Collective Quadrupole Modes in Nuclei – New Insights into Old Problems*

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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

Identification of Mixed-Symmetry States: Interacting Boson Model

- Pairing of nucleons to s- / d-bosons
- F-Spin: π boson: $F_0 = 1/2$
  υ boson: $F_0 = -1/2$

$$\frac{|N_\pi - N_\upsilon|}{2} \leq F \leq F_{max} = \frac{N_\pi + N_\upsilon}{2}$$

⟶ $F = F_{max}$: symmetric states

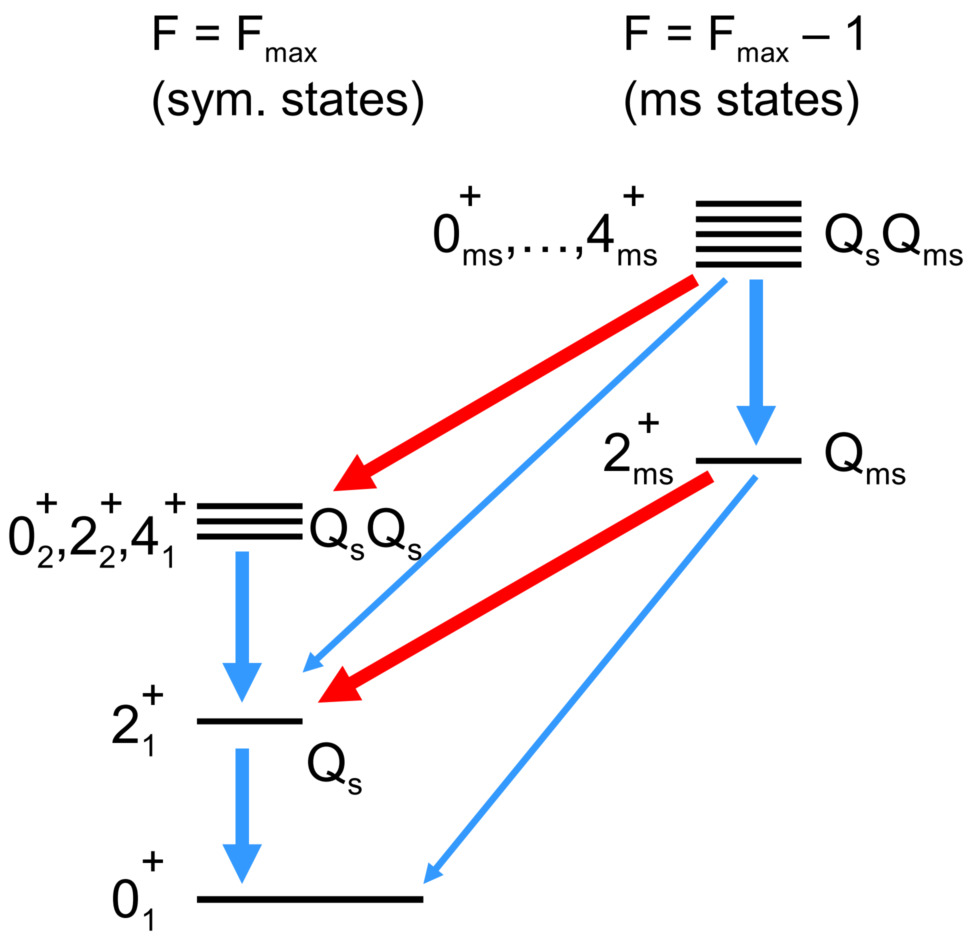
⟶ $F < F_{max}$: mixed-symmetry states (ms)

- Q-phonon scheme:

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

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

Identification of Mixed-Symmetry States: Q-Phonon Scheme



- Strong E2 transitions for decay of symmetric Q-phonon
- Weak E2 transitions for decay of ms Q-phonon
- Strong M1 transitions for decay of ms states to symmetric states

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´)
  $\longrightarrow$ isoscalar / isovector decomposition
  $\longrightarrow$ sensitive to one-phonon components of the wave function

Identification of Mixed-Symmetry States: Experiments

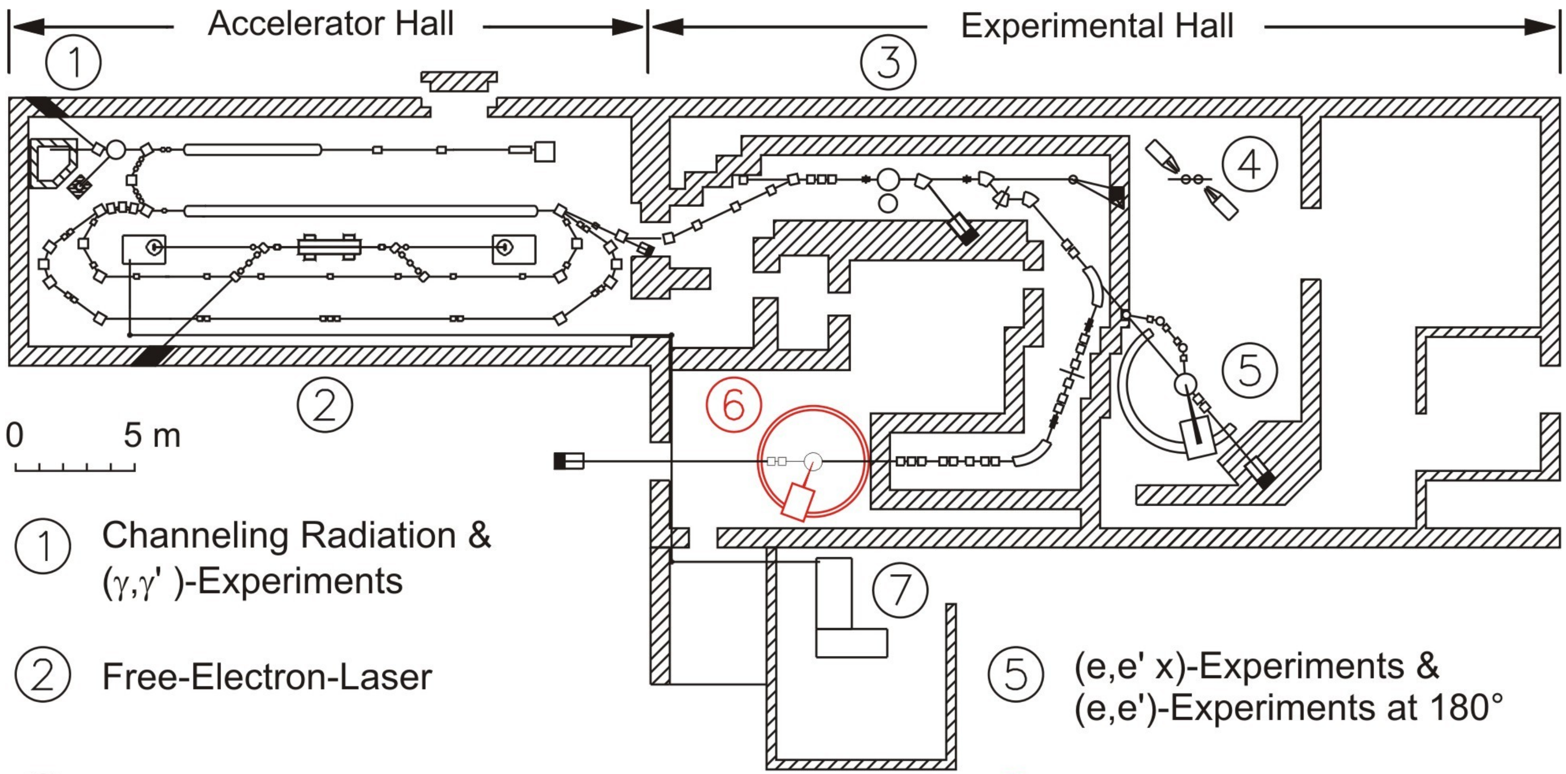
- High resolution required to resolve all 2^+ states below 4 MeV
- Lateral dispersion matching techniques
- (e,e´):
  S-DALINAC, TU Darmstadt

  E_e = 70 MeV
  Θ = 93°- 165°
  Δ E = 30 keV (FWHM)

- (p,p´):
  SSC, iThemba LABS

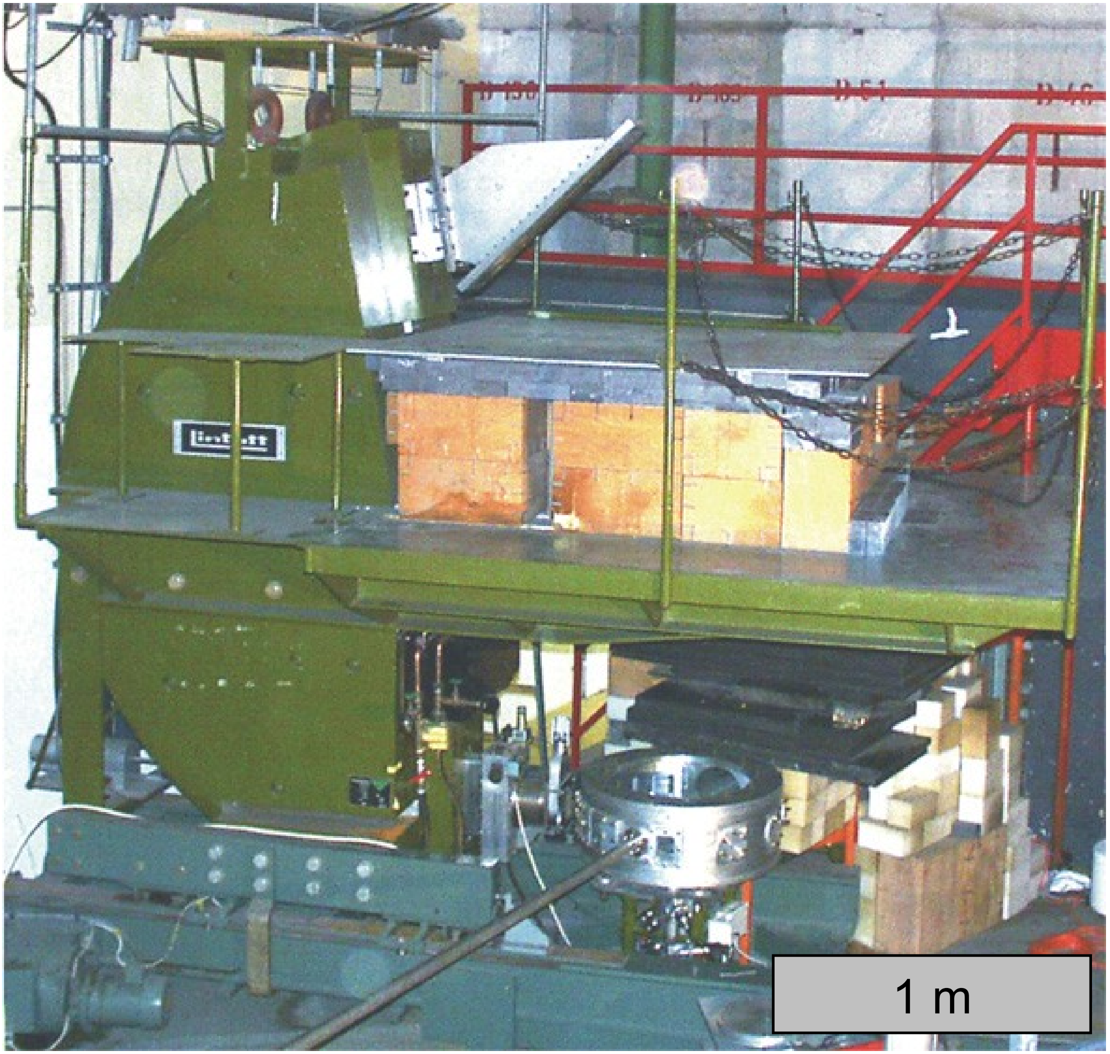
  E_p = 200 MeV
  Θ = 7°- 26°
  Δ E = 35 keV (FWHM)

S-DALINAC and its Experimental Facilities

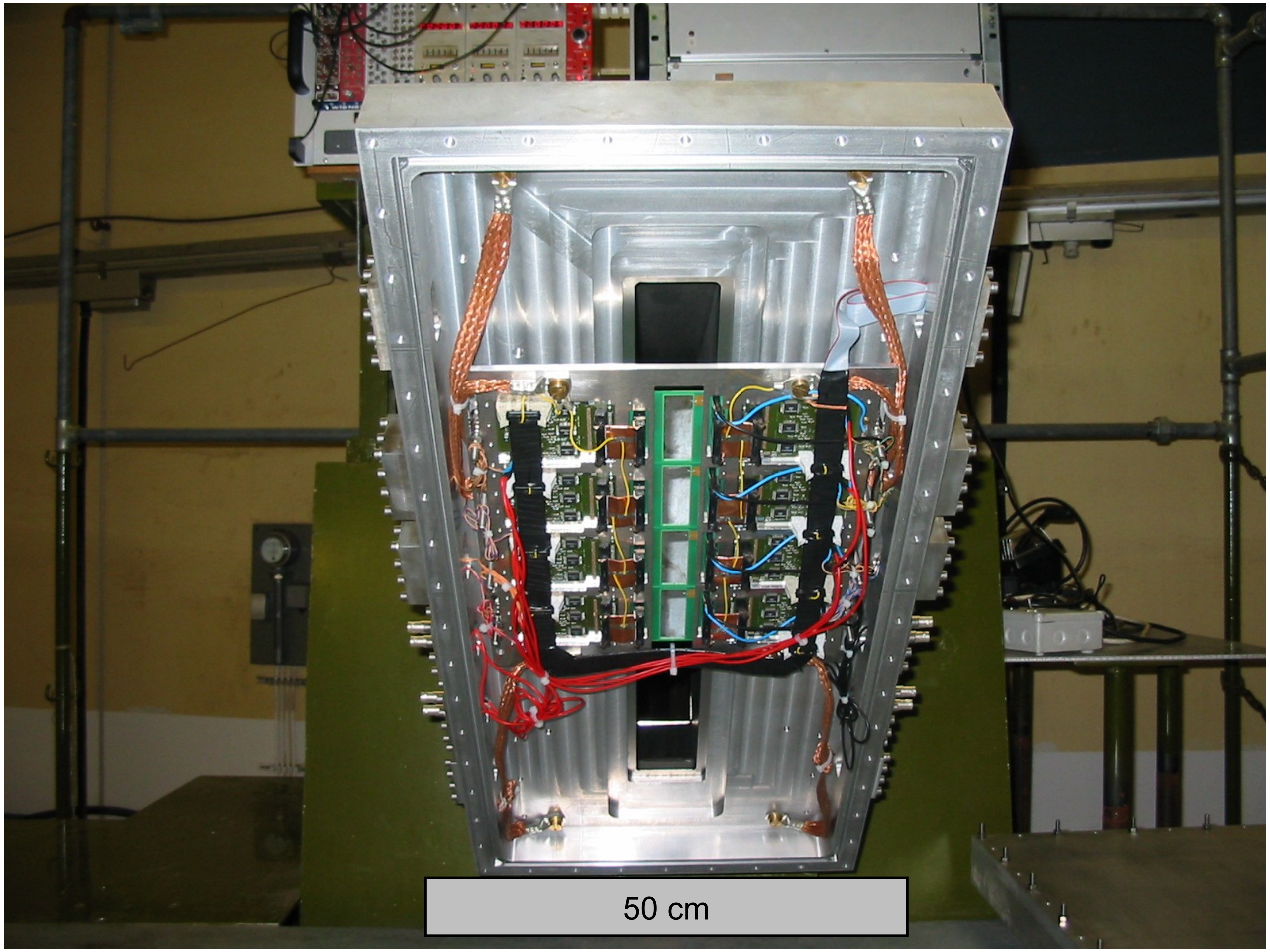


1. Channeling Radiation & (γ,γ')-Experiments
2. Free-Electron-Laser
3. High Energy Radiation Physics
4. Compton Scattering on Nucleons
5. (e,e' x)-Experiments & (e,e')-Experiments at 180°
6. (e,e')-Experiments
7. Optics Experiments

