Tests of the Brink-Axel Hypothesis with High-Resolution Small-Angle Inelastic Proton Scattering

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- Polarized (p,p') at forward angles: a spectroscopic tool for the GSF across particle threshold
- E1 part of GSF
- M1 part of GSF
- Level Densities
- Examples: ^{208}Pb, ^{96}Mo, ^{154}Sm

Supported by DFG under contract SFB 1245

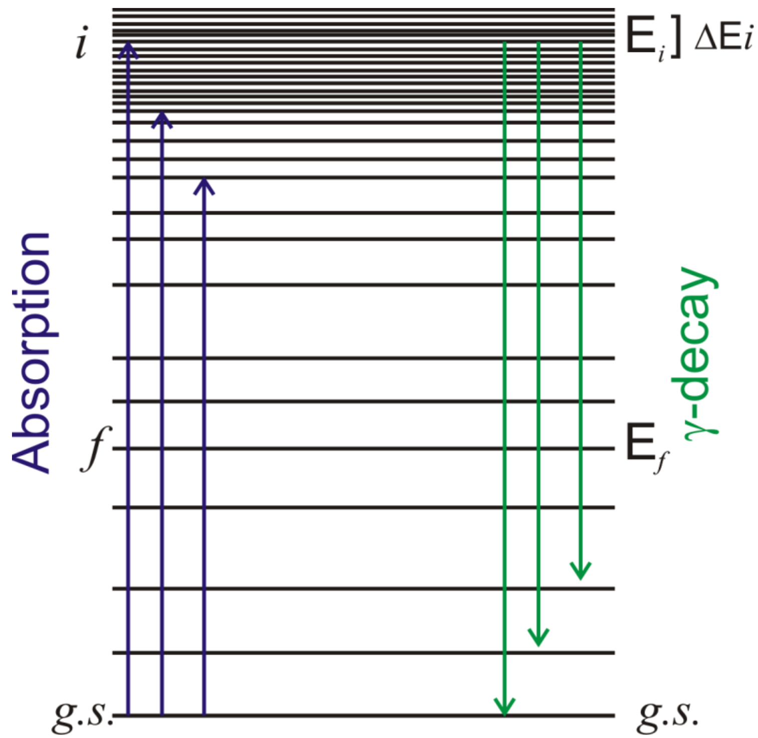
Gamma Strength Function (GSF)

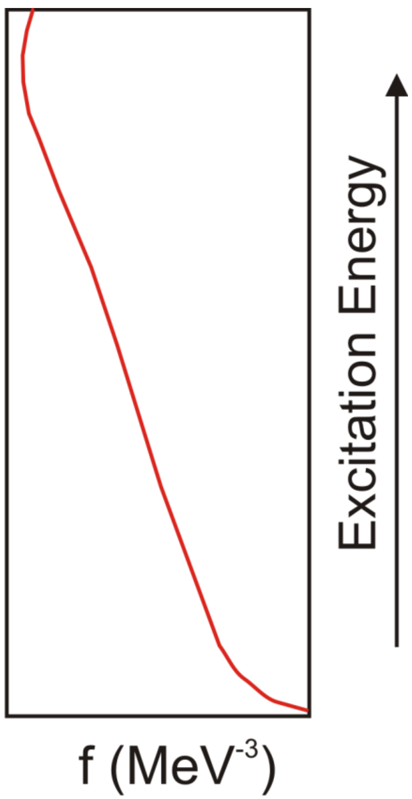
$$\langle\Gamma(E_i)\rangle = \frac{1}{\rho(E_i)} \cdot \int_0^{E_i} E_\gamma^3 f^{E1}(E_\gamma)\rho(E_i - E_\gamma)\, dE_\gamma$$

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

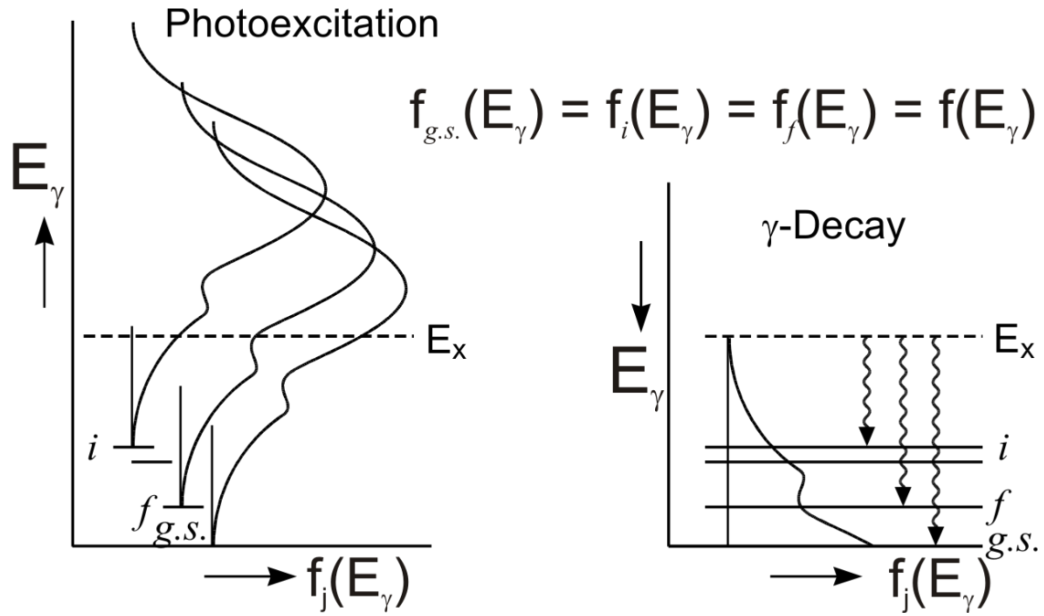
$$\Updownarrow$$

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





Axel-Brink Hypothesis

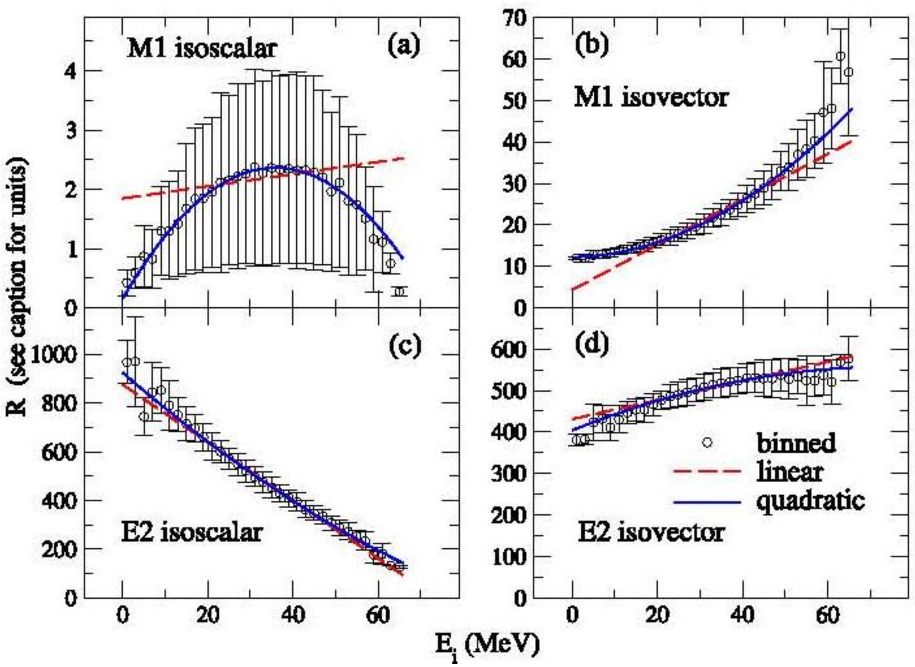


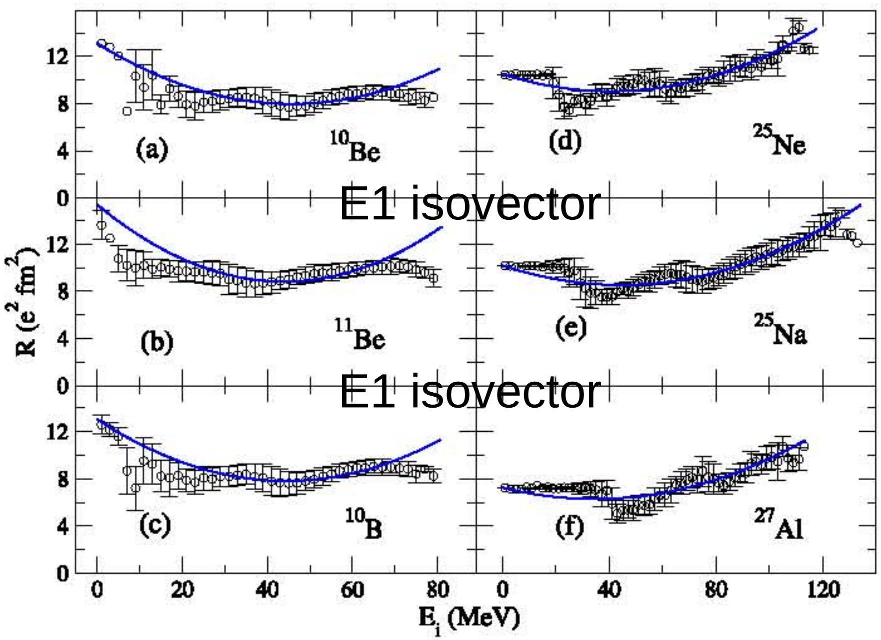
- Strength
  - depends only on E_γ
  - is independent of the initial and final state structure: E_x, J^π,…

- Same GSF for γ absorption and emission

Shell-Model Study of Brink-Axel Hypothesis

C.W. Johnson, Phys. Lett. B 750 (2015) 72

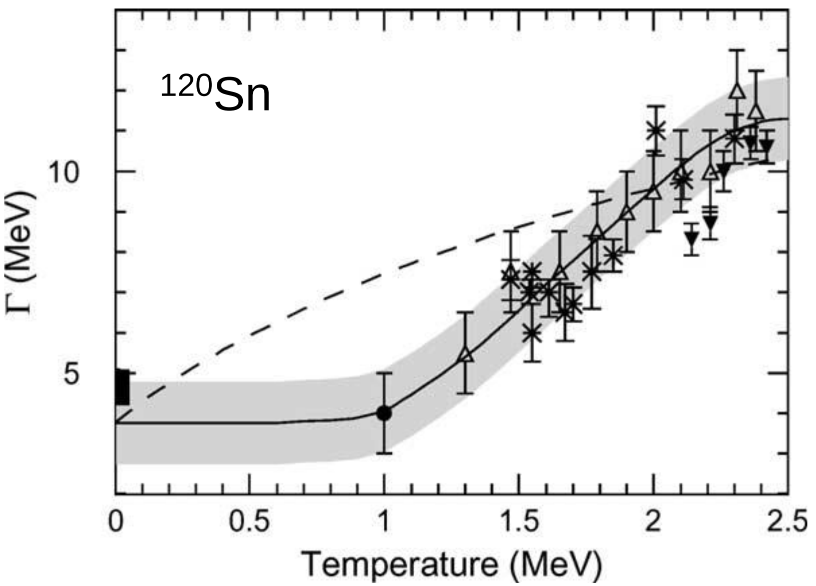




- Brink-Axel hypothesis does not hold in general for collective modes (and is not expected to)
- Holds approximately for E1

