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

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- Complete dipole strength: what can be learned?
- Polarized protons scattering at RCNP
- Results
- Summary and outlook

SFB 634

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Complete dipole strength: what can be learned?

- Spinflip M1 strength
- Electric pygmy dipole resonance (PDR)

$\Big\}$ Test of microscopic models

- Dipole polarizability $\rightarrow$ Measure of neutron skin and symmetry energy

- Characteristic scales of the GDR fine structure $\rightarrow$ Dominant damping mechanism

- 1^- states level density from the fine structure of the GDR
- Photon strength function

$\Big\}$ Test of the Axel-Brink hypothesis

Spinflip M1 Strength

- 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 $\rightarrow$ ^{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° $\rightarrow$ selectivity on $\Delta L=0$ 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 density dependence of the asymmetry energy
- Strength distribution around neutron threshold relevant for nucleosynthesis (r-process)

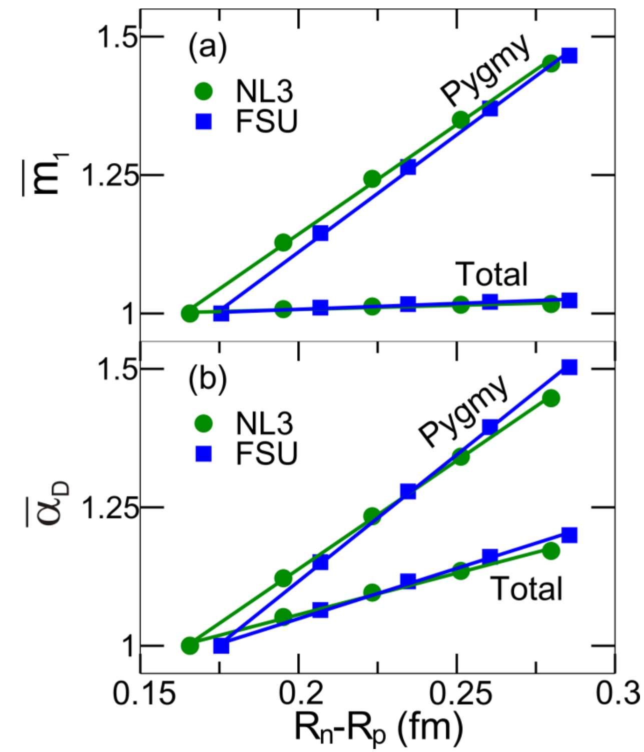
Nuclear Dipole Polarizability

- Static nuclear dipole polarizability

$$\alpha_D \propto \sum_i B(E1)_i \, / \, E_{x,i}$$

P.G. Reinhard, W. Nazarewicz, PRC 81 (2010) 051303 (R)
J. Piekarewicz, arXiv:1012.1803v1 [nucl-th] 8 Dec 2010

$\rightarrow$ measure of the neutron skin



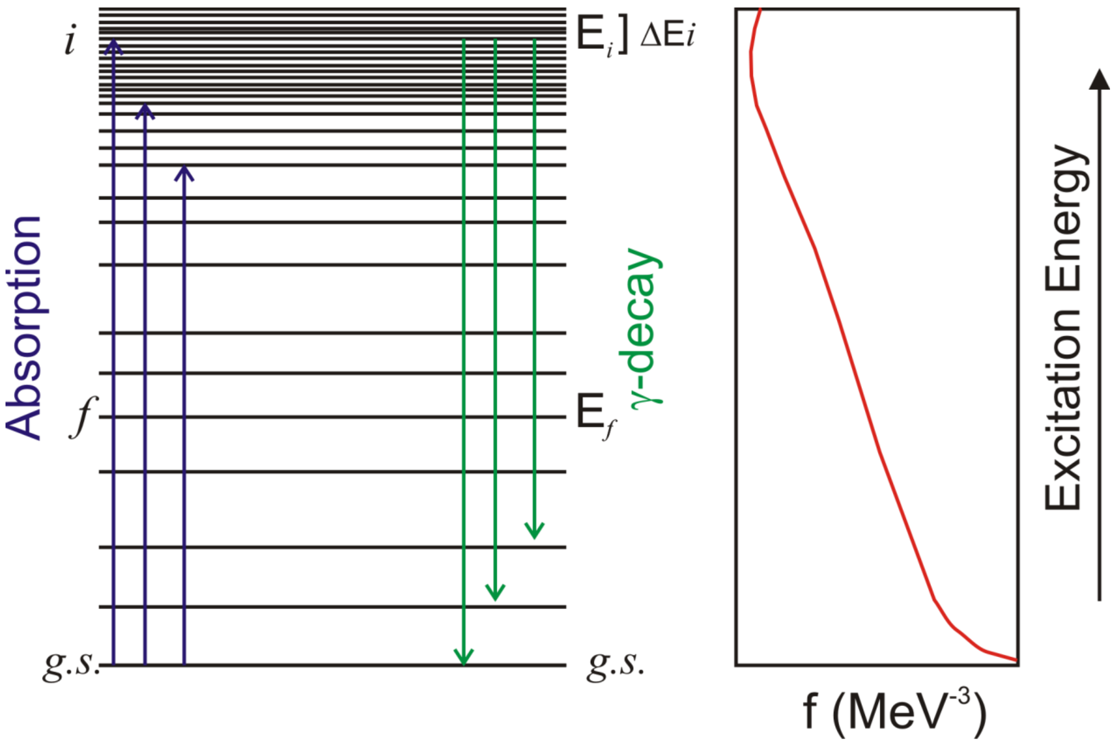
PDR strength ? **Polarizability**

Neutron skin

EoS of neutron-rich matter

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)



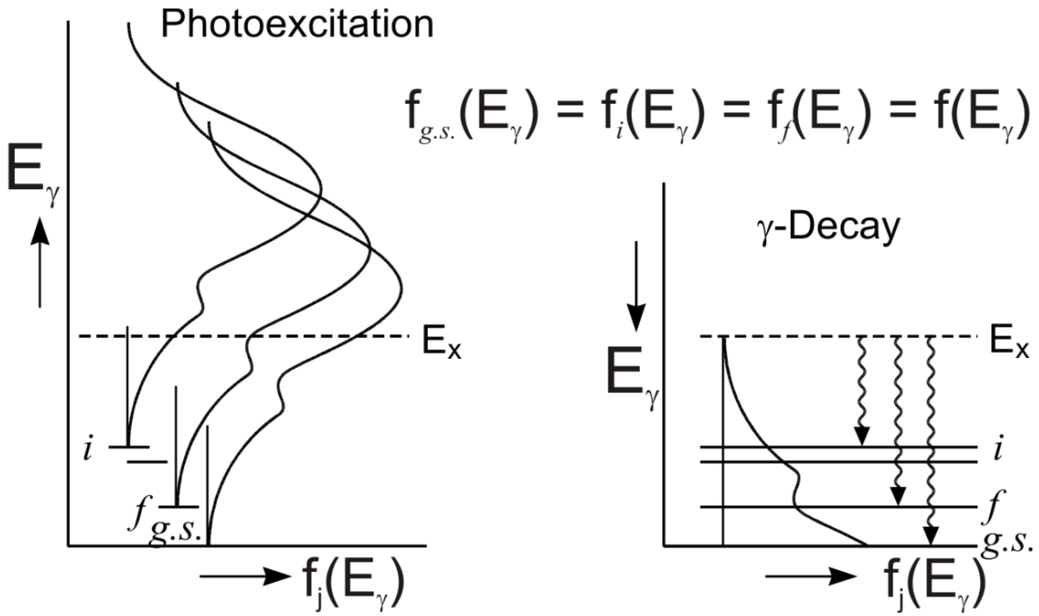
Average decay width from level i to g.s.

