Complete dipole response in ^{208}Pb from high-resolution polarized proton scattering at 0°*

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RCNP

- Complete dipole strength: what can be learned?
- Polarized protons scattering at RCNP
- Results
  - Spinflip / non-spinflip cross section decomposition
  - B(E1) Strength
  - Dipole Polarizability
  - Level Densities
  - Photon Strength Function
- Summary and outlook

SFB 634

***Supported by the DFG within SFB 634 and 446 JAP 113/267/0-2**

Spinflip M1 Strength in ^{208}Pb

- Isovector part: analog of GT modes with $T = T_0$
- Spinflip M1 resonance is quenched
  - in fp-shell nuclei similar to GT strength
  - in heavy nuclei – little data → ^{208}Pb as a test case
- Problem studied in the 80's but:
  - large experimental uncertainties
  - improved model calculations
- new experimental access by (p,p´)
  - intermediate energy region optimal for spin-isospin excitations
  - at 0° → selectivity on ΔL=0 transitions
  - isovector spinflip M1 transitions enhanced

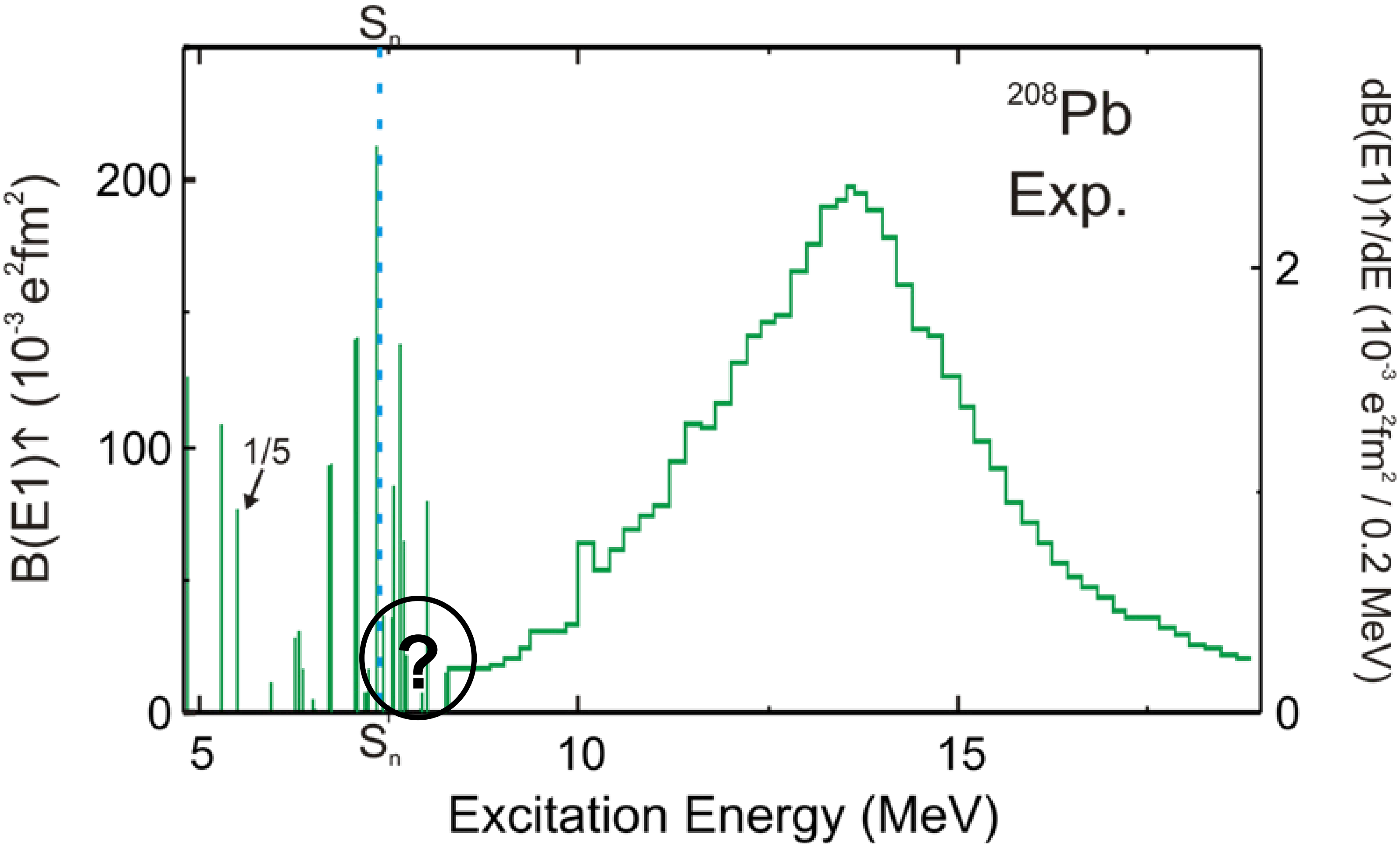
Electric Pygmy Dipole Resonance (PDR)

- PDR: resonance-like structure, typically close to neutron threshold

- Strength related to neutron excess
  $\longrightarrow$ measure of neutron skin
  $\longrightarrow$ measure of the isospin dependence of the asymmetry energy

- Strength distribution around neutron threshold relevant for nucleosynthesis (r-process)

E1 Response in ^{208}Pb



N. Ryezayeva et al., PRL 89 (2002) 272502

Problems

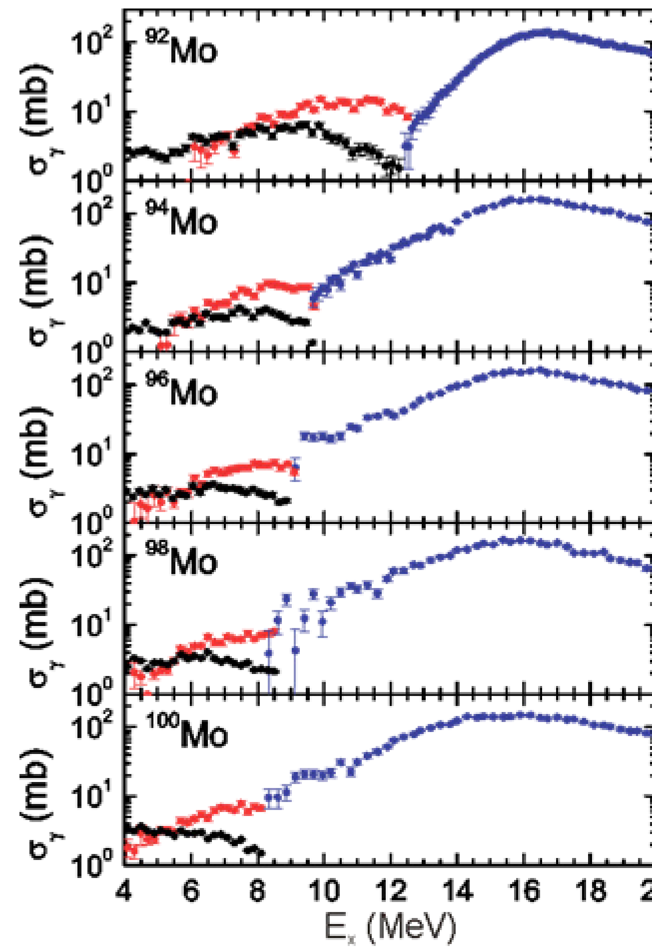
- Experimental: Missing strength
  - (γ,γ') reaction measures strength (roughly) up to threshold only
  - Experimental quantity $\propto \Gamma_0 \cdot \frac{\Gamma_0}{\Gamma}$

    $\rightarrow$ assumption in most analyses

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

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

- Theoretical: mean-field dependence of microscopic predictions (e.g. Sn isotope chain)



G. Rusev et al., PRC 79 (2009) 061302

Complete E1 Strength Distributions

- Consistent test of microscopic models
- Extract polarizability $\alpha_D \propto \sum_i B(E1)_i / E_{x,i}$

  → measure of the neutron skin rather than PDR?
  P.G. Reinhard, W. Nazarewicz, PRC 81 (2010) 051303 (R)
- Extract level density from fine structure of the GDR
- Extract photon strength function → test of Axel-Brink hypothesis

Complete E1 and M1 Strength Distributions

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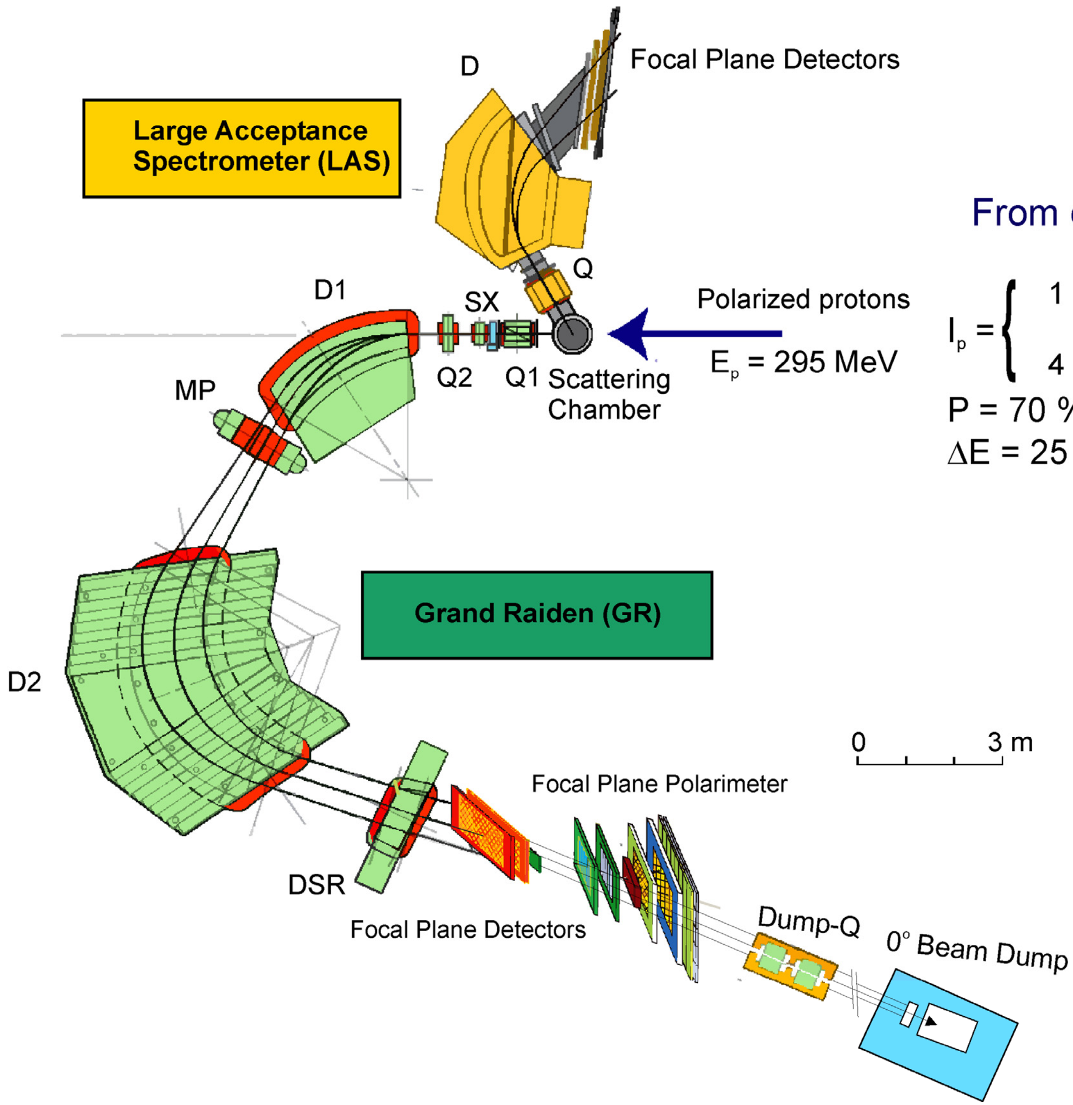
- Polarized proton scattering at 0°
  - -intermediate energy: 300 MeV optimal
  - -high resolution: ΔE = 25 keV (FWHM)
  - -angular distributions: E1 / M1 separation
  - -polarization observables: spinflip / non-spinflip separation

- ^{208}Pb as a reference case

0^o Setup at RCNP



From cyclotrons:

$$I_p = \begin{cases} 1\ \text{nA}\ (\Theta = 0^\circ) \\ 4\ \text{nA}\ (2.5^\circ < \Theta < 10^\circ) \end{cases}$$

P = 70 %

ΔE = 25 - 30 keV

Measured observables:

