

V



Elementary Quadrupole Modes in High-Resolution Electron and Proton Scattering and Configuration Mixing*

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First Part: Low-Energy Quadrupole Vibrations

- Quadrupole phonons as building blocks of low-energy structure
- High-resolution electron and proton scattering
- The case of ^{94}Mo
 - symmetric and mixed-symmetric phonons
 - purity of two-phonon states



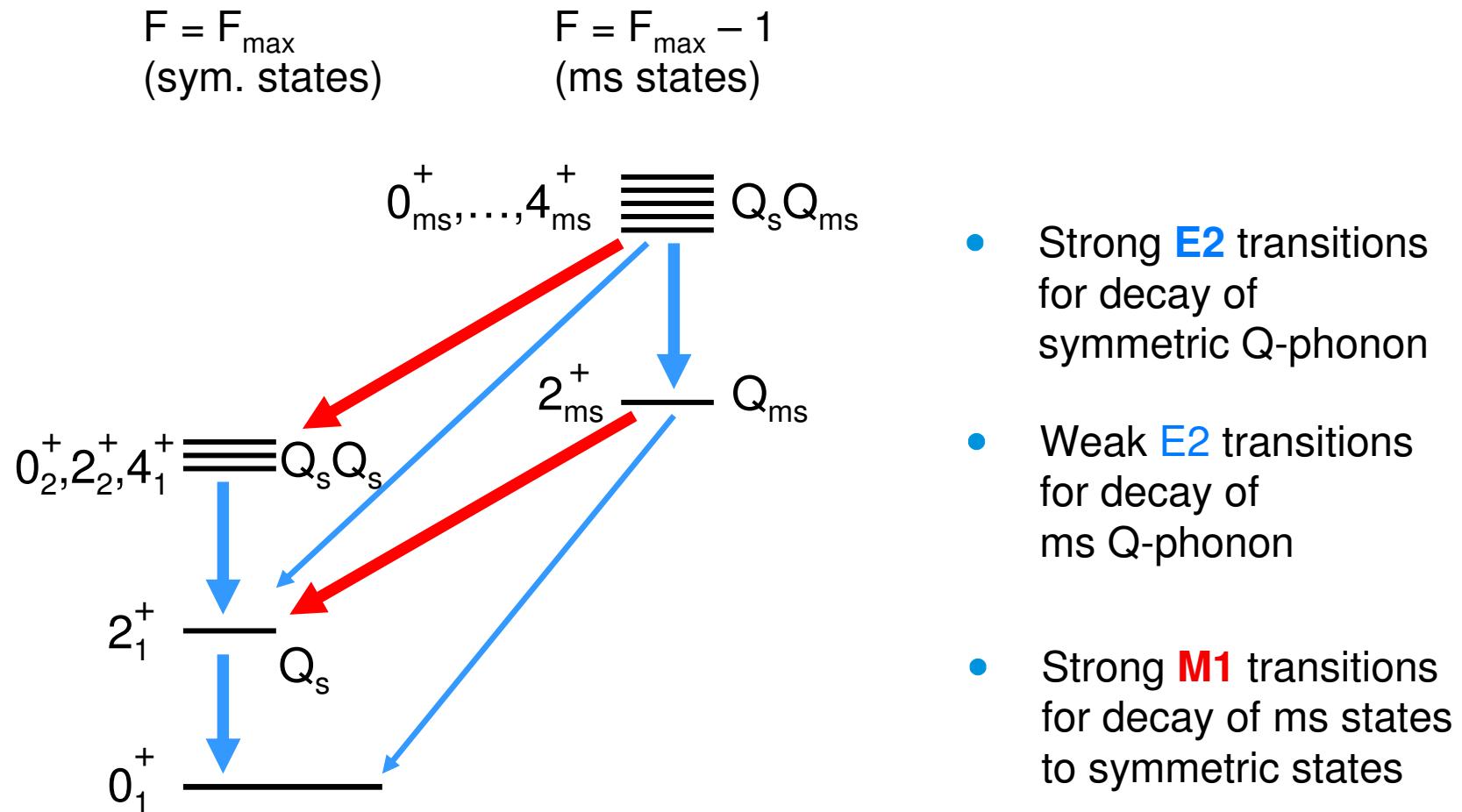
- Pairing of nucleons to s- / d-bosons
- F-Spin: π boson: $F_0 = 1/2$ $\frac{|N_\pi - N_\nu|}{2} \leq F \leq F_{\max} = \frac{N_\pi + N_\nu}{2}$
 ν boson: $F_0 = -1/2$
- $F = F_{\max}$: symmetric states
- $F < F_{\max}$: mixed-symmetry states (ms)
- Q-phonon scheme:

$$Q_s = Q_\pi + Q_\nu \quad |2_1^+\rangle \propto Q_s |0_1^+\rangle$$

$$Q_{ms} = \frac{N}{2} \left(\frac{Q_p}{N_\pi} - \frac{Q_\nu}{N_\nu} \right) \quad |2_{ms}^+\rangle \propto Q_{ms} |0_1^+\rangle$$



Identification of Mixed-Symmetry States: Q-Phonon Scheme





Why ^{94}Mo ?

- The low-energy spectrum of ^{94}Mo is well studied and most one- and two-phonon states have been identified
 - N.Pietrella et al, Phys. Rev. Lett. 83 (1999) 1303
 - N.Pietrella et al, Phys. Rev. Lett. 84 (2000) 3775
 - C.Fransen et al, Phys. Lett. B 508 (2001) 219
 - C.Fransen et al, Phys. Rev. C 67 (2003) 024307
- Structure of basic phonons
- Purity of two-phonon states
- Study of 2^+ states with (e,e') and (p,p')
 - isoscalar / isovector decomposition
 - sensitive to one-phonon components of the wave function

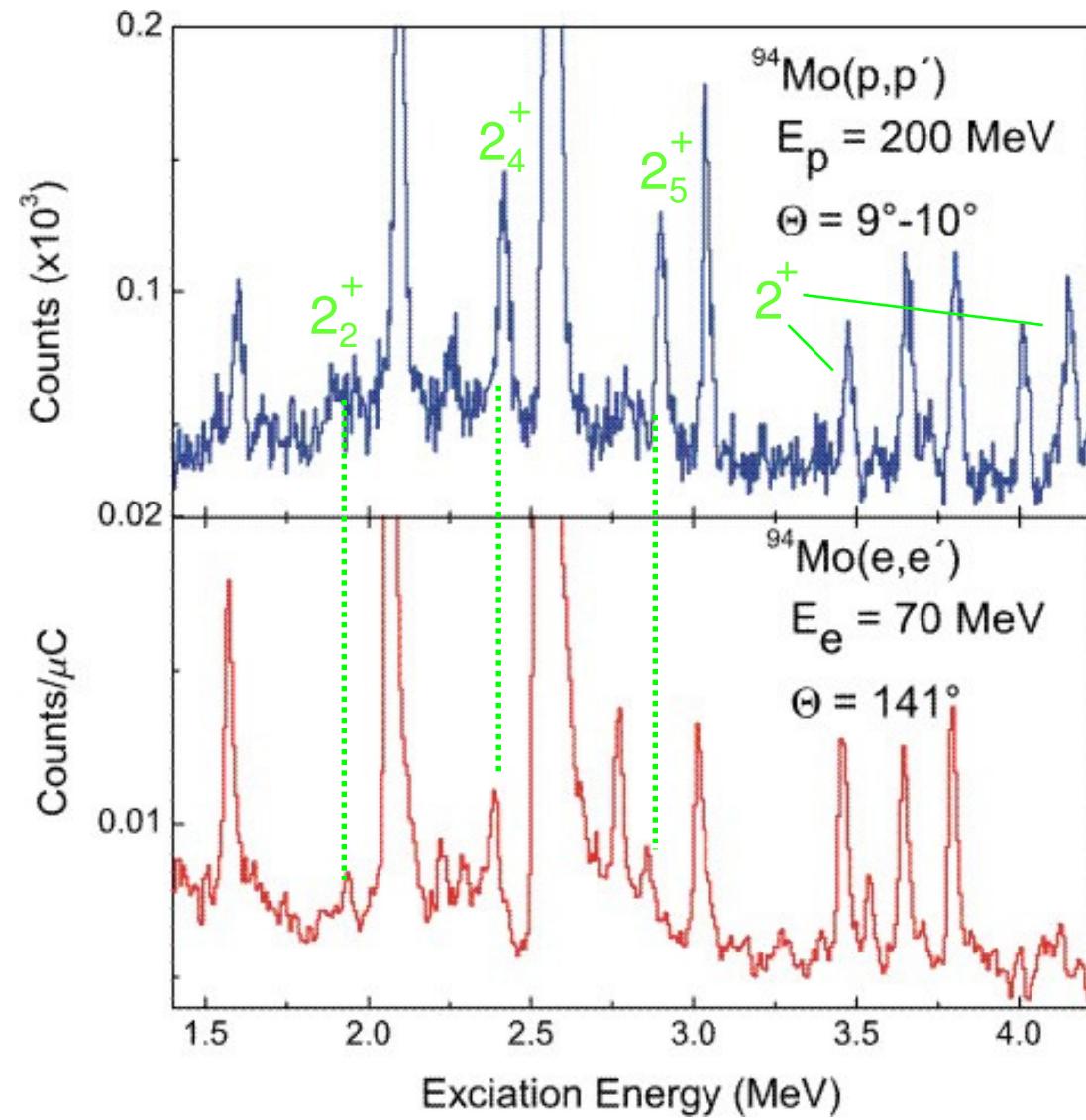


Identification of Mixed-Symmetry States: Experiments

- High resolution required to resolve all 2^+ states below 4 MeV
- Lateral dispersion matching techniques
- (e, e') :
S-DALINAC, TU Darmstadt
 - $E_e = 70 \text{ MeV}$
 - $\Theta = 93^\circ - 165^\circ$
 - $\Delta E = 30 \text{ keV (FWHM)}$
- (p, p') :
SSC, iThemba LABS
 - $E_p = 200 \text{ MeV}$
 - $\Theta = 7^\circ - 26^\circ$
 - $\Delta E = 35 \text{ keV (FWHM)}$



Measured Spectra





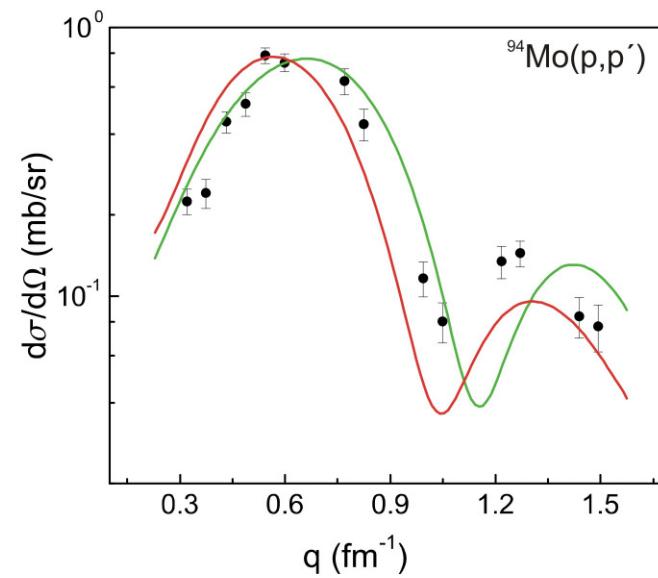
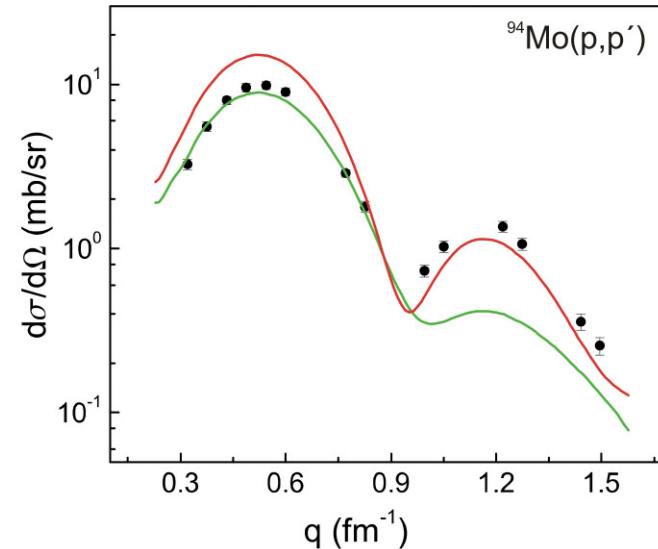
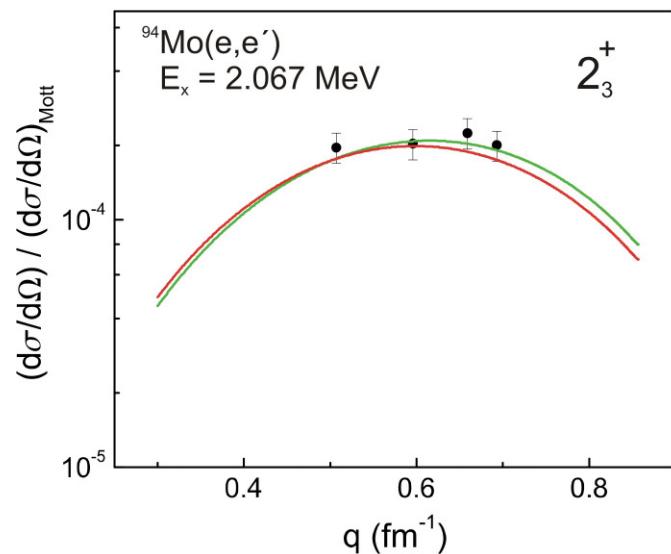
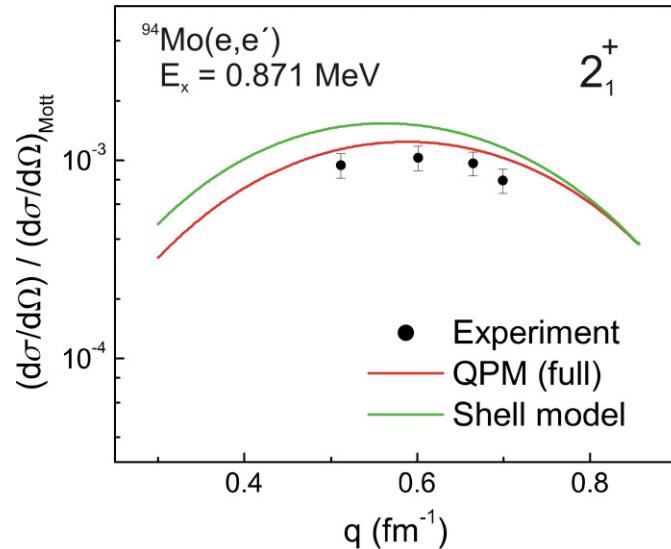
Theoretical Calculation of Cross Sections

Wave functions:

- Quasi-Particle Phonon Model (QPM)
 - pure one- and two-phonon states
 - full (up to 3 phonons)
- Shell Model
 - ^{88}Sr core
 - Surface Delta Interaction (SDI)
- Cross sections
 - DWBA treatment
 - Effective nucleon-target interaction
(Paris, Love-Franey)

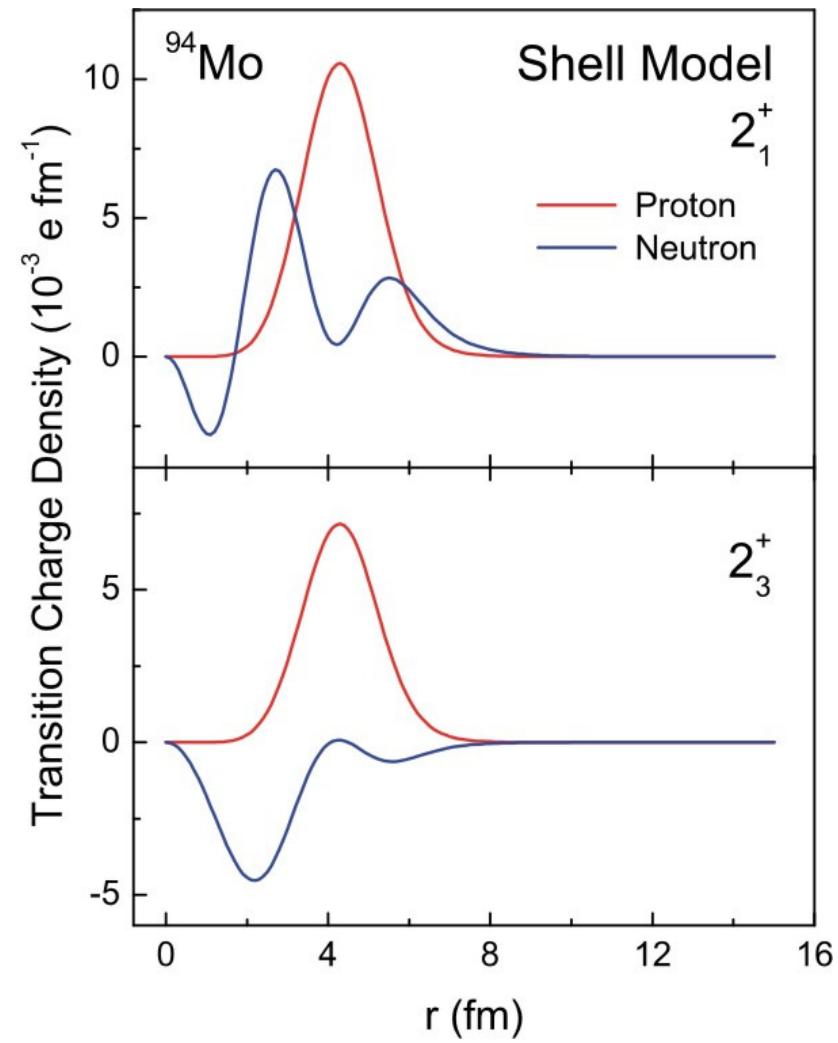
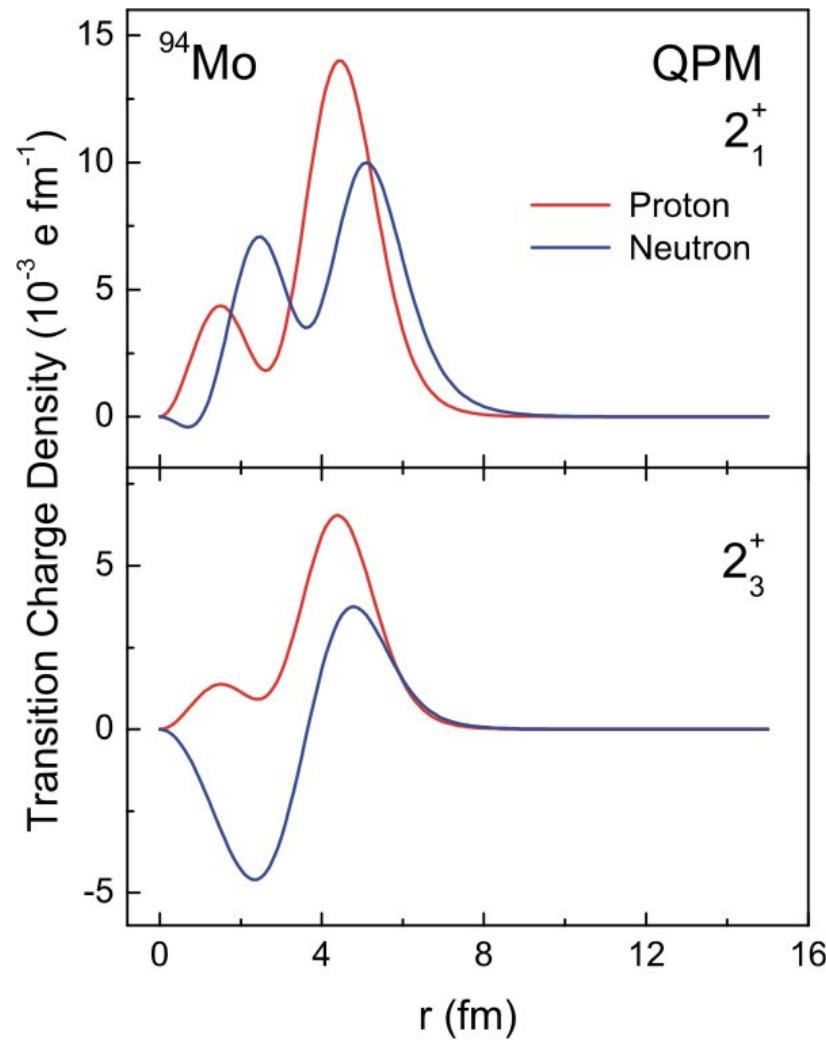


