Complete Dipole Strength Distributions from High-Resolution Polarized Proton Scattering at 0°

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- Complete electric dipole strength distributions
  - what can be learned

- High-resolution polarized proton scattering as a spectroscopic tool

- The case of ^{208}Pb

SFB 634

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

Complete Dipole Strength: What can be Learned?

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- Pygmy dipole resonance (PDR)
- Dipole polarizability

} Test of microscopic models

Neutron skin and symmetry energy

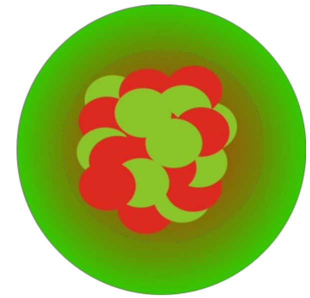
- Level densities
- Photon strength function

} Test of Hauser-Feshbach approach in large-scale reaction network calculations

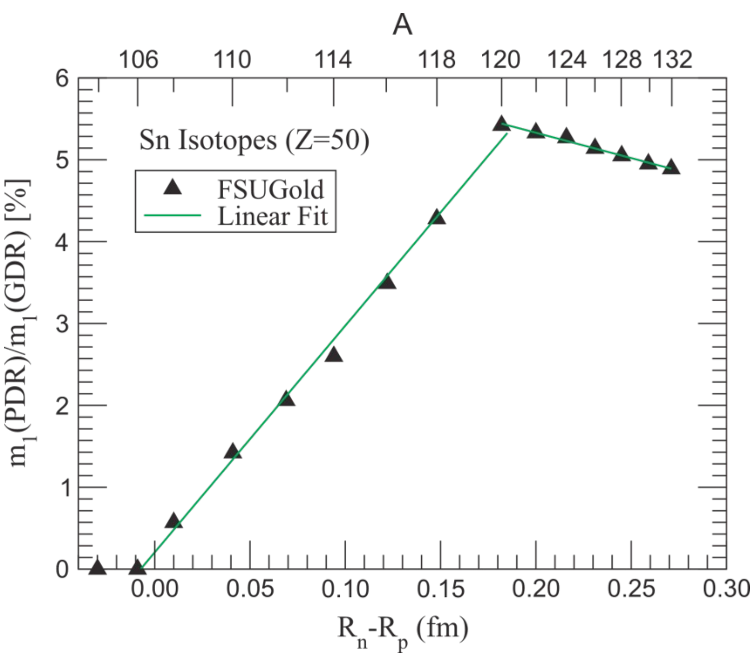
Test of Axel-Brink hypothesis

Pygmy Dipole Resonance

- Soft E1 mode due to oscillation of neutron skin
  vs. approximately isospin-saturated core

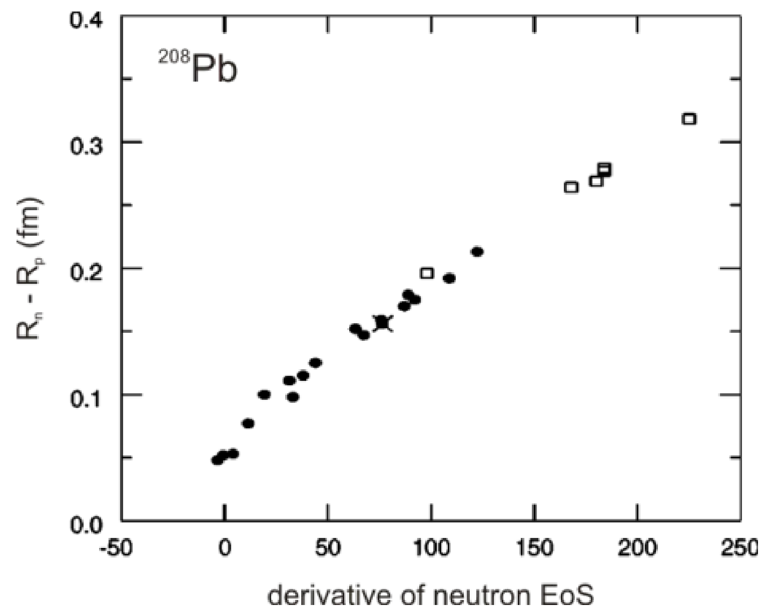


- PDR strength related to neutron skin



J. Piekarewicz, PRC 73 (2006) 044325.

- Neutron skin related to neutron-matter EOS



S. Typel, B. A. Brown, PRC 64 (2001) 027302

Polarizability

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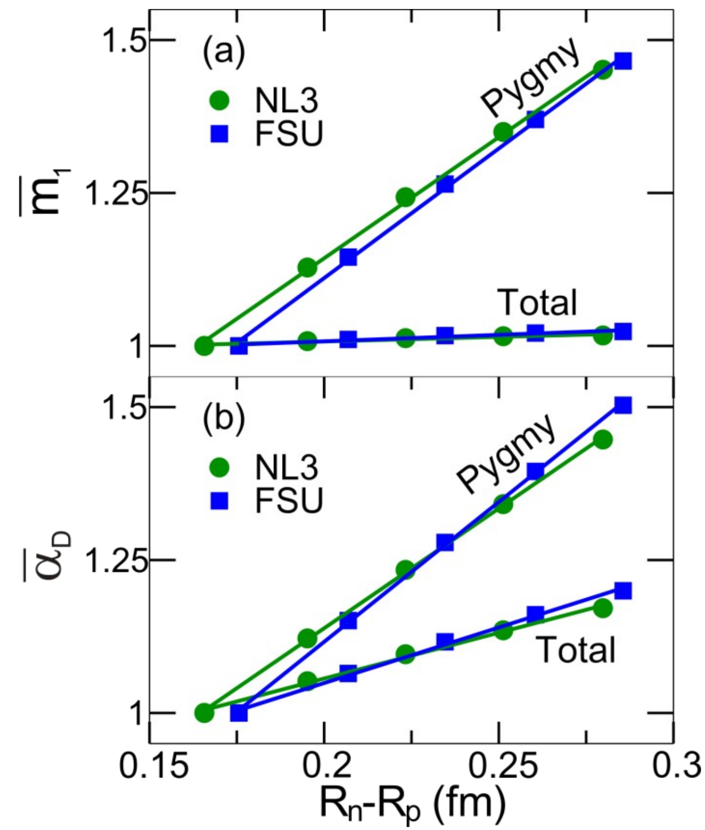
- Static nuclear dipole polarizability

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

$$= \frac{8\pi}{9} \cdot \sum \frac{B(E1)(E_x)}{E_x} \quad \left[{fm^3}/{e^2} \right]$$



- α_D is measure of neutron skin

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

J. Piekarewicz, arXiv:1012.1803

Hauser-Feshbach calculations

- Statistical model approach to reaction cross sections in astrophyiscal large-scale network calculations

- Required input
  - Photon strength function
  - Level densities
  - Axel-Brink hypothesis (thermal population of excited states)

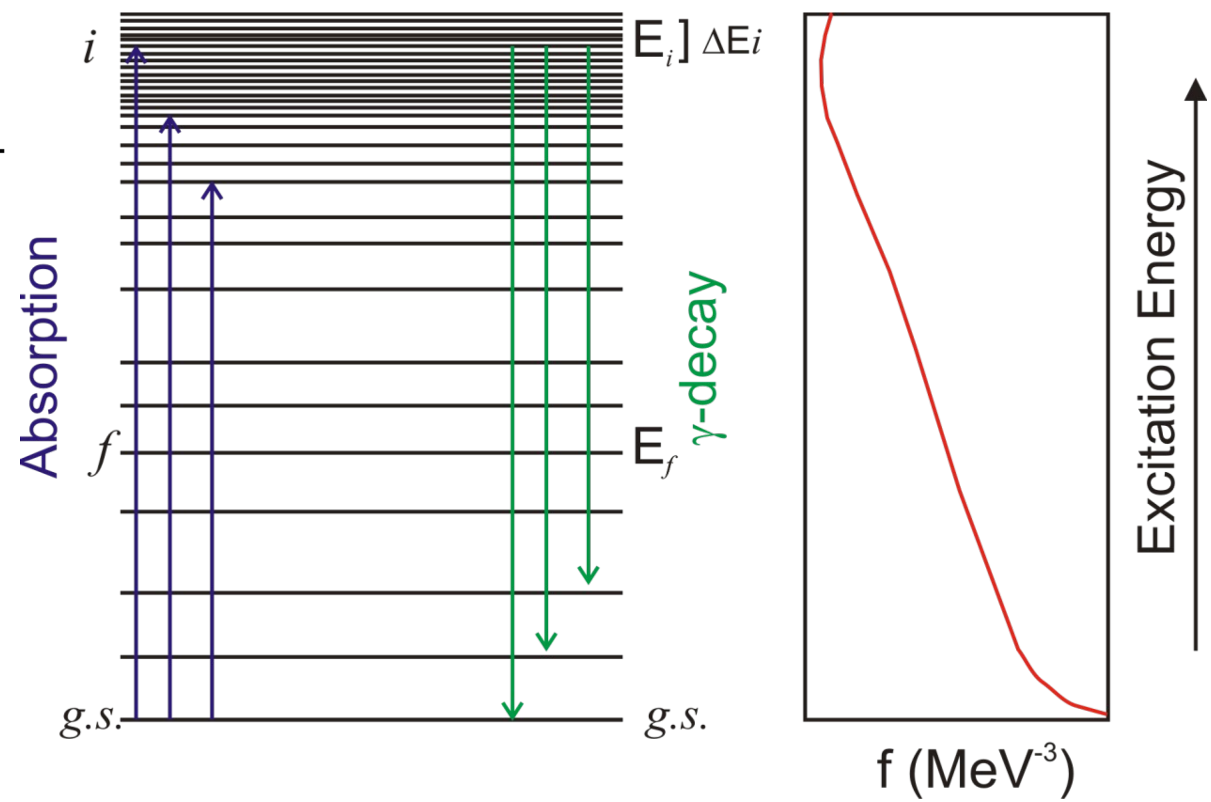
Photon Strength Function (PSF)

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

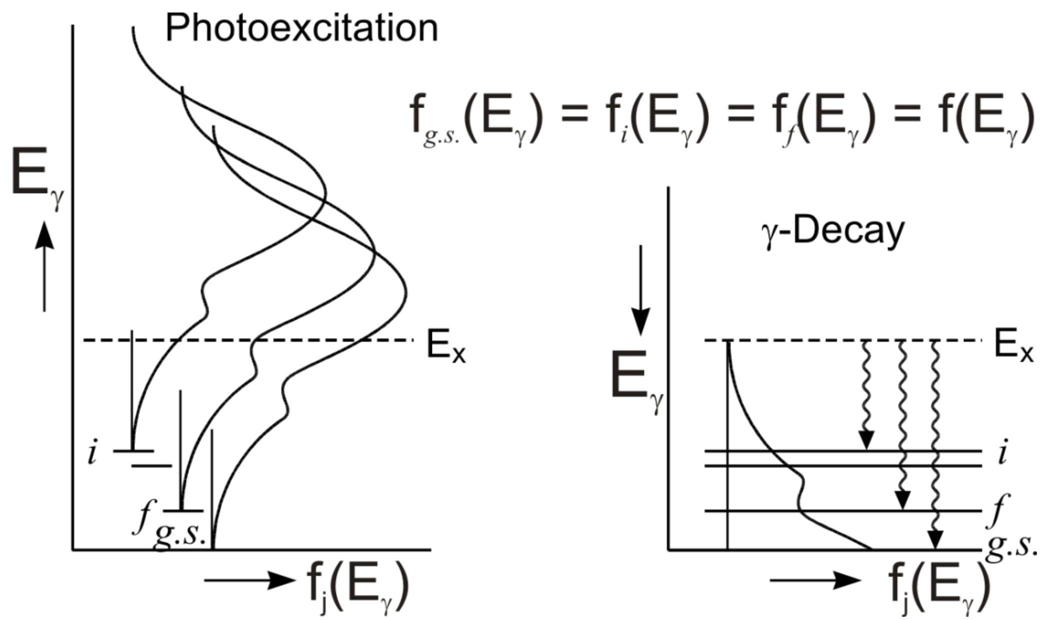
$$\langle \Gamma_{i\rightarrow g.s.} \rangle = \frac{f^{E1}(E_\gamma)\cdot E_\gamma^3}{\rho(E_i)}$$

