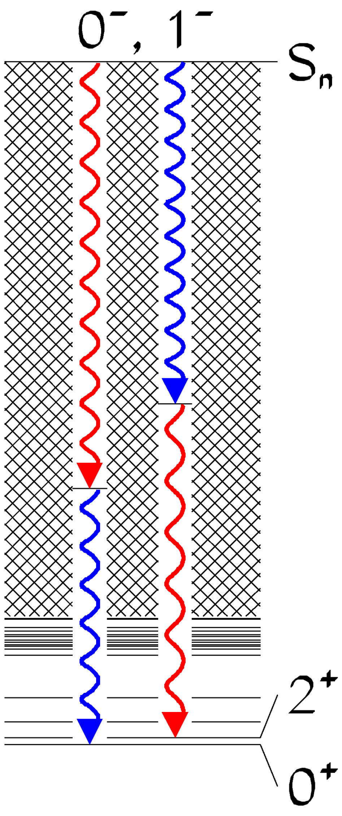


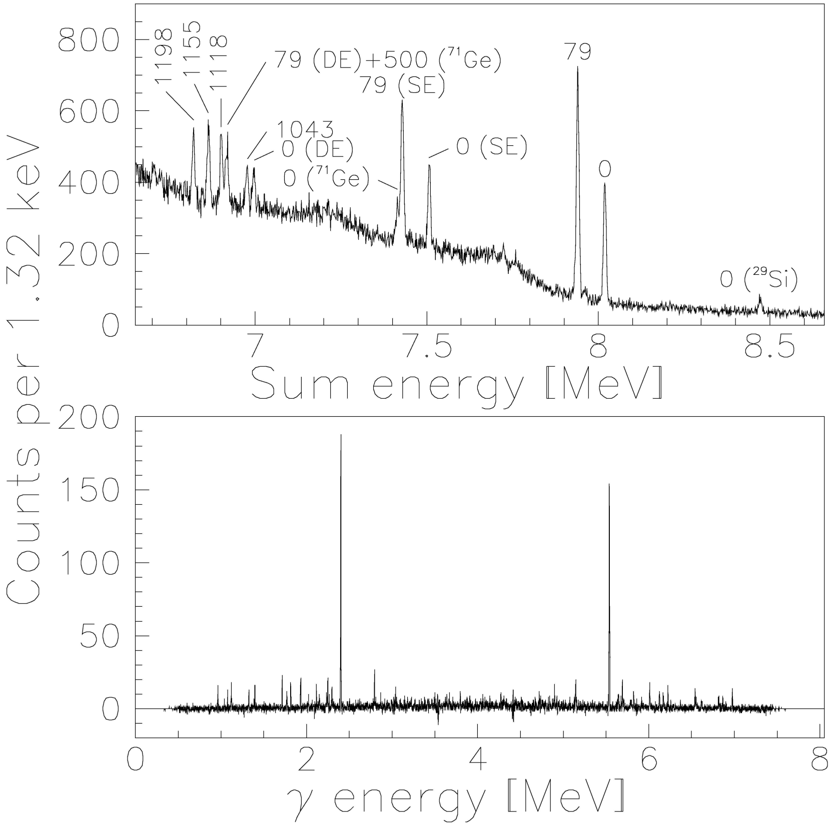
Is the soft resonance E1 or M1?



Two-step-cascade method

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



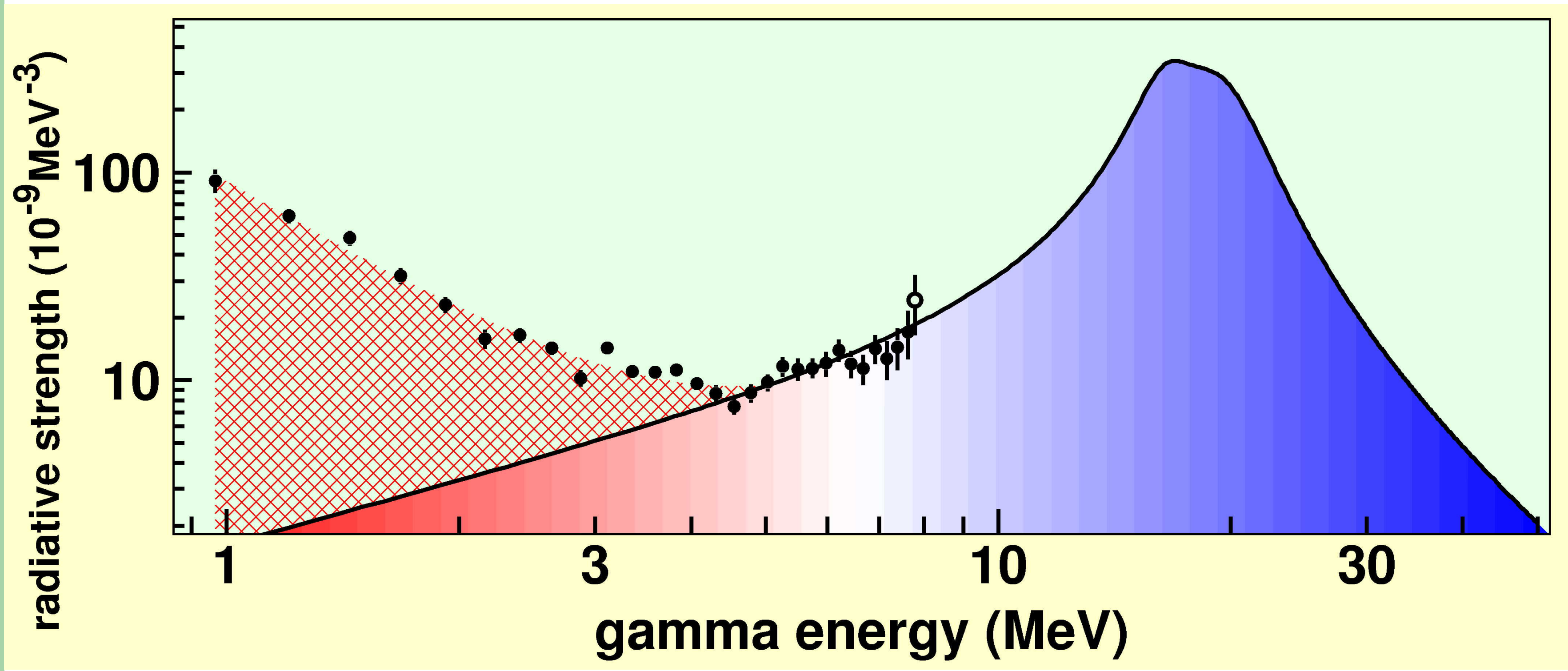


Results from experiment

- 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: $B(M1\uparrow)=6.5\mu_N^2$