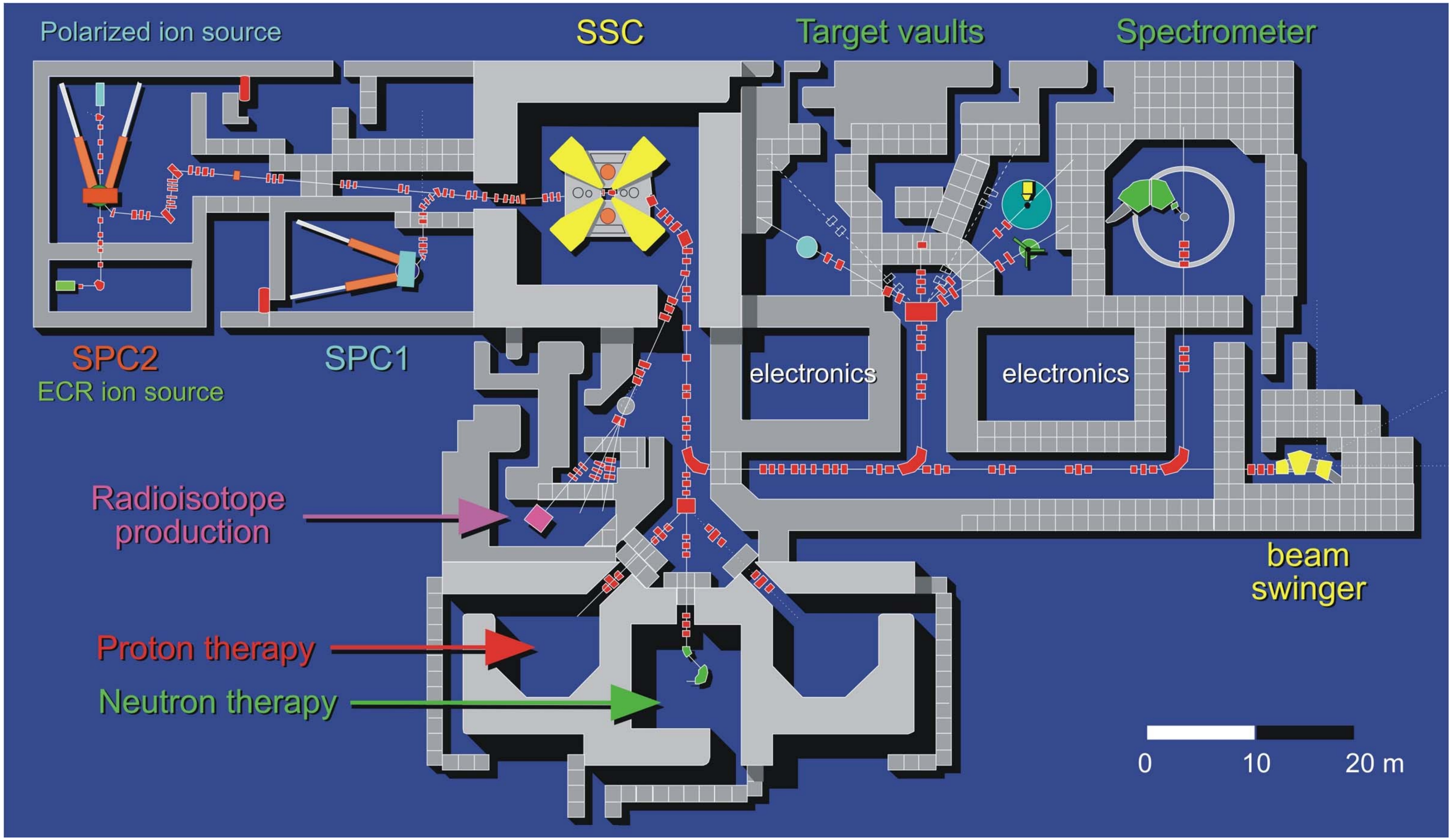
LINTOTT- Spectrometer



Focal Plane Detector System: Si-Microstrip Detectors



Separated-Sector Cyclotron Facility



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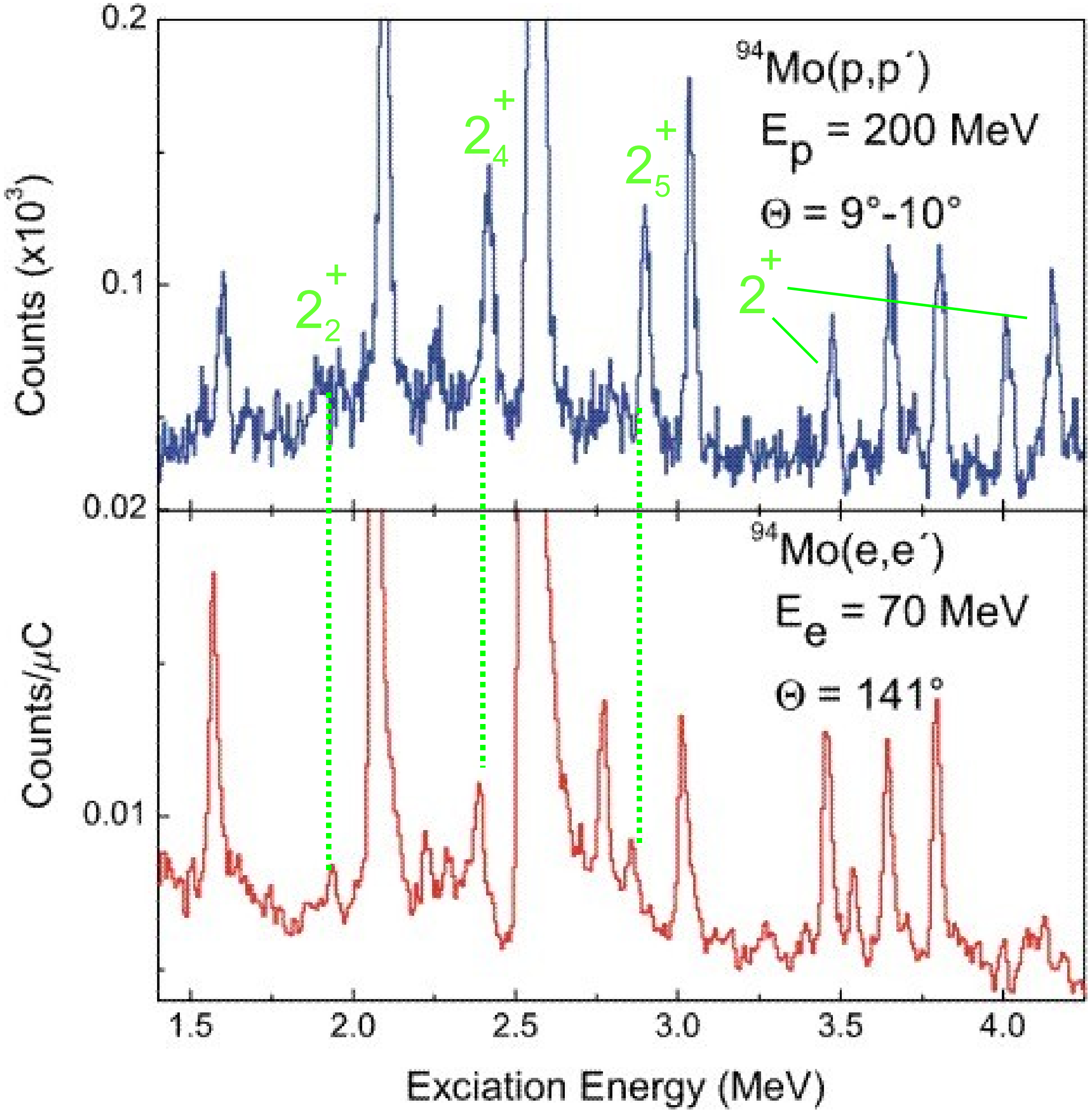
SFB 634

Measured Spectra

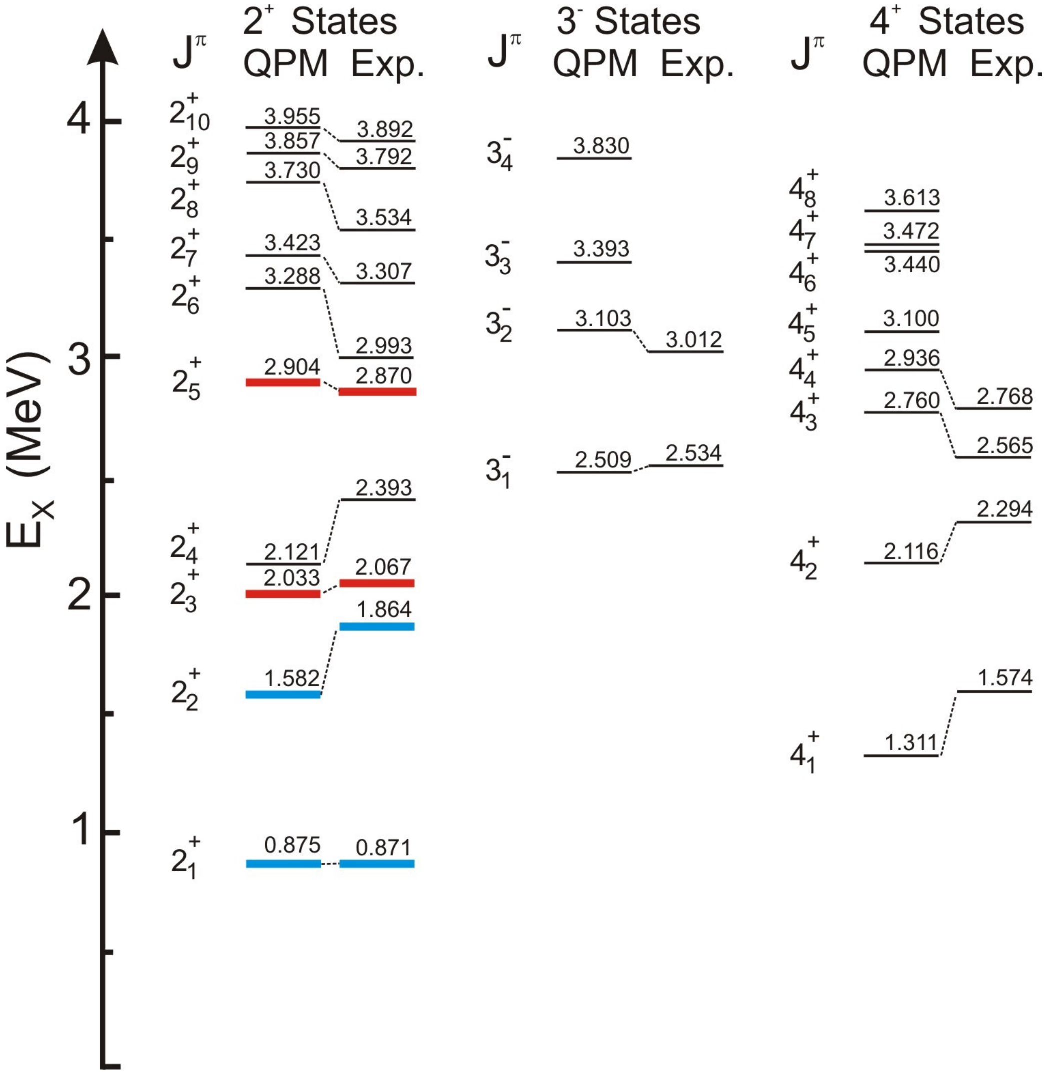


Theoretical Calculation of Cross Sections

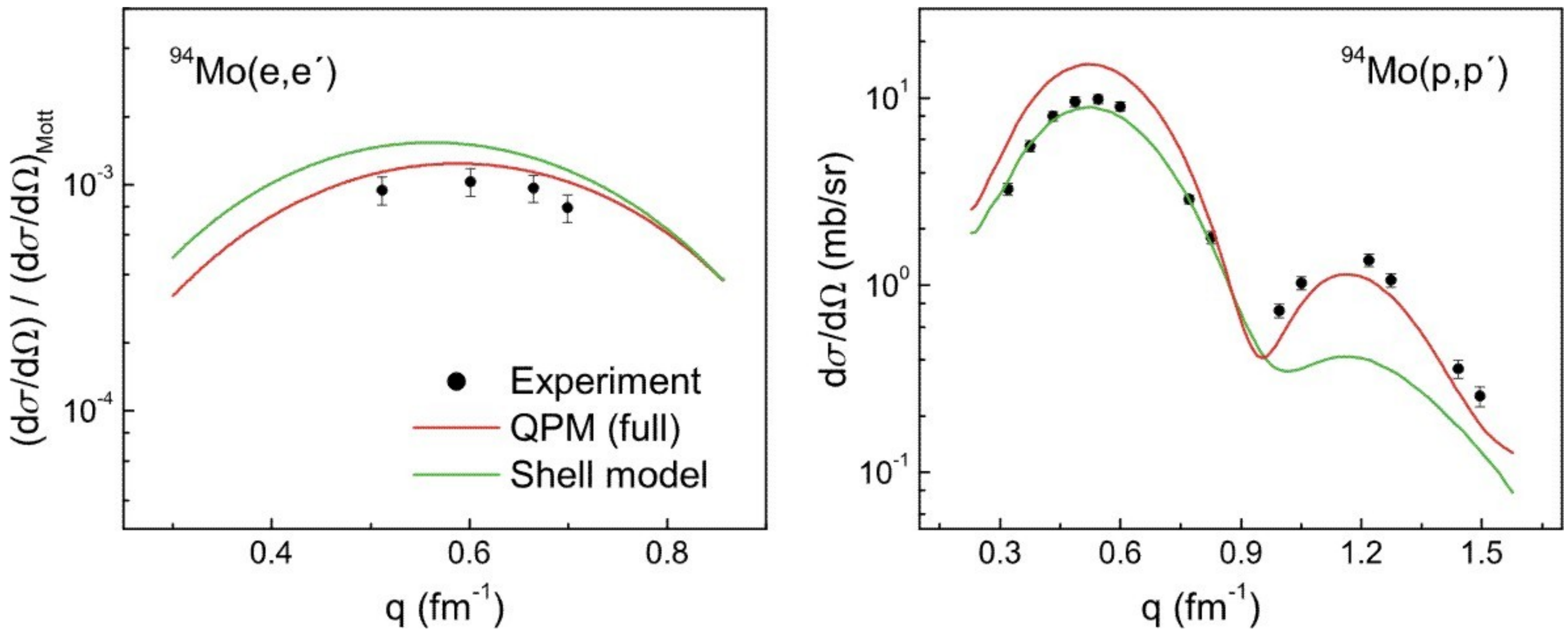
Wave functions:

- 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)