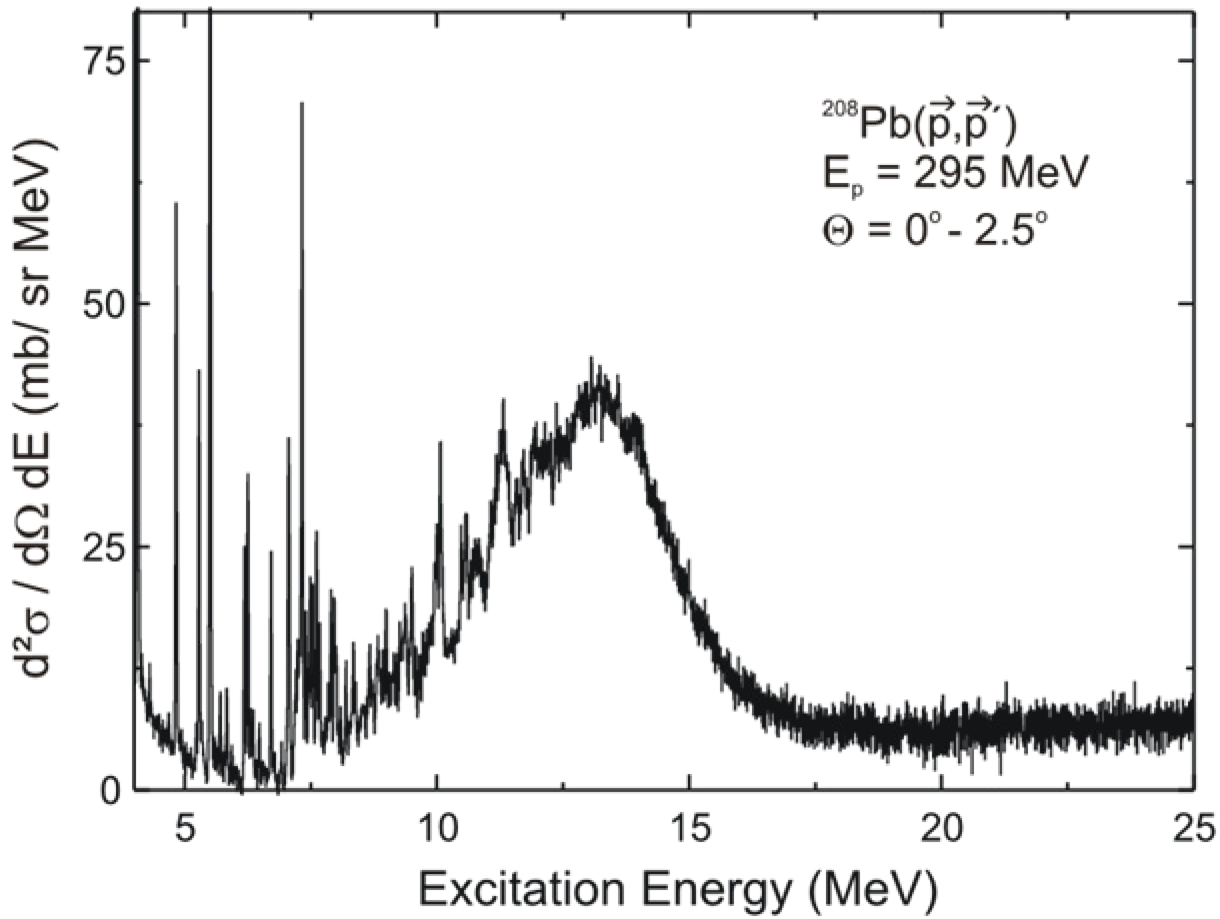
$d\sigma/d\Omega$ - angular distributions $0° \leqslant \Theta \leqslant 10°$

A_y - asymmetry

D_{SS} at 0° - sideways polarization observables

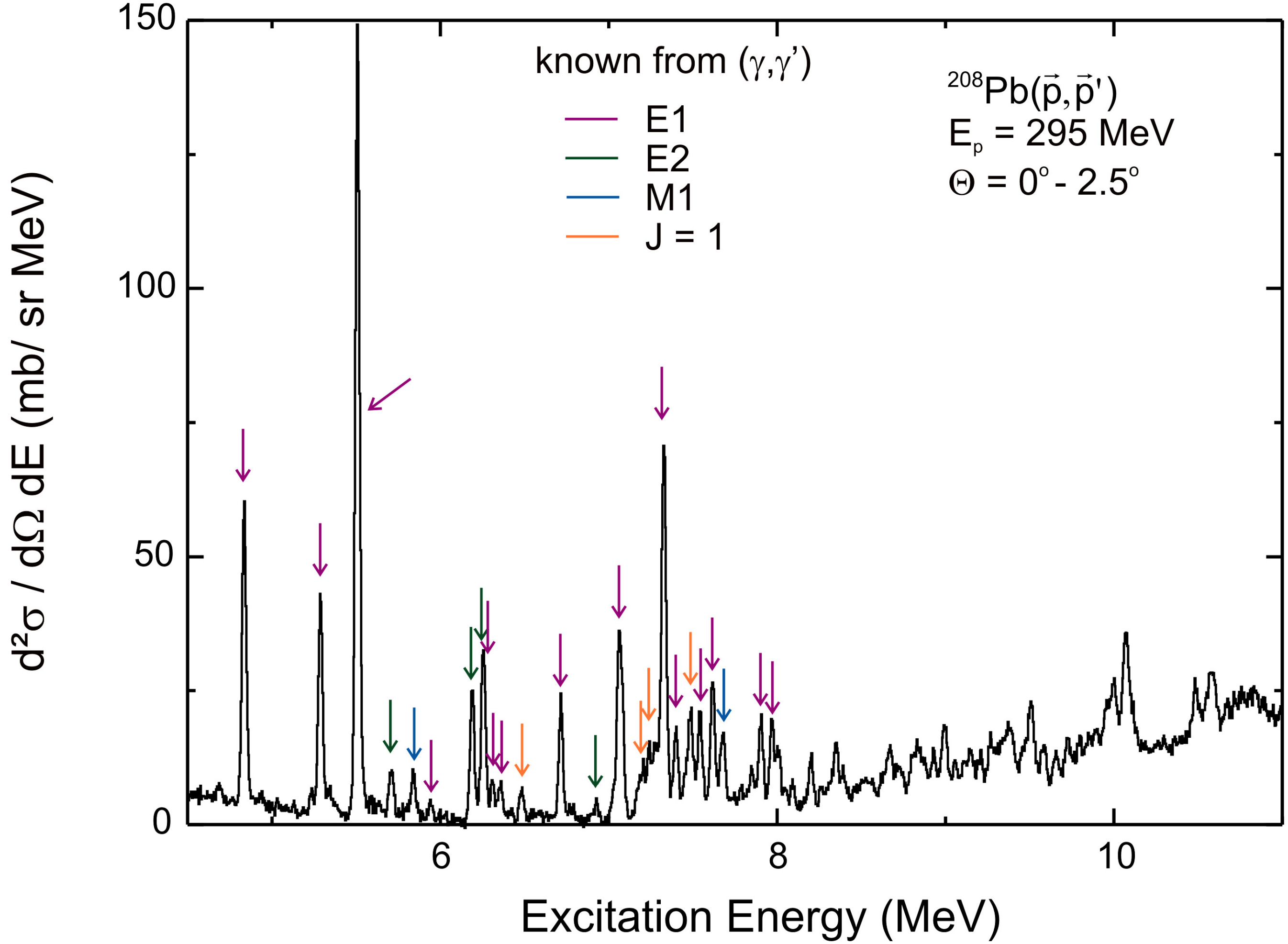
D_{LL} at 0° - longitudinal polarization observables

Measured Spectrum
Background-Subtracted Spectrum



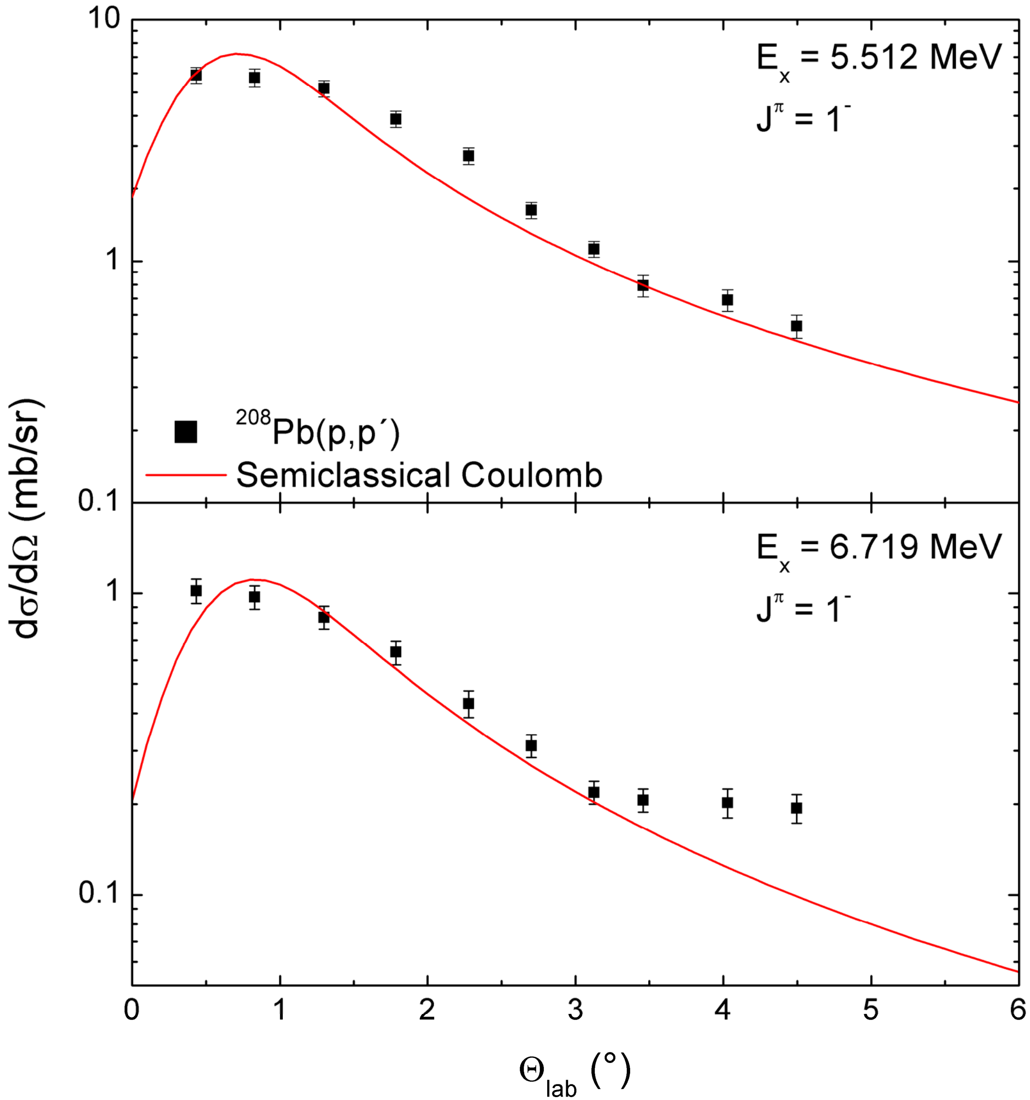
- Pronounced fine structure of the GDR is recognized
- Strong Coulomb excitation of the GDR at 0°

Measured Spectrum: Low-Energy Part

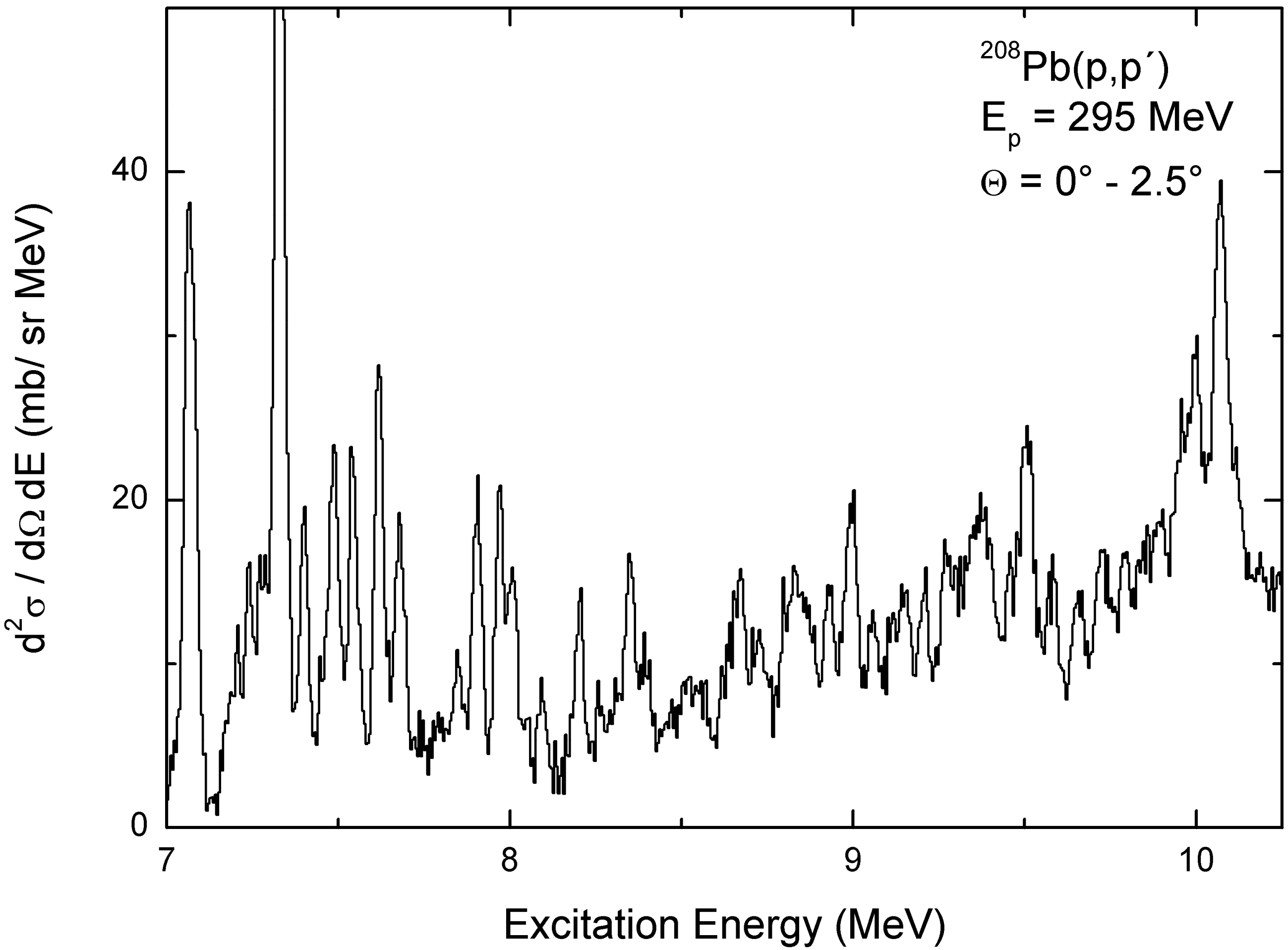


- All dipole transitions known from (γ,γ´) are observed

Coulomb Exitations of 1⁻ States



Spectrum: Overlapping Region



- Overlapping region of PDR and spinflip M1 resonance

E1/M1 Decomposition by Spin Observables

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

  (model-independent)