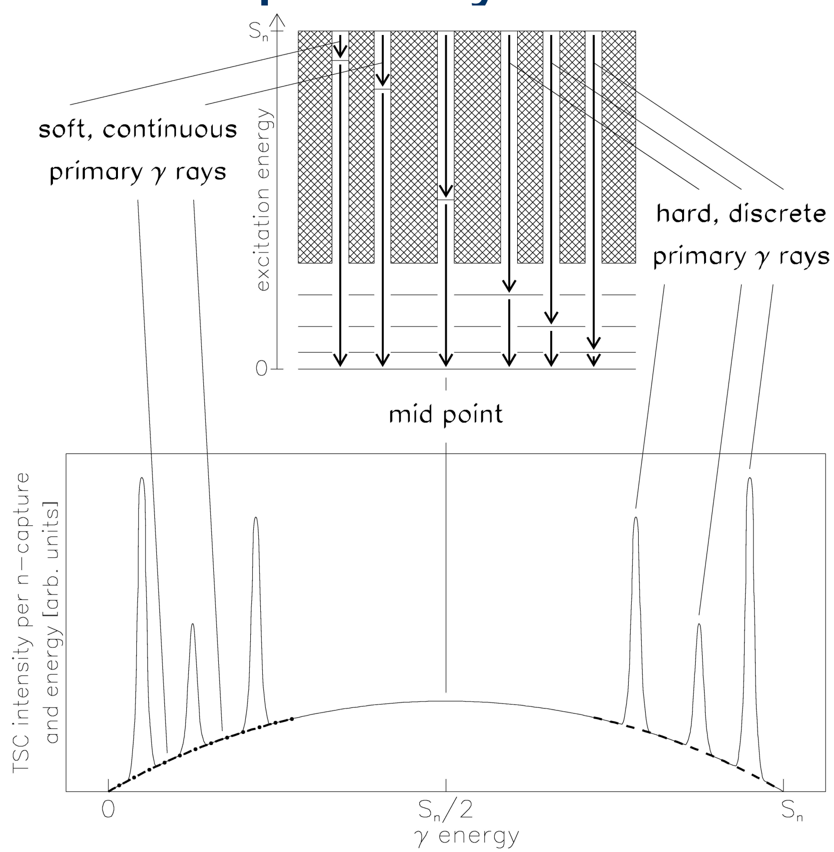
An unexpected discovery

- Soft transitions between warm states in Fe



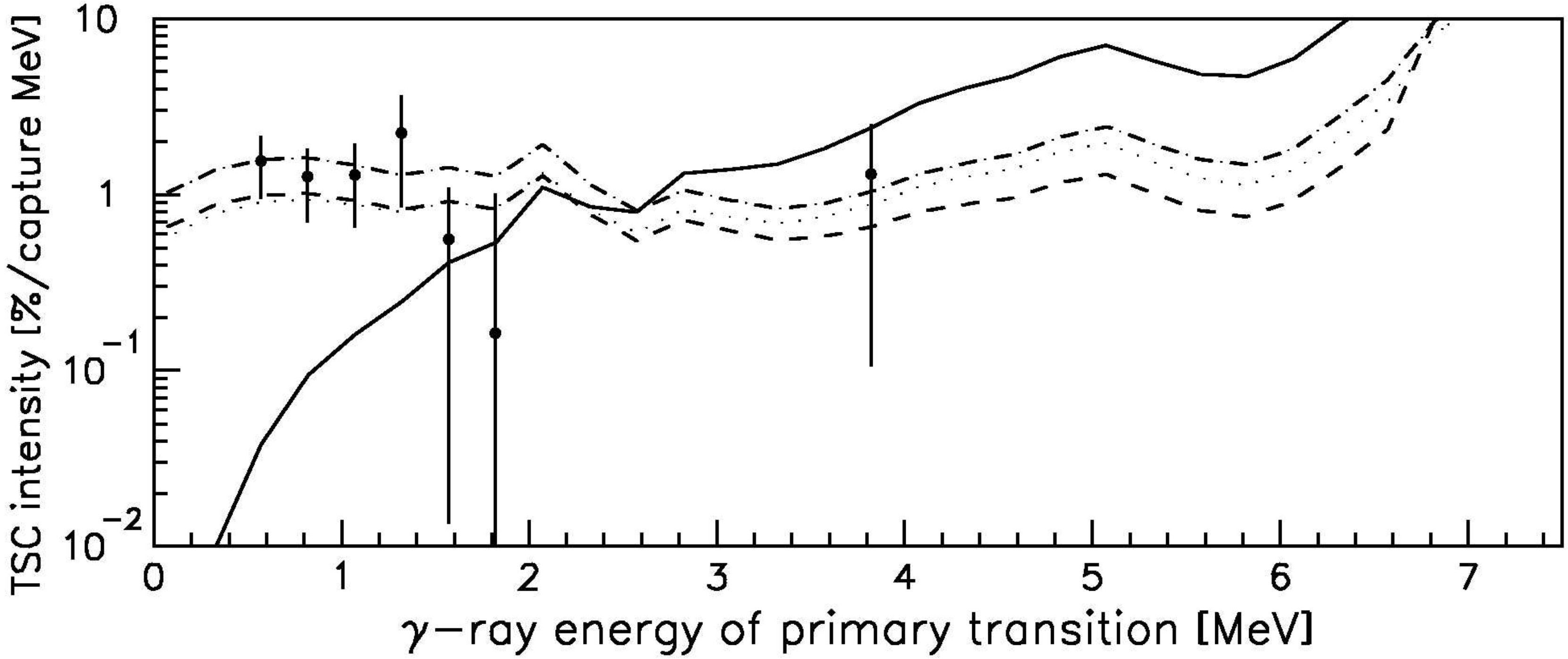
Support from TSC intensities

- Extraction of soft primary transitions

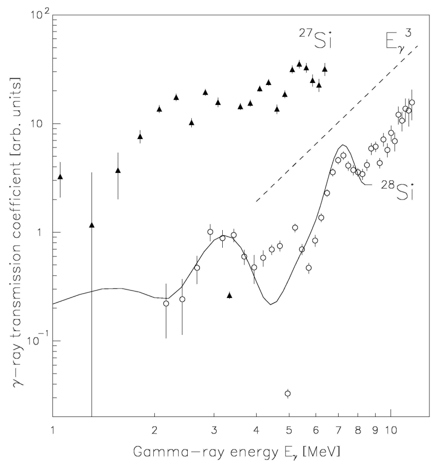


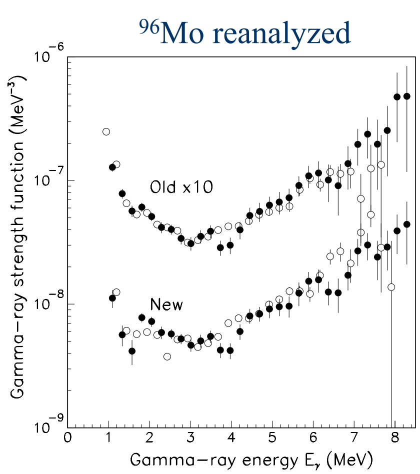
Experimental result

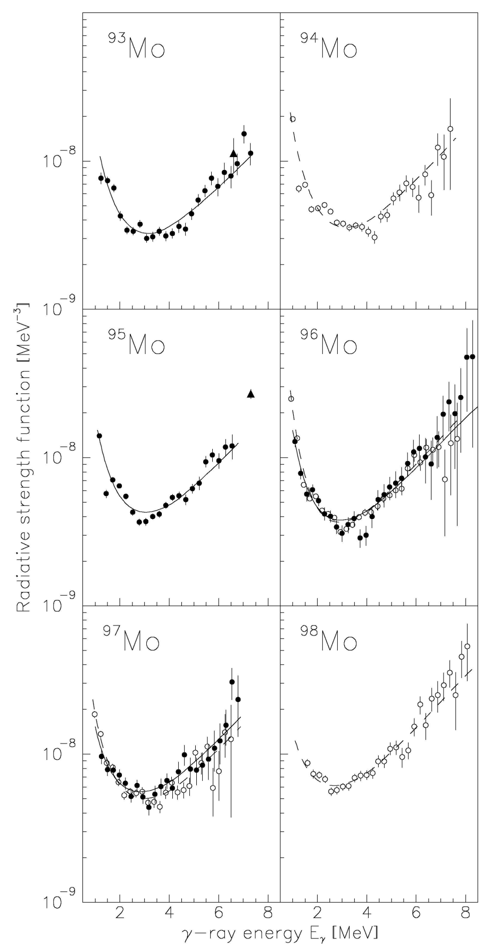
- Description of TSC intensities with Oslo results

