Fine Structure of Giant Resonances Revisited Experimentally and Theoretically

- Nature of the pygmy dipole resonance: the case of ^{208}Pb
- M2 and spin dipole modes
- Fine structure and characteristic scales
  - ISGQR at shell closures
  - GT resonance in ^{90}Nb

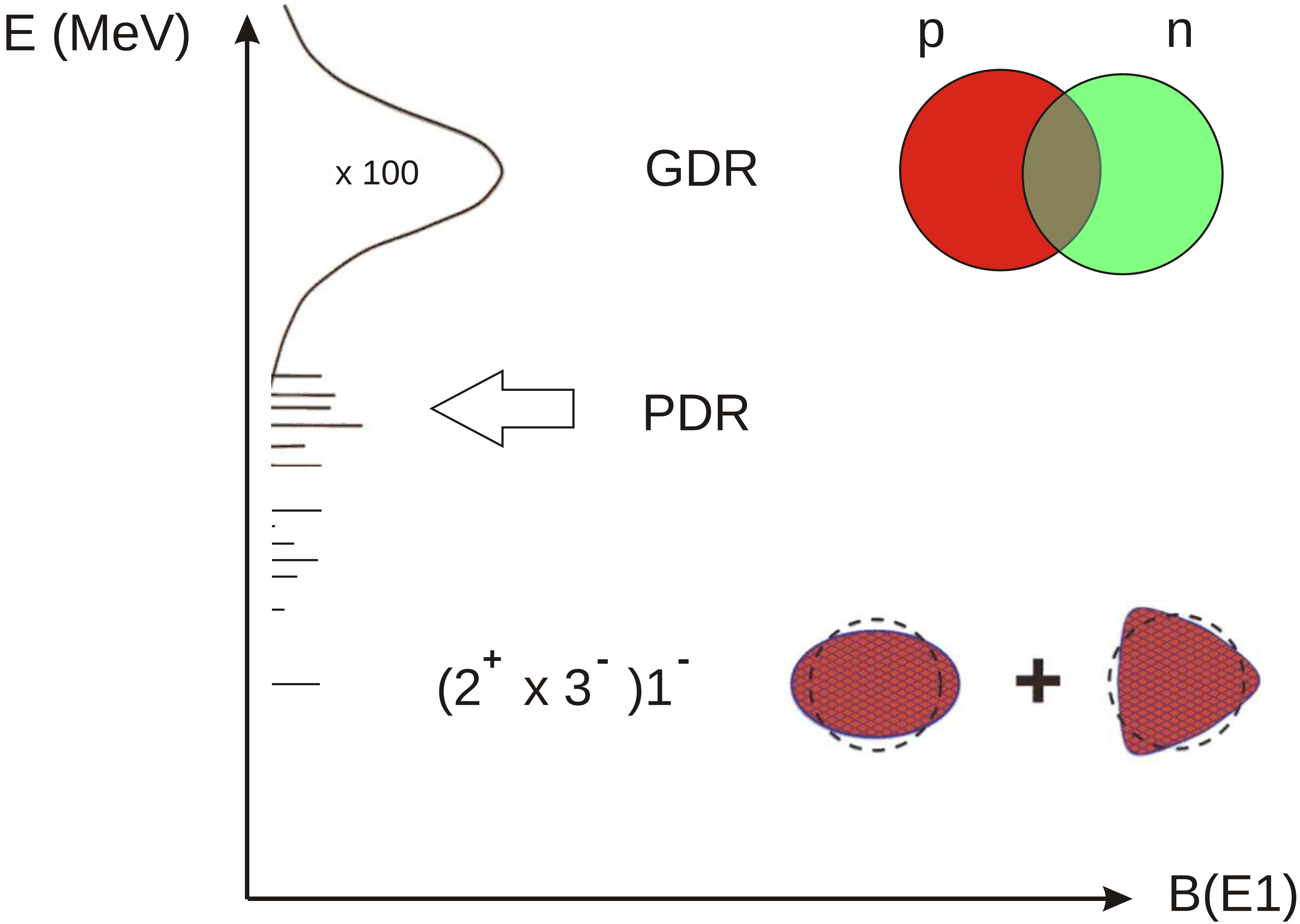
F. Hofmann, Y. Kalmykov, P. von Neumann-Cosel, V. Ponomarev,
A. Richter, N. Ryezayeva, A. Shevchenko, J. Wambach

Darmstadt / Groningen / iThembaLAB / Münster / Osaka Collaborations

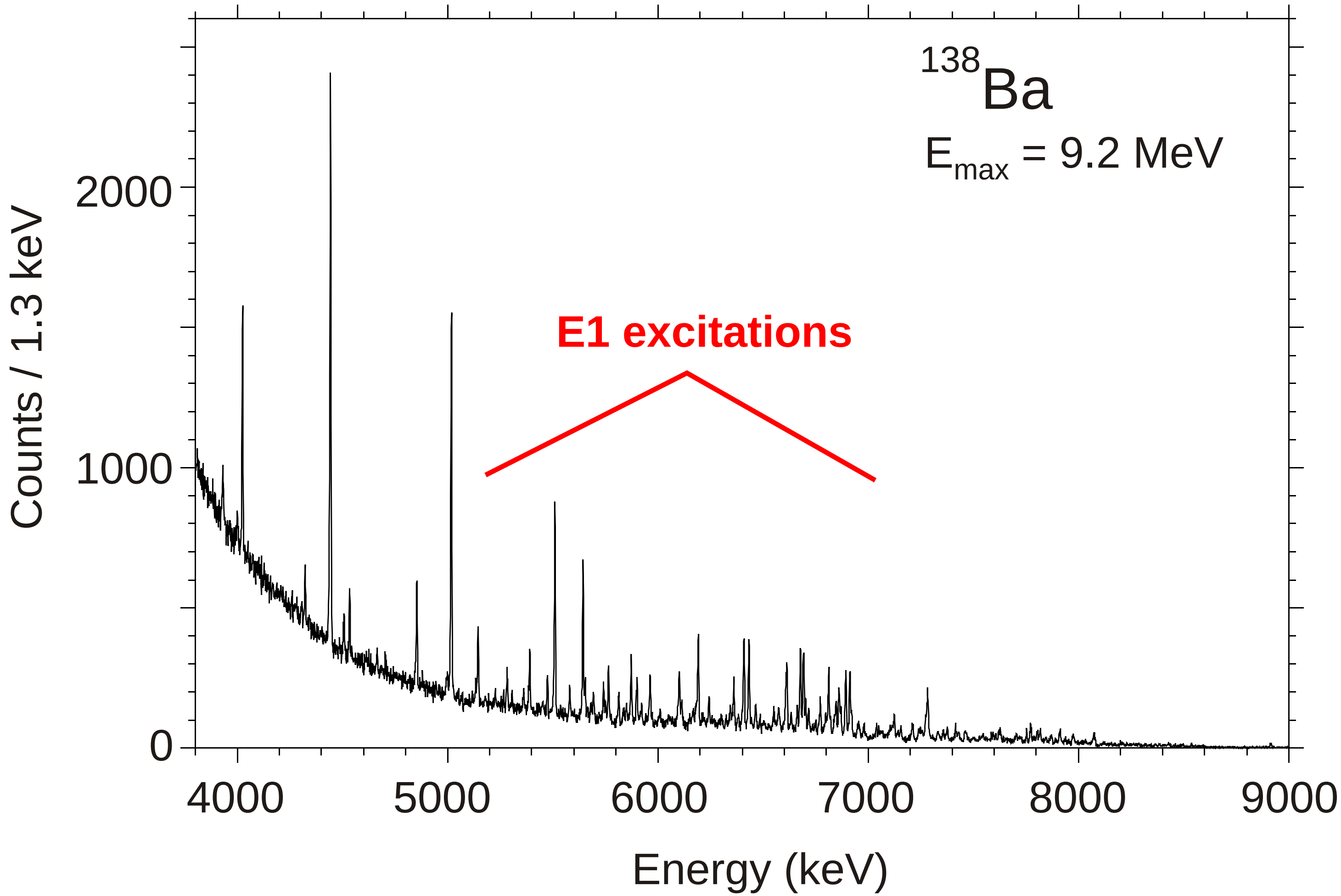
Supported by DFG under Contract FOR 272 / 2 - 2

Nature of the pygmy dipole resonance: the case of ^{208}Pb

E1 Response in Nuclei



Photon Scattering off ^{138}Ba



- A. Zilges et al., Phys. Lett. B 542, 43 (2002)

PHYSICAL REVIEW C, VOLUME 63, 047301

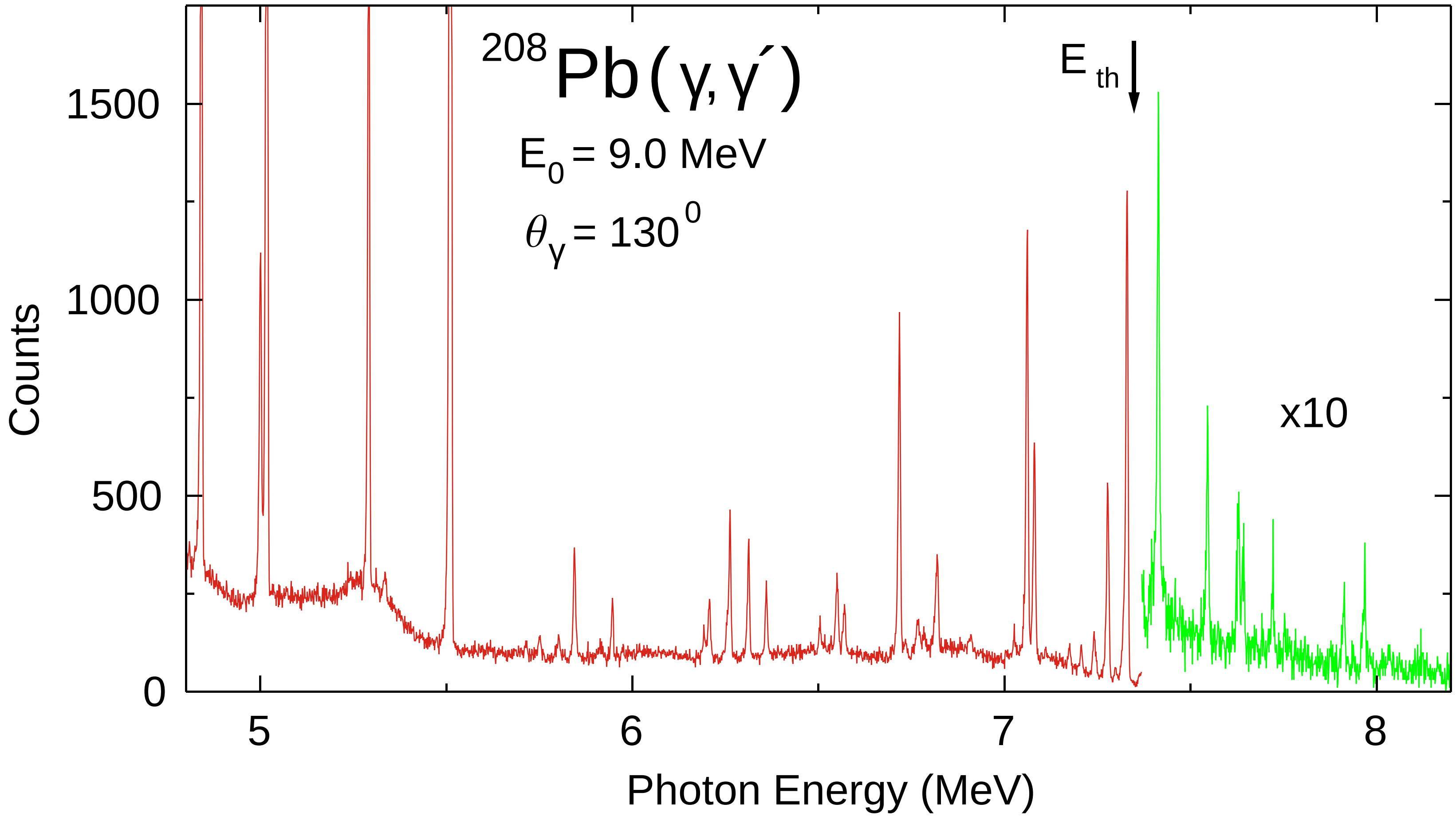
Pygmy dipole resonances in the relativistic random phase approximation

D. Vretenar,[1,2] N. Paar,[1] P. Ring,[1] and G. A. Lalazissis[1,3]

The isovector dipole response in ^{208}Pb is described in the framework of a fully self-consistent relativistic random phase approximation. The NL3 parameter set for the effective mean-field Lagrangian with nonlinear meson self-interaction terms, used in the present calculations, reproduces ground state properties as well as the excitation energies of giant resonances in nuclei. In addition to the isovector dipole resonance in ^{208}Pb, the present analysis predicts the occurrence of low-lying $E1$ peaks in the energy region between 7 and 11 MeV. In particular, a collective state has been identified whose dynamics correspond to that of a dipole pygmy resonance: the vibration of the excess neutrons against the inert core composed of an equal number of protons and neutrons.

