Excitation of E1Pygmy in Inelastic Proton Scattering and RCNP Activities

Atsushi Tamii

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

COMEX5
5th International Conference on
Collective Motion in Nuclei under Extreme Conditions
Krakow, September 14-18, 2015

Excitation of E1 States in Inelastic Proton Scattering and RCNP Activities

spin-M1 and future exp.

Atsushi Tamii

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

COMEX5
5th International Conference on
Collective Motion in Nuclei under Extreme Conditions
Krakow, September 14-18, 2015

Excitation of E1 States in Inelastic Proton Scattering and RCNP Activities

spin-M1 and future exp.

Other RCNP activities covered by

(α,α') U. Garg, Y. Gupta,

(^{3}He,t) Y. Fujita, D. Frekers

DCEX M. Takaki

also by M.H. Harakeh

Contents

1. Electric Dipole Responses

   Electric Dipole Polarizability
   Pygmy Dipole Resonance
   (Neutron Skin)
   Symmetry Energy

2. Spin-M1 Responses

   Quenching of IS/IV Spin-M1 Strengths
   np-pairing Correlation, Nuclear Spin (Magnetic) Susceptibility

3. Future Experiment

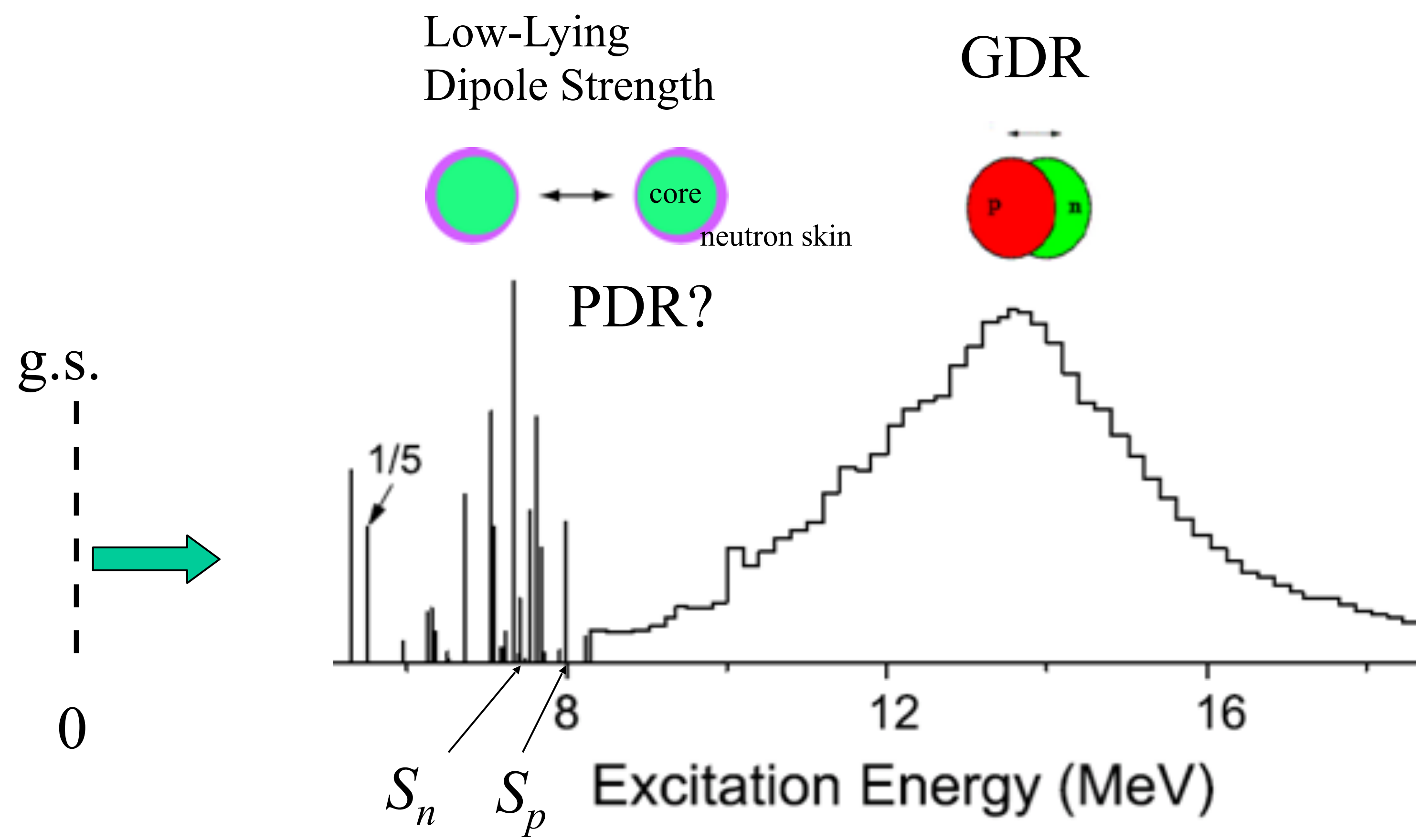
   GR + Gamma coincidence (CAGRA+GR)

Electric Dipole Response

is one of most basic responses of nuclei

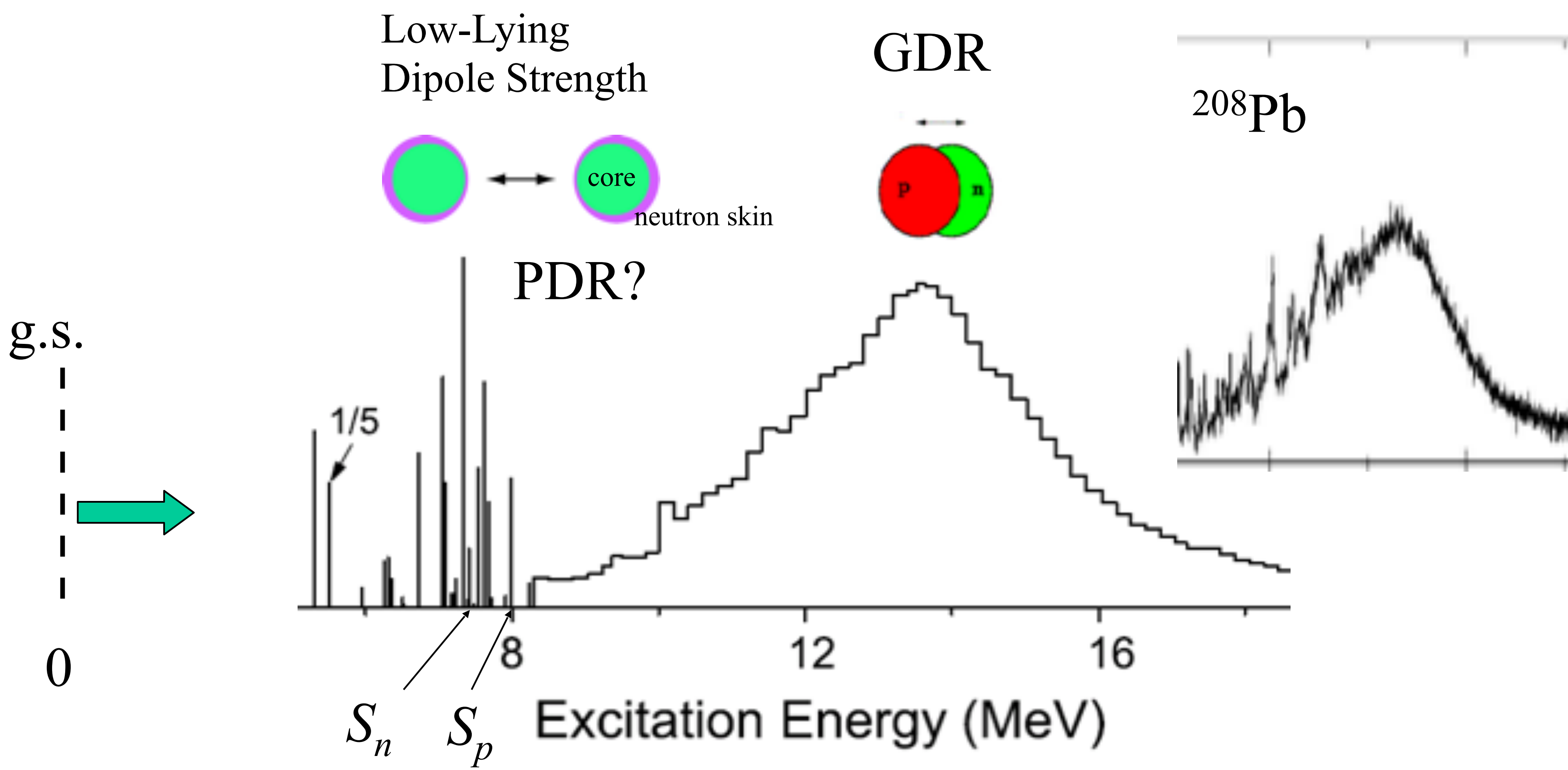
but is not fully understood yet.

Electric Dipole Response of Nuclei



- Nature of the PDR, the existence of the toroidal modes
- Fine structure of the GDR
- Sum rules, dipole polarizability → Symmetry Energy

Electric Dipole Response of Nuclei



- Nature of the PDR, the existence of the toroidal modes
- Fine structure of the GDR
- Sum rules, dipole polarizability → Symmetry Energy

Nuclear Equation of State (EOS)

at zero temperature

Nuclear equation of state

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

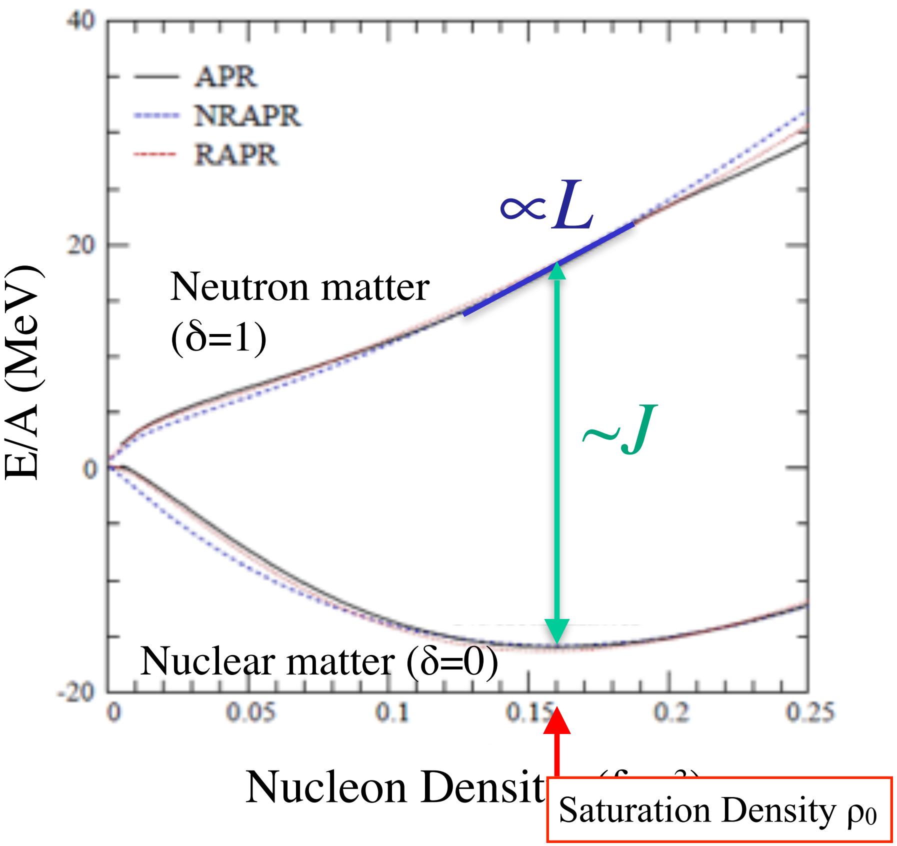
Symmetry energy

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

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

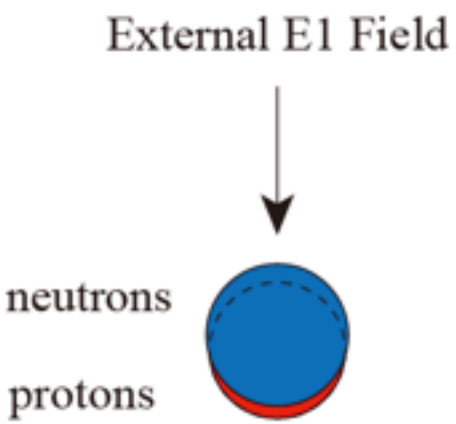
$$\delta(r)=\frac{\rho_n(r)-\rho_p(r)}{\rho_n(r)+\rho_p(r)}$$

Saturation Density ~0.16 fm^{-3}

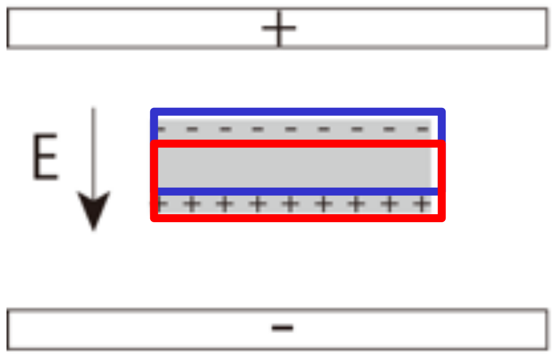


Steiner et al., Phys. Rep. 411 325(2005)

Electric Dipole Polarizability (α_D)



Electric Dipole Polarizability α_D



Electric Dipole Polarization

$$\vec{P} = N\alpha\vec{E}$$

α: dipole polarizability of an atom

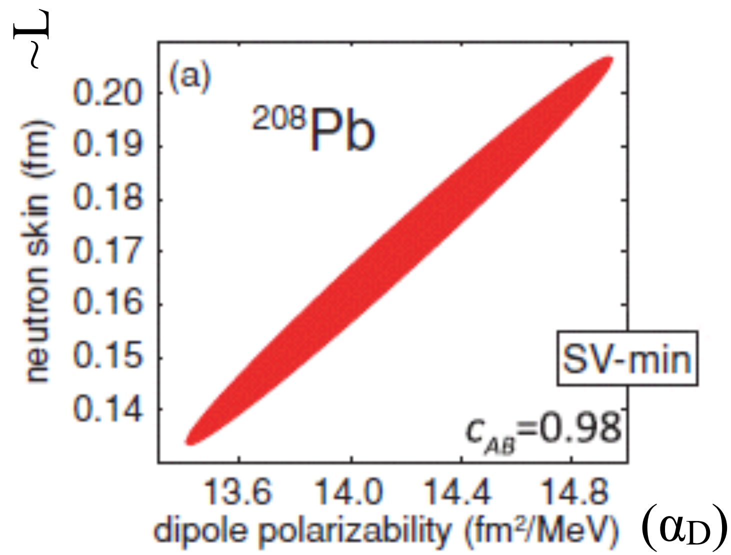
Restoring force ← symmetry energy

Inversely energy weighted sum-rule of B(E1)

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

→ Requires the $B(E1)$ distribution

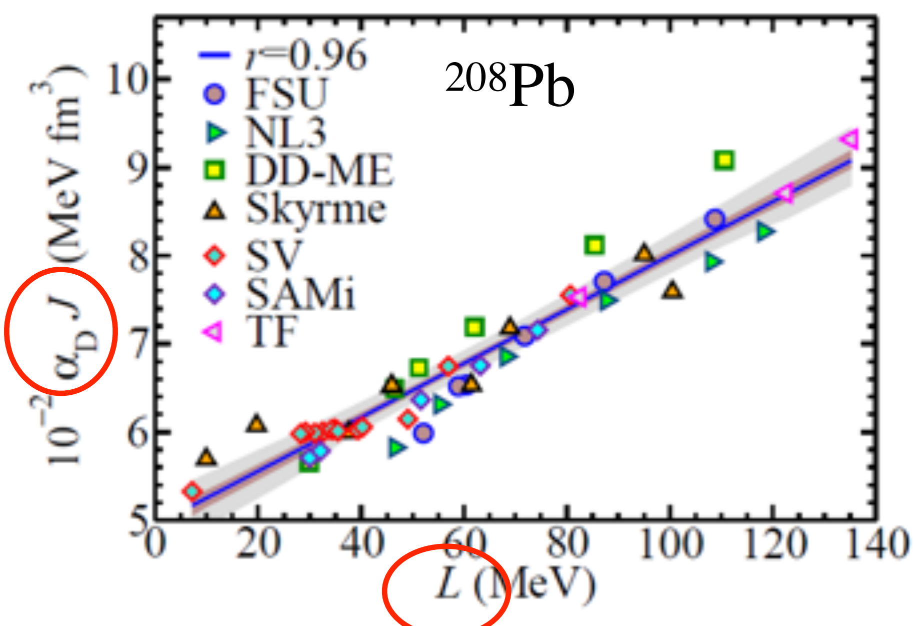
Electric Dipole Polarizability (α_D)



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

Covariance analysis with SV-min interaction in the framework of the nuclear energy density functional.

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



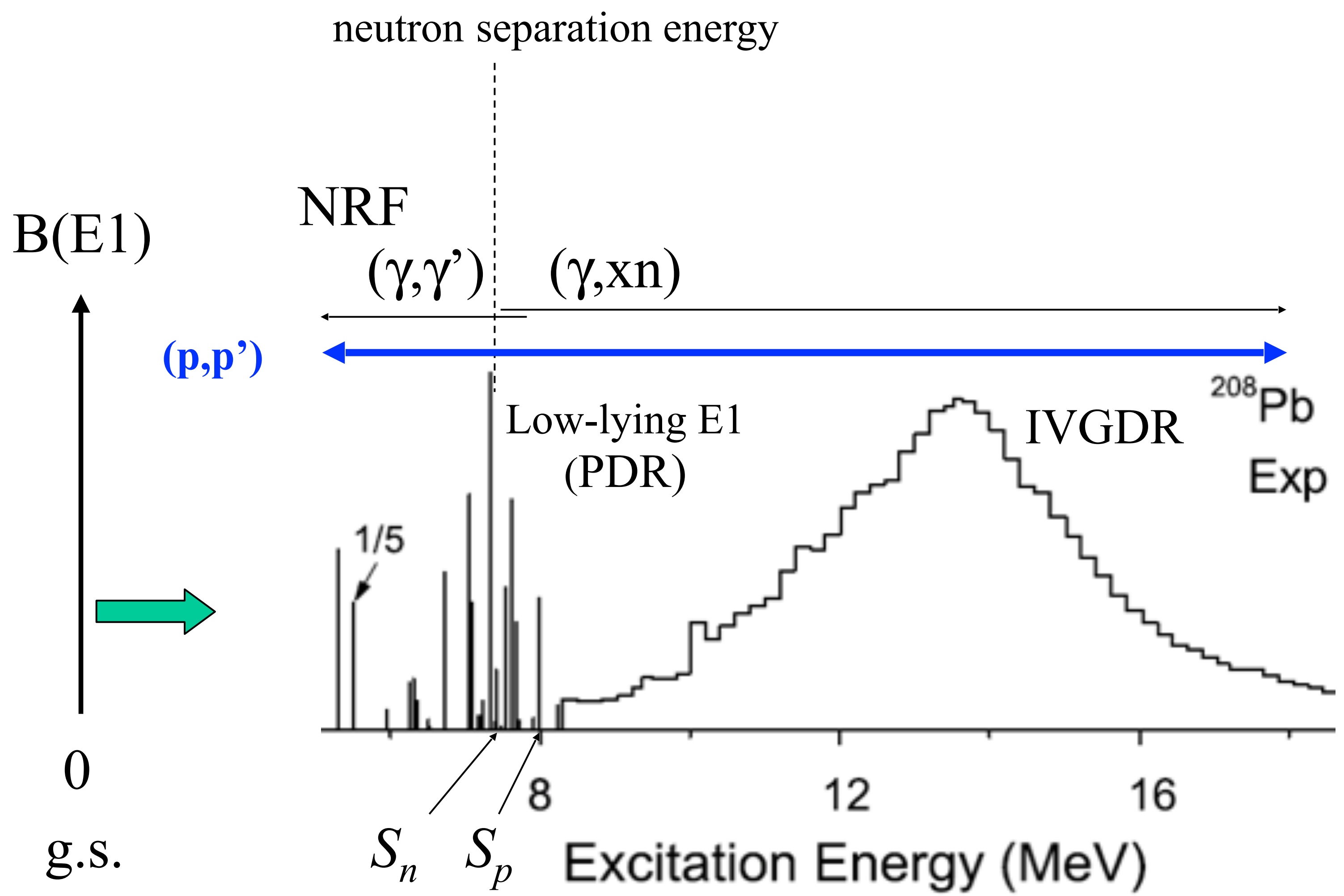
X. Roca-Maza *et al*., PRC**88**, 024316(2013)

Correlations observed in various interaction sets.

$$\alpha_D^{\mathrm{DM}} \approx \frac{\pi e^2}{54} \frac{A\langle r^2 \rangle}{J} \left[1 + \frac{5}{3} \frac{L}{J} \epsilon_A \right]$$

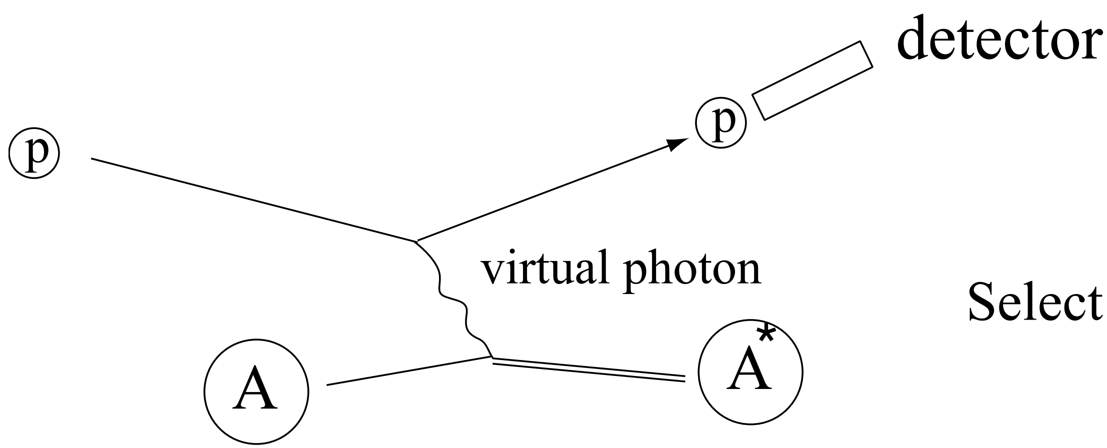
insights from the droplet model

Electric Dipole Response of Nuclei



Probing the E1 response of nuclei

Missing Mass Spectroscopy by Virtual Photon Excitation

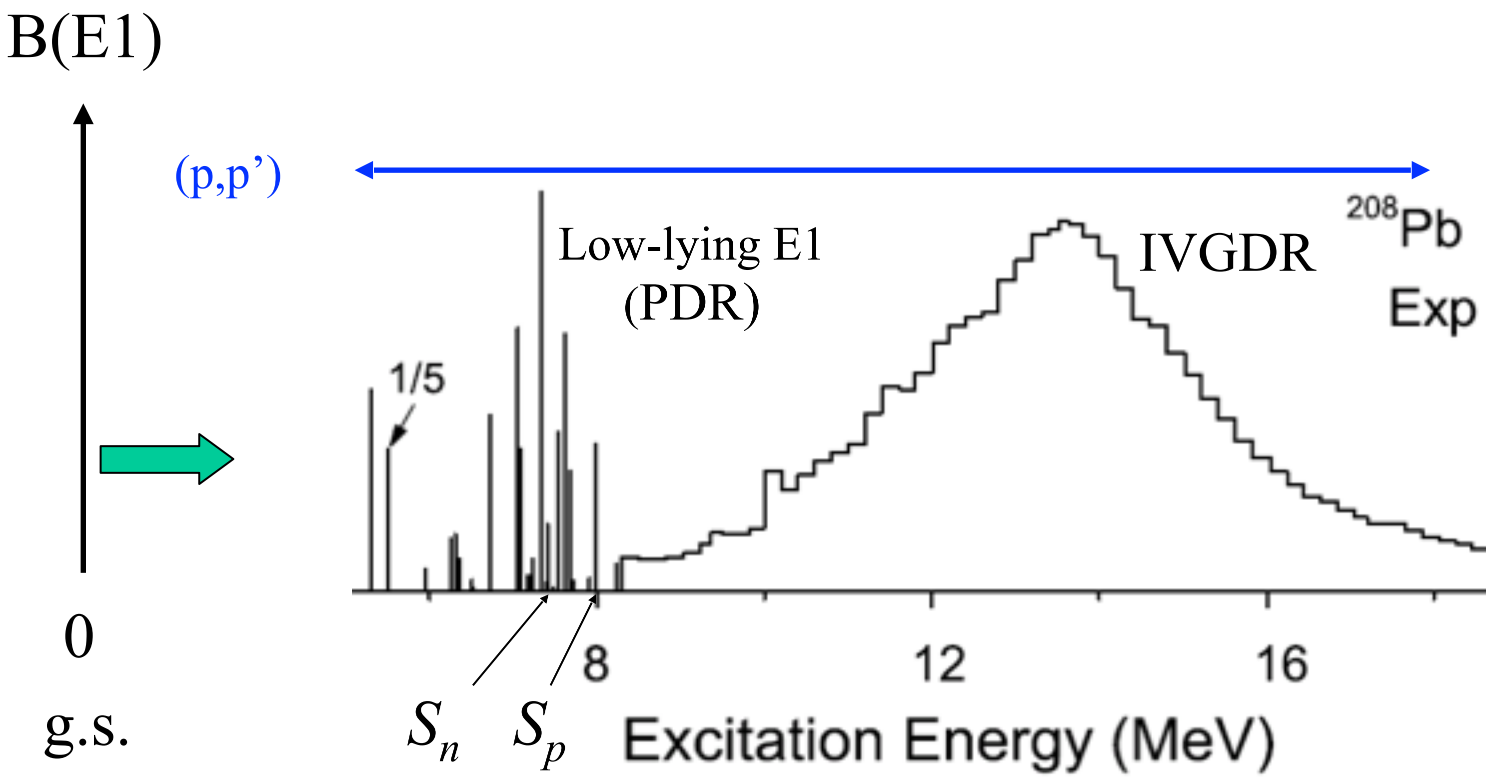


Select q~0 (~0 deg.)

- **Missing mass spectroscopy**:
  Total strength is measured independently of the decay channels.
- **Multipole decomposition** of the strength in the continuum:
  Includes the contribution of unresolved small states
- **Coulomb excitation**:
  Absolute determination of the transition strength.

EM Interaction is well known
(model independent)

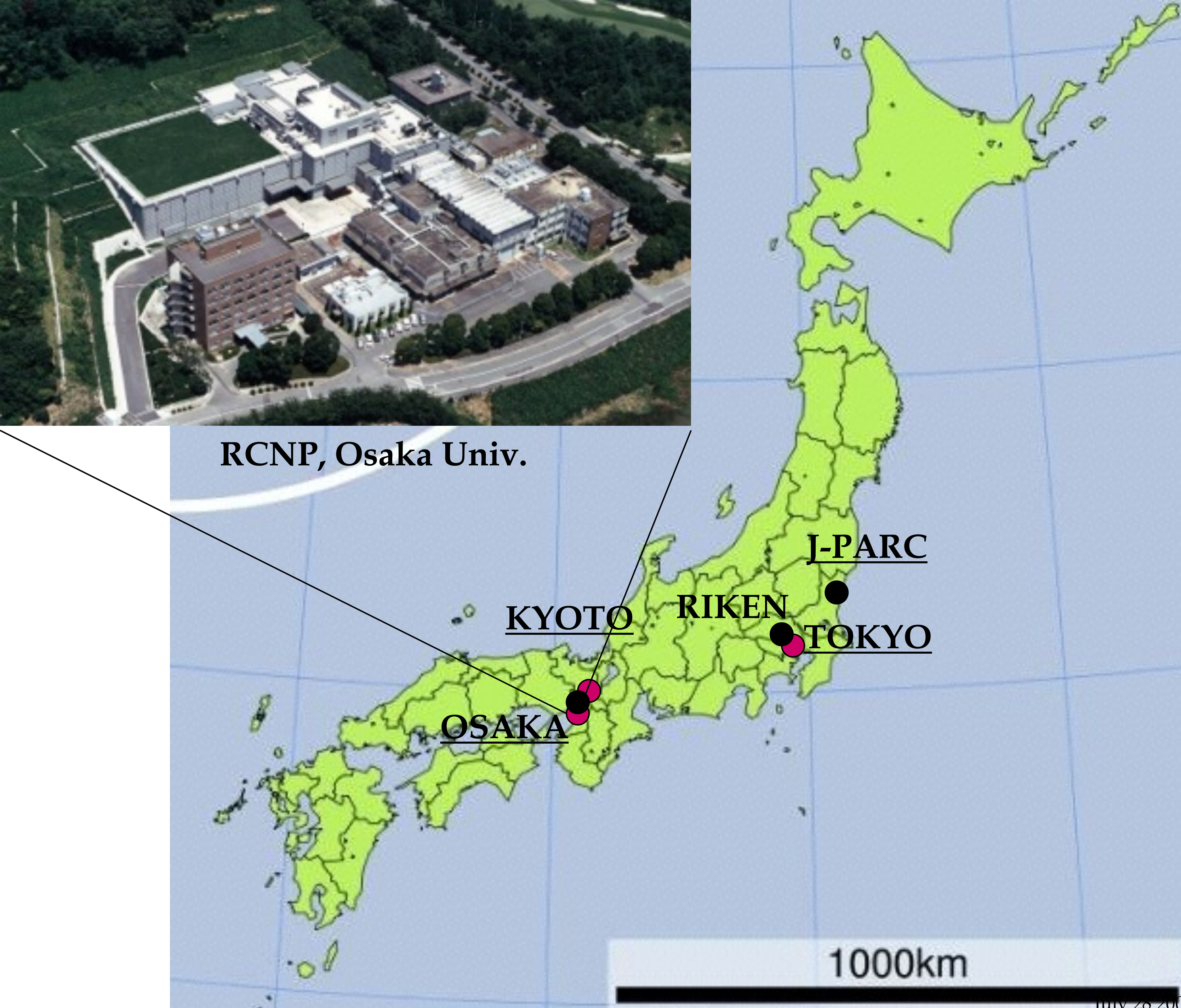
Probing the E1 response of nuclei



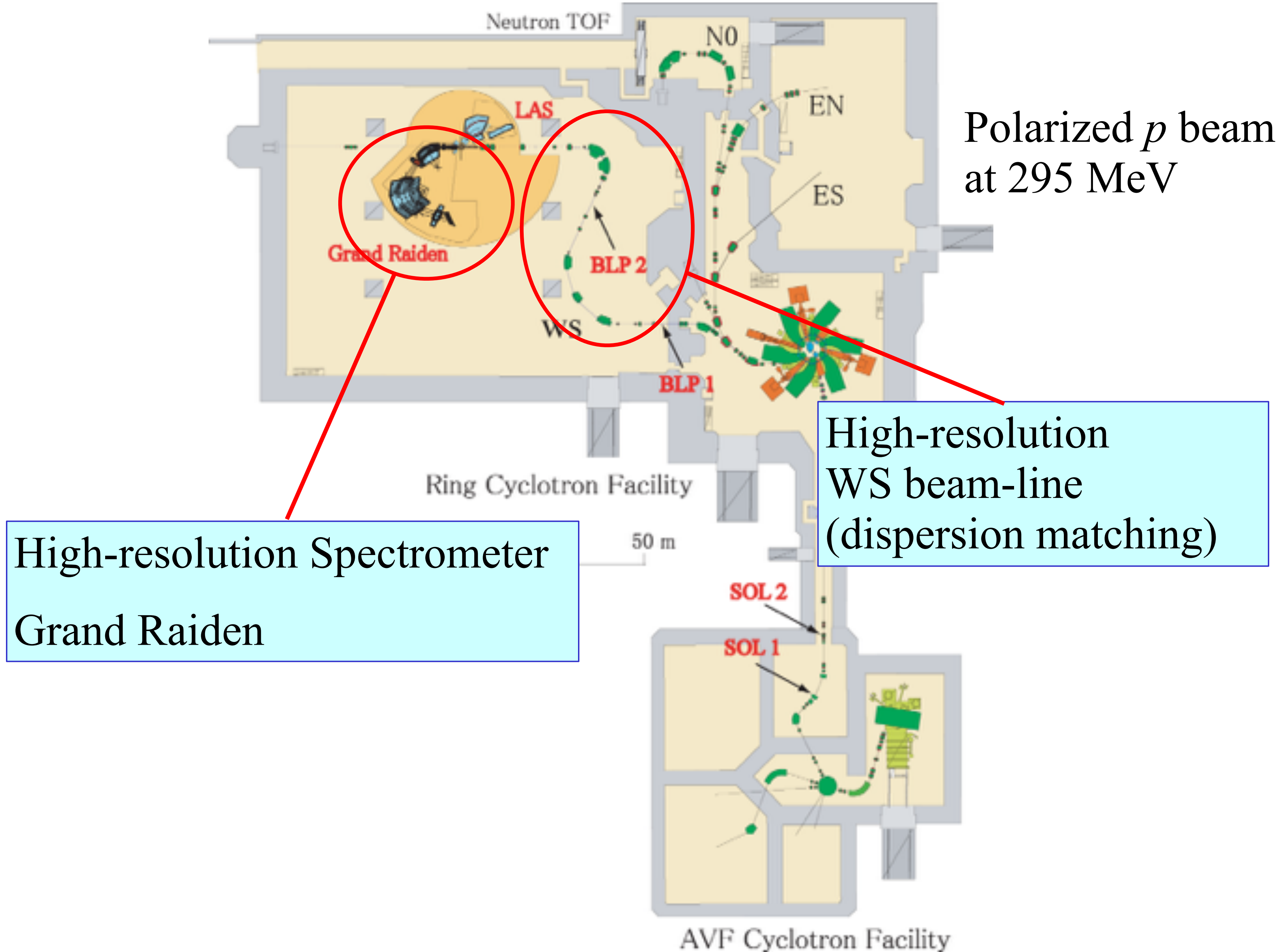
- Single shot measurement across S_n in E_x = 5-22 MeV.
- Uniform detection efficiency (80-90%) and solid angle
- High energy resolution (20-30 keV)
- Polarized beam, polarization detection → extraction of E1
- Isotopically enriched target with a few mg/cm^2 thickness

Experimental Method

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


RCNP, Osaka Univ.
J-PARC
RIKEN
KYOTO
TOKYO
OSAKA
1000km

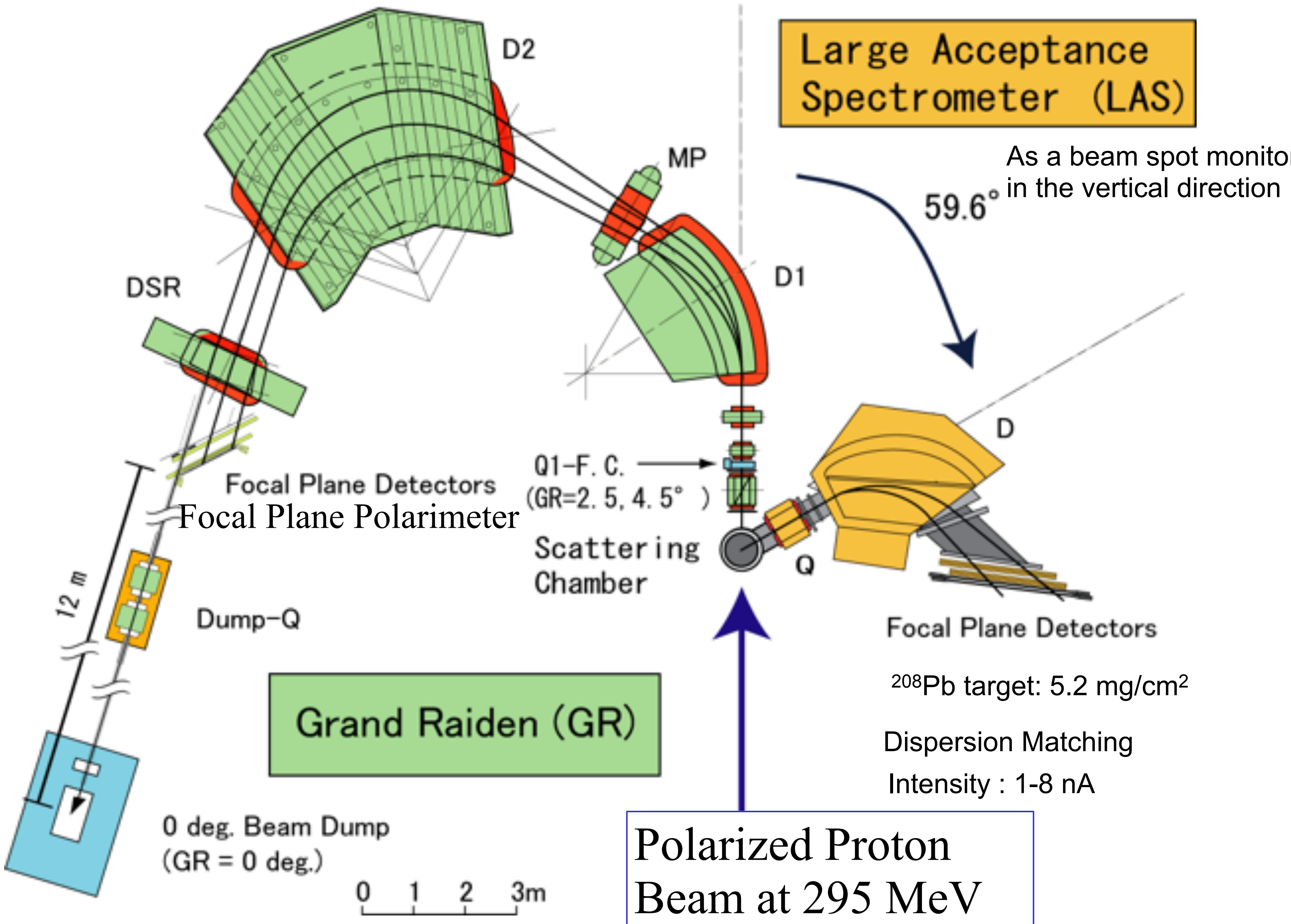
Research Center for Nuclear Physics (RCNP), Osaka University



Polarized p beam at 295 MeV

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

AT et al., NIMA605, 326 (2009)

