Giant resonances, fine structure, wavelets and spin- and parity-resolved level densities

- Motivation
- Experimental data
- Fluctuation analysis
- Discrete wavelet transform and determination of background
- Results and test of models
- Summary and outlook

Y. Kalmykov, K. Langanke, G. Martínez-Pinedo, P. von Neumann-Cosel, C. Özen, A. R.

S-DALINAC / iThemba LABS / RCNP / KVI
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Level densities: Recent results

- Back-shifted Fermi gas model*
  semiempirical approach, shell and pairing effects

- Many-body density of states**
  two-component Fermi gas, shell effects, deformations, periodic orbits

- HF-BCS***
  microscopic statistical model, MSk7 force, shell effects, pairing correlations, deformation effects, collective excitations

* T. Rauscher, F.-K. Thielemann, and K.-L. Kratz, Phys. Rev. C56 (1997) 1613

T. von Egidy and D. Bucurescu, Phys. Rev. C72 (2005) 044311; Phys. Rev. C73 (2006) 049901(E)

** P. Leboeuf and J. Roccia, Phys. Rev. Lett. 97 (2006) 010401

*** P. Demetriou and S. Goriely, Nucl. Phys. A695 (2001) 95

Level densities: Recent results

- HFB*

  microscopic combinatorial model, MSk13 force, shell effects, pairing correlations, deformation effects, collective excitations

- Large-scale prediction of the parity distribution in the level density**

  macroscopic-microscopic approach, deformed Wood-Saxon potential, BCS occupation numbers, back-shifted Fermi Gas model

- Monte-Carlo shell model***

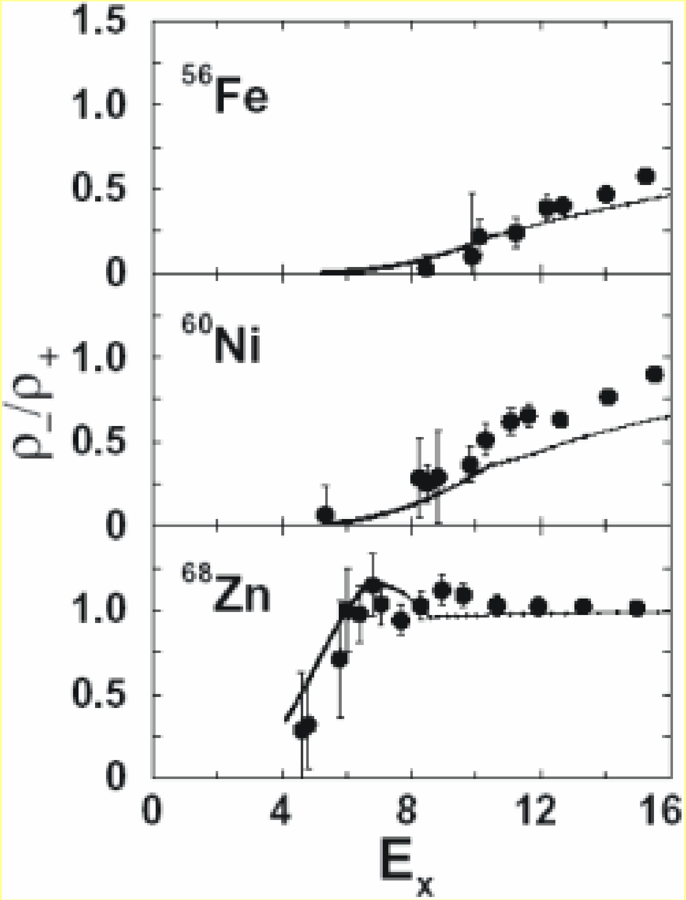
  microscopic model, large model space, pairing+quadrupole force

* S. Hilaire and S. Goriely, Nucl. Phys. A779 (2006) 63

** D. Mocelj et al., Phys. Rev. C75 (2007) 045805

*** C. Özen, K. Langanke, G. Martinez-Pinedo, and D.J. Dean, nucl-th/0703084 (2007)

Monte-Carlo shell model predictions: pf + $g_{9/2}$ shell



$\Delta_{pf-g_{9/2}}$ small

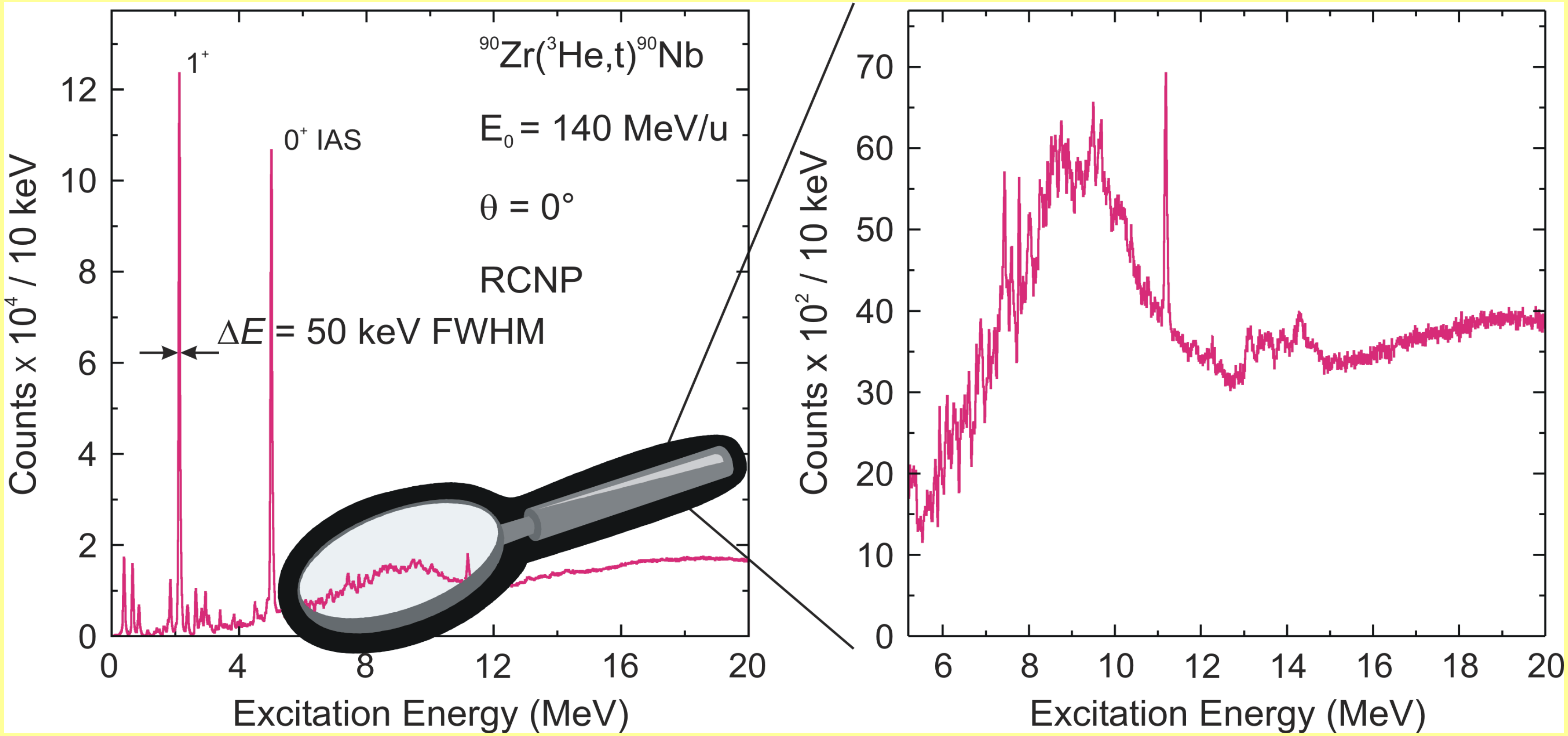
ρ_- important at low energies

- Total level density (not spin projected) shows strong parity dependence*
- Questioned by recent experiments (^{45}Sc)**

* Y. Alhassid, G.F. Bertsch, S. Liu, and H. Nakada, Phys. Rev. Lett. 84 (2000) 4313

** S.J. Lokitz, G.E.Mitchell, and J.F. Shriner, Jr., Phys. Rev. C71 (2005) 064315

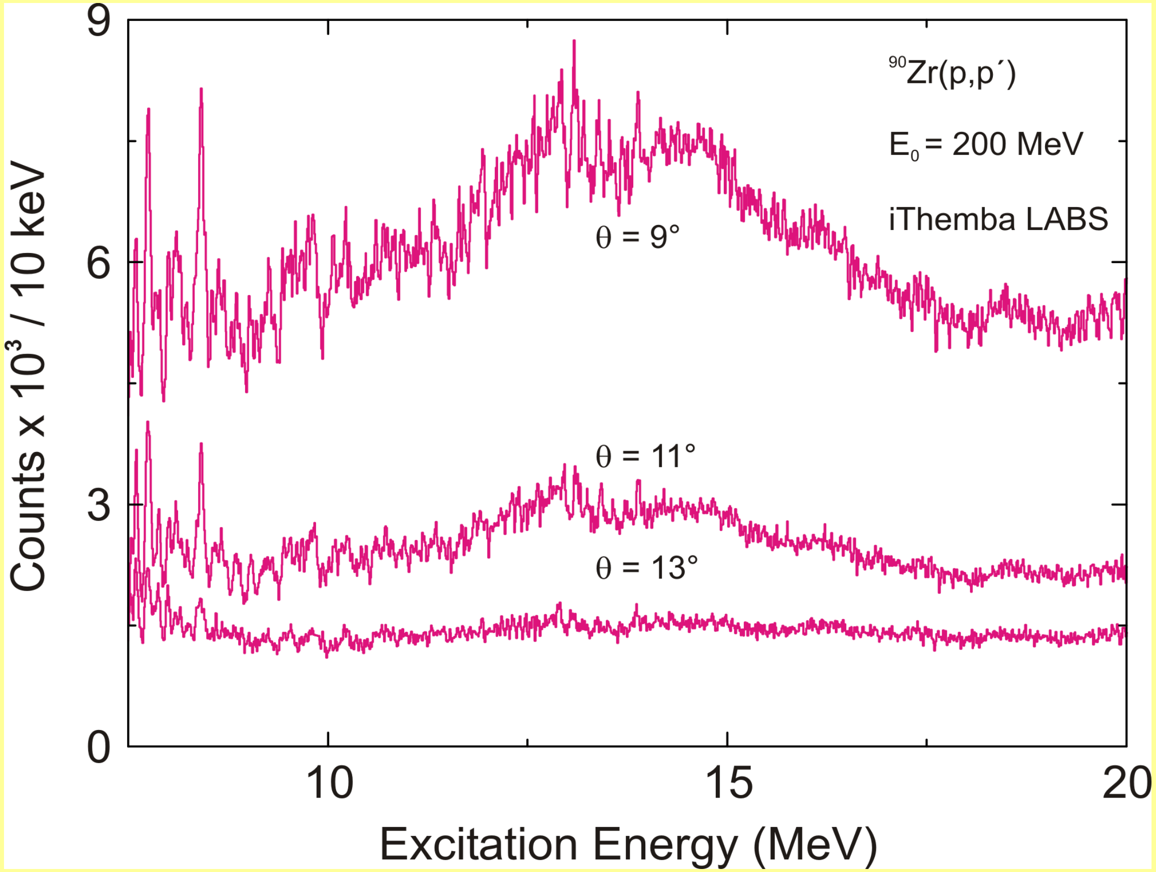
Fine structure of the spin-flip GTR: A = 90



