# Test of the Brink-Axel Hypothesis with Gamma Strength Functions from Forward Angle Inelastic Proton Scattering

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- Gamma strength functions and Brink-Axel hypothesis
- The case of $^{208}$Pb
- The case of $^{96}$Mo
- Level densities from fine structure

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# Gamma Strength Function (GSF)

$$\langle \Gamma(E_i) \rangle = \frac{1}{\rho(E_i)} \int_0^{E_i} E_\gamma^3 \, f^{E/M\lambda}(E_\gamma)\, \rho\big(E_f\big) dE_\gamma$$

- GSF describes average γ decay probability
- Depends on level densities at initial and final energies
- Sum over all multipolarities but E1 dominates
- Applications in astrophysics (large-scale reaction network calculations), reactor modeling and waste transmutation

# Brink-Axel Hypothesis

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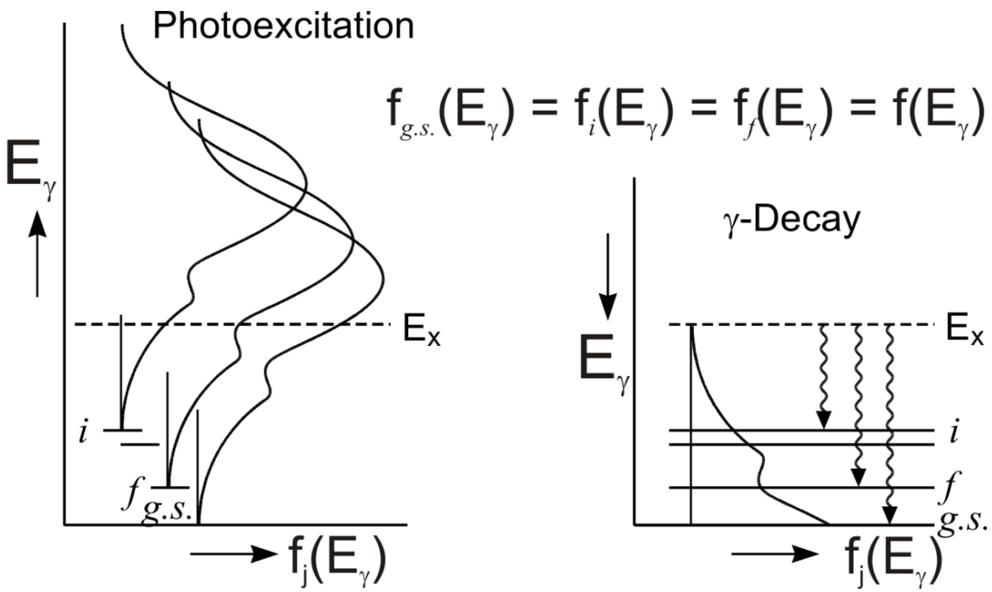


- Strength
  - depends only on $E_\gamma$
  - is independent of the initial and final state structure: $E_x$, $J^\pi$,…
- Central assumption for modeling finite temperature effects in astrophysical reaction network calculations
- Same GSF for γ absorption and emission → needs to be tested

# Electric Dipole Response in Nuclei

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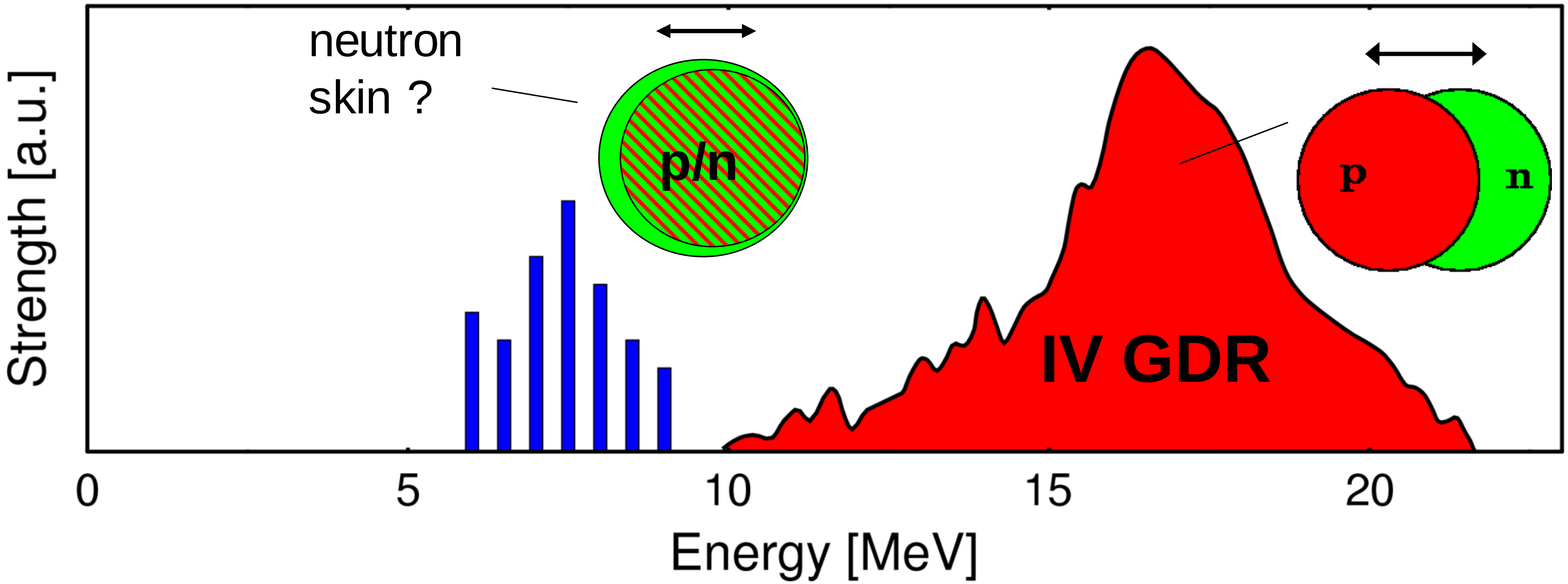


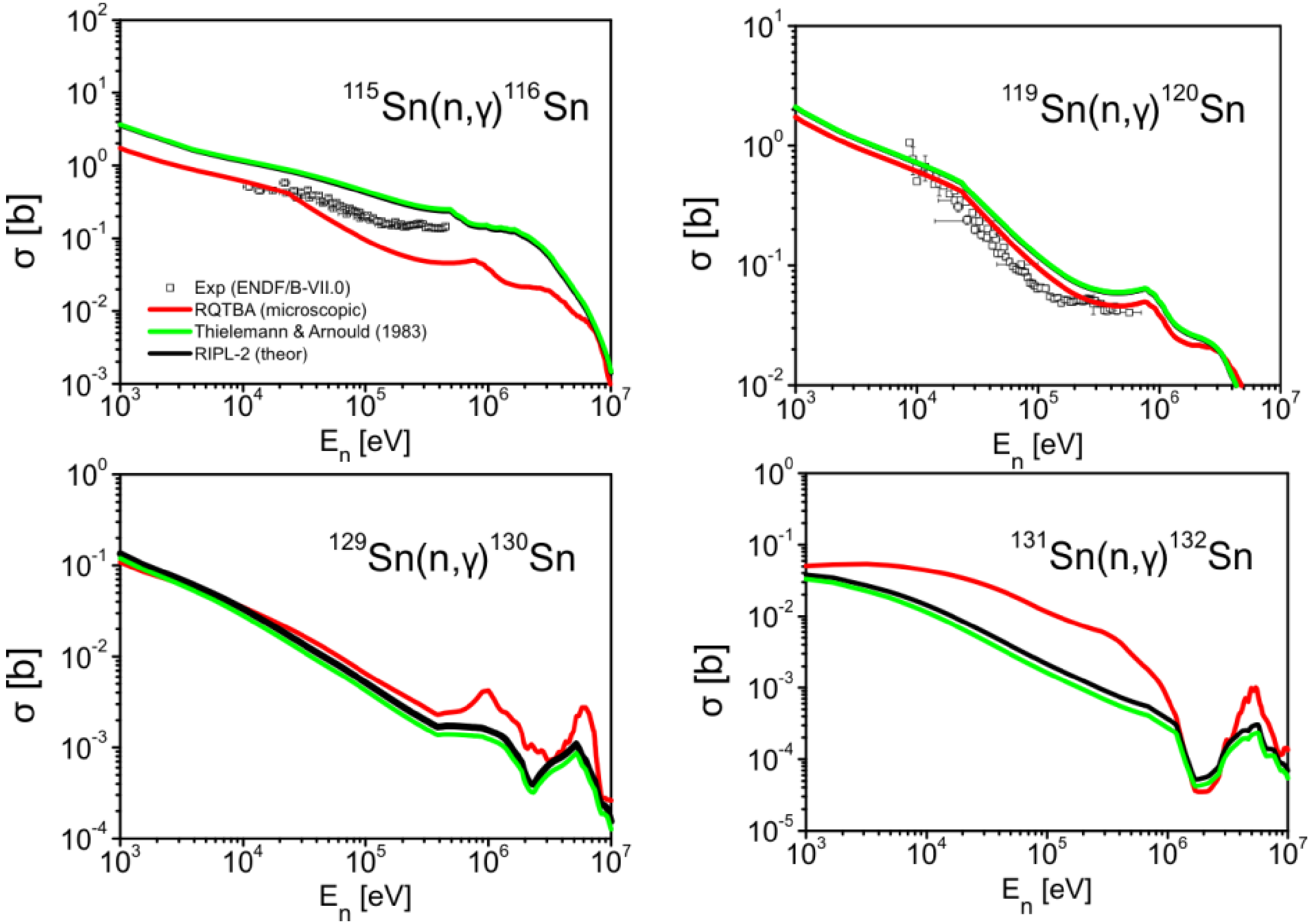

Oscillations of neutron skin against N ≈ Z core
Pygmy Dipole Resonance (PDR)

Oscillations of neutrons against protons
Giant Dipole Resonance (GDR)

- BA hypothesis approximately holds in GDR region for temperatures < 1.5 MeV
- What about the PDR region?