One-Phonon Symmetric and Mixed-Symmetric States



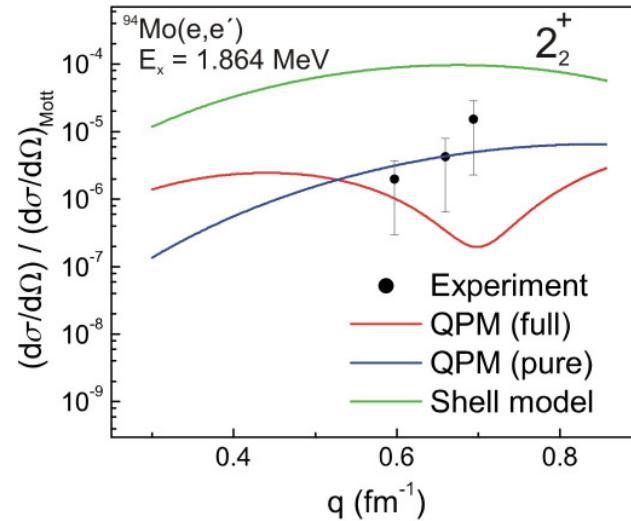


Radial Transition Charge Densities

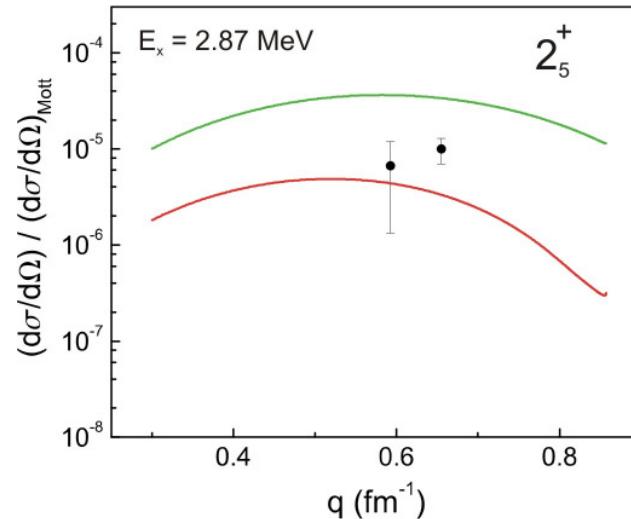




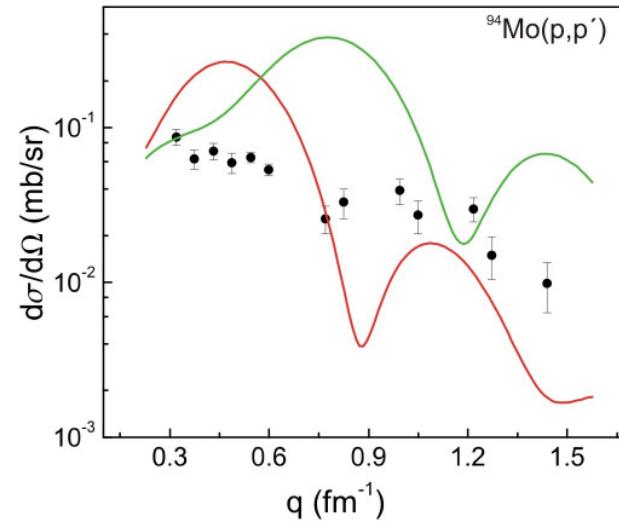
Two-Phonon Symmetric and Mixed-Symmetric States



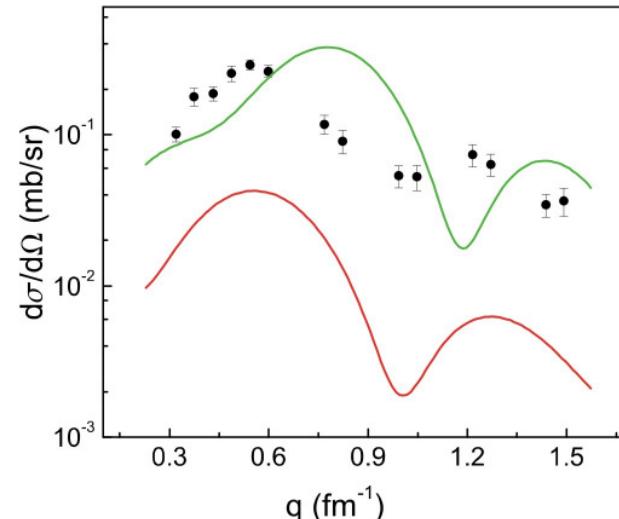
- pure two-phonon state



- 5 – 10 % one-phonon admixture



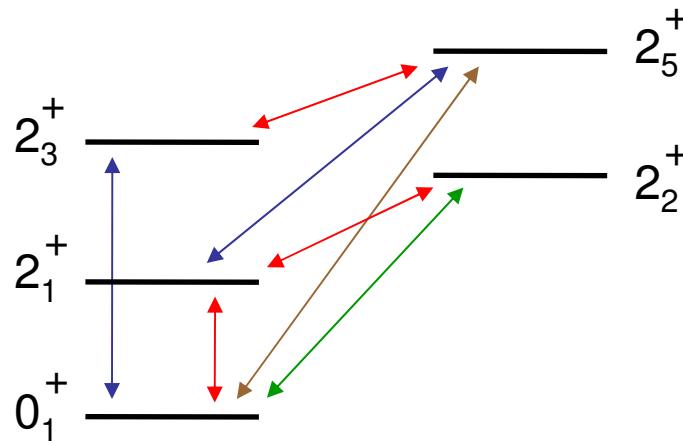
- two-step contributions?



- two-step contributions?



Coupled-Channel Analysis



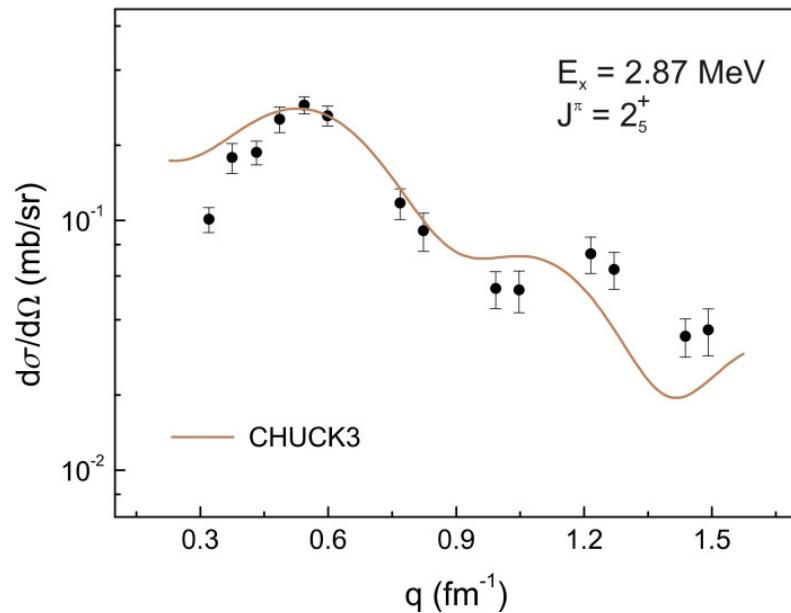
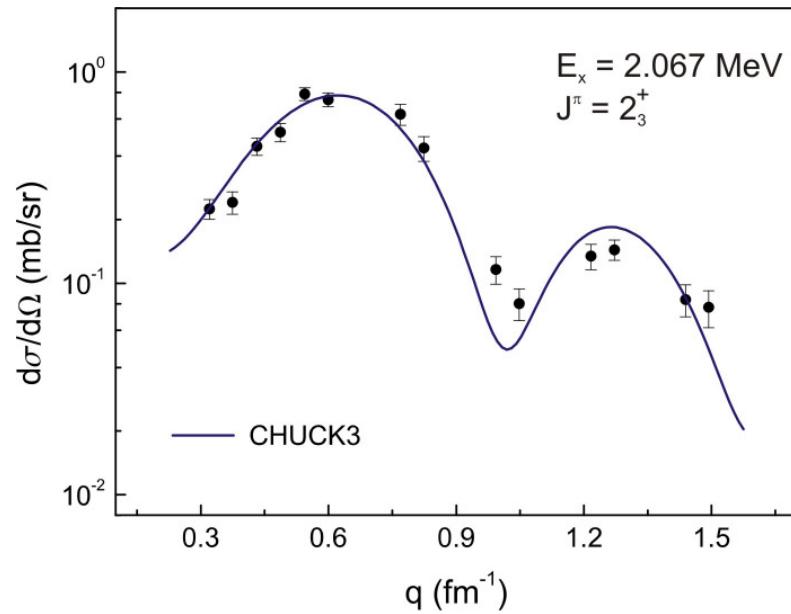
$$\beta = 1.23$$

$$\beta = 0.0$$

$$\beta = 0.35$$

$$\beta = 0.2$$

- admixtures of non-symmetric state confirmed





Summary: First Part

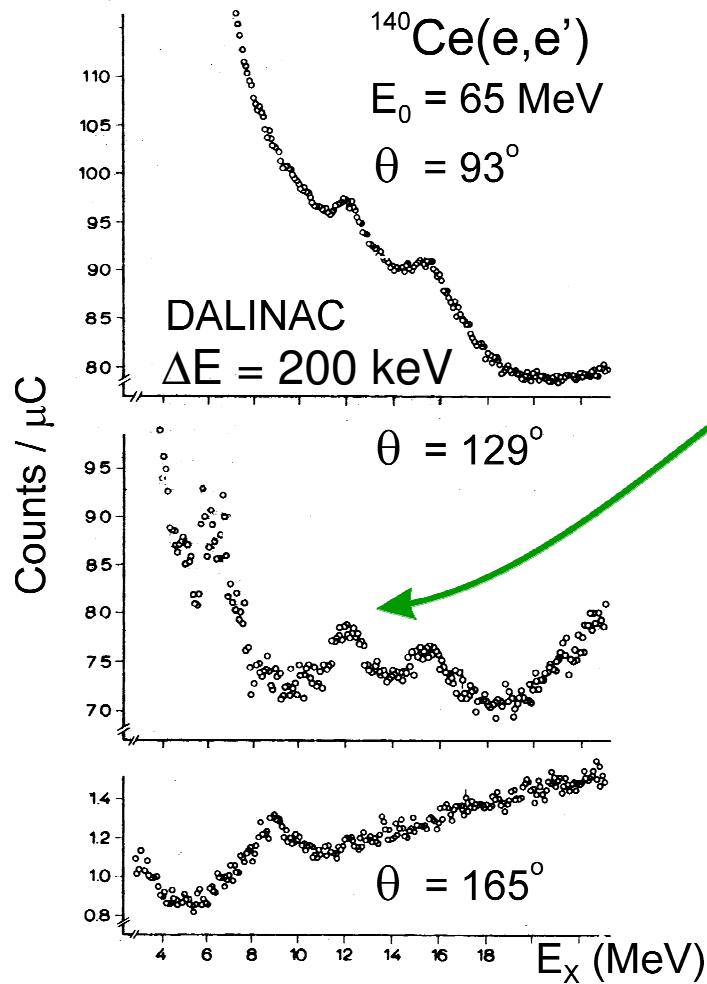
- Study of one- and two-phonon 2^+ states in ^{94}Mo with high-resolution (e,e') and (p,p') experiments
- Combined analysis with QPM reveals
 - symmetric and mixed-symmetric character of one-phonon states
 - two-phonon symmetric state extremely pure
 - about 25% admixtures in the two-phonon mixed-symmetric wave function (mostly 3-phonon)
 - quantitatively consistent results after inclusion of two-step processes in (p,p')
- Shell model description moderate to poor
 - limited model space



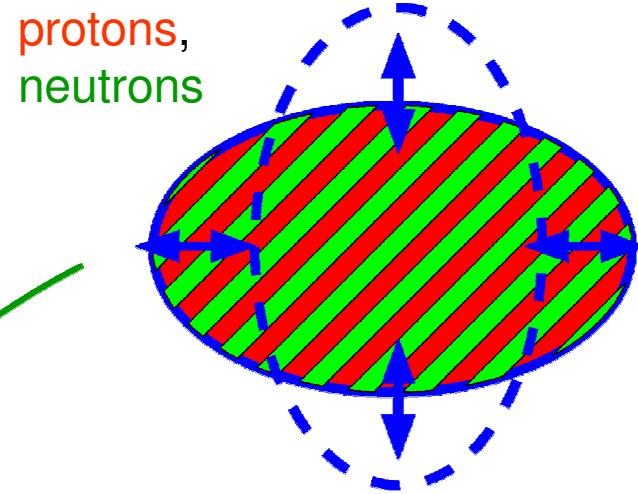
Second Part: Fine Structure of the ISGQR

- Introduction: Damping of giant resonances
- Evidence for fine structure of giant resonances
- Wavelet analysis and characteristic scales
- Dominant damping mechanisms
- Summary and outlook

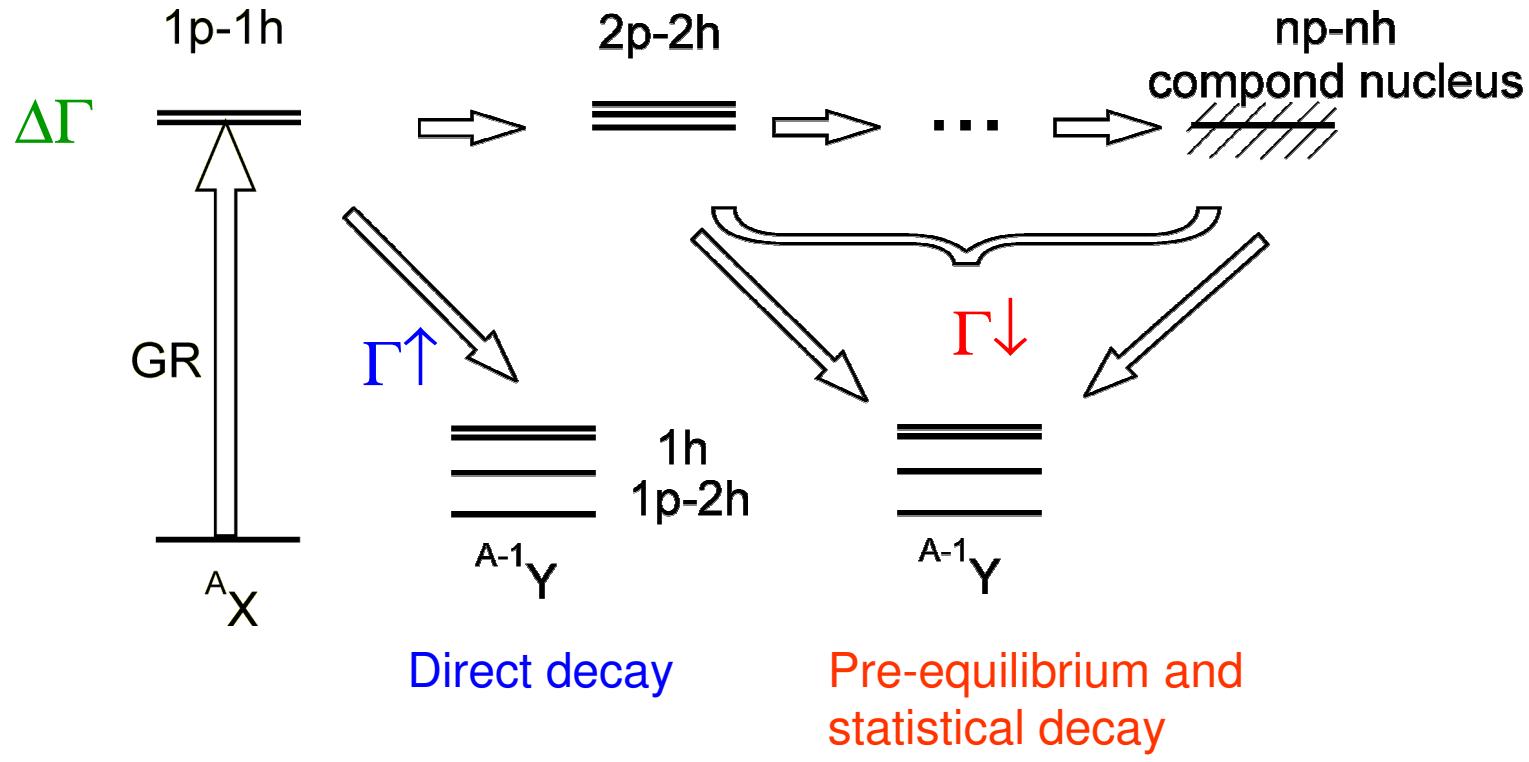
Damping of GR: Isoscalar Quadrupole Mode



