Electric Dipole Polarizability Studied by Proton Scattering

Atsushi Tamii

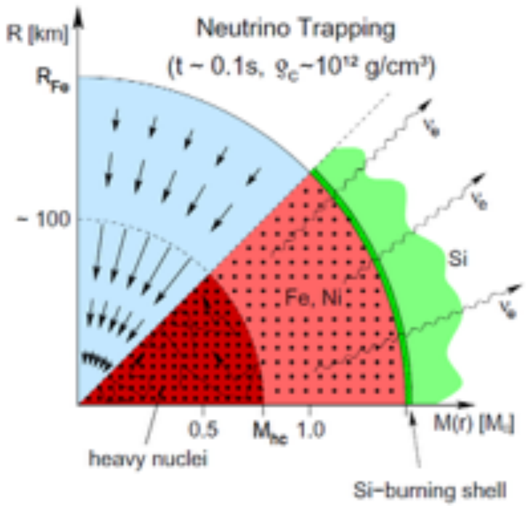
Research Center for Nuclear Physics (RCNP)
Osaka University, Japan

MITP Conference on Neutron Skin
Mainz, May 17-27, 2016

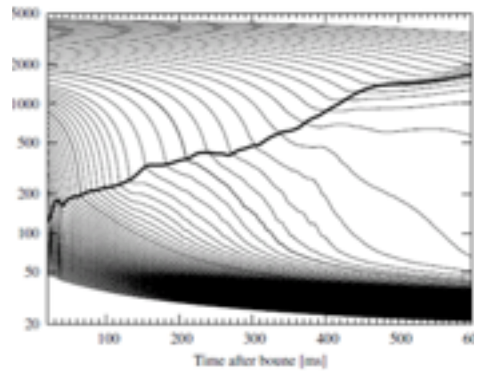
Symmetry Energy of the Nuclear Equation of State

is important for nuclear physics and nuclear-astrophysics

Core-collapse supernova



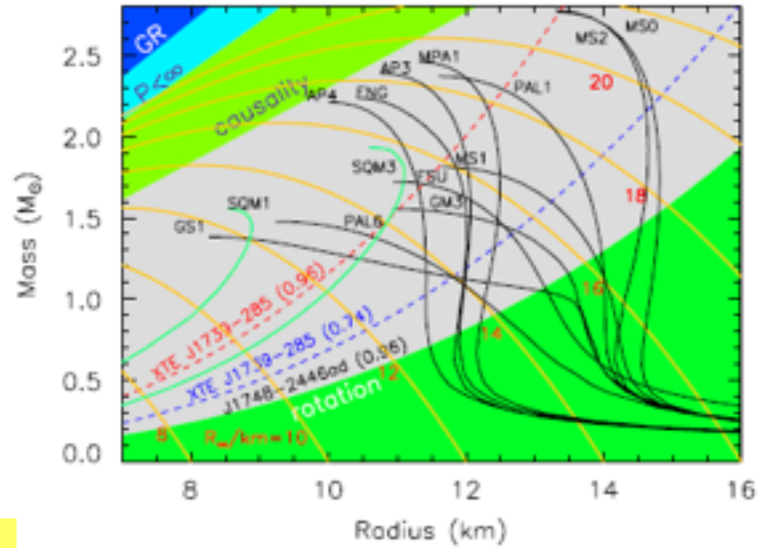
Langanke and Martinez-Pinedo



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

Nucleosynthesis

Neutron star mass vs radius

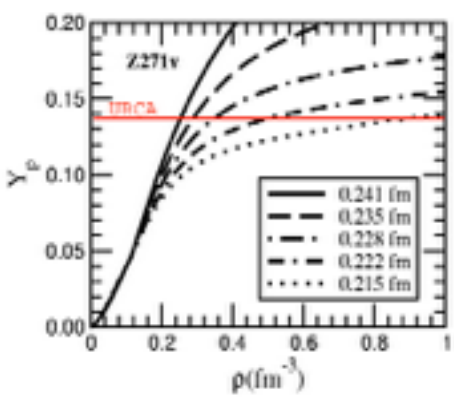


Lattimer et al., Phys. Rep. 442, 109(2007)

Neutron Star Merger Gravitational Wave

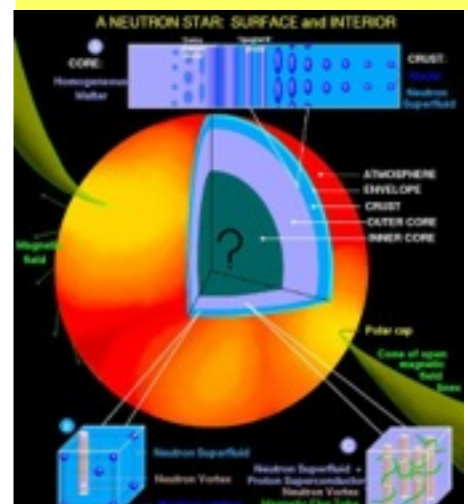
https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



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

Neutron star structure



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

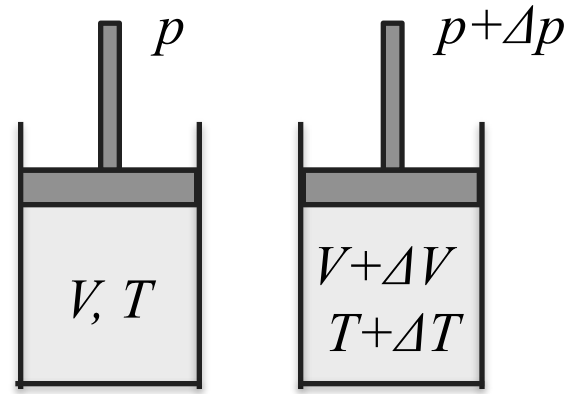
Studying the Equation of State

Thermodynamics

Give a "small perturbation"

then observe how the system changes = response

$$\kappa = -\frac{1}{V}\left(\frac{dV}{dp}\right)_S$$



equilibrium

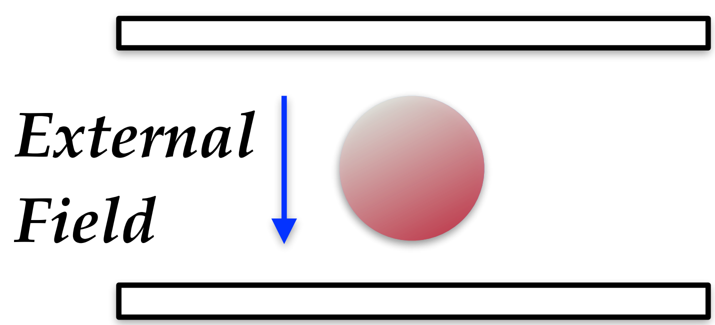
This is a natural and straightforward way for studying the equation of state.

Nuclear EOS

Small perturbation by an external field

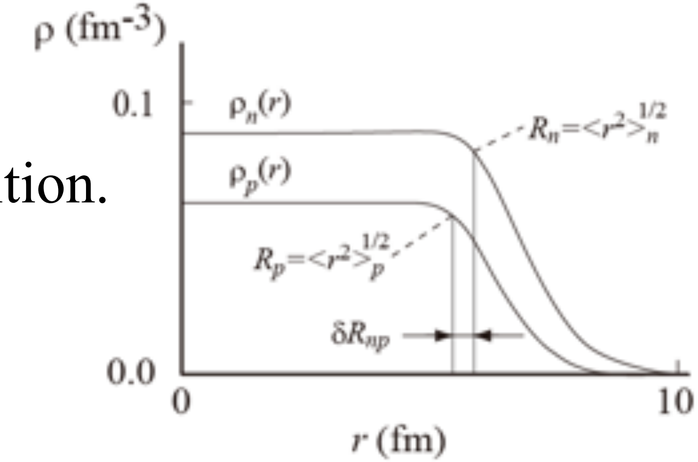
observe how the system change

nuclear response



Electric Dipole Response

is relevant to the isovector property of the nuclear EOS



Ground state is

the lowest energy state in the equilibrium condition.

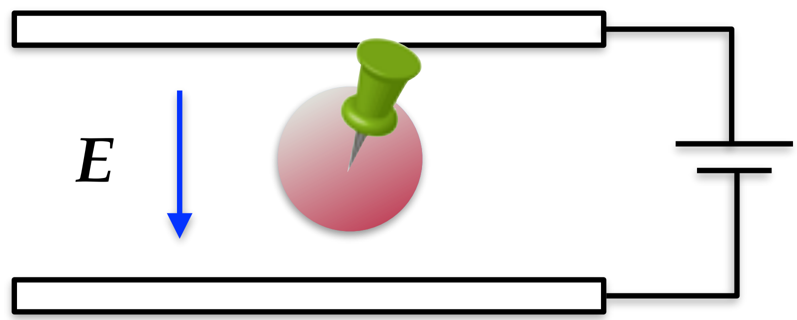
The proton and neutron density distributions are determined as the system has the lowest energy.

Any perturbation on the density distribution makes system energy larger.