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

$$\Downarrow$$

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

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 Discrepancies in PSF

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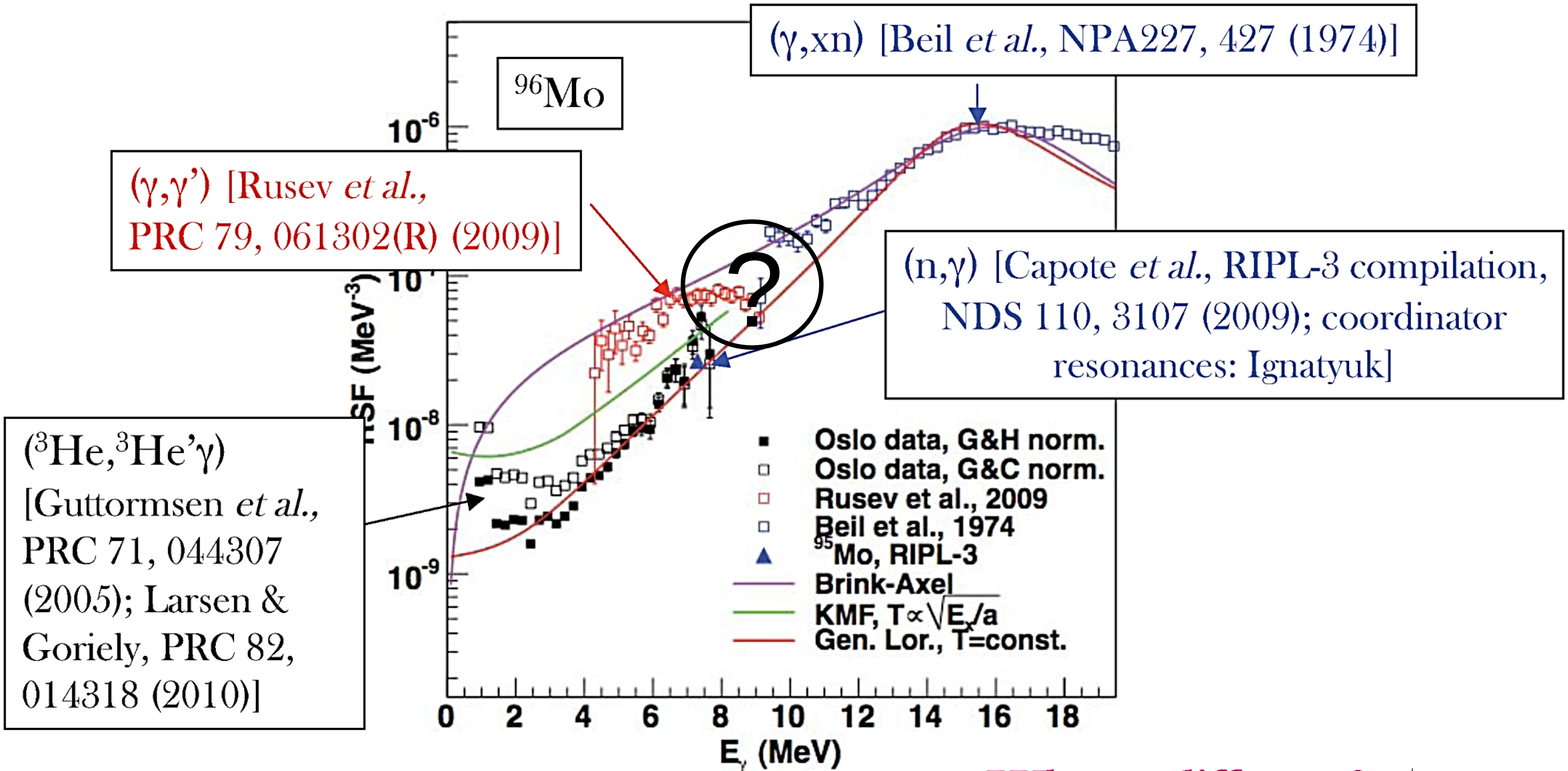


Why so different?

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

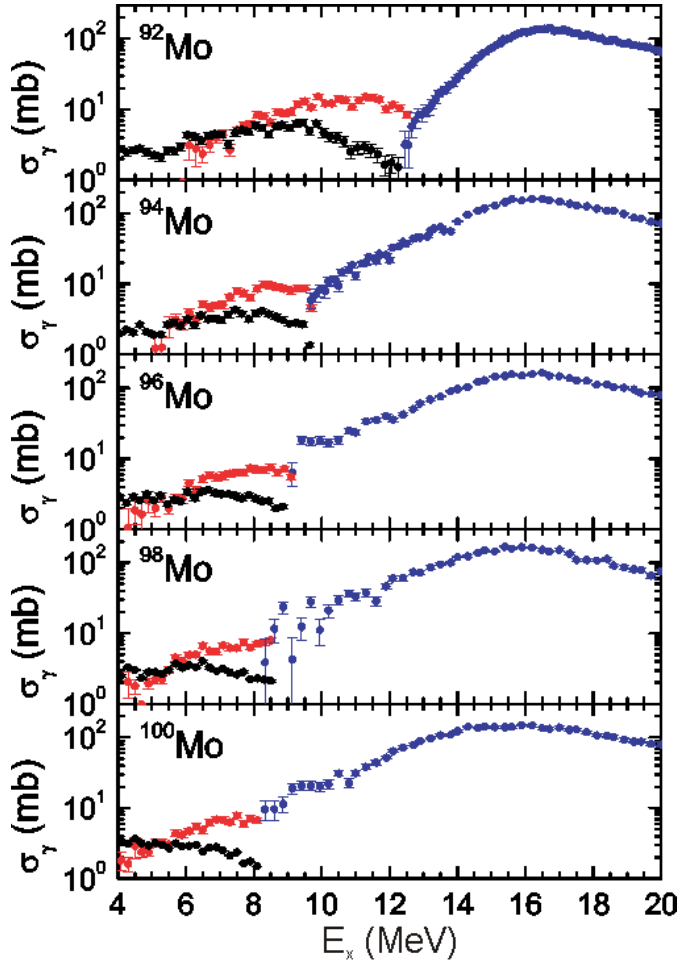
Problems

- 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

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

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



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

Problems (continued)

- (γ,xn) reactions provide information only above threshold

- Decay reactions
  $\rightarrow$ normalization at the S_n energy
  $\rightarrow$ Level densities needed

$\Downarrow$

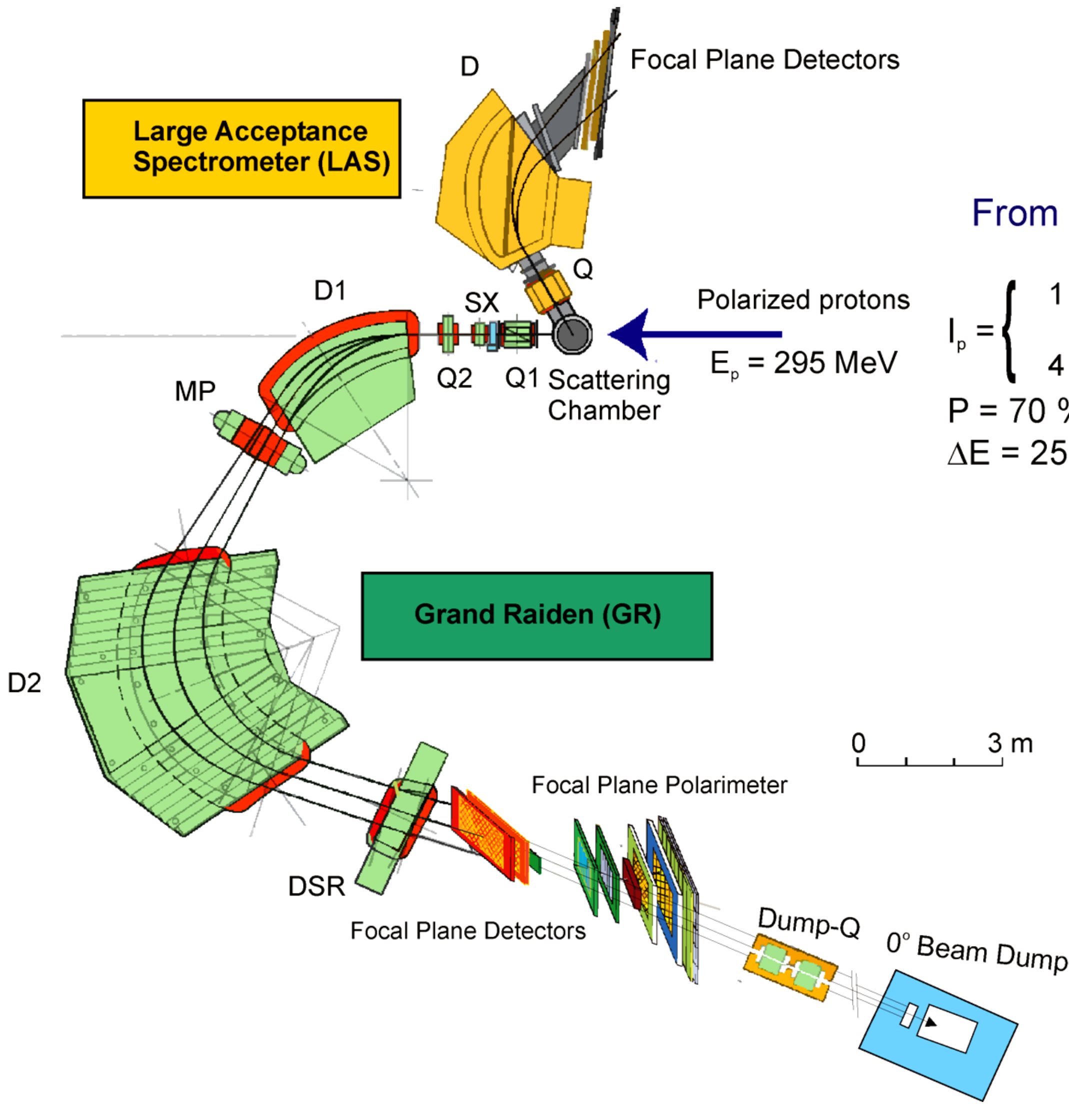
Consistent measurements below and above the threshold needed