↕

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



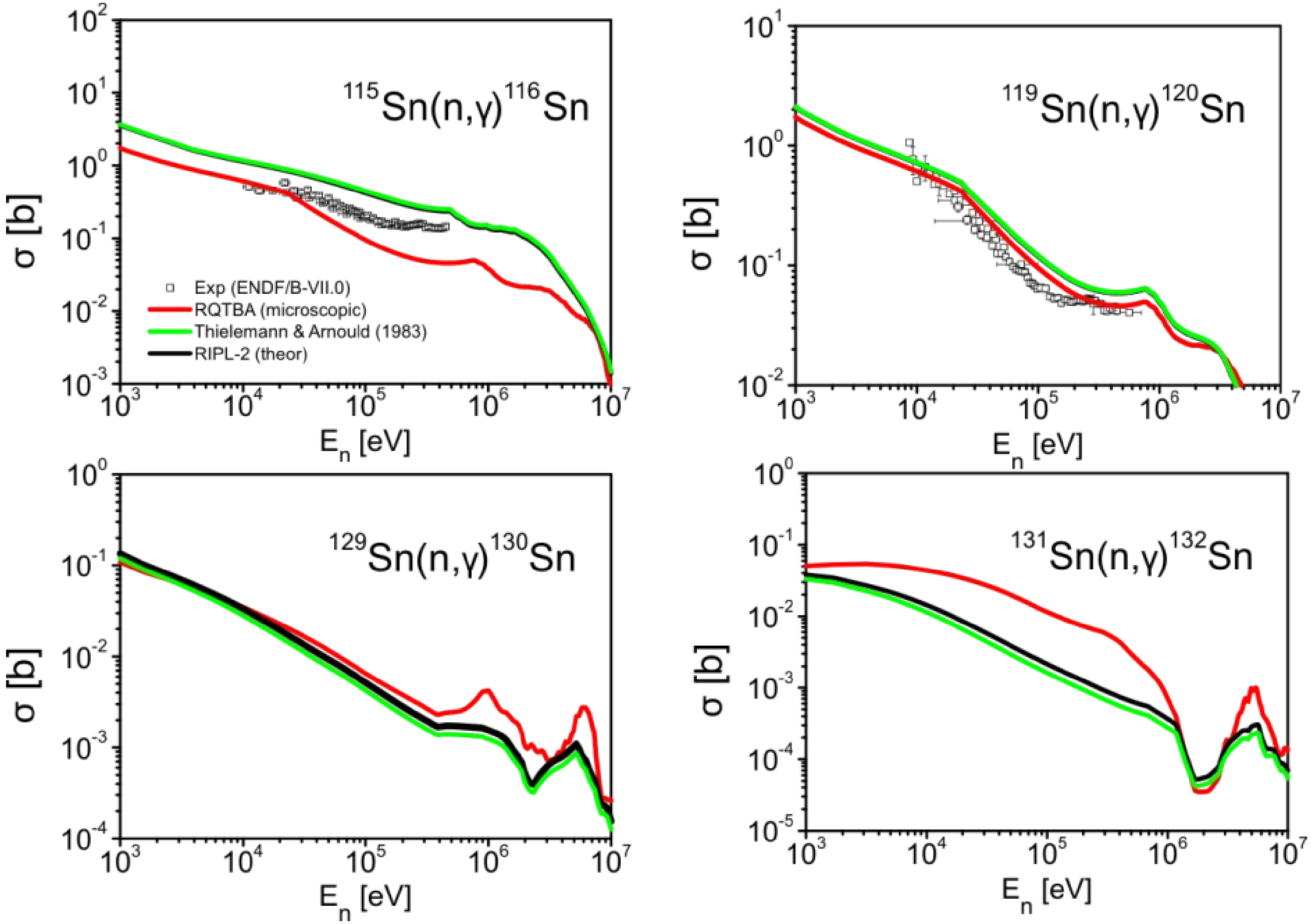
Axel-Brink Hypothesis



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

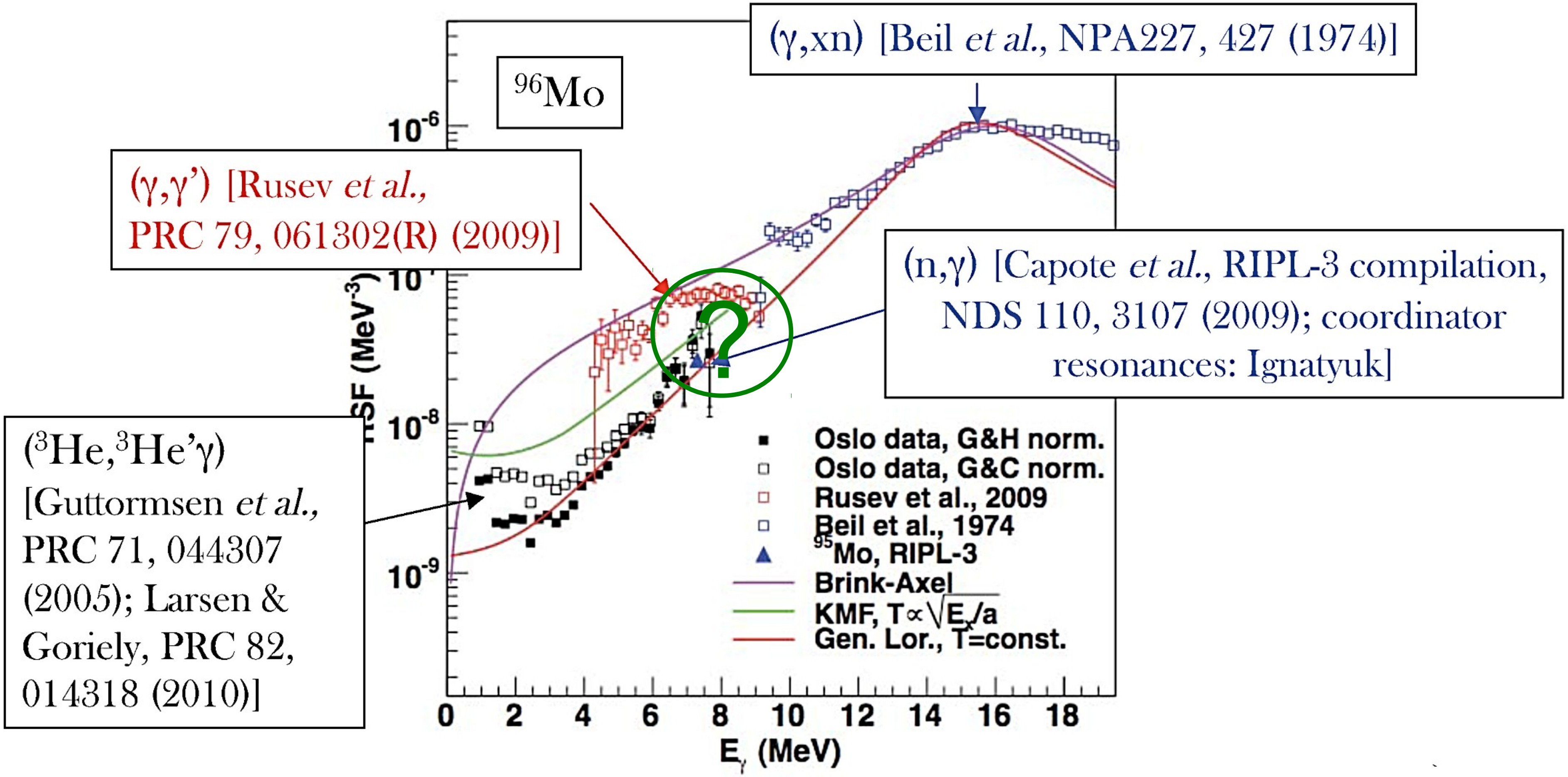
- Same PSF for γ absorption and emission

Influence of the PDR



E. Litvinova, Workshop on Gamma Strength and Level Density, Dresden-Rossendorf, August 2010
E. Litvinova et al., NPA 823 (2009) 26

Experimental Discrepances in PSF



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

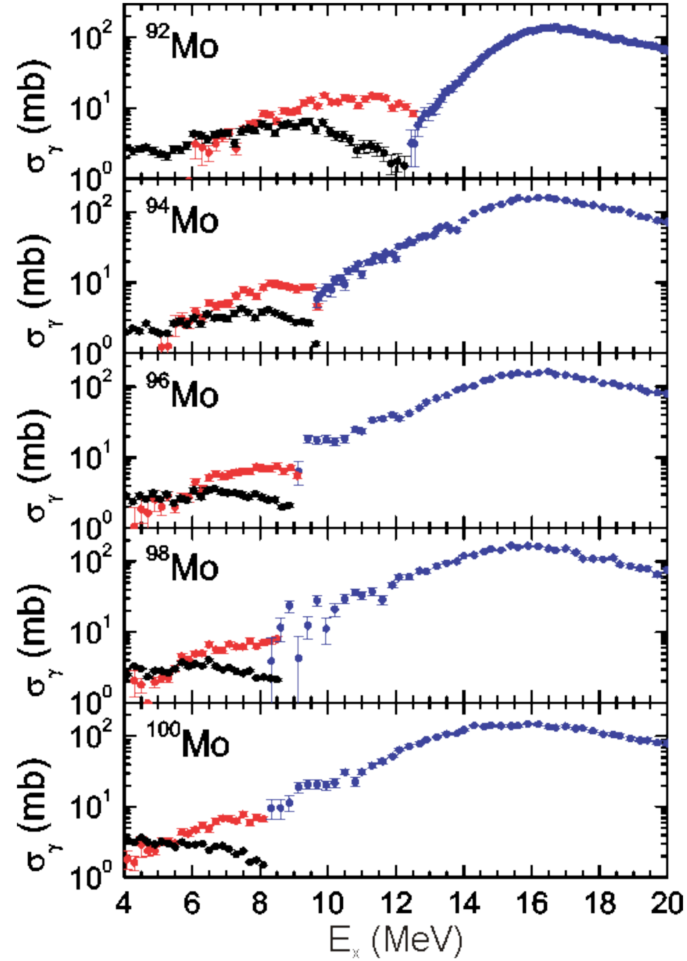
Problems

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

    $\rightarrow$ assumption in most analyses

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

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



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

Problems (continued)

- (γ,xn) reactions provide information above threshold only and little sensitivity close to threshold

- Decay of compound nuclei
  → normalization at S_n
  → level densities needed

↓

Consistent data on E1 strength below and above the neutron threshold highly important

