Electric Dipole Response from Forward-Angle Polarized Proton Scattering, Neutron Skin and the Neutron Equation of State

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- Equation of State of neutron matter and neutron skin
- Polarized proton scattering at 0° and electric dipole response
- Dipole polarizability of ^{208}Pb
- Dipole polarizability of ^{120}Sn

SFB 634

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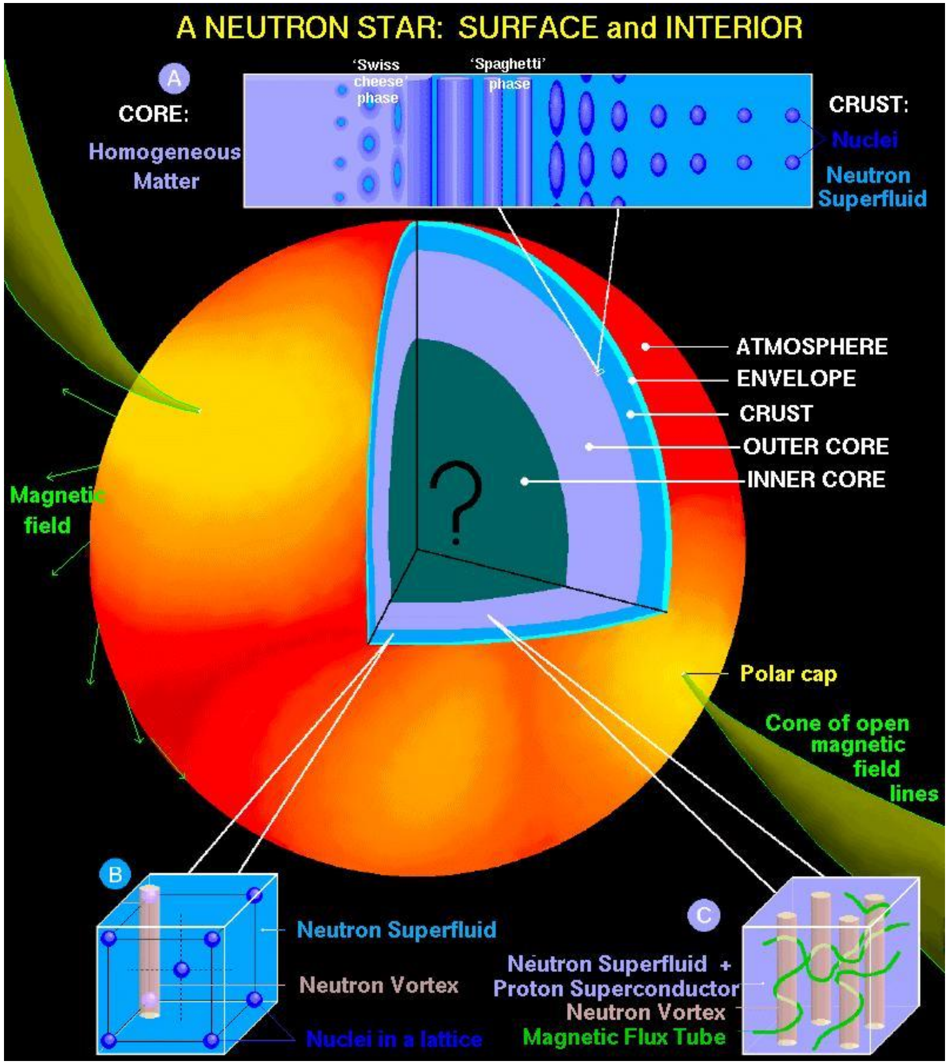
Neutrons Stars

- Neutron stars are remnants of the supernova explosion of massive stars

- Extremely high densities and exotic forms of nuclear matter

- Properties depend on the Equation Of State (EOS) of neutron matter



Mass – Radius Relation of Neutron Stars

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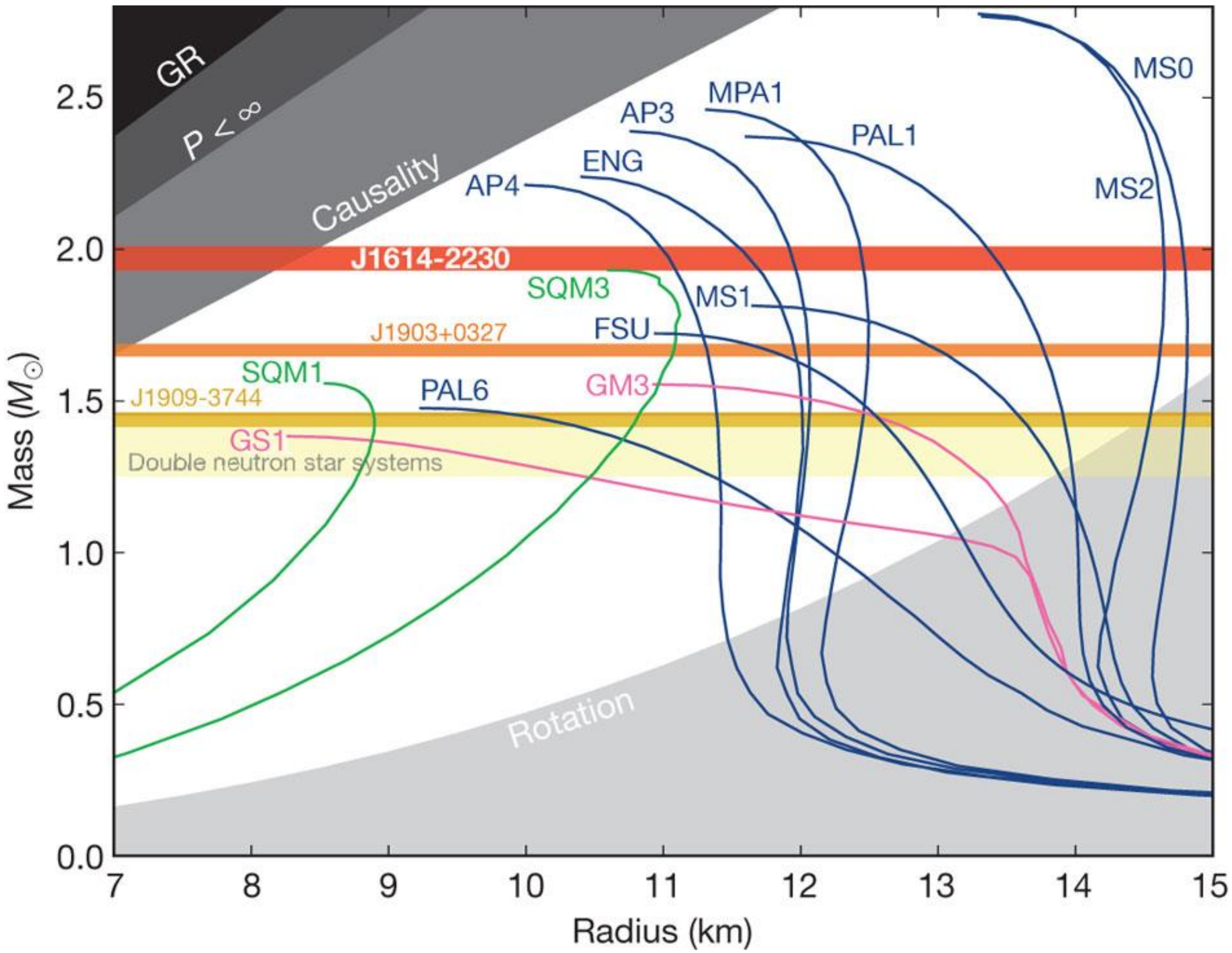
P. B. Demorest et al., Nature 467, 1081 (2010)



Binding Energy of (Infinite) Neutron Matter

$$B(A,Z) = \underbrace{a_v A}_{\text{volume}} - \underbrace{\cancel{a_s A^{2/3}}}_{\text{surface}} - \underbrace{\cancel{a_c Z(Z-1)/A^{1/3}}}_{\text{Coulomb}} - \underbrace{a_{sym}(A-2Z)^2/A}_{\text{symmetry}} + \underbrace{\cancel{}}_{\text{pairing}}$$

- For (infinite) neutron matter the pairing contribution is small enough to be neglected (at least for low densities)

  → only volume and symmetry term contribute

- The volume term can be estimated from the saturation properties

↓

- The symmetry energy represents the largest uncertainty for the EOS of neutron matter

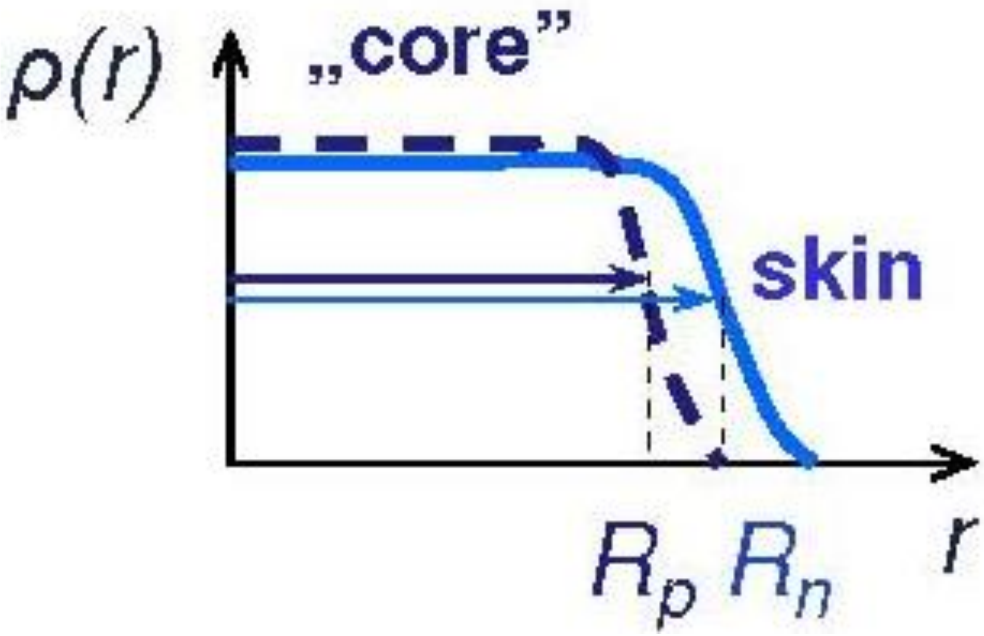
Symmetry Energy and Neutron Skin of Nuclei

- Nuclear force leads to constant density in the interior (saturation)

- In heavy stable nuclei *N* > *Z* because the symmetry energy is balanced by the Coulomb repulsion between protons