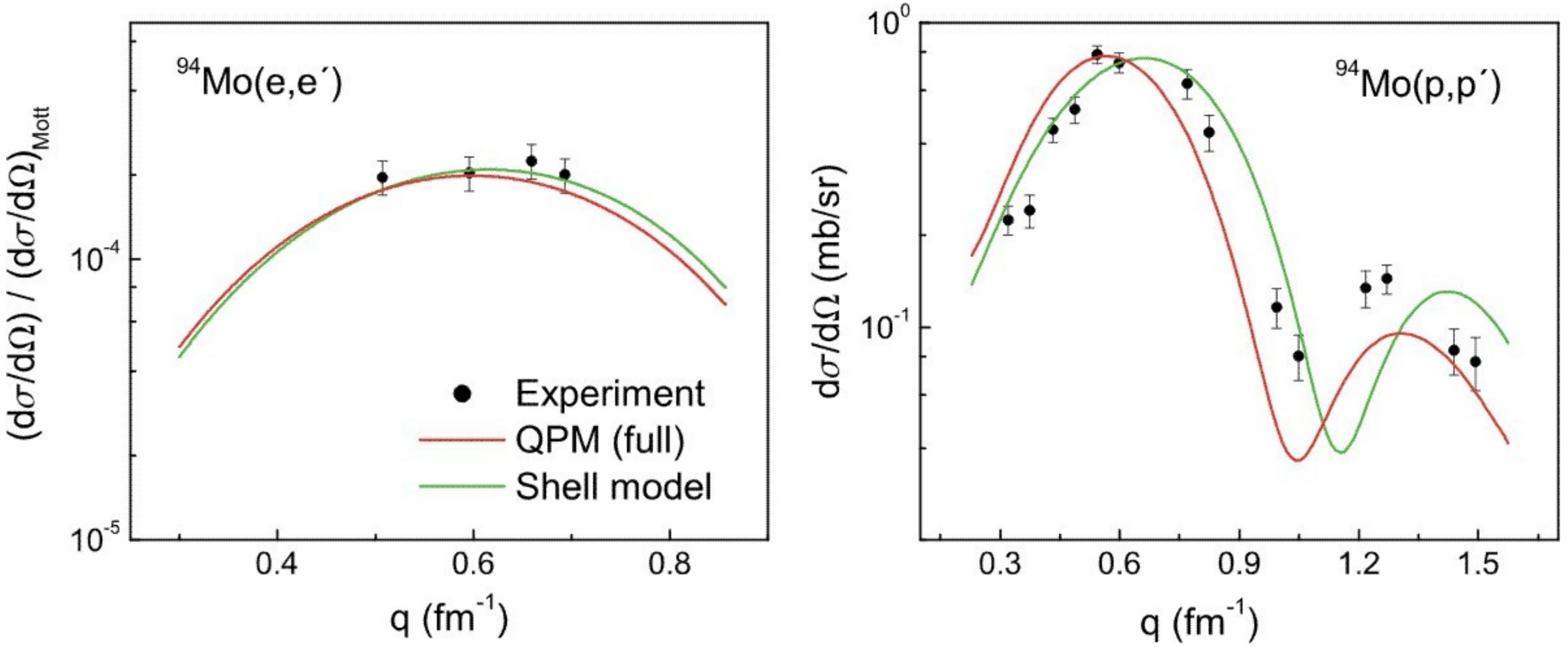
QPM Predictions



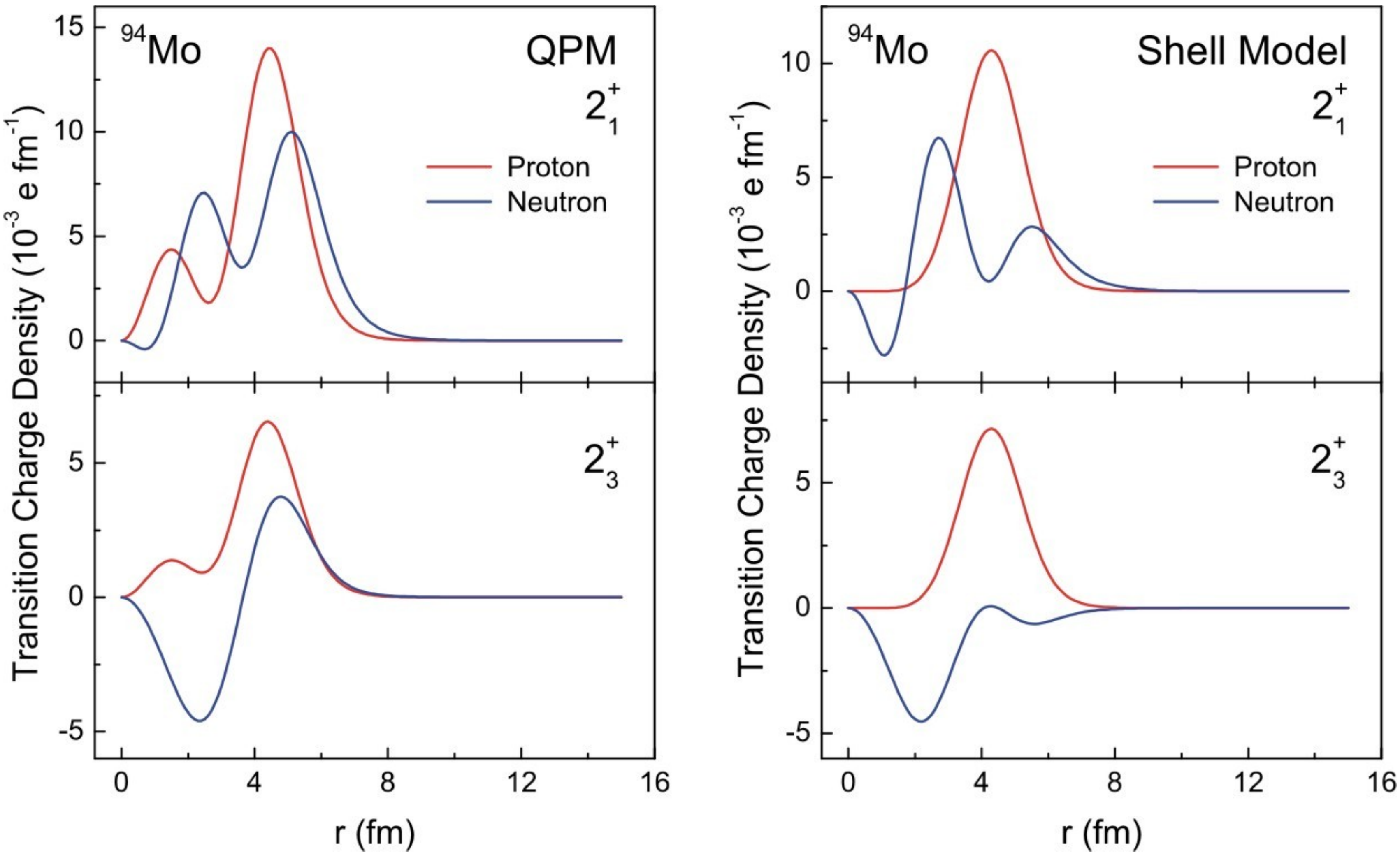
One-Phonon Symmetric State: E_x = 0.871 MeV



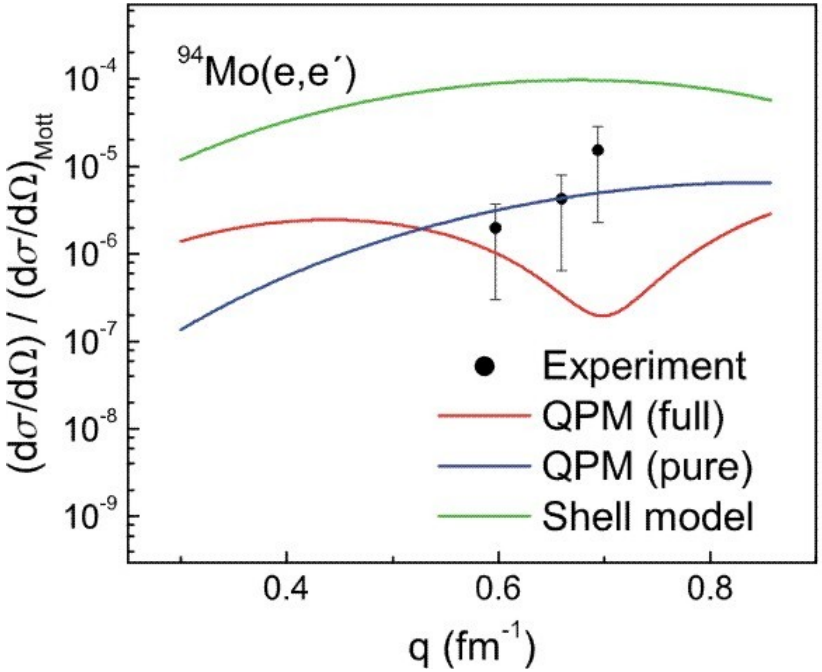
One-Phonon Mixed-Symmetry State: E_x = 2.067 MeV

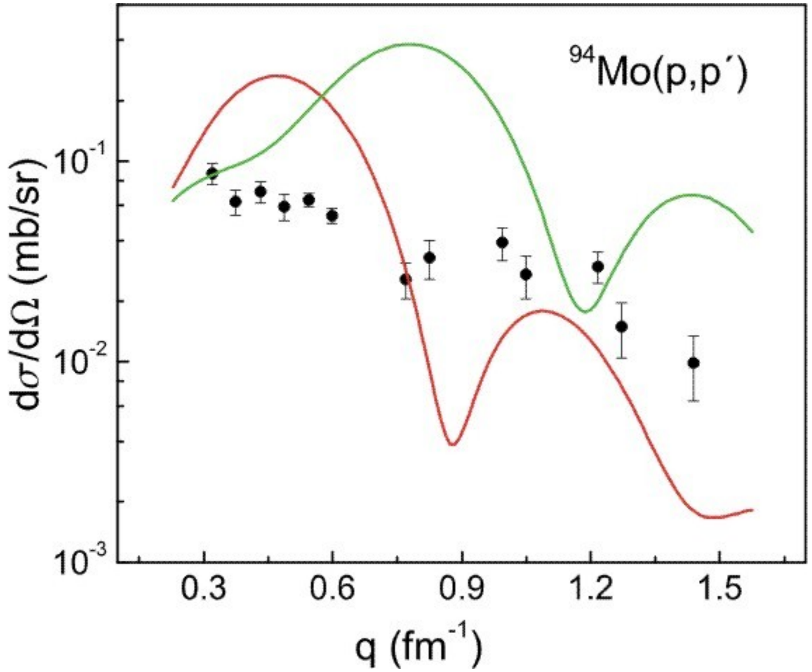


Radial Transition Charge Densities



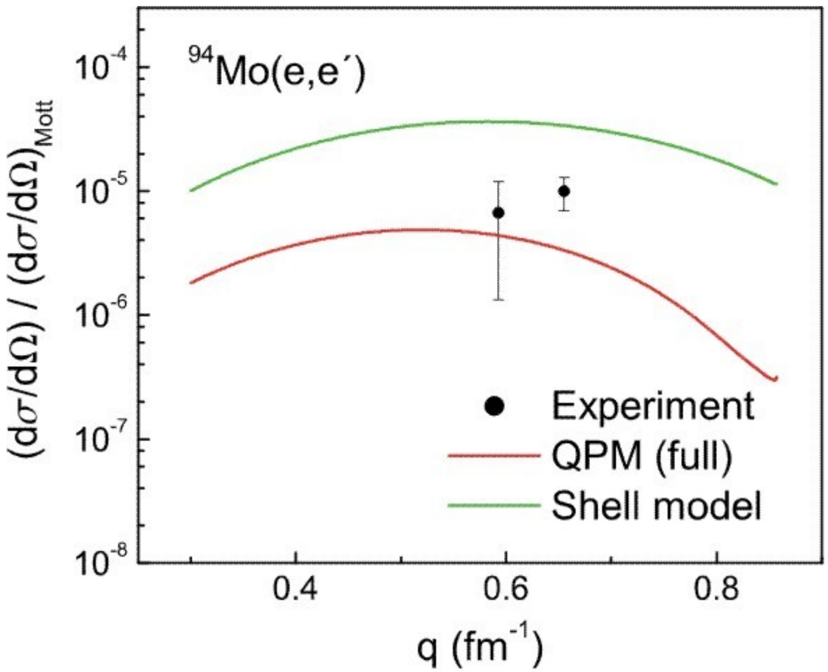
Two-Phonon Symmetric State: E_x = 1.864 MeV

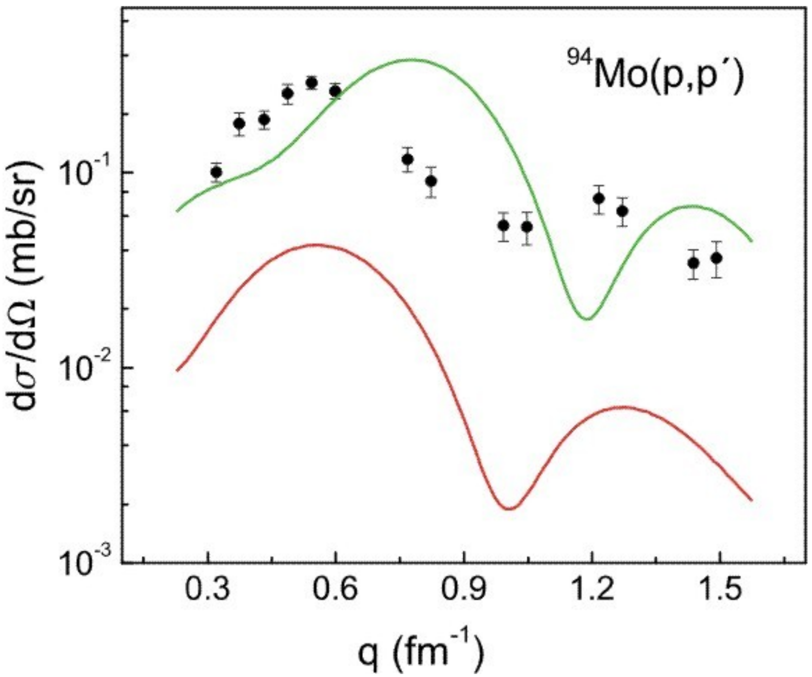




- pure two-phonon state
- two-step contributions?

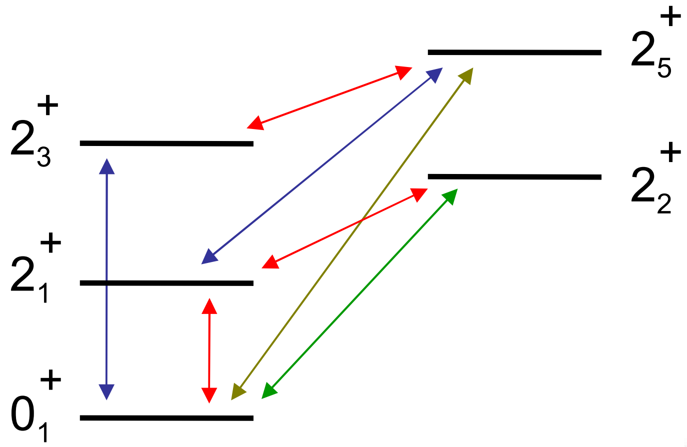
Two-Phonon Mixed-Symmetry State: E_x = 2.87 MeV





- 5 – 10 % one-phonon admixture
- two-step contributions?

Coupled-Channel Analysis

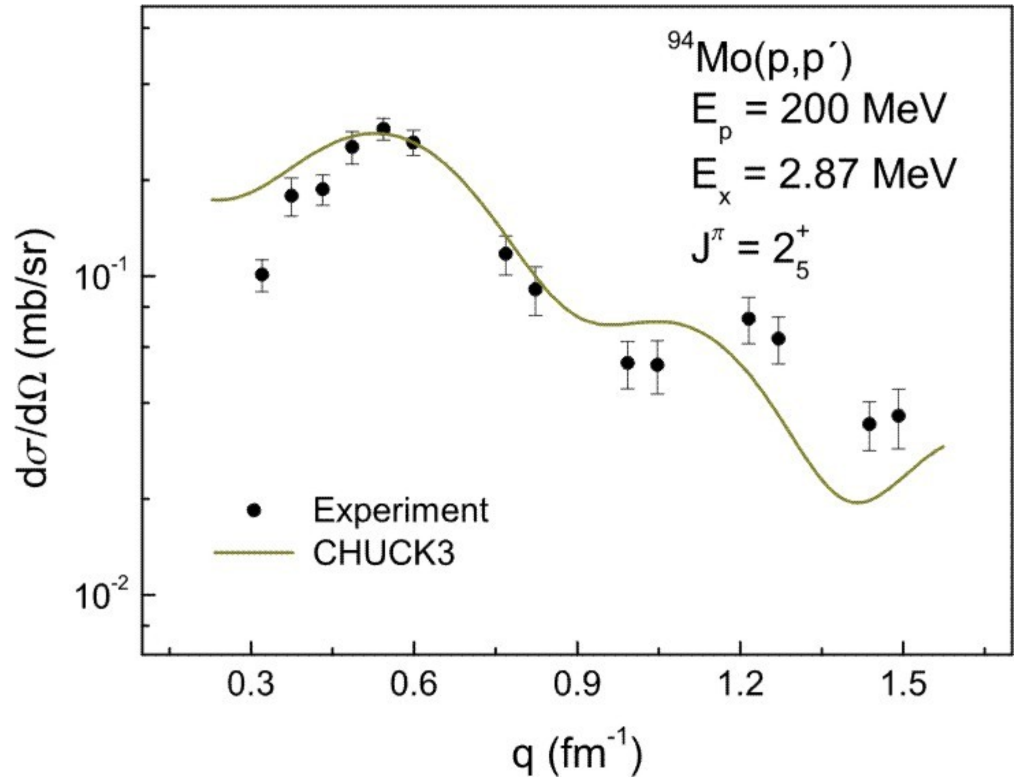


β = 1.23

β = 0.35

β = 0.0

β = 0.2



- Admixture to two-phonon symmetric state confirmed

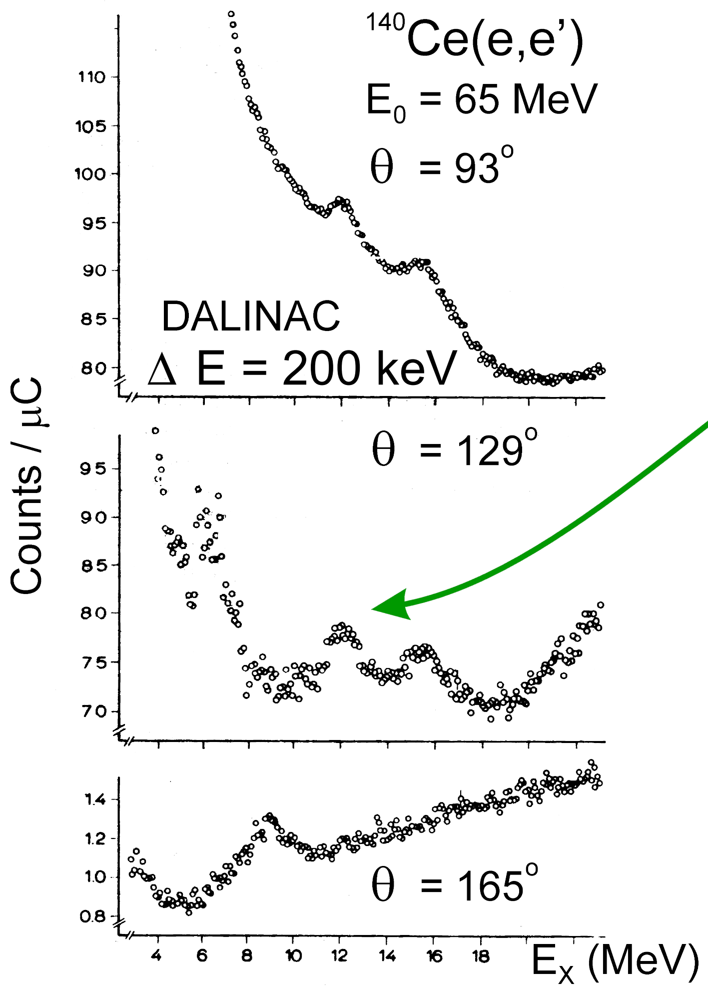
Summary: First Part

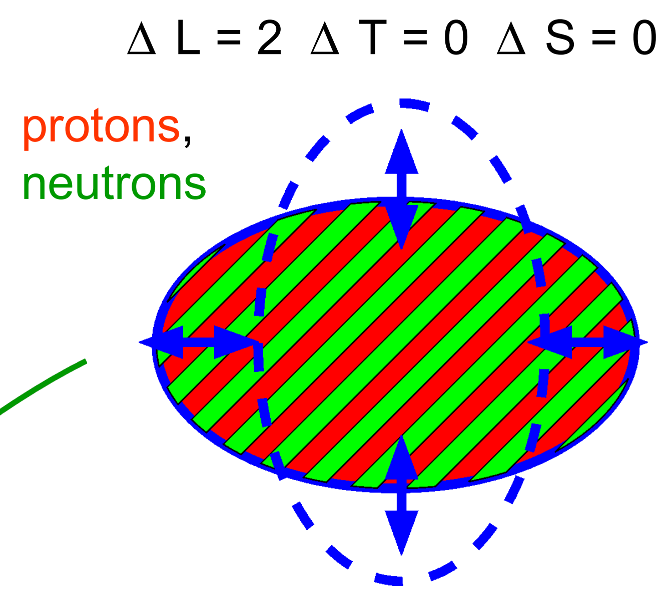
- Study of one- and two-phonon 2^+ states in ^{94}Mo with high-resolution (e,e´) and (p,p´) experiments
- Combined analysis with QPM reveals
  - → symmetric and mixed-symmetric character of one-phonon states
  - → two-phonon symmetric state extremely pure
  - → about 25% admixtures in the two-phonon 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