- Selective excitation of 1^+ states

Y. Kalmykov et al., Phys. Rev. Lett. 96 (2006) 012502

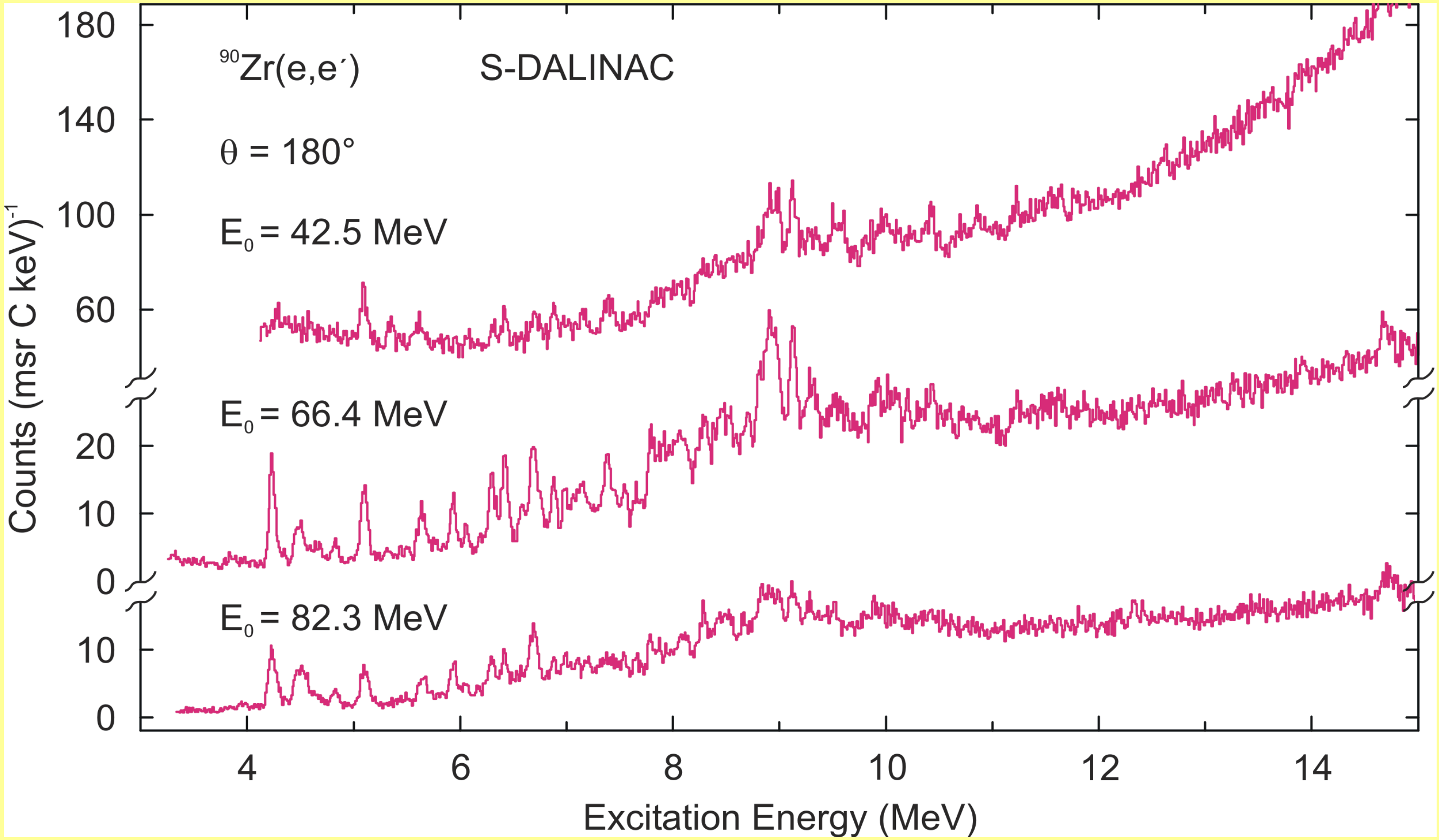
Fine structure of the ISGQR: A = 90



- Selective excitation of 2^+ states

A. Shevchenko et al., Phys. Rev. Lett. 93 (2004) 122501

Fine structure of the M2 resonance: A = 90



- Selective excitation of 2^- states

P. von Neumann-Cosel et al., Phys. Rev. Lett. 82 (1999) 1105

Summary of experiments

A = 58

- $^{58}Ni(^{3}He,t)^{58}Cu$

  $J^{\pi} = 1^{+}$

- $^{58}Ni(e,e')$

  $J^{\pi} = 2^{-}$

- $^{58}Ni(p,p')$

  $J^{\pi} = 2^{+}$

A = 90

- $^{90}Zr(^{3}He,t)^{90}Nb$

  $J^{\pi} = 1^{+}$

- $^{90}Zr(e,e')$

  $J^{\pi} = 2^{-}$

- $^{90}Zr(p,p')$

  $J^{\pi} = 2^{+}$

Experimental techniques

- Selectivity
  hadron scattering at extremely forward angles and intermediate energies
  electron scattering at 180° and low momentum transfers

- High resolution
  lateral and angular dispersion matching
  faint beam method*

- Level density
  fluctuation analysis**

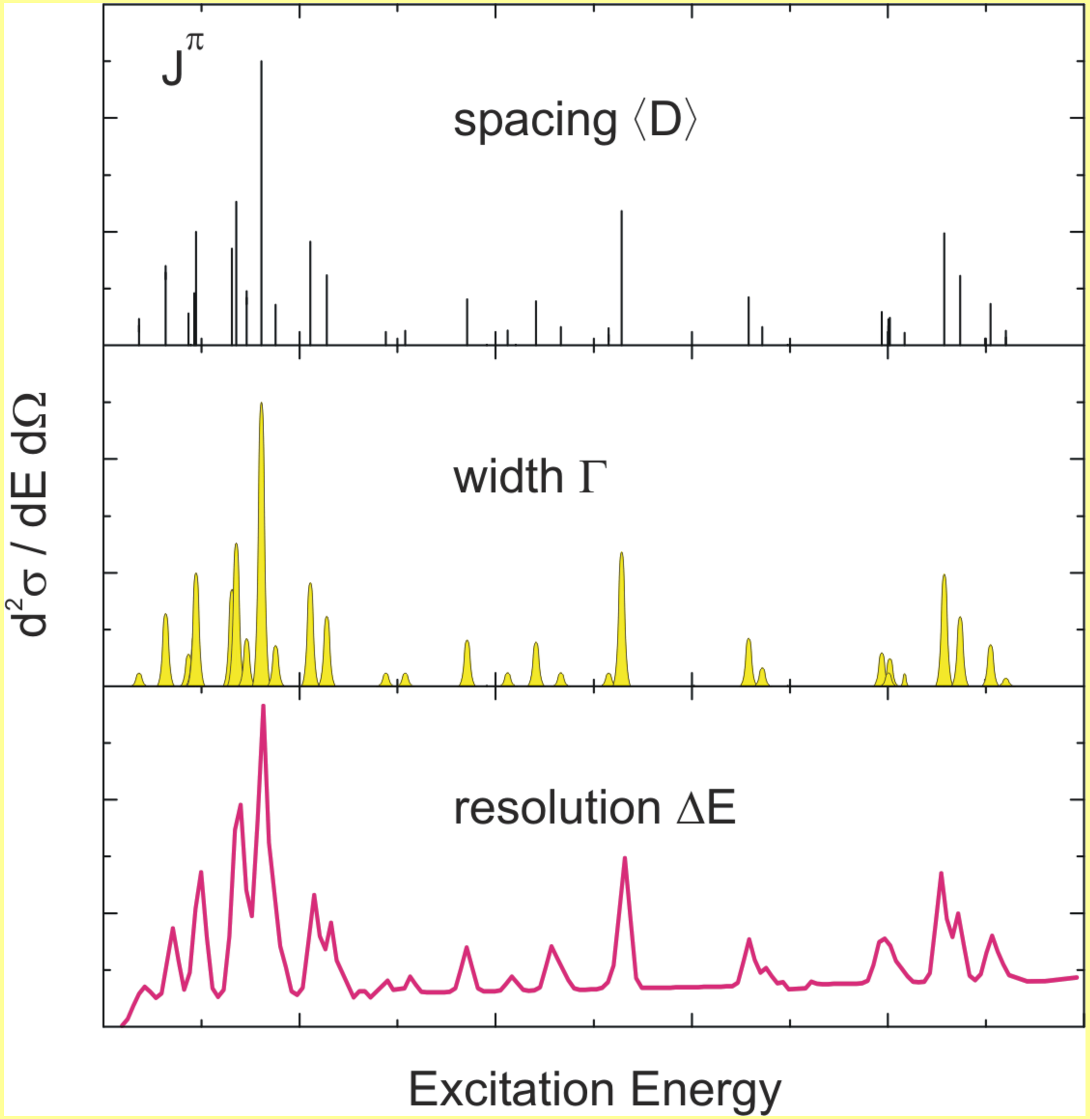
- Background
  discrete wavelet transform***

