Electric Dipole Response of Nuclei and the Symmetry Energy of the Nuclear Equation of State

Atsushi Tamii

Research Center for Nuclear Physics (RCNP)
Osaka University, Japan

for RCNP-E282, E316 Collaborations

The 12th International Conference on Nucleus-Nucleus Collisions (NN2015), Catania, Italy, June 21st - 26th, 2015.

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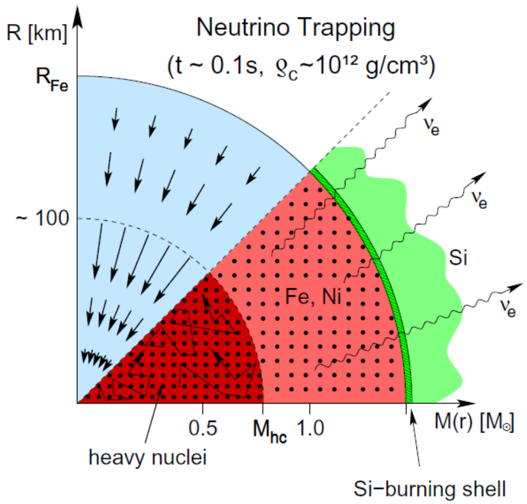
   ^{208}Pb and ^{120}Sn
   Constraints on the symmetry energy parameters

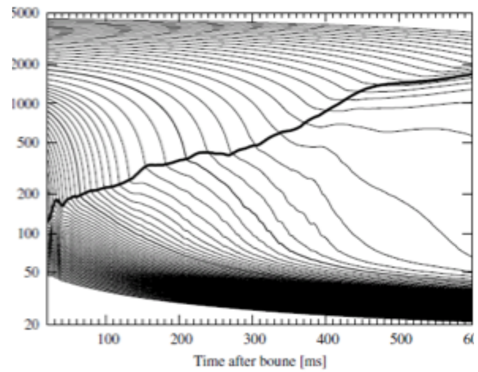
Symmetry Energy of Nuclear EOS

is important in nuclear physics and nuclear-astrophysics

Core-collapse supernova



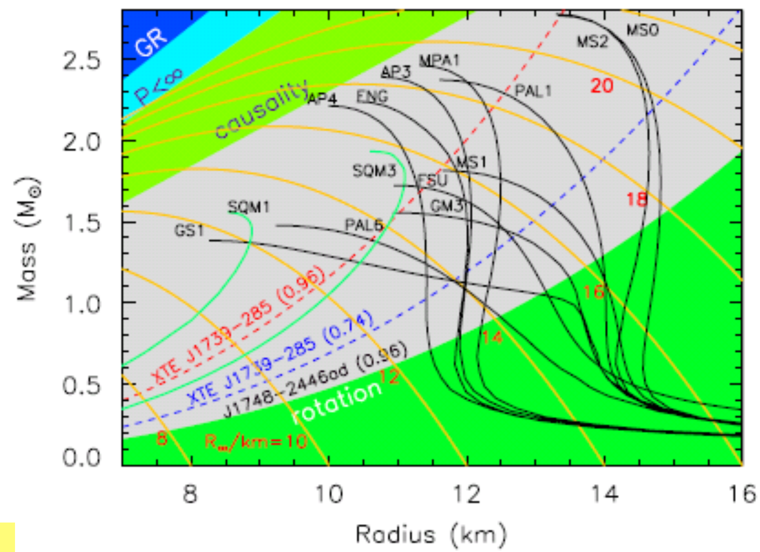
Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

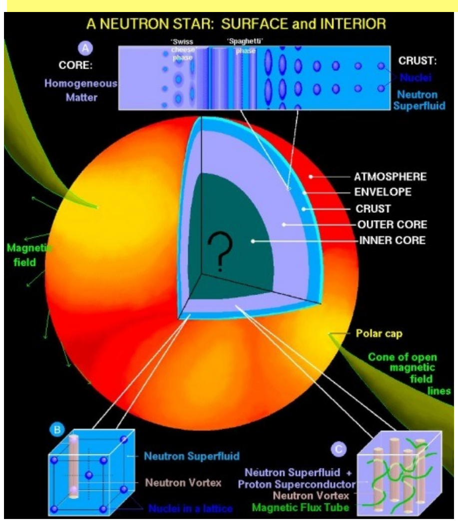
Nucleosynthesis

Neutron star mass vs radius



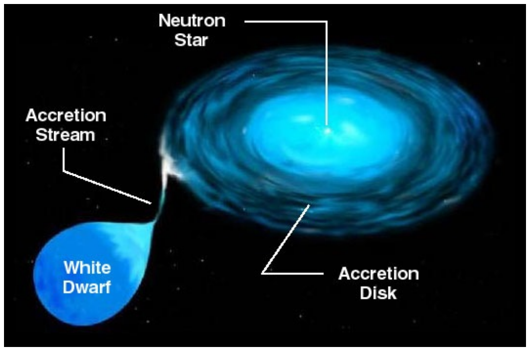
Lattimer et al., Phys. Rep. 442, 109(2007)

Neutron star structure

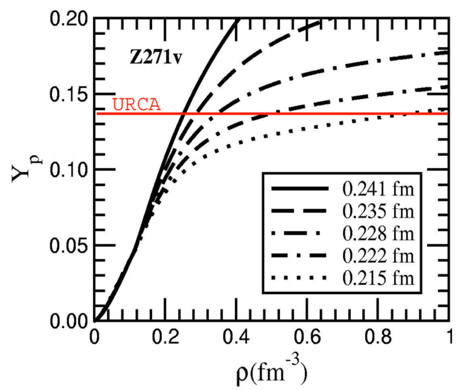


http://www.astro.umd.edu/~miller/nstar.html

Accreting neutron star X-ray burst



Neutron star cooling



Lattimer and Prakash, Science 304, 536 (2004).

Nuclear Equation of State (EOS)
at zero temperature

$$\rho(r) = \rho_n(r) + \rho_p(r)$$

$$\delta(r) = \frac{\rho_n(r) - \rho_p(r)}{\rho_n(r) + \rho_p(r)}$$

EOS for Energy per nucleon

$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho, 0) + S(\rho)\delta^2 + \ldots$$

Symmetry energy

ρ_0 : Saturation Density ~0.16 fm^{-3}

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \ldots$$

S: symmetry energy at the saturation density
L (slope parameter): density dependence

Determination of the symmetry energy parameters especially L is becoming important.

$$L \propto P \propto R^4_{\mathrm{n-star}}$$

(Baryonic Pressure)

Nuclear Equation of State (EOS)

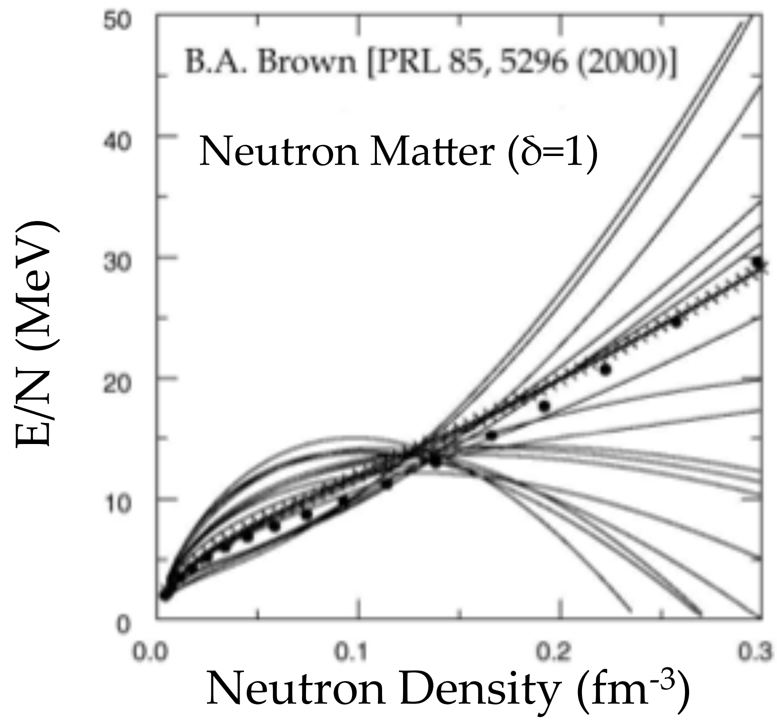
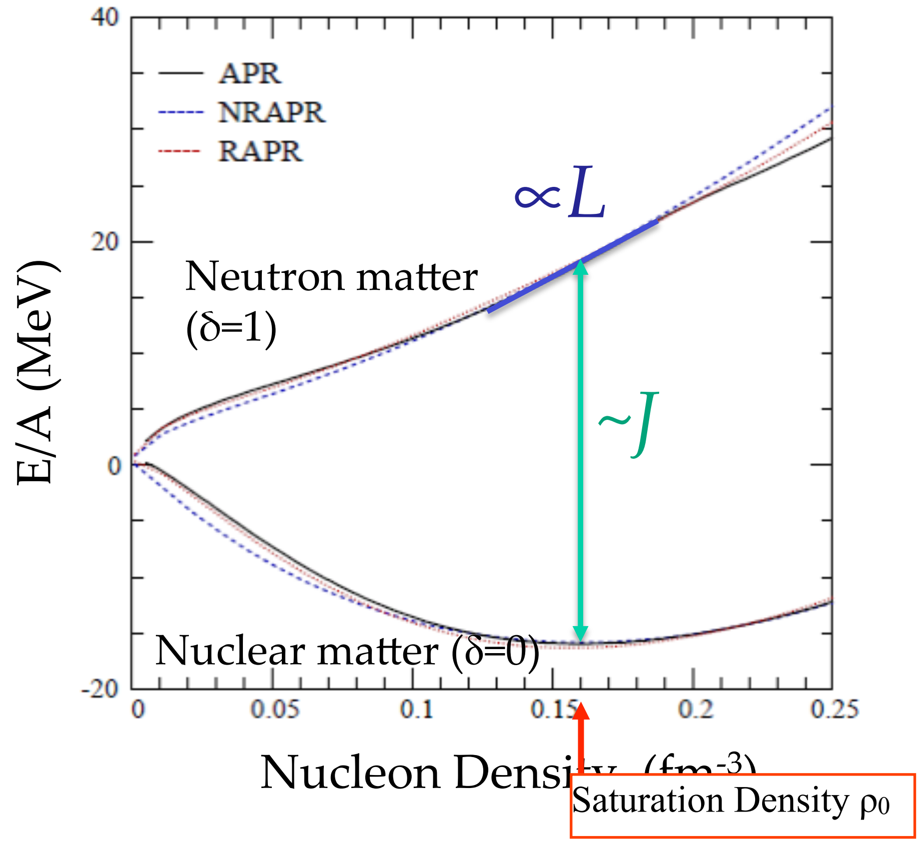


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.



Steiner et al., Phys. Rep. 411 325(2005)

Prediction of the neutron matter EOS is much model dependent.

