TU DARMSTADT

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Magnetic Dipole and Gamow-Teller Modes: Quenching, Fine Structure and Astrophysical Implications

- Why study the magnetic dipole response in nuclei ?
  - 50 years Arima-Horie effect
  - quenching of spin-isospin strength and the rôle of (2p – 2h) configurations: ^{48}Ca revisited
- Current developments in the field
  - N=28 isotones: fine structure distribution of M1 strength and "state of the art" shell-model calculations
  - fine structure of the spin-flip GTR, fluctuations, wavelets, scales and configuration mixing
- Astrophysical applications of high-precision M1 and GTR data
  - supernova dynamics and nucleosynthesis

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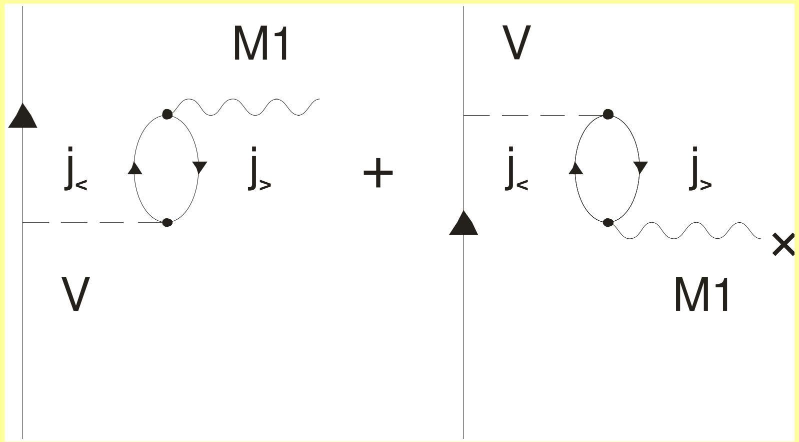
S-DALINAC

Why study the magnetic dipole response in nuclei ?

(i) Magnetic moments: *diagonal* matrix elements of **T**(M1)

$\vec{\mu}_j$ → $\vec{\mu}_l$, $\vec{\mu}_s$ $\neq$ Schmidt value → mesonic currents, configuration mixing

$\delta\vec{\mu}$ in 1st order (Arima + Horie, 1954)



Now: effect is treated in large scale SM calculations (often with operator $\vec{\mu}_{eff}$)

Why study the magnetic dipole response in nuclei ?

(ii) Magnetic dipole transitions: *off-diagonal* matrix elements of **T**(M1)

$$B(M1) \sim \left| \left\langle \vec{j}_f \left| e^{i\vec{q}\vec{r}} \sum_i (g_l^i \vec{l}_i + g_s^i \vec{s}_i) \right| \vec{j}_i \right\rangle \right|^2$$

- *neutron* M1 *spin-flip* excitations
  - $0\hbar\omega$ … $n\hbar\omega$; subnuclear dof's
  - quenching of μ's and B(M1)'s

- *neutron* and *proton* M1 excitations
  - spin and orbital effects
  - isovector and isoscalar effects

- *proton* M1 excitations
  - orbital ("scissors mode")

Why study the magnetic dipole response in nuclei ?

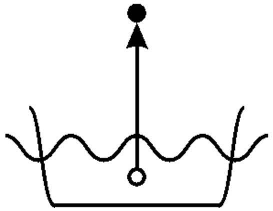
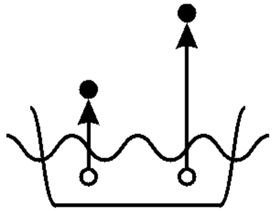
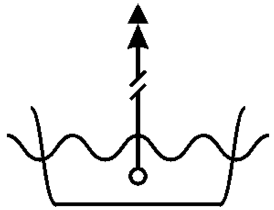
(iii) Connection to other processes involving the *spin operator*

- GT β decay, GT GR's, (p,n), (n,p), (p,p´), (d,^{2}He), (^{3}He,t) … reactions

- quenching of $\vec{\sigma} \cdot \vec{\tau}$ strength: a mechanism similar to 2nd order configuration mixing (2p – 1h) of 2p – 2h configurations is mostly responsible

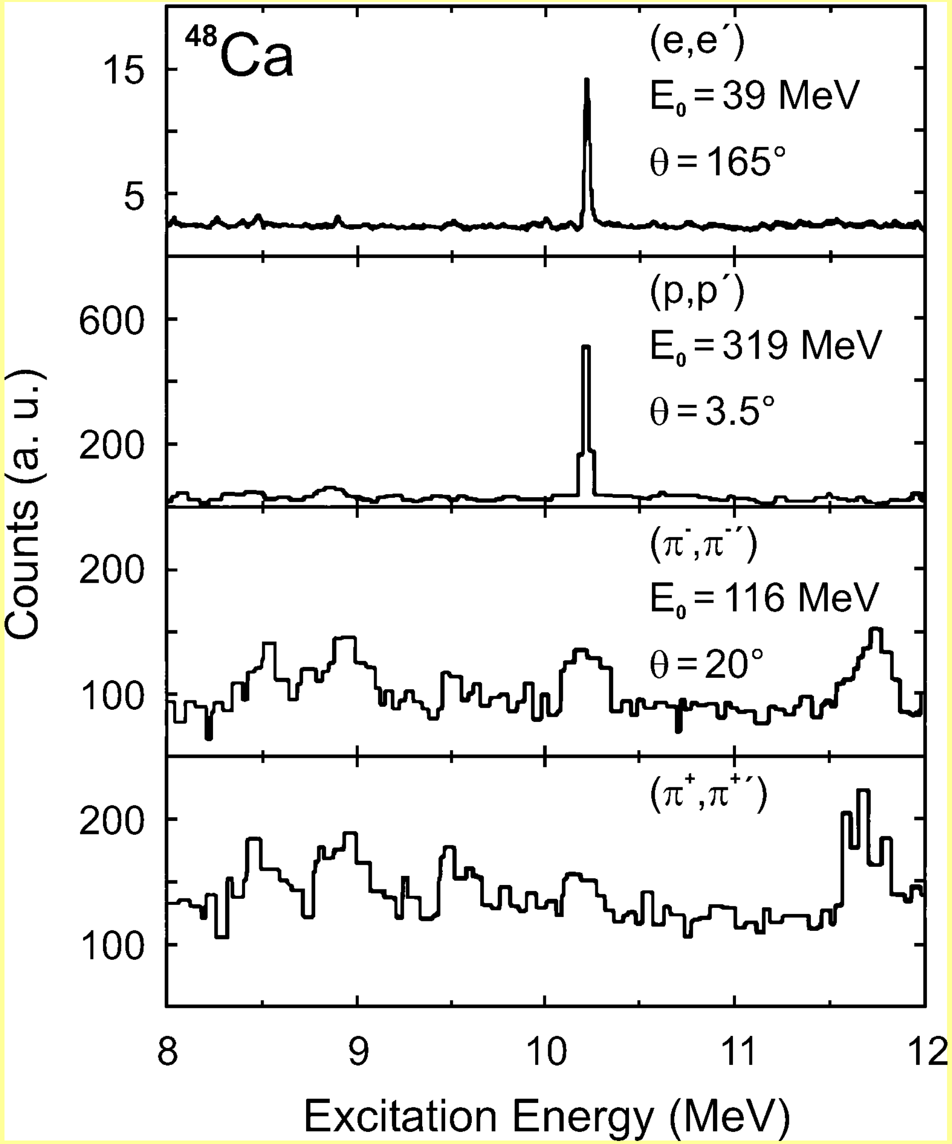
(iv) Astrophysical implications

Spin-isospin strength suppression

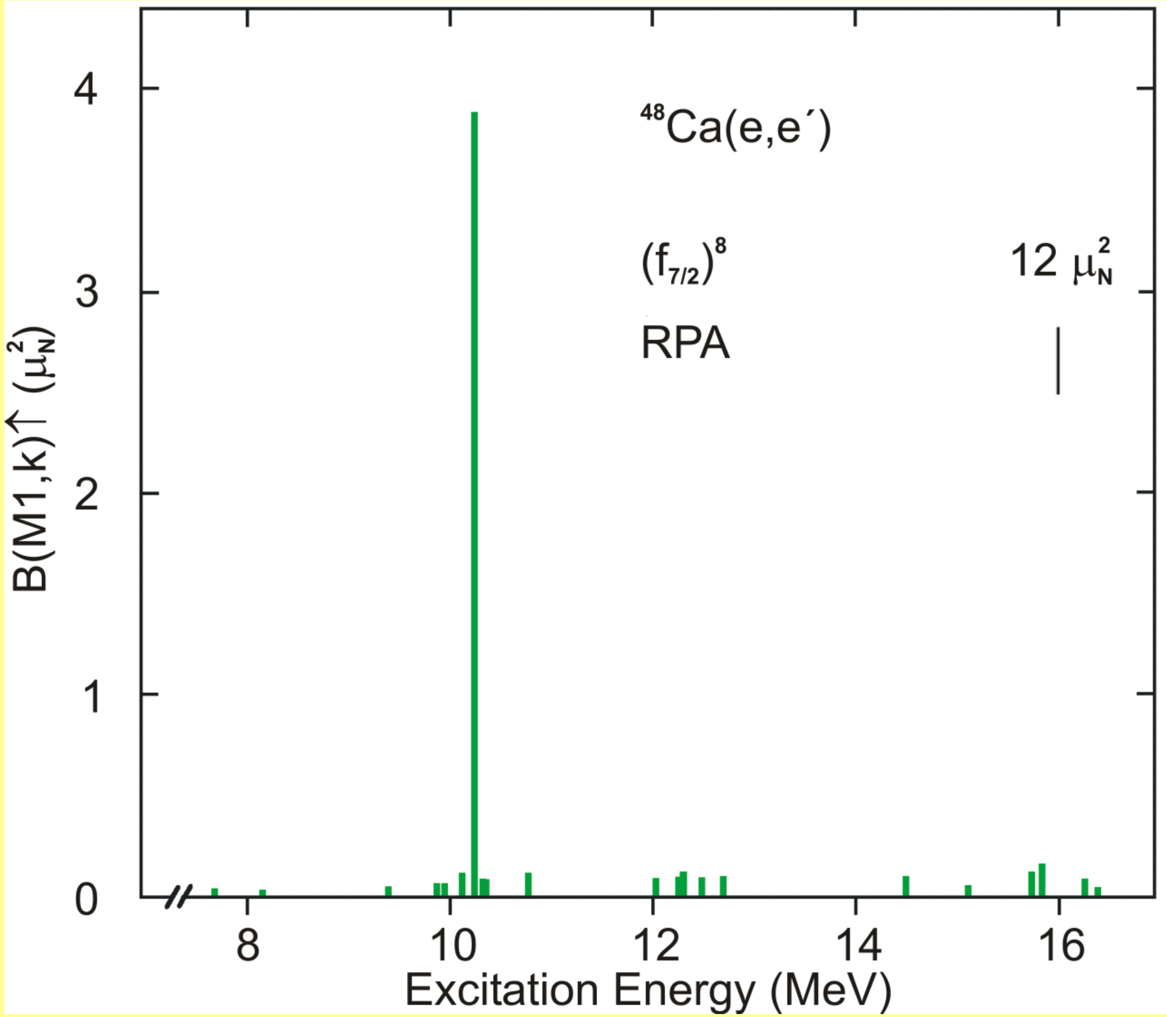
mechanism / probing field $\vec{\sigma}\cdot\vec{\tau}e^{i\vec{q}\vec{r}}$, $q \to 0$	highly excited (1p-1h) 	configuration mixing (2p-2h); tensor 	Δ-admixture (Δ - N^{-1}) 
M1	≈0	≳40%	≲10%
GT			
M2			
M3	increase		decrease
.			
.			
.			
Mλ (high spin)	≈10%	≳40%	