* H. Fujita et al., Nucl. Instr. and Meth. A484 (2002) 17

** P.G. Hansen, B. Jonson, and A. Richter, Nucl. Phys. A518 (1990) 13

*** Y. Kalmykov et al., Phys. Rev. Lett. 96 (2006) 012502

Fluctuations and level densities



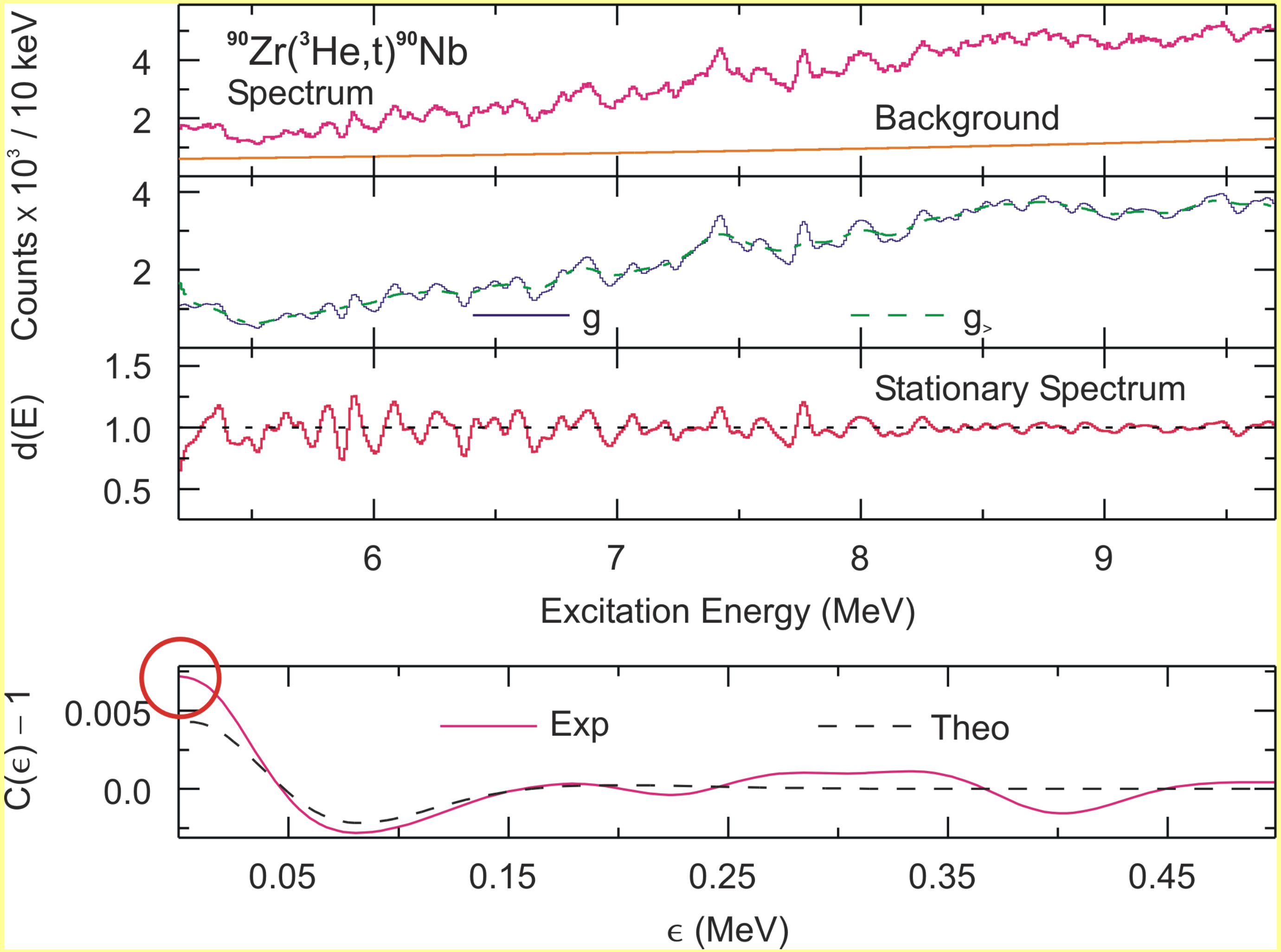
- D / ⟨D⟩   Wigner

  I / ⟨I⟩   Porter-Thomas

- Γ < ⟨D⟩

- Γ < ⟨D⟩ < ΔE

Fluctuation analysis



- Background
- Statistics, local features
- Local fluctuations
- Autocorrelation function

Autocorrelation function and mean level spacing

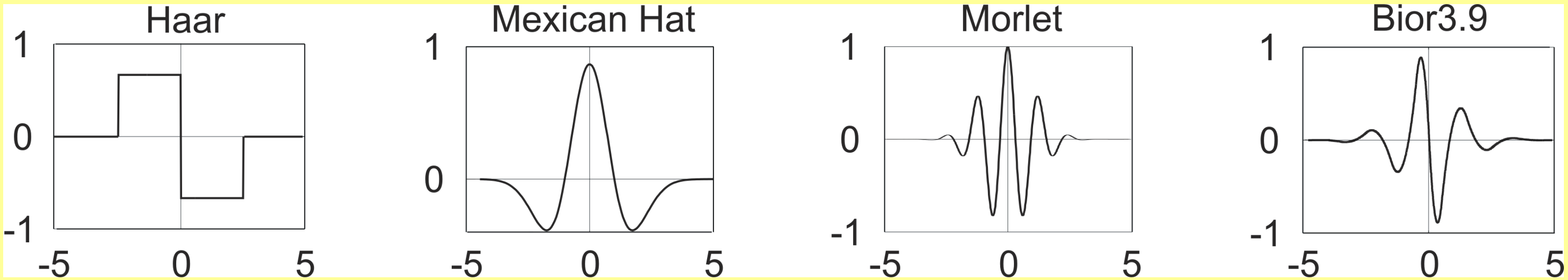
- $C(\varepsilon)=\dfrac{\langle d(E_X)d(E_X+\varepsilon)\rangle}{\langle d(E_X)\rangle\langle d(E_X+\varepsilon)\rangle}$ autocorrelation function
- $C(\varepsilon=0)-1=\dfrac{\langle d^2(E_X)\rangle-\langle d(E_X)\rangle^2}{\langle d(E_X)\rangle^2}$ variance
- $C(\varepsilon)-1=\dfrac{\alpha\langle D\rangle}{2\sigma\sqrt{\pi}}\times f(\sigma,\varepsilon)$ level spacing $\langle D\rangle$
- $\alpha=\alpha_{PT}+\alpha_W$ selectivity
- σ resolution

S. Müller, F. Beck, D. Meuer, and A. Richter, Phys. Lett. 113B (1982) 362

P.G. Hansen, B. Jonson, and A. Richter, Nucl. Phys. A518 (1990) 13

How to determine
the background in the spectra?