Complete E1 and M1 Strength Distributions

- Polarized proton scattering at 0º
  - intermediate energy: 300 MeV optimal for spin/isospin excitations
  - 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

0º 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:

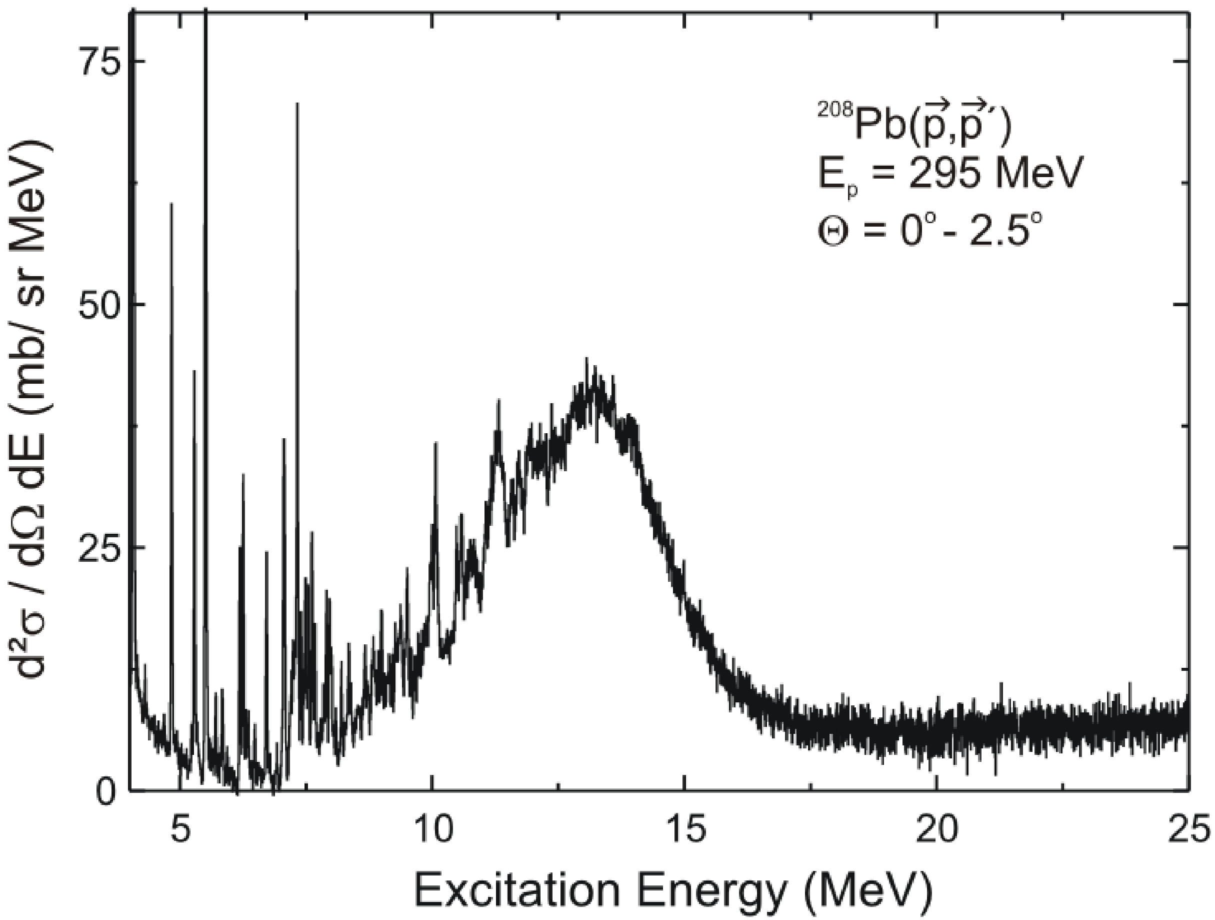
$d\sigma/d\Omega$ - angular distributions $0^\circ \leqslant \Theta \leqslant 10^\circ$

A_y - asymmetry

D_{SS} at 0° - sideways polarization observables

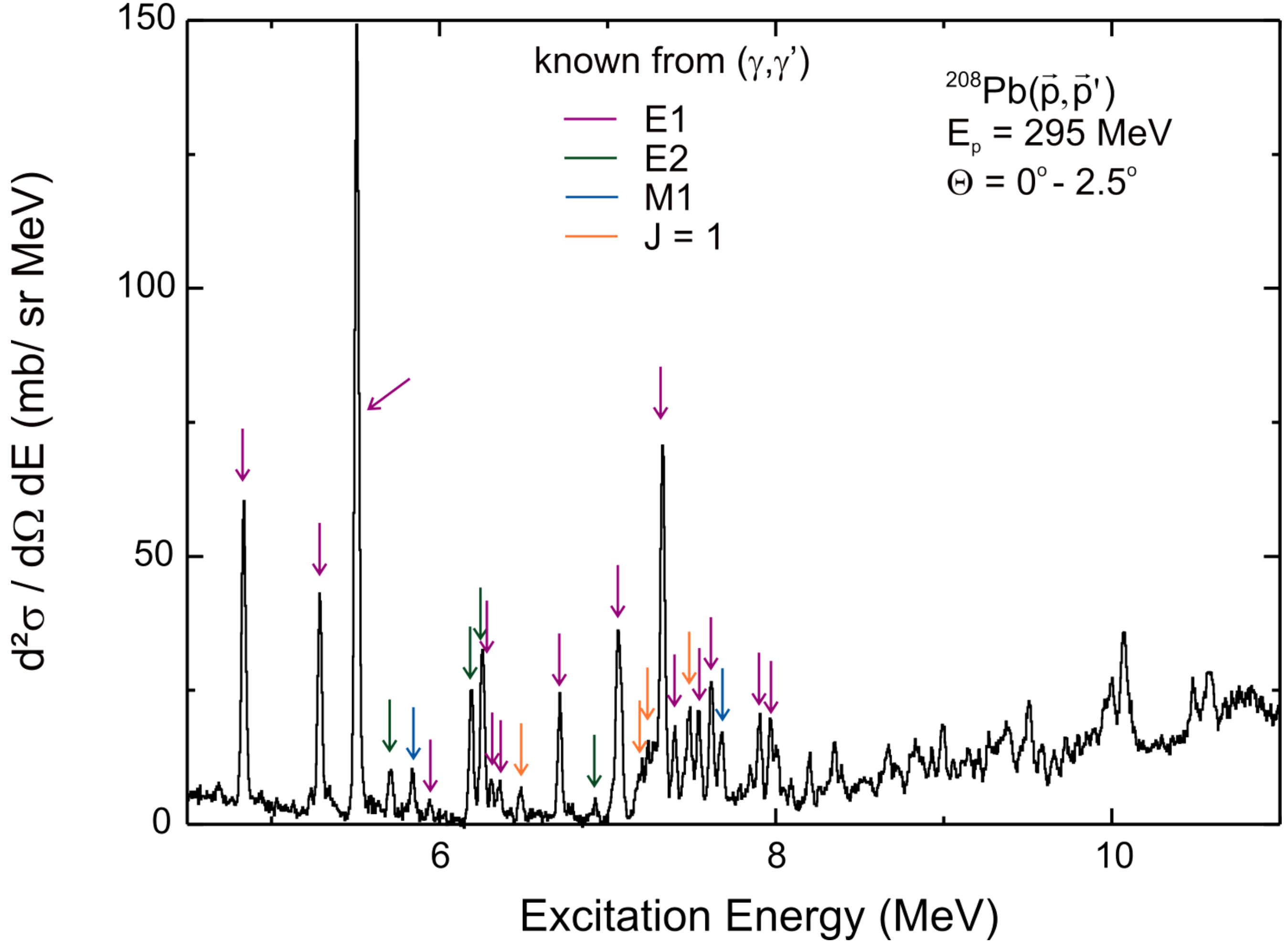
D_{LL} at 0° - longitudinal polarization observables

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

E1/M1 Decomposition by Spin Observables

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

(model-independent)