- $\vec{\sigma}\cdot\vec{\tau}$ strength ≈ 50% reduced

^{48}Ca as a prime example of quenching



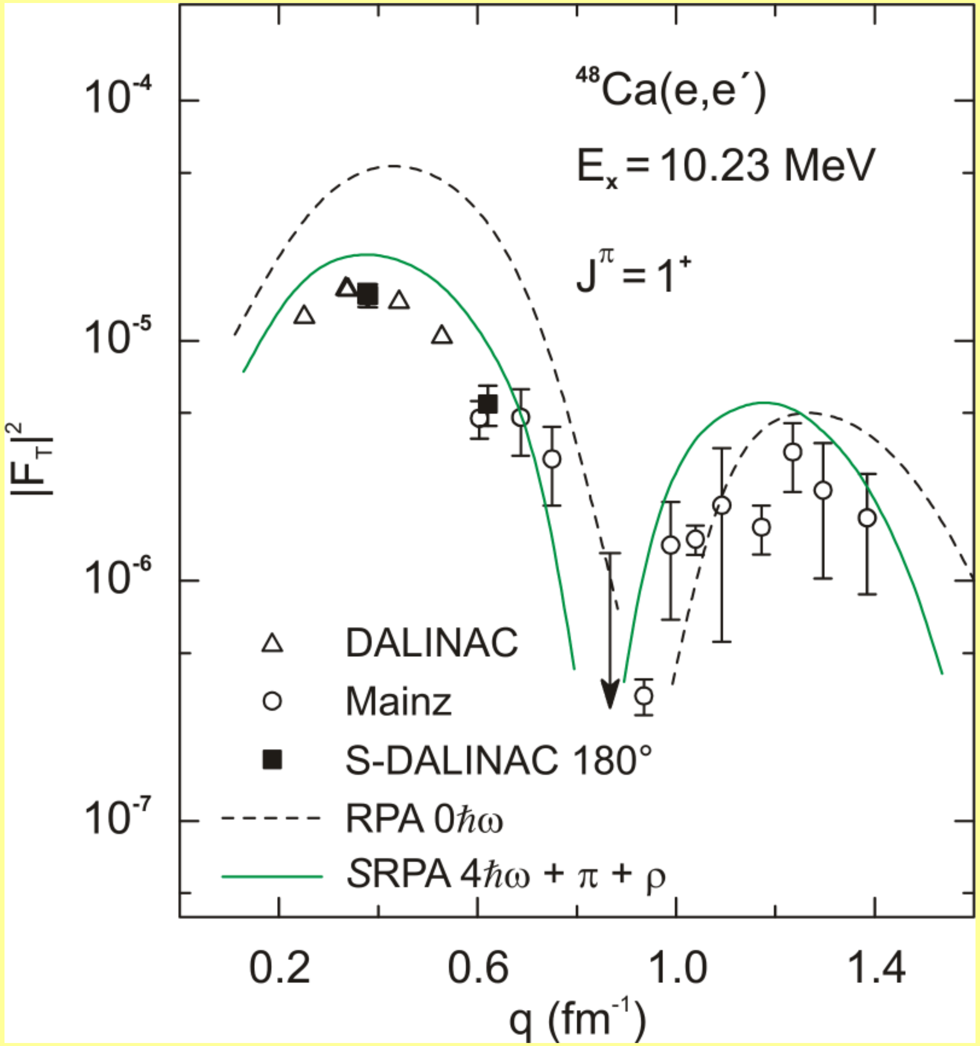
^{48}Ca as a prime example of quenching



K. Takayanagi,
K. Shimizu,
A. Arima
(1988)

- $B(M1)_{exp} \lesssim B(M1)_{the}$

^{48}Ca as a prime example of quenching

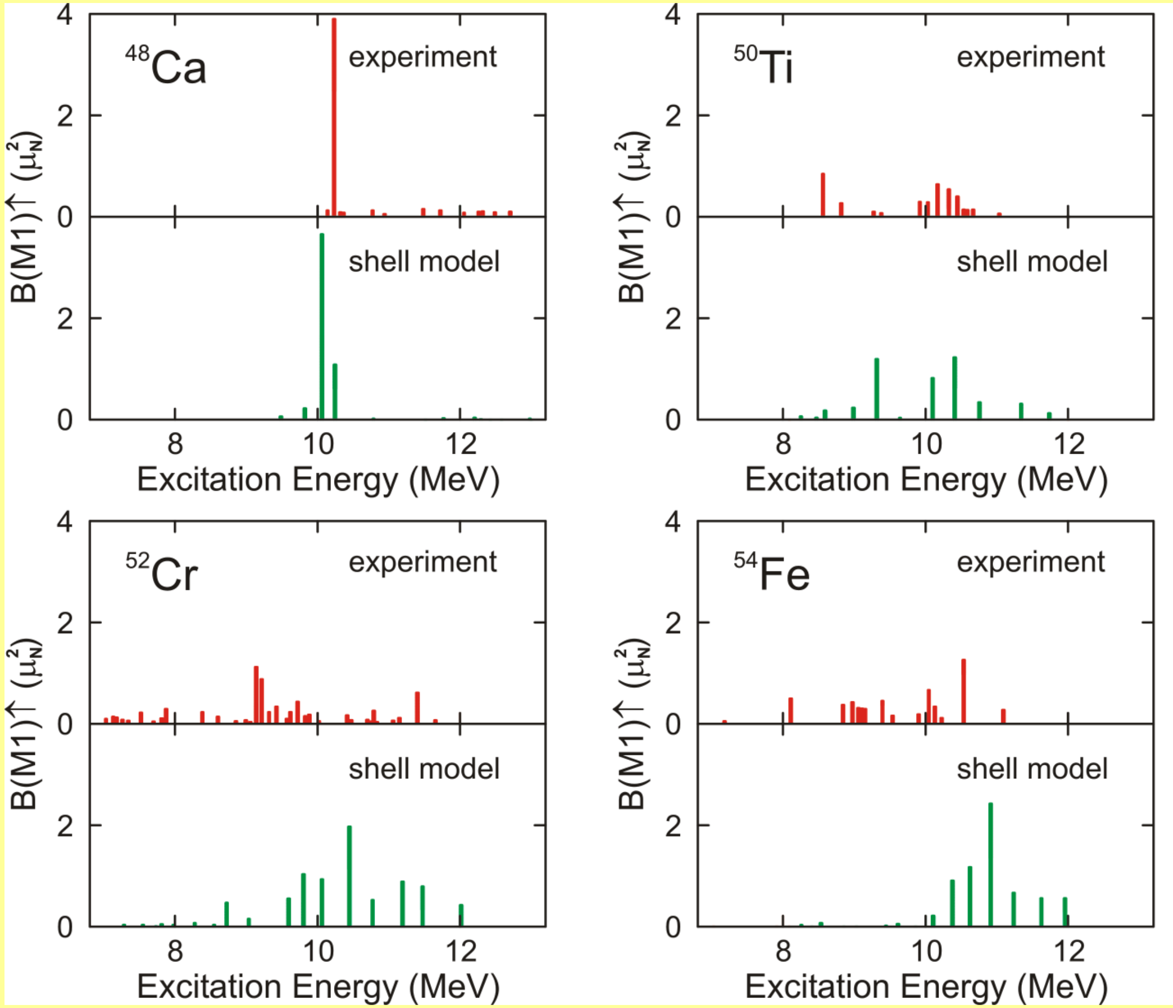


- still sizable discrepancies between experiment and theory

M1 strength: two alternative approaches

- 2^{nd} RPA (2p - 2h) + $n\hbar\omega$
- SM (np - nh) + $0\hbar\omega$ (one major shell)
- examples: N=28 isotones

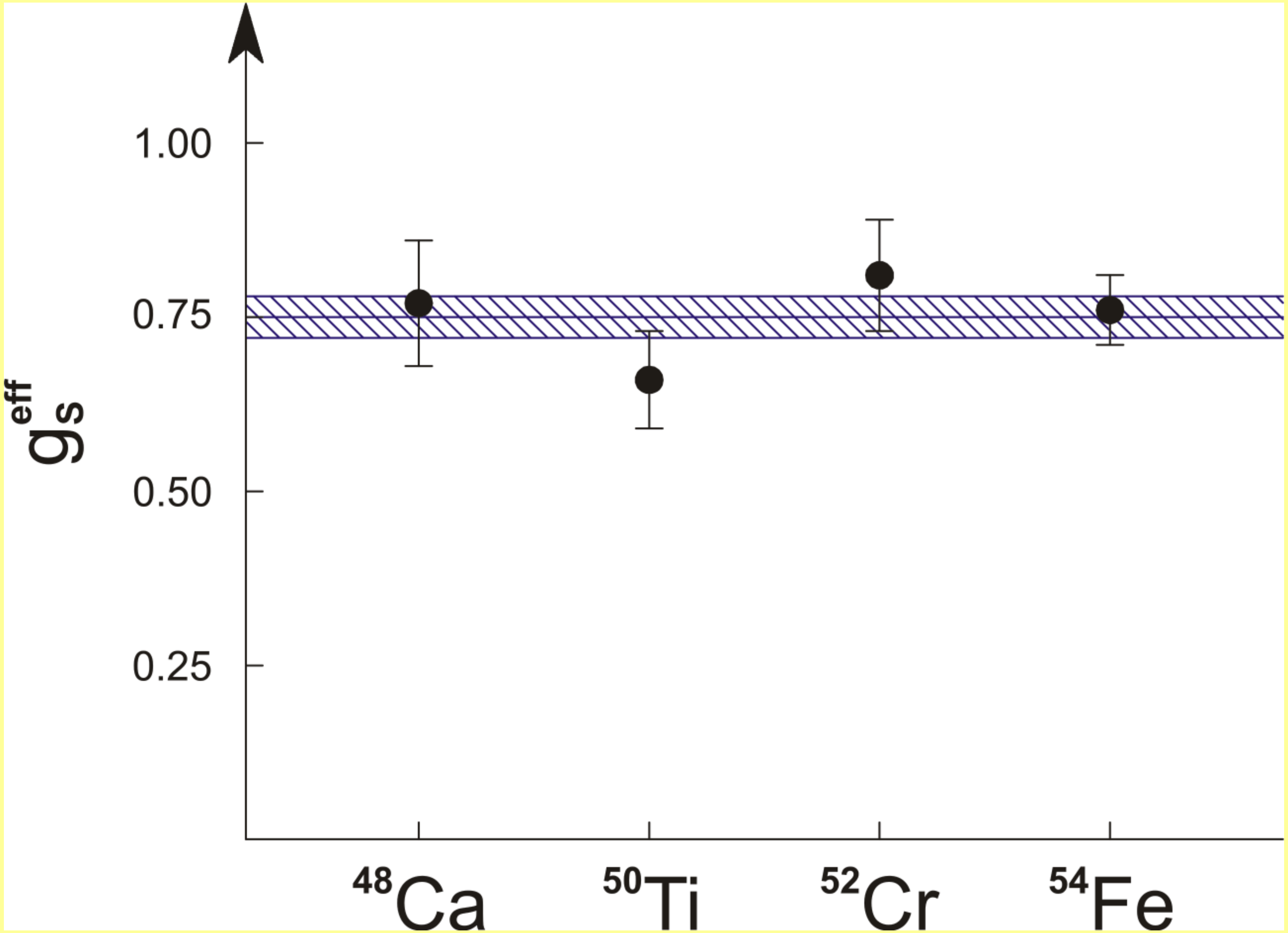
N=28 isotones: experiment vs. shell model predictions