$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S = 1\text{, M1 excitations} \\ 3 \text{ for } \Delta S = 0\text{, E1 excitations} \end{cases}$$

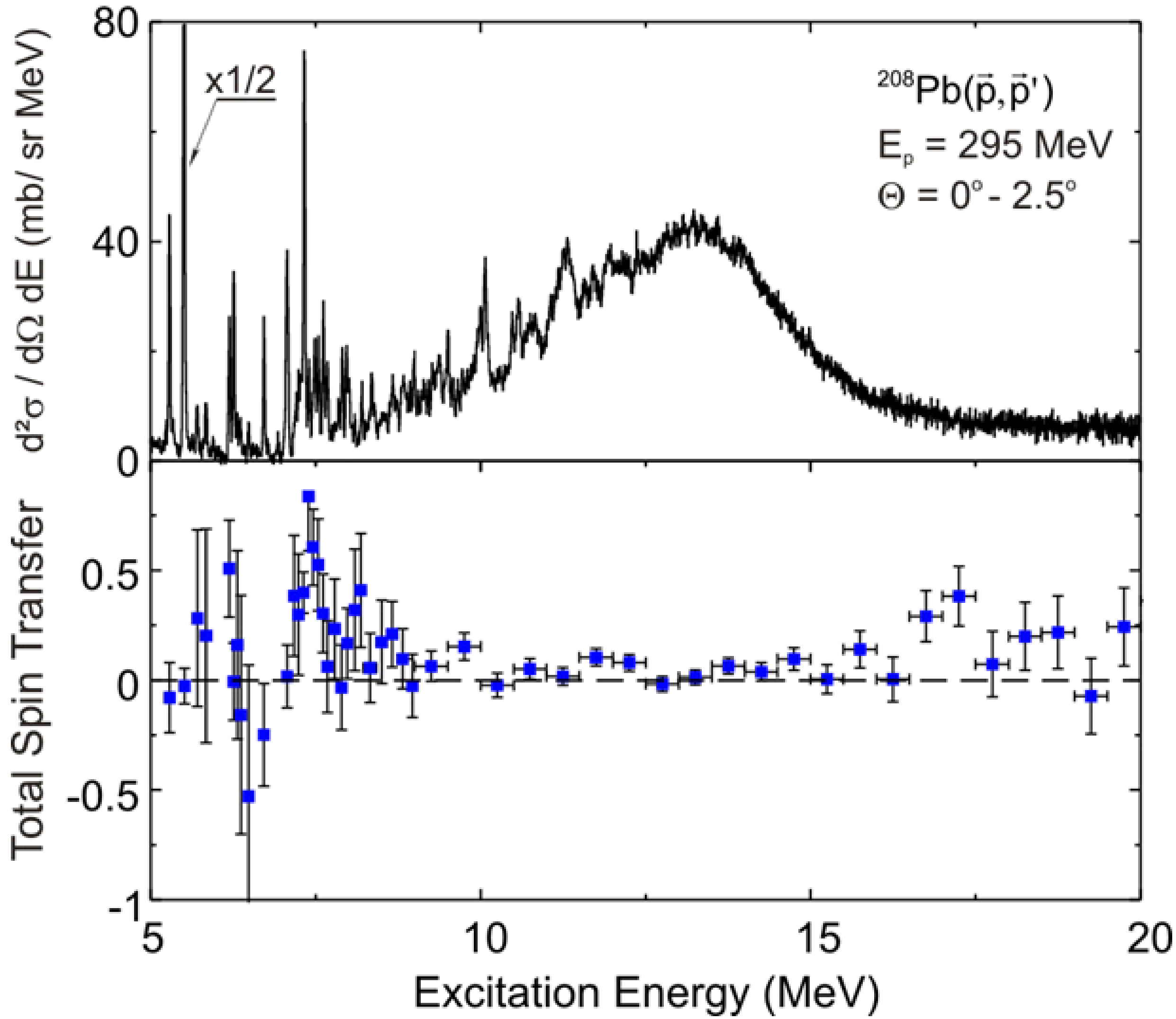
➡ E1 and M1 cross sections can be decomposed

At 0° $D_{SS} = D_{NN}$

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

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

Decomposition into Spinflip / Non-Spinflip Cross Sections



Multipole Decomposition of Angular Distributions

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{data} = \sum_{J^\pi} a_{J^\pi} \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{DWBA}$$

- Restrict angular distribution to $\Theta \leqslant 4°$

- too complex response at larger angles

- $\Delta L = 0$

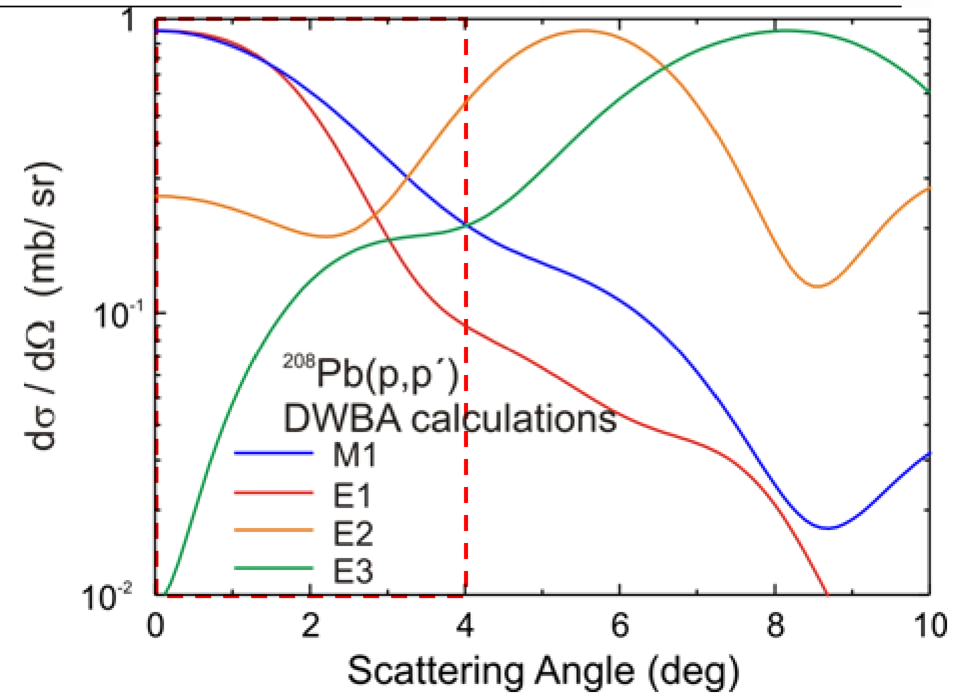
  - $d\sigma/d\Omega$ for Isovector M1

- $\Delta L = 1$

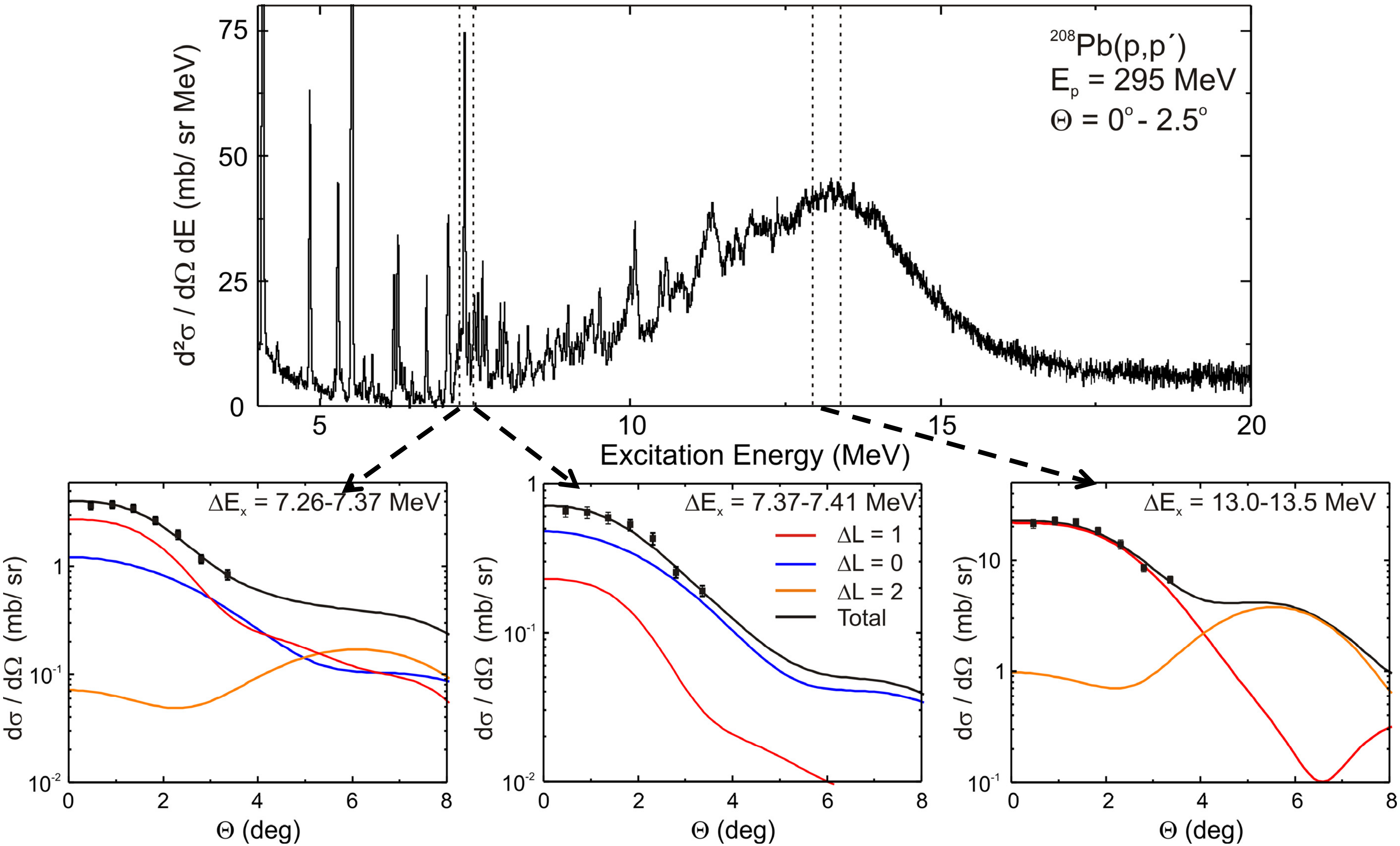
  - Coulomb dominated $d\sigma/d\Omega$ for E1

- $\Delta L > 1$

  - E2 substitute for all $\Delta L > 1$ (alternatively E3)



Multipole Decomposition of Angular Distributions



Multipole Decomposition in GDR Region

$$\left.\frac{d\sigma(\theta)}{d\Omega}\right|_{data} = \sum_{J^\pi} a_{J^\pi} \left.\frac{d\sigma(\theta)}{d\Omega}\right|_{DWBA}$$