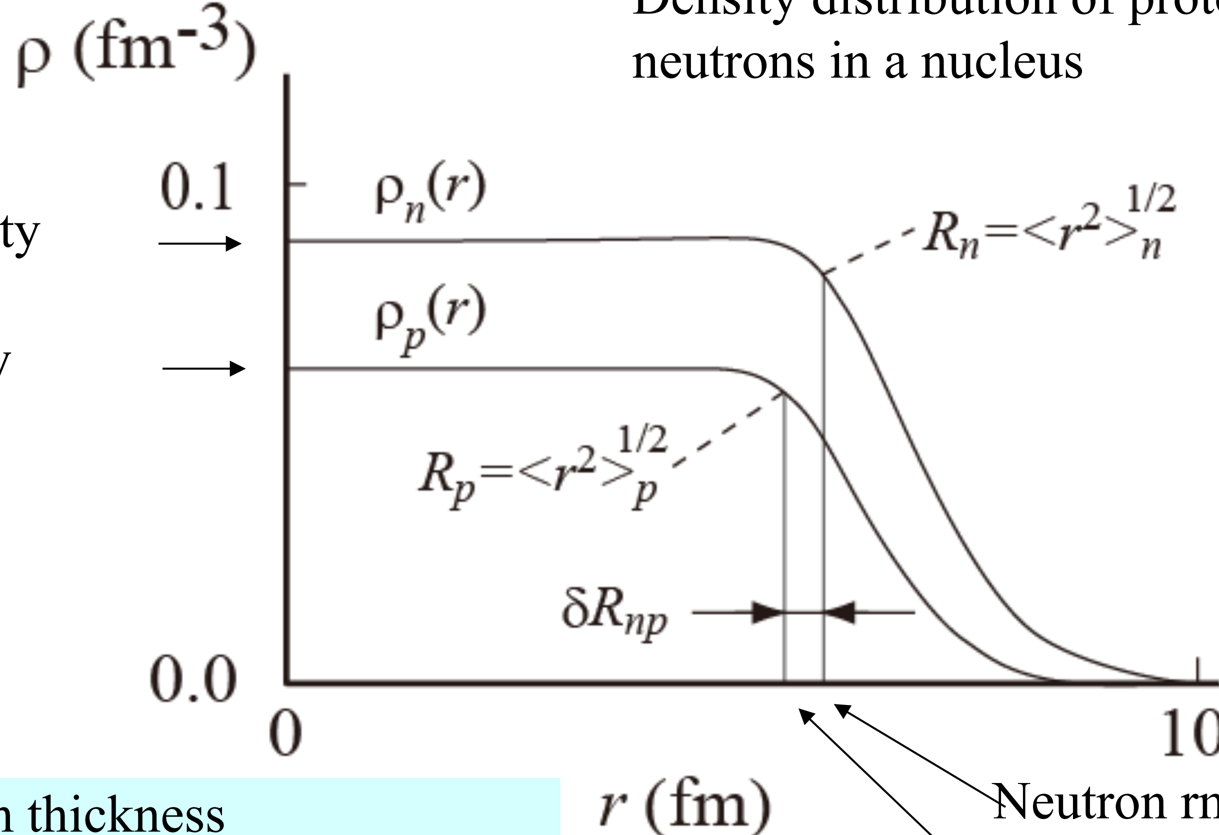
Neutron Skin and Density Dependence of the Symmetry Energy

Density distribution of protons and neutrons in a nucleus

^{208}Pb

Neutron density →

Proton density →



Neutron rms radius

Proton rms radius

Neutron skin thickness

⇕

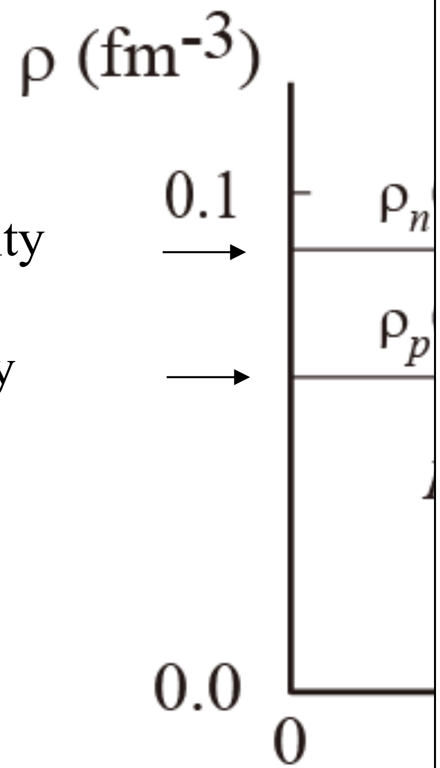
Density dependence of the symmetry energy

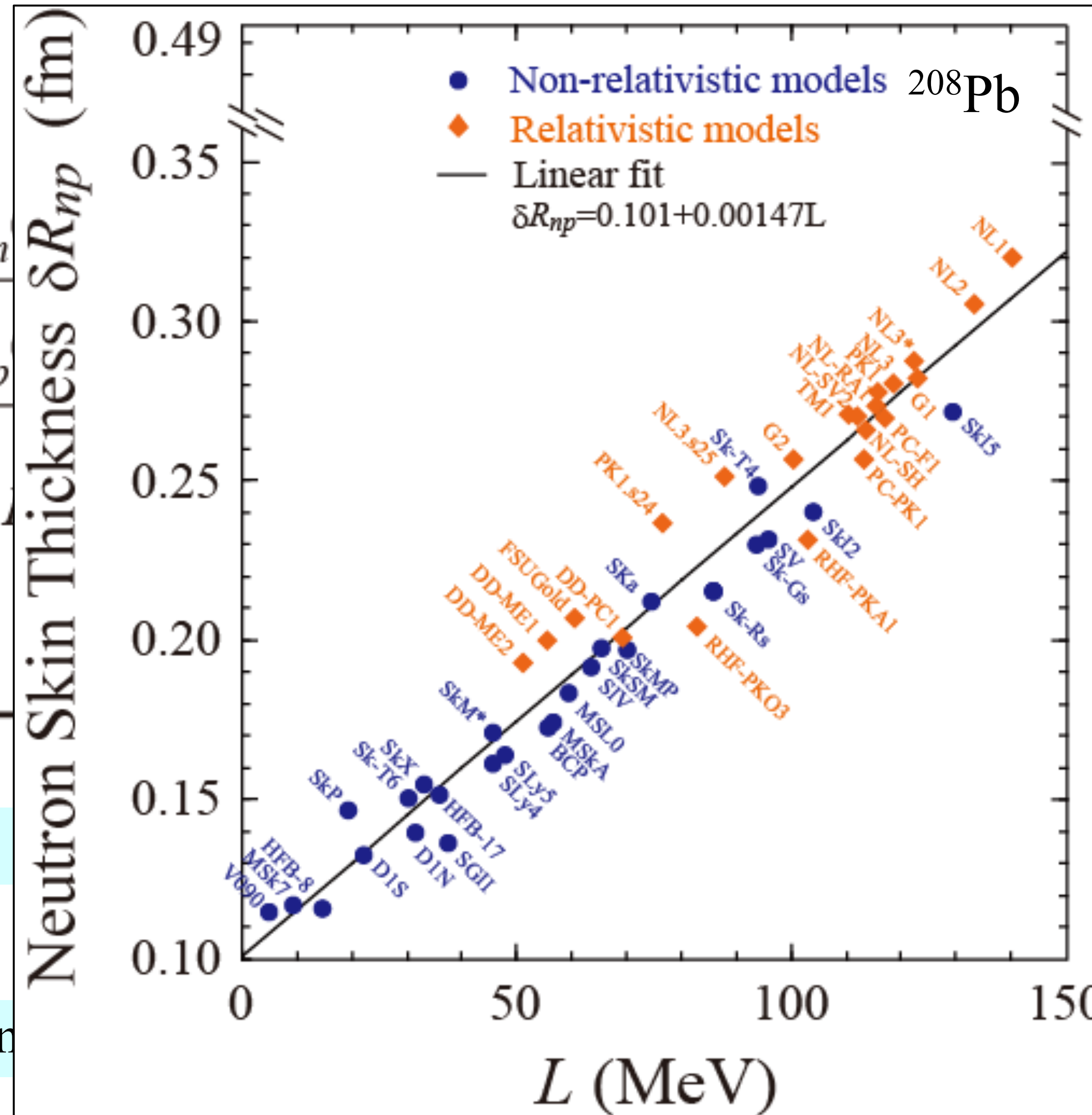
Neutron Skin and Density Dependence of the Symmetry Energy

X. Roca-Maza *et al.*, PRL**106**, 252501 (2011)

Neutron density

Proton density



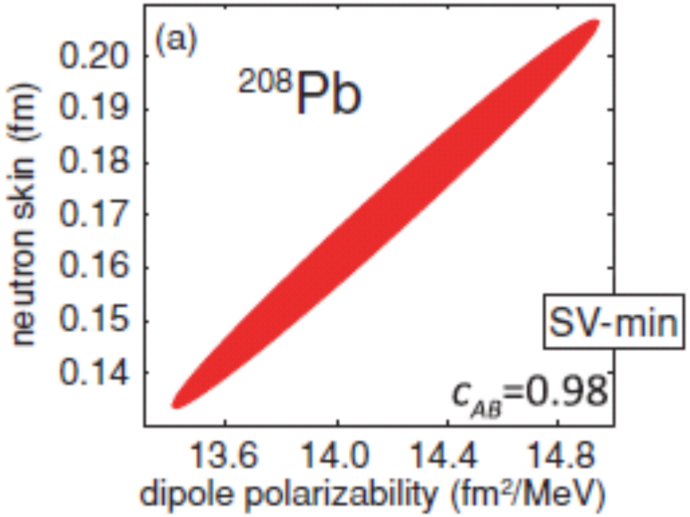


Neutron skin thickness

Density dependence of the symm

Correlation Between the Dipole Polarizability (α_D) and L (and the neutron skin thickness)

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

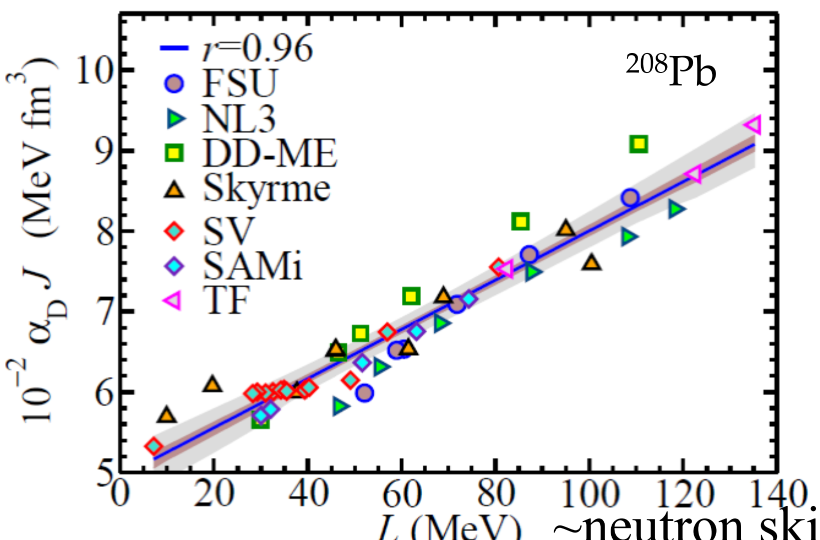


~L

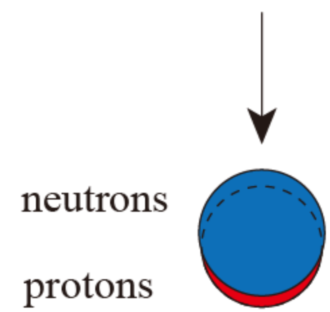
(α_D)

Strong correlation between the dipole polarizability and the neutron skin of ^{208}Pb