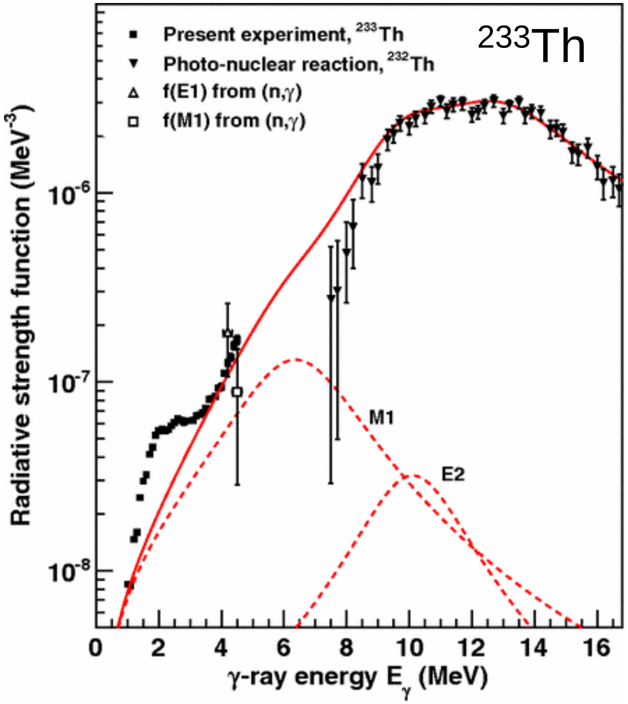
Some Experimental Tests of BA Hypothesis

P. Heckman et al., Phys. Lett. B 555 (2003) 43



- BA holds approximately for GDR at not too high temperatures

M. Guttormsen et al., Phys. Rev. Lett. 109 (2012) 162503



- Violation of BA hypothesis for orbital M1 strength (scissors mode)

Some Experimental Tests of BA Hypothesis

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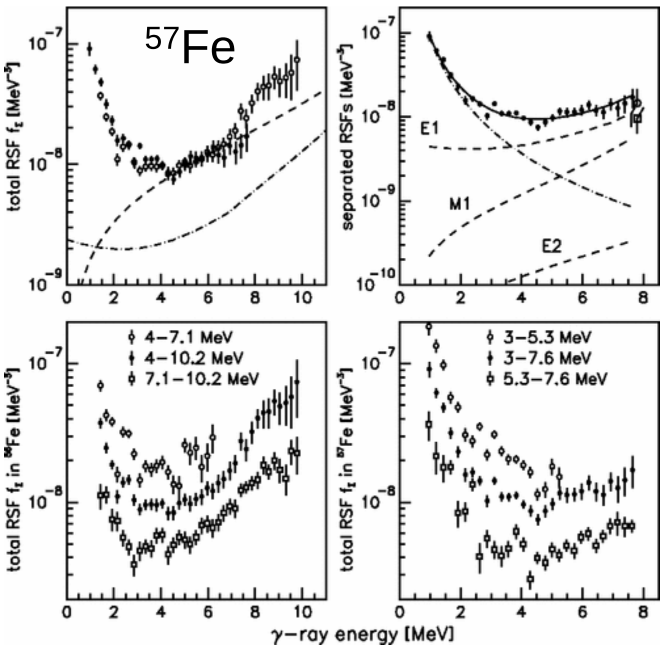
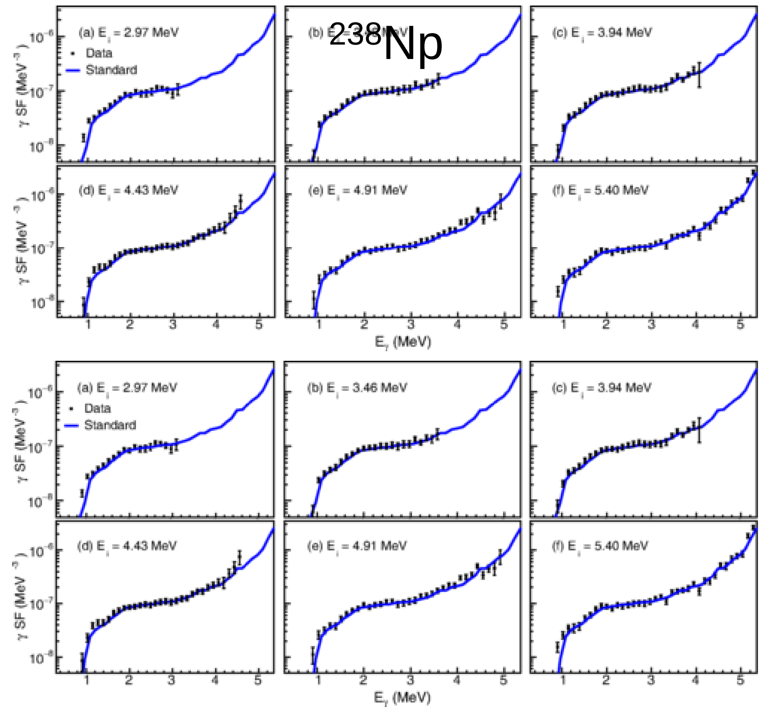
A. Voinov et al., Phys. Rev. Lett. 93 (2004) 142504

M. Guttormsen et al., Phys. Rev. Lett. 116 (2016) 012502



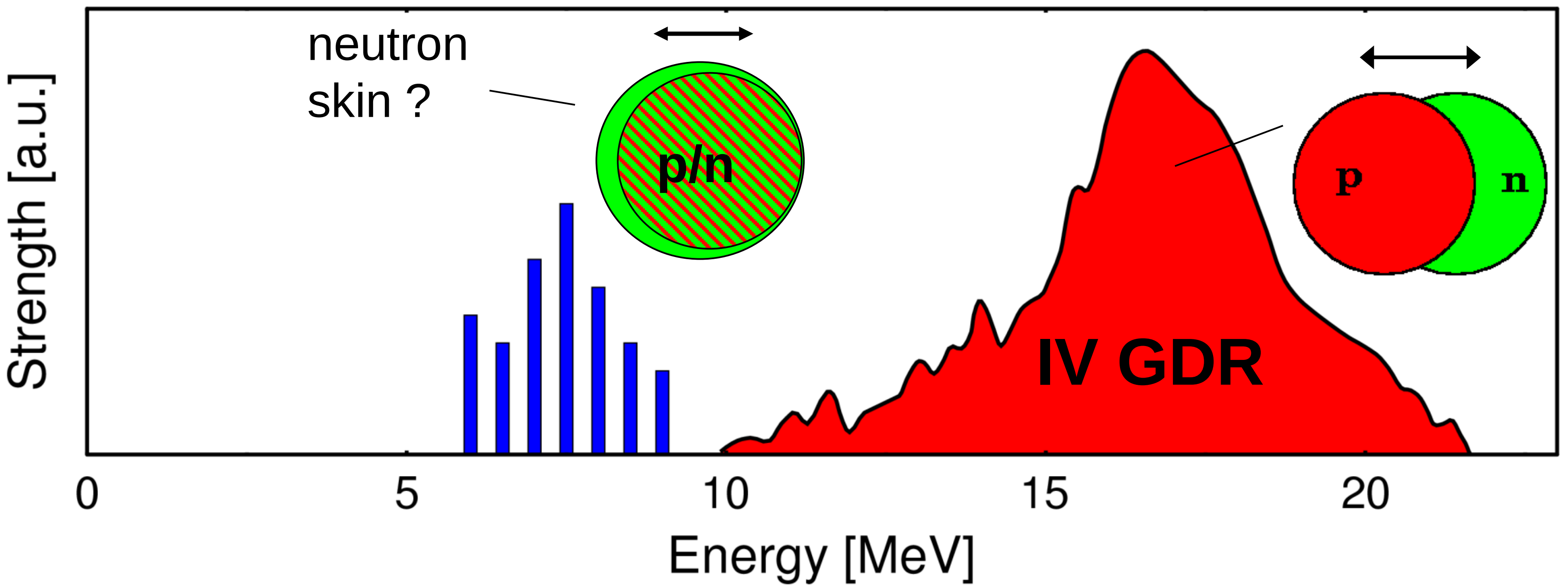


E_i

E_f

- Low-energy enhancement of GSF in compound-nucleus decay obviously violates BA hypothesis
- GSF is independent of initial and final energy in compound-nucleus decay

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)

- Does the BA hypothesis hold for the PDR energy region?

A New Experimental Tool for Complete Dipole Strength Distributions

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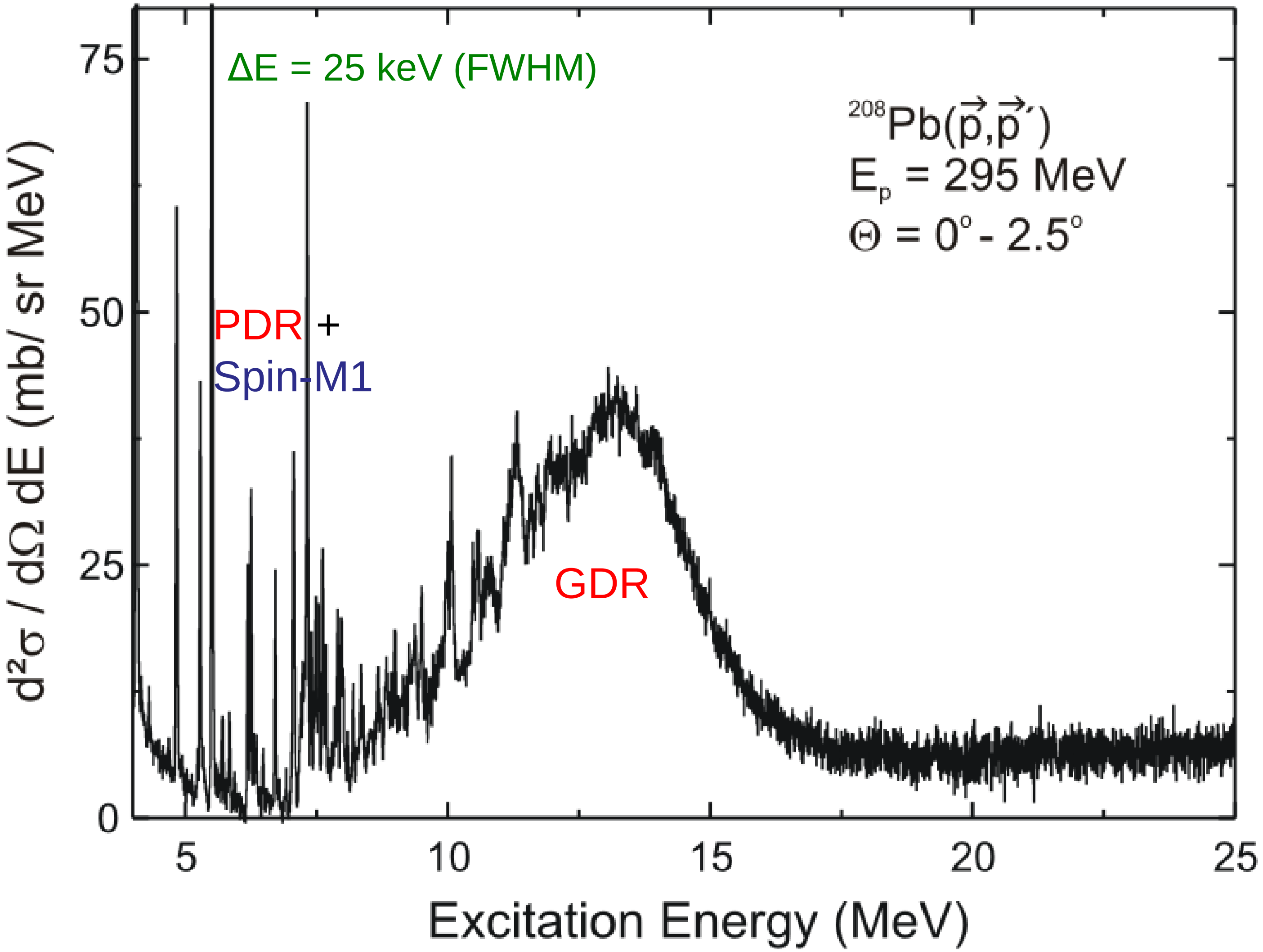
- Polarized proton scattering at 0º
  - intermediate energy: 300 MeV optimal for spin-isospin excitations
  - strong Coulomb excitation of 1^- states
  - high resolution: ΔE = 25 keV (FWHM)
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation

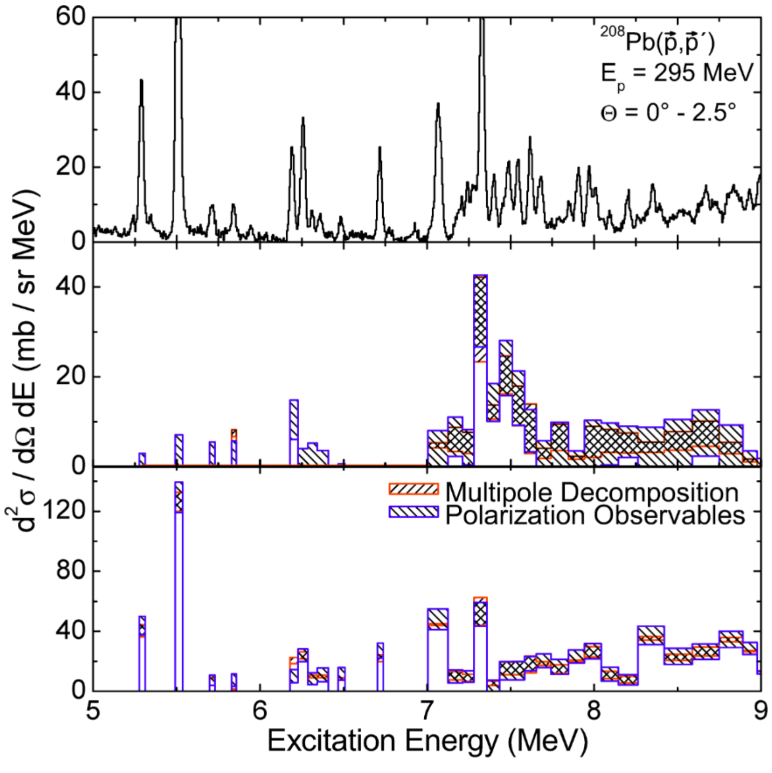
- ^{208}Pb and ^{120}Sn as reference cases

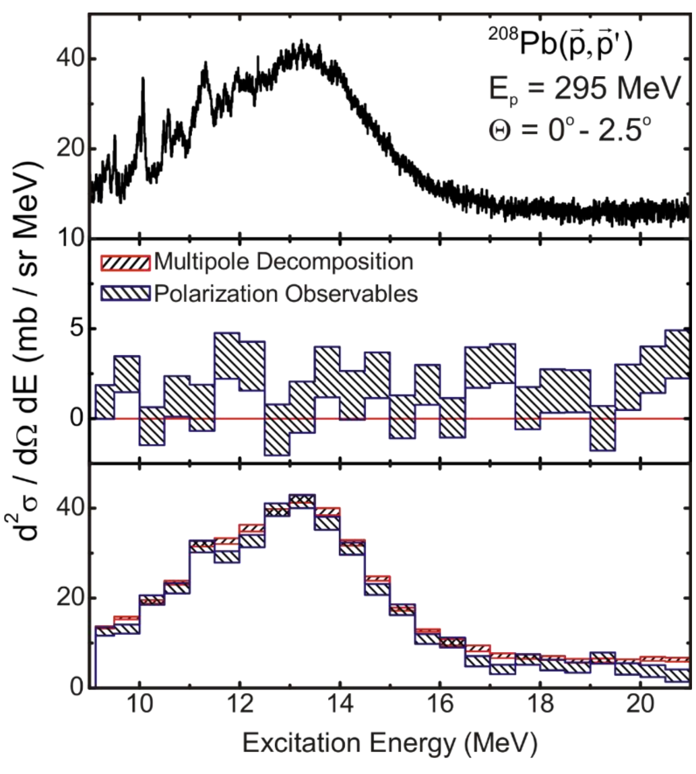
  A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062502
  I. Poltoratska et al., Phys. Rev. C 85 (2012) 041304(R)
  A.M. Krumbholz et al., Phys. Lett. B 744 (2015) 7
  T. Hashimoto et al., Phys. Rev. C 92 (2015) 031305(R)

Measured Spectrum



E1/M1 Decomposition





Total

ΔS = 1
(M1)

ΔS = 0
(E1)

Coulomb Exitations of 1^- States

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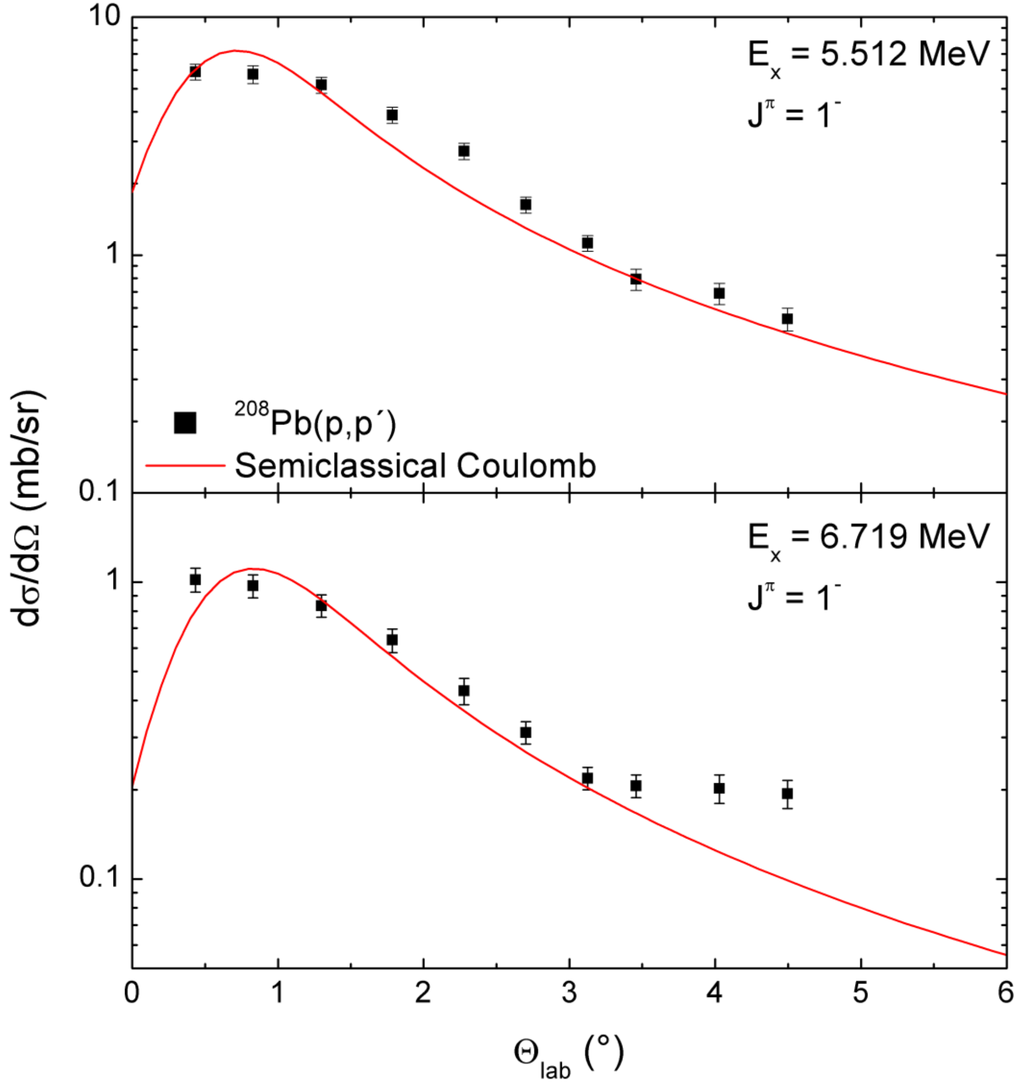
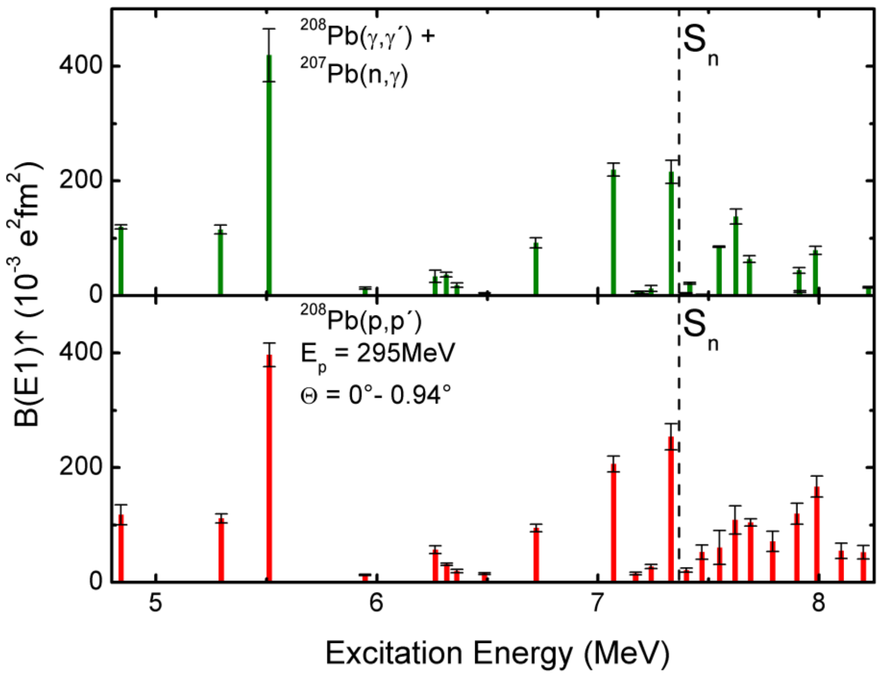
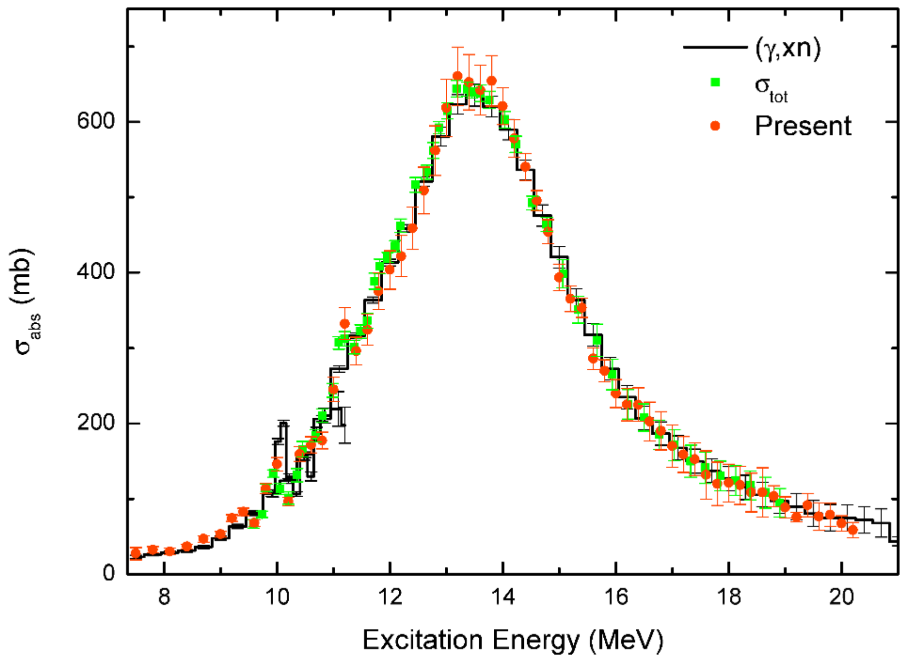