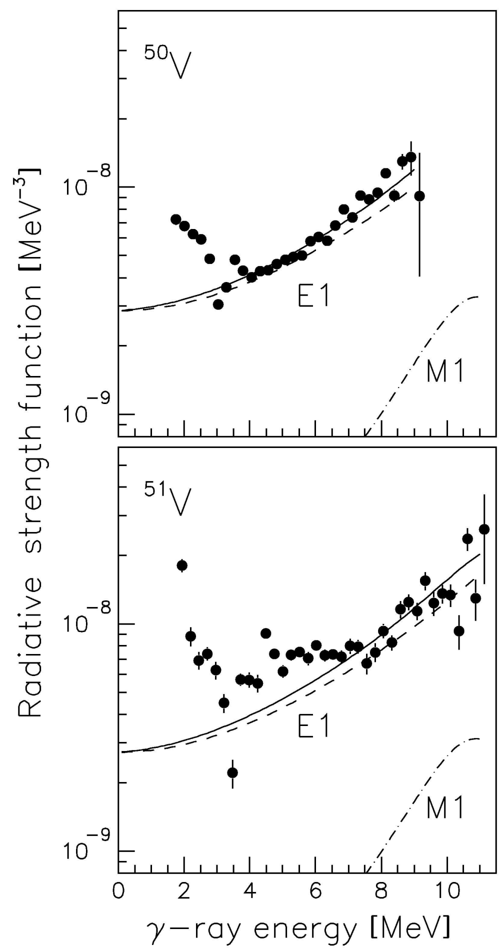


Low-energy RSF enhancement

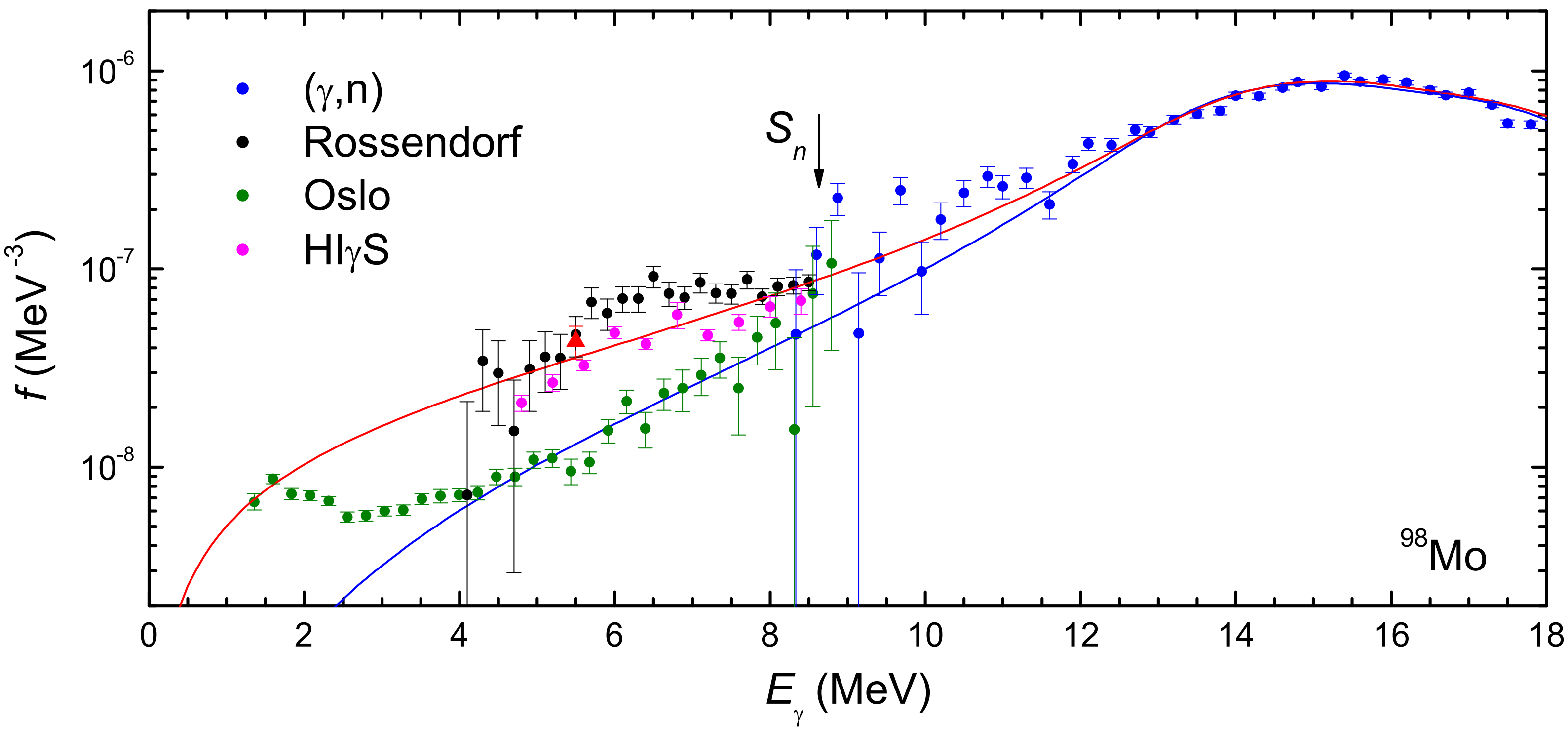




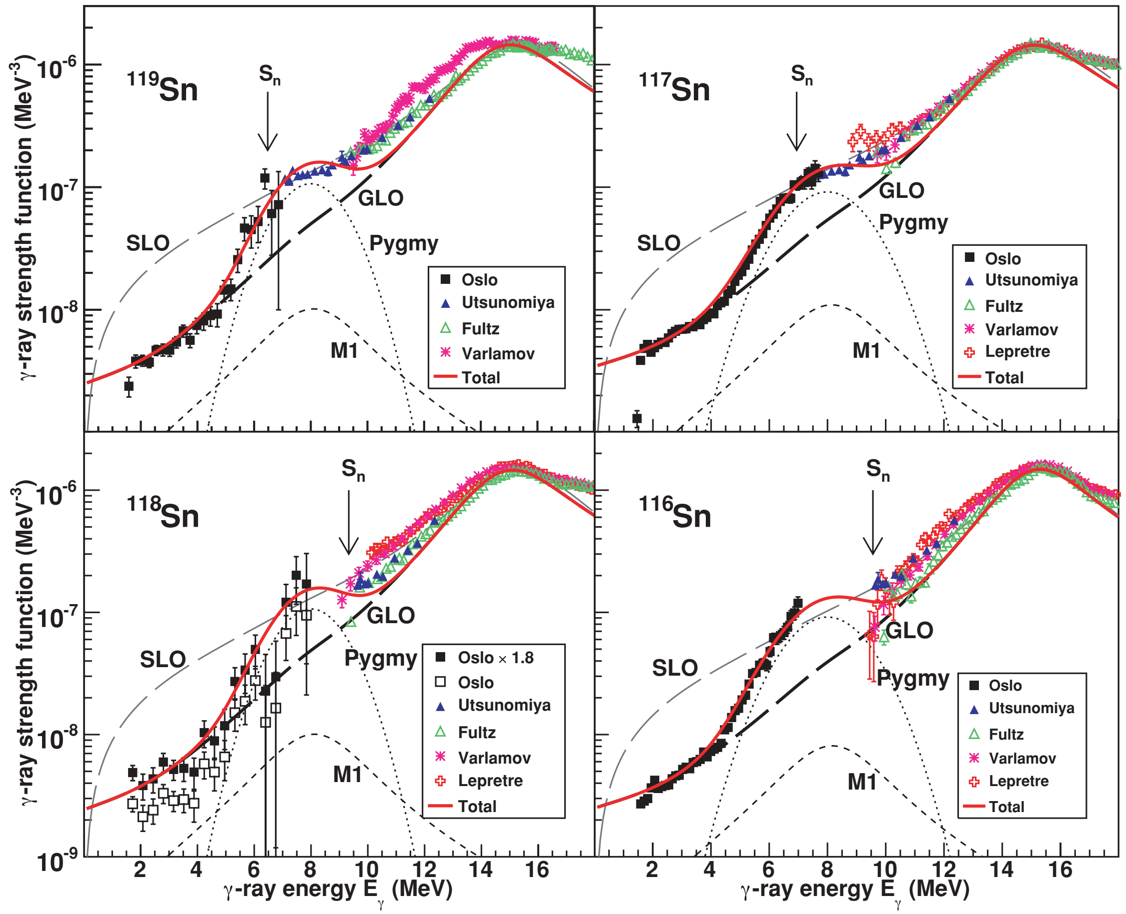




Mo radiative strength function



Pygmy resonance in Sn isotopes



Open questions

- Change of giant resonance parameters with shell structure, deformation, temperature
- Coupling to the continuum
- Astrophysical impact

Hot GDR width systematics

- Compilation of 347 hot GDR parameter sets
- All parameter sets brought on common footing
- At. Data Nucl. Data Tables 93, 549 (2007)
- Γ(A,J,T) scaling law