- ΔL = 1

  - Coulomb dominated dσ/dΩ for E1

- ΔL >1

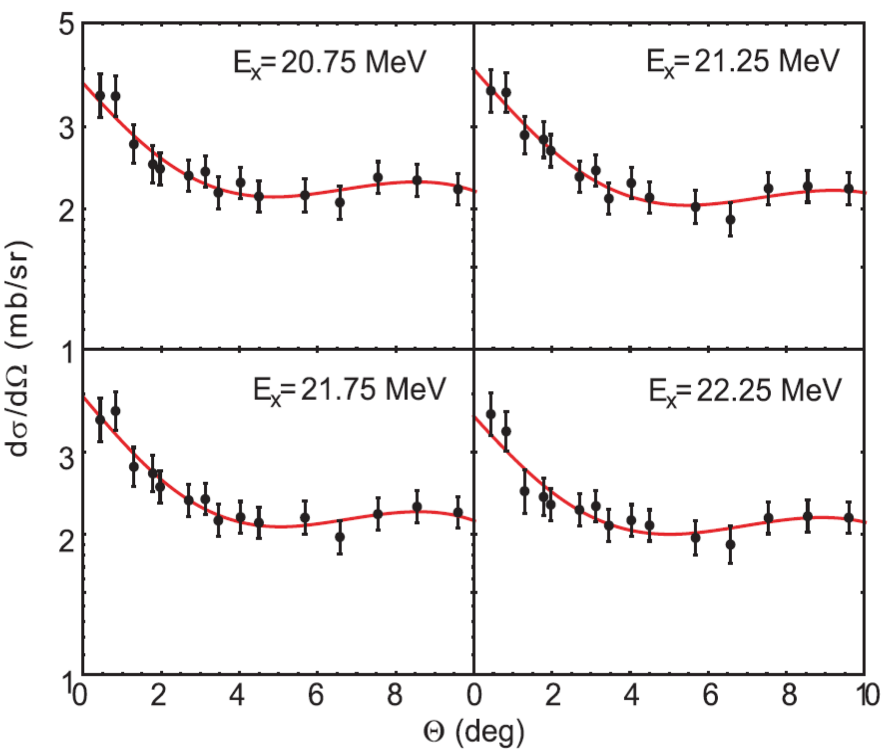
  - E2 substitute for all ΔL > 1 (alternatively E3)

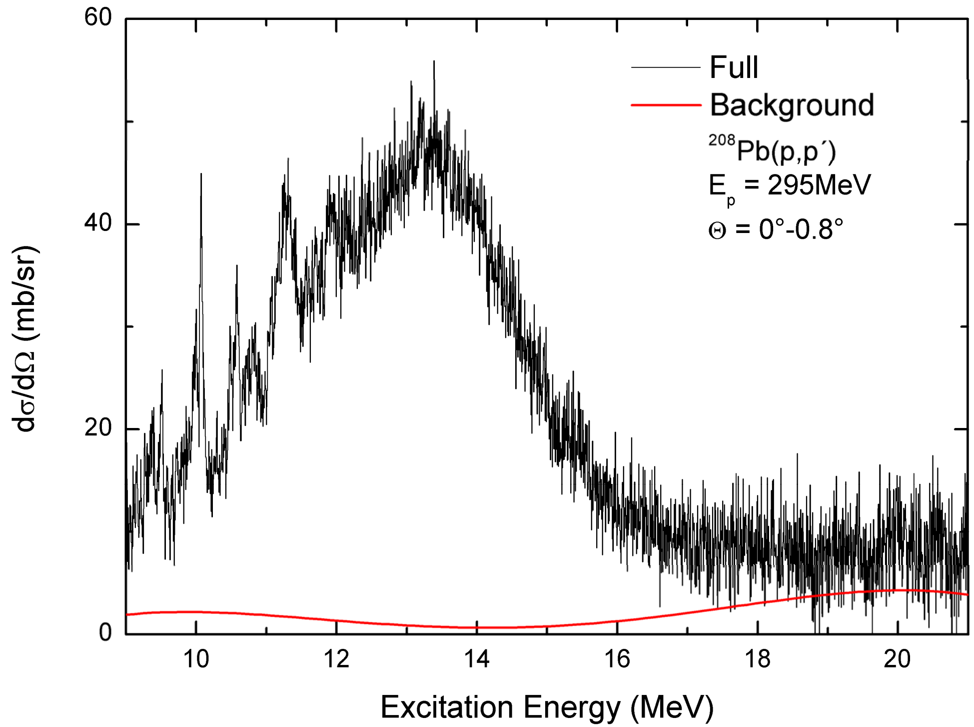
- ~~ΔL = 0~~

  - ~~dσ/dΩ for Isovector M1~~

+ Phenomenological background

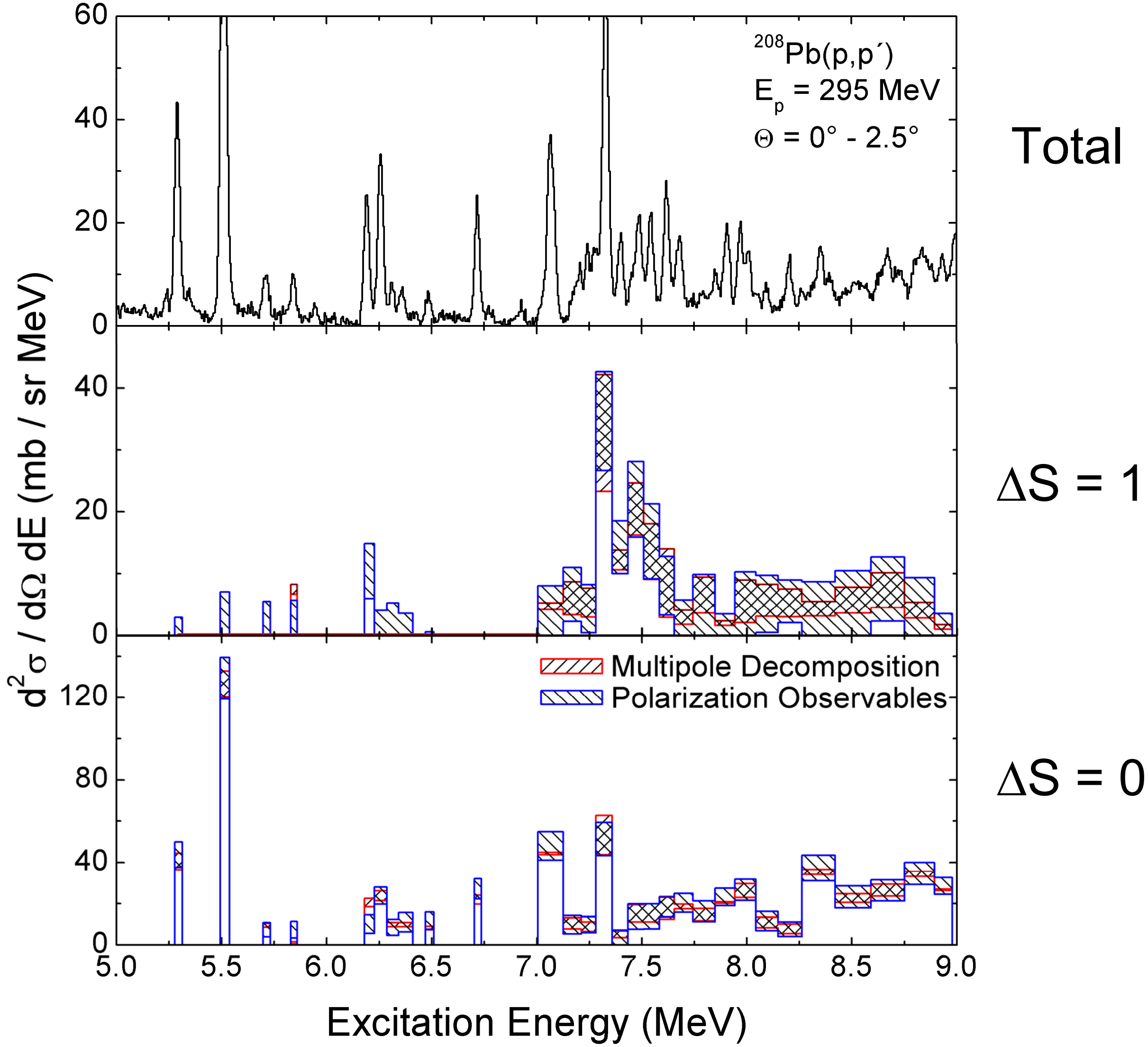
Multipole Decomposition in the GDR Region