B(E1) Strength in ^{208}Pb





Spin M1 and GT Strength

- (p,n) at 0°

$$\frac{d\sigma_{pn}^{GT}}{d\Omega}(0°) = \hat{\sigma}_{GT} F(q,\omega) B(GT)$$

- (p,p‘) at 0°

$$\frac{d\sigma_{pp'}^{GT}}{d\Omega}(0°) = \hat{\sigma}_{M1} F(q,E_x) B(M1_{\sigma\tau})$$

- Transition strengths

$$B(GT) = \frac{C_{GT}^2}{2(2T_f+1)} |\langle f ||| \sum_k^A \sigma_k \tau_k ||| i \rangle|^2$$

$$B(M1_{\sigma\tau}) = \frac{C_{M1}^2}{4(2T_f+1)} |\langle f ||| \sum_k^A \sigma_k \tau_k ||| i \rangle|^2$$

- Isospin symmetry

$$\boxed{\hat{\sigma}_{M1} \simeq \hat{\sigma}_{GT}}$$

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

Spin M1 and B(M1) Strength

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- B(M1) strength

$$B(\mathrm{M1}) = \frac{3}{4\pi} |\langle f|| g_l^{\mathrm{IS}} \vec{l} + \frac{g_s^{\mathrm{IS}}}{2} \vec{\sigma} - (g_l^{\mathrm{IV}} \vec{l} + \frac{g_s^{\mathrm{IV}}}{2} \vec{\sigma}) \tau_0 || i\rangle|^2 \, \mu_{\mathrm{N}}^2$$

Spin M1 and B(M1) Strength

- B(M1) strength

$$B(\mathrm{M1}) = \frac{3}{4\pi}\left|\langle f || \cancel{g_l^{\mathrm{IS}}}\vec{l} + \cancel{\frac{g_s^{\mathrm{IS}}}{2}}\vec{\sigma} - (\cancel{g_l^{\mathrm{IV}}}\vec{l} + \frac{g_s^{\mathrm{IV}}}{2}\vec{\sigma})\tau_0 || i\rangle\right|^2 \mu_{\mathrm{N}}^2$$

$$\boxed{B(\mathrm{M1}) \cong \frac{3}{4\pi}\left(g_s^{\mathrm{IV}}\right)^2 B(\mathrm{M1}_{\sigma\tau})\,\mu_{\mathrm{N}}^2}$$

Application to ^{208}Pb

R.M. Laszewsi et al., PRL 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

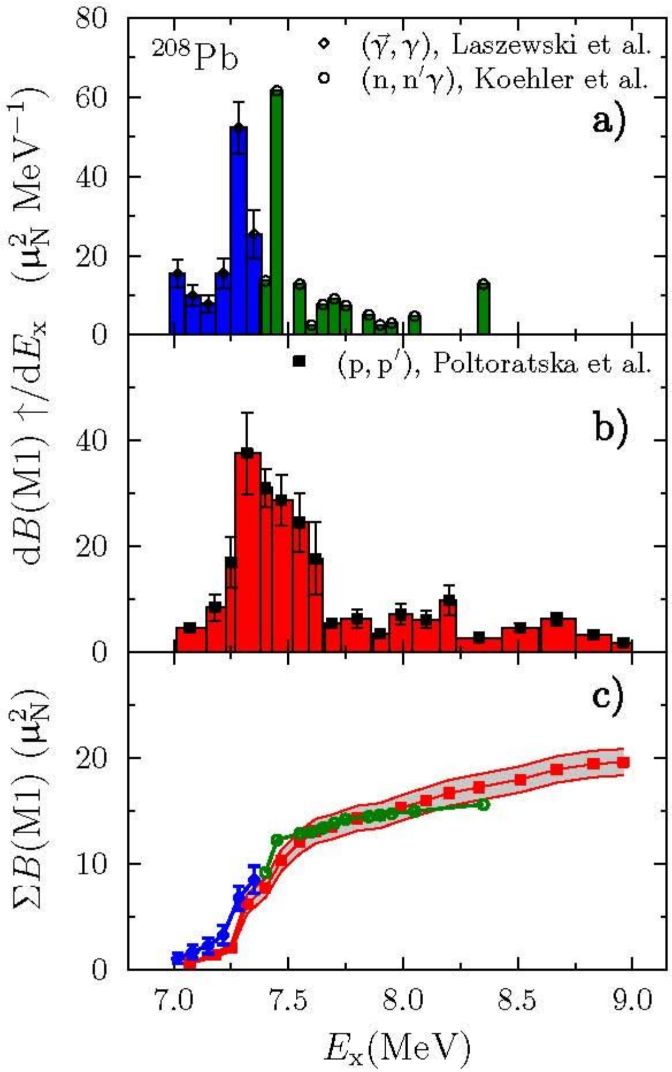
I. Poltoratska et al., PRC 85, 041304 (2012)

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

for $E_x \leq 8$ MeV

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

for full resonance



Contributions to GSF in ^{208}Pb

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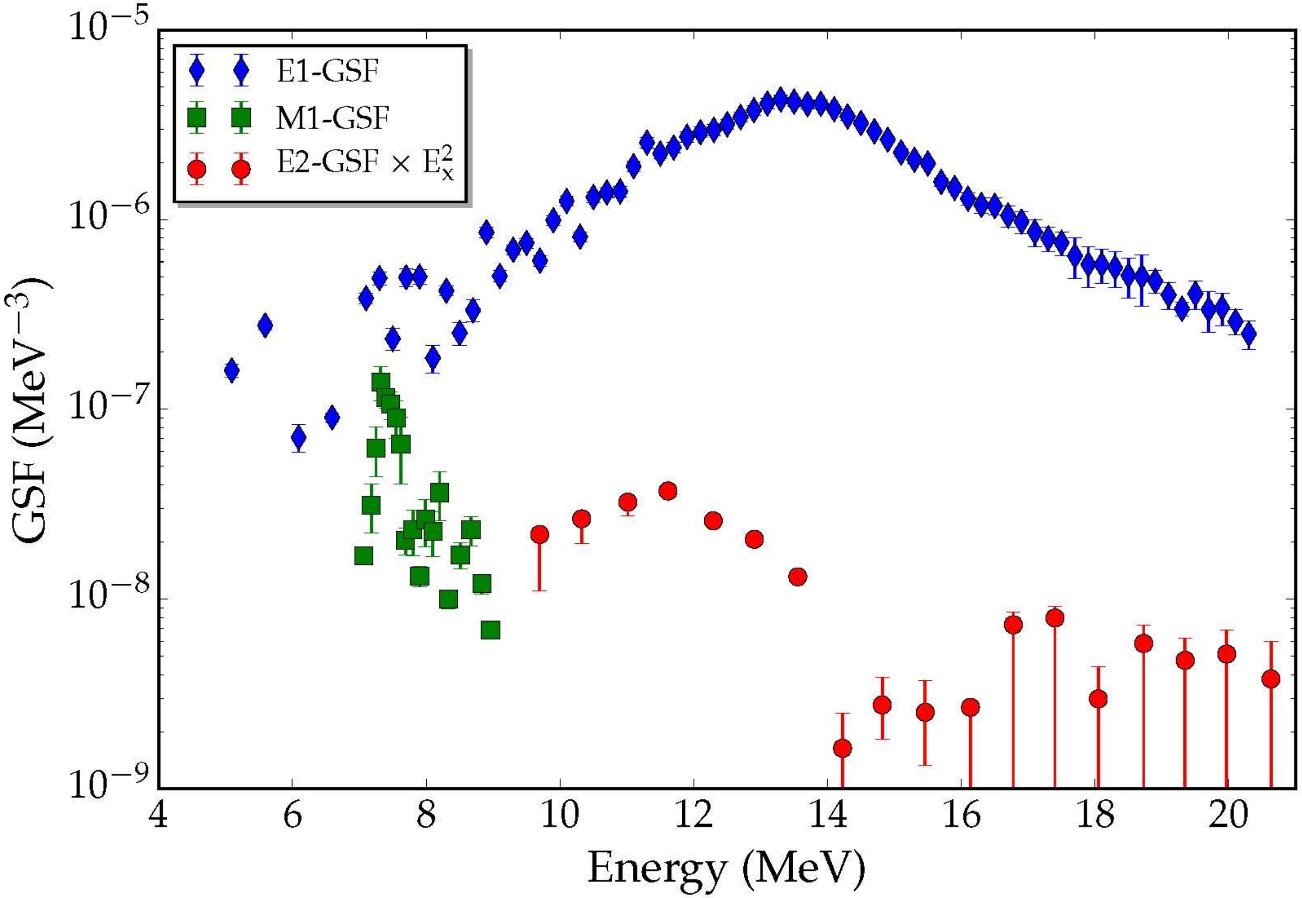
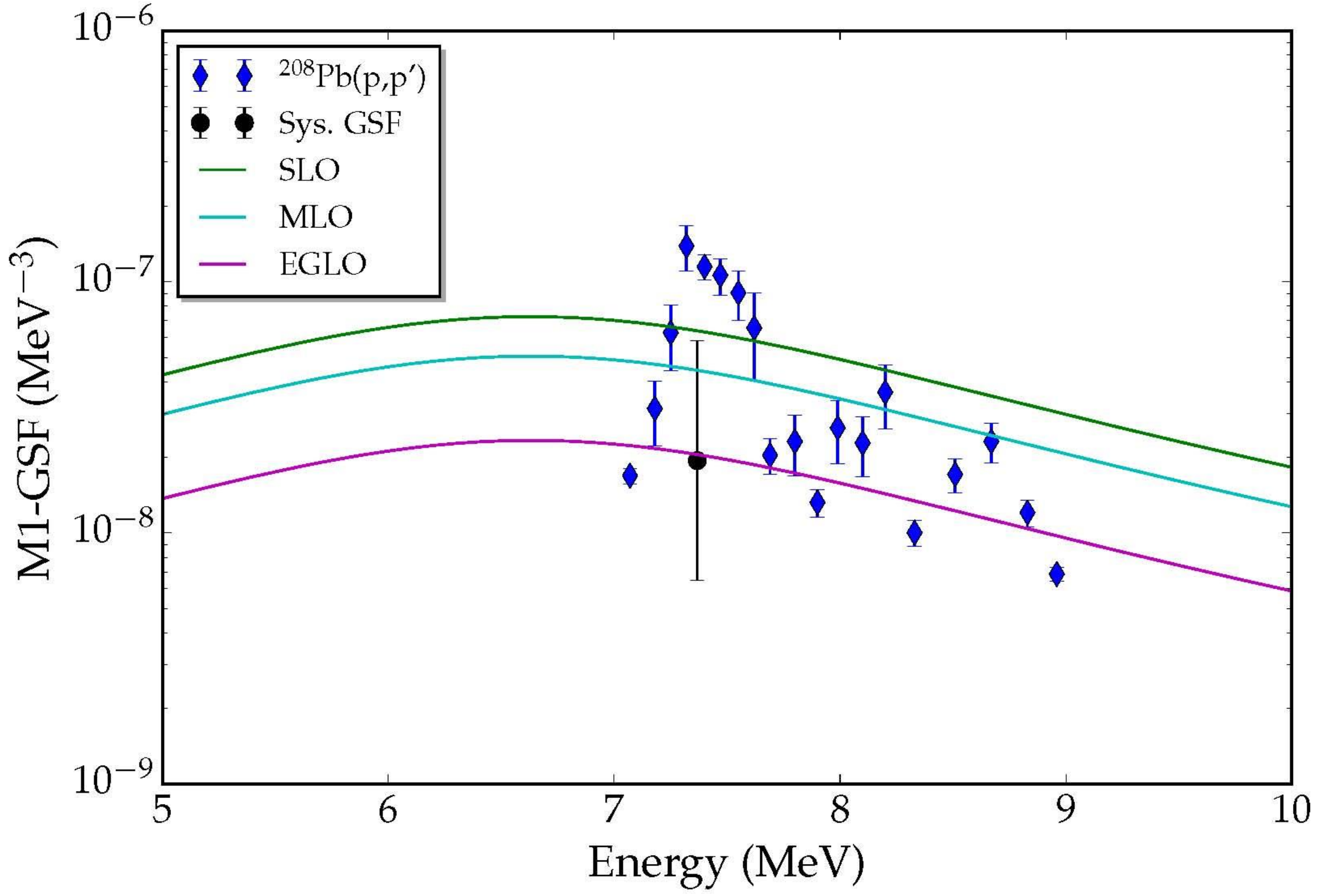
S. Bassauer, PvNC, A. Tamii, Phys. Rev. C 94 (2106) 054313