- Extra neutrons concentrate on the surface
  ➡ formation of a neutron skin

- Neutron skin thickness depends on the parameters of the symmetry energy



Symmetry Energy and Neutron Skin

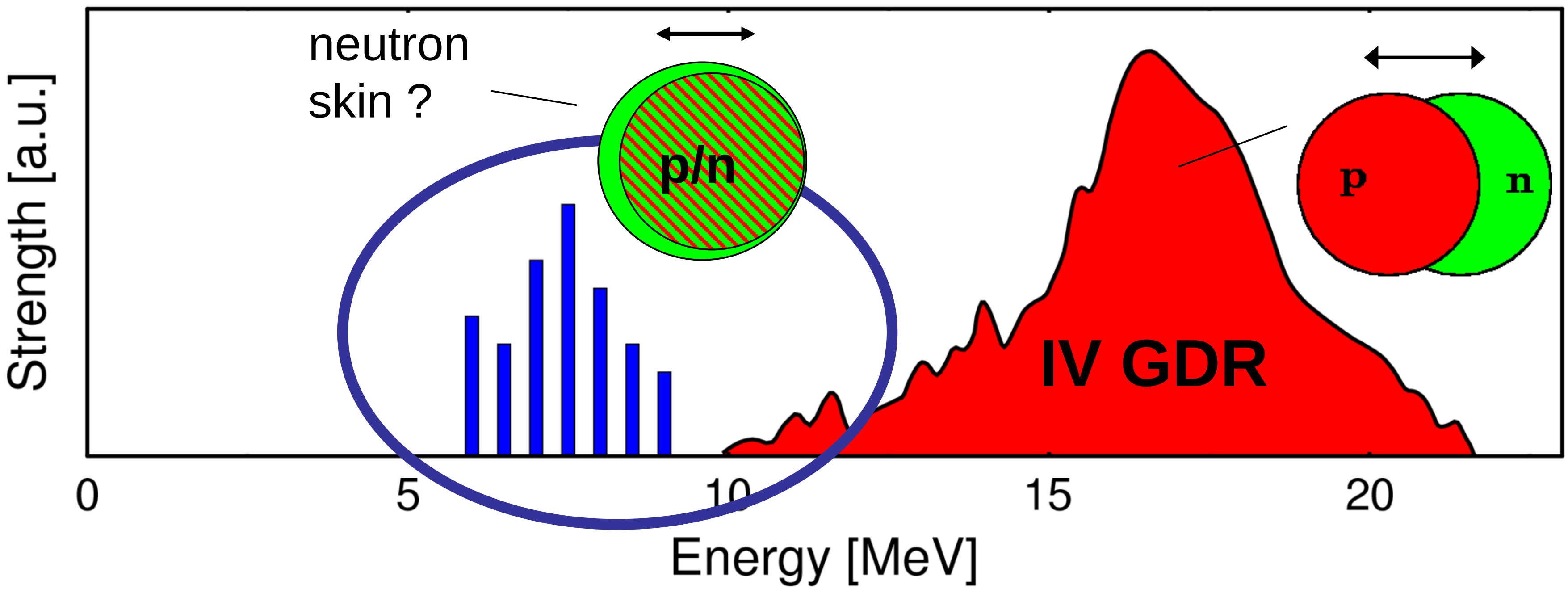
$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}_2(\rho) + \ldots$$

$$= \left(\varepsilon_0 + \frac{1}{2}K_0 x^2 + \ldots\right) + \alpha^2\left(J + Lx + \frac{1}{2}\cancel{K_{\mathrm{sym}}}\, x^2 + \ldots\right) + \ldots$$

$$\boxed{P_{\mathrm{PNM}}(\rho_0) = \tfrac{1}{3}\rho_0 L} \qquad \left[\alpha = (N-Z)/A; \quad x = (\rho-\rho_0)/3\rho_0\right]$$

- Symmetry energy approximately determined by *J* and *L*
- *L* describes density dependence (stiff or soft EOS)

Electric Dipole (E1) Response in Nuclei



- Oscillations of neutrons against protons:
  Giant Dipole Resonance (GDR)

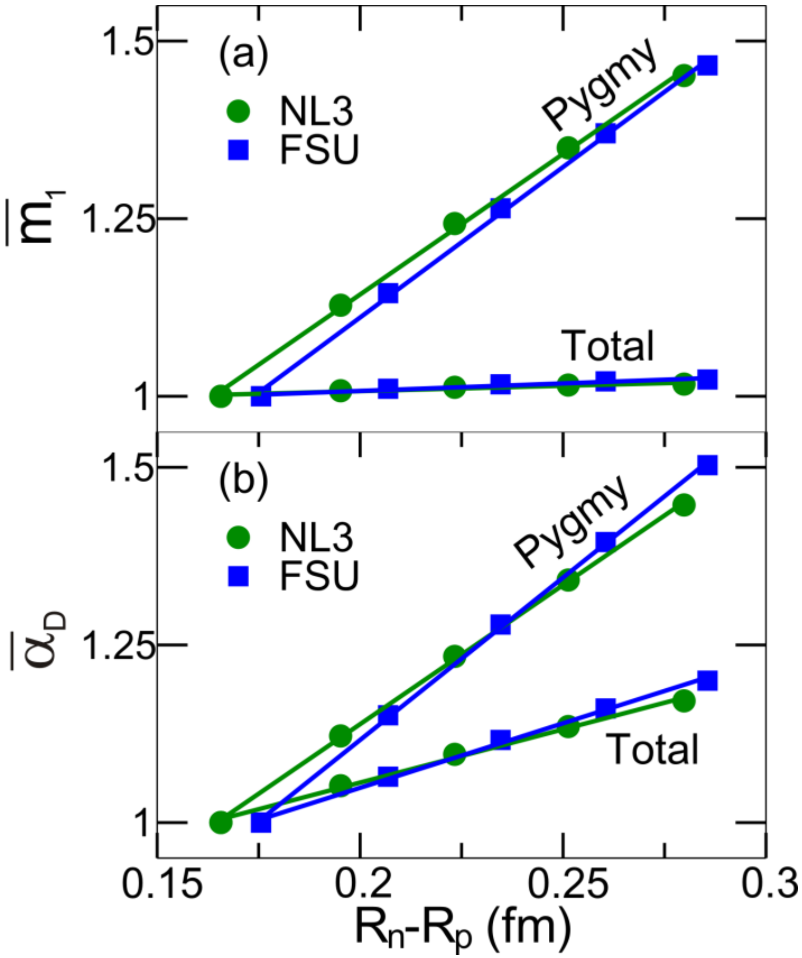
- Oscillations of neutron skin against core with N≈ Z
  Pygmy Dipole Resonance (PDR)

Polarizability

J. Piekarewicz, Phys. Rev. C 83, 034319 (2011)

- Static nuclear dipole polarizability

$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{S_{E1}(\omega)}{\omega} d\omega$$



- α_D is measure of neutron skin

  P.G. Reinhard, W. Nazarewicz,
  Phys. Rev. C 81, 051303(R) (2010)

A New Experimental Tool for Complete E1 Strength Distributions

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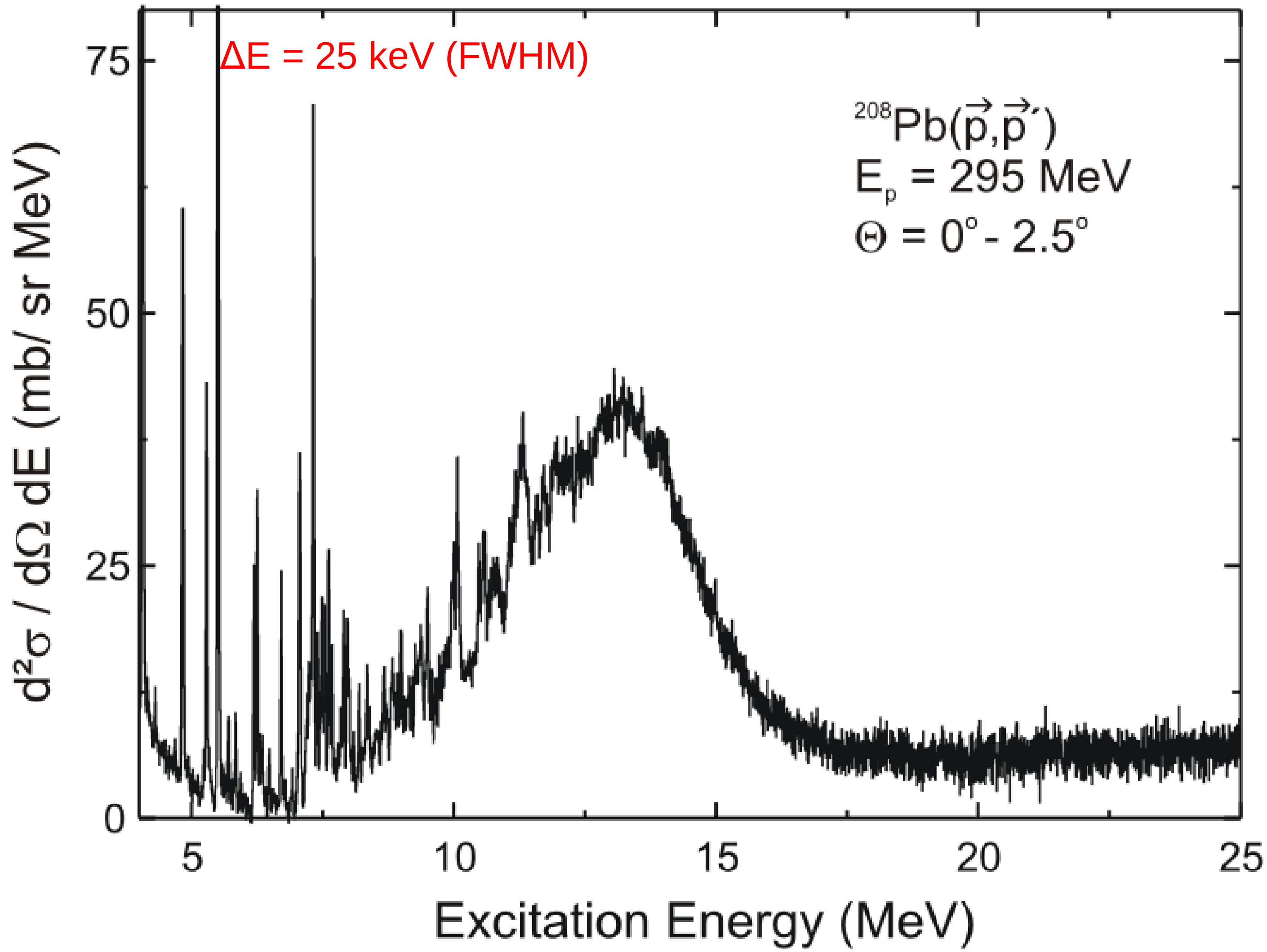
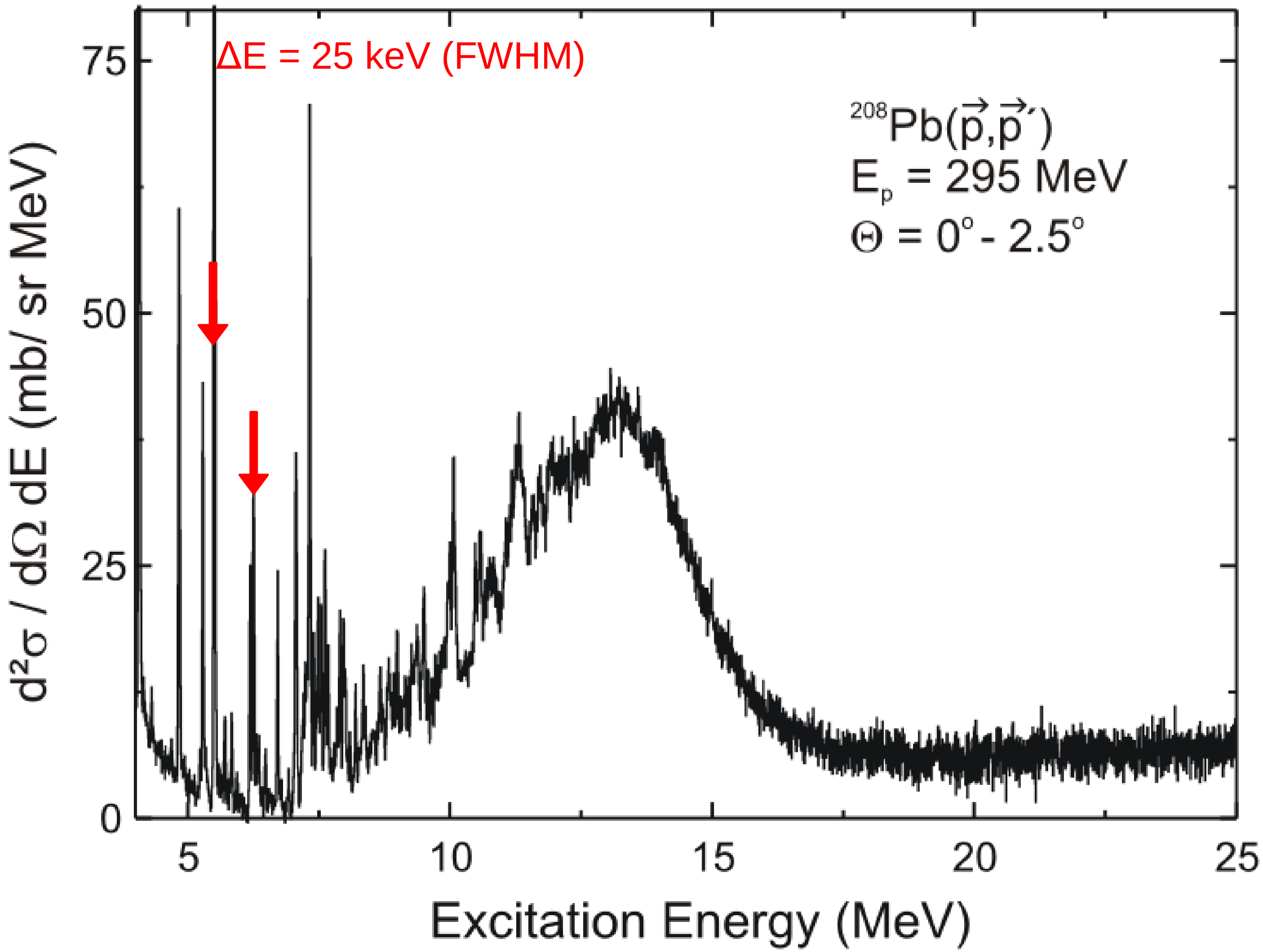
- Intermediate-energy polarized proton scattering at 0º
  - E1 strength form relativistic Coulomb excitation
  - high energy resolution: $\Delta E/E < 10^{-4}$
  - angular distributions: E1 / M1 separation
  - polarization observables: spinflip / non-spinflip separation
  - complete response from 5 - 20 MeV
- Experiments at RCNP Osaka, Japan
- Results for ^{208}Pb and ^{120}Sn

