Gamma Strength Functions and Level Densities from High-Resolution Inelastic Proton Scattering at Forward Angles

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- Polarized (p,p') at forward angles: a spectroscopic tool for the Gamma Strength Function across particle threshold
- The case of ^{208}Pb
- The case of ^{120}Sn
- The case of ^{96}Mo
- Level densities of $J^{\pi} = 1^{-}$ states in the GDR region

SFB 634

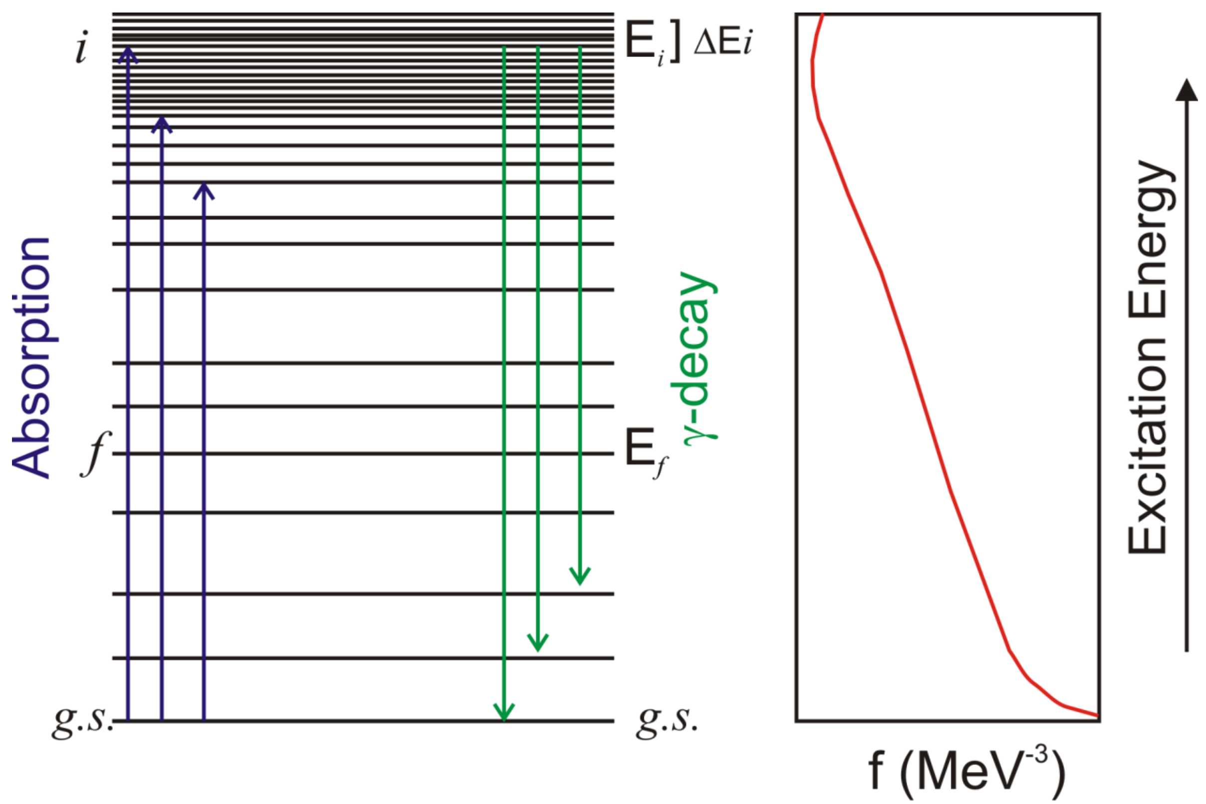
Supported by DFG under contracts SFB 634 and NE 679/3-1

Gamma Strength Function (GSF)

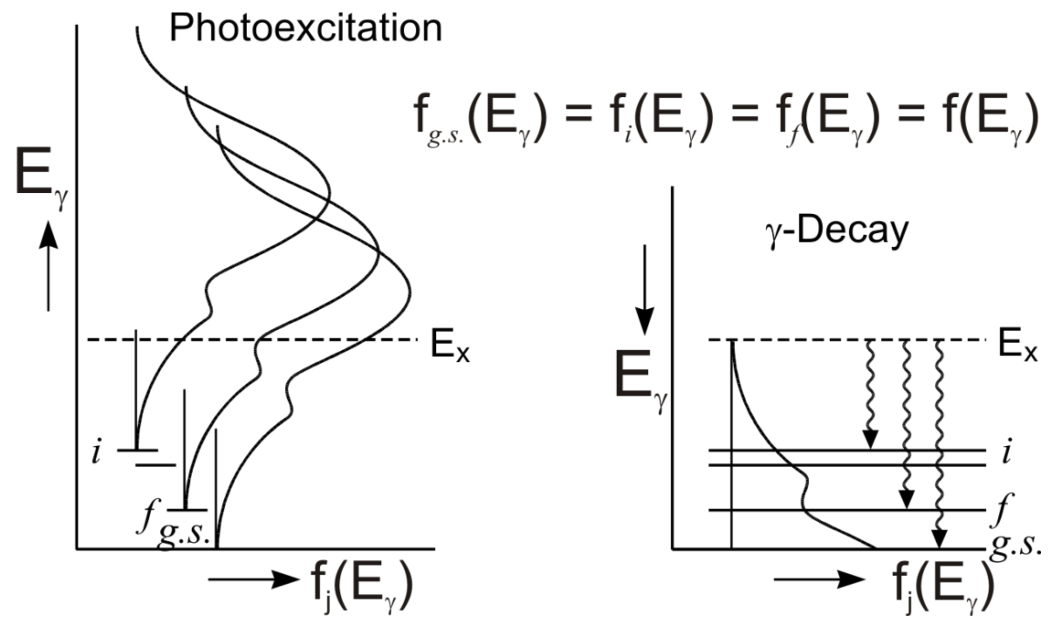
$$\langle \Gamma(E_i) \rangle = \frac{1}{\rho(E_i)} \cdot \int_0^{E_i} E_\gamma^3 f^{E1}(E_\gamma) \rho(E_i - E_\gamma)\, dE_\gamma$$

$$\langle \, \Gamma_{i \to g.s.} \, \rangle = \frac{f^{E1}(E_\gamma) \cdot E_\gamma^3}{\rho(E_i)}$$

$$f^{E1}(E_\gamma) = \frac{\sigma_{abs}(E_i)}{3(\pi \hbar c)^2 \cdot E_\gamma}$$



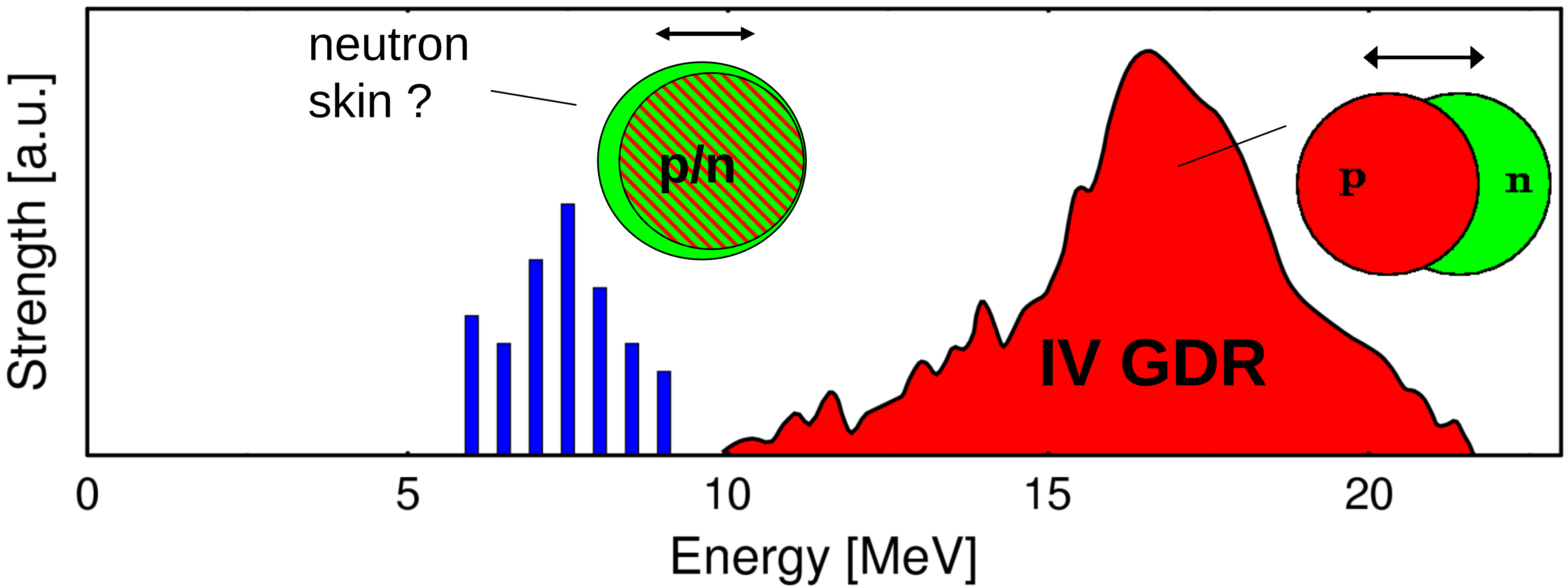
Axel-Brink Hypothesis



- Strength
  - depends only on E_γ
  - is independent of the initial state structure: E_x, J^π,…

- Same GSF for γ absorption and emission

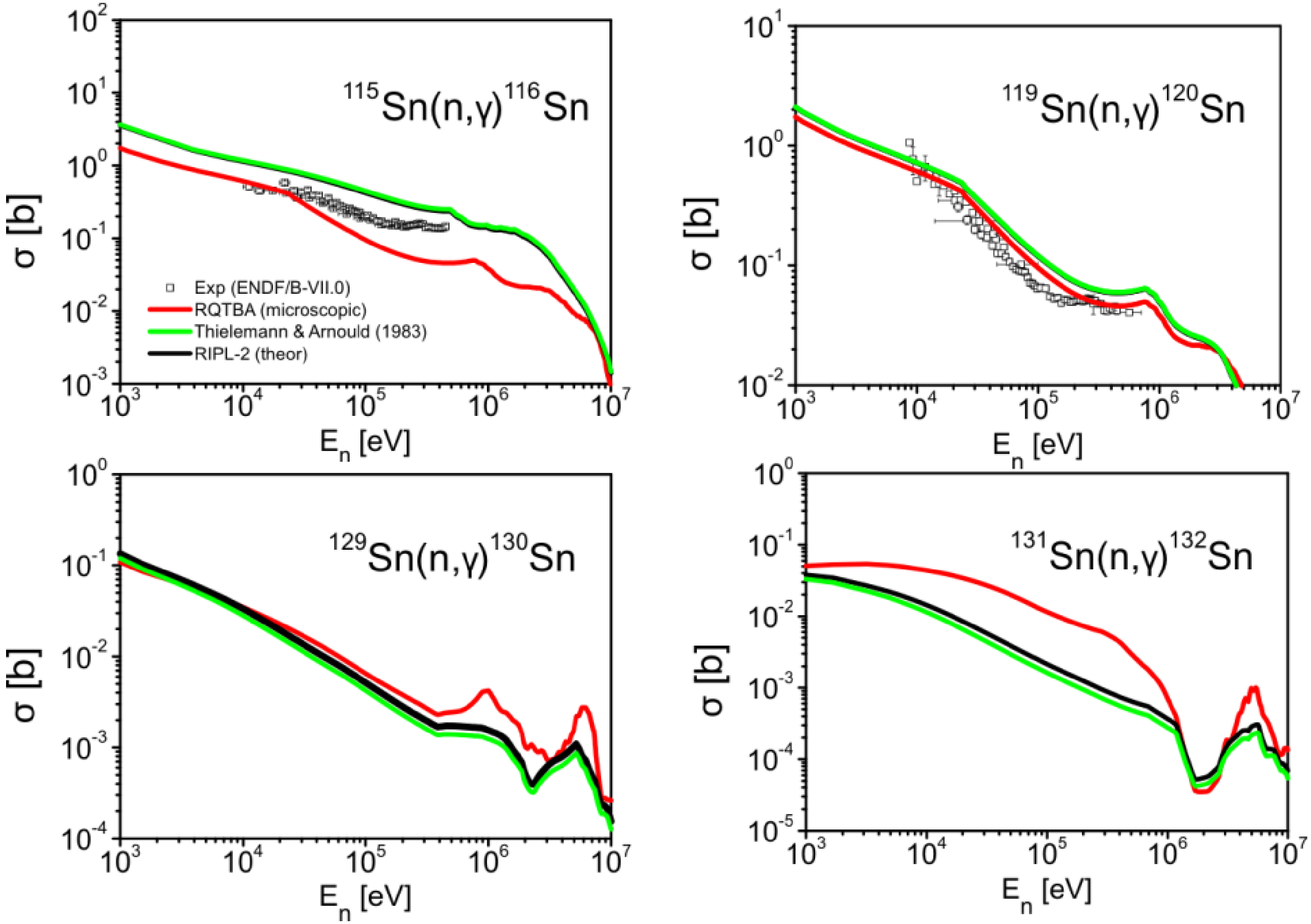
Electric Dipole Response in Nuclei



Oscillations of neutron skin against N ≈ Z core
Pygmy Dipole Resonance (PDR)

Oscillations of neutrons against protons
Giant Dipole Resonance (GDR)

Influence of the PDR



E. Litvinova et al., Nucl. Phys. A 823, 26 (2009)

GSF: Experimental Problems

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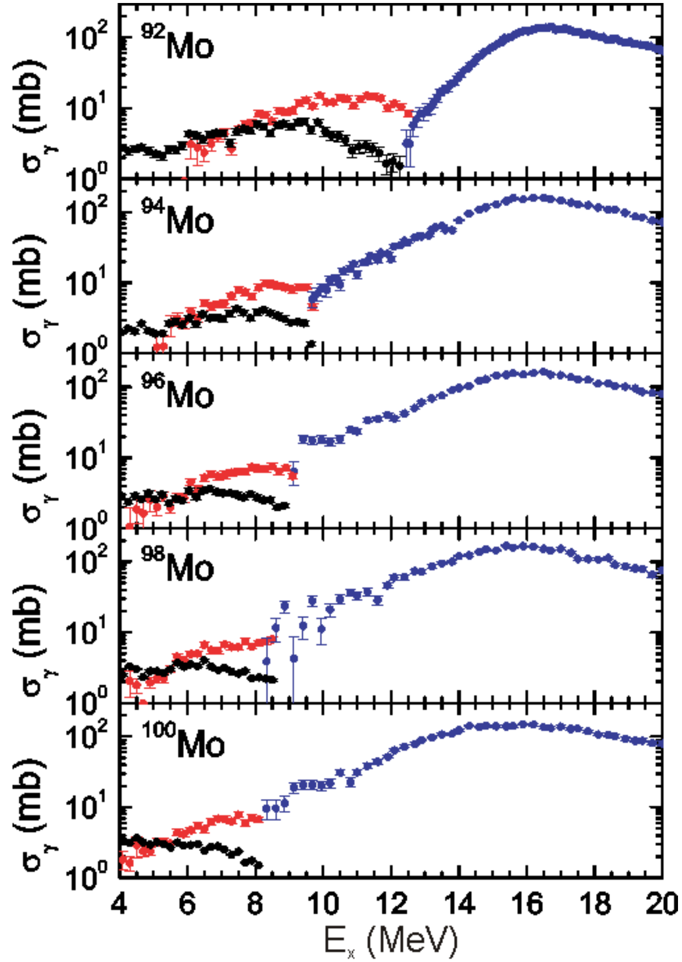
- Experimental:
  - (γ,γ') reaction measures strength (roughly) up to threshold only
  - Experimental quantity $\propto \Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$

    $\longrightarrow$ assumption in most analyses

    $$\frac{\Gamma_0}{\Gamma} = 1 \rightarrow \text{lower limit}$$

    $\longrightarrow$ alternatively correction with statistical model calculation $\rightarrow$ upper limit