GSF in ^{208}Pb: M1 Part



- RIPL-3 parameterizations: strength factor 2 - 5 too large, width too large

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

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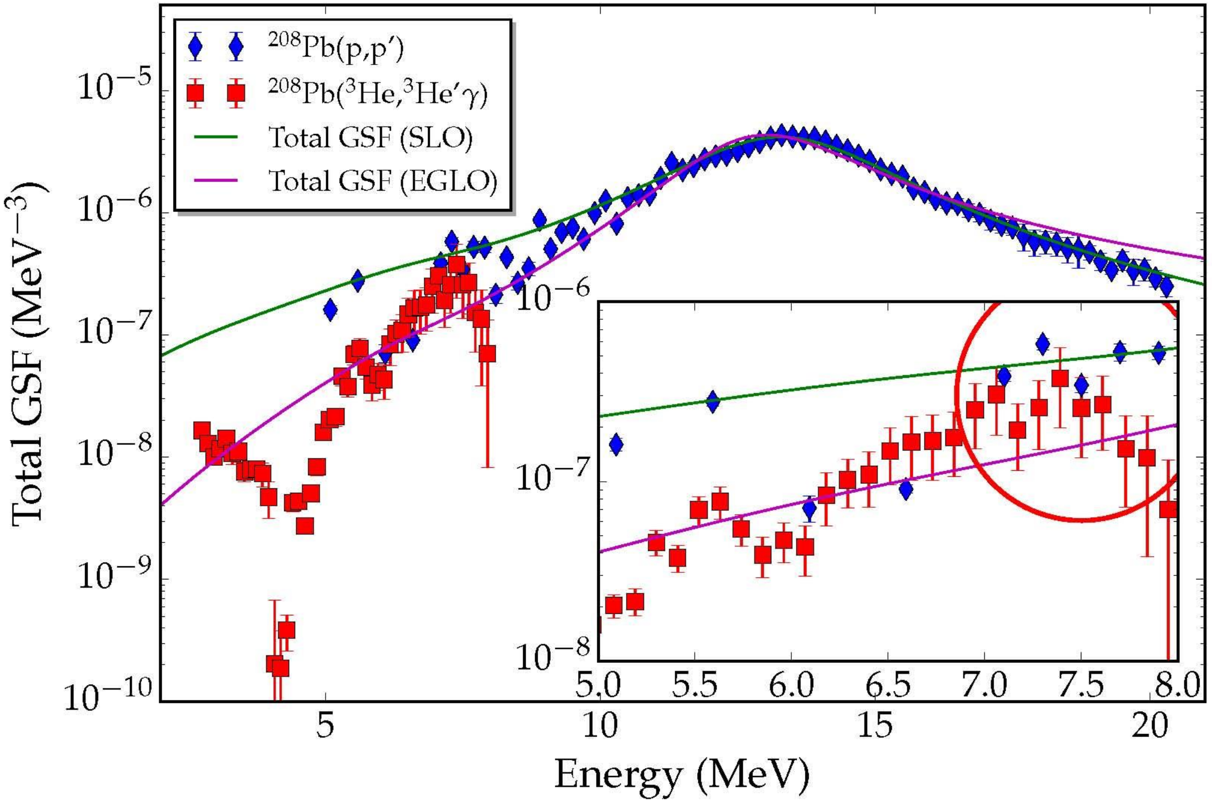
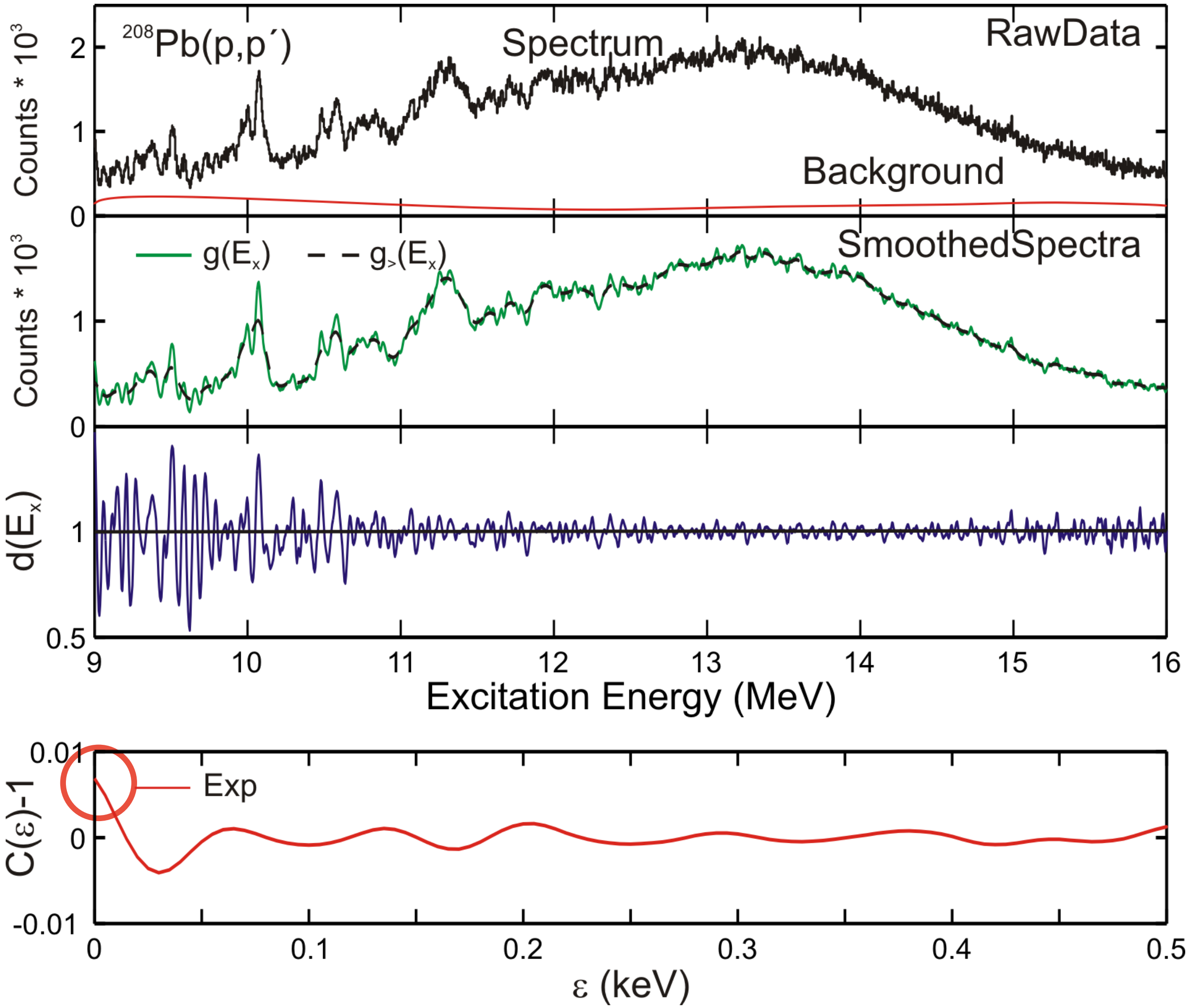
(^{3}He,^{3}He'γ): N.U.H. Syed et al., Phys. Rev. C 79, 024316 (2009); reanalyzed by M. Guttormsen (priv. comm.)