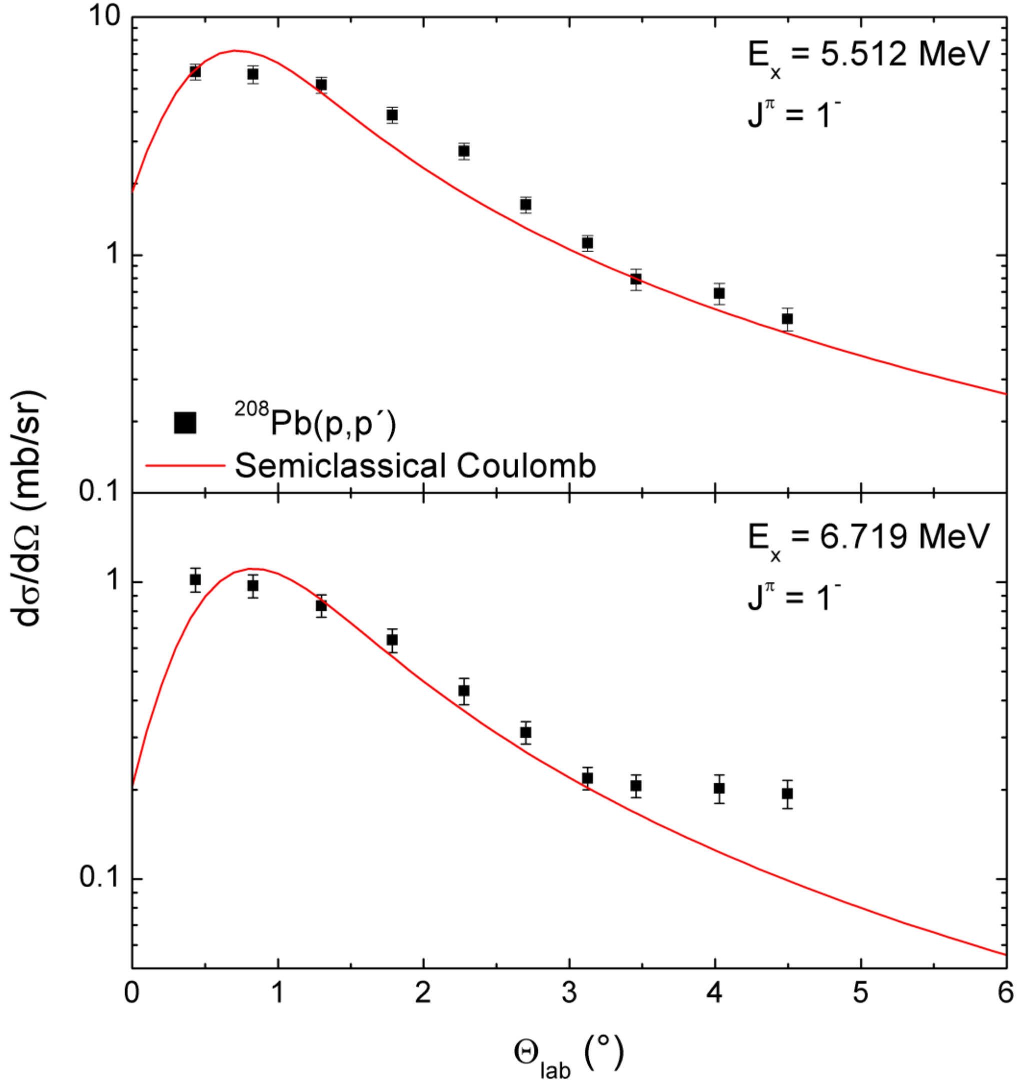
^{208}Pb: Measured Spectrum



^{208}Pb: Measured Spectrum

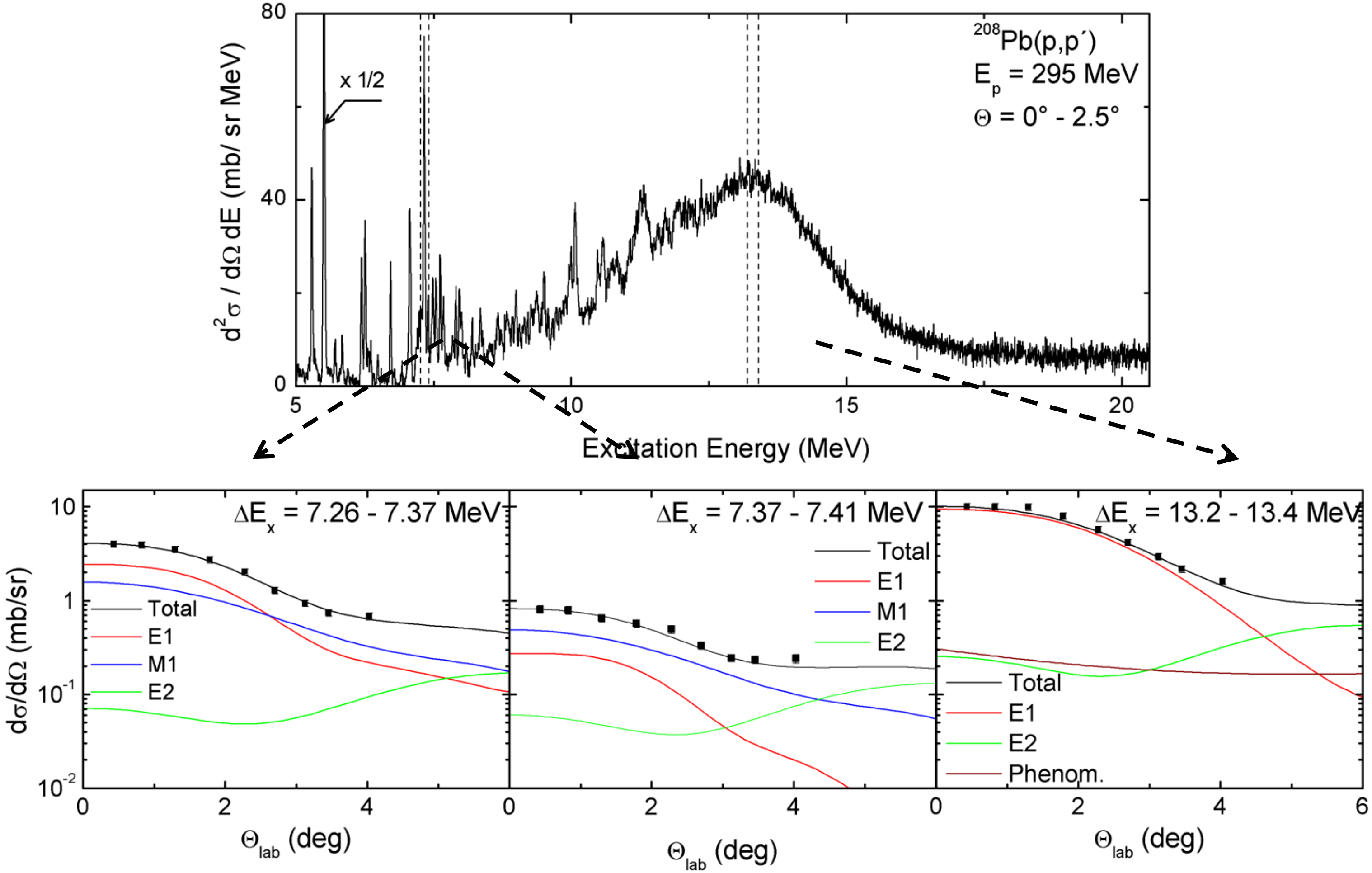


Coulomb Exitations of 1$^-$ States



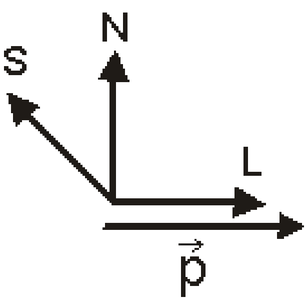
Multipole Decomposition of Angular Distributions