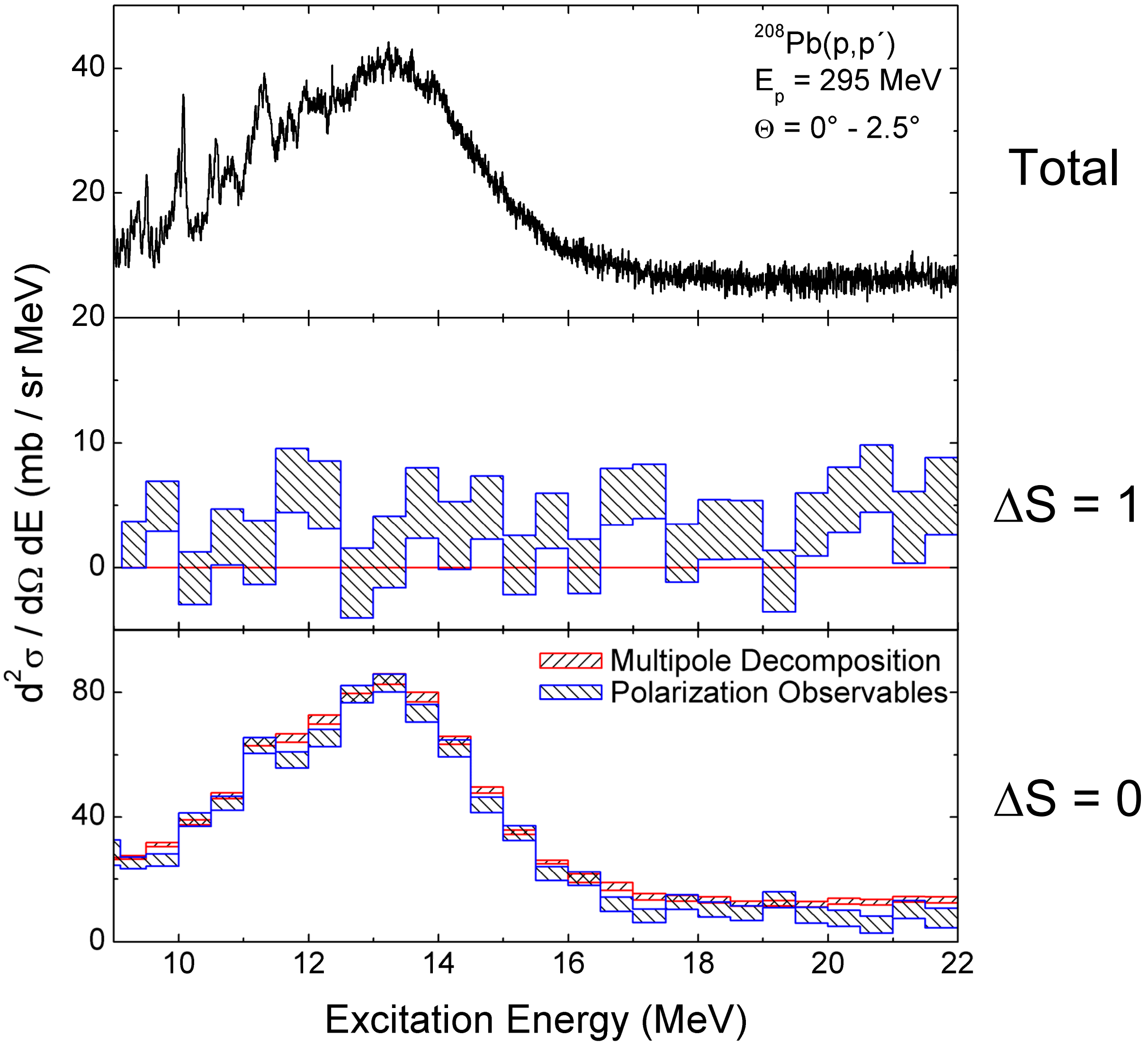


- identical angular distributions
- determines phenomenological background

Comparison of Both Methods I

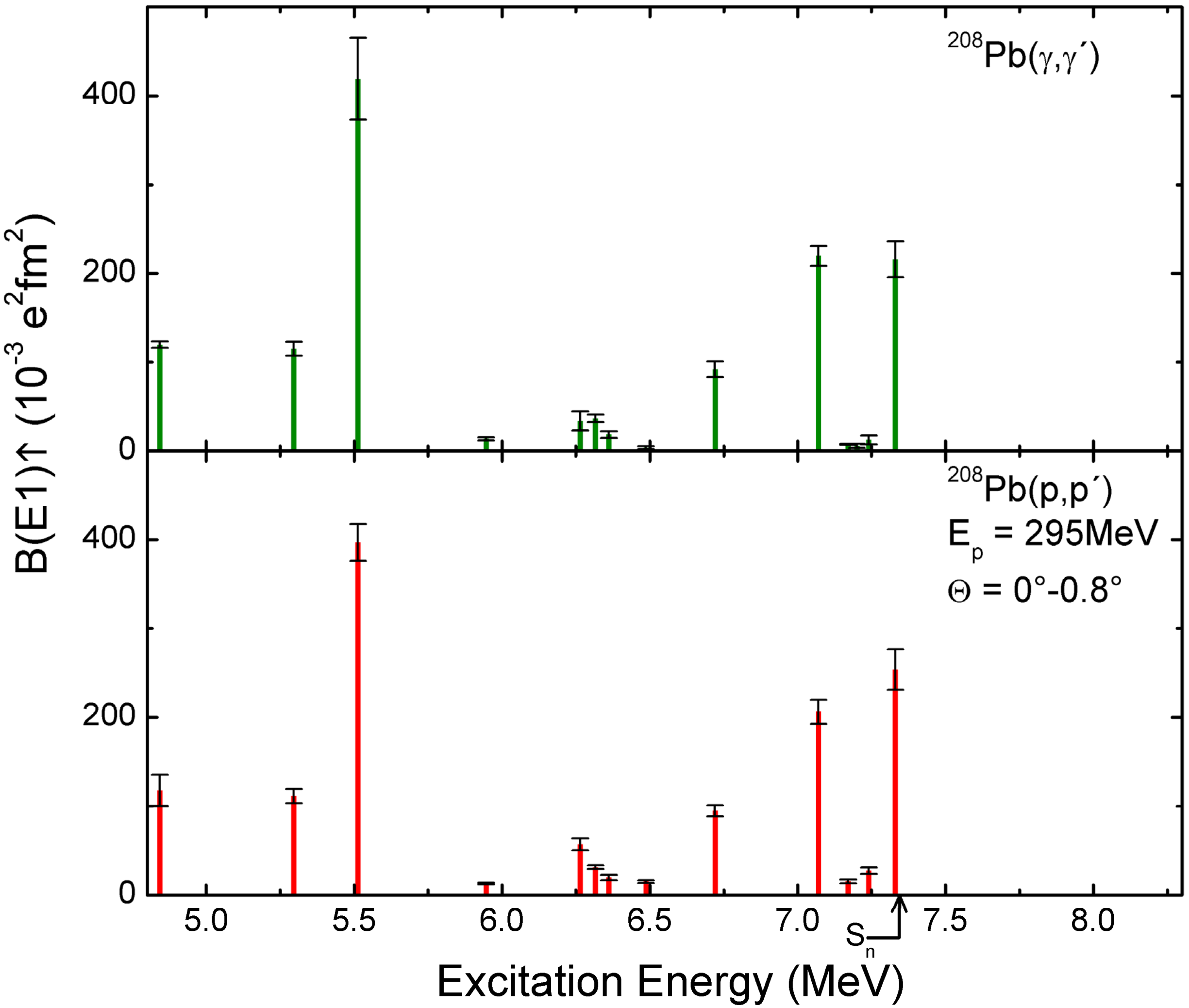


Comparison of Both Methods II



- Total B(E1) Strength Extraction

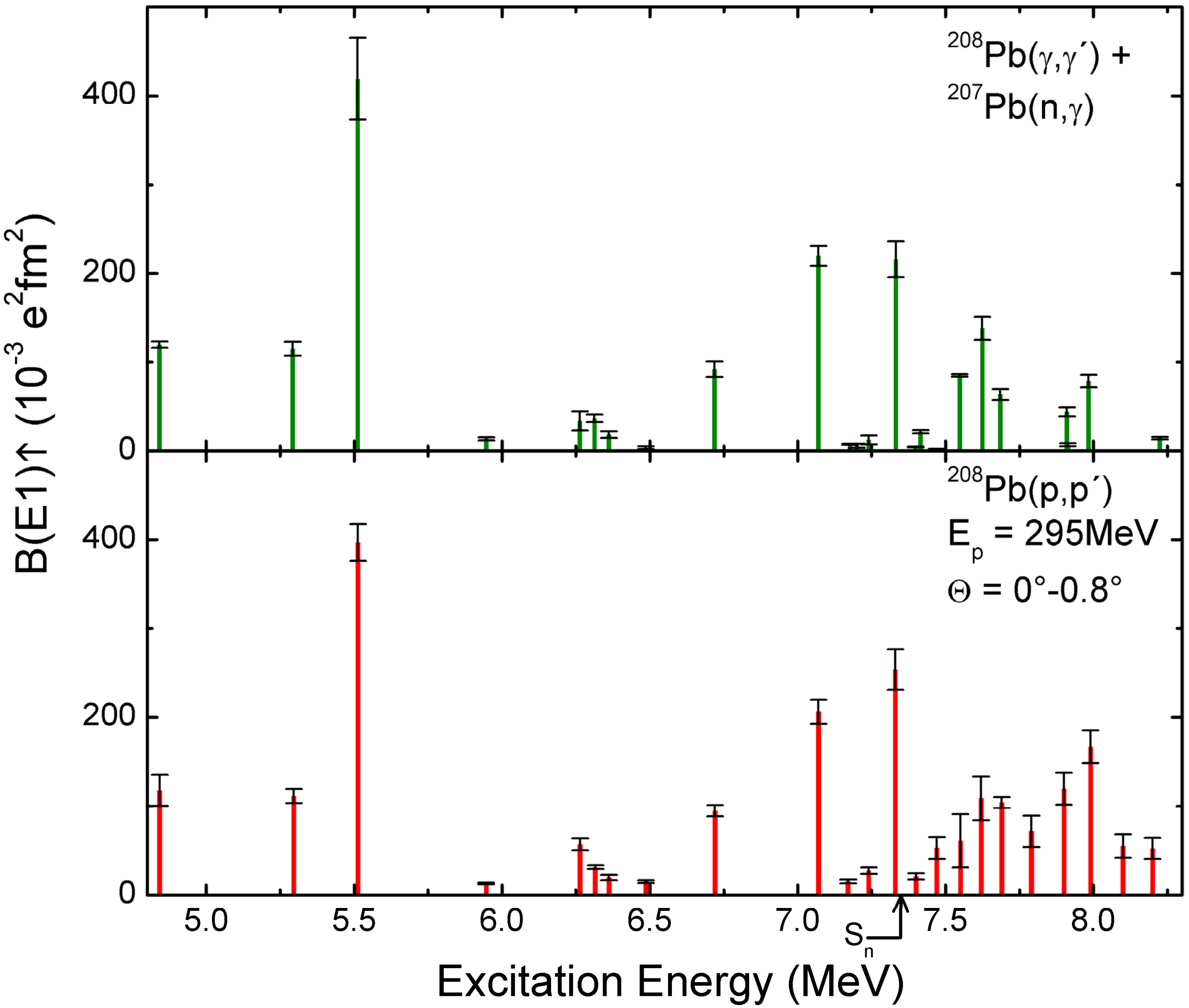
B(E1) Strength: Low-Energy Region



N. Ryezayeva et al., PRL 89 (2002) 272502
J. Enders et al., NPA 724 (2003) 243
R. Schwengner et al., PRC 81 (2010) 054315
T. Shizuma et al., PRC 78 (2008) 061303(R)

- Extracted assuming semiclassical Coulomb excitation

B(E1) Strength: Low-Energy Region



$$\sum_{E_x=6.2MeV}^{8.2MeV} B(E1)\uparrow = 1.10 \pm 0.11\ e^2fm^2$$

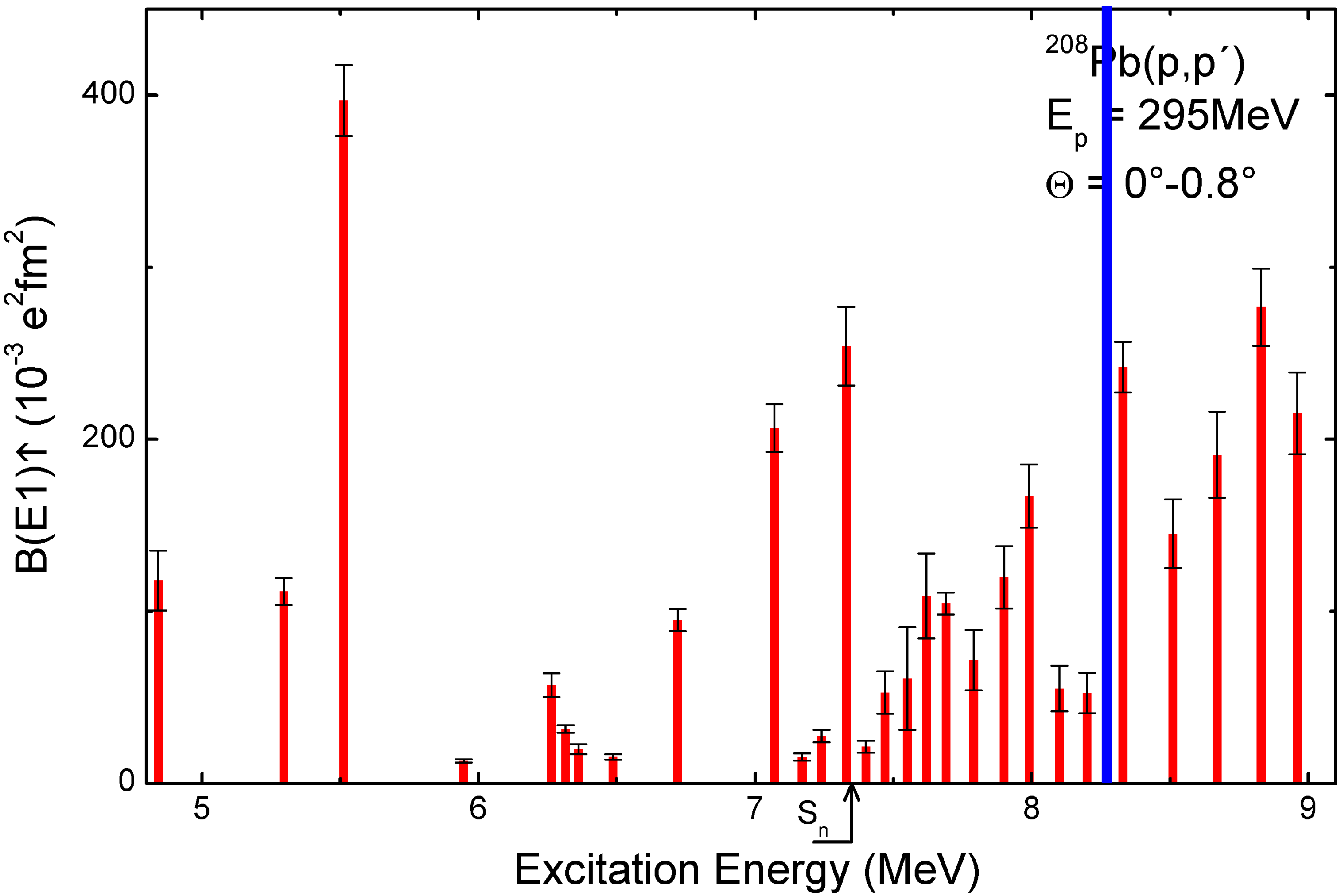
E_c = 7.3 MeV

$$\sum_{E_x=6.2MeV}^{8.2MeV} B(E1)\uparrow = 1.54 \pm 0.16\ e^2fm^2$$

E_c = 7.43 MeV

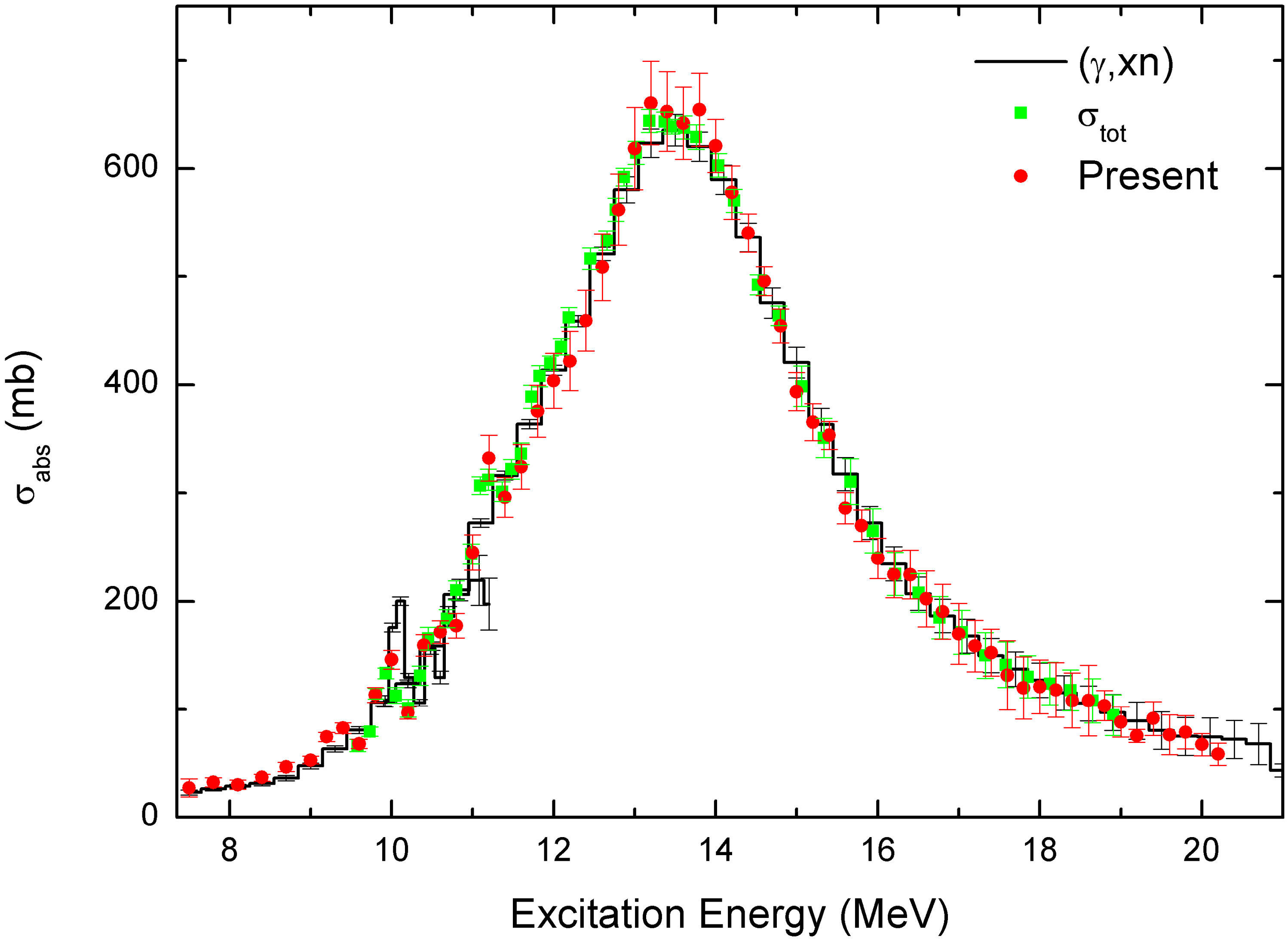
- Extracted assuming semiclassical Coulomb excitation