# Influence of the PDR on r-Process Rates






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

# New Experimental Tool for Complete Dipole Strength Distributions

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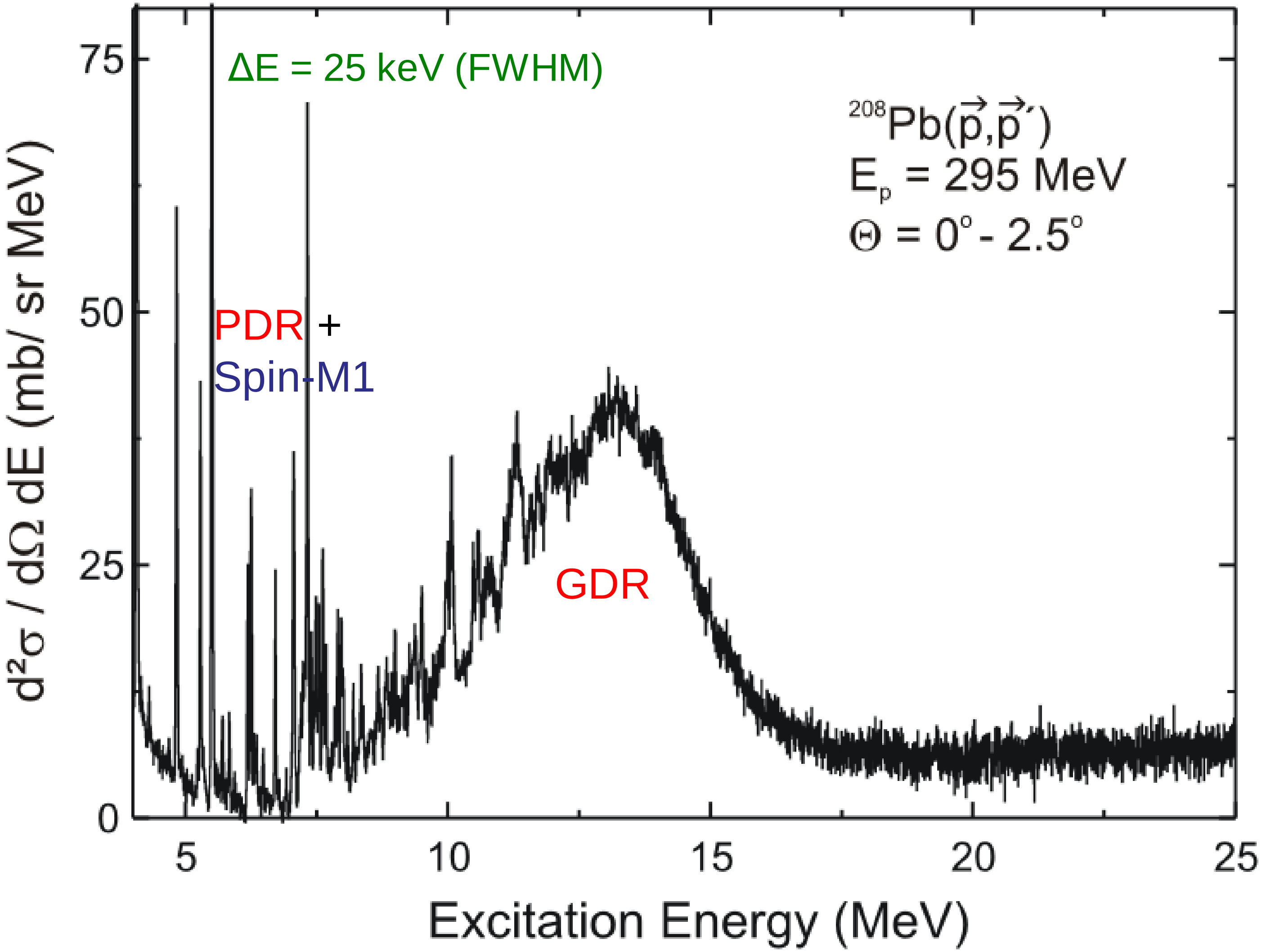
- Polarized proton scattering at 300 MeV and 0° at RCNP
  - relativistic Coulomb excitation dominates: E1 strength
  - Spinflip-M1 cross sections separated: M1 strength
  - high resolution ΔE ≈ 25 keV (FWHM): level density of $1^-$ states

- $^{208}$Pb and $^{120}$Sn as reference cases

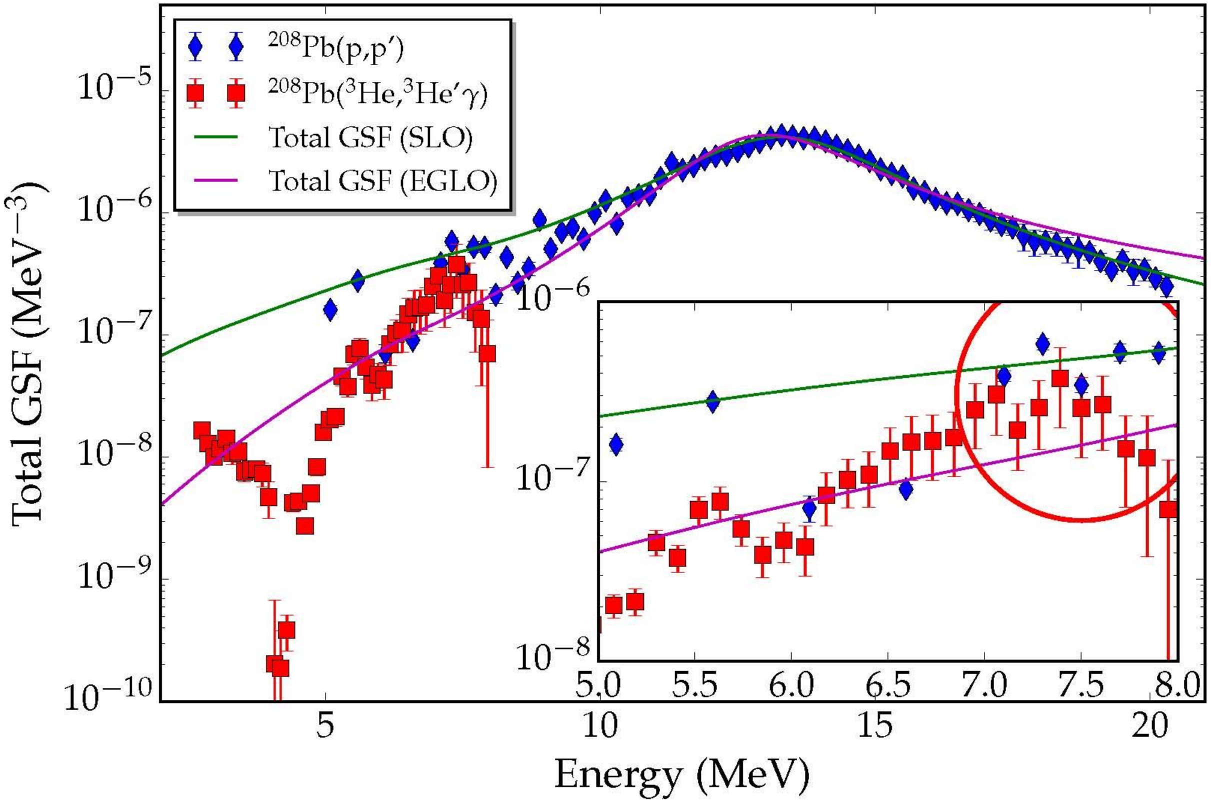
A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062502
I. Poltoratska et al., Phys. Rev. C 85 (2012) 041304(R)
A.M. Krumbholz et al., Phys. Lett. B 744 (2015) 7
T. Hashimoto et al., Phys. Rev. C 92 (2015) 031305(R)
J. Birkhan et al., Phys. Rev. C 93 (2016) 041302(R)

# $^{208}$Pb Spectrum



# GSF in $^{208}$Pb: Comparison with Oslo Data

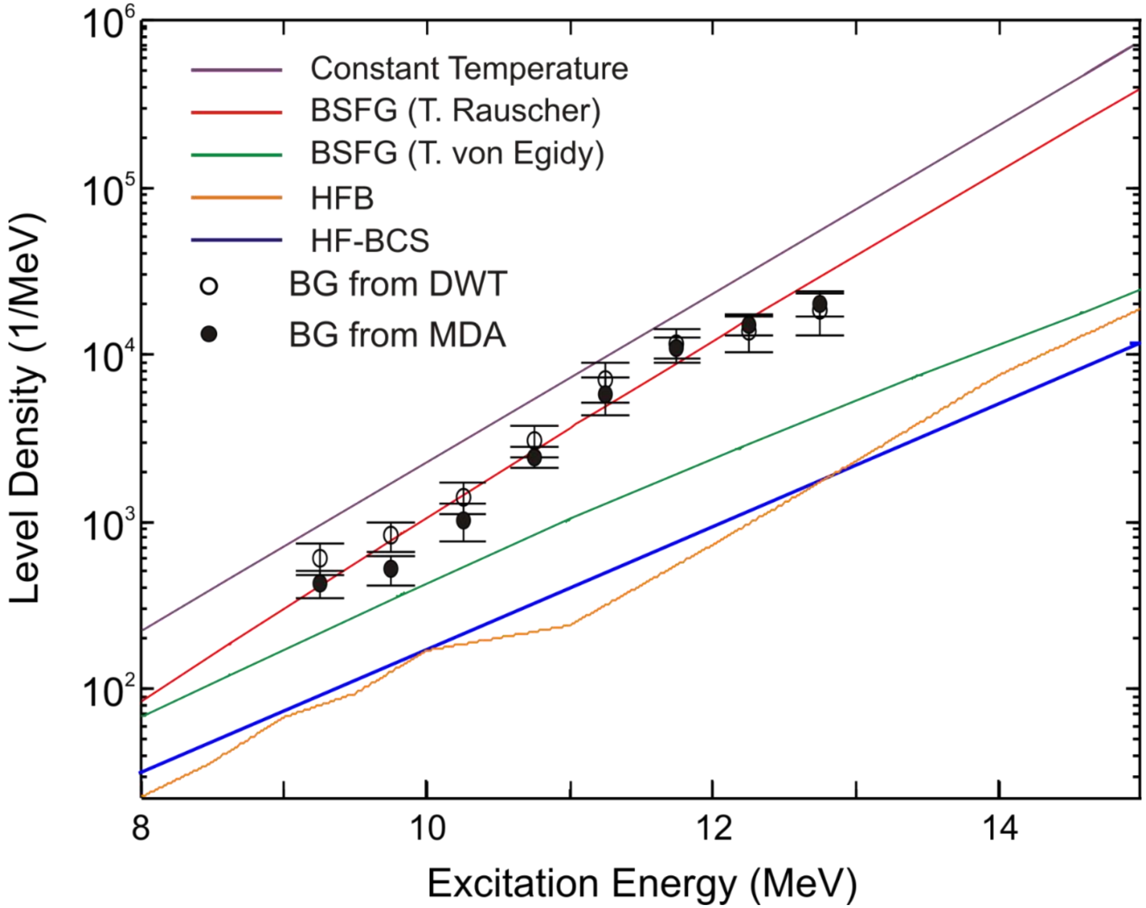
(p,p‘): S. Bassauer, PvNC, A. Tamii, Phys. Rev. C (submitted)
($^3$He,$^3$He‘γ): N.U.H. Syed et al., Phys. Rev. C 79, 024316 (2009); reanalyzed by M. Guttormsen (priv. comm.)




- Violation of BA hypothesis in the PDR region?
- Problem of decomposition of GSF and level densities in Oslo method?