X. Roca-Maza *et al.*, PRC**88**, 024316(2013)



~neutron skin thickness



$$\vec{P} = \alpha_D \vec{E}$$

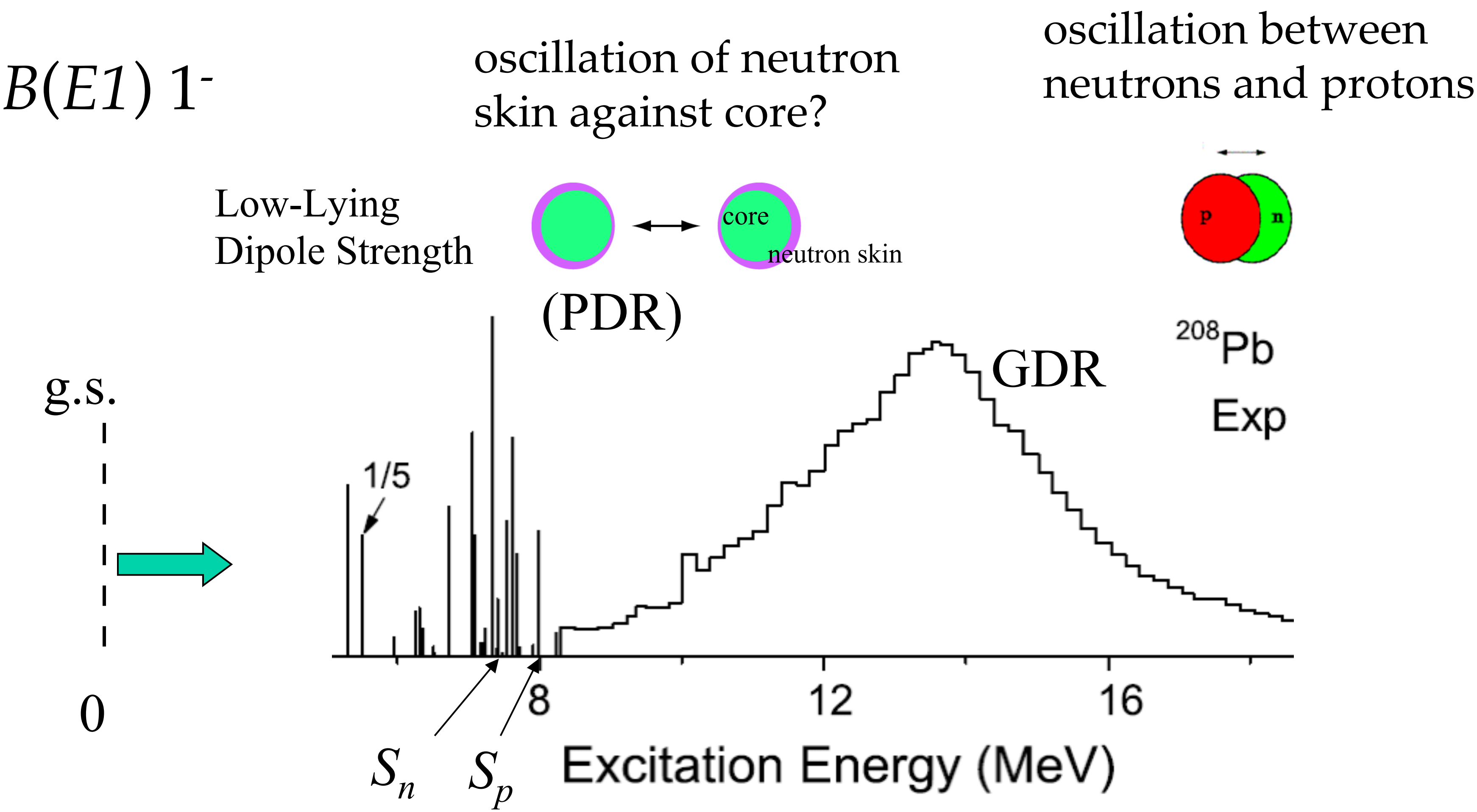
Electric Dipole Polarizability

Restoring force ← symmetry energy

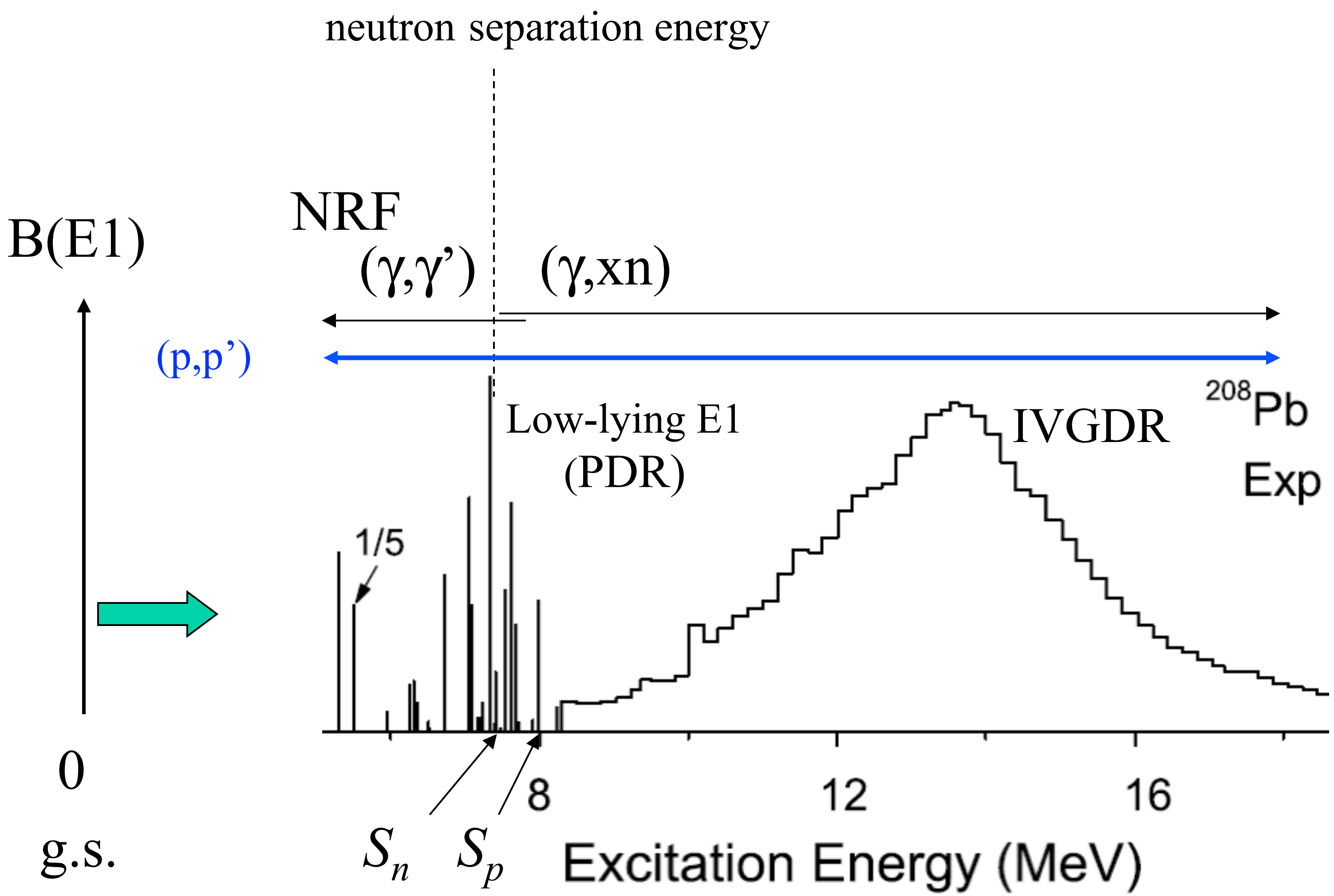
Inversely energy weighted sum-rule of B(E1)

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

Electric Dipole Response of Nuclei

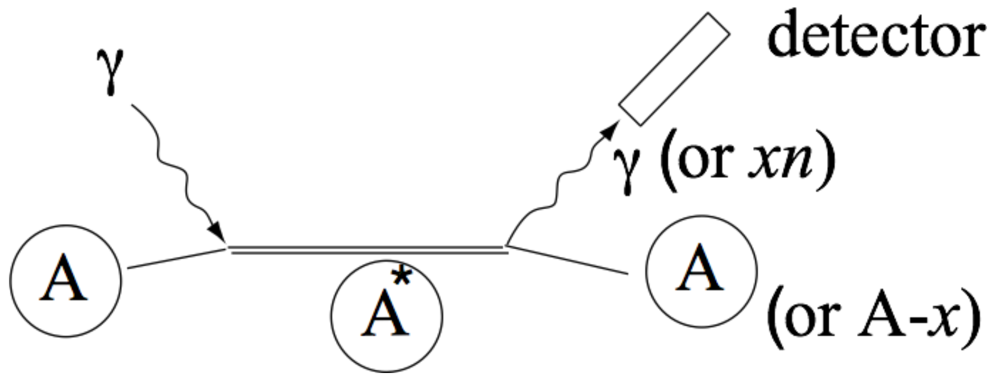


Electric Dipole (E1) Response of Heavy Nuclei



Probing the EM response of the target nucleus

Real Photon Measurements, NRF or (γ,xn)

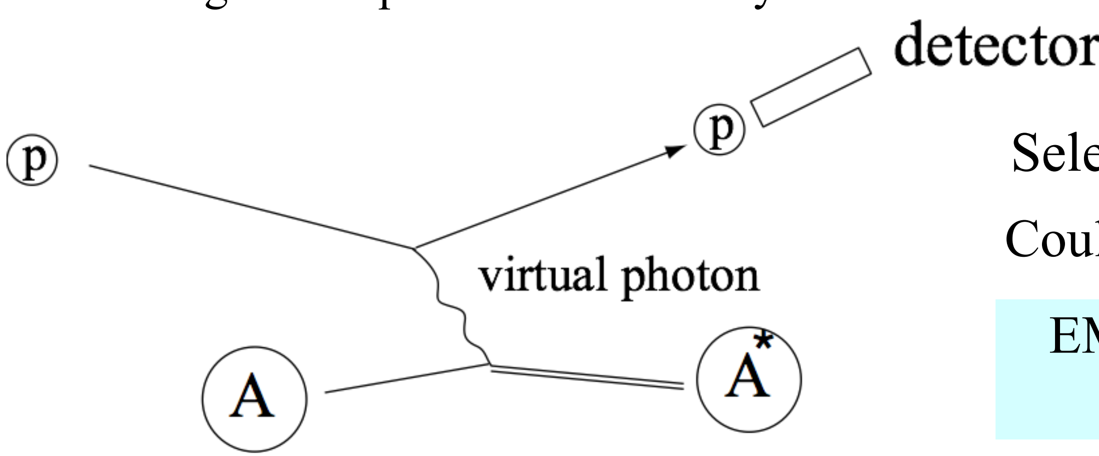


Decay γ or *n* is detected.

Missing Mass Spectroscopy with Virtual Photon

Only the excitation part is probed.
→ total strengths independent of the decay channel

Scattered *p* is detected.



Select *q*~0 (~0 deg.)