G. Rusev et al., Phys. Rev. C 79, 061302 (2009)

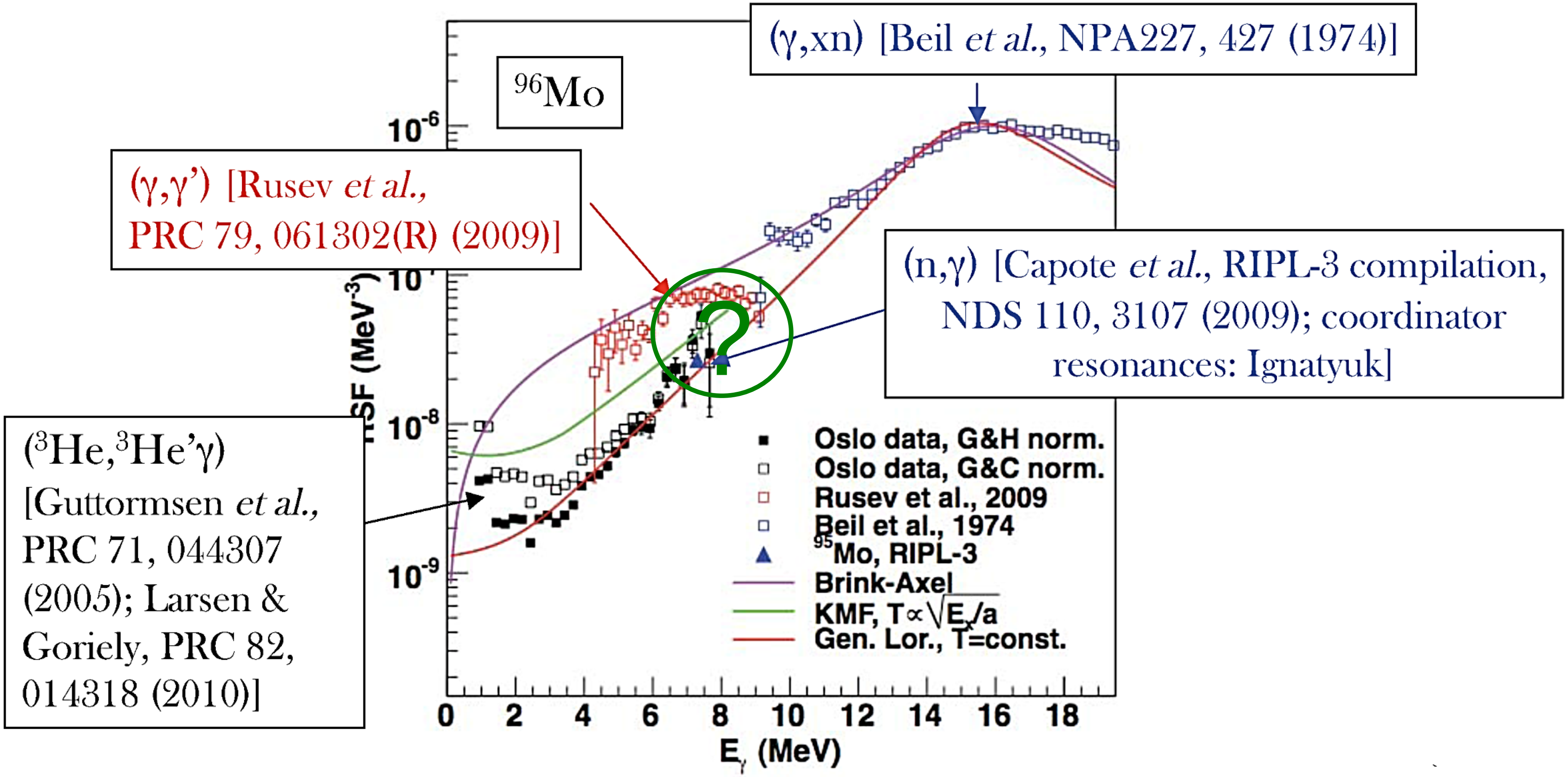
GSF: Experimental Problems (continued)

- (γ,xn) reactions provide information above threshold only and little sensitivity close to threshold
- Decay of compound nuclei (Oslo method)
  $\rightarrow$ normalization at S_n: level densities needed
- Spin-M1 resonance poorly known in heavy nuclei
  $\rightarrow$ empirical parametrizations for GSF questionable

$\Downarrow$

Consistent data on E1 and spin-M1 strength distributions below and above the neutron threshold highly important

Experimental Discrepancies in GSF: ^{96}Mo



Ann-Cecilie Larsen, Workshop on Gamma Strength and Level Density, Dresden-Rossendorf, August 2010

A New Experimental Tool for Complete Dipole Strength Distributions

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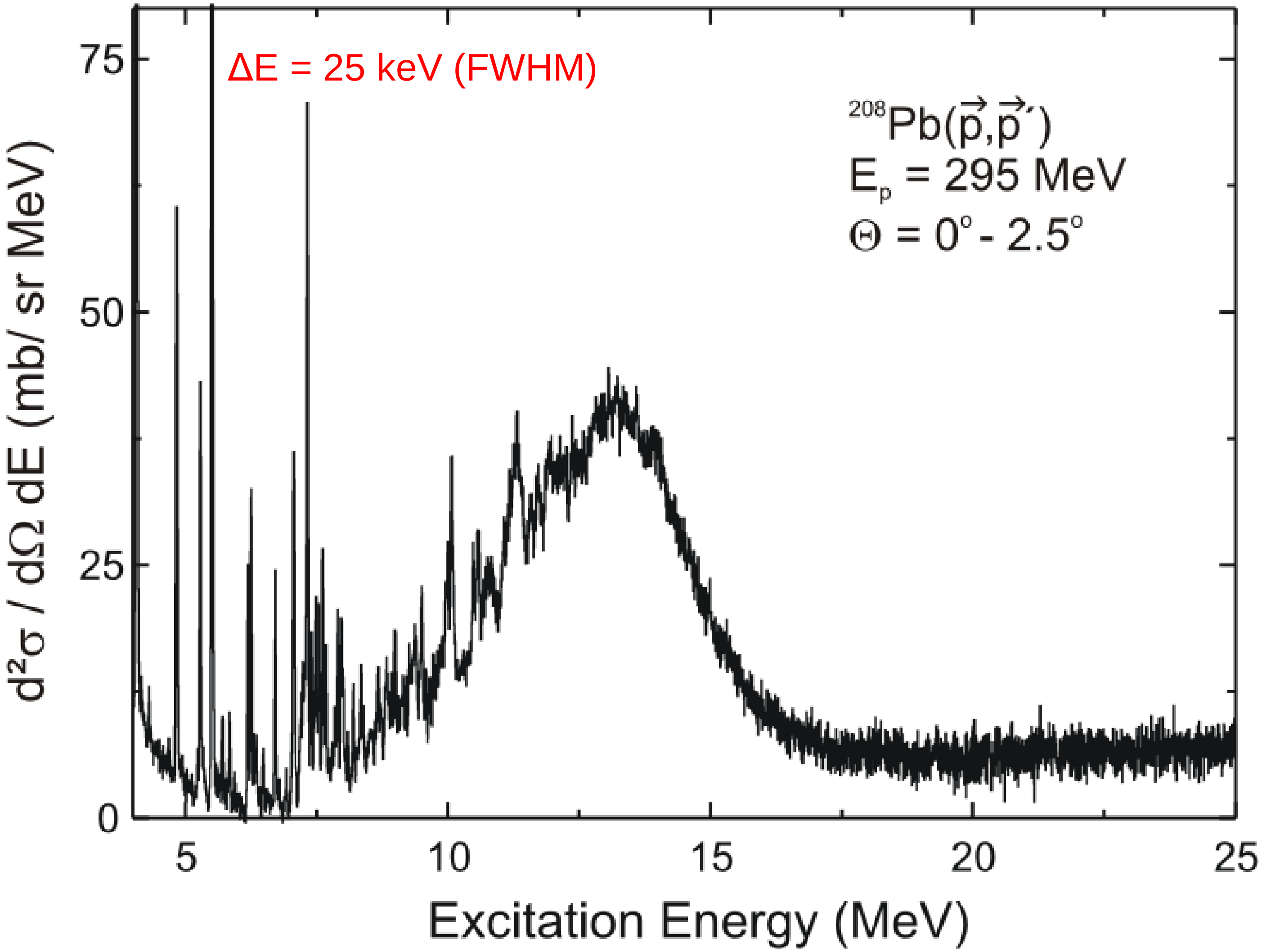
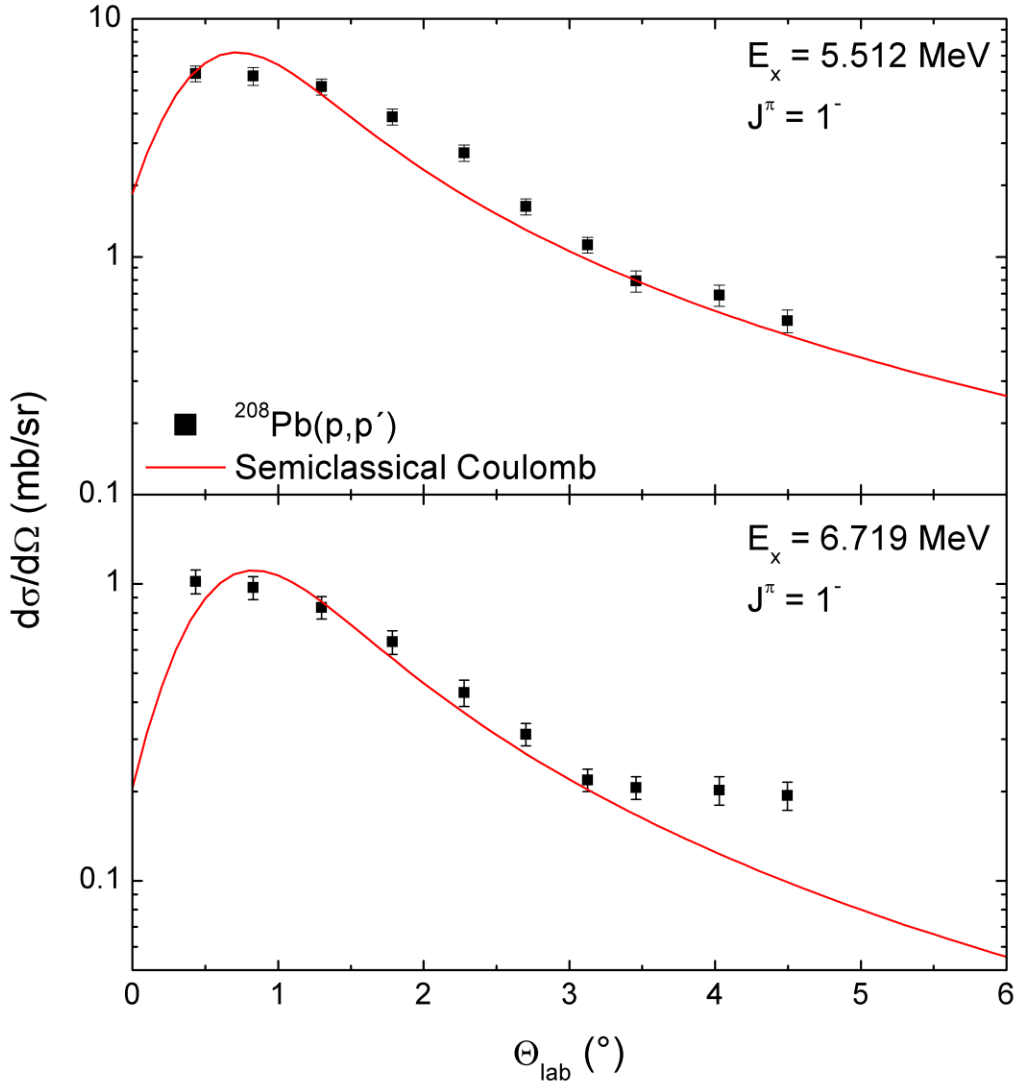
- Polarized proton scattering at 0º
  - intermediate energy: 300 MeV optimal for spin-isospin excitations
  - strong Coulomb excitation of 1^- states
  - high resolution: ΔE = 25 keV (FWHM)
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation

- ^{208}Pb as a reference case

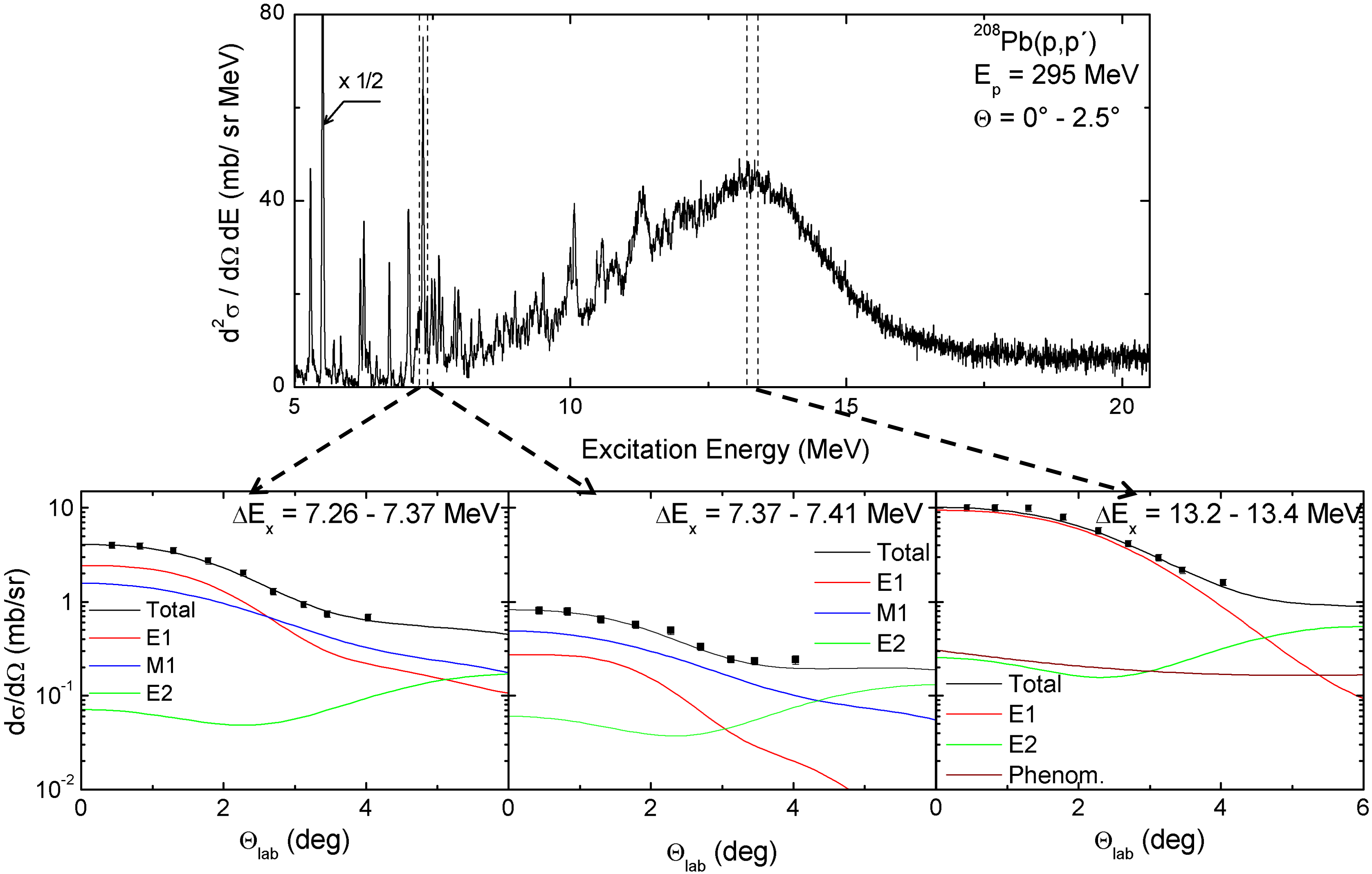
Measured Spectrum



Coulomb Exitations of 1^- States



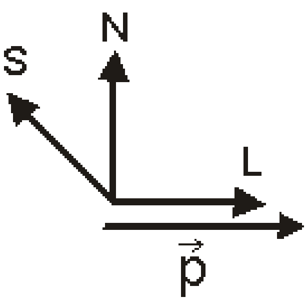
Multipole Decomposition of Angular Distributions



E1/M1 Decomposition by Spin Observables

Polarization observables at 0° ➡ spinflip / non-spinflip separation

(model-independent)