B(E1) Strength: Low-Energy Region

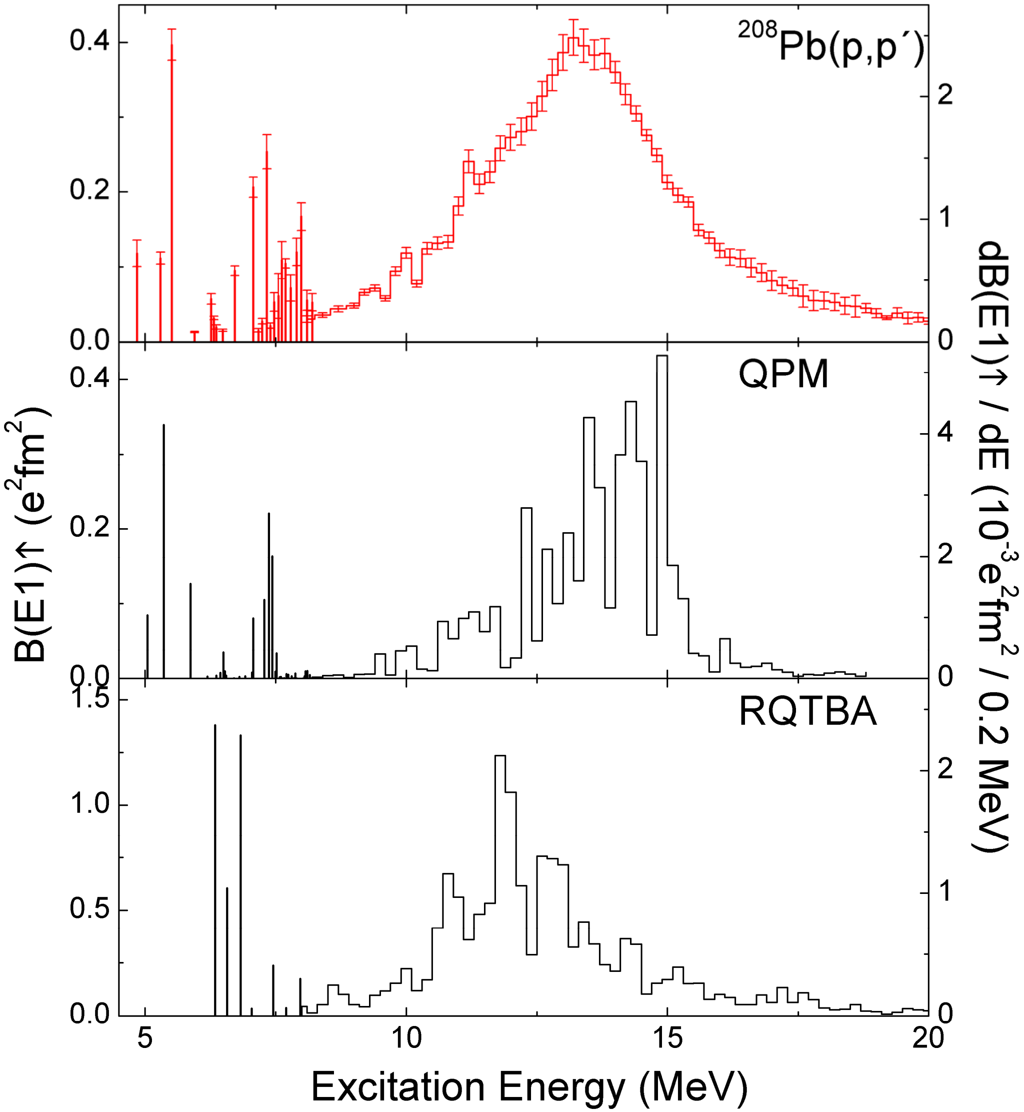


- Extracted assuming semiclassical Coulomb excitation

B(E1) Strength: GDR



E1 Response in ^{208}Pb: Experiment vs. Theory



V.Yu. Ponomarev

E. Litvinova et al.,
PRC 78 (2008) 014312,
PRC 79 (2009) 054312

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- Nuclear Dipole Polarizability as a Measure of Neutron Skin?

Polarizability as a Measure of the Neutron Skin I

P.G. Reinhard and W. Nazarewicz PRC 81 (2010) 051303

- Covariance analysis within the framework of Density Functional Theory using Skyrme force SV-min*

- Parameter set $p = p_0 + \Delta p$ determined by Nuclear Matter Properties from SV-min

$$C_{AB} = \frac{\left|\overline{\Delta A \Delta B}\right|}{\sqrt{\overline{\Delta A^2}\,\overline{\Delta B^2}}}$$

correlation coeff. between observables A(p) and B(p)

$C_{AB} = 1$ – fully correlated

$C_{AB} = 0$ – totally uncorrelated

*P. Klüpfel, et al. PRC 79 (2009) 034310

Polarizability as a Measure of the Neutron Skin

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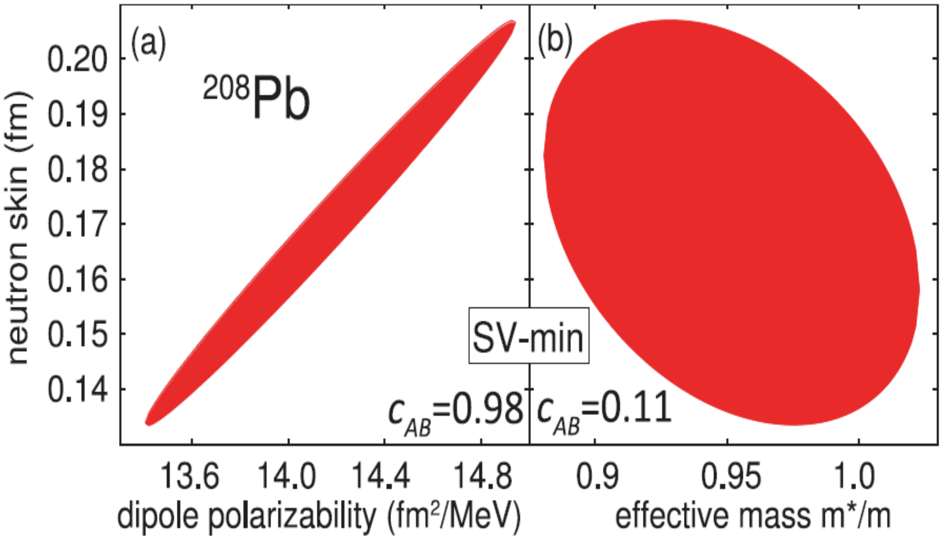
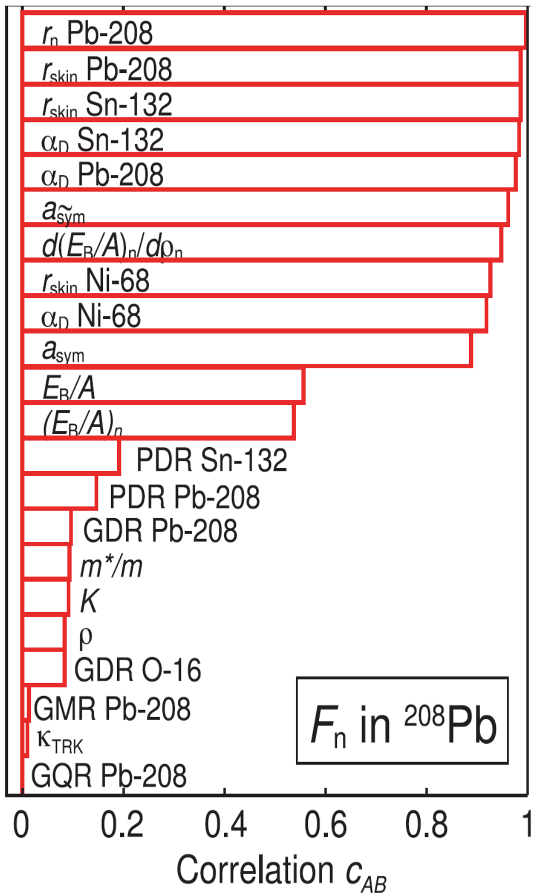
Examples of Correlations with Neutron Skin





F_n – point-neutron distribution FF at q = 0.45 fm^{-1} (PREX)