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

Fluctuation Analysis of High-Resolution Data



- 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

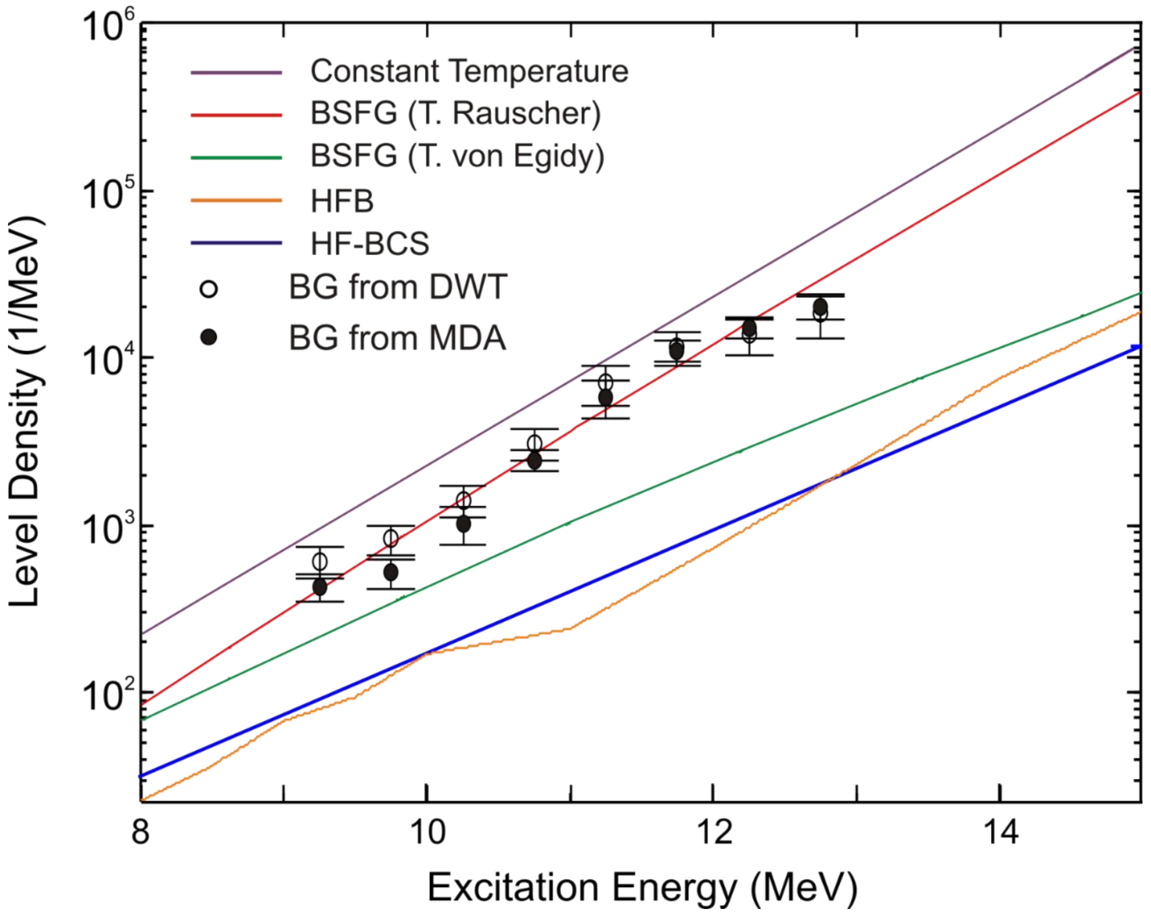
- $$C(\varepsilon=0)-1=\frac{\alpha\langle D\rangle}{2\sigma\sqrt{\pi}}$$ level spacing ⟨D⟩

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

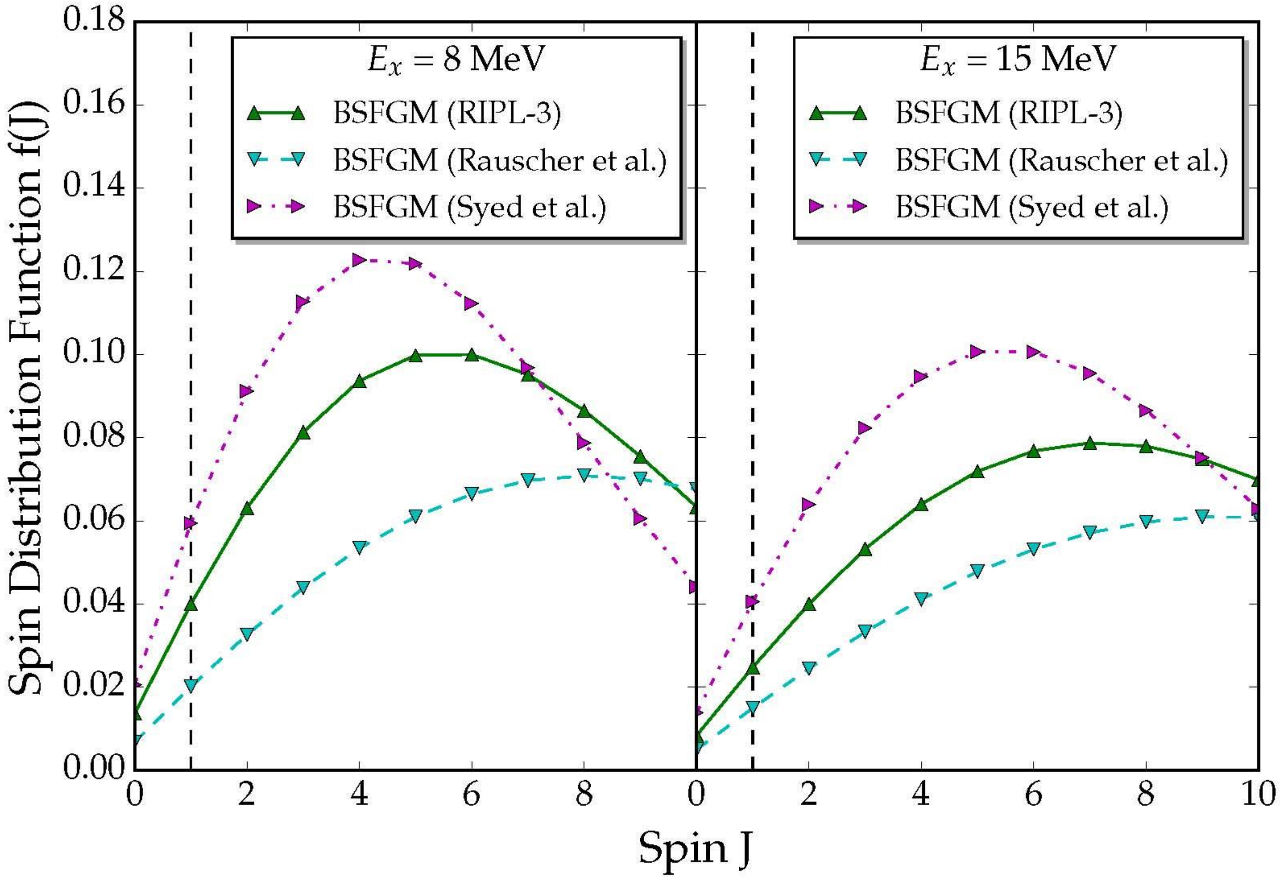
- σ resolution

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

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



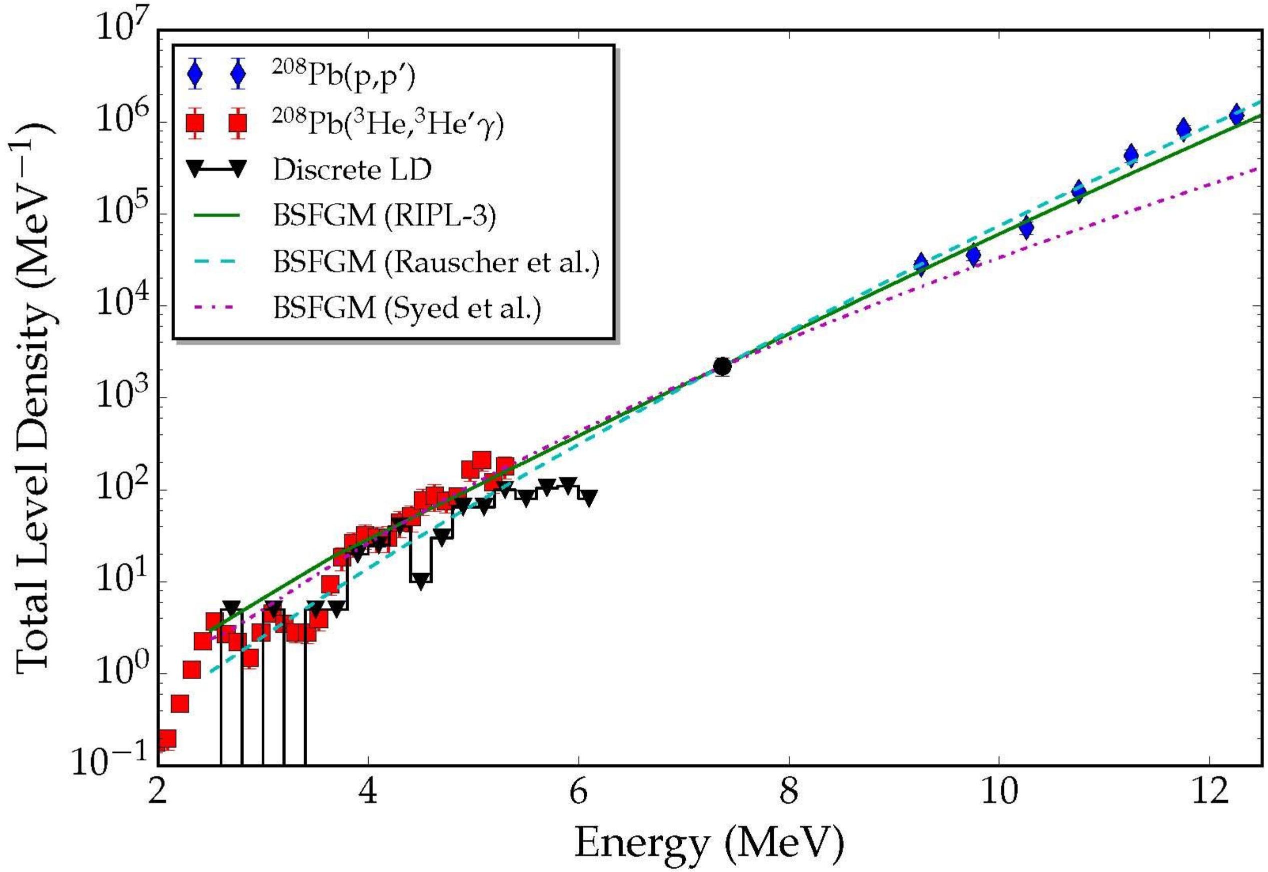
Spin Distribution Function



- Average over different models

Total Level Density in ^{208}Pb

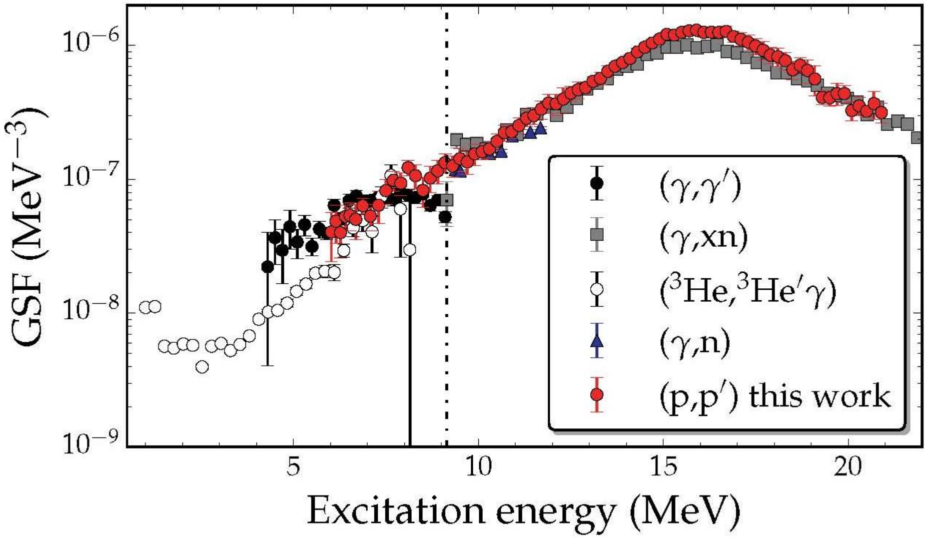
S. Bassauer, PvNC, A. Tamii, Phys. Rev. C 94 (2106) 054313