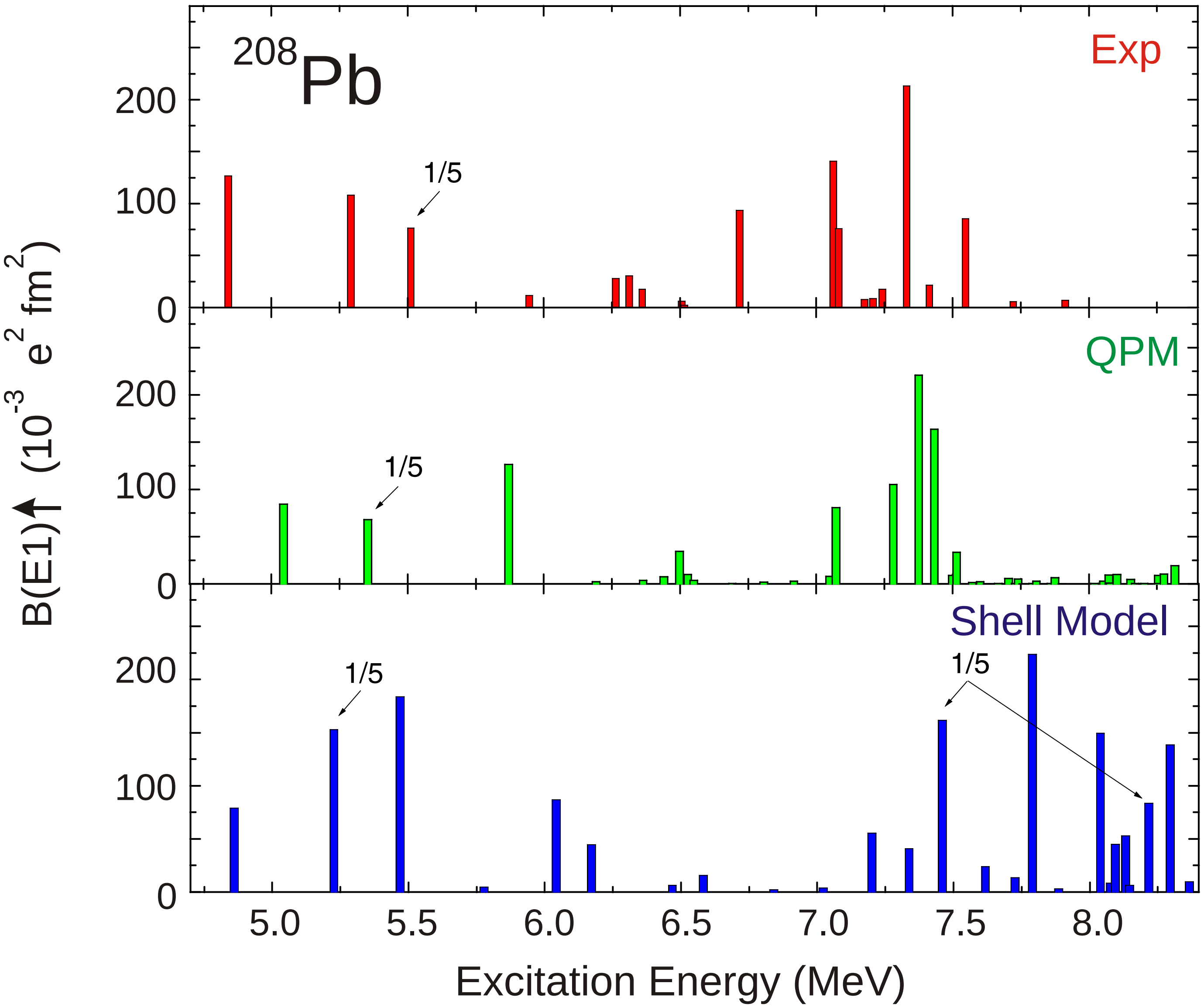
... Experimental information on the fragmentation of $E1$ strength in ^{208}Pb is, however, only available in the energy window 8–12 MeV [11–13], and below 6.5 MeV [14]. In order to test the predictions of the present analysis, it would be important to obtain experimental data also in the energy region between 6 and 8 MeV.

NRF Spectrum



- N. Ryezayeva et al., Phys. Rev. Lett. 89, 272502 (2002)

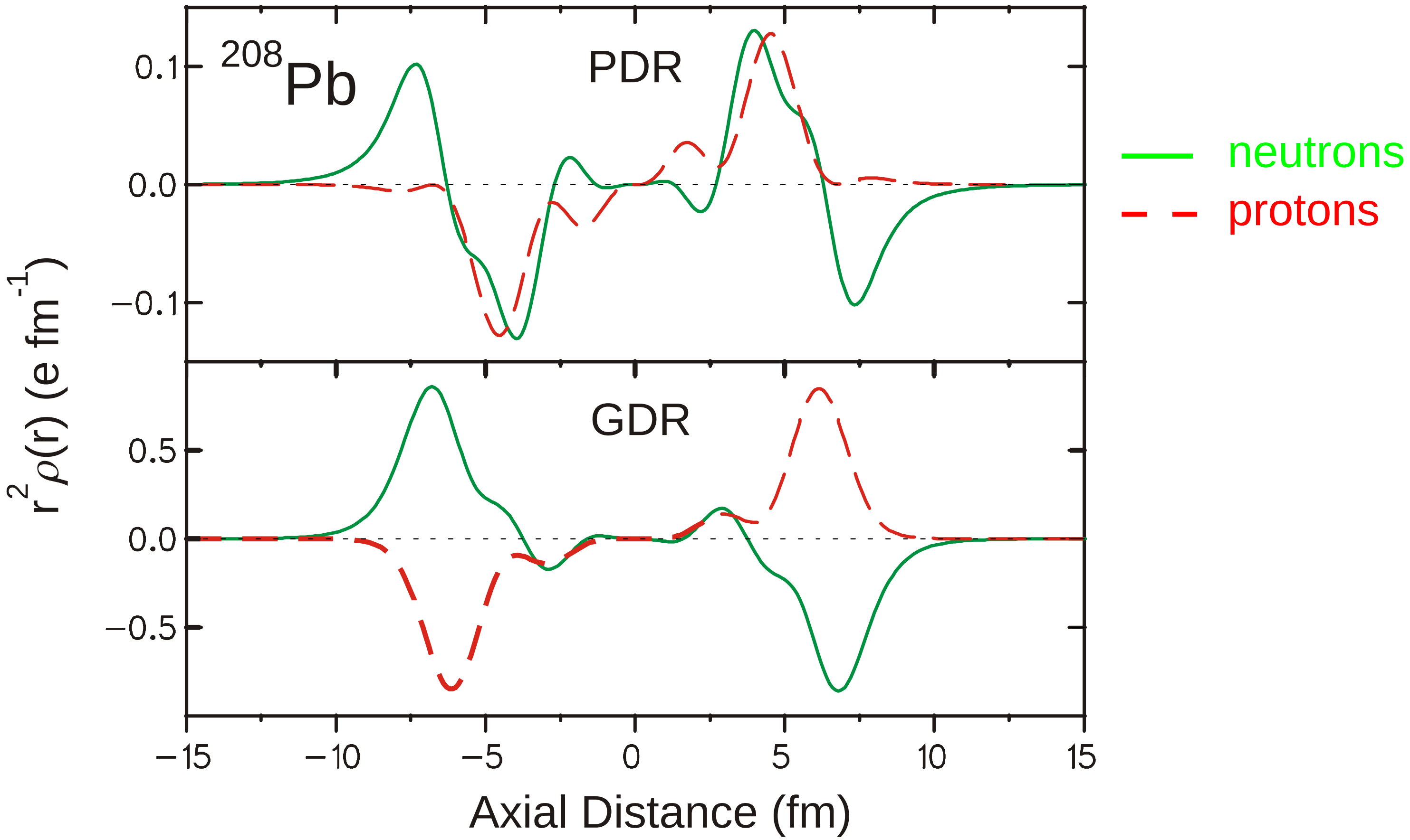
B(E1)↑ in ^{208}Pb



Ponomarev (2002)

Brown (2002)

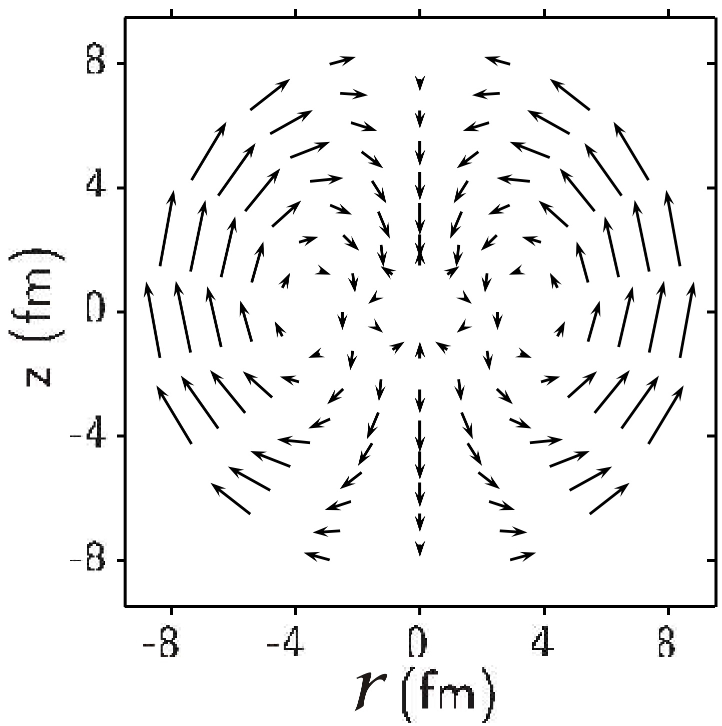
Electric Dipole Response of Neutrons and Protons



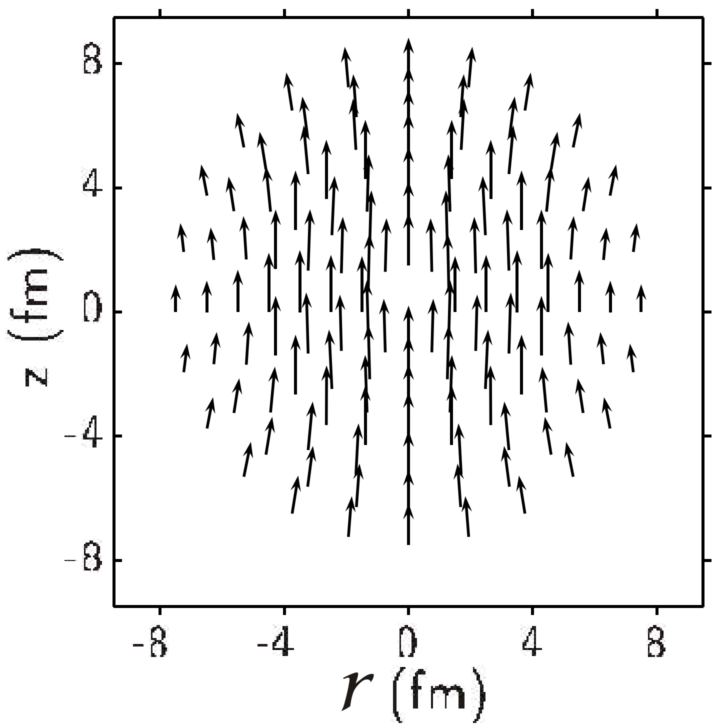
- PDR largely isoscalar
- Evidence for surface neutron density oscillations
- Similar results from the Milano and Munich groups

"Snapshots" of Velocity Distribution in ^{208}Pb

PDR



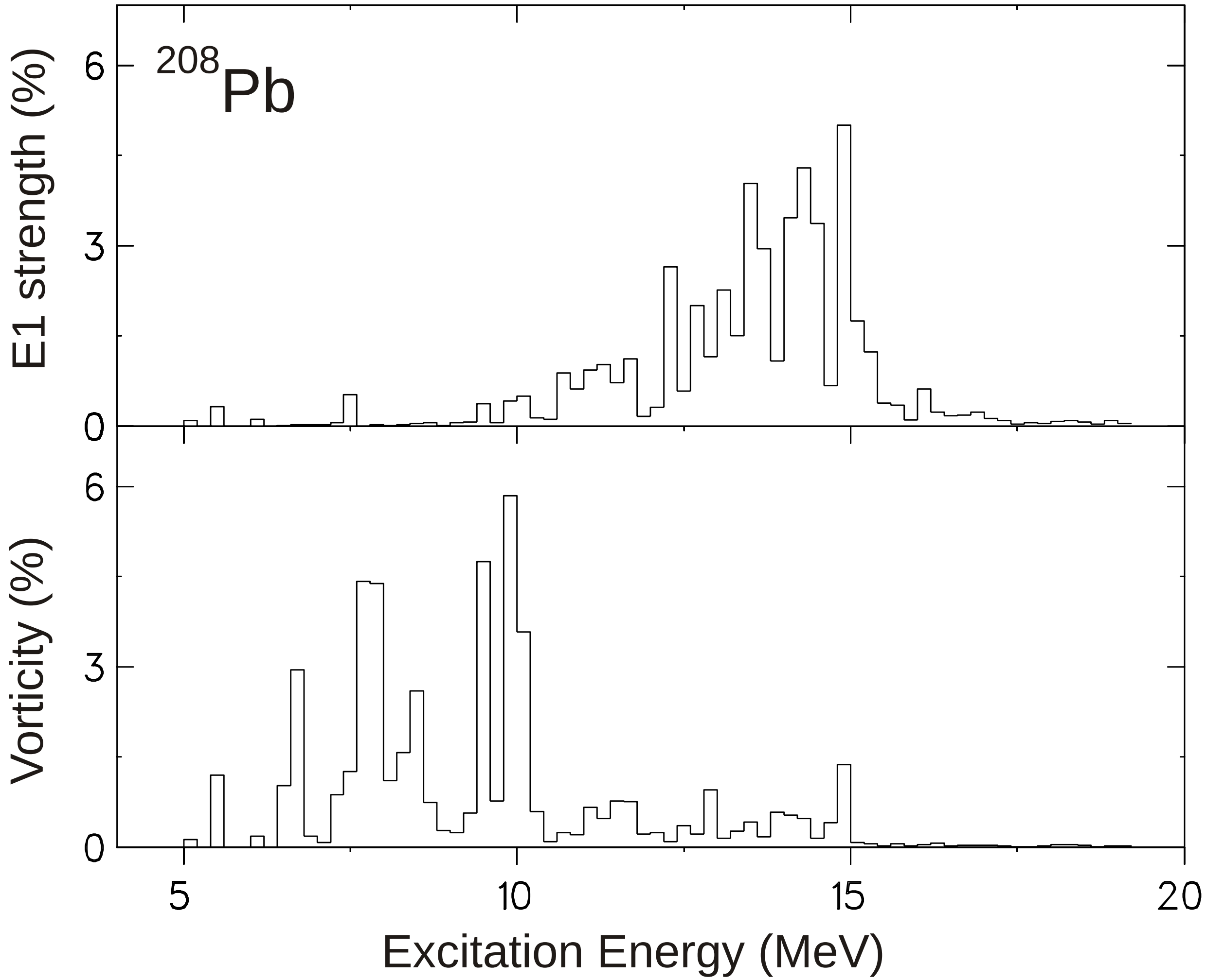
GDR



- Toroidal (current) mode: zero sound wave
- Restoring force is not of hydrodynamic nature but elastic