P. Von Neumann-Cosel, A. Poves, J. Retamosa, A. Richter (1998)

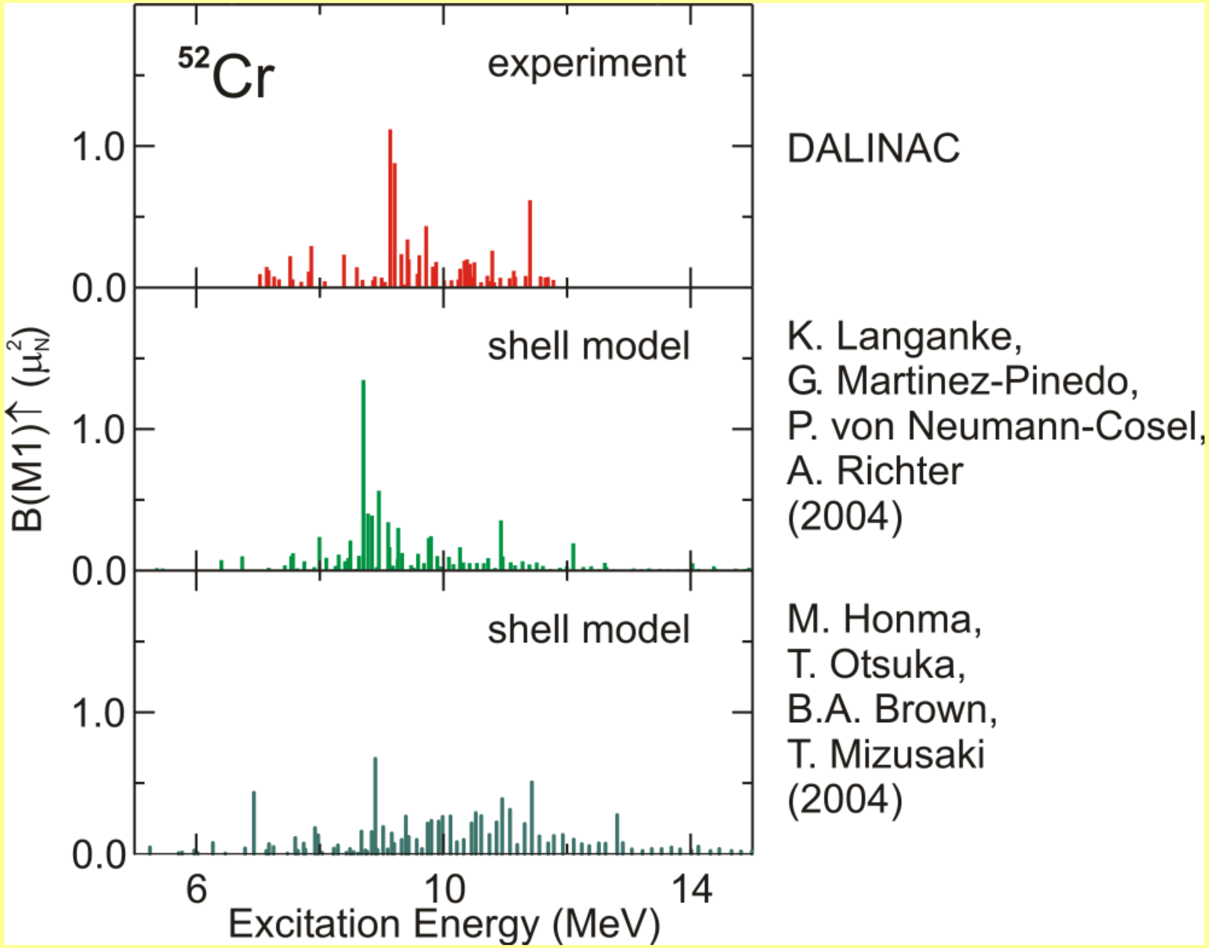
- data show considerable fine structure: sign of configuration mixing
- global description quite good (apart from the interaction)

N=28 isotones: extraction of quenching factor



- quenching factor agrees with quenching of g_A in fp-shell

^{52}Cr: experiment vs. "state of the art" SM calculations



- still significant differences between different effective interaction
- knowledge of these strength distributions are important for astrophysics

First example: ν scattering cross sections on nuclei

(i) Important for

- r process
- ν process
- ν detectors
- supernova physics
  - opacities and thermalization during collapse phase
  - delayed explosion mechanism
  - explosive nucleosysnthesis

(ii) ν scattering so far not included in supernova modeling

Experimental information

- direct: ^{12}C, $J^{\pi} = 1^{+}$, T = 1, E_x = 15.11 MeV
- indirect: low energy ν's ➡ low multipolarity transitions
- idea: extract GT_0 strength in nuclei from M1 response

$$T(M1)_{\text{iv}} = \sqrt{\frac{3}{4\pi}} \sum_i [\vec{l}_i \vec{t}_{zi} + (g_s^p - g_s^n) \vec{s}_i \vec{t}_{zi}] \mu_N$$

⬍

$$T(GT_0) = 2 \sum_i [\vec{s}_i \vec{t}_{zi}]$$

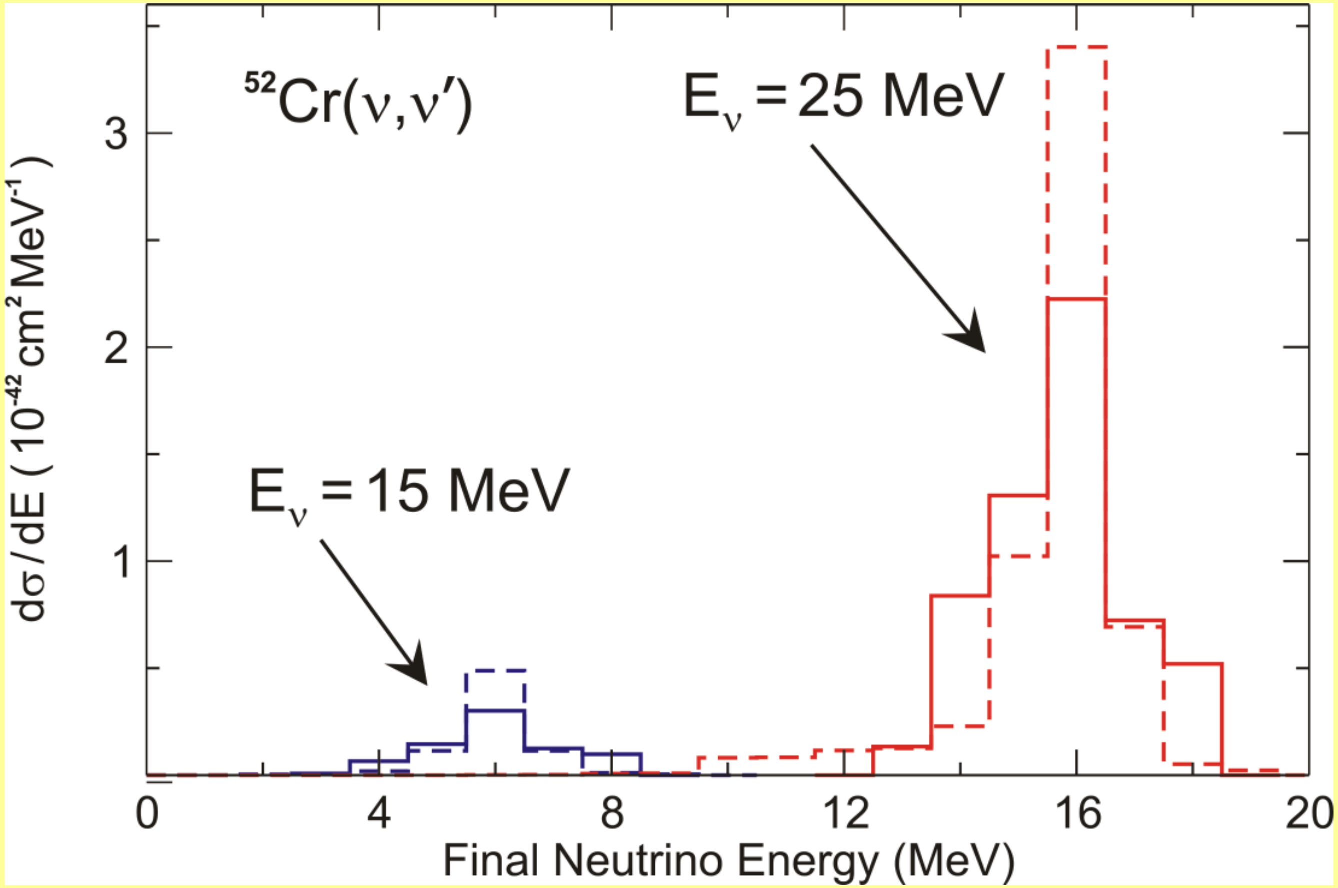
ν nucleus scattering cross section

- $$\sigma(i \rightarrow f) = \frac{G_F^2}{\pi}(E_\nu - E_x)^2 B(GT_0)$$

- $B(GT_0)$ from isovector M1 strength
  - orbital and isoscalar pieces small

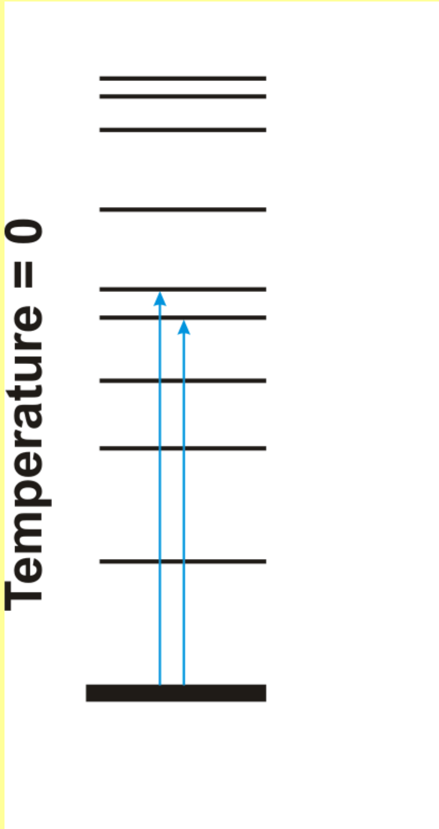
- test cases: ^{50}Ti, ^{52}Cr, ^{54}Fe with precision data on M1 strength from (e,e´) experiments

Differential ν nucleus cross section



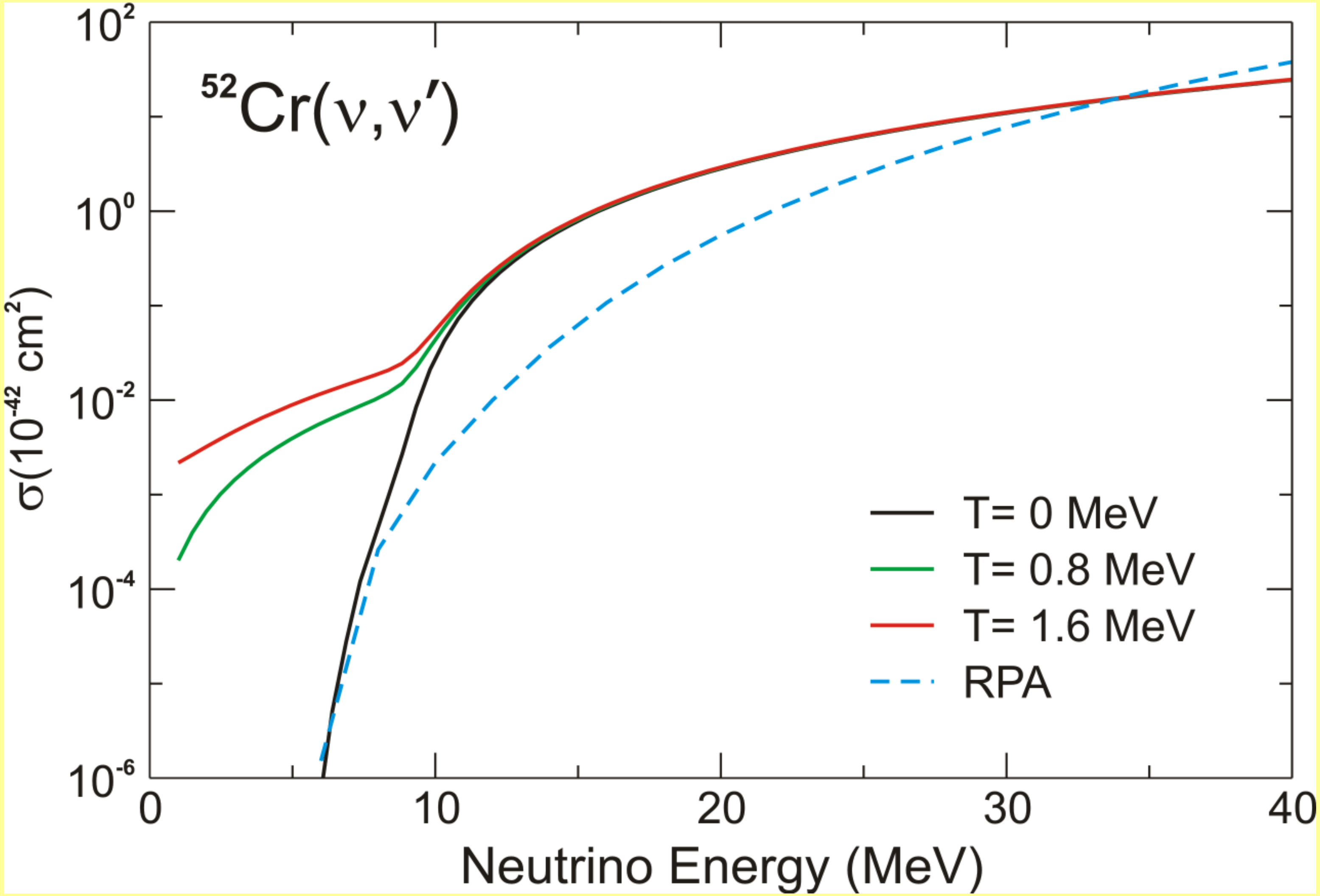
- $E_\nu(final) = E_\nu - E_x(GT_-)$
- good agreement between experiment and theory ➡ shell-model results can be used for systematic treatment