Electric dipole moment

$$= \alpha_D \times E$$

α_D: electric dipole polarizability



nucleus

in a static electric field

with fixing the c.m. position

Nuclear Equation of State (EOS)
at zero temperature

Nuclear equation of state (neglecting Coulomb)

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

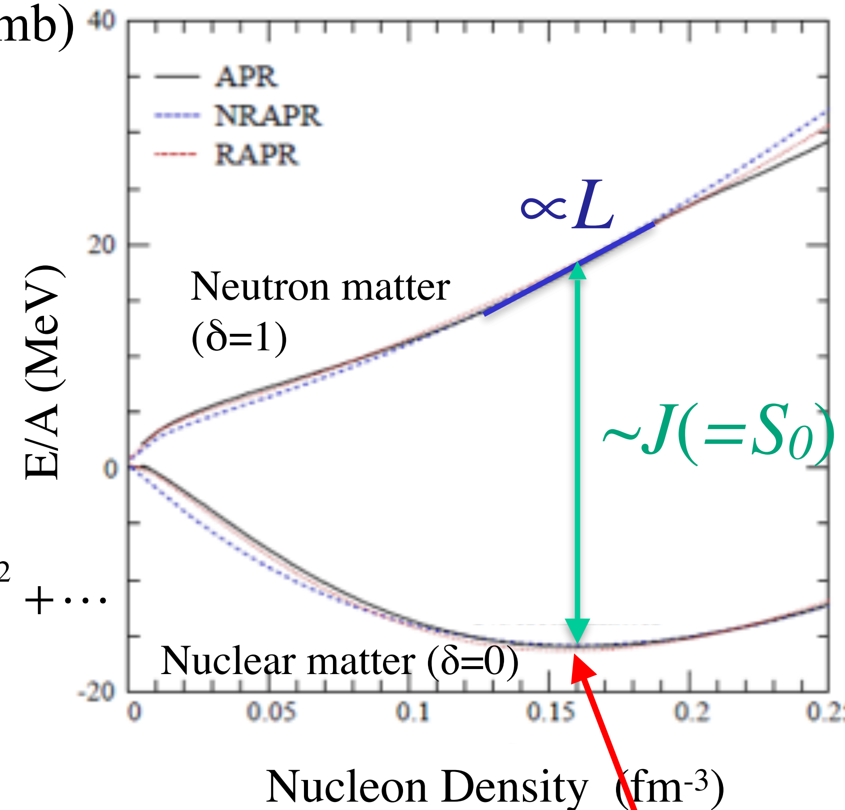
$$\delta(r)\equiv\frac{\rho_n(r)-\rho_p(r)}{\rho_n(r)+\rho_p(r)}$$

Symmetry energy

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

ρ_0: Saturation Density ~0.16 fm^{-3}

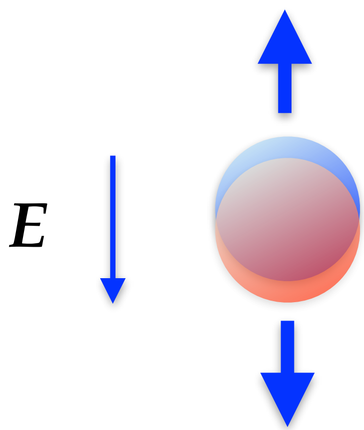
⇔ difference between *p*-*n* chemical potentials: $\mu_n - \mu_p$



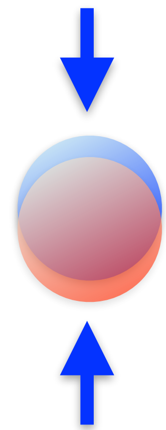
Saturation Density ρ_0

Electric Dipole Response

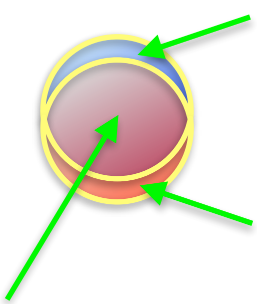
is relevant to the isovector property of the nuclear EOS



Electric force for separating p and n.



Symmetry energy for restoring force.



ρ_n : increase, ρ_p: decrease

ρ_n : decrease, ρ_p: increase

inner volume: decrease

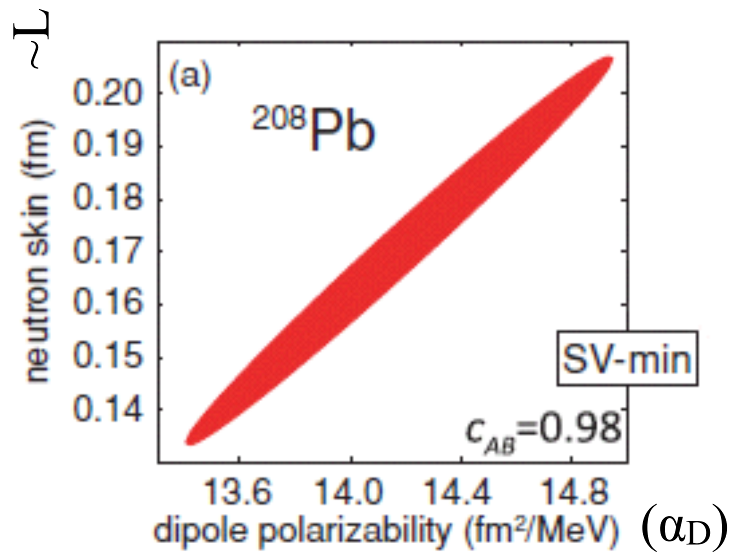
Symmetry Energy

- Volume term
- Surface term

Surface Effect

- Surface diffuseness
- Neutron Skin

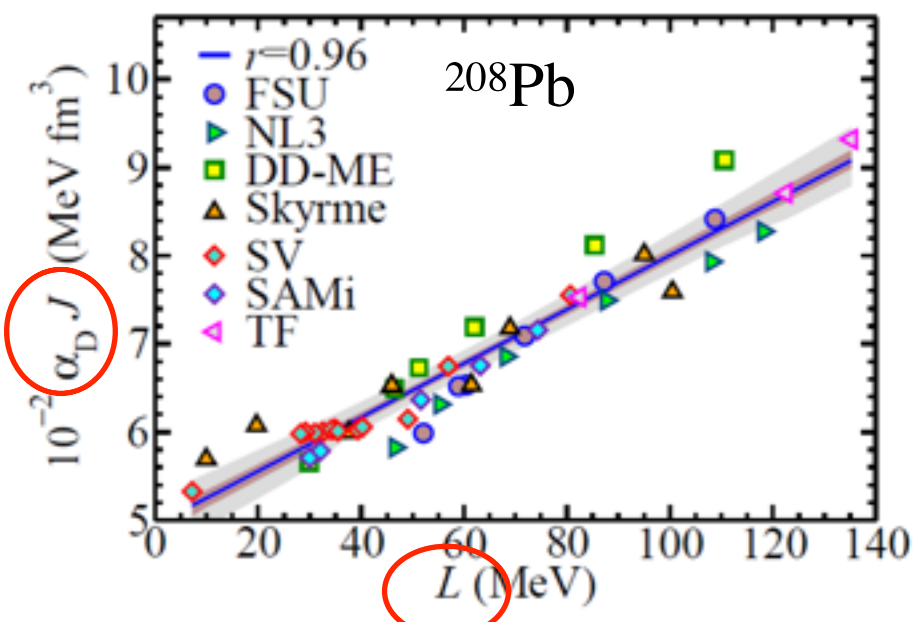
Electric Dipole Polarizability (α_D)



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

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

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



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 Polarizability

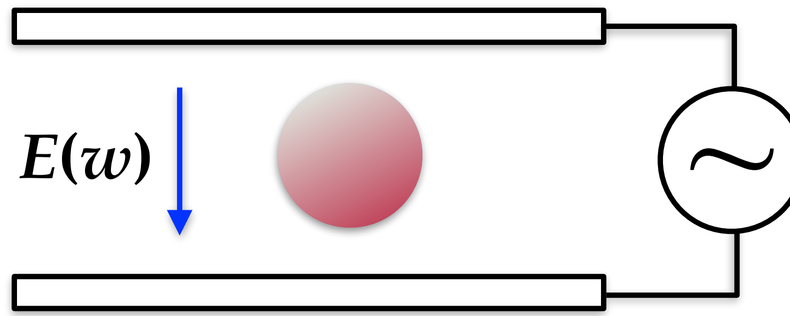
Inversely energy weighted sum-rule of B(E1)

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

σ_{abs} : photo absorption cross section
B(E1) : E1 reduced transition probability

first order perturbation calc.