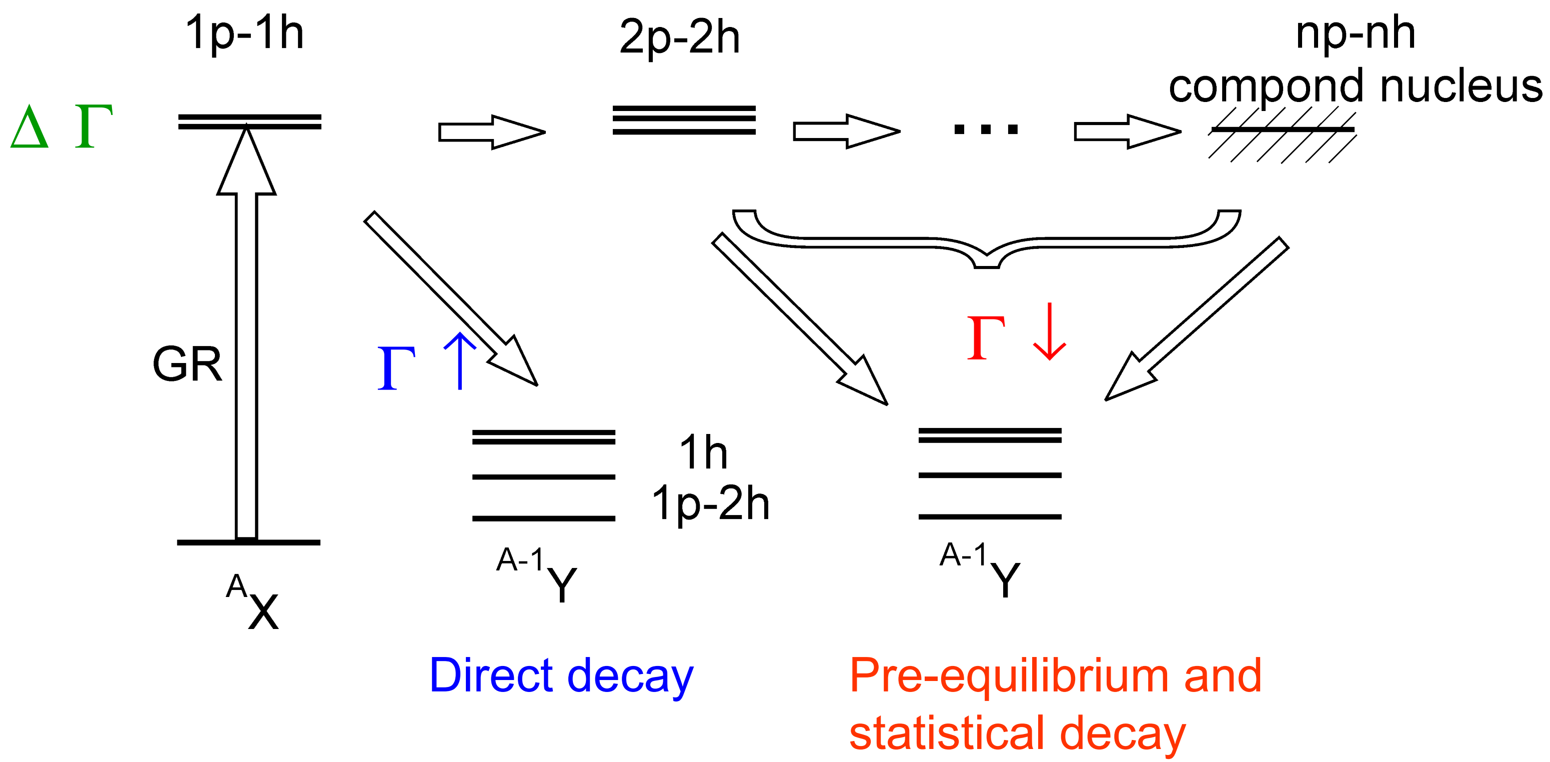
Damping of GR: Isoscalar Quadrupole Mode





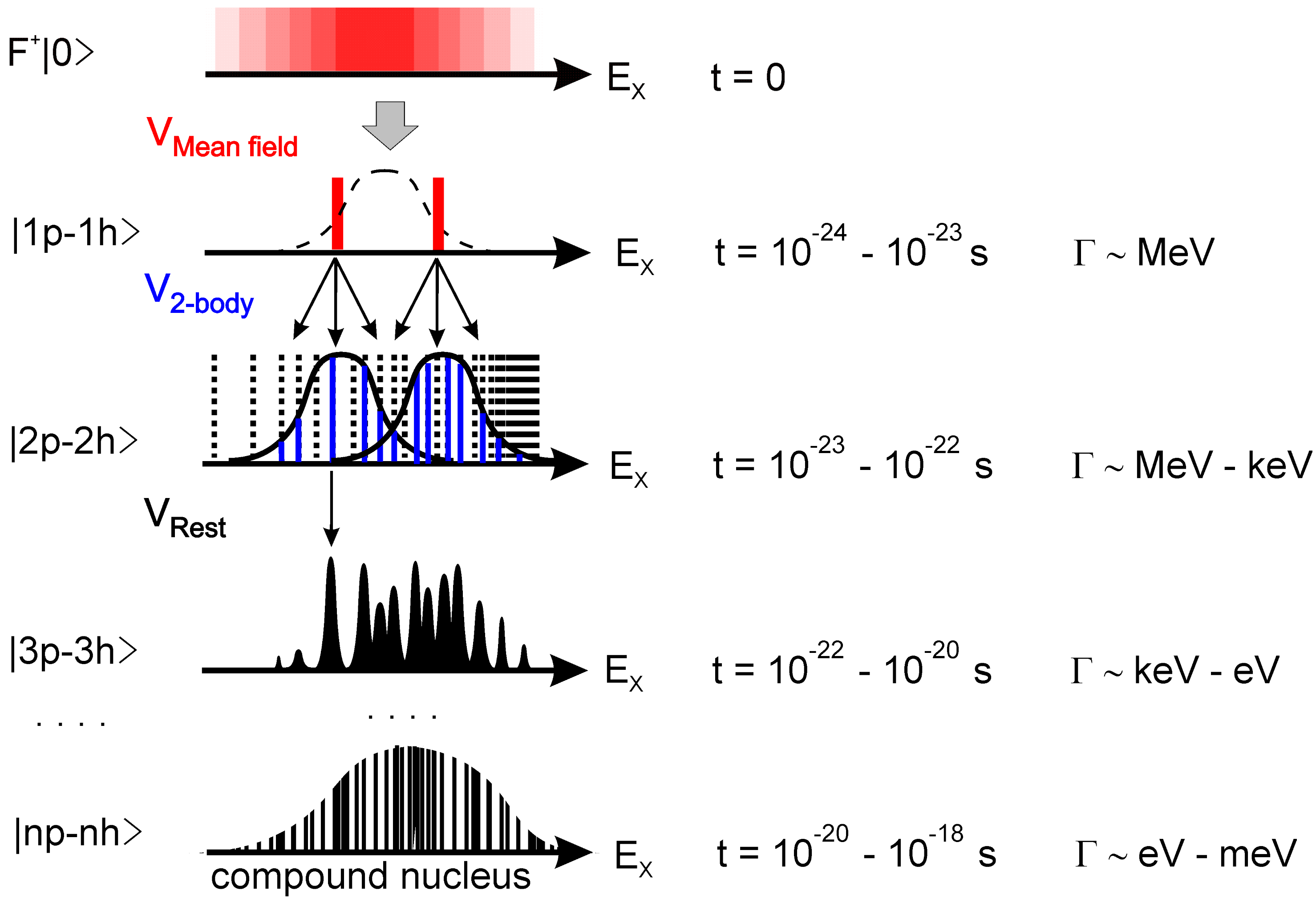
- Pitthan and Walcher (Darmstadt, 1972)
- Centroid energy: $E_c \sim 63\ A^{-1/3}$ MeV
- Width
- Damping mechanisms?

Excitation and Decay of Giant Resonances

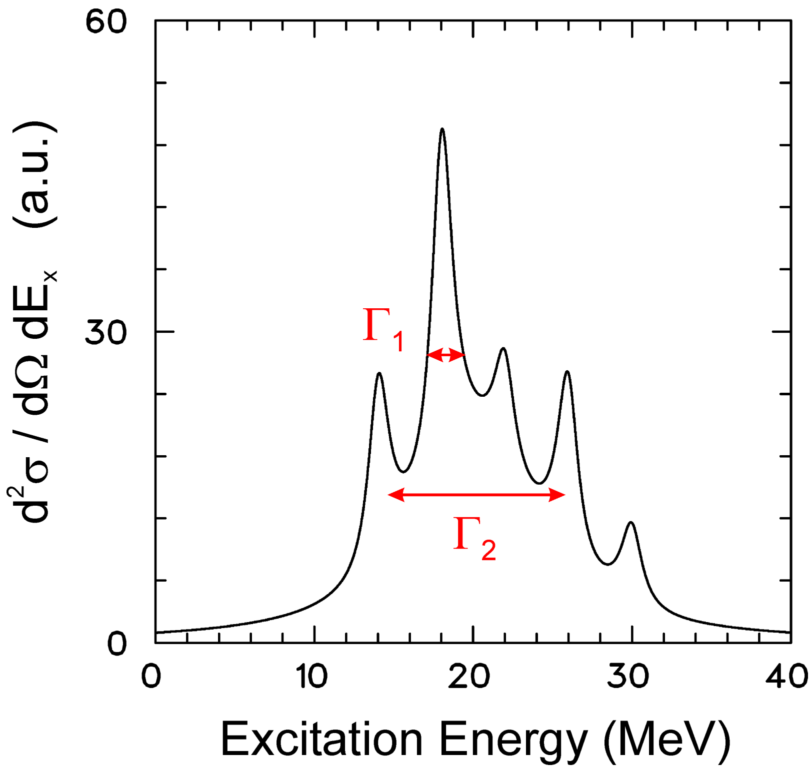


Resonance decay width: $\Gamma = \Delta\Gamma + \Gamma\uparrow + \Gamma\downarrow$

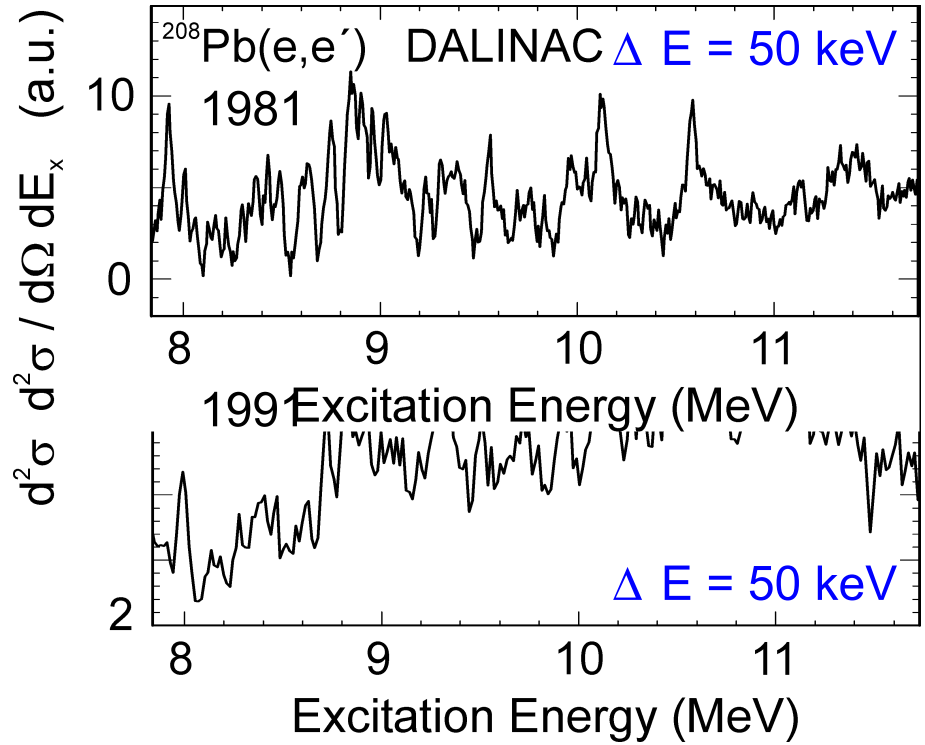
Doorway-State Model



Fine Structure of Giant Resonances



ISGQR in ^{208}Pb



- High resolution is crucial
- Different probes but similar structures

Fine Structure of Giant Resonances

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

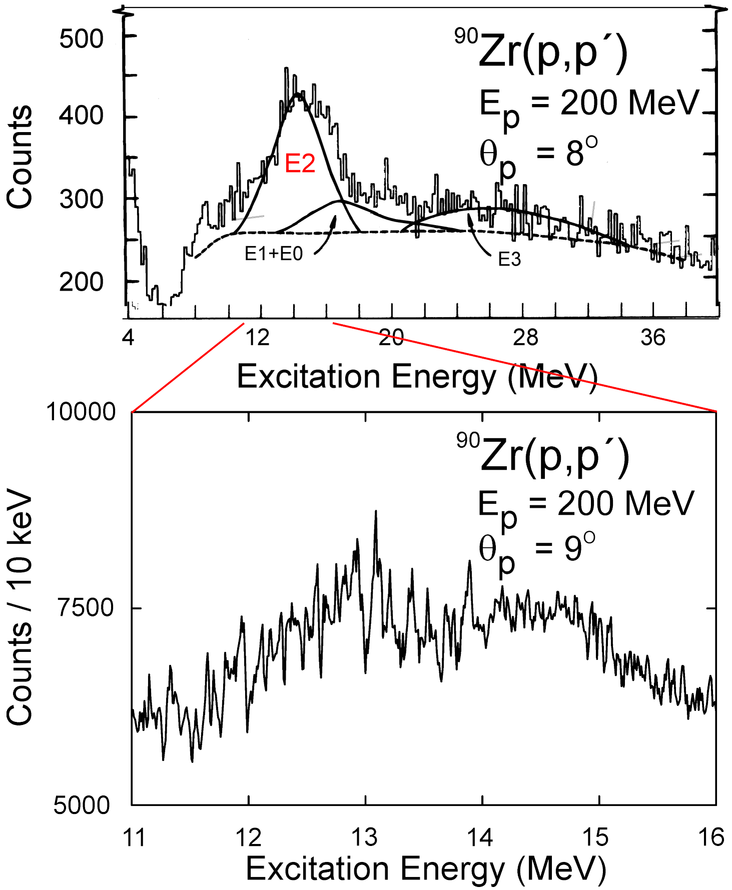
New Experiments

Place:	iThemba LABS, South Africa	RCNP, Osaka
Reaction:	ISGQR from (p,p´)	GT from (^{3}He,t)