Influence of finite temperature



- thermally populated excited states in the nucleus
- increase of GT_0 strength
- upscattering of neutrinos

Influence of finite temperature



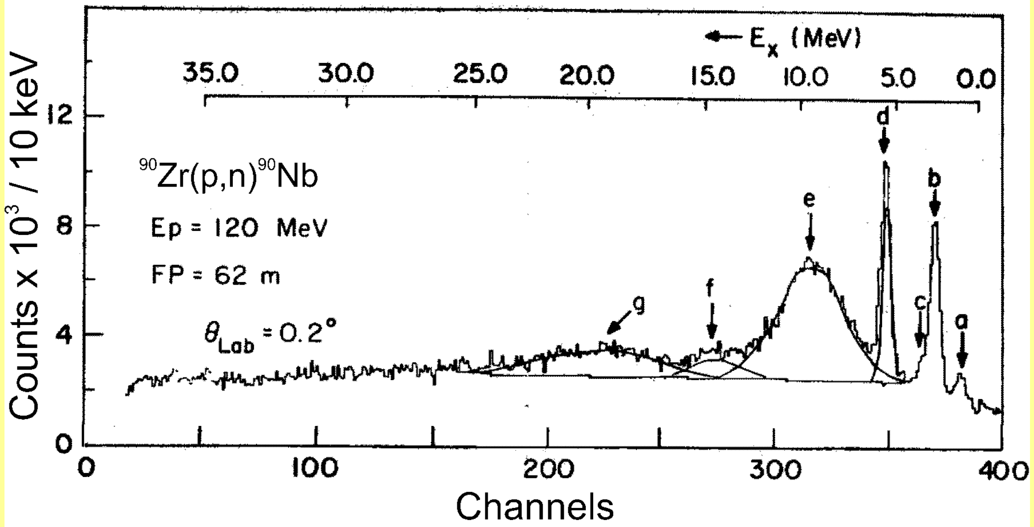
- upscattering of neutrinos increases cross section at low energies

Return to fine structure in the strength distribution: sign of configuration mixing

A=58: GT_- , GT_0 and GT_+ strength distributions

- fine structure is evident in all 3 excitation modes
- complete isospin decomposition possible
- great experimental progress is a challenge to theory

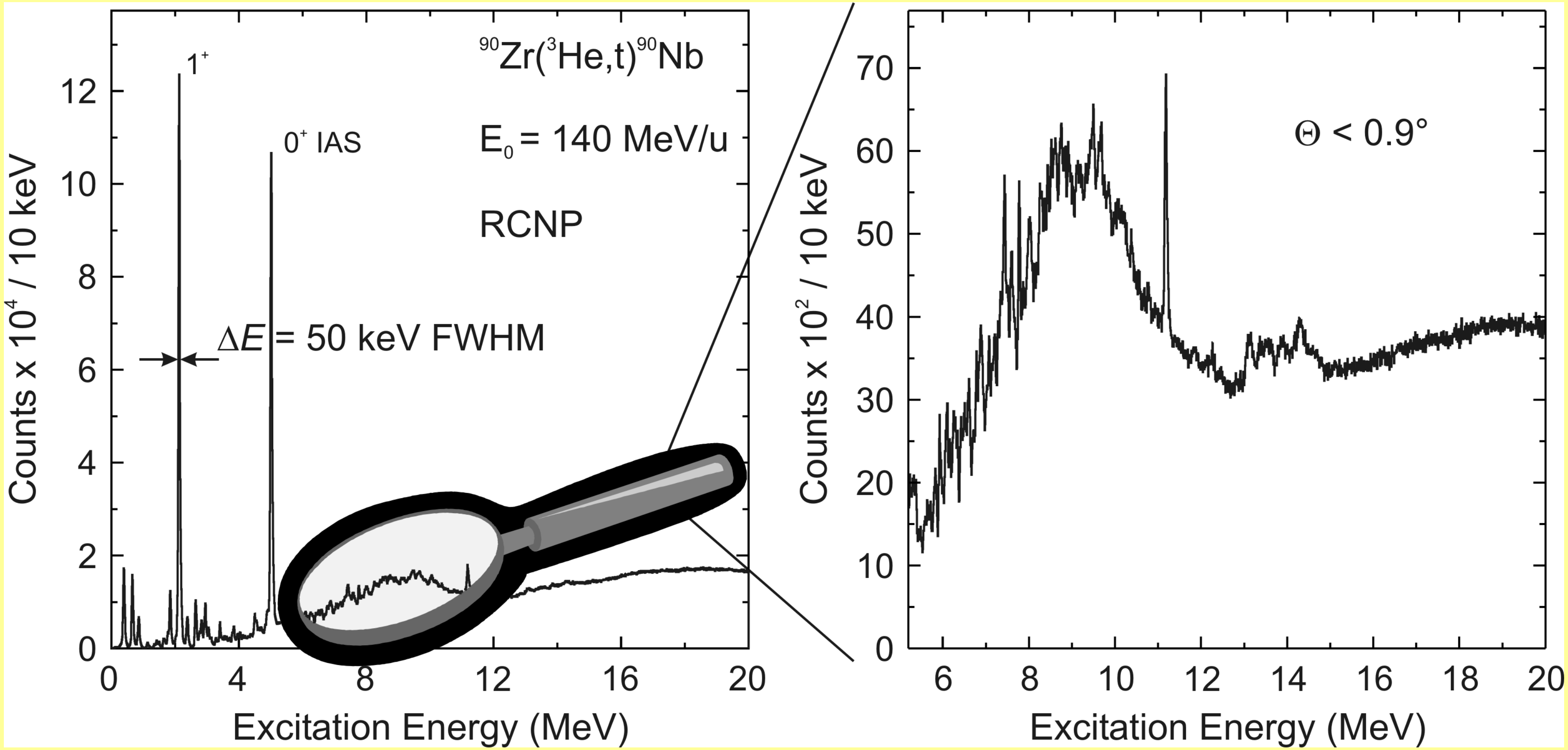
Fine structure of the spin-flip GTR in a heavy nucleus



D. Bainum et al.,
(1980)

- fine structure observed for the first time

Fine structure of the spin-flip GTR



- high energy resolution
- asymmetric fluctuations

What is the physics behind the fluctuations ?

- characteristic scales
  - wavelet analysis

- comparison of those scales with nuclear model predictions including various levels of configuration mixing

- results: 2p - 2h mixing is predominant ➡ spreading of strength ➡ quenching

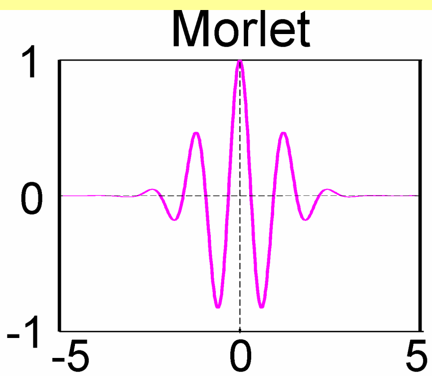
- method is complementary to Hide Sakai’s approach where this spreading of strength to high excitation energy is directly determined

Wavelet analysis

$$\int_{-\infty}^{\infty} \Psi^*(x)\, dx = 0$$

and

$$\int_{-\infty}^{\infty} \left|\Psi^*(x)\right|^2 dx < \infty$$



$$\Psi(x) = \cos(2\pi\omega x)\, e^{-x^2/2}$$

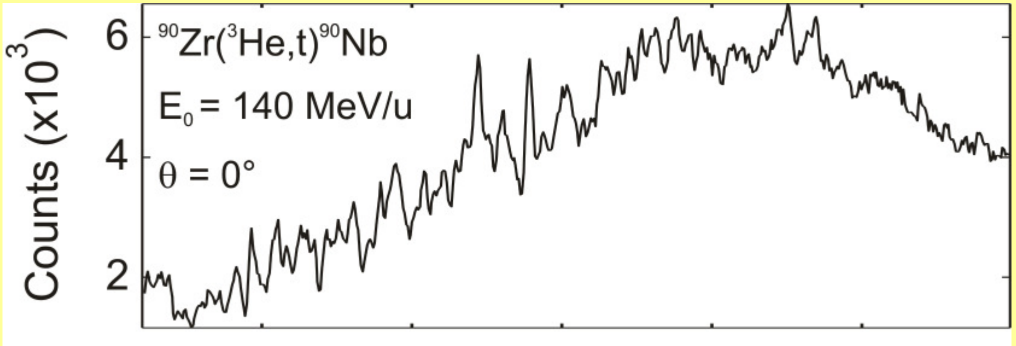
Wavelet coefficients:

$$C(\delta E, E_x) = \frac{1}{\sqrt{\delta E}} \int \sigma(E)\ \Psi^*\left(\frac{E_x - E}{\delta E}\right) dE$$

scale (δE), position (E_x), spectrum ($\sigma(E)$), wavelet (Ψ^*)