A.B. Migdal: 1944



in an oscillating electric field

Electric Dipole Polarizability

Clear definition

Unambiguous in the integration range

↔ Pygmy Dipole Strength

Inversely energy weighted sum-rule

More sensitive to the low-energy strengths

Good convergence in the excitation energy

↔ energy-weighted (TRK) sum rule

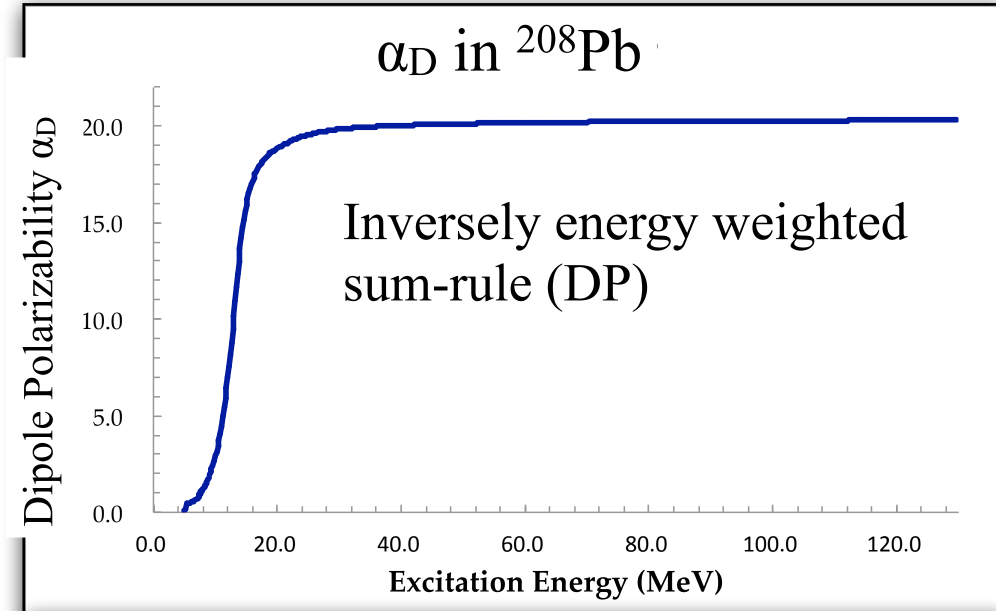
Sum-rule for all the transitions

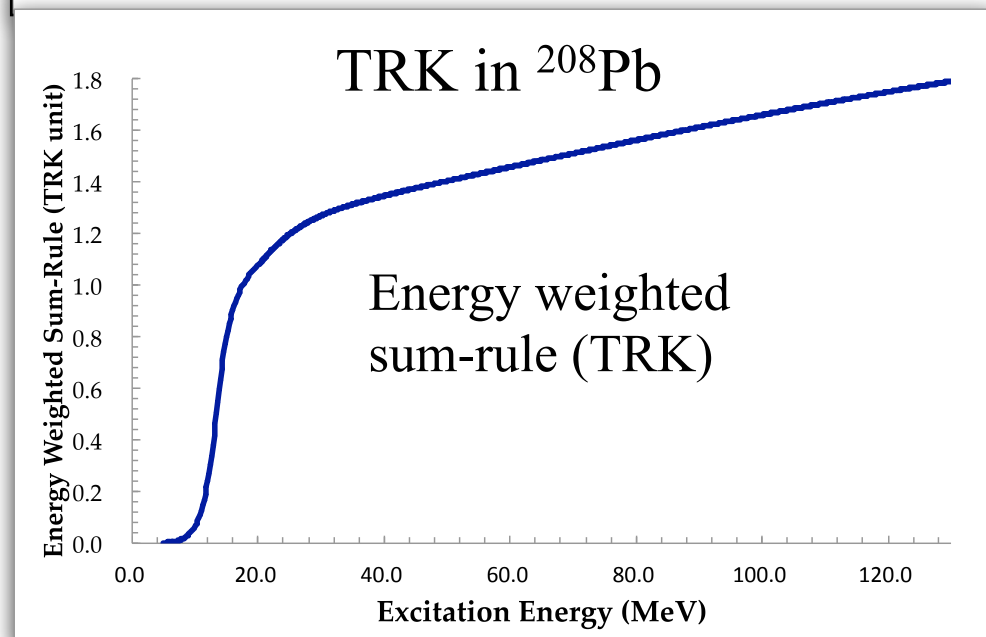
= Ground state property

↔ easier comparison with theoretical predications

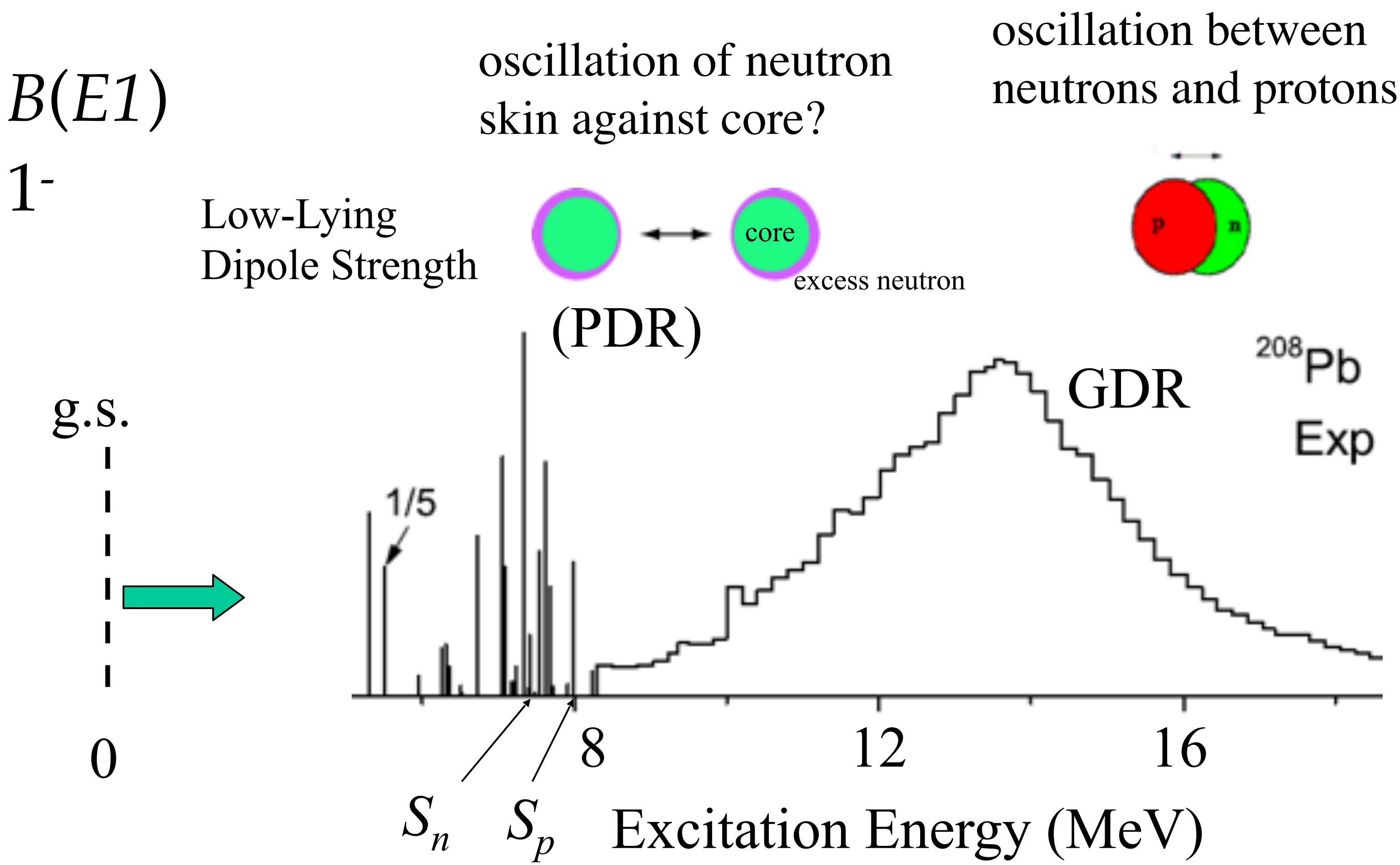
- Measurements in a broad E_x range is required.