$$\Delta L = 2 \quad \Delta T = 0 \quad \Delta S = 0$$

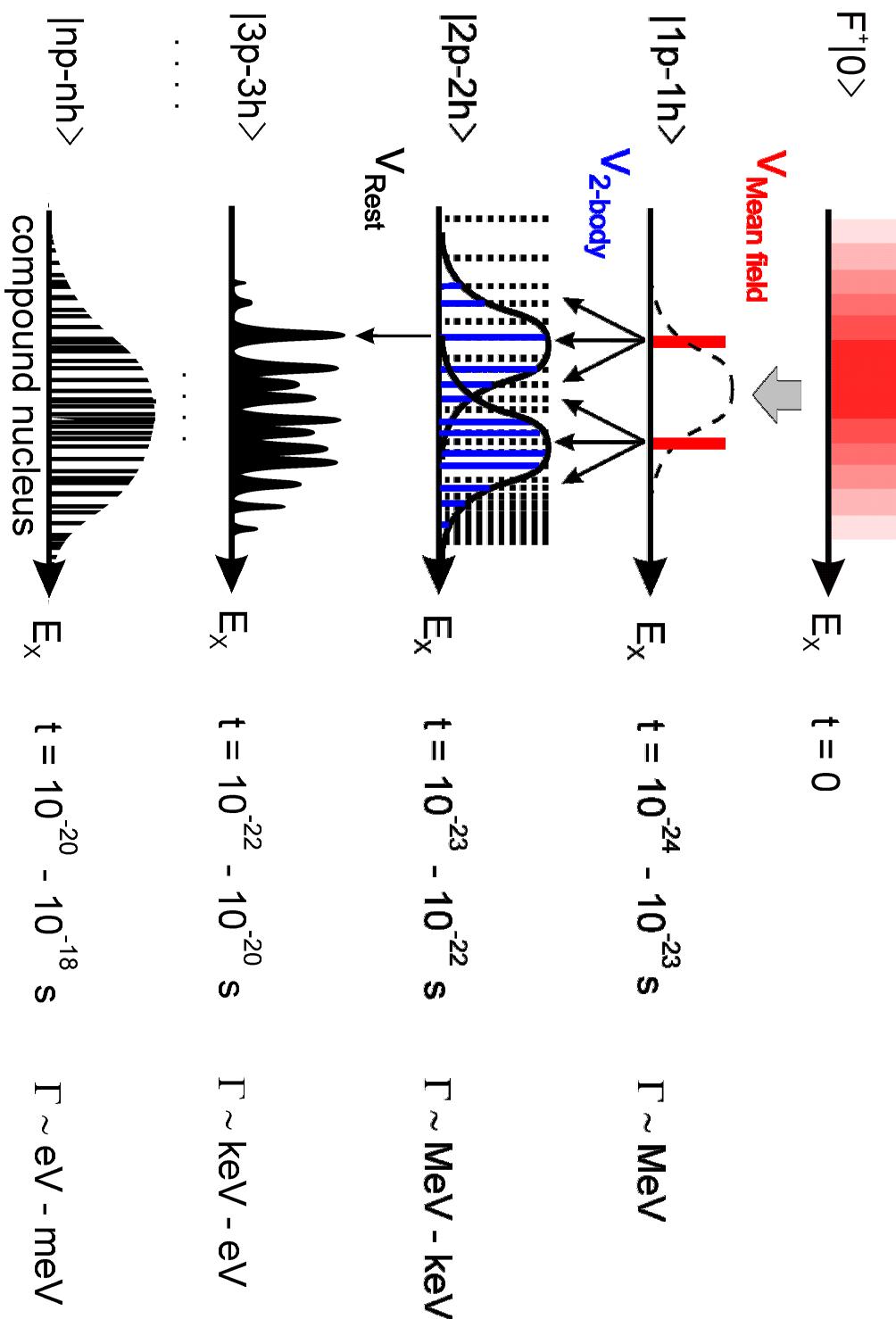


- Pitthan and Walcher (Darmstadt, 1972)
- Centroid energy: $E_c \sim 63 A^{-1/3} \text{ MeV}$
- Width
- Damping mechanisms?



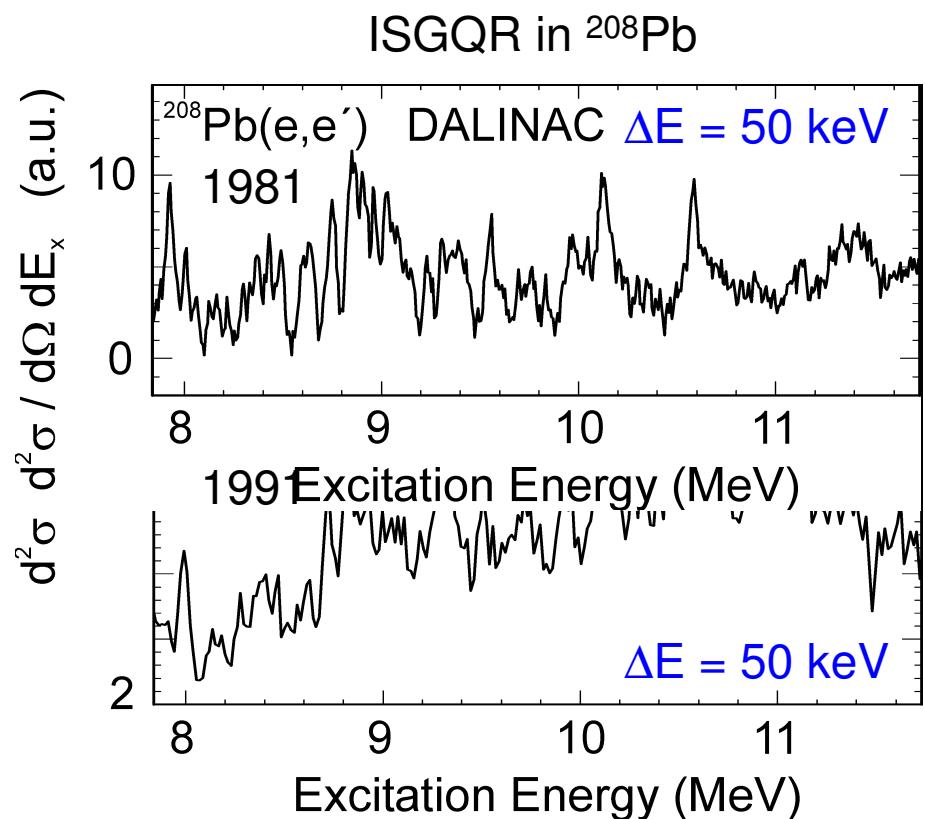
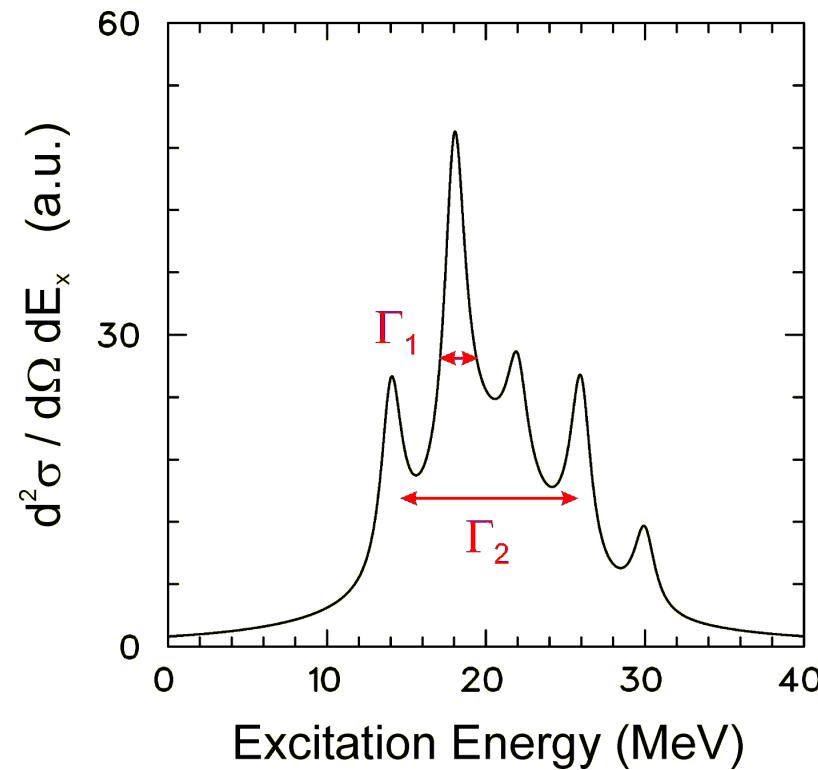
Resonance decay width: $\Gamma = \Delta\Gamma + \Gamma \uparrow + \Gamma \downarrow$

Doorway-State Model





Fine Structure of Giant Resonances



- High resolution is crucial
- Different probes but similar structures



- Global phenomenon?
 - Other nuclei
 - Other resonances
- Methods for characterization of fine structure?
- Goal: Dominant damping mechanisms



New Experiments

Place:

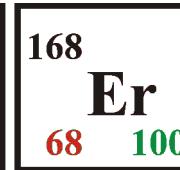
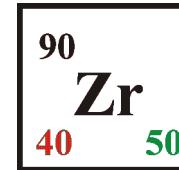
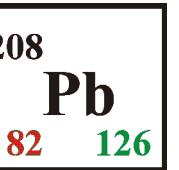
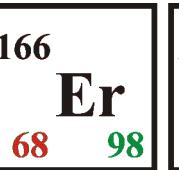
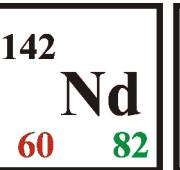
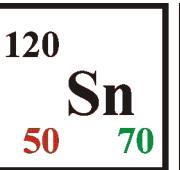
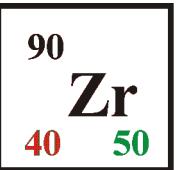
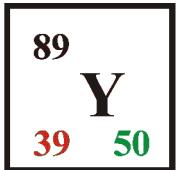
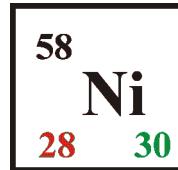
iThemba LABS,
South Africa

RCNP, Osaka

Reaction:

ISGQR from (p, p')

GT from (${}^3\text{He}, t$)



Beam energy:

200 MeV

140 MeV/u

Scattering angles:

$8^\circ - 10^\circ$
($\Delta L = 2$)

0°
($\Delta L = 0$)

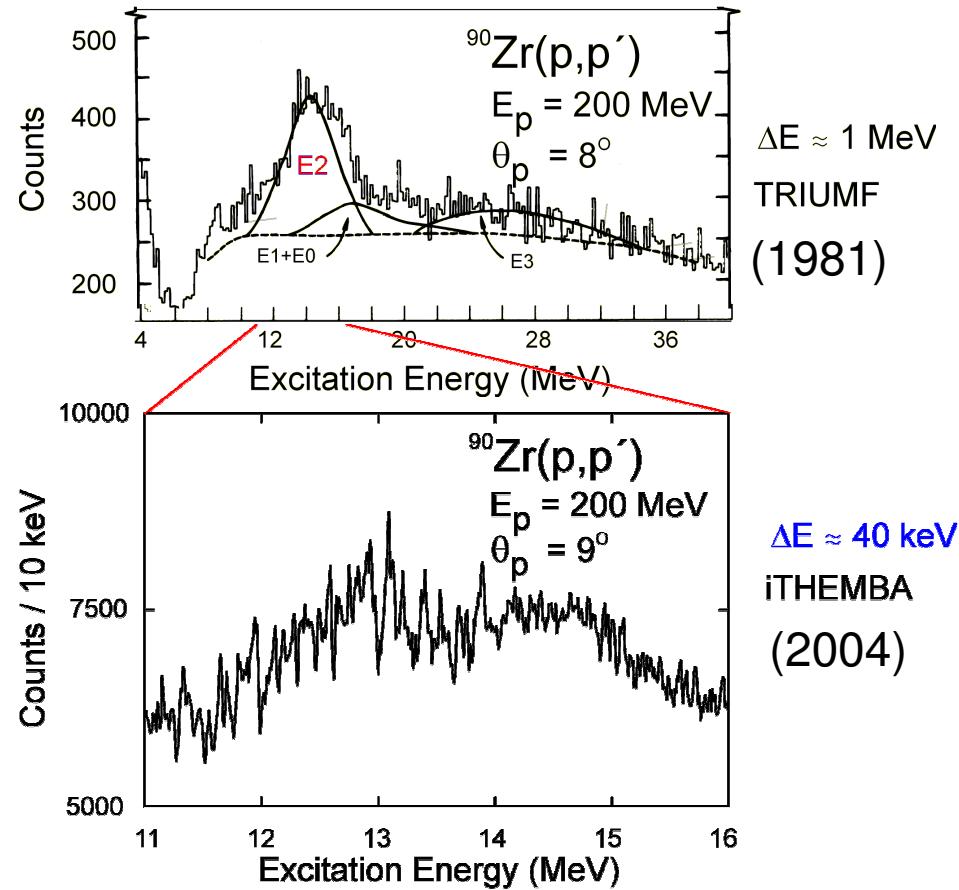
Energy resolution:
(FWHM)

$\Delta E = 35 - 50 \text{ keV}$

$\Delta E = 50 \text{ keV}$

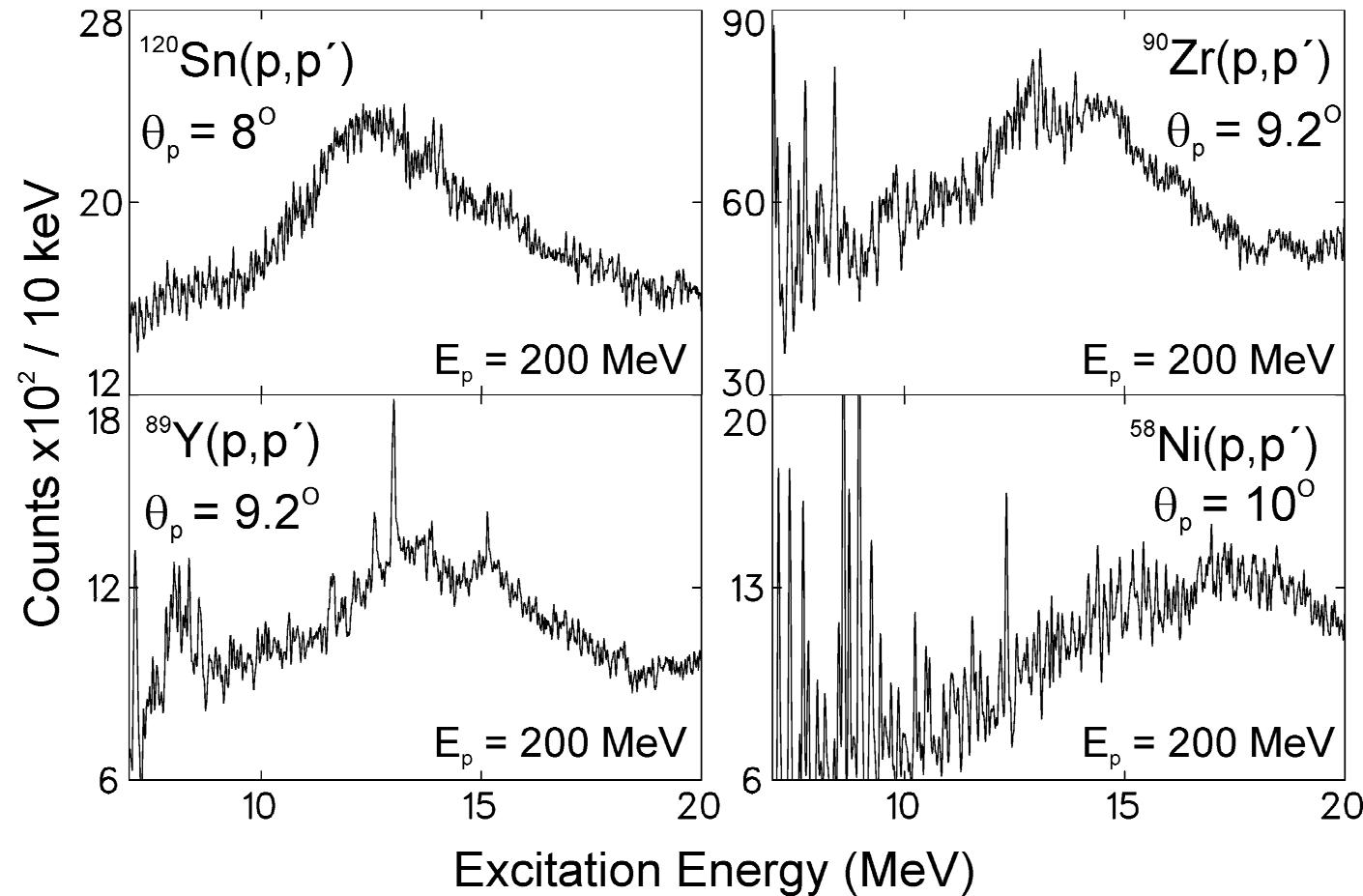


Fine Structure of the ISGQR



- Not a Lorentzian

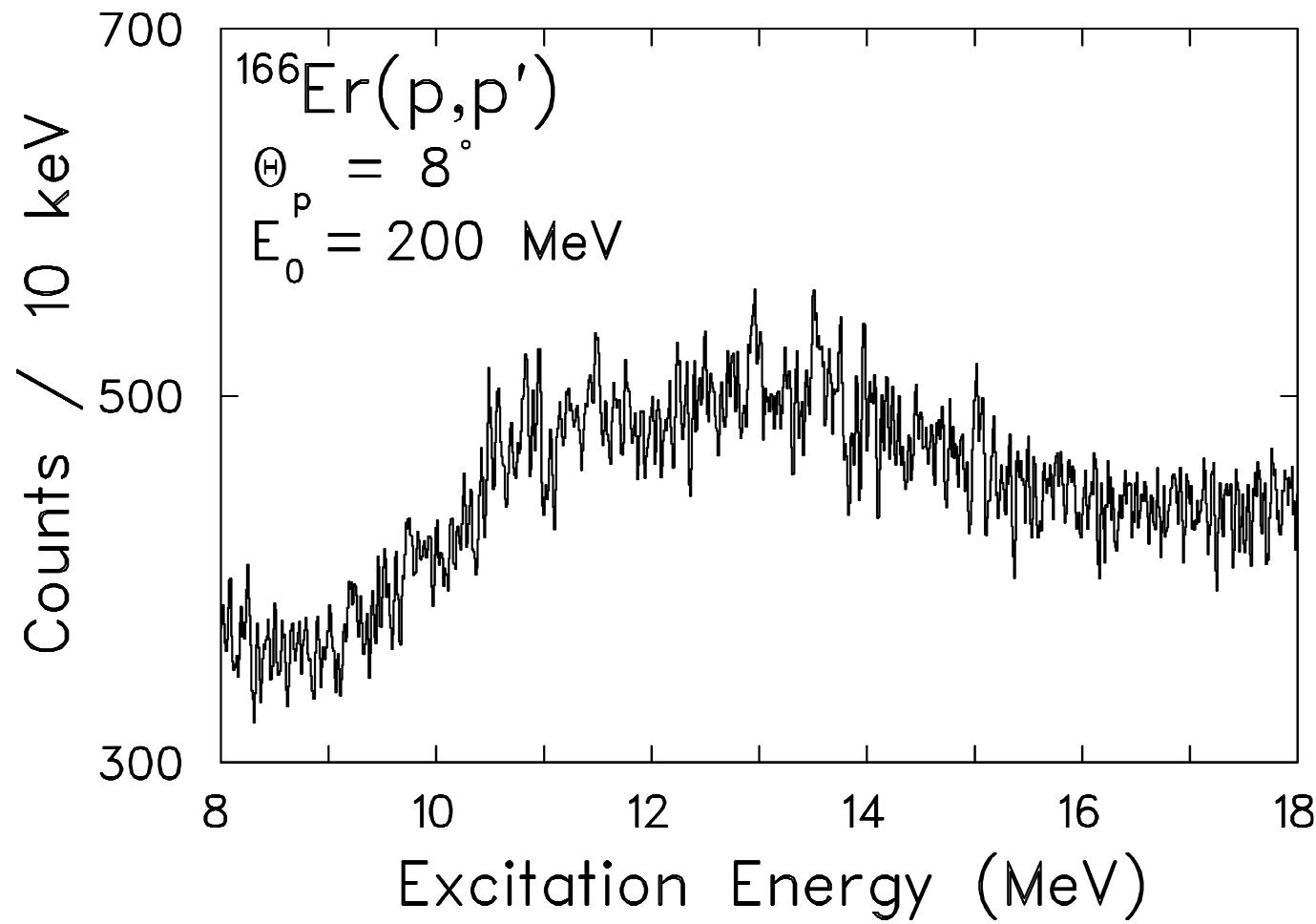
Fine Structure of the ISGQR in Other Nuclei