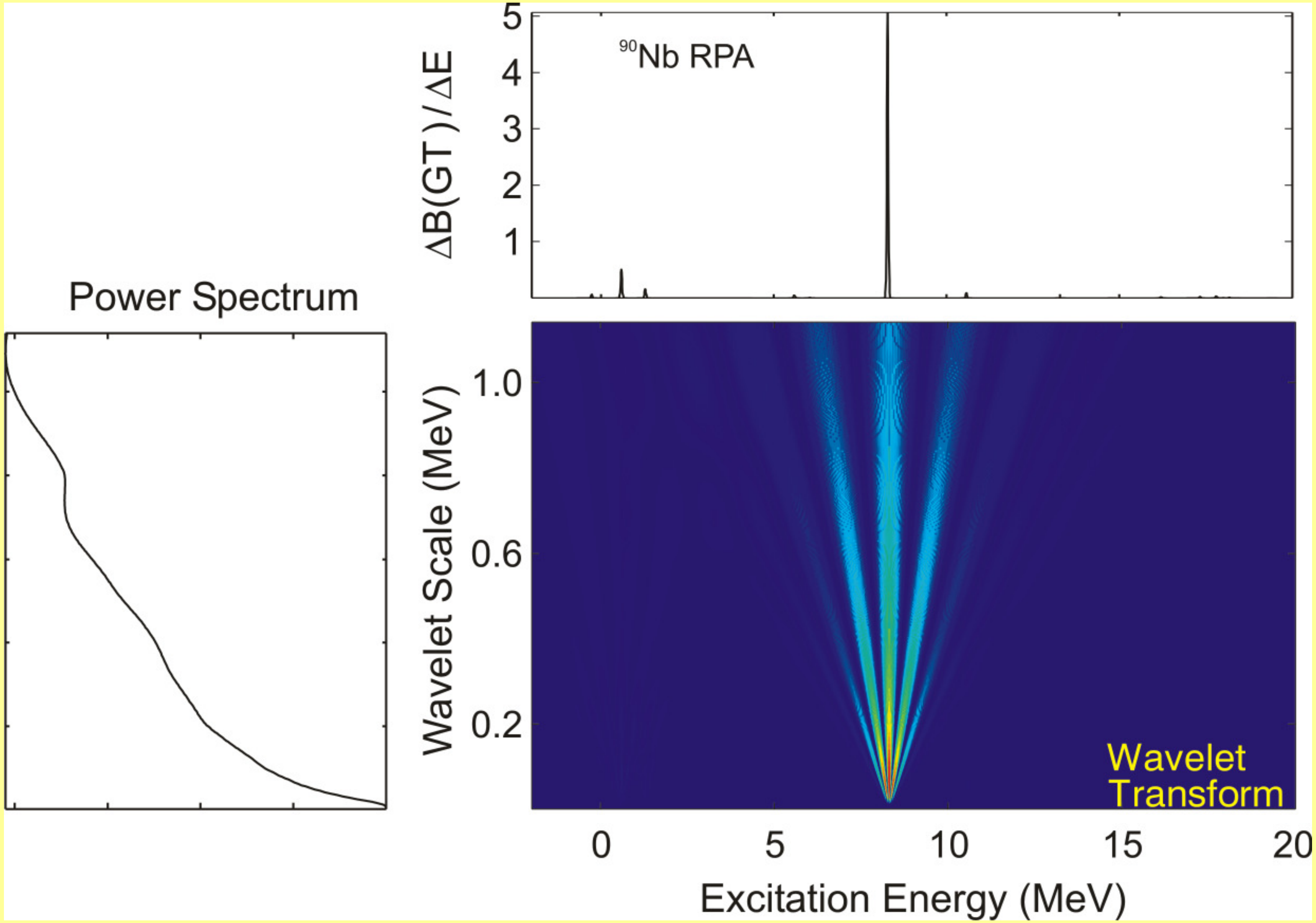
Continuous: δE, E_x are varied continuously

Extraction of scales from the data



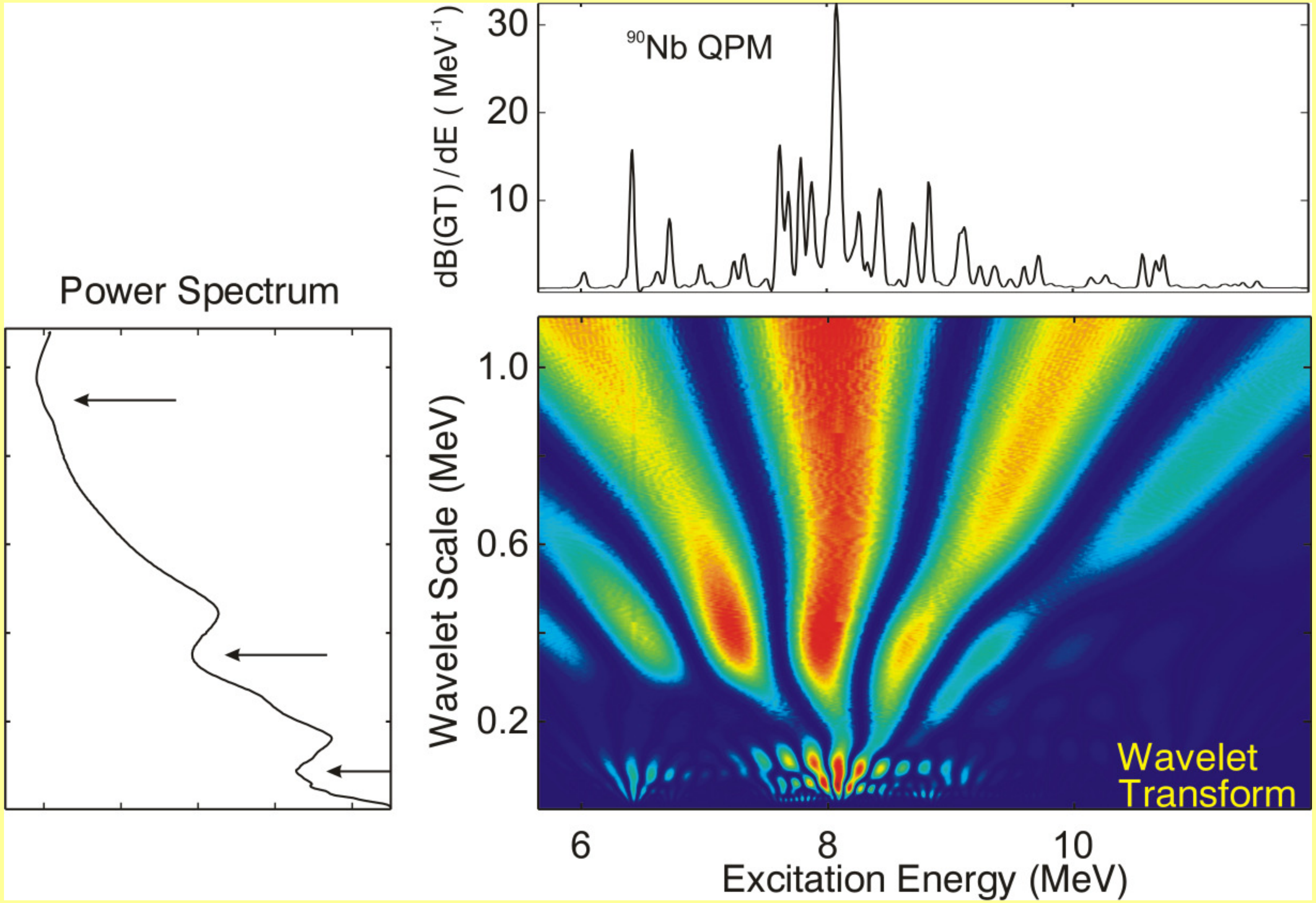
- scales at 80, 300, 950, 2500 keV

Extraction of scales from the RPA



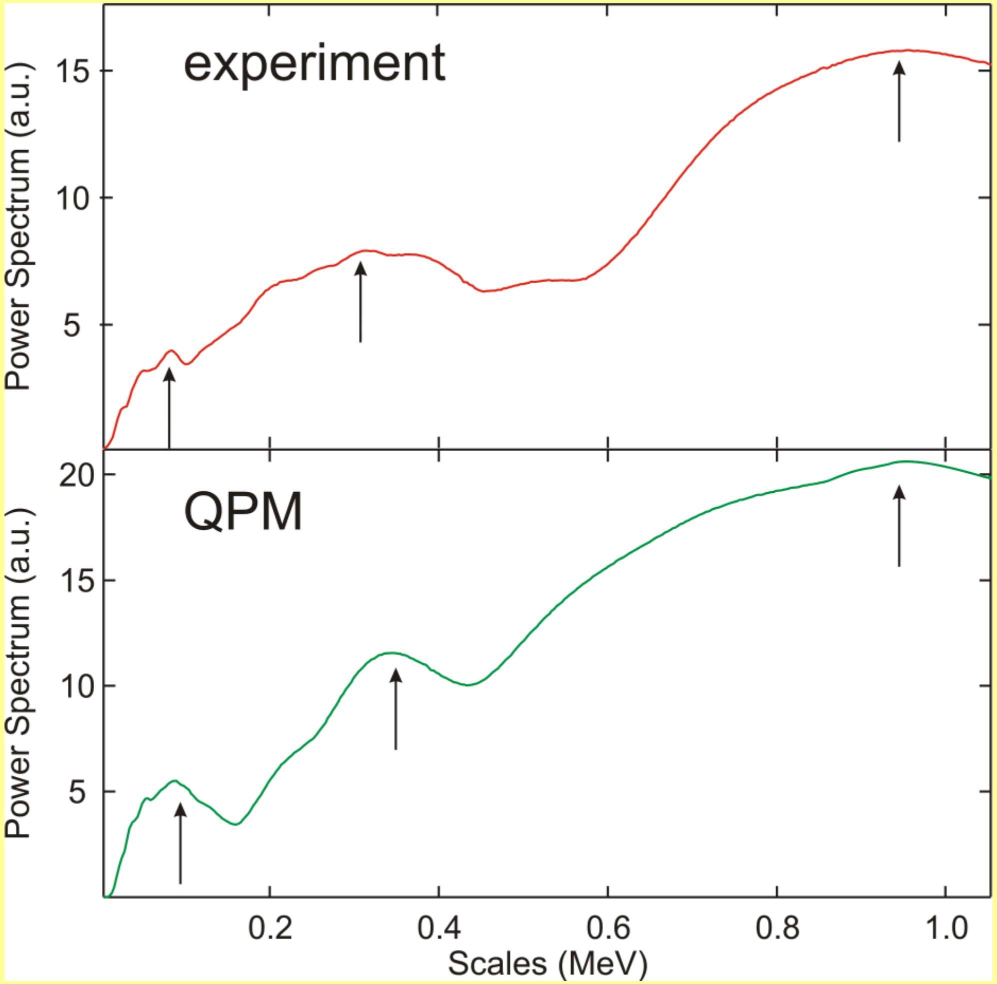
- no scales in 1p − 1h RPA

Extraction of scales from the QPM



- 2 phonon QPM is equivalent to 2nd RPA and yields scales at 100, 380, 950, 1600 keV very similar to experiment

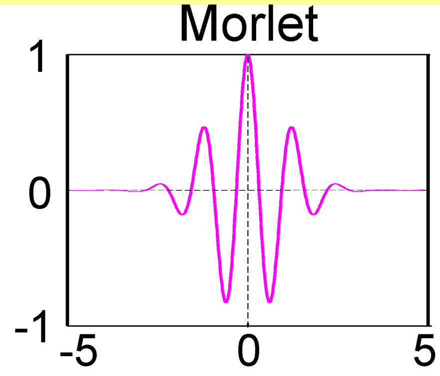
Scales of the spin-flip GTR in ^{90}Nb



- very similar scales
- scales are a global phenomenon of giant resonances (GQR, GDR, …)