A New Experimental Tool for Complete Dipole Strength Distributions

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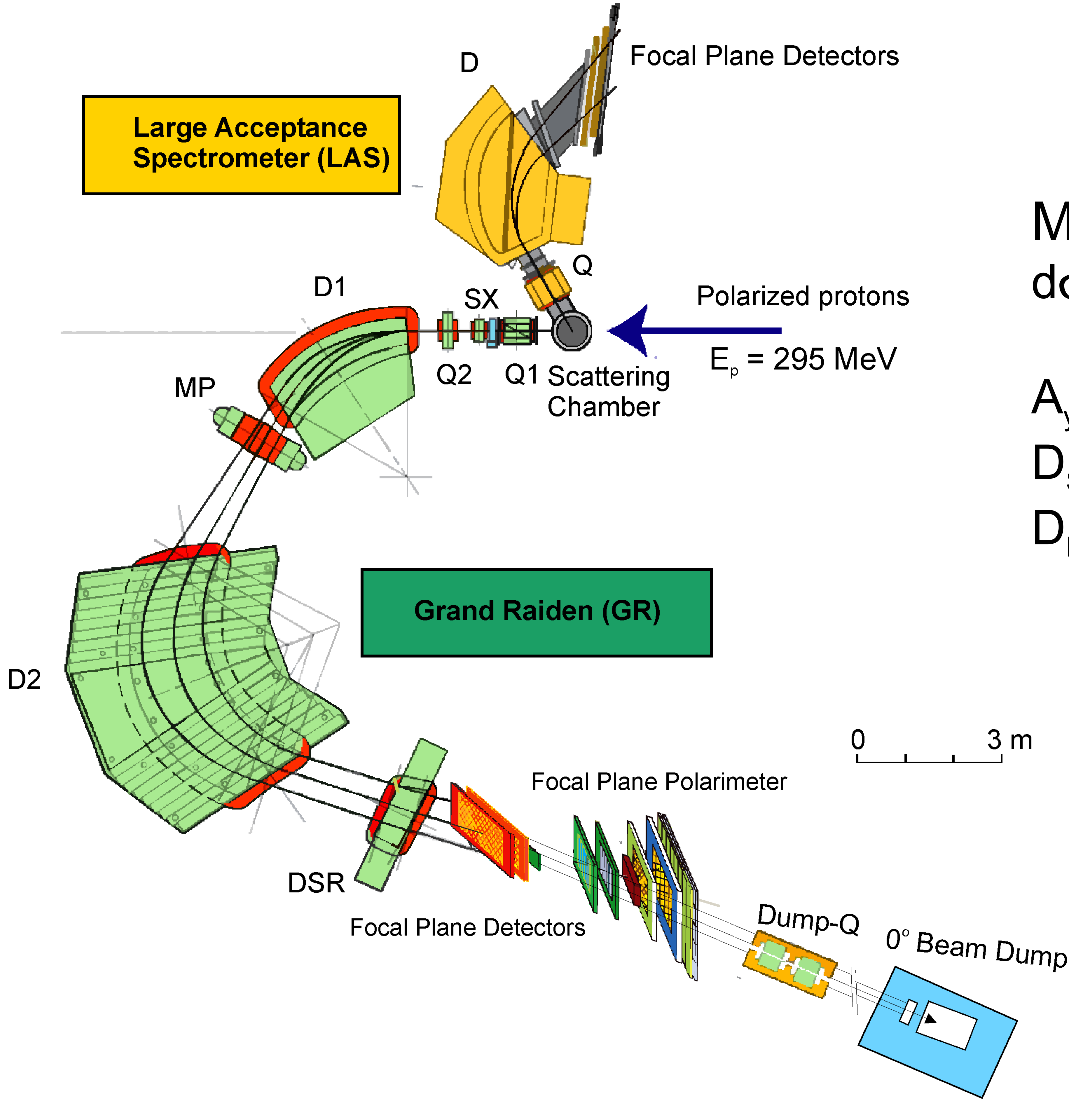
- Polarized proton scattering at 0°
  - intermediate energy: 300 MeV optimal for spin/isospin excitations
  - Coulomb excitation of 1^- states
  - high resolution: ΔE = 25 keV (FWHM)
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation

- ^{208}Pb as a reference case

0° Setup at RCNP

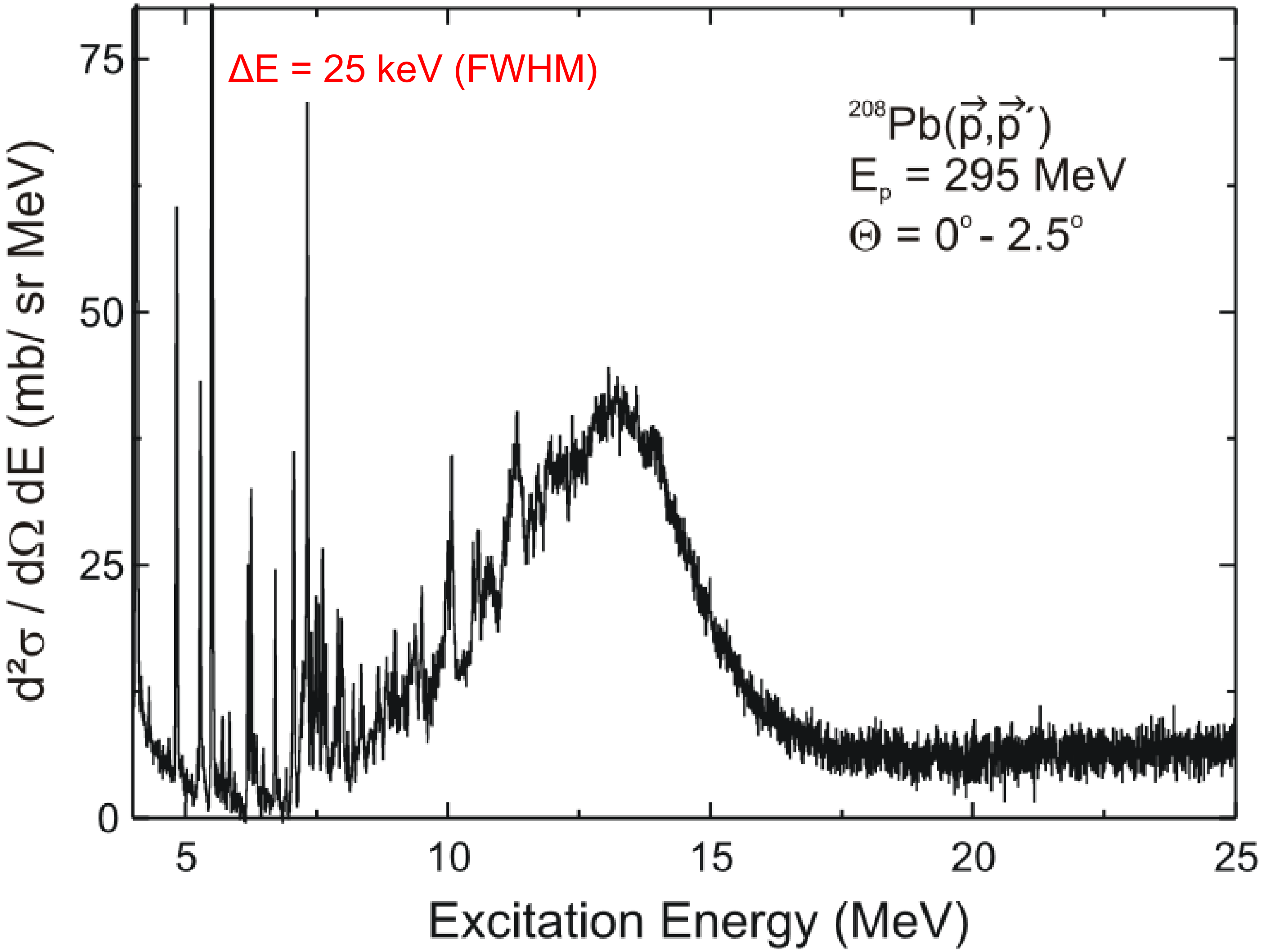


Measured observables

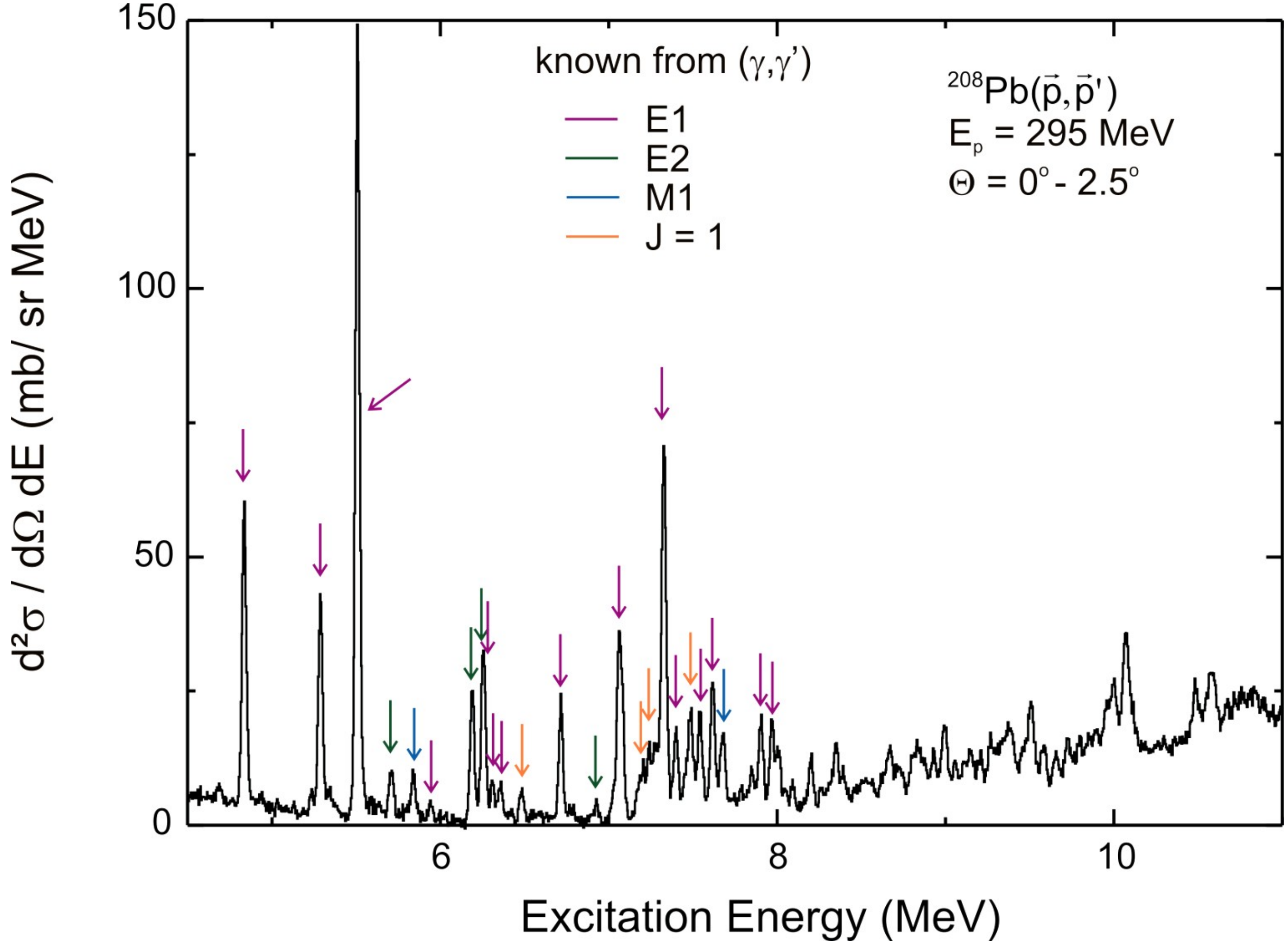
$d\sigma/d\Omega$	- angular distributions ($0° \leq \Theta \leq 10°$)
A_y	- asymmetry
D_{SS} at 0°	- sideways polarization
D_{LL} at 0°	- longitudinal polarization

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

Measured Spectrum



Measured Spectrum: Low-Energy Part



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

E1/M1 Decomposition by Spin Observables

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

(model-independent)