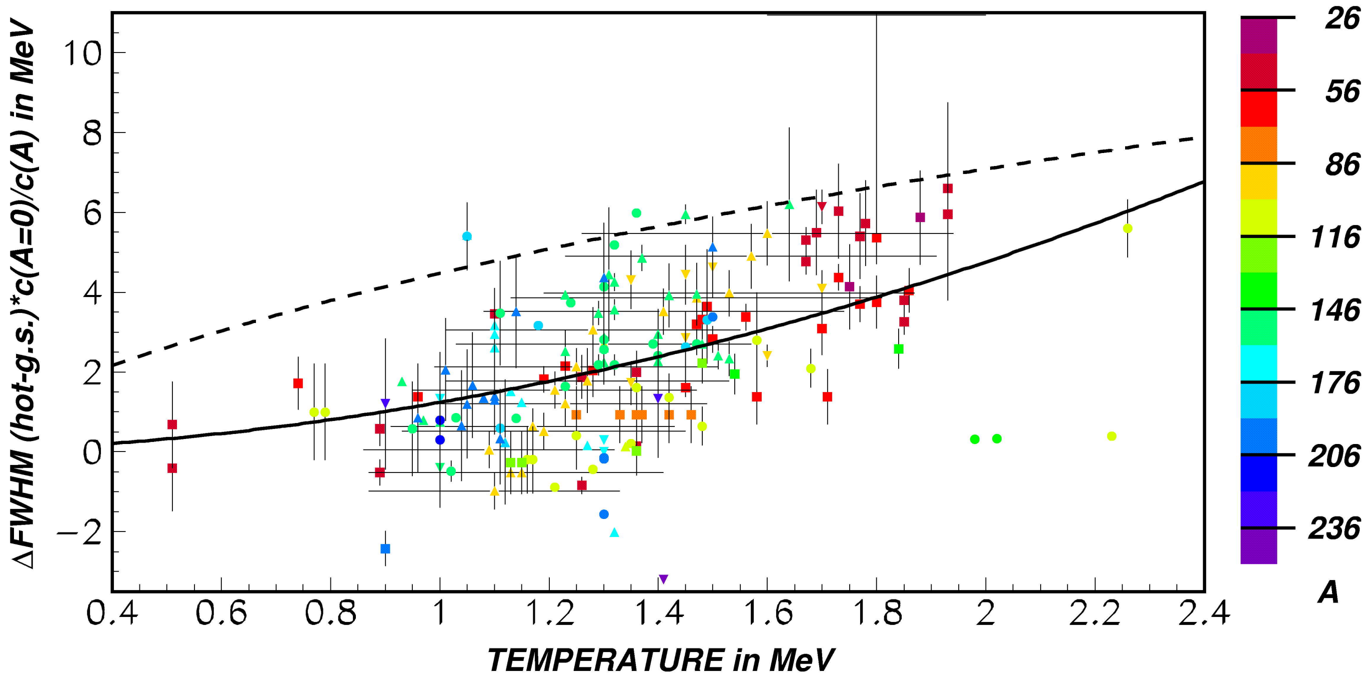
$$\Gamma(A,J,T) = \left(\Gamma_0(A) + c(A) \cdot \log\left[1 + T/T_0 \right] \right) \cdot L(\xi)^{4/(3+T/T_0)}$$

$\Rightarrow$ plot $\Delta\Gamma(\text{hot - cold}) / c(A)$

≈ 1 for $\xi = J / A^{5/6} \leq 0.6\hbar$

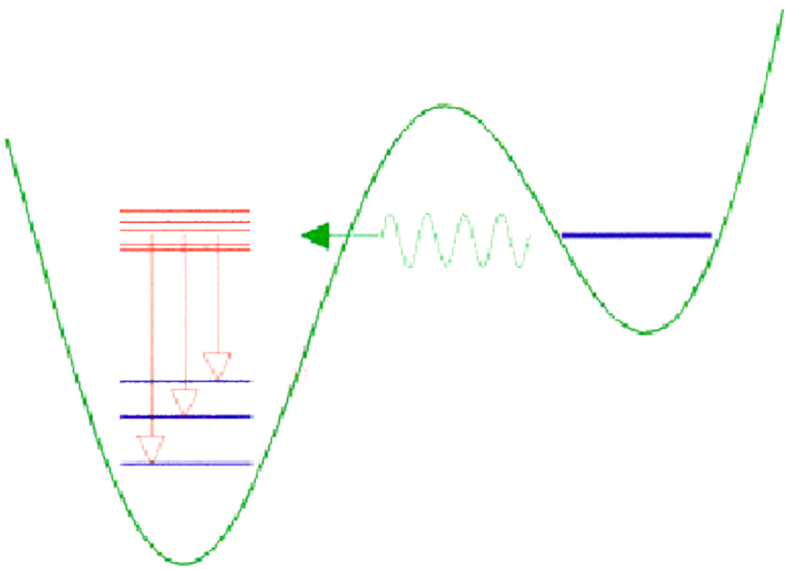
Hot GDR width scaling

- Minimal bias, 183 world data
- Power-law fit → $\Delta\Gamma/c(A)=1.24\cdot T^{1.91}$



Decay out of SD band

- Similar situation as in neutron capture
  - One (or few) initial levels, parity known
  - One (or few) final levels, parity known
  - Statistical γ decay
  - Energies known
  - Gretina or Agata
  - Lifetime of SD state?