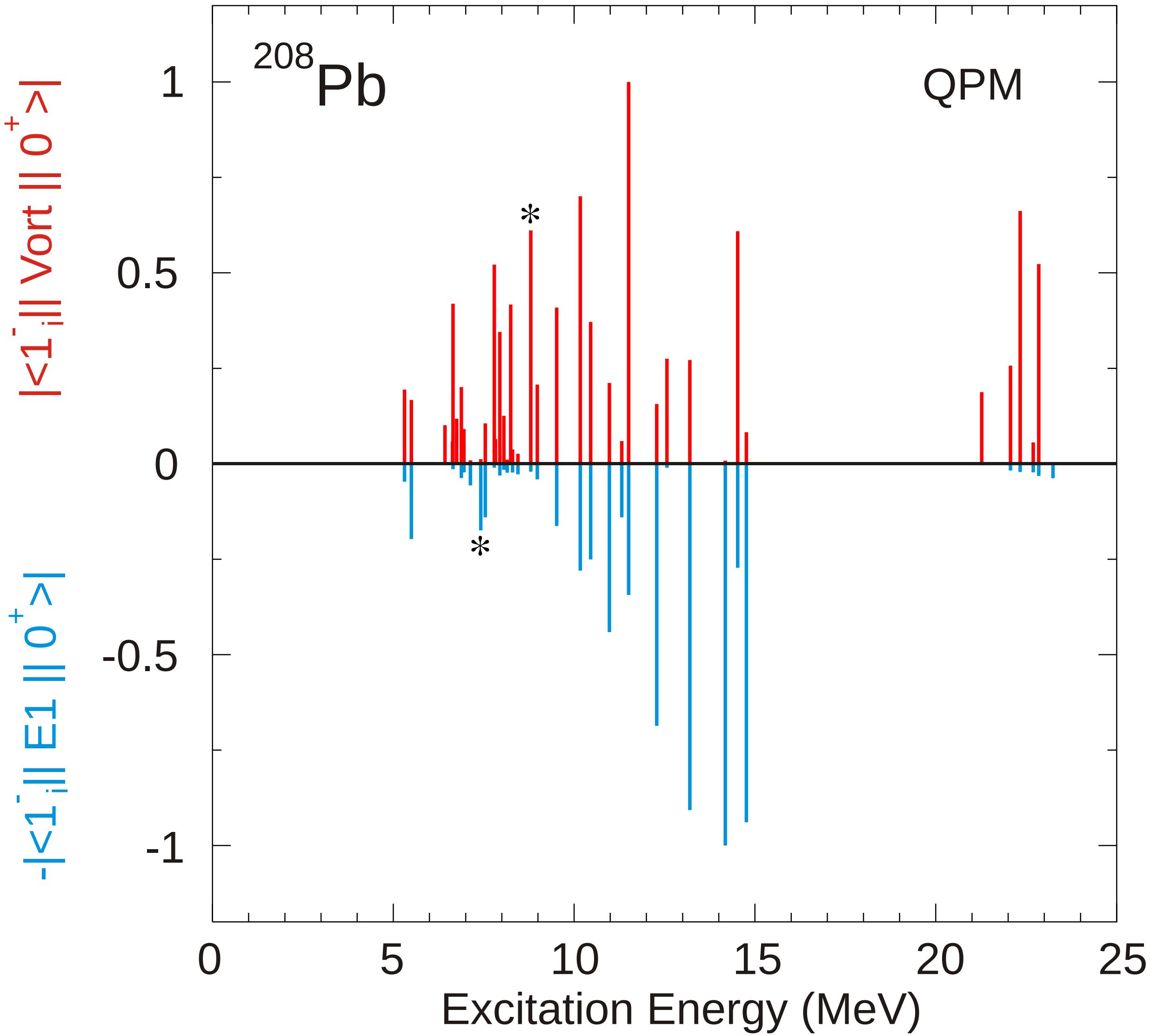
- Vibrational mode

Electric Dipole Strength and Vorticity

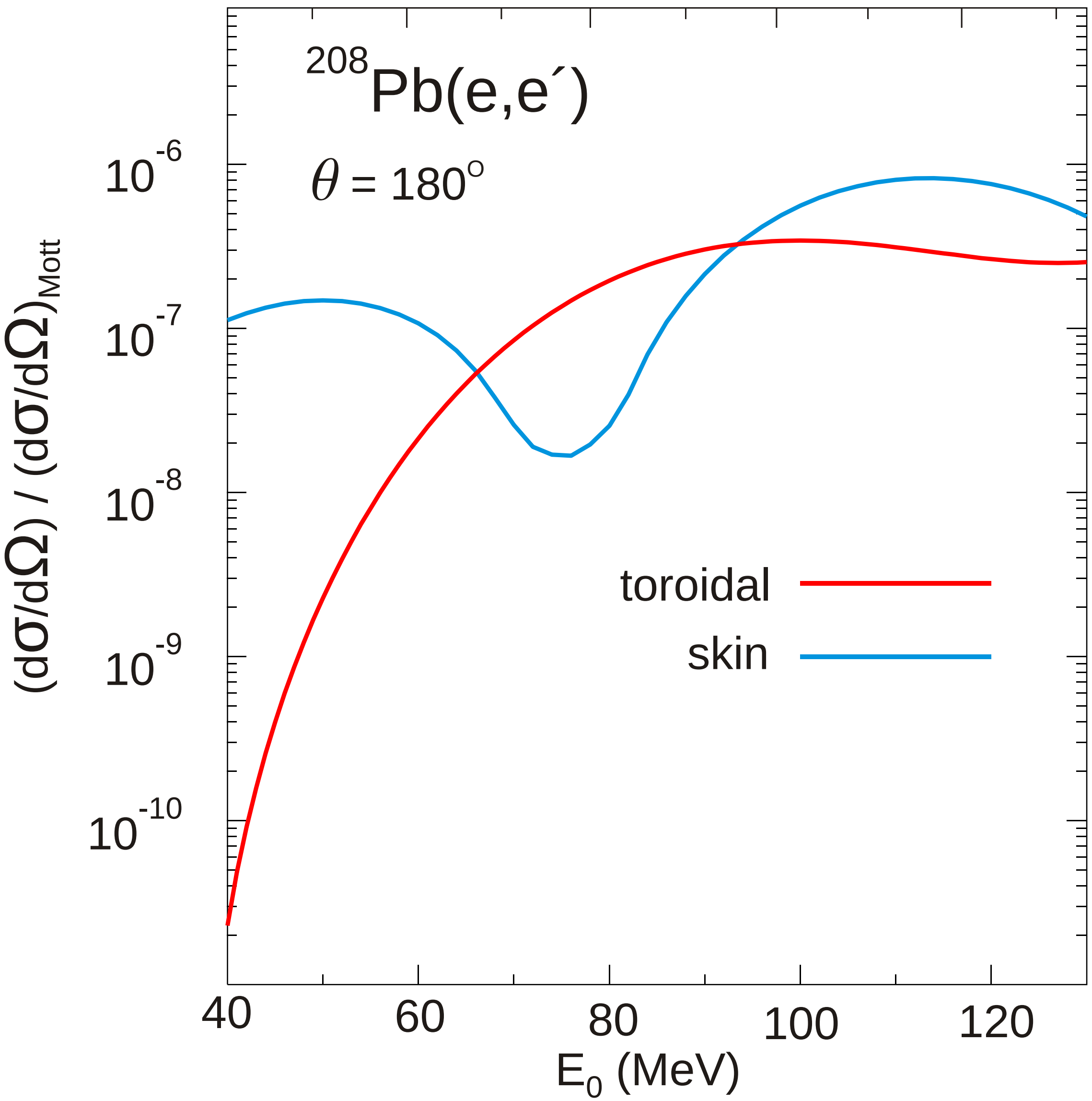


- Vorticity density: measure for the strength of the transverse current

E1 Strength vs. Vorticity

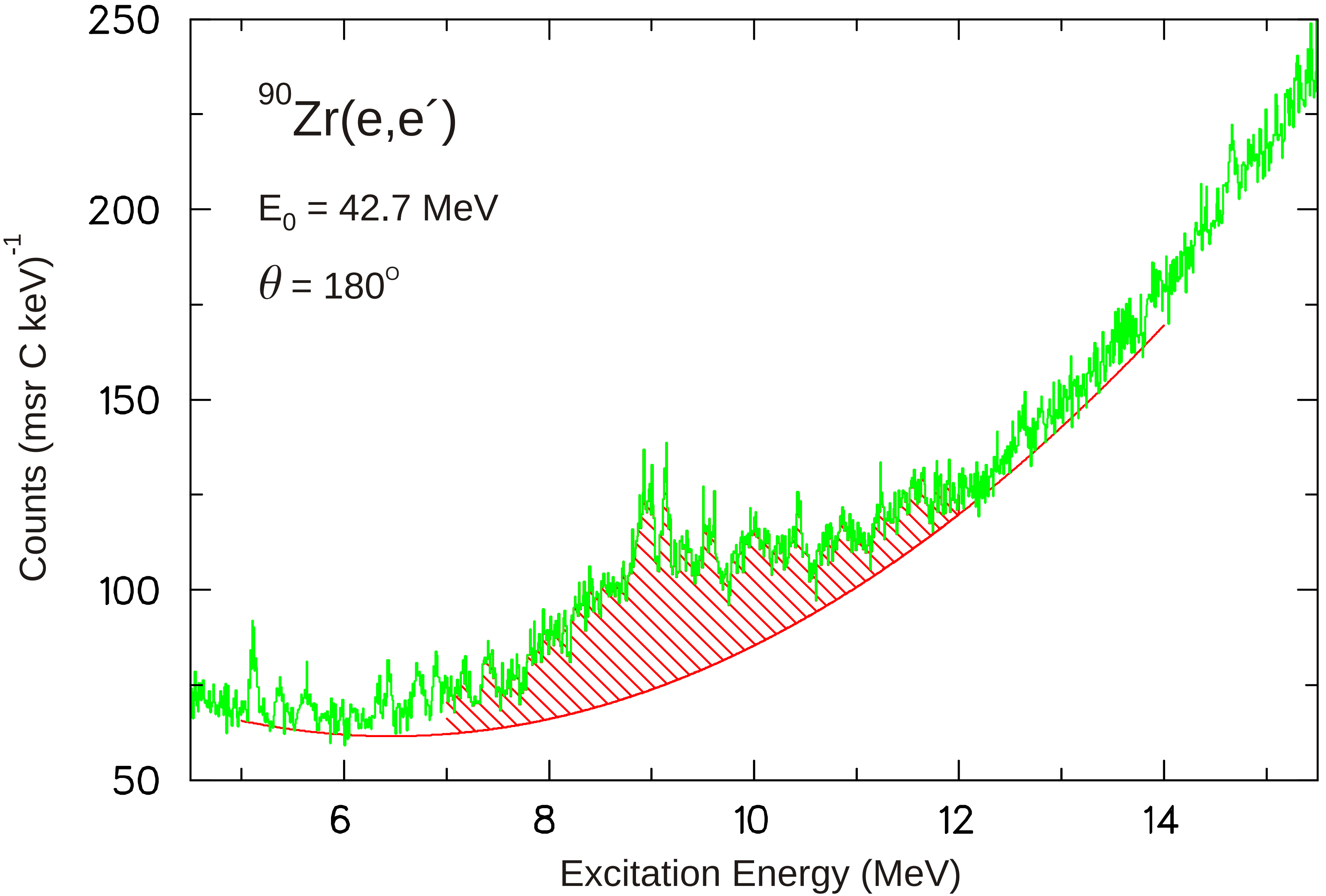


Form Factors of Toroidal and Skin Modes

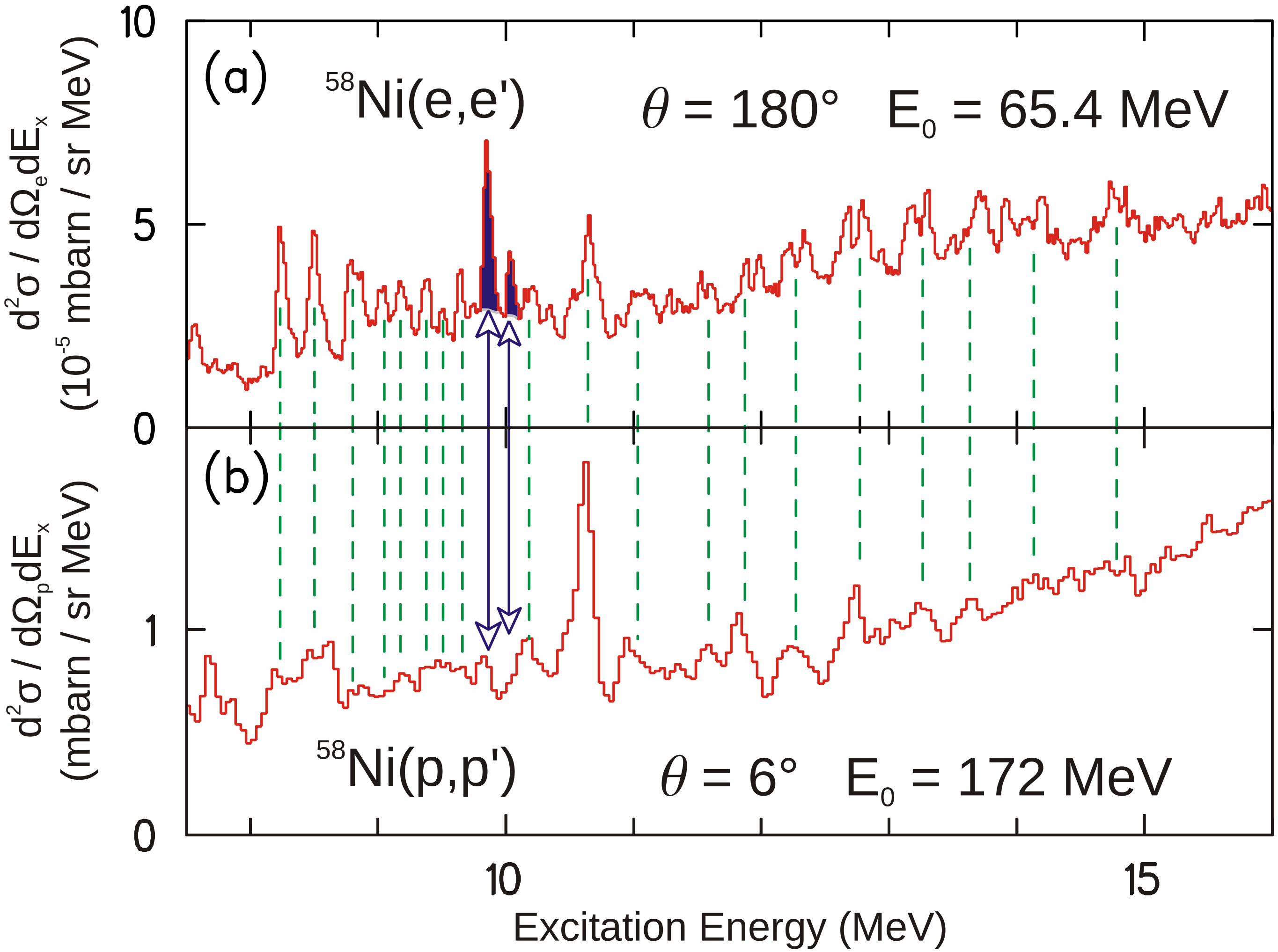


M2 and Spin Dipole Modes

180° Electron Scattering: Selectivity



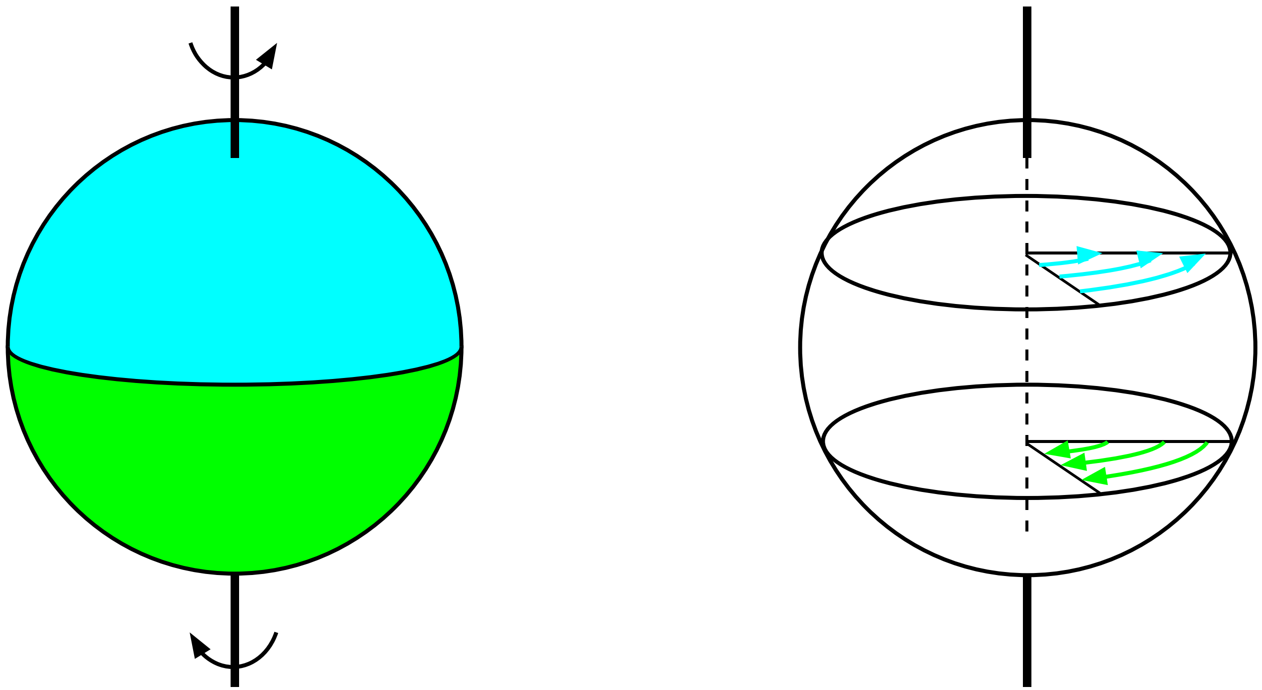
Direct Evidence for the Twist Mode



- B. Reitz et al., Phys. Lett. B 532, 179 (2002)

The $J^{\pi} = 2^{-}$ Twist Mode

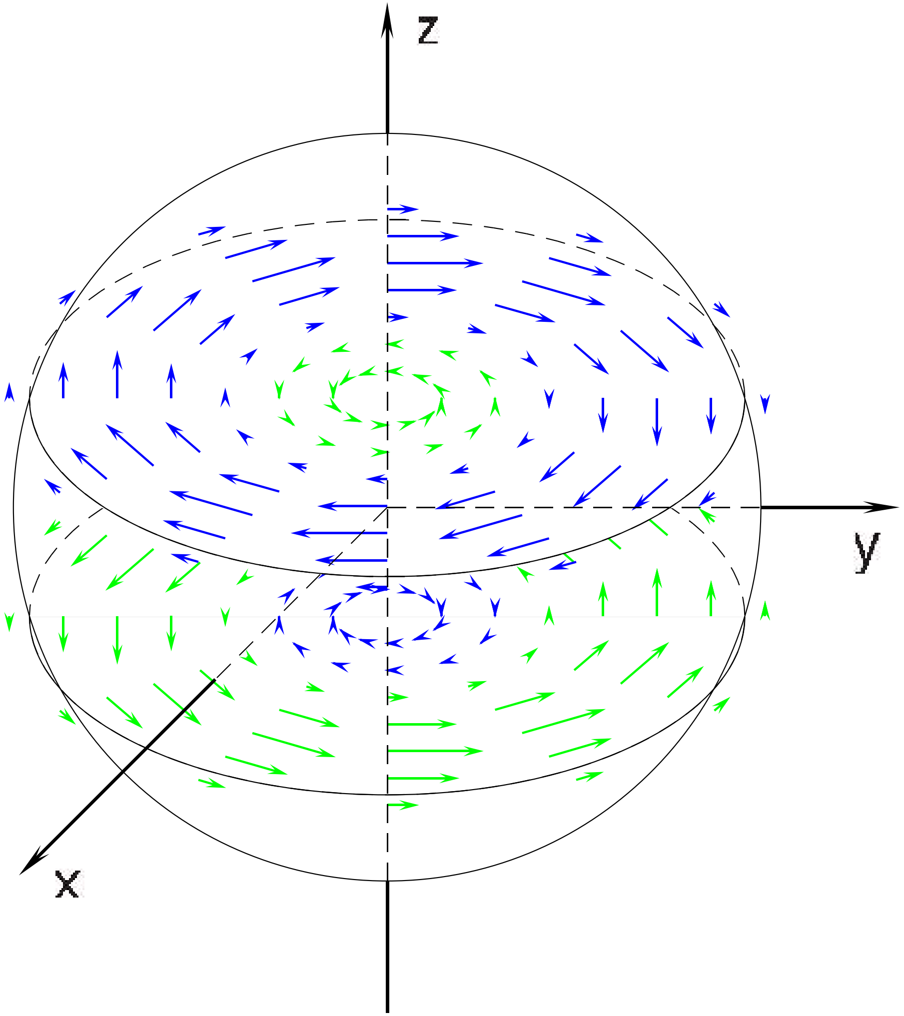
G. Holzwarth, G. Eckart, Z. Phys A283 (1977) 219.



$$\text{shear module } \mu/\rho = \begin{cases} 15.3 \text{ MeV} & \text{nuclear matter} \\ 6.3 \text{ MeV} & {}^{48}\text{Ca} \\ 7.2 \text{ MeV} & {}^{90}\text{Zr} \end{cases}$$