Dipole Polarizability of ^{208}Pb

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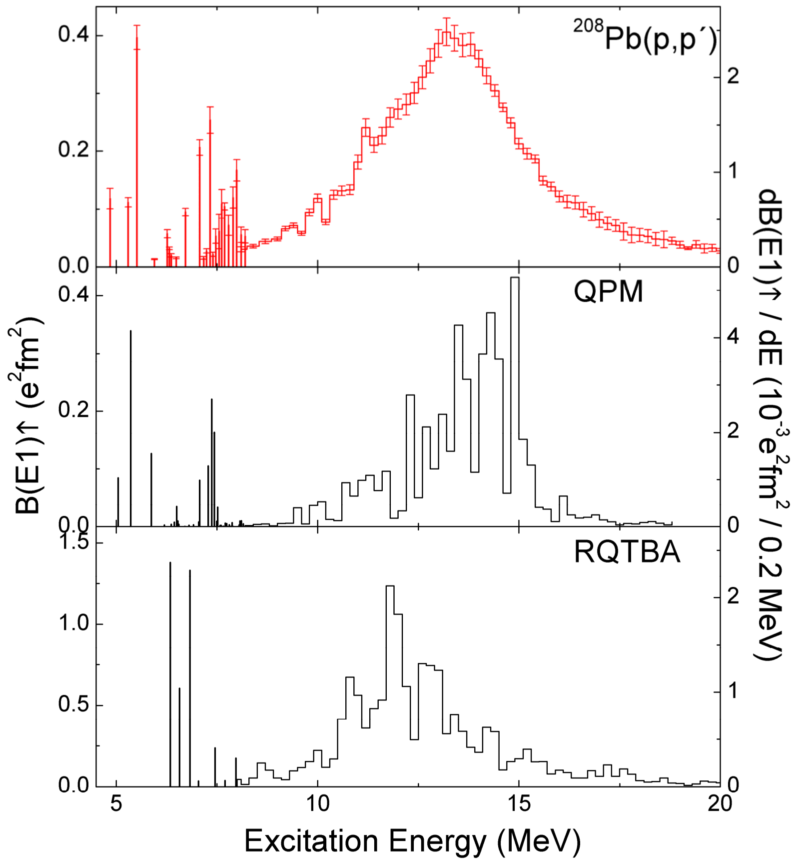
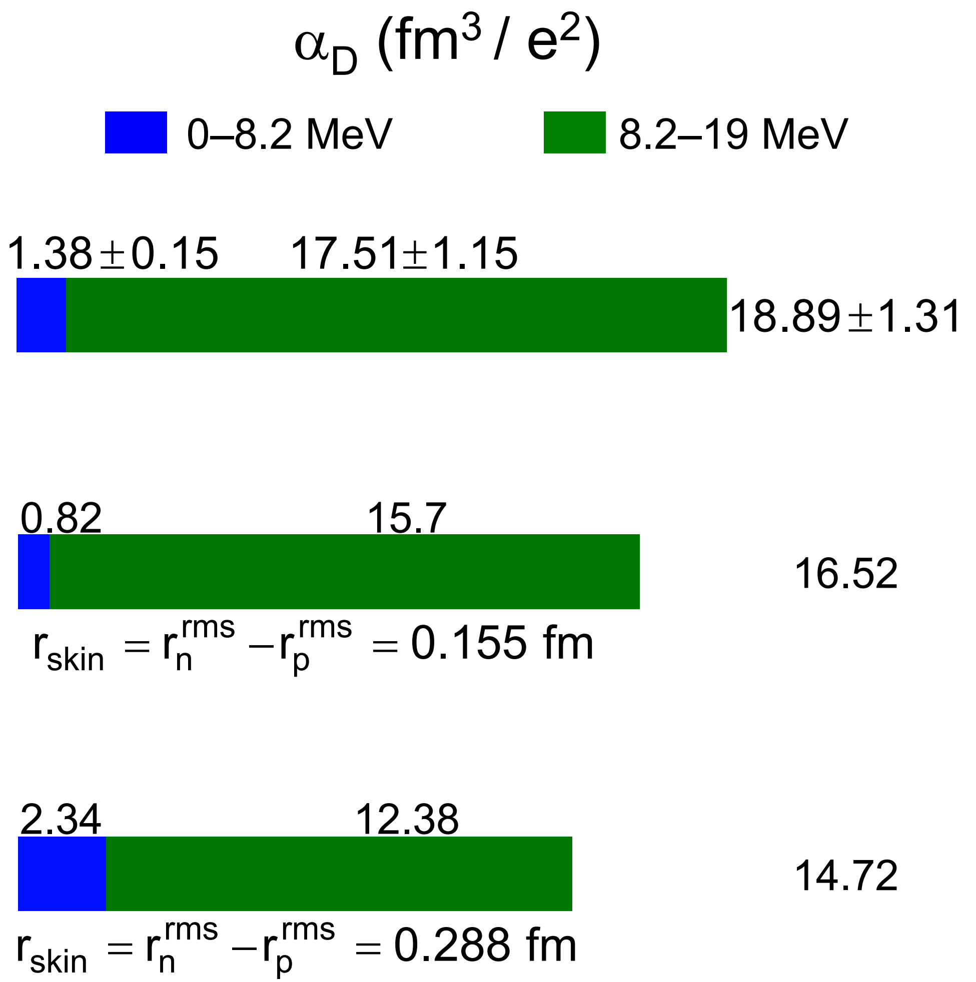
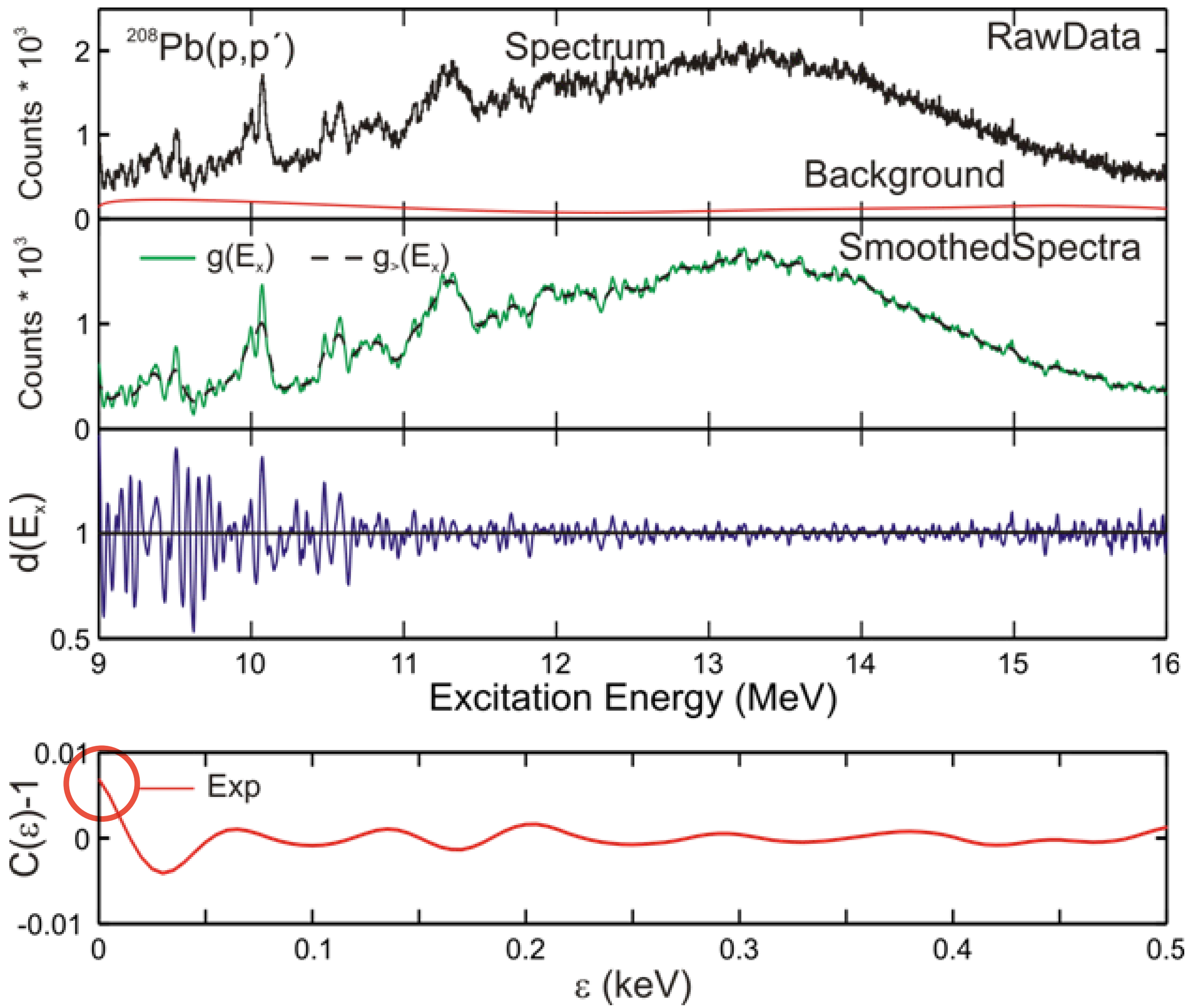
$$\alpha_D = \frac{\sigma_{-2}}{2\pi^2} \cdot \frac{\hbar c}{e^2} = \sum \frac{\sigma_{abs}(E)}{E^2} \cdot \frac{\hbar c}{2\pi^2 e^2}$$





- Extraction of level density from fine structure of the E1 strength distribution using fluctuation analysis

Fluctuation Analysis

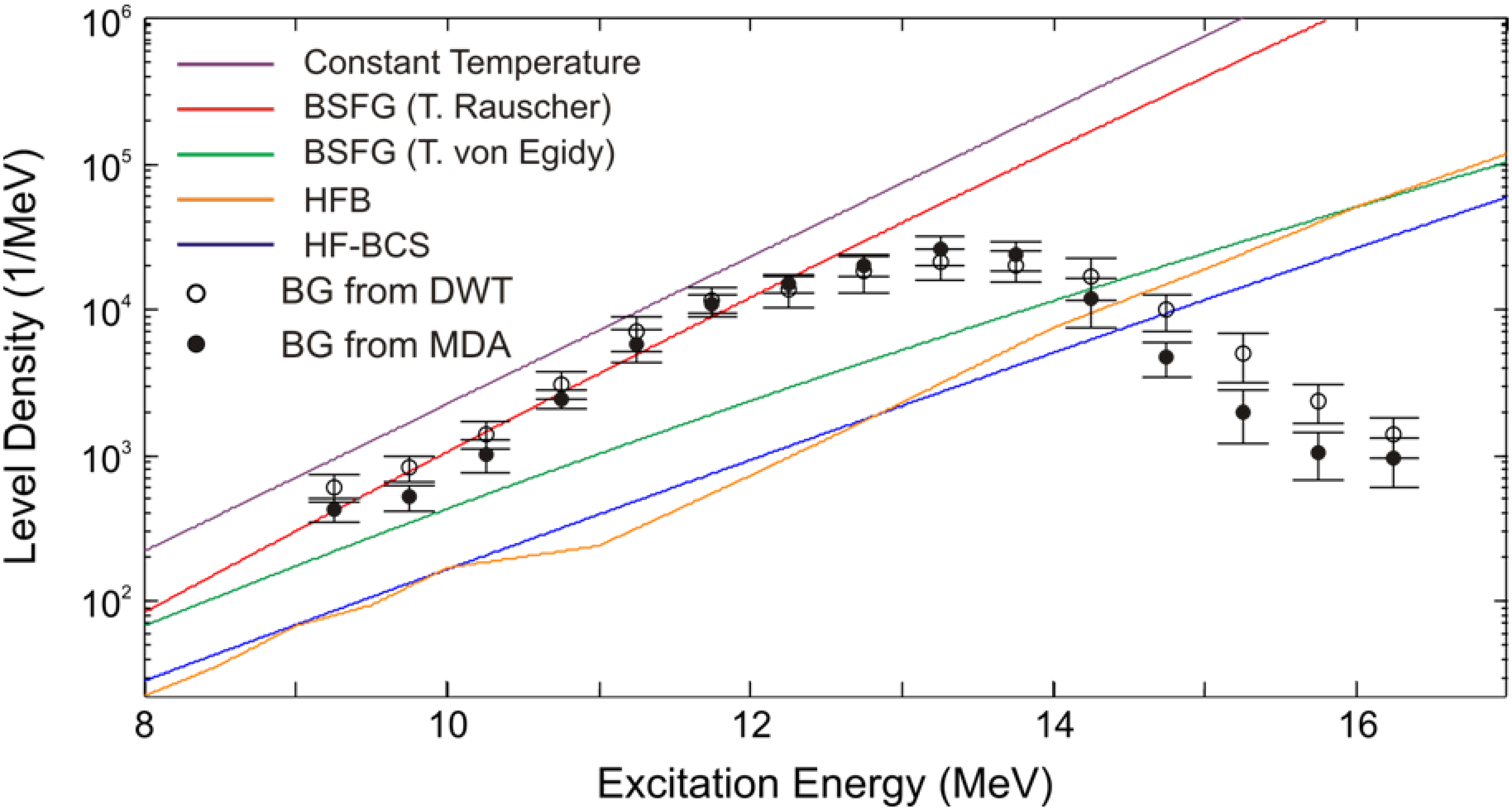


- Background from MDA
- Stationary spectrum $\dfrac{g(E_x)}{g_>(E_x)}$
- Autocorrelation function

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

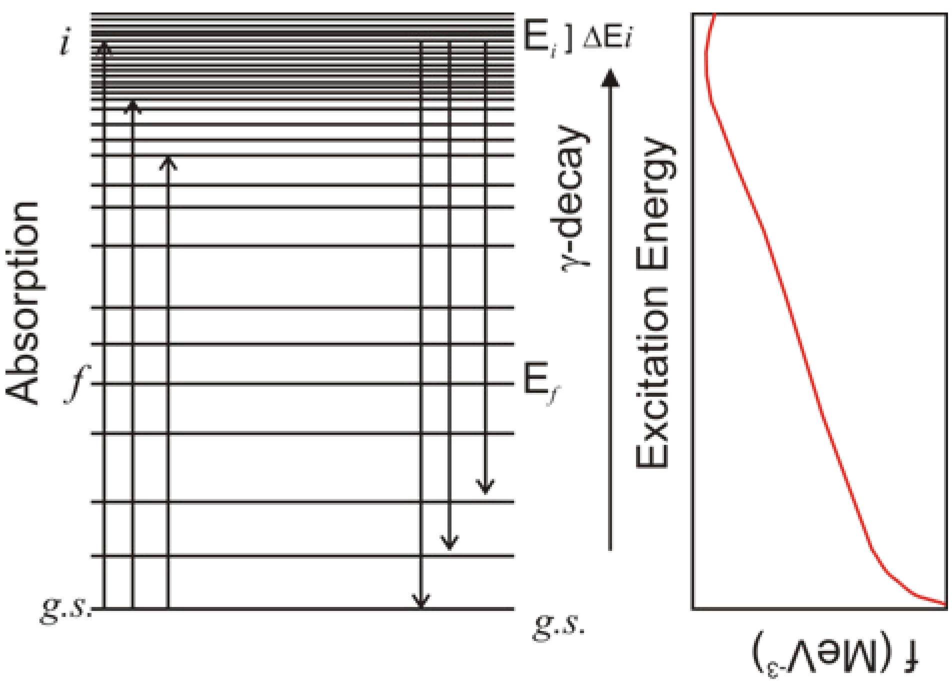
Level Density in ^{208}Pb



- Extraction of the Photon Strength Function

Photon Strength Function (PSF)

- Describes the (average) energy distribution of photon emission from highly-excited states or cross section for photon absorption (principle of detailed balance)