Wavelets and wavelet transform

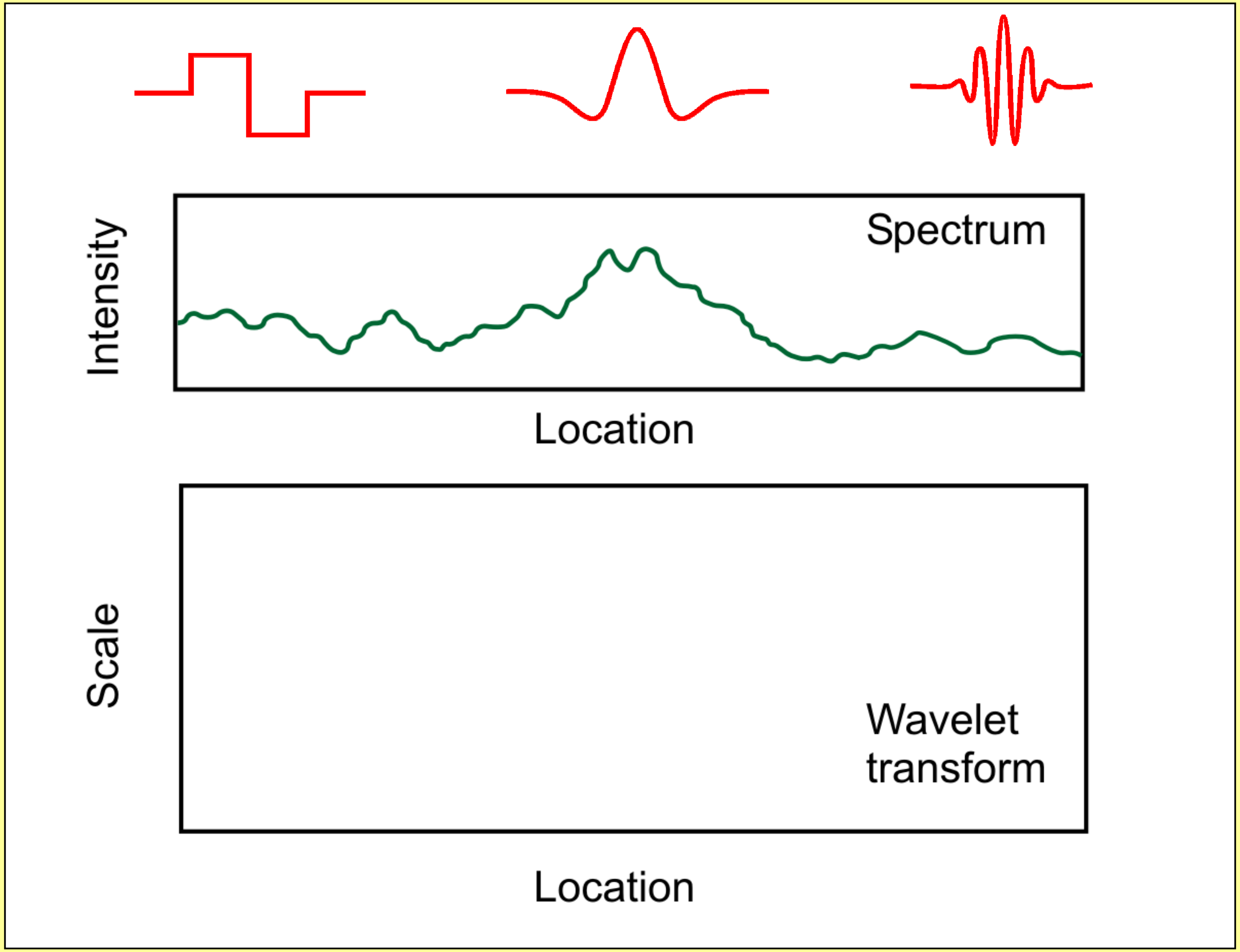


- $$\int_{-\infty}^{+\infty} \Psi^*(E)\,dE = 0$$ wavelet

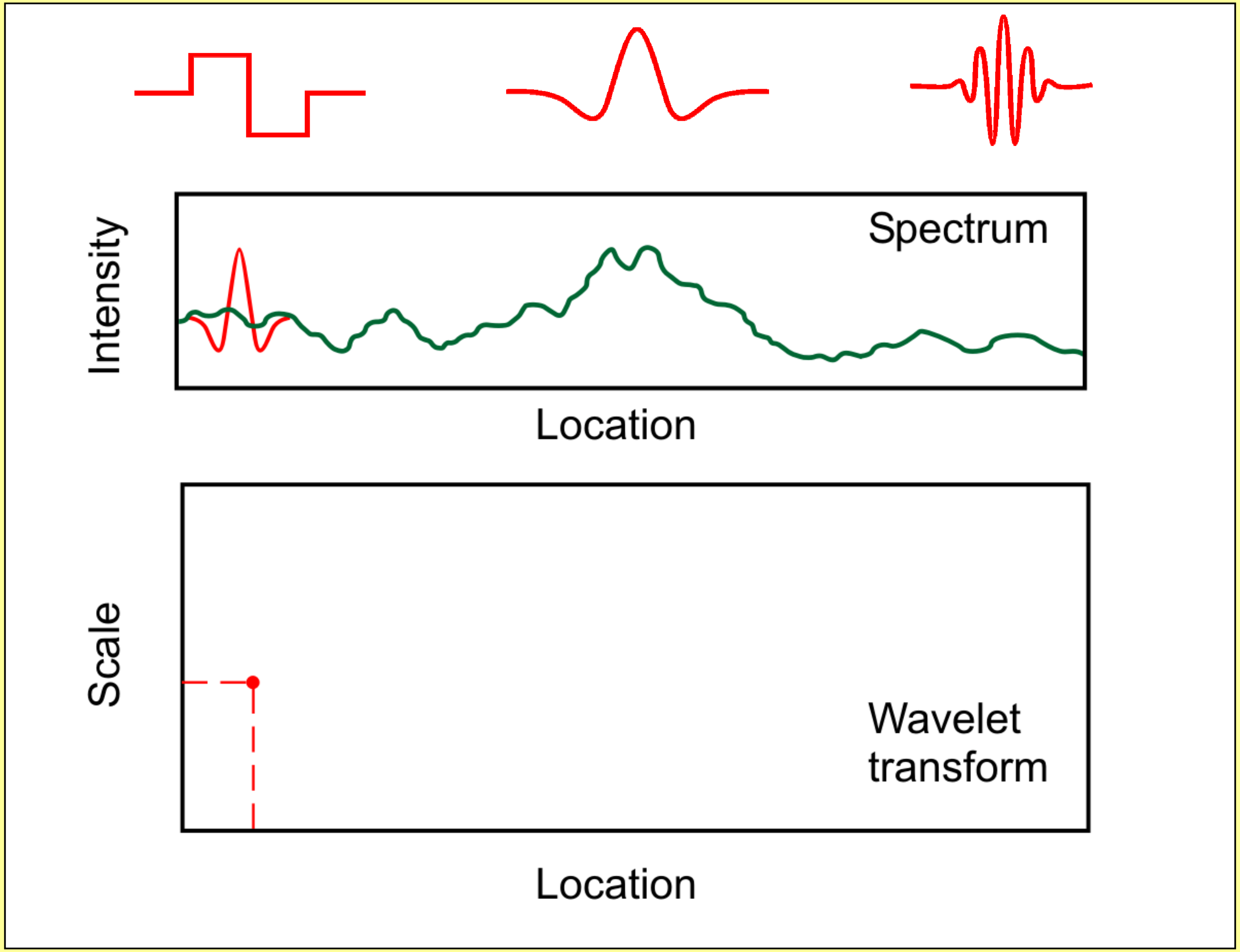
- $$\int_{-\infty}^{+\infty} \left|\Psi^*(E)\right|^2 dE < \infty$$ finite support (square integrable)

- $$C(\delta E, E_X) = \frac{1}{\sqrt{\delta E}} \int_{-\infty}^{+\infty} \sigma(E)\,\Psi^*\left(\frac{E_X - E}{\delta E}\right) dE$$ wavelet coefficients

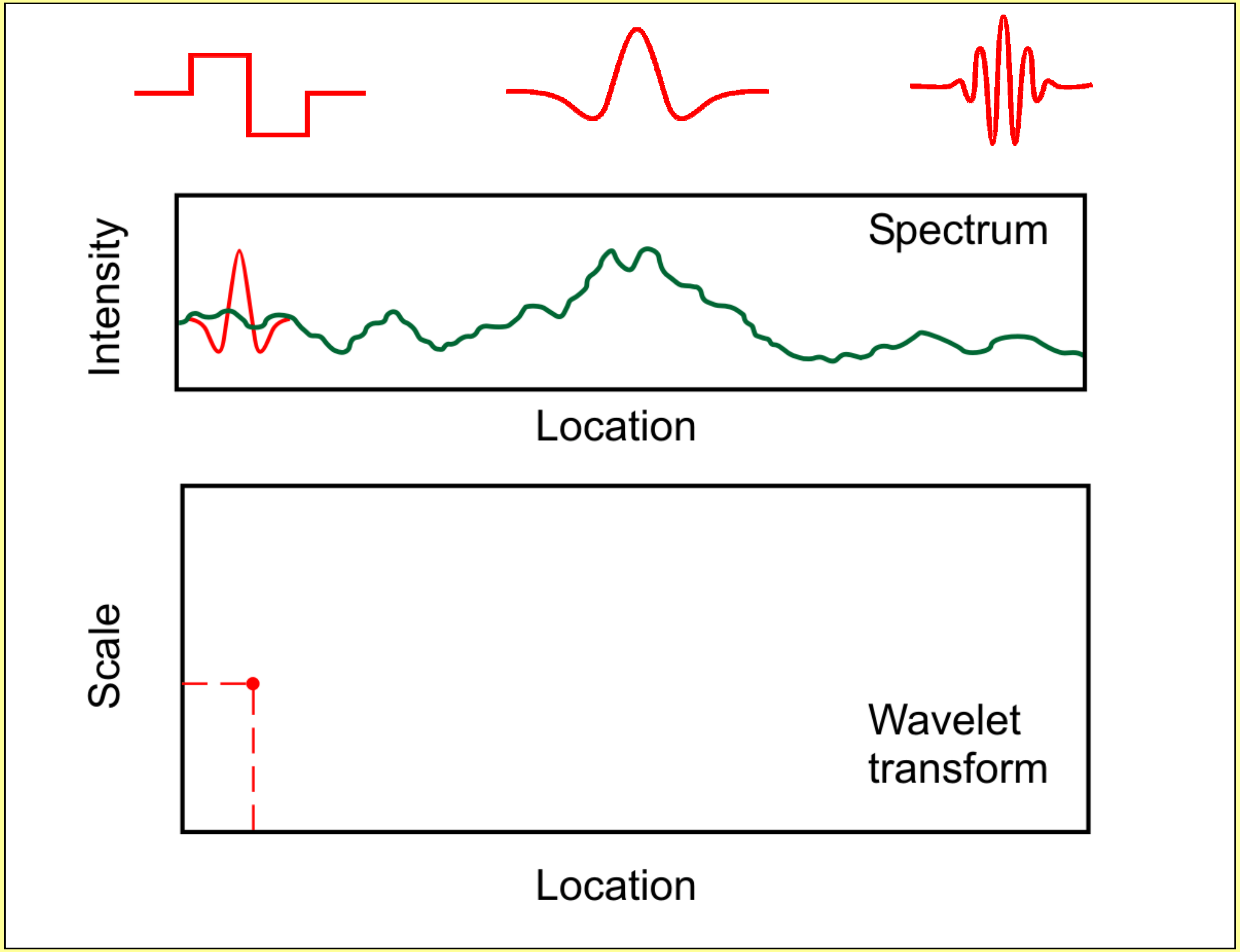
Wavelet analysis



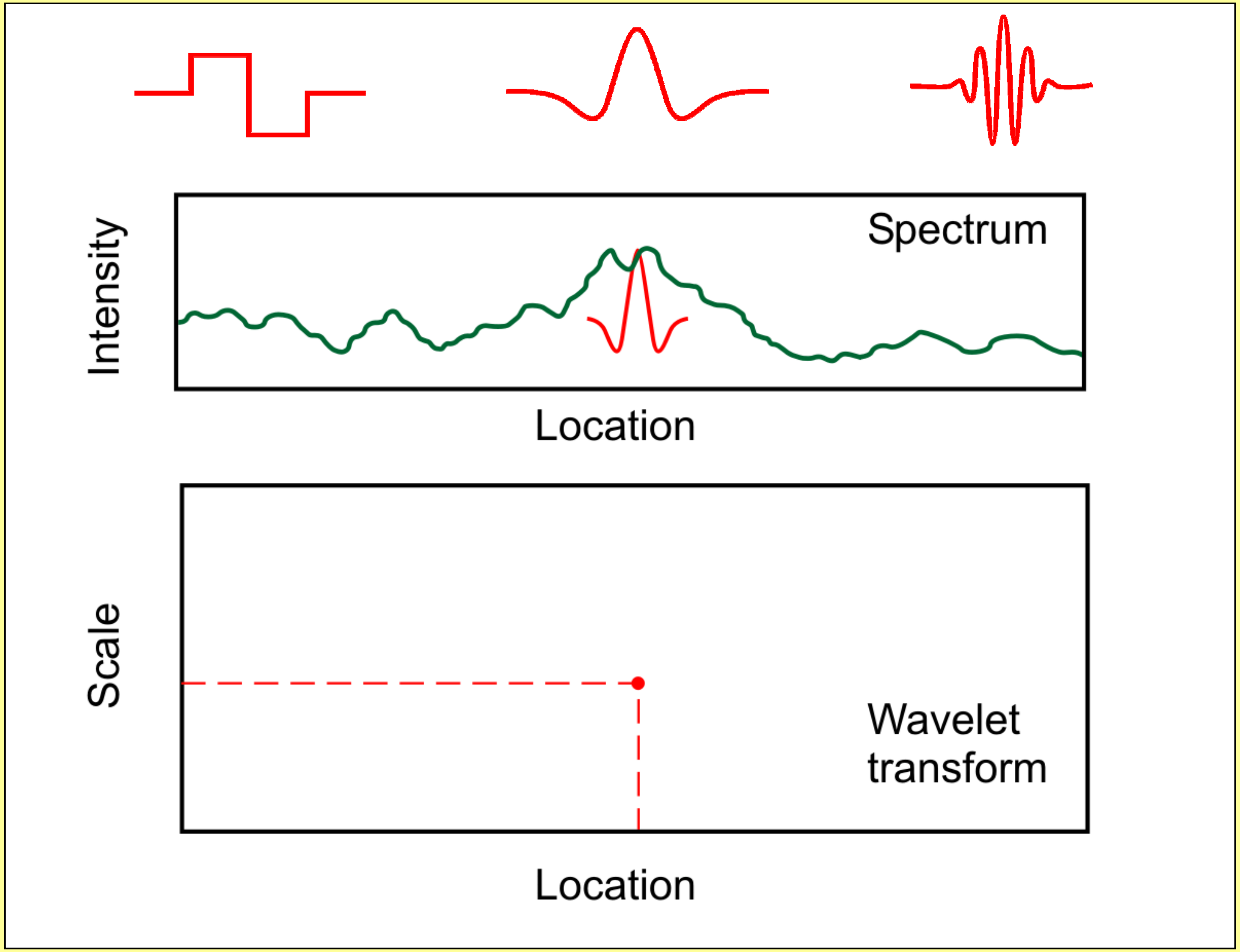
Wavelet analysis



Wavelet analysis



Wavelet analysis



Discrete wavelet transform

- $$C(\delta E, E_X) = \frac{1}{\sqrt{\delta E}} \int_{-\infty}^{+\infty} \sigma(E) \Psi^* \left(\frac{E_X - E}{\delta E} \right) dE$$ wavelet coefficients