I. Poltoratska et al., Phys. Rev. C 85, 041304(R) (2012)



E1/M1 Decomposition by Spin Observables

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



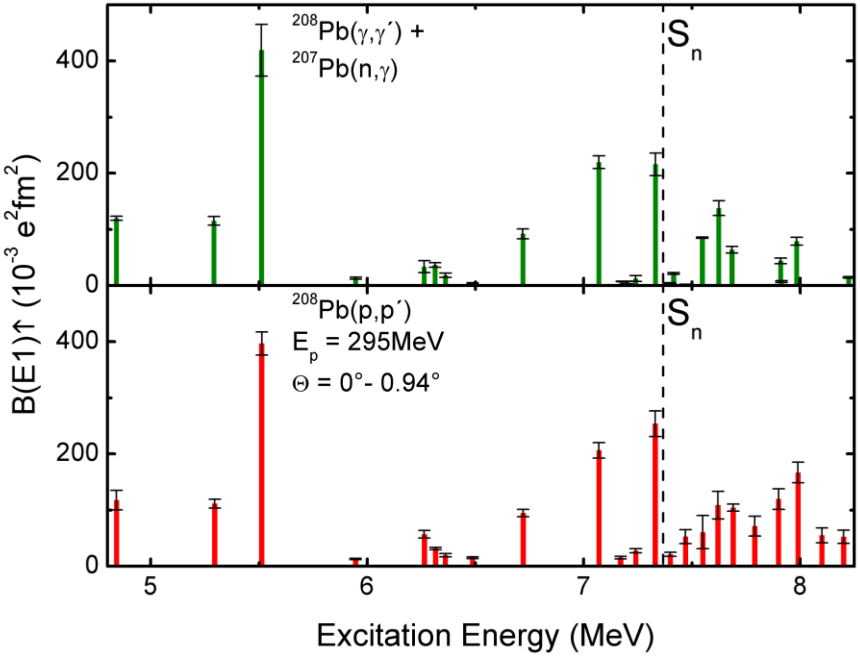
$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S=1 & \rightarrow 1^+ \\ 3 \text{ for } \Delta S=0 & \rightarrow 1^- \end{cases}$$

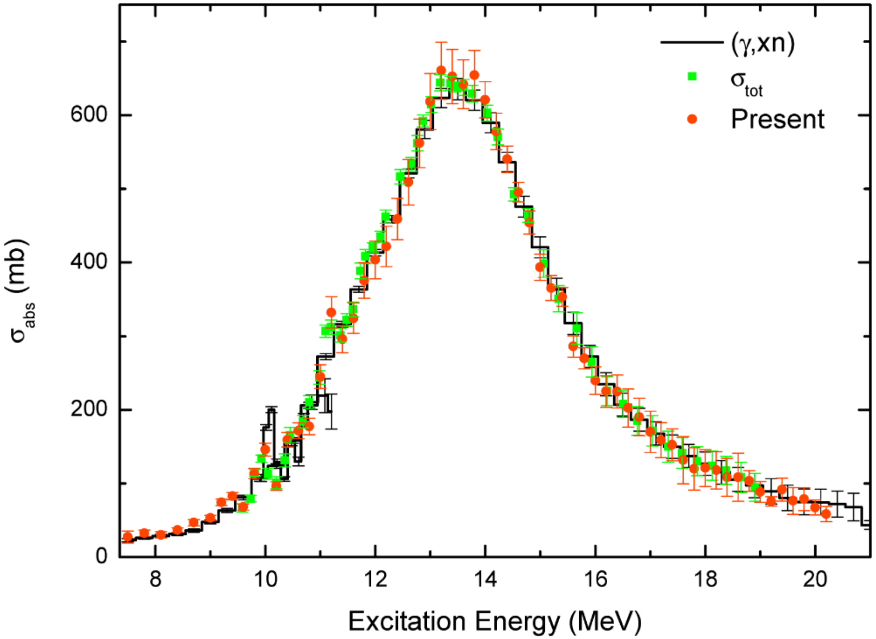
sideway | normal | longitudinal

At 0° $D_{SS} = D_{NN}$ ➡ $\text{TotalSpinTransfer}\ \Sigma \equiv \dfrac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 \\ 0 \text{ for } \Delta S = 0 \end{cases}$

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

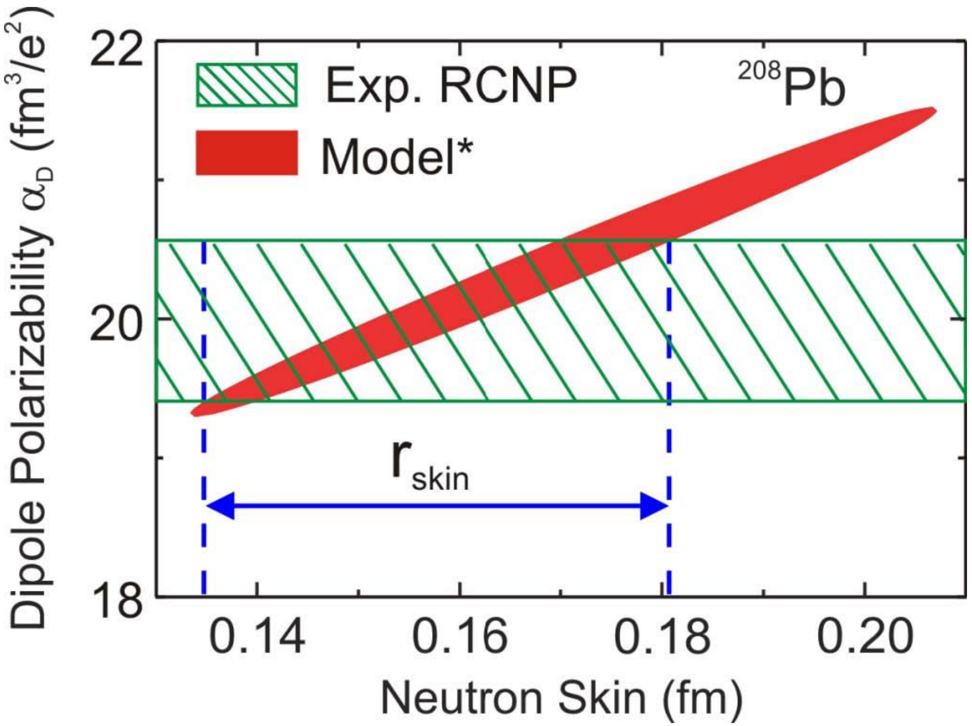
Extracted B(E1) Strength in ^{208}Pb





Polarizability and Neutron Skin

- Precision value: $\alpha_D(^{208}Pb)$ = 20.09(59) fm^3/e^2 = 13.95(41) fm^2/MeV

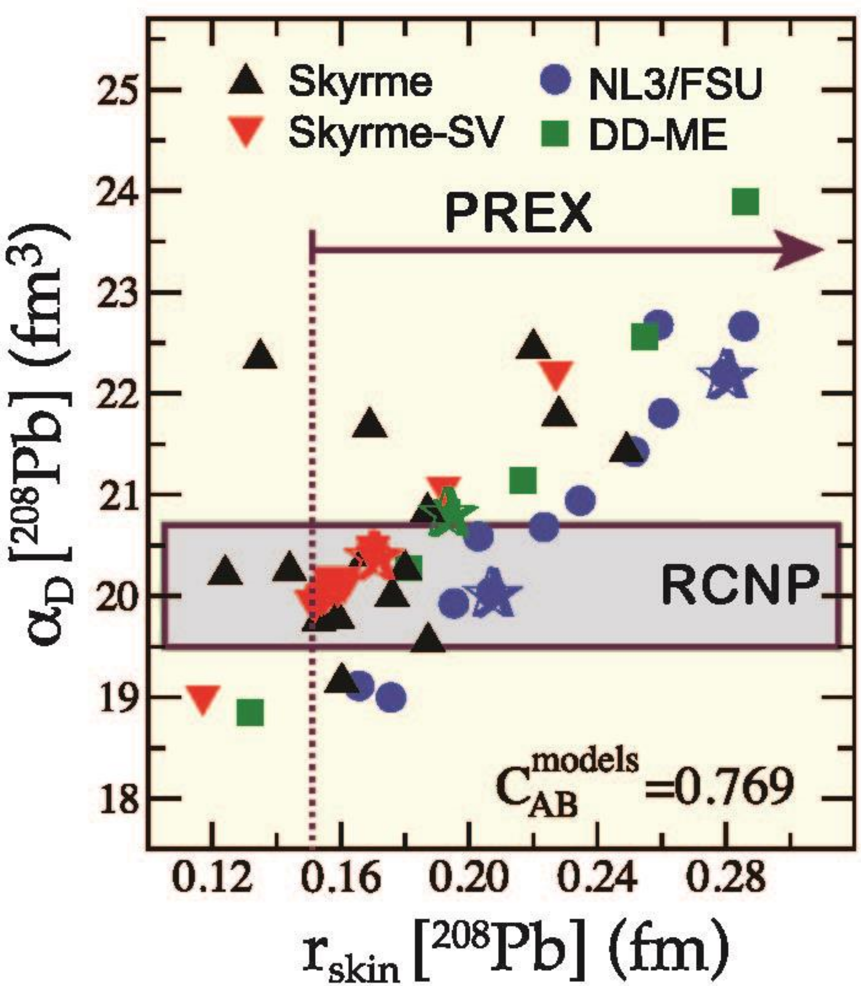


- Within the model of Reinhard and Nazarewicz $\Rightarrow$ r_{skin} = 0.155(23) fm

A. Tamii et al., Phys. Rev. Lett. 107, 062502 (2011)

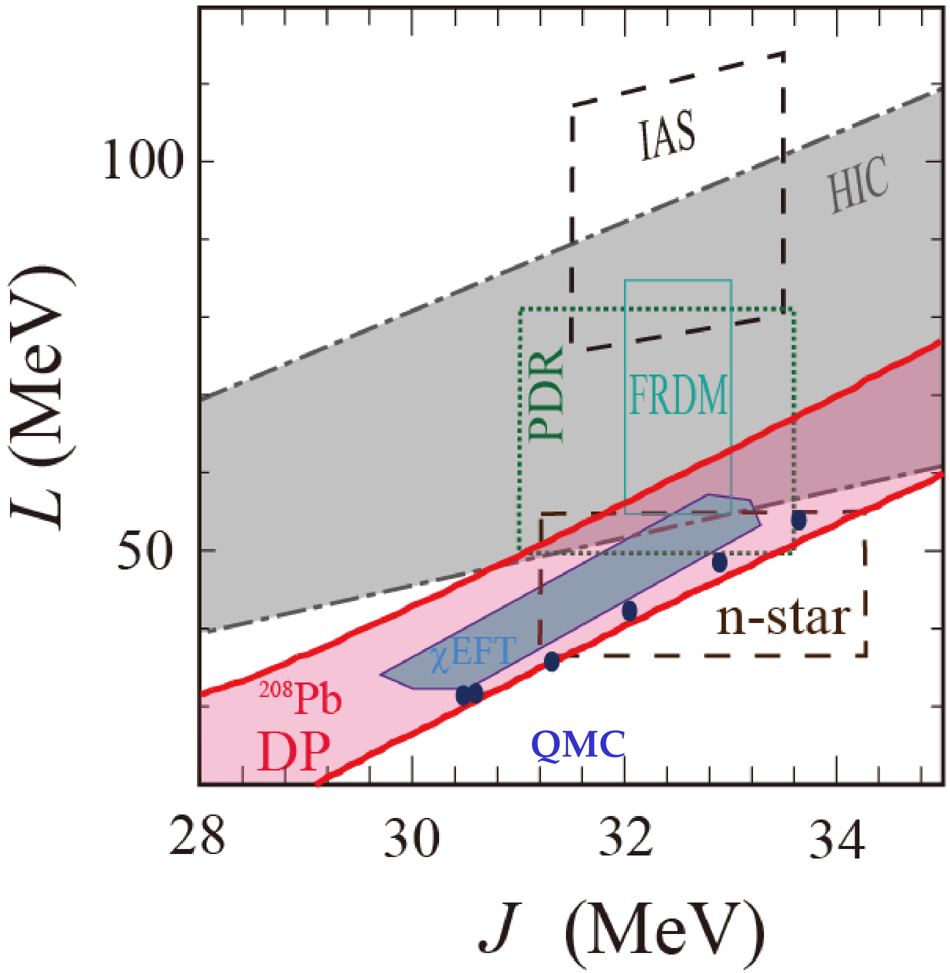
Constraints on Energy Density Functionals