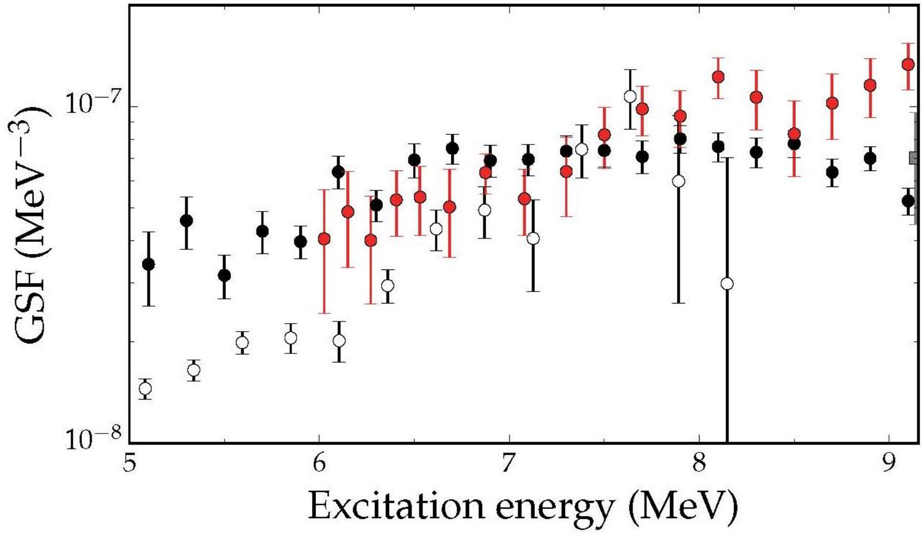


- Good agreement with Oslo results

GSF in ^{96}Mo

(p,p‘): D. Martin et al., arXiv:1611.01789
(^{3}He,^{3}He‘γ): A.C. Larsen, S. Goriely, Phys. Rev. C 82, 014318 (2010)
(γ,γ‘): G. Rusev et al., Phys. Rev. C 79, 061302 (2009)