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

Orbital Transition Currents of the Twist Mode



- Shear module $\mu/\rho \approx 6.5$ MeV (^{58}Ni)

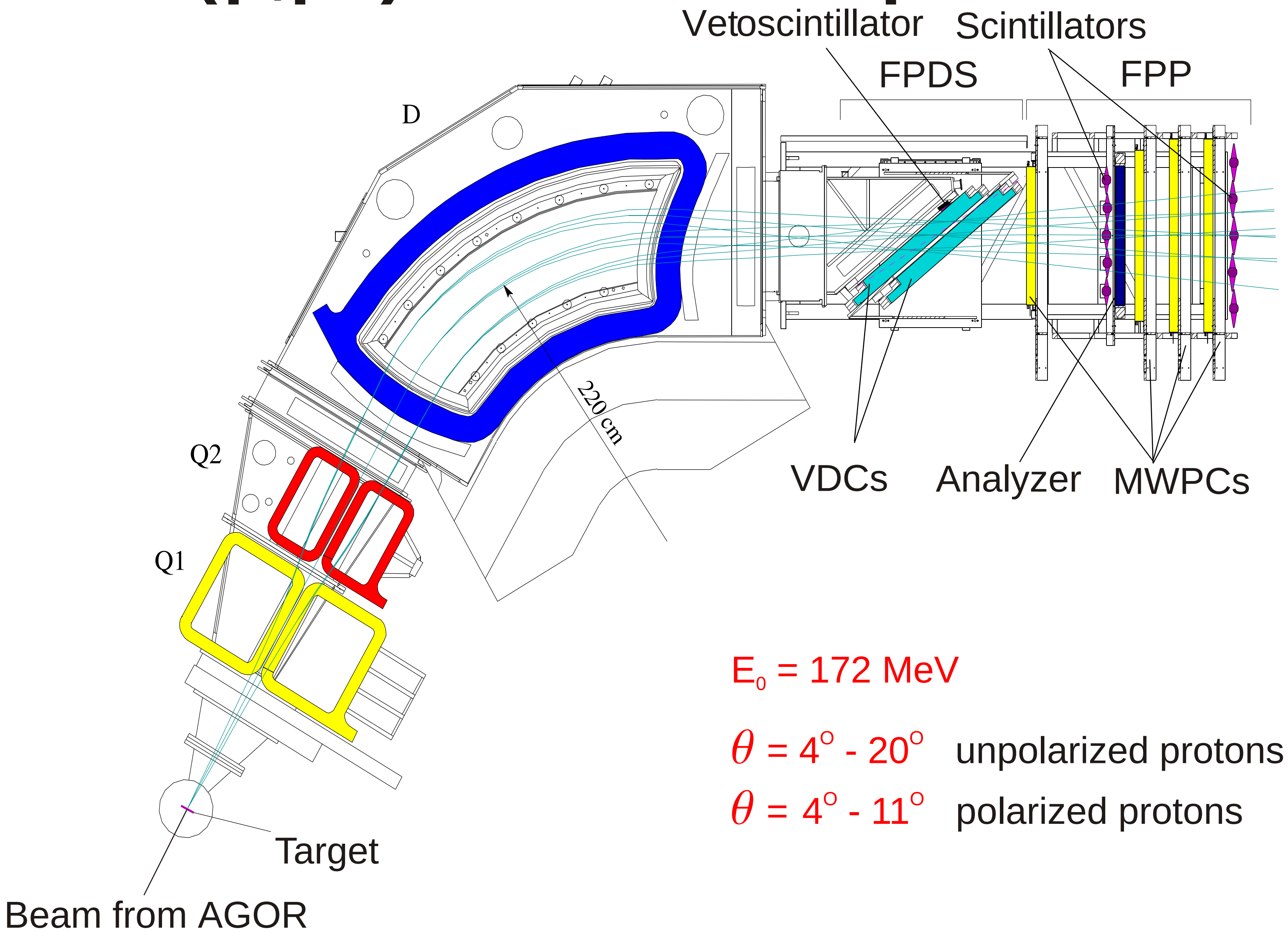
Spin Dipole Modes

- Transition operator: $r\,[\sigma \quad Y_1]_{0^-,\,1^-,\,2^-}$

  Strongest

- (p,p') and $(\vec{p},\vec{p}\,')$: ^{58}Ni as a test case
  - $d^2\sigma/d\Omega dE$
  - $S_{nn'}\, d^2\sigma/d\Omega dE$
  - $S_{nn'}$
- Comparison with model predictions
- EUROSUPERNOVA collaboration

^{58}Ni($\vec{p}$,$\vec{p}\,'$) Reaction: Experimental Setup



E_0 = 172 MeV

θ = 4° - 20° unpolarized protons

θ = 4° - 11° polarized protons

Effective NN Interaction

Model I: G-Matrix + Paris Potential ⇨ von Geramb

Model II: G-Matrix + Bonn potential ⇨ Karataglidis et al.