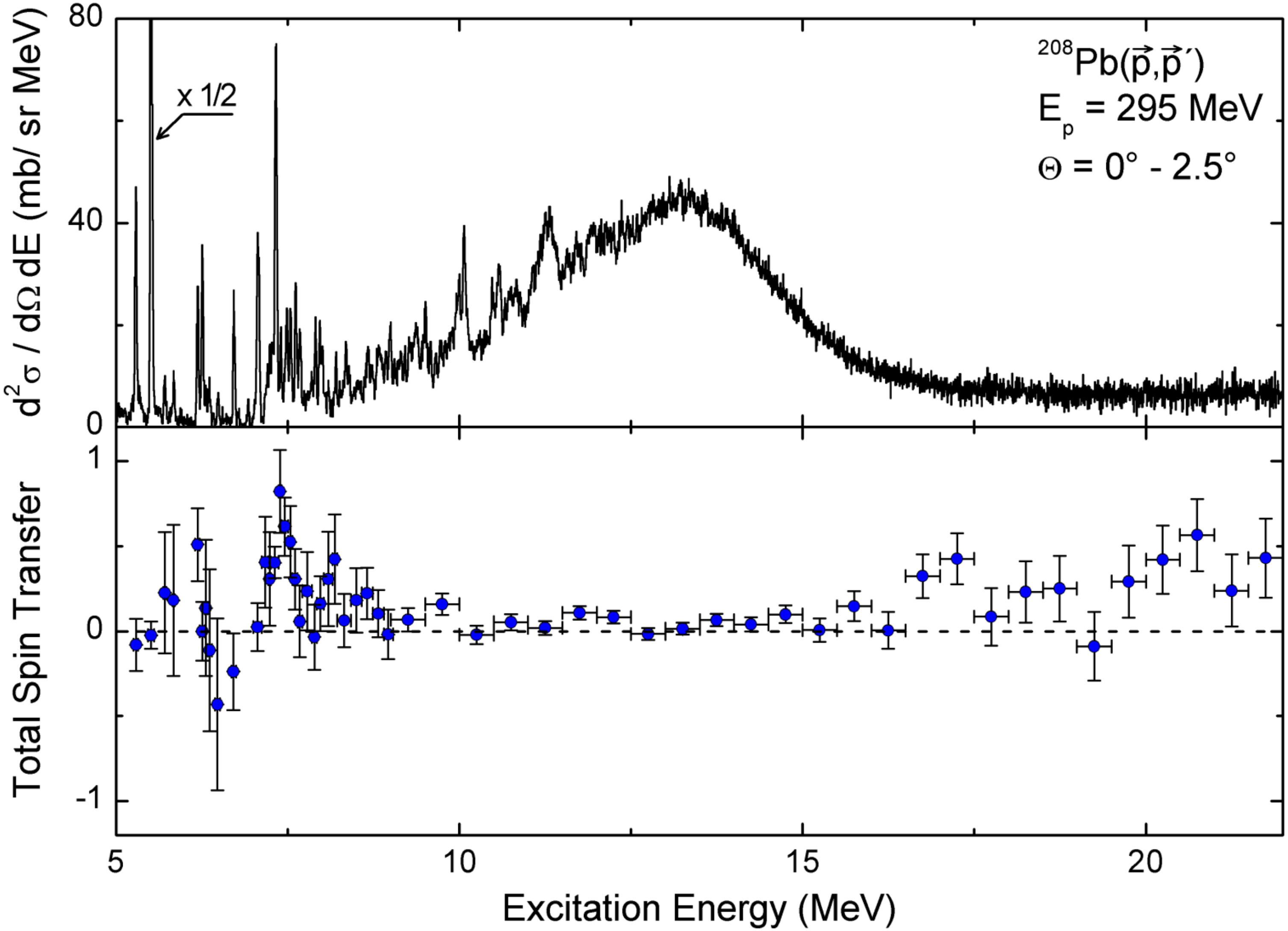
$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S=1 \rightarrow 1^{+} \\ 3 \text{ for } \Delta S=0 \rightarrow 1^{-} \end{cases}$$

sideway   normal   longitudinal

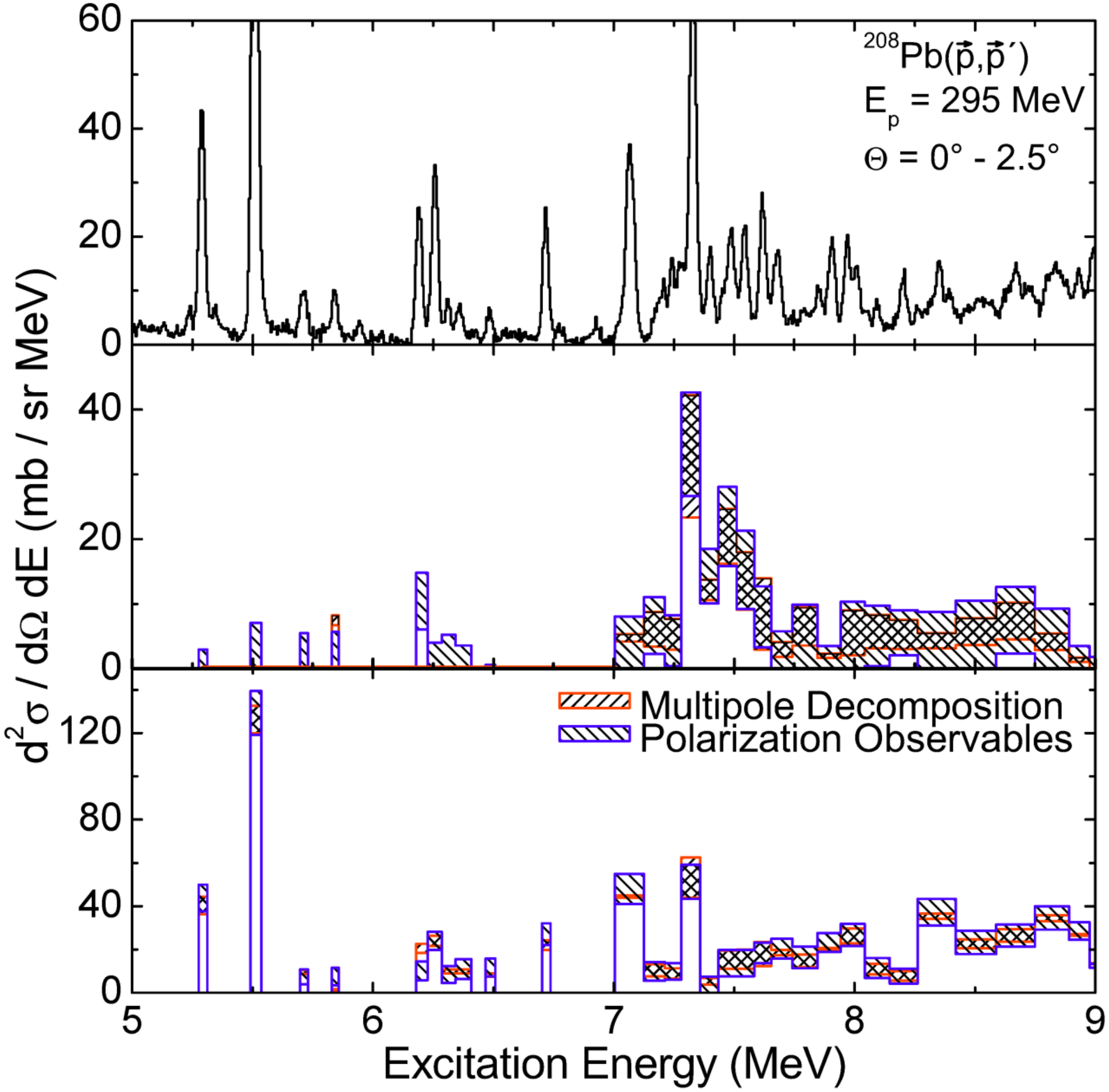
At 0° $D_{SS} = D_{NN}$ ➡ $\text{TotalSpinTransfer } \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