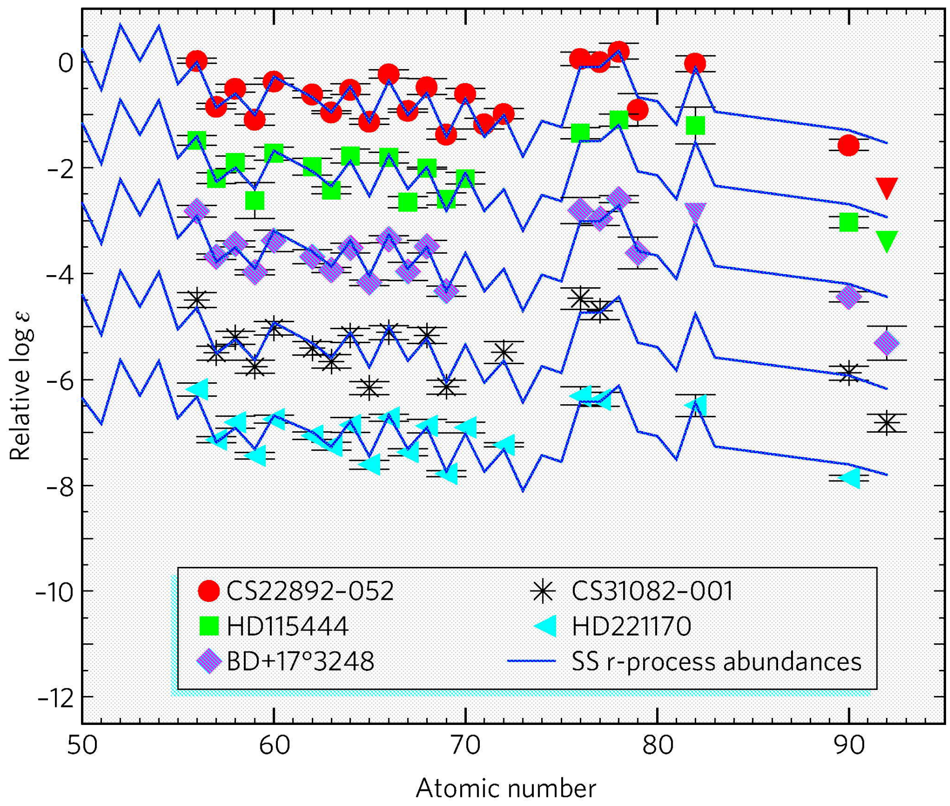


Nuclear astrophysics

- Understanding r-process in absence of $(\gamma,n) \leftrightarrow (n,\gamma)$ equilibrium
  - High entropy, fast freeze-out scenarios
  - Inhomogeneous big-bang nucleosynthesis
- Astrophysics will provide Y_e, S, t, n_n, etc.
- Nuclear physics has to provide S_n, $t_{1/2}$, P_n, (n,γ) and (γ,n) cross sections

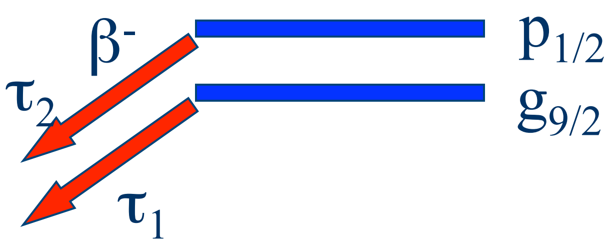
General abundance patterns

- Five galactic halo stars [Cowan & Sneden, Nature, **440**, 1151 (2006)]

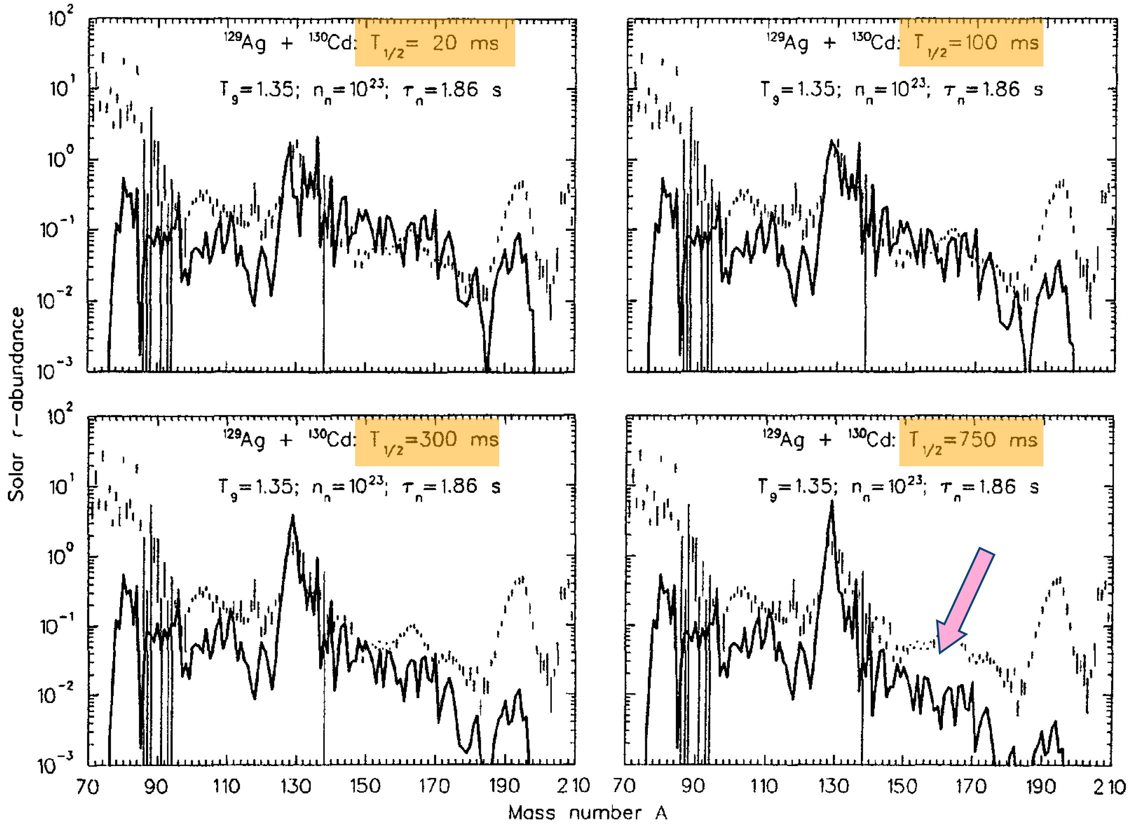


Sensitivity to nuclear data

- $t_{½}$ of ^{129}Ag, ^{130}Cd
- Effective $t_{½}$!