- Fine structure of the ISGQR is global



Fine Structure in Deformed Nuclei?





Methods for Fine Structure Studies

- Fluctuation analysis using autocorrelation function
 - Doorway-state analysis
 - Fourier analysis
 - Entropy index method (Lacroix, Chomaz, 1999)
 - Local scaling dimension (Aiba, Matsuo, 1999)
- Wavelet transform from signal processing**

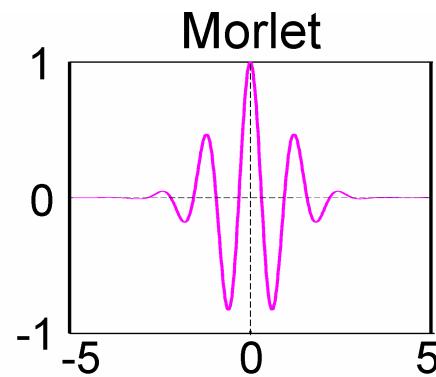
Wavelet coefficients:

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

↑ ↑
scale position ↑ ↑
 spectrum wavelet

Continuous: $\delta E, E_x$ are varied continuously

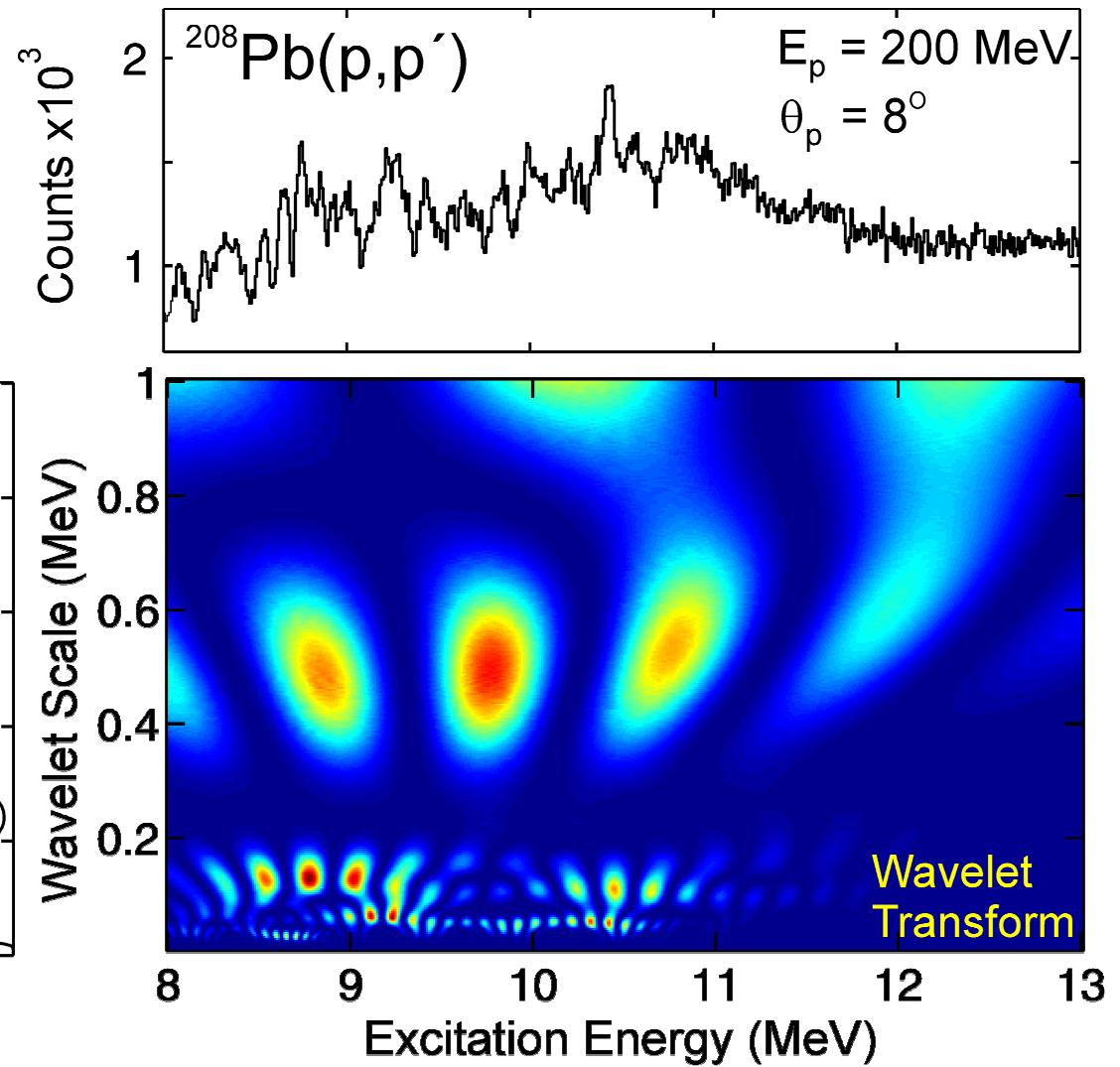
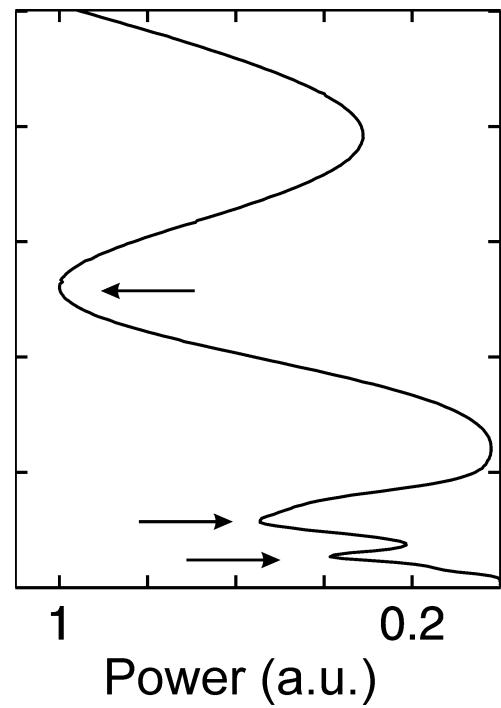
$$\int_{-\infty}^{\infty} \Psi^*(x) dx = 0 \quad \text{and} \quad \int_{-\infty}^{\infty} |\Psi^*(x)|^2 dx < \infty$$



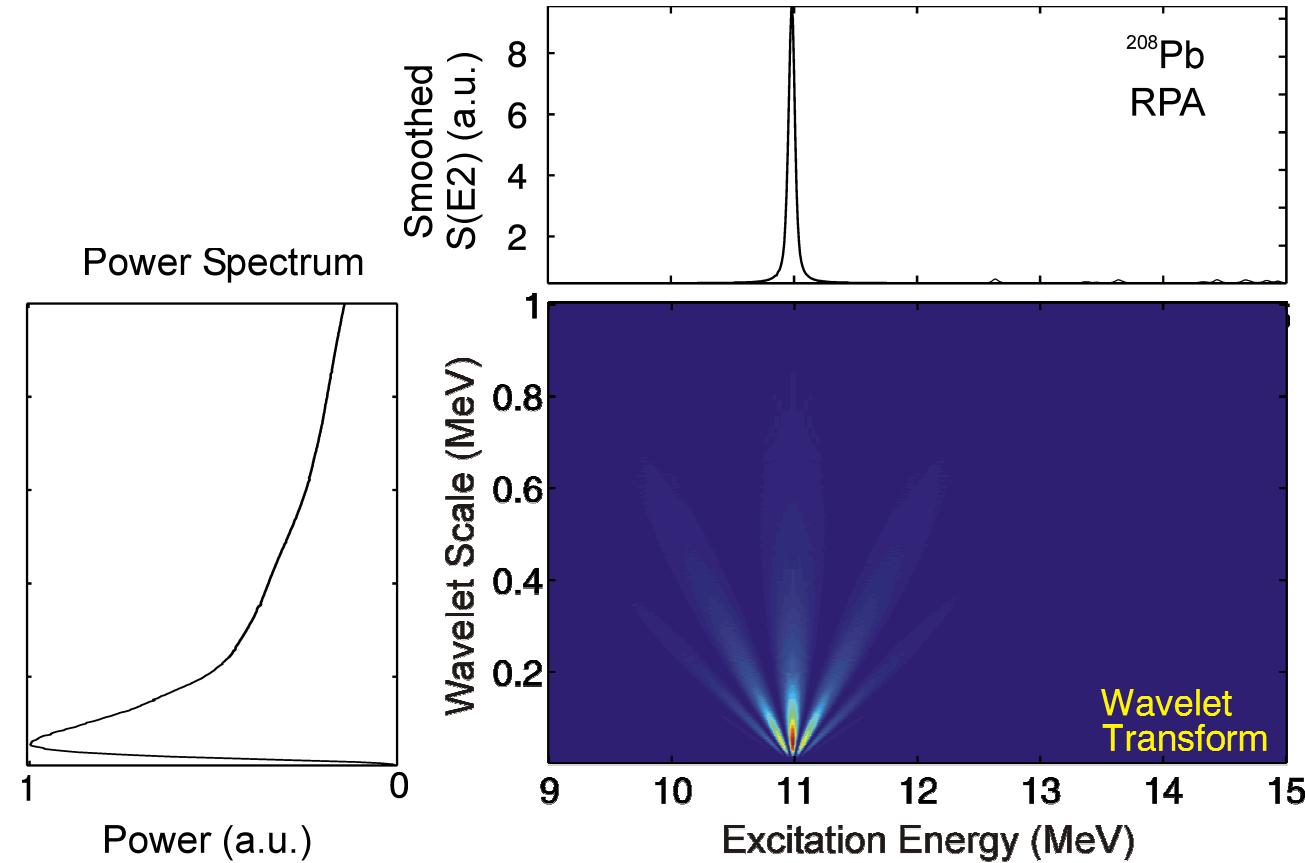
$$\Psi(x) = \cos(2\pi\omega x) e^{-x^2/2}$$



Application: ISGQR in $^{208}\text{Pb}(\text{p},\text{p}')$



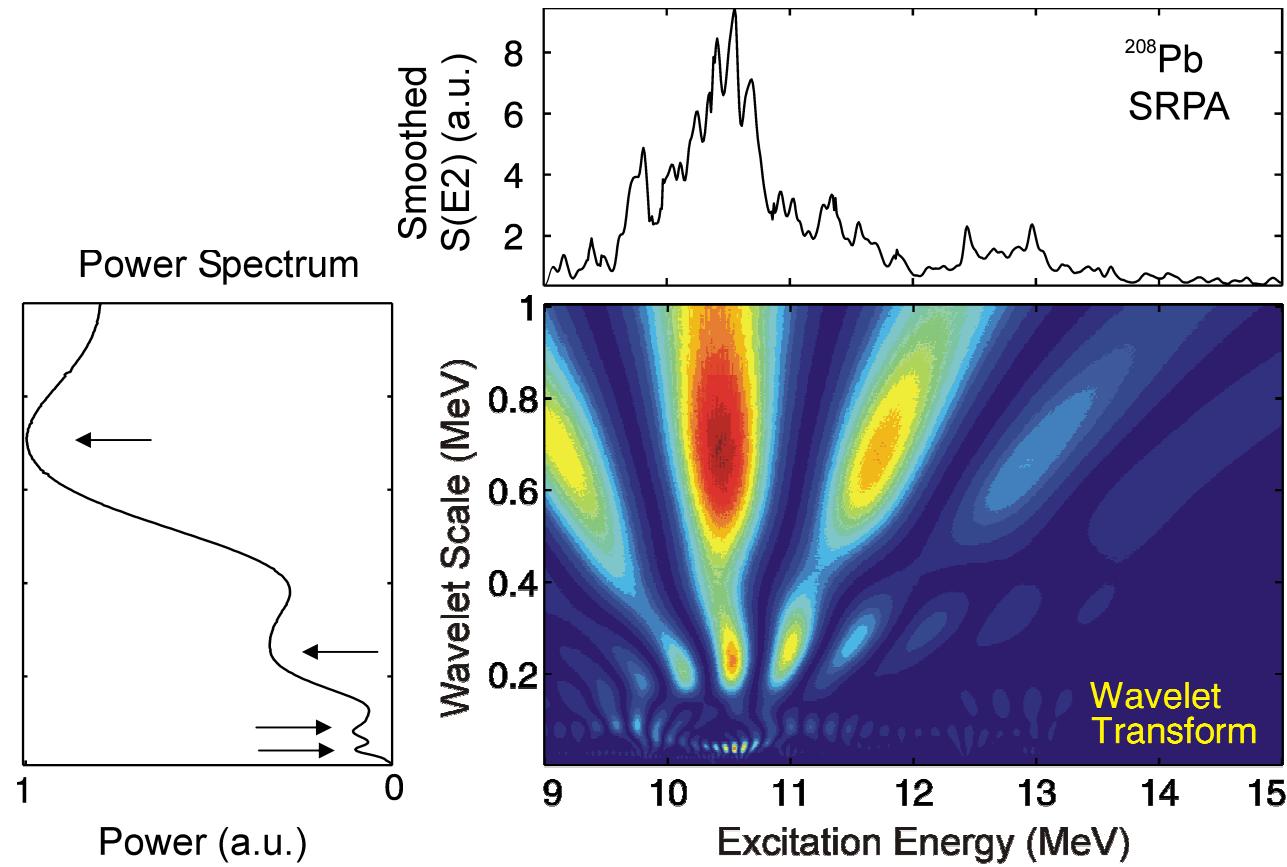
Scales (keV) : 110, 500, 1500, 2600



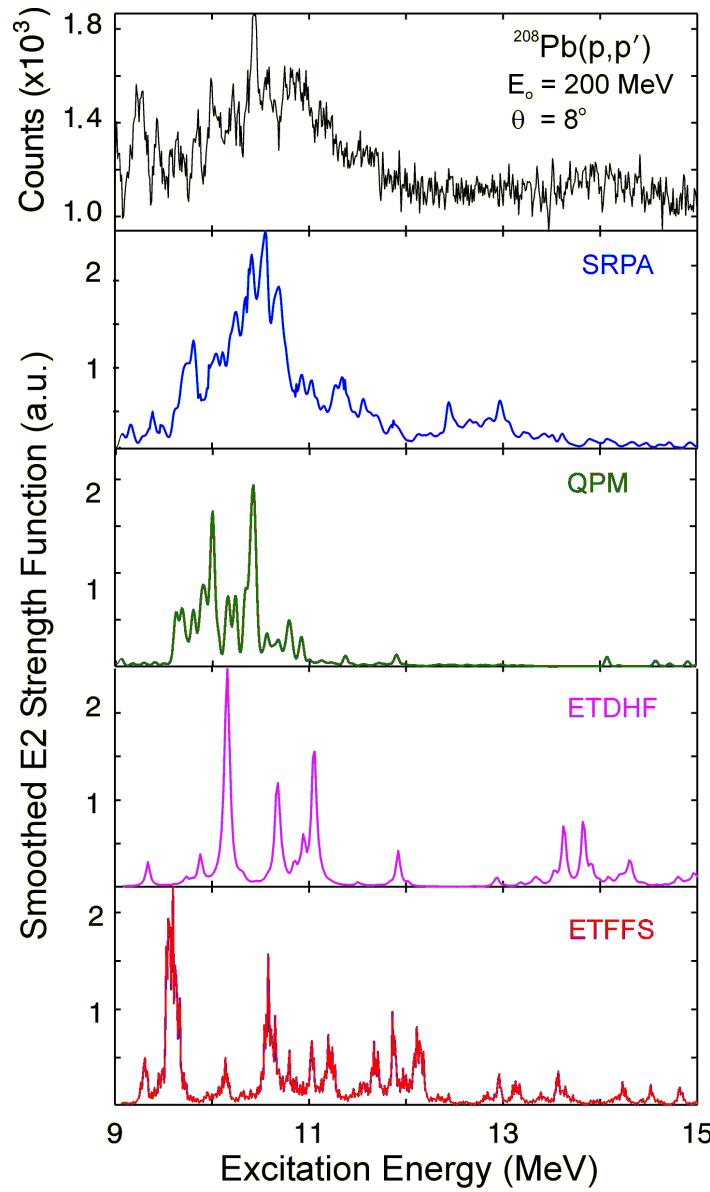
- No scales from 1p-1h states



^{208}Pb : Second RPA



- Coupling to 2p-2h generates fine structure and scales

Microscopic Models: Case of ^{208}Pb 

Wambach et al. (2000)