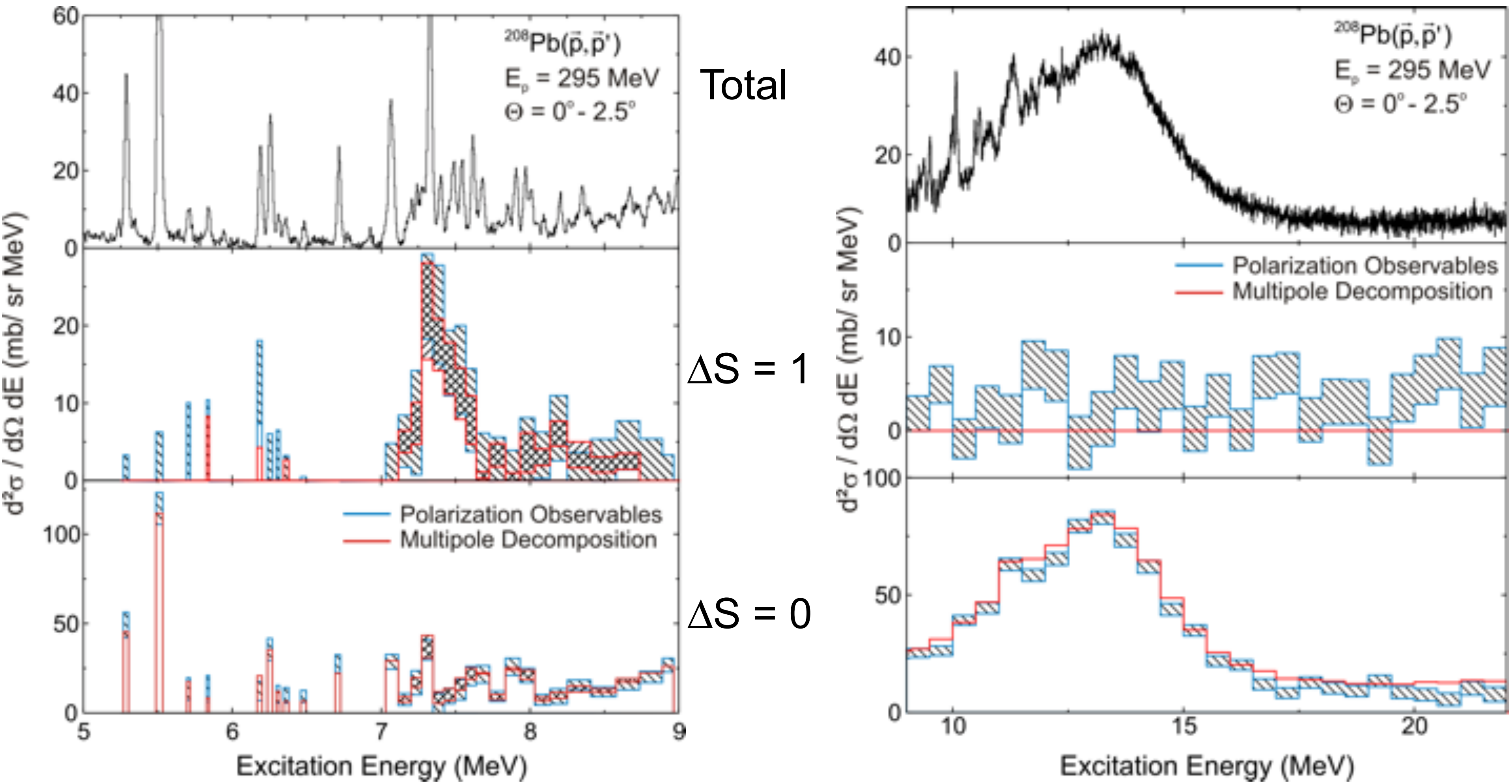


^{208}Pb target: 5.2 mg/cm^2

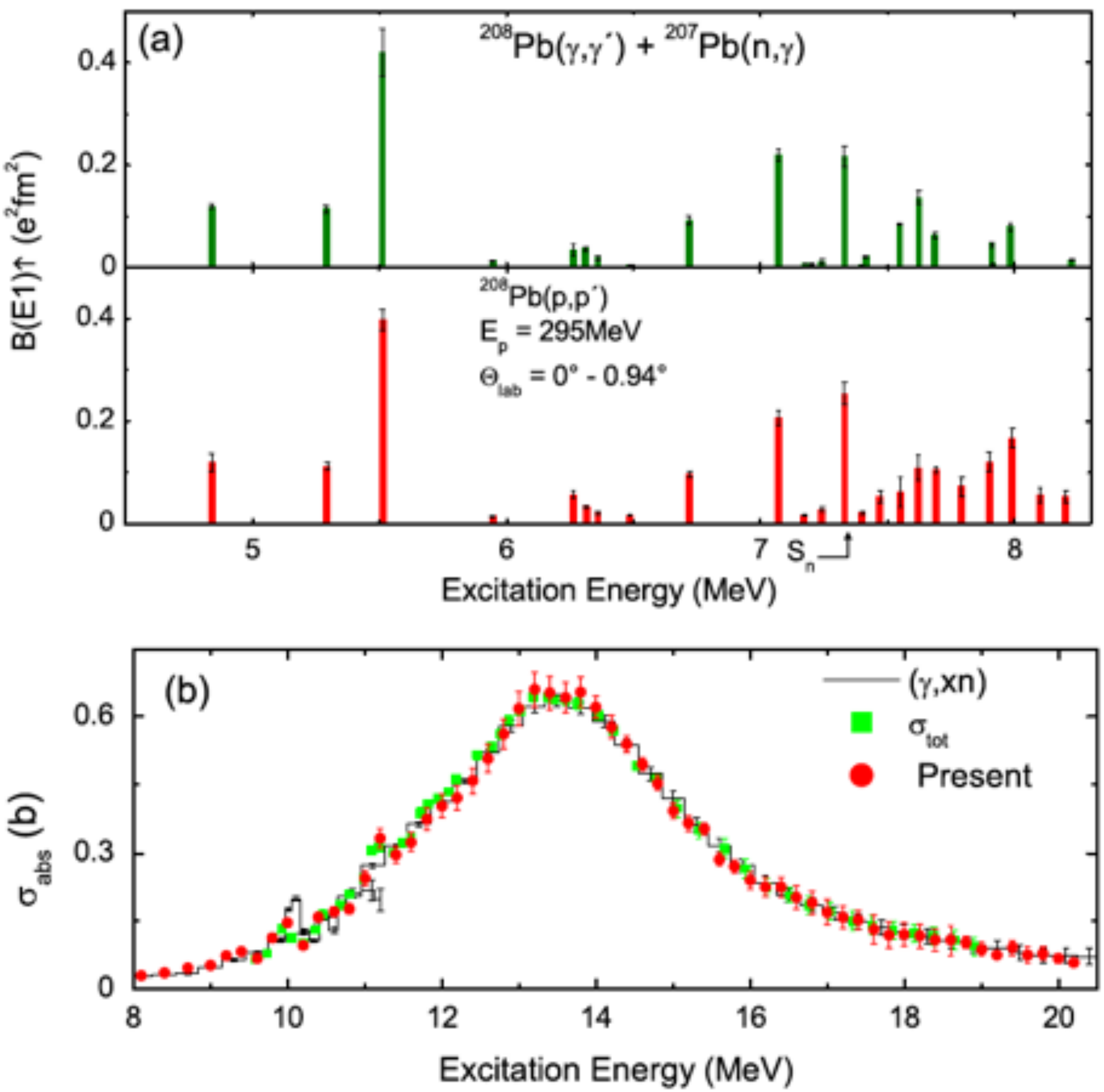
Dispersion Matching

Intensity : 1-8 nA

Comparison between the two methods
for the decomposition of E1 and spin-M1



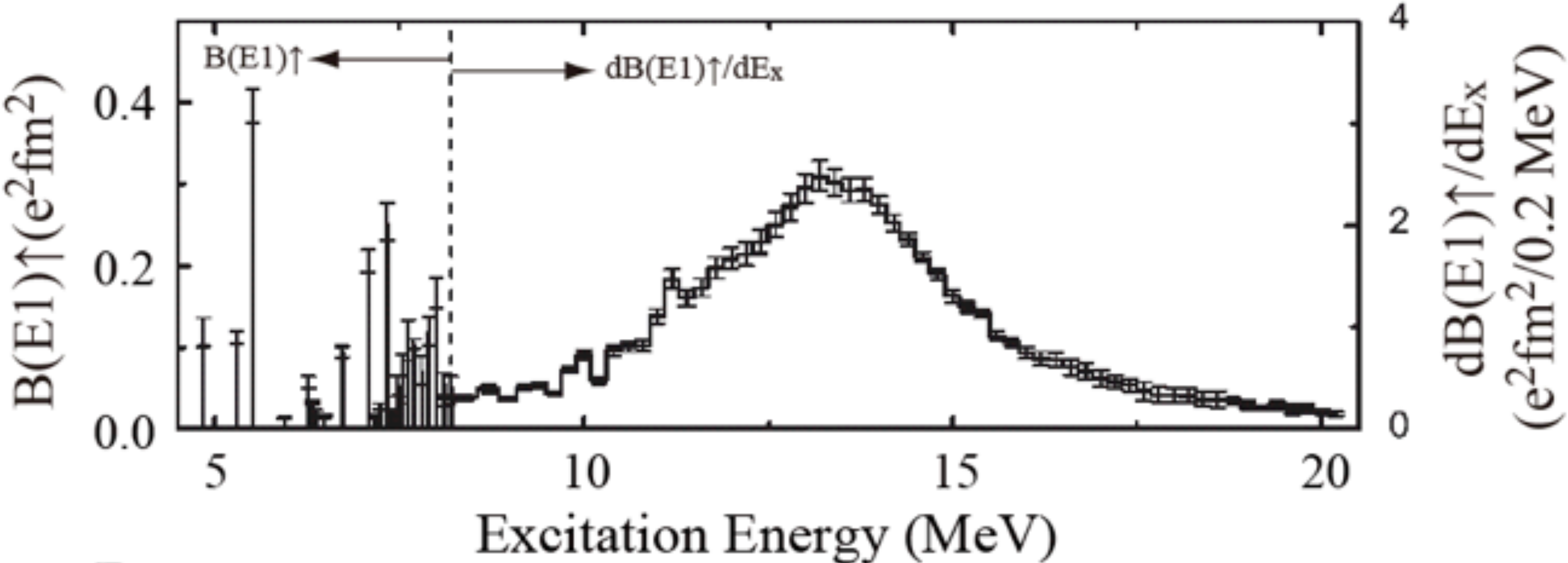
Comparison with (γ,γ') and (γ,xn)



low-lying discrete states

GDR region

E1 Response of ^{208}Pb and α_D



E_x	0 – 10	10 – 20	20 – 130 MeV
α_D	2.7	16.2	1.2 fm³

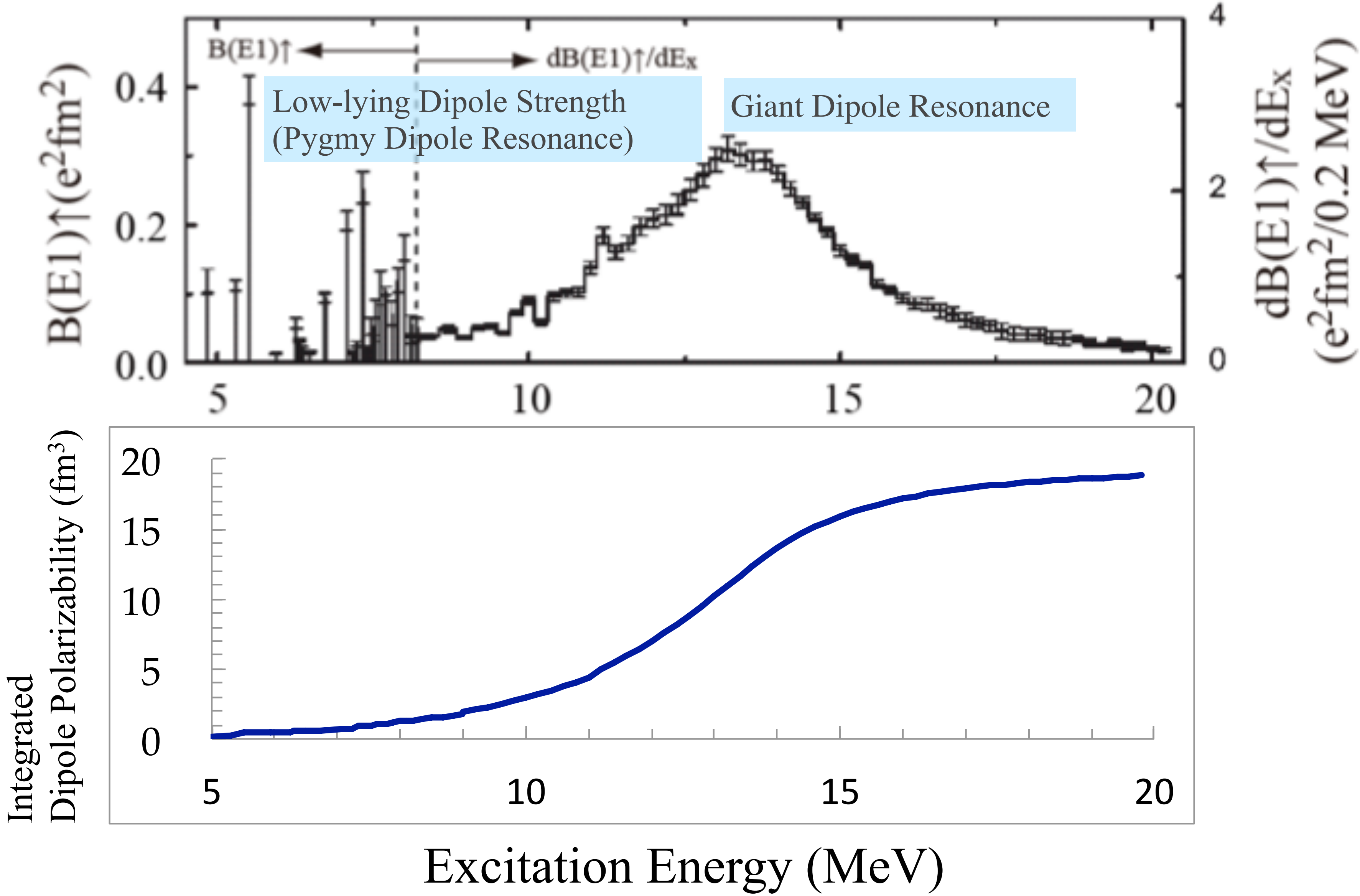
total 20.1±0.6 fm³

combined data

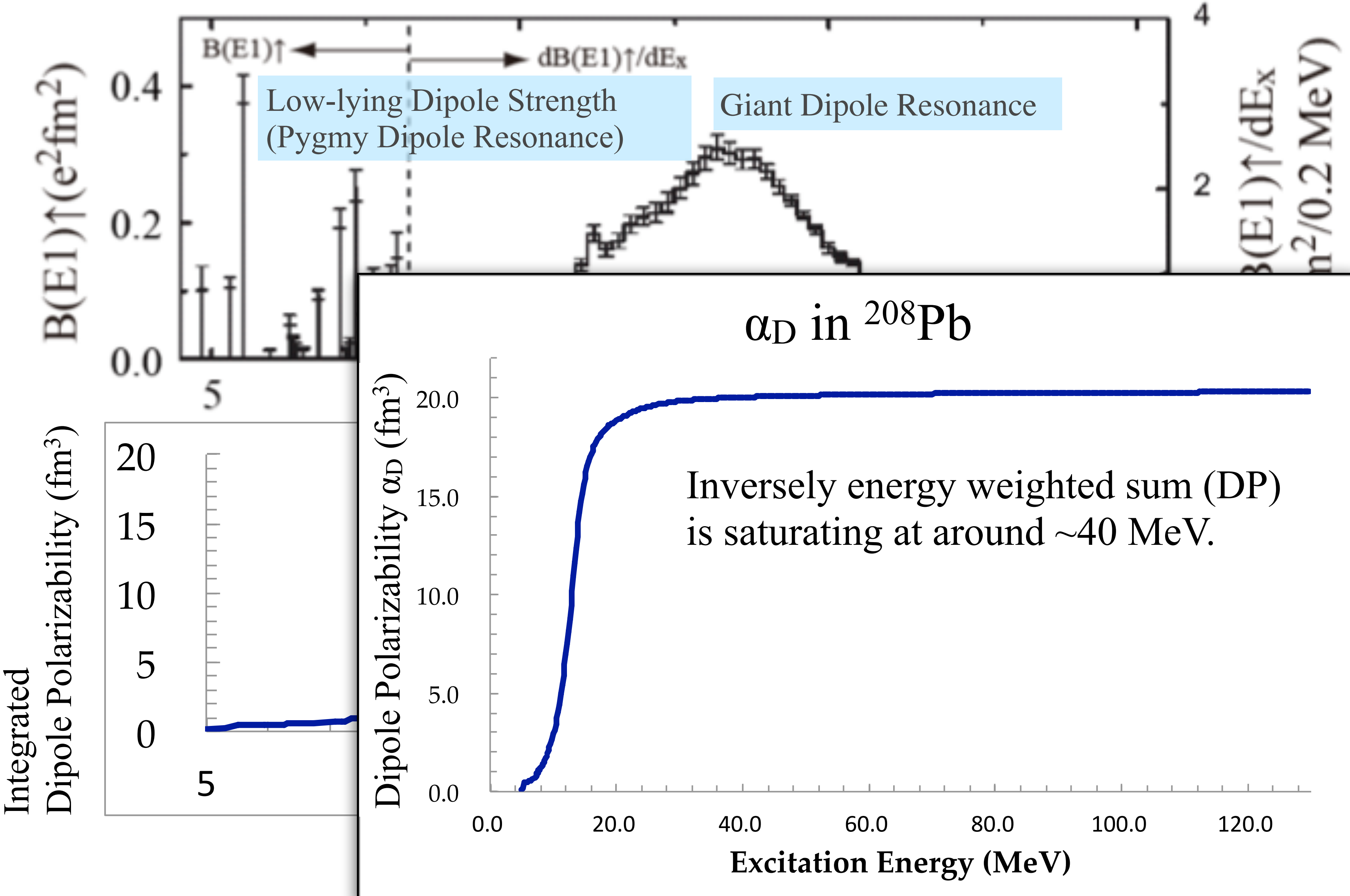
The dipole polarizability of ^{208}Pb has been precisely determined.

AT et al., PRL107, 062502(2011)

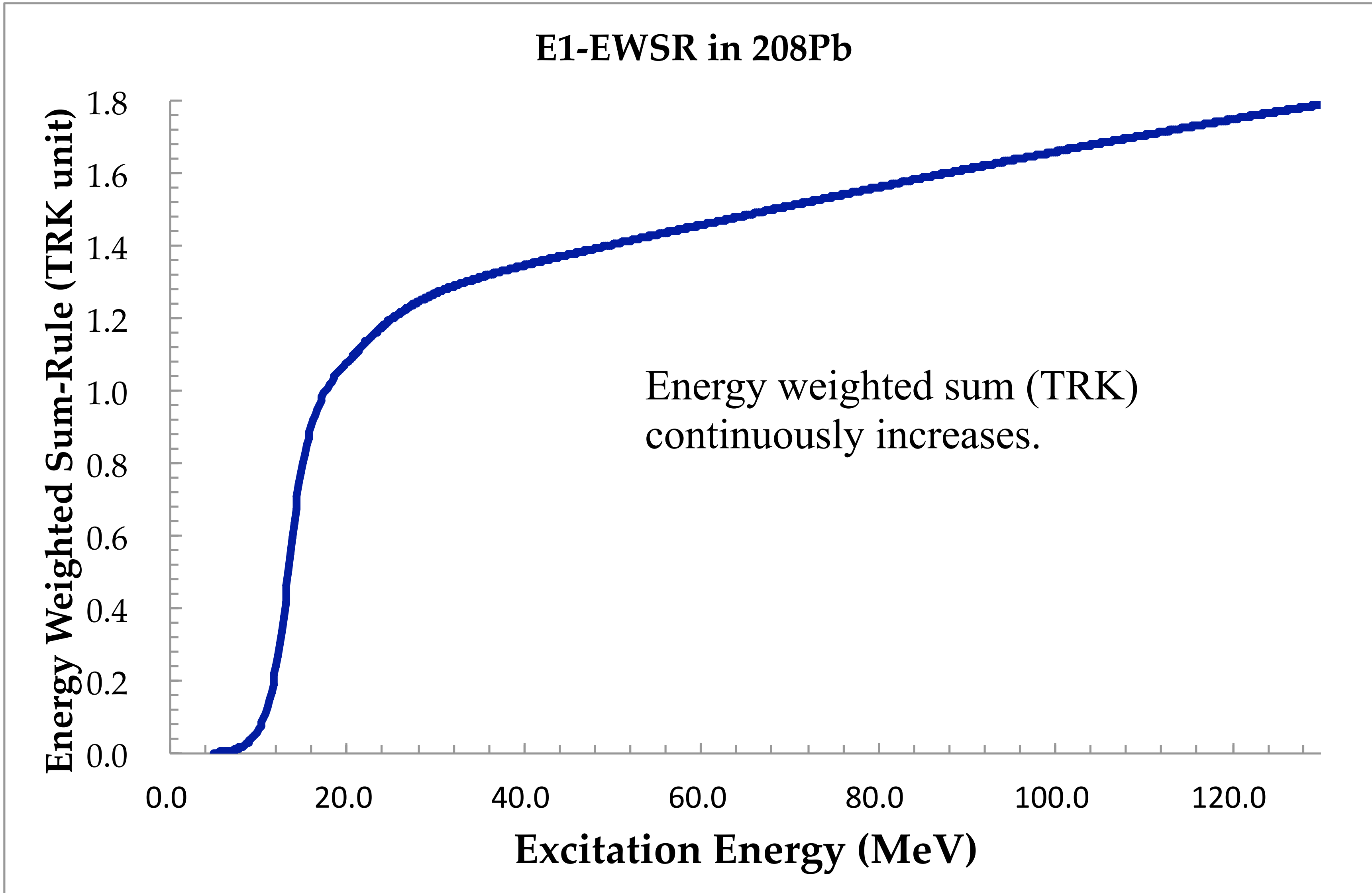
Electric Dipole Response of ^{208}Pb



Electric Dipole Response of ^{208}Pb



Energy Weighted (TRK) Sum-Rule of ^{208}Pb



Quasi-Deuteron Excitation Contribution?

Photon absorption by a virtual deuteron in the nucleus

^{208}Pb

$\alpha_D(^{208}\text{Pb})$: 20.1 ± 0.6 fm^3

quasi-*d*: 0.51 ± 0.15 fm^3

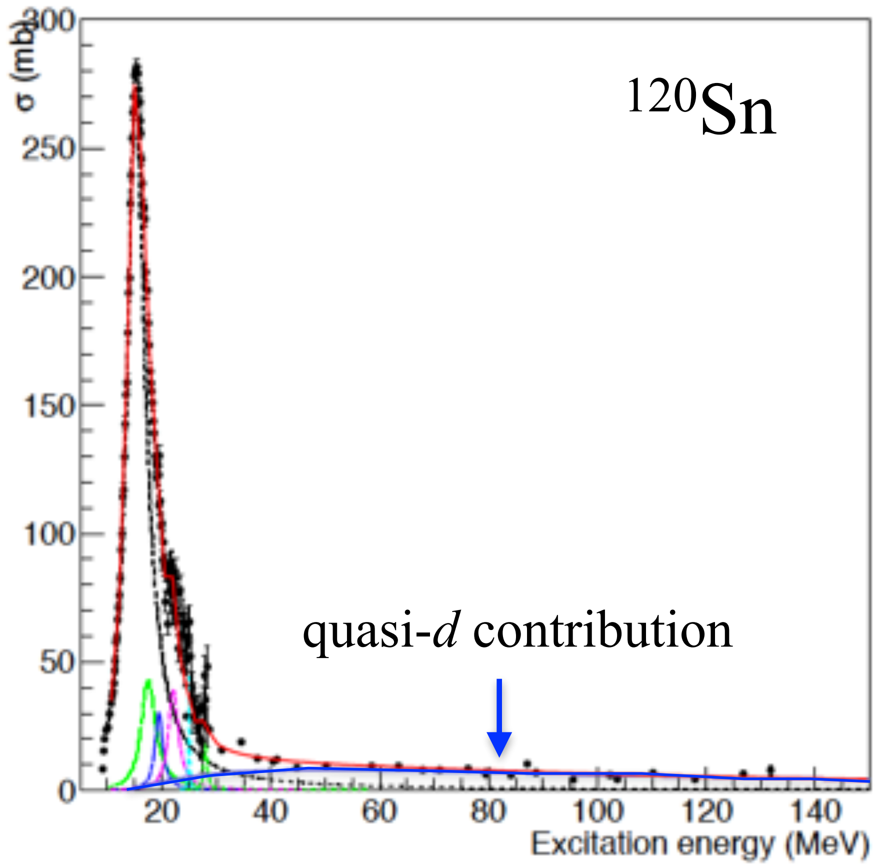
w/o quasi-*d*: 19.6 ± 0.6 fm^3

^{120}Sn

$\alpha_D(^{120}\text{Sn})$: 8.93 ± 0.36 fm^3

quasi-*d*: 0.34 ± 0.08 fm^3

w/o quasi-*d*: 8.59 ± 0.37 fm^3

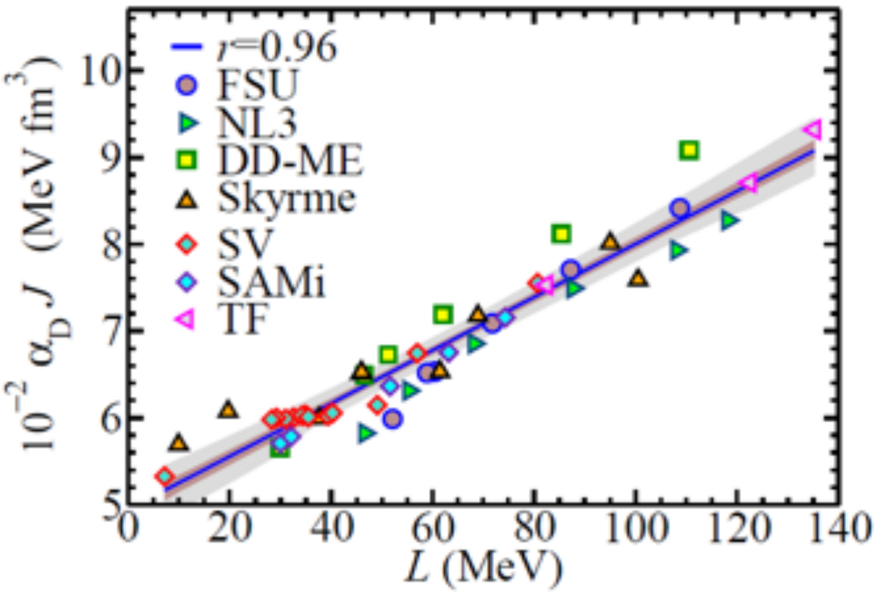


The quasi-d contribution may need be subtracted for comparison with the present theoretical predications. (Not adapted yet in the following discussions)

Constraints

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

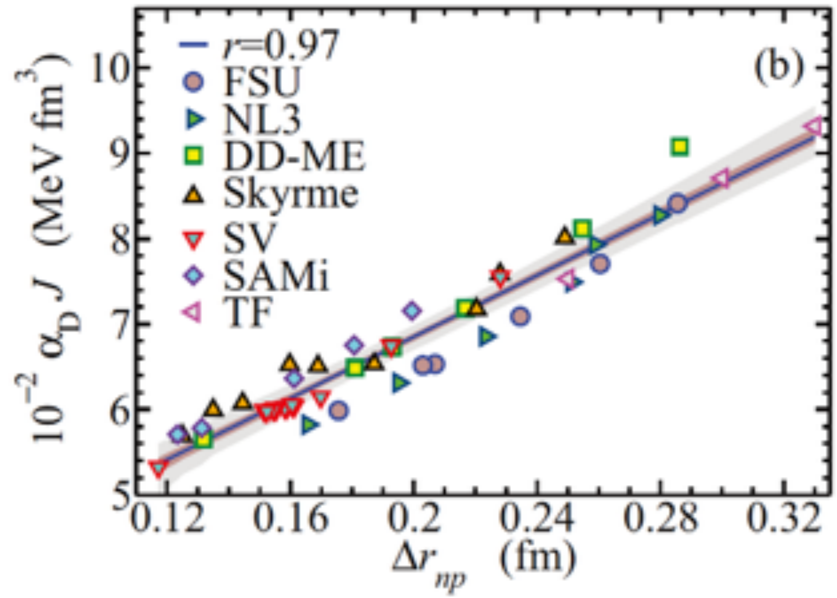
Symmetry Energy Parameters



Experimental Value = α_D

➔ Constraint in the *J*-*L* plane

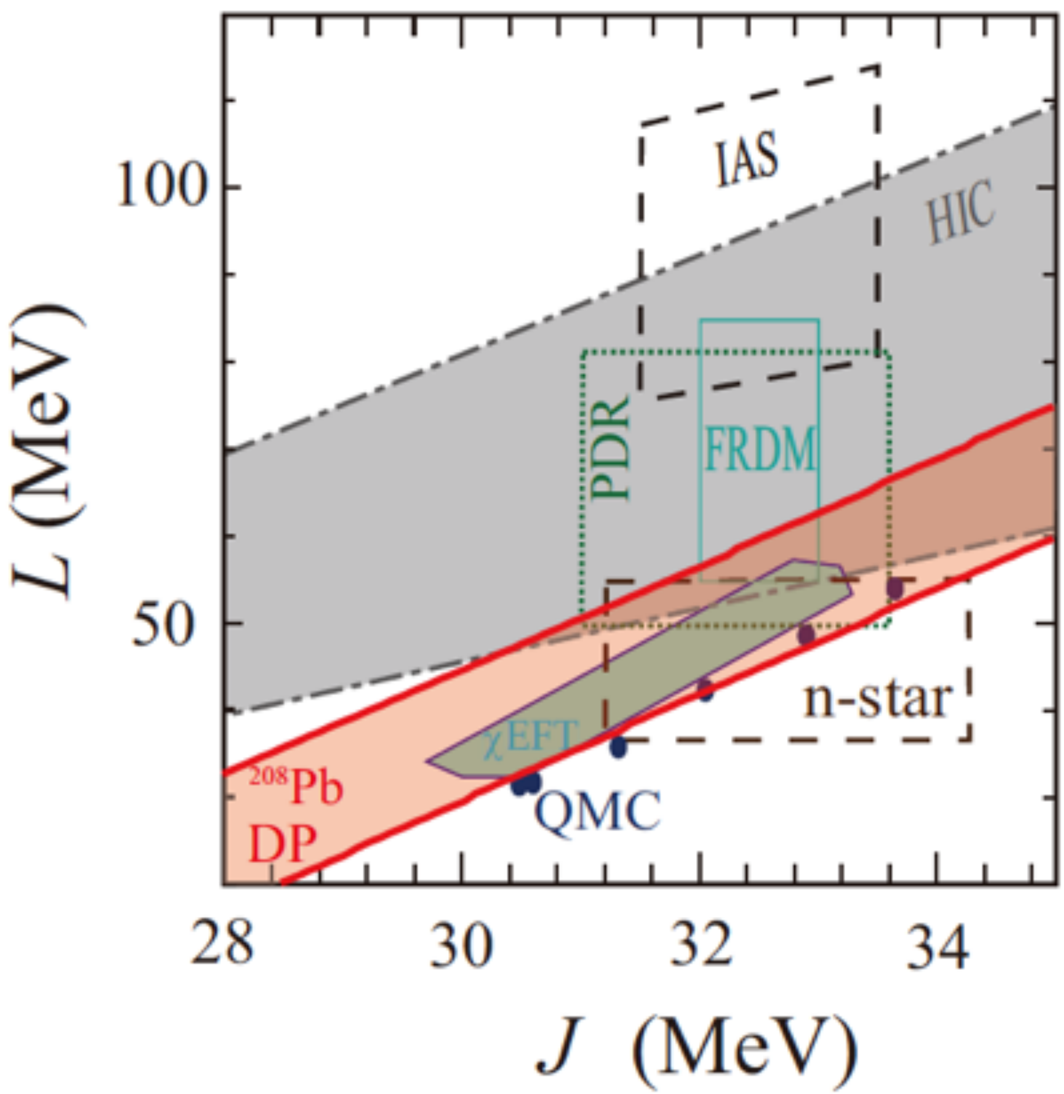
Neutron Skin Thickness



$\Delta r_{np} = 0.165 \pm (0.009)_{expt} \pm (0.013)_{theor} \pm (0.021)_{est}$ fm

for the estimated $J = 31 \pm (2)_{est}$

Constraints on J and L



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

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

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

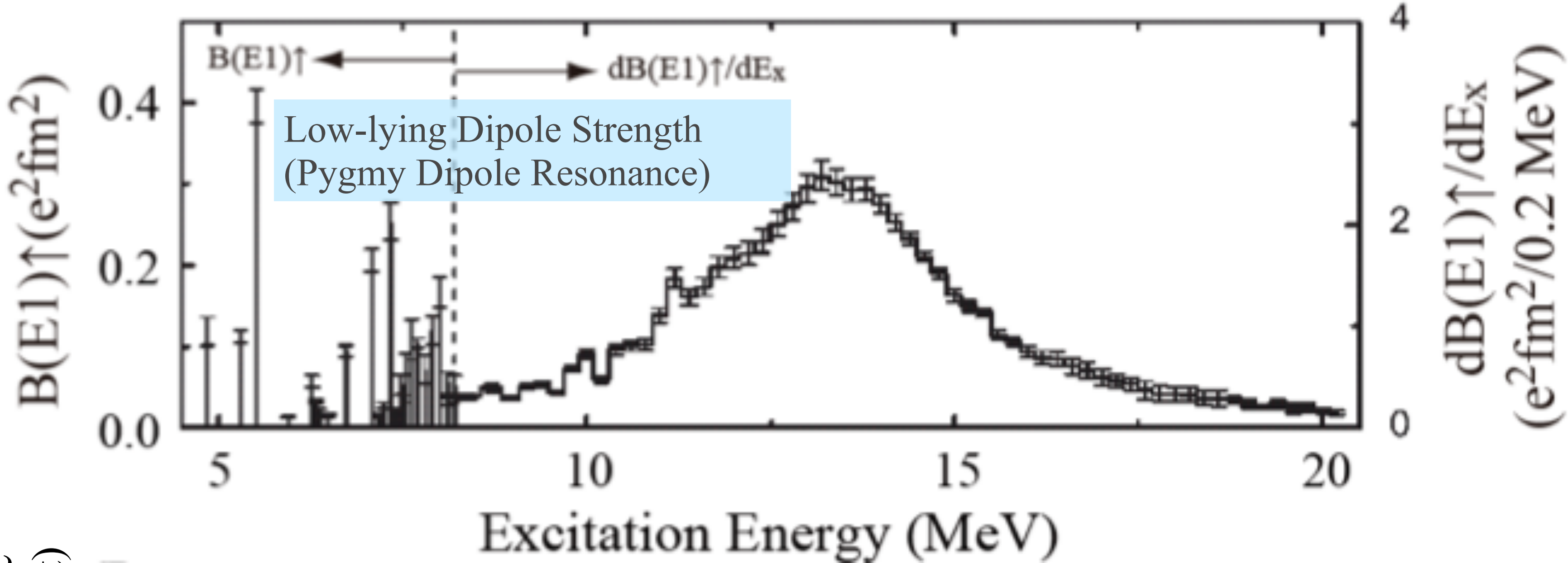
DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

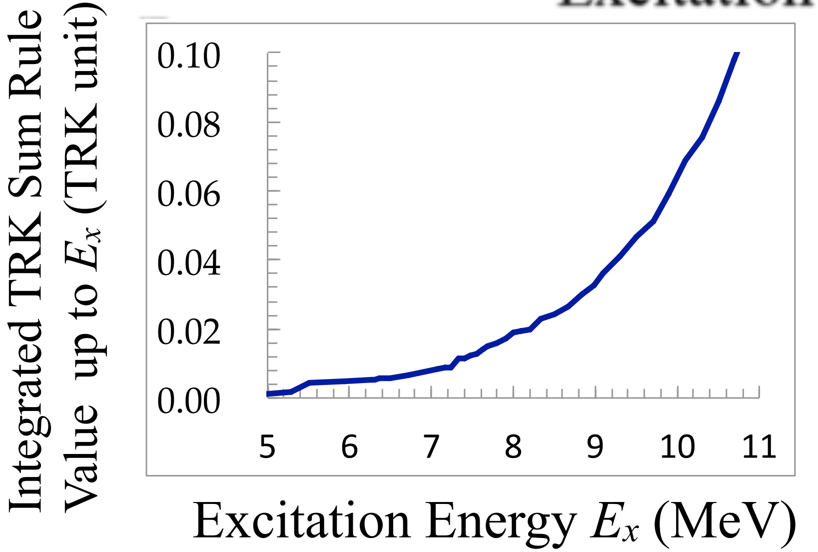
QMC: S. Gandolfi, EPJA50, 10(2014).