- Relation between α_D and r_{skin} is model-dependent
- Important constraint by ^{208}Pb result



J. Piekarewicz et al., Phys. Rev. C 85 (2012) 041302(R)

Constraints on *J* and *L*



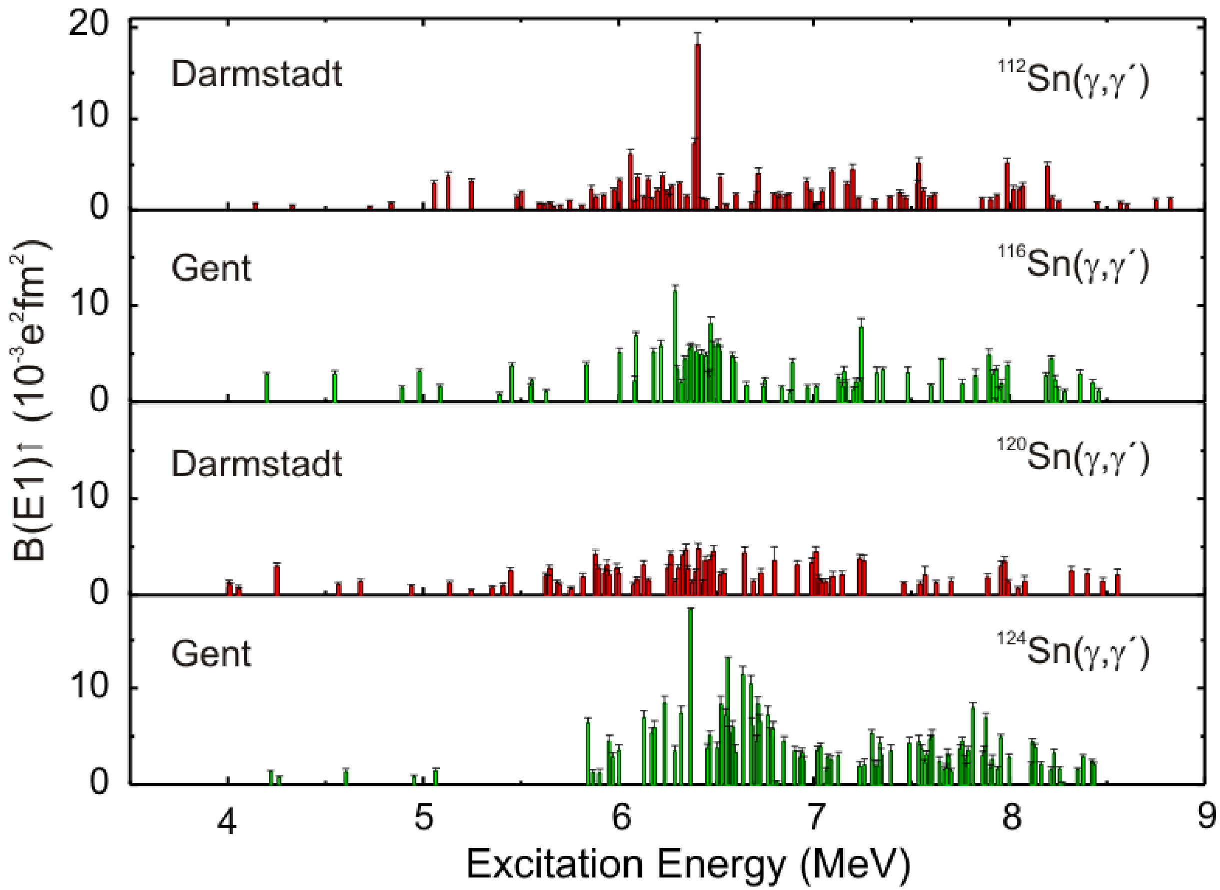
M.B. Tsang et al., Phys. Rev. C 86 (2012) 015803

I. Tews et al., Phys. Rev. Lett. 110 (2013) 032504

DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

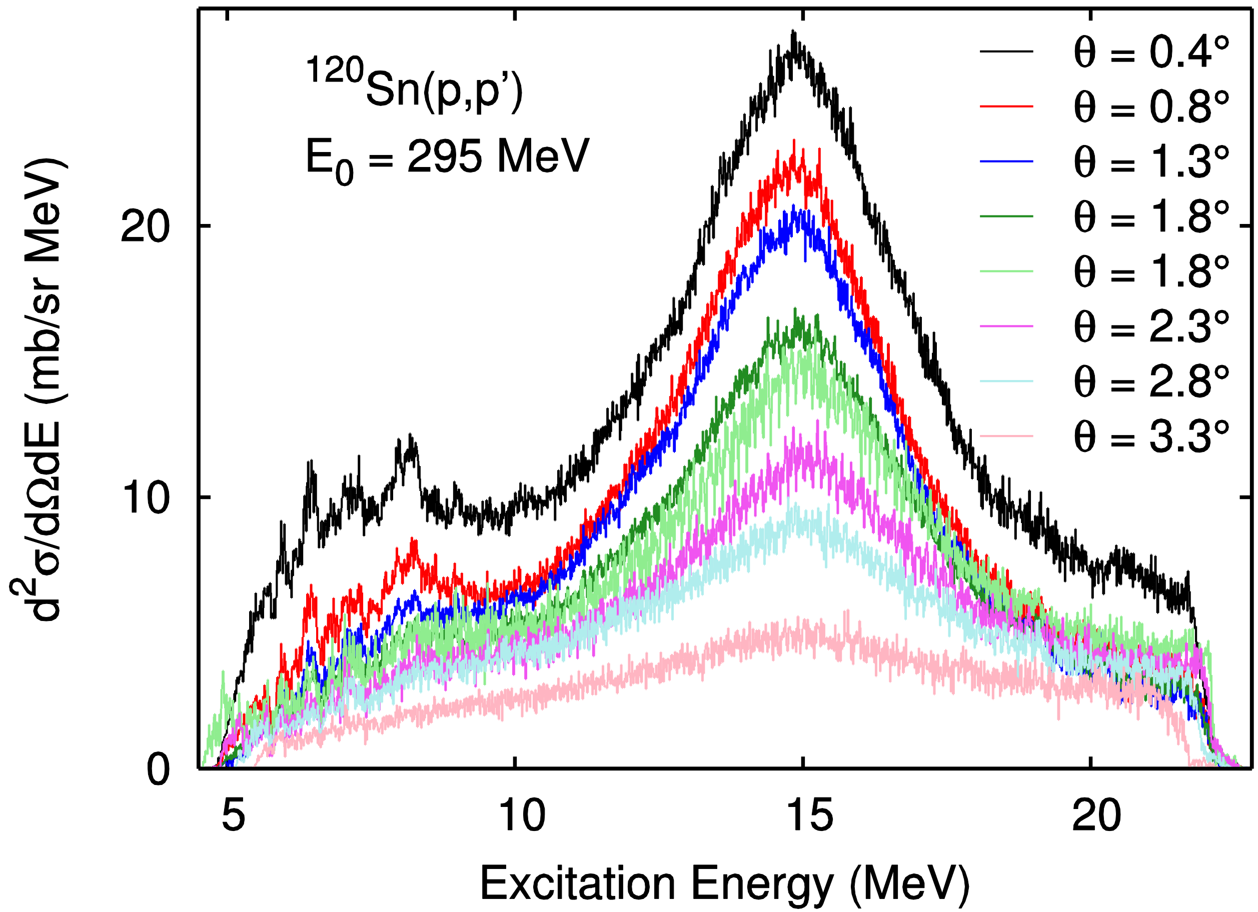
A. Tamii, PvNC, I. Poltoratska, Eur. Phys. J. A 50, 28 (2014)

Low-Energy E1 Strength in Tin Isotopes



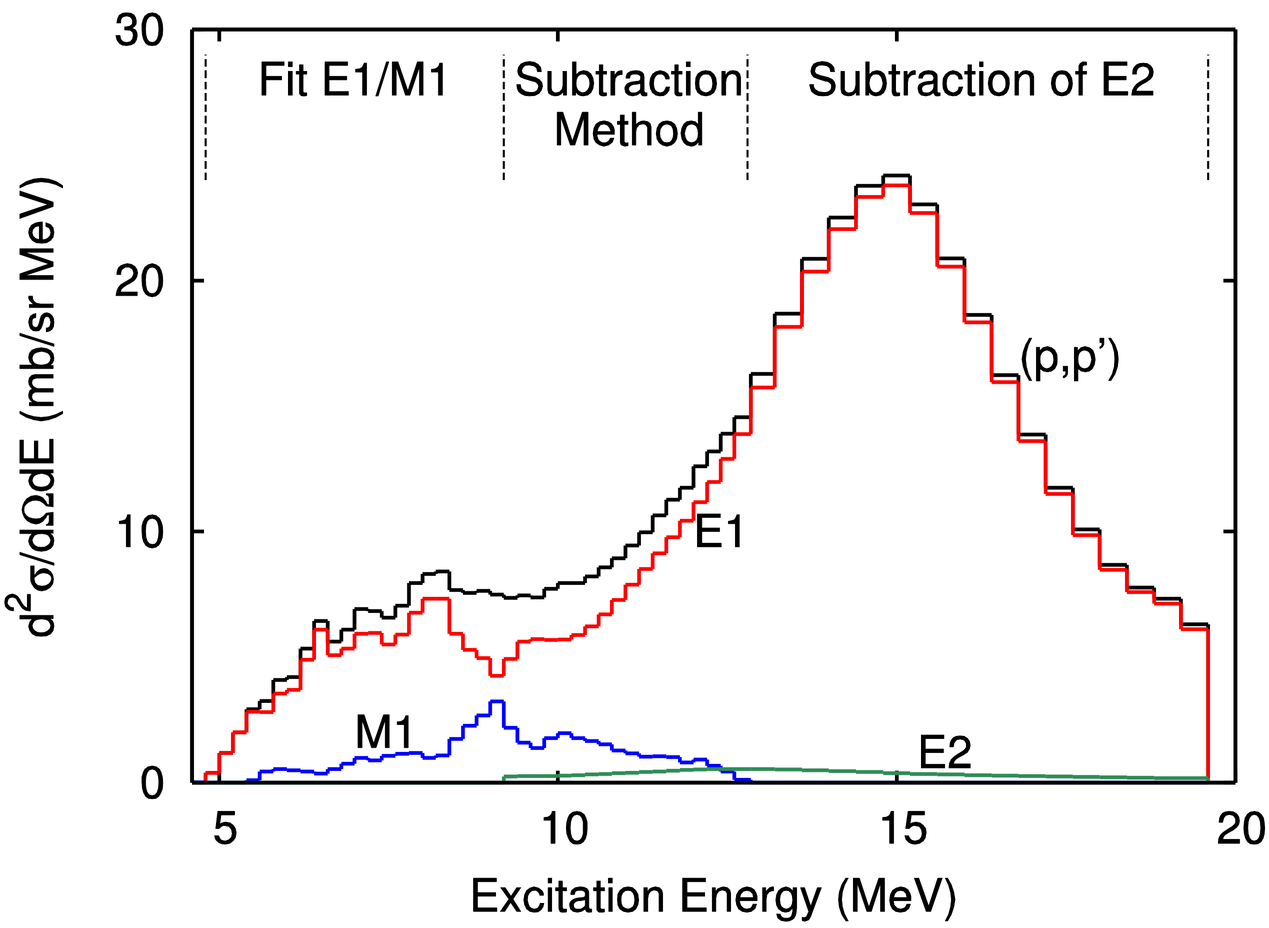
K. Govaert et al., Phys. Rev. C 58, 2229 (1998)
B. Özel-Tashenov et al., Phys. Rev. C 90, 024304 (2014)