- Discrete wavelet transform*

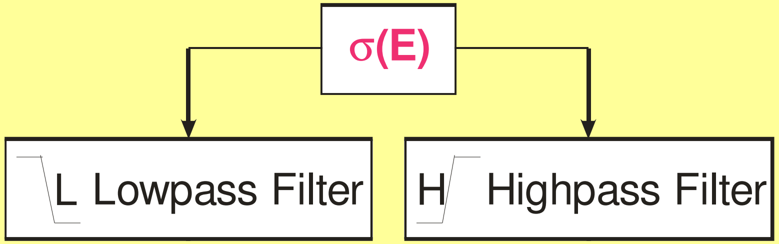
  $\delta E = 2^j$ and $E_X = k \cdot \delta E$ with j, k = 1,2,3, …
  exact reconstruction is possible
  is fast

- $$\int_{-\infty}^{+\infty} E^n \Psi^* \left(\frac{E_X - E}{\delta E} \right) dE = 0, \quad n = 0,1 \ldots m-1$$ vanishing moments

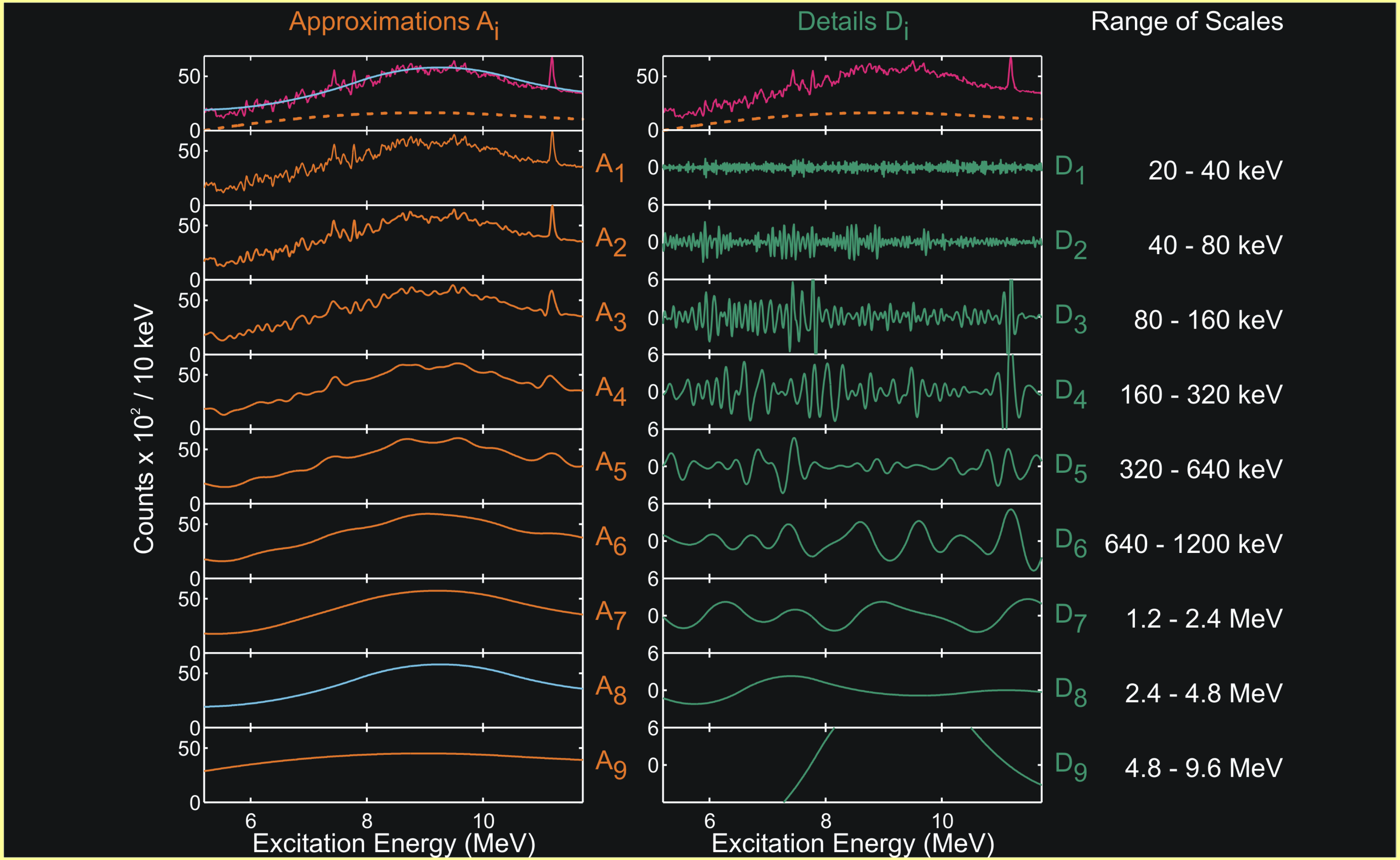
  this defines the shape and magnitude of the background