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

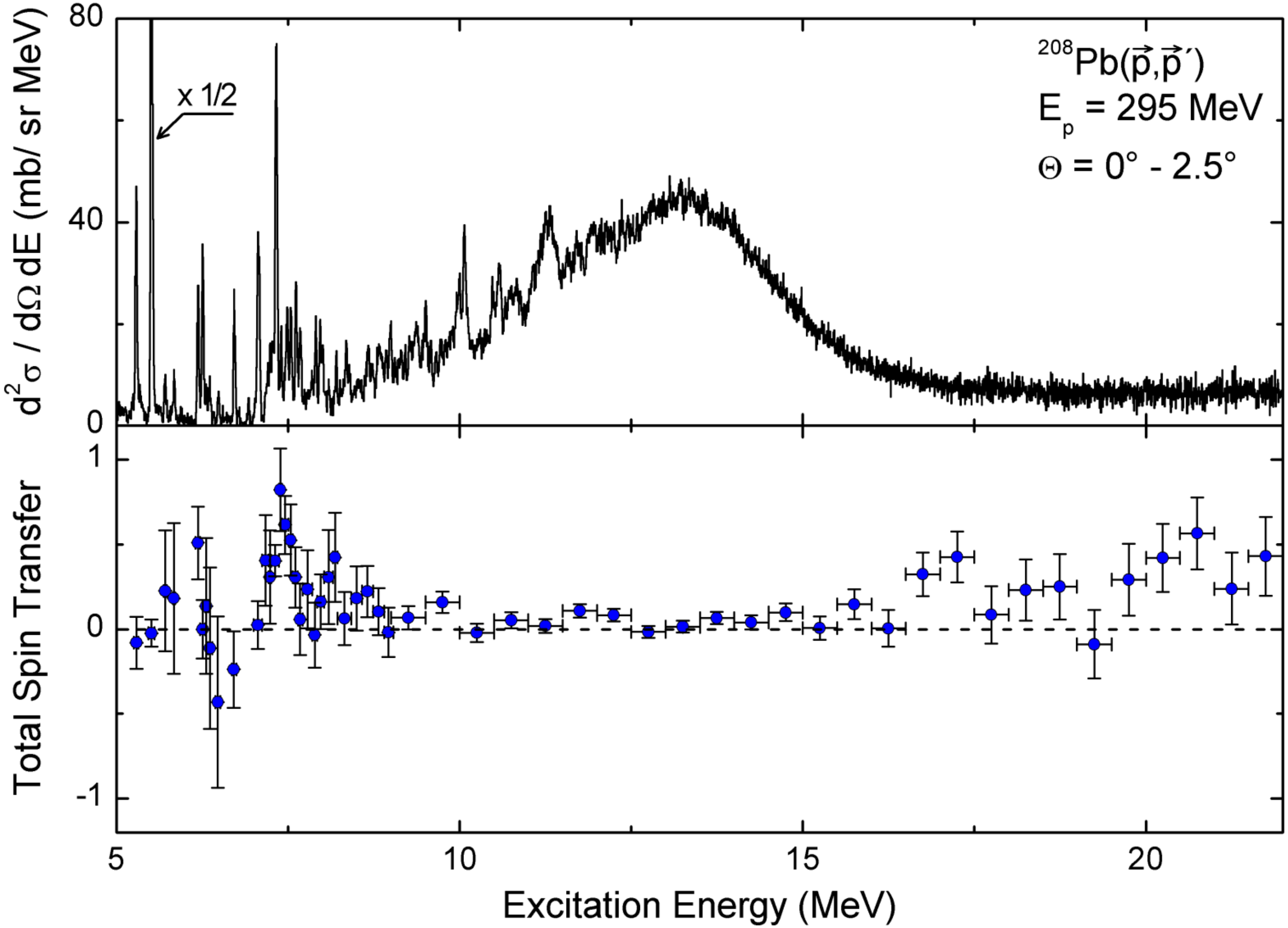
➡ E1 and M1 cross sections can be decomposed

At 0° $D_{SS} = D_{NN}$

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

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

Decomposition into Spinflip / Non-Spinflip Cross Sections



Multipole Decomposition of Angular Distributions

$$\left.\frac{d\sigma(\Theta_{lab}, E_x)}{d\Omega}\right|_{data} = \sum_{J^\pi} a_{J^\pi} \cdot \left.\frac{d\sigma(\Theta_{lab}, E_x, J^\pi)}{d\Omega}\right|_{DWBA}$$

$$\left.\begin{array}{l}\text{DWBA07} \\ \text{QPM wave functions} \\ \text{Love\&Franey effective interaction}\end{array}\right\} \rightarrow \left.\frac{d\sigma(\Theta_{lab}, E_x, J^\pi)}{d\Omega}\right|_{DWBA}$$

- Restrict angular distribution to $\Theta \leqslant 4°$
  - too complex response at larger angles
- Low-energy region ($E_x \leq 9$ MeV)
  - Isovector M1 $\rightarrow$ $\Delta L = 0$
  - Coulomb dominated $d\sigma/d\Omega$ for E1 $\rightarrow$ $\Delta L = 1$
  - E2 (alternatively E3) substitute for $\Delta L > 1$
- GDR region:
  - $\Delta L = 0$ replaced by Phenomenological background

Multipole Decomposition of Angular Distributions

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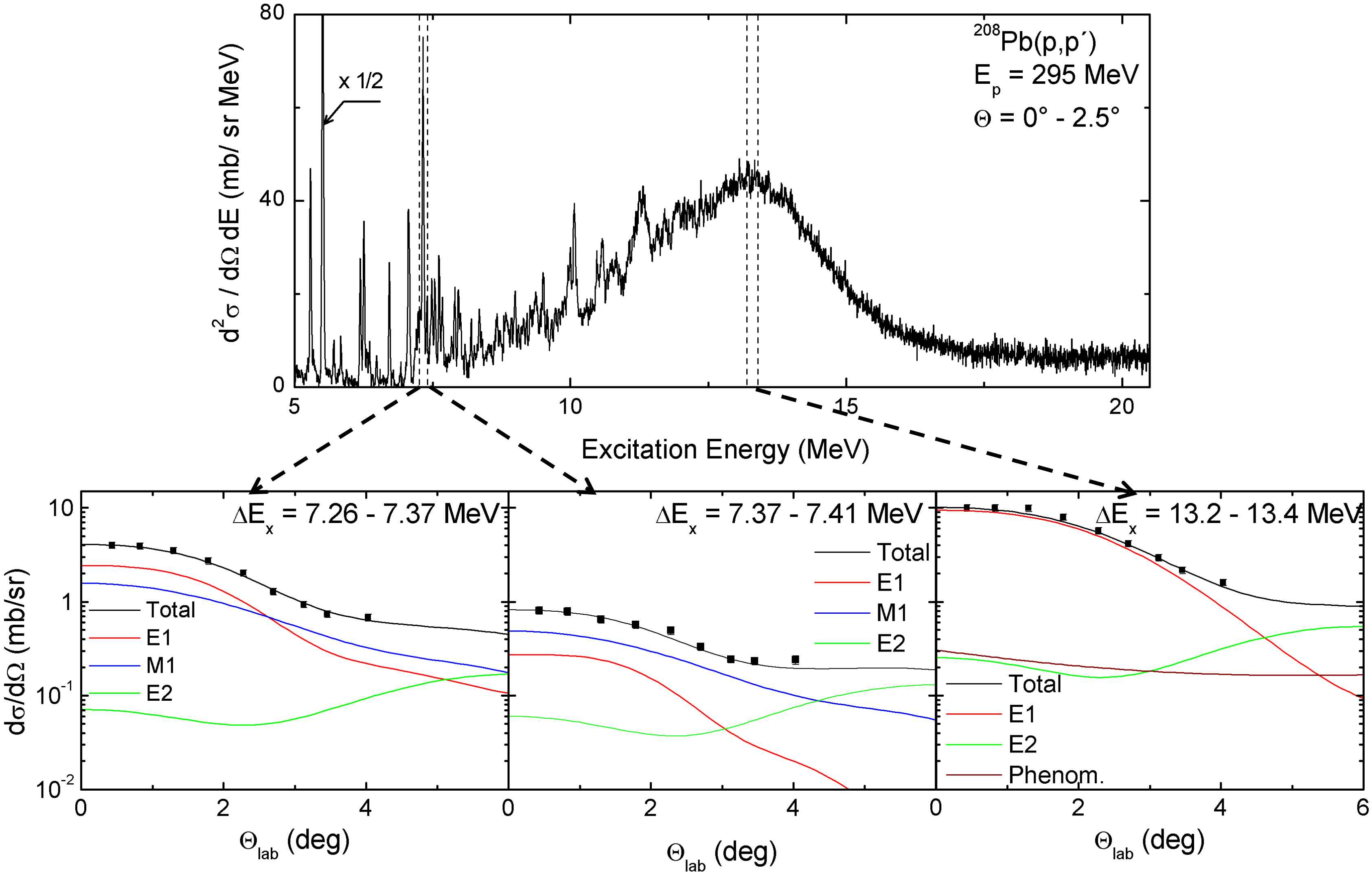
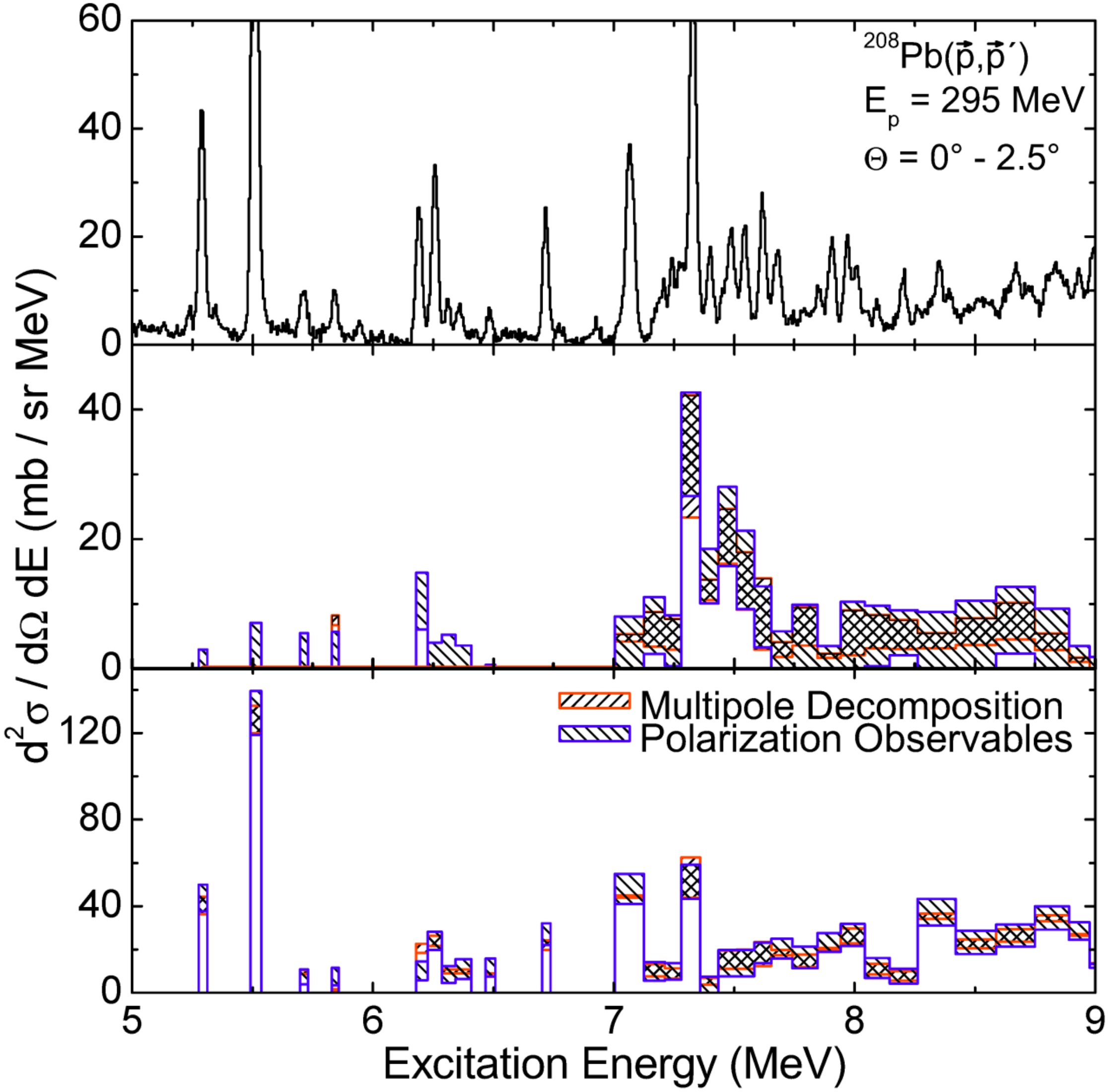