^{120}Sn (p,p‘): Spectra

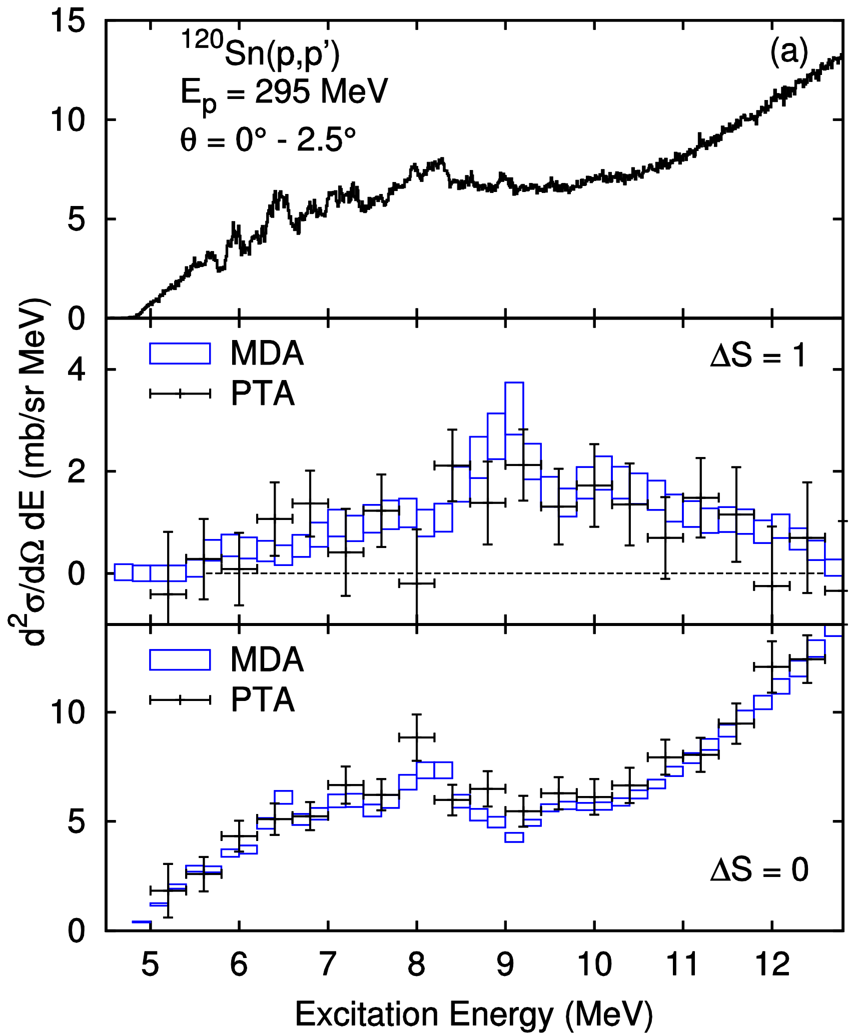


A.M. Krumbholz, Doctoral thesis, TU Darmstadt (2014)