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

Electric Dipole Response of ^{208}Pb

2% of TRK

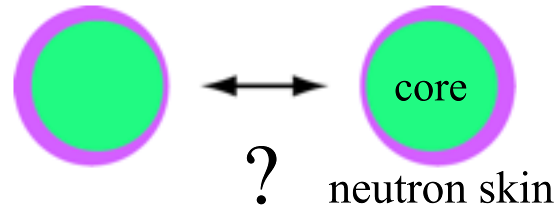




Cluster Dipole Sum-Rule of PDR

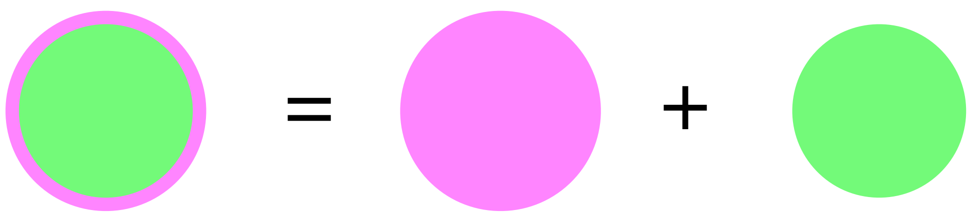
Assuming that the PDR is formed by the dipole oscillation of the neutron skin against the other part (core),

PDR



Y. Alhassid, M. Gai and G.F. Bertsch, PRL49, 1482(1982)
H. Sagawa and M. Honma, PLB251,17(1990)
R. de Diego, E. Garrido et al., PRC77, 024001 (2008)

Cluster Dipole Sum-Rule



$$60\frac{(Z_sA_c - Z_cA_s)^2}{AA_sA_c}$$

A,N,Z $\quad A_s, N_s, (Z_s = 0)$ $\quad A_c, N_c, (Z_c = Z)$

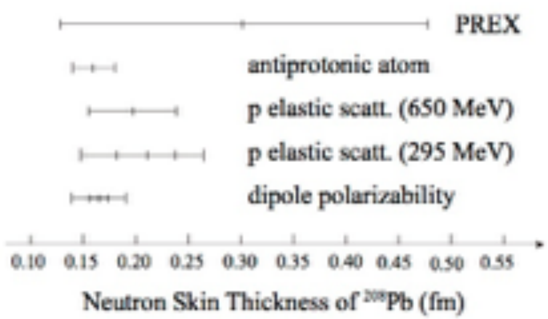
TRK: $60\frac{NZ}{A}$

Number of neutrons in the skin: N_s

2% TRK $\rightarrow N_s \sim 12$

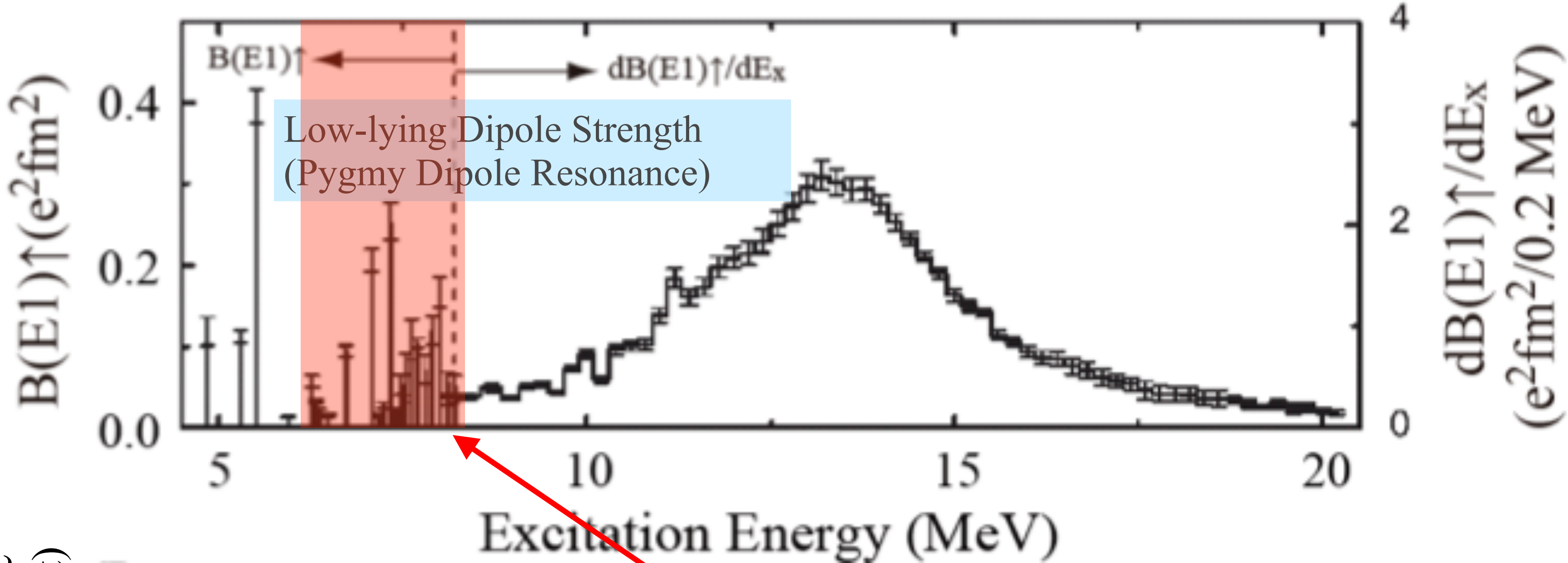
R_n=5.66 and $\delta R_{np} = 0.168\pm0.022$

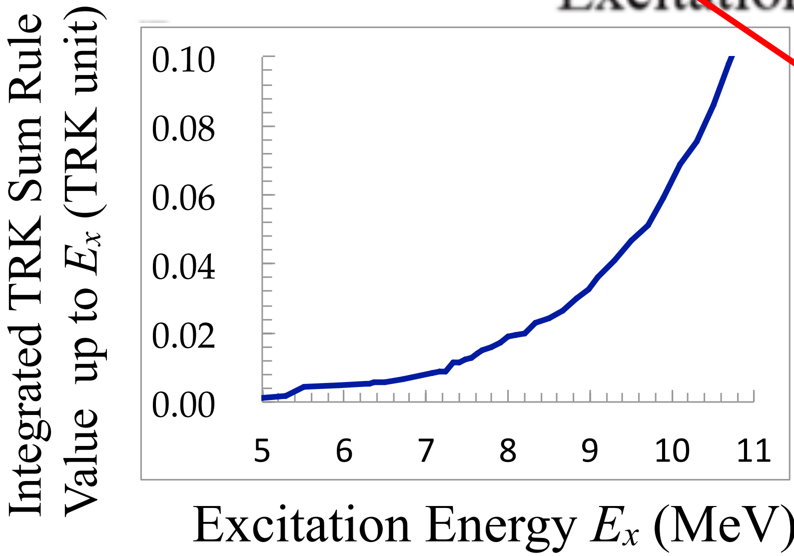
$\rightarrow N_s = 10.9\pm1.4$



The numbers look consistent to each other

Electric Dipole Response of ^{208}Pb

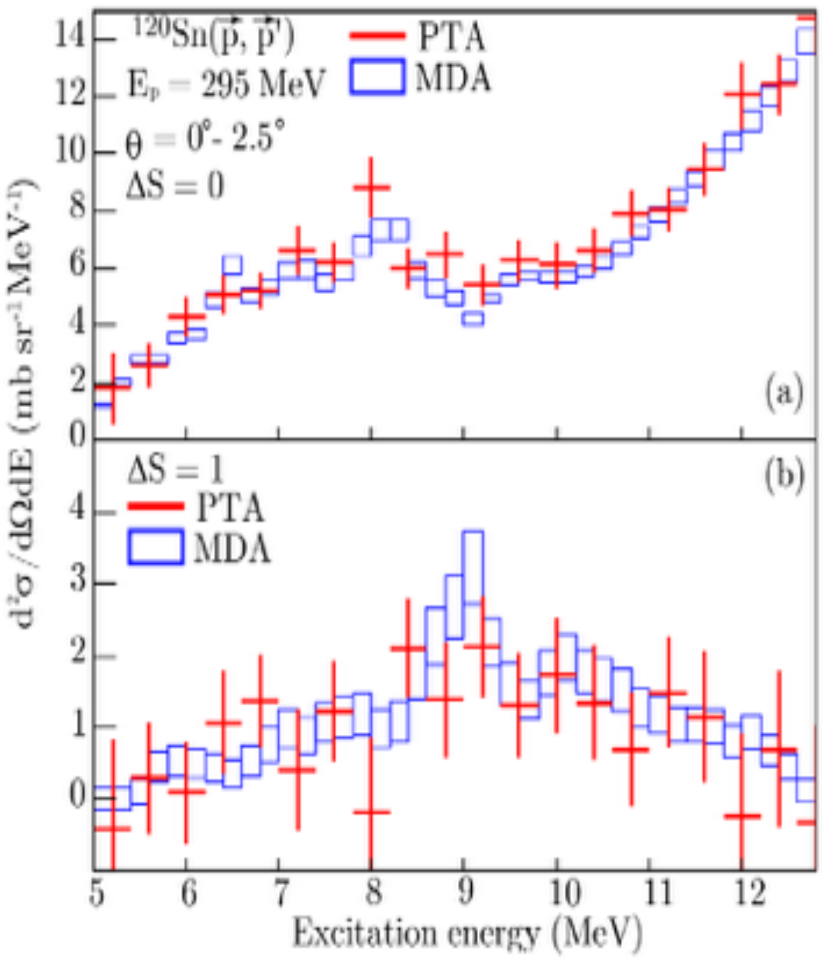


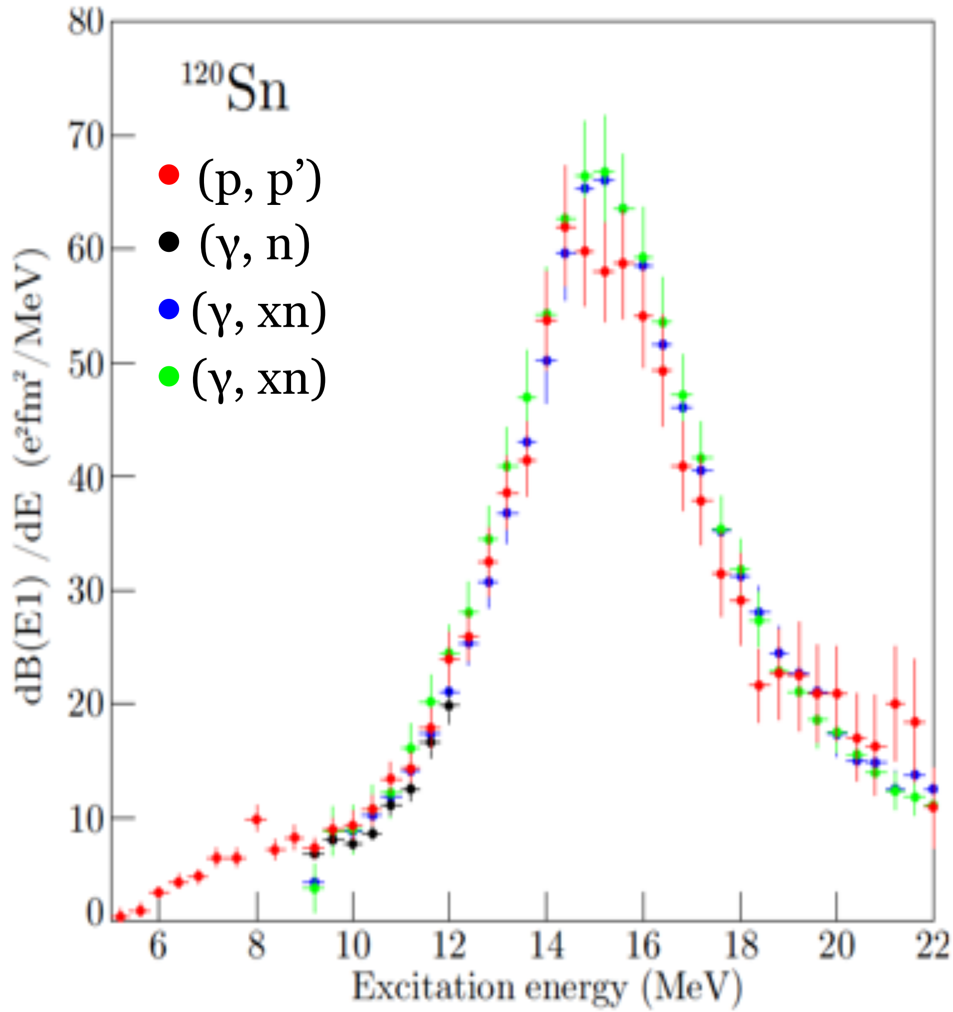


This amount of the E1 strength corresponds to the neutron skin oscillation predicted by the cluster sum-rule.

Dipole Polarizability of ^{120}Sn

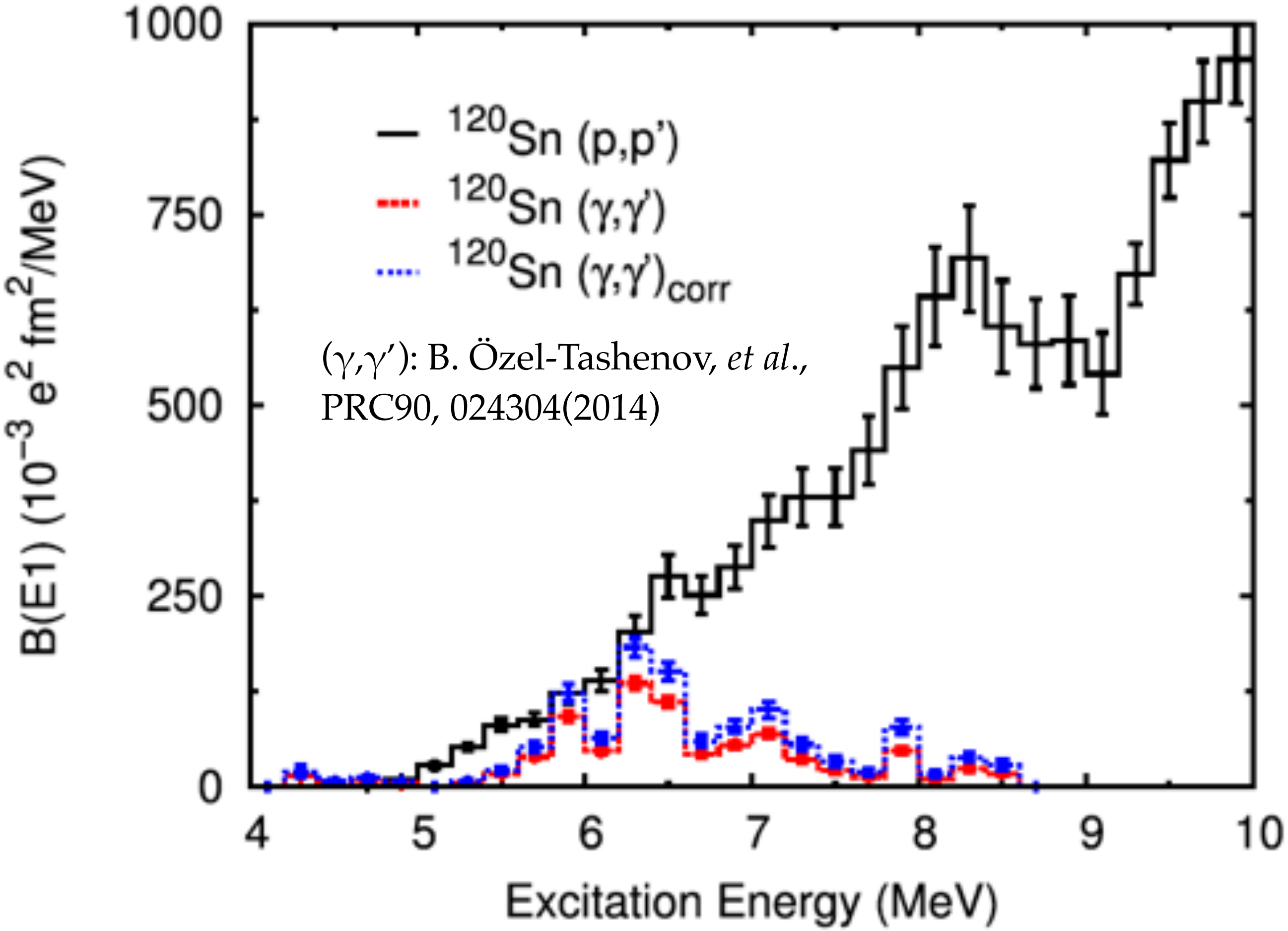
T. Hashimoto *et al*., to be published in PRC





PDR in ^{120}Sn

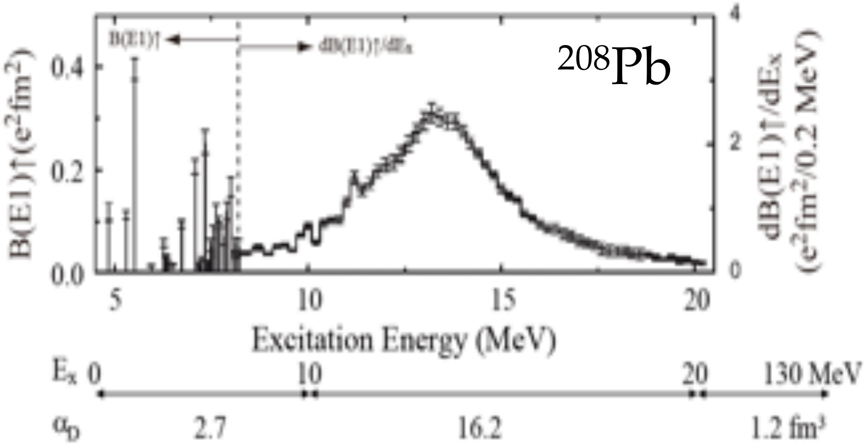
A.M. Krumbholtz *et al.*, PLB744, 7(2015)



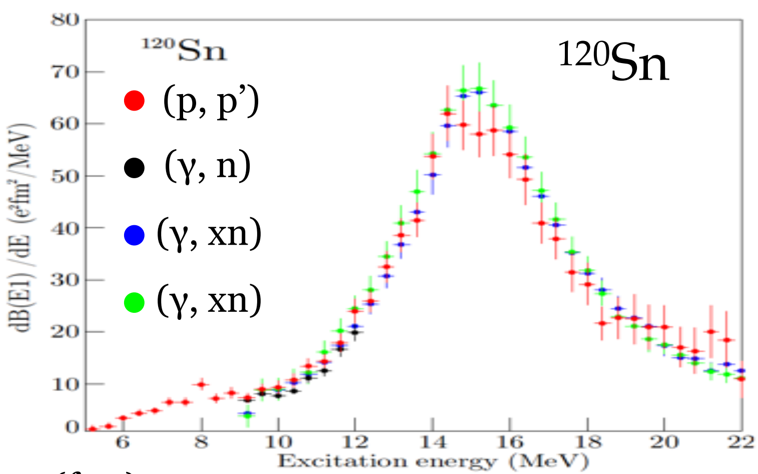
The observed strength by (p,p') is significantly larger than (γ,γ')

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

T. Hashimoto *et al.*, to be published in PRC



Total: $\alpha_D = 20.1 \pm 0.6$ fm^3

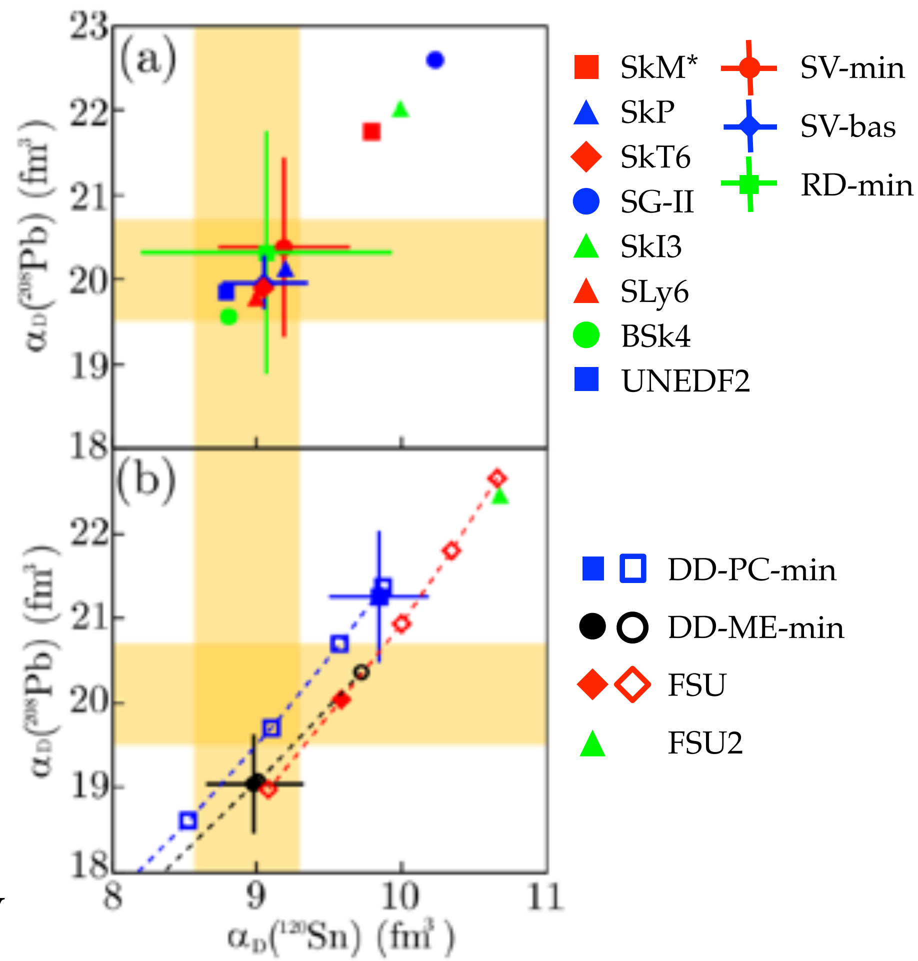


α_D (fm^3) 135 MeV

1.12 ± 0.07 7.00 ± 0.29 0.82 ± 0.12

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

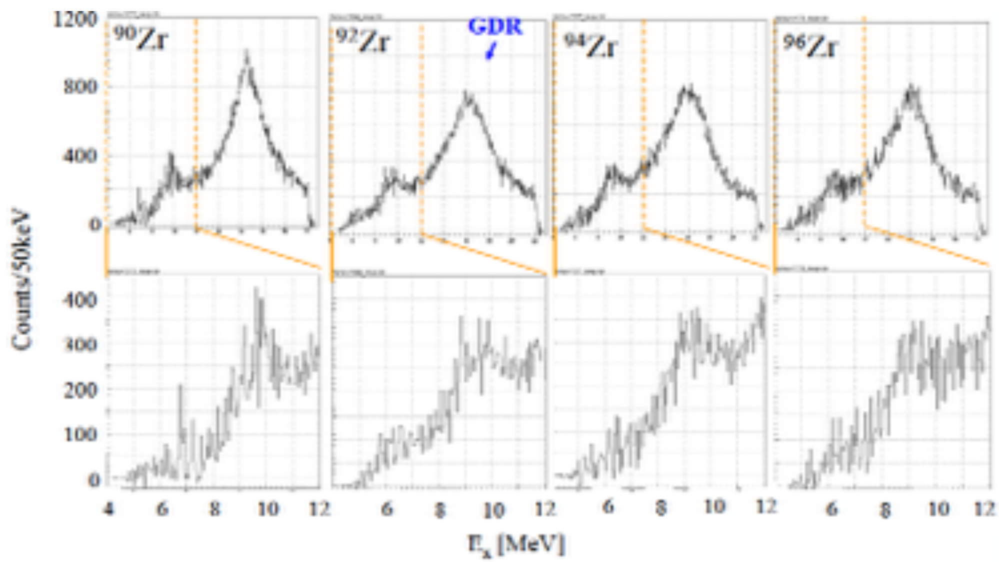
calc. by P.-G. Reinhard



Plans in Near Future

- Measurements on ^{112}Sn, ^{124}Sn and on ^{92}Zr, ^{94}Zr, ^{96}Zr, have been done in May-June, 2015.
- Data analyses on ^{48}Ca, ^{90}Zr, ^{96}Mo, and ^{154}Sm

Zr isotopes: presentation by C. Iwamoto on Tuesday

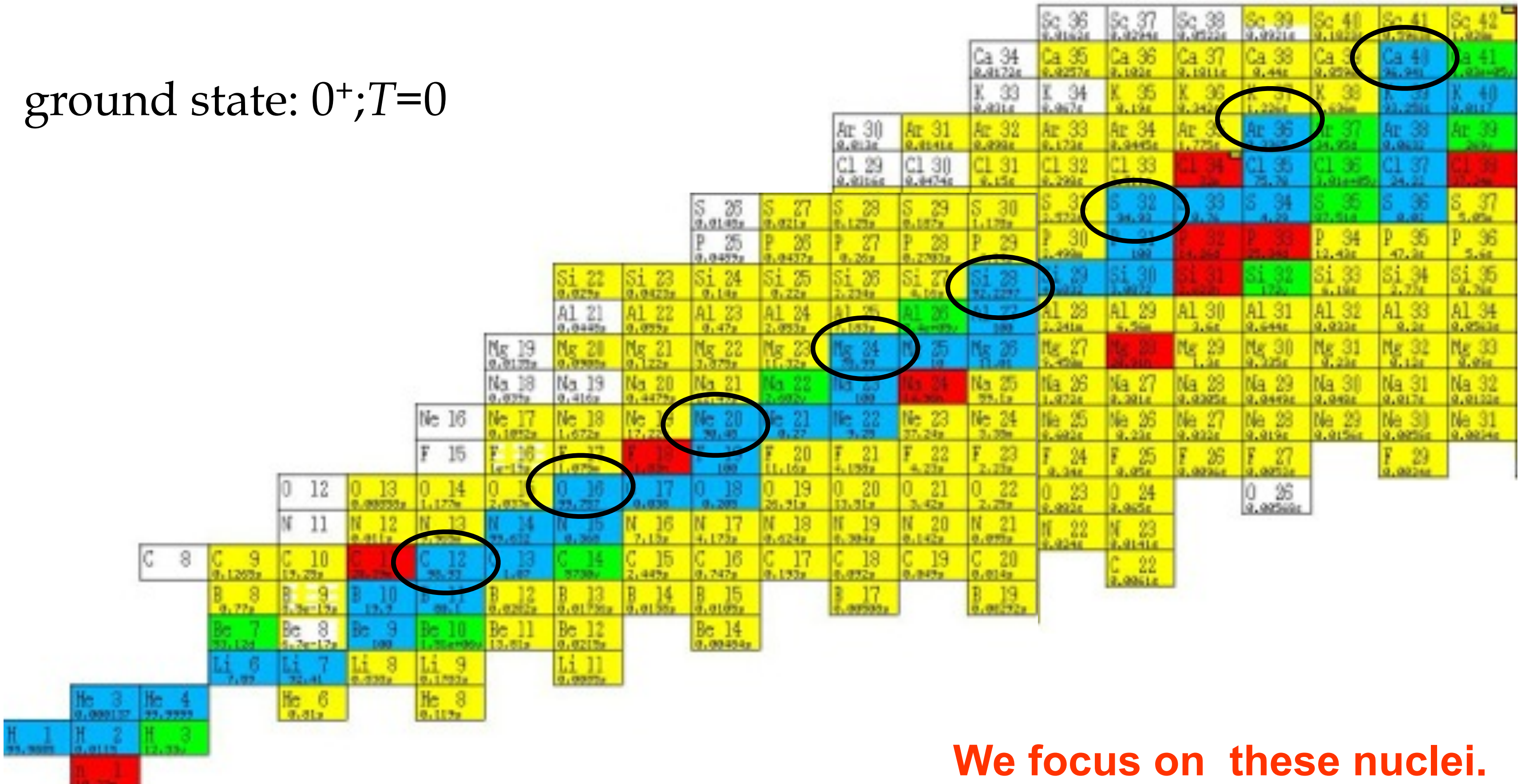


Spin-M1 Responses and Quenching of IS/IV Spin-M1 Strengths

H. Matsubara et al., PRL**115**, 102501 (2015)

Self-Conjugate (*N*=*Z*) even-even Nuclei

ground state: $0^{+}; T=0$

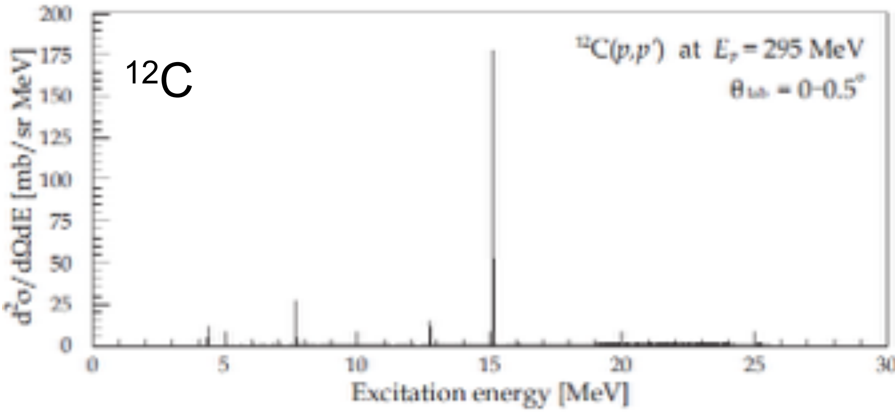


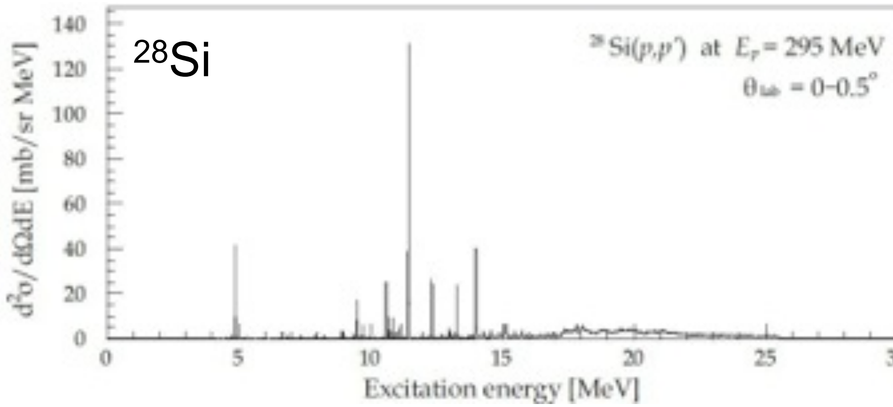
We focus on these nuclei.

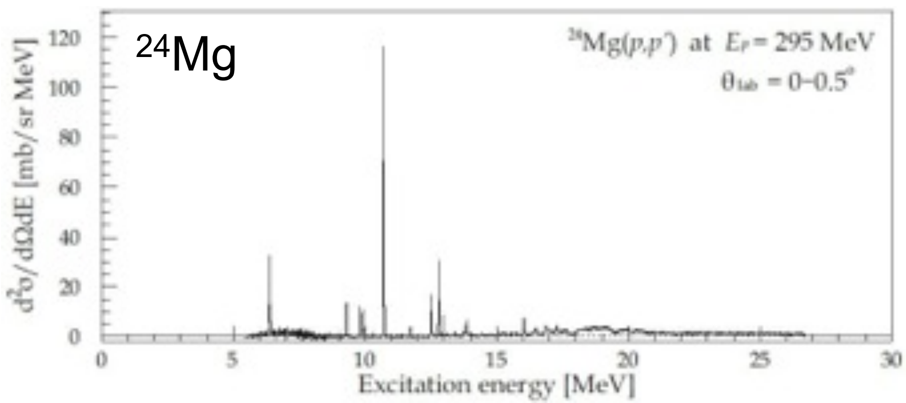
Stable self-conjugate even-even nuclei:

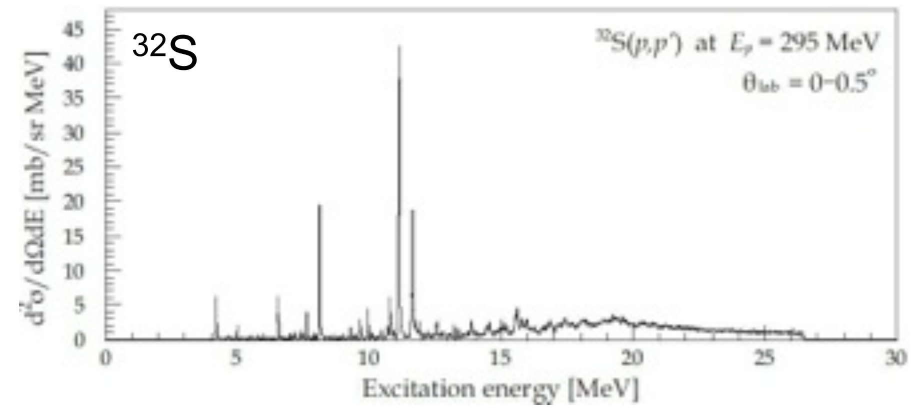
(^{4}He), ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca

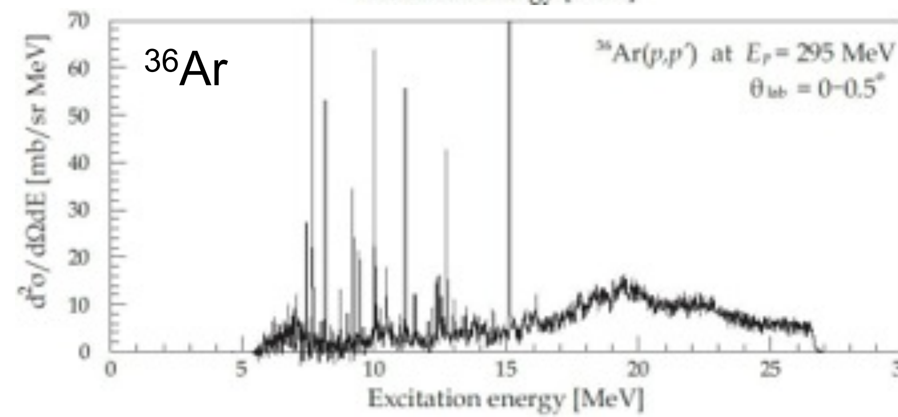
Energy spectra at 0-degrees



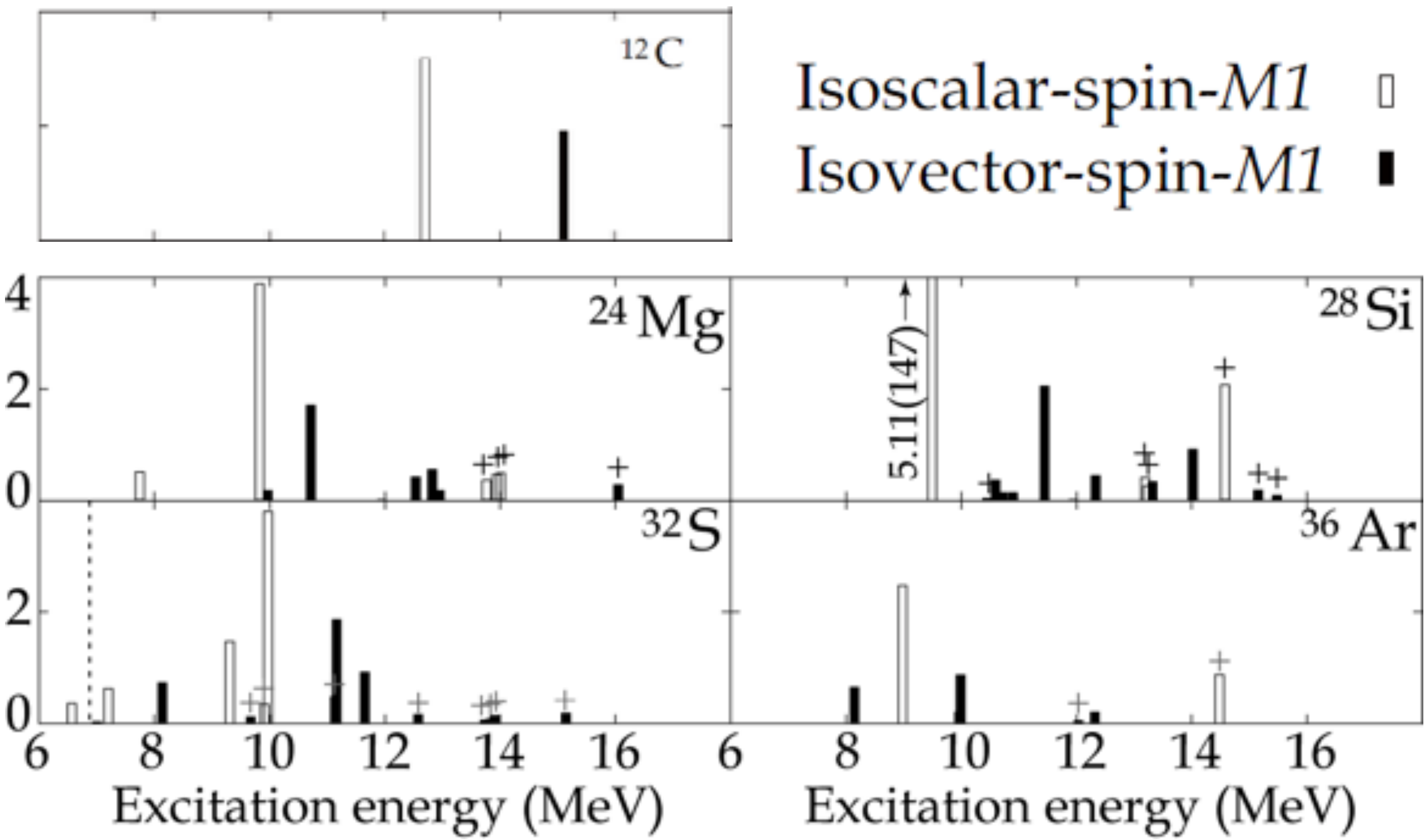








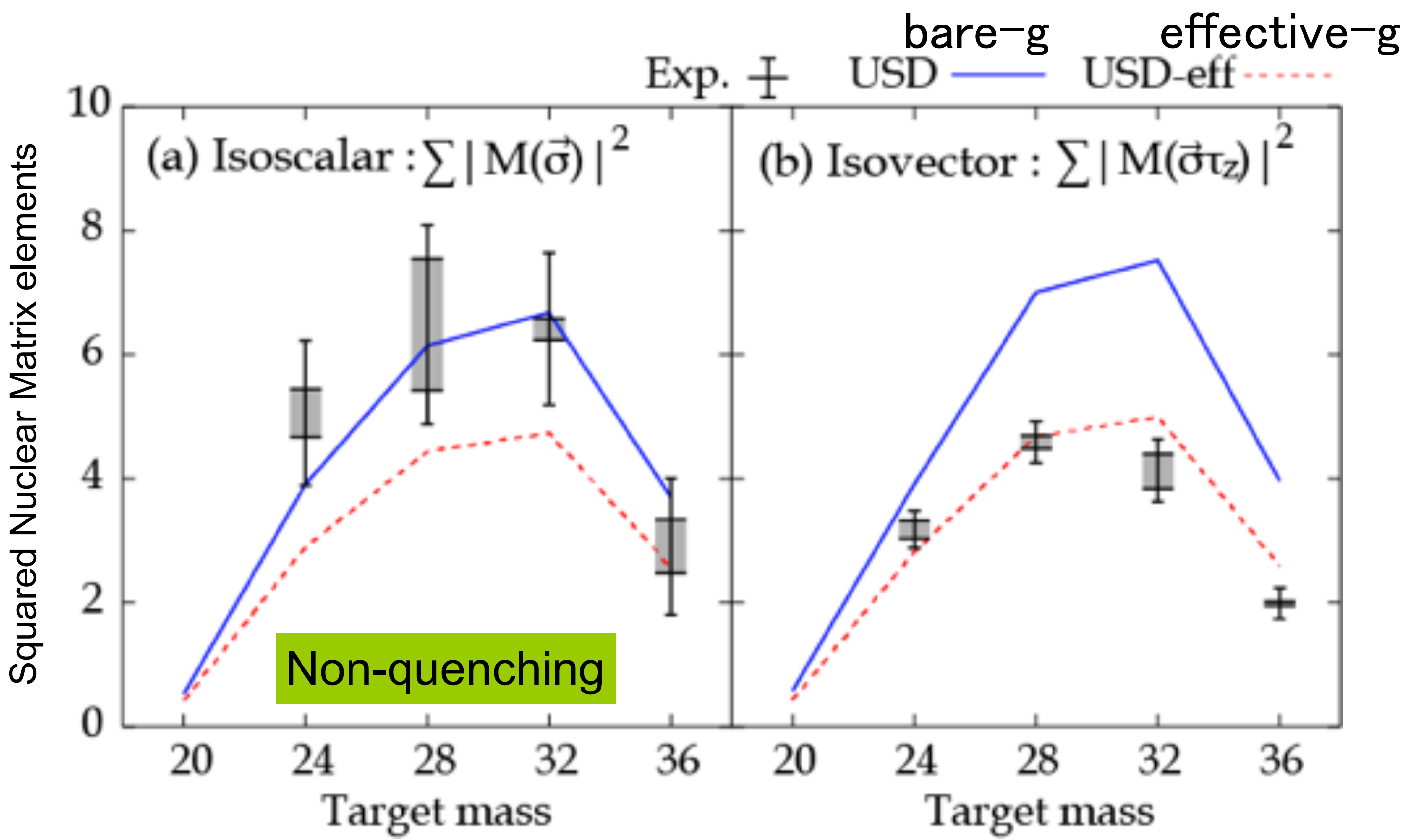
IS / IV-spin-M1 distribution



Spin-M1 SNME

H. Matsubara et al., PRL**115**, 102501 (2015)

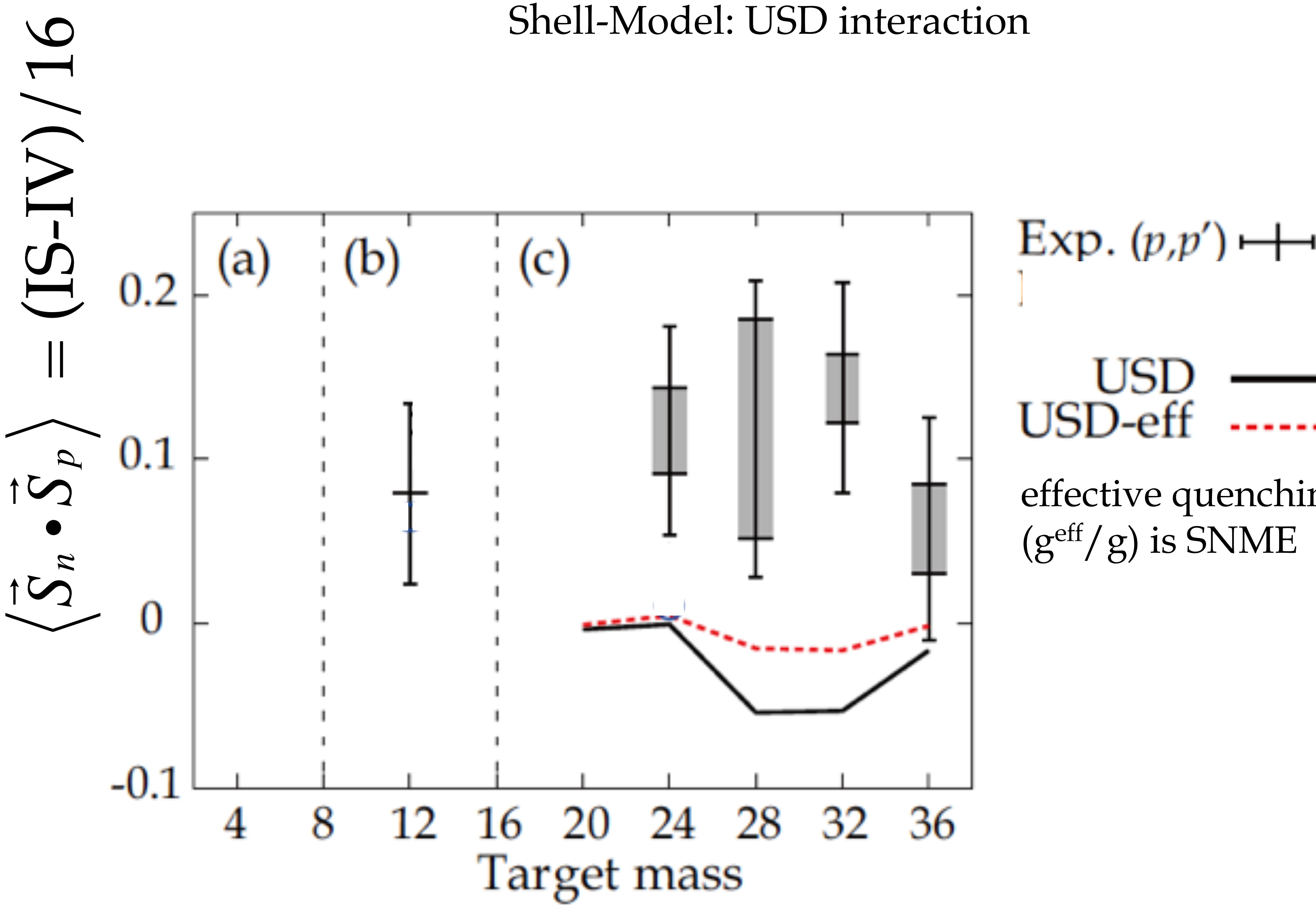
- Summed <u>up to **16 MeV**</u>.
- Compared with shell-model predictions using the USD interaction