T. Suzuki, Prog. Theo. Phys. 103, 859 (2000)

Decomposition into Spinflip / Non-Spinflip Cross Sections



Comparison of Methods

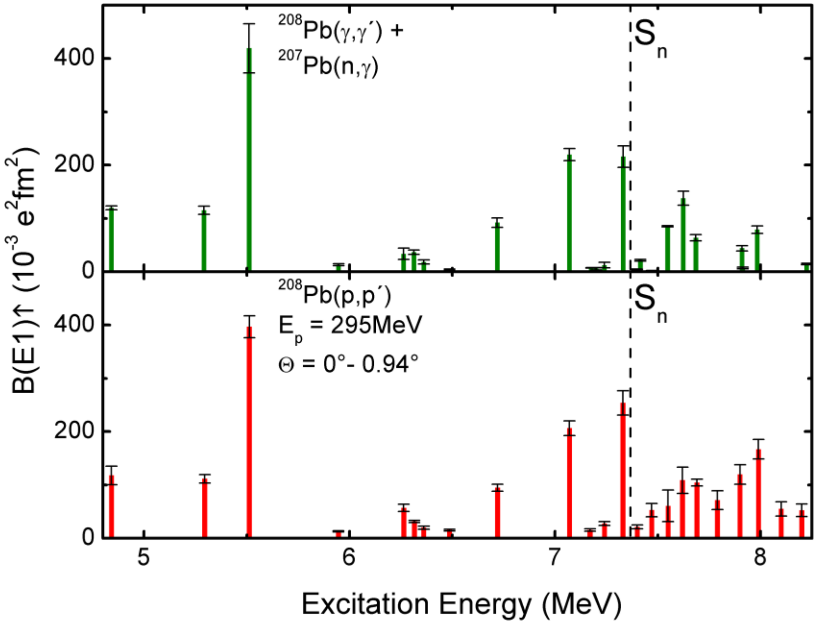


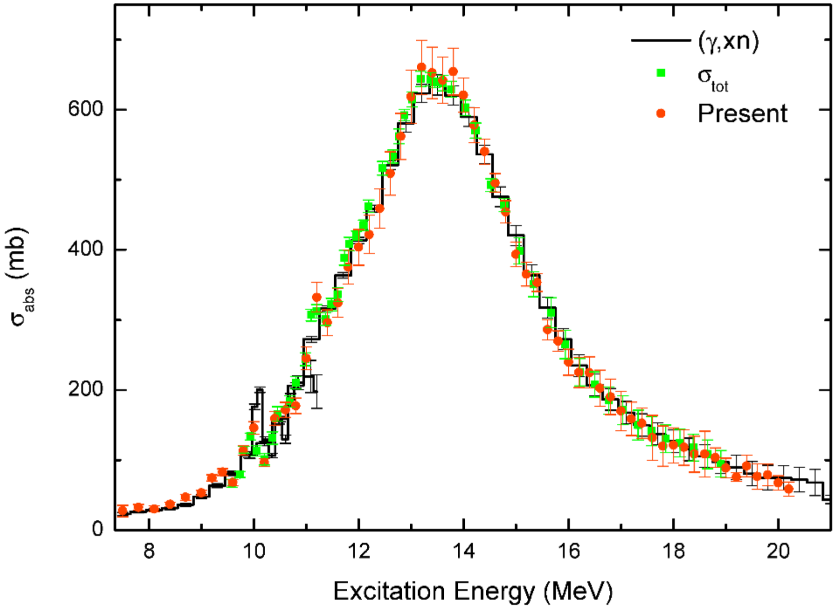
Total

ΔS = 1

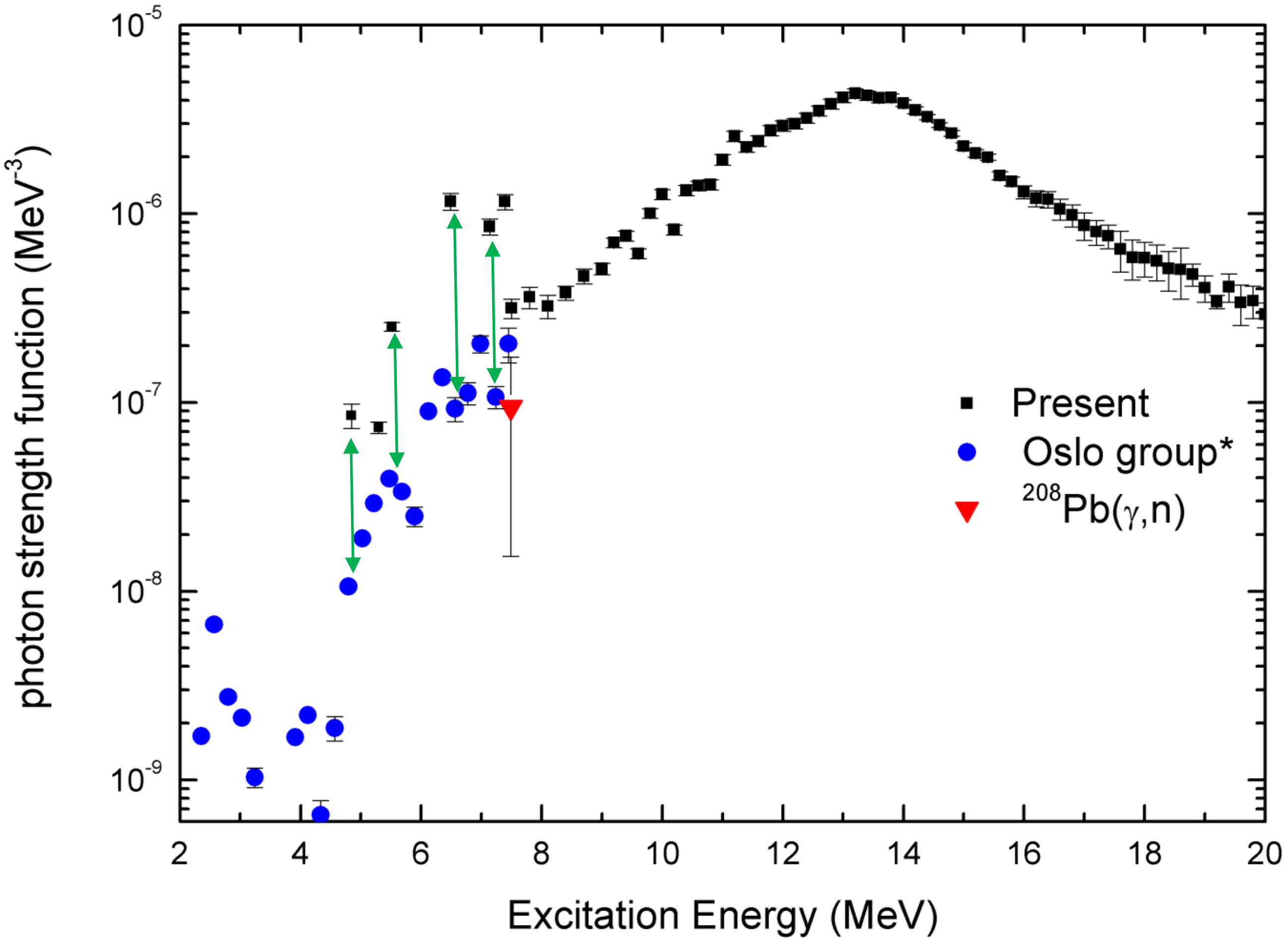
ΔS = 0

B(E1) Strength in ^{208}Pb



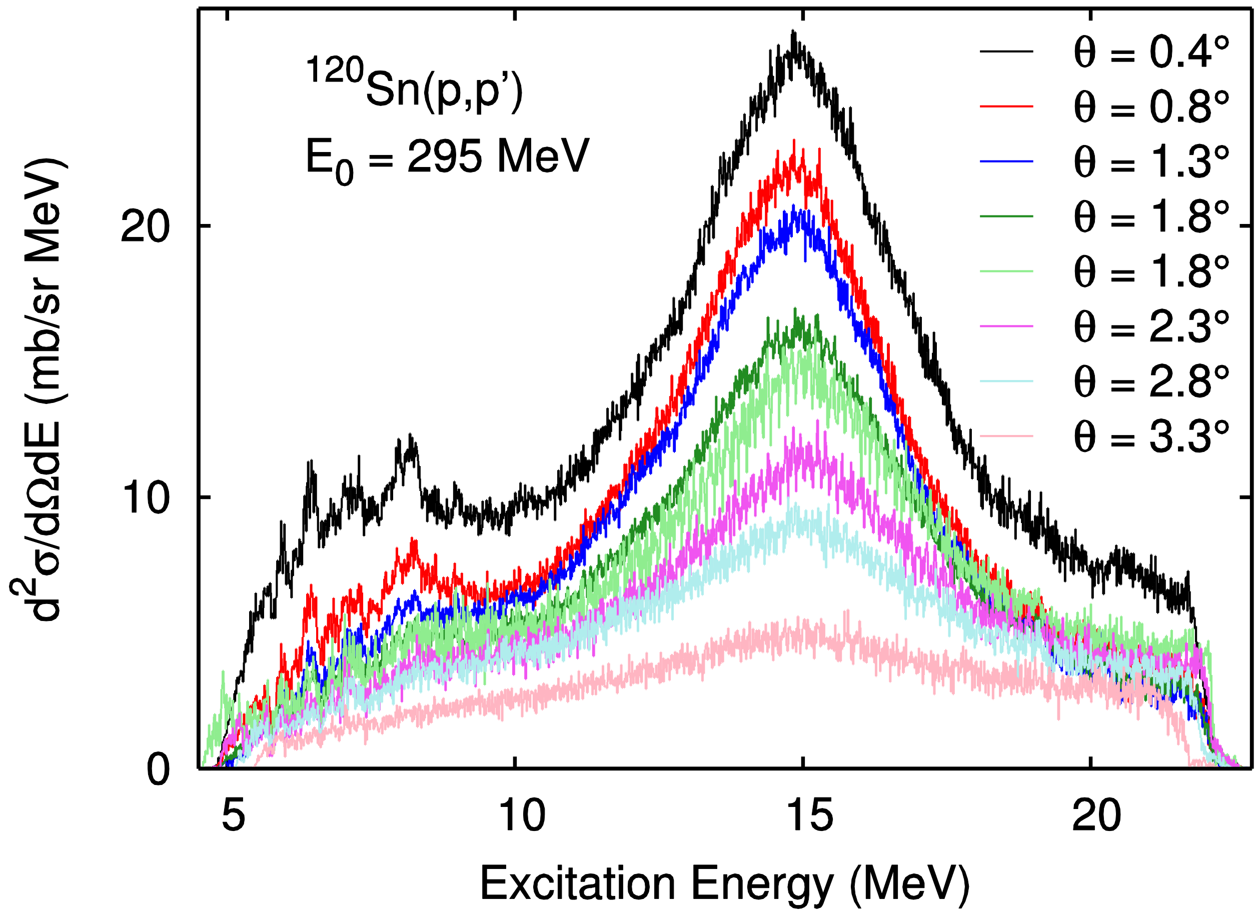


GSF in ^{208}Pb



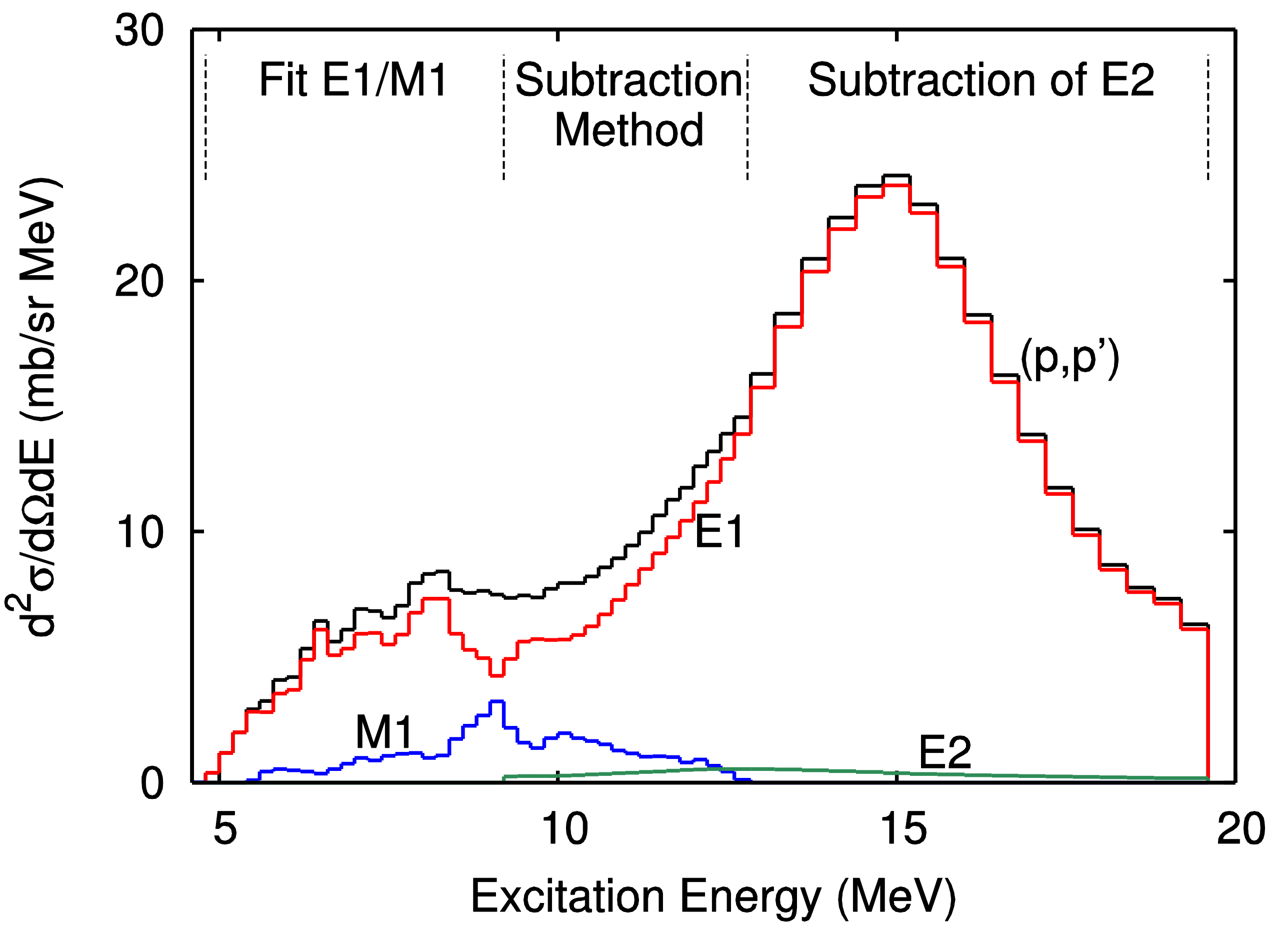
*N.U.H. Syed et al., Phys. Rev. C 79, 024316 (2009)

$^{120}Sn(p,p')$: Spectra

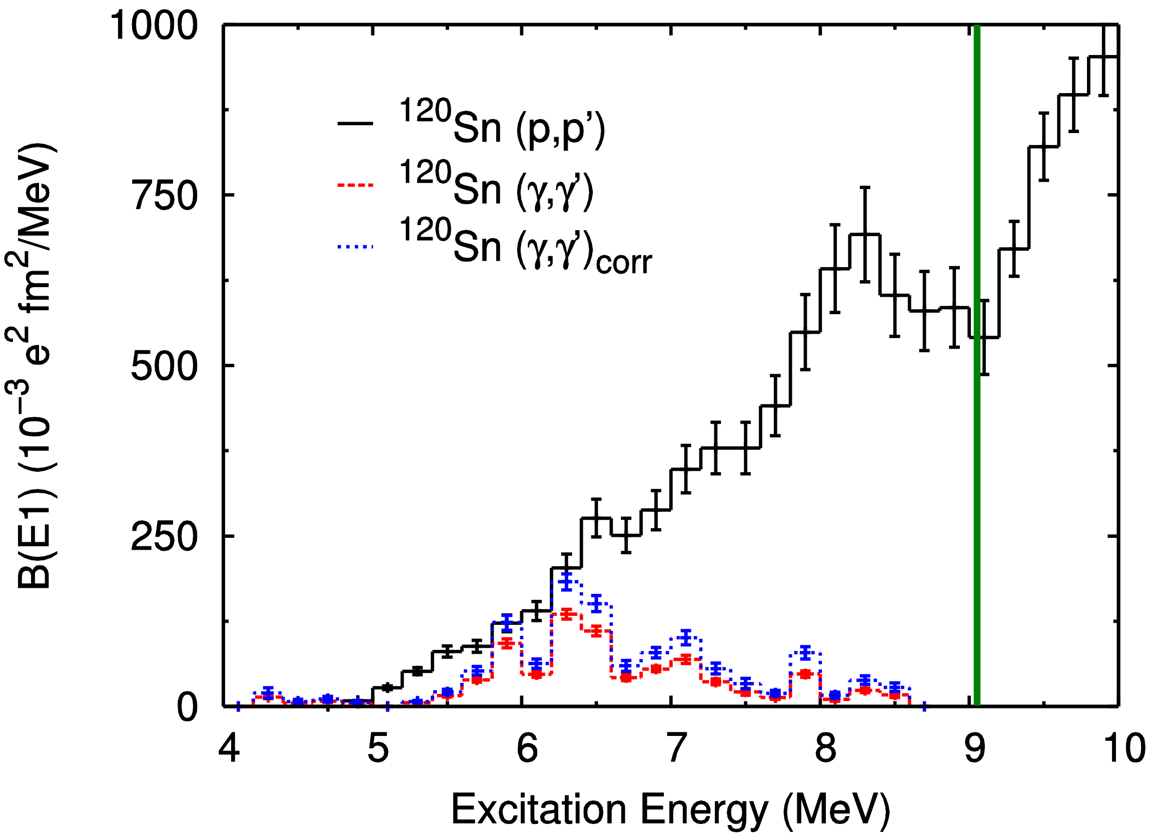


A.M. Krumbholz, PhD thesis, TU Darmstadt (2014)

E1/M1 Decomposition



^{120}Sn: Low-Energy E1 Strength

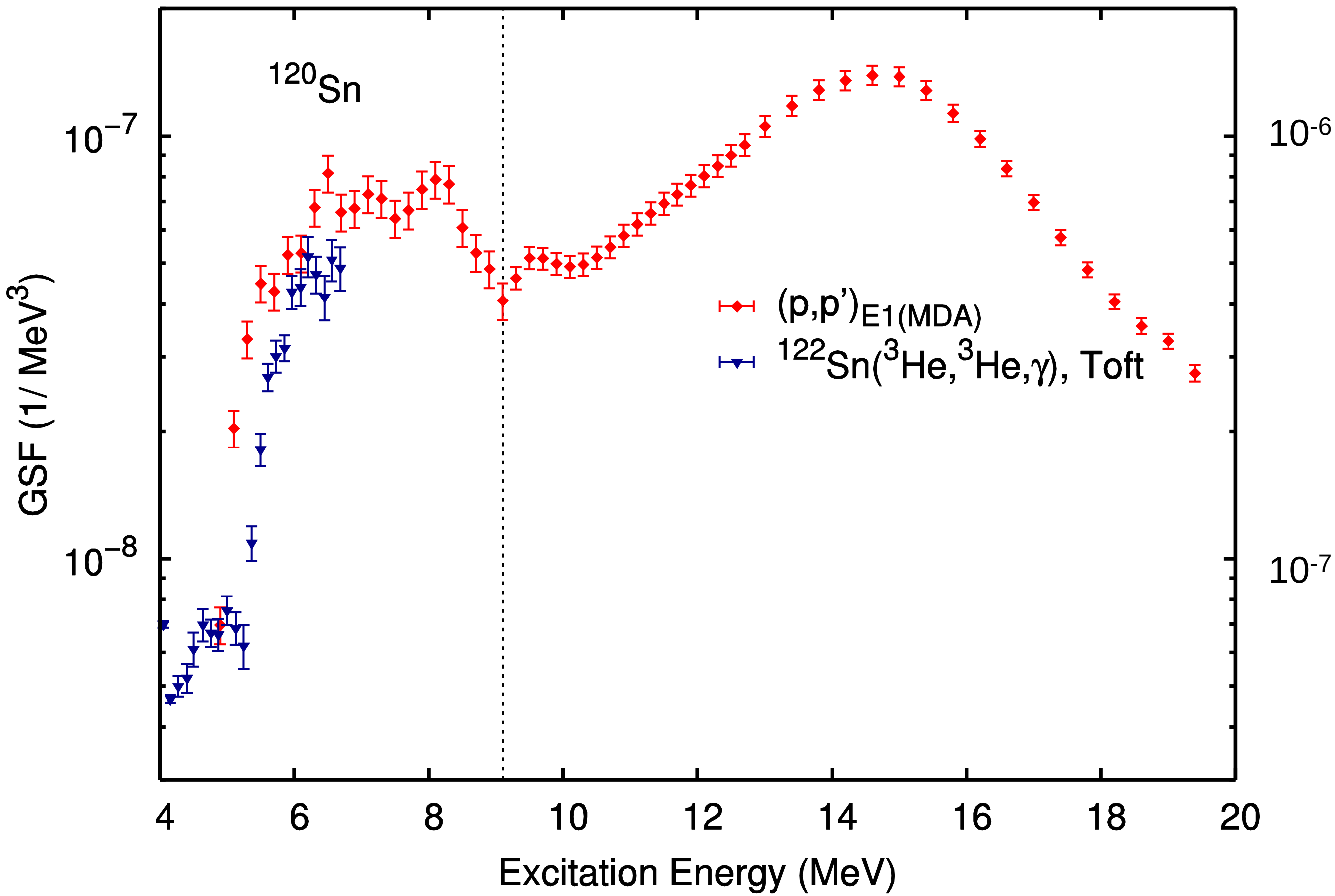


E1 strength up to 9 MeV:

about 2.4% of EWSR

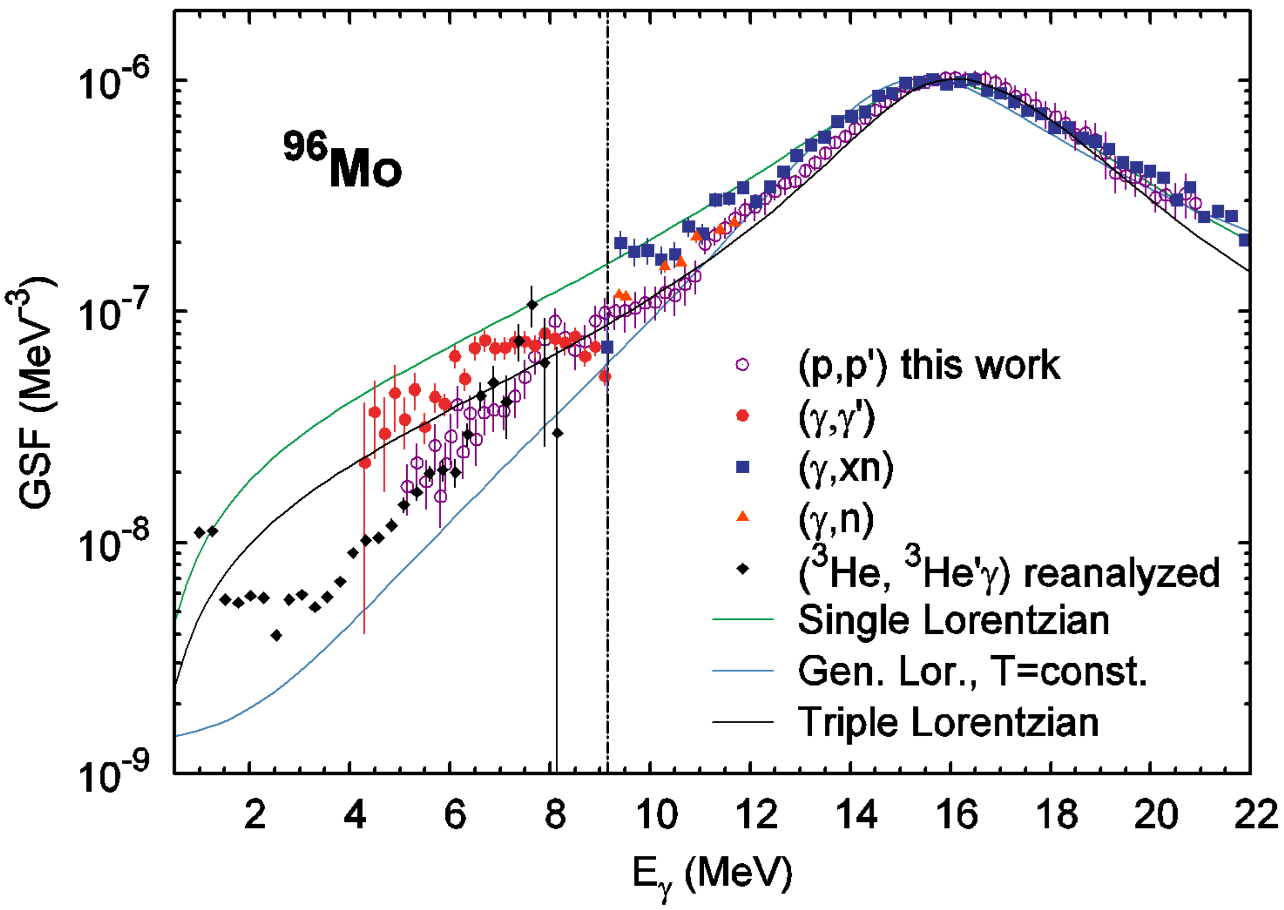
^{120}Sn(γ,γ'): B. Özel-Tashenov et al., Phys. Rev. C 90, 024304 (2014)
^{120}Sn(p,p'): A.M. Krumbholz et al., Phys. Lett. B 744, 7 (2015)