Coulomb excitation dominates

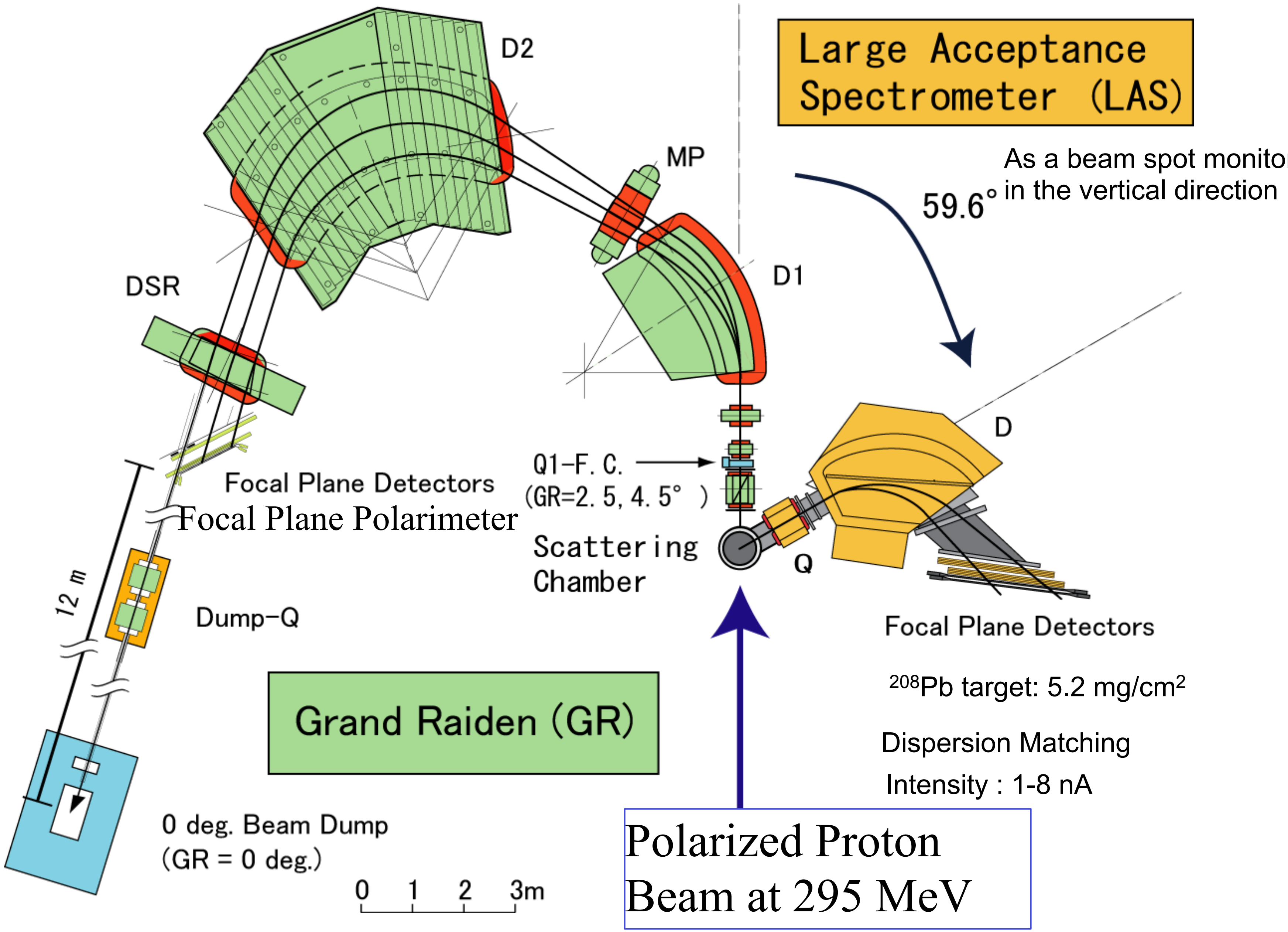
EM Interaction is well known
(model independent)

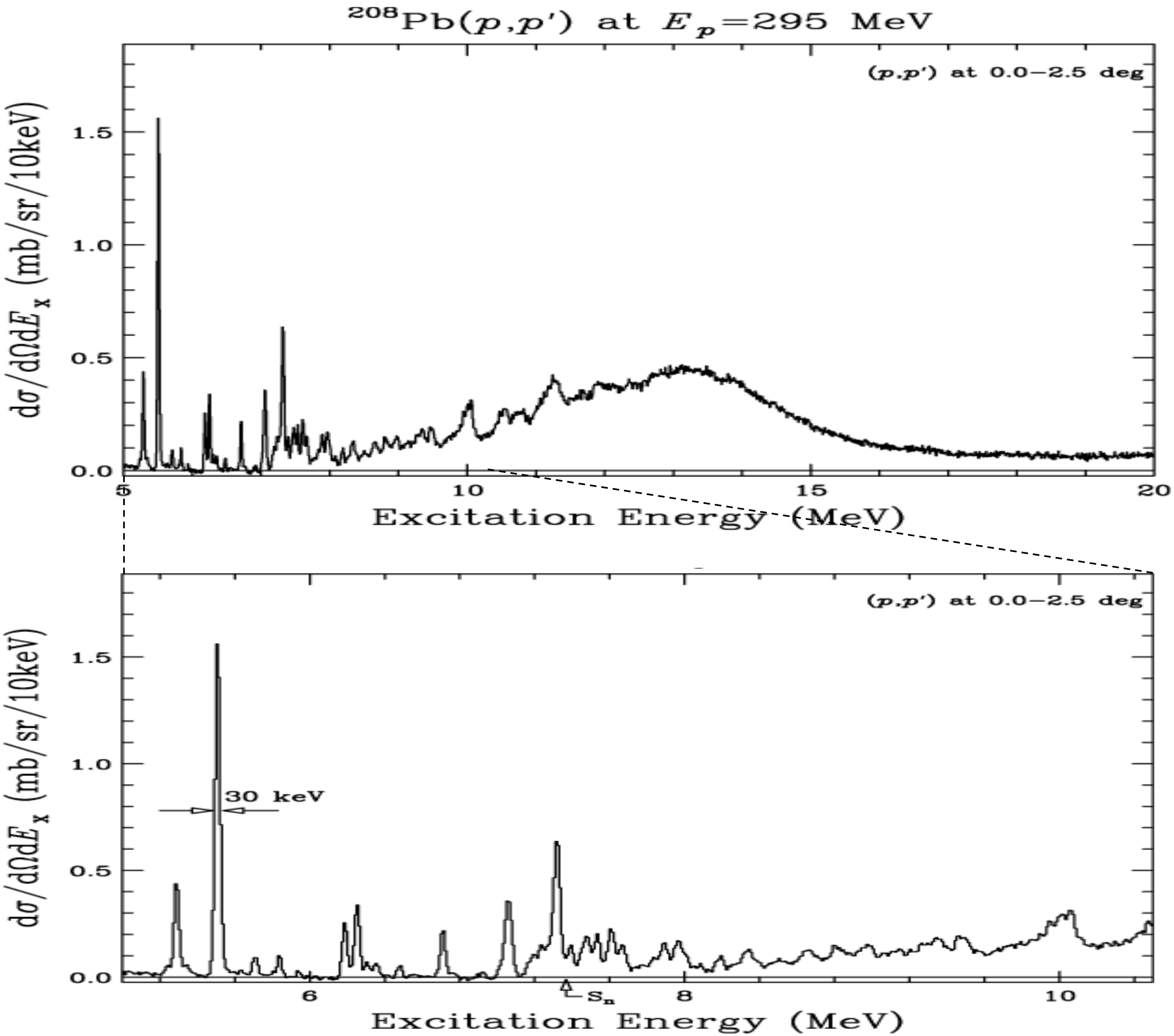
Experimental Method

High-resolution polarized (*p*,*p*’) measurement
at zero degrees and forward angles

Spectrometers in the 0-deg. experiment setup at RCNP, Osaka

AT et al., NIMA605, 326 (2009)

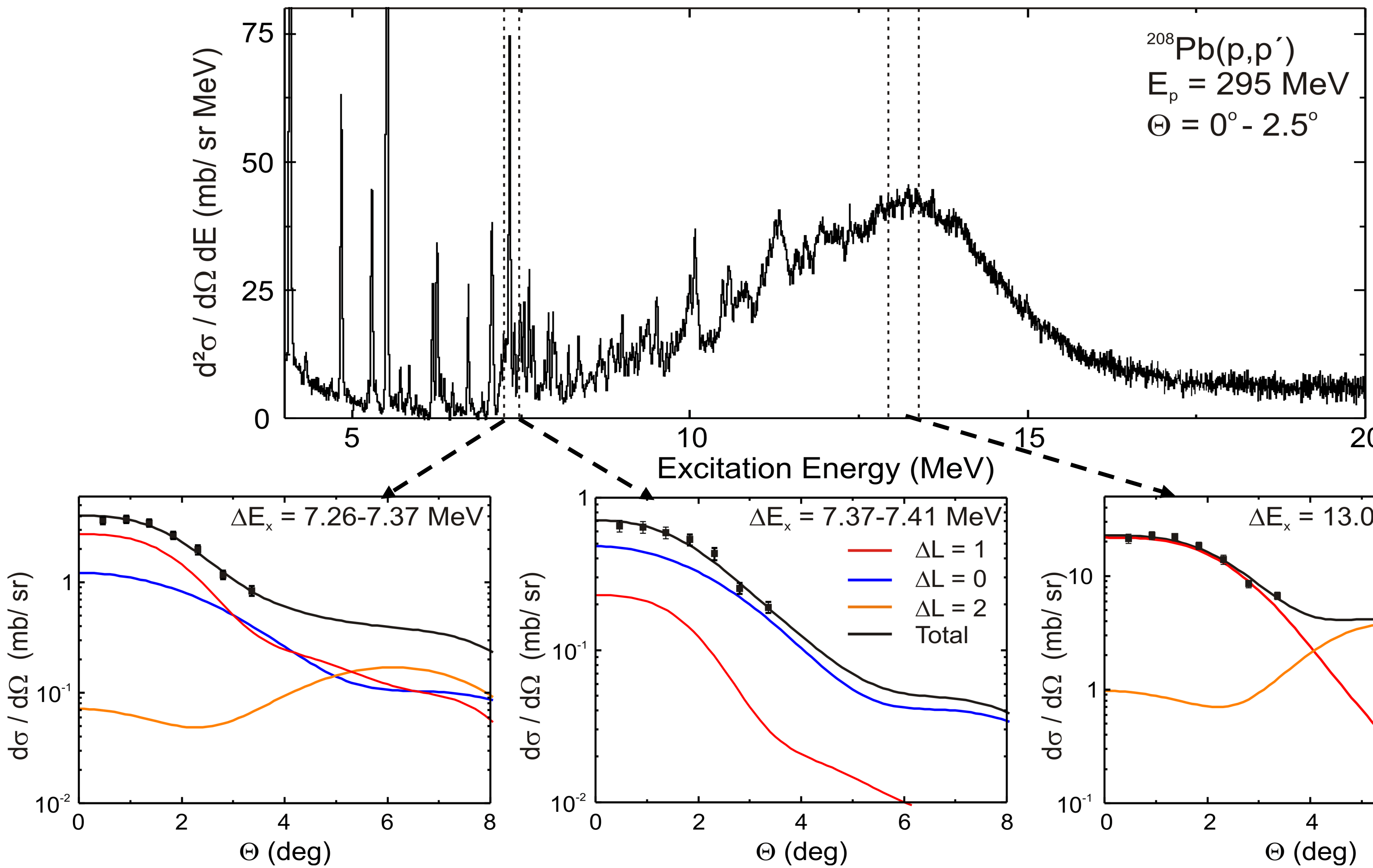




^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE$_x$ (mb/sr/10keV)
0.0
0.5
1.0
1.5
5
10
15
20
Excitation Energy (MeV)
(p,p') at 0.0–2.5 deg
30 keV
S_n
6
8
10
Excitation Energy (MeV)