Model III: t-Matrix ⇨ Love and Franey

Ground State and Excited States

2p2h **Q**uasiparticle **P**honon **M**odel ⇨ Ponomarev

E0 - E5, M0 -M6 transitions up to E_x = 25 MeV

Observations

- Quality of model description of experimental observables improves for

$$d^2\sigma / d\Omega\, dE_x \rightarrow S_{nn'}\, d^2\sigma / d\Omega\, dE_x \rightarrow S_{nn'}$$

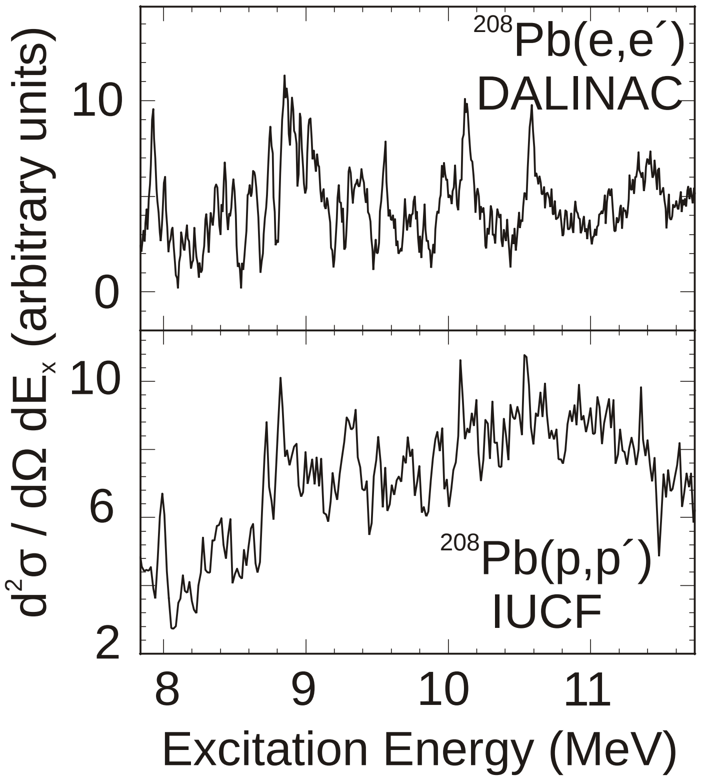
- Possible reason: reaction part - in particular the non-spin part of the continuum is not correctly described

- Nuclear structure part seems to be correct

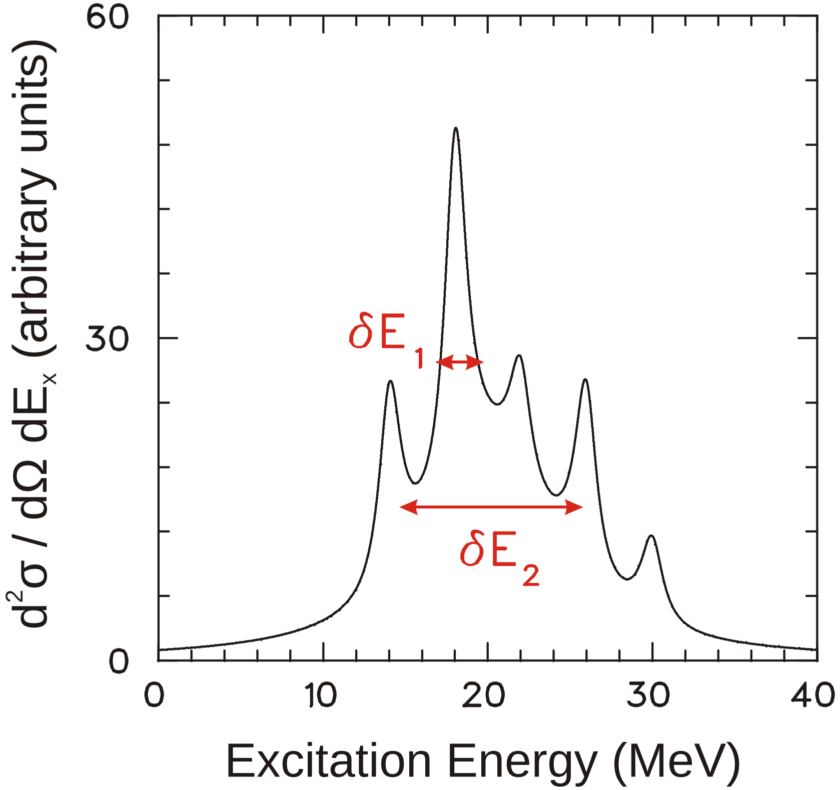
Fine Structure and Characteristic Scales

Fine Structure of Giant Resonances

Different Probes - Similar Structures



Multiple Scales of Fluctuations



Search for characteristic energy scales of fluctuations:

- Entropy Index Method
- Local Scaling Dimension: Aiba, Matsuo (1999)
- Wavelet Analysis

Entropy Index Method

D. Lacroix and P. Chomaz, Phys. Rev. C **60**, 064307 (1999)

- Spectrum ΔE divided into n bins with binwidth δE

  $(\Delta E = n\ \delta E) \implies \delta E$ sets the scales

- Define coefficient

$$D_j(\delta E) = \int_{E_{j-1}}^{E_j} dE\ \sigma(E)\,\Omega_j(E)$$

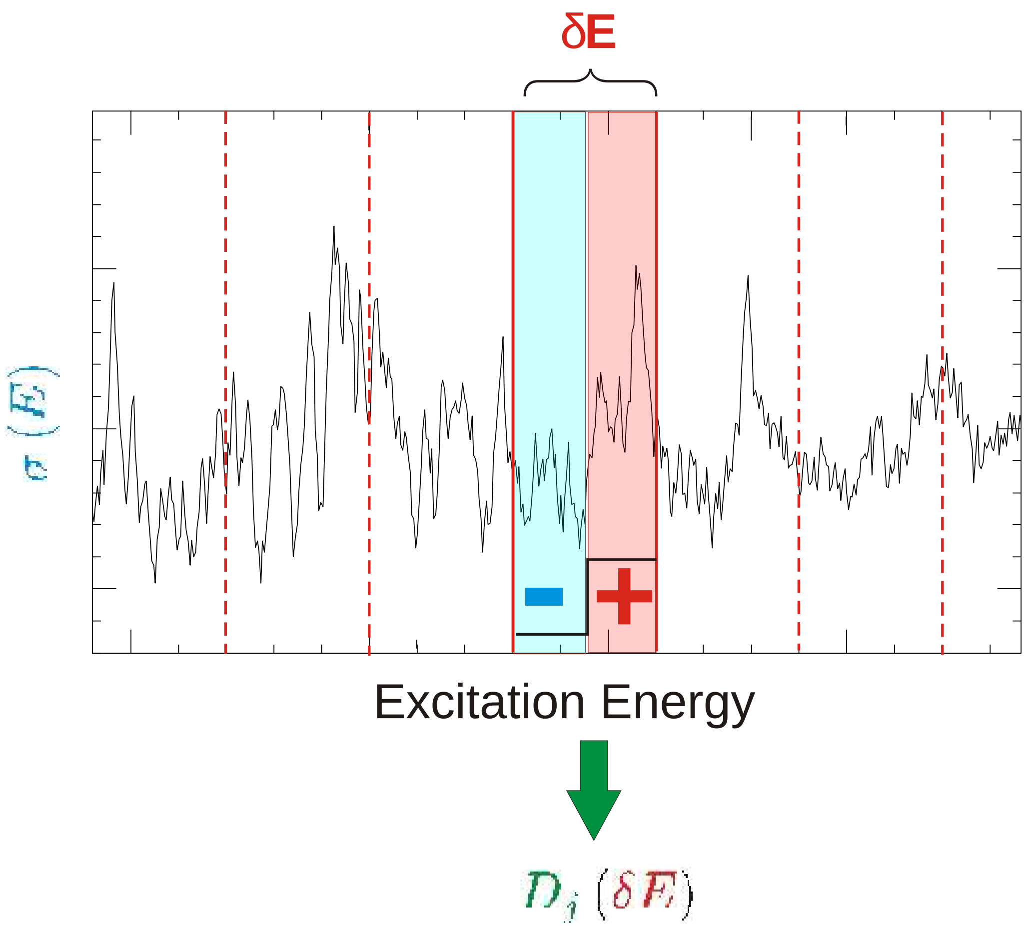
with $\Omega_j(E) = \mathrm{sign}\,(E - (j - 1/2)\,\delta E)$

(Haar Wavelet)

- Define $W_j(\delta E) = |D_j| \,/\, \langle |D_j| \rangle$

- and entropy

$$K(\delta E) = -\frac{1}{n}\sum_{j=1}^{n} W_j(\delta E)\log W_j(\delta E)$$



Entropy Index Properties

$$K(\delta E) = -\frac{1}{n}\sum_{j=1}^{n} W_j(\delta E)\log W_j(\delta E)$$

- for statistical fluctuations of D_j around the mean value

  ➡ $K(\delta E) =$ const

- for the appearence of characteristic scales

  ➡ $K(\delta E)$ varies

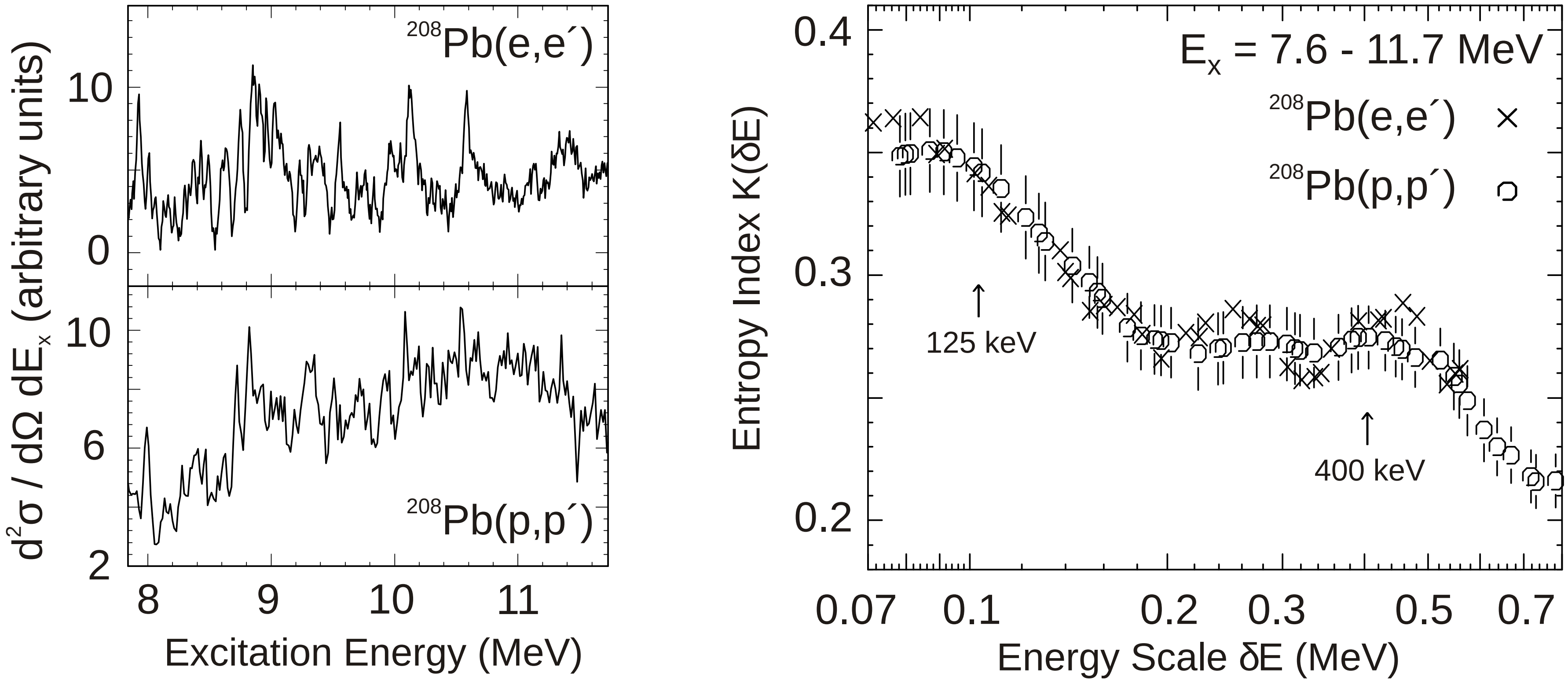
- for scales with the most complex configuration

  ➡ $K(\delta E)$ is maximal

- $K(\delta E)_{\text{np-nh}}$ > $K(\delta E)_{\text{mp-mh}}$ > .... > $K(\delta E)_{\text{1p-1h}}$ where n>m

  ➡ change of $K(\delta E)$ $\Longleftrightarrow$ onset of a new scale

Scales in (e,e') and (p,p'): The Example ^{208}Pb



- Experimental evidence for scales at 1.1 MeV, 400 keV, 125 keV
- Scales are independent of the probes
- Similar scales are found in SRPA: D. Lacroix et al., Phys. Lett. B479 (2000) 15

Scales in the Fine Structure of Giant Resonances

- Global phenomenon?
  - Other nuclei
  - Other resonances
- Is the wavelet analysis unique?
- Final goal: physics of the scales ➡ $\Gamma\uparrow$, $\Gamma\downarrow$, CRPA, ...