http://www.mathworks.com/products/wavelet/

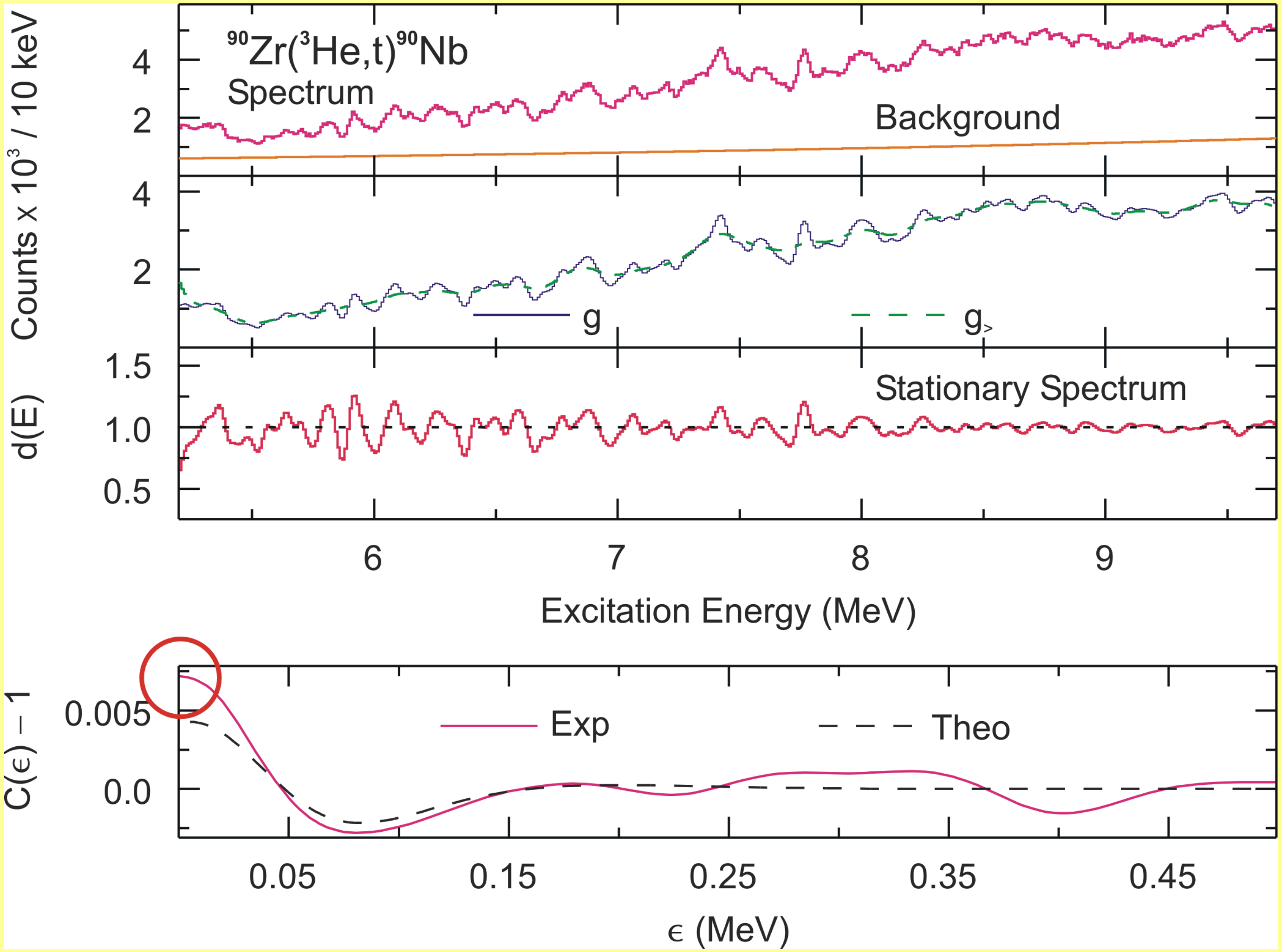
Decomposition of spectra



Application: Decomposition of $^{90}Zr(^{3}He,t)^{90}Nb$ spectrum

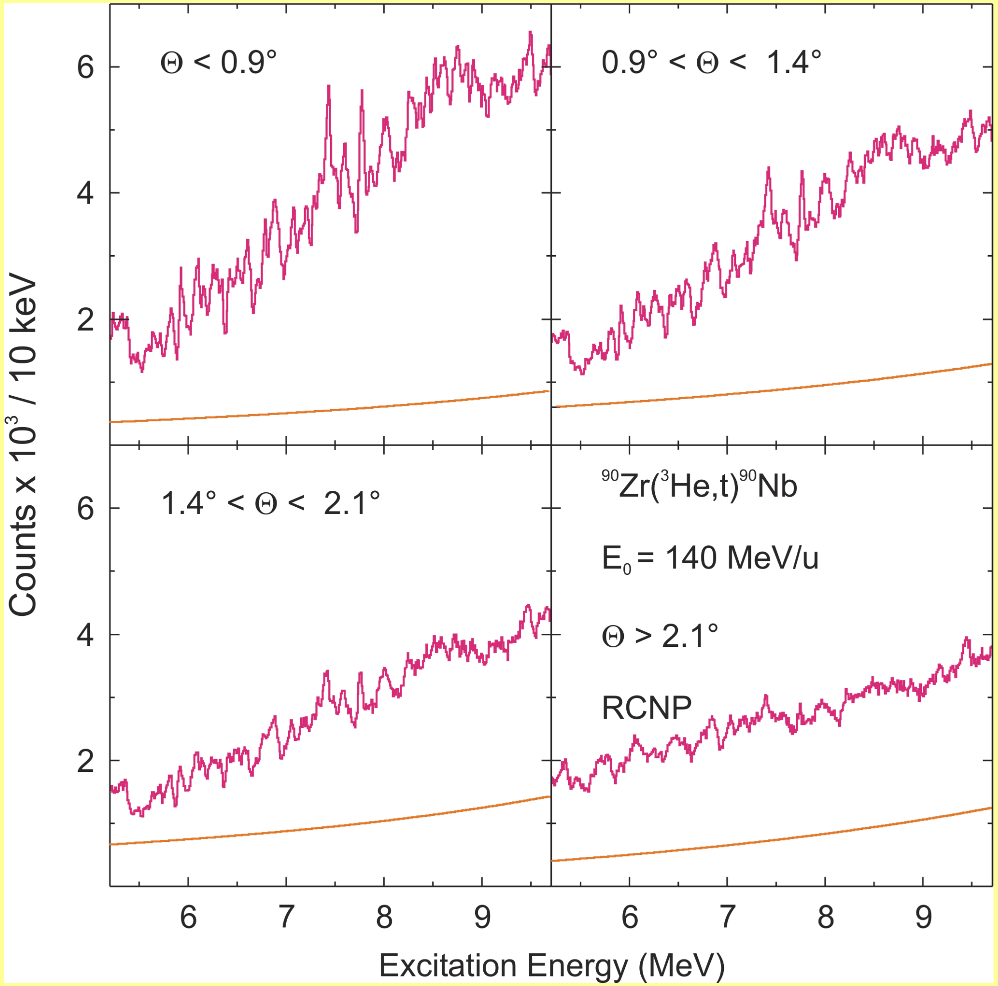


Fluctuation analysis



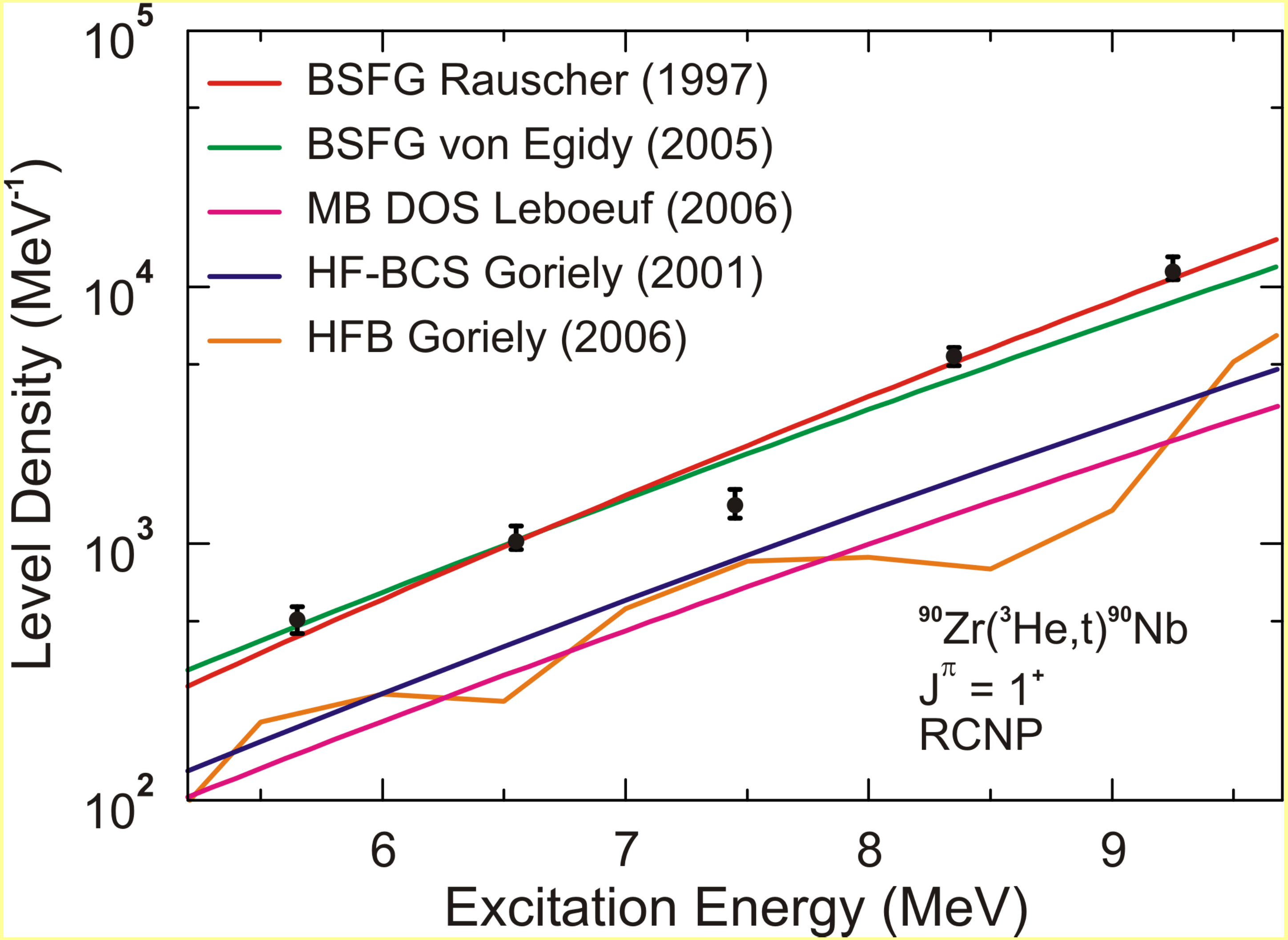
- Background from wavelet analysis
- Statistics, local features
- Local fluctuations
- Autocorrelation function

Angular distribution: $^{90}Zr(^{3}He,t)^{90}Nb$



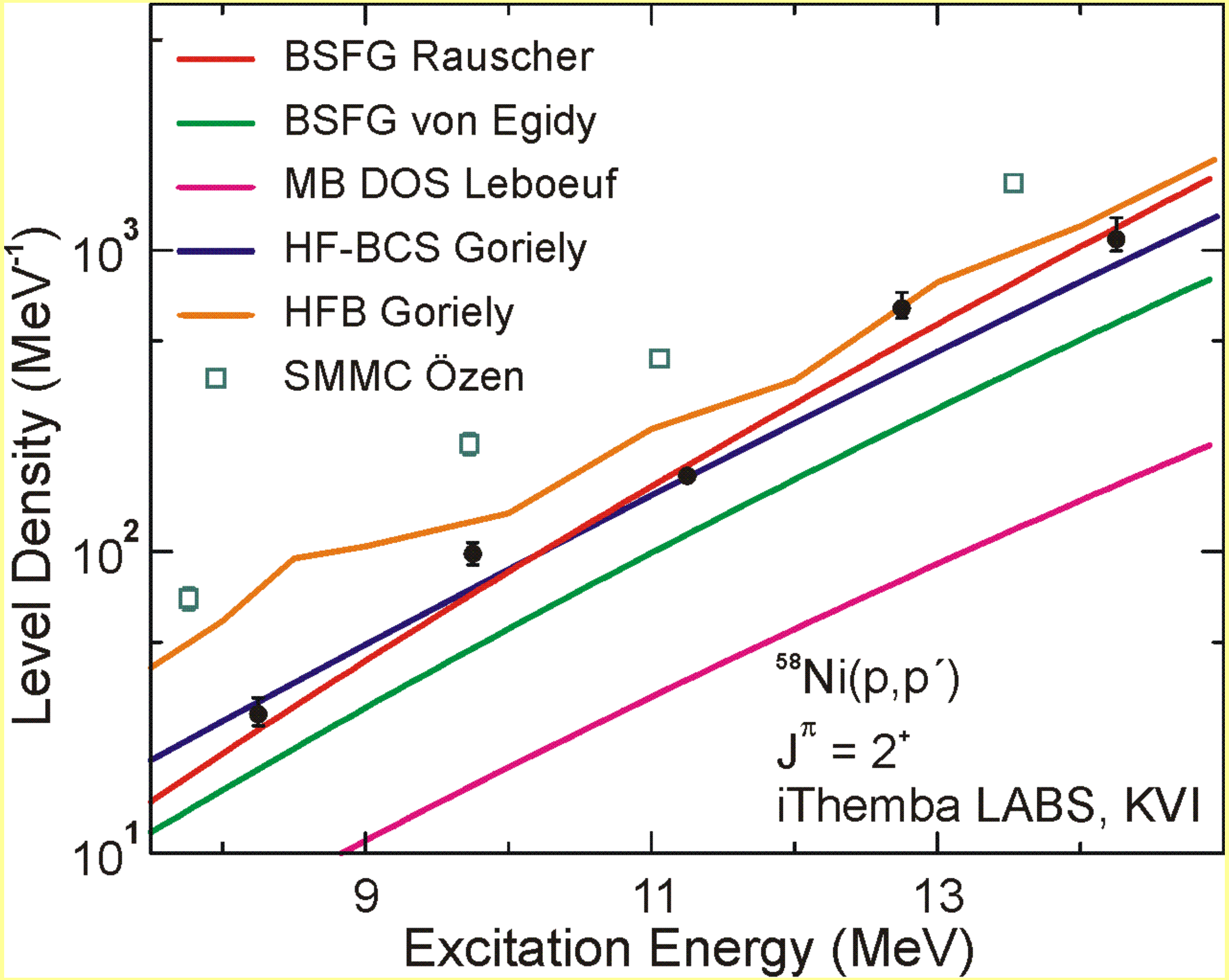
- The requirement of a constant level density in all spectra is a constraint in the analysis

Results and model predictions: A = 90, $J^{\pi} = 1^{+}$



Y. Kalmykov et al., Phys. Rev. Lett. 96 (2006) 012502

Results and model predictions: A = 58, $J^{\pi} = 2^{+}$



Phenomenological and microscopic models

- Different quality of model predictions

- BSFG, MB DOS
  parameters fitted to experimental data
  no distinction of parity