Ponomarev (2003)

Lacroix et al. (2001)

Kamerdziev et al. (1997)



Experiment vs. Model Predictions

	I	II	III
Exp / keV	110	550	1500 2600
Models / keV			
SPRA	80	250 800	2100
QPM	110	770	1400
ETDHF	120	230	1000
ETFFS	130	310 570	2500

- Three classes of scales as in experiment
- Strong variations of class II and class III scales



Two types of dissipation mechanisms:

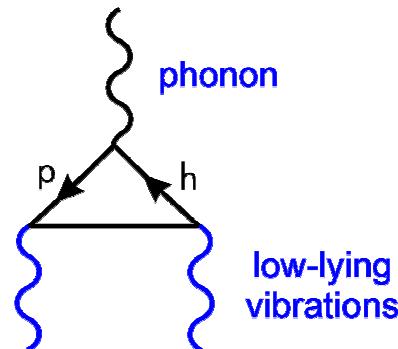
collective damping



low-lying surface vibrations



$1p - 1h \otimes \text{phonon}$



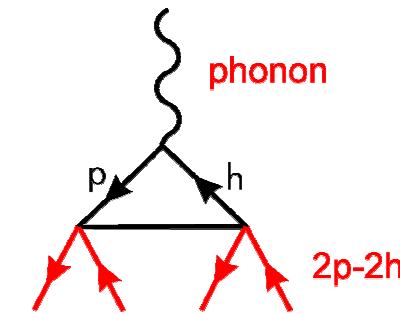
non-collective damping



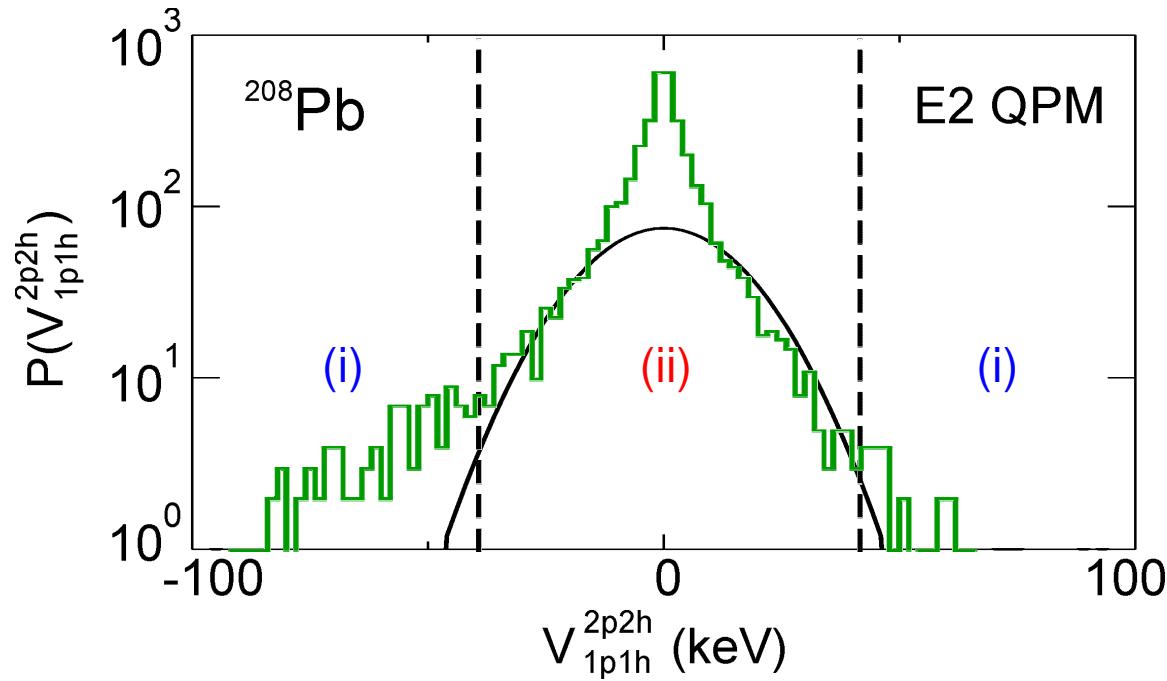
background states



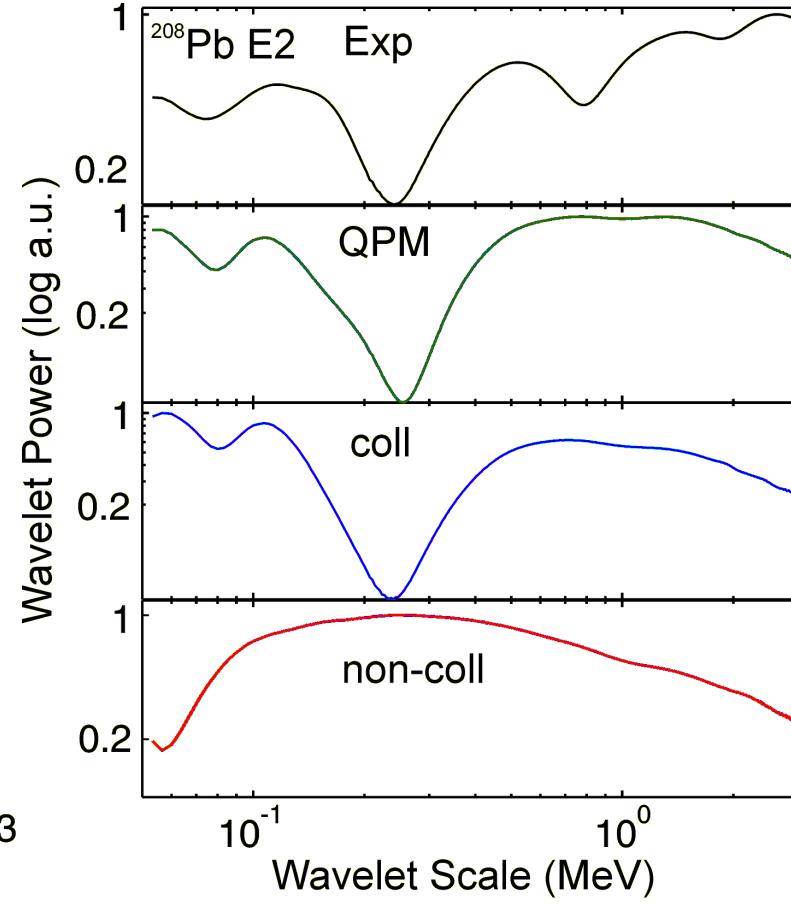
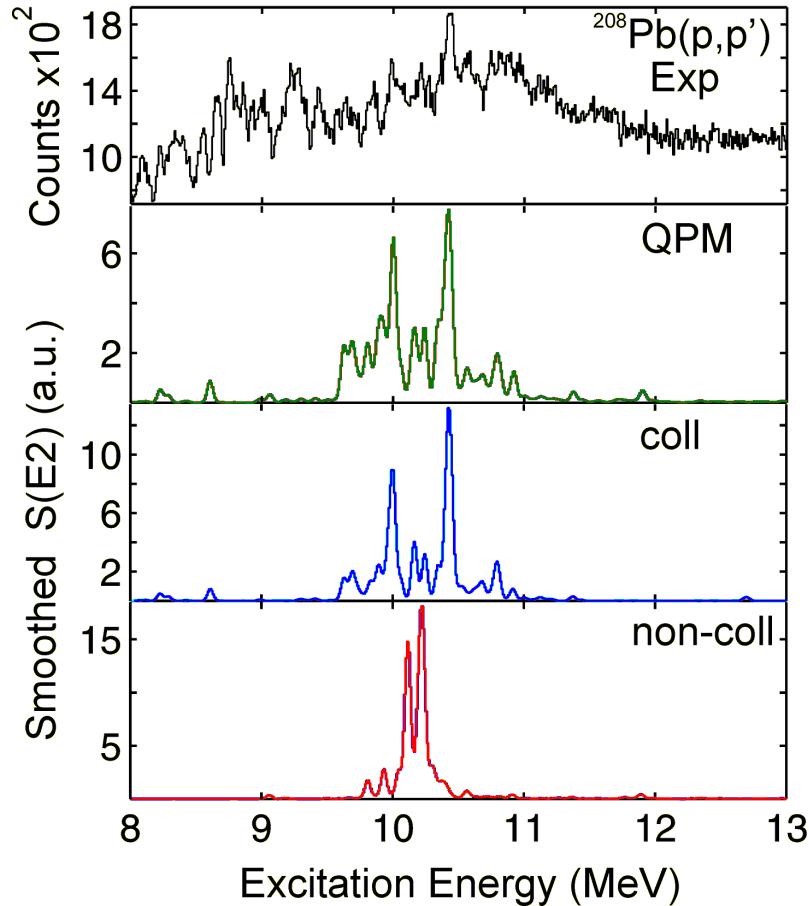
coupling to $2p - 2h$ states



Distribution of the Coupling Matrix Elements



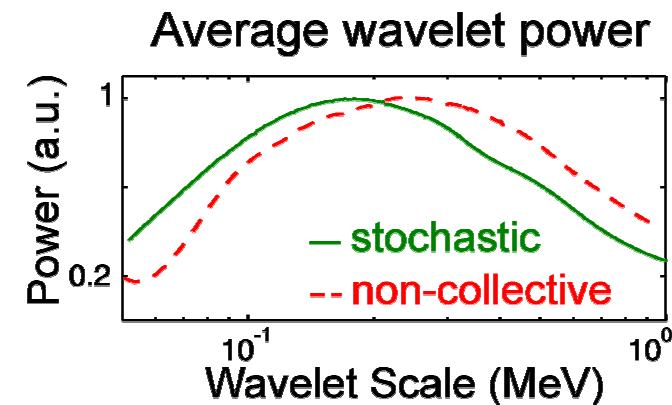
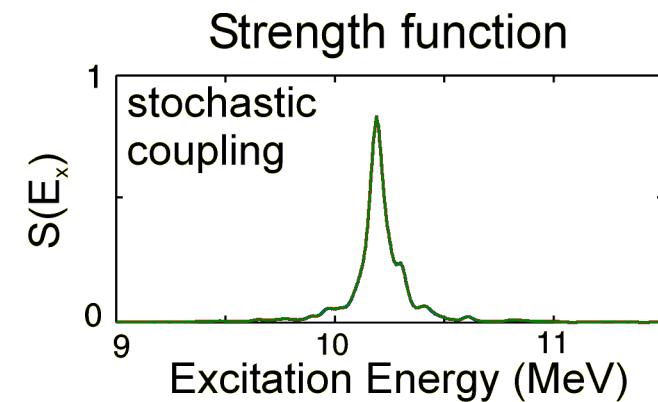
- RMT: Gaussian distribution for $\langle 1p1h | V_{1p1h}^{2p2h} | 2p2h \rangle$
- QPM: deviations at large and at small m.e.
- Large m.e. define the **collective damping** mechanism
- Small m.e. are responsible for the **non-collective damping**

Collective vs. Non-collective Damping in ^{208}Pb 

- Collective part: all scales
- Non-collective part: no prominent scales

Stochastic Coupling Model

- Gaussian distribution for coupling matrix elements (RMT)
- Level spacing distribution according to GOE
- Average over statistical ensemble



- Similar results as for the non-collective damping mechanism
- Generic behavior of the non-collective damping?



Summary

- Fine structure is a general phenomenon of giant resonances
 - over a whole mass range
 - in different types of resonances
- Quantitative analysis with wavelets
- Origin of scales
 - collective damping: low-lying surface vibrations
 - non-collective damping: stochastic coupling
- Relevance of scales from discrete wavelet transforms
- Model-independent level densities

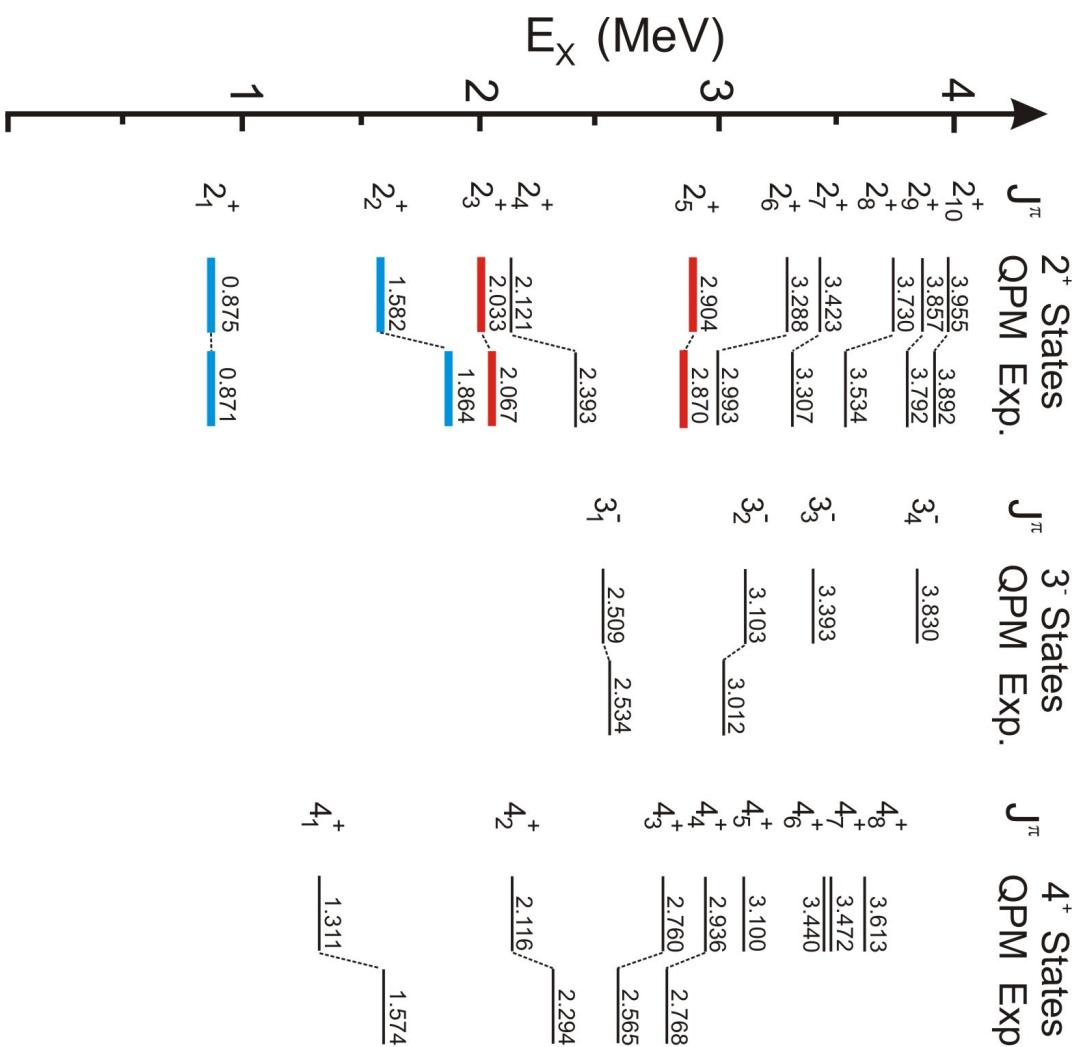


Outlook

- Goal: next step in the hierarchy 3p-3h
 - improvement of experimental resolution
- Contribution of other damping mechanisms
 - escape width
 - Landau damping
- Quantitative analysis of scales
 - new experiments and models