Electric Dipole Polarizability

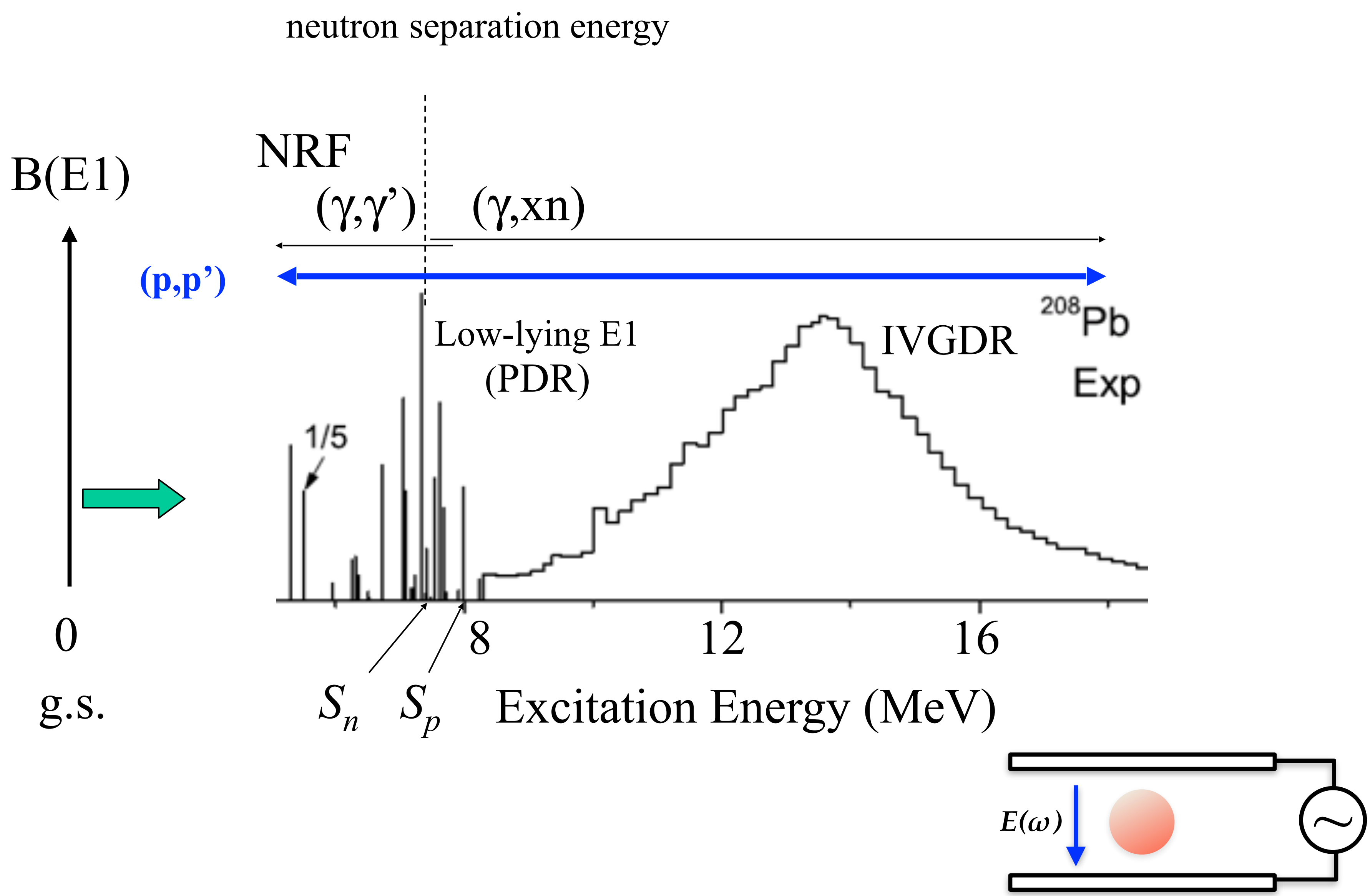




Electric Dipole (*E1*) Response of Nuclei



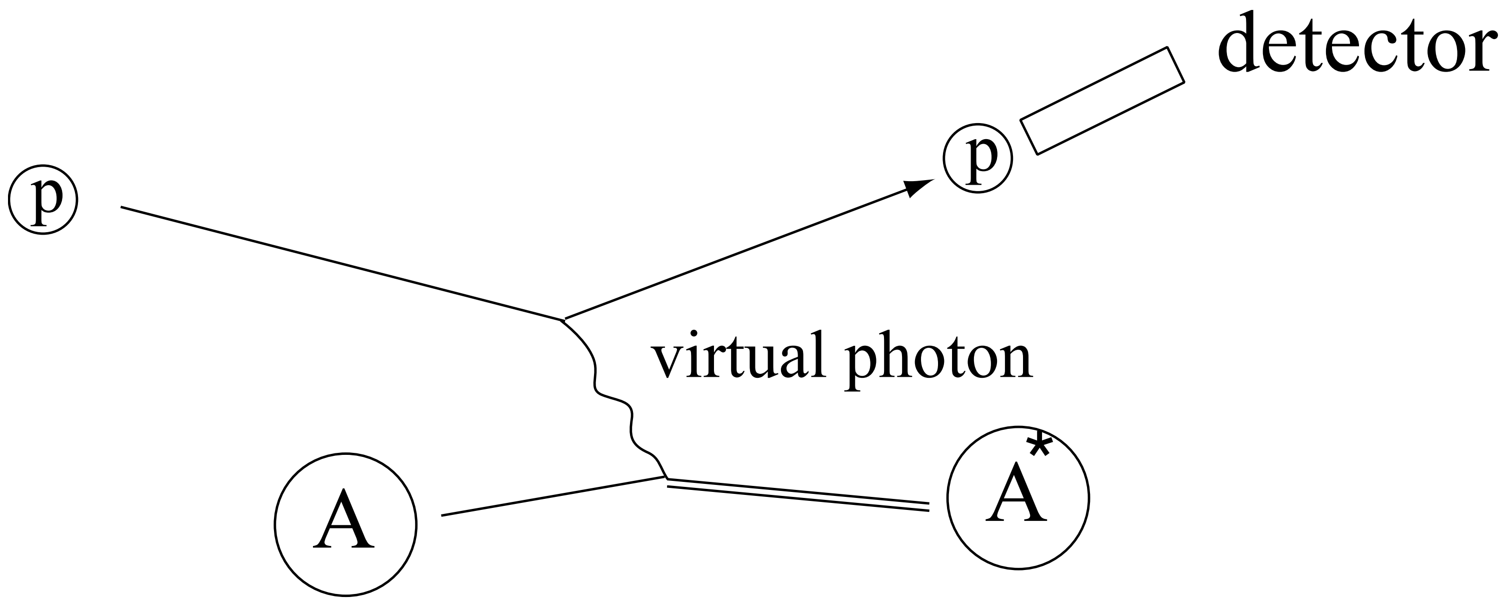
Electric Dipole (*E1*) Response of Nuclei



Probing the E1 Response by Proton Scattering

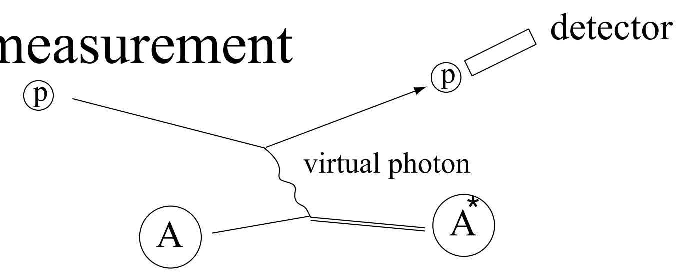
Missing Mass Spectroscopy by Virtual Photon Excitation

Select q~0 (~0 deg.) condition



Proton Inelastic Scattering at $q \sim 0$

is suitable for the full E1 response measurement



Electromagnetic Probe

Electromagnetic interaction is well known ⟷ strong interaction

Absolute determination of the transition strength.

Missing mass spectroscopy (inclusive measurement)

Total E1 strength independent on the decay channels

Multipole decomposition analysis

Extraction of the full strength including unresolved small strengths

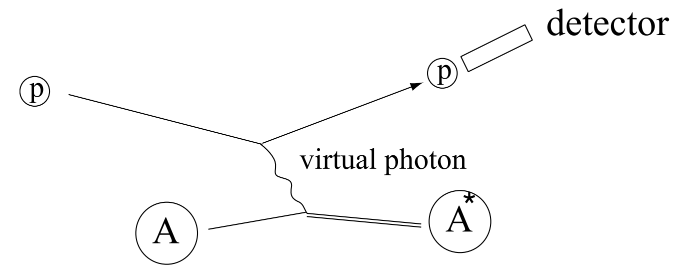
Single shot measurement

From low (~5) to high (~20) excitation energies across S_n

Uniform proton detection efficiency

Virtual photon number decreases as E_x increases

Proton Inelastic Scattering at q~0



High-resolution of 20-30 keV

Spin observables

Model independent decomposition of ΔS=0 and 1 transitions

Small amount of isotopically enriched target (several mg)

A **few days for cross sections**, 7-10 days for spin-transfer

- Requirement of a halo-free high-quality beam
- Some nuclear interaction contribution

Two Approaches for the Neutron Skin Thickness

Probing the matter/neutron/weak-charge distribution

Takes the difference from the charge (or p) distribution $\rightarrow \Delta R_{np}$

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

$$\frac{\sigma(\Delta R_{np})}{R_p} \sim \frac{0.02\ fm}{5.45\ fm} \sim 4\times 10^{-3}$$

PREX, CREX, MREX

p elastic scattering

coherent π_0 production

Both approaches are important.

Probing the difference between the p/n distribution

- Requires theoretical models
- Data can be less accurate

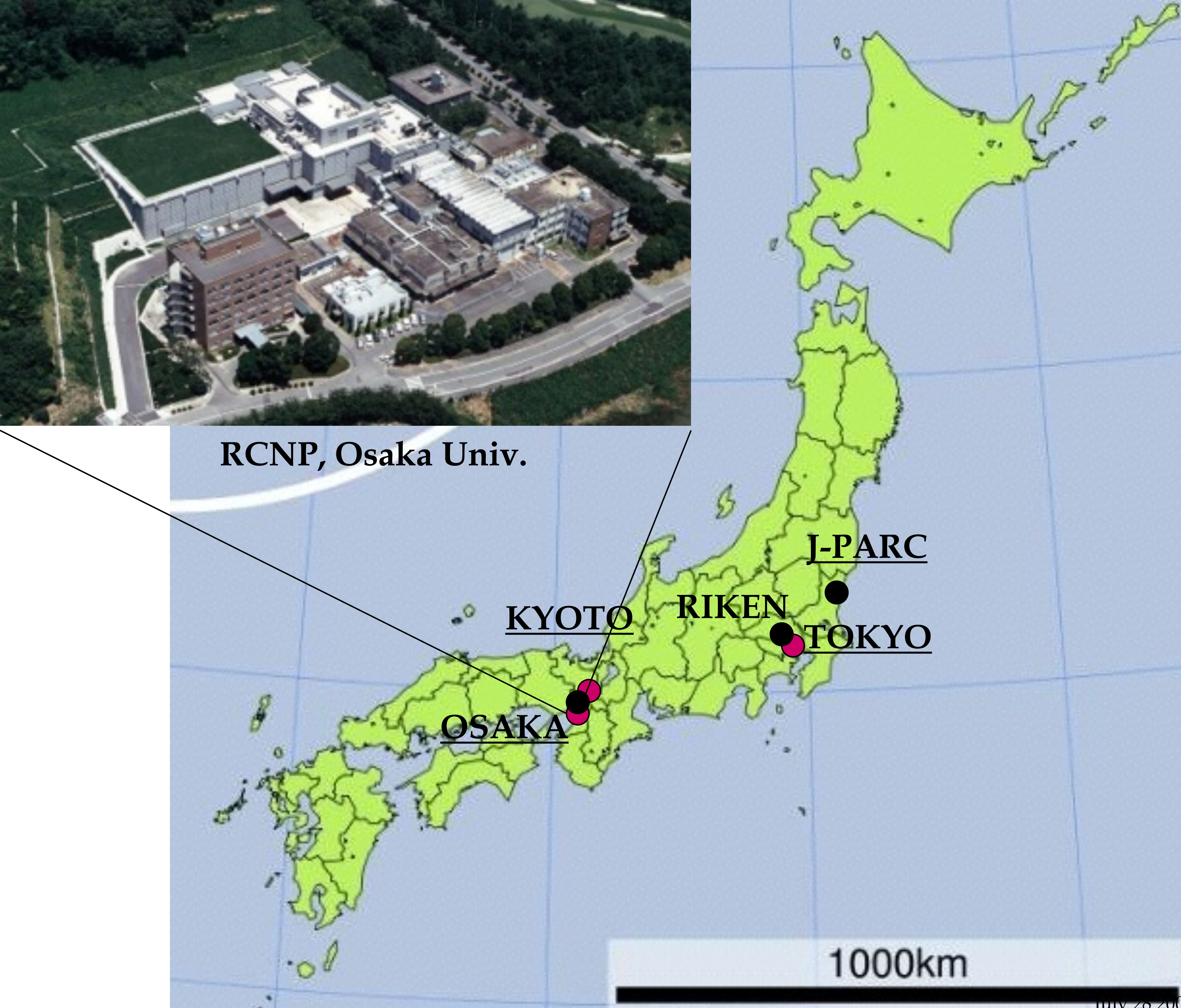
$$\frac{\sigma(\Delta R_{np})}{\Delta R_{np}} \sim \frac{0.02\ fm}{0.2\ fm} \sim 10^{-1}$$