Comparison of Both Methods I

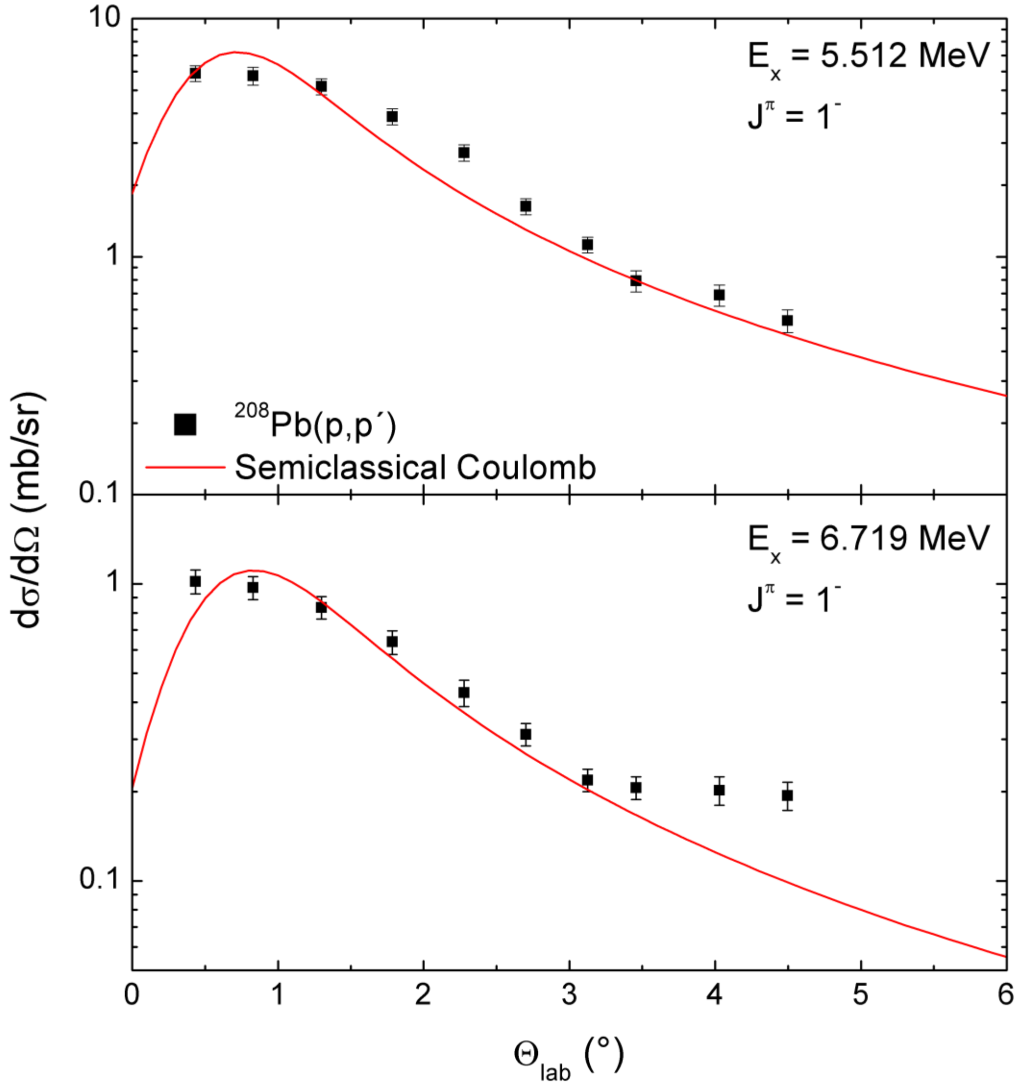


Total

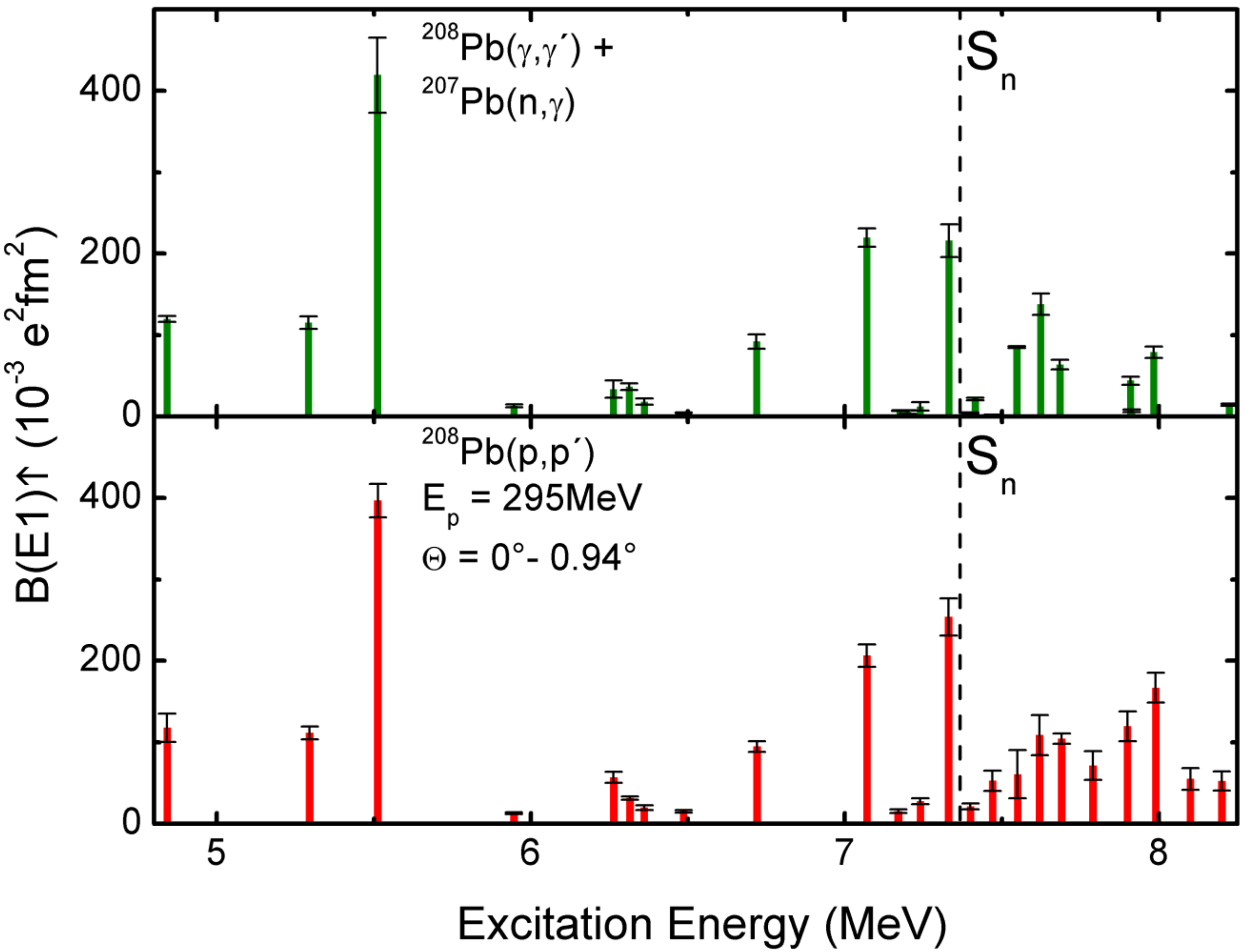
ΔS = 1

ΔS = 0

Coulomb Exitations of 1^- States



B(E1) Strength: Low-Energy Region



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

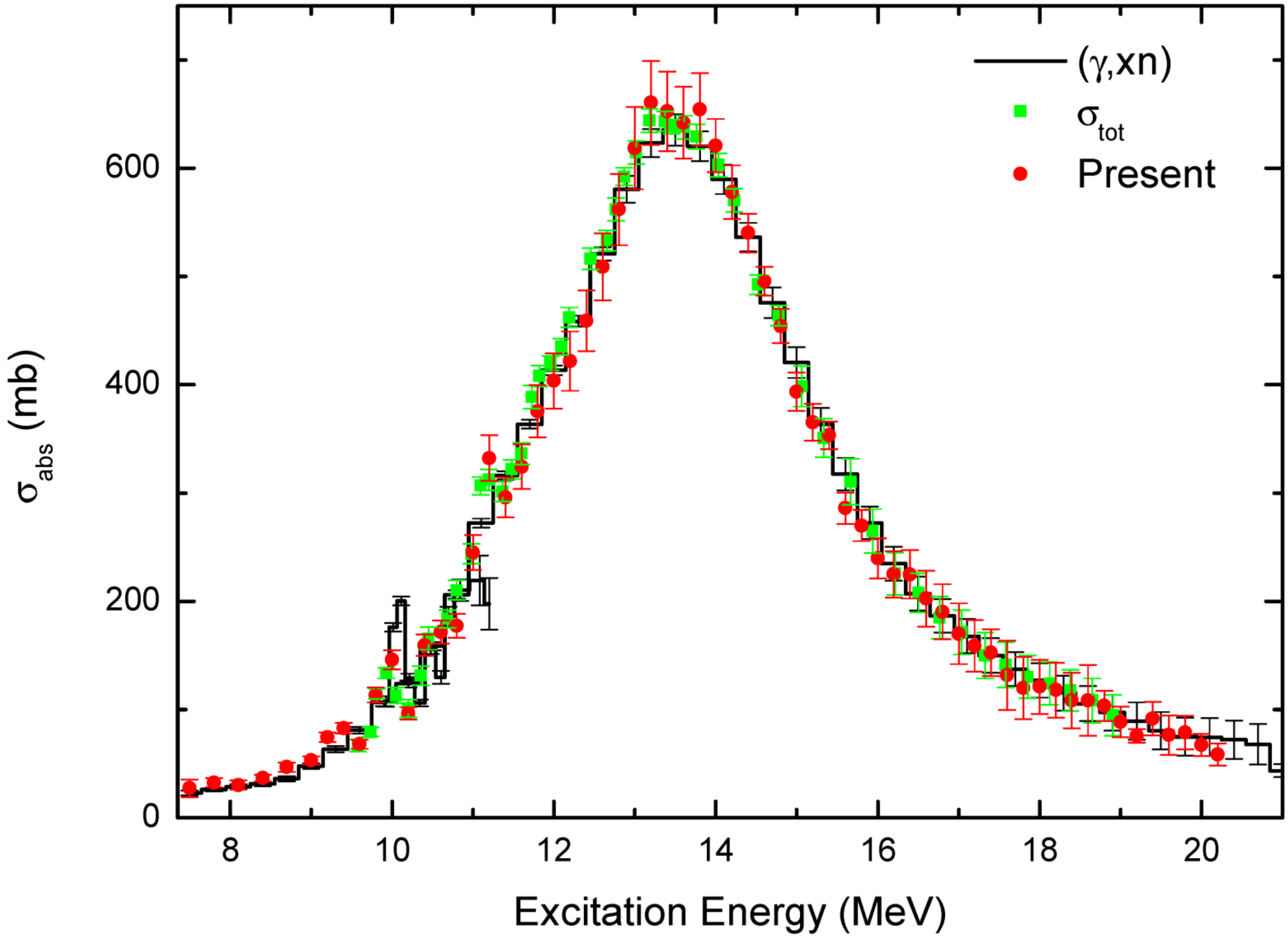