➡ Posters by Kalmykov et al.,
Shevchenko et al.

Recent Experiments

Place: iThemba LABS in South Africa

Reaction: (p,p´)

Targets: ${}^{208}_{82}\mathrm{Pb}_{126}$ ${}^{120}_{50}\mathrm{Sn}_{70}$ ${}^{90}_{40}\mathrm{Zr}_{50}$ ${}^{89}_{39}\mathrm{Y}_{50}$ ${}^{58}_{28}\mathrm{Ni}_{30}$

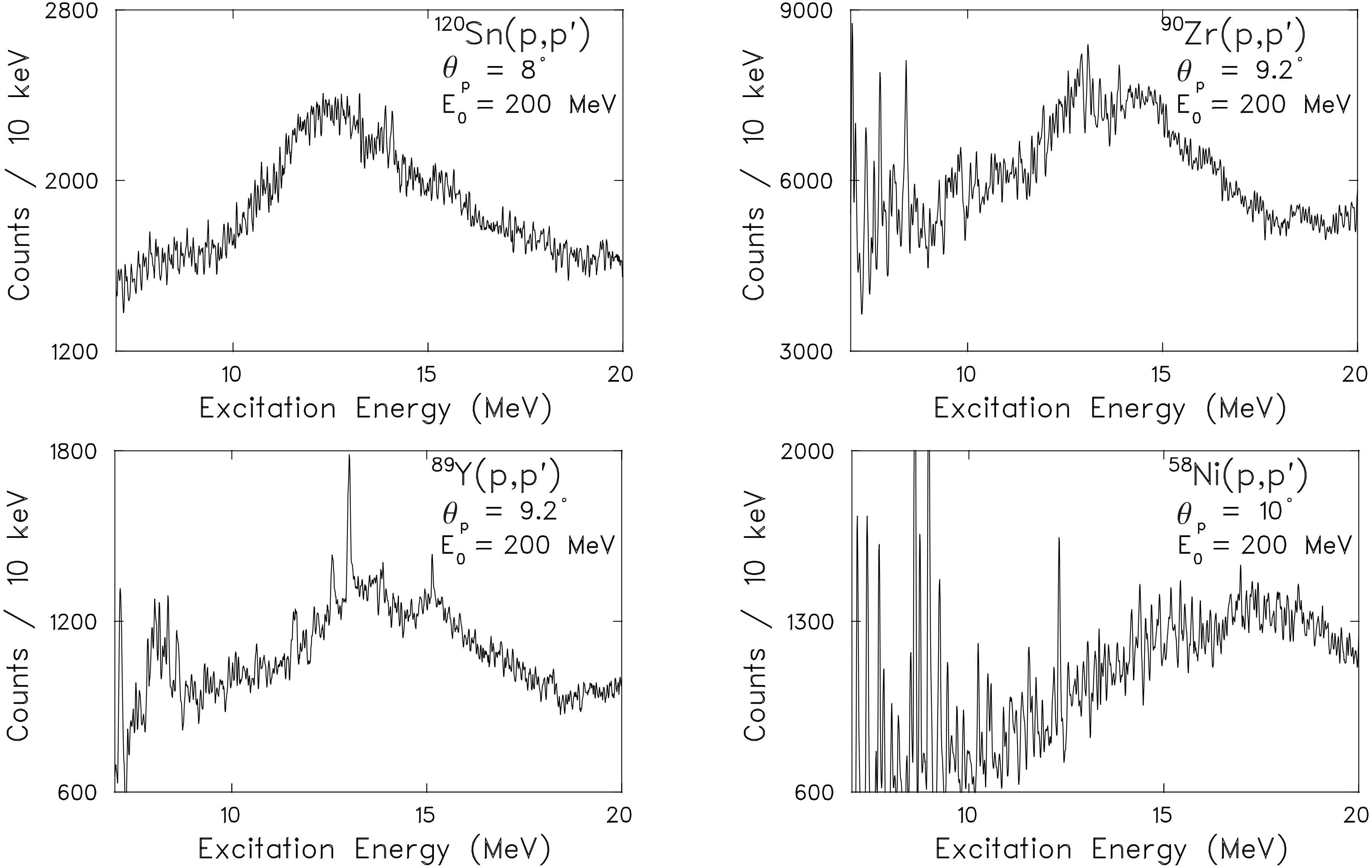
Beam Energy: E_0 = 200 MeV

Excitation Energy Range: E_x = 0 - 23 MeV

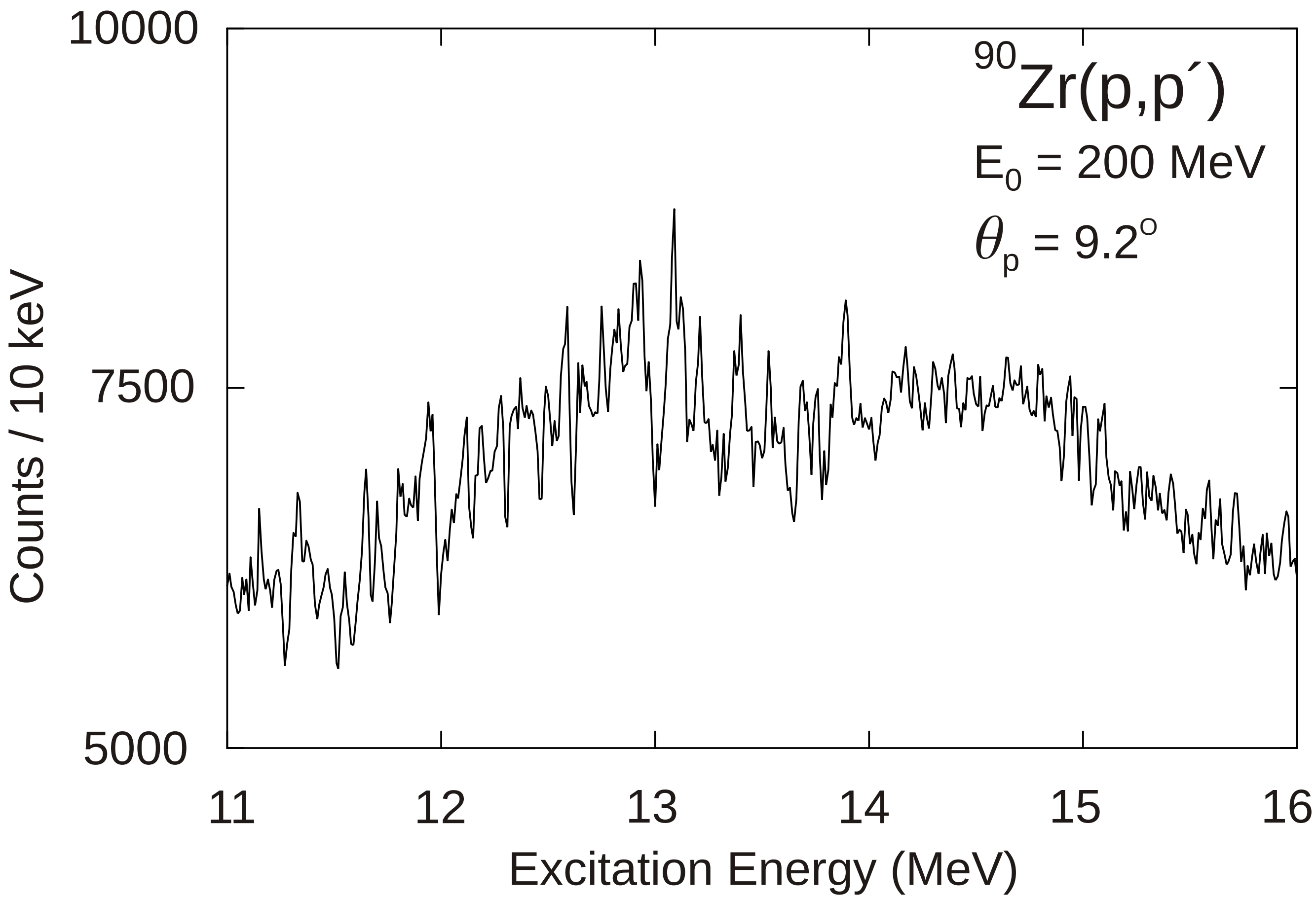
Energy Resolution (FWHM): ΔE = 35 - 50 keV

Scattering Angles: 8^o - 10^o
(close to maximum of ΔL=2 transitions)
6^o - 14^o
(check contributions of different multipoles)

Fine Structure of the ISGQR: A Global Phenomenon?

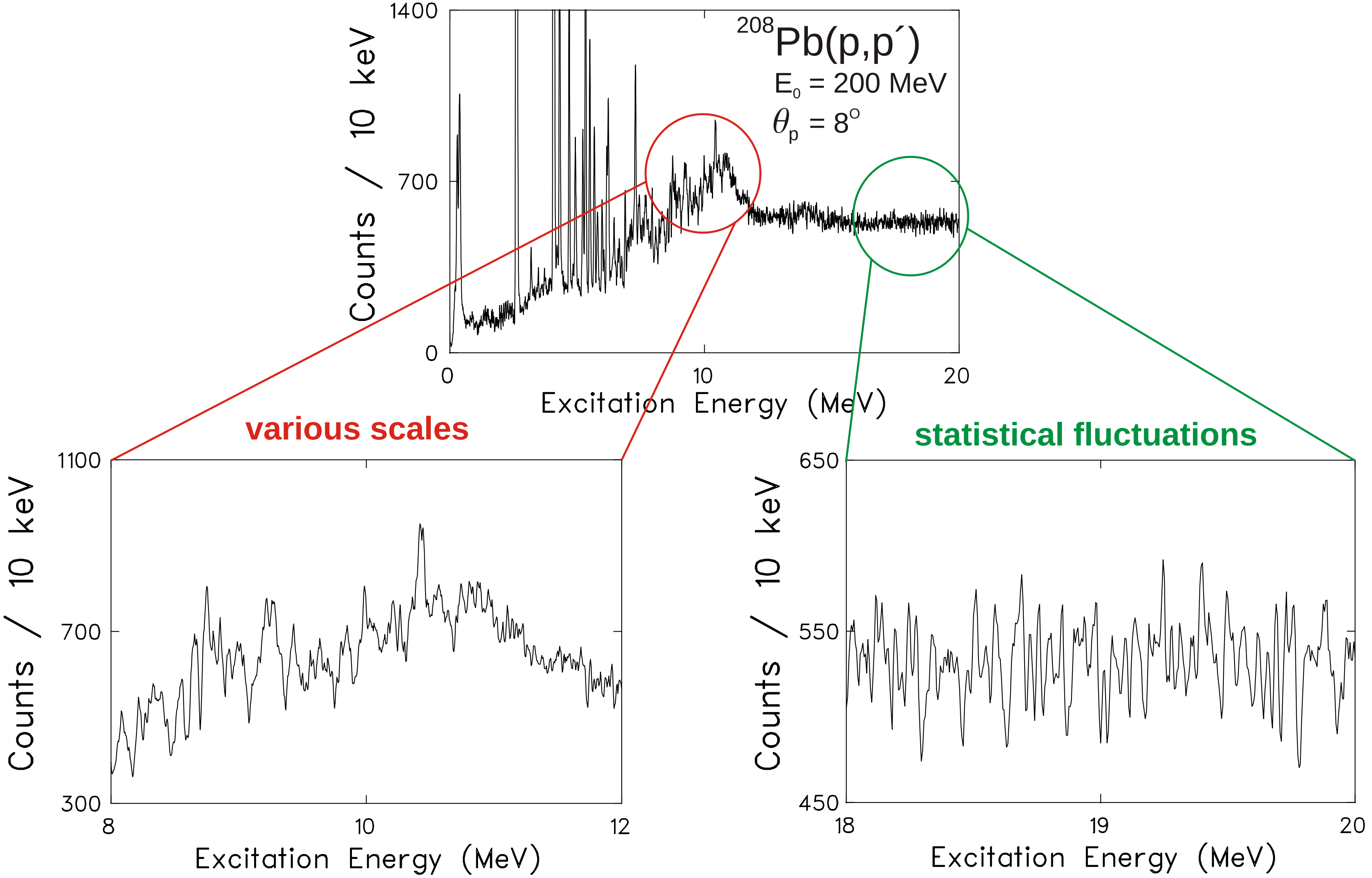


Details of the Fine Structure



- Not a Lorentzian
- Fluctuations of different strength and scales

Scales and Fluctuations

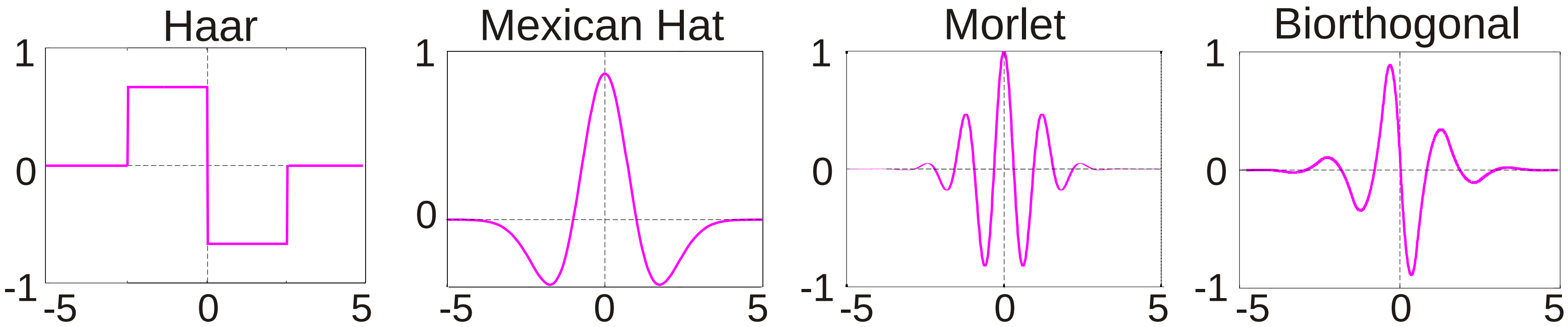


Wavelet Analysis

- Entropy Index Method is limited
  - ⇨ no information on localization of scales
  - ⇨ no reconstruction of original spectrum possible
- Another possibility: **D**iscrete **W**avelet **T**ransform from signal processing