Dipole Polarizability

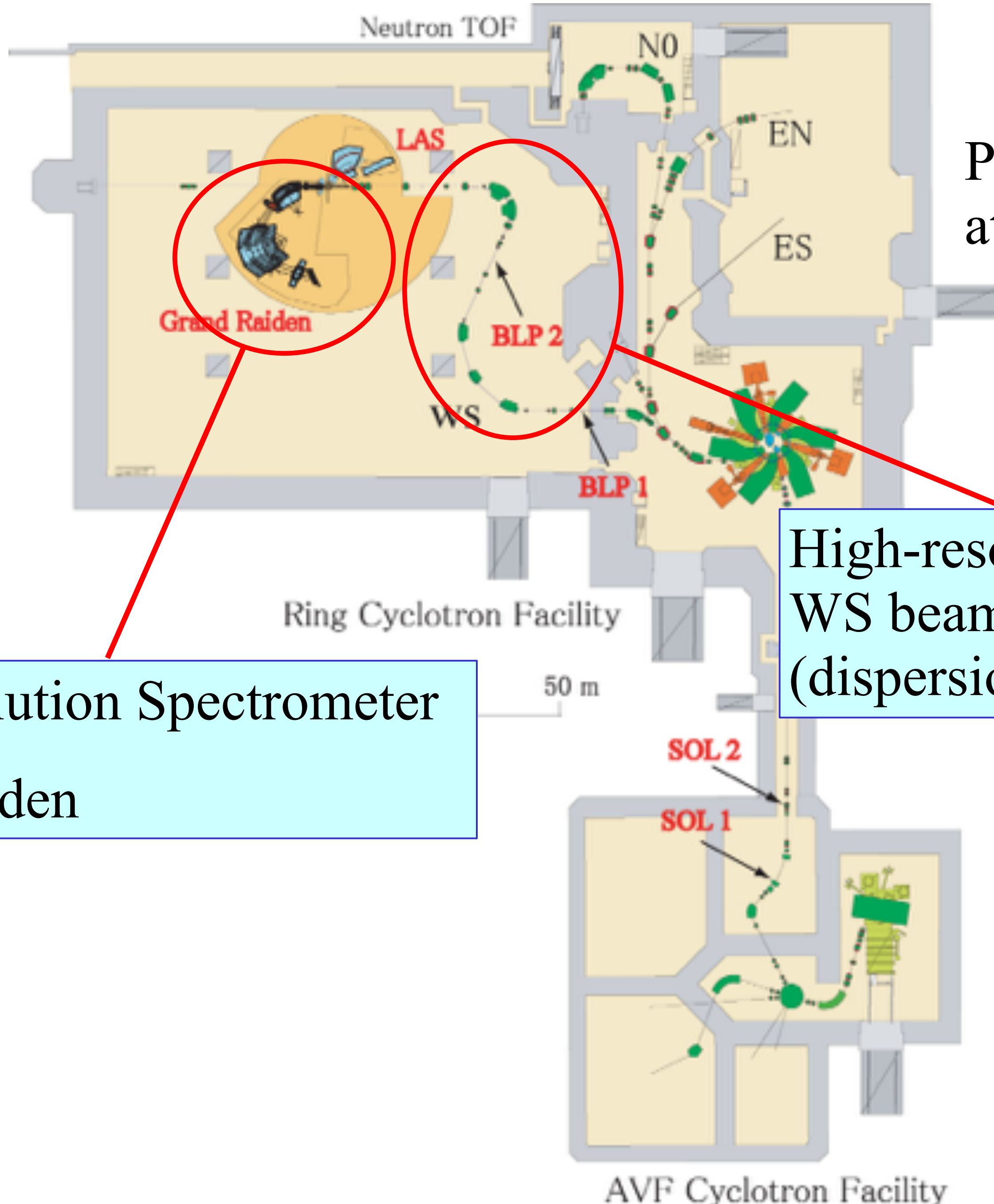
PDR, GDR

anti-protonic atom

Experimental Method


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

Research Center for Nuclear Physics (RCNP), Osaka University



Polarized p beam at 295 MeV

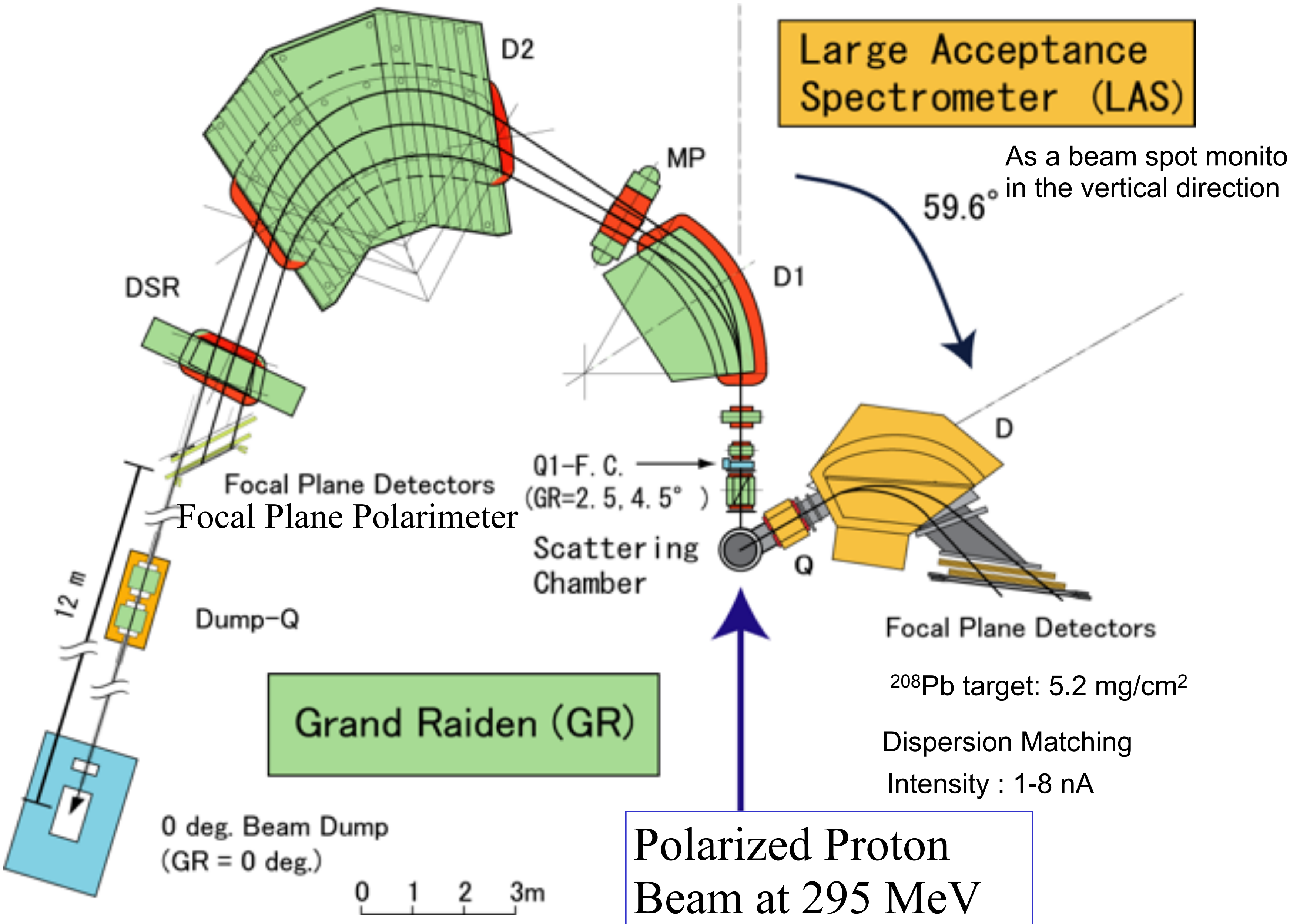
High-resolution Spectrometer

Grand Raiden

High-resolution WS beam-line (dispersion matching)

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

AT et al., NIMA605, 326 (2009)

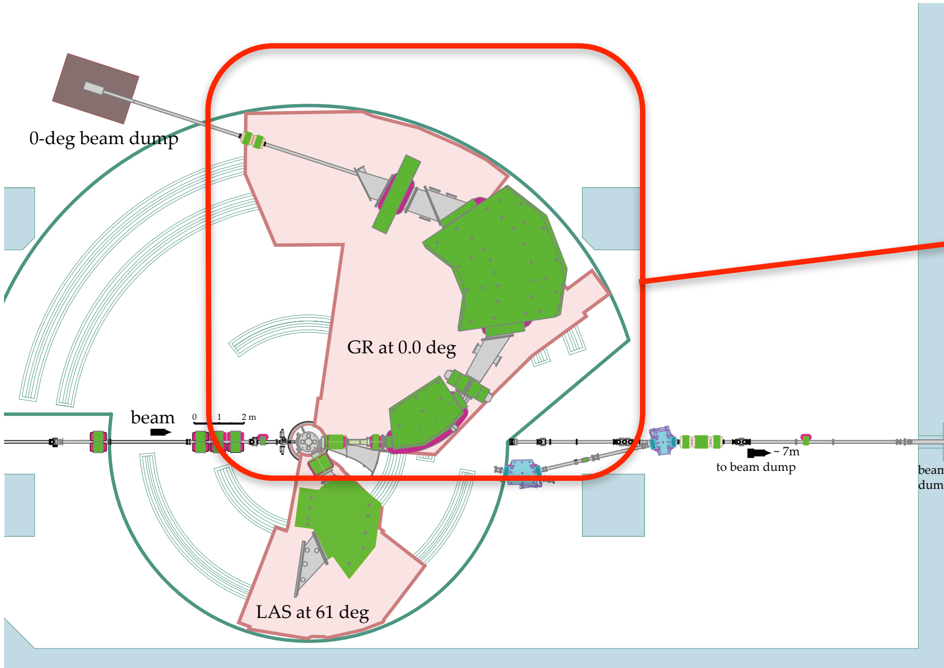


^{208}Pb target: 5.2 mg/cm^2

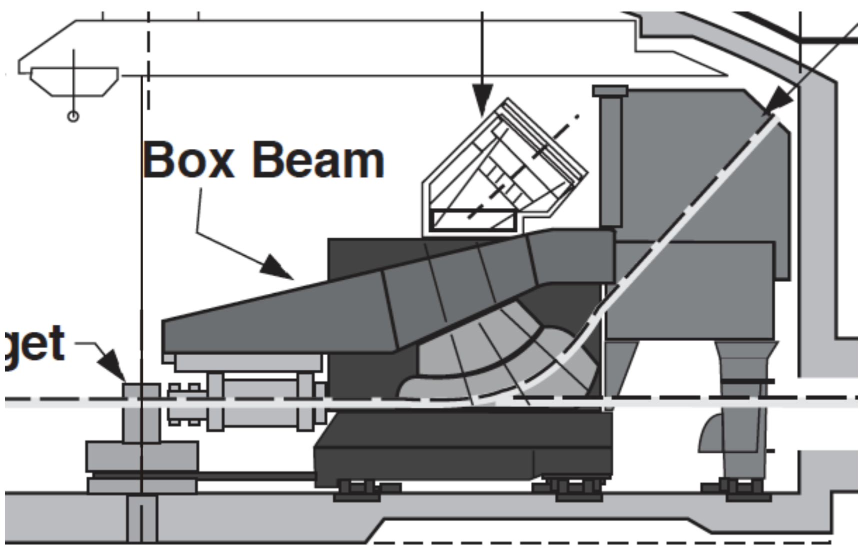
Dispersion Matching

Intensity : 1-8 nA

High-Resolution Spectrometer Grand Raiden and HRS Scaled



Grand Raiden at RCNP
(Top View)