E_c = 7.30 MeV

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

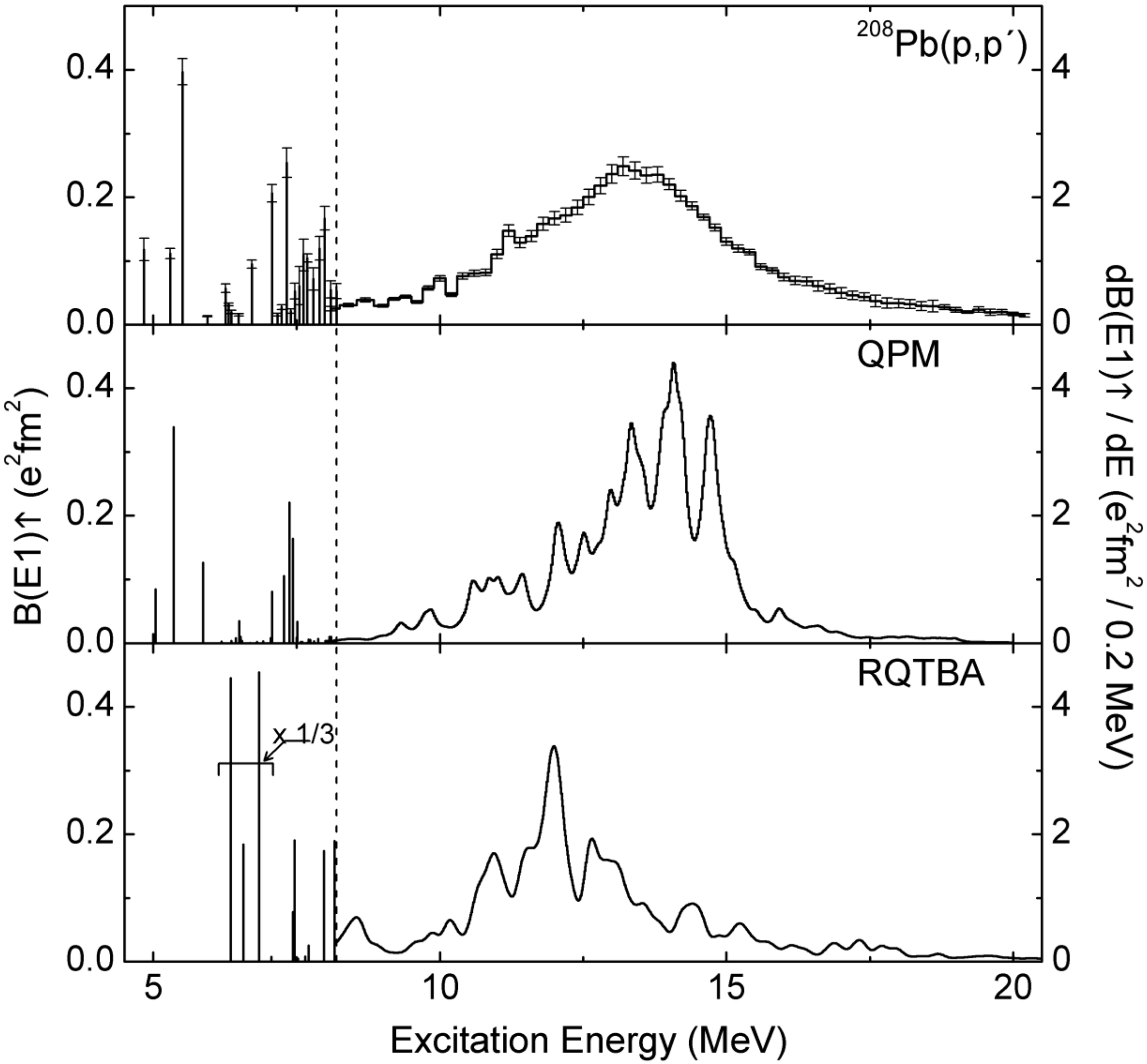
E_c = 7.43 MeV

- Extracted assuming semiclassical Coulomb excitation

B(E1) Strength: GDR



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

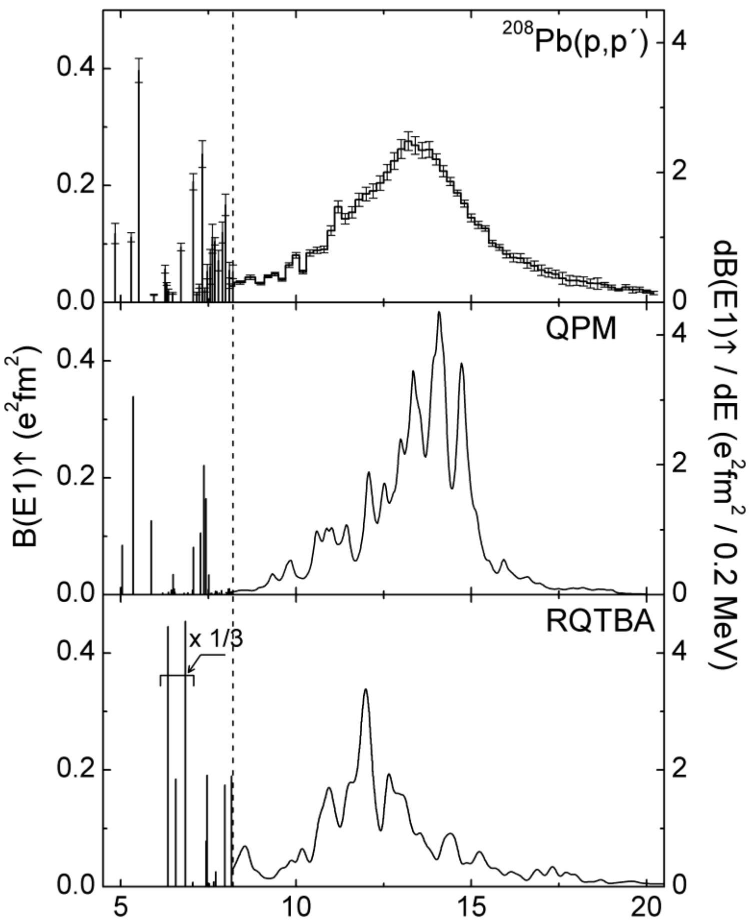