Discrete Wavelet Analysis

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

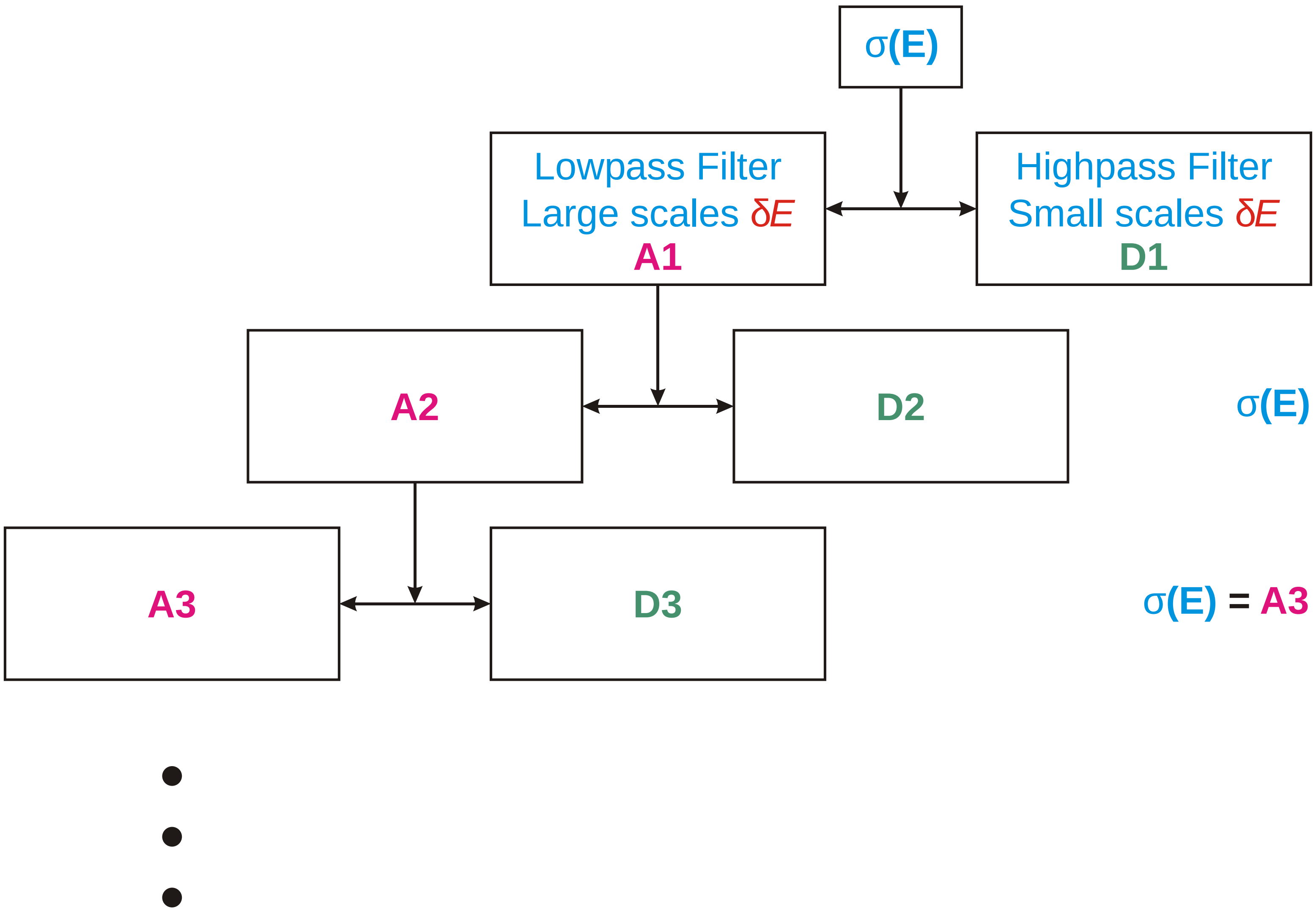


Wavelet Coefficients: $$C(\delta E, E_x) = \frac{1}{\sqrt{\delta E}} \int \sigma(E)\, \Psi^*\left(\frac{E_x - E}{\delta E}\right) dE$$