	^{58}Ni	^{89}Y	^{90}Zr	^{120}Sn	^{142}Nd	^{166}Er	^{208}Pb		^{90}Zr	^{168}Er
A	58	89	90	120	142	166	208		90	168
Z	28	39	40	50	60	68	82		40	68
N	30	50	50	70	82	98	126		50	100

Beam energy:	200 MeV	140 MeV/u
Scattering angles:	8° – 10° (Δ L = 2)	0° (Δ L = 0)
Energy resolution: (FWHM)	Δ E = 35 - 50 keV	Δ E = 50 keV

Fine Structure of the ISGQR



$\Delta E \approx 1$ MeV

TRIUMF

(1981)

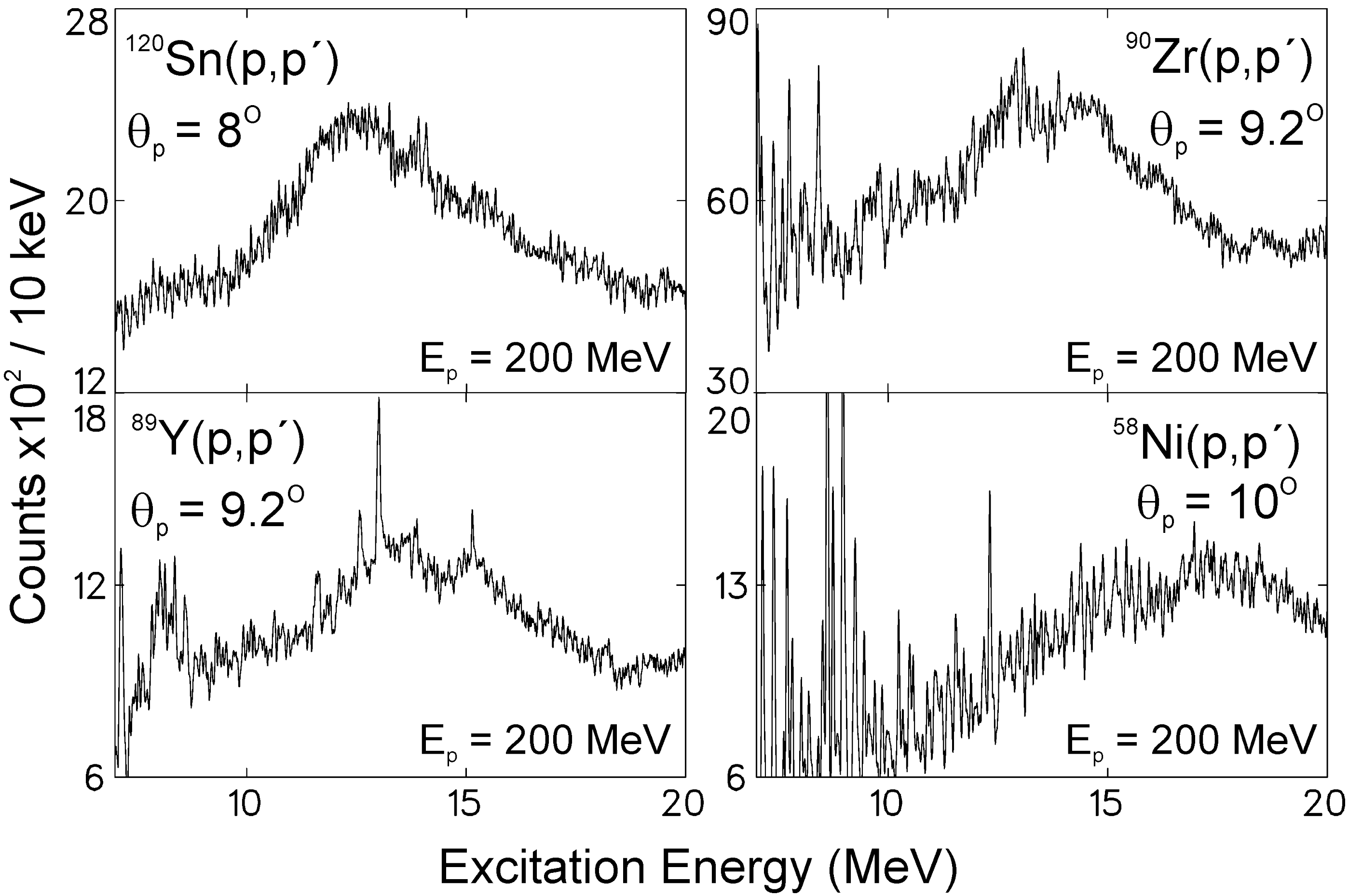
$\Delta E \approx 40$ keV

iTHEMBA

(2004)

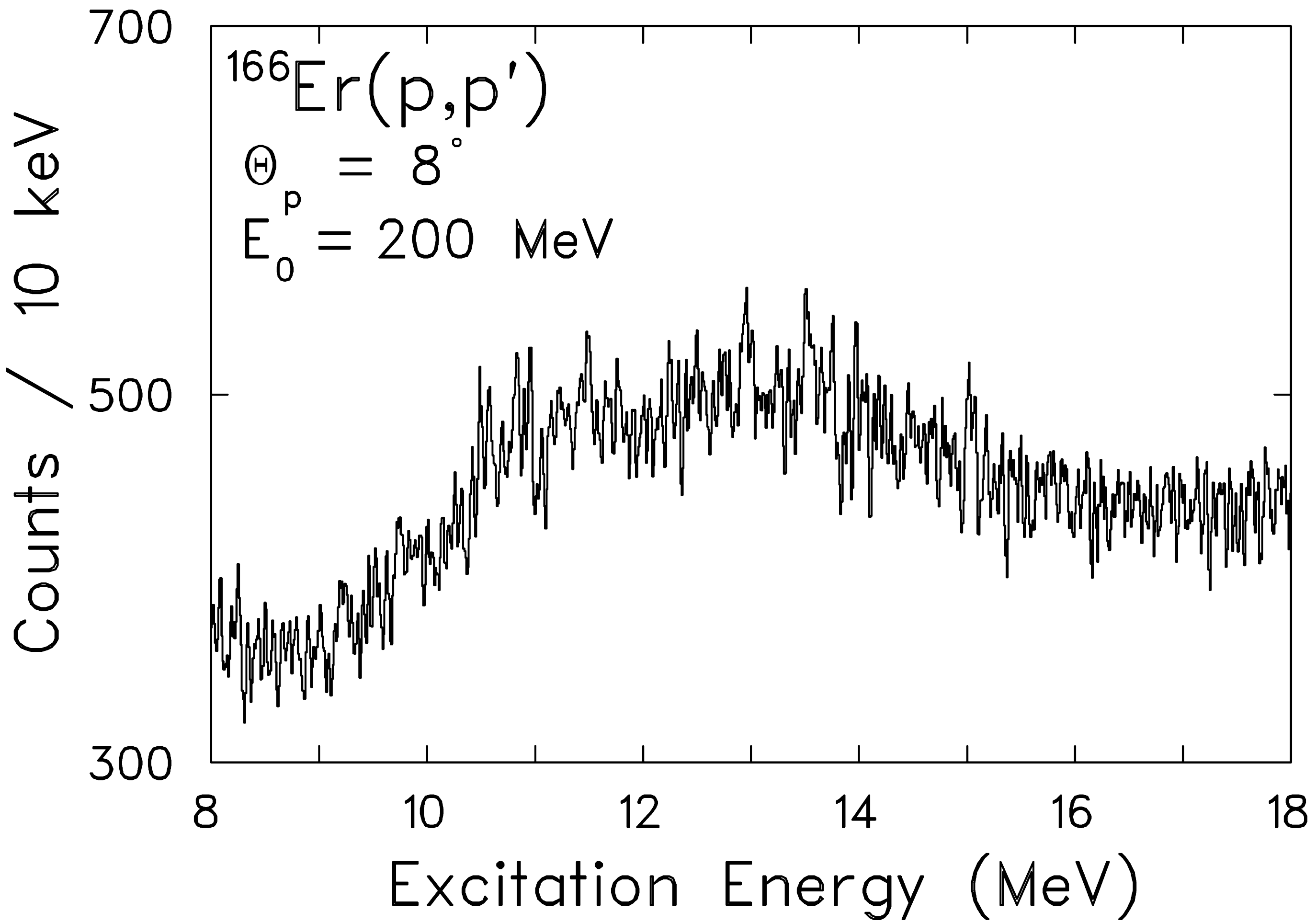
- Not a Lorentzian

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
- Local scaling dimension

→ **Wavelet transform from signal processing**

Wavelet Analysis

Wavelet coefficients:

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

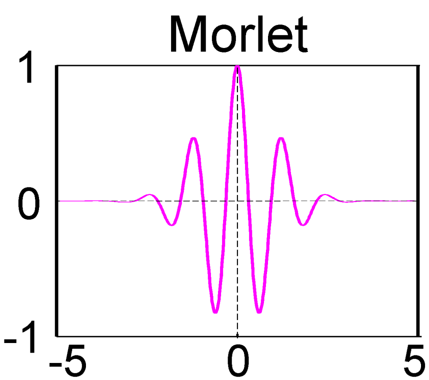
scale (δE) — position (E_x) — spectrum (σ(E)) — wavelet (Ψ*)

Continuous: δE, E_x are varied continuously

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

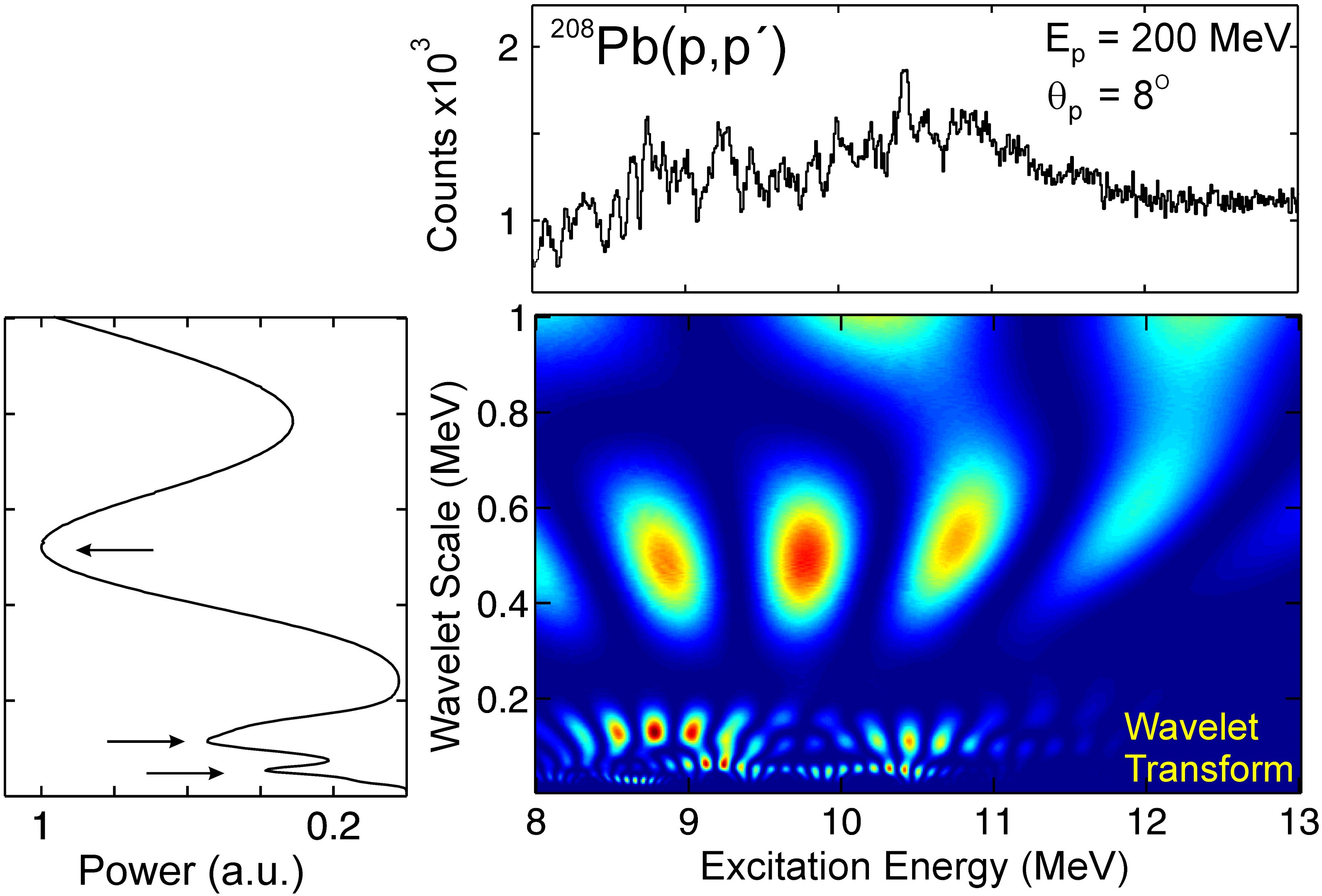
and

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



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

Application: ISGQR in ^{208}Pb(p,p´)

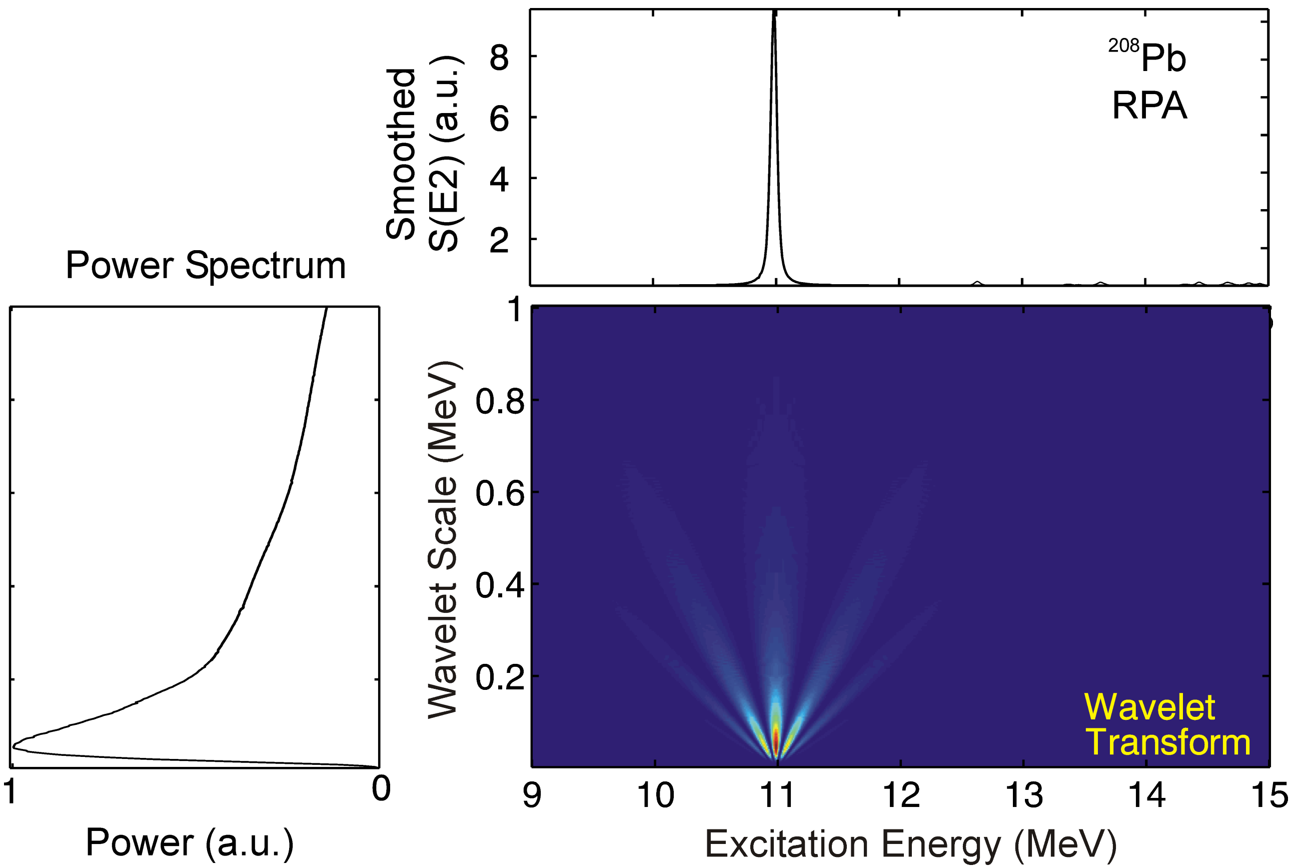


Summary of Scales

		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
	^{166}Er	150	250 880	2260 3260
GTR	^{90}Nb	80	300 950	2500