Test of physical significance of these scales: discrete wavelet analysis

$$\int_{-\infty}^{\infty} \Psi^*(x)\, dx = 0 \quad \text{and} \quad \int_{-\infty}^{\infty} \left|\Psi^*(x)\right|^2 dx < \infty$$



$$\Psi(x) = \cos(2\pi\omega x)\, e^{-x^2/2}$$

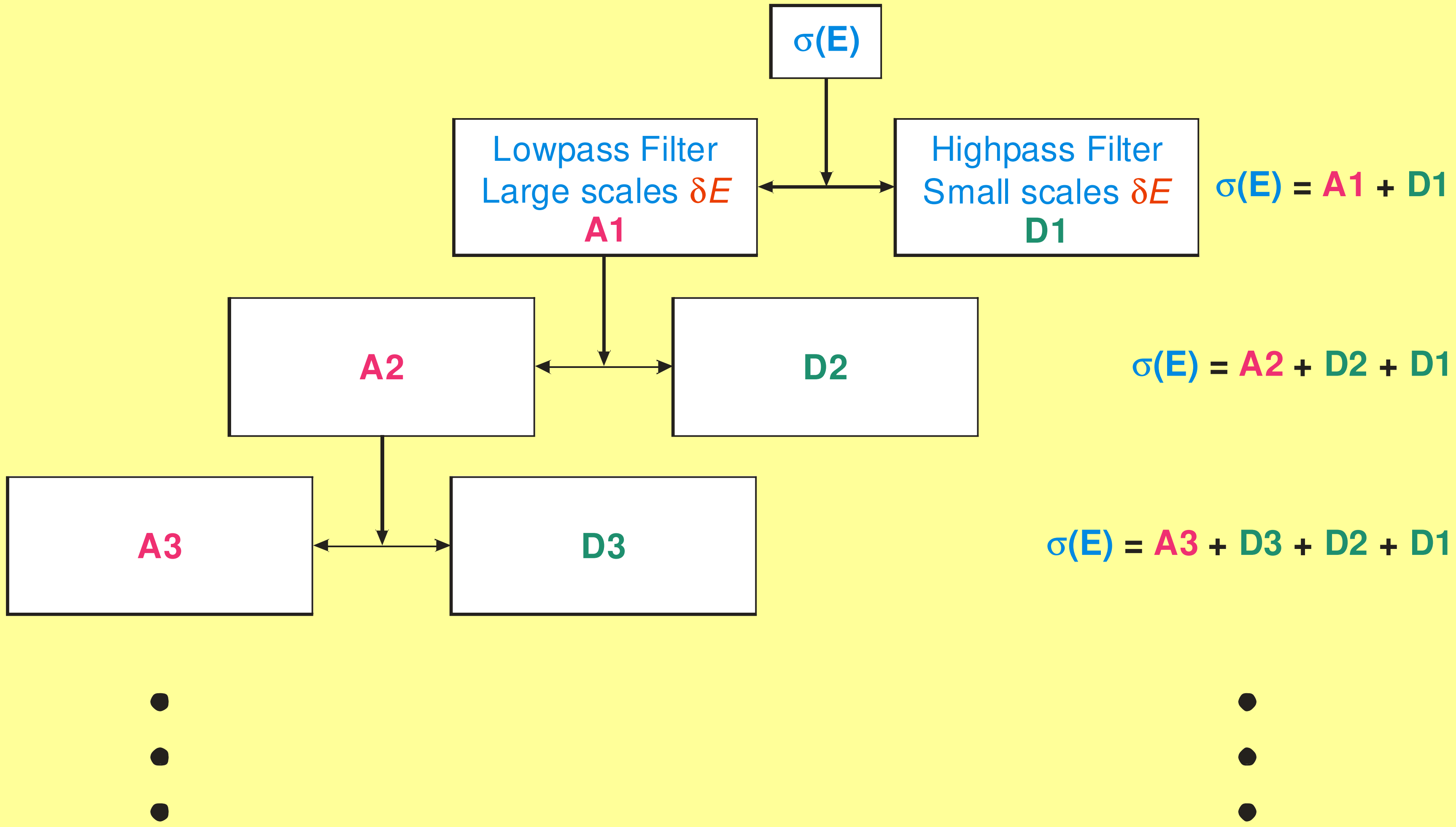
Wavelet coefficients:

$$C(\delta E, E_x) = \frac{1}{\sqrt{\delta E}} \int \sigma(E)\, \Psi^*\left(\frac{E_x - E}{\delta E}\right) dE$$

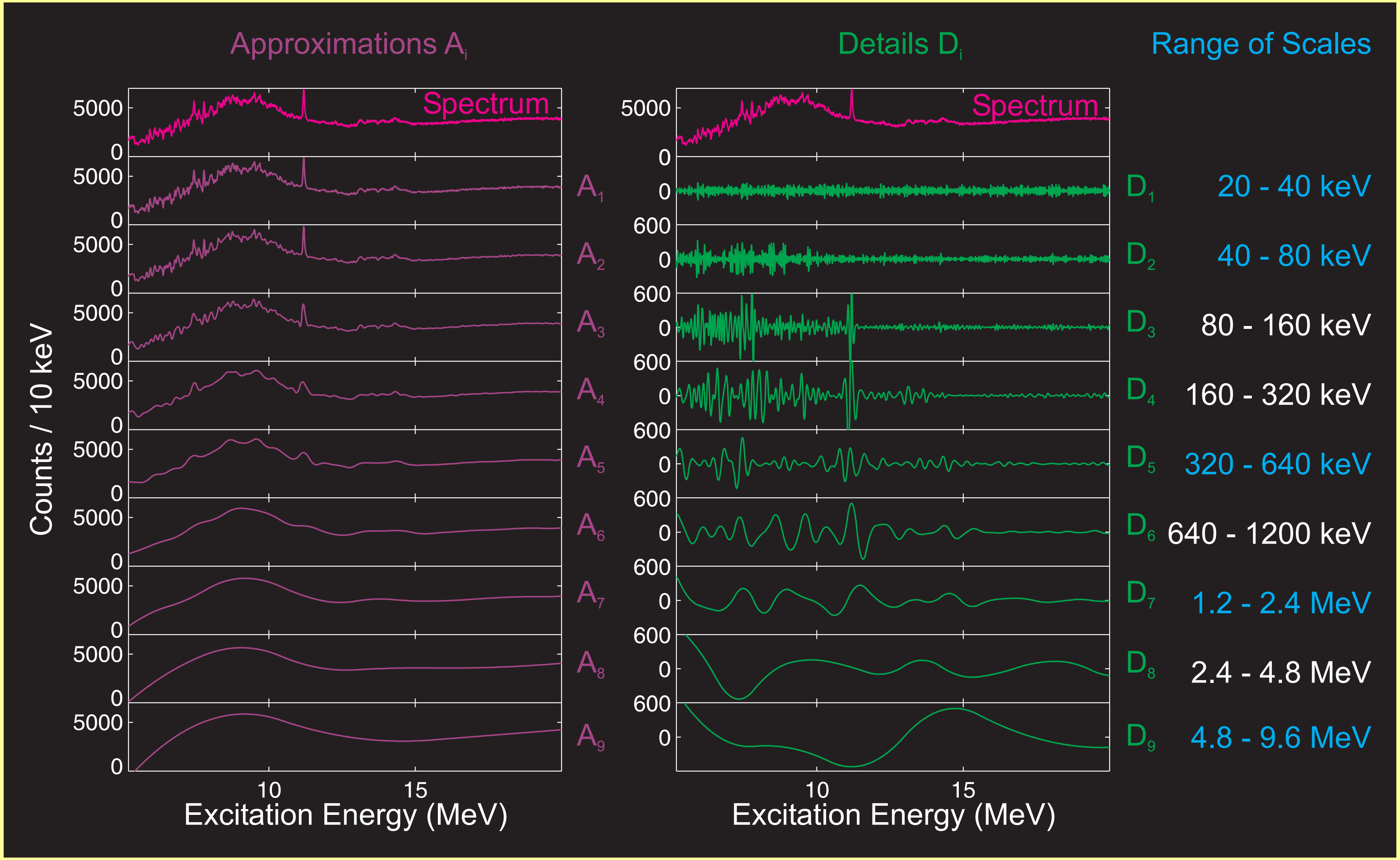
scale position spectrum wavelet

Discrete: $\delta E = 2^j$ *and* $E_x = k\delta E$ with $j, k = 1, 2, 3, \ldots$

Decomposition of spectra



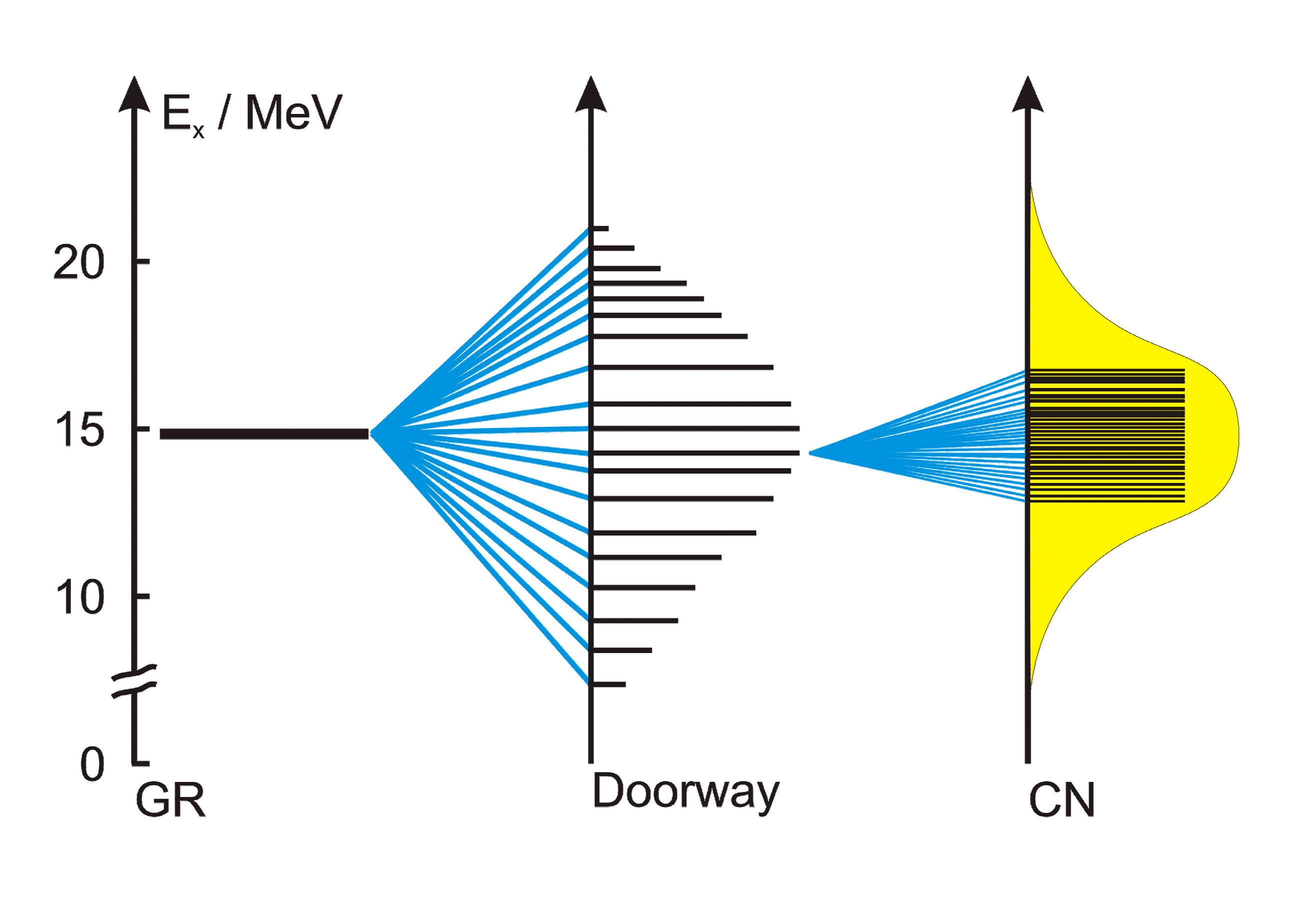
Decomposition of $^{90}Zr(^{3}He,t)^{90}Nb$ spectrum