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

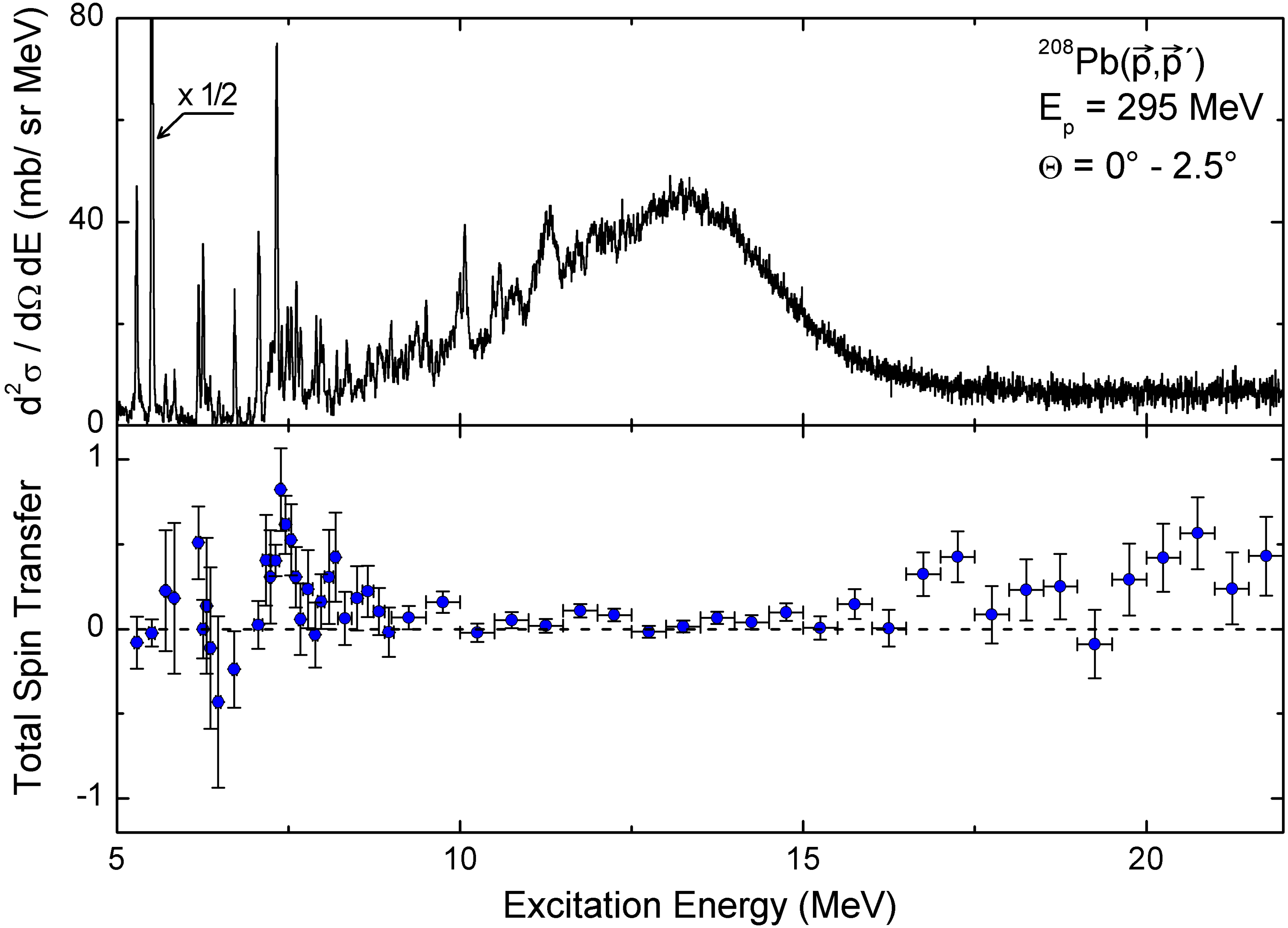
➡ E1 and M1 cross sections can be decomposed

At 0° $D_{SS} = D_{NN}$

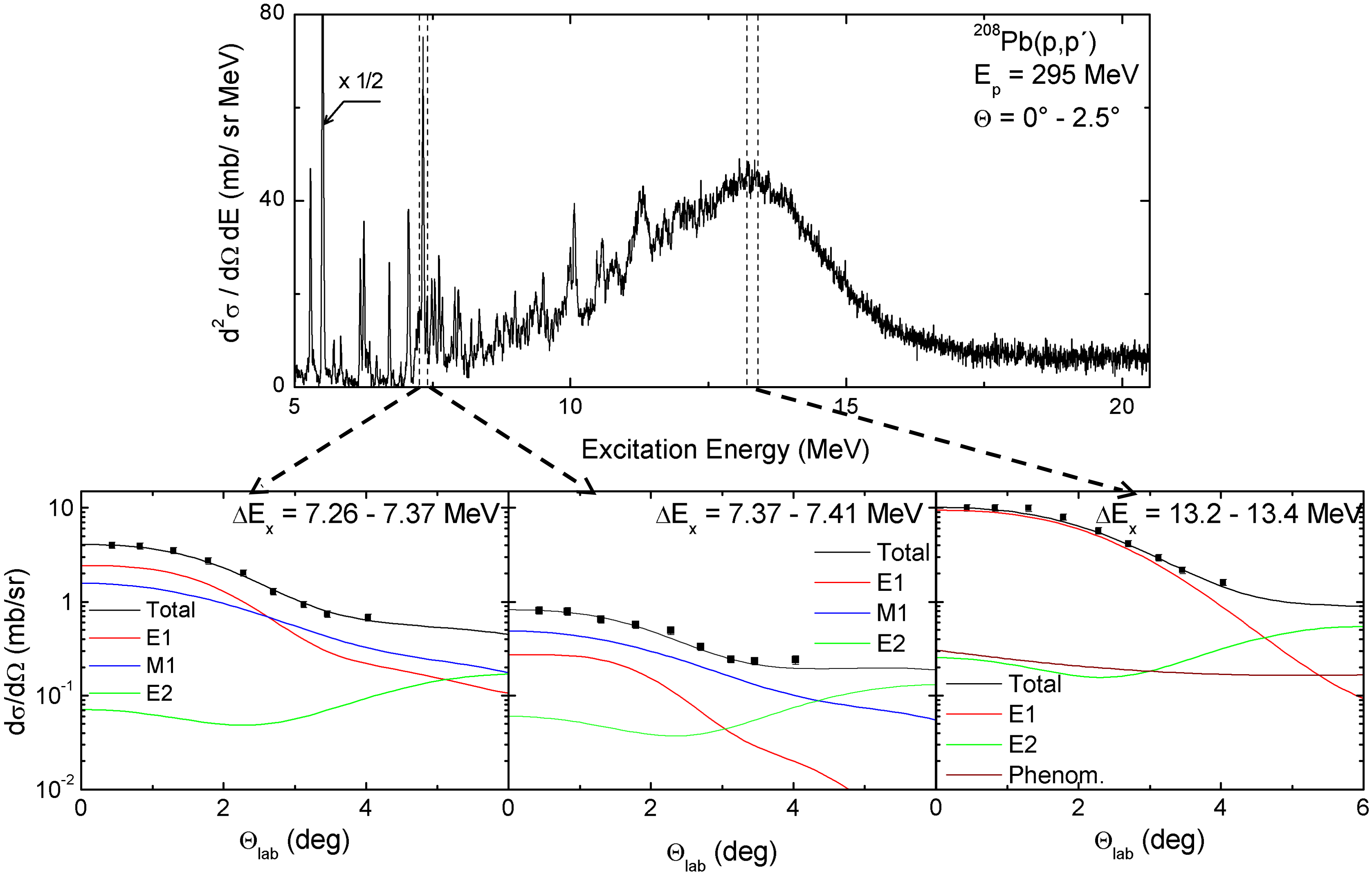
Total Spin Transfer $\Sigma \equiv \frac{3 - (2 D_{SS} + D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

T. Suzuki, PTP 103 (2000) 859

Decomposition into Spinflip / Non-Spinflip Cross Sections



Multipole Decomposition of Angular Distributions



Comparison of Both Methods

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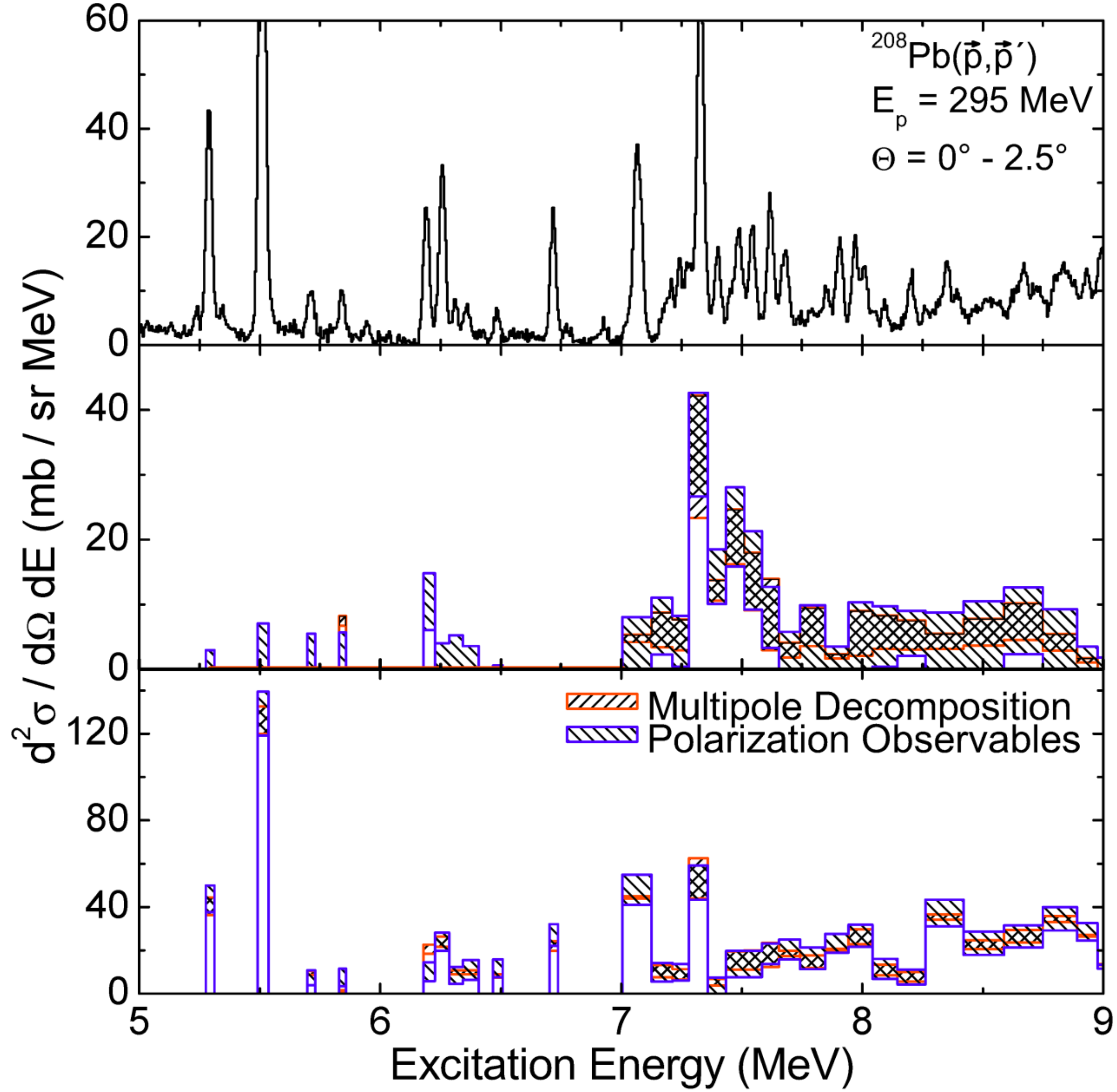