GSF of ^{120}Sn



H. K. Toft et al., Phys. Rev. C 83, 044320 (2011)

GSF of ^{96}Mo



D. Martin et al., to be published

Fluctuation Analysis

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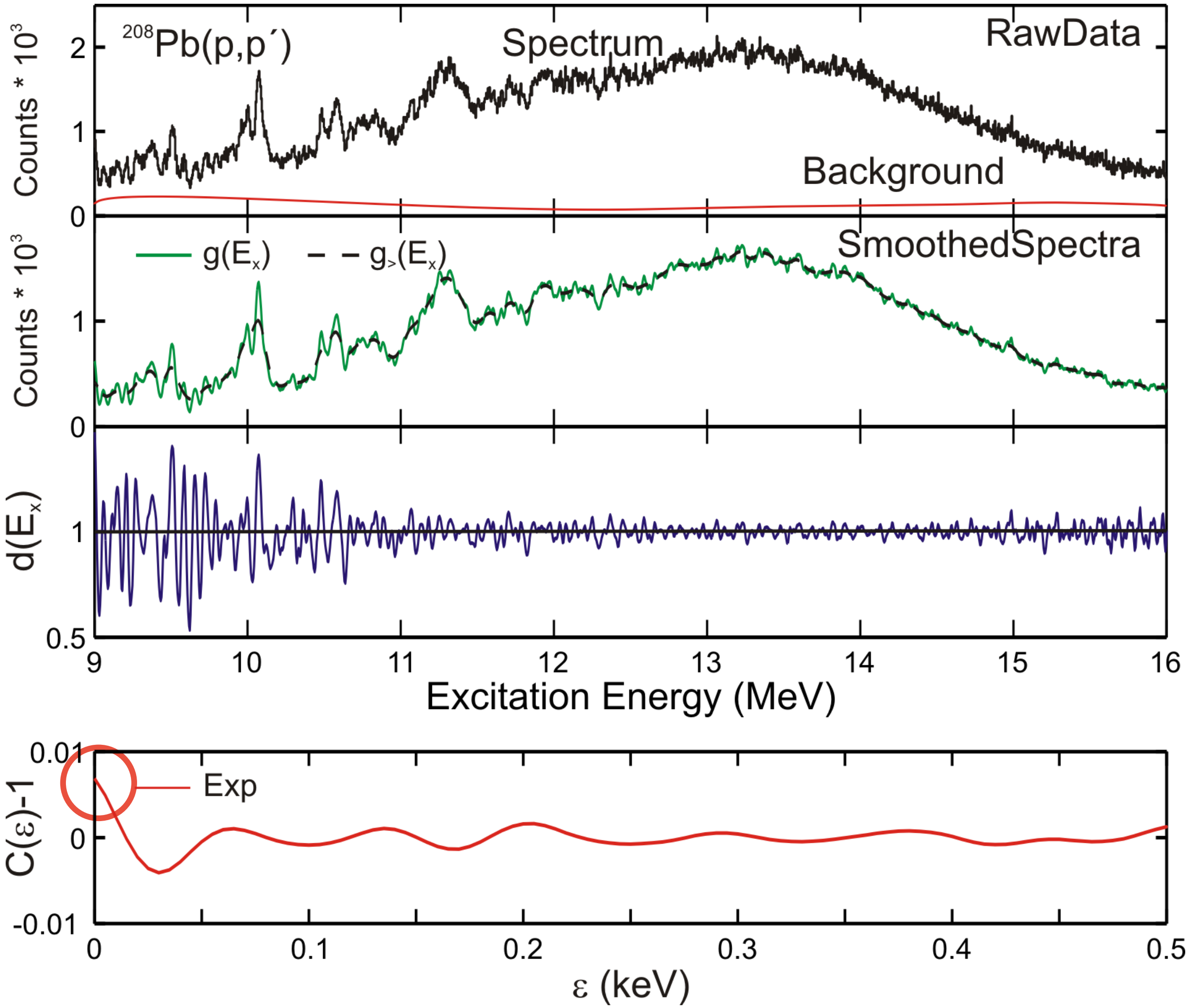


- Background from MDA
- Stationary spectrum $\frac{g(E_x)}{g_>(E_x)}$
- Autocorrelation function

Autocorrelation Function and Mean Level Spacing

- $$C(\varepsilon) = \frac{\langle d(E_x) \cdot d(E_x + \varepsilon) \rangle}{\langle d(E_x) \rangle \cdot \langle d(E_x + \varepsilon) \rangle}$$ autocorrelation function

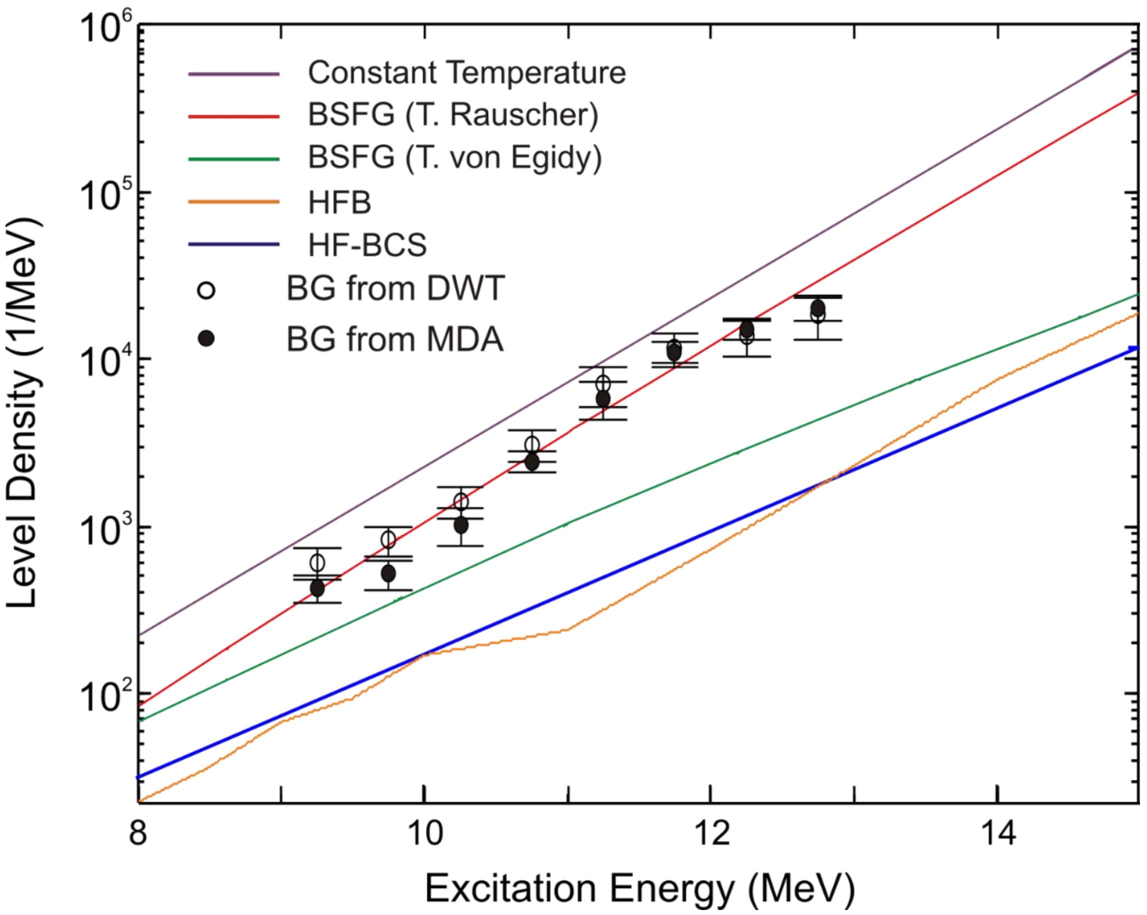
- $$C(\varepsilon = 0) - 1 = \frac{\langle d^2(E_x) \rangle - \langle d(E_x) \rangle^2}{\langle d(E_x) \rangle^2}$$ variance

- $$C(\varepsilon = 0) - 1 = \frac{\alpha \langle D \rangle}{2\sigma\sqrt{\pi}}$$ level spacing ⟨D⟩

- $$\alpha = \alpha_{PT} + \alpha_W$$ statistical properties

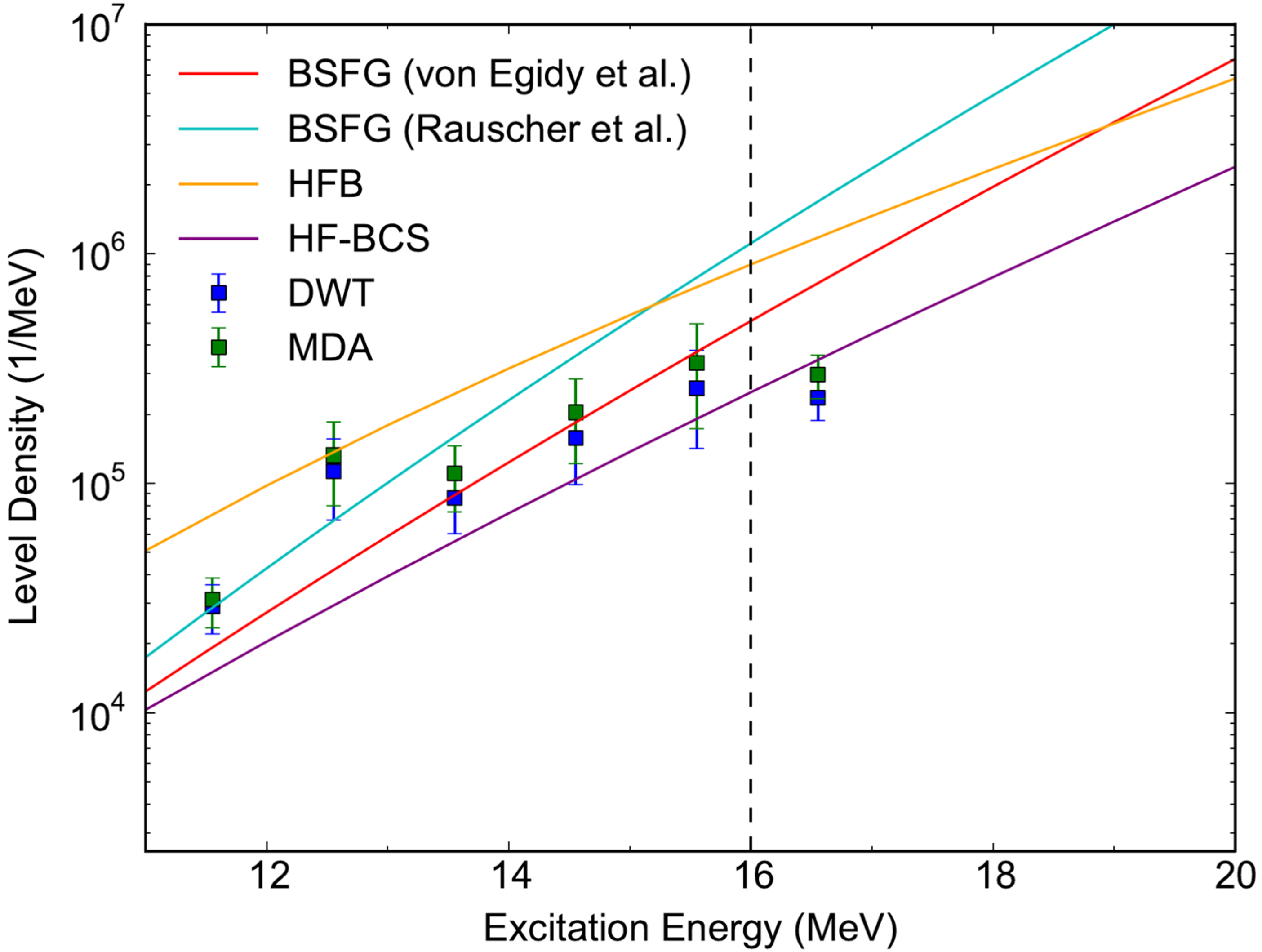
- σ resolution

Level density of $J^{\pi} = 1^{-}$ states in ^{208}Pb



I. Poltoratska et al., Phys. Rev. C 89, 054322 (2014)

Level Density of $J^{\pi} = 1^{-}$ States in ^{96}Mo



Summary and Outlook

- Polarized intermediate energy proton scattering at 0°:
  a new tool to extract the complete electric dipole response in nuclei

- Extraction of GSF and level densities from the same data

- Low-energy E1 strength in stable nuclei is sizable (2-3% of EWSR)

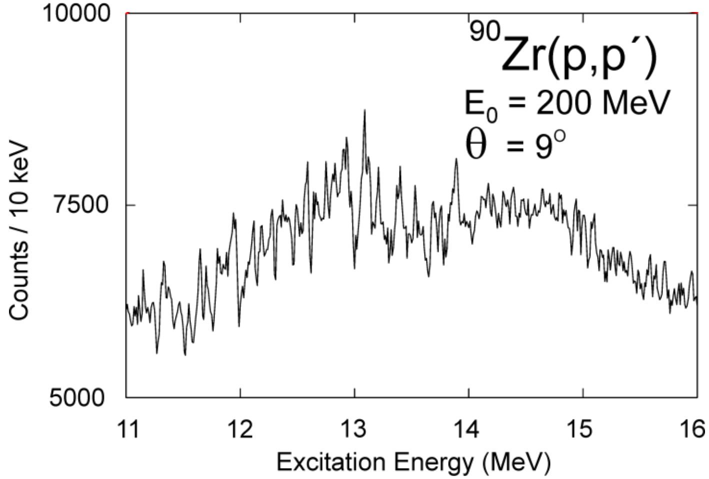
- Axel-Brink hypothesis seems to hold for ^{96}Mo

- Systematics of spin-M1 resonance in heavy nuclei

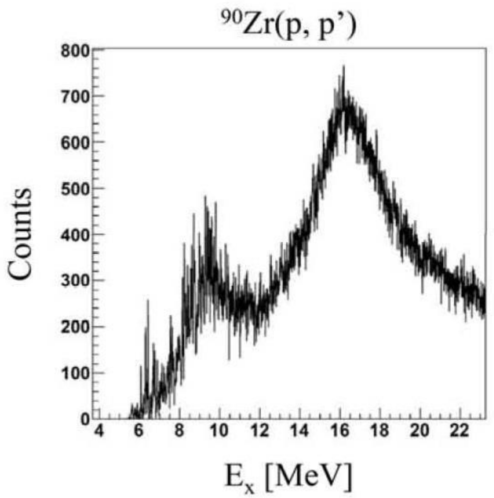
- Role of deformation: K-splitting of the PDR?