Discrete wavelet transform: reconstructed spectra

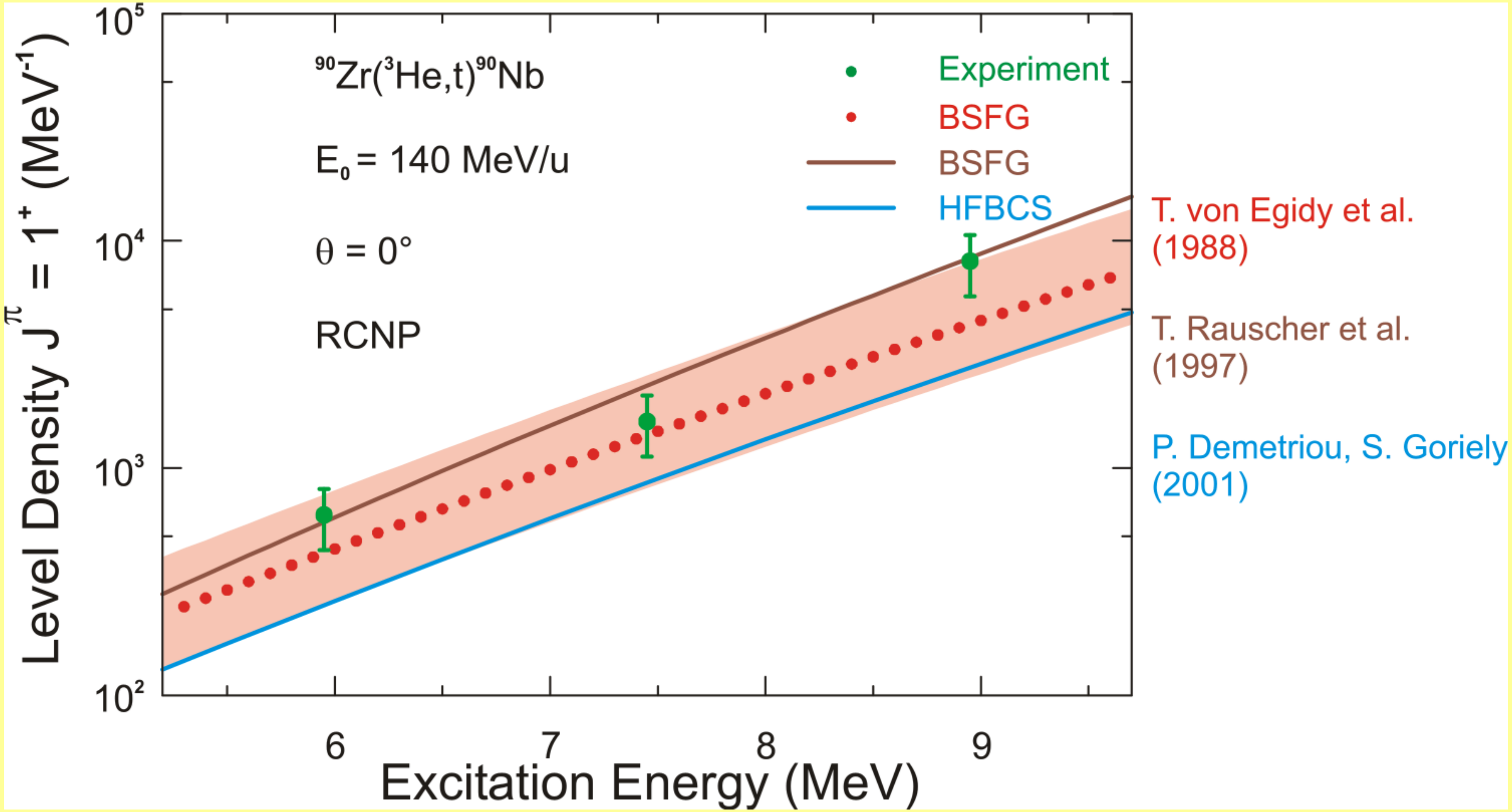
- DWT and CWT give the same range of scales
- scales are quantitative measure of 2p - 2h configuration mixing

Spreading of a GR due to the coupling to doorway states and decay into compound nucleus states

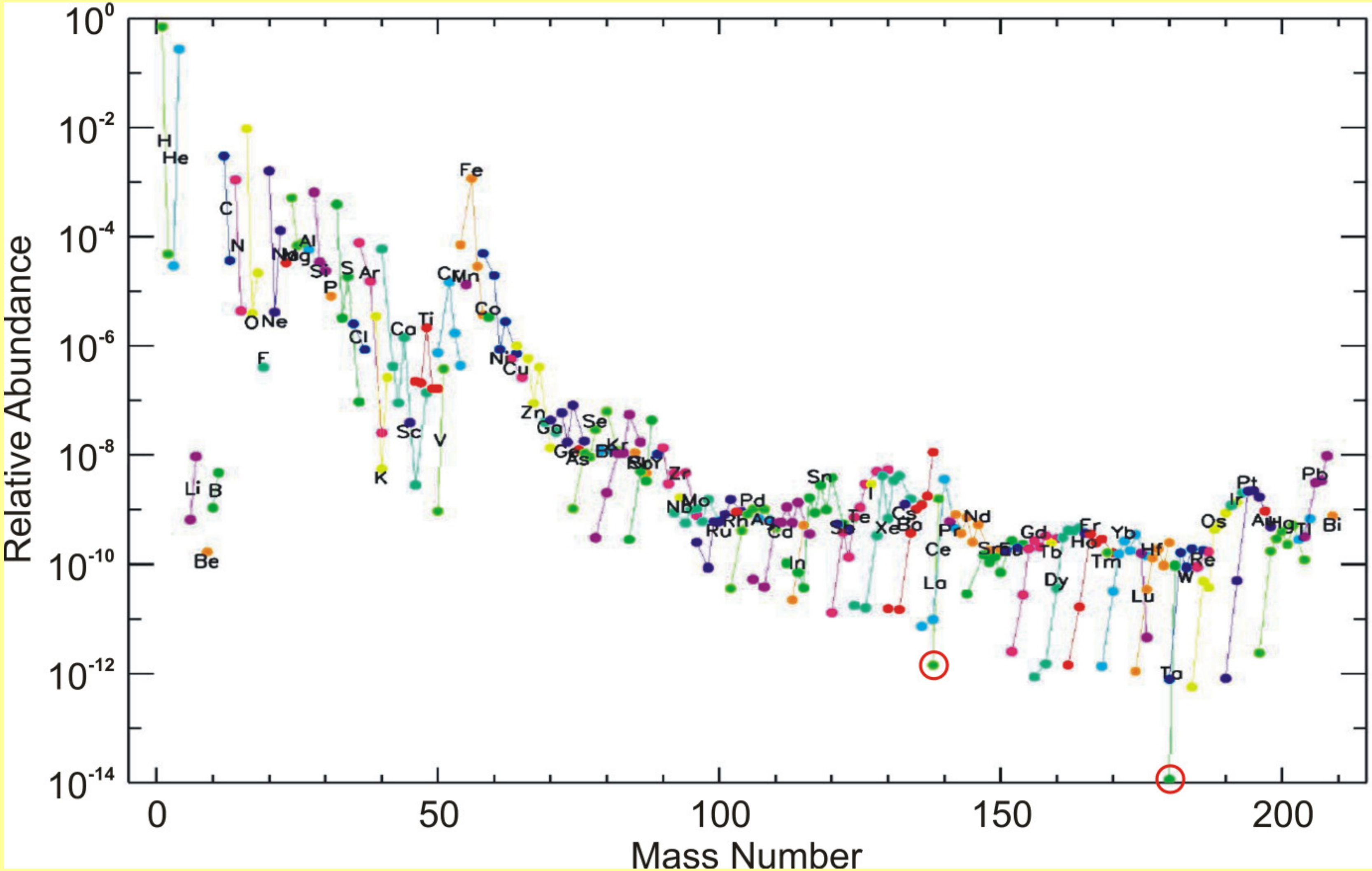


- with present energy resolution 2p – 2h doorway states have been identified

Second example: determination of spin and parity separated level densities – important for astrophysics



Third example: nucleosynthesis of ^{138}La and ^{180}Ta and the rôle of the GT strength distribution



Possible production mechanisms

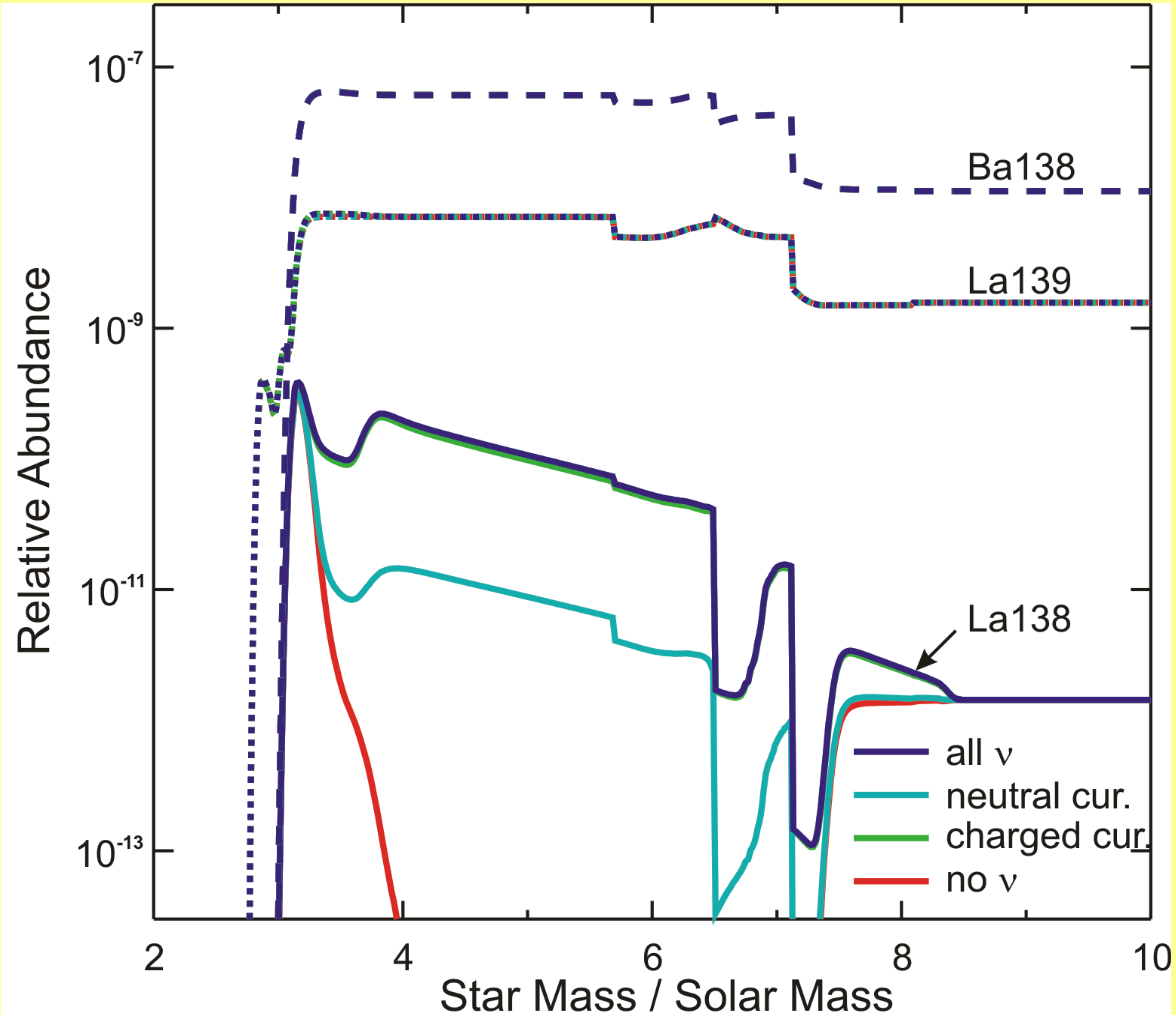
- s and r processes are most likely excluded

- p process: $^{139}La(\gamma,n)$, $^{181}Ta(\gamma,n)$

- ν process: $^{139}La(\nu,\nu'\,n)$, $^{181}Ta(\nu,\nu'\,n)$
  $^{138}Ba(\nu_e,e^-)$, $^{180}Hf(\nu_e,e^-)$