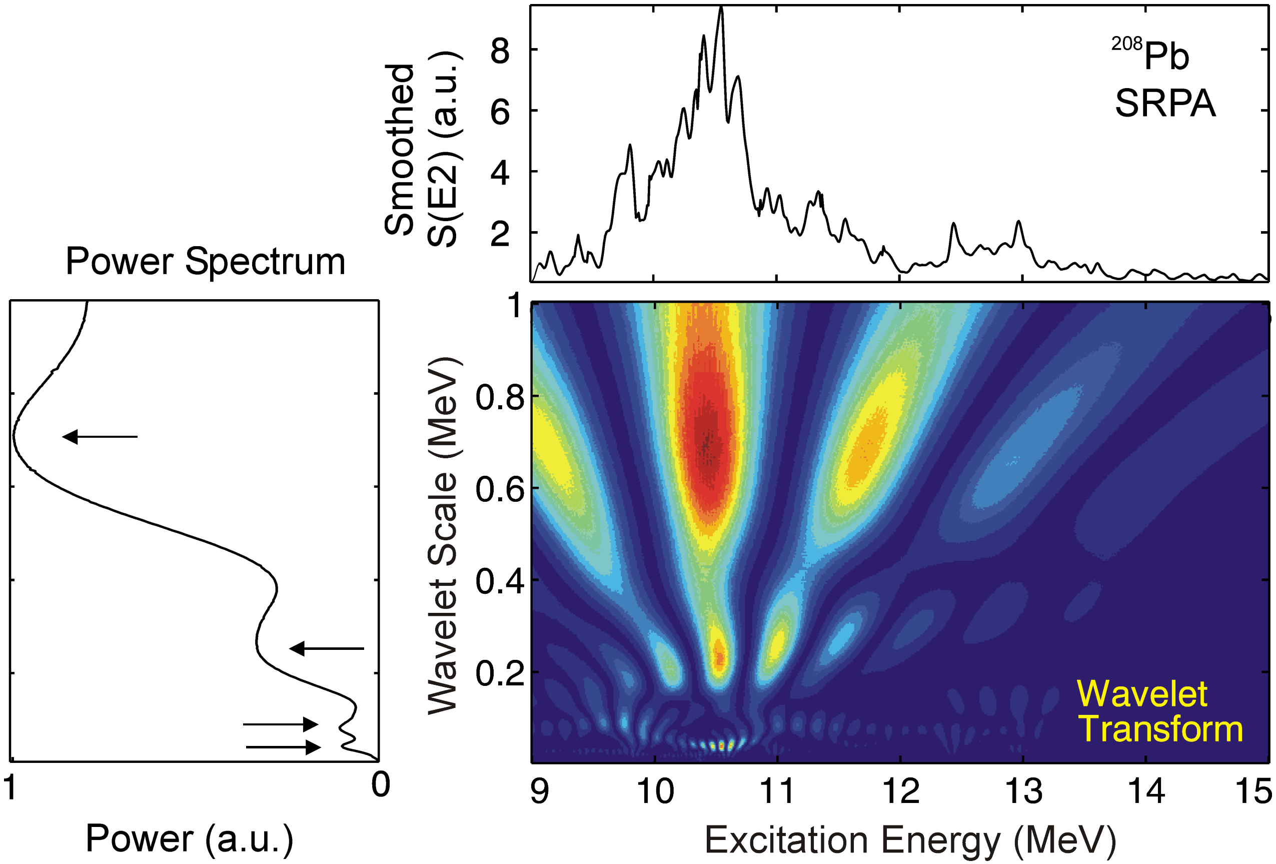
- Three classes of scales
- Class I scales appear in all nuclei
- Class II scales change with mass number
- Class III scales gross structure (e.g. width)

^{208}Pb: Random Phase Approximation



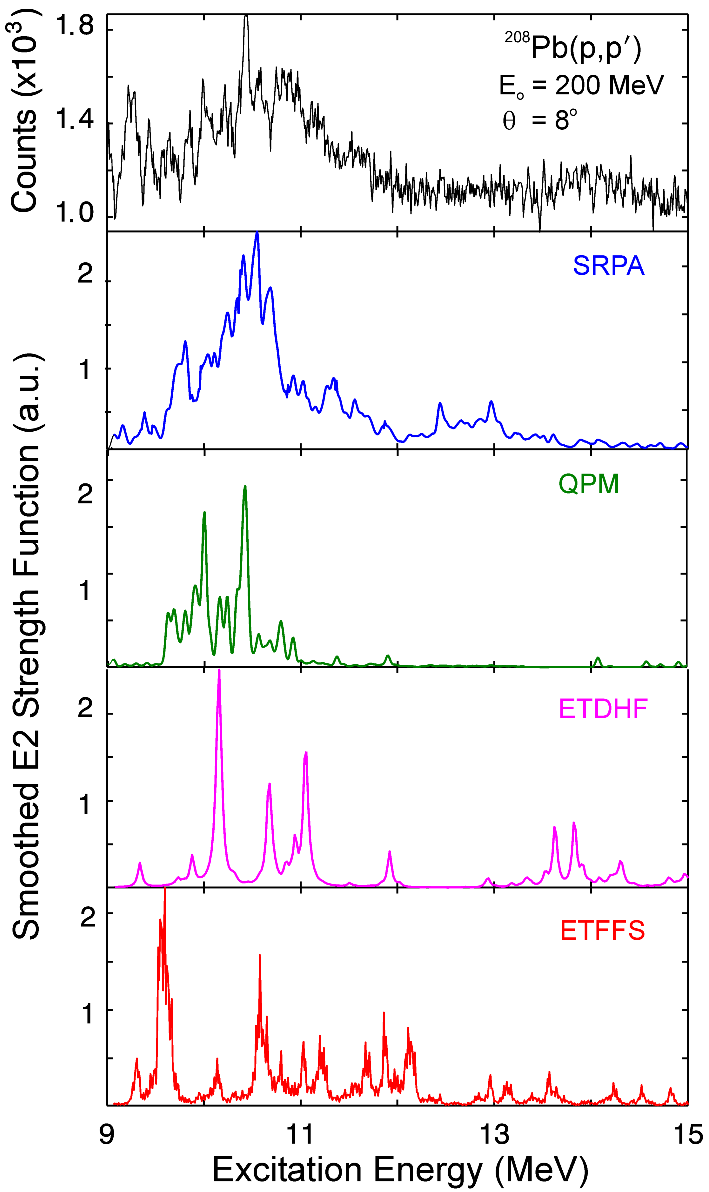
- No scales from 1p-1h states

^{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			
SRPA	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

Dissipation Mechanisms

Two types of dissipation mechanisms:

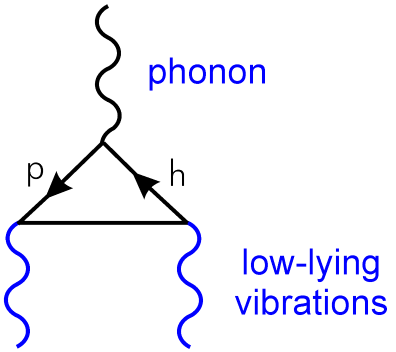
collective damping

↓

low-lying surface vibrations

↓

$1p-1h \otimes$ phonon



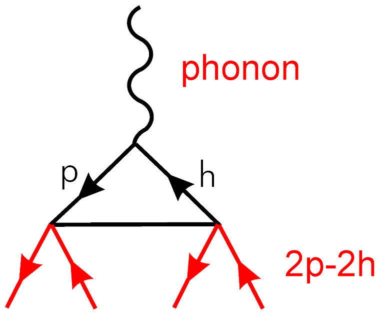
non-collective damping

↓

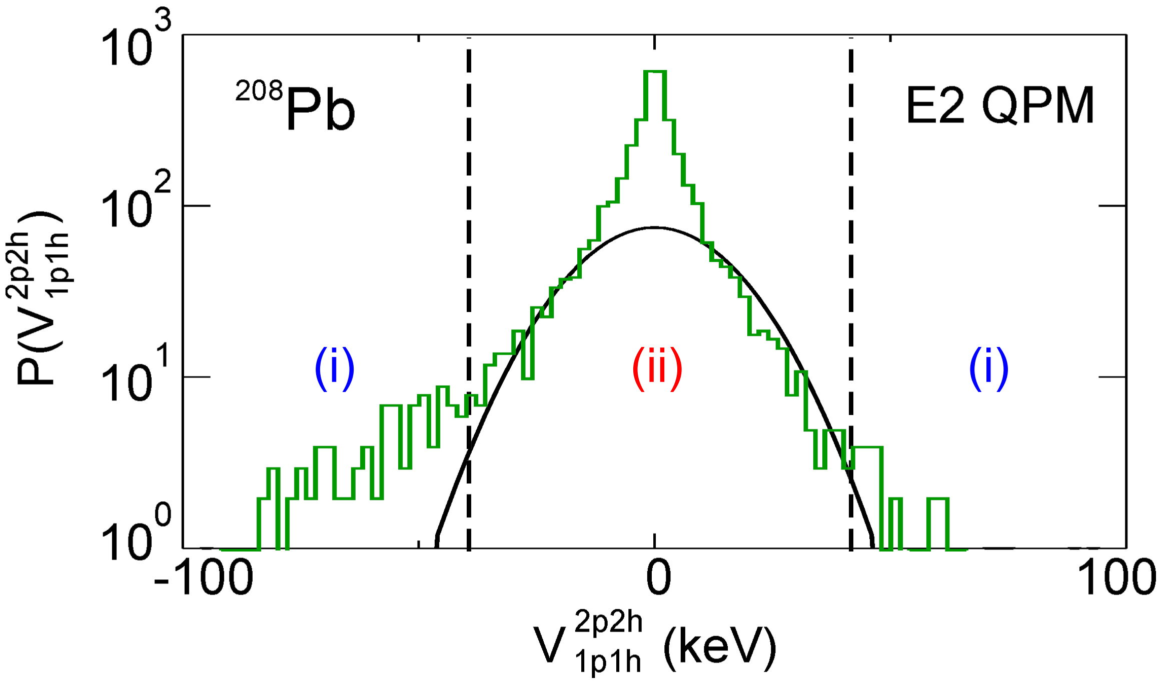
background states

↓

coupling to $2p-2h$ states

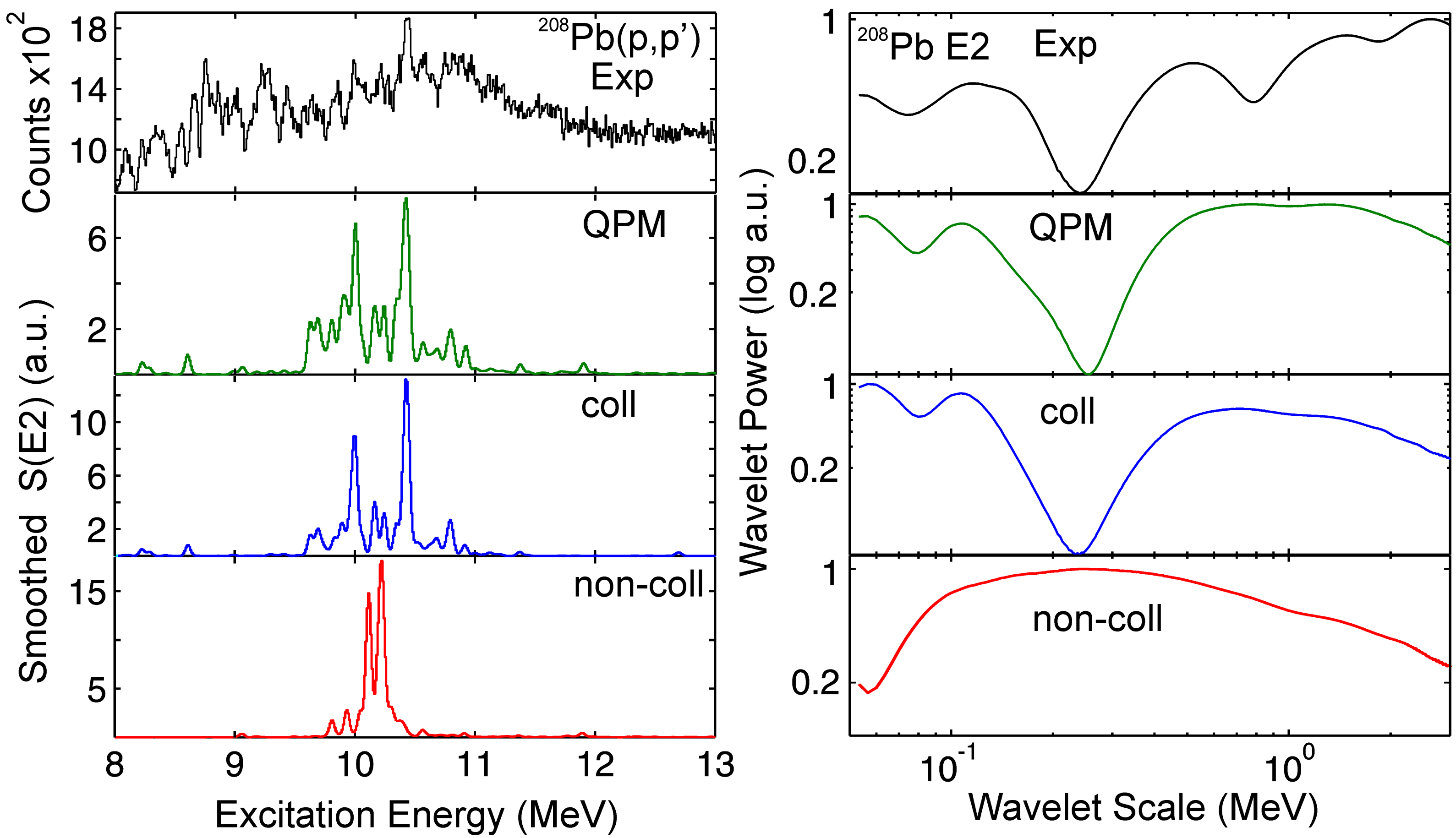


Distribution of the Coupling Matrix Elements



- RMT: Gaussian distribution for $\langle 1p1h \mid V^{2p2h}_{1p1h} \mid 2p2h \rangle$
- 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

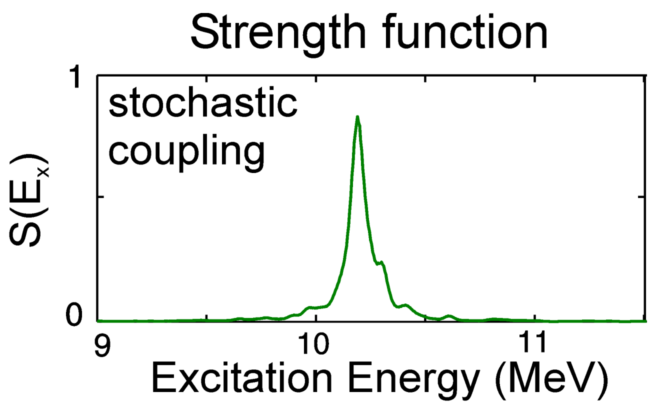
Collective vs. Non-collective Damping in ^{208}Pb