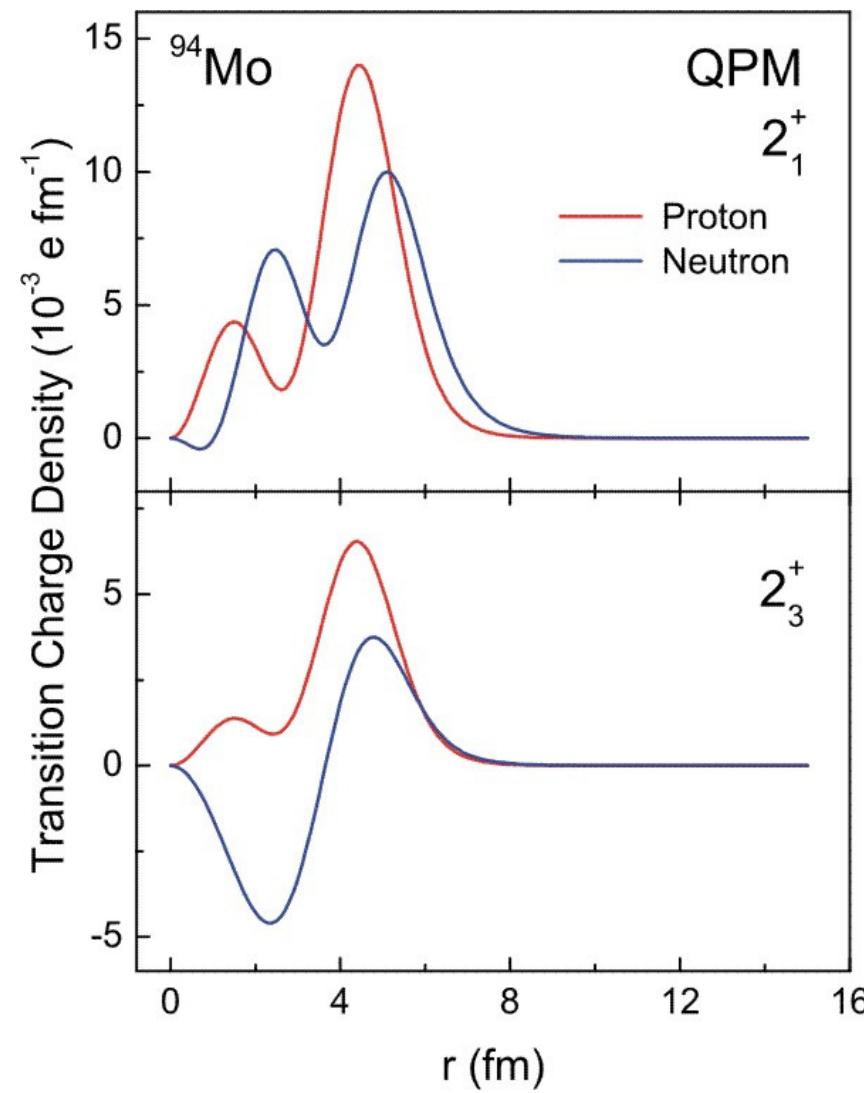
V

QPM Predictions



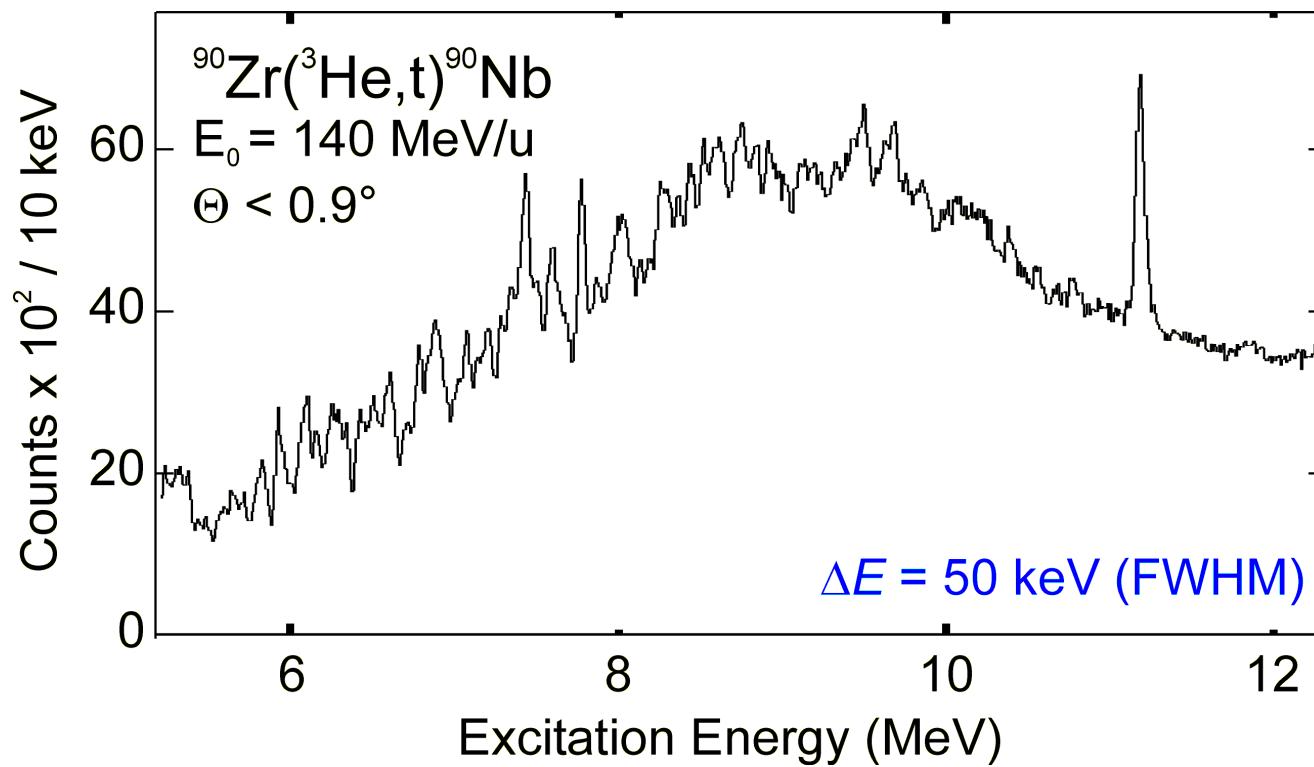


Radial Transition Charge Densities





Fine Structure of the Spin-Flip GTR



- Observed for the first time in a heavy nucleus
- Asymmetric fluctuations
- Selectivity: $J^\pi = 1^+ \rightarrow$ level density



Wavelet coefficients:

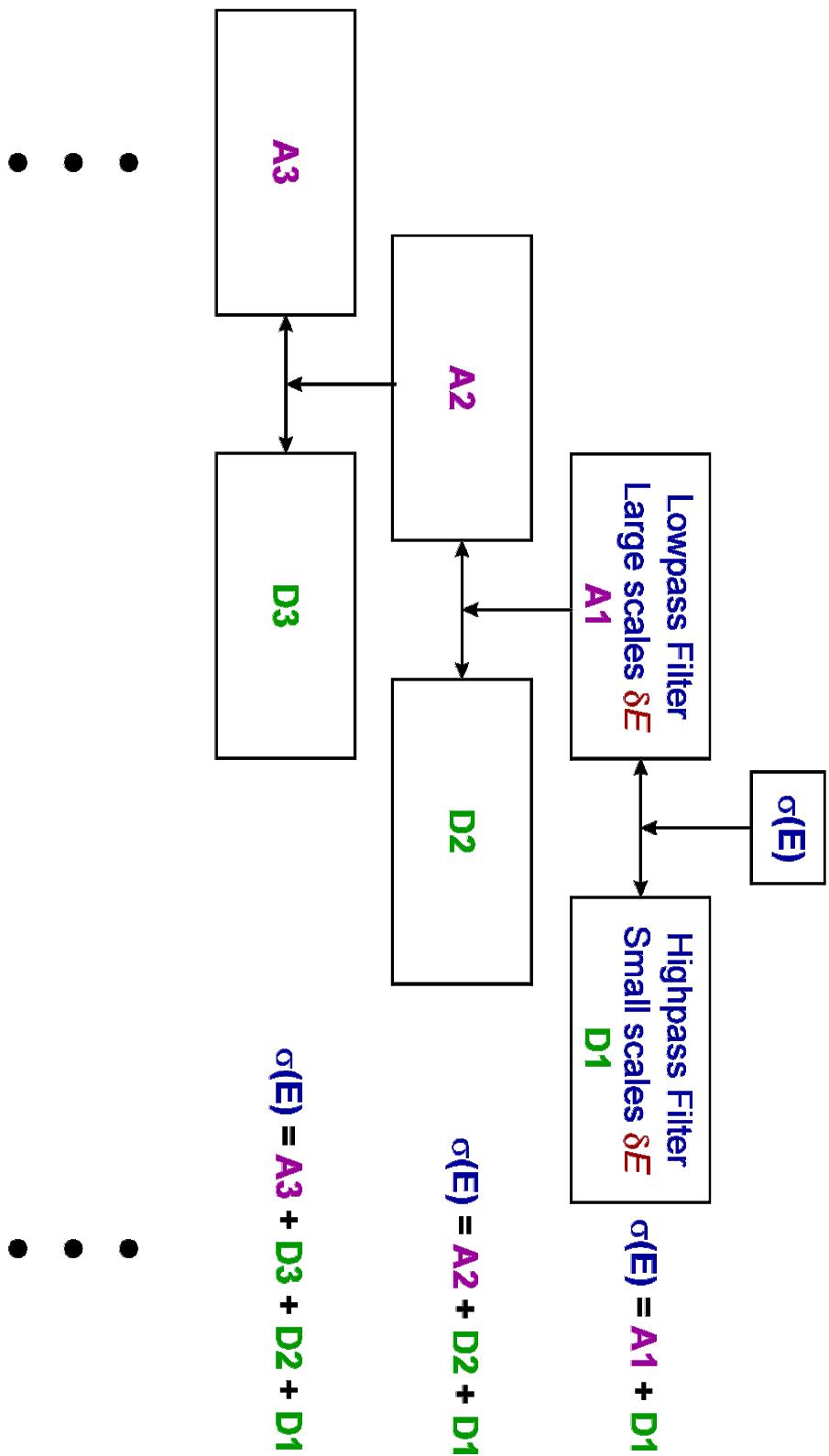
$$C(\delta E, E_x) = \frac{1}{\sqrt{\delta E}} \int \sigma(E) \Psi^*\left(\frac{E_x - E}{\delta E}\right) dE$$

↑ ↑ ↑ ↑
scale position spectrum wavelet

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

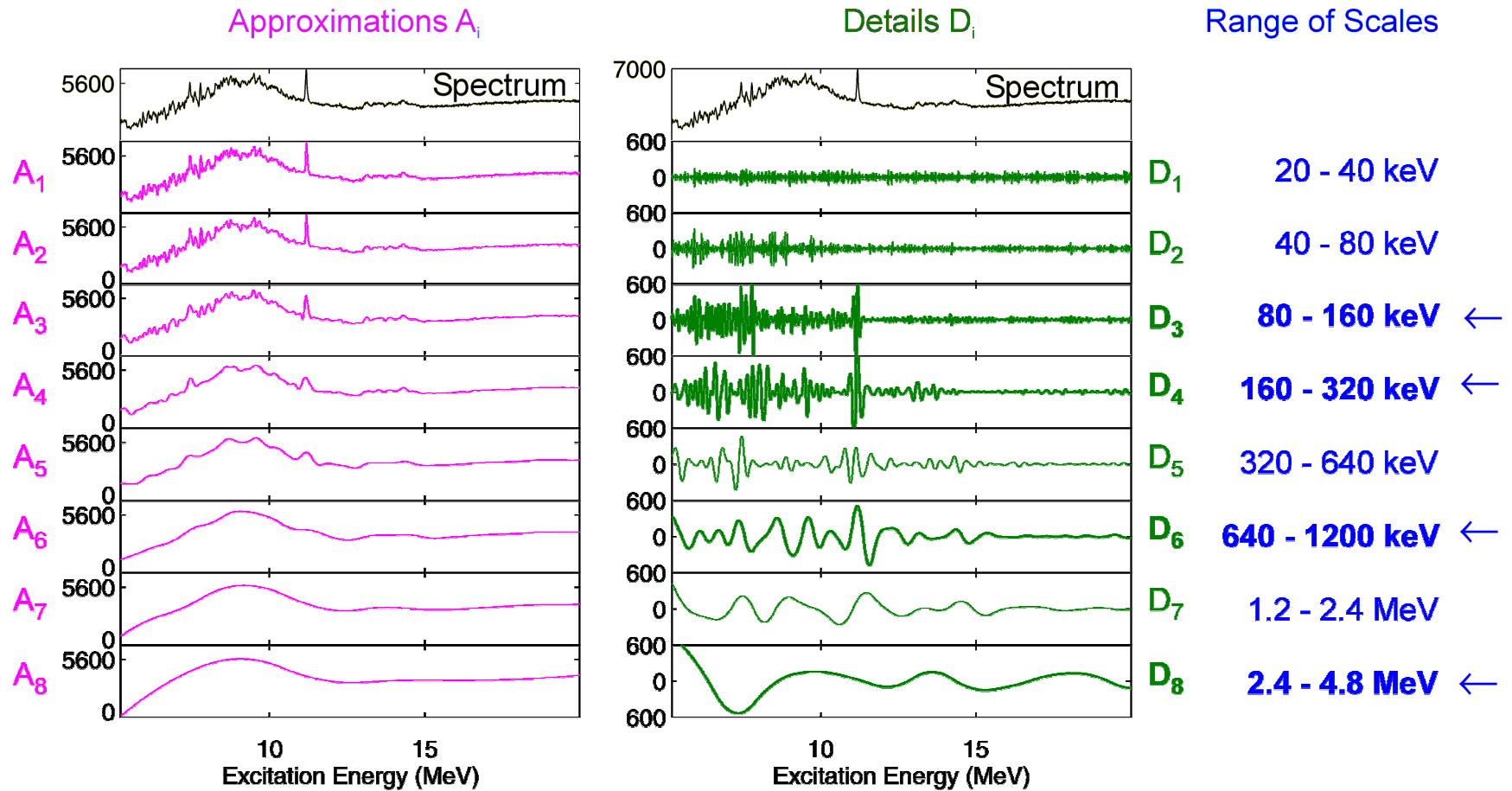
- Orthogonal basis of wavelet functions
- Exact reconstruction of the spectrum is possible
- Relevance of scales
- ☺ Resolution is limited to ranges of scales

Decomposition





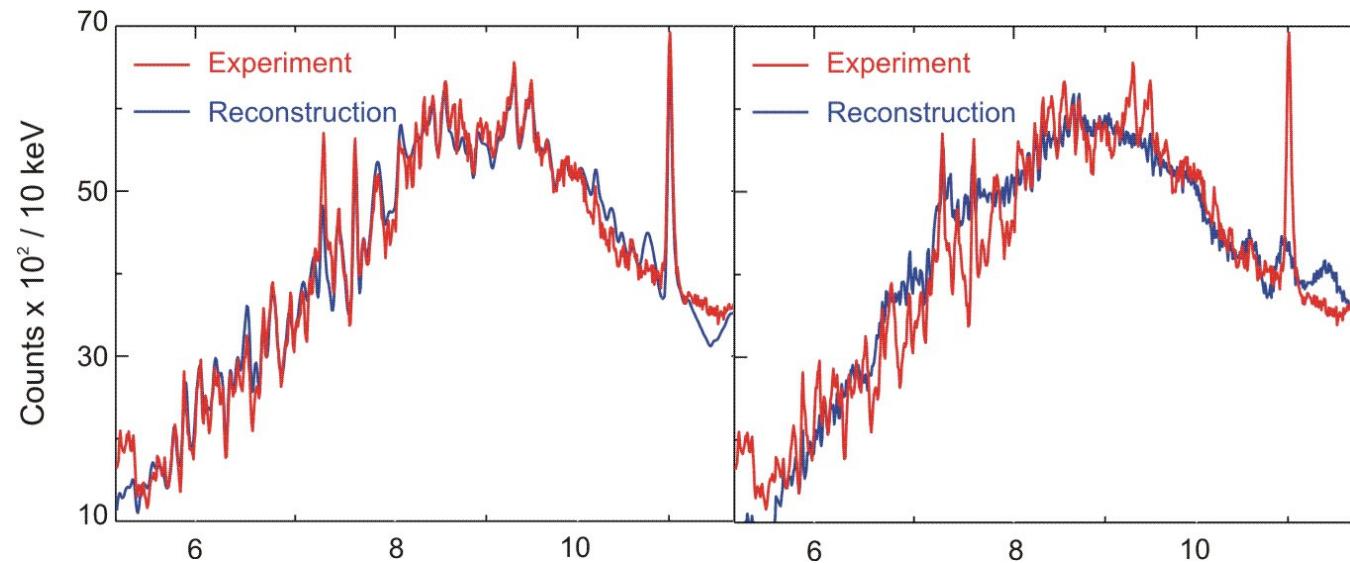
Application: GTR from $^{90}\text{Zr}(^3\text{He},t)^{90}\text{Nb}$



- Reconstruct the spectrum using important scales

DWT: Reconstruction of the Spectrum

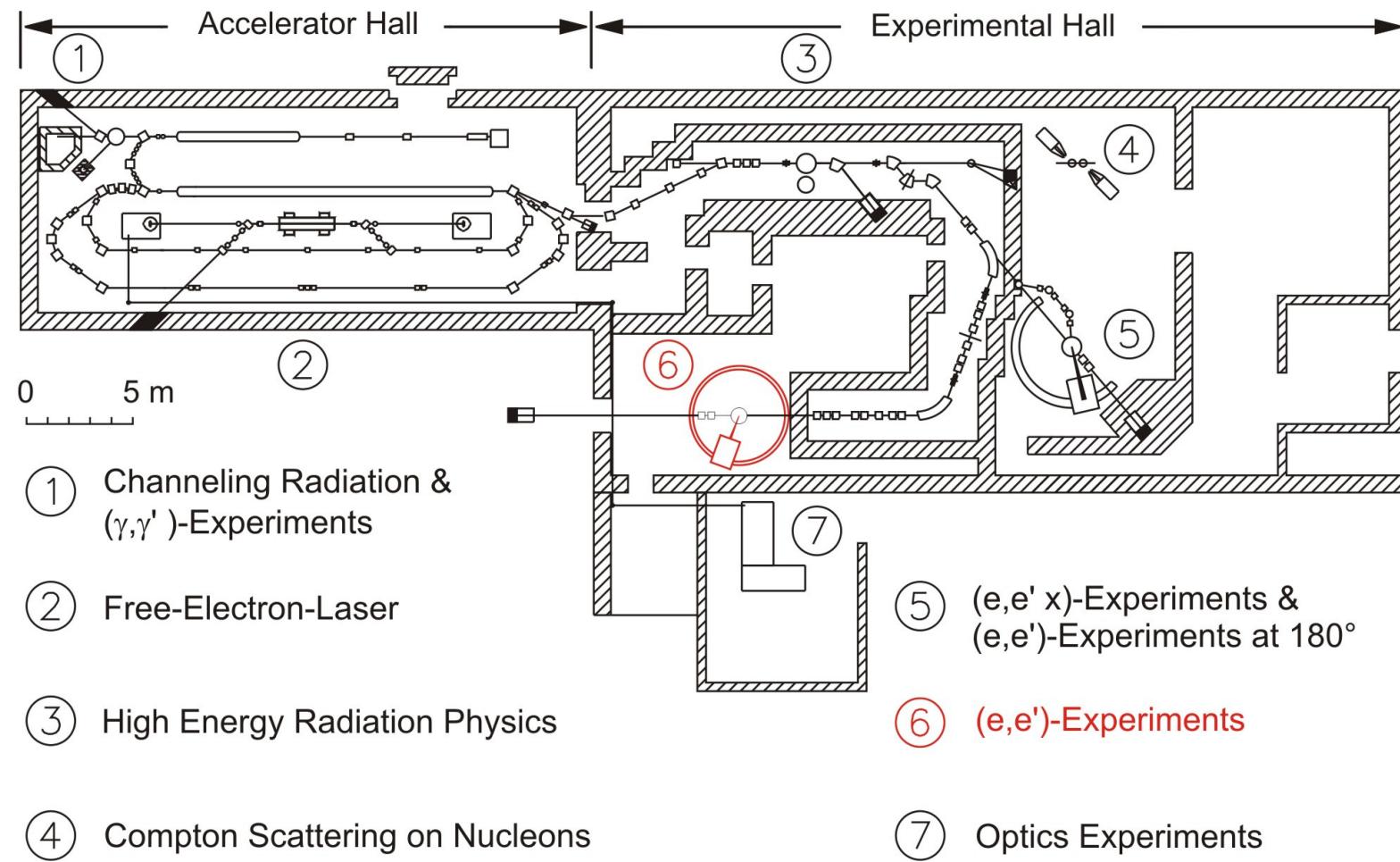
$$\sigma_r(E) = A8 + D8 + D6 + D4 + D3 \quad \sigma_r(E) = A8 + D7 + D5 + D2 + D1$$