scale position spectrum wavelet

Steps: $\delta E = 2^j$ with j = 1, 2, 3, ... and $E_x = \delta E$

Decomposition



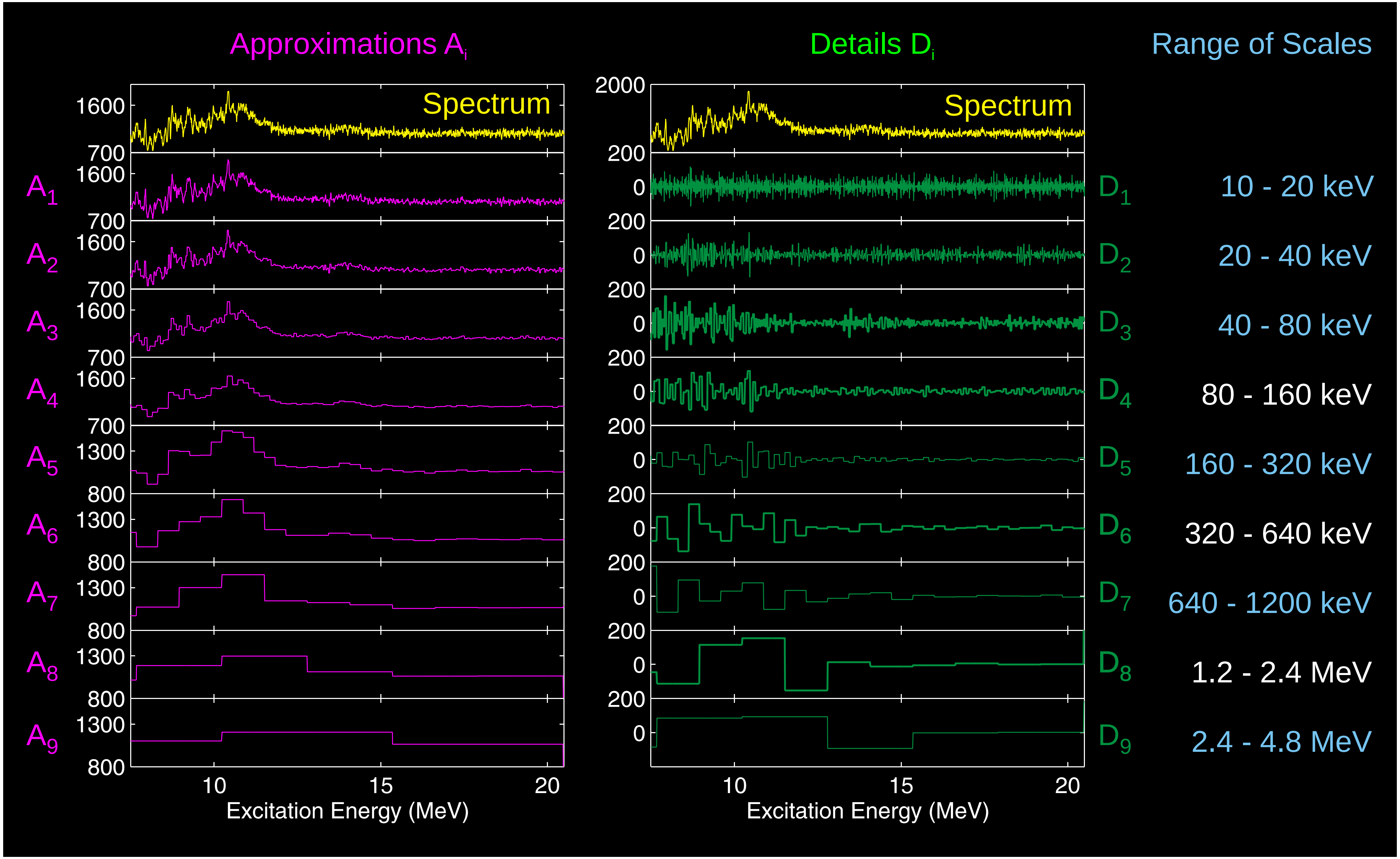
$\sigma(E) = A1 + D1$

$\sigma(E) = A2 + D2 + D1$

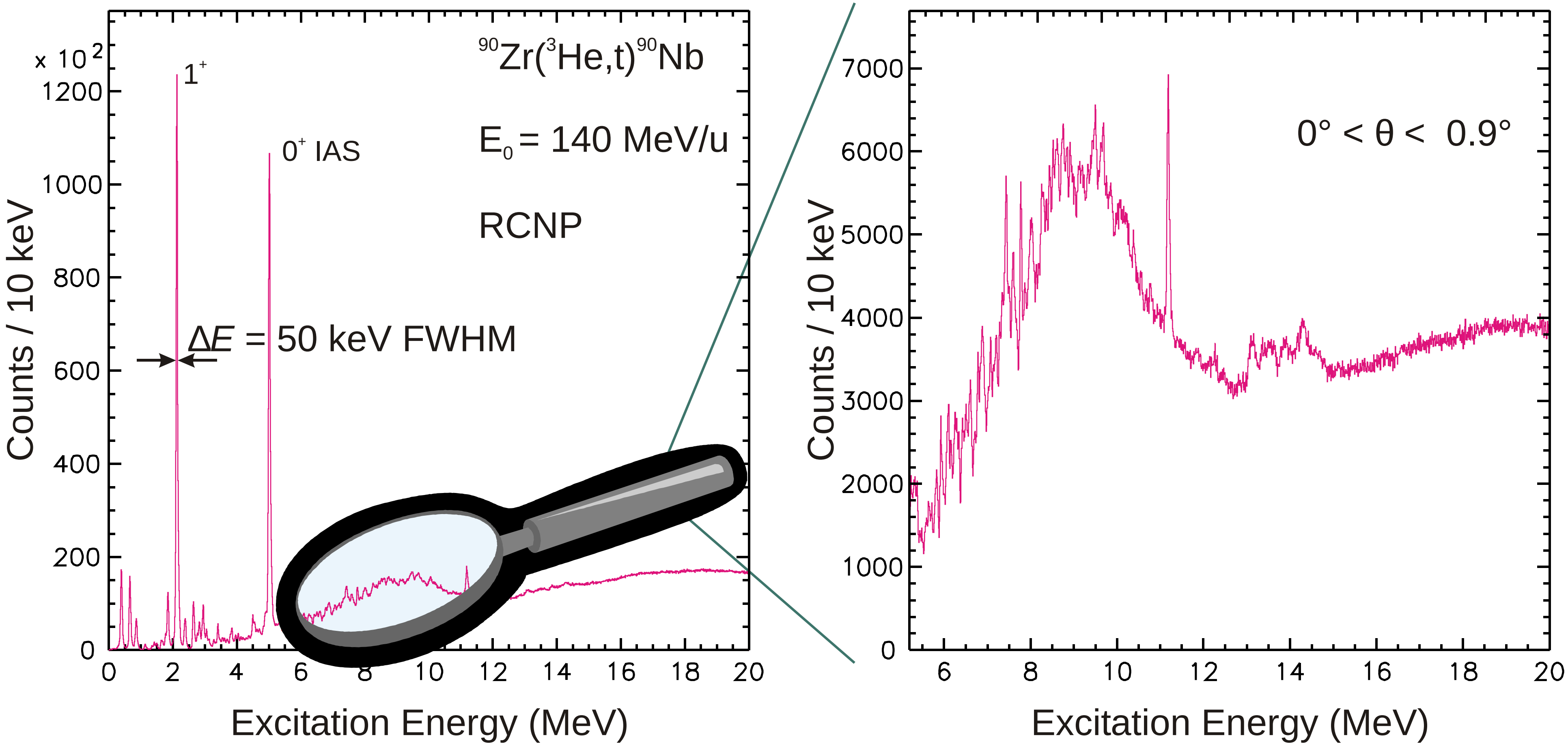
$\sigma(E) = A3 + D3 + D2 + D1$

$\vdots$

Decomposition of $^{208}Pb(p,p')$ Spectrum

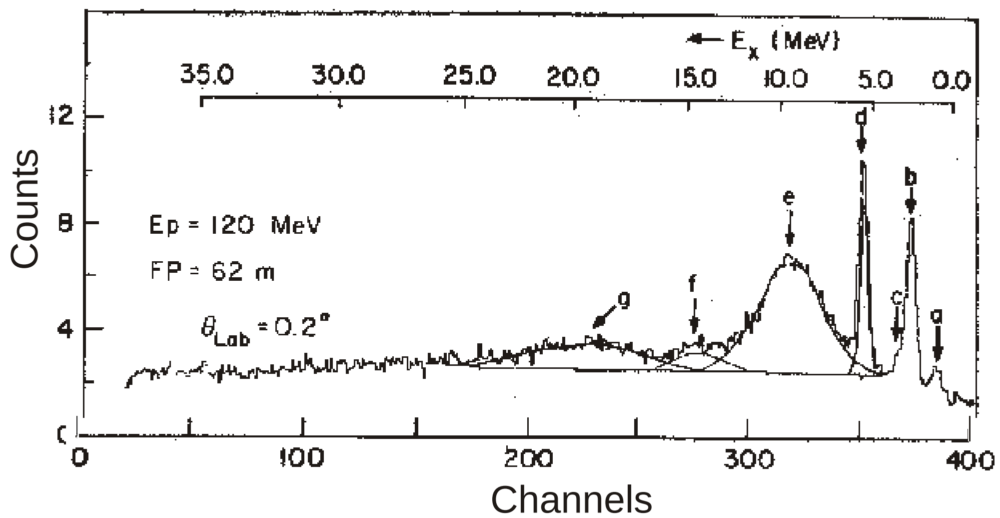


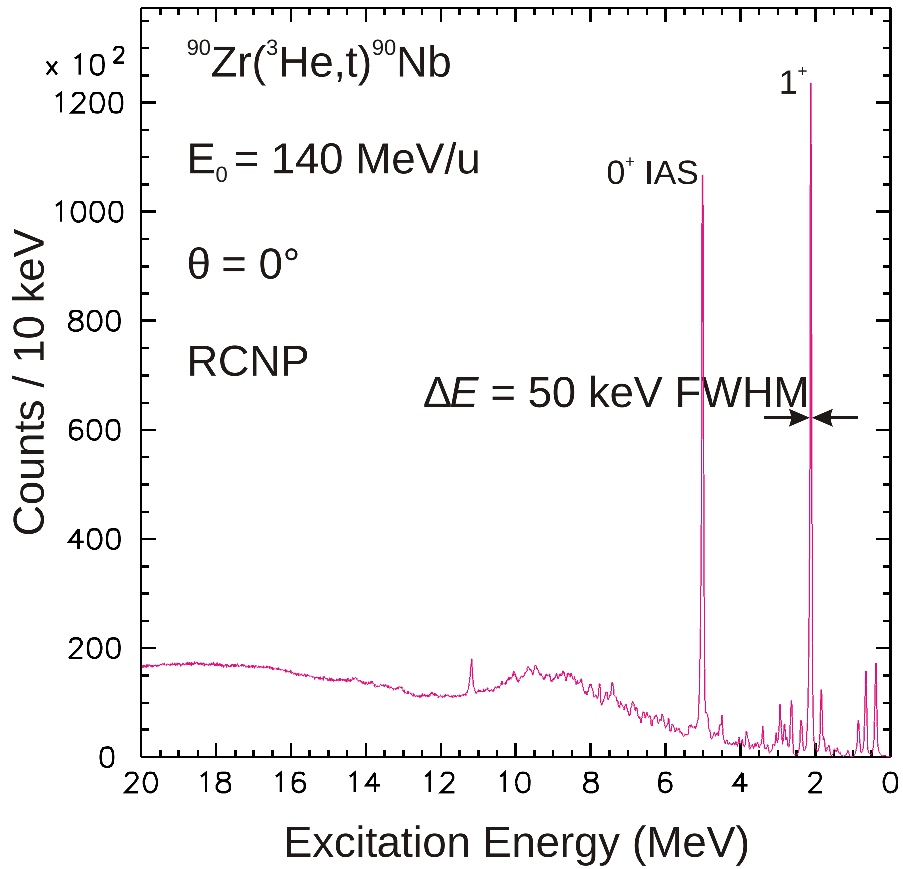
Fine Structure of the Spin-Flip GTR



Fine Structure of the Spin-Flip GTR

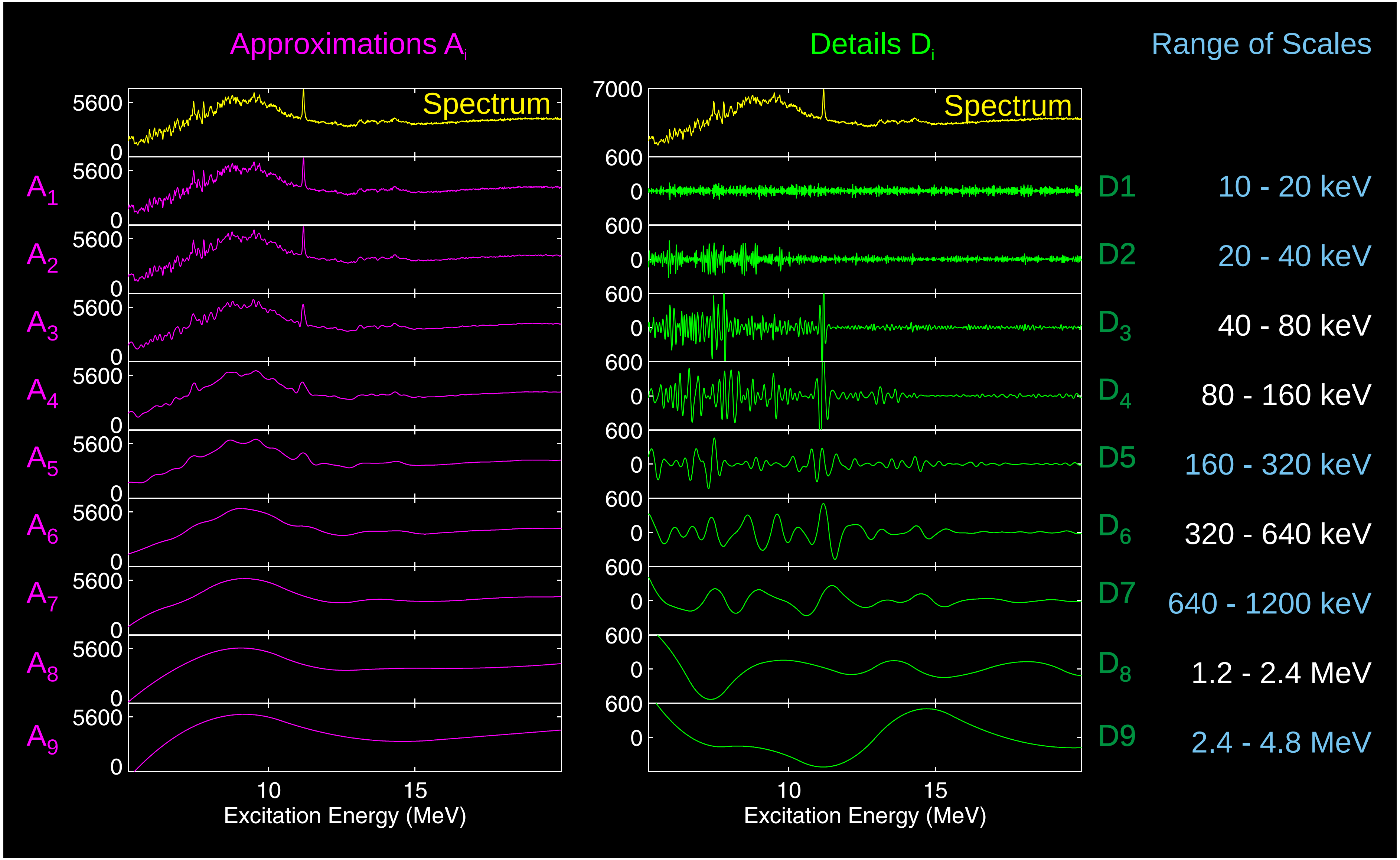
^{90}Zr(p,n)^{90}Nb D. Bainum et al., Phys. Rev. Lett., **44** (1980) 1751



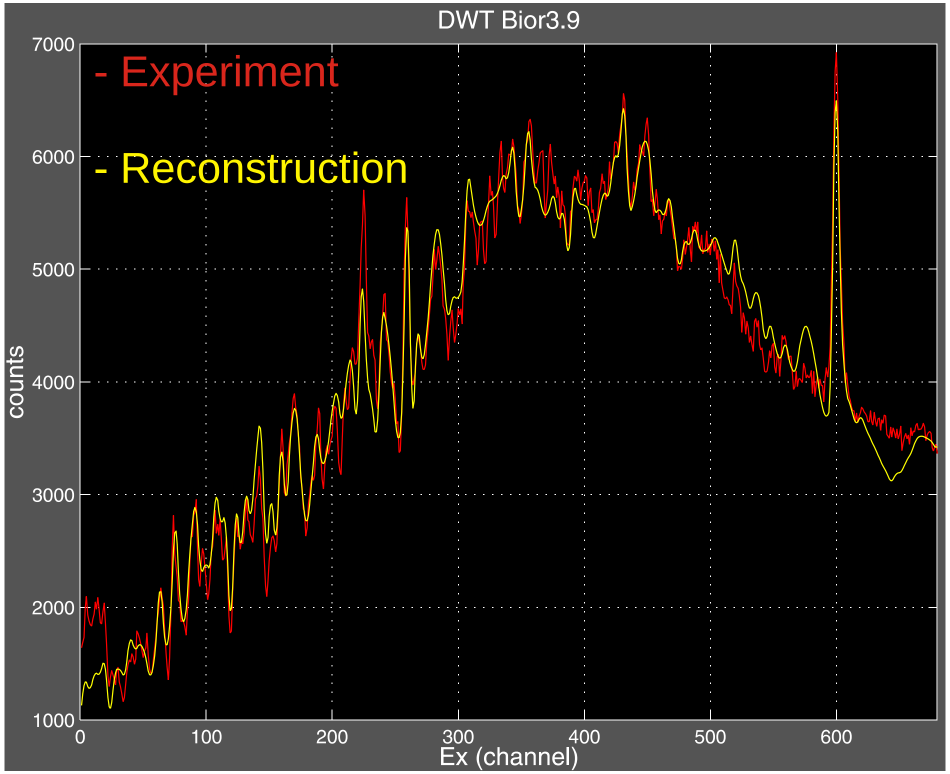


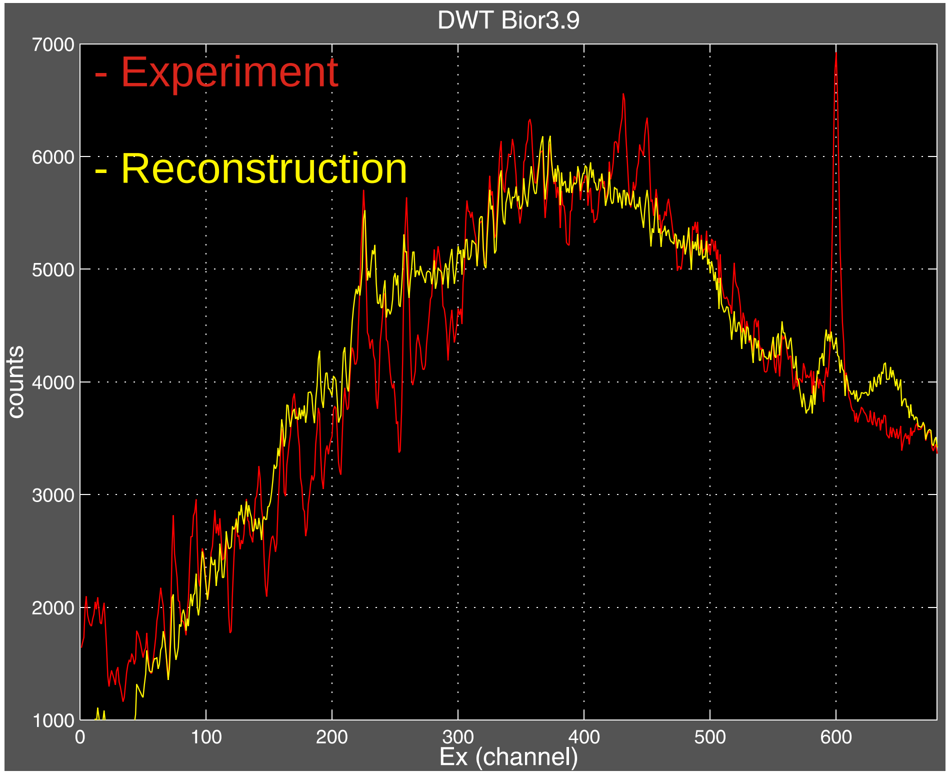
- observed for the first time
- scales $\rightarrow$ $\Gamma\downarrow$ vs. $\Gamma\uparrow$ and comparison with electric GR's
- selectivity: $J^\pi = 1^+$ $\rightarrow$ level density

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



Discrete Wavelet Transform: Reconstructed Spectra





$\sigma_r(E)$ = A8 + D8 + D6 + D4 + D3

$\sigma_r(E)$ = A8 + D7 + D5 + D2 + D1

Conclusion

- PDR:
  - ➔ neutron surface density oscillations
  - ➔ toroidal (current) mode might be present
- M2 and Spin Dipole Modes:
  - ➔ direct evidence for twist mode
  - ➔ extraction of spin dipole strength from proton scattering
  - ➔ comparison with model predictions
- Fine structure of GR's and characteristic scales:
  - ➔ fine structure is a global phenomenon
  - ➔ preliminary results of fast wavelet analysis are encouraging

Photon Scattering
(Nuclear Resonance Fluorescence)