Spin Dependence of Level Densities

ISGQR	IVGDR + M1	ISGMR



A. Shevchenko et al.,
Phys. Rev. Lett. 93, 122501 (2004);
Phys. Rev. C 79, 044305 (2009)



C. Iwamoto et al.,
Phys. Rev. Lett. 108, 262501 (2012)

High-resolution study with ^{90}Zr(α,α') reaction at iThemba LABS

J^{π} = 0,1,2 level densities in the same nucleus → test of spin dependence

Collaboration

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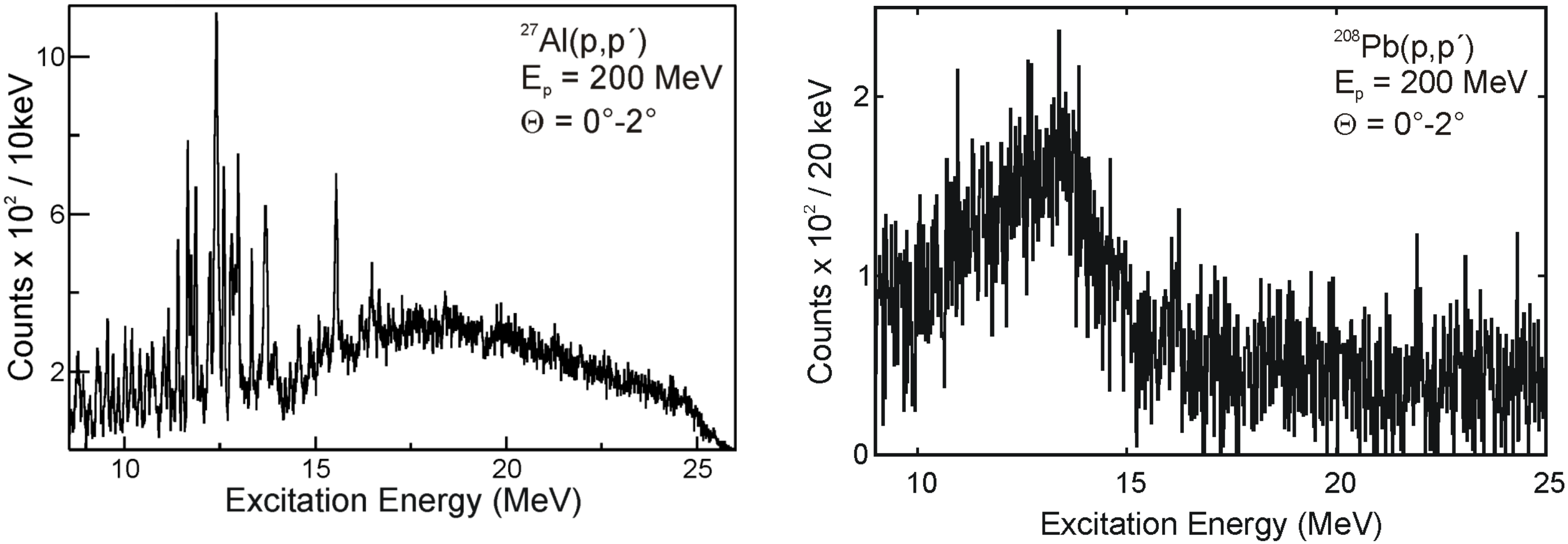
J. Birkhan, A. Krugmann, A.M. Krumbholz, D. Martin, P. von Neumann-Cosel, I. Poltoratska, N. Pietralla, V.Yu. Ponomarev, A. Richter, J. Wambach

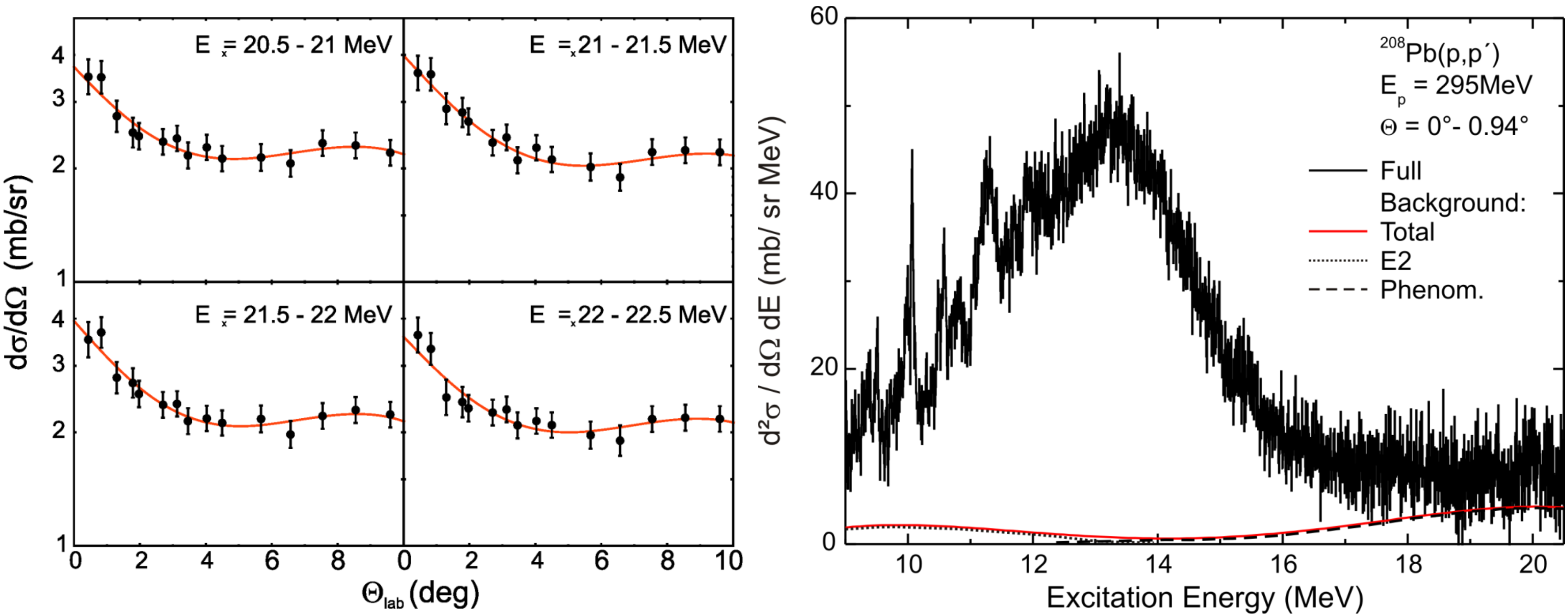
First 0° Proton Scattering Experiments at iThemba LABS, South Africa

U Cape Town / TU Darmstadt / iThemba LABS / U Osaka / RCNP Osaka / U Witwatersrand collaboration



R. Neveling et al., NIMA A654 (2011) 29

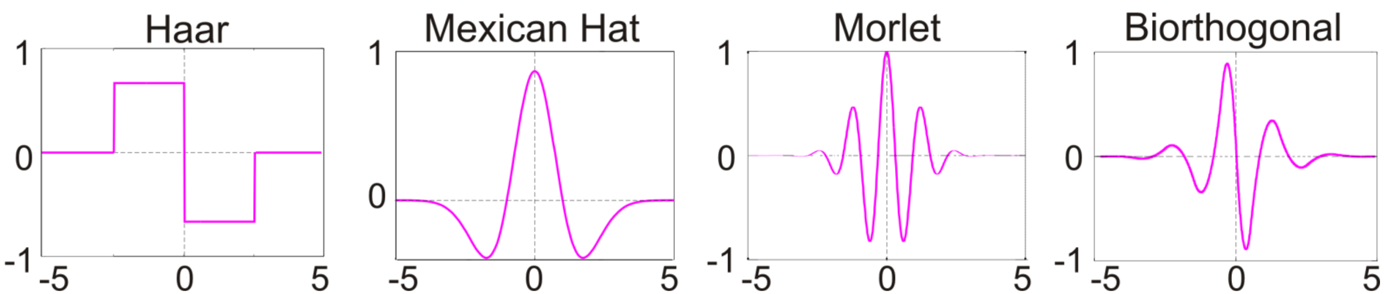
Multipole Decomposition in the GDR Region



- identical angular distributions
- determines phenomenological background

Wavelets

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



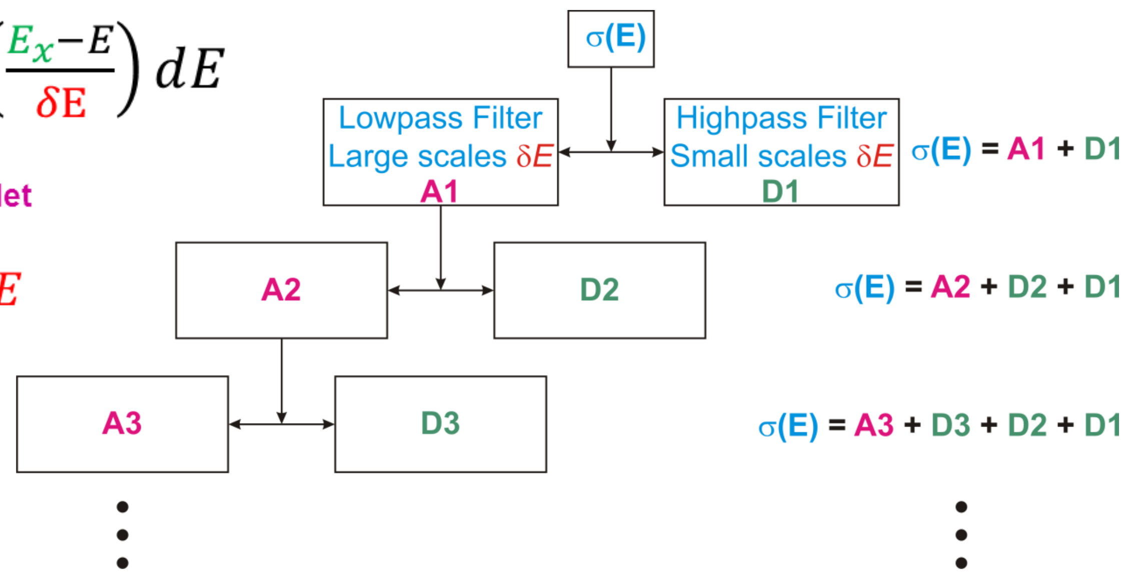
- Wavelet coefficients:

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

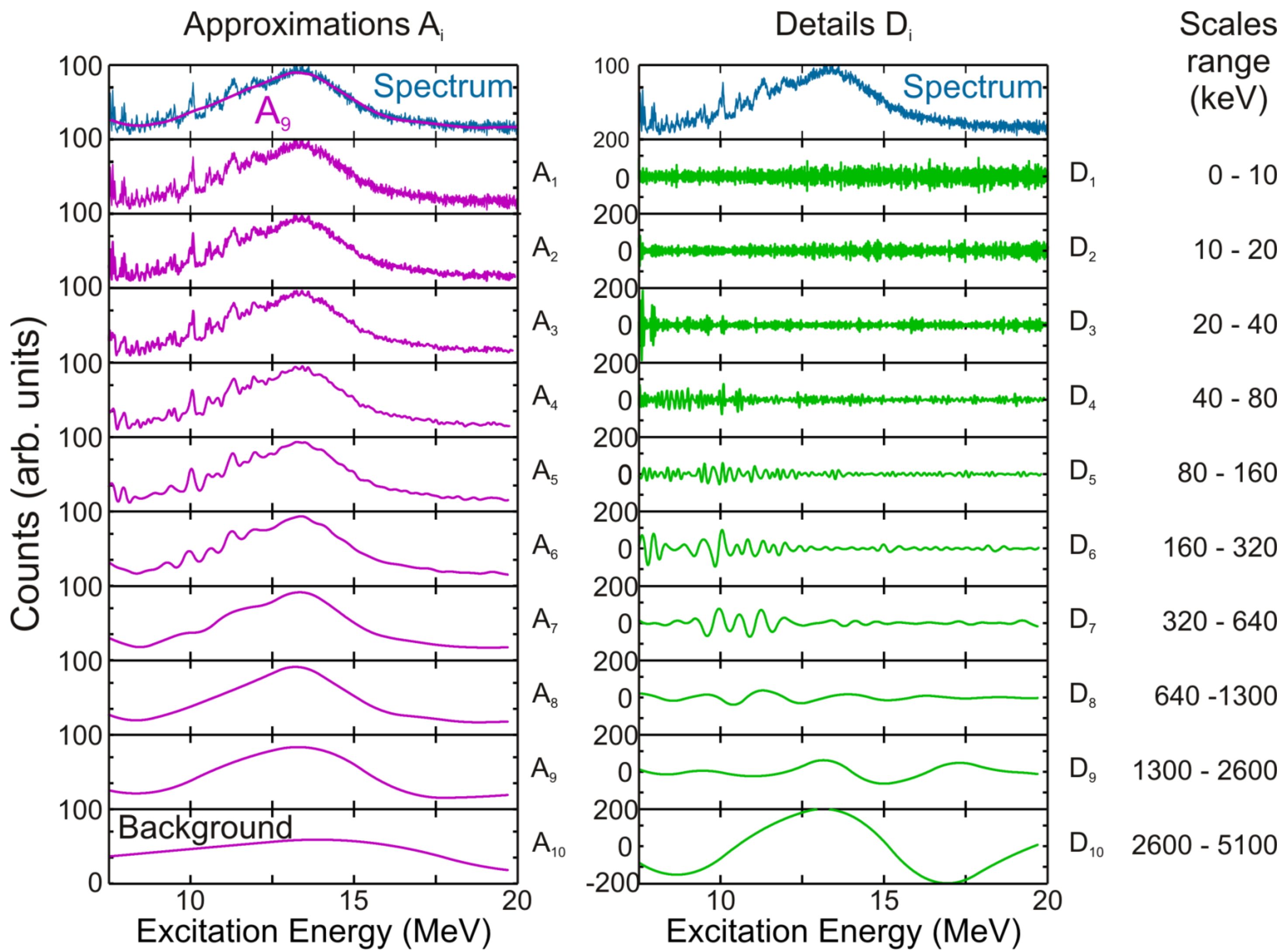
↑ **scale** ↑ **position** ↑ **spectrum** ↑ **wavelet**

- Discrete: $\delta E = 2^j$ and $E_x = k\delta E$

  with $k, j = 1, 2, 3, \ldots$



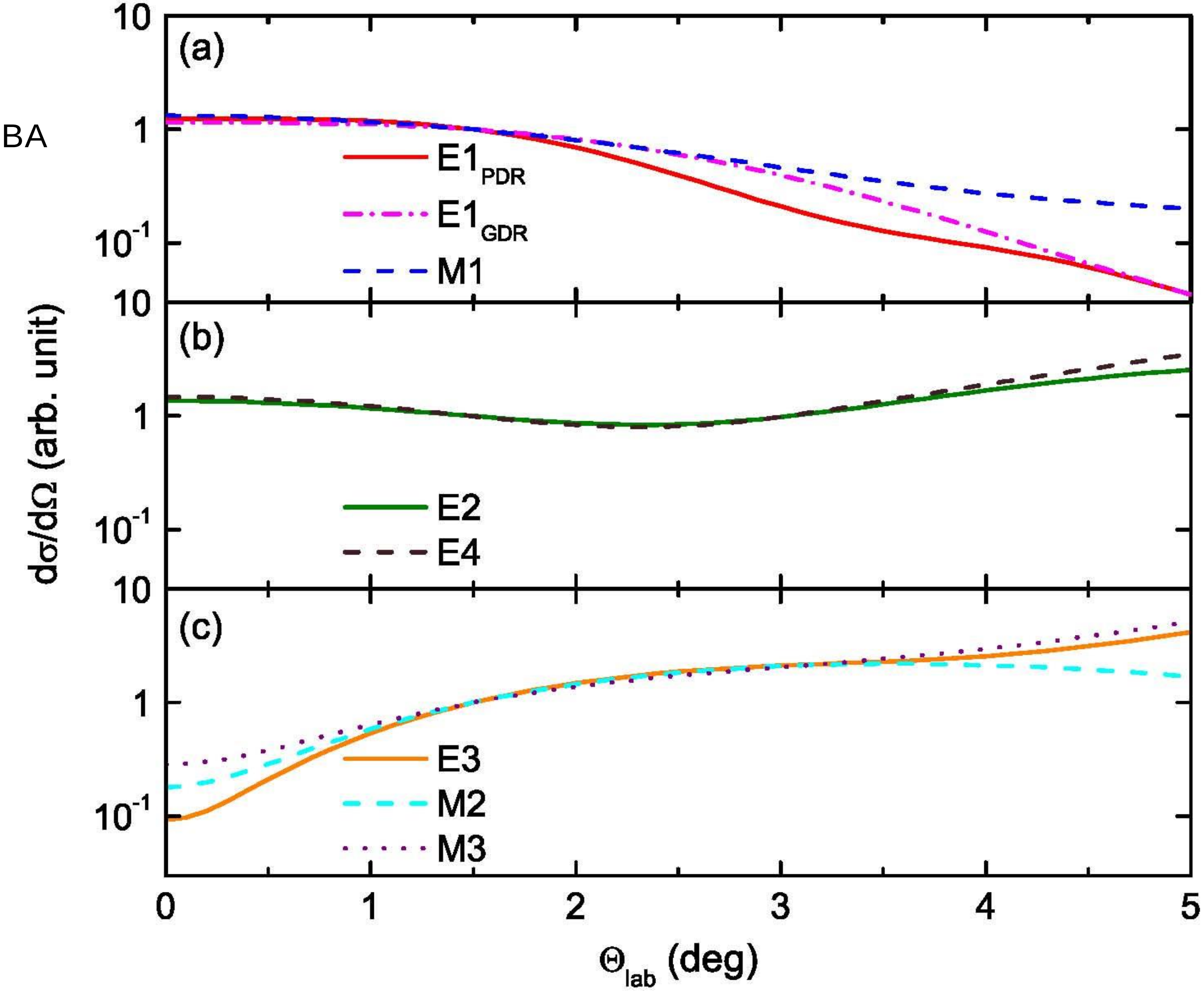
DWT of ^{208}Pb spectrum



Multipole Decomposition of Cross Section
Angular Distributions

$$\left.\frac{d\sigma(\Theta)}{d\Omega}\right|_{\text{data}} = \sum_{\Delta L} a_{\Delta L} \left.\frac{d\sigma(\Theta)}{d\Omega}\right|_{\text{DWBA}}$$

- Restrict data to $\Theta \leq 4°$
- ΔL = 0 → spin M1
- ΔL = 1 → E1 (Coulomb + nuclear)
- ΔL > 1 → only E2 (or E3) considered
- GDR region: ΔL = 0 replaced by phenome-nological background