Total

ΔS = 1

ΔS = 0

B(E1) Strength: Low-Energy Region

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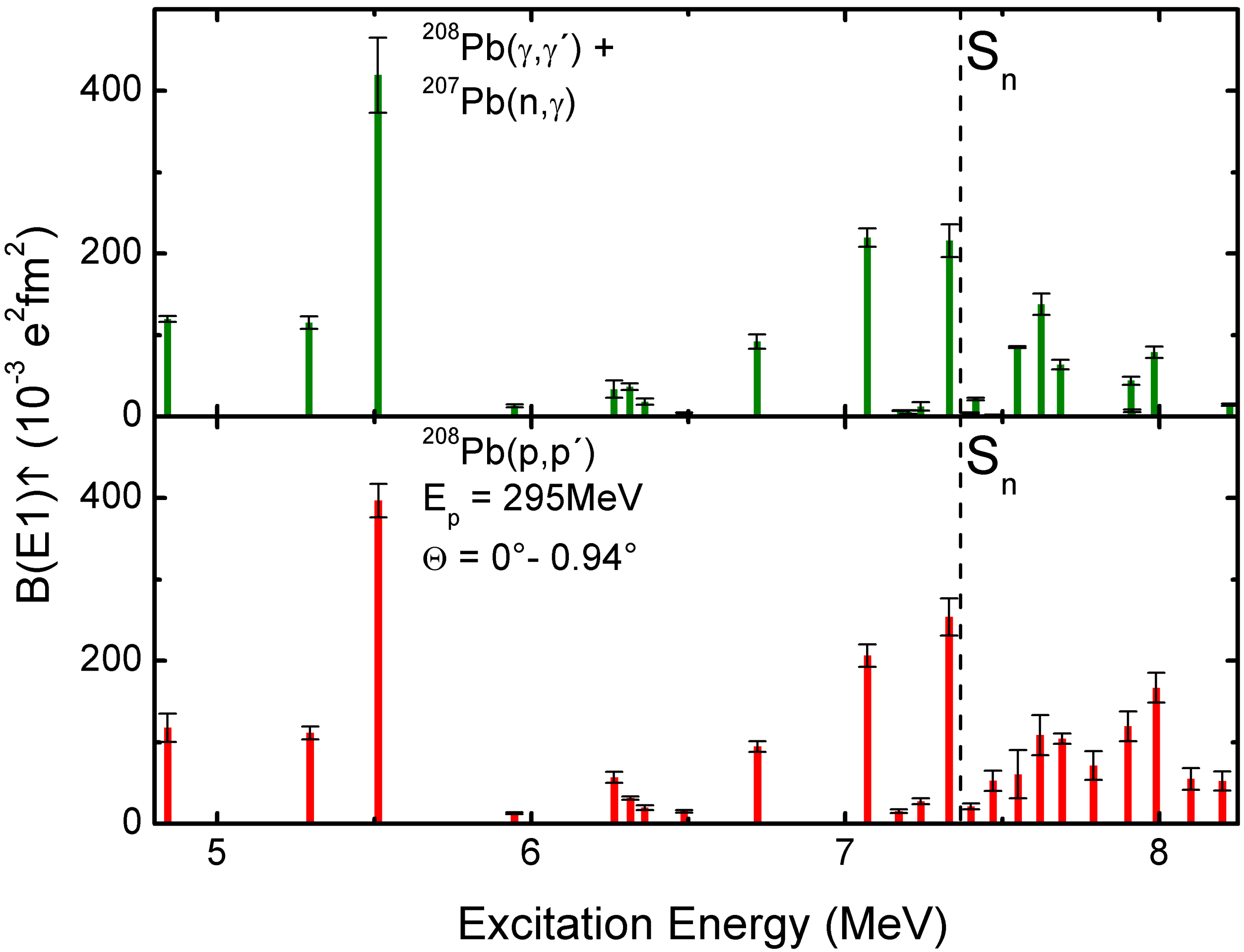


$$\sum_{E_x=6.2MeV}^{8.2MeV} B(E1)\uparrow = 1.10 \pm 0.11\ e^2fm^2$$

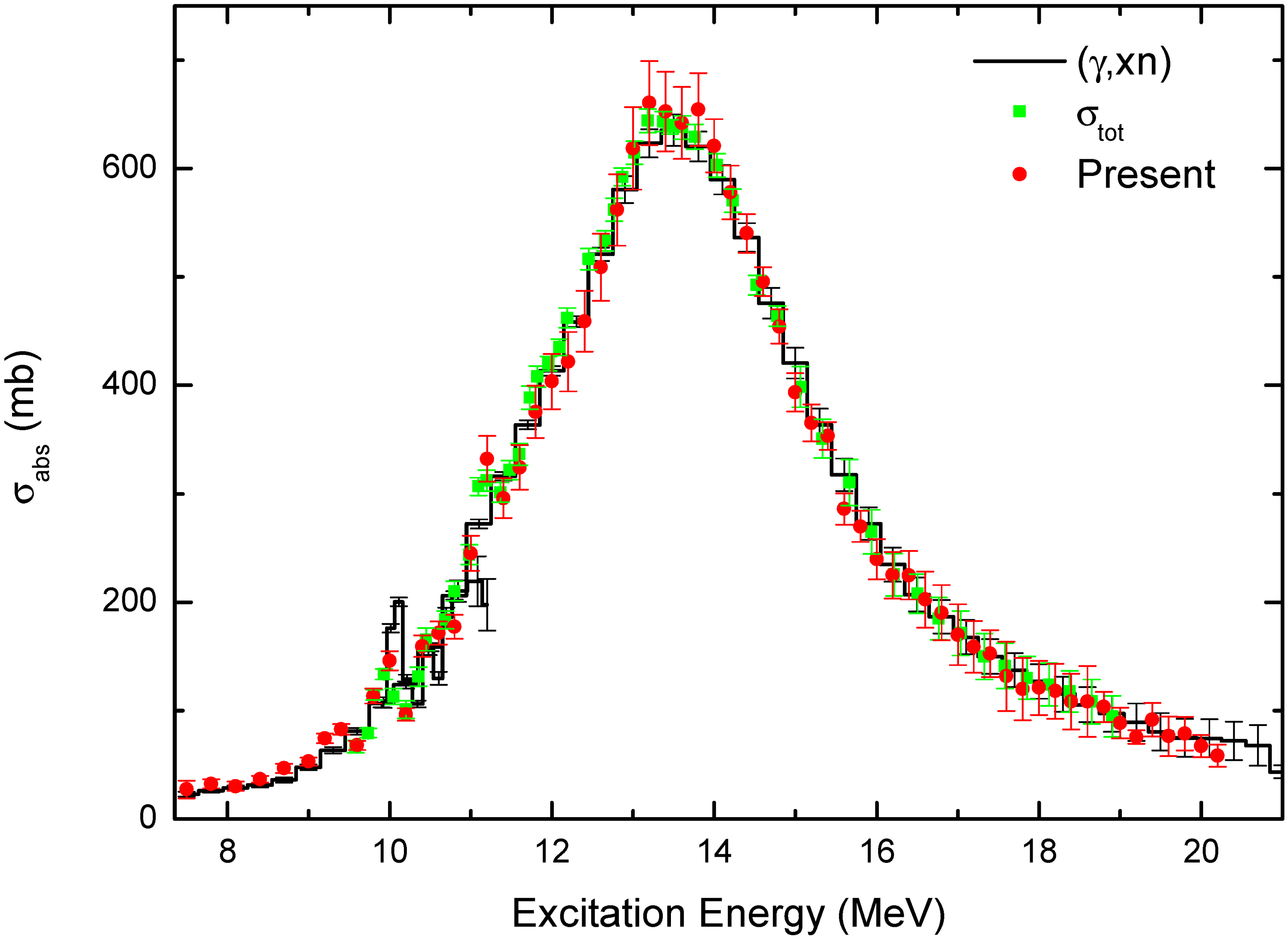
E_c = 7.30 ± 0.03 MeV

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

E_c = 7.43 ± 0.02 MeV

- Extracted assuming semiclassical Coulomb excitation

B(E1) Strength: GDR



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

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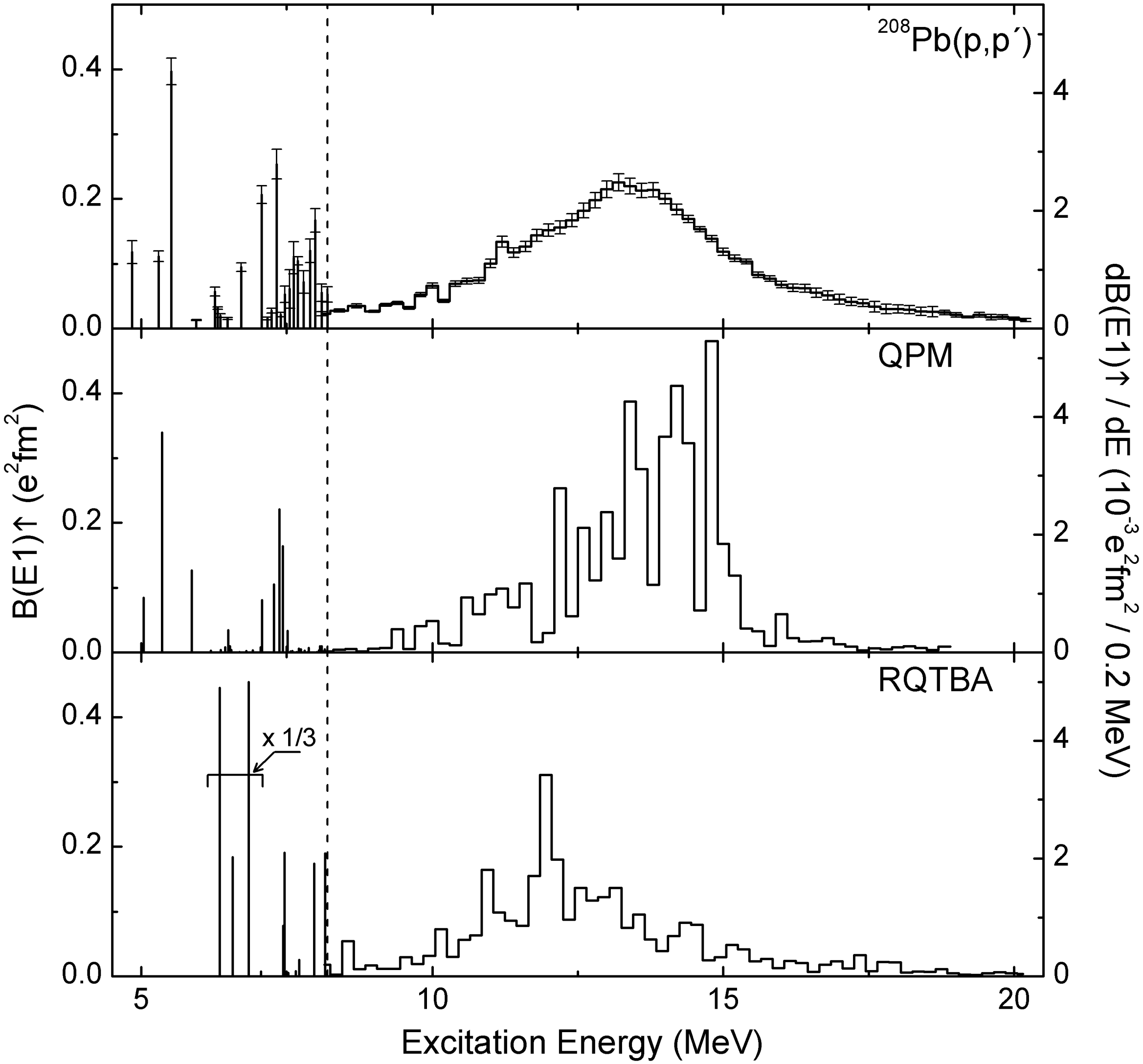

V.Yu. Ponomarev
3p3h ($E_x \leq 10$ MeV), 2p2h for GDR

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

E. Litvinova
1p1h ⊗ phonon

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

Polarizability and neutron skin

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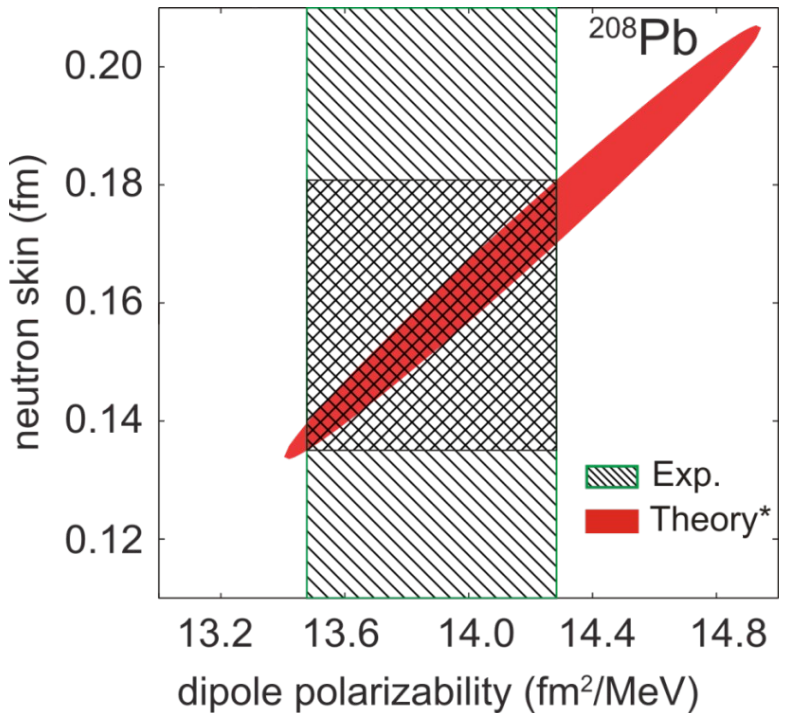
- Precision value: $\alpha_D(^{208}Pb)$ = 19.98(58) fm^3/e^2 = 13.88(41) fm^2/MeV