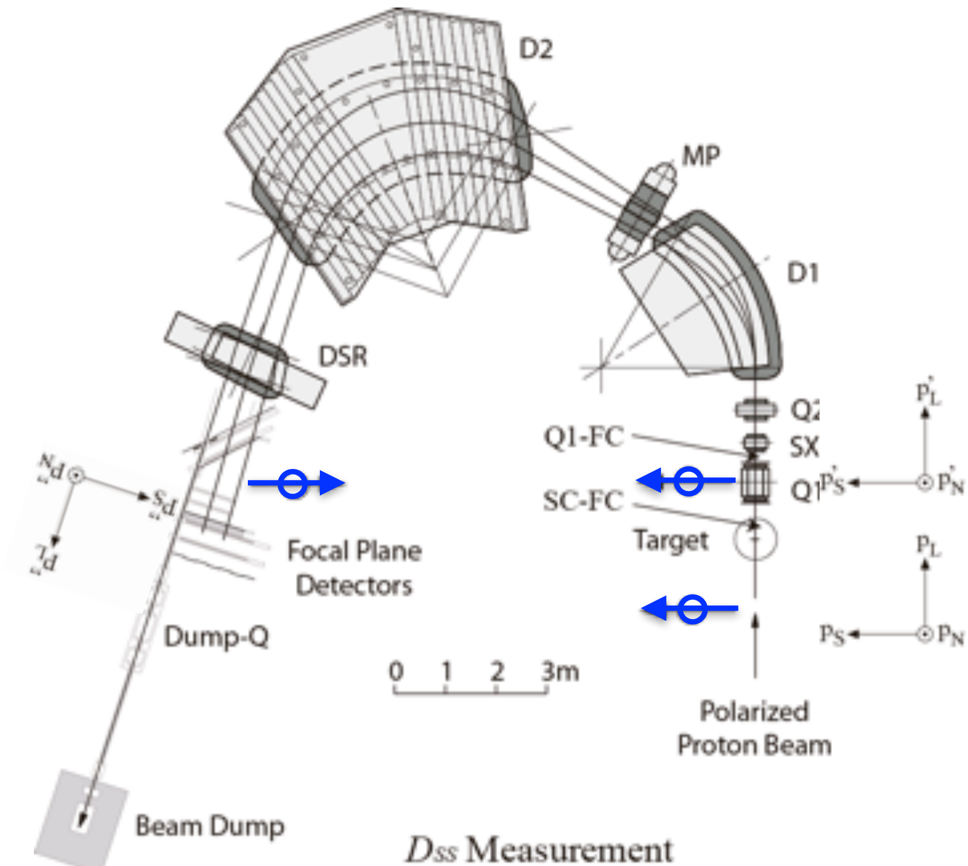


HRS at J-LAB Hall-A
(Side View)

Spin Precession in the Spectrometer

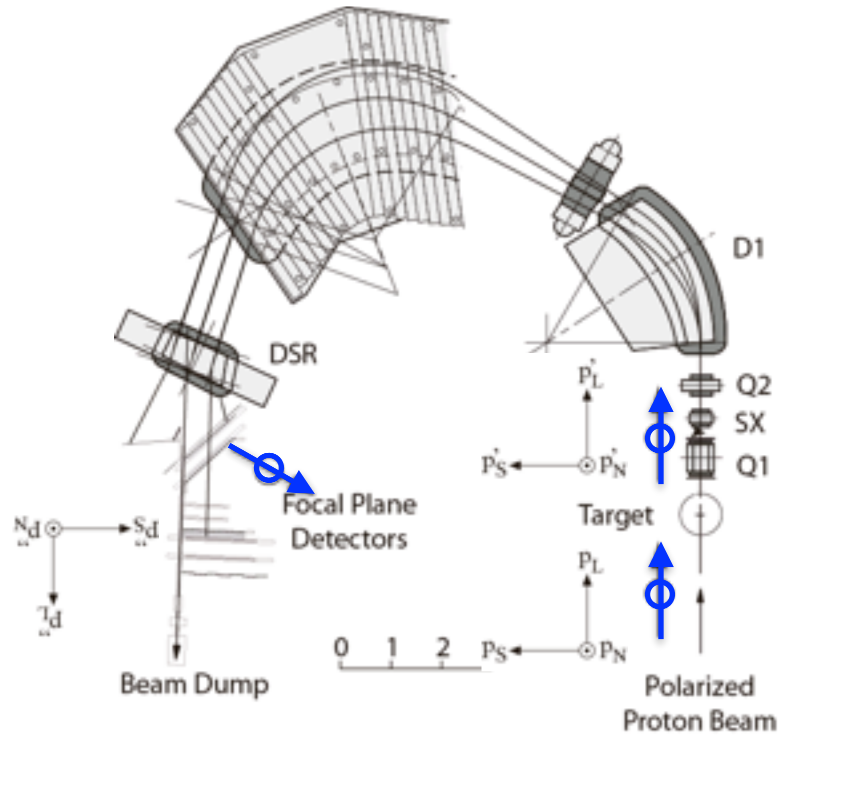
$$\theta_p = \gamma\left(\frac{g}{2} - 1\right)\theta_b$$

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

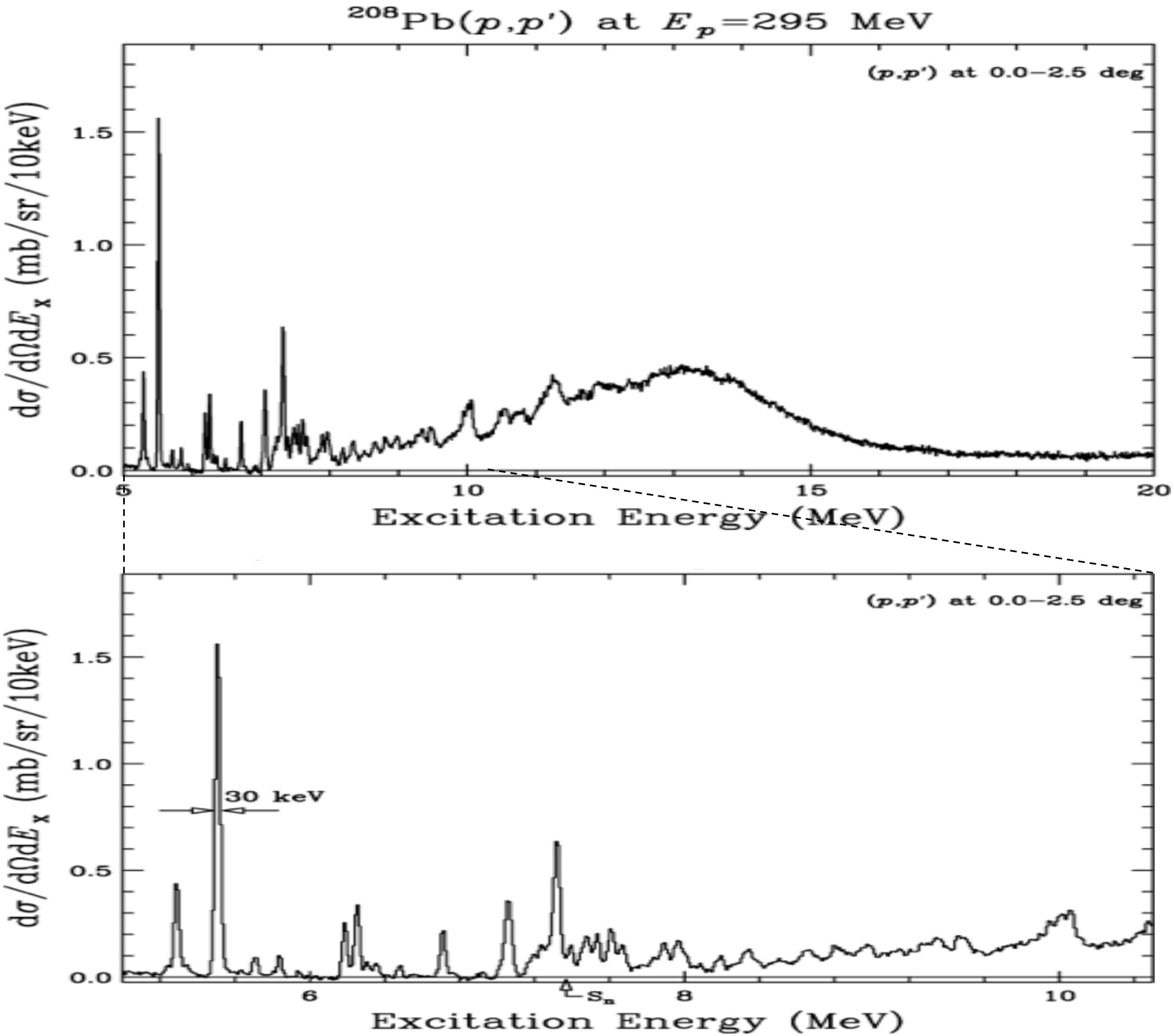
$\theta_b \cong 162°$



DLL Measurement

$\theta_b \cong 180°$

Setup for E282&E316



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

B(E1): continuum and GDR region

Method 2: Decomposition by Spin Observables

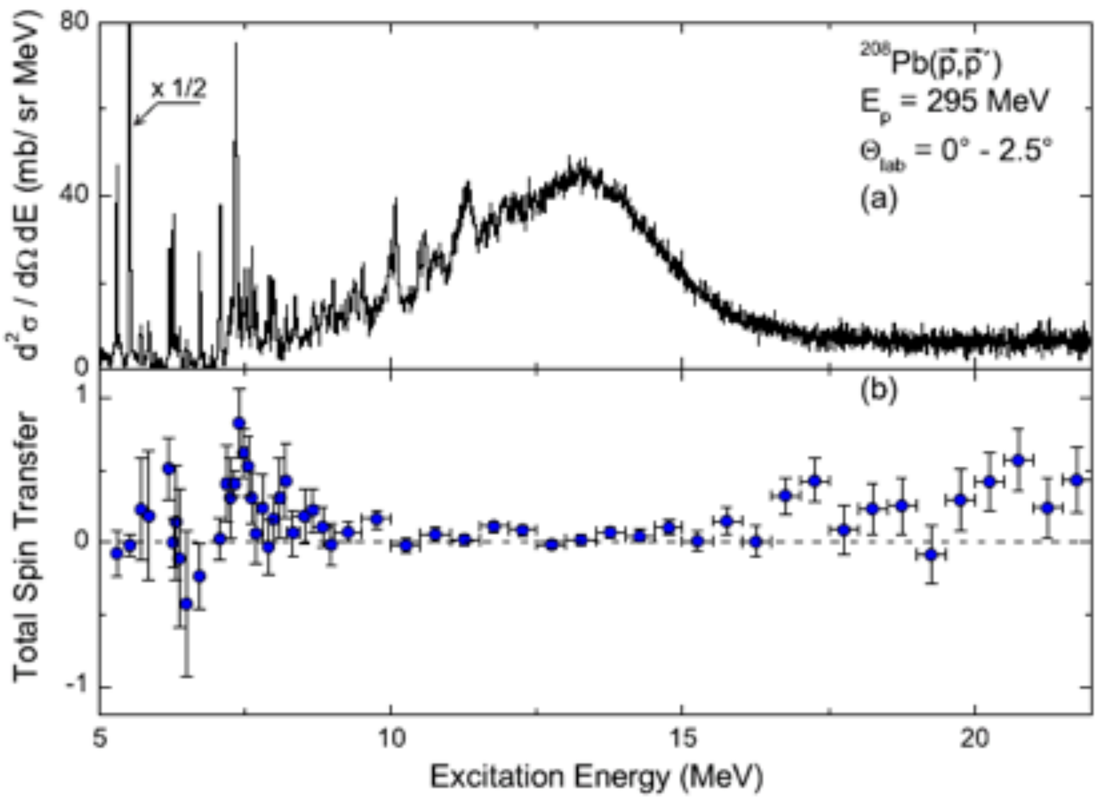
- Polarization observables at 0° → spinflip / non-spinflip separation