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

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



# Total Level Density in $^{208}$Pb

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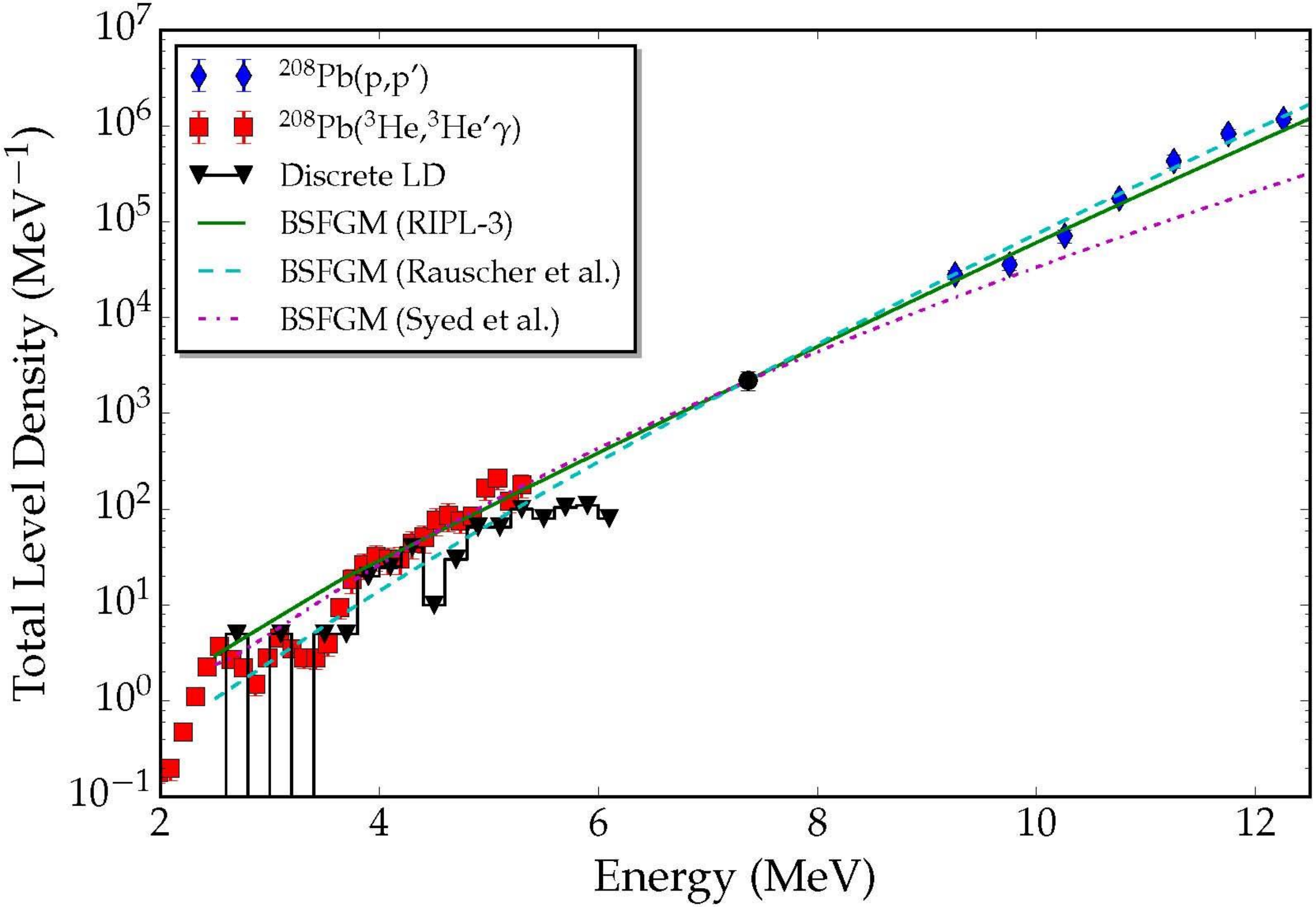
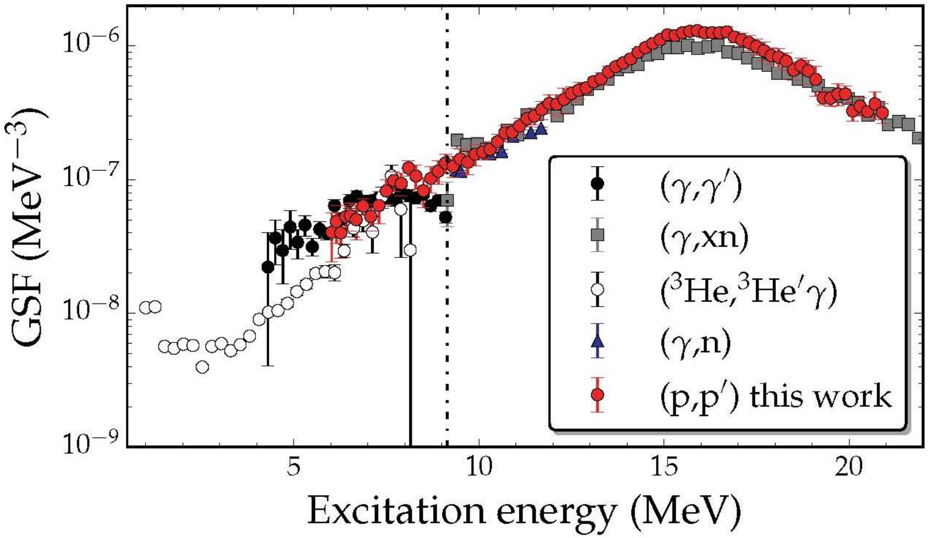
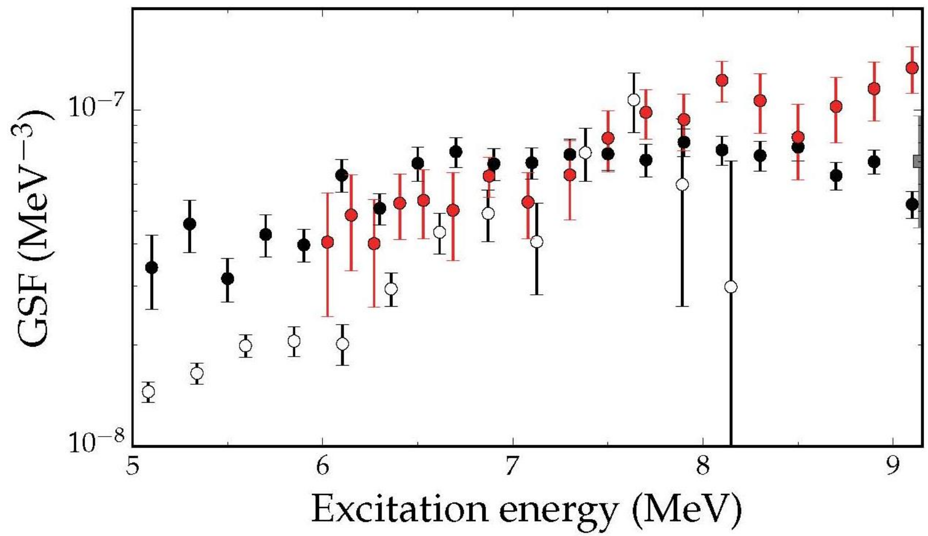



- Good agreement with Oslo results

# GSF in $^{96}$Mo

(p,p‘): D. Martin et al., to be published
($^{3}$He,$^{3}$He‘): A.C. Larsen, S. Goriely, Phys. Rev. C 82 (2010) 014318