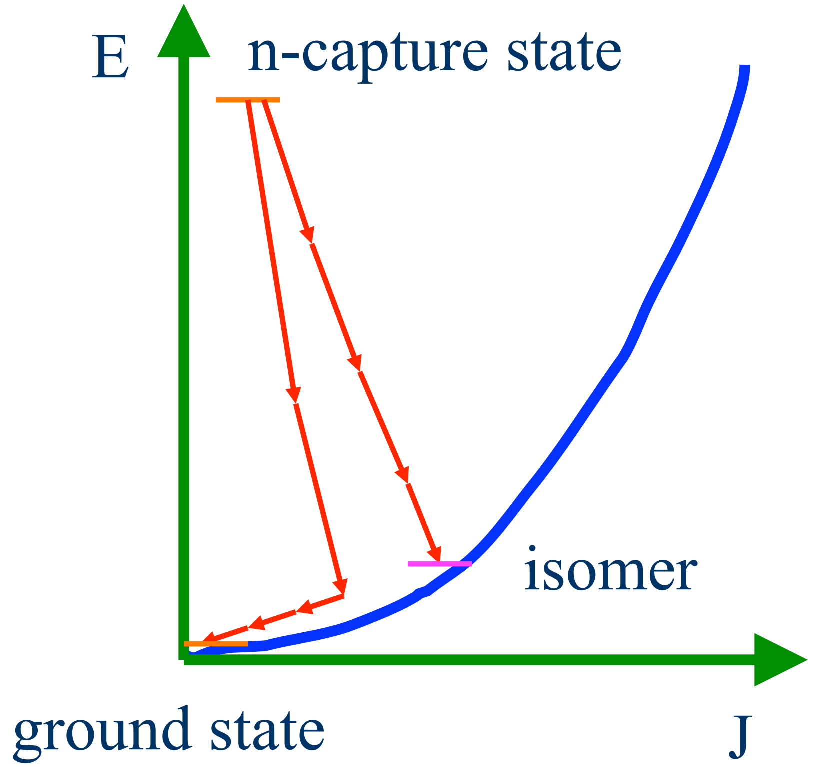


$$\tau_{eff}=p_1\cdot\tau_1+p_2\cdot\tau_2$$



Isomeric production and effective $t_{½}$

- n-capture populates 2 spins and 1 parity
- Slope of RSF determines γ multiplicity
- Isomeric production can depend strongly on γ multiplicity
- Similarly in branchpoint s-process nuclei
- Also important in rare isotope production facilities



RSF of radioactive nuclei

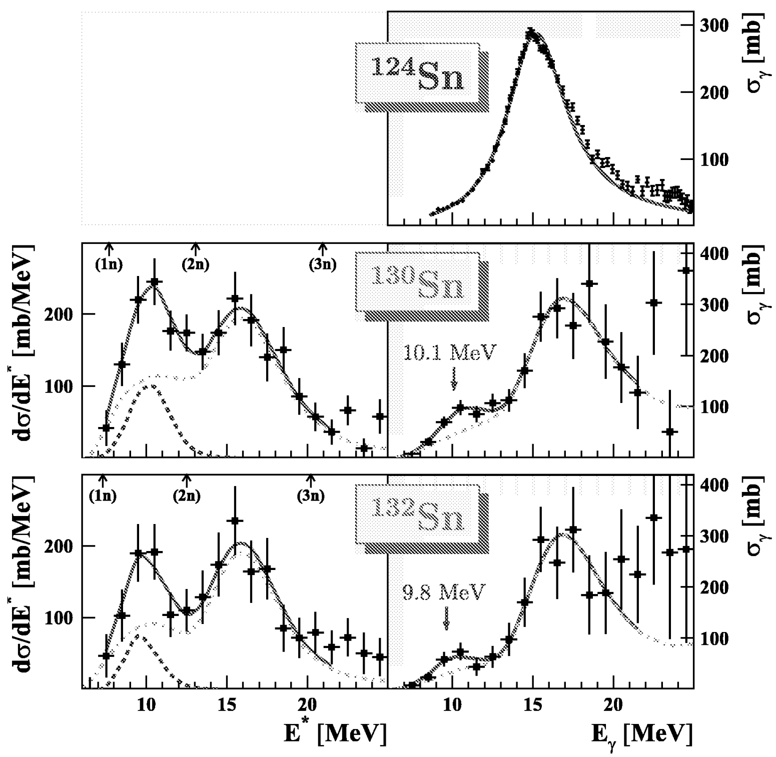
- Measure Coulomb-breakup cross section

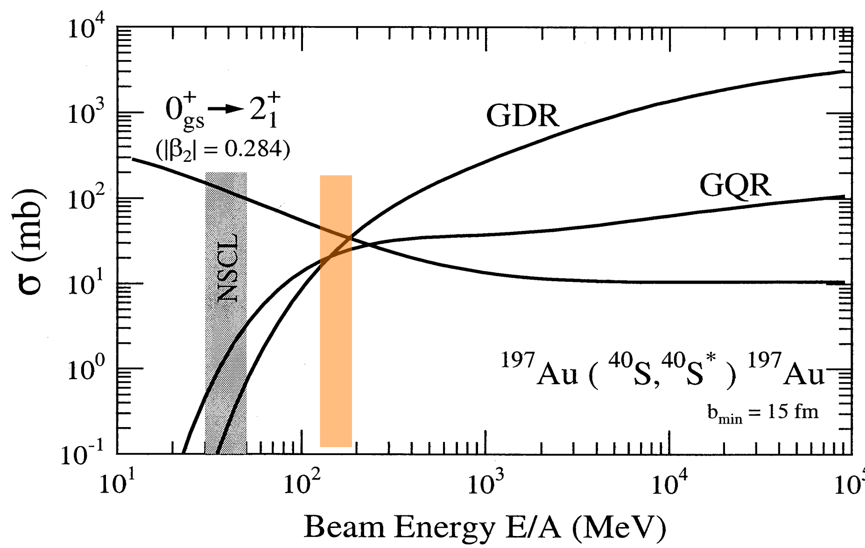
$$\frac{\mathrm{d}^2\sigma_{E1}}{\mathrm{d}\Omega_{\mathrm{CM}}\,\mathrm{d}E_{\mathrm{rel}}} = \frac{16\pi^3}{9\hbar c}\cdot\frac{\mathrm{d}N_{E1}(\theta_{\mathrm{CM}},E_\gamma)}{\mathrm{d}\Omega_{\mathrm{CM}}}\cdot\frac{\mathrm{d}B(E1\uparrow)}{\mathrm{d}E_\gamma}$$

$$= 3(\pi\hbar c)^2 f_{E1}(E_\gamma)\cdot\frac{\mathrm{d}N_{E1}(\theta_{\mathrm{CM}},E_\gamma)}{\mathrm{d}\Omega_{\mathrm{CM}}}$$

- Calculate virtual photon flux $N(\theta_{CM},E_\gamma) \rightarrow \sigma(\gamma,n)$
- Relate $\sigma(\gamma,n)$ to $\sigma(n,\gamma)$ by detailed balance