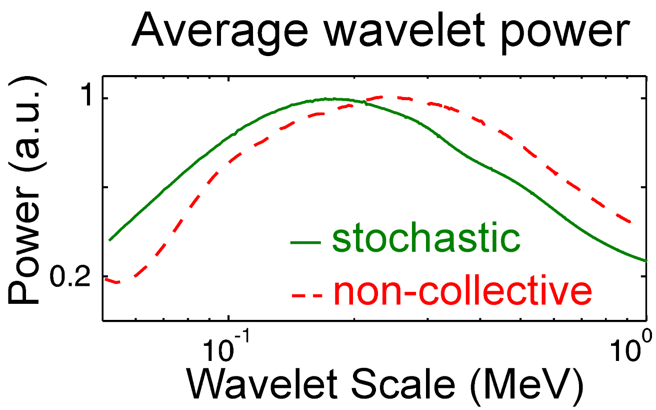


- Collective part: all scales
- Non-collective part: no prominent scales

Stochastic Coupling Model

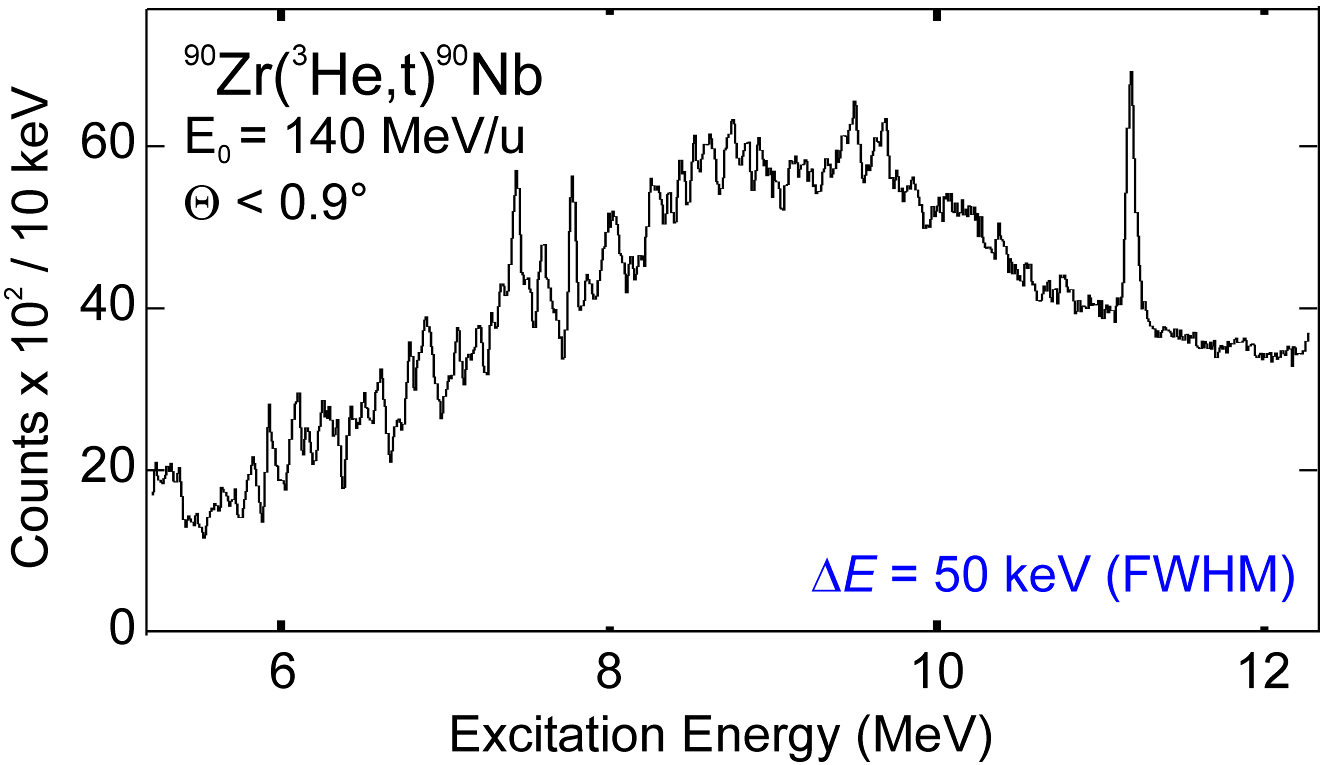
- Gaussian distribution for coupling matrix elements (RMT)
- Level spacing distribution according to GOE
- Average over statistical ensemble





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

Fine Structure of the Spin-Flip GTR



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

Discrete Wavelet Analysis

Wavelet coefficients:

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

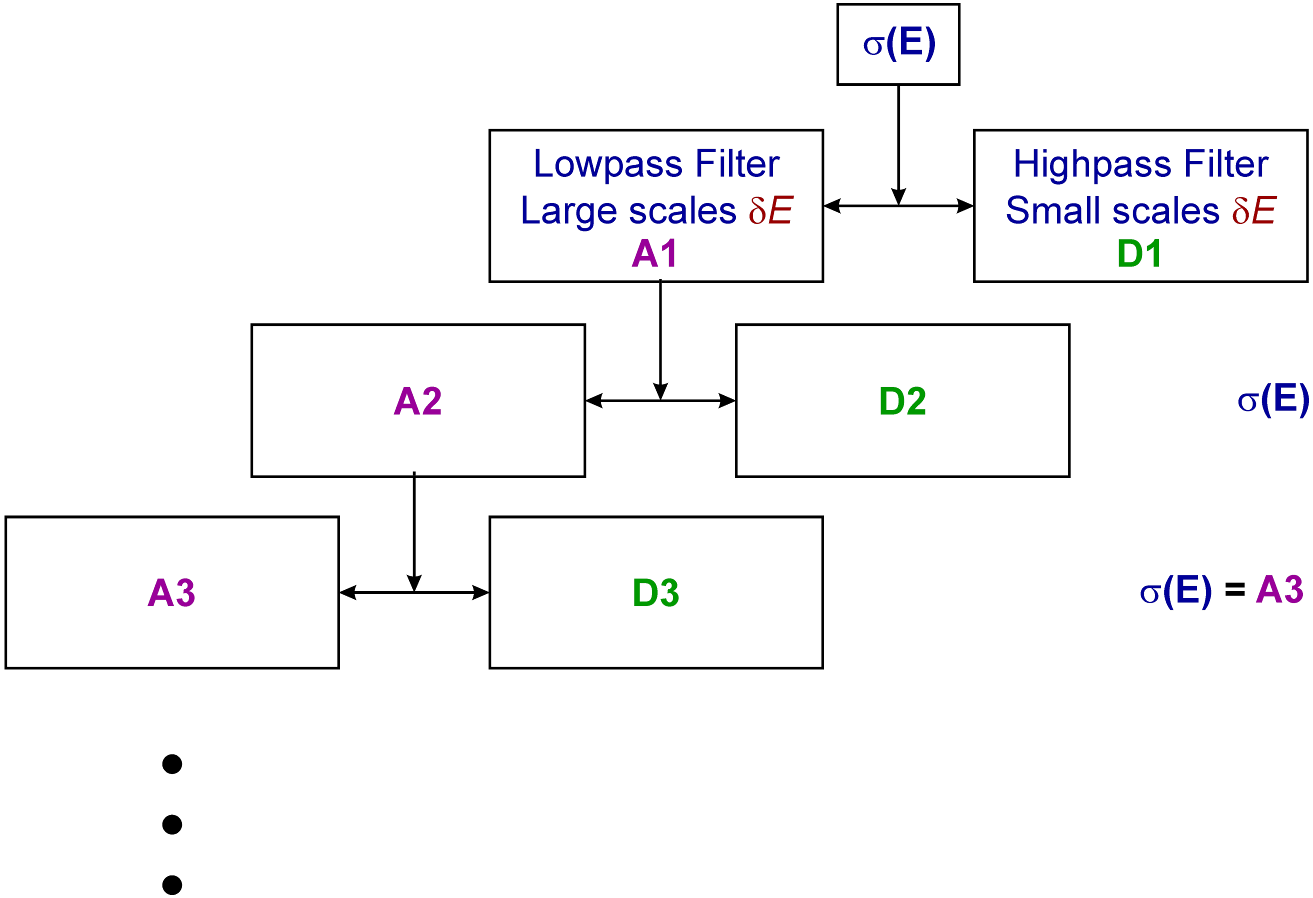
scale (δE), position (E_x), spectrum ($\sigma(E)$), wavelet (Ψ^*)

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

- Orthogonal basis of wavelet functions
- Exact reconstruction of the spectrum is possible
- Relevance of scales

  Resolution is limited to ranges of scales

Decomposition



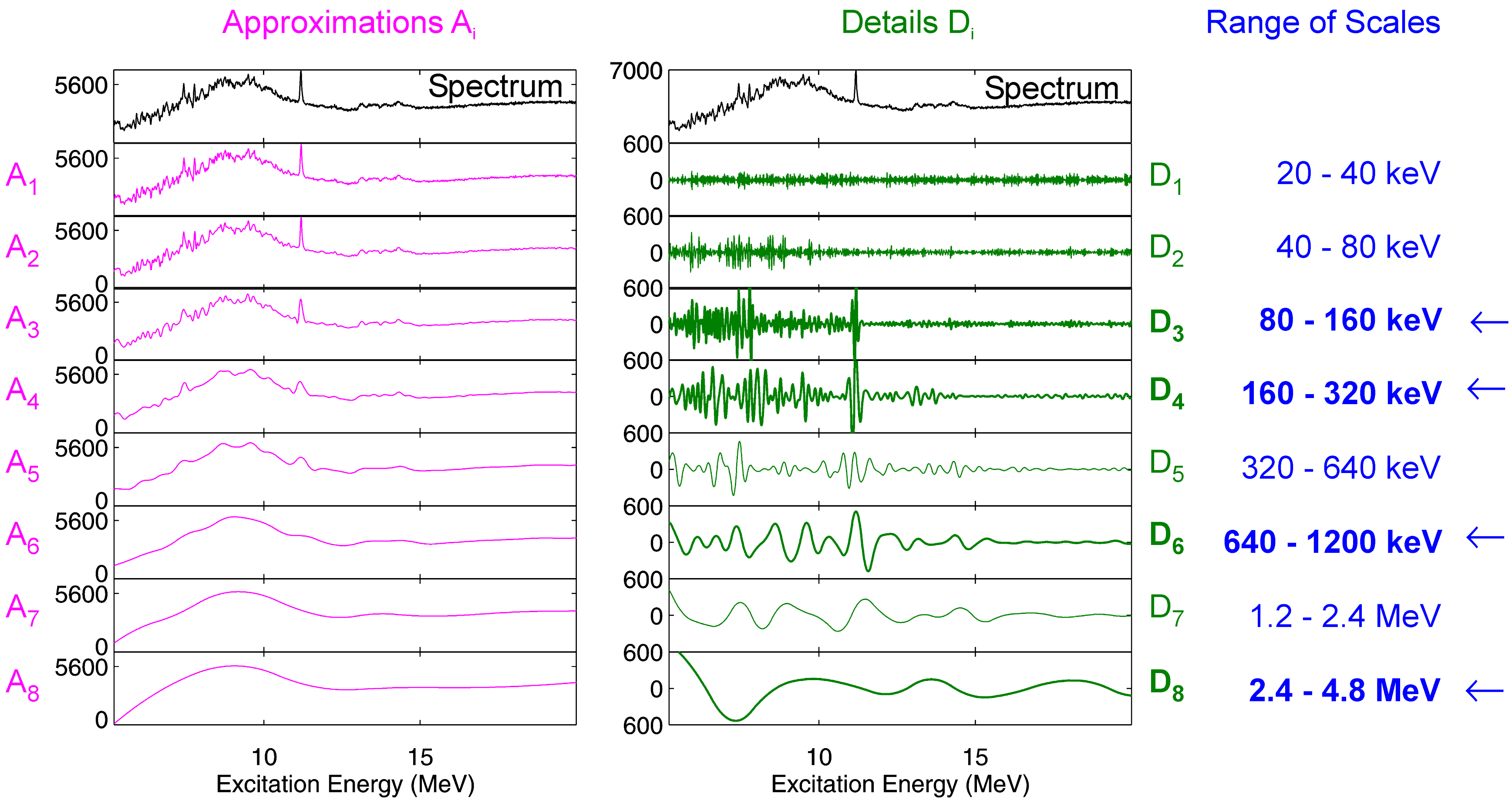
$\sigma(E)$ = A1 + D1

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

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

⋮

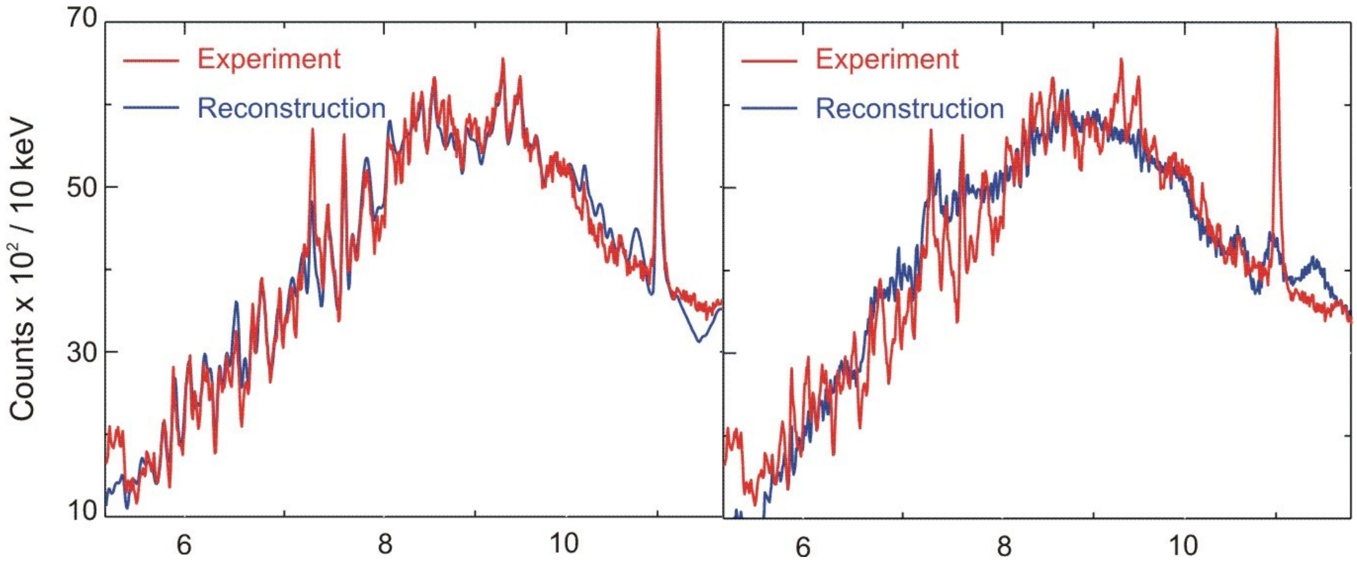
Application: GTR from $^{90}Zr(^3He,t)^{90}Nb$



- Reconstruct the spectrum using important scales

DWT: Reconstruction of the Spectrum

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



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

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 for discrete wave transform
- Model-independent level densities

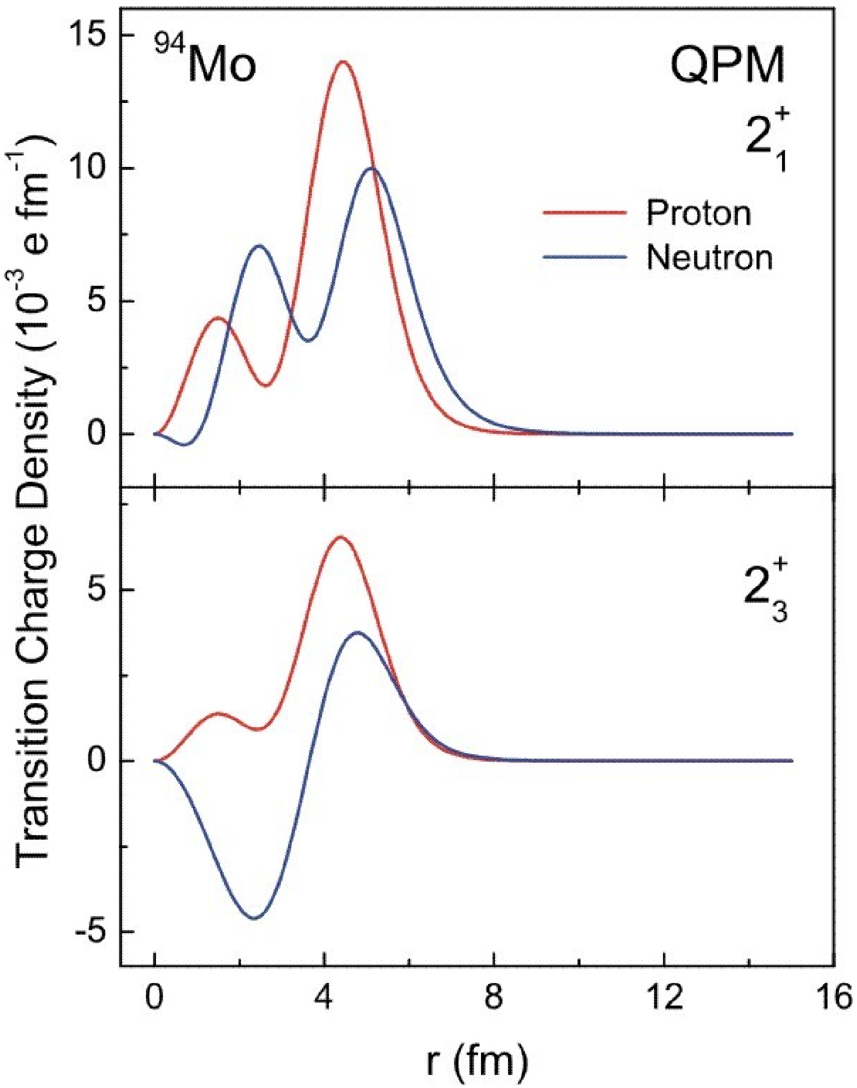
Outlook

- Goal: next step in the hierarchy: 3p-3h
  → improvement of experimental resolution