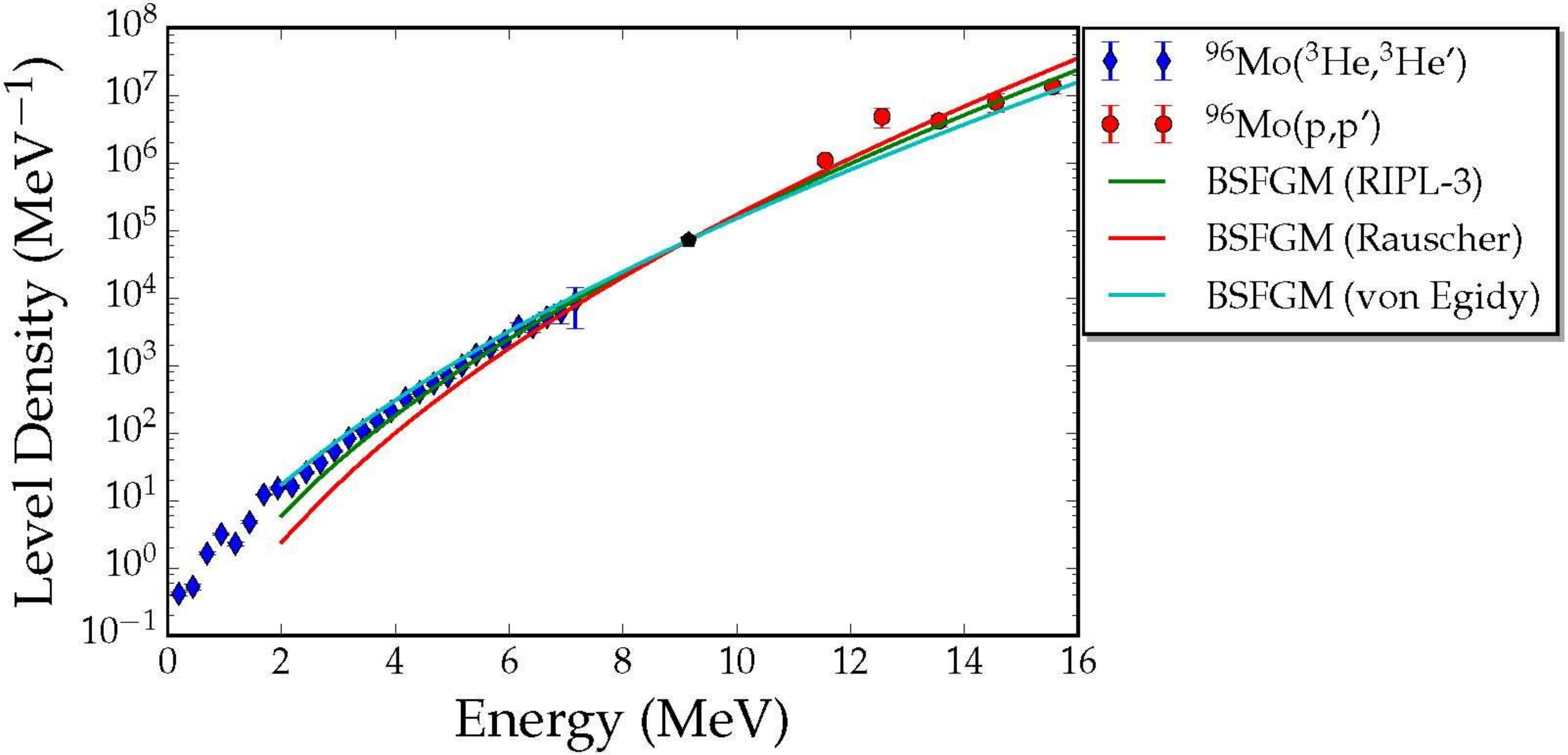



- Consistent with decay results in the PDR region

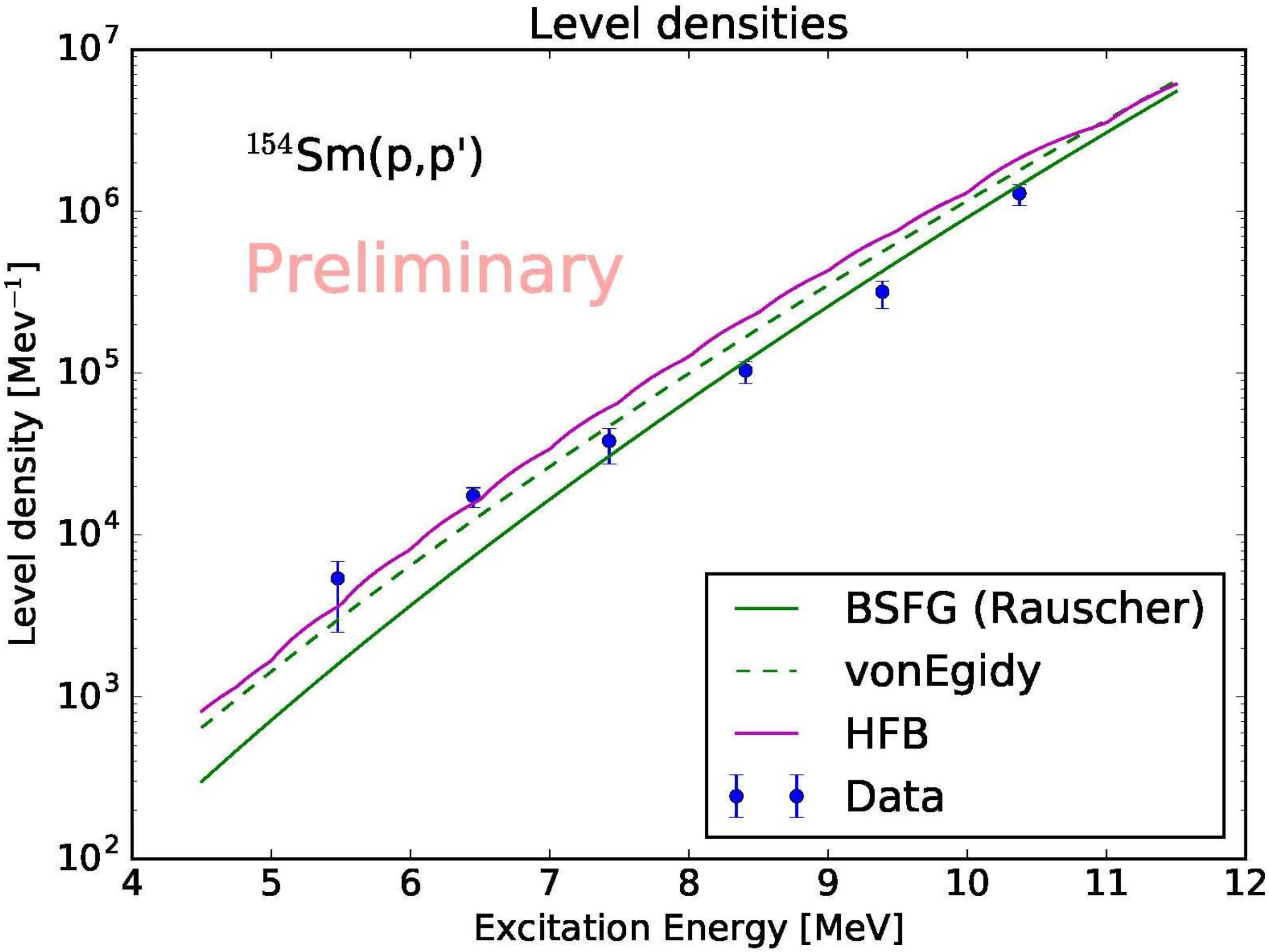
# Total Level Density in $^{96}$Mo

D. Martin et al., to be published




- Consistent with results from decay experiments

# J = 1 Level Densities in Heavy Deformed $^{154}$Sm



# Summary

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- Polarized proton scattering at 300 MeV and 0°: a new experimental tool
- Extraction of GSF (E1 and M1) and level densities from the same data
- Level densities in $^{96}$Mo and $^{208}$Pb agree with those from Oslo data
- Disagreement of GSF with Oslo data in the PDR region for $^{208}$Pb: large intensity fluctuations because of too small level density?
- Brink-Axel hypothesis seems to hold in the PDR region for $^{96}$Mo

# Collaboration

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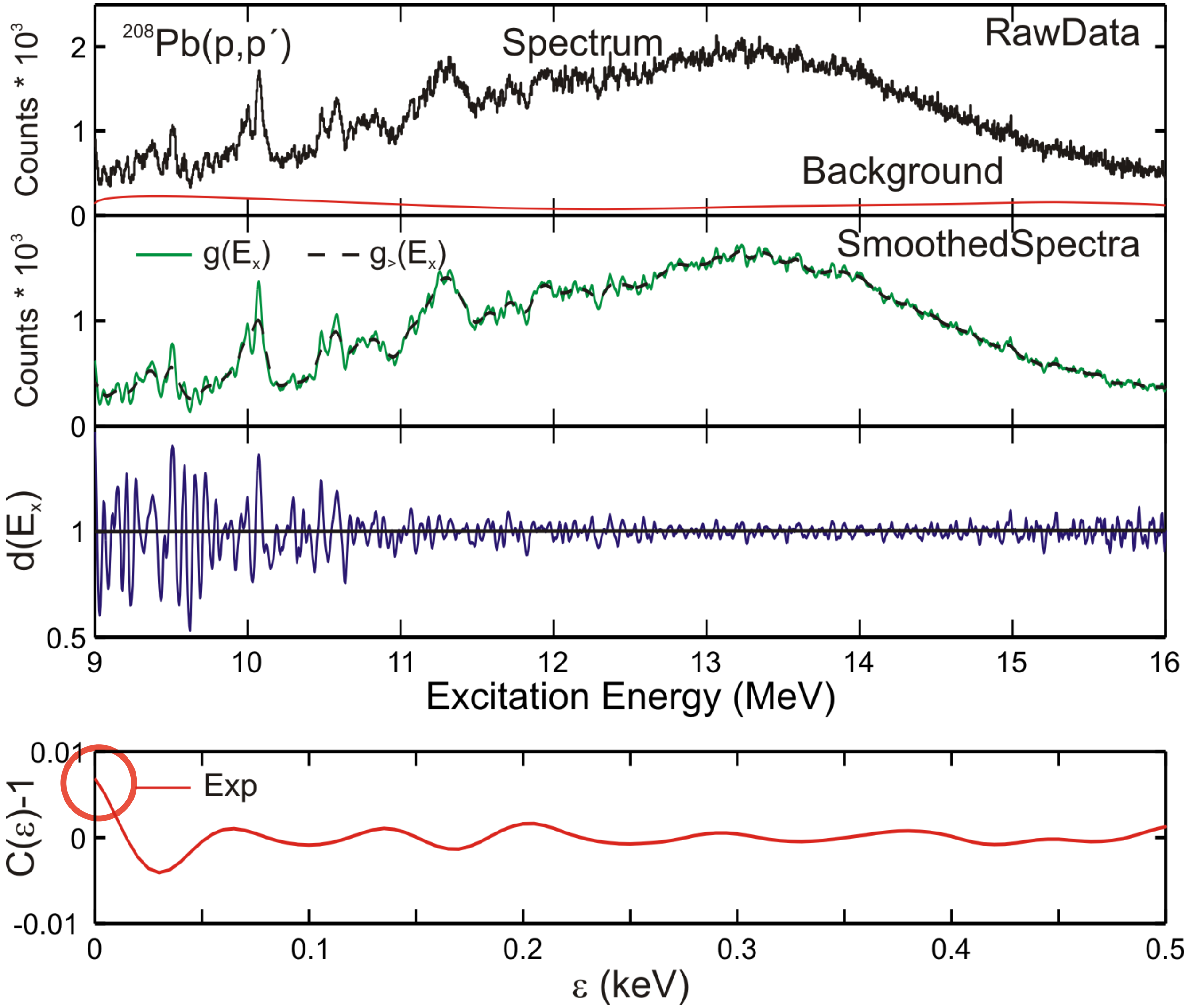
*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
*Institute for Nuclear Science and Technology Hanoi, Vietnam*
*Physics Department, Istanbul University, Turkey*
*Department of Physics, Kyoto University, Japan*
*Department of Physics, Osaka University, Japan*
*RCNP, Osaka University, Japan*
*Cyclotron and Radioisotope Center, Tohoku University, Sendai, Japan*
*iThemba LABS, Somerset West, South Africa*
*CNS, University of Tokyo, Japan*
*RIKEN Nishina Center, Tokio, Japan*
*IFIC-CSIC, Valencia, Spain*

Special thanks to S. Bassauer, D. Martin, I. Poltoratska, A. Tamii

# Fluctuation Analysis




- 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
- $\sigma$ resolution

# M1 Strength in $^{208}$Pb

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

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

for $E_x \leq 8$ MeV

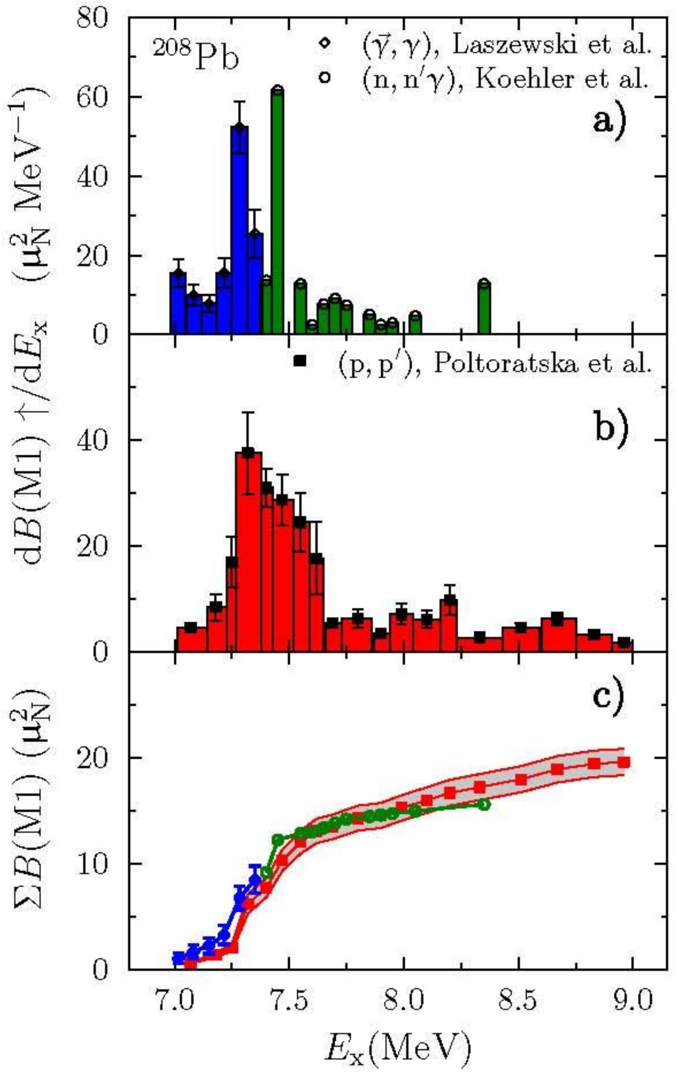
J. Birkhan et al., Phys. Rev. C 93, 041302(R) (2016)