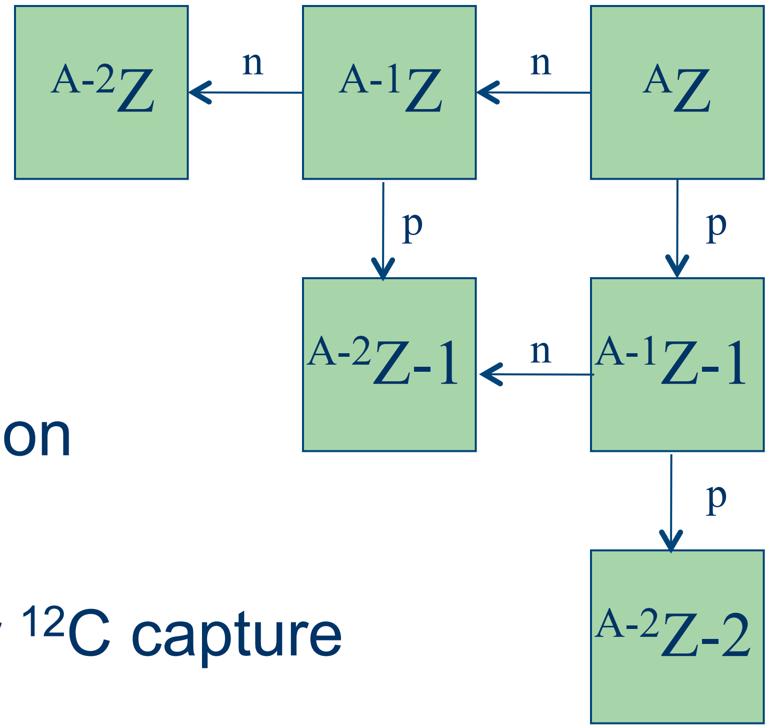
Coulomb breakup





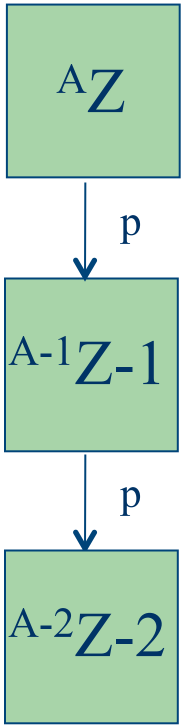
Level density of radioactive nuclei

- Integral measurements
- A from FMA
- protons + gammas
  - Microball
  - Gammasphere
  - isotopic differentiation
- Proton rich nuclei
  - produced by ^{9}Be or ^{12}C capture



Level density of radioactive nuclei

- Spectral measurement
- A from FMA
- Proton spectra from Microball
  - excitation energy index
  - gamma spectrum from Gammasphere
- Two proton spectra
  - TSC method for particles
- Very proton rich nuclei
  - Inverse kinematics, low Q value



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
  - Probably also with (γ,γ')

Outlook

- Hot GDR width systematic, deformation dependence
- Adapt TSC method to decay out of SD well?
- Coulomb breakup → RSF of radioactive nuclei
- Astrophysical applications (r-process)
- Isomeric production cross sections
- Evaporation/γ spectra from inverse-kinematics reactions using radioactive beams?

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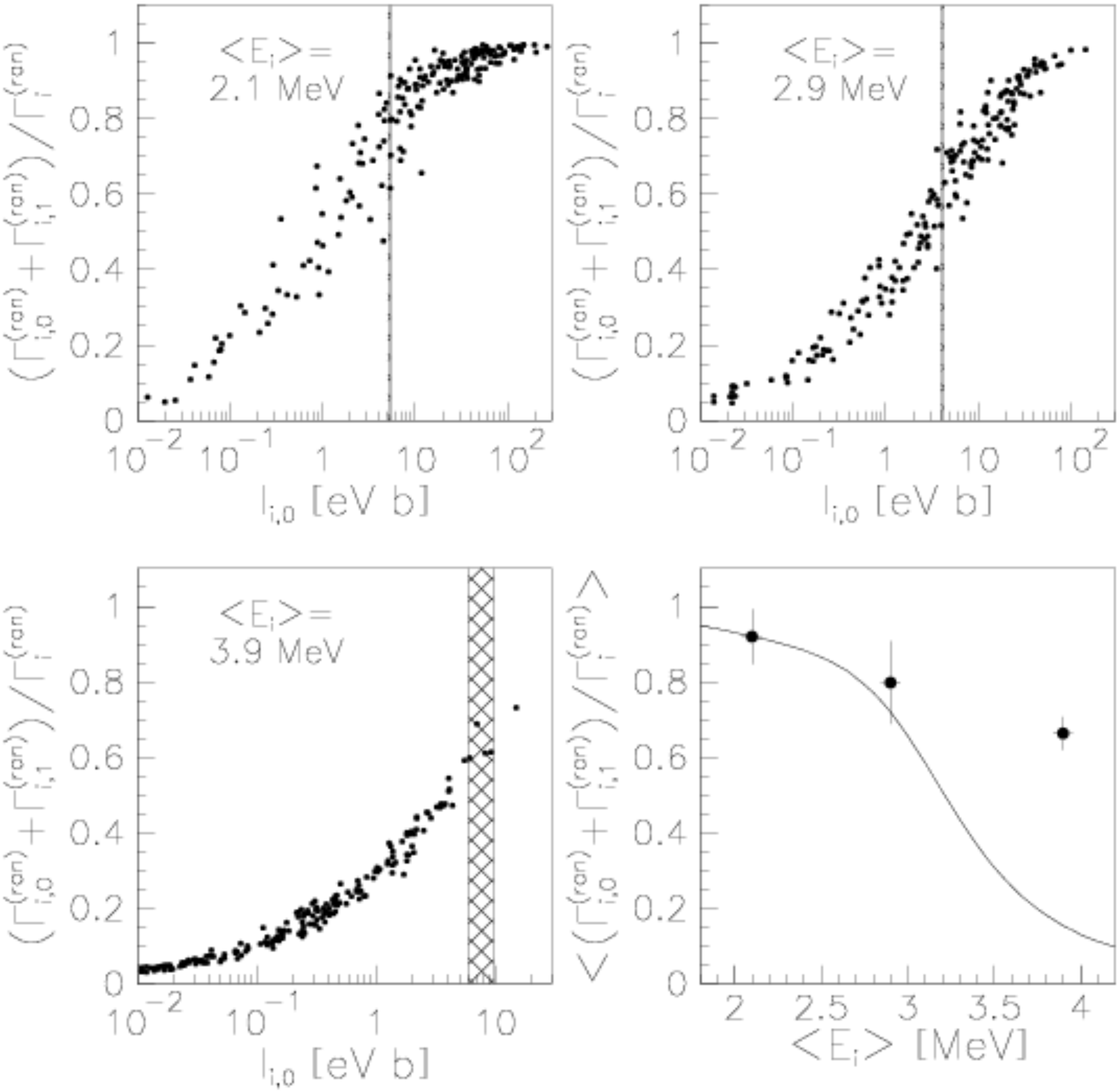

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2.9 MeV
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3.9 MeV
I_i,0 [eV b]
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