  model-independent

  E1 / spin-M1 decomposition

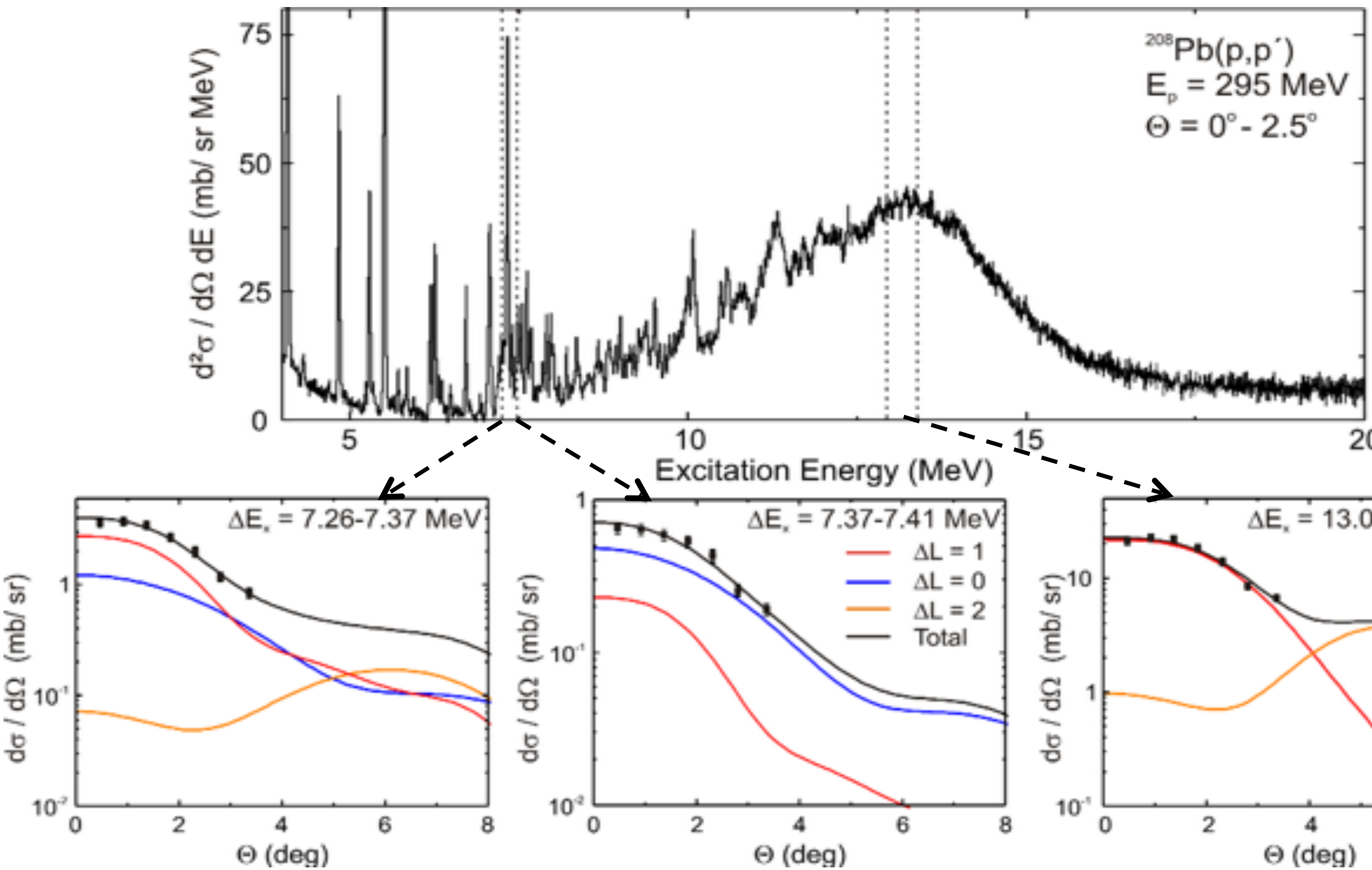
  T. Suzuki, PTP 103 (2000) 859

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



B(E1): continuum and GDR region

Method 1: Multipole Decomposition

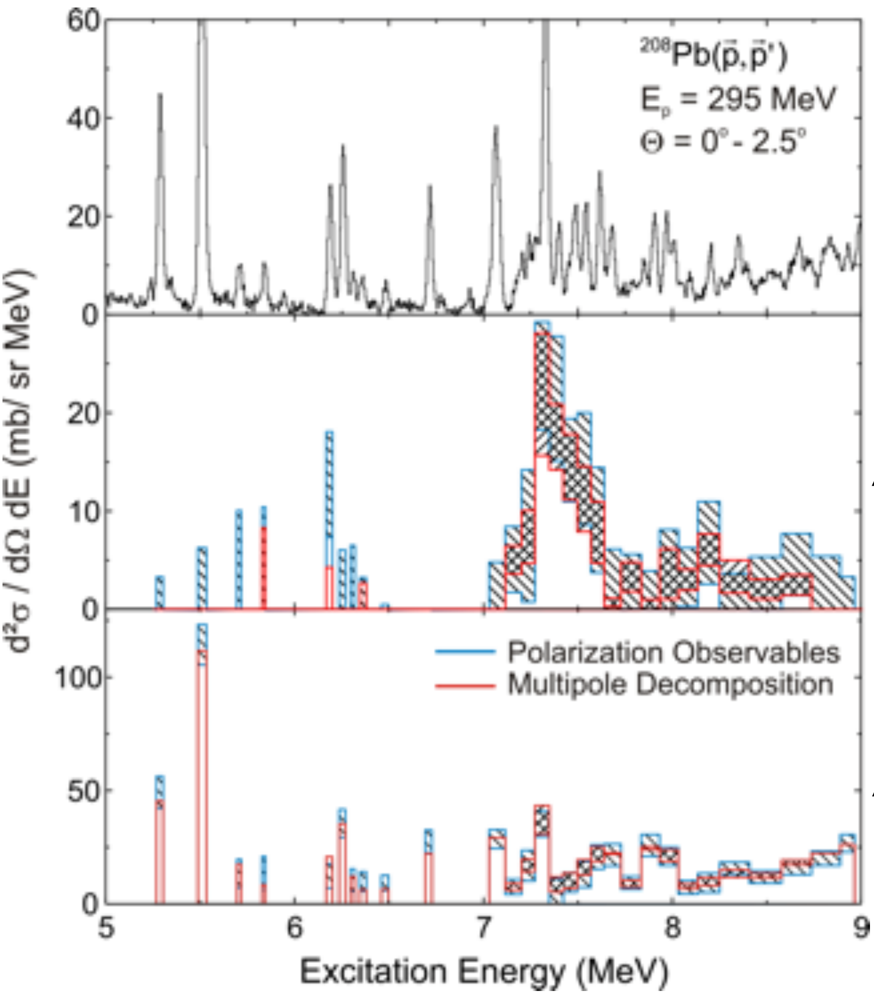


- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

Comparison between the two methods

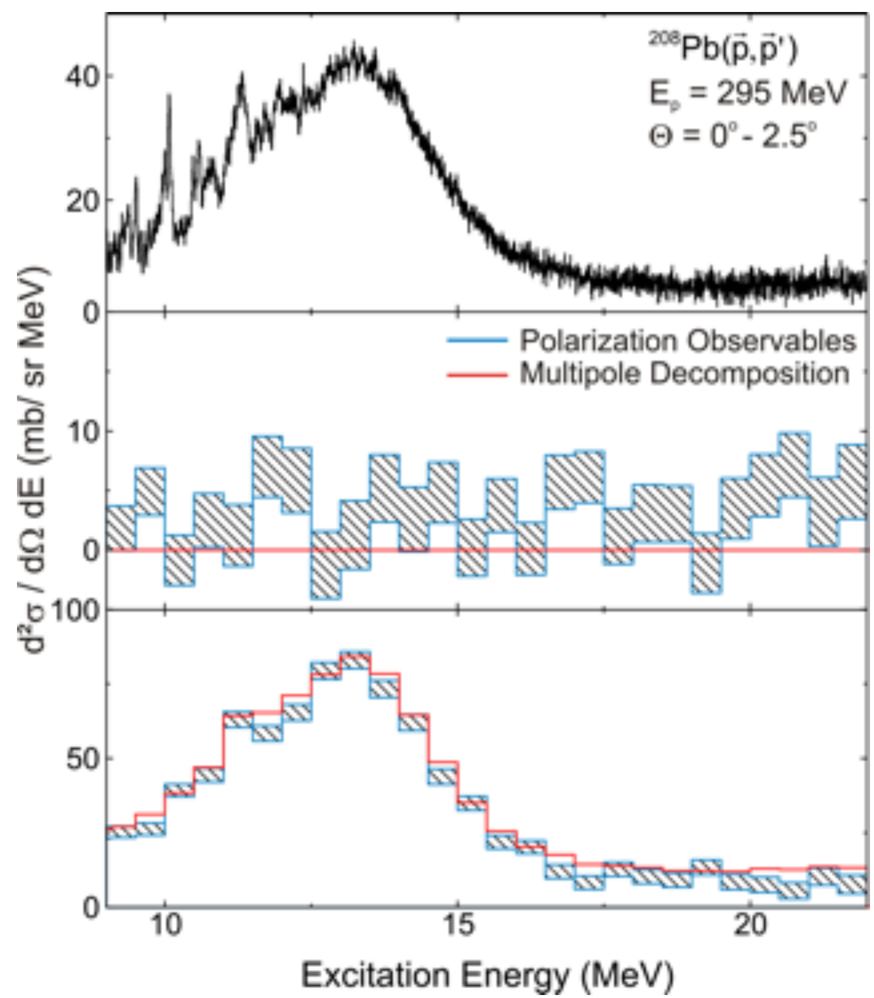