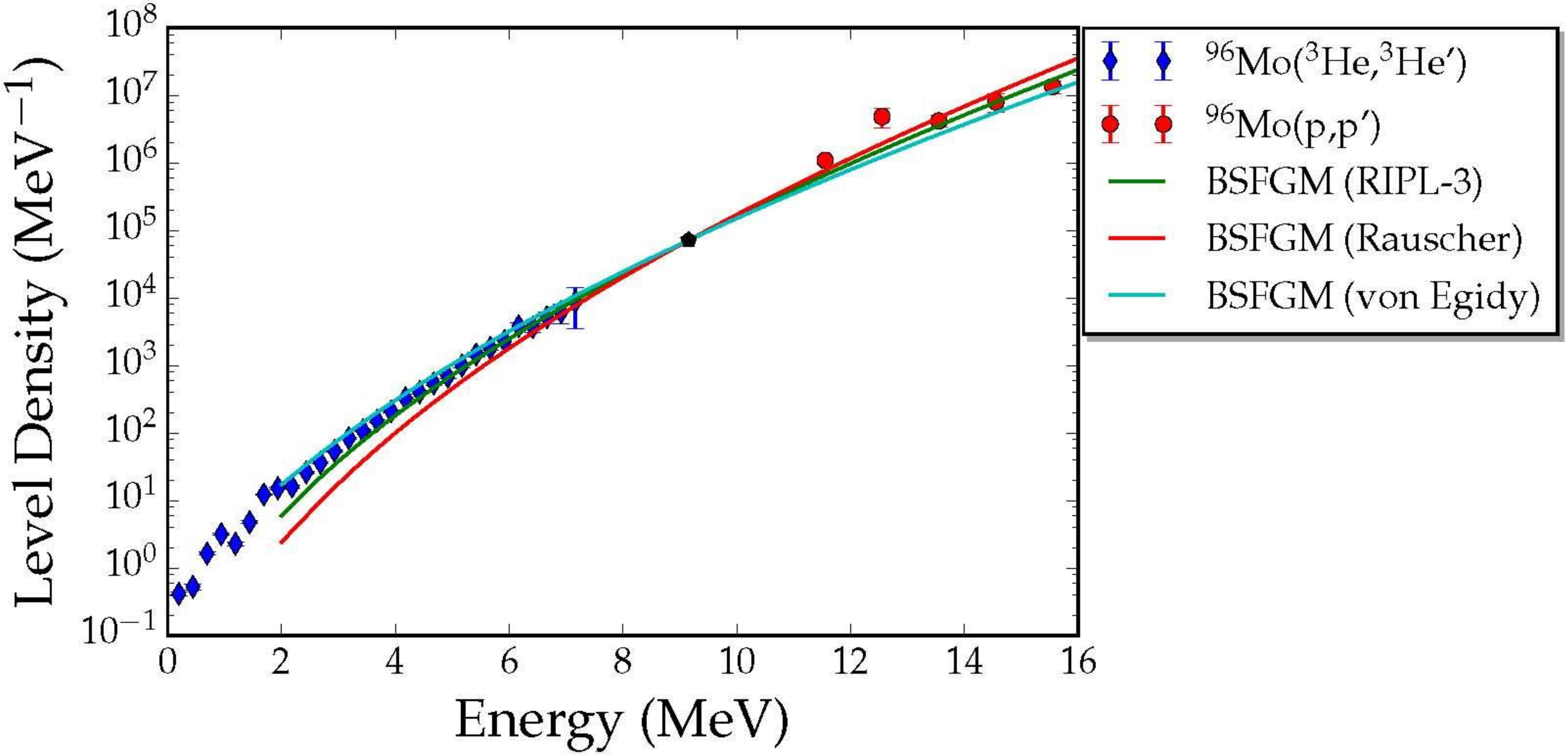




- Better agreement with Oslo results in the PDR region

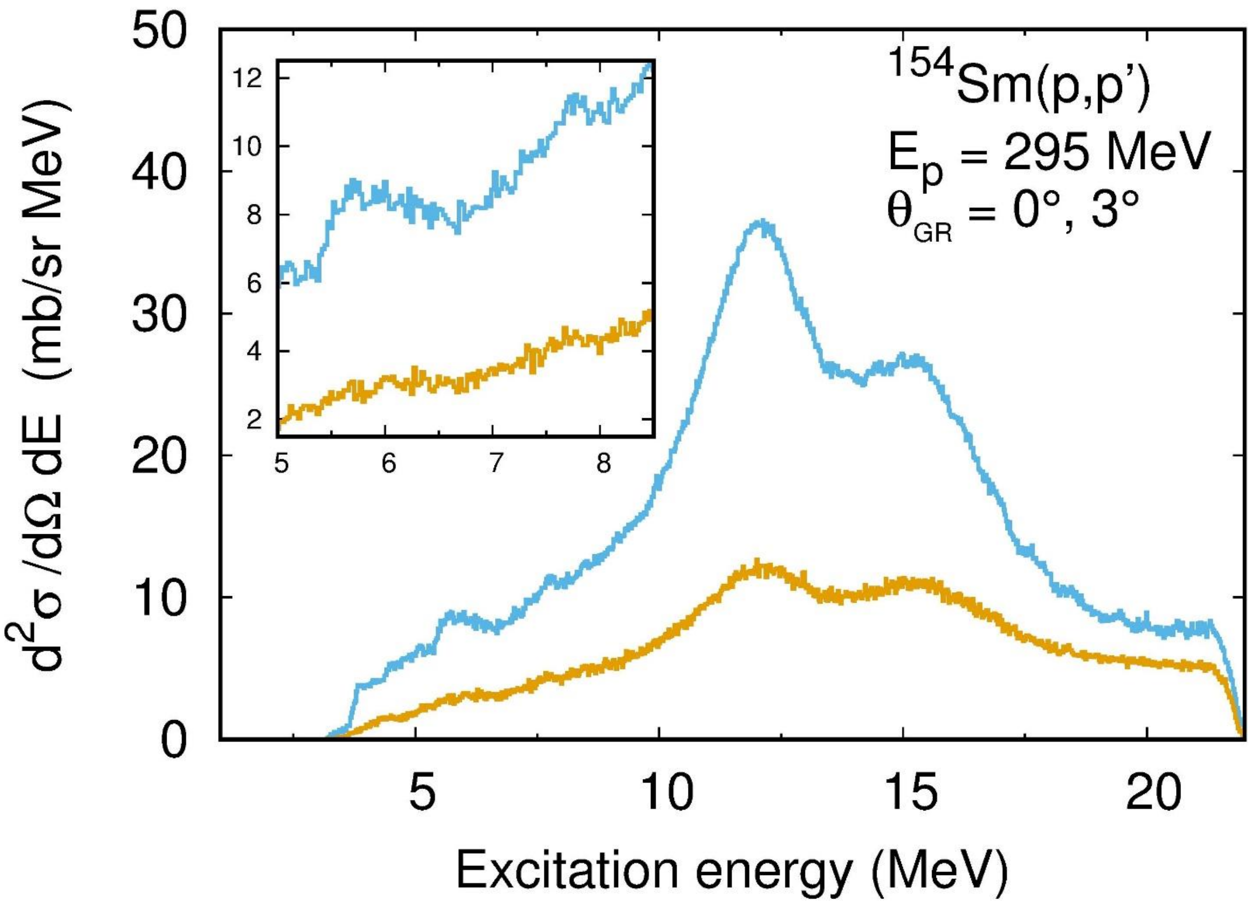
Total Level Density in ^{96}Mo

D. Martin et al., arXiv 1611.01789

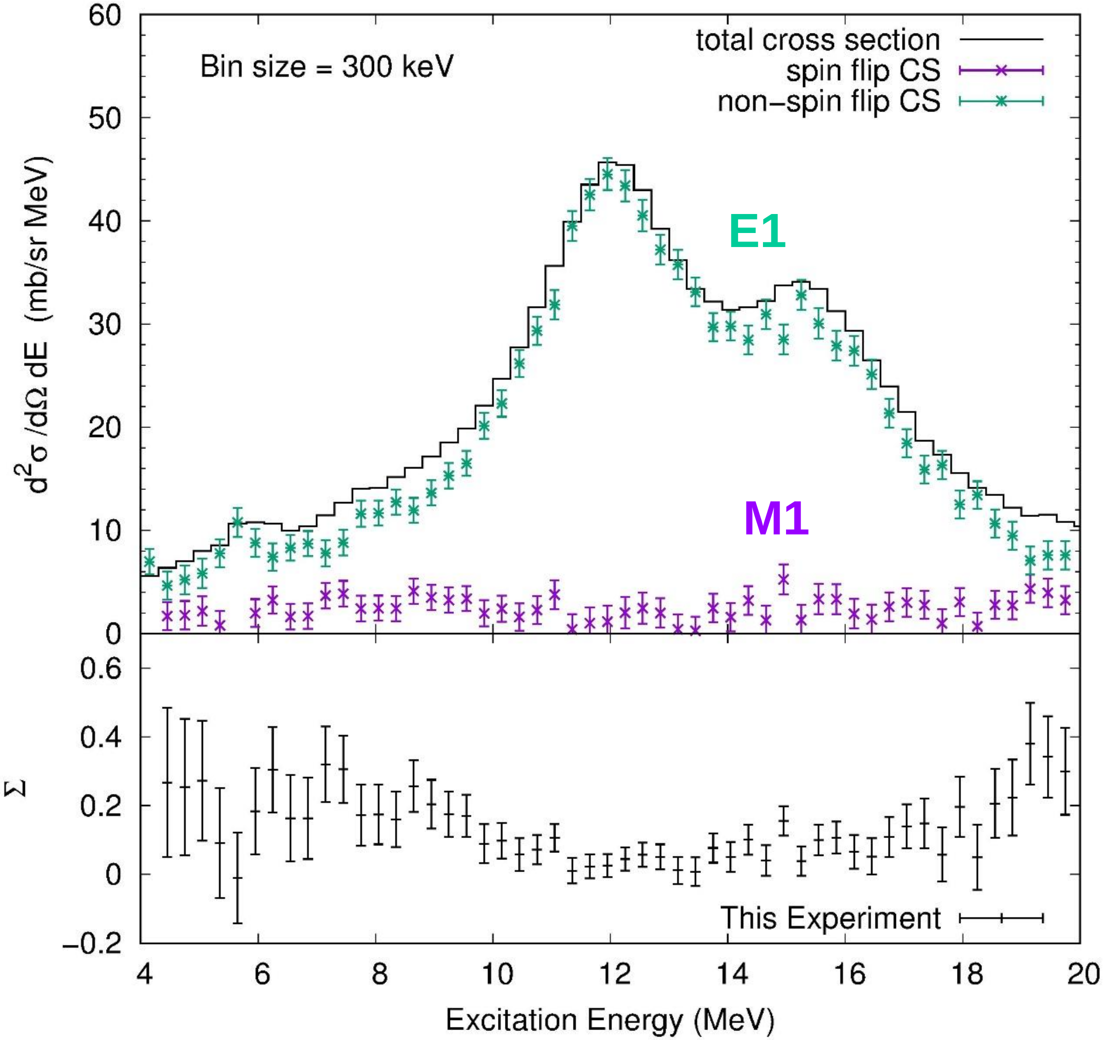


- Consistent with results from Oslo method

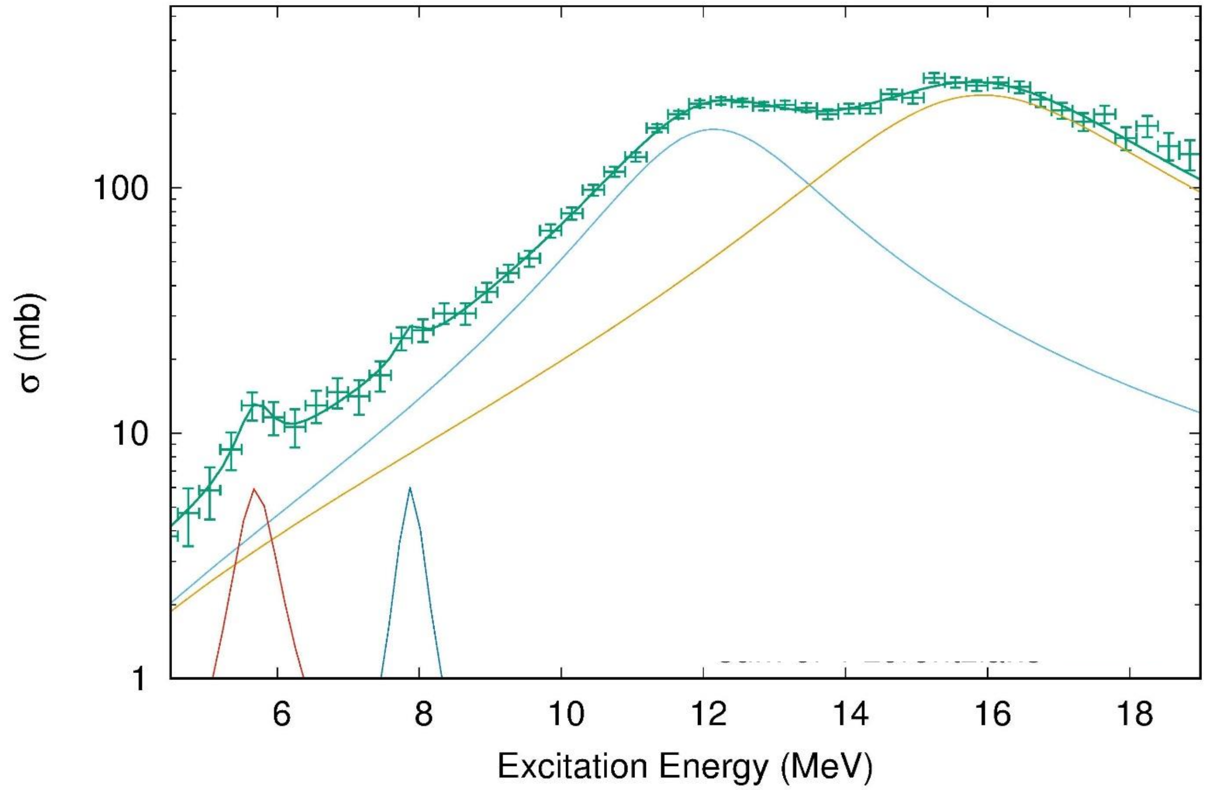
Search for the PDR in ^{154}Sm



^{154}Sm: E1/M1 Decomposition



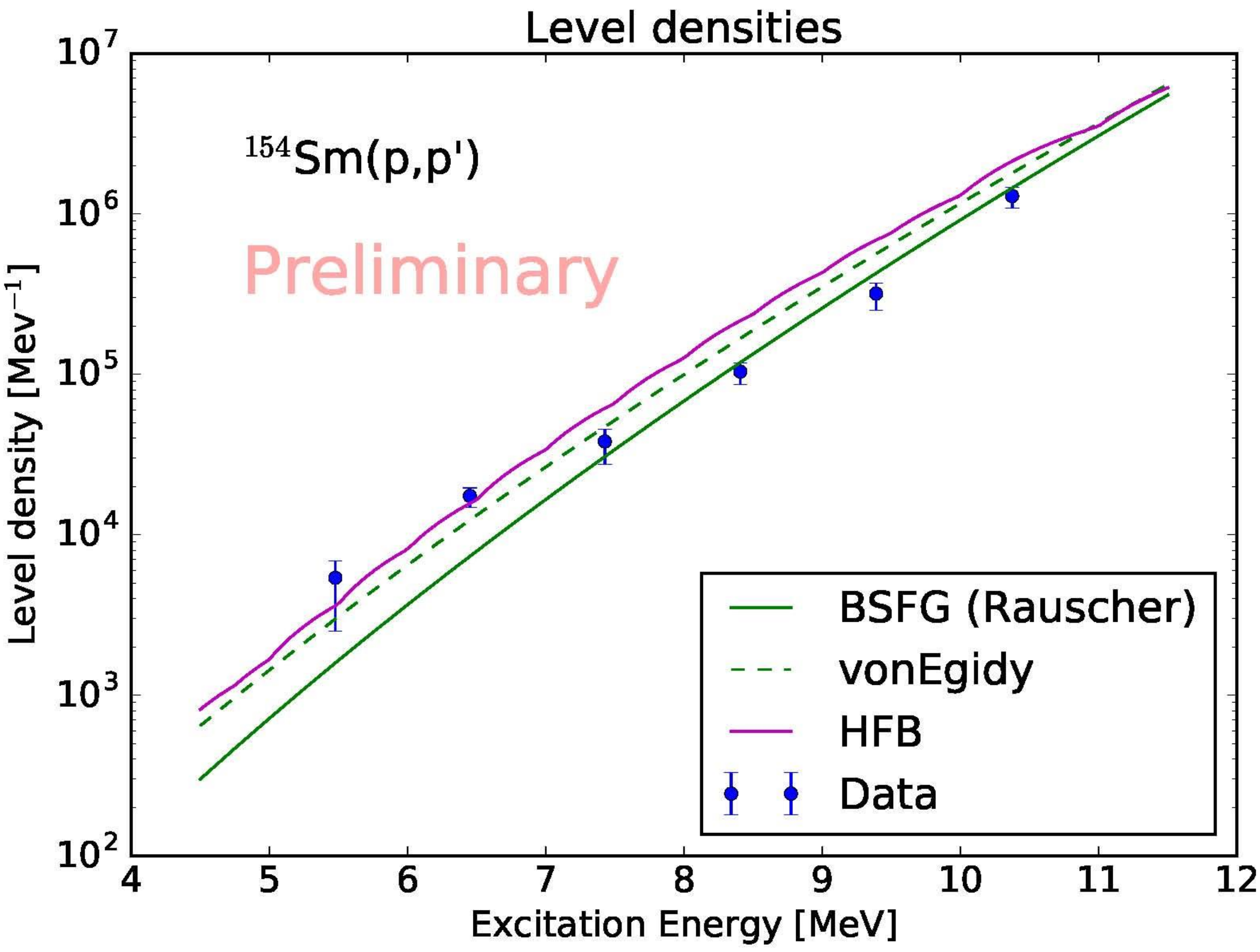
^{154}Sm: Photoabsorption Cross Sections



- Low-energy bumps: signature of K-splitting?

- 5.5 MeV peak consistent with (α,α‘γ) → Luna Pellegri‘s talk

J = 1 Level Densities in ^{154}Sm



Summary

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

- Extraction of GSF (E1 and M1) and level densities from the same data

- Level densities agree well with those from Oslo data

- Disagreement with Oslo data in the PDR region for ^{208}Pb:
  large PT fluctuations because of too small level density?

- Brink-Axel hypothesis seems to hold in the PDR region for ^{96}Mo

- First observation of the PDR in a heavy deformed nucleus ^{154}Sm:
  Oslo-method experiment presently analyzed

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

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D. Martin, I. Poltoratska, A. Tamii