- Within the model of P.G. Reinhard and W. Nazarewicz, PRC 81 (2010) 051303

⟹ r_{skin} = 0.155(23) fm



- Combined with model-independent measurement of r_{skin} by PREX

⟹ true constraint for isovector properties of any microscopic interaction

Level densities

- Extracted from a fluctuation analysis of the fine structure of the GDR

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

  P.G. Hansen, B. Jonson, and A. Richter, NPA518 (1990) 13

- Depends on the background determined from

  - multipole decomposition analysis

  - discrete wavelet analysis of the spectrum

    Y. Kalmykov et al., PRL 96 (2006) 012502

1^- states level densities in ^{208}Pb

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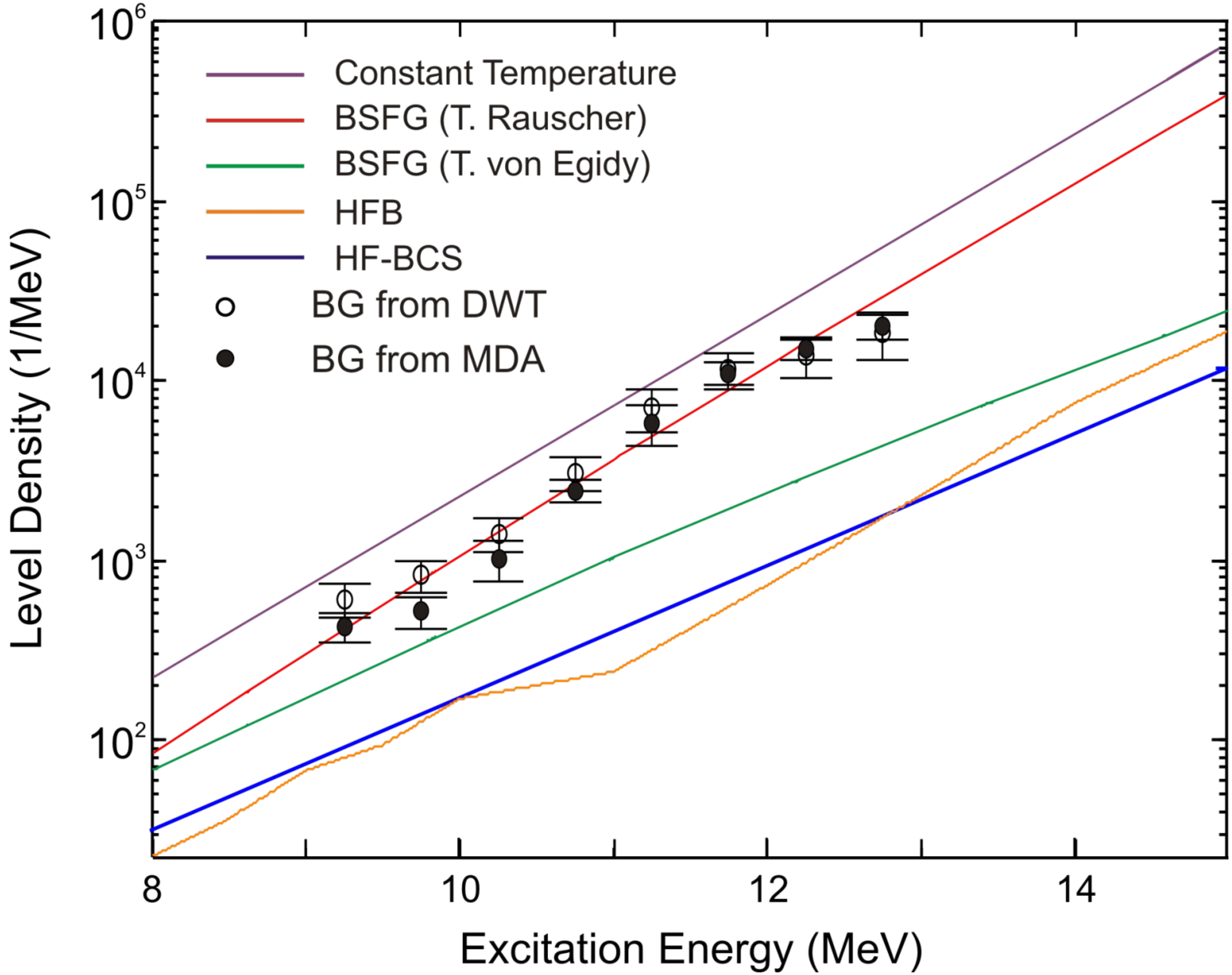

Photon Strength Function in ^{208}Pb

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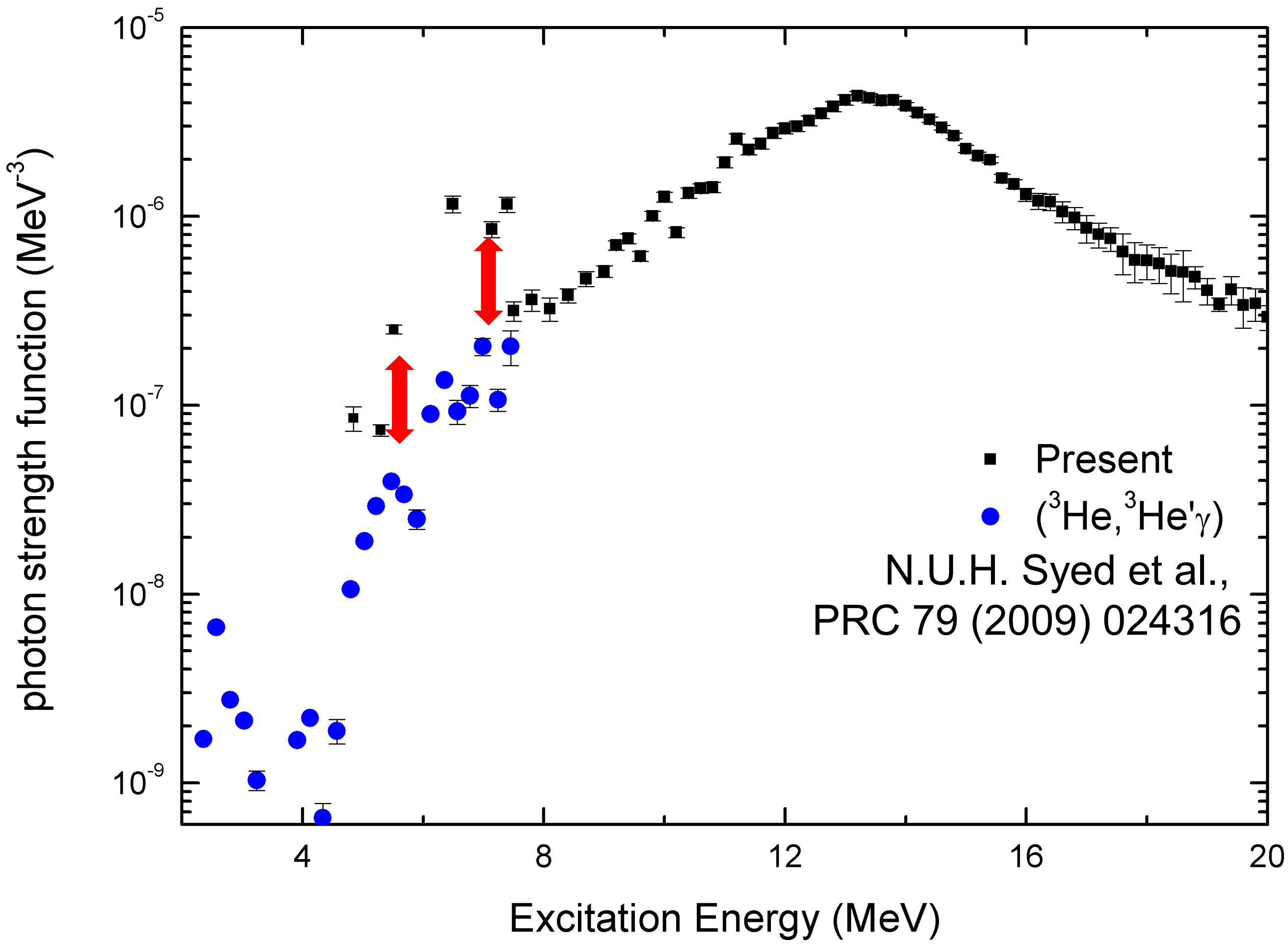

Summary and Outlook

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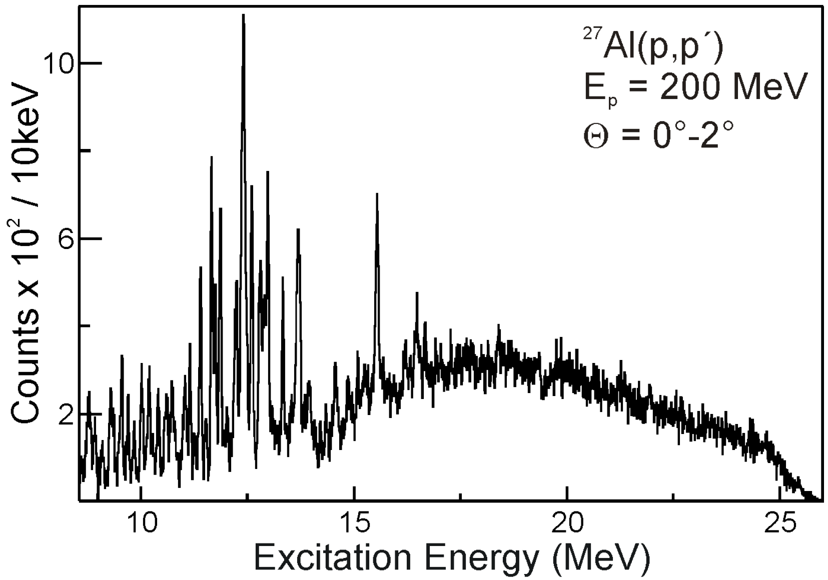
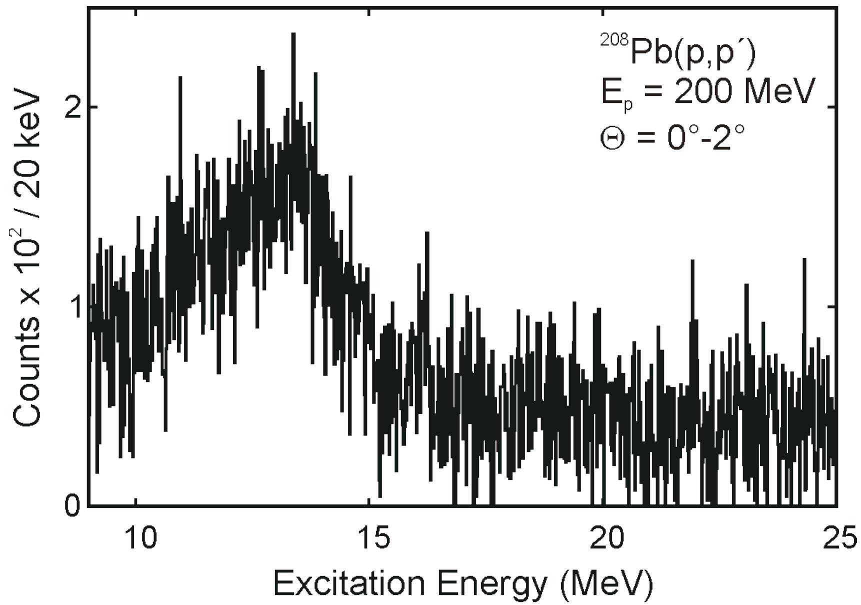
- Polarized intermediate energy proton scattering at 0°:
  a new tool to extract the complete dipole response in nuclei
  - Spinflip / non-spinflip cross section separation
  - B(E1) strength
  - Dipole polarizability
  - Level Densities of 1^- states
  - Photon Strength Function
- Experiment on ^{120}Sn: extraction of complete PDR strength
- Experiment on ^{154}Sm: PDR in a heavy deformed nucleus