V.Yu. Ponomarev
3p – 3h for $E_x \leq 10$
2p – 2h for GDR
Priv. com.

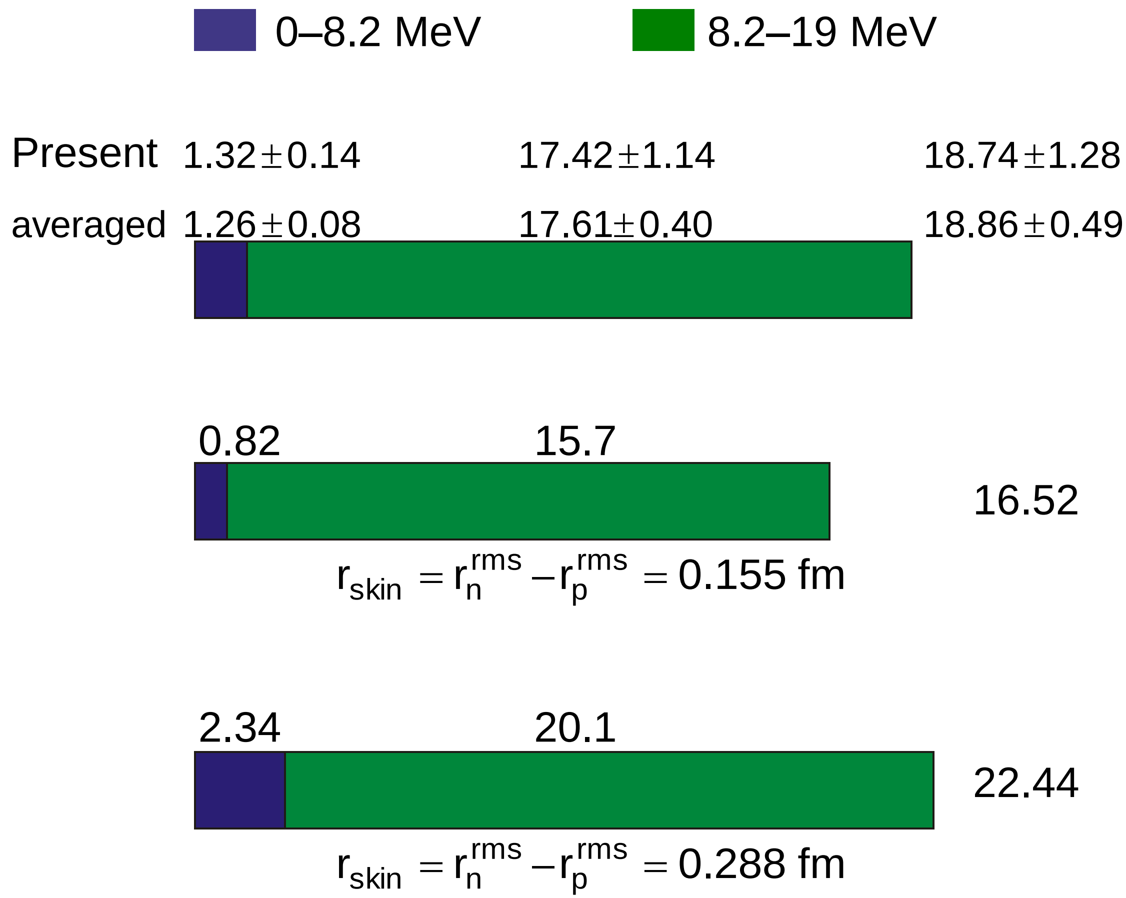
E. Litvinova et al.,
1p - 1h ⊗ phonon

PRC 78 (2008) 014312,
PRC 79 (2009) 054312

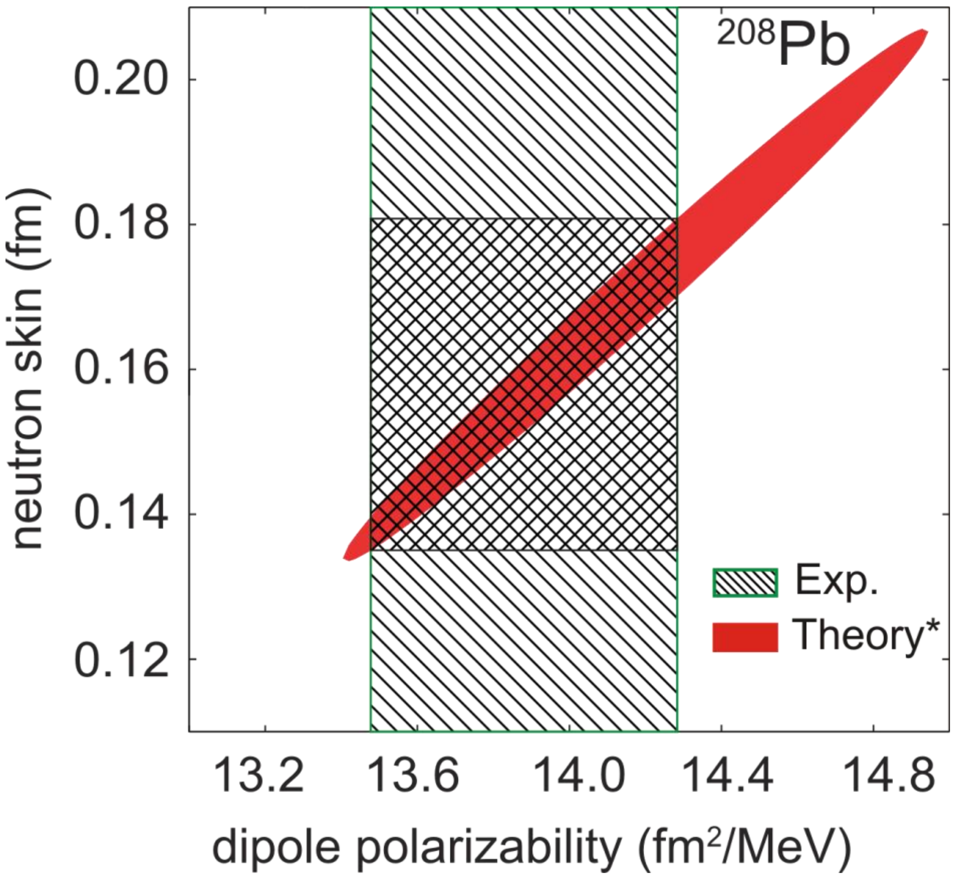
Dipole Polarizability of ^{208}Pb



α_D (fm^3 / e^2)