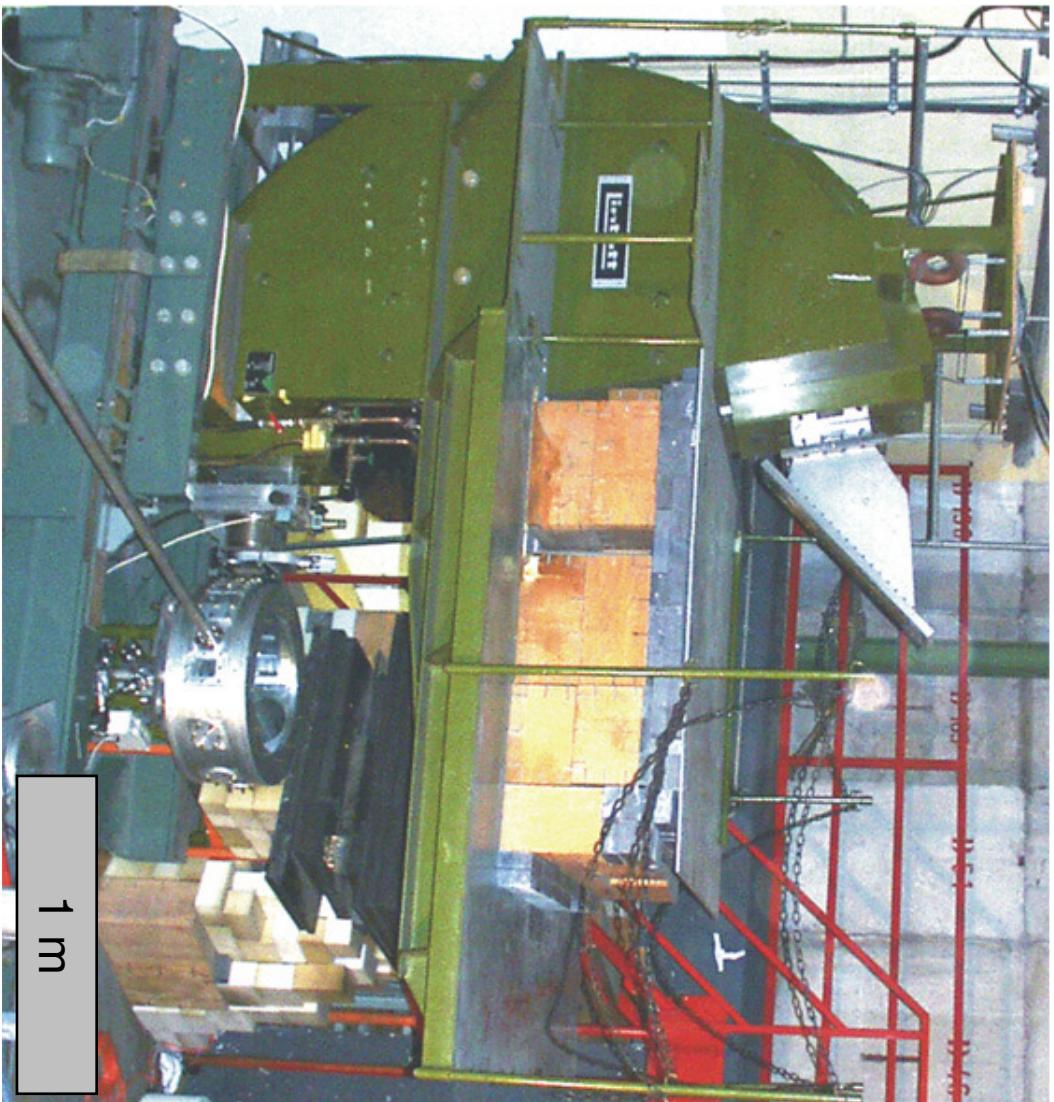


- Relevance of scale regions can be tested
- DWT and CWT results are consistent



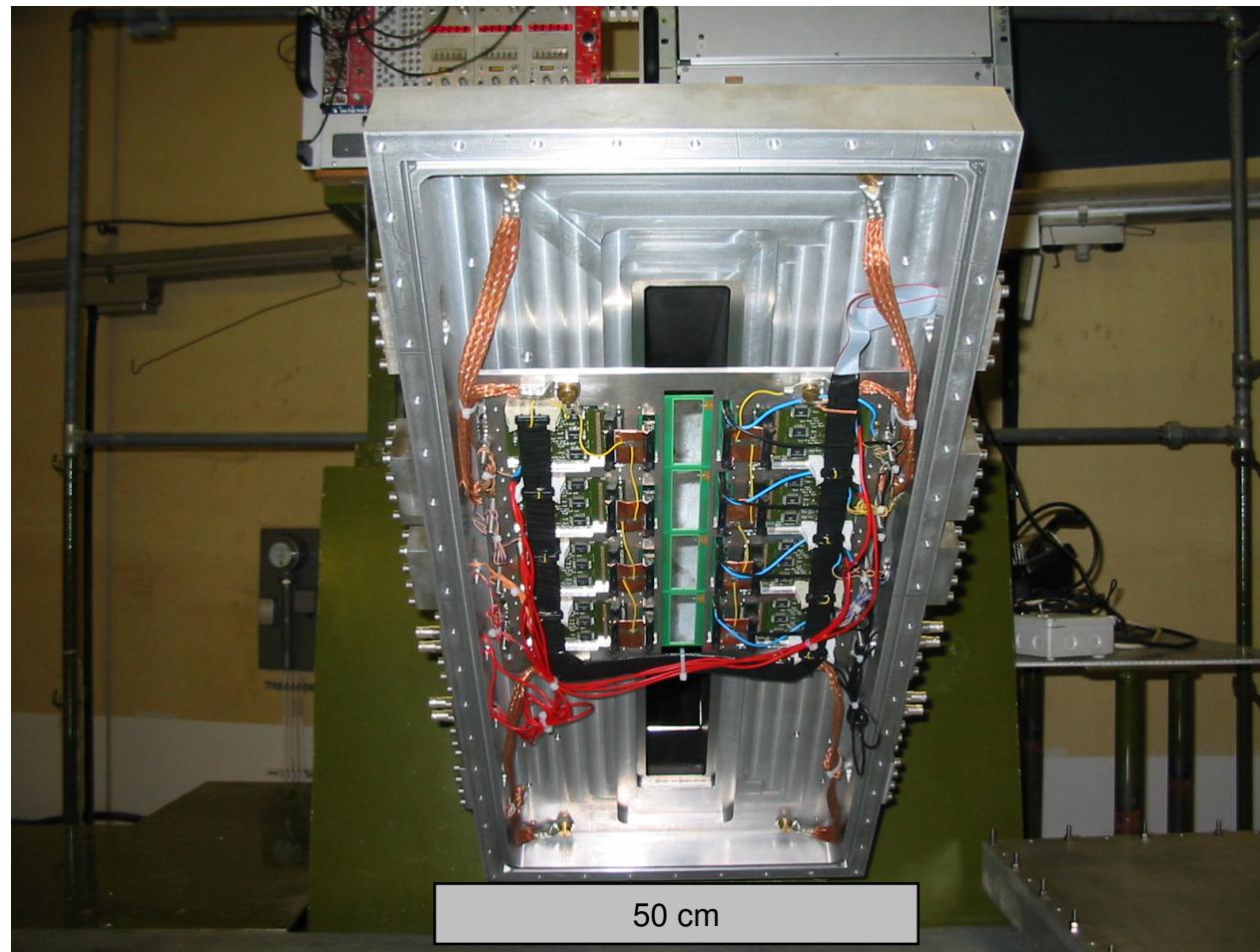
S-DALINAC and its Experimental Facilities





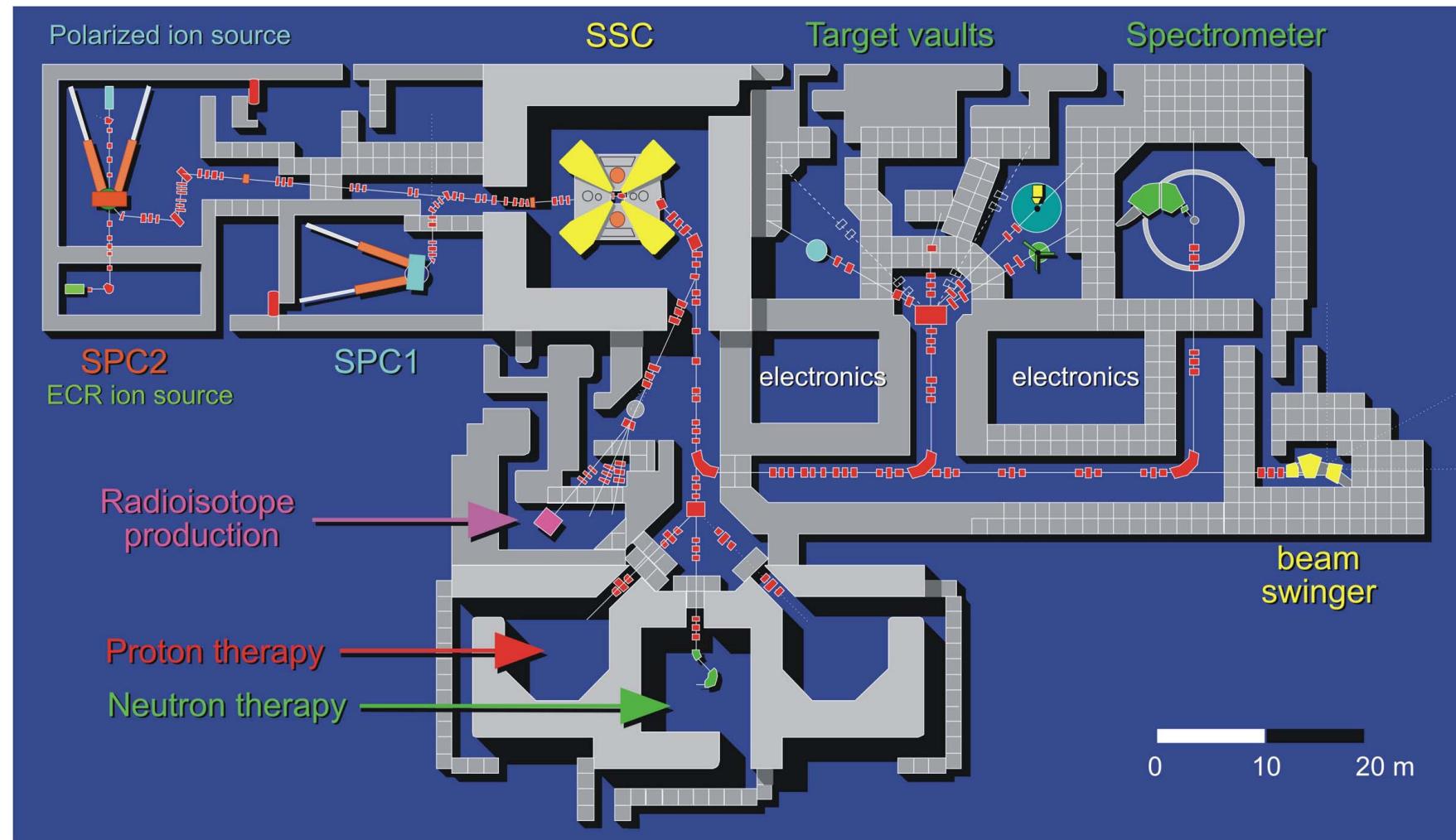


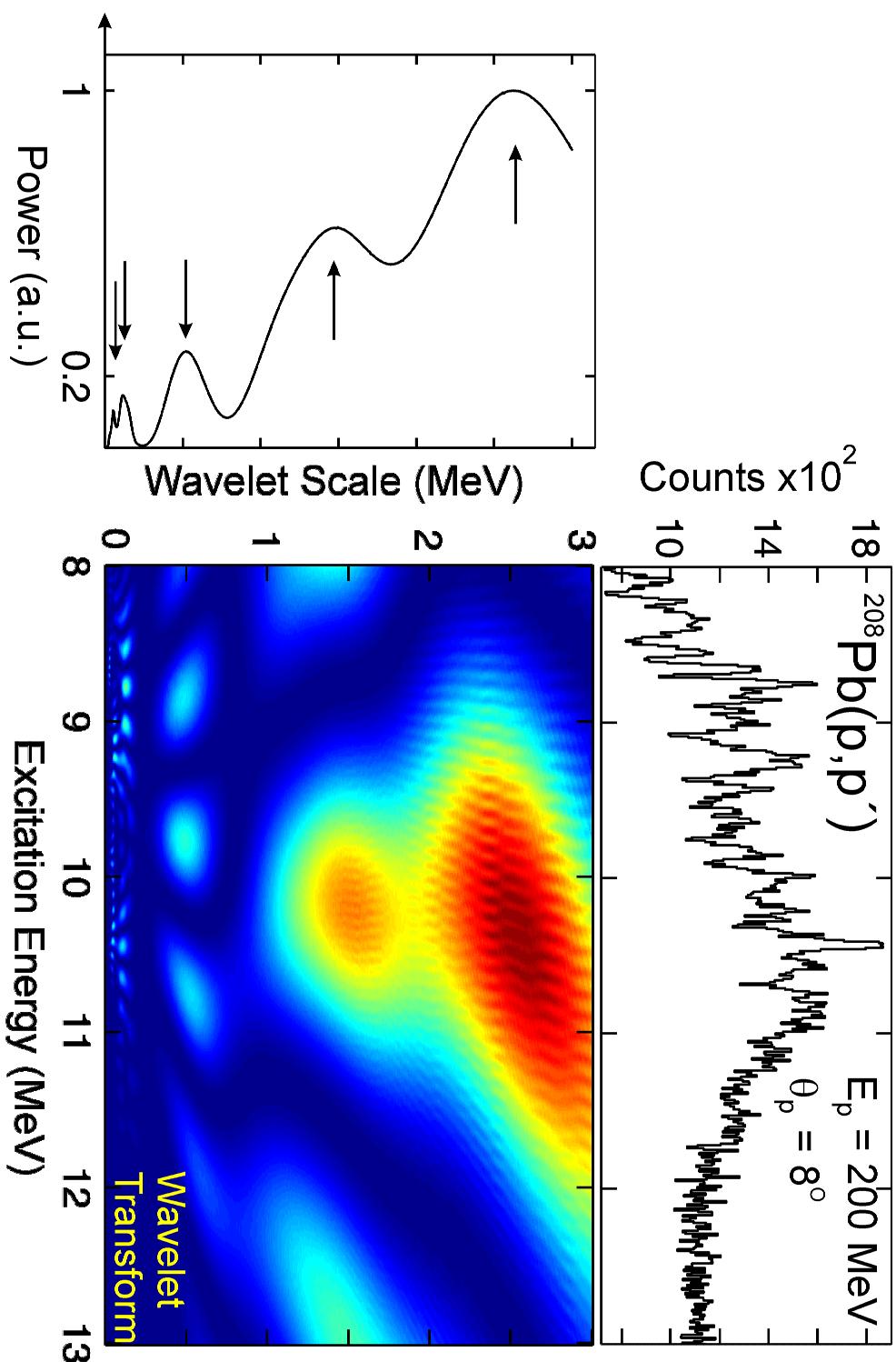
Focal Plane Detector System: Si-Microstrip Detectors





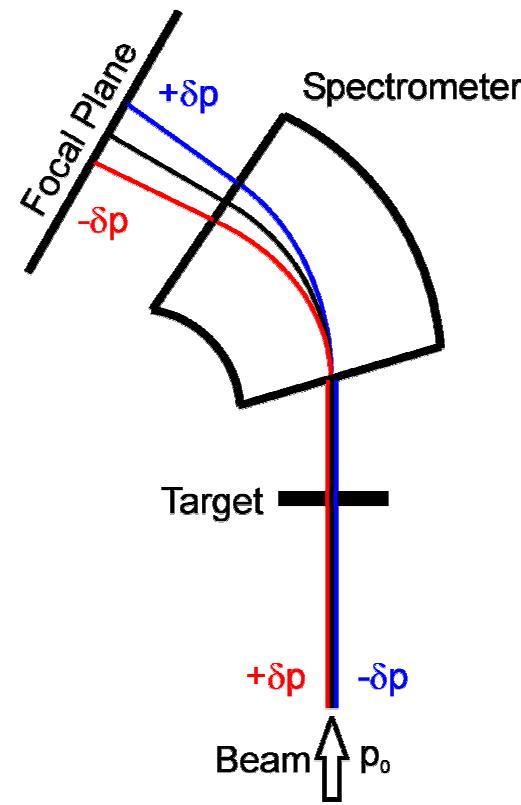
Separated-Sector Cyclotron Facility



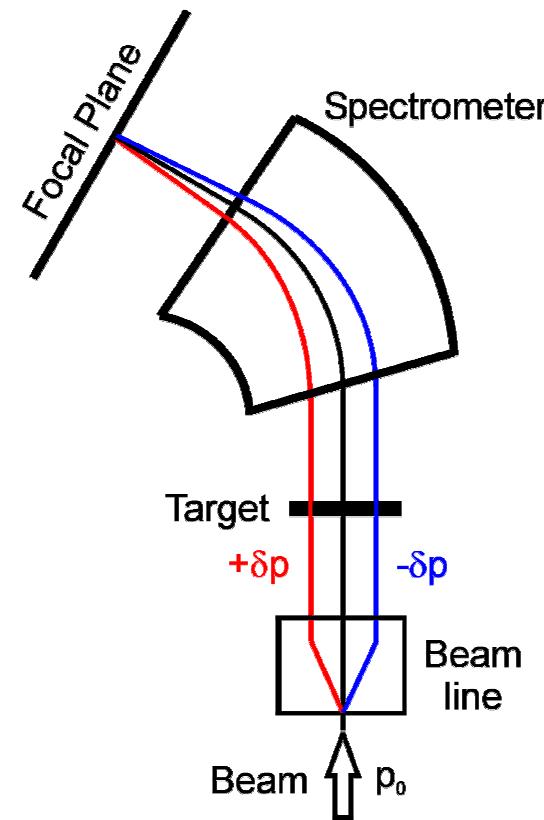
Application: $^{208}\text{Pb}(\text{p},\text{p}')$ 