B(E1): continuum and GDR region

Method 1: Multipole Decomposition



- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

B(E1): continuum and GDR region

Method 2: Decomposition by Spin Observables

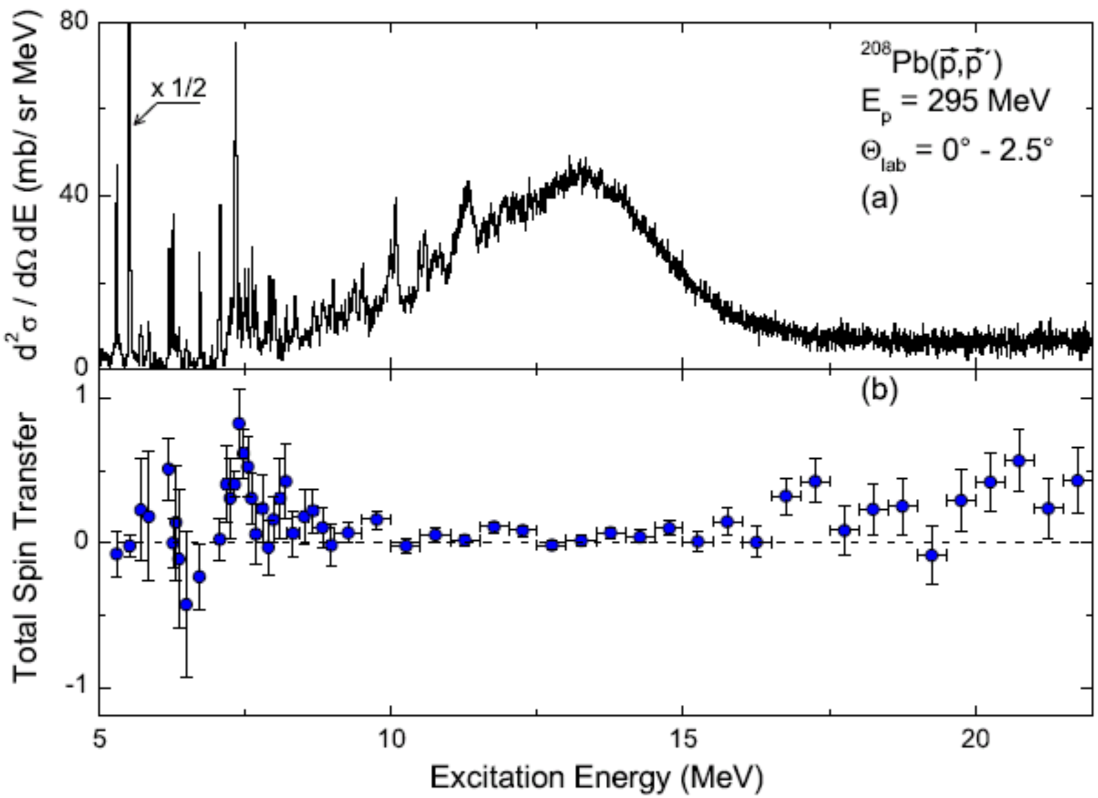
- Polarization observables at 0° ➡ spinflip / non-spinflip separation

model-independent

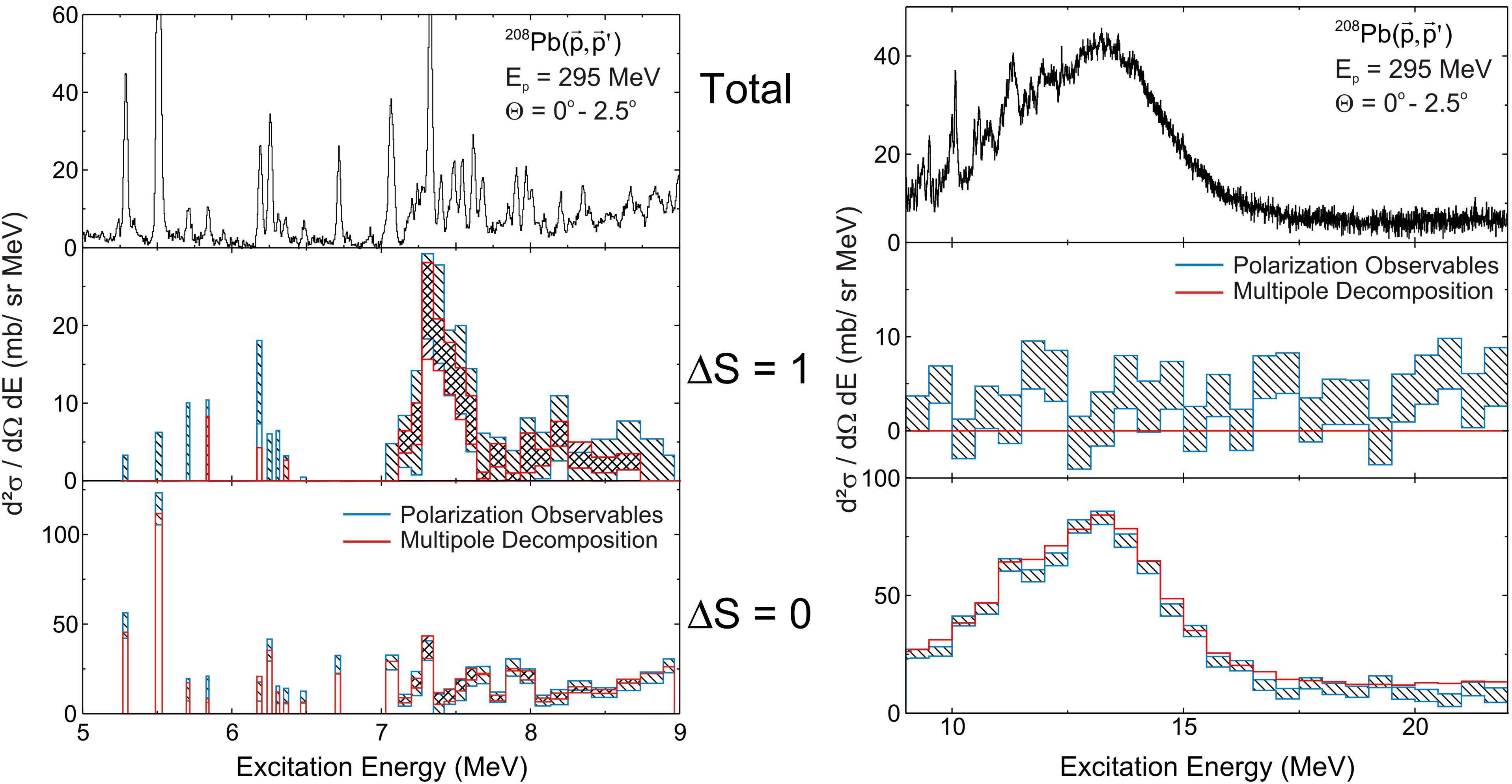
T. Suzuki, PTP 103 (2000) 859

E1 / spin-M1 decomposition

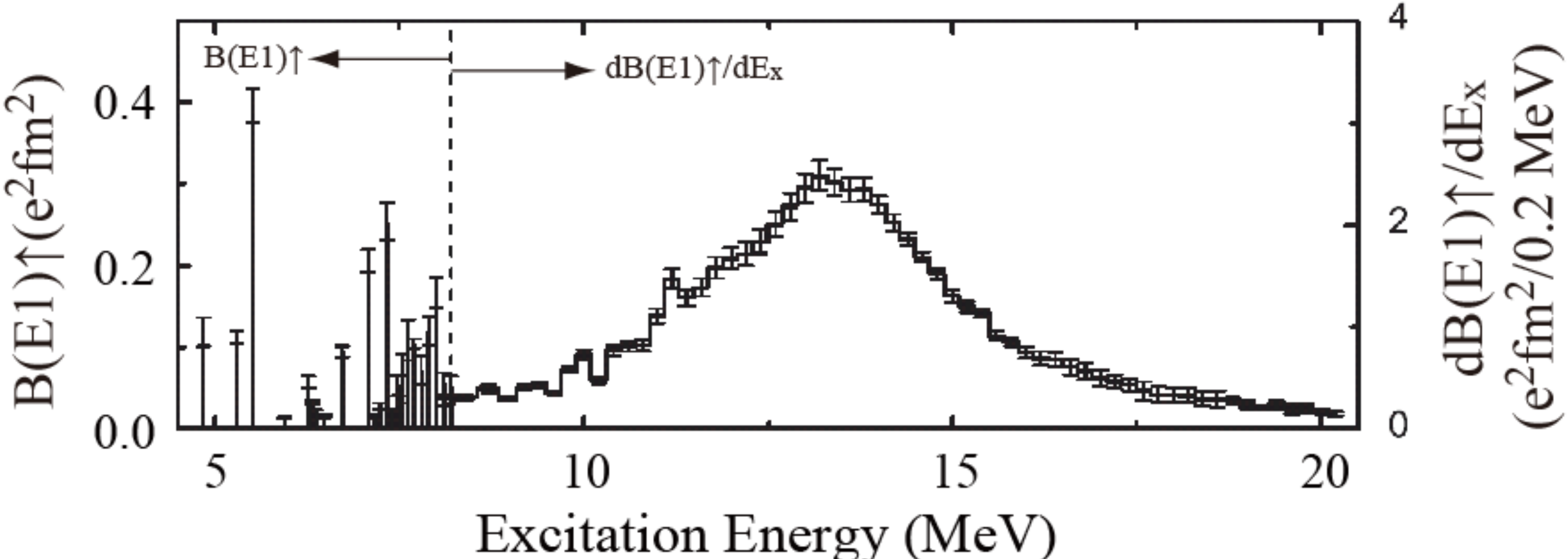
$$\text{Total Spin Transfer } \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 & \text{spin-M1} \\ 0 \text{ for } \Delta S = 0 & \text{E1} \end{cases}$$



Comparison between the two methods



E1 Response of ^{208}Pb and α_D



E_x 0 — 10 — 20 — 130 MeV

α_D 2.7 | 16.2 | 1.2 fm^3

total 20.1±0.6 fm^3

combined data

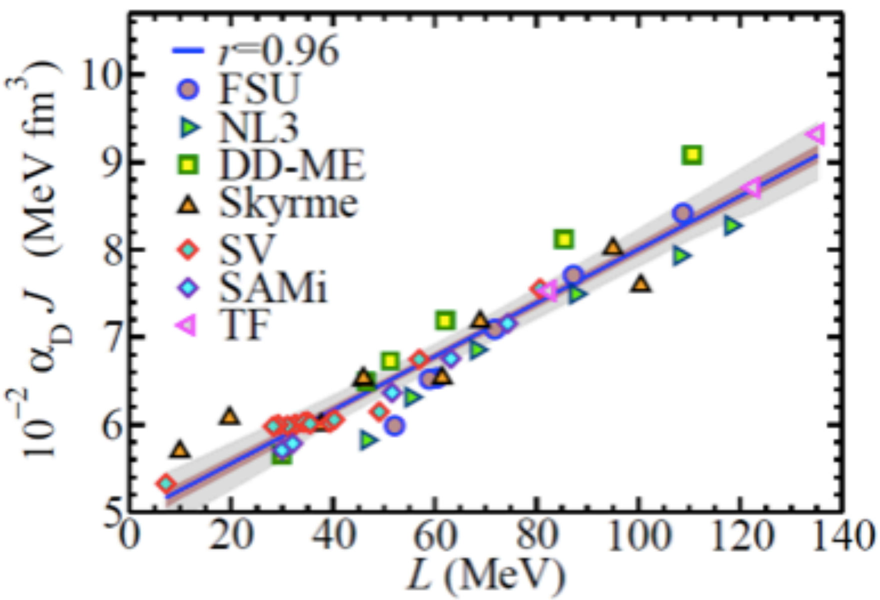
The dipole polarizability of ^{208}Pb has been precisely determined.