$$\sum B(M1) = 16.0(1.2)\,\mu_N^2$$

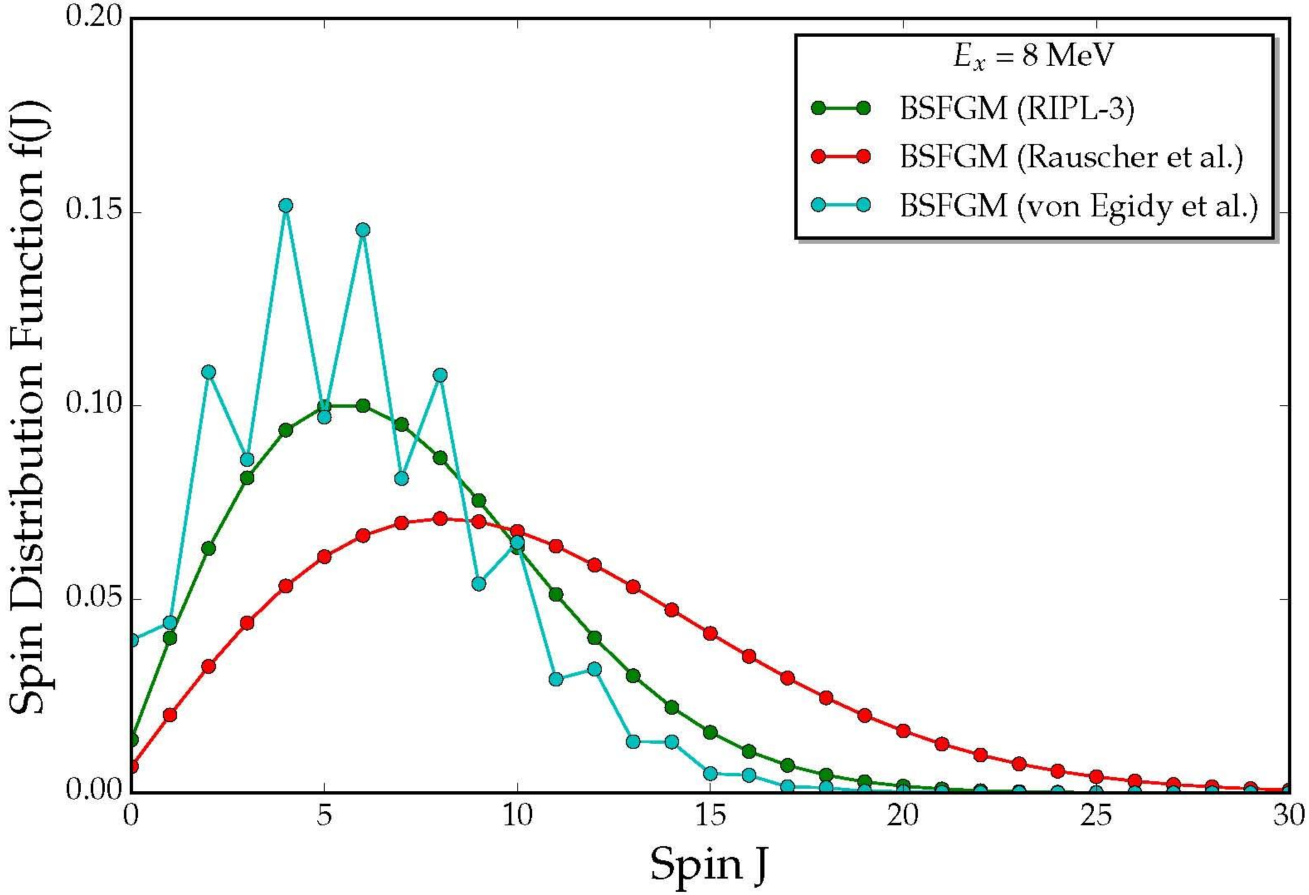
for $E_x \leq 8$ MeV

$$\sum B(M1) = 20.5(1.3)\,\mu_N^2$$

for full resonance

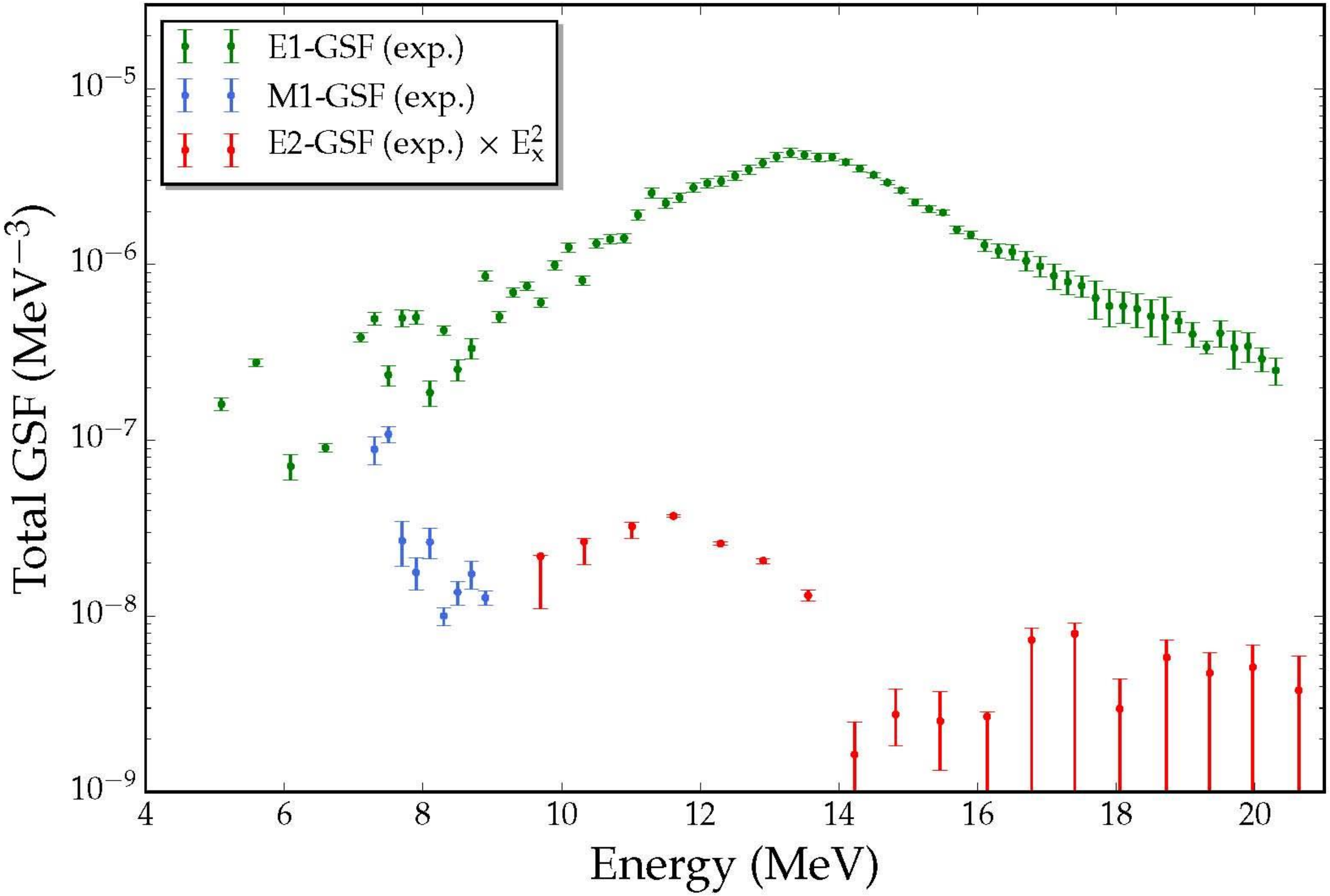


# Level Density Spin Distribution in $^{208}$Pb




- Average over different models

# GSF in $^{208}$Pb: Contributions

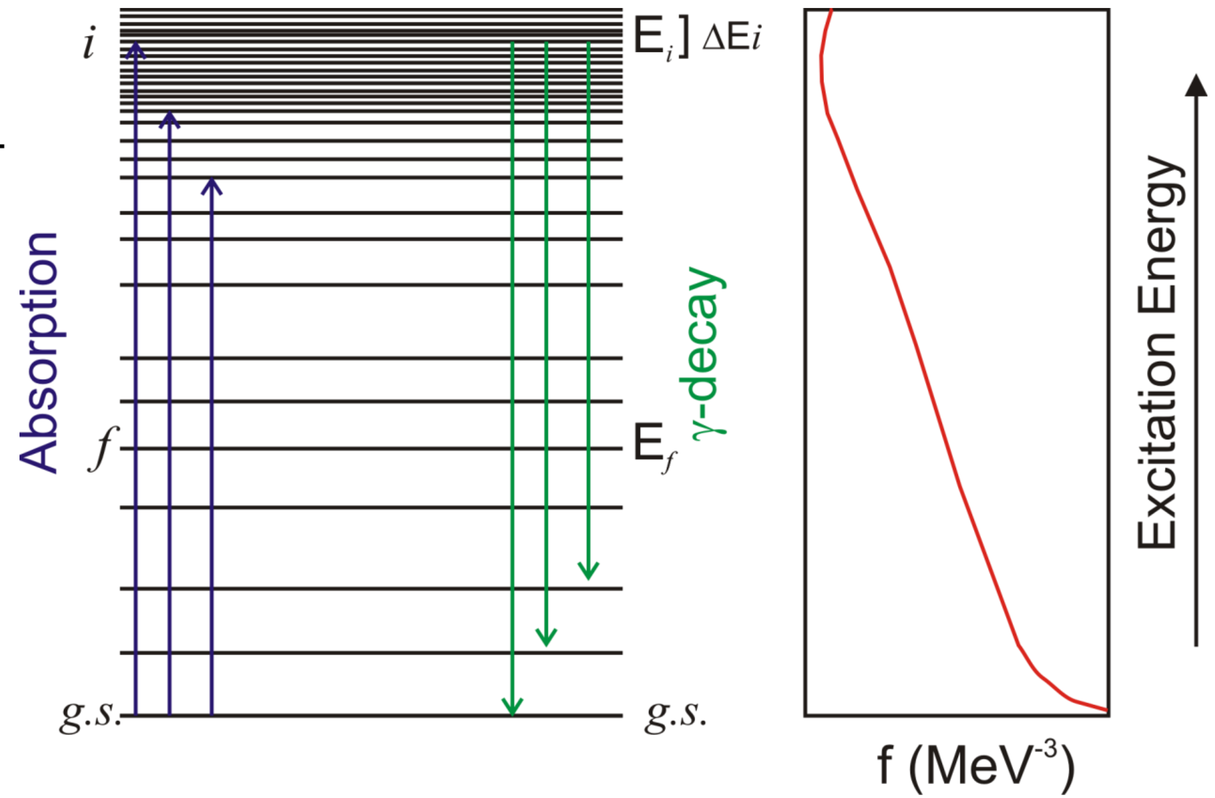


# Gamma Strength Function (GSF)

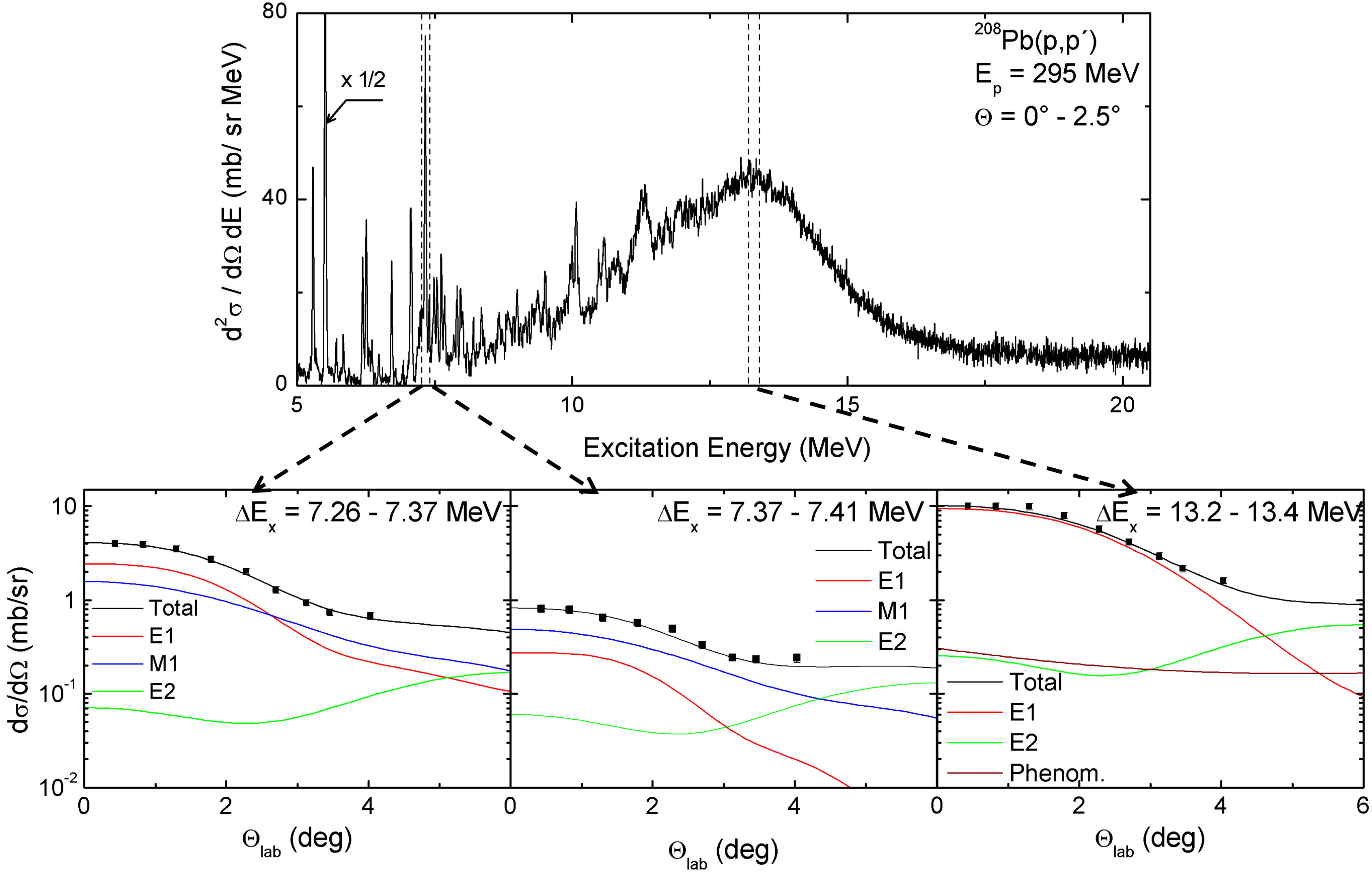
$$\langle\Gamma(E_i)\rangle = \frac{1}{\rho(E_i)} \cdot \int_0^{E_i} E_\gamma^3 f^{E1}(E_\gamma)\rho(E_i - E_\gamma)\, dE_\gamma$$

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

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