Polarizability as a Measure of the Neutron Skin



α_D^{Exp}(E$_x$ = 0 – 130 MeV)
19.98(58) fm^3/e^2 = 13.88(41) fm^2/MeV

r_{skin} = 0.155(23) fm

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

Extraction of level density

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- Determined from fluctuation analysis of the fine structure of the GDR

  S. Müller, F. Beck, D. Meuer, and A. Richter, Phys. Lett. 113B (1982) 362

  P.G. Hansen, B. Jonson, and A. Richter, Nucl. Phys. A518 (1990) 13

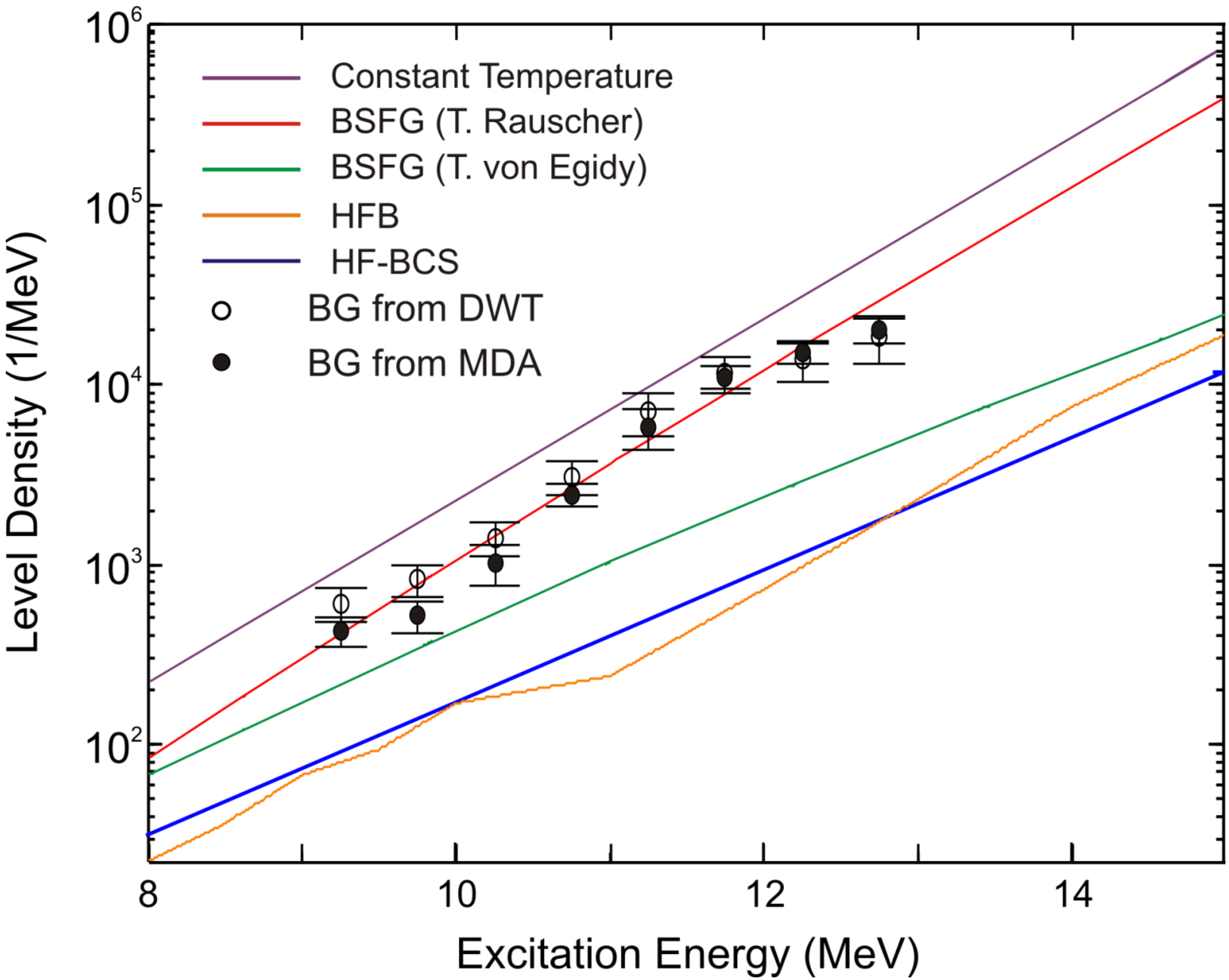
- Depends on the background form:

  - from multipole decomposition analysis

  - from discrete wavelet transform

    Y. Kalmykov et al., Phys. Rev. Lett. 96 (2006) 012502

1^- States Level Density in ^{208}Pb



Photon Strength Function in ^{208}Pb

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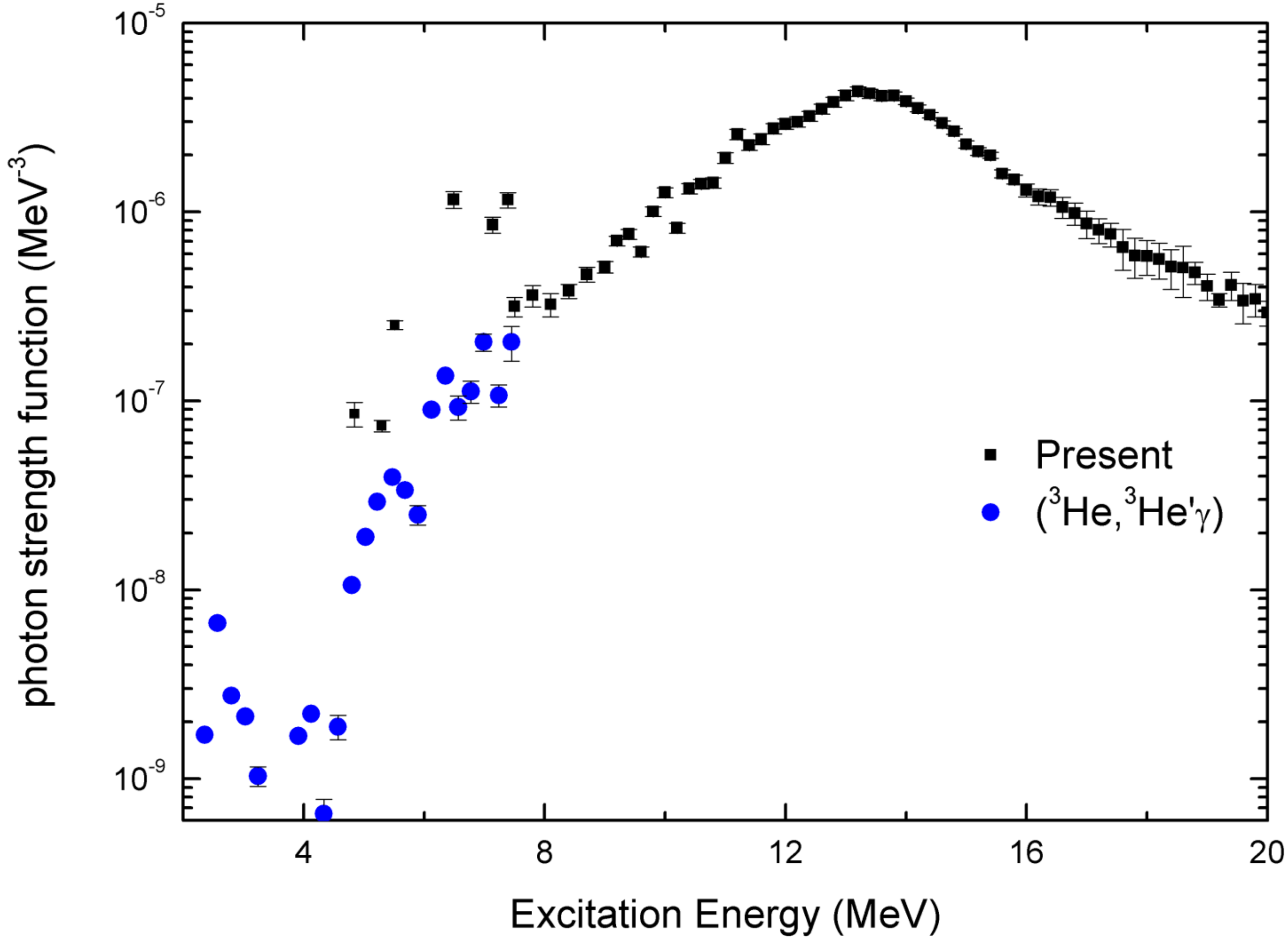

*N.U.H. Syed et al., PRC 79 (2009) 024316

Summary and Outlook

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- 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 !!