Spin M1 and GT Strength

- GT unit cross section $$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(q=0)=\hat{\sigma}_{\mathrm{GT}}F(q,E_x)B(\mathrm{GT})$$
- Spin M1 unit cross section $$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(q=0)=\hat{\sigma}_{\mathrm{M1}}F(q,E_x)B(\mathrm{M1}_{\sigma\tau})$$
- Transition strength $$B(\mathrm{GT},\mathrm{M1})=\frac{1}{2}\frac{C^2}{2T_{\mathrm{f}}+1}|\langle f||\sum_k^A \sigma_k\tau_k||i\rangle|^2$$
- Relation etablished by two assumptions
  - analog states have the same matrix elements
  - cross sections of (p,p‘) and (p,n) are analogous

$$\boxed{\frac{\hat{\sigma}_{M1}}{\hat{\sigma}_{\mathrm{GT}}}=\frac{1}{2}\frac{T_0+1}{T_0}}$$

- Equivalent M1 strength $$B(\mathrm{M1})\cong B(\mathrm{M1})_{\sigma\tau}=\frac{3}{8\pi}\left(\frac{g_s^{\mathrm{IV}}}{2}\right)^2 B(\mathrm{M1}_{\sigma\tau})\,[\mu_N^2]$$

Application to ^{208}Pb

R.M. Laszewski et al., Phys.Rev. Lett. 61, 1710 (1988)
R. Köhler et al., Phys. Rev. C 35, 1646 (1987)

$$\sum B(M1) = 14.8^{+1.9}_{-1.5}\,\mu_N^2$$

for $E_x < 8$ MeV

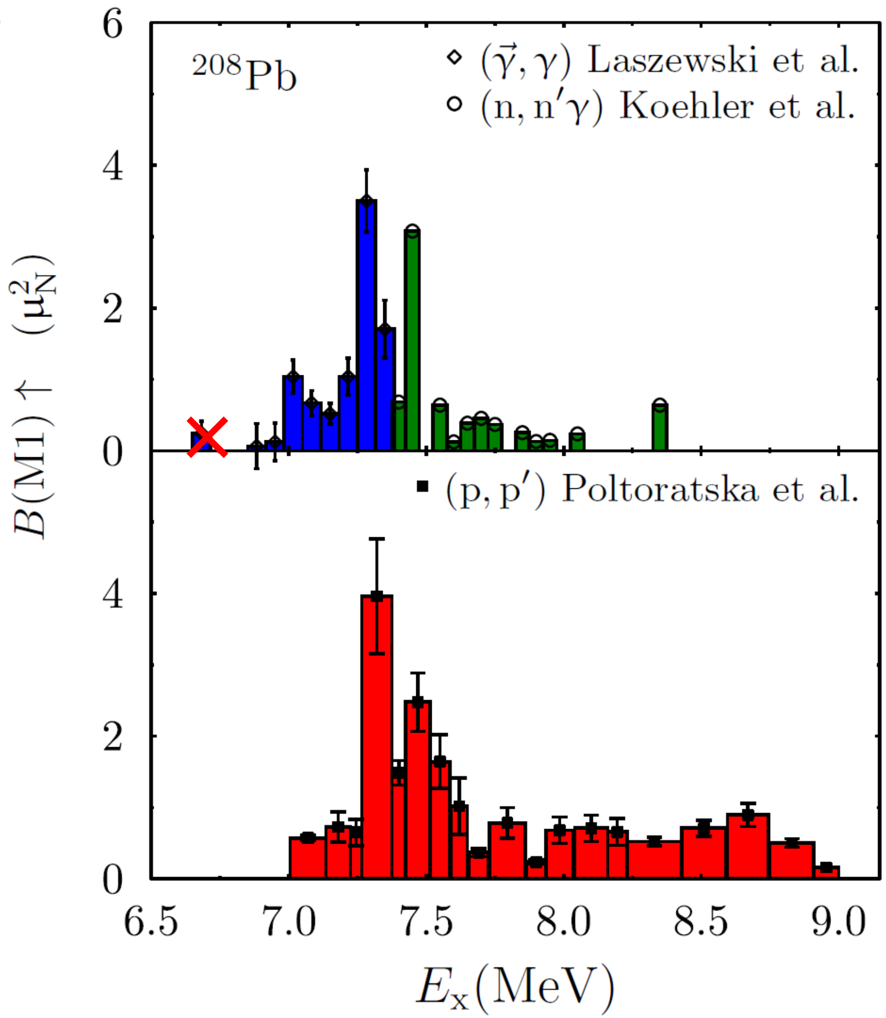
I. Poltoratska et al., Phys. Rev C 85, 041304 (2012)

$$\sum B(M1) = 16.0(12)\,\mu_N^2$$

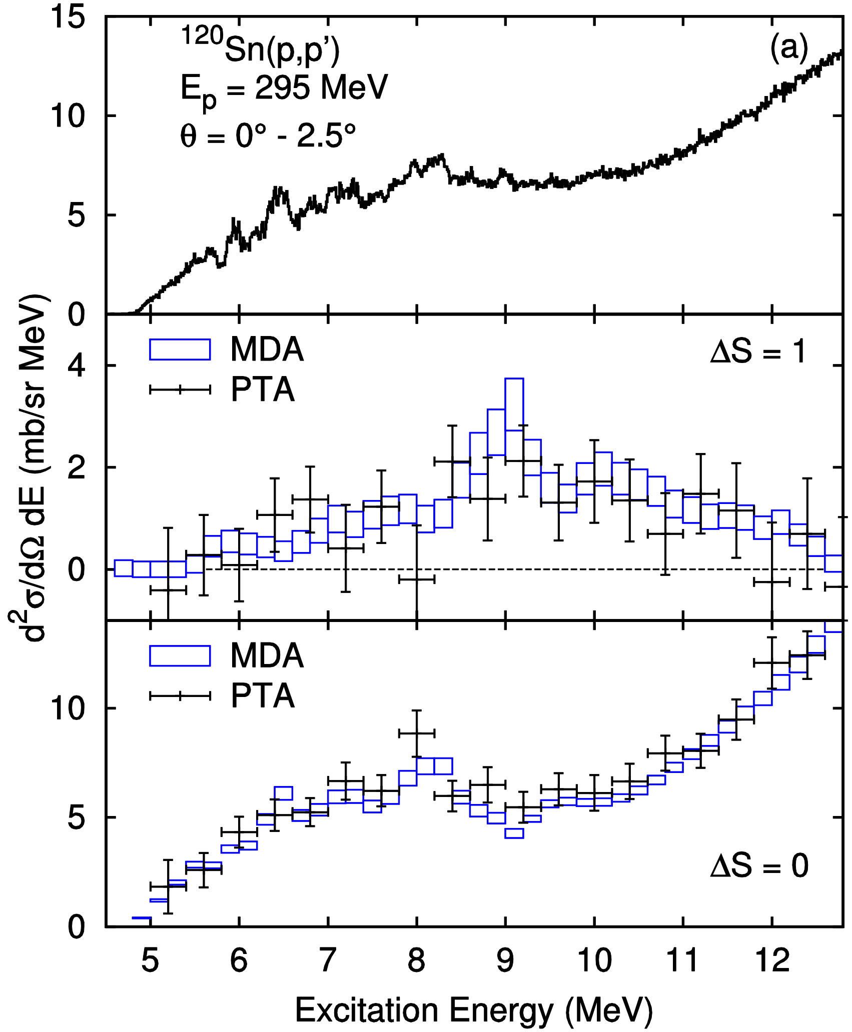
for $E_x < 8$ MeV

$$\sum B(M1) = 20.5(13)\,\mu_N^2$$

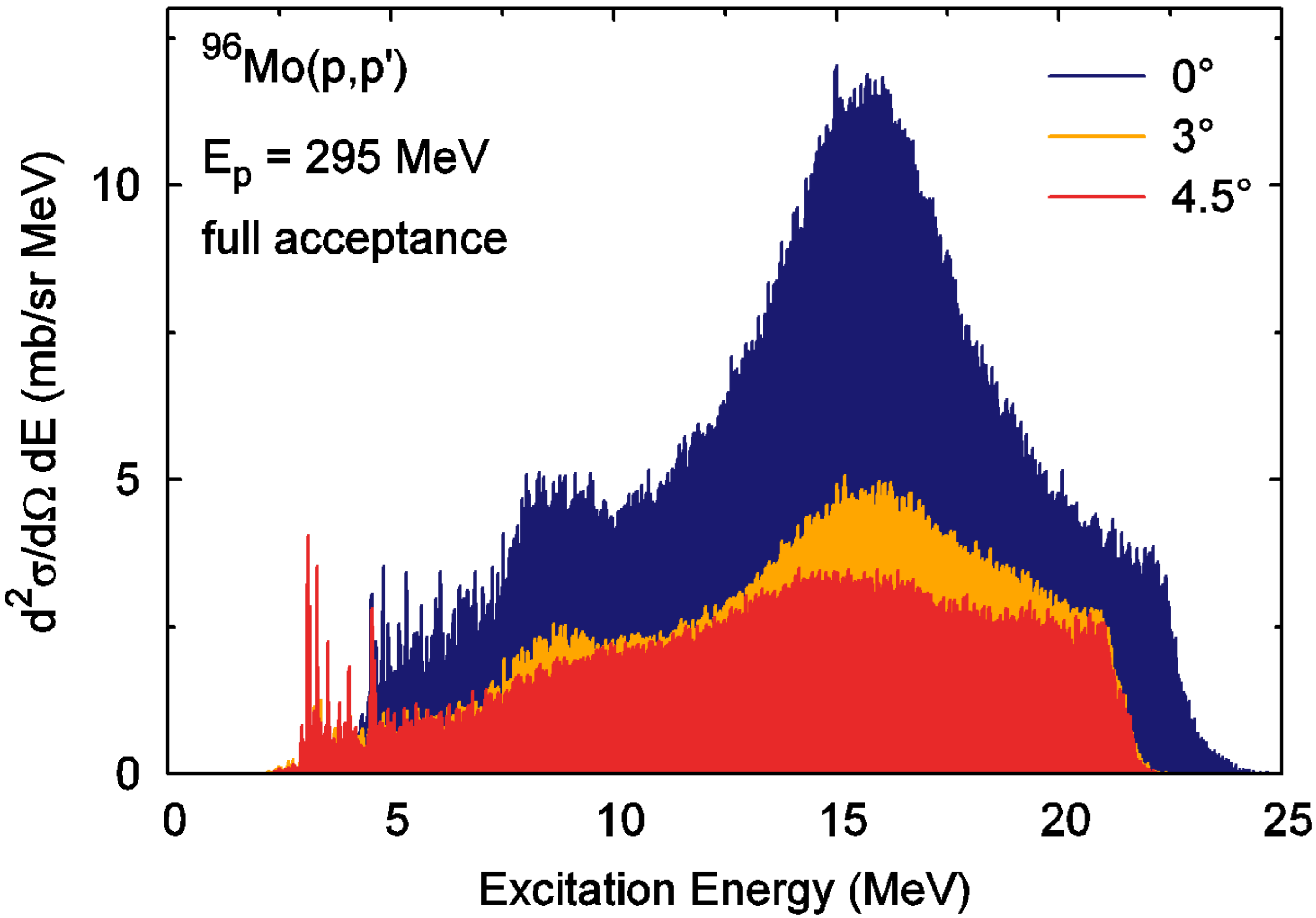
for full resonance



E1/M1 Decomposition



Differential Cross Sections



Polarization Transfer Observables in ^{96}Mo

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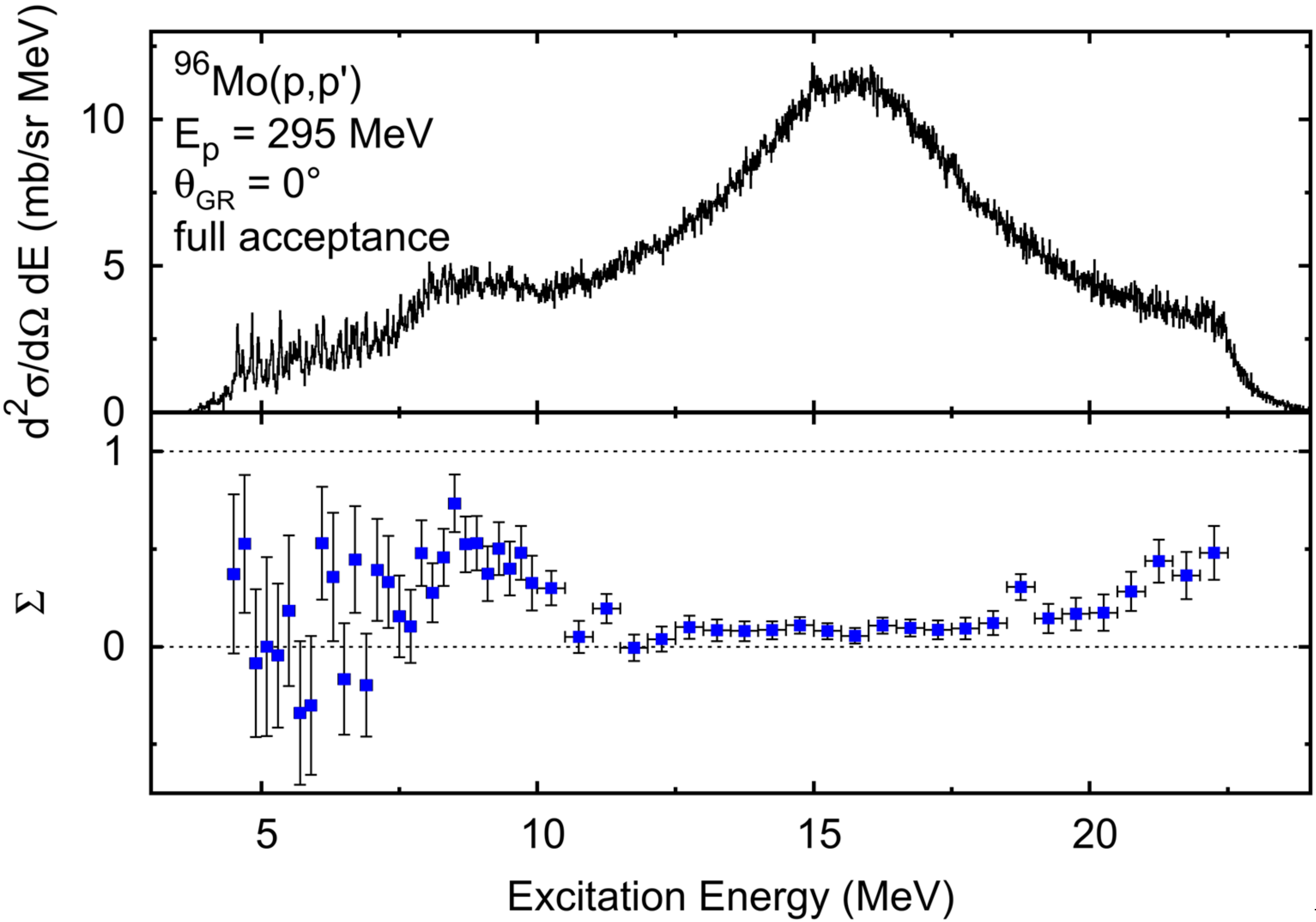
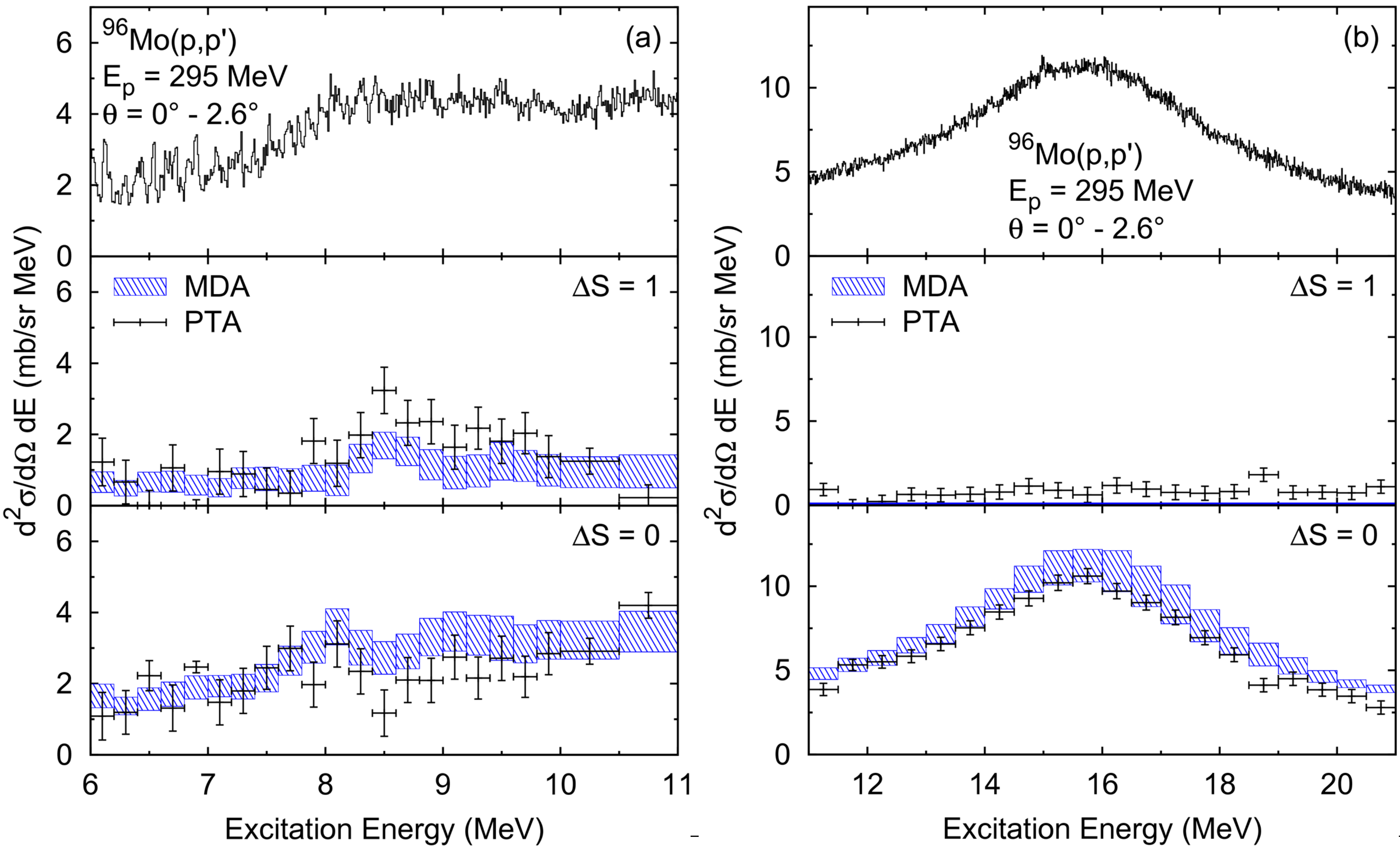
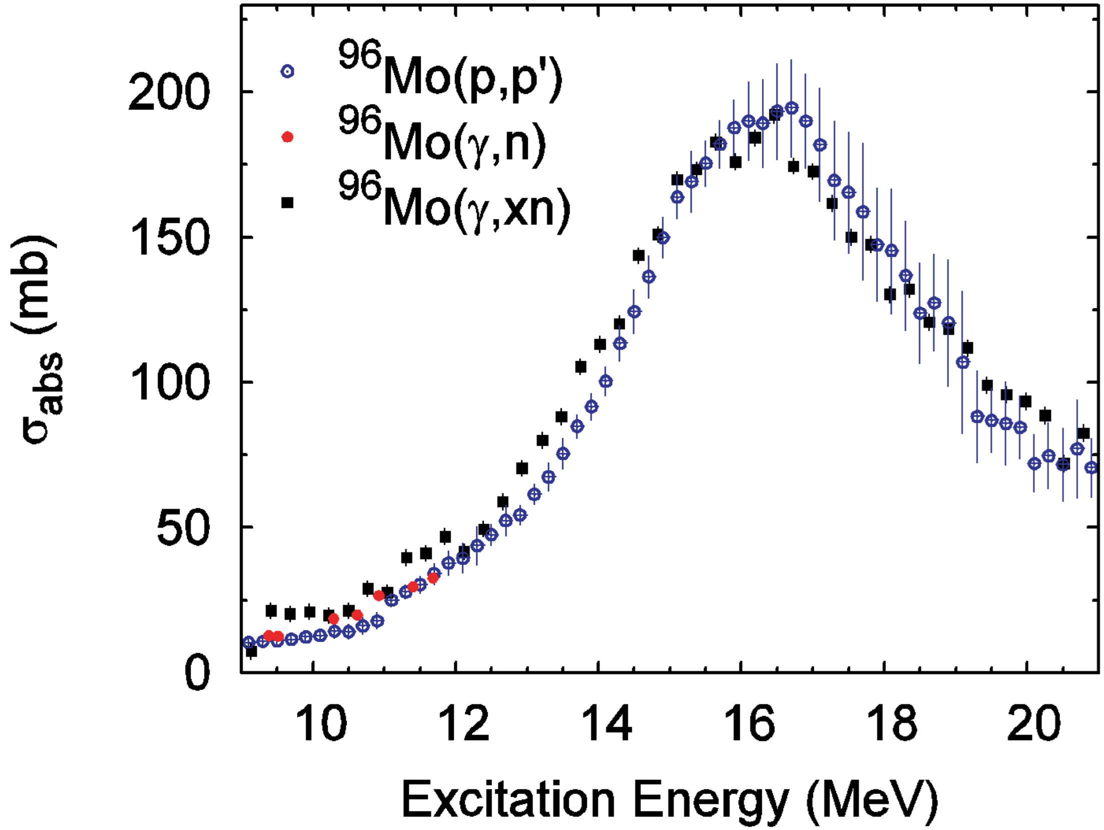