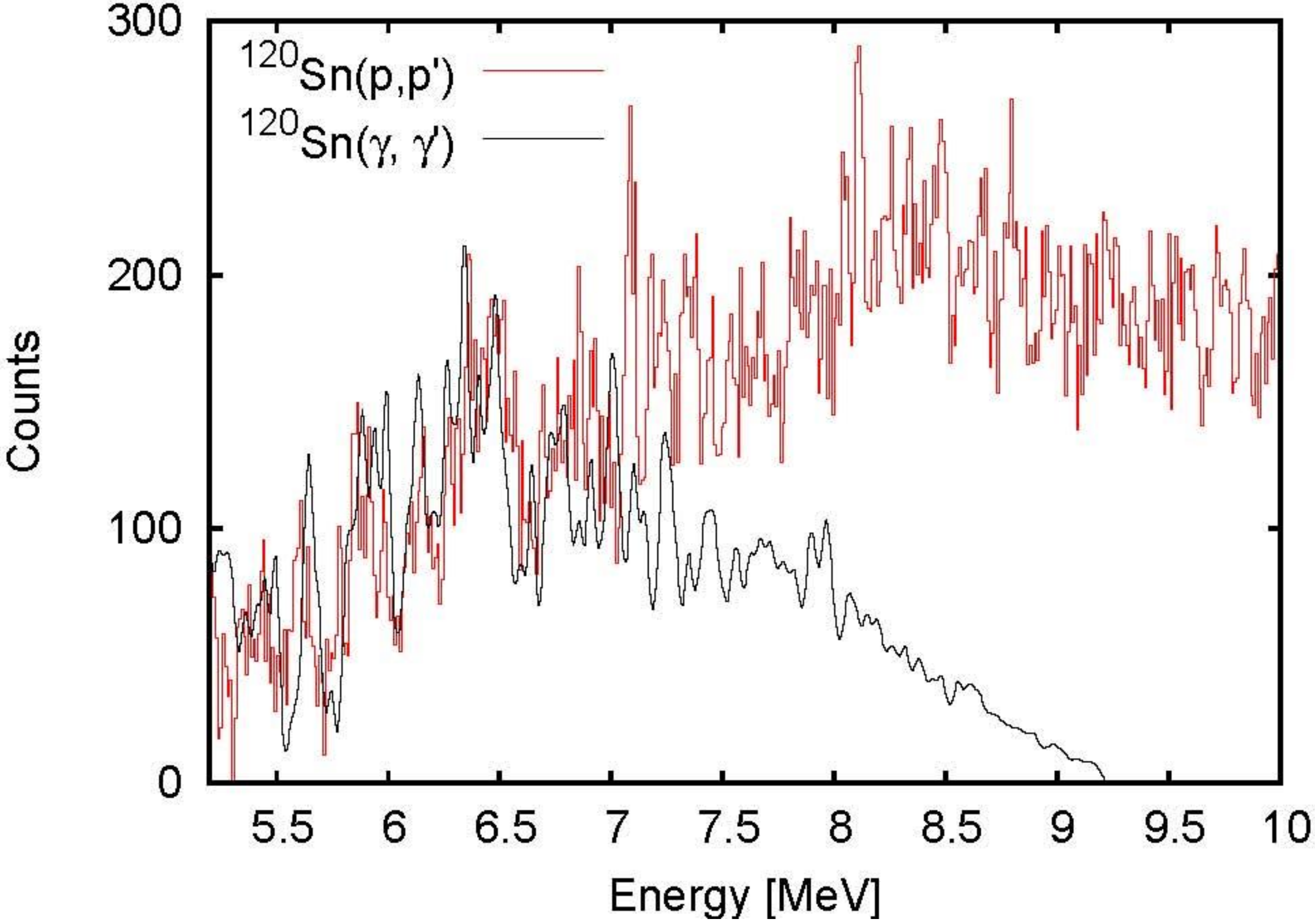
E1/M1 Decomposition



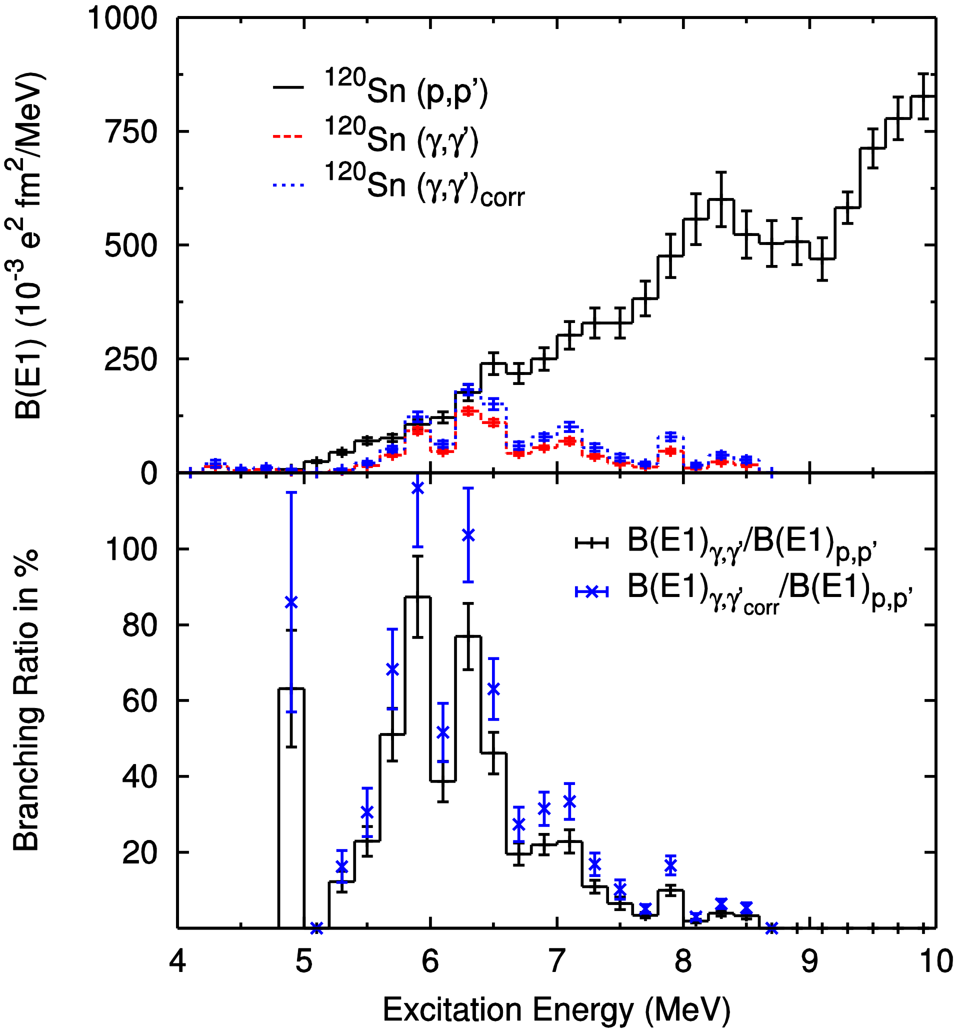
E1/M1 Decomposition



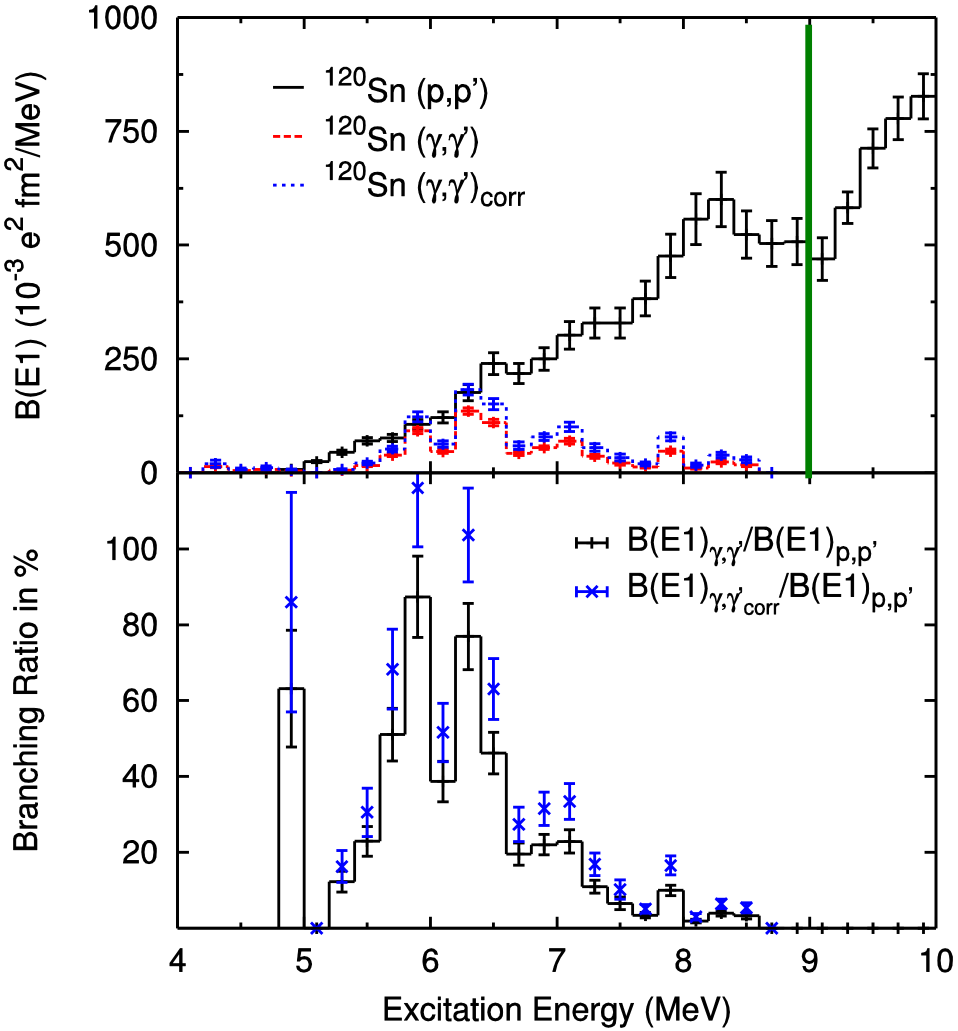
^{120}Sn(p,p‘) vs. (γ,γ‘)



^{120}Sn: Low-Energy E1 Strength



^{120}Sn: Low-Energy E1 Strength



E1 strength up to 9 MeV:

about 2.4% of EWSR

about 9% of α_D

^{120}Sn: Low-Energy E1 Strength

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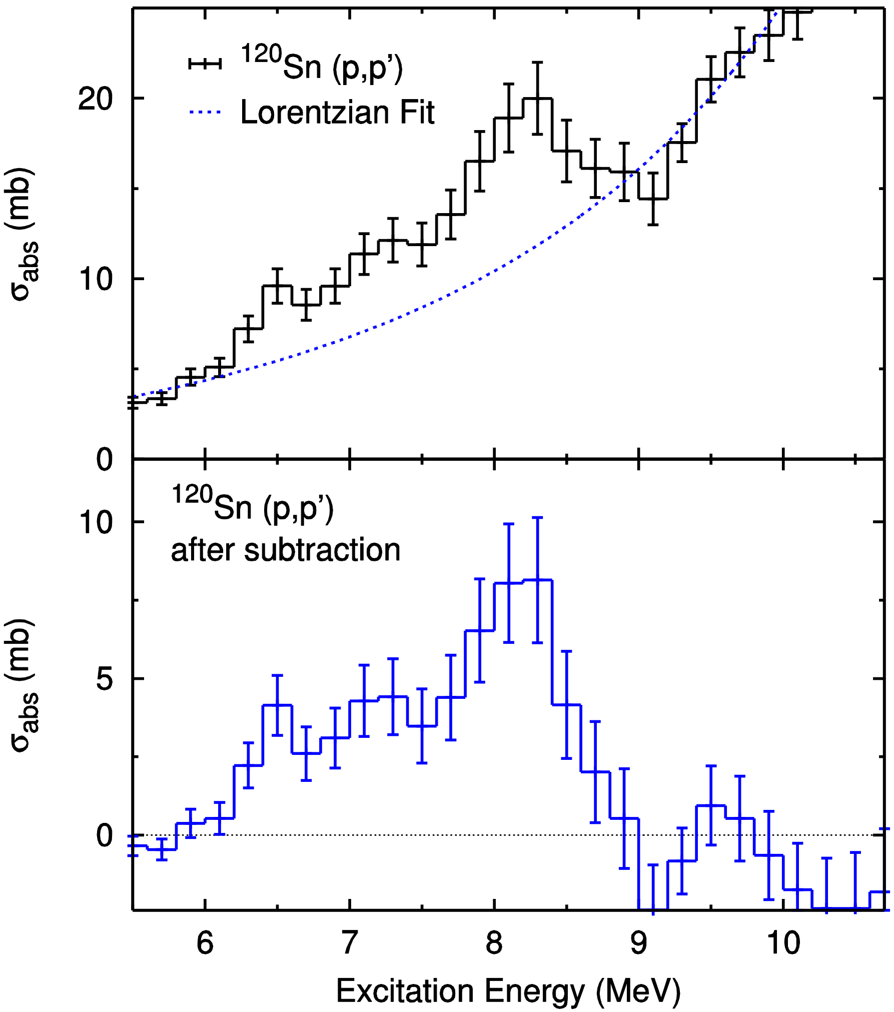
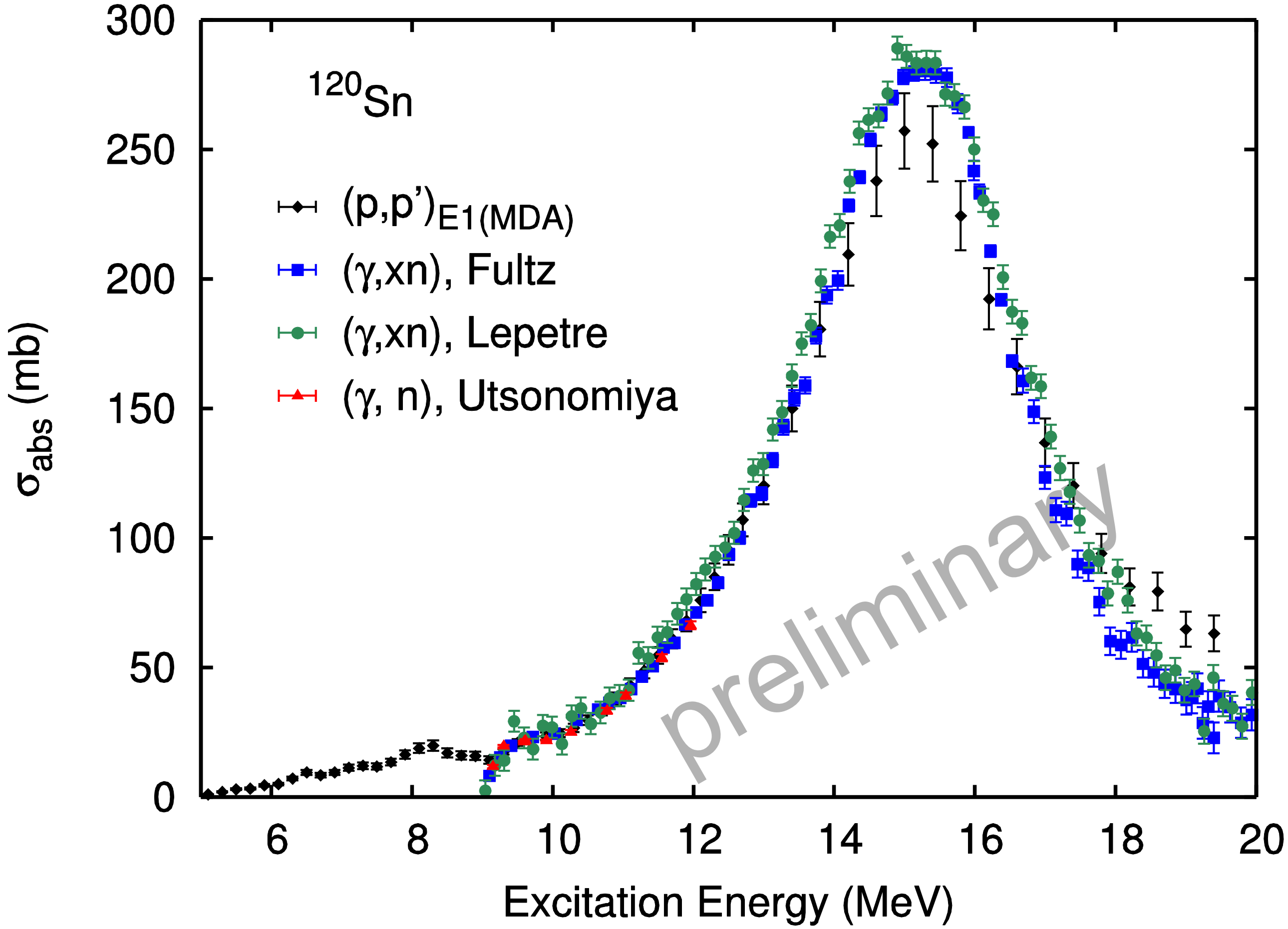
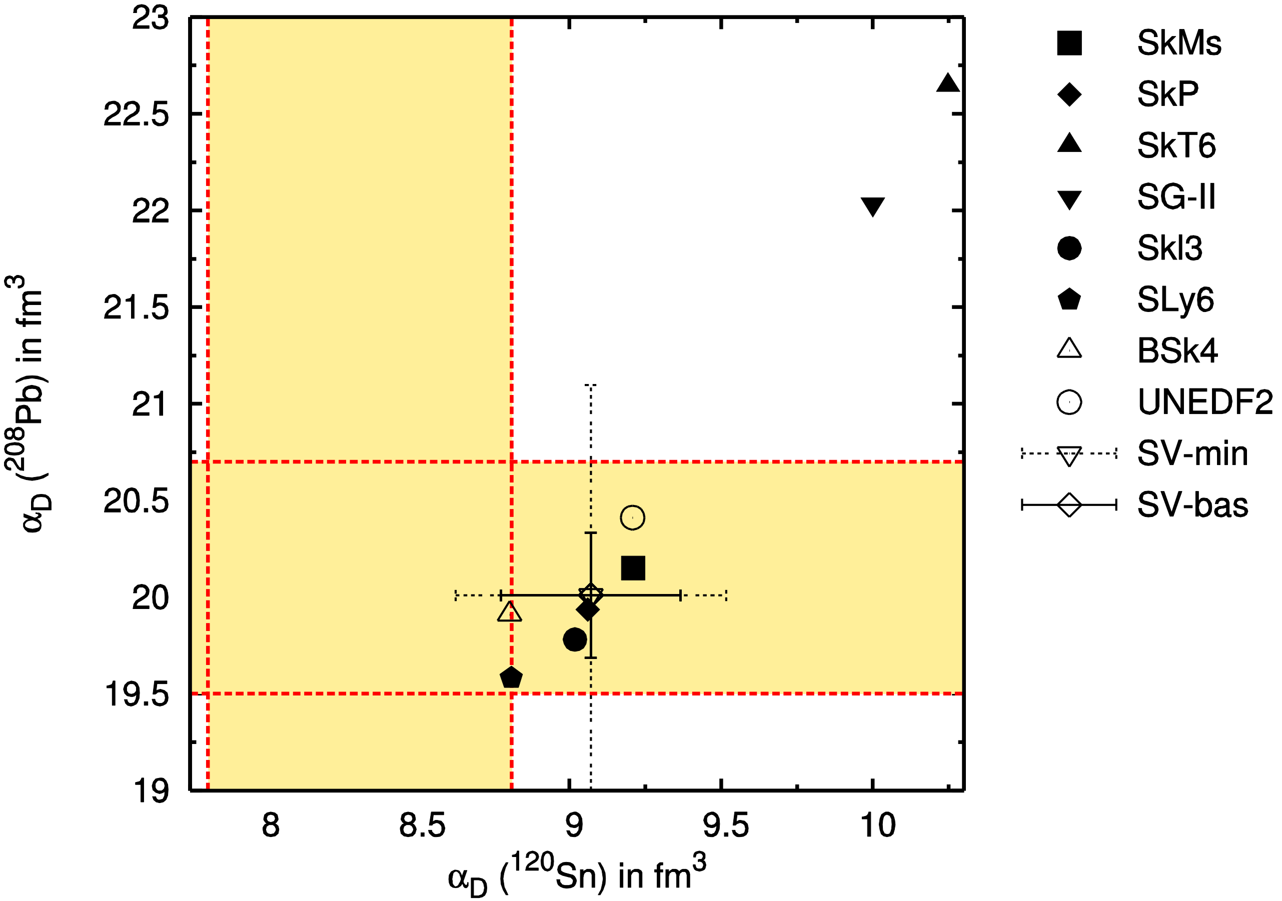