Isoscalar spin-M1 SNME is NOT quenching.

np Spin Correlation Function

Shell-Model: USD interaction



effective quenching (g^{eff}/g) is SNME

np spin correlation function

$$\vec{S}_n \equiv \sum_i^N \vec{s}_{n,i} \qquad \vec{S}_p \equiv \sum_i^Z \vec{s}_{p,i}$$

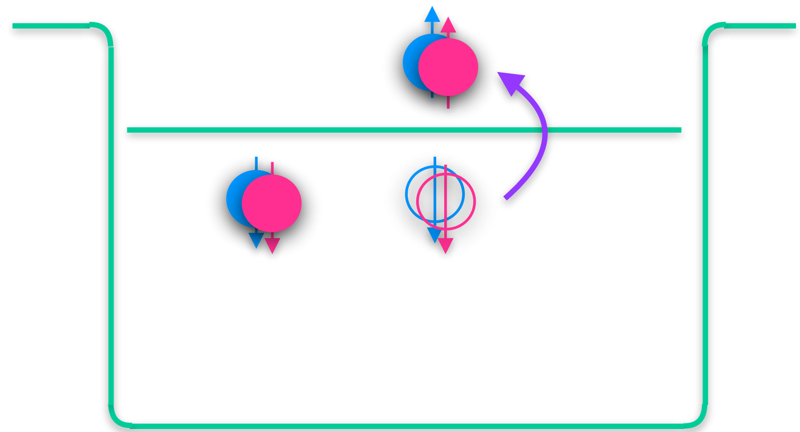
$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = \frac{1}{4}\left\langle \left(\vec{S}_n + \vec{S}_p\right)^2 - \left(\vec{S}_n - \vec{S}_p\right)^2 \right\rangle$$

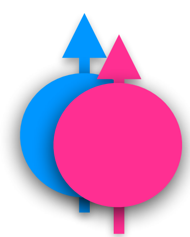
$$= \frac{1}{16}\left(\sum \left| M\left(\vec{\sigma}\right)\right|^2 - \sum \left| M\left(\vec{\sigma}\tau_z\right)\right|^2 \right)$$

: np spin correlation function

of the nuclear ground state

→ hints isoscalar np-pairing



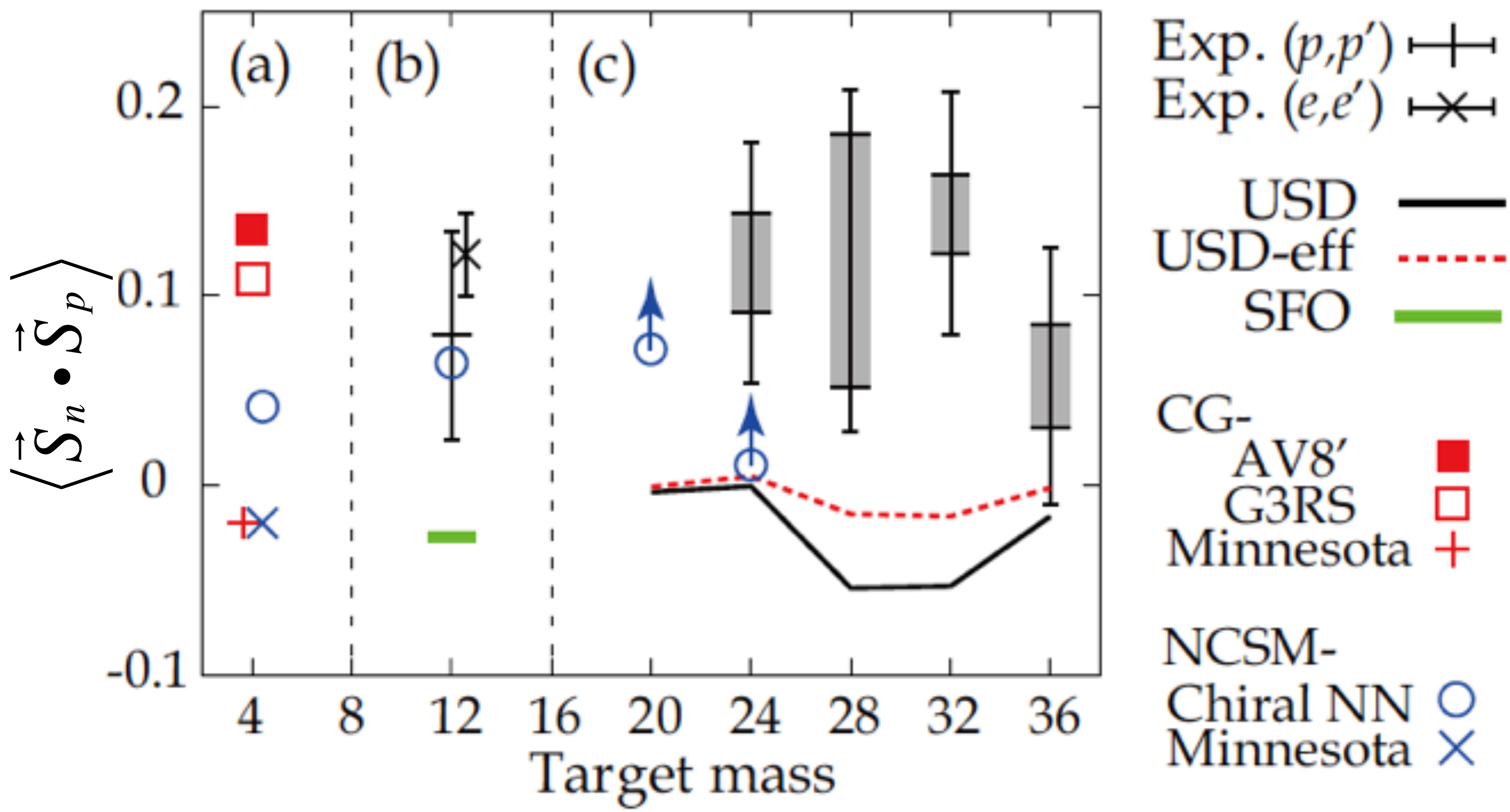


spin aligned np-pair

$$\left\langle \vec{s}_n \cdot \vec{s}_p \right\rangle > 0$$

np Spin Correlation Function

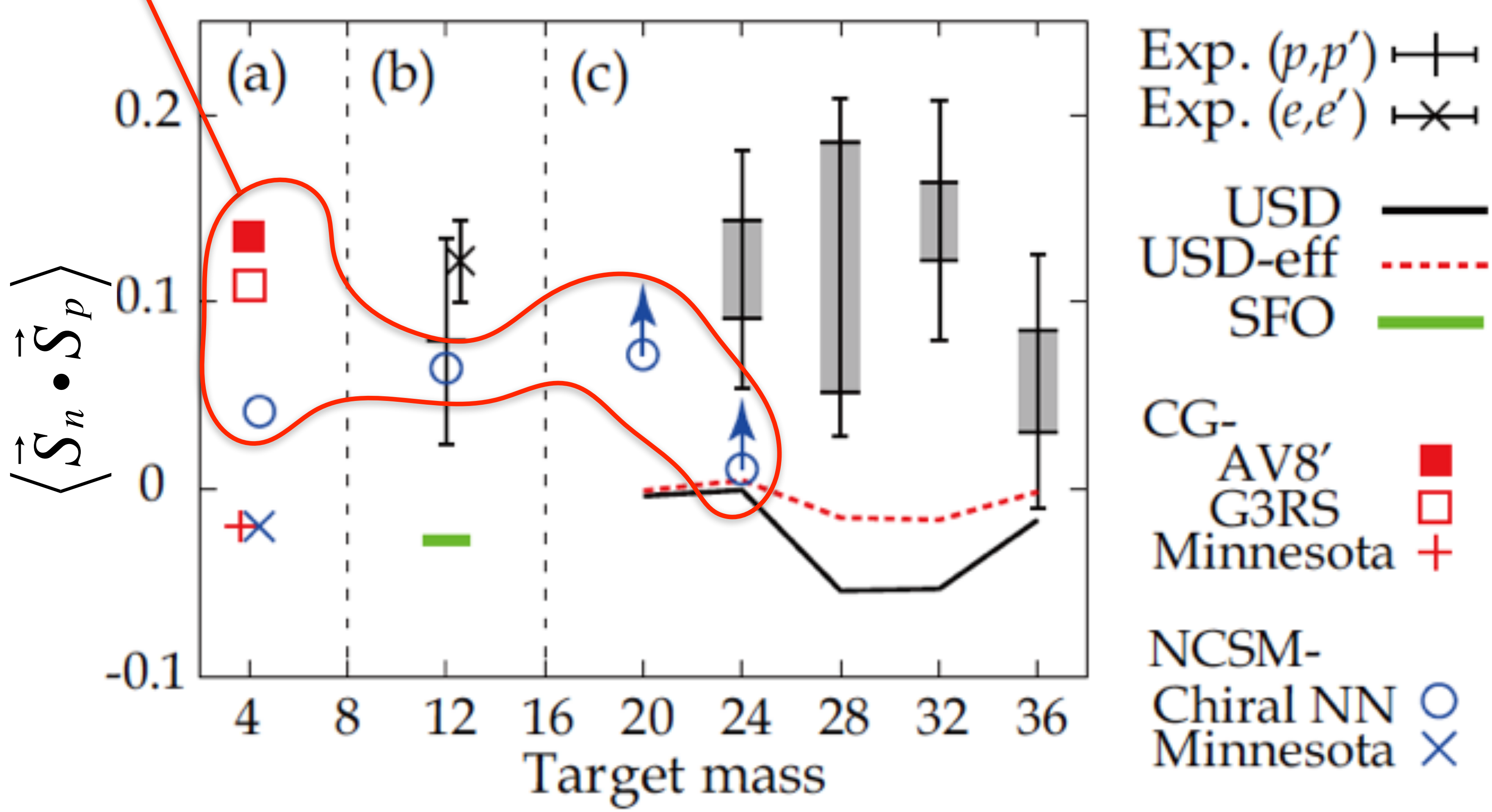
Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil



np Spin Correlation Function

ab-initio type calc.
with realistic NN int.

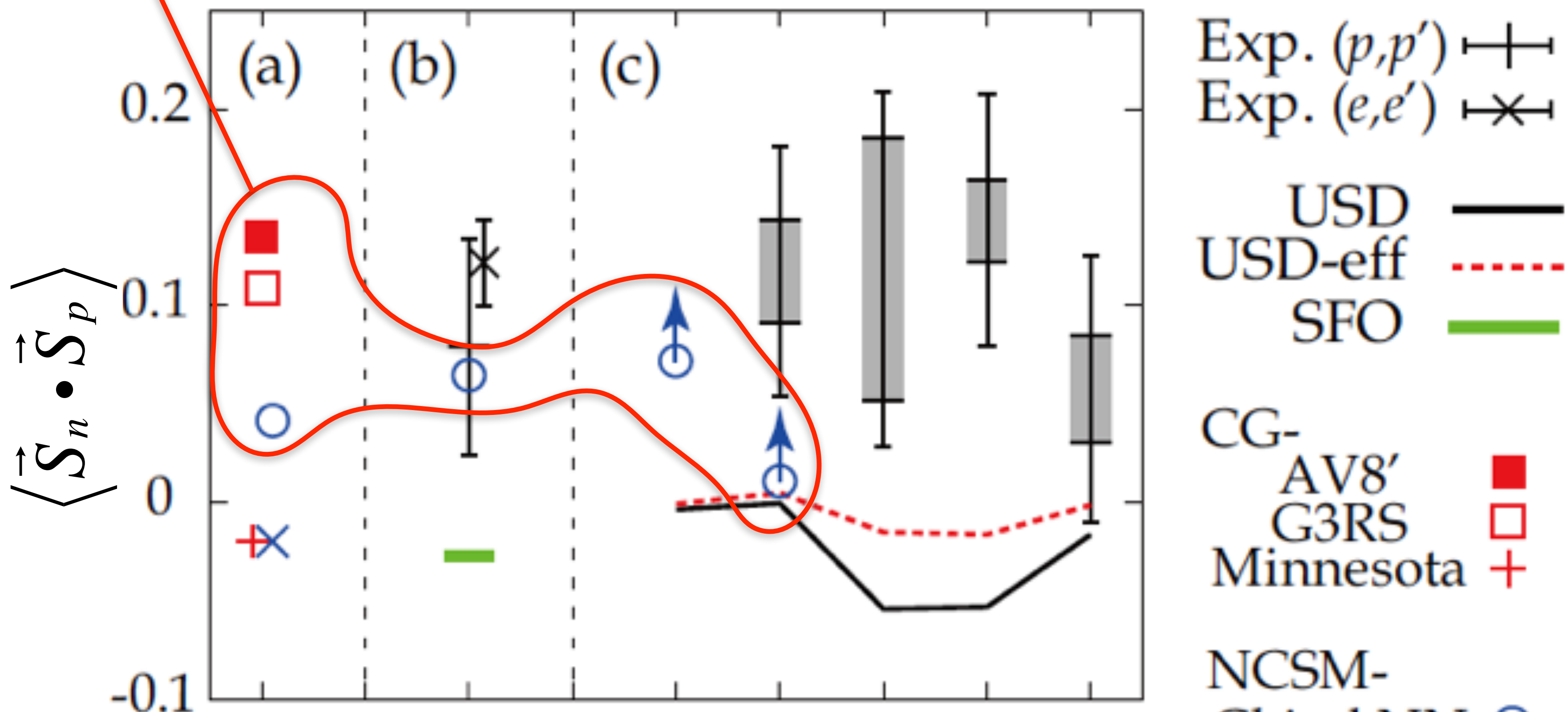
Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil



np Spin Correlation Function

ab-initio type calc.
with realistic NN int.

Shell-Model: USD interaction
Correlated Gaussian Method: W. Horiuchi
Non-Core Shell Model: P. Navratil

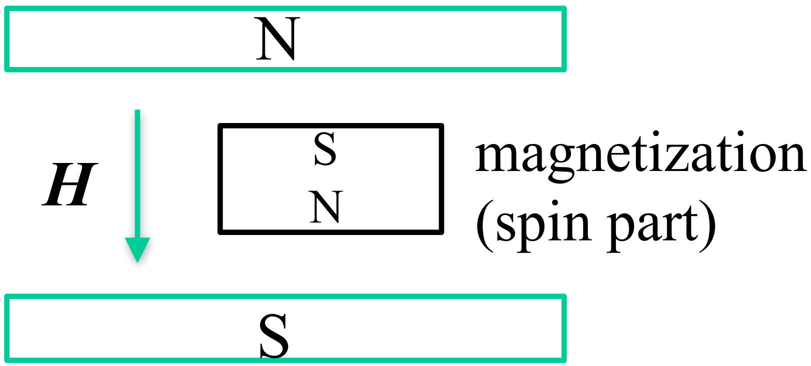


Further theoretical studies are interesting:
large scale shell model, non-core shell model, coupled cluster calc, etc.

Spin Susceptibility Very Preliminary

Inversely energy-weighted sum rule of the spin-M1 strengths

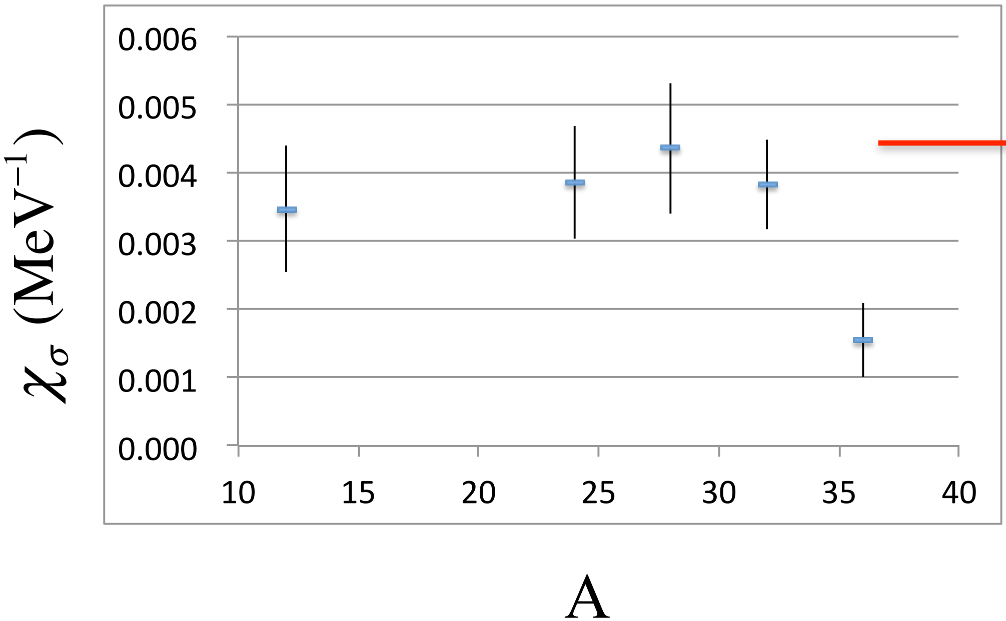
$$\chi_\sigma = \frac{8}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$



$$\mathbf{M} = \chi_\sigma \mathbf{H}$$

χ_σ: spin magnetic susceptibility.

Spin Susceptibility of *N*=*Z* Nuclei



0.0044(7) MeV^{-1} at ρ=0.16 fm^{-3}

Neutron matter calc.
by AFDMC model

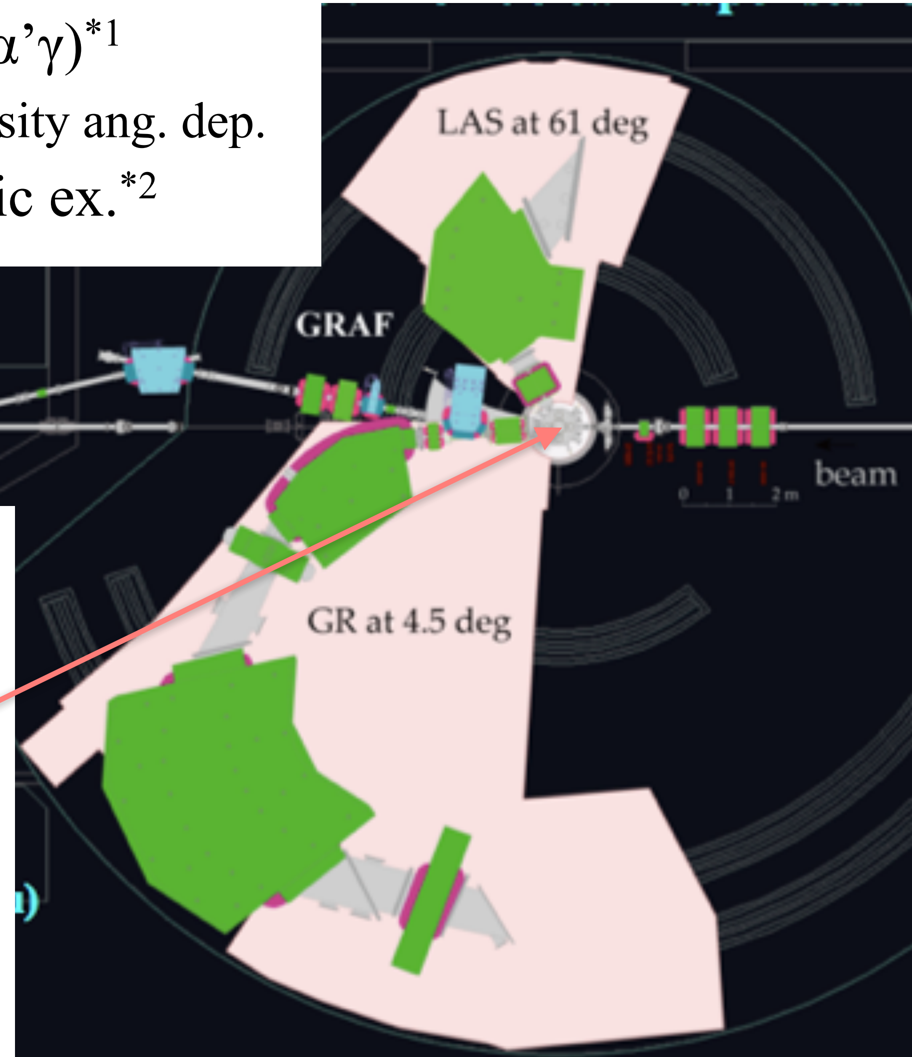
G. Shen et al., PRC**87**, 025802 (2013)

- magnetic response of nuclear matter
- ν-emissivity
- ν-transportation

Conclusion/Future

CAGRA+GR Campaign Exp. in 2016

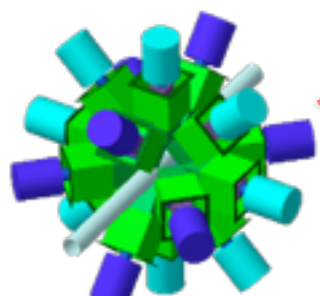
- Study on PDR by (p, p'γ) and (α,α'γ)*1
  isospin/surface property, transition density ang. dep.
- (^{6}Li,^{6}Li'γ) for IV spin-flip inelastic ex.*2



CAGRA(Clover Ge Array)

E. Ideguchi and M. Carpenter

for γ-coincidence measurements



also plans for LaBr3 detectors

spokespersons:

*1 A. Bracco, F. Crespi, V. Derya, M.N. Harakeh, T. Hashimoto, C. Iwamoto, P. von Neumann-Cosel, N. Pietralla, D. Savran, A. Tamii, V. Werner, and A. Zilges *et al.*

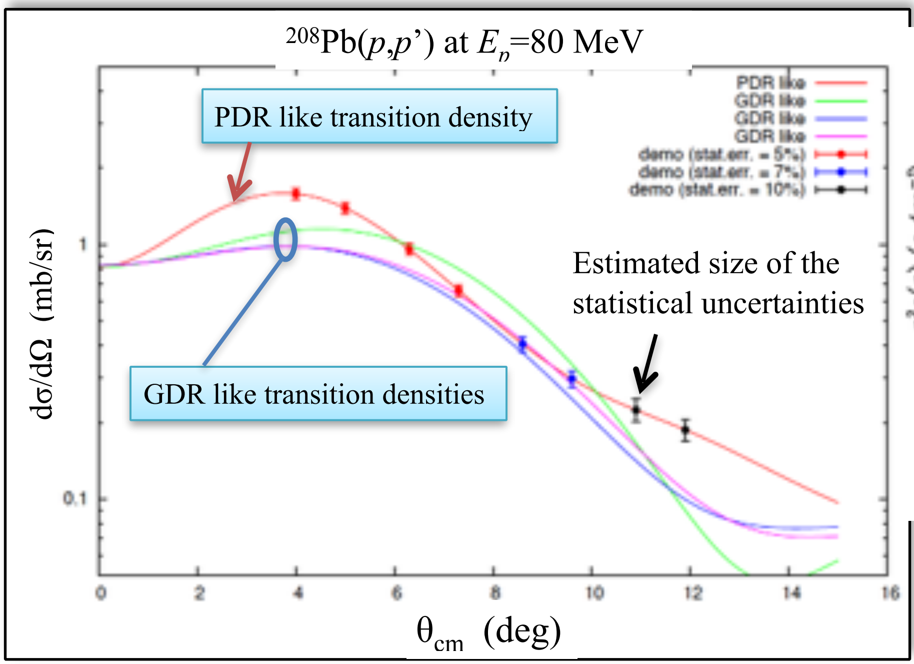
*2 S. Noji, R.G.T. Zegers *et al.*,

Conclusion/Future

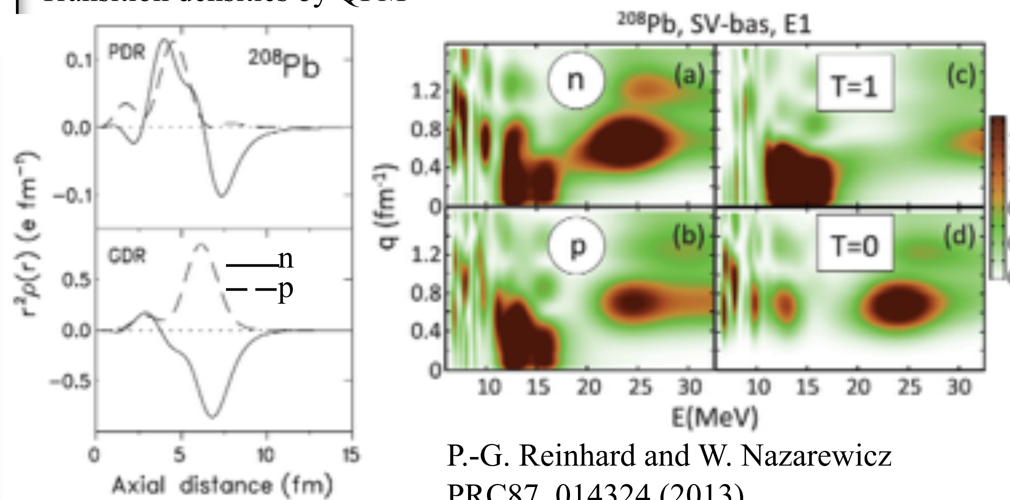
CAGRA+GR Campaign Exp. in 2016

E441 5.0 days (^{6}Li,^{6}Li'γ) for IV spin-flip inelastic excitation
E450 25.0 days (p,p'γ) and (α,α'γ) for PDR
E454 6.0 days (p,p'γ) at 300 MeV and (α,α'γ) for PDR
Total 36.0 days.

(p,p'γ) and (α,α'γ) for PDR in ^{64}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb



Transition densities by QPM



P.-G. Reinhard and W. Nazarewicz PRC87, 014324 (2013)

Collaborators

A. Bracco*, F. Crespi*, F. Camera*, O. Wieland*, …
D. Savran*, A. Zilges*, V. Derya*, J. Isaak*,…
M.N. Harakeh*,
A. Tamii*, C. Iwamoto*, T. Hashimoto, N. Nakatsuka*…
P. von Neumann-Cosel, N. Pietralla, V. Werner, …
A. Maj*, B. Wasilewska*, M. Krzysiek*, …
R.G.T. Zegers*, S. Noji, S. Lipscutz*, …

***Participants in COMEX5**

A new collaborative project of Angela and Adam.

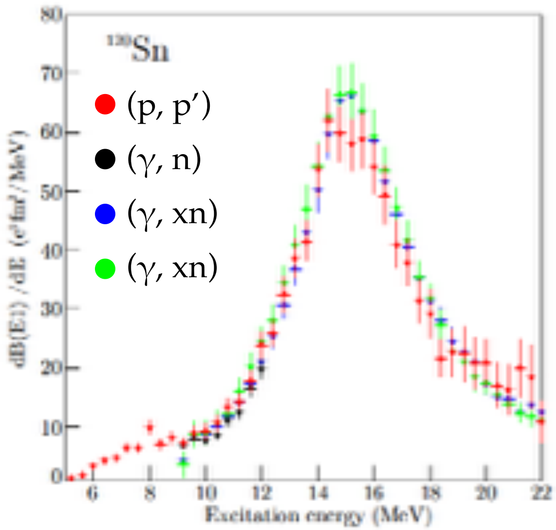
Conclusion/Future

- Electric dipole response of ^{208}Pb and ^{120}Sn: Measured precisely by proton inelastic scattering.

→ IV properties of the effective interaction:

- Constraints on the symmetry energy
- Neutron skin thickness, pygmy dipole excitations

Isotope dependence on Sn and Zr have been measured.

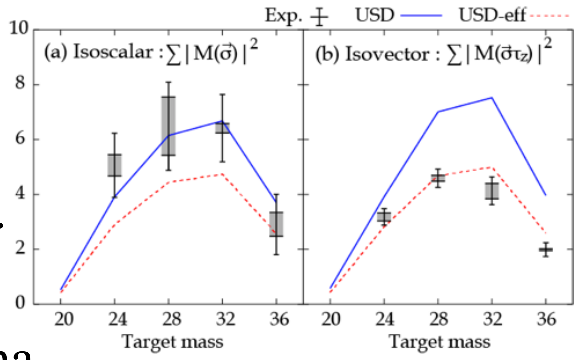


T. Hashimoto *et al.*, to be published in PRC.

- Non-quenching IS spin-*M1* matrix elements in *sd*-shell.

↔ Quenching of IV spin-*M1* and GT matrix elements.

- Requires further knowledge on the quenching phenomena.
- Hints IS *np*-pairing correlation in the ground state.



H. Matsubara *et al.*, PRL115, 102501 (2015)

^{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

spin-M1 RCNP-E241 & E299 Collaboration

H. Matsubara,[1,†] A. Tamii,[1] H. Nakada,[2] T. Adachi,[1] J. Carter,[3] M. Dozono,[5,‡] H. Fujita,[1] K. Fujita,[1,§]
Y. Fujita,[1] K. Hatanaka,[1] W. Horiuchi,[6] M. Itoh,[7] T. Kawabata,[4,||] S. Kuroita,[5] Y. Maeda,[9] P. Navrátil,[10]
P. von Neumann-Cosel,[11] R. Neveling,[12] H. Okamura,[1,*] L. Popescu,[13,¶] I. Poltoratska,[11] A. Richter,[11] B. Rubio,[14]
H. Sakaguchi,[1] S. Sakaguchi,[4,§] Y. Sakemi,[7] Y. Sasamoto,[4] Y. Shimbara,[15,**] Y. Shimizu,[4,††] F. D. Smit,[12] K. Suda,[1,††]
Y. Tameshige,[1,‡‡] H. Tokieda,[4] Y. Yamada,[5] M. Yosoi,[1] and J. Zenihiro[8,††]

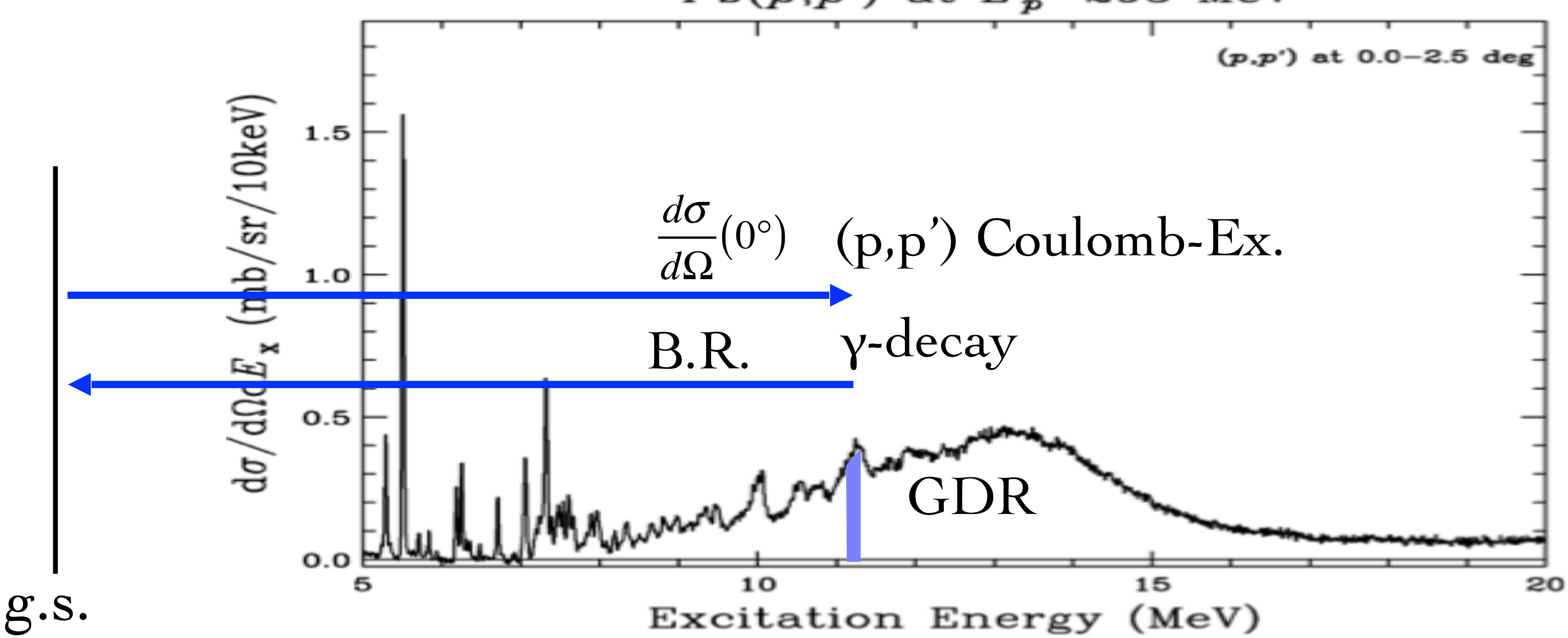
[1]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*
[2]*Department of Physics, Chiba University, Inage, Chiba 263-8522, Japan*
[3]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[4]*Center for Nuclear Study (CNS), University of Tokyo, Bunkyo, Tokyo 113-0033, Japan*
[5]*Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*
[6]*Department of Physics, Hokkaido University, Sapporo 060-0810, Japan*
[7]*Cyclotron and Radioisotope Center (CYRIC), Tohoku University, Sendai, Miyagi 980-8578, Japan*
[8]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[9]*Department of Applied Physics, Miyazaki University, Miyazaki 889-2192, Japan*
[10]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[11]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[12]*iThemba LABS, National Research Foundation, Somerset West 7129, South Africa*
[13]*Vakgroep Subatomaire en Stralingsfysica, Universiteit Gent, B-9000 Gent, Belgium*
[14]*Instituto of Fisica Corpuscular, CSIC-University de Valencia, E-46071 Valencia, Spain*
[15]*Graduate School of Science and Technology, Niigata University, Niigata 950-2102, Japan*

Thank you

Fine Structure of GDR and its direct g.s. gamma decay

(under discussion)

fine structure of GDR



$$\frac{d\sigma}{d\Omega}(0°) \rightarrow B(E1) \rightarrow \Gamma_0$$

$$B.R. = \frac{\Gamma_0}{\Gamma}$$

The total width Γ will be determined for each part of the GDR.

pioneering works:
J. R. Beene et al.,PRC41, 920(1990)
A. Bracco et al., PRC39, 725(1989)

Unit cross section (UCS)

- Conversion factor from cross-section to Squared Nuclear Matrix Elements (SNME)
- Calibration from β andγ-decay measurements
  <u>(on the assumption of the isospin symmetry)</u>.

$$\frac{d\sigma}{d\Omega}(0^\circ) = \hat{\sigma}_T F(q, E_x) \left| M_f(O) \right|^2$$

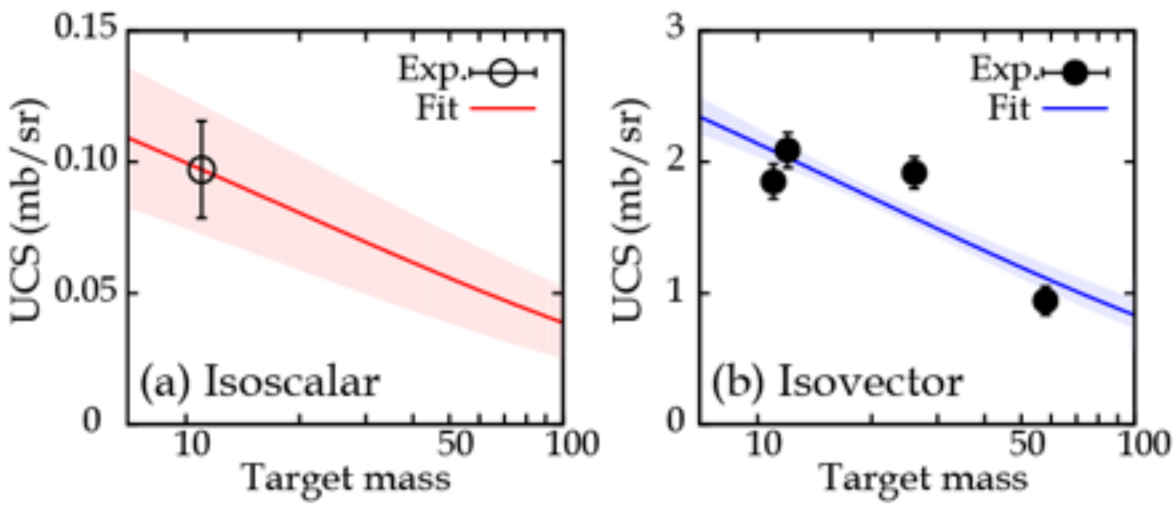
(*T*= IS or IV)

UCS Kinematical factor SNME

$$\hat{\sigma}_T(A) = N \exp\left(-xA^{1/3}\right)$$

T.N. Taddeucci, NPA469 (1987).

- Function taken from the mass dependence of GT UCS



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).

$$\alpha_D(^{208}\mathrm{Pb}) = 20.1 \pm 0.6\ \mathrm{fm}^3$$

$$\alpha_D(^{120}\mathrm{Sn}) = 8.93 \pm 0.36\ \mathrm{fm}^3$$

- 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.