Comparison: PTA vs. MDA

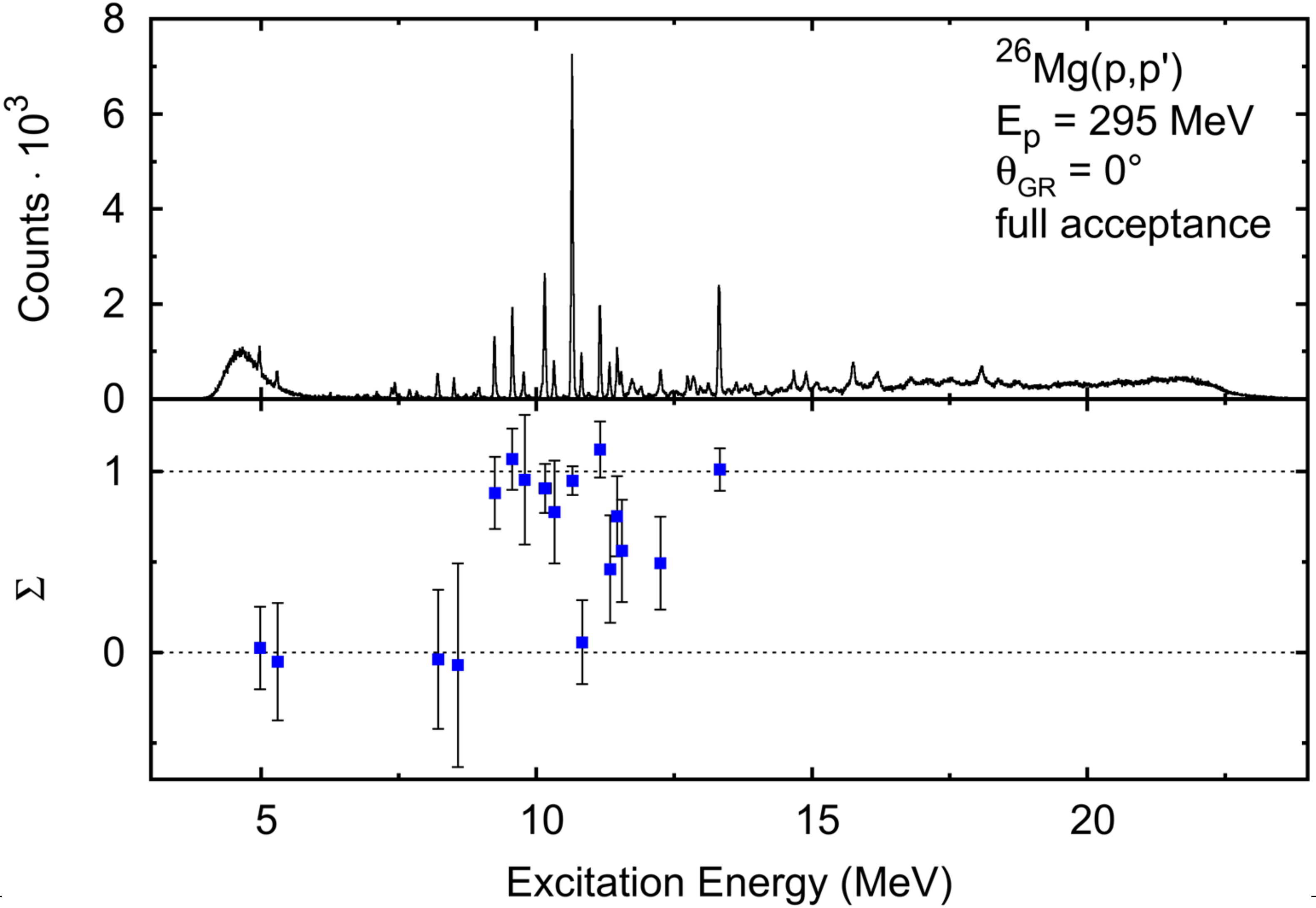


Photoabsorption Cross Sections

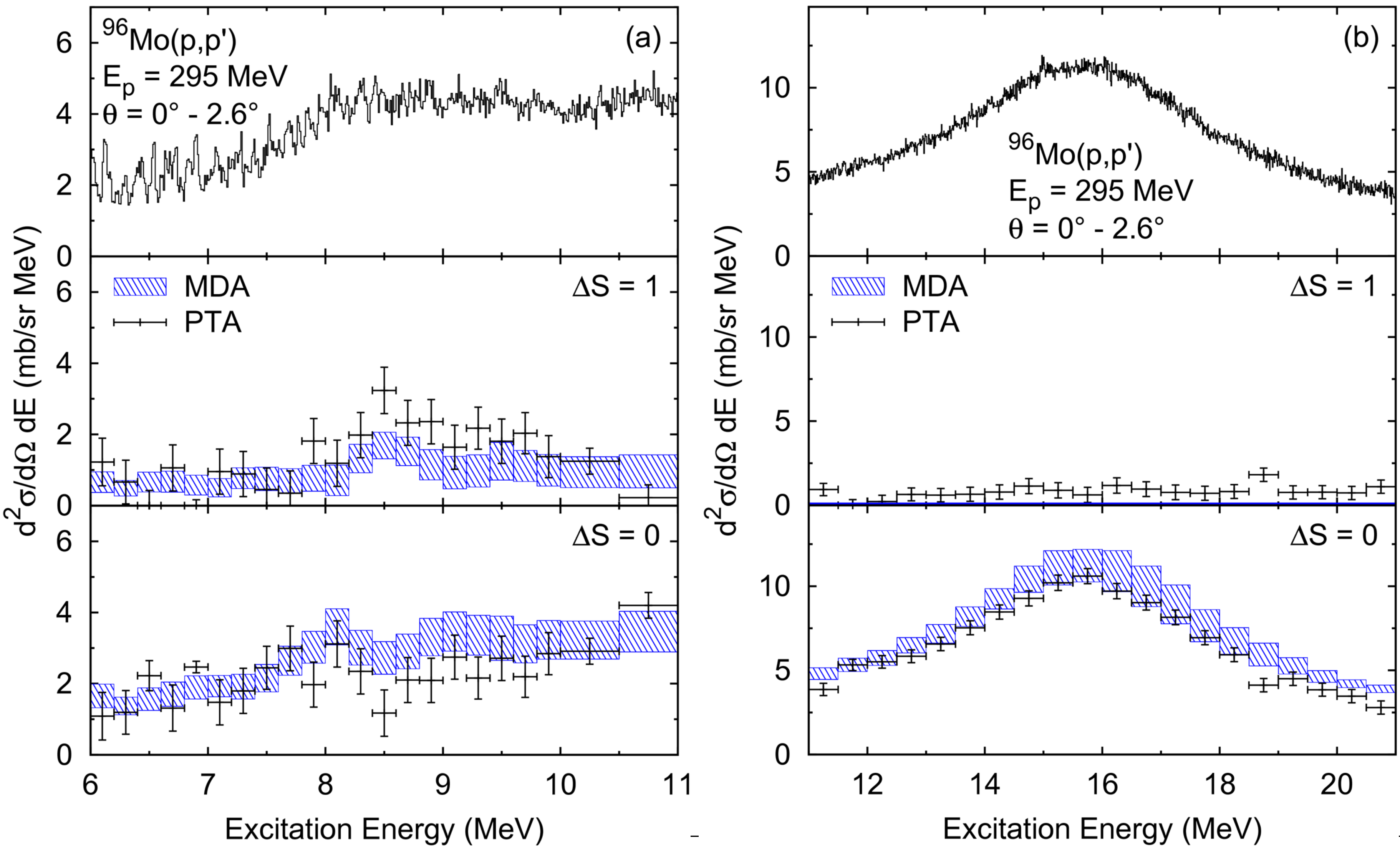


- Normalized to (γ,xn) data near the GDR maximum
- Good agreement with recent (γ,n) measurement

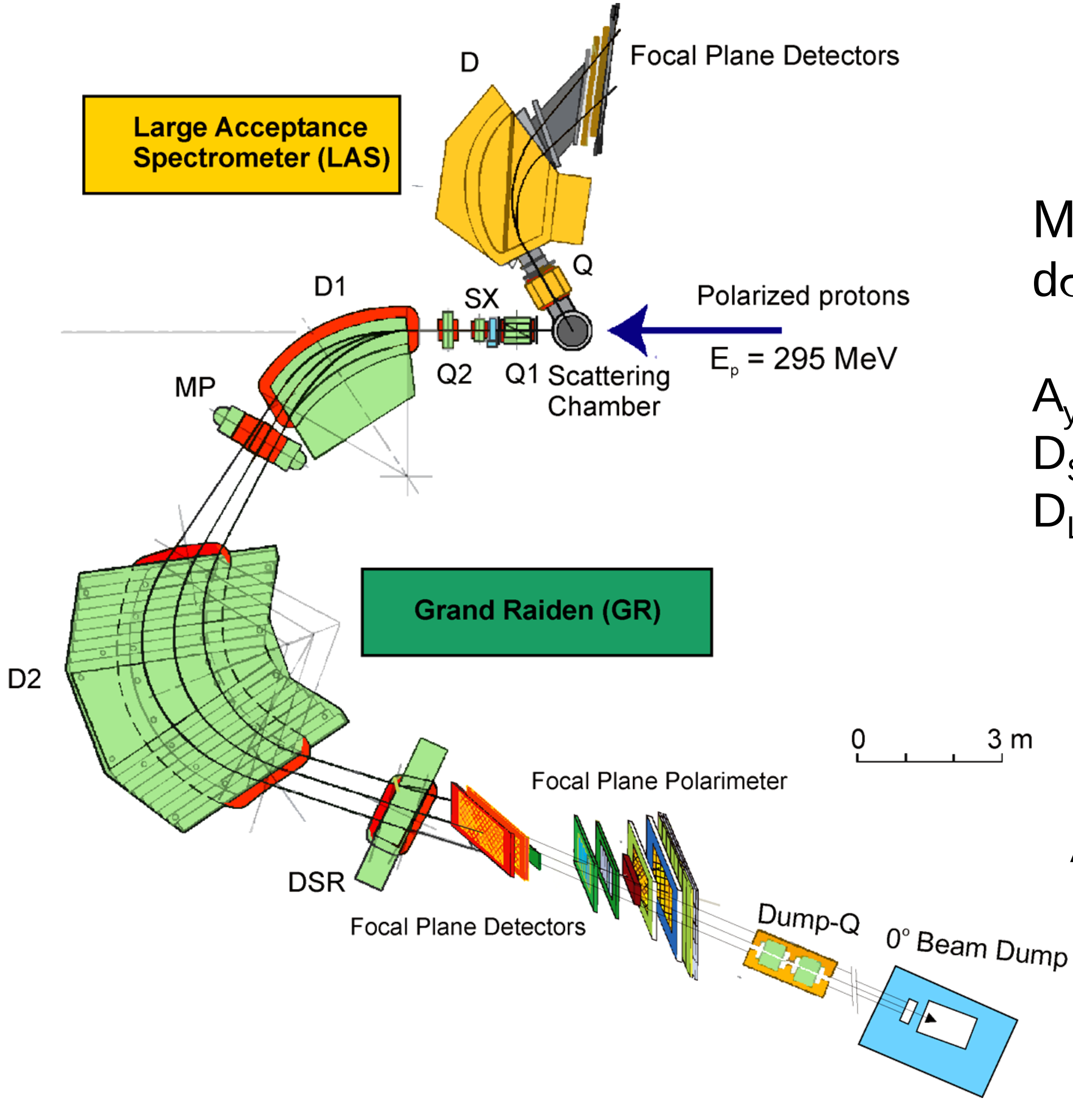
Polarization transfer observables in ^{26}Mg



Comparison: PTA vs. MDA



0^o Setup at RCNP



Measured observables

$d\sigma/d\Omega$ - angular distributions ($0° \leq \Theta \leq 10°$)

A_y - asymmetry

D_{SS} at 0° - sideways polarization

D_{LL} at 0° - longitudinal polarization

A. Tamii et al., NIMA 605 (2009) 326