Dispersion Matching

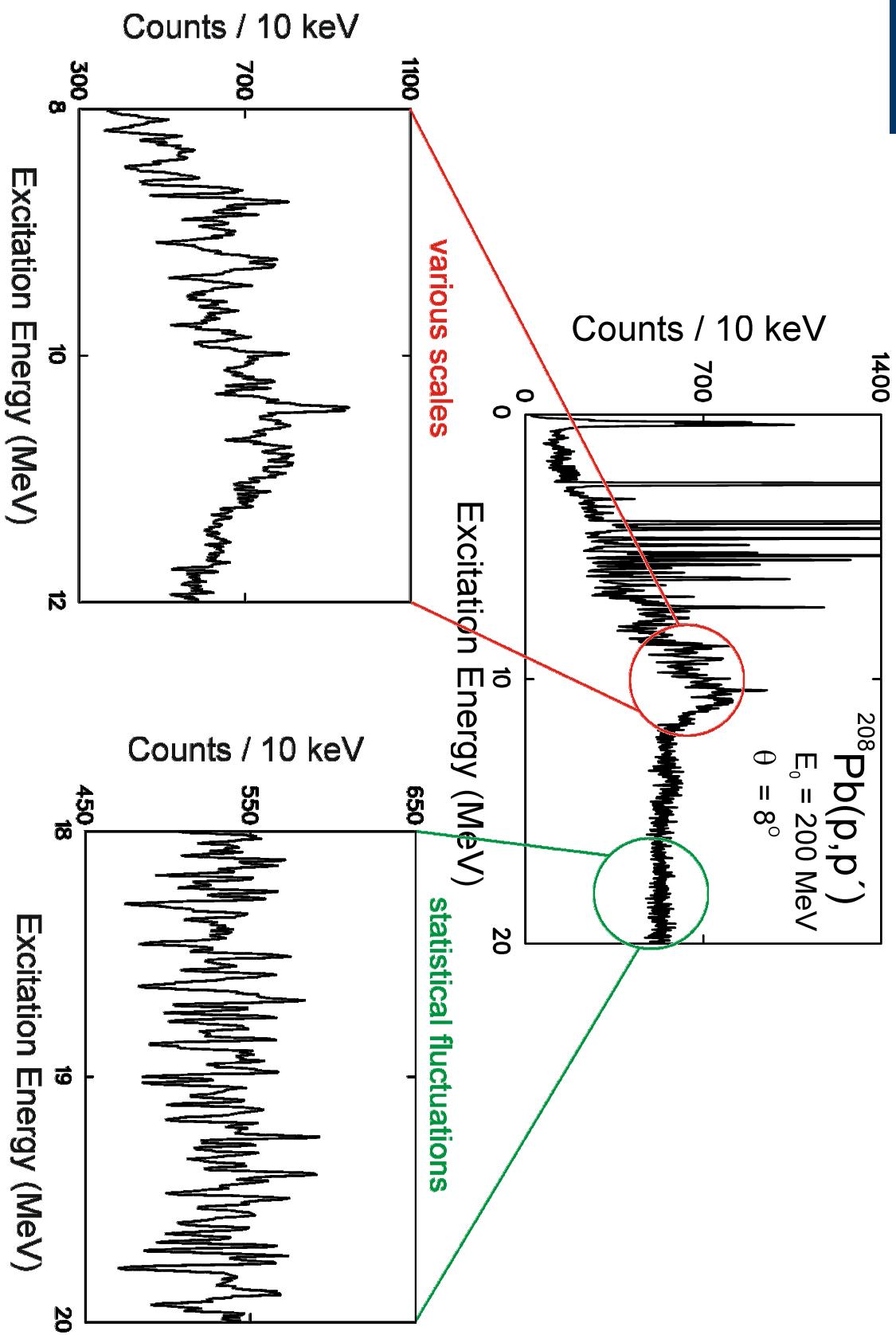
Achromatic mode

 $\Delta E \sim 100 \text{ keV}$

Lateral dispersion matching

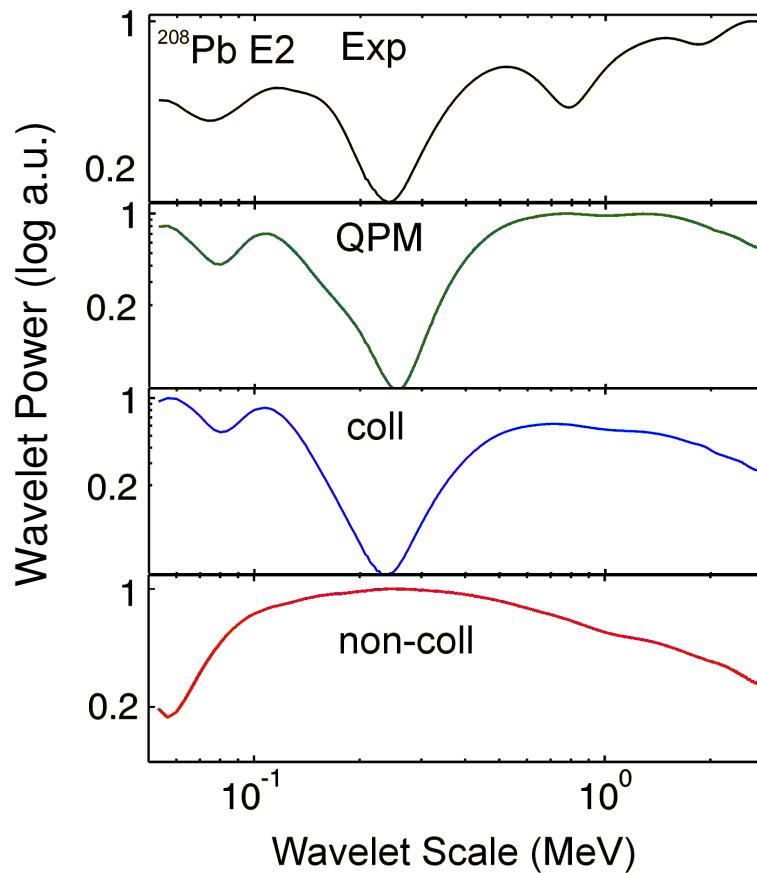
 $\Delta E \sim 30 \text{ keV}$

Scales and Fluctuations





Collective vs. Non-collective Damping in ^{208}Pb

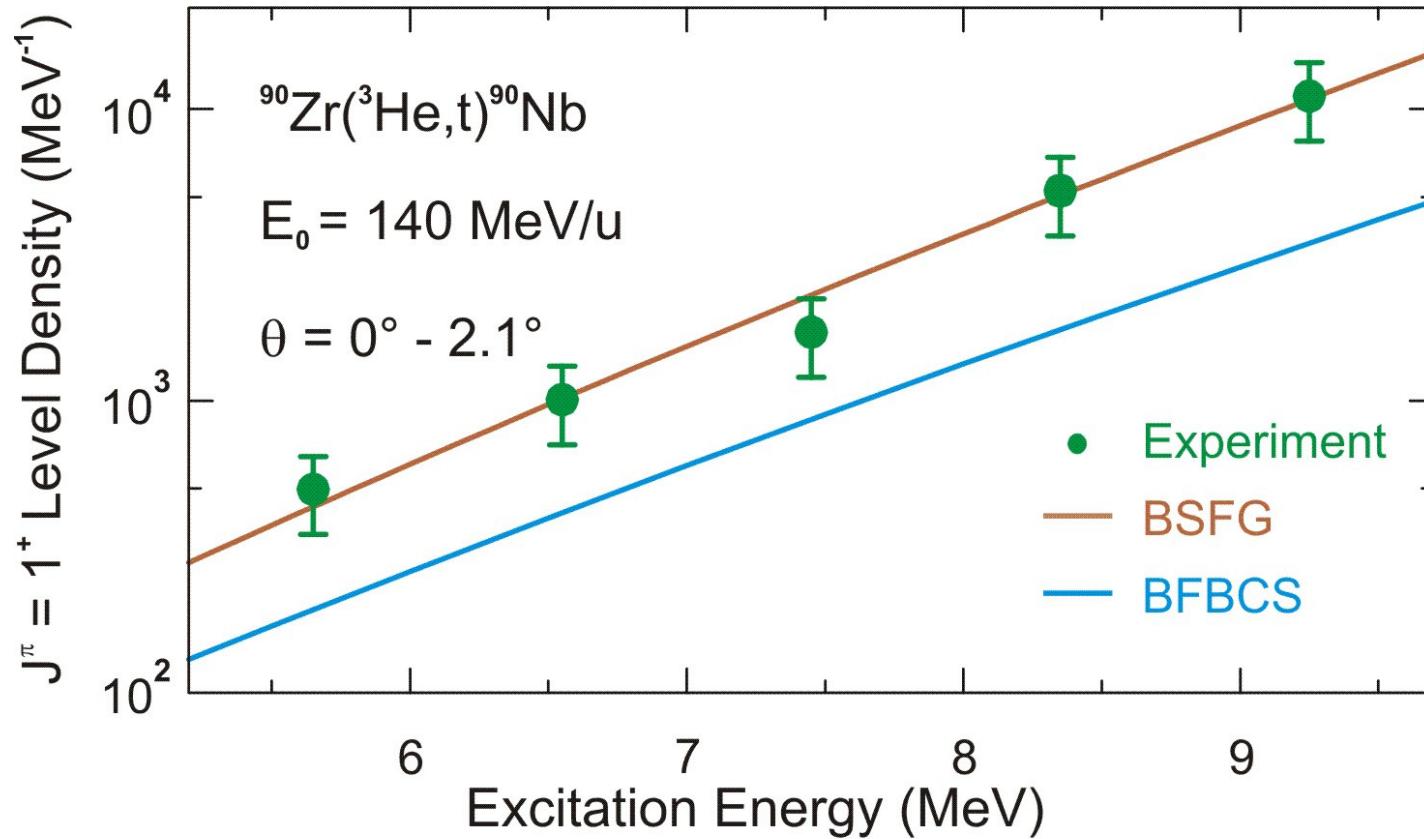


- Collective part: all scales
- Non-collective part: no prominent scales



Stochastic coupling

Spin and Parity Separated Level Densities



T. Rauscher et al. (1997)
P. Demetriou, S. Goriely (2001)

- Important for astrophysics network calculations



Application to Fluctuation Analysis

Autocorrelation function of stationary spectrum $d(E_x)$

$$C(\epsilon) = \frac{\langle d(E_x) \cdot d(E_x + \epsilon) \rangle}{\langle d(E_x) \rangle \cdot \langle d(E_x + \epsilon) \rangle}$$



Proportional to the mean level spacing

$$C(\epsilon = 0) - 1 \sim \langle D \rangle$$



Background?

Wavelet transform of spectrum $\sigma(E)$

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



Vanishing moments m of wavelet function Ψ

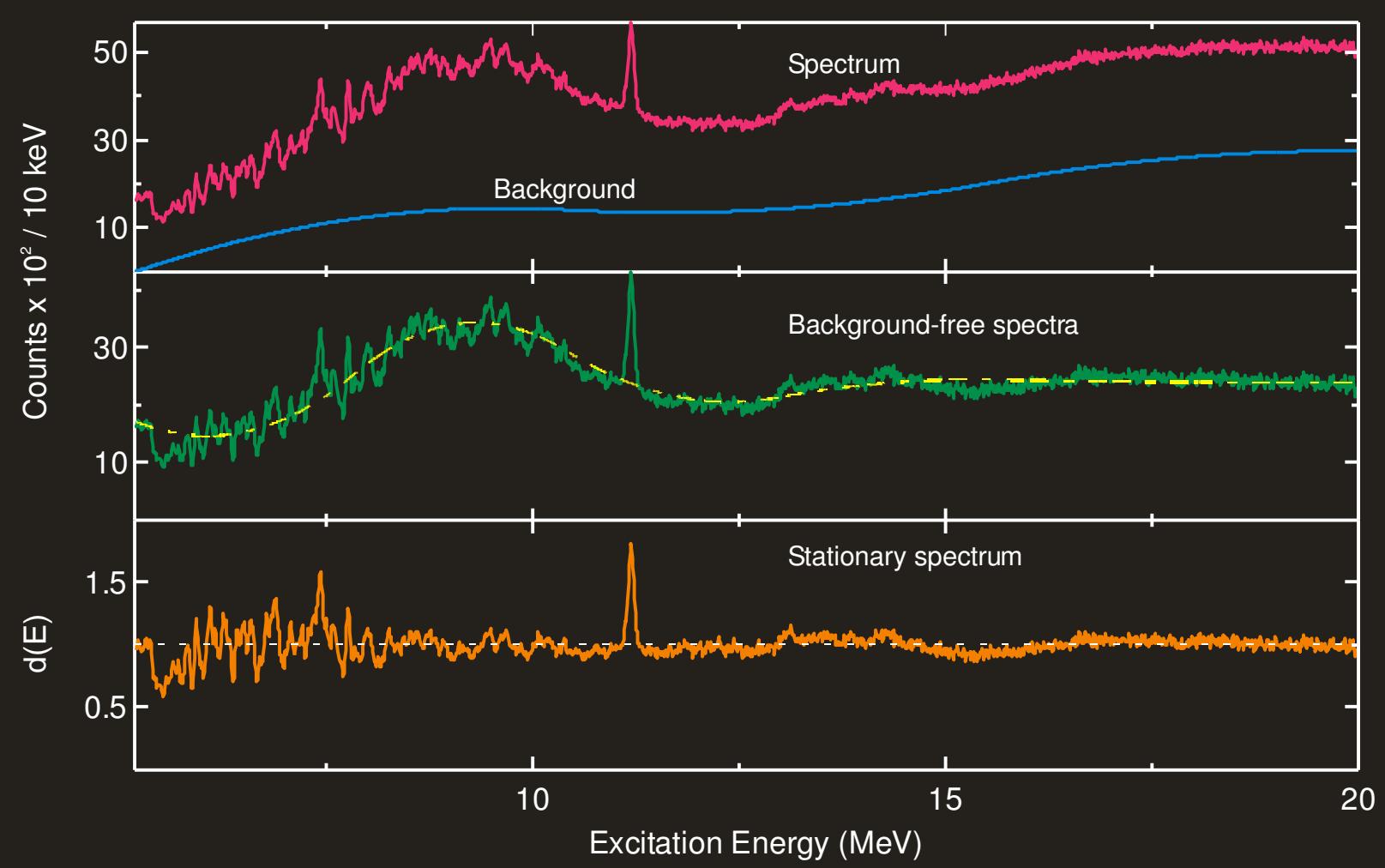
$$\int_{-\infty}^{\infty} E^n \Psi(E) dE = 0, \quad n = 0, 1 \dots m-1$$



Background suppression

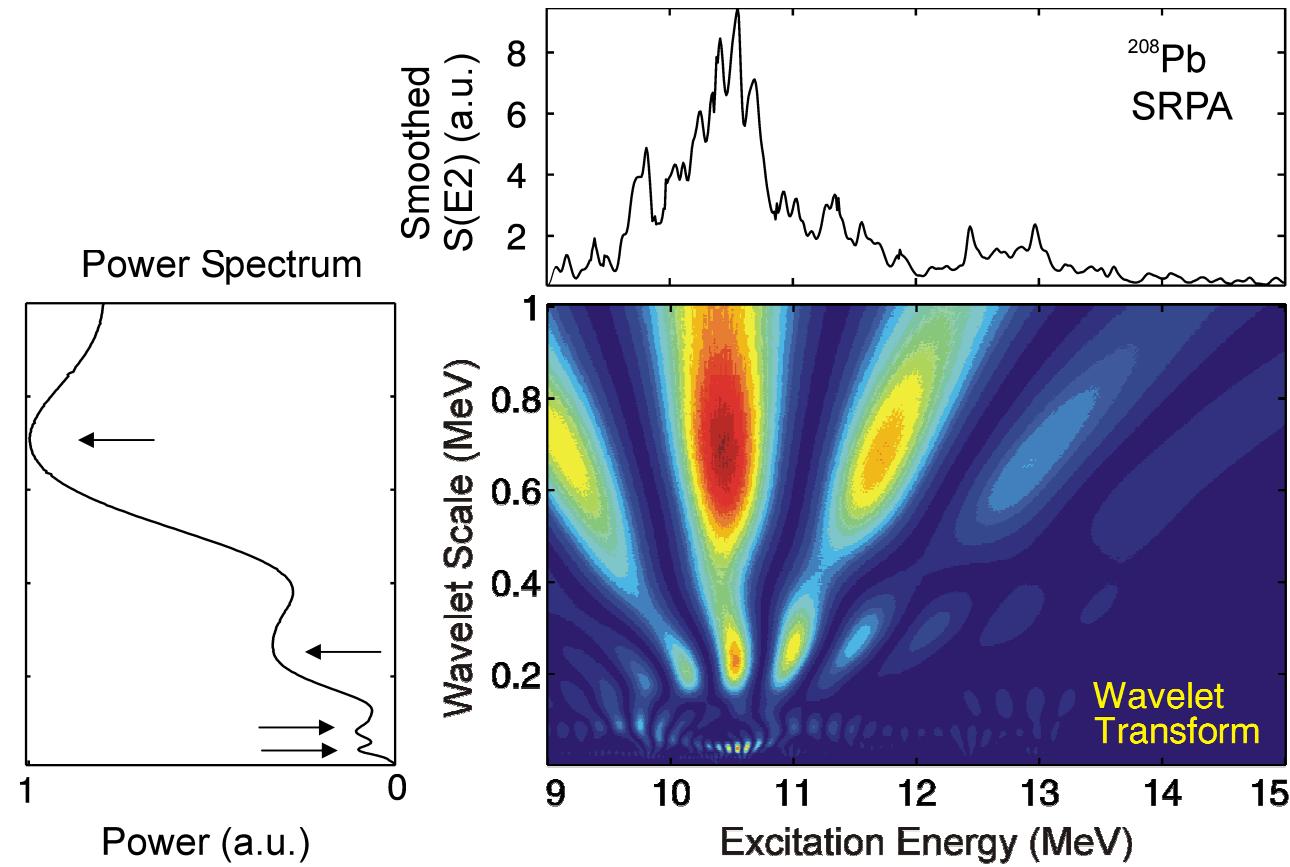
Extraction of the mean level spacing

DWT: Background and Stationary Spectrum





^{208}Pb : Second RPA



- Coupling to 2p-2h generates fine structure and scales



Summary of Scales

		Scales (keV)				
		I	II			III
ISGQR	^{58}Ni	130	360	580	850	2800 4700
	^{89}Y	120	540	830		3100
	^{90}Zr	70	540			3100
	^{120}Sn	80	220	330	470	3200
	^{142}Nd	130	420			1200 3200
	^{208}Pb	110	500			1500 2600
GTR	^{166}Er	150	250	880		2260 3260
	^{90}Nb	80	300	950		2500

- Three classes of scales
- Class I scales appear in all nuclei
- Class II scales change with mass number
- Class III scales gross structure (e.g. width)