- HF-BCS
  microscopic
  no distinction of parity

- HFB, SMMC
  fully microscopic calculation of levels
  with spin and parity

- HFB
  fine structure of level densities

Ingredients of HFB

- Nuclear structure: HFB calculation with a conventional Skyrme force
  - single particle energies
  - pairing strength for each level
  - quadrupole deformation parameter
  - deformation energy

- Collective effects
  - rotational enhancement
  - vibrational enhancement
  - disappearance of deformation at high energies

Ingredients of SMMC

- Partition function of many-body states with good J^{π}

$$Z_J^{\pi}(\beta) = \mathrm{Tr}_{J,\pi}\, e^{-\beta H}$$

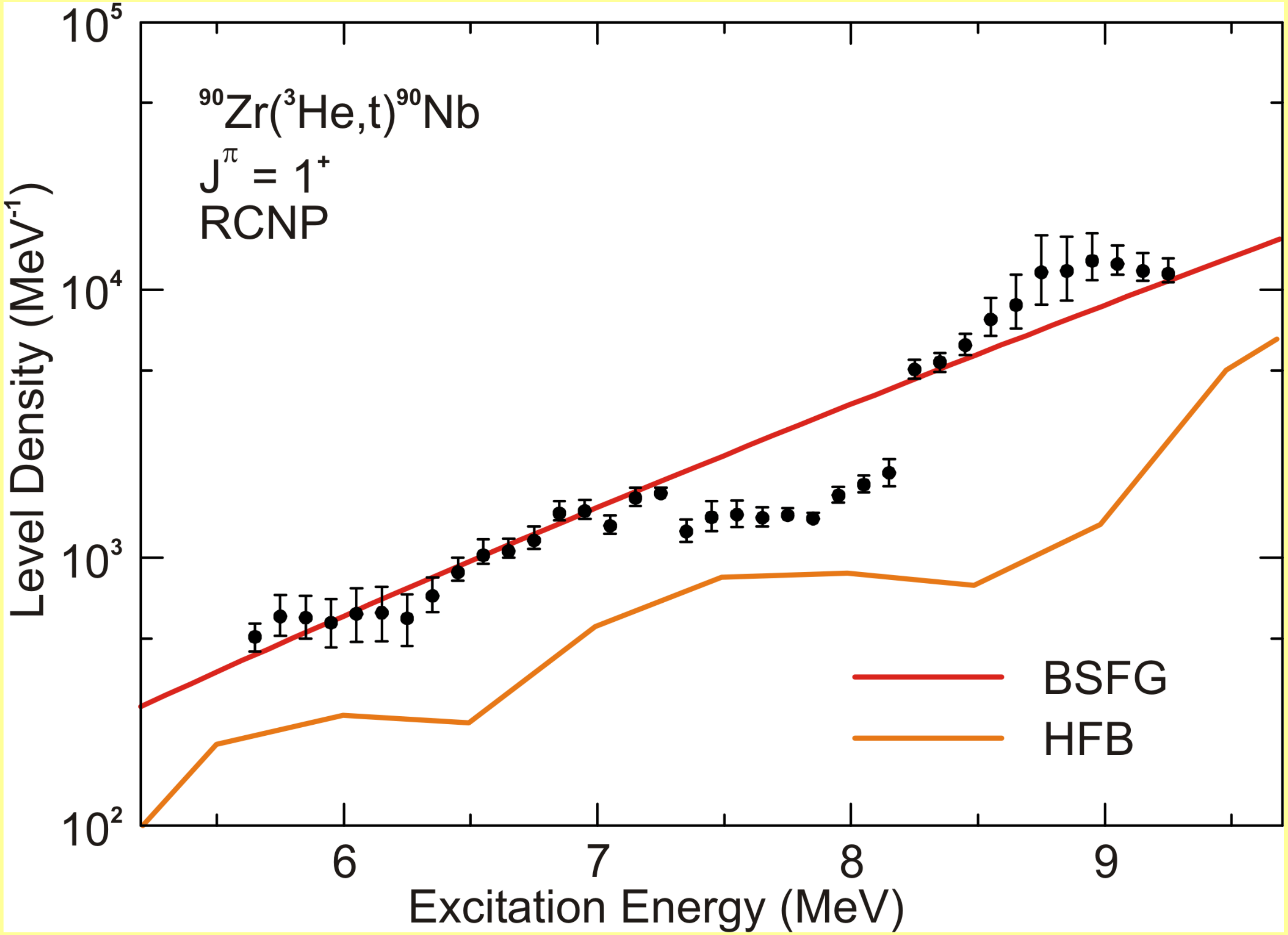
- Expectation values at inverse temperature $\beta = 1/kT$

$$E_J^{\pi}(\beta) = \frac{\int dE' e^{-\beta E'} E' \rho_J^{\pi}(E')}{Z_J^{\pi}(\beta)}$$

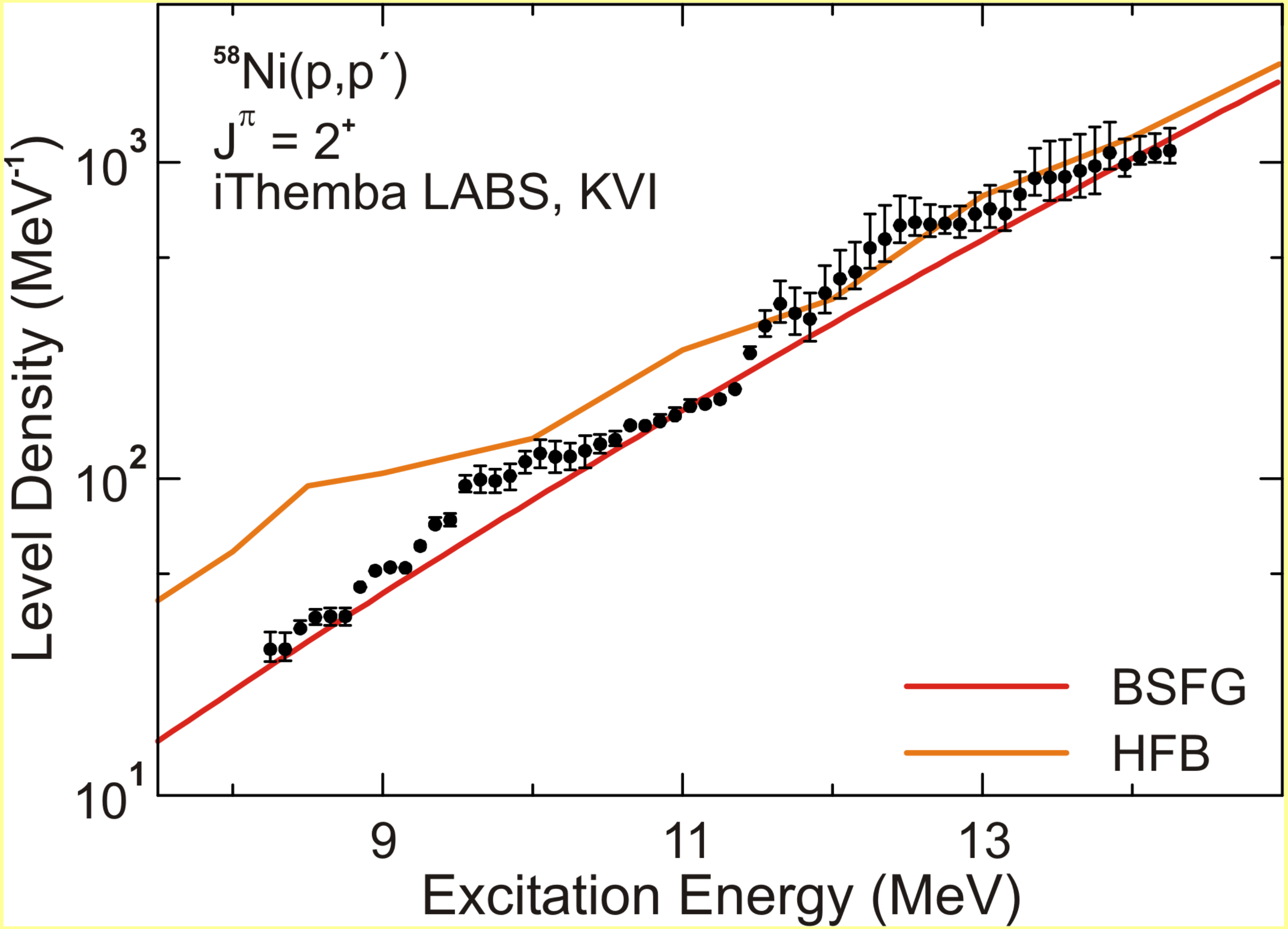
- Level density from inverse Laplace transform in the saddle-point approximation

$$\rho_J^{\pi}(E) = \frac{e^{\beta E_J^{\pi} + \ln Z_J^{\pi}(\beta)}}{\sqrt{-2\pi \dfrac{dE_J^{\pi}(\beta)}{d\beta}}}$$