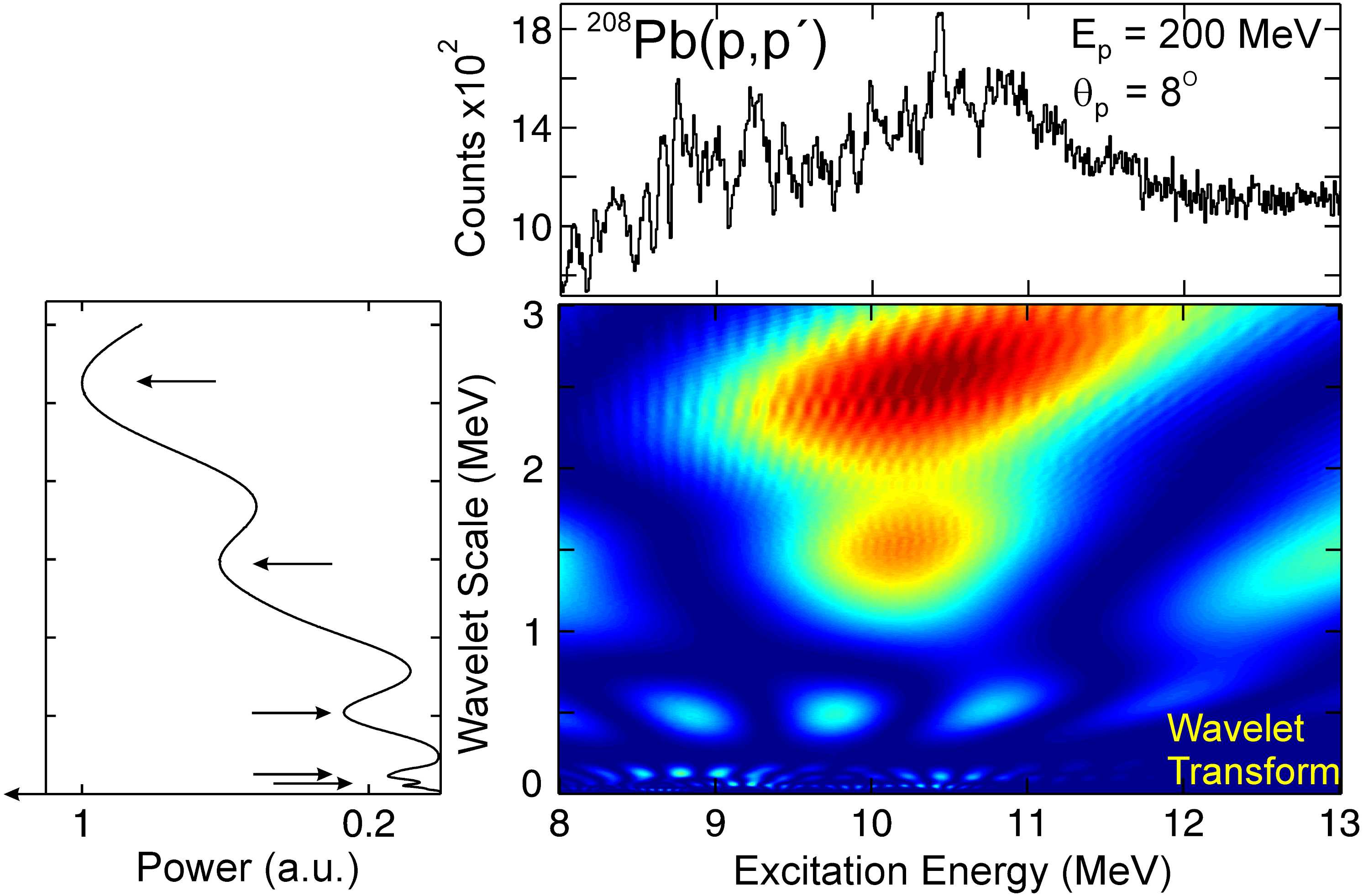
- Contribution of other damping mechanisms
  → escape width
  → Landau damping

- Quantitative analysis of scales:
  → experiment and models

Radial Transition Charge Densities

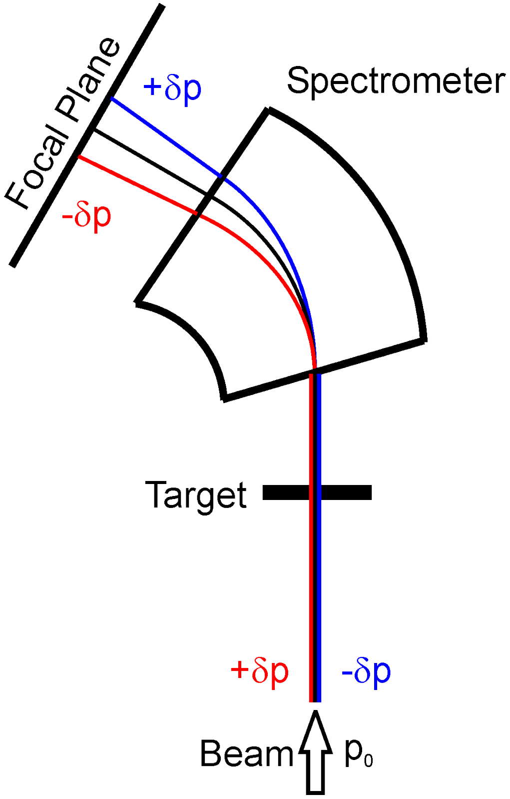


Application: ^{208}Pb(p,p´)



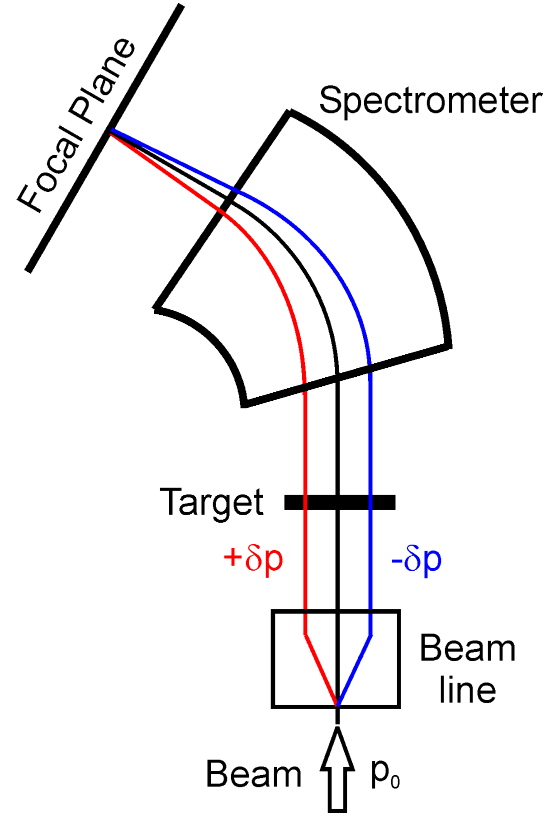
Dispersion Matching

Achromatic mode



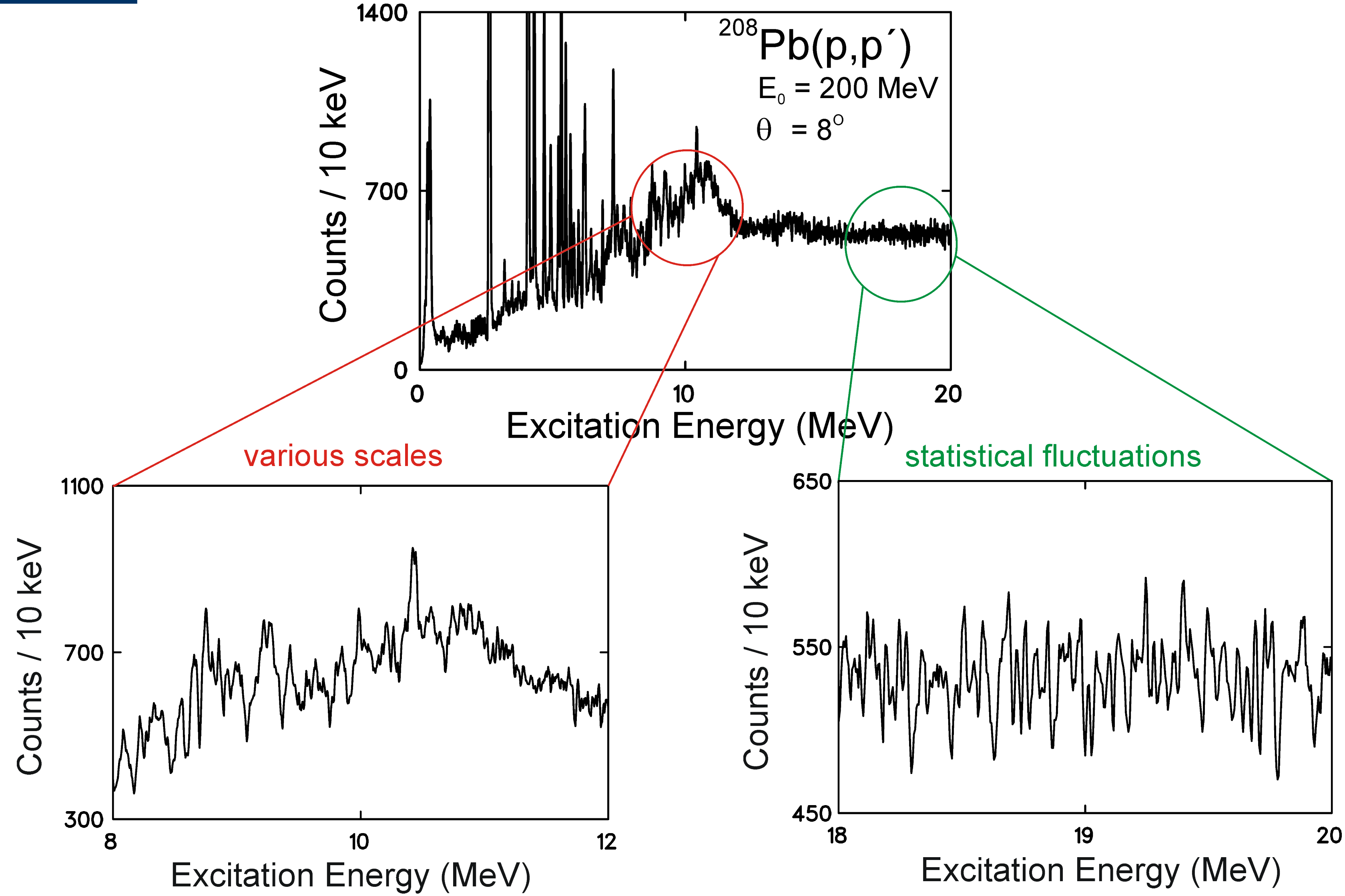
Δ E ~ 100 keV

Lateral dispersion matching

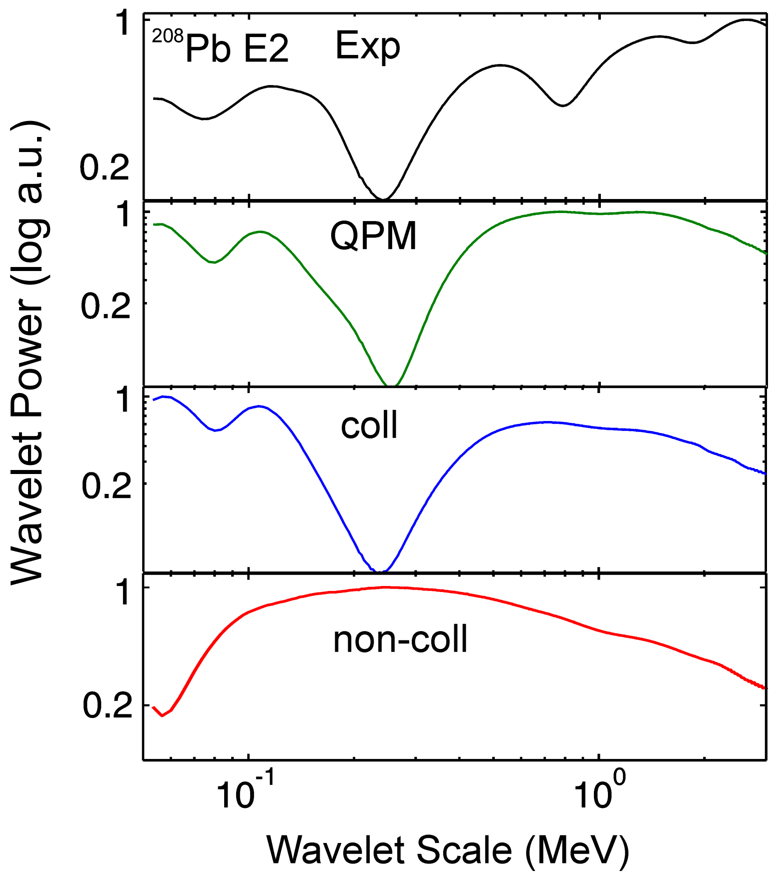


Δ E ~ 30 keV

Scales and Fluctuations



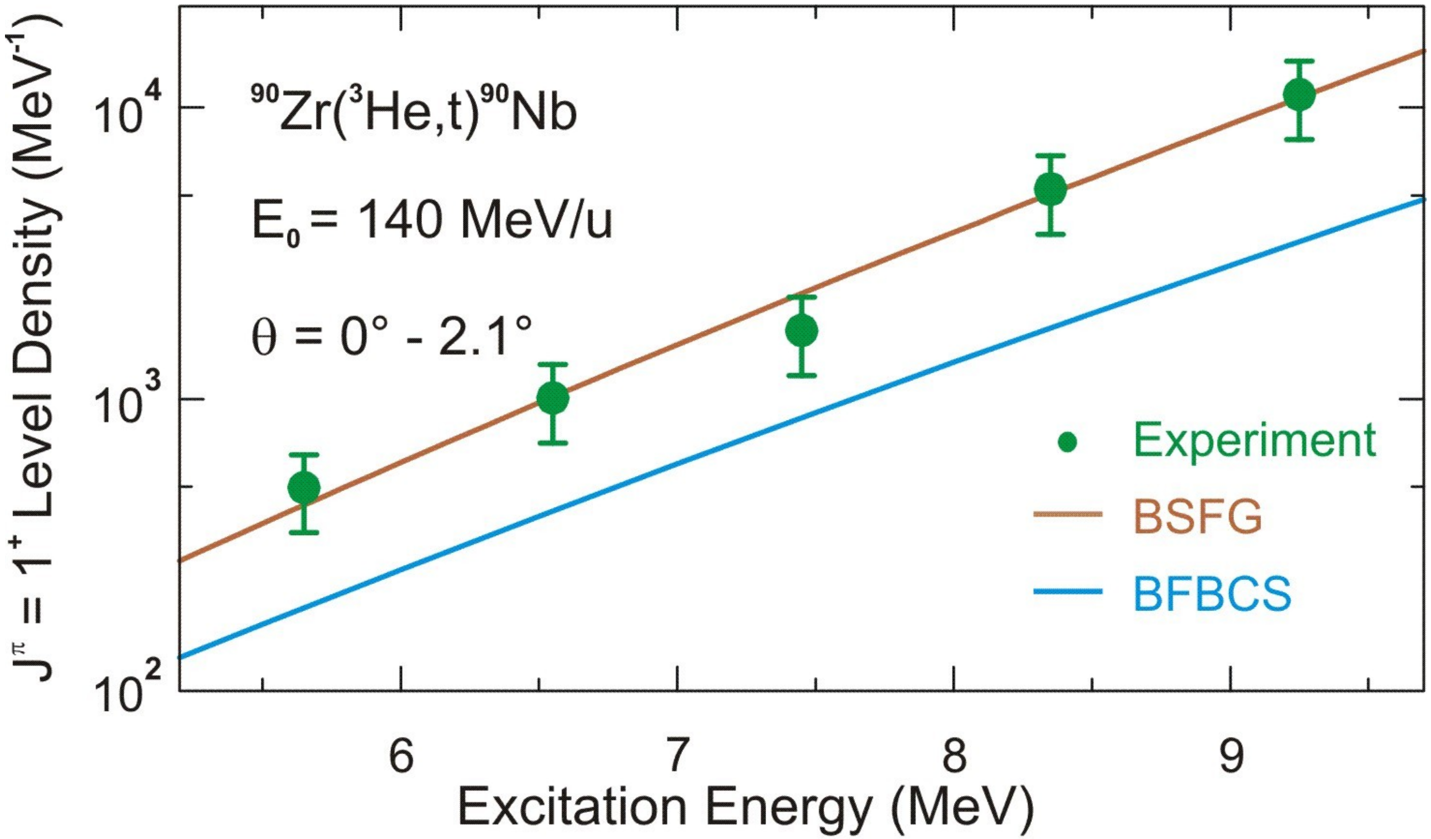
Collective vs. Non-collective Damping in ^{208}Pb



- 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$_x$)*

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

↓

Proportional to the mean level spacing

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

↓

Background?

Wavelet transform of spectrum σ (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

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

↓

Background suppression

Extraction of the mean level spacing

DWT: Background and Stationary Spectrum