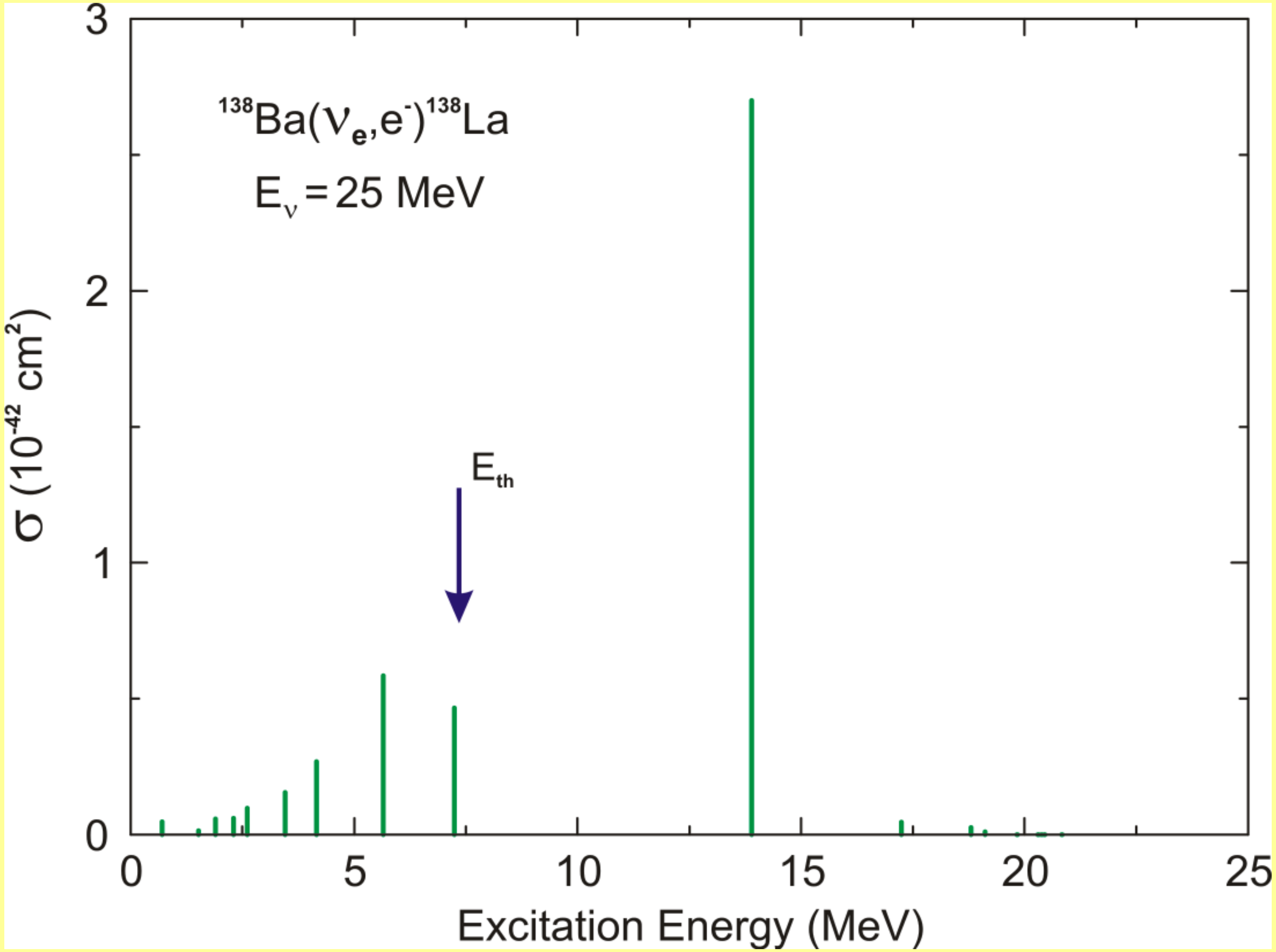
- prediction of production rates in massive starts exists (Rauscher et al., 2002)

Importance of different processes



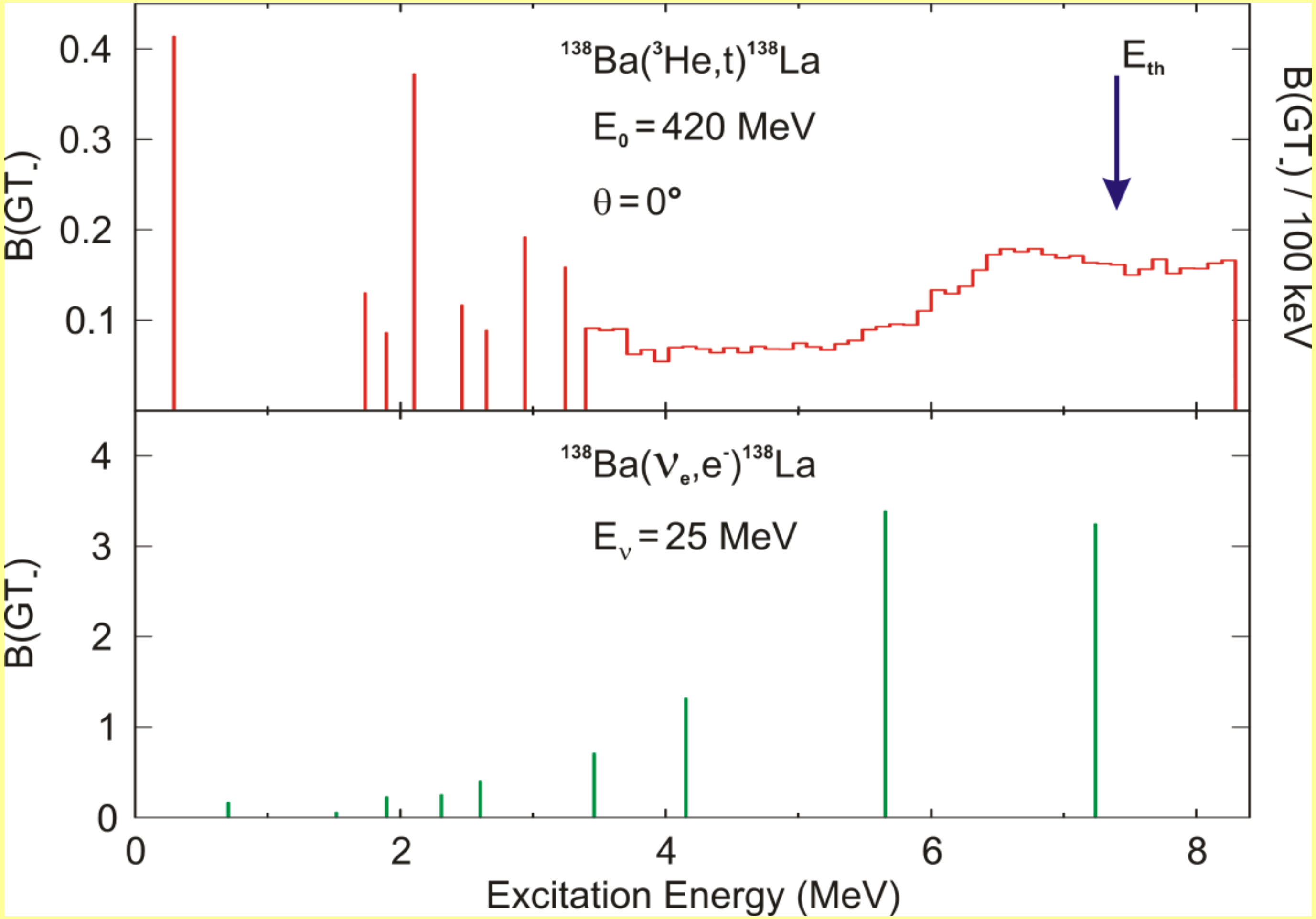
- ^{138}La: produced in a pure ν process of the type (ν_e,e^-) ➡ GT_- dominant

Prediction of the cross section



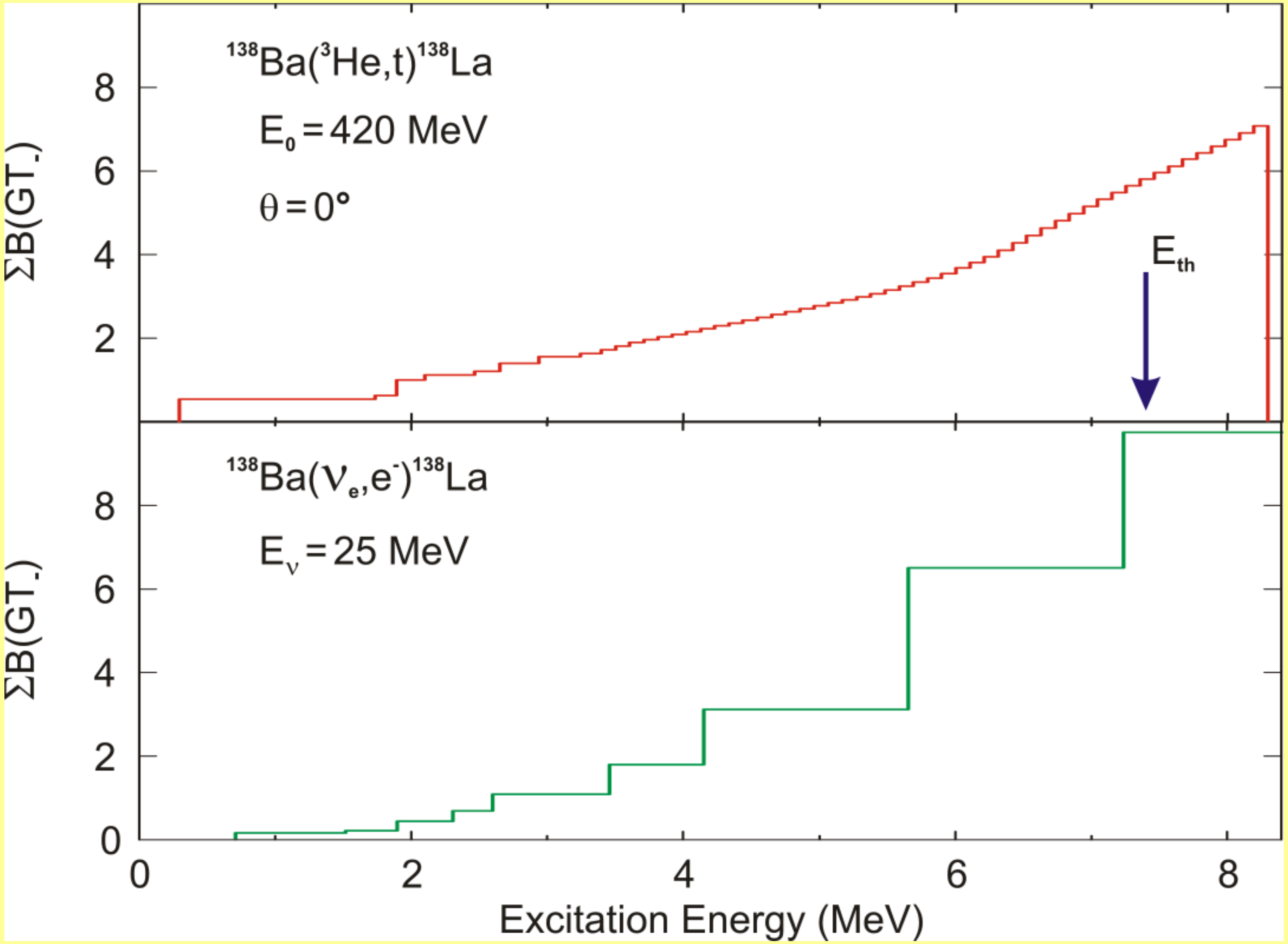
- RPA predicts main GT_- strength well above neutron threshold
  - but sizeable GT_- strength below E_{th}
  - high-resolution measurement of GT_- strength distribution in ^{138}La and ^{180}Ta is mandatory

Comparison of experiment with RPA prediction



- absolute normalization of $B(GT_-)$ from comparison of (^{3}He,t) to β decay
- configuration mixing leads to large differences between experiment and RPA

Comparison of experiment with RPA prediction



- $B(GT_-)_{exp} \approx \frac{1}{2} B(GT_-)_{the}$ ➡ problem
- use of experimental $B(GT_-)$ in supernova models is underway

Conclusions

- study of M1 and GT modes are ideal testing grounds for configuration mixing which has been proposed first by Arima and Horie 50 years ago for magnetic moments
- most of the information rests in the fine structure of spectra ➡ highest experimental energy resolution is a prerequisite to obtain this information
- first rate nuclear structure experiments and many-body calculations are very important for astrophysics