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 (submitted)

Collaboration

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Multipole Decomposition of Angular Distributions

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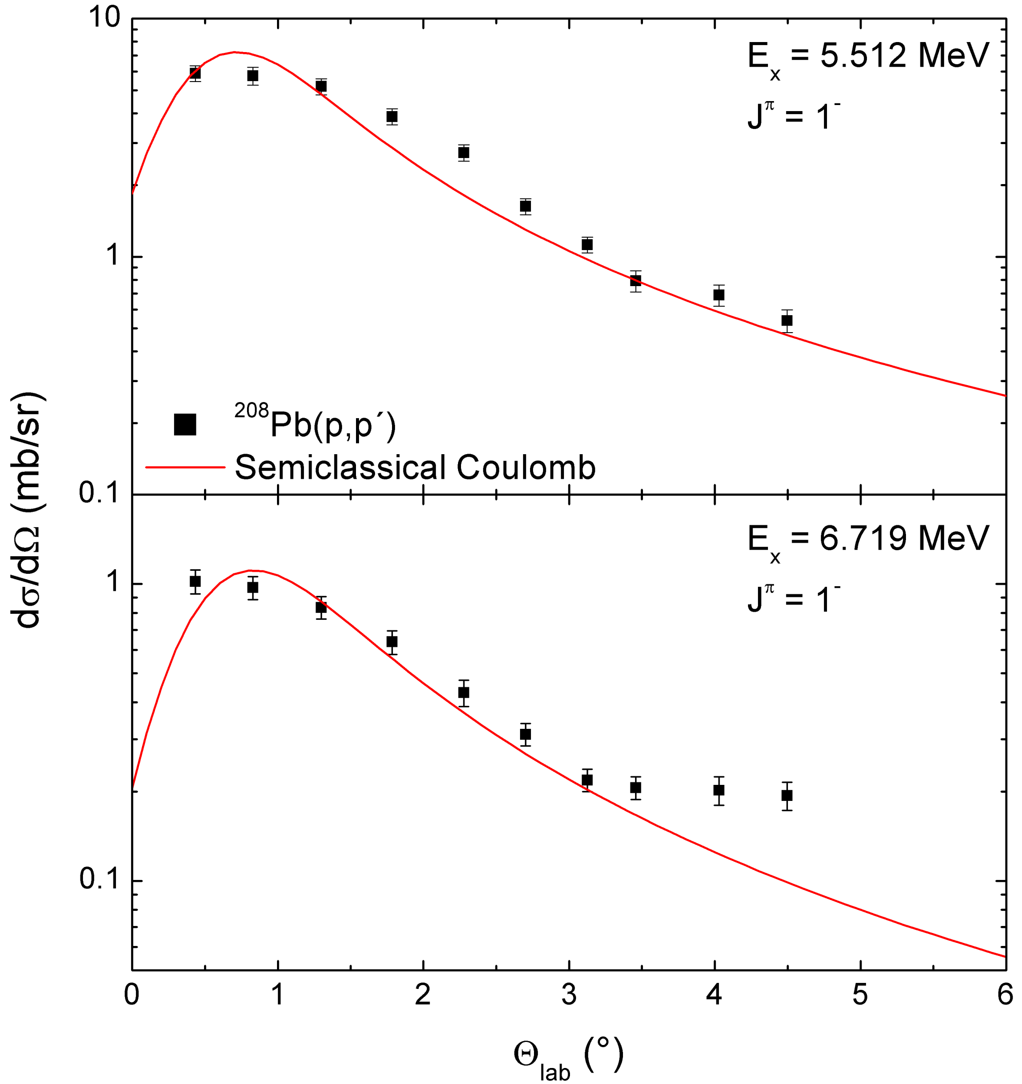
$$\left.\frac{d\sigma(\Theta_{lab},E_x)}{d\Omega}\right|_{data} = \sum_{J^\pi} a_{J^\pi} \cdot \left.\frac{d\sigma(\Theta_{lab},E_x,J^\pi)}{d\Omega}\right|_{DWBA}$$

DWBA07
QPM wave functions
Love&Franey effective interaction

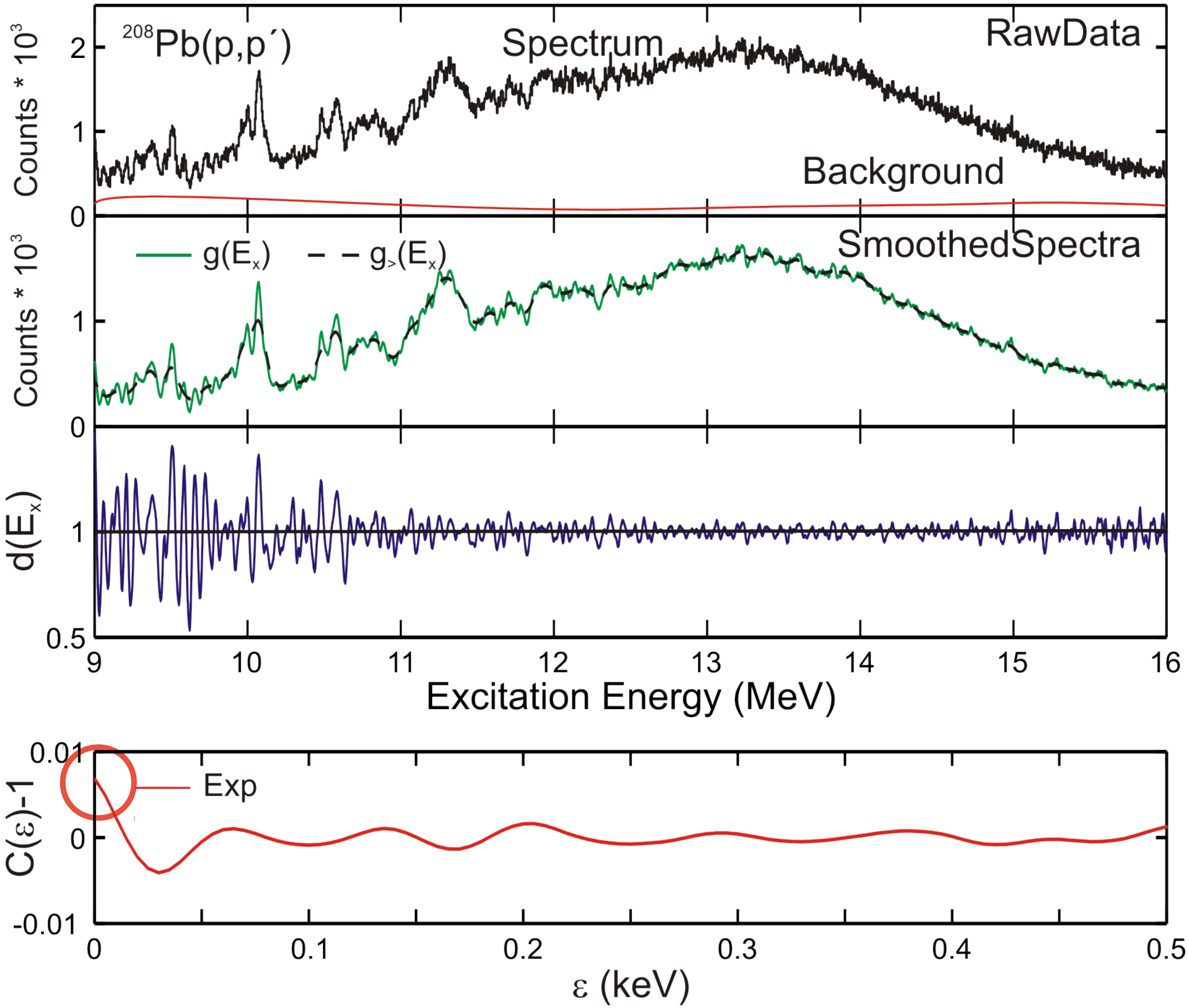
$$\left.\right\} \rightarrow \left.\frac{d\sigma(\Theta_{lab},E_x,J^\pi)}{d\Omega}\right|_{DWBA}$$

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

Coulomb Exitations of 1⁻ States



Fluctuation Analysis



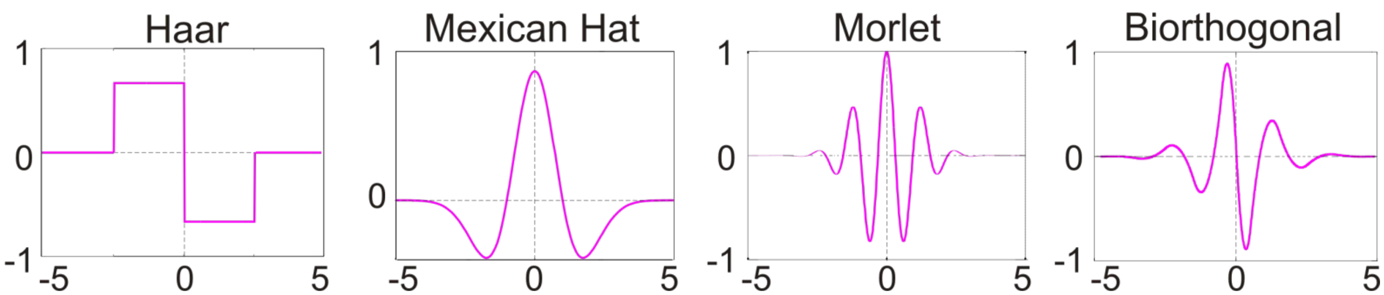
- Background from MDA
- Stationary spectrum $\frac{g(E_x)}{g_>(E_x)}$
- Autocorrelation function

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
- σ resolution

Wavelets

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



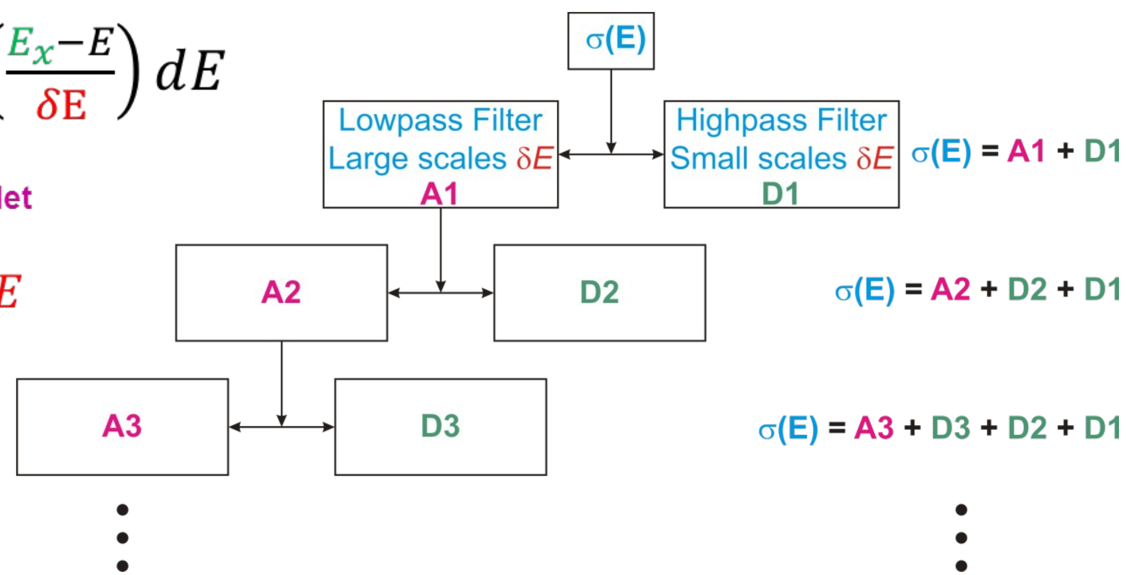
- Wavelet coefficients:

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

↑ 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

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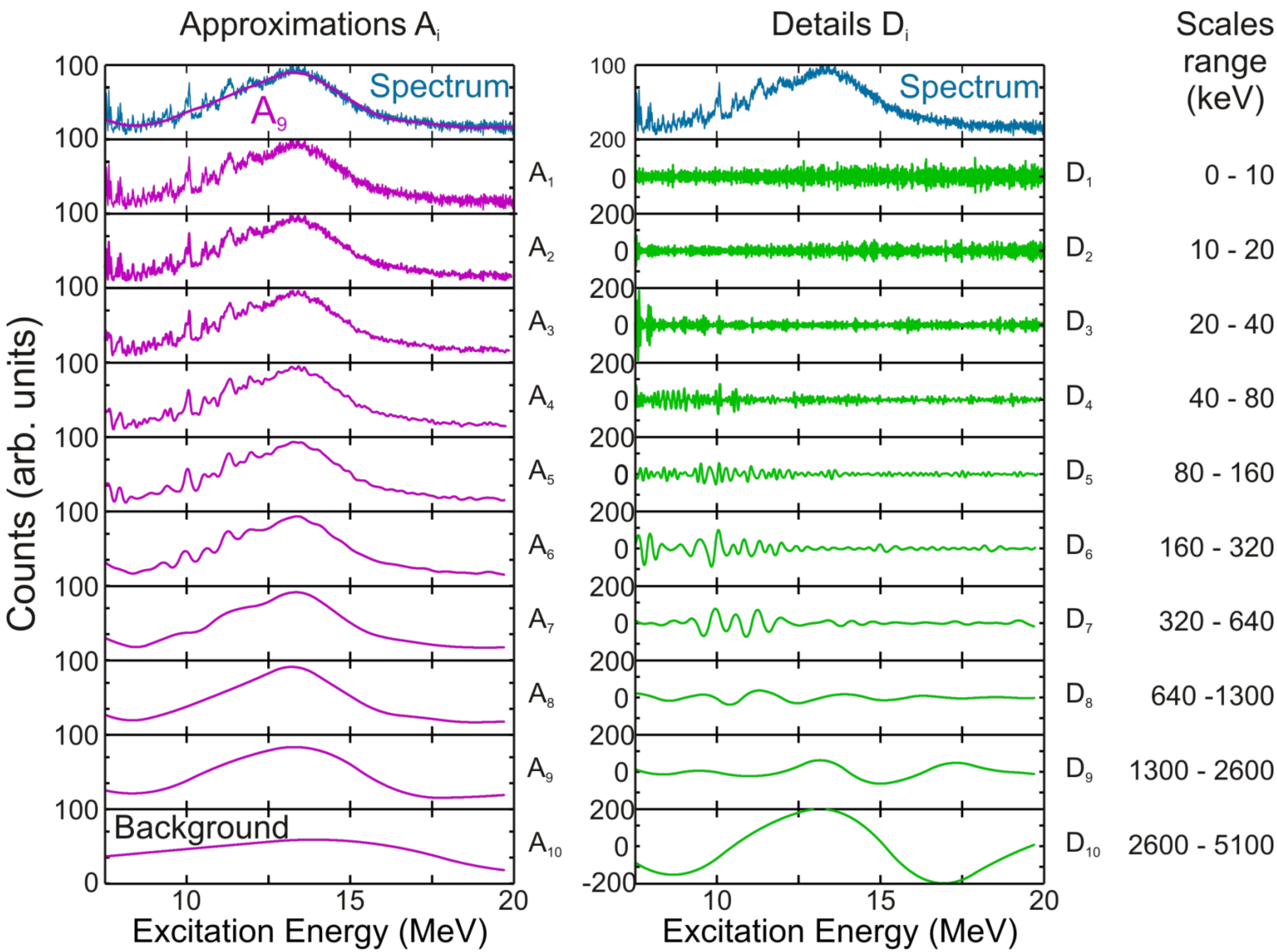

Multipole Decomposition in the GDR Region

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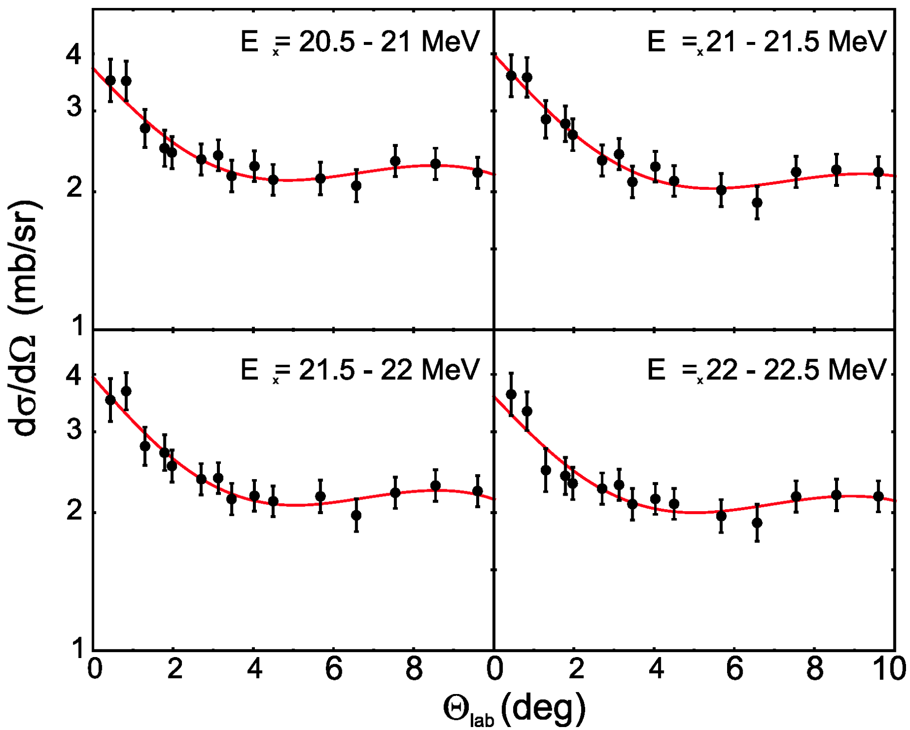
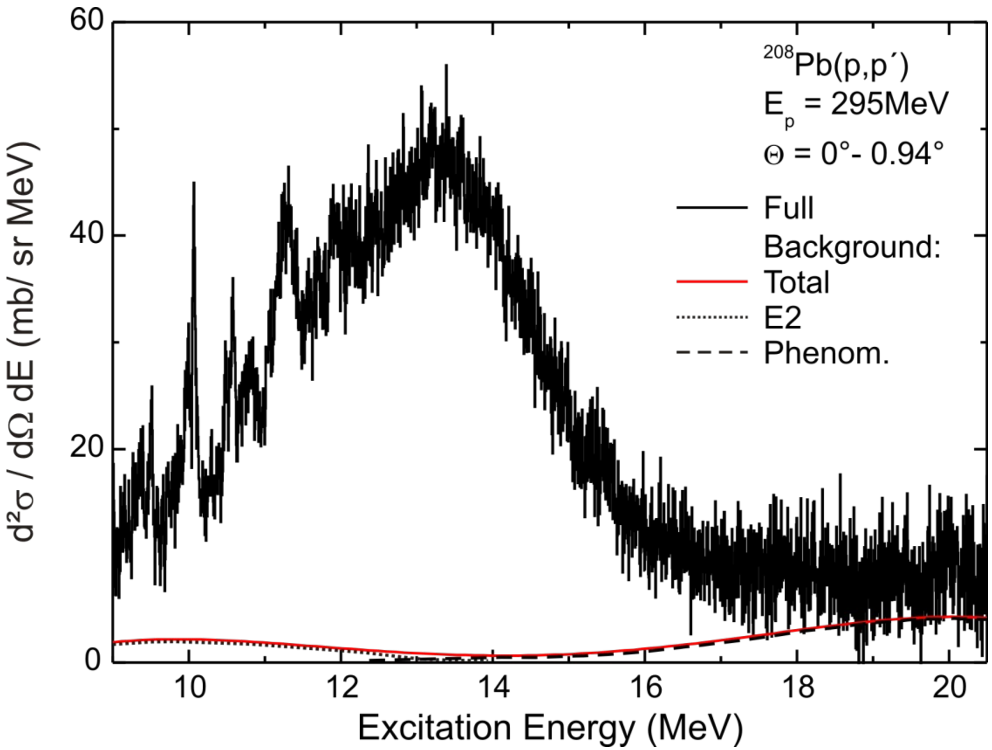
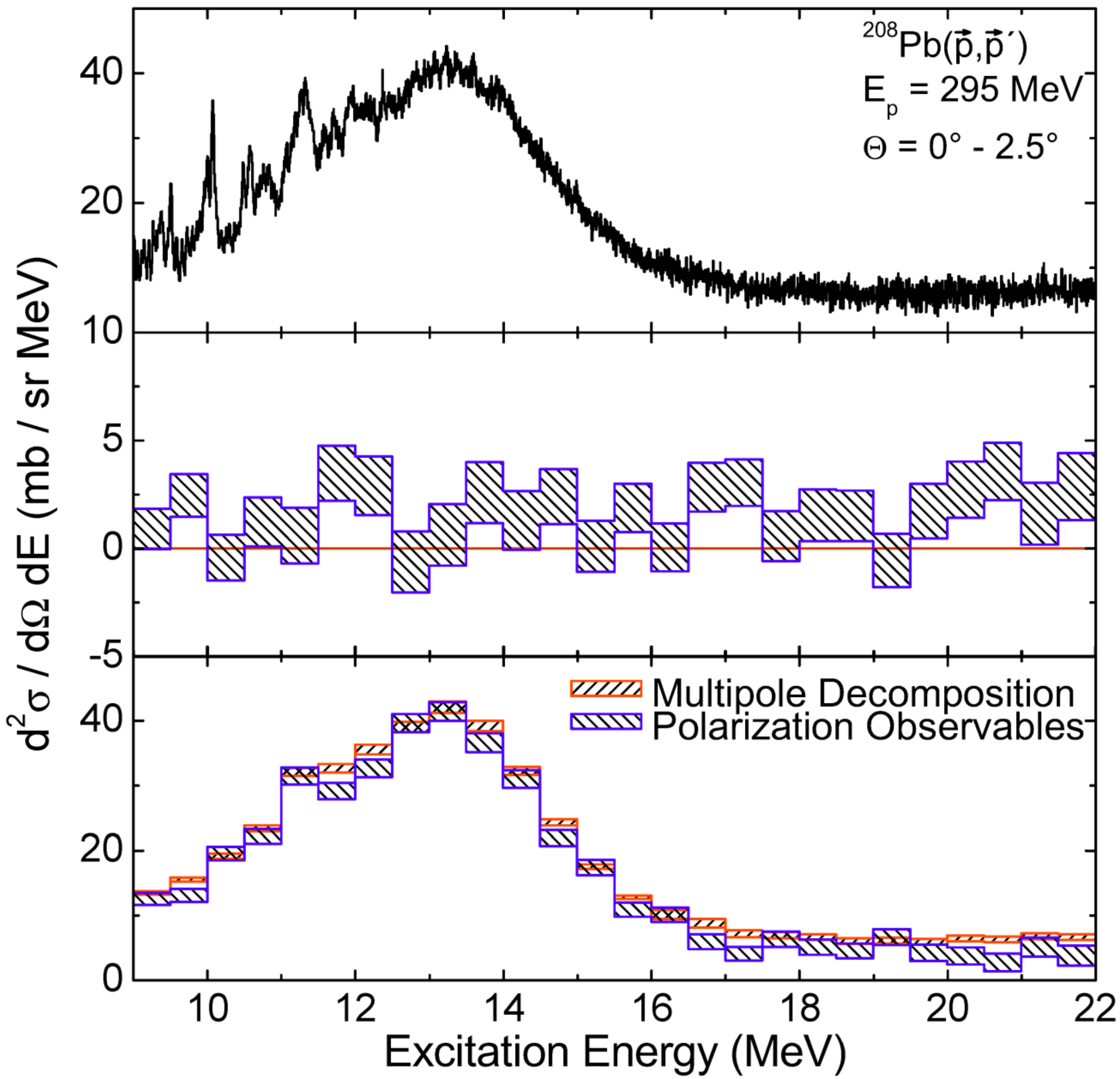




- identical angular distributions
- determines phenomenological background

Comparison of Both Methods II



Total

ΔS = 1

ΔS = 0

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