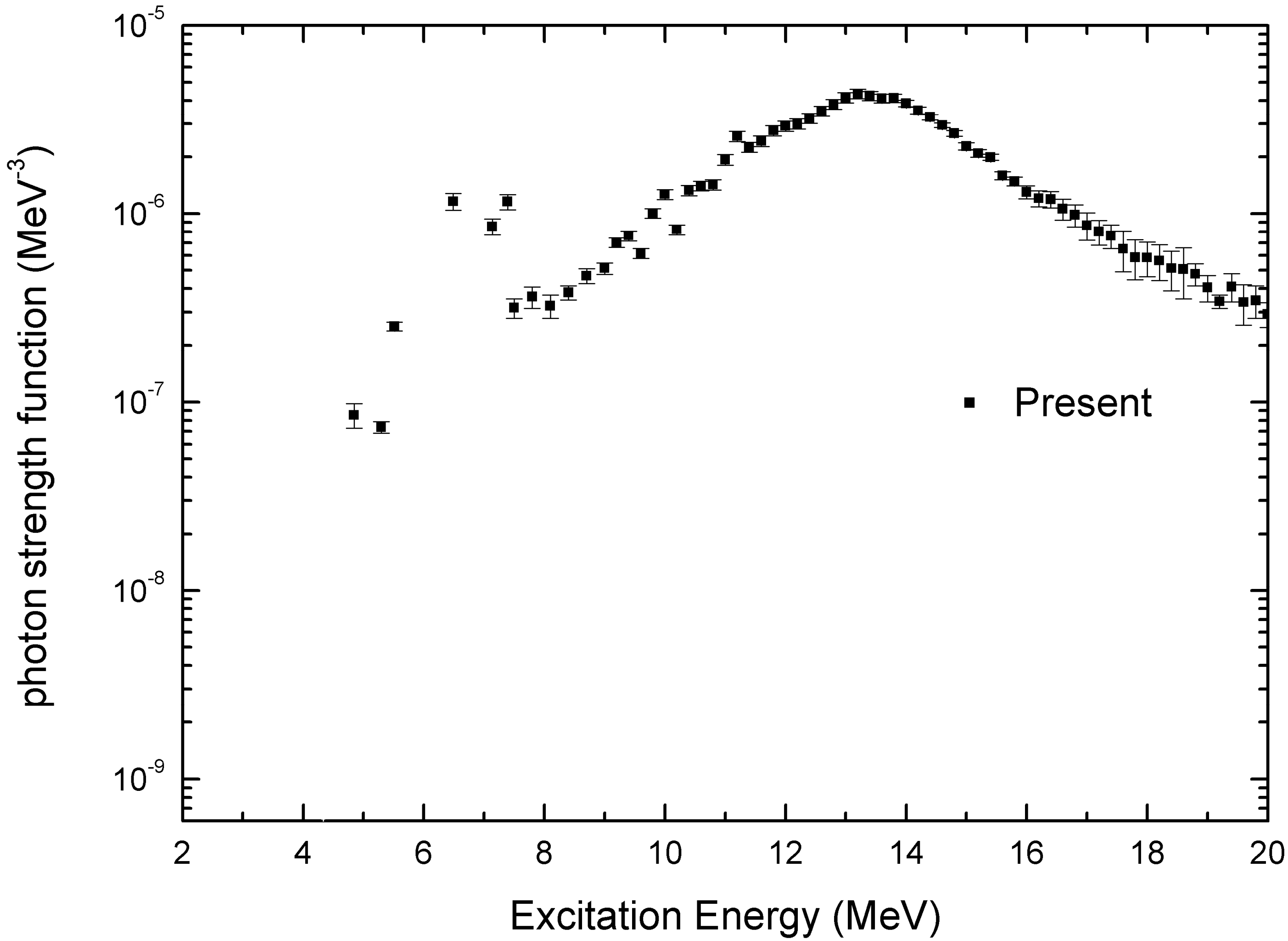
Average decay width from level i to $g.s.$

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

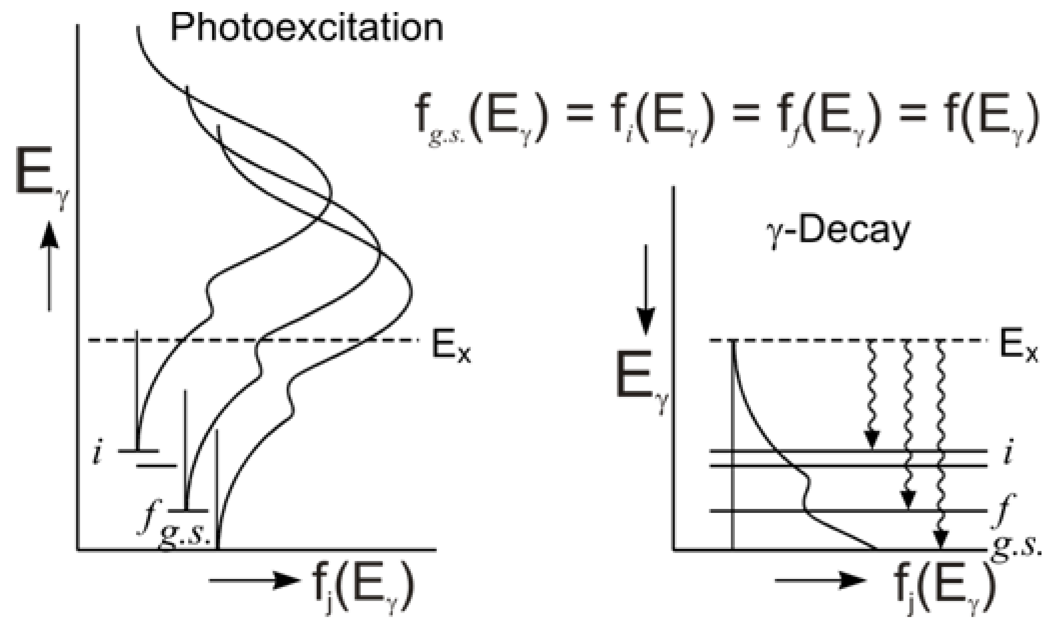
$\Downarrow$

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

Photon Strength Function in ^{208}Pb

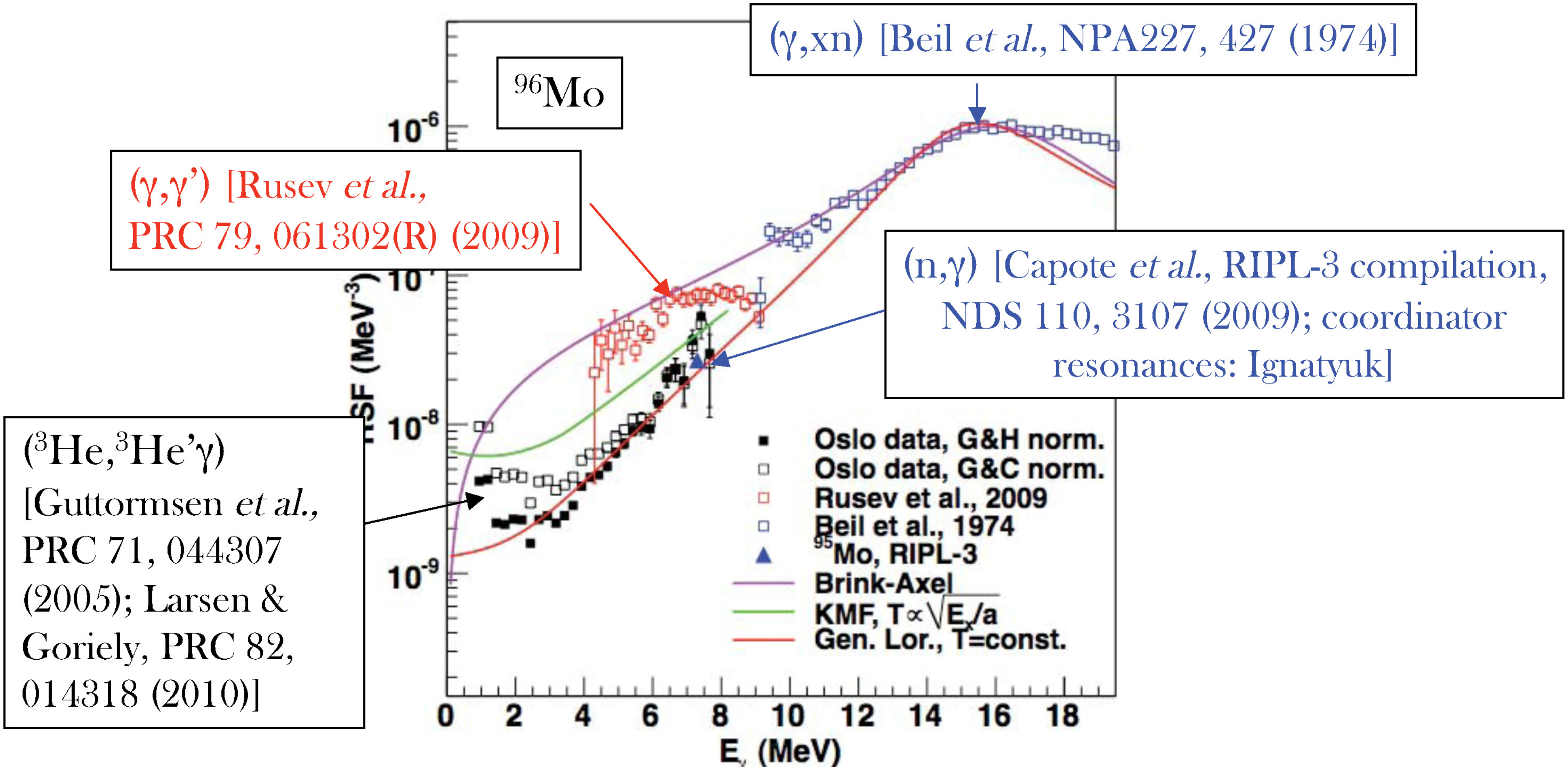


Axel-Brink Hypothesis



- Strength:
  - depends only on E_γ
  - is independent of the initial state structure: excitation energy (T), J^π,…
- Same PSF holds for absorption and gamma emission

Experimental Discrepances in PSF



Why so different?

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

Photon Strength Function in ^{208}Pb

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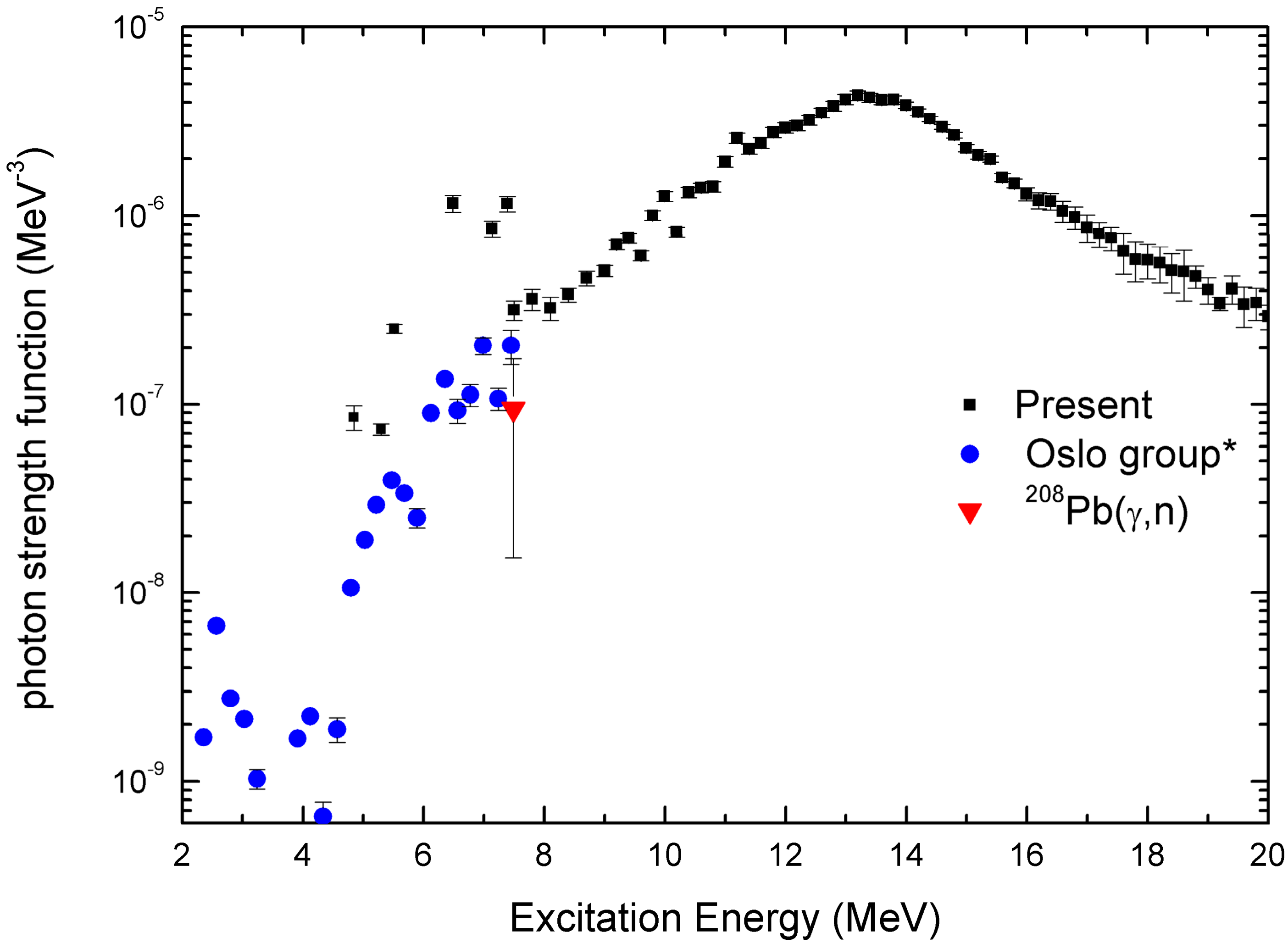

*N.U.H. Syed, PRC 79 (2009) 024316

Summary and Outlook

- Polarized intermediate energy proton scattering at 0°: a new tool to extract complete dipole responce in nuclei
  - → Spinflip / non-spinflip cross section separation
  - → B(E1) strength
  - → Dipole polarizability
  - → Level Densities of 1^- states
  - → Photon Strength Function

- Extraction of the B_σ(M1) strength distribution

- Investigation of the dipole strength in ^{120}Sn and ^{154}Sm

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Thank you !!