Backup Slides

Nuclear Equation of State (EOS)

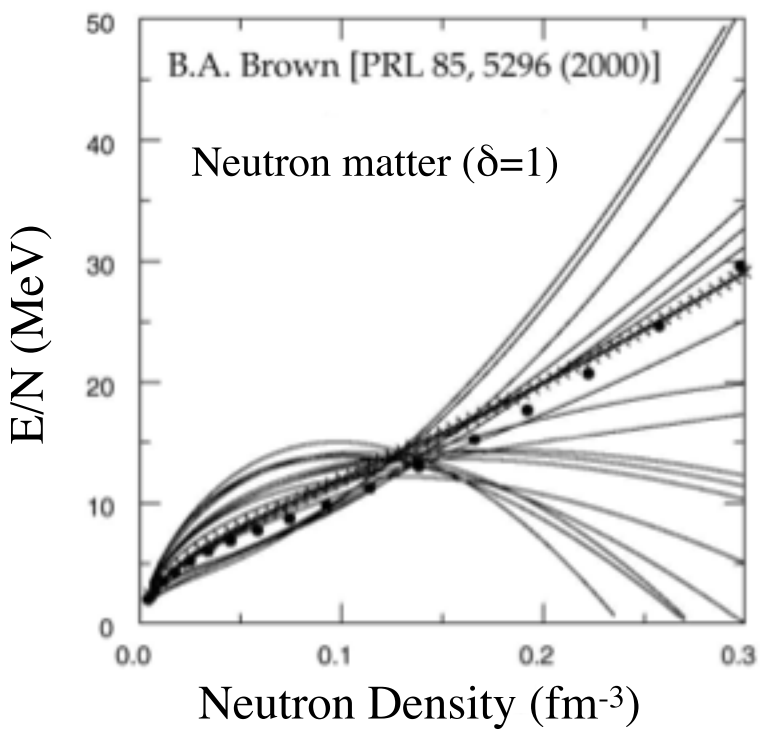
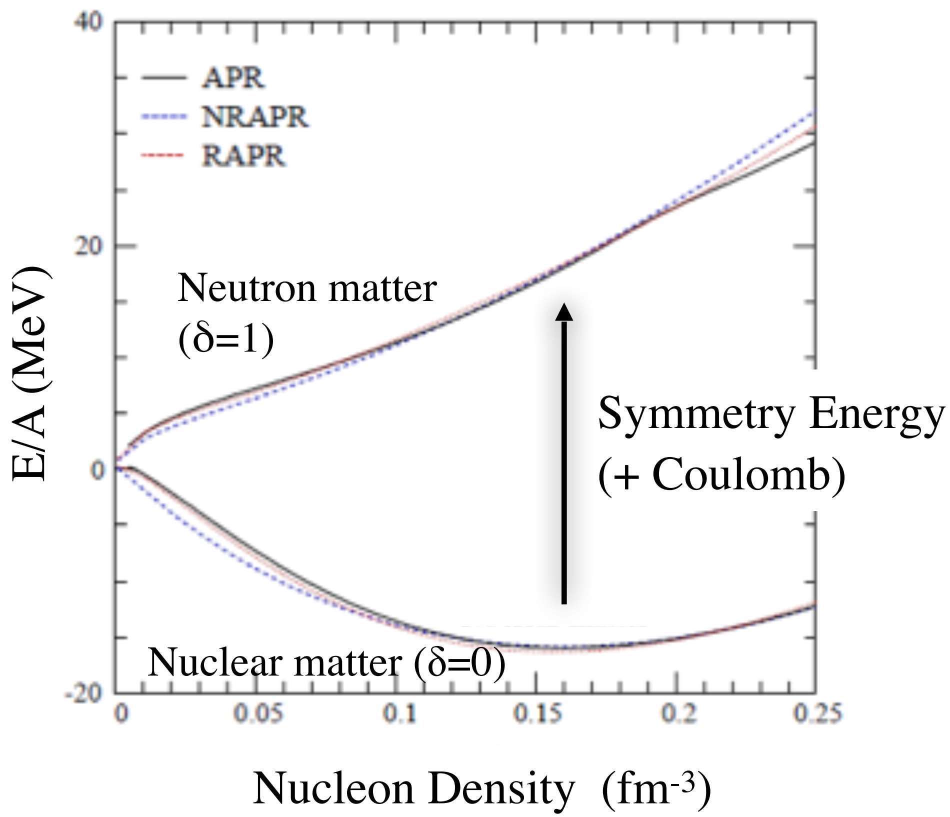


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

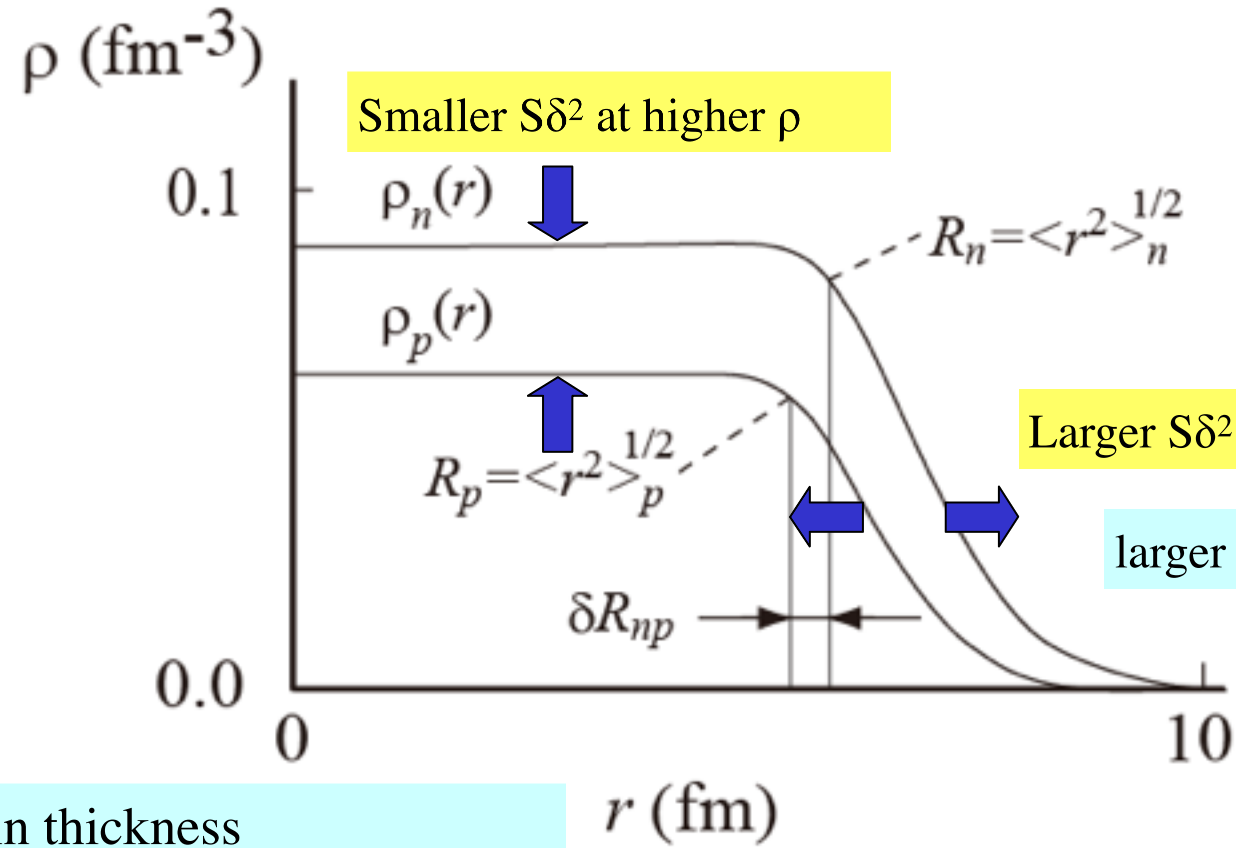


Steiner et al., Phys. Rep. 411 325(2005)

Prediction of the neutron matter EOS is much model dependent.

Neutron Skin and Density Dependence of the Symmetry Energy

For larger *L*:



Larger $S\delta^2$ at lower ρ

larger neutron skin

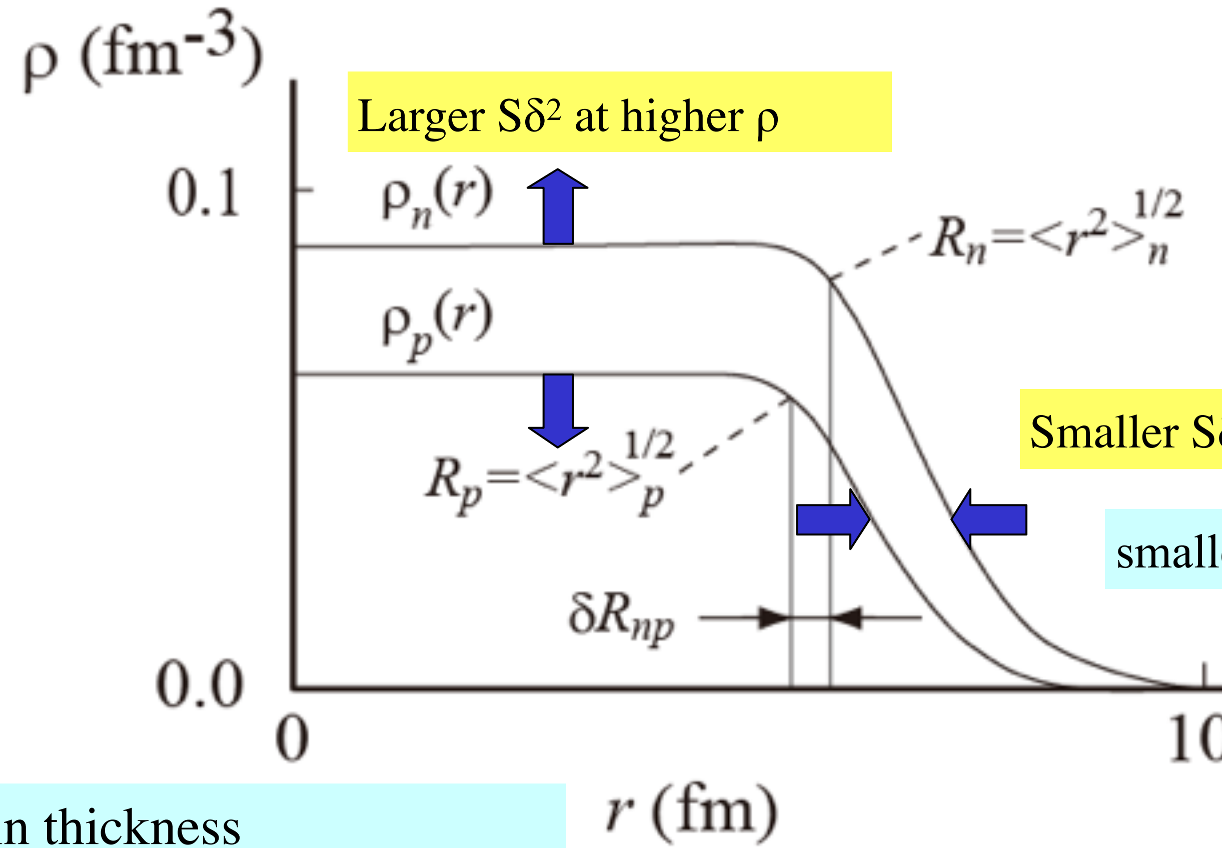
Neutron skin thickness

Density dependence of the symmetry energy

Energy minimum (equilibrium)

Neutron Skin and Density Dependence of the Symmetry Energy

For smaller *L*:



Smaller $S\delta^2$ at lower ρ

smaller neutron skin

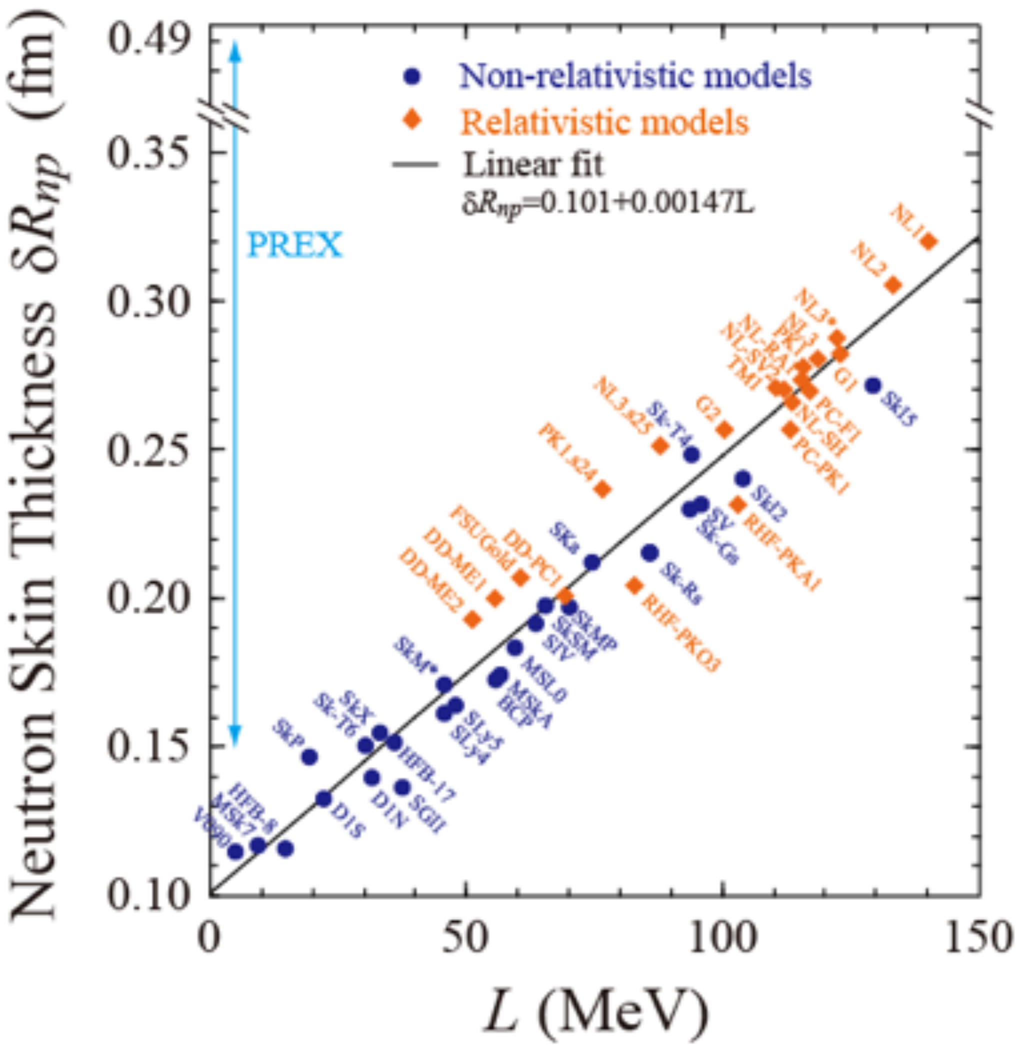
Neutron skin thickness

Density dependence of the symmetry energy

Energy minimum
(equilibrium)

Neutron Skin Thickness Measurement by Electroweak Interaction

PREX



PREX Result: S. Abrahamyan *et al.*, PRL**108**, 112502 (2012)

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

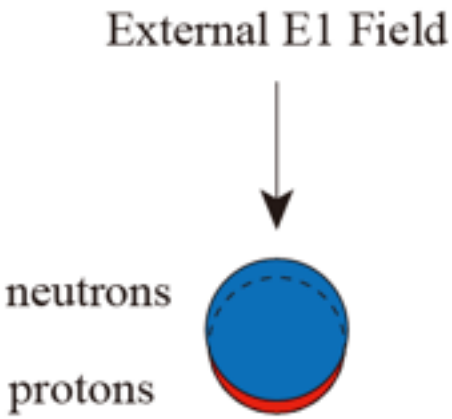
Future measurements:

PREX-II: factor of 3 smaller statistical uncertainty for ^{208}Pb

CREX: for ^{48}Ca

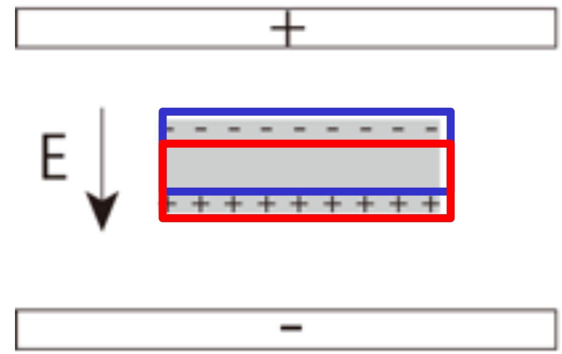
The model independent determination of δR_{np} by PREX important but the present accuracy is limited.

Electric Dipole Polarizability (α_D)



Electric Dipole Polarizability α_D

Restoring force ← symmetry energy



Electric Dipole Polarization

$$\vec{P} = \alpha N \vec{E}$$

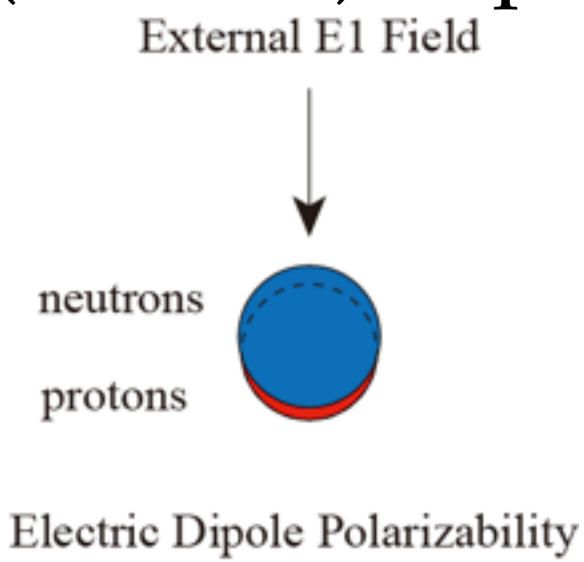
α: dipole polarizability of an atom

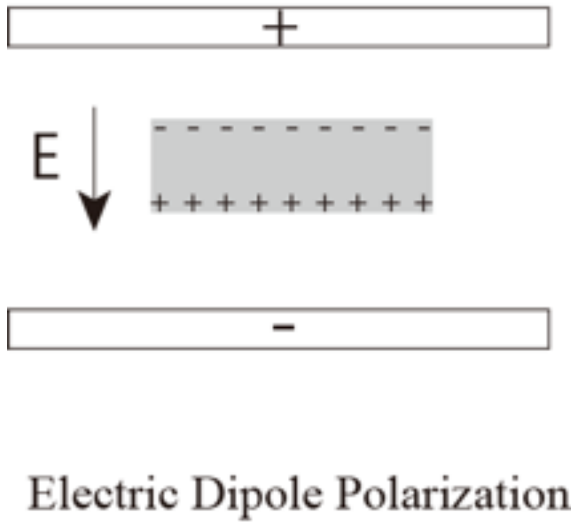
Inversely energy weighted sum-rule of B(E1)

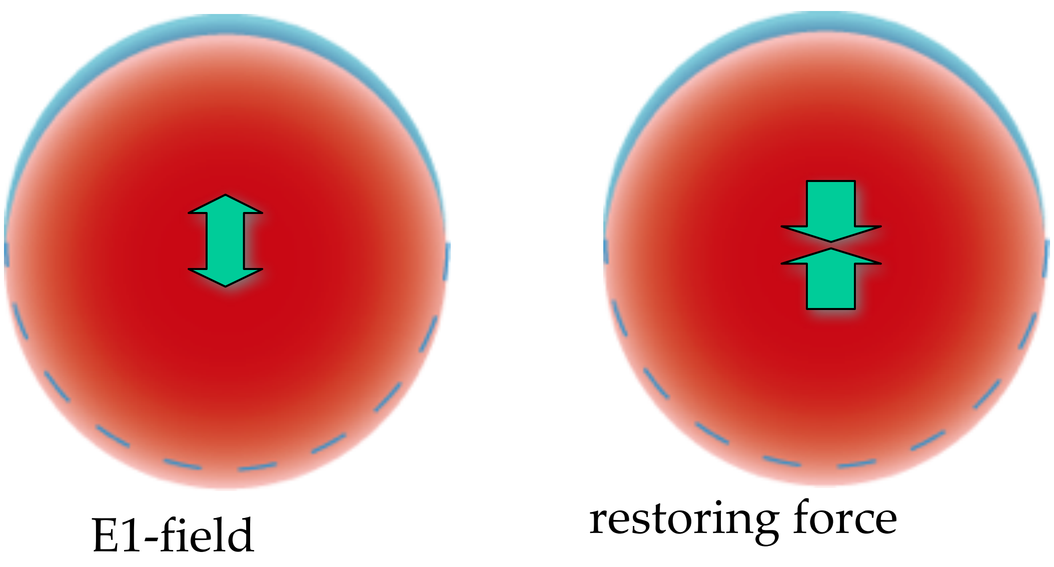
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{\mathrm{abs}}^{E1}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

→ Requires the $B(E1)$ distribution

(Electric) Dipole Polarizability





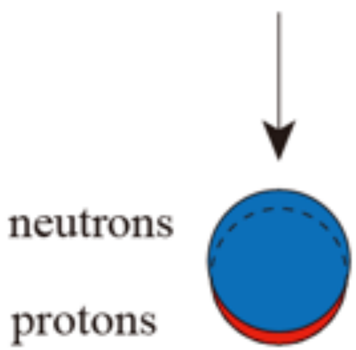


balanced

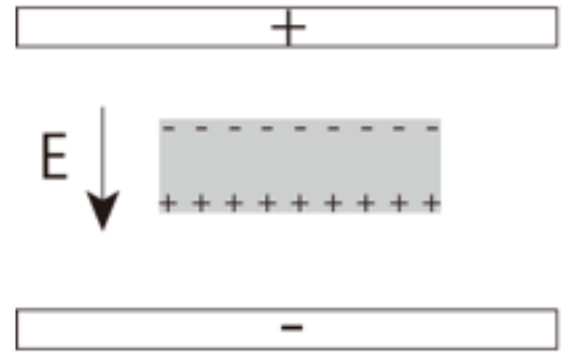
symmetry energy

(Electric) Dipole Polarizability

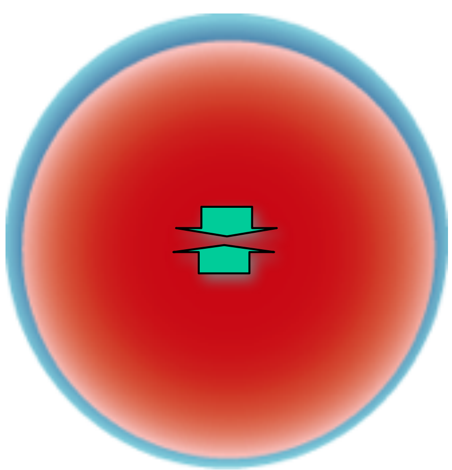
External E1 Field



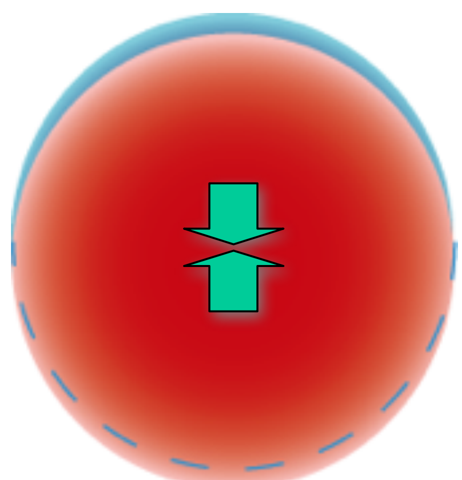
Electric Dipole Polarizability



Electric Dipole Polarization

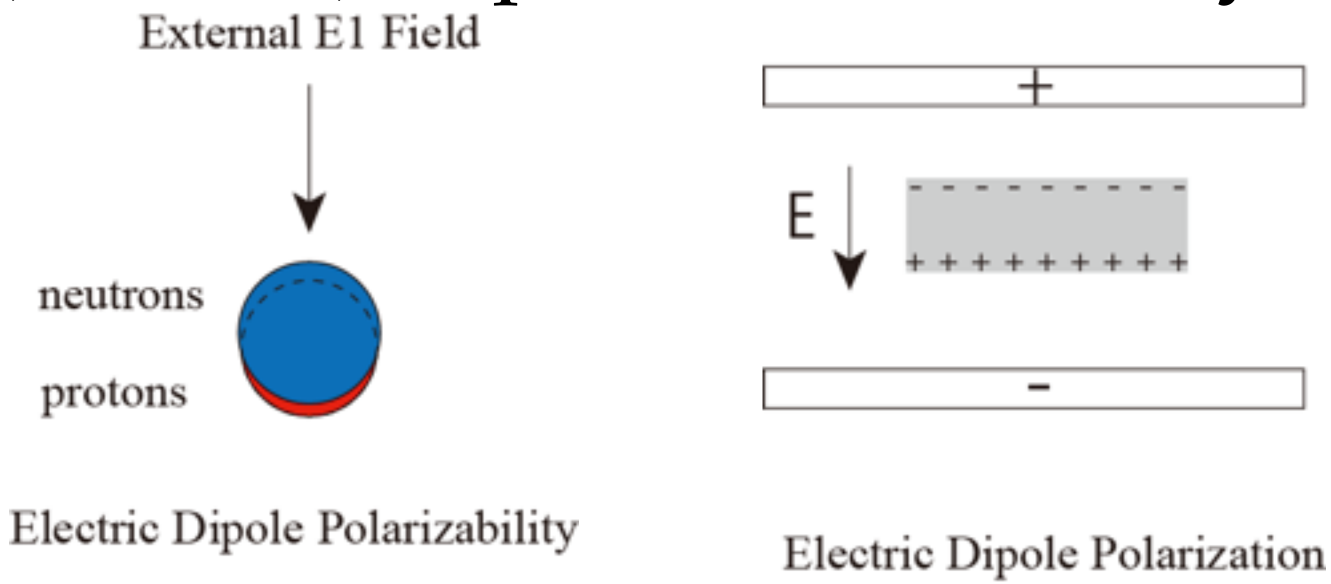


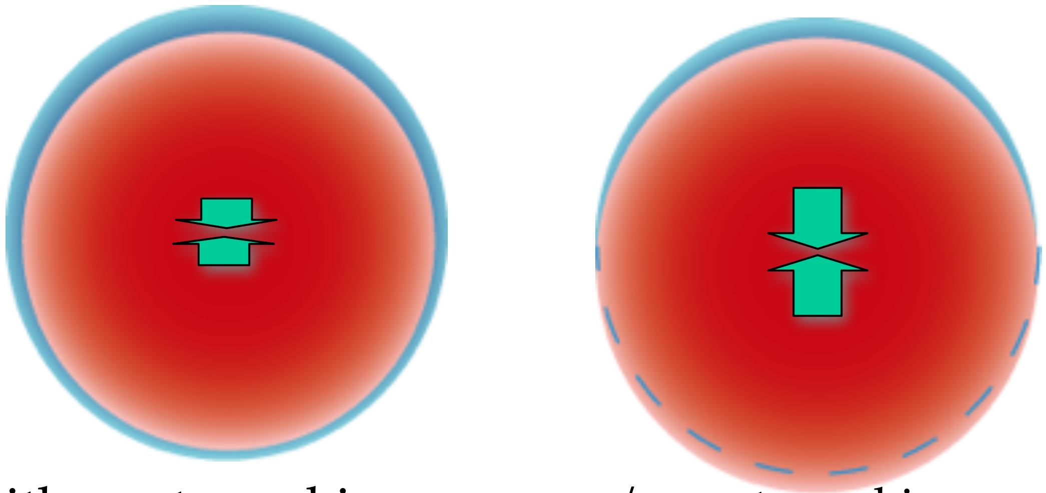
with neutron skin
smaller restoring force



w/o neutron skin
larger restoring force

(Electric) Dipole Polarizability



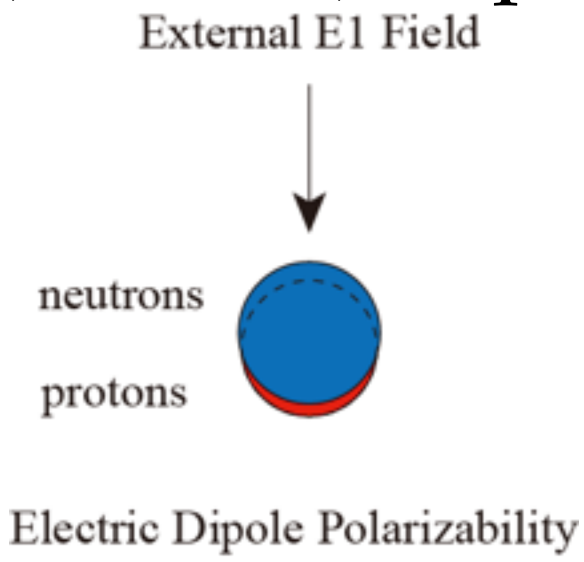


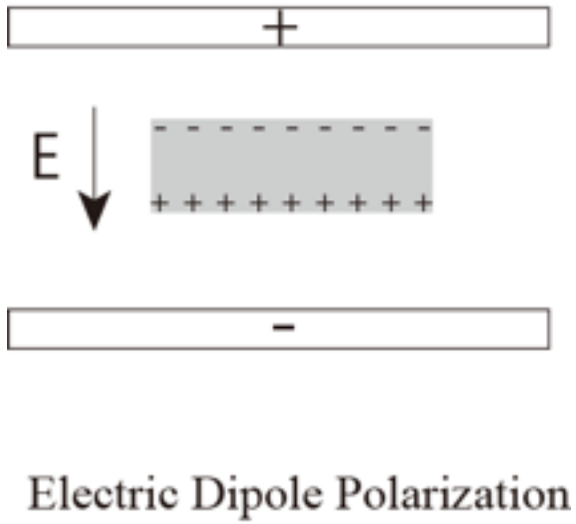
with neutron skin
smaller restoring force

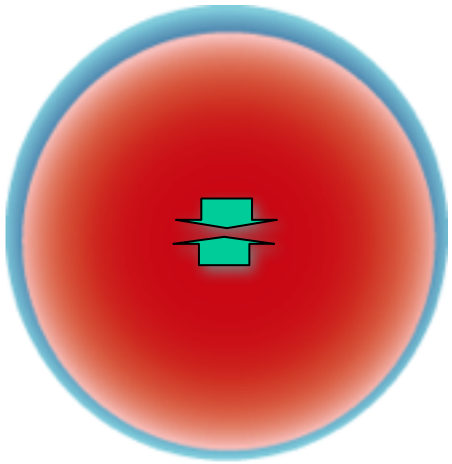
w/o neutron skin
larger restoring force

thicker neutron skin
⇕
smaller restoring force
⇕
larger displacement
⇕
larger dipole polarizability

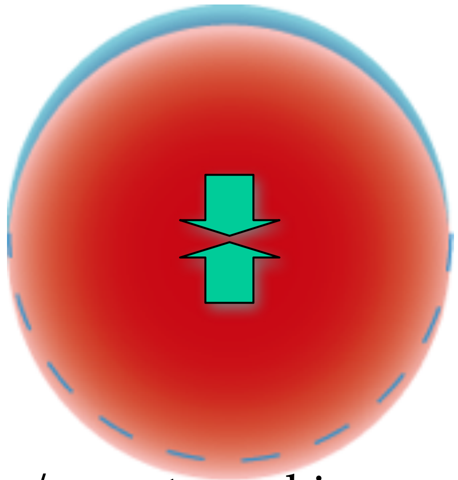
(Electric) Dipole Polarizability







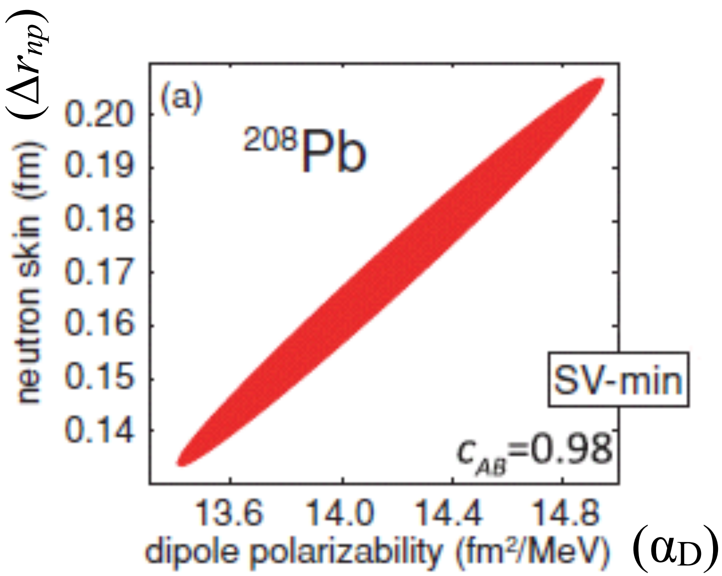
with neutron skin
smaller restoring force



w/o neutron skin
larger restoring force

Sensitive to the difference between the proton and neutron density distribution.

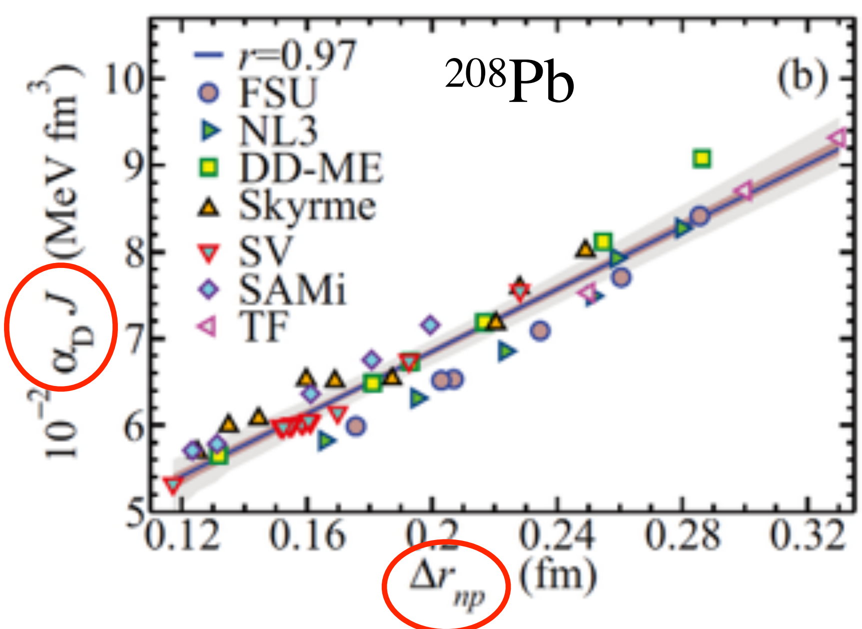
Neutron Skin Thickness and Dipole Polarizability (α_D)



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

Covariance analysis with SV-min interaction in the framework of energy density functional.

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



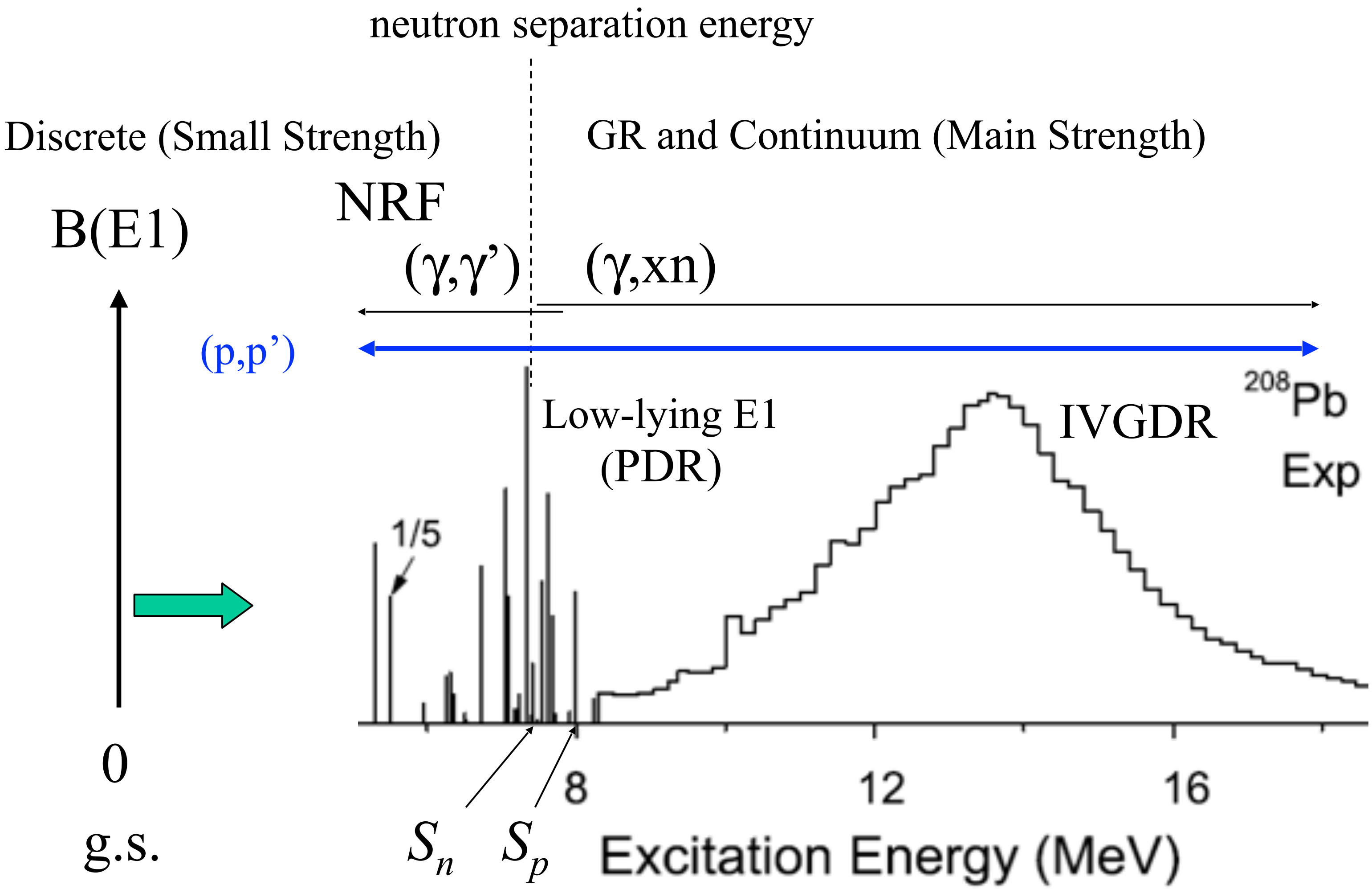
X. Roca-Maza *et al*., PRC**88**, 024316(2013)

Correlations observed in various interaction sets.

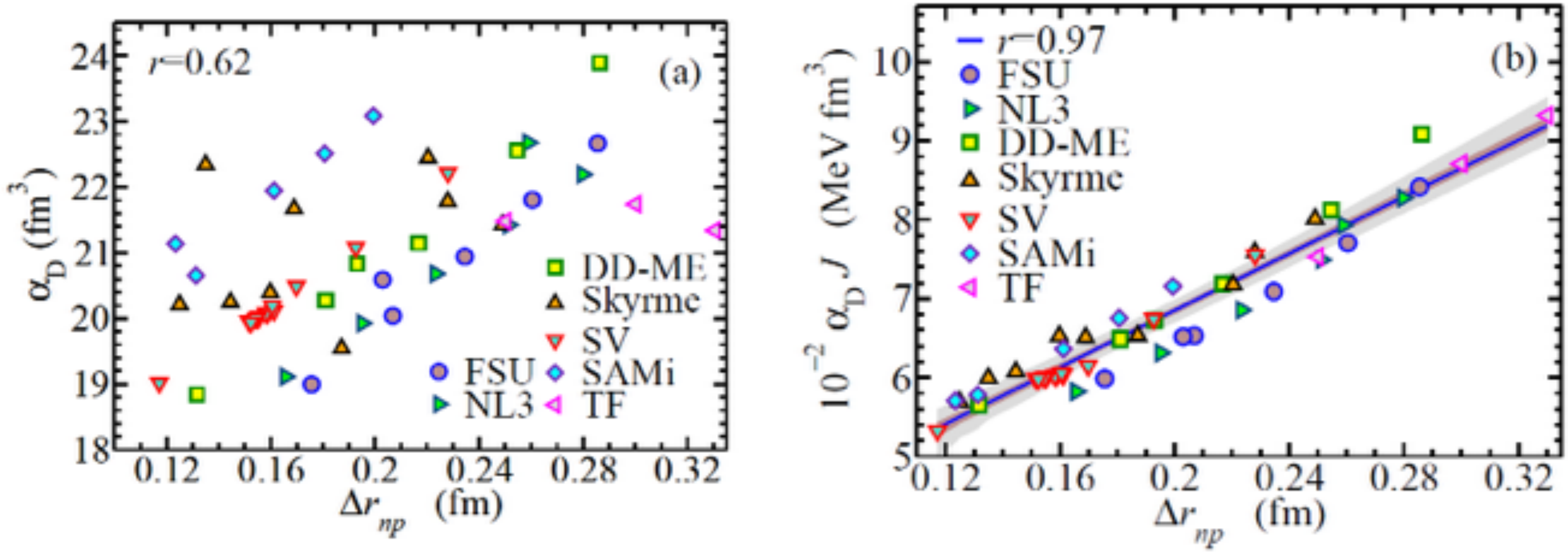
$$\alpha_D^{\rm DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

insights from the droplet model

Electric Dipole (E1) Response of Heavy Nuclei



X. Roca-Maza et al., arXiv:1307.4806



$$10^{-2}\alpha_D J = (3.25 \pm 0.14) + (17.99 \pm 0.70)\Delta r_{np}$$

a_D J is a strong isovector indicator.

Insights from the droplet model

$$\alpha_D^{DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

Two Approaches for the Neutron Skin Thickness

Probing the matter/neutron/weak-charge distribution

Takes the difference from the charge (or *p*) distribution → ΔR_{np}

- Less/no model dependence
- Data must be highly accurate

$$\sigma\left(\Delta R_{np}\right) \quad 0.02\ fm \quad 4\times10^{-3}$$

PREX

p elastic scattering

coherent π production

Both approaches are important.

Probing the difference between the *p/n* distribution

- Requires theoretical models
- Data can be less accurate

$$\frac{\sigma\left(\Delta R_{np}\right)}{\Delta R_{np}} \sim \frac{0.02\ fm}{0.2\ fm} \sim 10^{-1}$$

Dipole Polarizability

PDR

GDR

Two Approaches for the Neutron Skin Thickness

Probing the matter/neutron/weak-charge distribution

Takes the difference from the charge (or *p*) distribution → ΔR_{np}

- Less/no model dependence
- Data must be highly accurate

PREX

p elastic scattering

coherent π production

$\sigma(\Delta R_{np})$ 0.02 *fm* 4×10⁻³

Both approaches are important.