^{120}Sn: Photoabsorption in the GDR Region



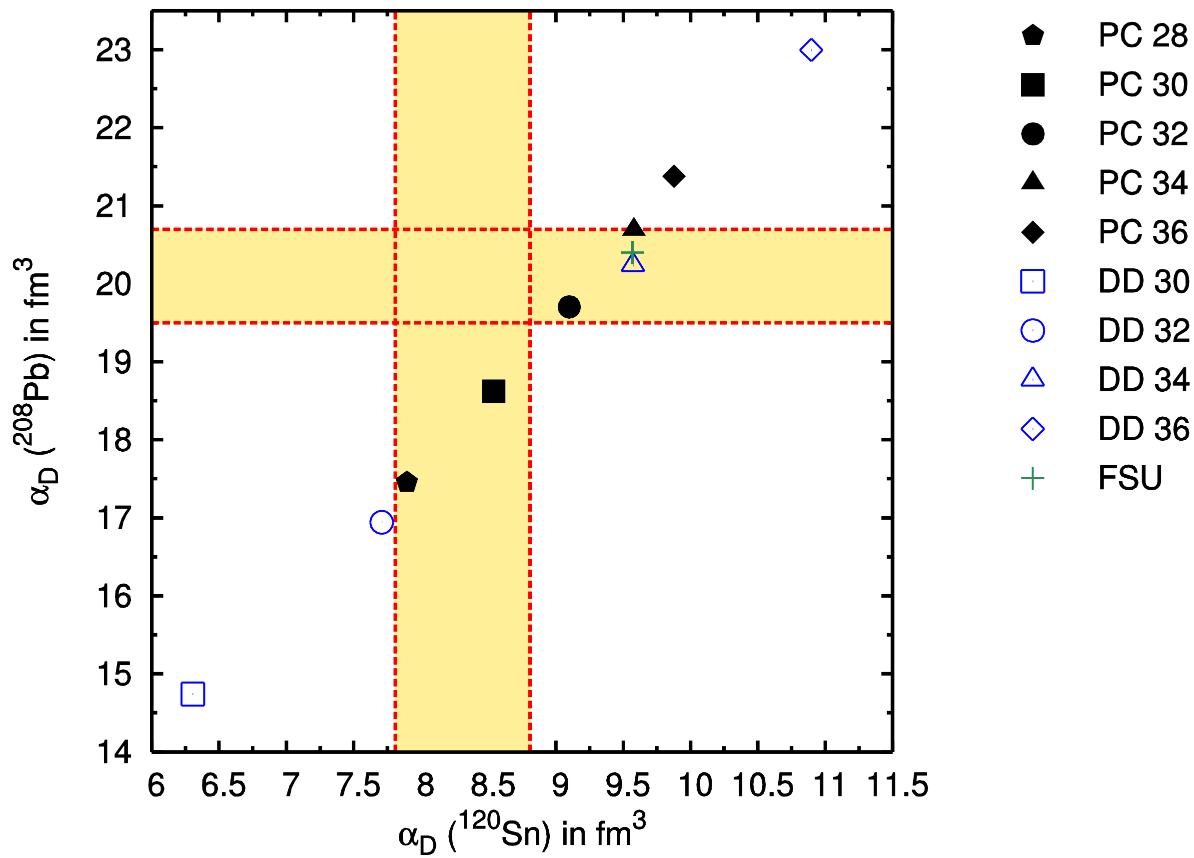
S.C. Fultz et al., Phys. Rev. 186, 1255 (1969)
A. Leprêtre et al., Nucl. Phys. A 219, 39 (1974)
H. Utsunomiya et al., Phys. Rev. C 84, 055805 (2011)

Polarizability: Constraints on Skyrme models



SKMs - BSK4: see M. Bender, P.-H. Heenen, and P.-G. Reinhard, Rev. Mod. Phys. 75, 121 (2003)
UNEDEF2: M. Kortelainen et al., Phys. Rev. C 89, 054314 (2014)
SV-min, SV-bas: P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 87, 014324 (2013)

Polarizability: Constraints on RMF models



PC: P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng, Phys. Rev. C 82, 054319 (2010)
DD: G. A. Lalazissis, T. Nikši´c, D. Vretenar, and P. Ring, Phys. Rev. C 71, 024312 (2005)
FSU: J. Piekarewicz, Phys. Rev. C 73, 044325 (2006)

Conclusions

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- Polarized proton scattering at 0°: A tool to extract the complete E1 response

- ^{208}Pb

  - polarizability determined with high precision
  - related to neutron skin and symmetry energy (but model-dependent)
  - constrains neutron matter EOS defining the properties of neutron stars

- ^{120}Sn

  - low-energy E1 strength very different from (γ,γ‘)
  - α_D small compared to most mean-field models based on Skyrme forces
  - correlation of ^{208}Pb and ^{120}Sn cannot be described by RMF approaches

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What Can Be Learned from (p,p') Experiments at 0°?

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- Pygmy dipole resonance (PDR)
- Dipole polarizability

neutron skin and symmetry energy

improve Energy Density Functionals

- Level densities
- Gamma strength function

test of statistical approach in reaction network calculations

test of Axel-Brink hypothesis

- Fine structure of GDR

dominant decay mechanism

- Spin-flip M1 resonance

largely unexplored in heavy nuclei

Neutron Skin Thickness and Symmetry Energy

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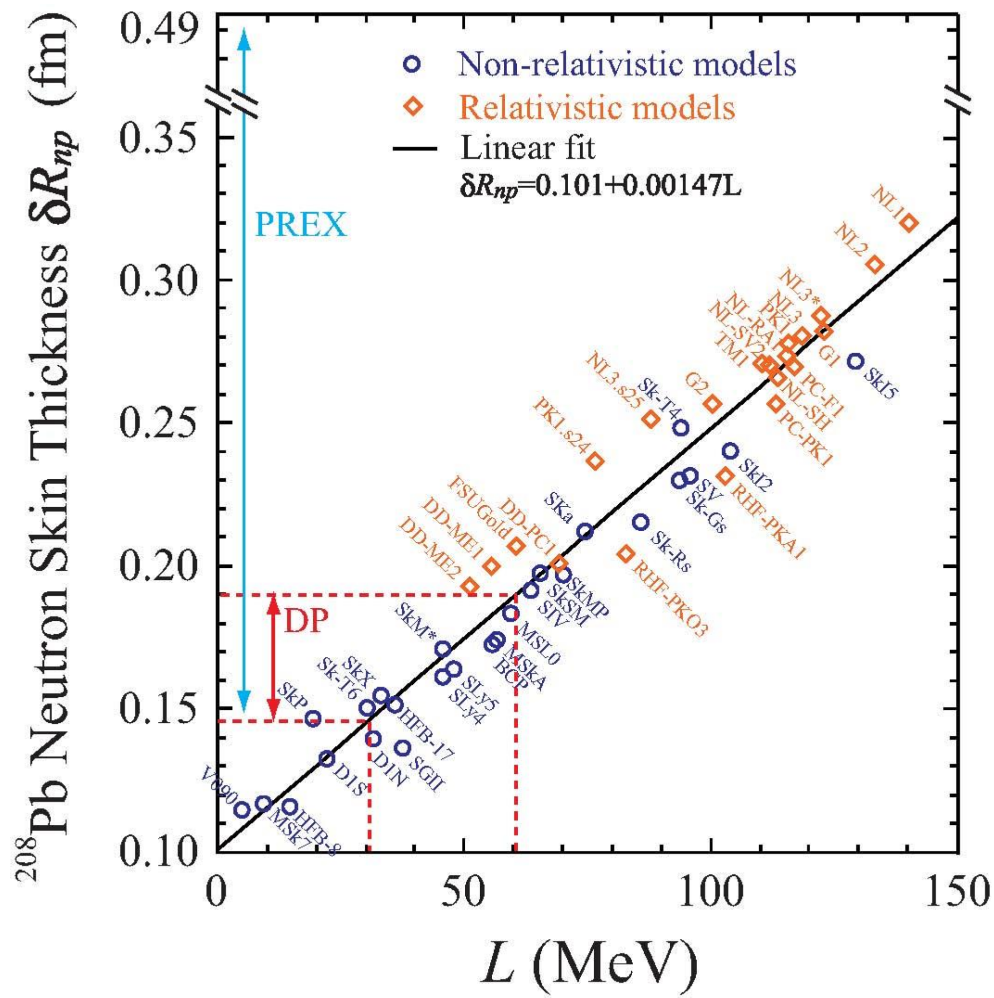
X. Roca-Maza et al., Phys.Rev. Lett. 106, 252501 (2011)



- Neutron skin thickness in ^{208}Pb translates into

  L = 46 ± 15 MeV

- In a similar fashion one finds

  J = 30.9 ± 1.5 MeV

A. Tamii, PvNC, I. Poltoratska, Eur. Phys. J. A 50, 28 (2104)

Neutron Skin Thickness and Symmetry Energy

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X. Roca-Maza et al., Phys.Rev. C 88 (2013) 024316