# Multipole Decomposition of Angular Distributions



# E1/M1 Decomposition by Spin Observables

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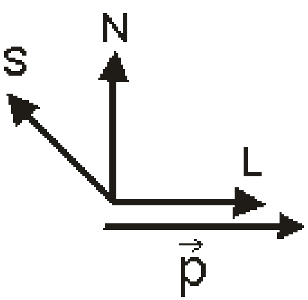
Polarization observables at 0° → spinflip / non-spinflip separation (model-independent)



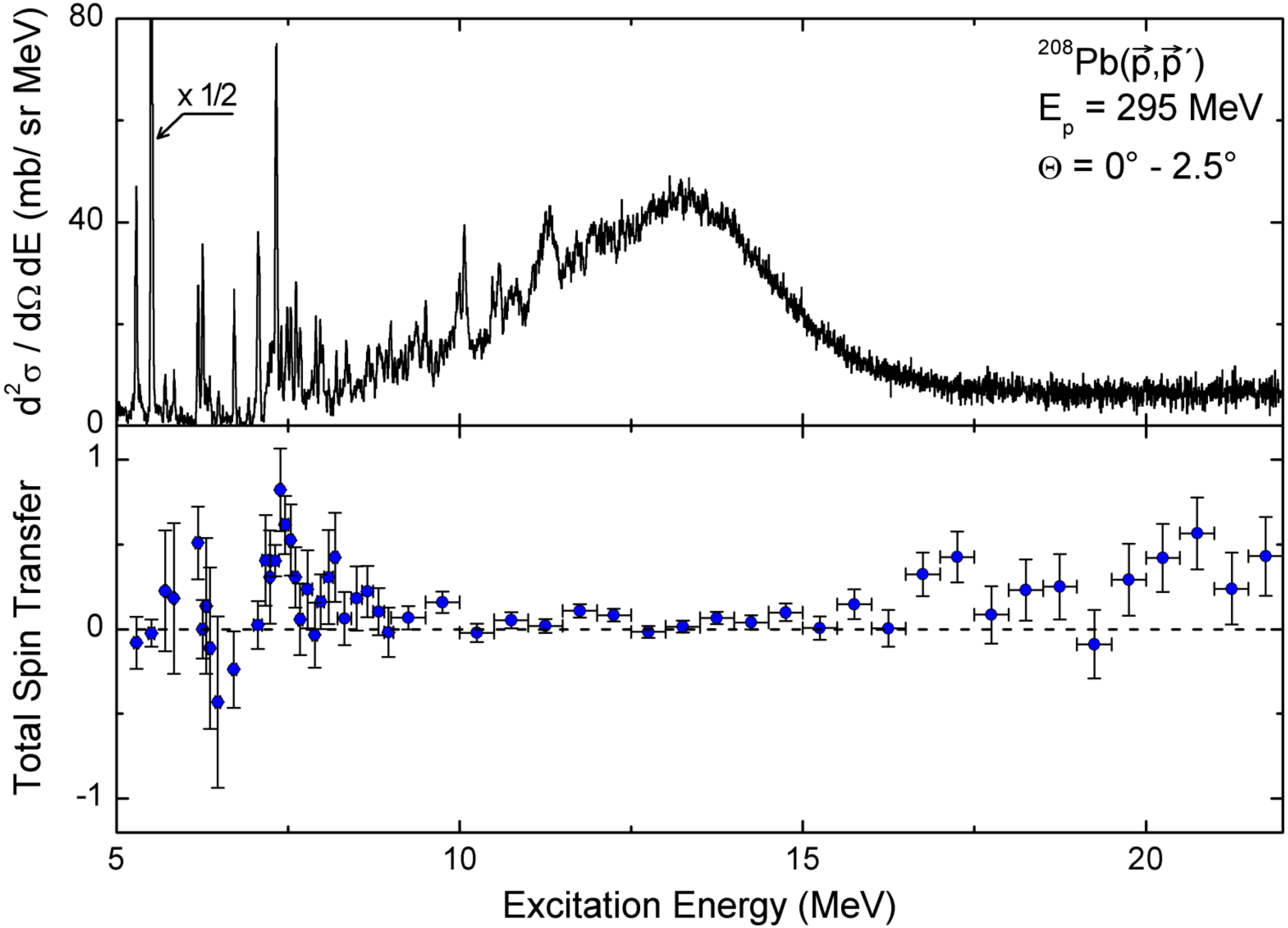

$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S=1 \rightarrow 1^{+} \\ 3 \text{ for } \Delta S=0 \rightarrow 1^{-} \end{cases}$$

sideway — normal — longitudinal

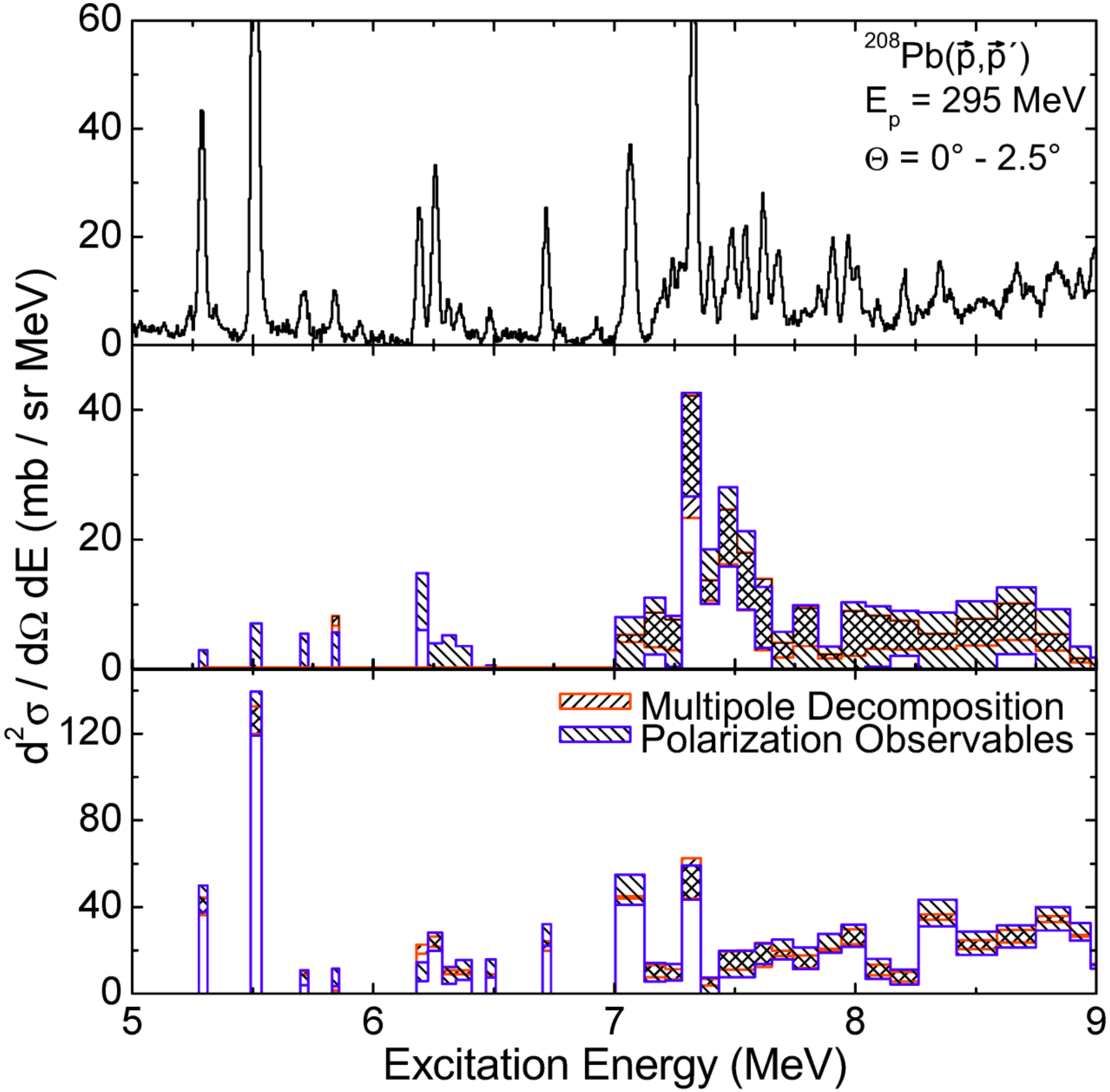
At 0° $D_{SS} = D_{NN}$ → Total Spin Transfer $\Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