Probing the difference between the *p/n* distribution

- Requires theoretical models
- Data can be less accurate

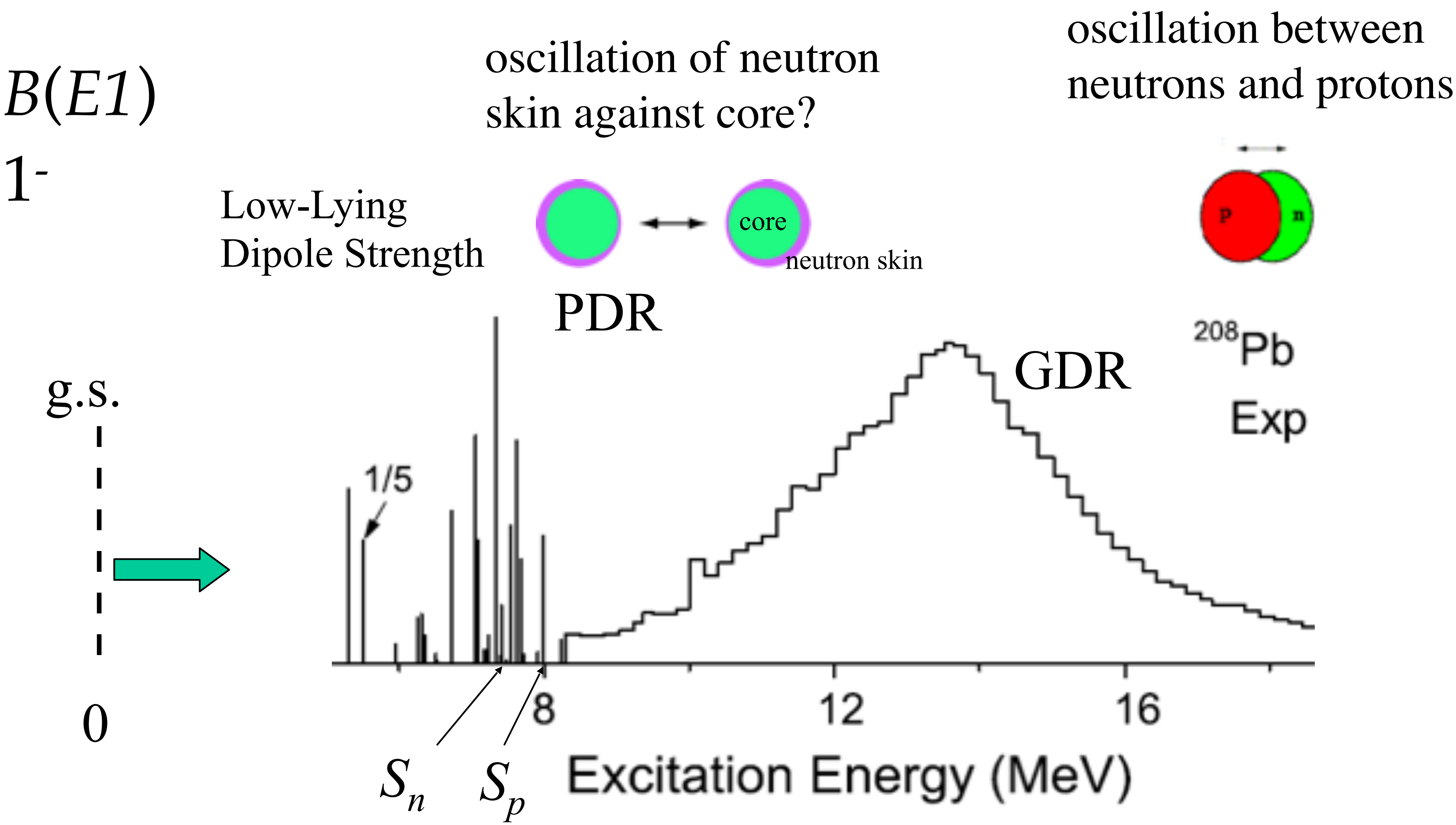
If *n* diffuseness is changed, the E1 response would change.

PDR

GDR

$$\frac{\sigma(\Delta R_{np})}{\Delta R_{np}} \sim \frac{0.02\ fm}{0.2\ fm} \sim 10^{-1}$$

Electric Dipole Response of Nuclei

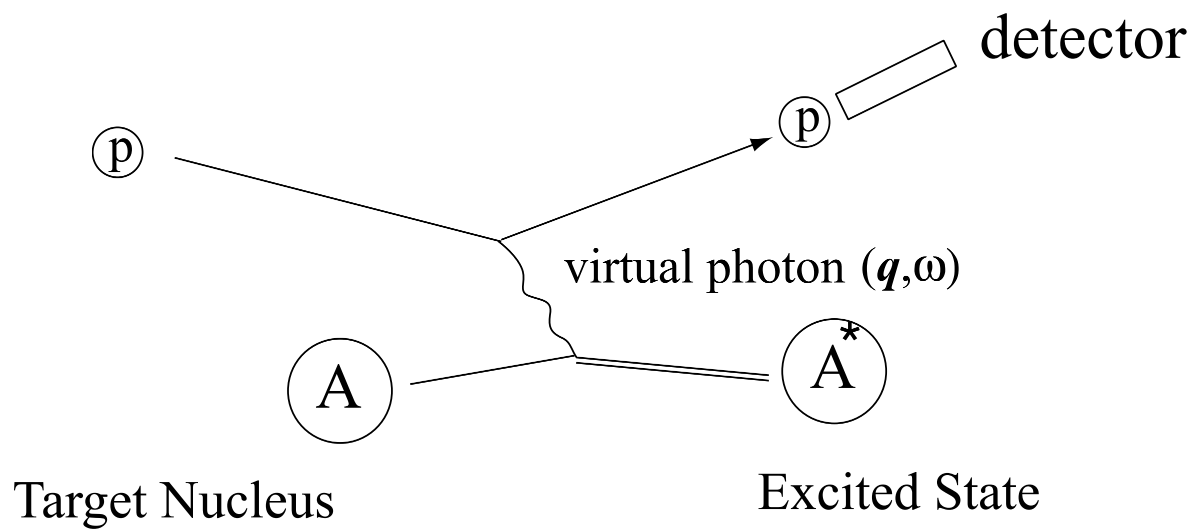


Proton inelastic scattering as an electro-magnetic probe of the electric dipole response

Missing Mass Spectroscopy with Virtual Photon

Insensitive to the decay channel.
Total strengths are measured.

Only the scattered protons are measured.



Select low momentum transfer (q~0) kinematical condition, i.e. at zero degrees

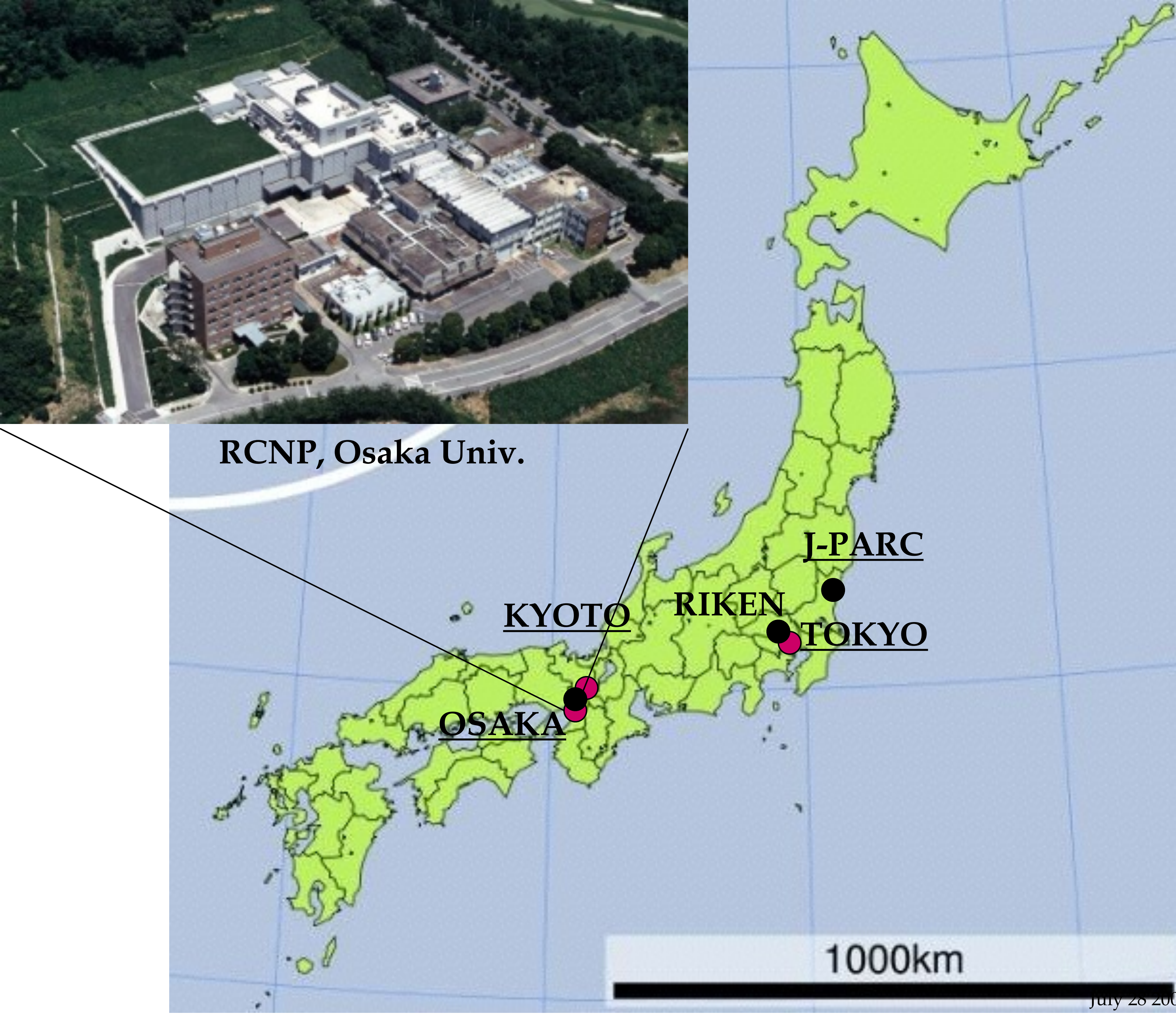
Coulomb Excitation at 0 deg.

EM Interaction is well known
(model independent)

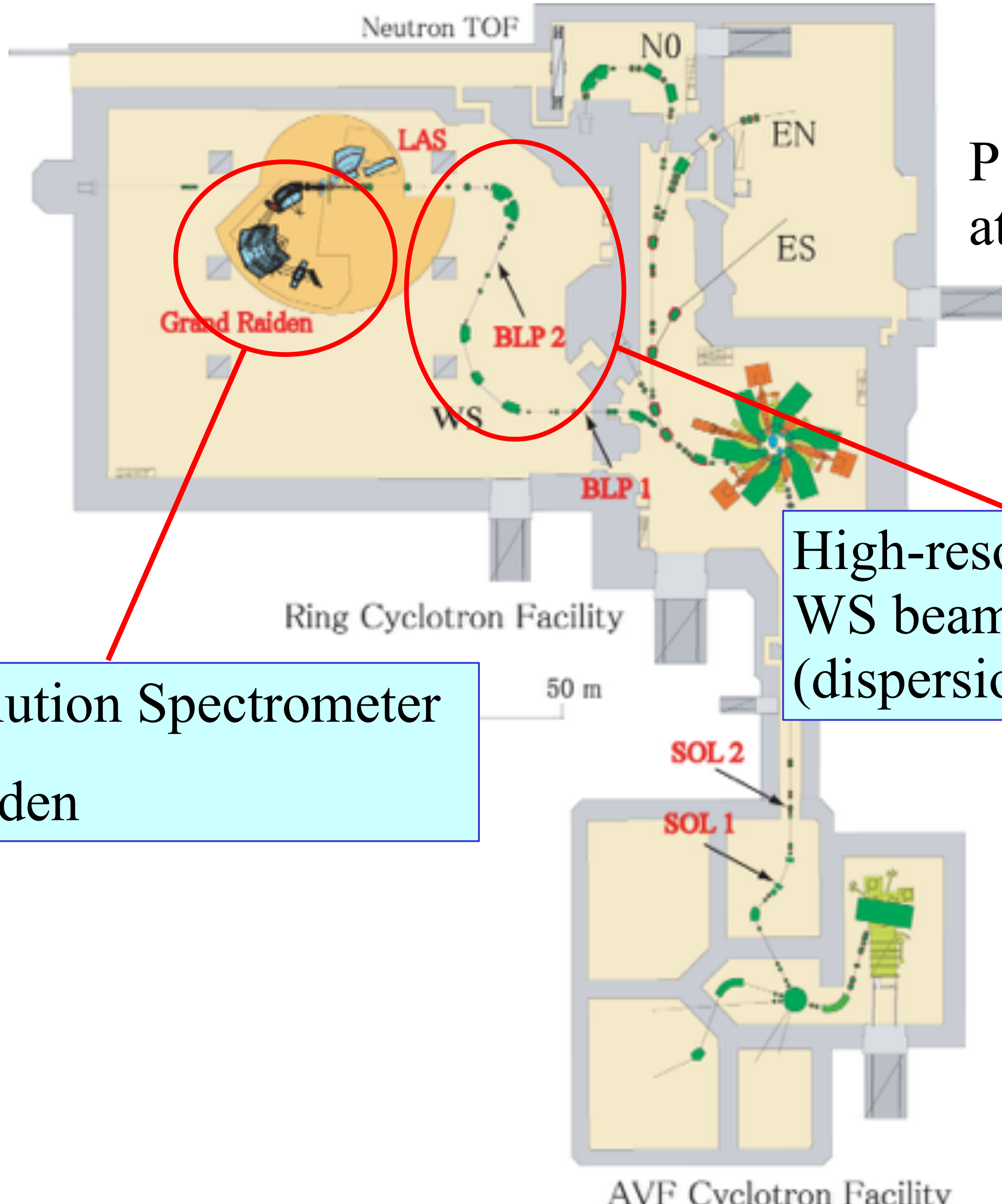
Relativistic Proton Inelastic Scattering at Forward Angles as a probe of electric dipole response of nuclei

- An **electromagnetic probe** (Coulomb excitation)
- **High-resolution** (20-30 keV), **high/uniform det. efficiency in E_x**
- Covers a broad **E_x of 5-22MeV**
- Insensitive to the decay channels (sensitive to the **total strength**)
- Requires a **small amount of target material** (several mili-gram) and a few days of beam time
- Applicable to stable nuclei

(Coulomb excitation/dissociation in inverse kinematics for unstable nuclei)


RCNP, Osaka Univ.
J-PARC
KYOTO
RIKEN
TOKYO
OSAKA
1000km

Research Center for Nuclear Physics (RCNP), Osaka University



Polarized p beam at 295 MeV

High-resolution
WS beam-line
(dispersion matching)

High-resolution Spectrometer

Grand Raiden

Spin Precession in the Spectrometer

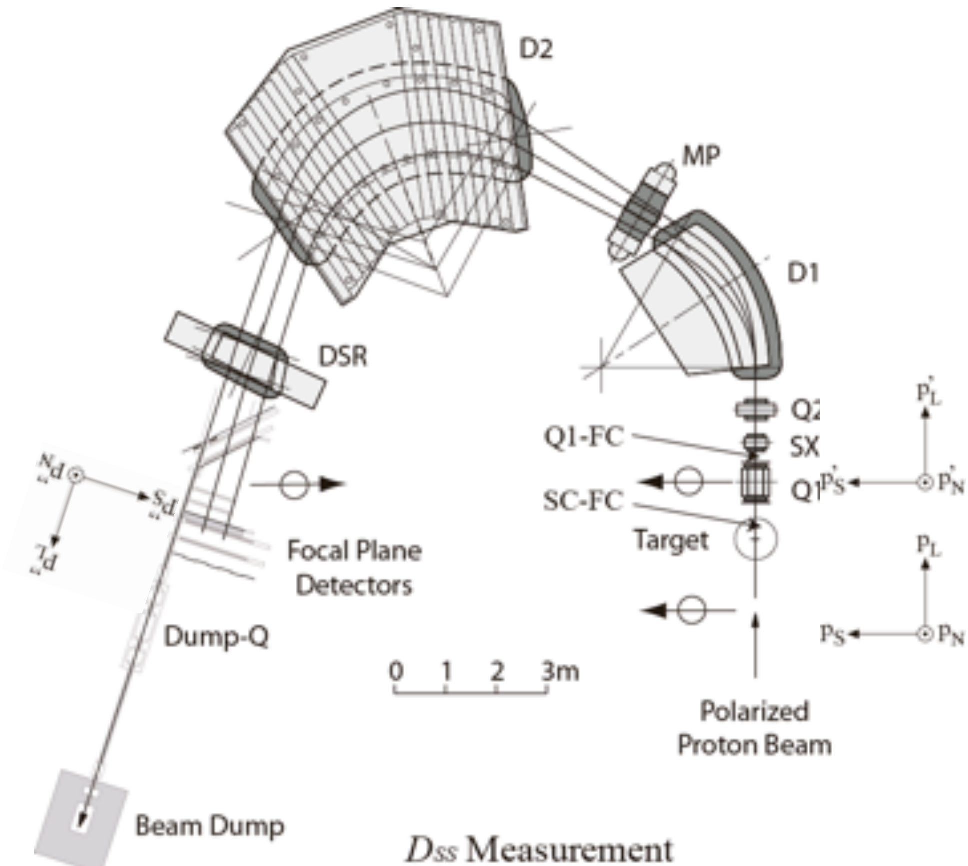
$$\theta_p = \gamma \left(\frac{g}{2} - 1\right)\theta_b$$

θ_p: precession angle with respect to the beam direction

θ_b: bending angle of the beam

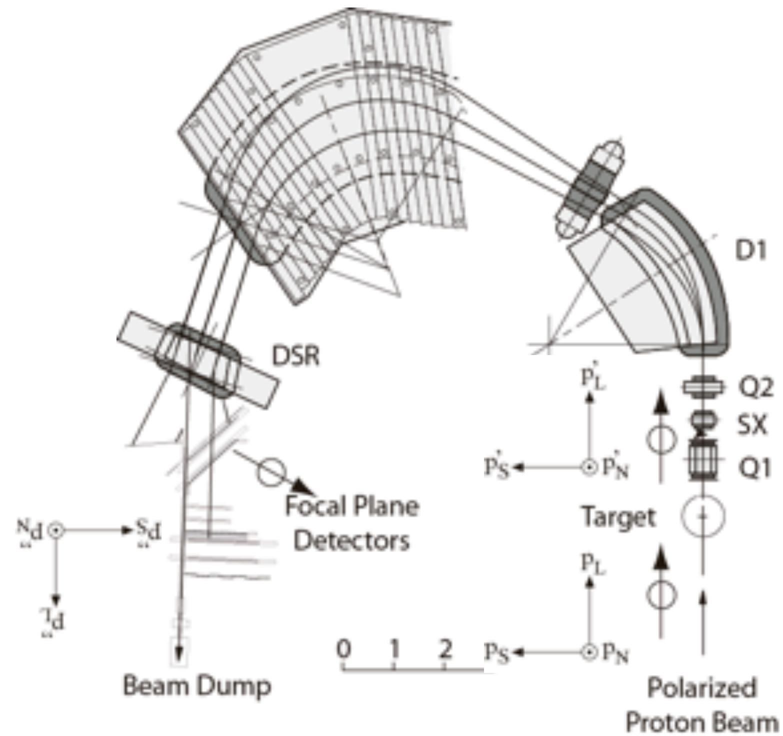
g: Lande’s g-factor

γ: gamma in special relativity



Dss Measurement

$\theta_b \cong 162°$



DLL Measurement

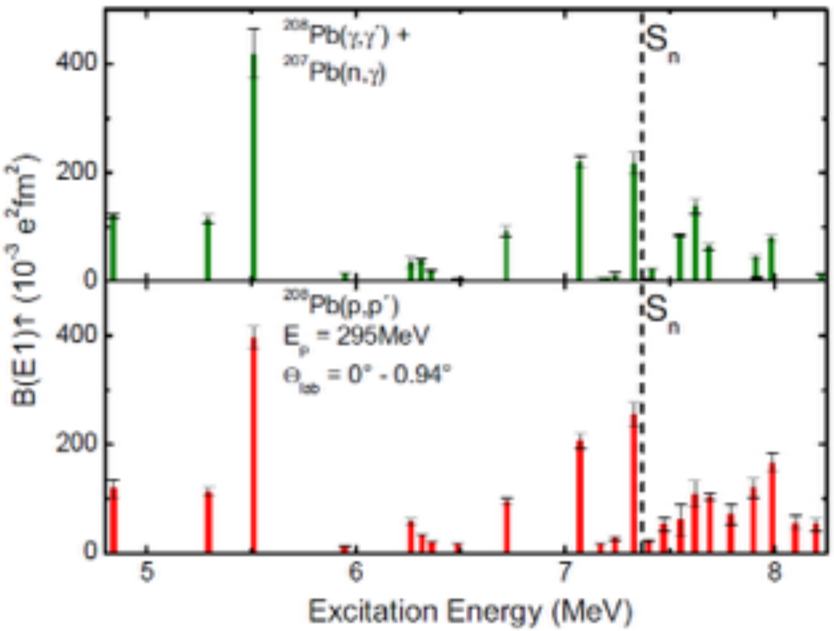
$\theta_b \cong 180°$

Setup for E282&E316

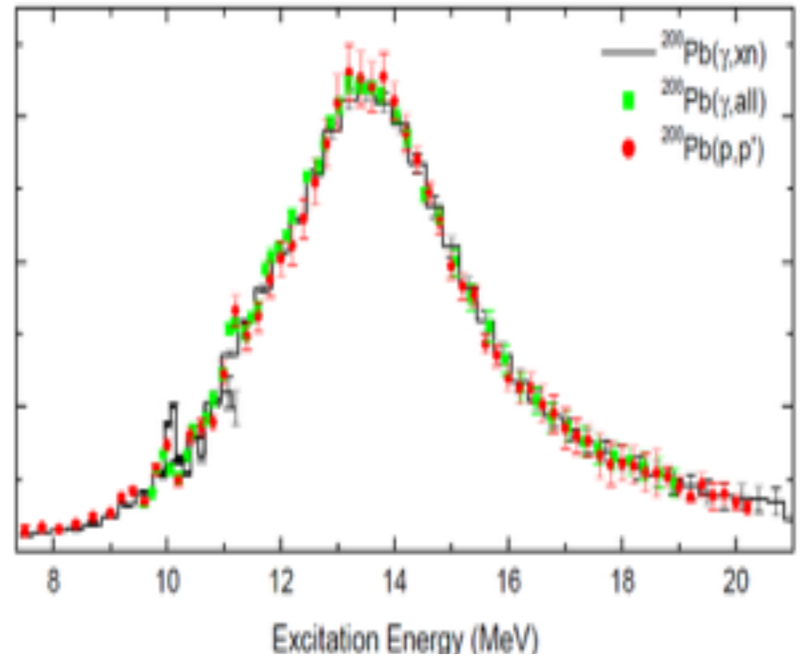
Distribution of B(E1)

I. Poltoratska, PhD thesis

low-lying discrete states

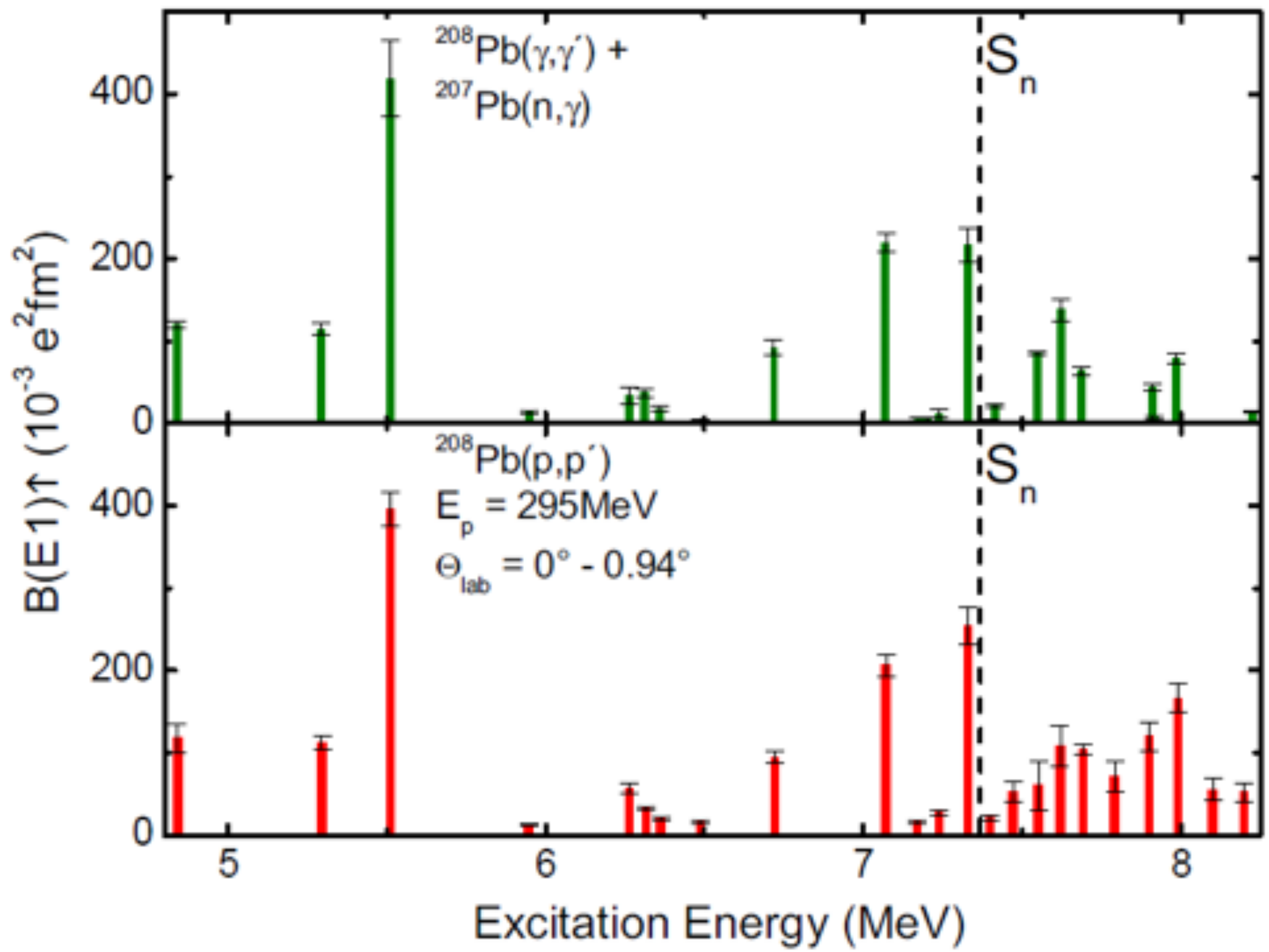


GDR region



Excellent agreement between
(p,p') and (γ,γ') below ~S_n

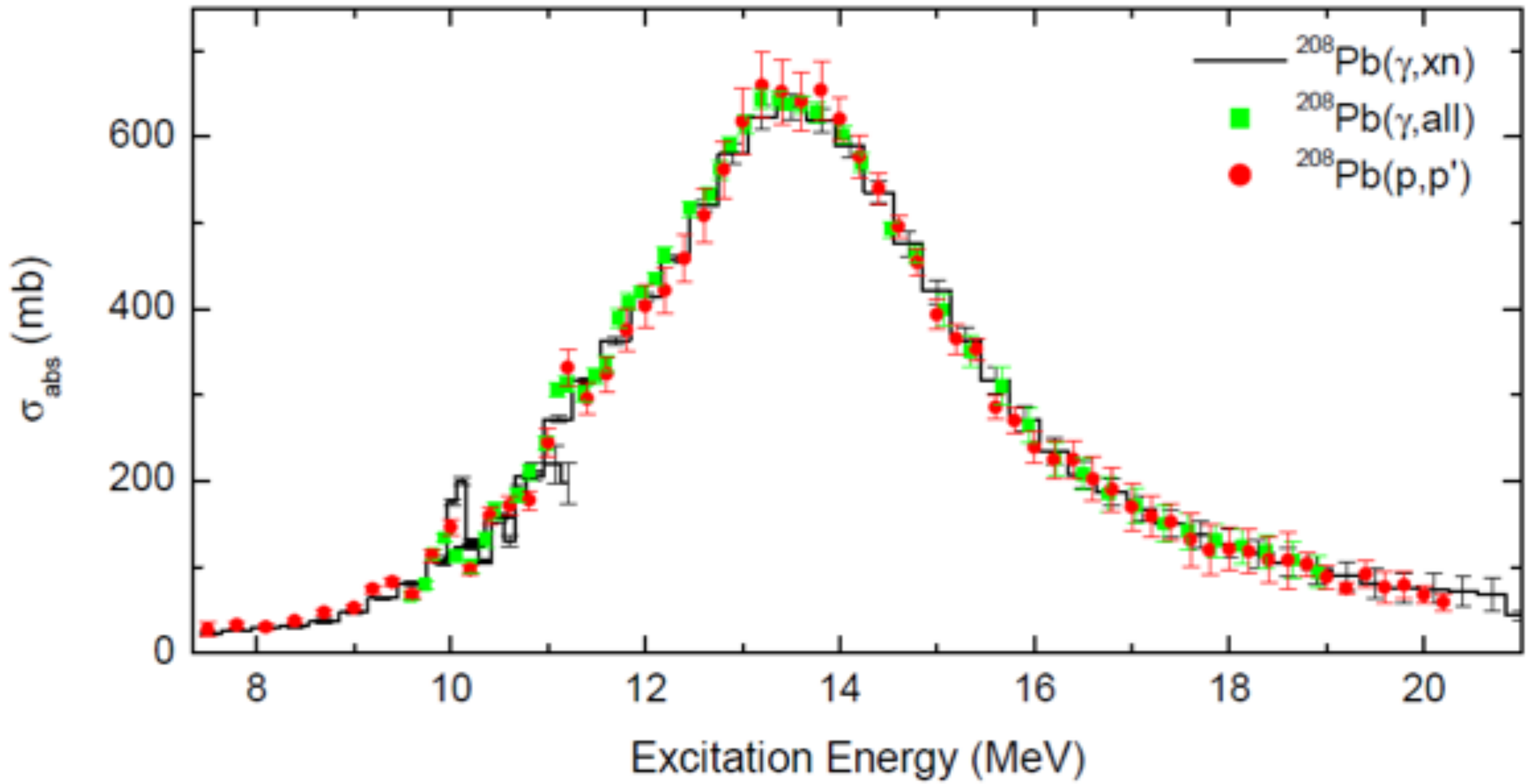
B(E1): low-lying discrete states



Excellent agreement between (p,p') and (γ,γ') below ~S_n

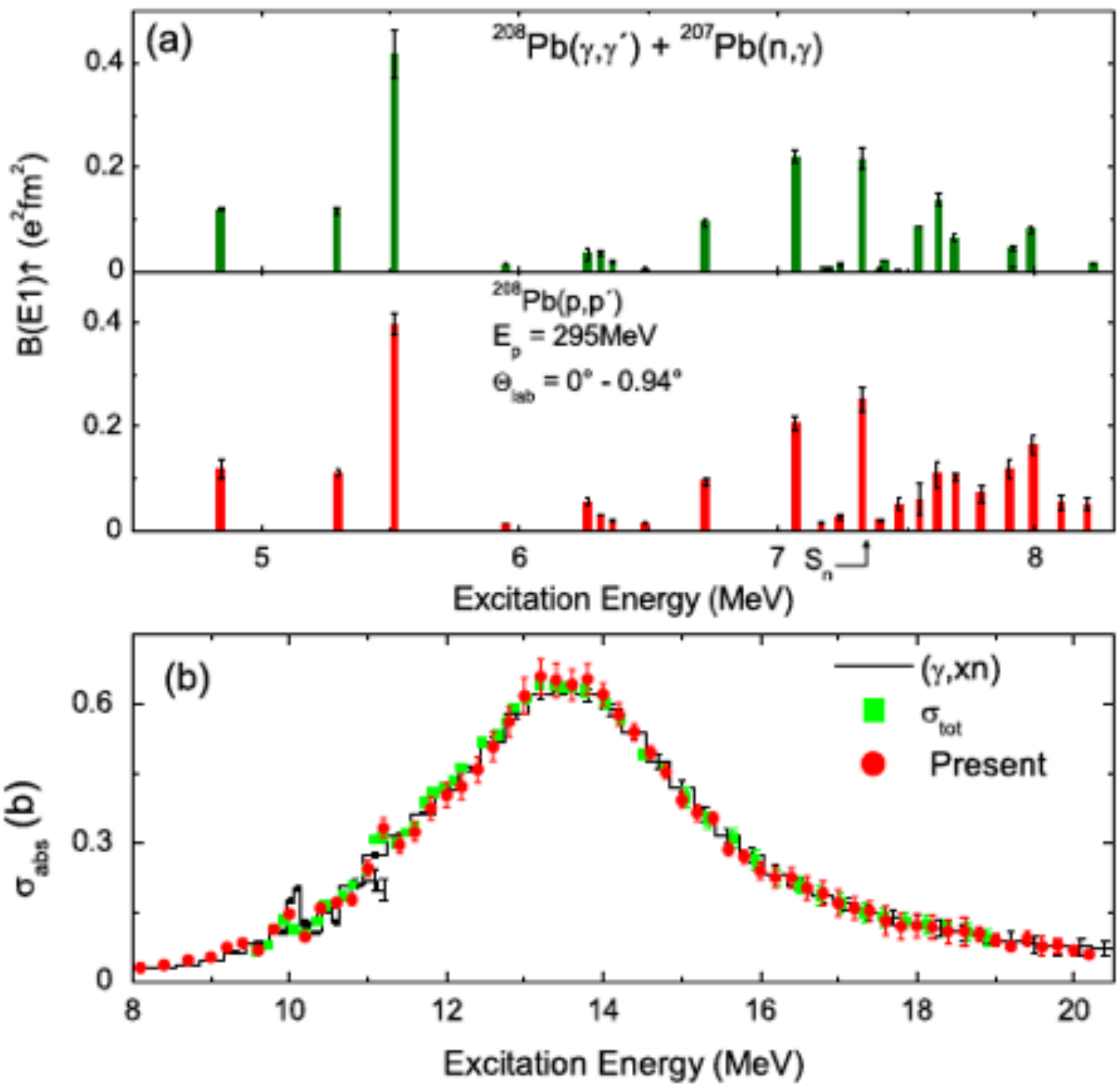
I. Poltoratska, PhD thesis

B(E1): GDR



Excellent agreement among three measurements in the GDR region

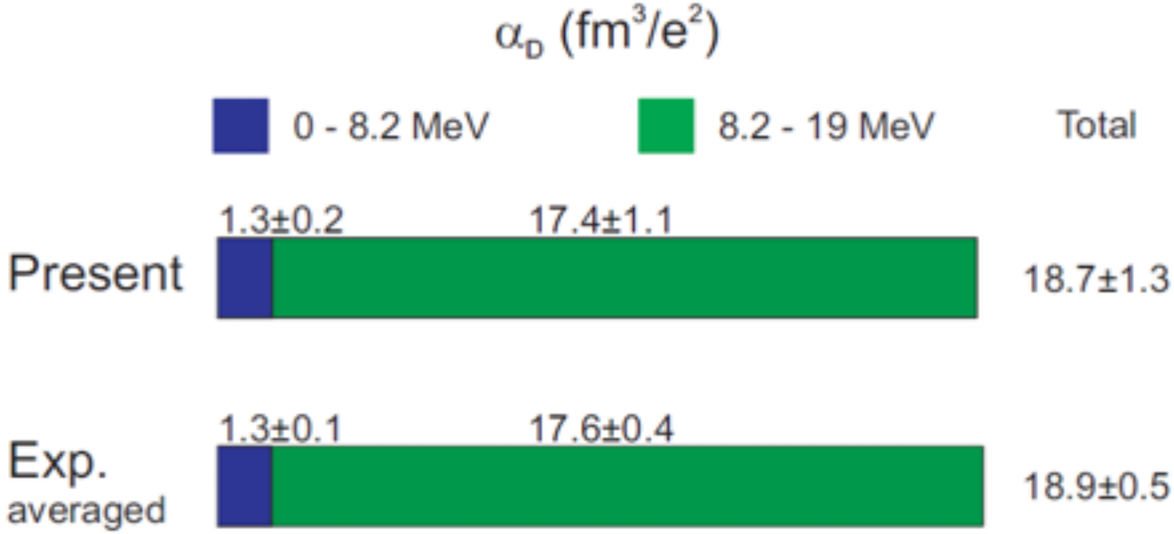
I. Poltoratska, PhD thesis



Excellent agreement with (γ,γ') below Sn, and with (γ,n) and (γ,abs) in the GDR region

AT et al., PRL107, 062502(2011)