AT et al., PRL107, 062502(2011)

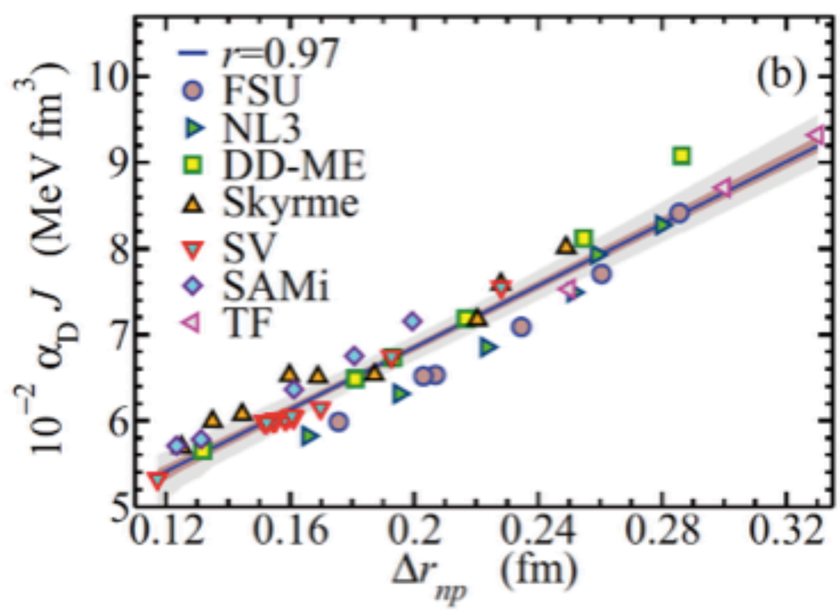
Constraints

X. Roca-Maza *et al.* PRC88, 024316 (2013)

Symmetry Energy Parameters



Neutron Skin Thickness

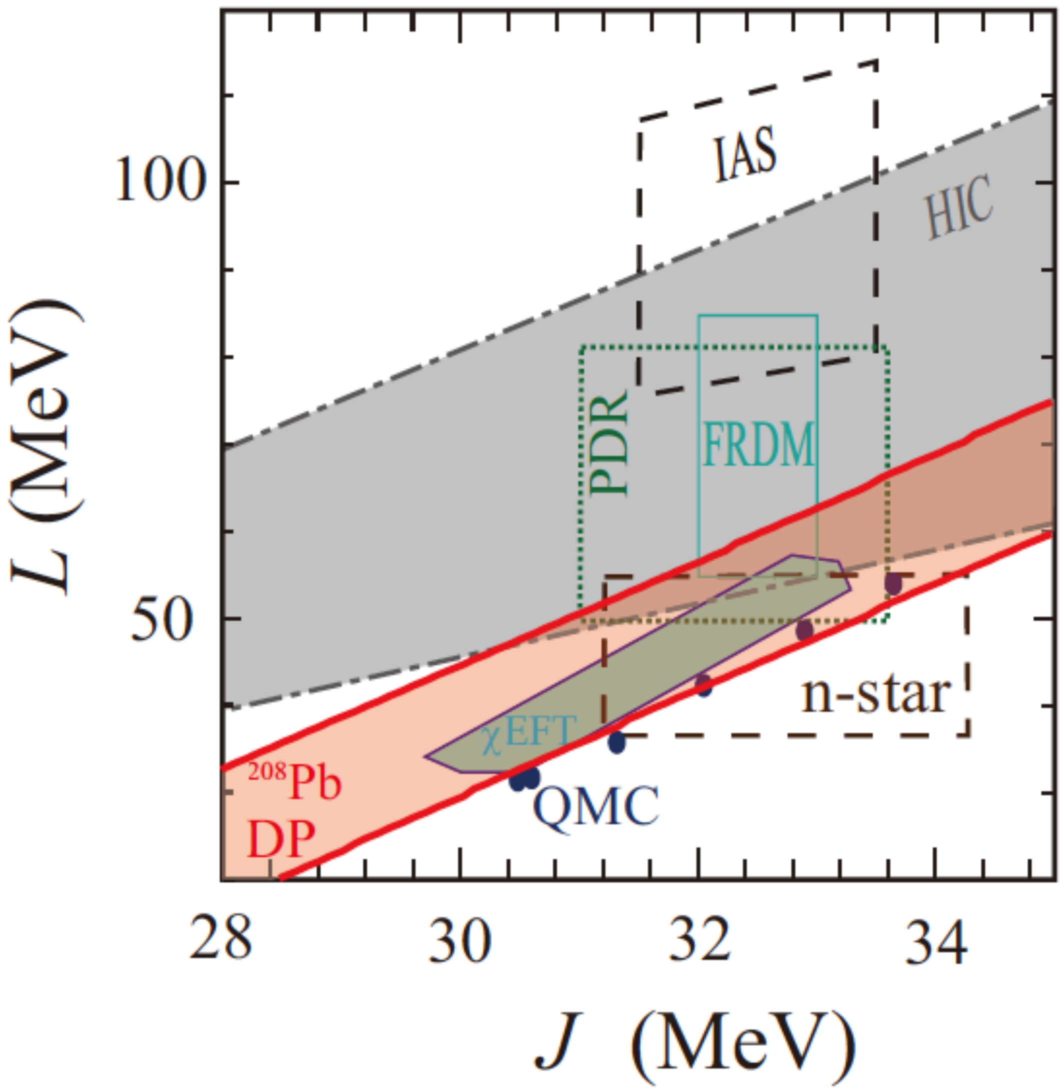


Experimental Value = α_D

→ Constraint in the *J*-*L* plane

$\Delta r_{np} = 0.165 \pm (0.009)_{expt}$
$\pm (0.013)_{theor} \pm (0.021)_{est}$ fm
for the estimated J=31 ± $(2)_{est}$

Constraints on J and L



AT et al., EPJA**50**, 28 (2014).

M.B. Tsang *et al.*, PRC**86**, 015803 (2012)

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

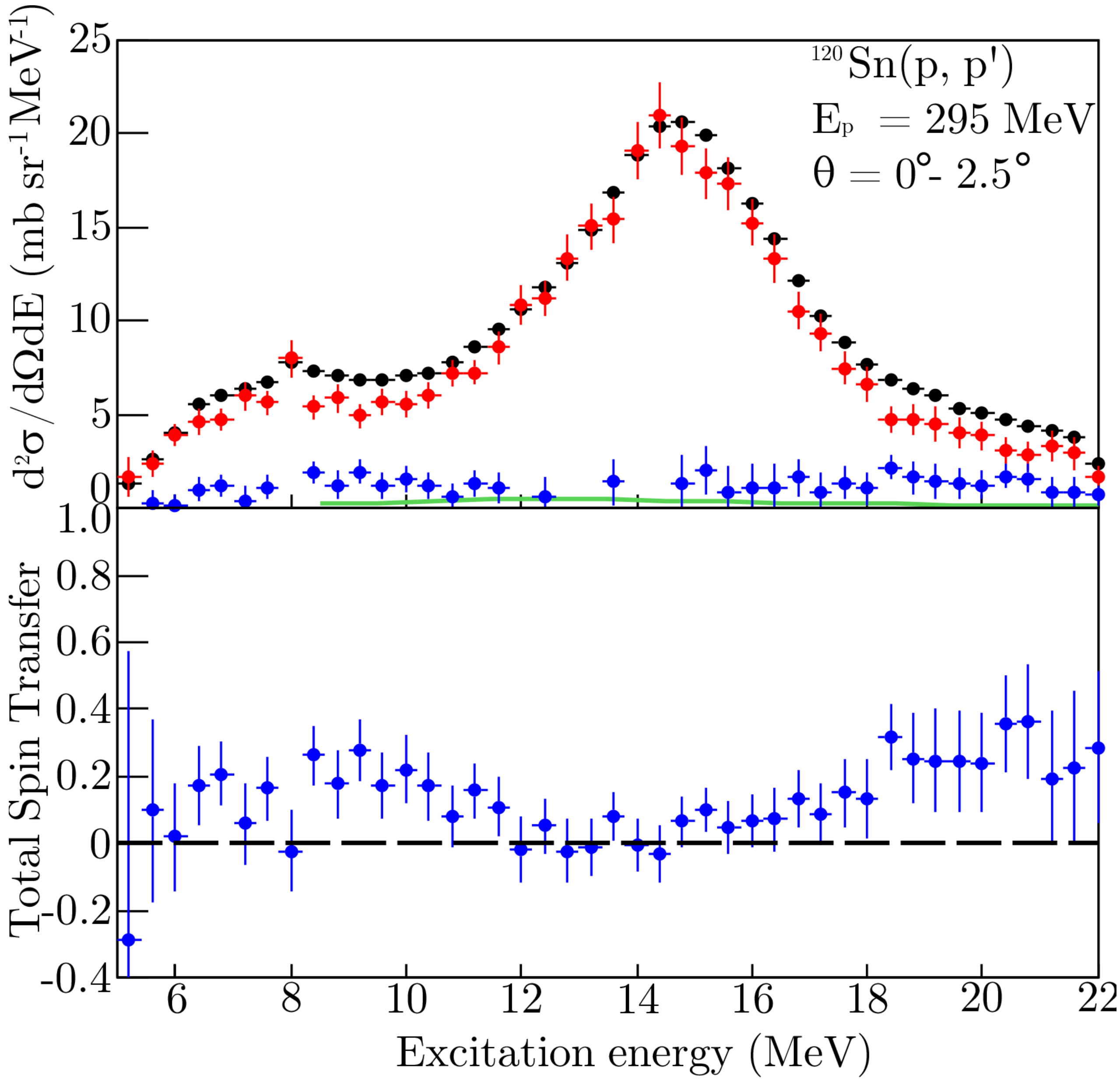
QMC: S. Gandolfi, EPJA50, 10(2014).

I. Tews et al., PRL110, 032504 (2013)

See also
C.J. Horowitz et al., JPG41, 093001 (2014)

Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al.*, submitted



Red: ΔS=0 → E1

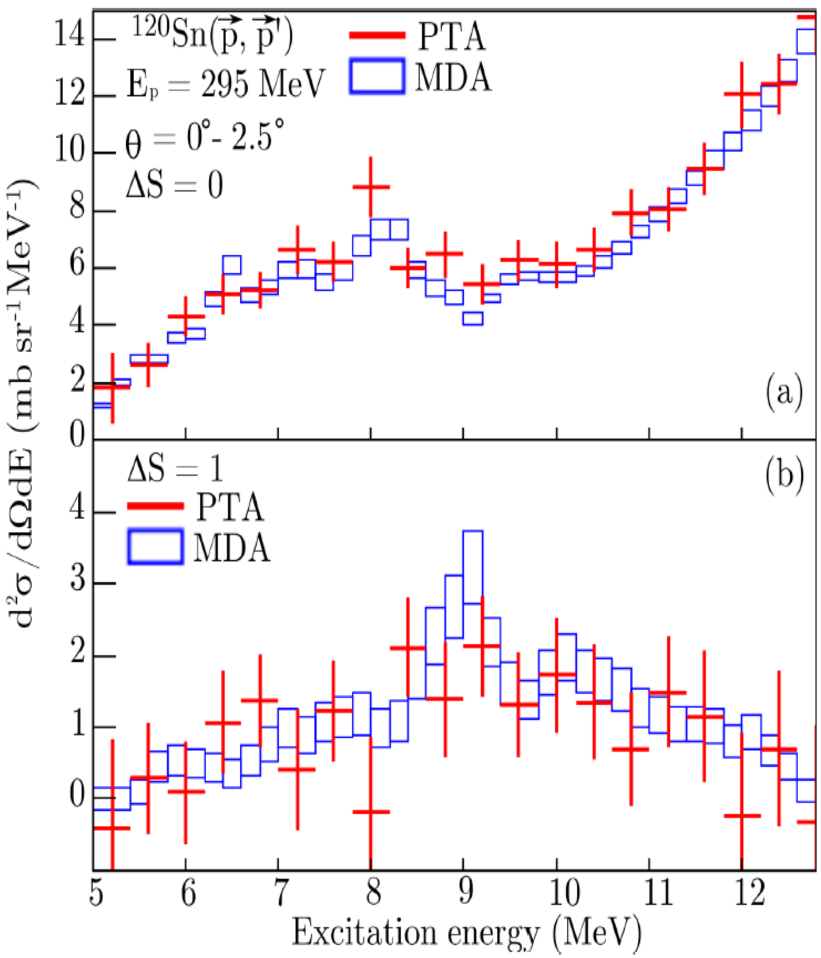
Blue: ΔS=1

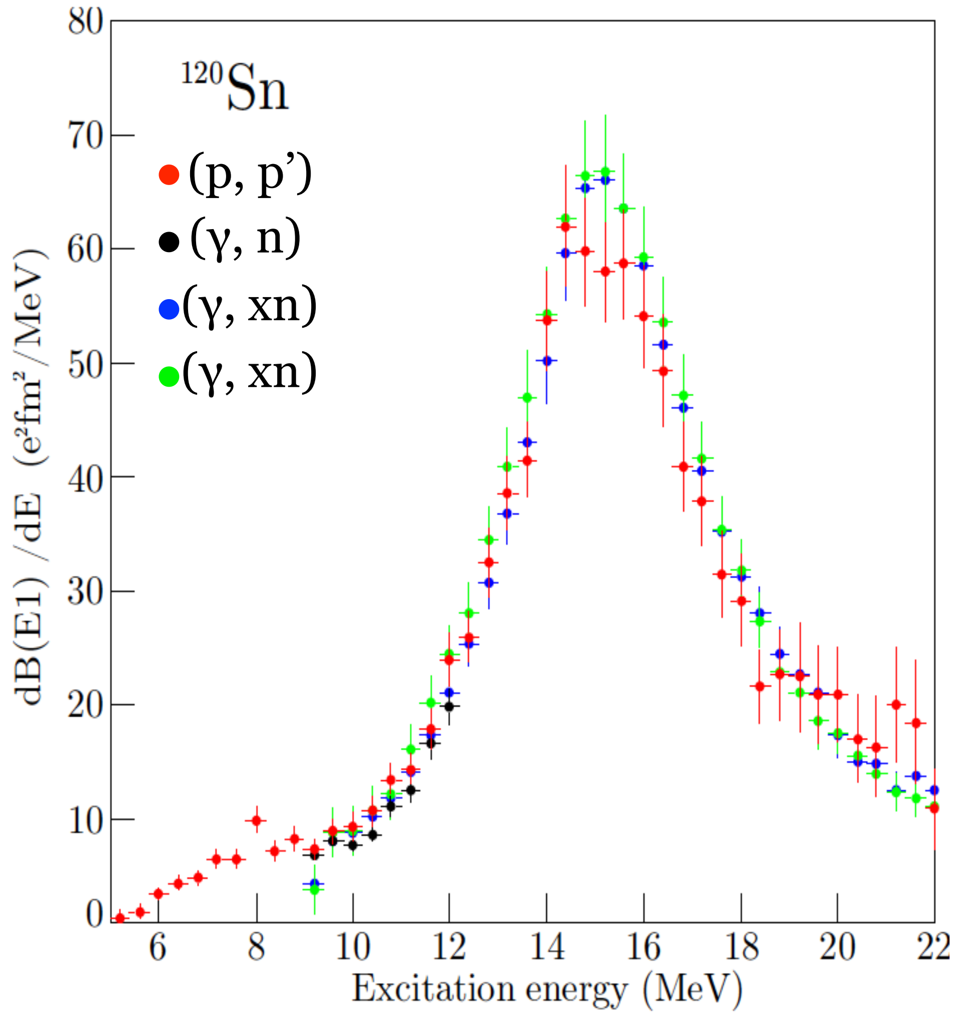
Black: total

Green: E2

Dipole Polarizability of ^{120}Sn

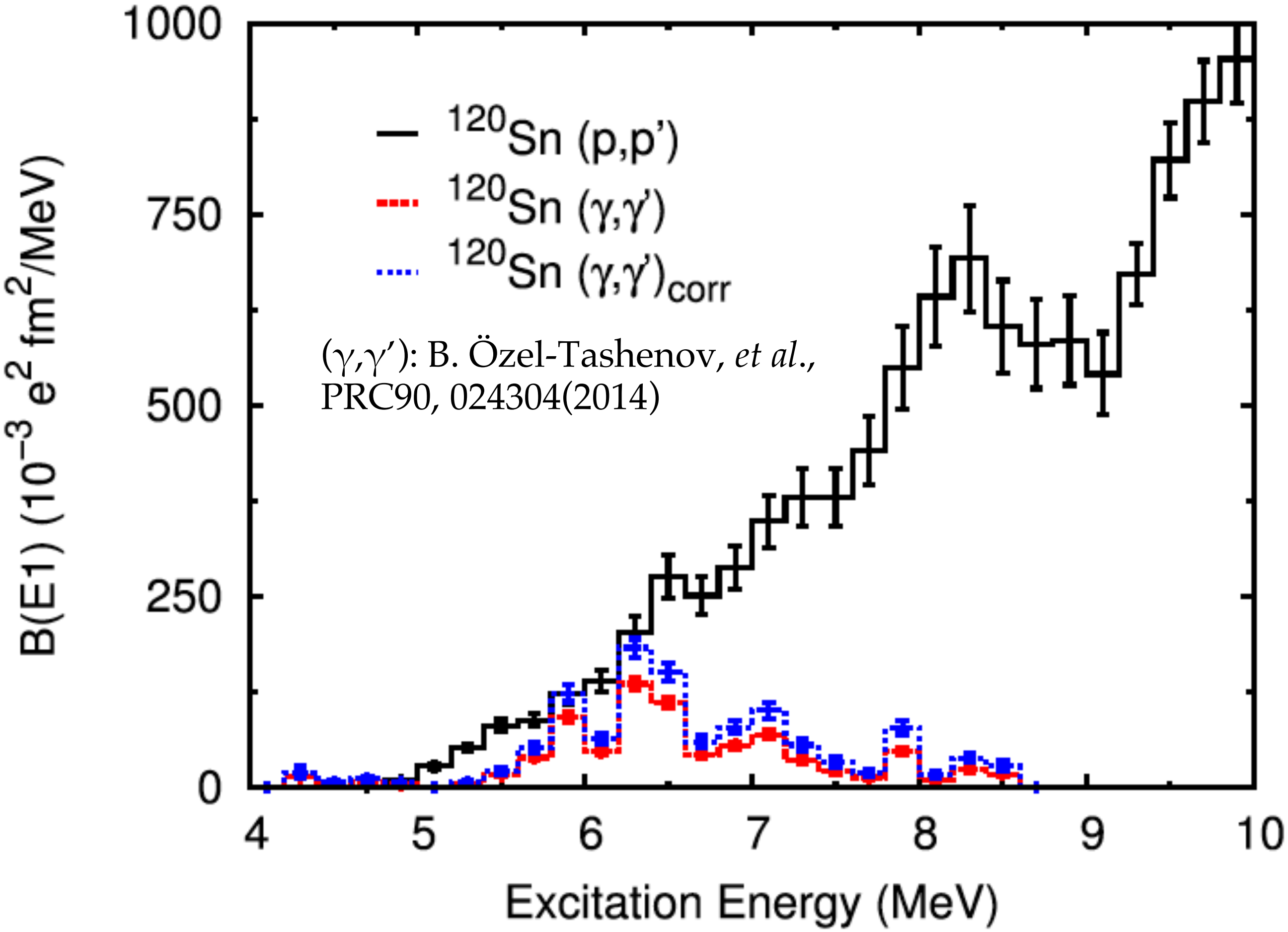
T. Hashimoto *et al.*, submitted





PDR in ^{120}Sn

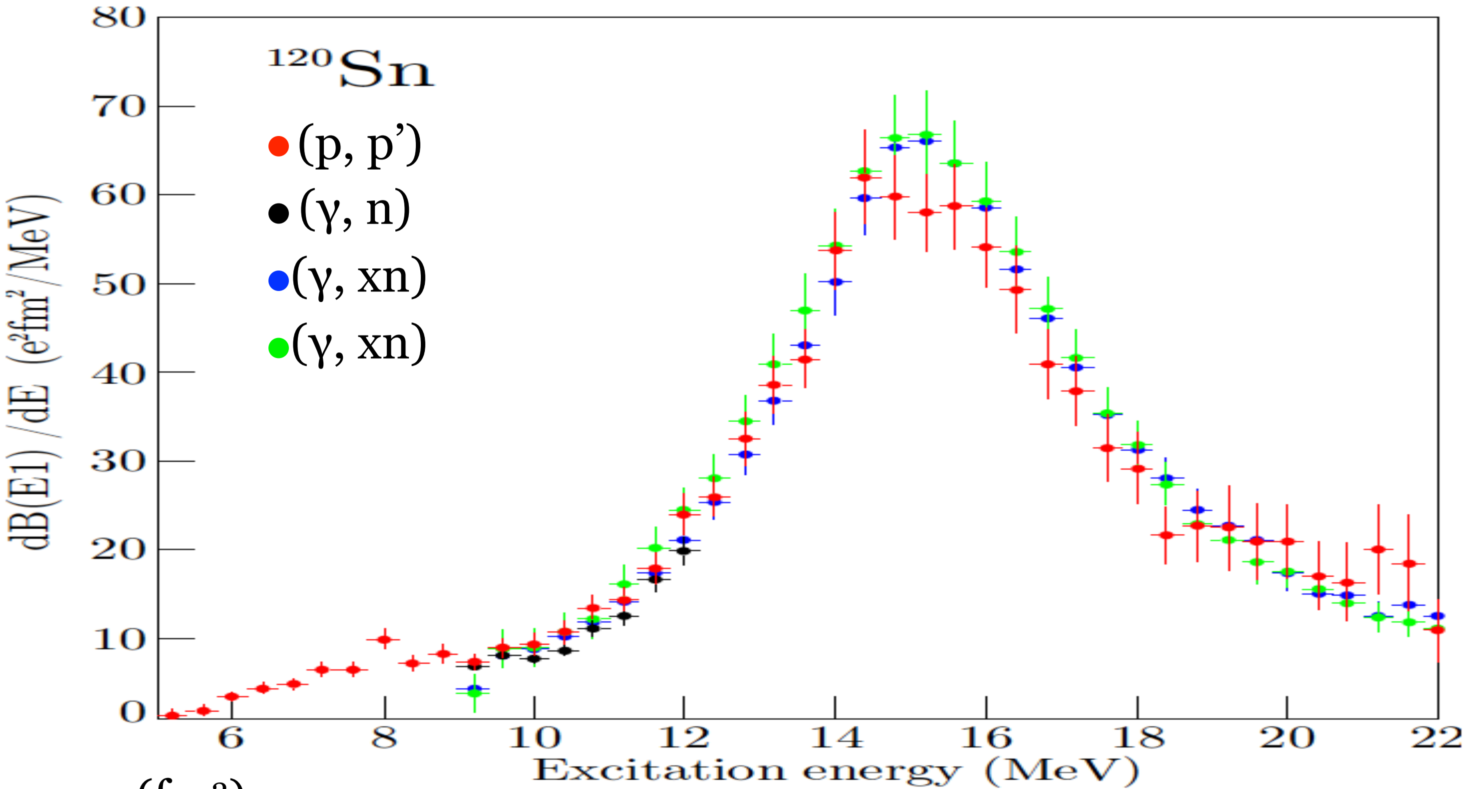
A.M. Krumbholtz *et al*., PLB744, 7(2015)



The observed strength by (γ,γ’) is significantly smaller than the present (p,p’) data.

Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al.*, submitted



α_D (fm³)

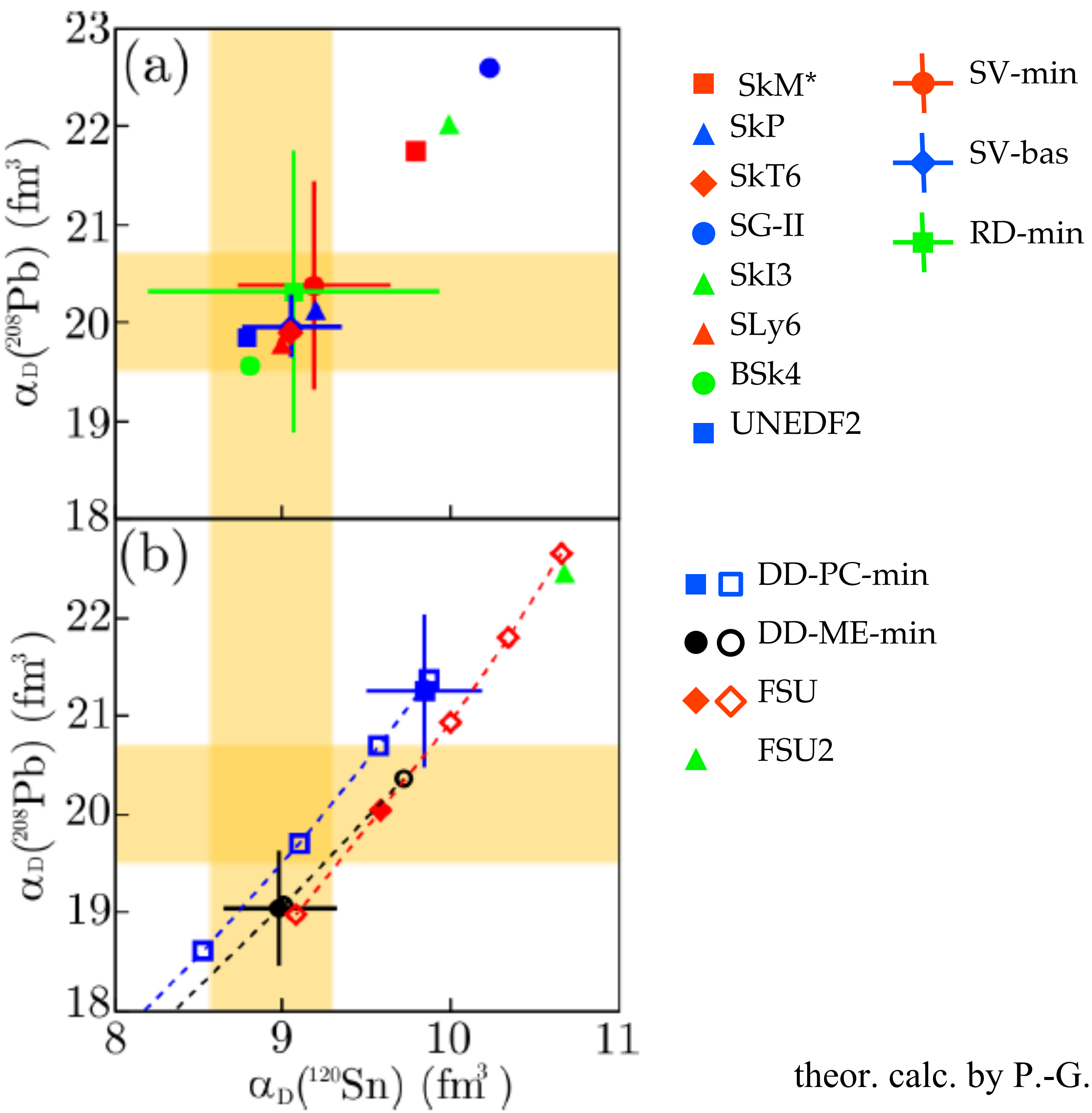
135 MeV

1.12 ± 0.07 | 7.00 ± 0.29 | 0.82 ± 0.12

Total: $\alpha_D = 8.93 \pm 0.36$ fm^3

Dipole Polarizability of ^{120}Sn and ^{208}Pb

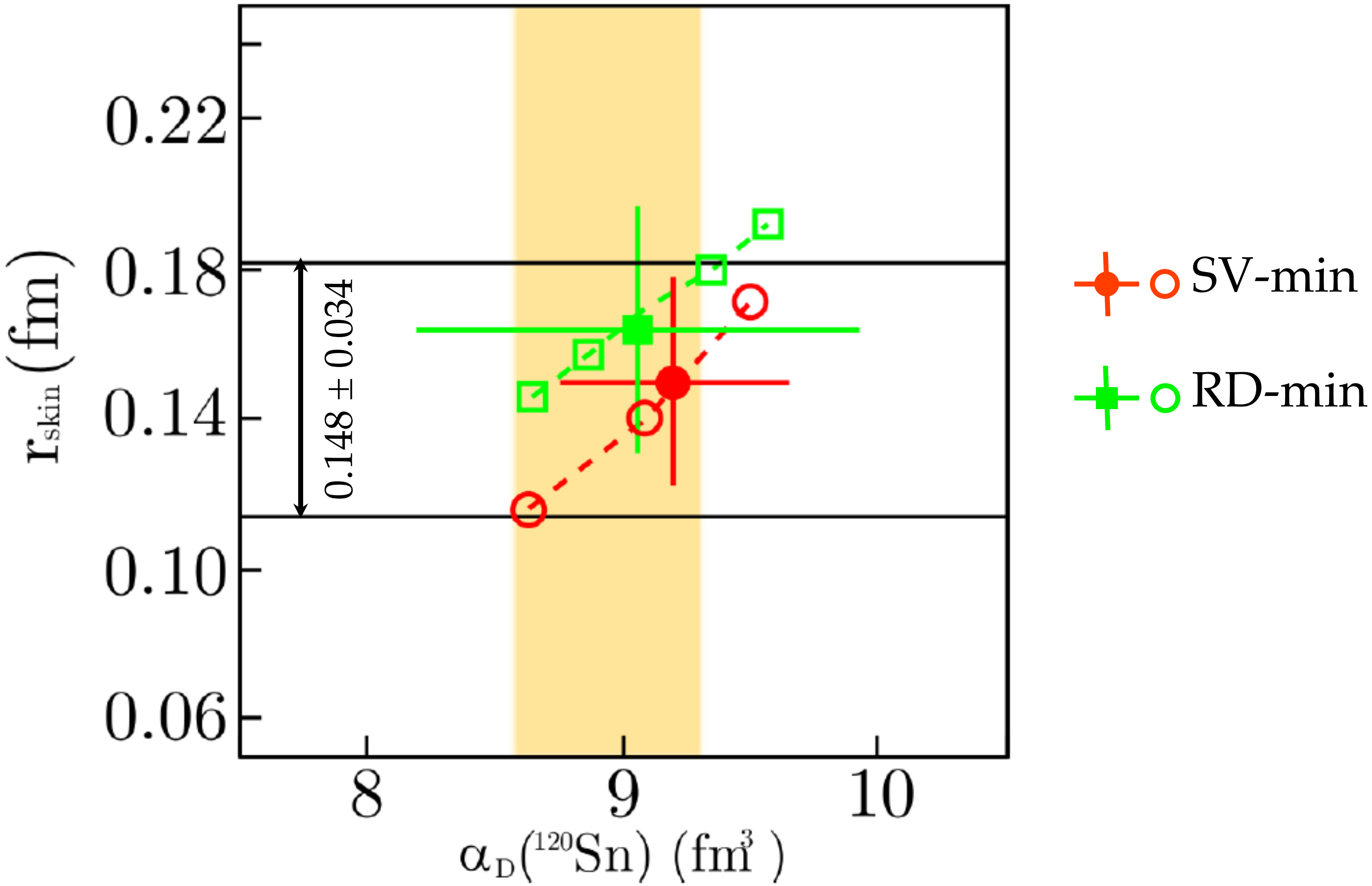
T. Hashimoto *et al.*, submitted



theor. calc. by P.-G. Reinhard

Neutron Skin Thickness of ^{120}Sn

T. Hashimoto *et al.*, submitted



Plans in Near Future

- Measurements on ^{112}Sn, ^{124}Sn and on ^{92}Zr, ^{94}Zr have been done in May-June, 2015.

- Data analyses on ^{90}Zr, ^{96}Mo, ^{48}Ca, and ^{154}Sm

^{208}Pb

RCNP-282 Collaboration

RCNP, Osaka University

A. Tamii, H. Matsubara, H. Fujita, K. Hatanaka,
H. Sakaguchi Y. Tameshige, M. Yosoi and J. Zenihiro

IKP, TU-Darmstadt

P. von Neumann-Cosel, A-M. Heilmann,
Y. Kalmykov, I. Poltoratska, V.Yu. Ponomarev,
A. Richter and J. Wambach

KVI, Univ. of Groningen

T. Adachi and L.A. Popescu

IFIC-CSIC, Univ. of Valencia

B. Rubio and A.B. Perez-Cerdan

Sch. of Science Univ. of Witwatersrand

J. Carter and H. Fujita

iThemba LABS

F.D. Smit

Texas A&M Commerce

C.A. Bertulani

GSI

E. Litivinova

Dep. of Phys., Osaka University

Y. Fujita

Dep. of Phys., Kyoto University

T. Kawabata

CNS, Univ. of Tokyo

K. Nakanishi,
Y. Shimizu and Y. Sasamoto

CYRIC, Tohoku University

M. Itoh and Y. Sakemi

Dep. of Phys., Kyushu University

M. Dozono

Dep. of Phys., Niigata University

Y. Shimbara

^{120}Sn

RCNP-316 Collaboration

T. Hashimoto†, A. M. Krumbholz[1], A. Tamii[2], P. von Neumann-Cosel[1], N. Aoi[2], O. Burda[2], J. Carter[3], M. Chernykh[2], M. Dozono[4], H. Fujita[2], Y. Fujita[2], K. Hatanaka[2], E. Ideguchi[2], N. T. Khai[5], C. Iwamoto[2], T. Kawabata[6], D. Martin[1], K. Miki[1], R. Neveling[7], H. J. Ong[2], I. Poltoratska[1], P.-G. Reinhard[8], A. Richter[1], F.D. Smit[6], H. Sakaguchi[2,4], Y. Shimbara[9], Y. Shimizu[4], T. Suzuki[2], M. Yosoi[1], J. Zenihiro[4], K. Zimmer[1]

†Institute for Basic Science, Korea
[1]IKP, Technische Universität Darmstadt, Germany
[2]RCNP, Osaka University, Japan
[3]Wits University, South Africa
[4]RIKEN, Japan
[5]Institute for Nuclear Science and Technology (INST), Vietnam
[6]Kyoto University, Japan
[7]iThemba LABs, South Africa
[8]Institut Theoretical Physik II, Universität Erlanen-Nürnberg, Germany
[9]CYRIC, Tohoku University, Japan

Summary

- Electric dipole response of ^{208}Pb and ^{120}Sn have been precisely measured. Proton inelastic scattering was used as an electro-magnetic probe (relativistic Coulomb excitation).

$$\alpha_{D(^{208}Pb)} = 20.1 \pm 0.6 \text{ fm}^3$$

$$\alpha_{D(^{120}Sn)} = 8.93 \pm 0.36 \text{ fm}^3$$

- Electric dipole polarizability (α_D) is sensitive to the difference between the proton and neutron distributions.

- The neutron skin thicknesses and the constraints on the symmetry energy parameters have been extracted with the help of mean field calculations.

Thank you