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

# Decomposition into Spinflip / Non-Spinflip Cross Sections



# Comparison of Methods

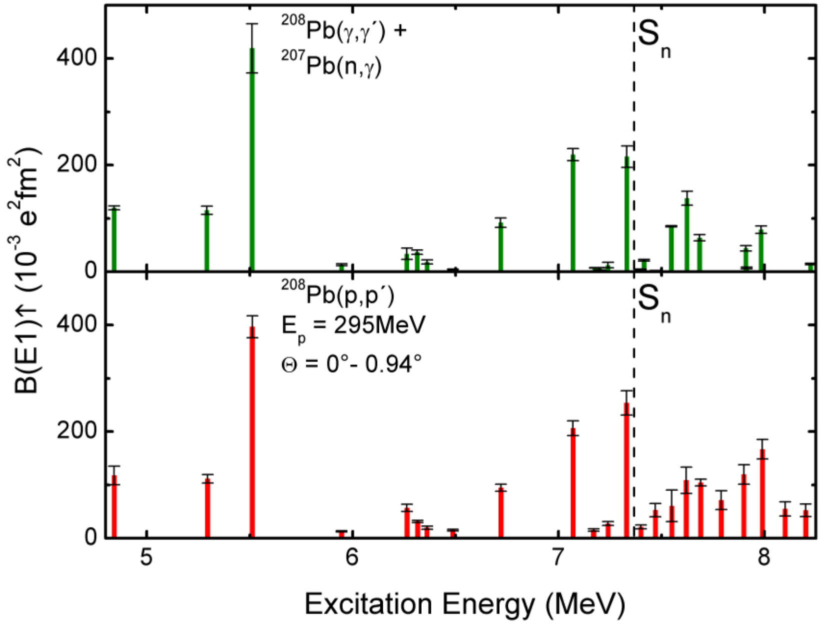


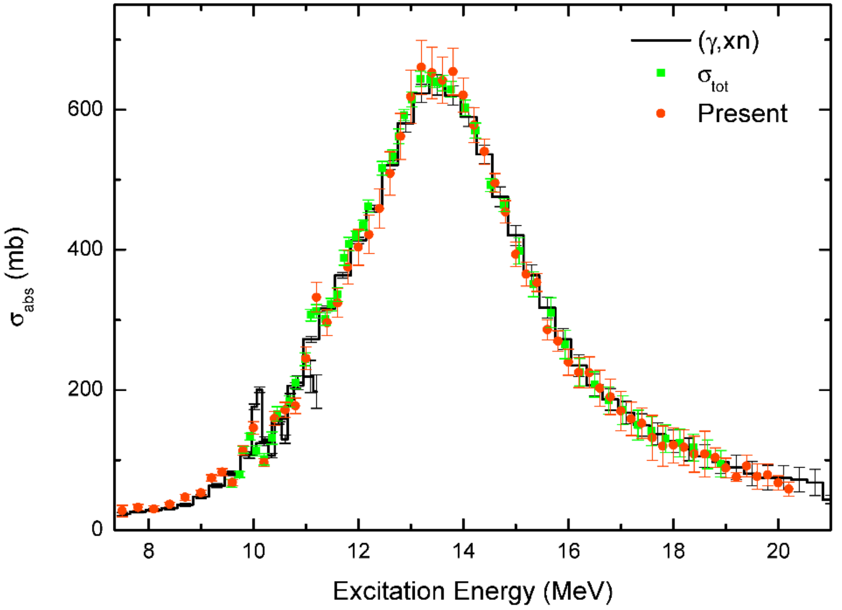

Total

ΔS = 1

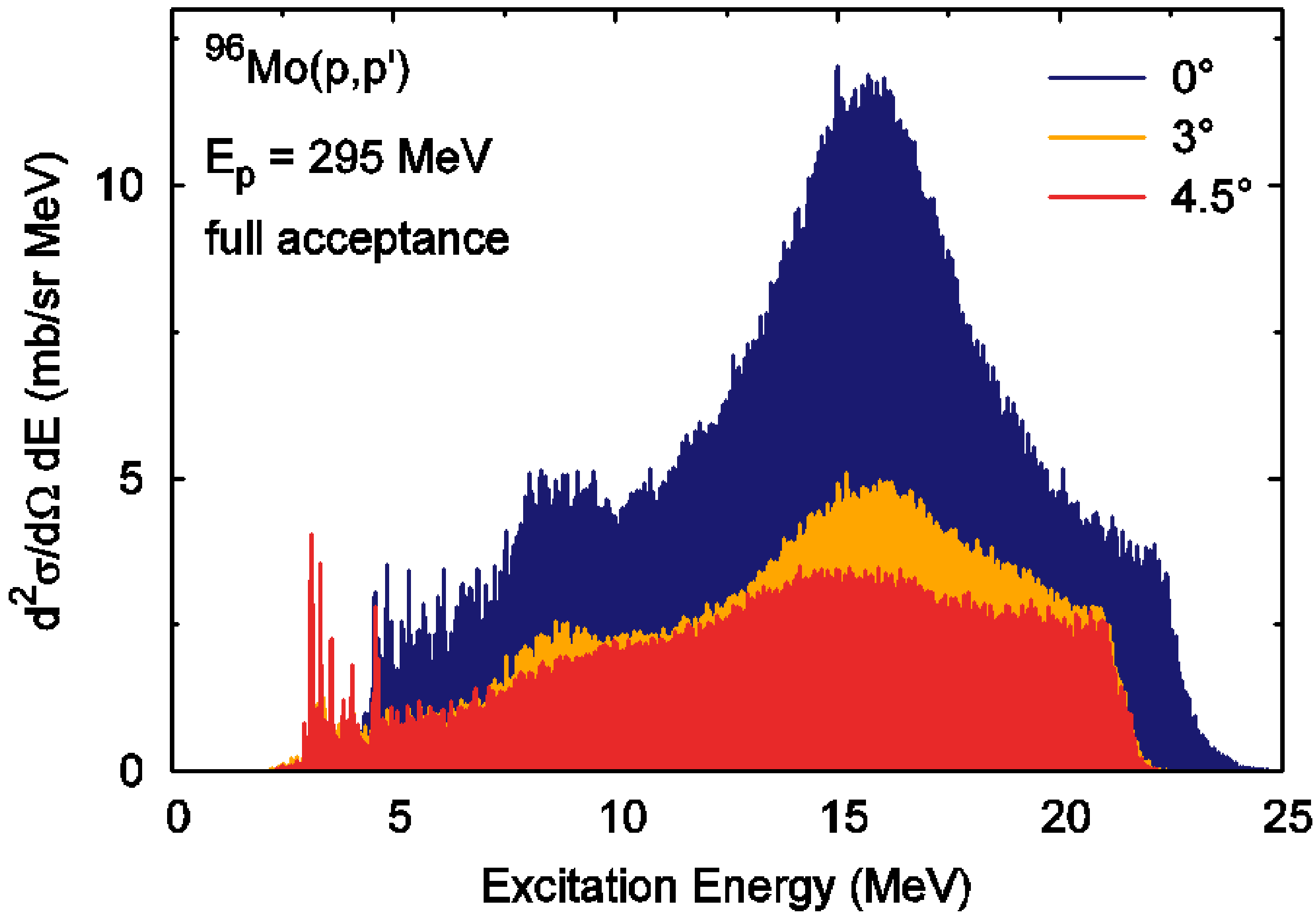
ΔS = 0

# B(E1) Strength in $^{208}$Pb



# Differential Cross Sections



# E1/M1 