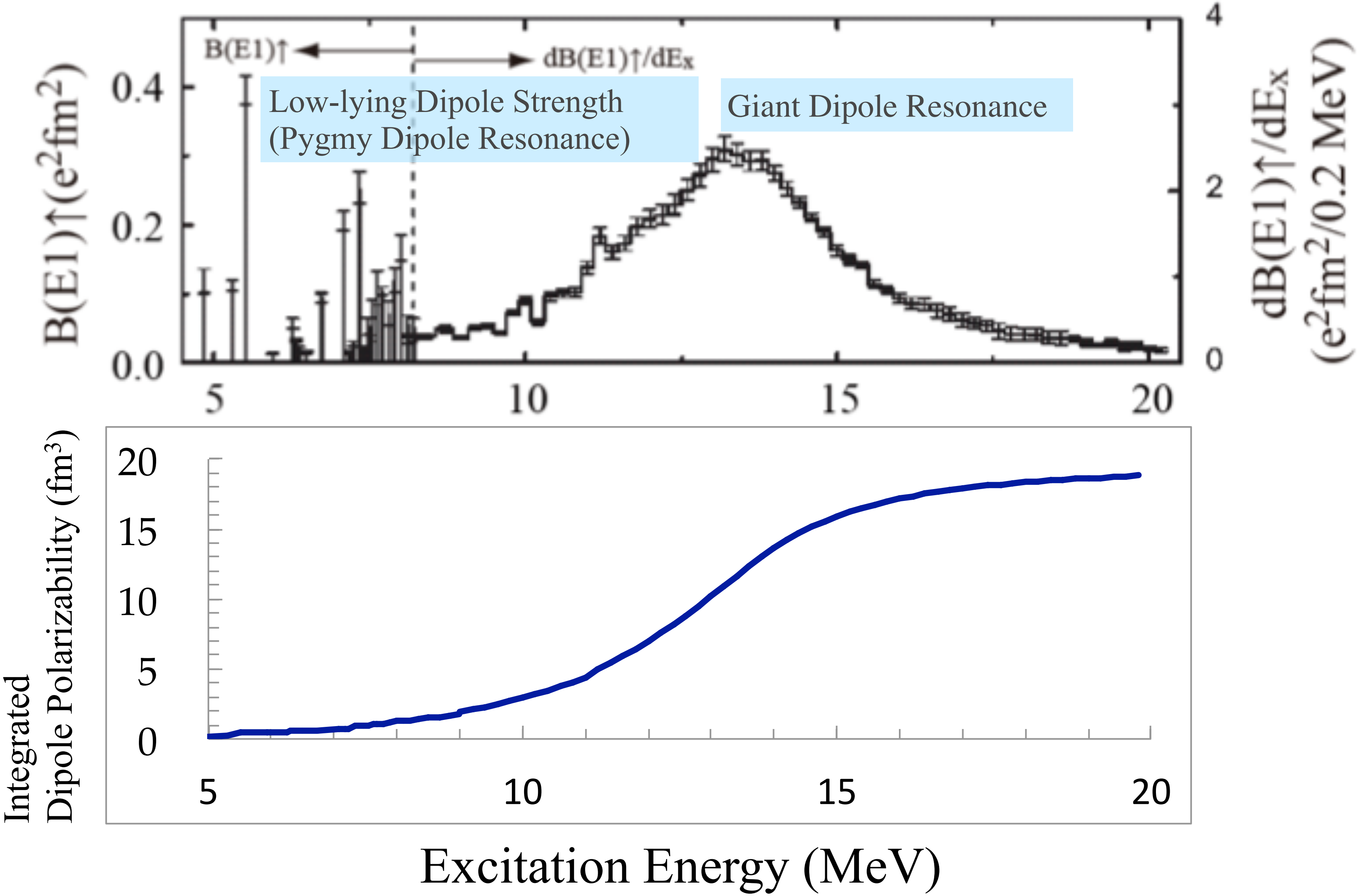
Electric Dipole Polarizability



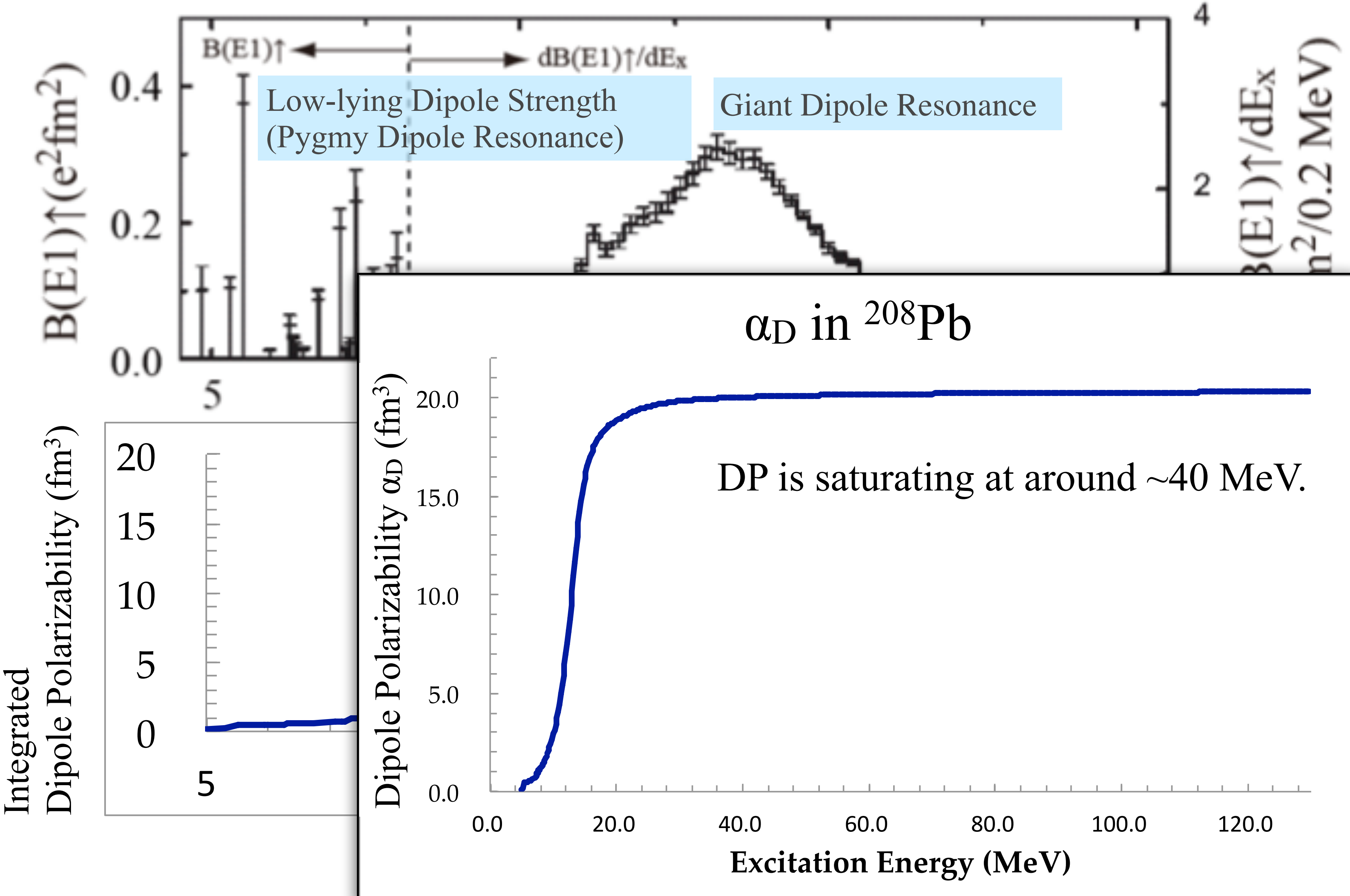
up to 130 MeV
20.1±0.6 fm^3/e^2

I. Poltoratska, PhD thesis

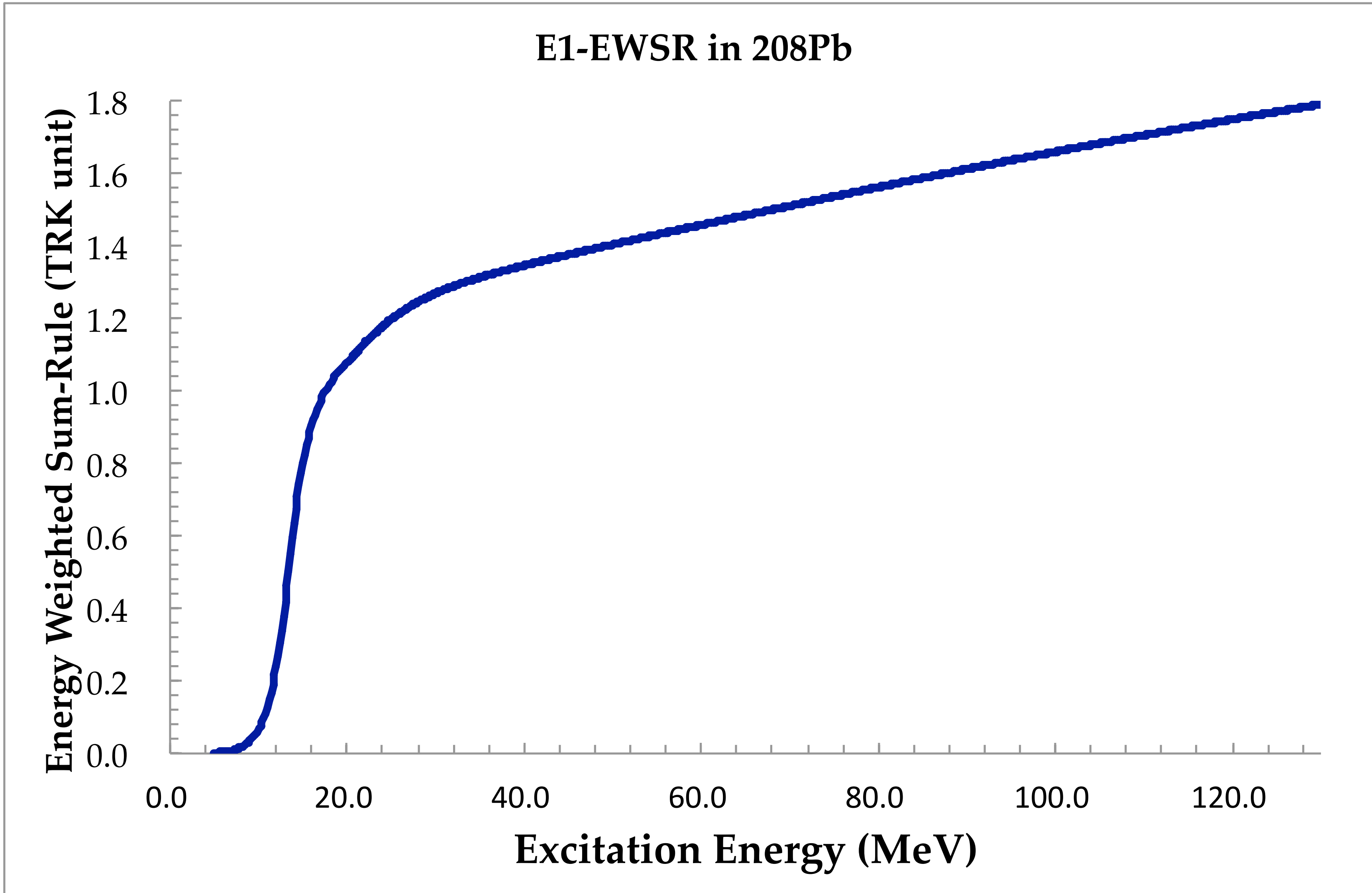
Electric Dipole Response of ^{208}Pb



Electric Dipole Response of ^{208}Pb



Energy Weighted (TRK) Sum-Rule of ^{208}Pb



Quasi-Deuteron Excitation Contribution?

Absorption of a photon by a virtual deuteron in nuclei.

^{208}Pb

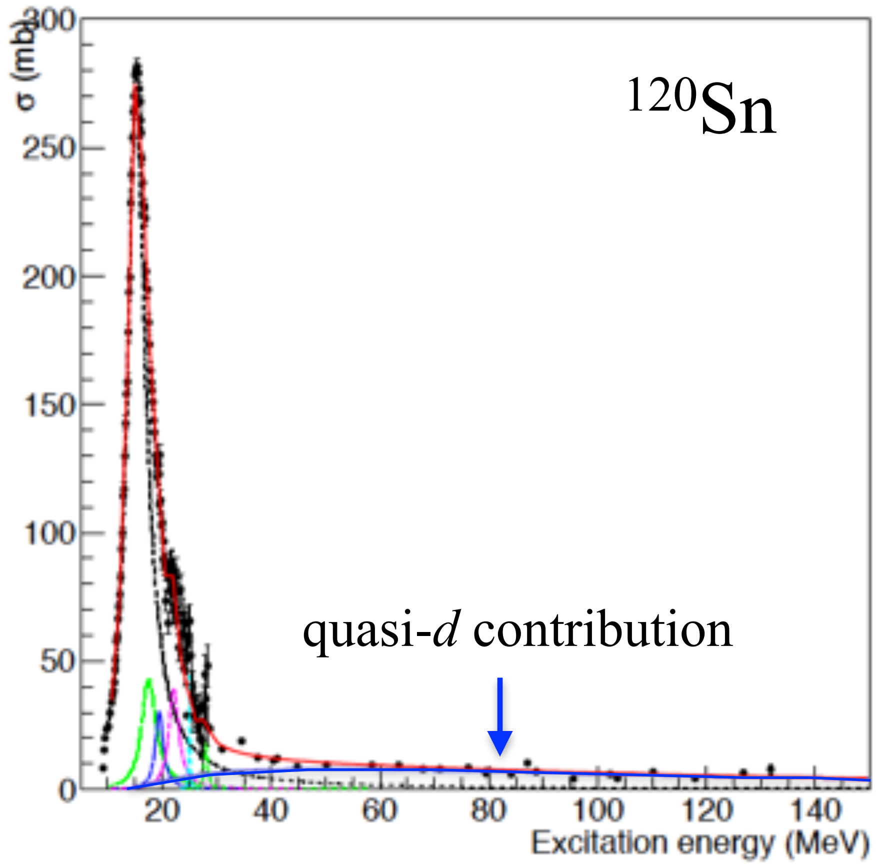
$\alpha_D(^{208}\text{Pb}) = 20.1 \pm 0.6$ fm^3

quasi-*d*: 0.51 ± 0.15 fm^3

^{120}Sn

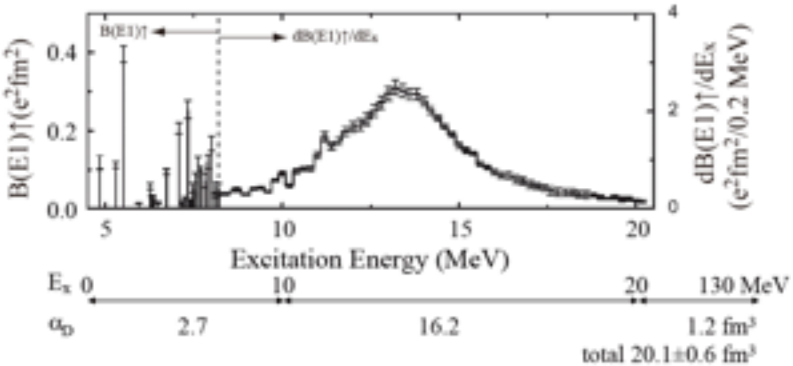
$\alpha_D(^{120}\text{Sn}) = 8.93 \pm 0.36$ fm^3

quasi-*d*: 0.34 ± 0.08 fm^3

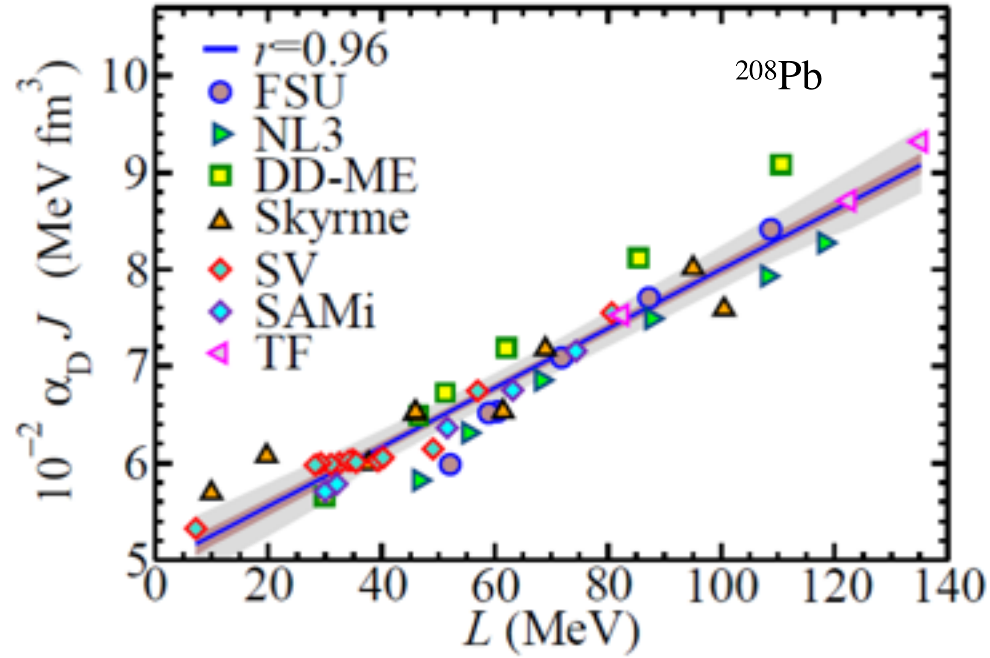


The contribution is small but is included in the numbers. it is unclear whether it should be removed it for comparison with theoretical predictions.

(Electric) Dipole Polarizability



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

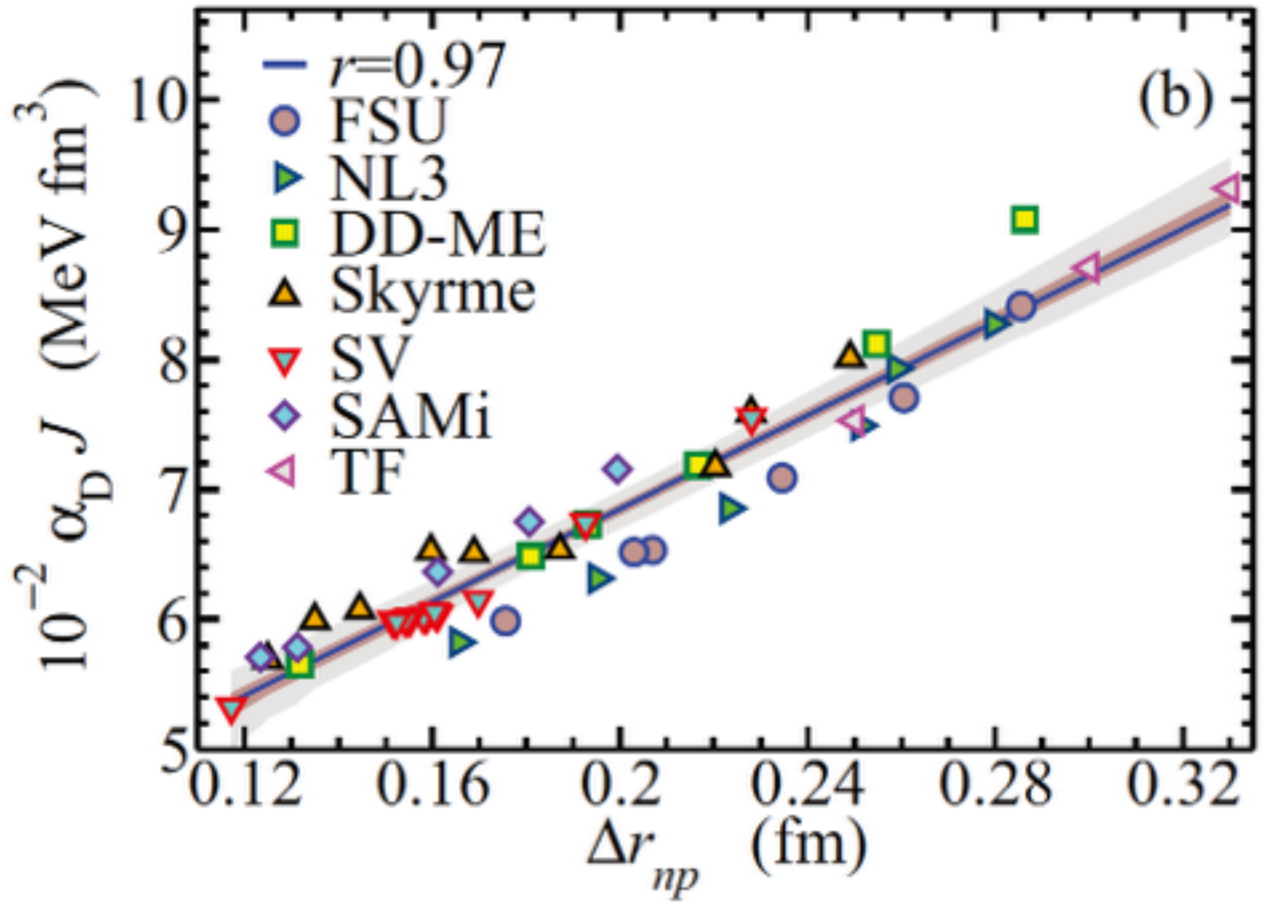


$$10^{-2}\alpha_D J = (4.94 \pm 0.09) + (0.031 \pm 0.001)L$$

$$\alpha_D^{\rm DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1 + \frac{5}{3}\frac{L}{J}\epsilon_A\right]$$

Neutron Skin Thickness of ^{208}Pb

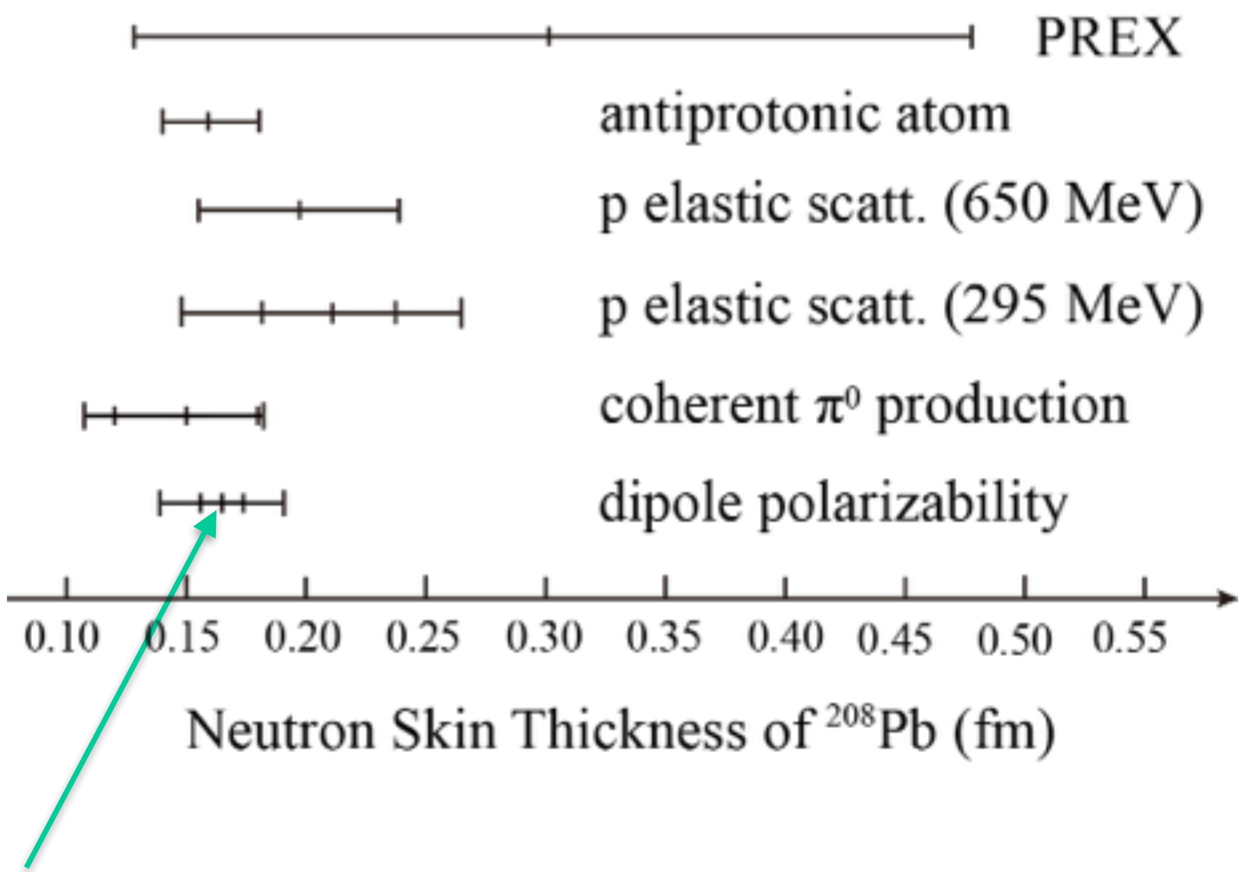
X. Roca-Maza *et al*. PRC88, 024316 (2013)



$$\Delta r_{np} = 0.165 \pm (0.009)_{\mathrm{expt}} \pm (0.013)_{\mathrm{theor}} \pm (0.021)_{\mathrm{est}}\ \mathrm{fm}$$

for the estimated $J = 31 \pm (2)_{\mathrm{est}}$

Neutron Skin Thickness of ^{208}Pb

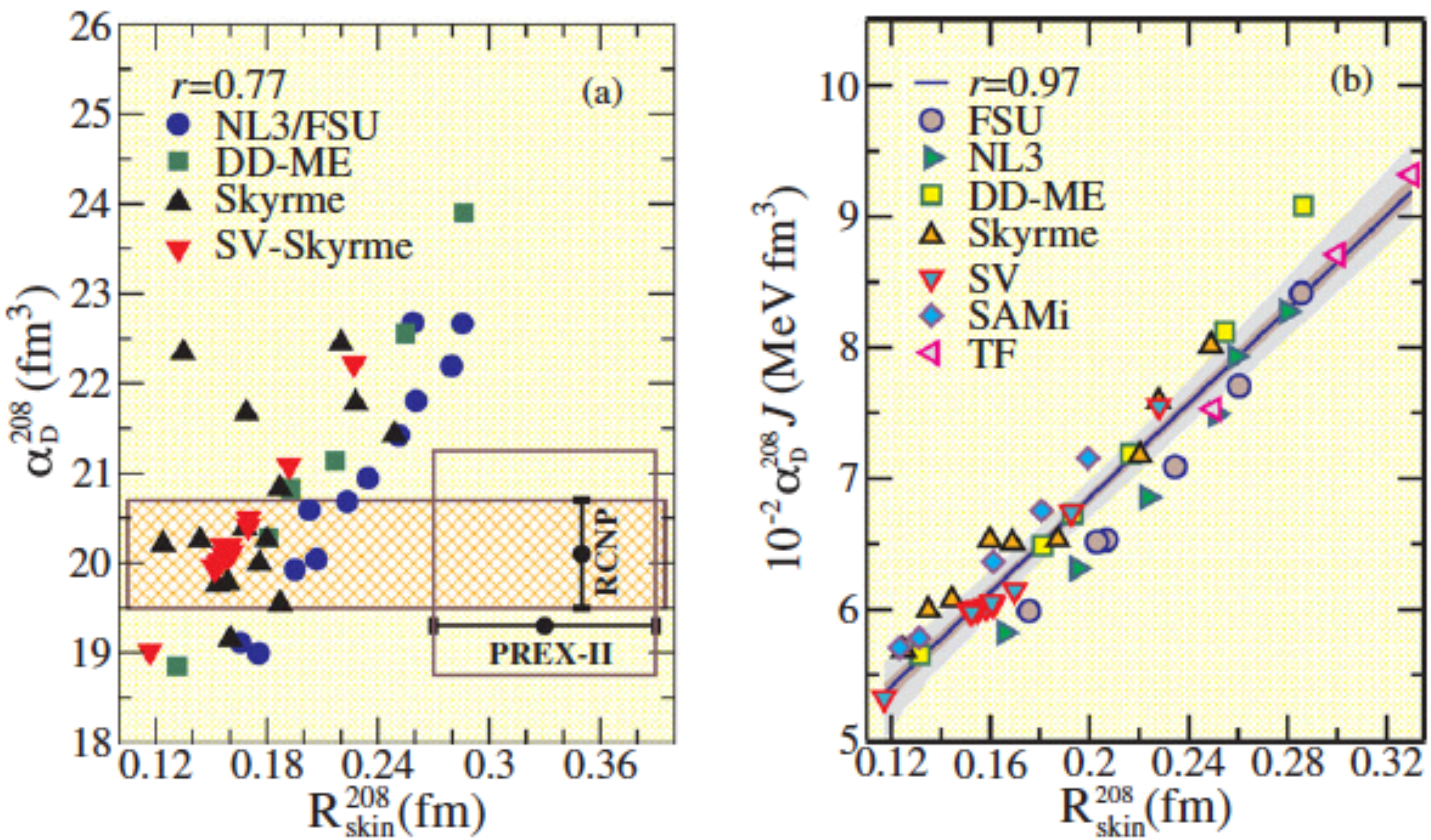


$\Delta R_{np} = 0.165 \pm (0.009)_{\mathrm{expt}} \pm (0.013)_{\mathrm{theor}} \pm (0.021)_{\mathrm{est}}$ fm

for the estimated J=31 $\pm$ $(2)_{\mathrm{est}}$

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

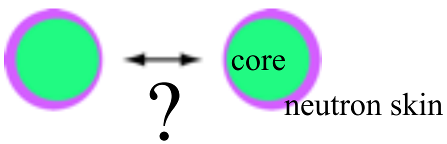
Neutron Skin Thickness of ^{208}Pb



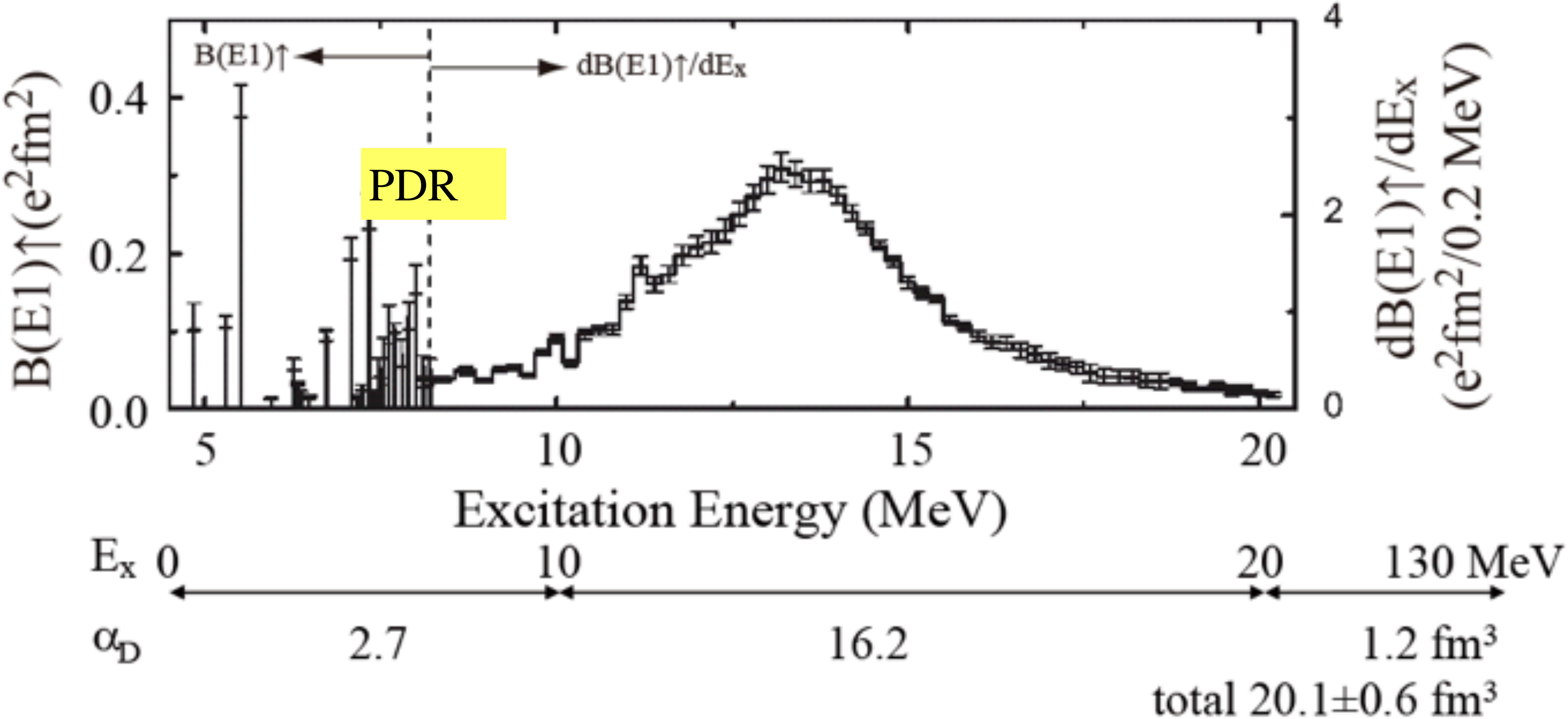
X. Roca-Maza et al., PRC88, 024316 (2013)

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

PDR strength

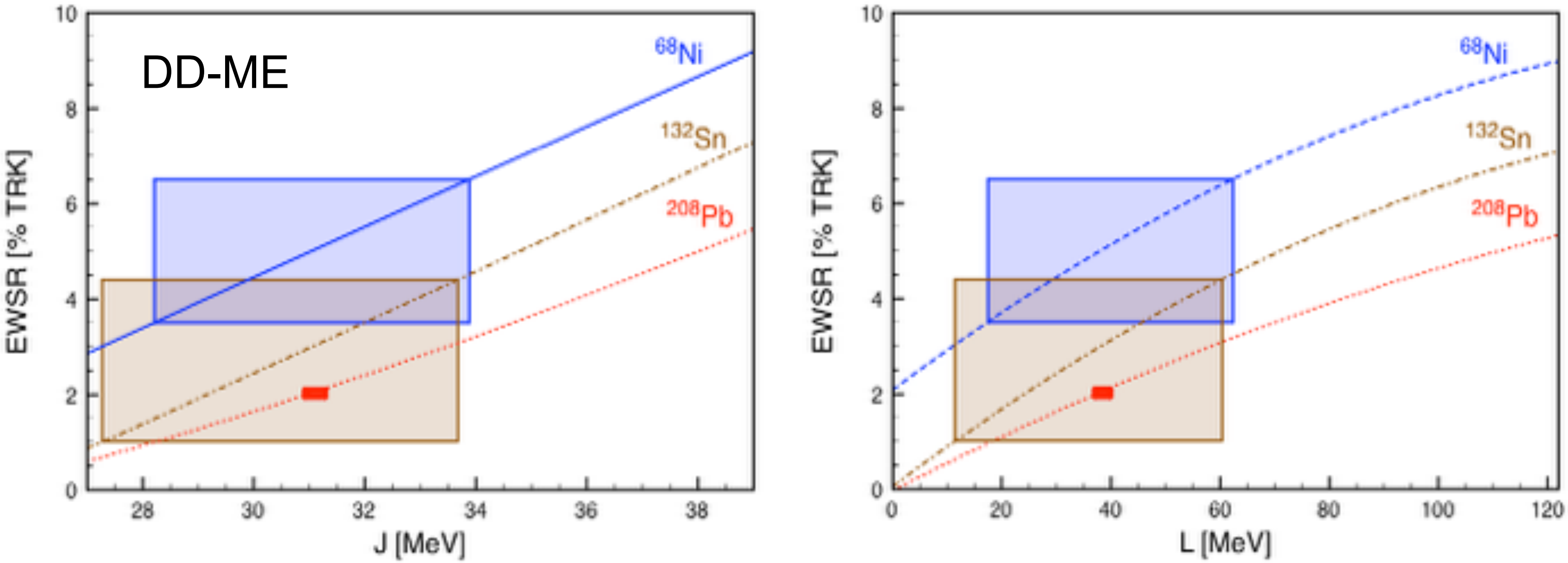


E1 Response of ^{208}Pb and α_D



AT et al., PRL107, 062502(2011)

• Theoretical dependences of pygmy EWSR on J and L are determined using relativistic energy density functionals spanning the range of J and L values. Available experimental data provide constraints on theoretical models.

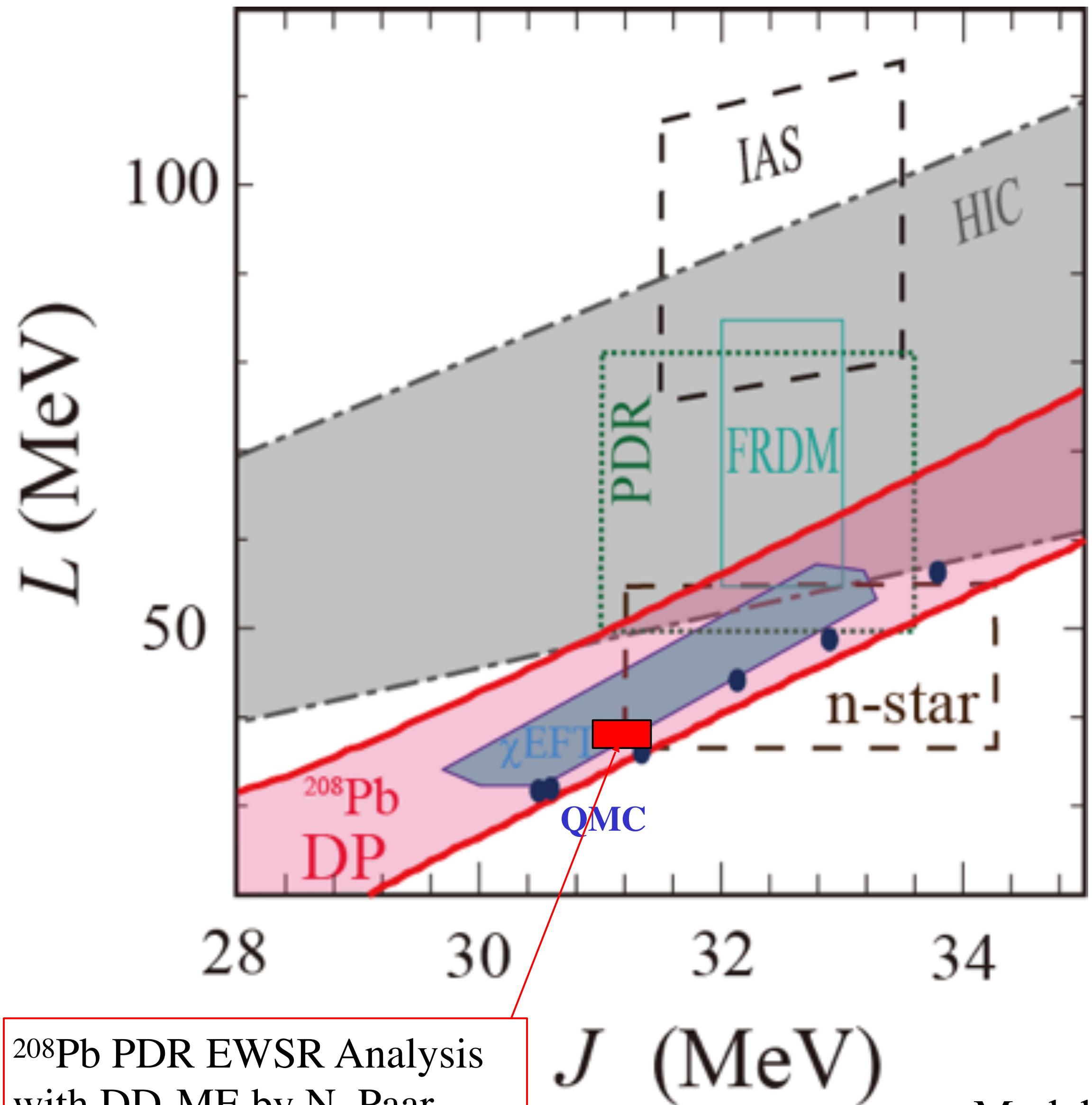


Similar approach but different theory ➔ A. Carbone et al, PRC 81, 041301(R) (2010)

Exp. Data: ^{68}Ni : O. Wieland et al, PRL 102, 092502 (2009)
^{132,130}Sn: A. Klimkiewicz et al., PRC 76, 051603 (R) (2007)
^{208}Pb: I. Poltoratska et al., PRC 85, 041304 (R) (2012)

Courtesy of N. Paar

Determination of Symmetry Energy



^{208}Pb PDR EWSR Analysis with DD-ME by N. Paar

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

C.J. Horowitz et al., to be published in JPG.

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 by S. Gandolfi et al

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

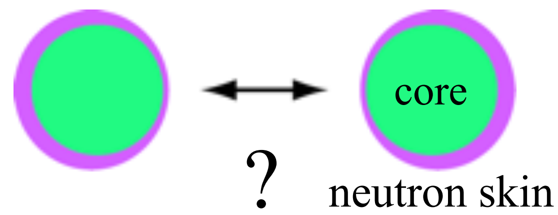
I. Tews et al., PRL110, 032504 (2013)

Model uncertainty should be evaluated.