Fine structure of level density: A = 90, $J^{\pi} = 1^+$

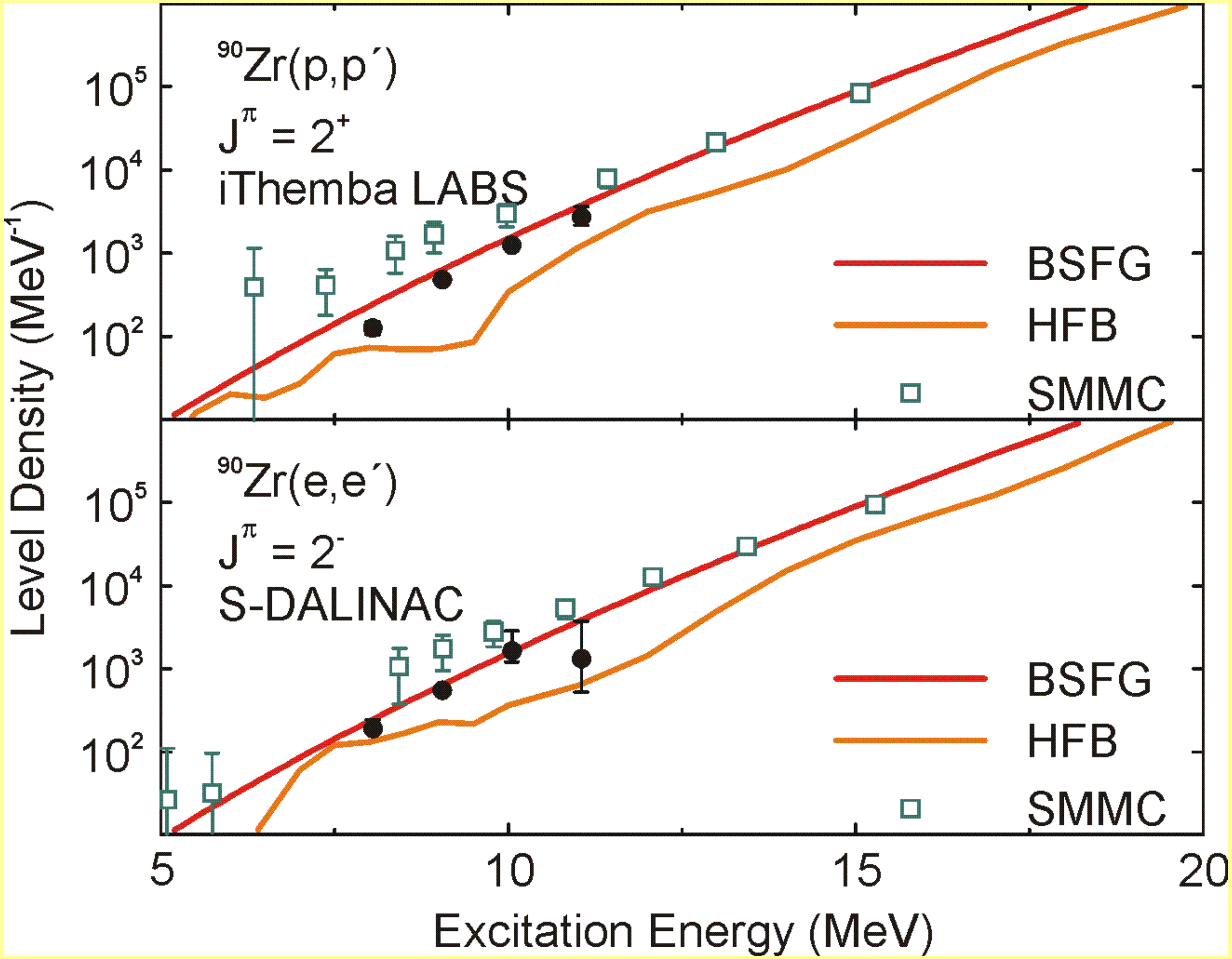


Fine structure of level density: A = 58, $J^\pi = 2^+$

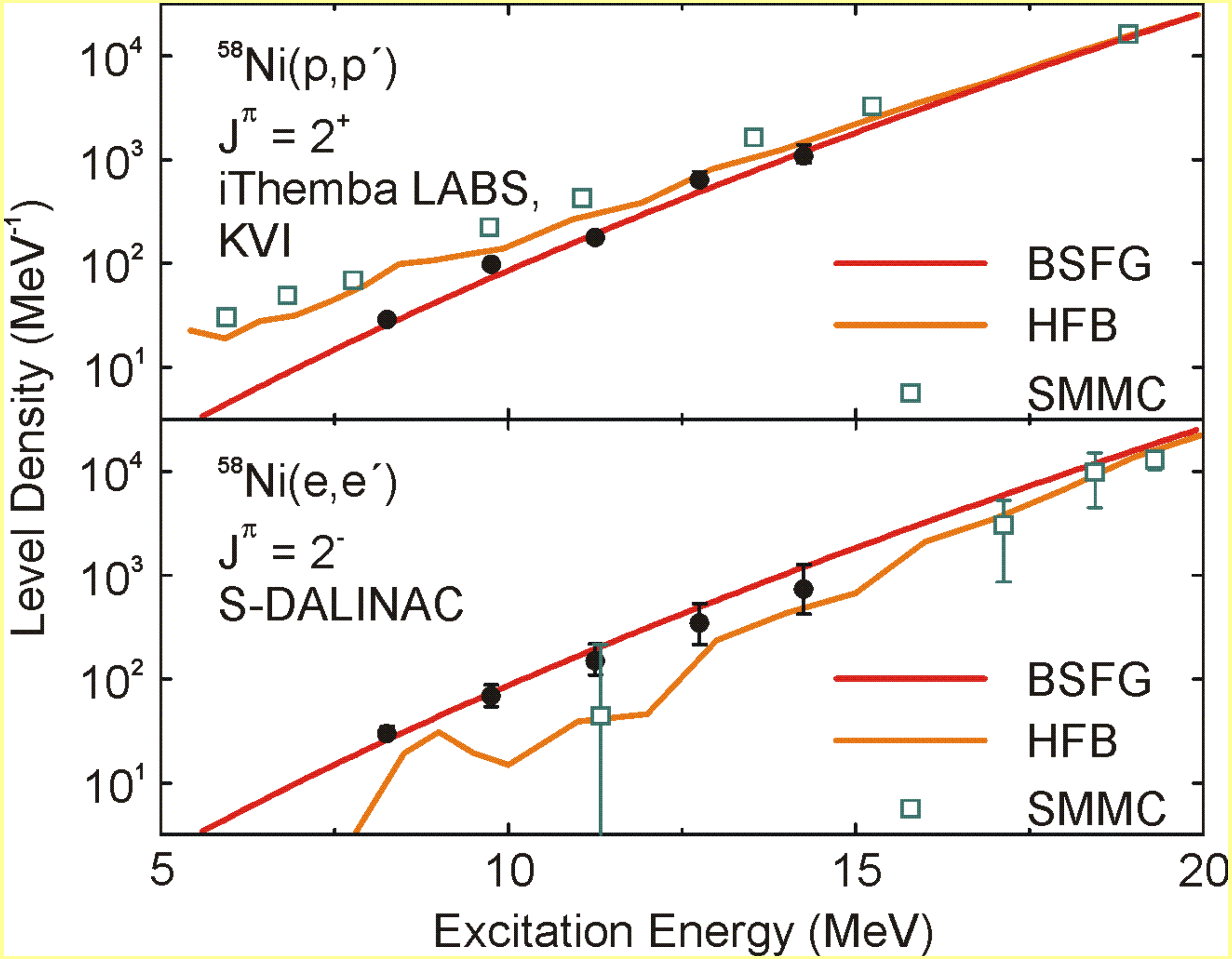


- Both for A = 90 and A = 58 level densities at this E_x seem not to be a smooth function

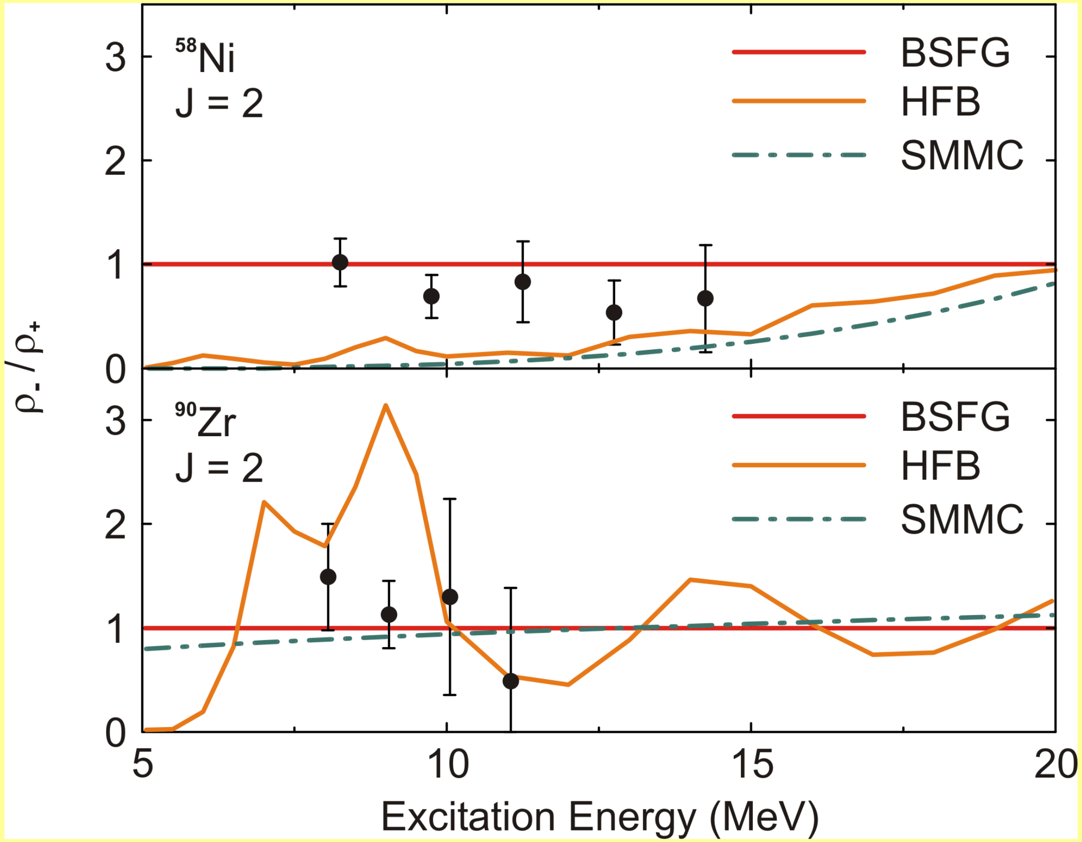
Level density of 2^+ and 2^- states: ^{90}Zr



Level density of 2^+ and 2^- states: ^{58}Ni



Test of parity dependence of level densities



- Experiments: no parity dependence
- HFB and SMMC
  - ^{58}Ni: strong parity dependence: $\rho_- \ll \rho_+$
  - ^{90}Zr: weak parity dependence: $\rho_- \approx \rho_+$
- Problem

Equilibration of parity-projected level densities

- ^{58}Ni

  $\rho_- \approx \rho_+$ at $E_x \approx 20$ MeV

- ^{90}Zr

  $\rho_- \approx \rho_+$ at $E_x \approx 5 – 10$ MeV

- Two energy scales which determine ρ_-/ρ_+

  pair-breaking

  ➡ 5 – 6 MeV for intermediate mass nuclei

  shell gap between opposite-parity states near the Fermi level

  ➡ depends strongly on the shell structure, e.g. ^{68}Zn $\Delta_{pf\text{-}g9/2}$ is small

- Core breaking

  e.g. near shell closure ^{58}Ni $\Delta_{sd\text{-}pf}$ transitions are important

  ➡ ρ_- would be enlarged

Summary and outlook

- Fine structure of giant resonances
- Wavelet analysis for a nearly model-independent background determination
- Fluctuation analysis
- Spin- and parity-resolved level densities in ^{58}Ni, ^{90}Zr, ^{90}Nb
- Comparison with current nuclear structure model predictions
- Indication for fine structure of level densities at high excitation energies
- No parity dependence for J = 2 in ^{58}Ni and ^{90}Zr
- Further applications to GTR, IVGDR, ISGQR … in a wide range of nuclei