Decomposition

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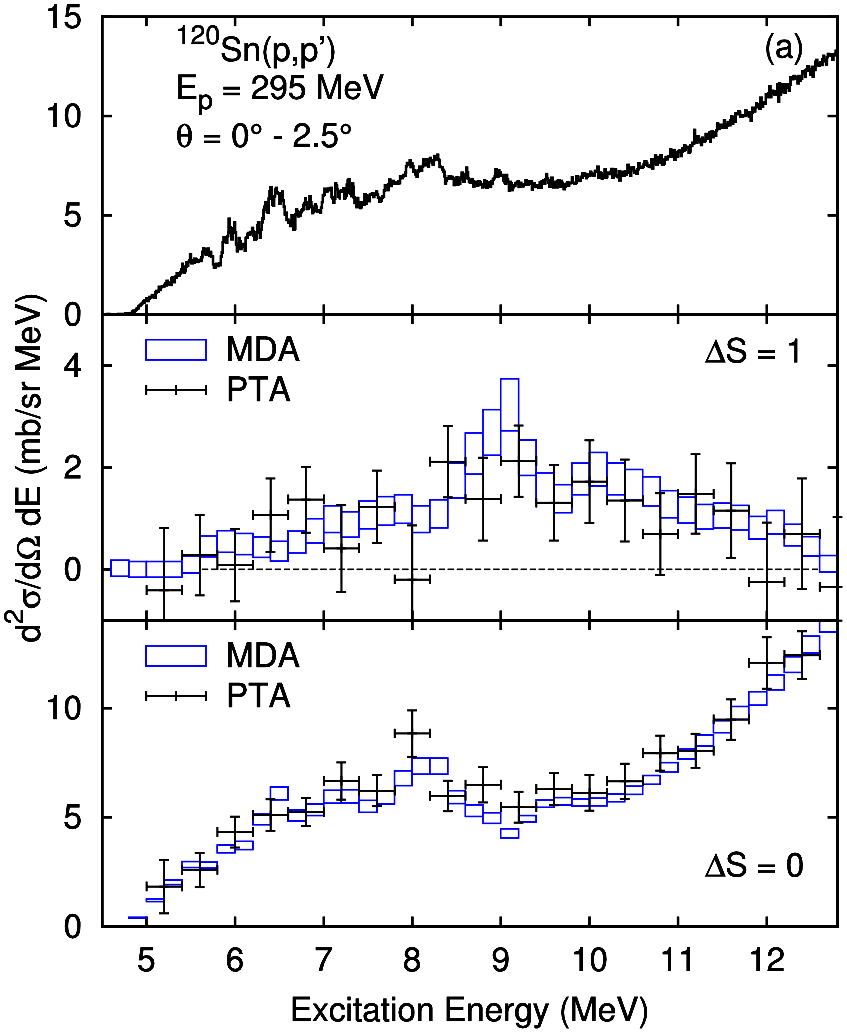
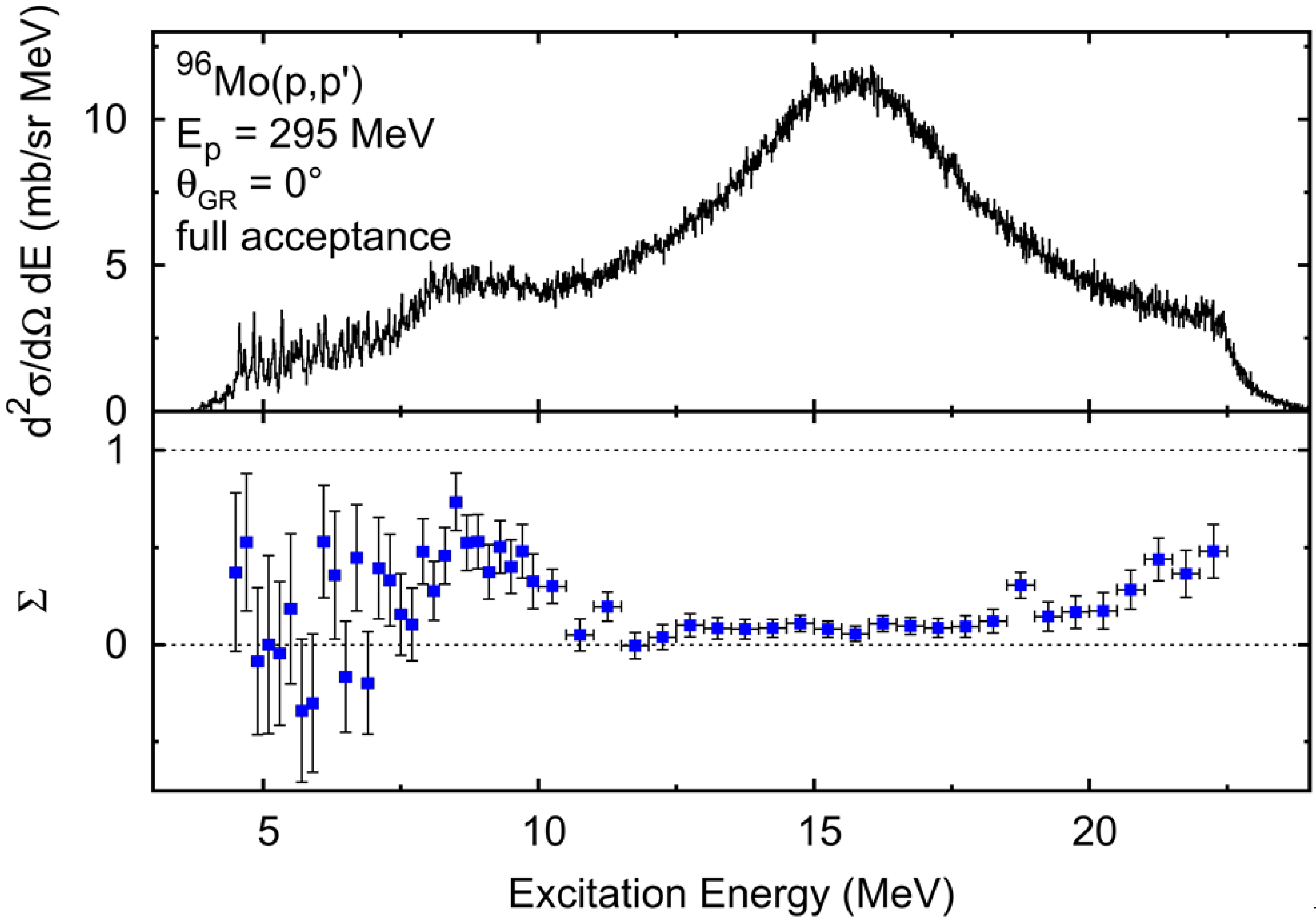
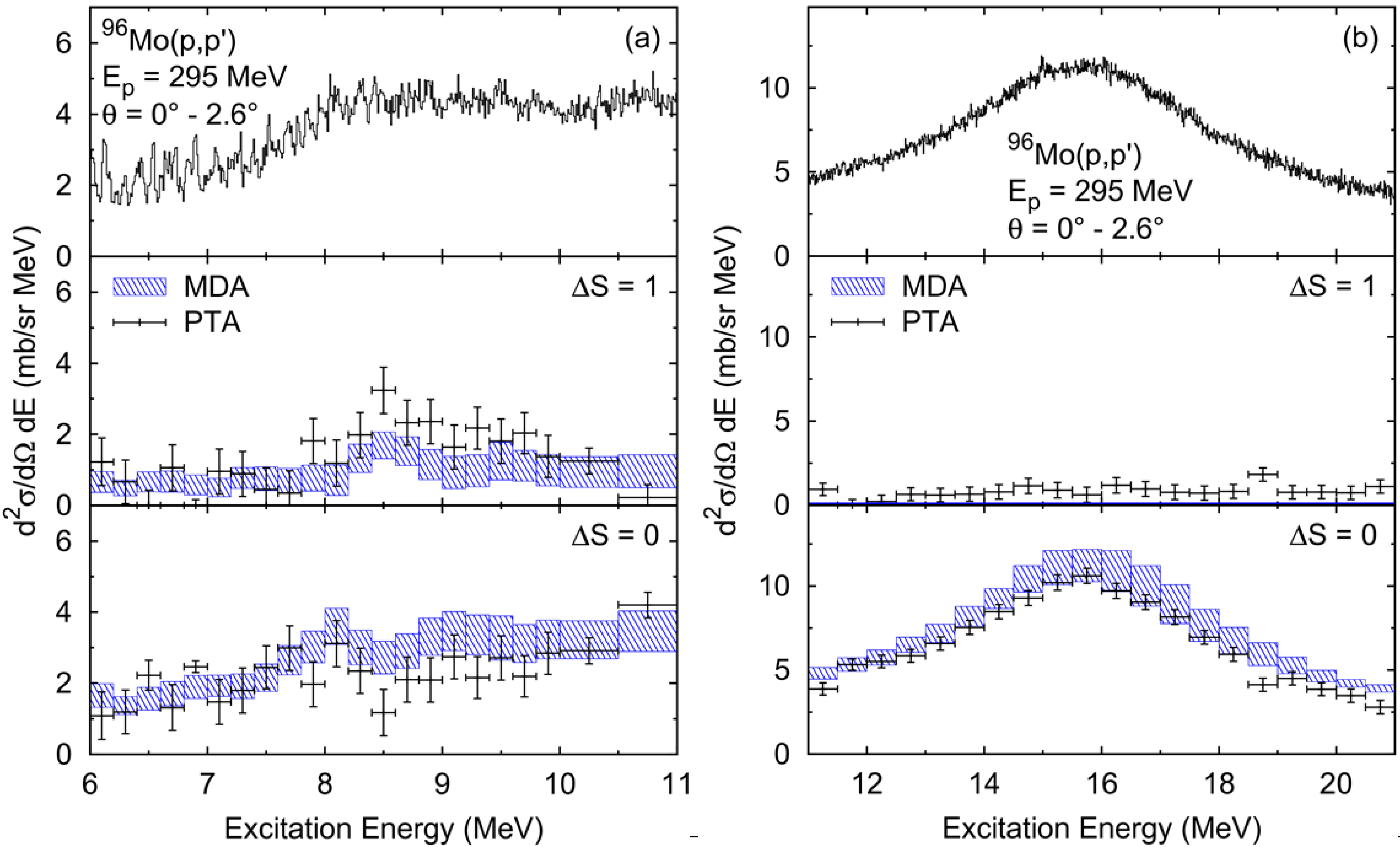


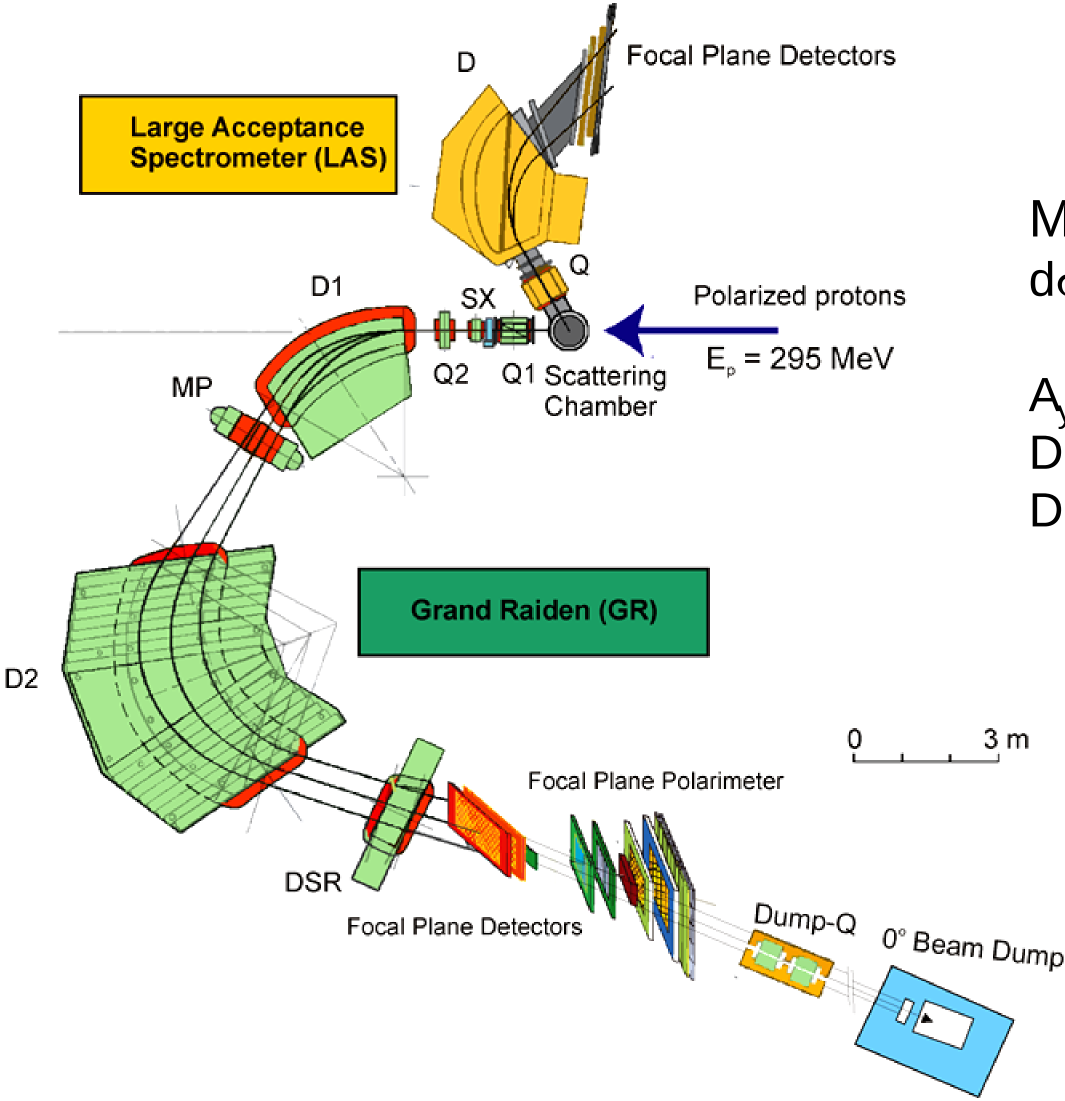
# Polarization Transfer Observables in $^{96}$Mo



# Comparison: PTA vs. MDA



# 0º 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