Cluster Dipole Sum-Rule of PDR

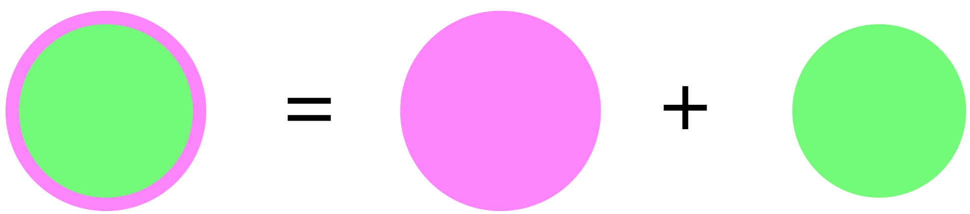
Assuming that the PDR is formed by the dipole oscillation of the neutron skin against the other part (core),

PDR



Y. Alhassid, M. Gai and G.F. Bertsch, PRL49, 1482(1982)
H. Sagawa and M. Honma, PLB251,17(1990)
R. de Diego, E. Garrido et al., PRC77, 024001 (2008)

Cluster Dipole Sum-Rule

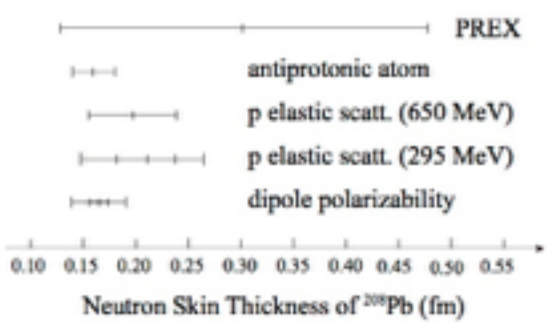


$$60\frac{\left(Z_s A_c - Z_c A_s\right)^2}{A A_s A_c}$$

A, N, Z $\quad$ $A_s, N_s, \left(Z_s = 0\right)$ $\quad$ $A_c, N_c, \left(Z_c = Z\right)$

TRK: $60\frac{NZ}{A}$

Number of neutrons in the skin: N_s



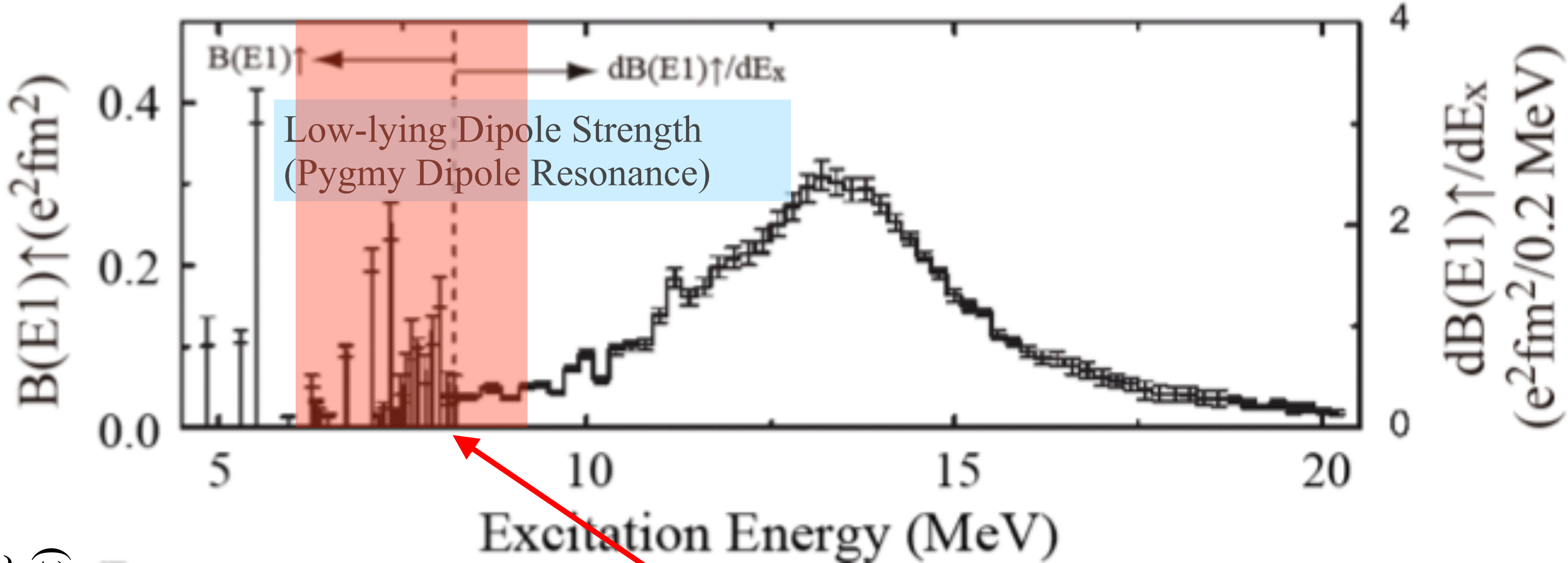
2% TRK $\rightarrow N_s$ (skin) ~ 12

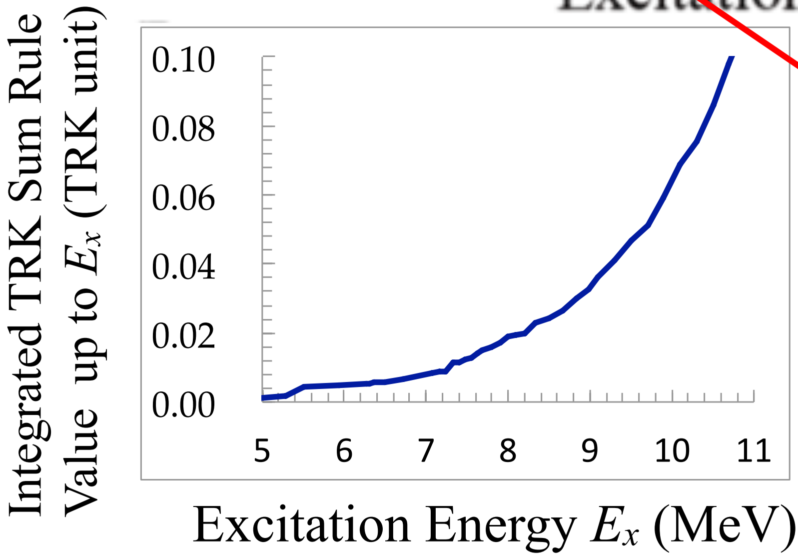
R_n=5.66 and $\delta R_{np} = 0.168 \pm 0.022$

$\rightarrow N_s = 10.9 \pm 1.4$

The numbers look consistent to each other

Electric Dipole Response of ^{208}Pb



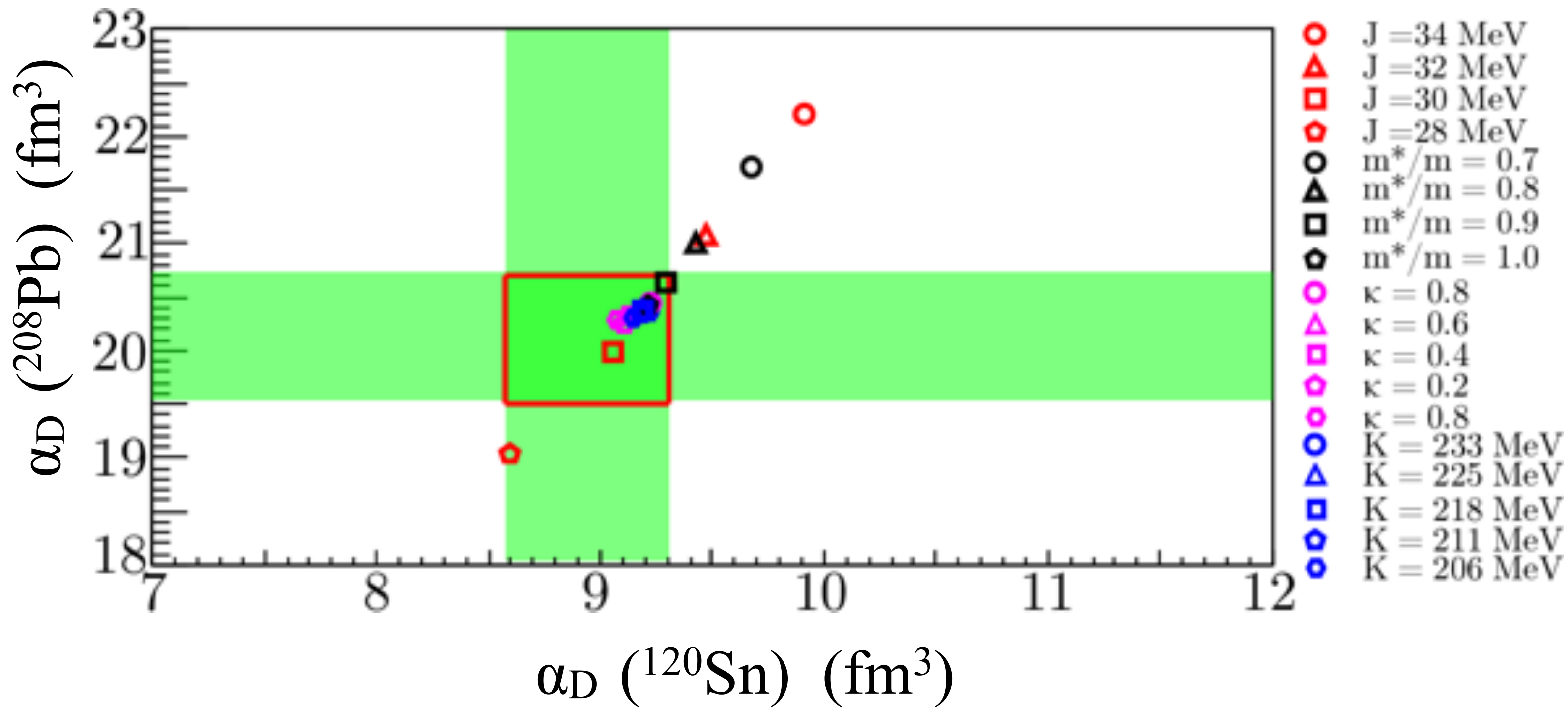


The amount of E1 strength which corresponds to the neutron skin oscillation predicted by the cluster sum-rule.

The correlation between the PDR strength and the neutron skin thickness will be discussed by the next speaker, Dr. Inakura.

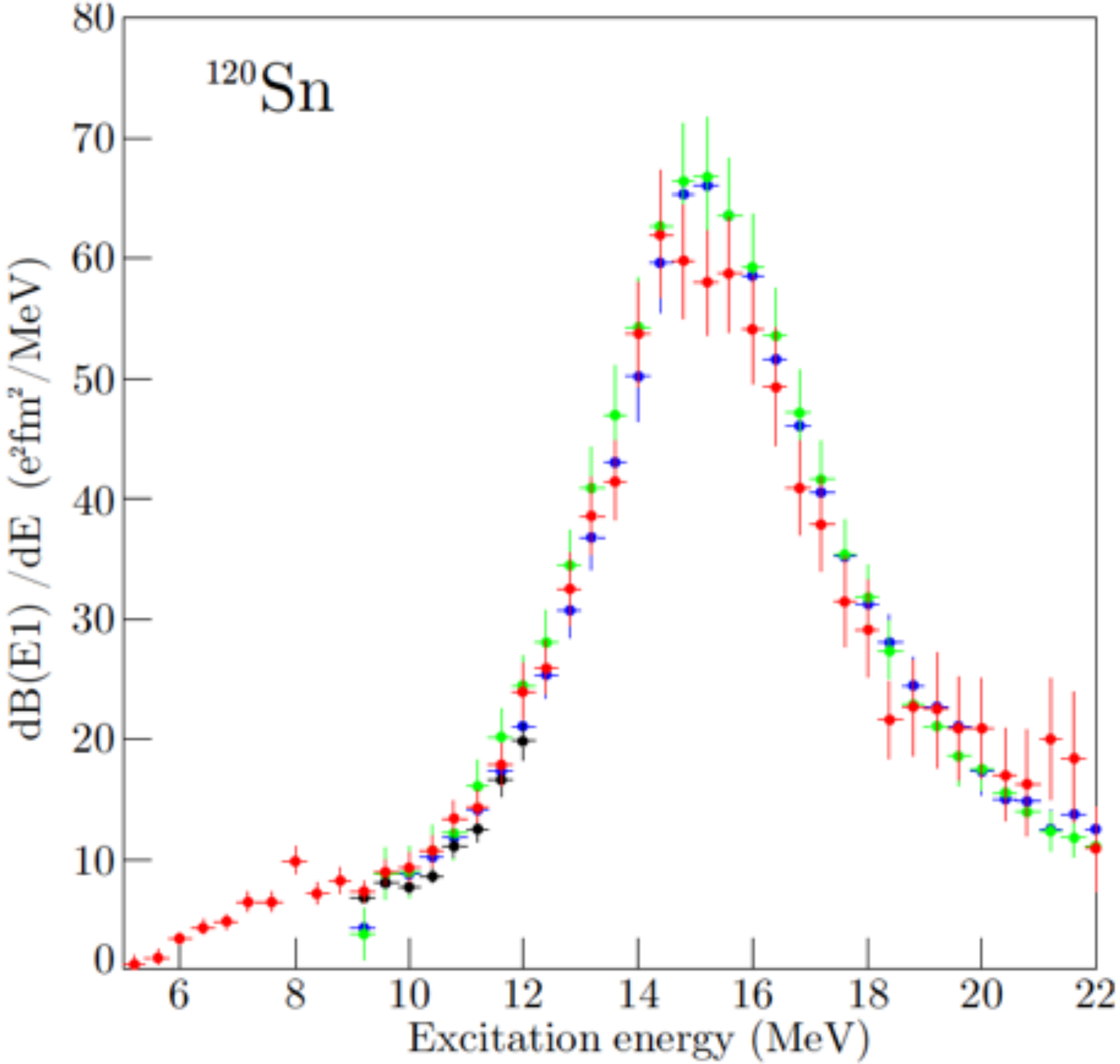
Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al*., submitted



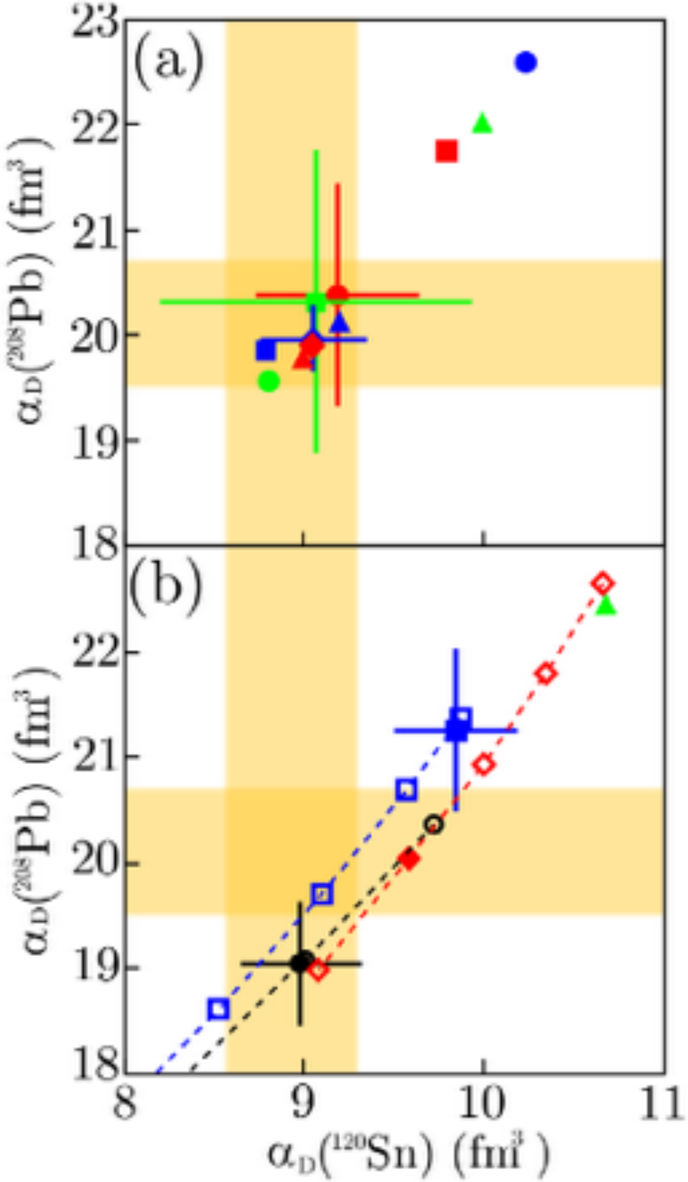
Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al.*, submitted



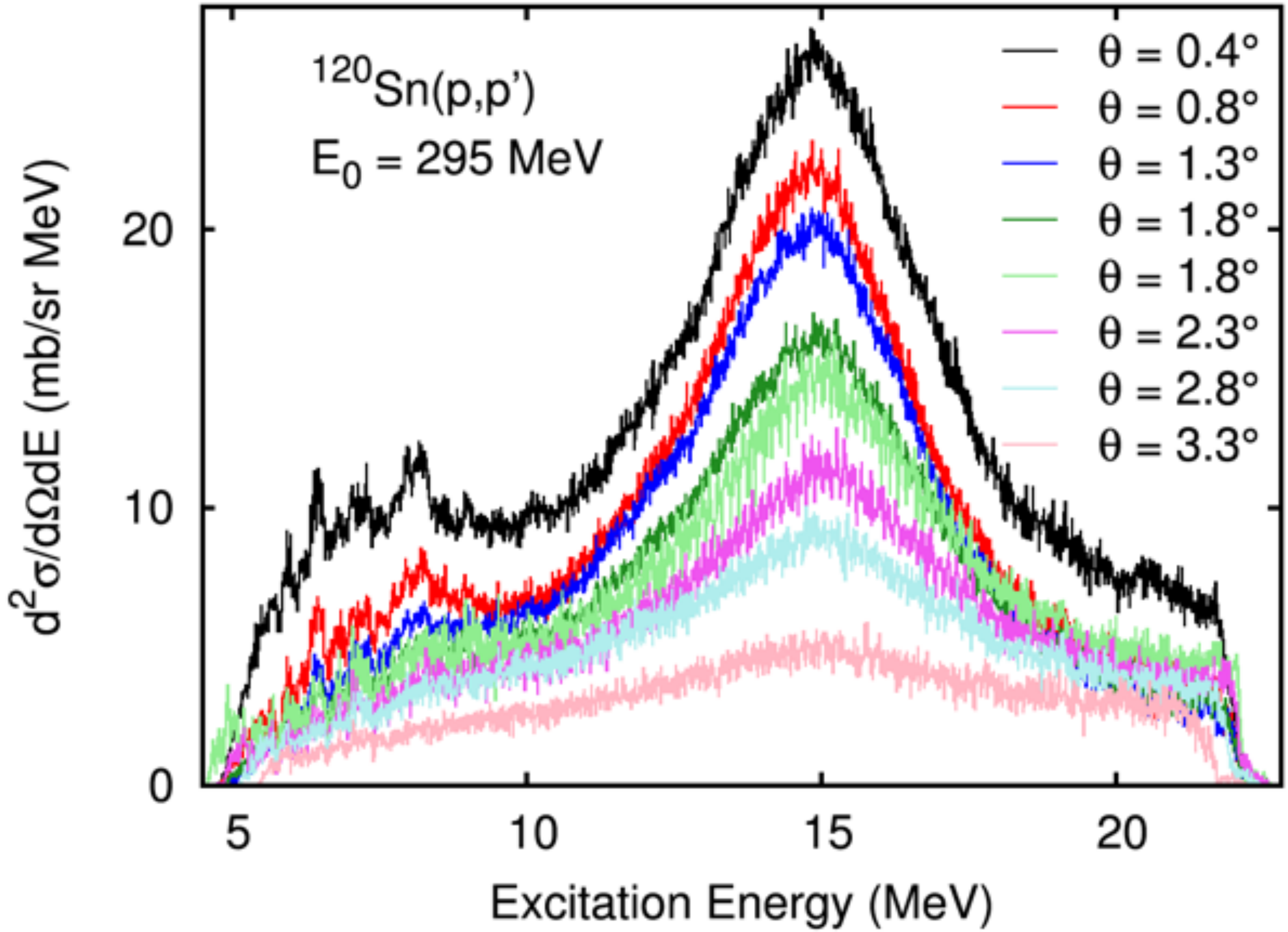
Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al.*, submitted



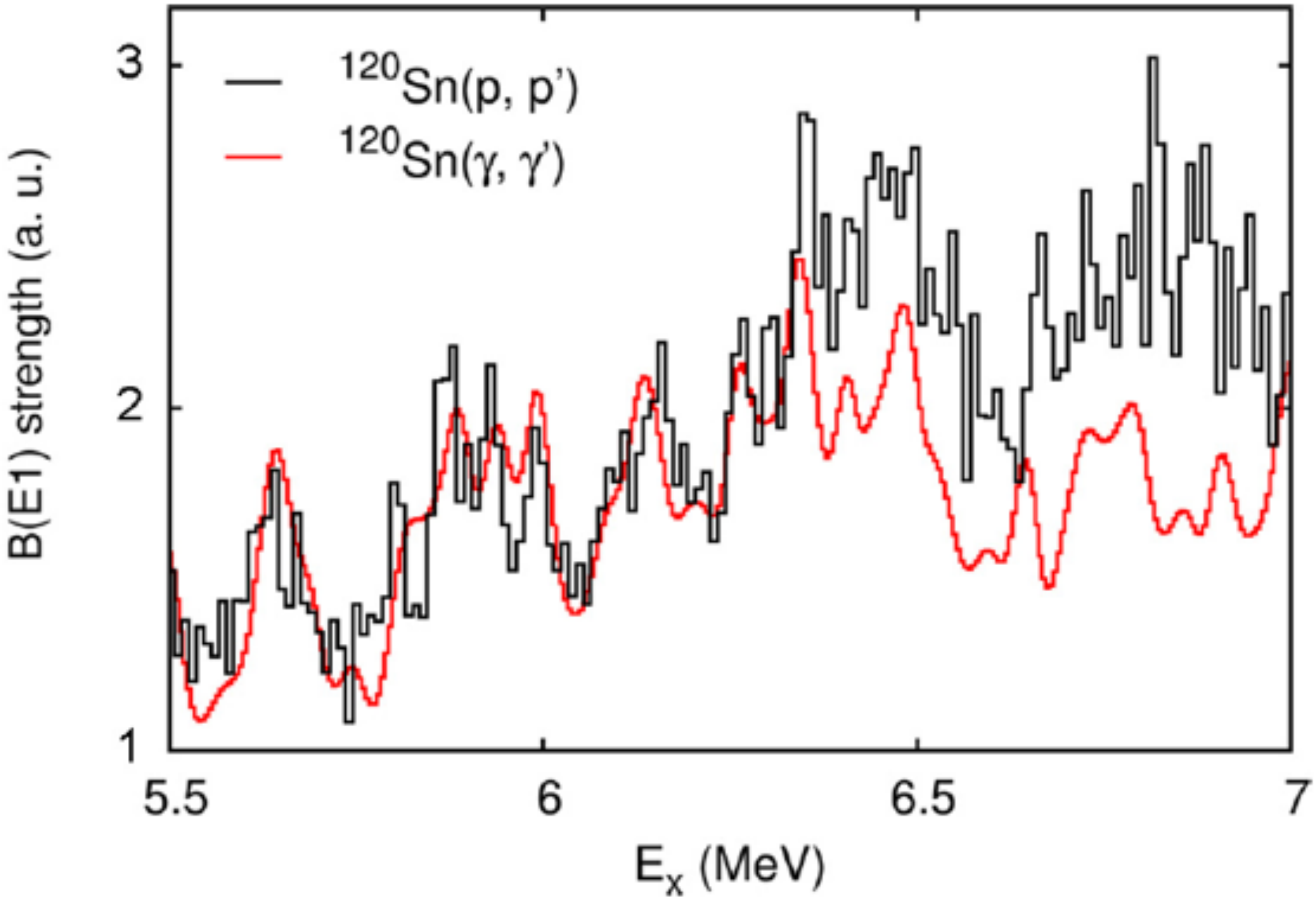
PDR in ^{120}Sn

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



PDR in ^{120}Sn

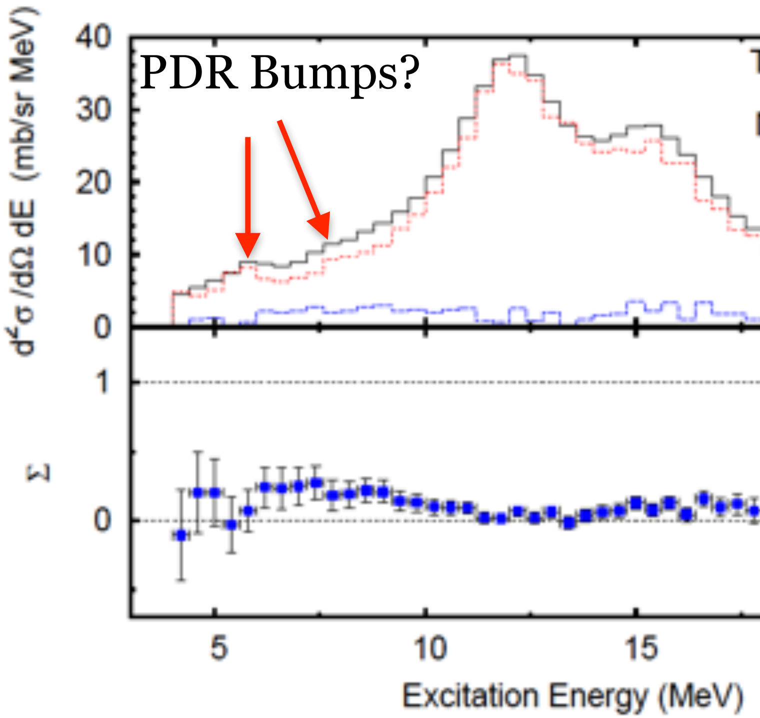
A.M. Krumbholtz *et al.*, PLB744, 7(2015)

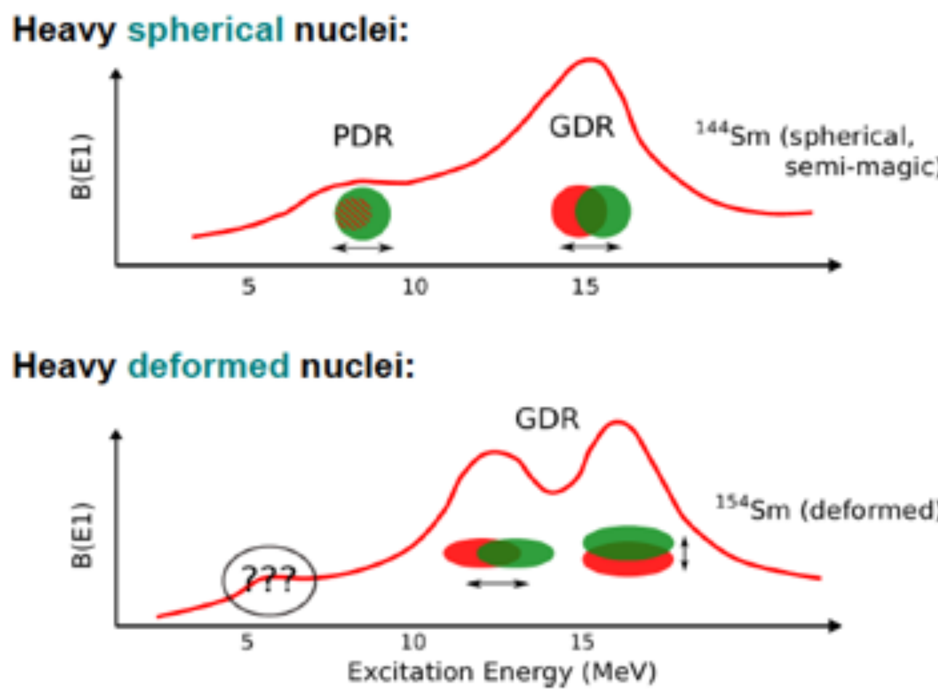


(γ,γ′): B. Özel-Tashenov, *et al.*, PRC90, 024304(2014)

PDR in Deformed Nuclei: ^{154}Sm

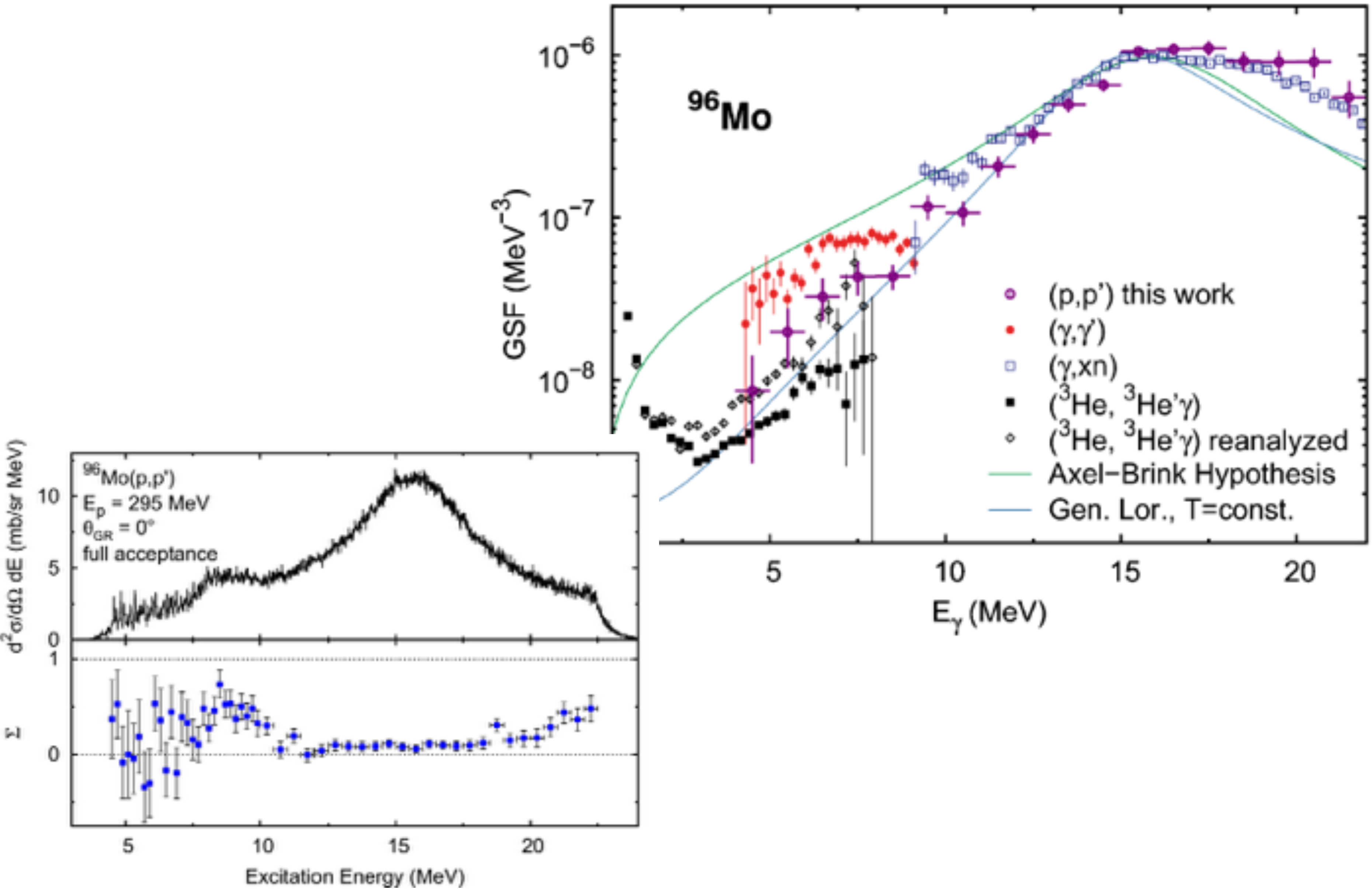
A. Krugmann et al. in the INPC2014 Proceedings





Gamma Strength Function: ^{96}Mo

D. Martin et al.



Summary

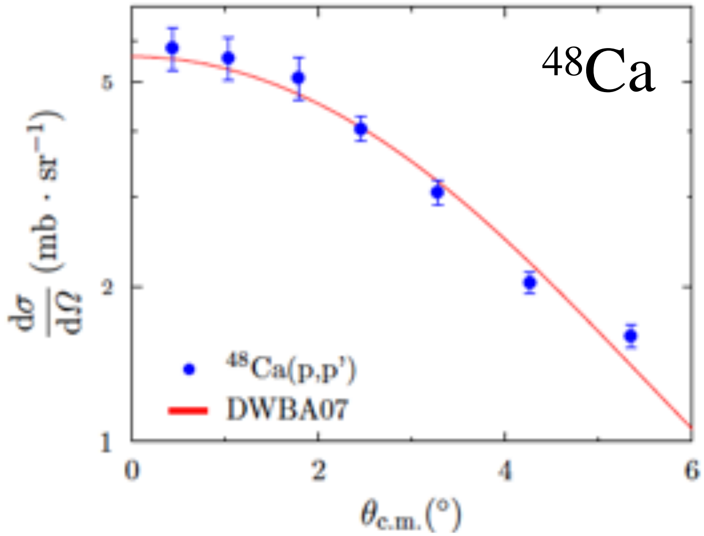
- Electric dipole response of ^{208}Pb and ^{120}Sn have been precisely measured. Proton inelastic scattering was used as an electro-magnetic probe (relativistic Coulomb excitation).
- Electric dipole polarizability (α_D) is sensitive to the difference between the proton and neutron distributions.
- α_D is clearly defined as the inversely energy weighted sum-rule of B(E1) with less ambiguity in the integration range and good convergence up to $E_x \sim 40$ MeV.
- The neutron skin thicknesses and the constraints on the symmetry energy parameters have been extracted with the help of mean field calculations.

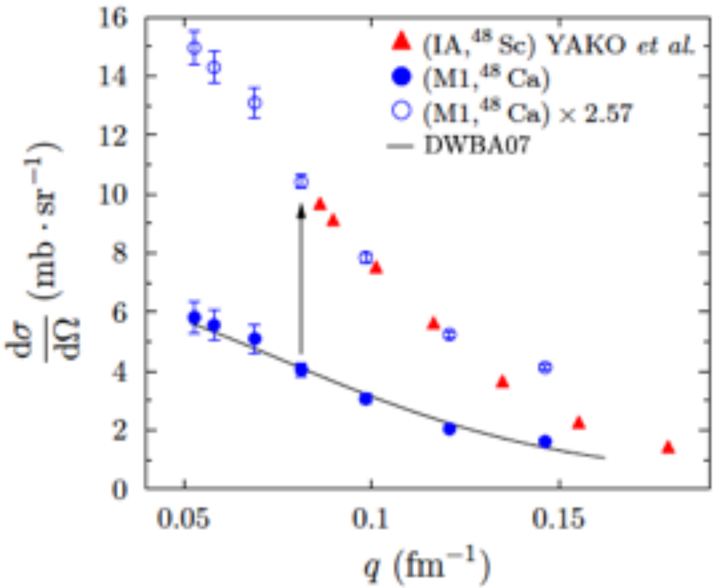
$$\Delta R_{np}\ (^{208}\mathrm{Pb}) = 0.165 \pm (0.009)_{\mathrm{expt}} \pm (0.013)_{\mathrm{theor}} \pm (0.021)_{\mathrm{est}}\ \mathrm{fm}$$

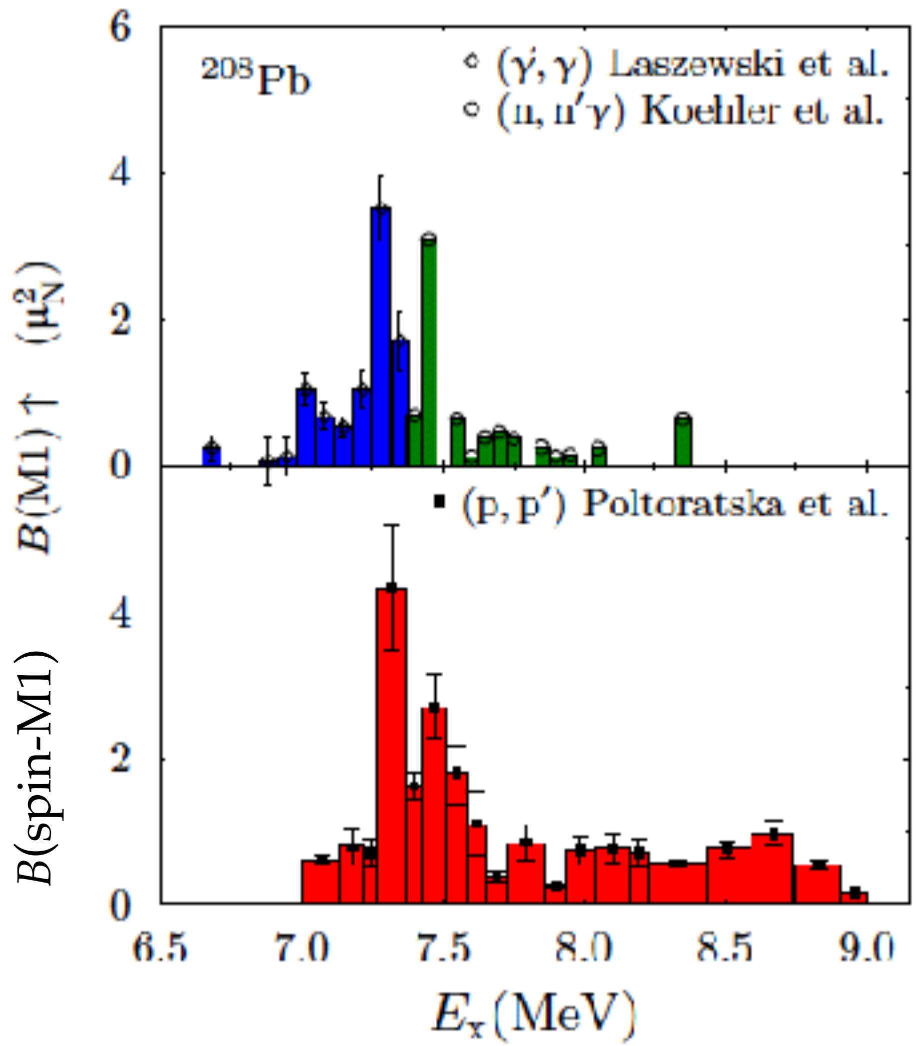
$$\Delta R_{np}\ (^{120}\mathrm{Sn}) = 0.148 \pm (0.034)_{\mathrm{expt+thor}}\ \mathrm{fm}$$

Spin-M1 Strength in ^{48}Ca and ^{208}Pb

J. Birkhan et al. submitted to PRL

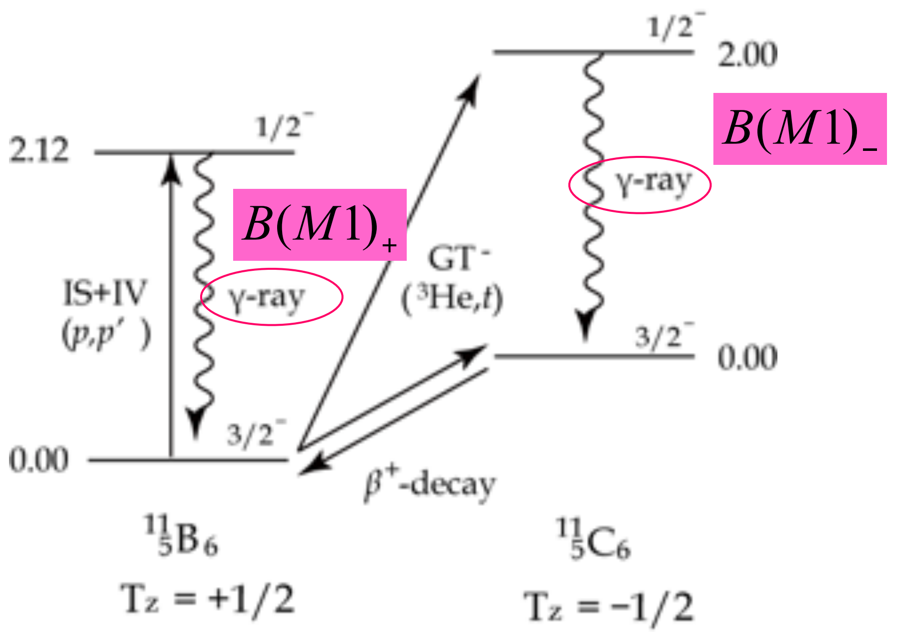






Unit cross section (UCS)

Mirror states of γ-decay widths of ^{11}B/^{11}C were employed to deduce $B(M1)_{IS}$.



$$B(M1)_{IS} = \frac{1}{4}\left[\sqrt{B(M1)_+} - \sqrt{B(M1)_-}\right]^2$$

$$\langle f | \sum_k \left(\vec{l}_k + \vec{s}_k\right) | g.s. \rangle = 0 \quad \Longrightarrow \quad B(M1)_\sigma = \left(\frac{g_s^{IS}}{g_s^{IS} - g_l^{IS}}\right)^2 \times B(M1)_{IS}$$

Summary

•The **dipole polarizability** of ^{208}Pb has been precisely measured as

$$\alpha_D = 20.1 \pm 0.6\ \mathrm{fm}^3/e^2$$

•**Constraint band on the symmetry energy parameters, *J* and *L***, has been extracted with a help of mean-field calculations.

•The picture of **neutron-skin oscillation of PDR** is not inconsistent with the prediction of **cluster dipole sum-rule** with the measured neutron skin thickness.

•The ***pn* spin correlation function** has been extracted from the measured IS/IV spin-M1 matrix elements for N=Z even-even nuclei. The function is expected to be sensitive to the **ground state tensor correlation**.

•Theoretical (e.g. ab. initio type calc.) prediction of mass/isospin dependence of *pn* spin correlation function is quite interesting.

$$\left\langle \vec{S}_n \bullet \vec{S}_p \right\rangle$$

•CAGRA+GR http://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/GRFBL/