for the decomposition of E1 and spin-M1



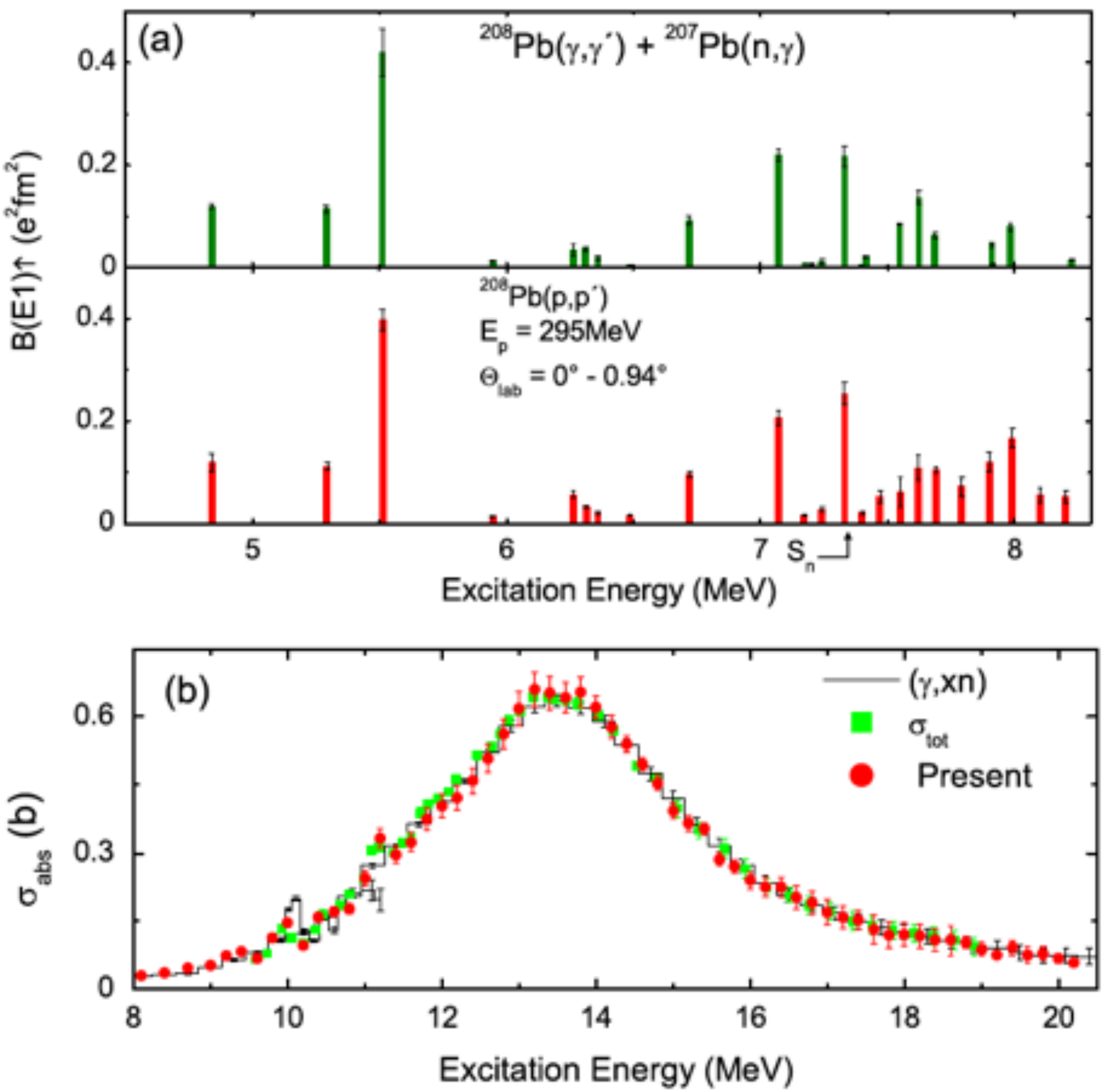
Total

ΔS = 1

ΔS = 0



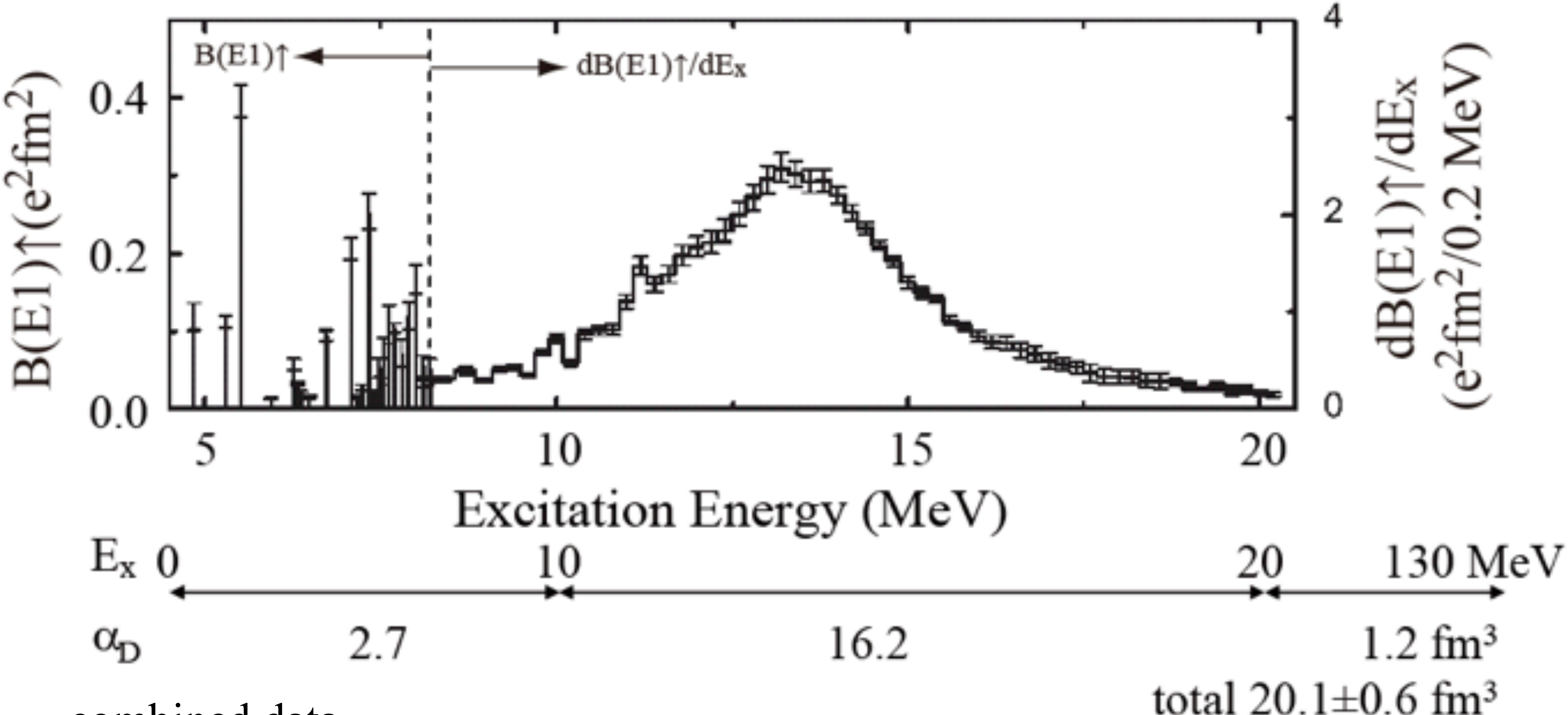
Comparison with (γ,γ’) and (γ,xn)



low-lying discrete states

GDR region

E1 Response of ^{208}Pb and α_D

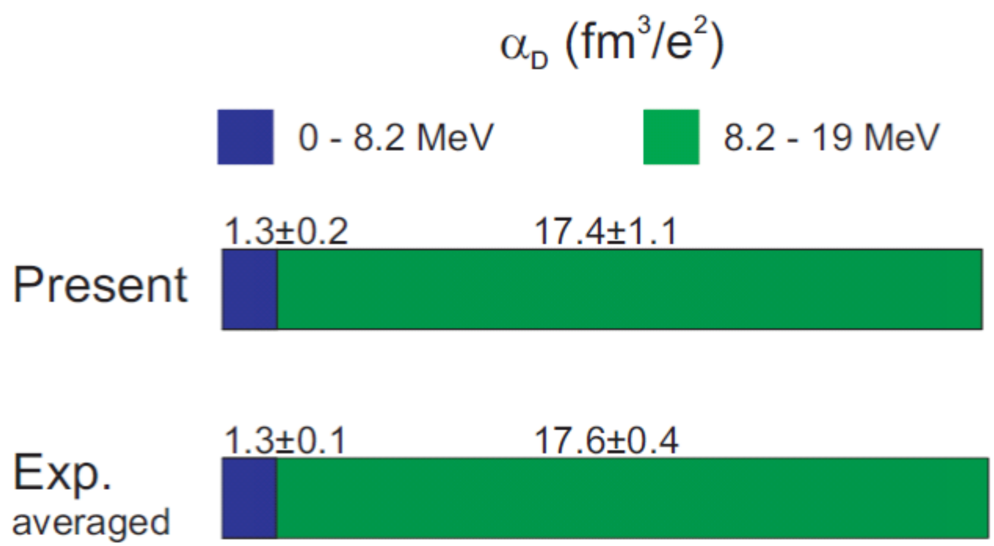


combined data

The full dipole response of ^{208}Pb has been determined.

AT et al., PRL107, 062502(2011)

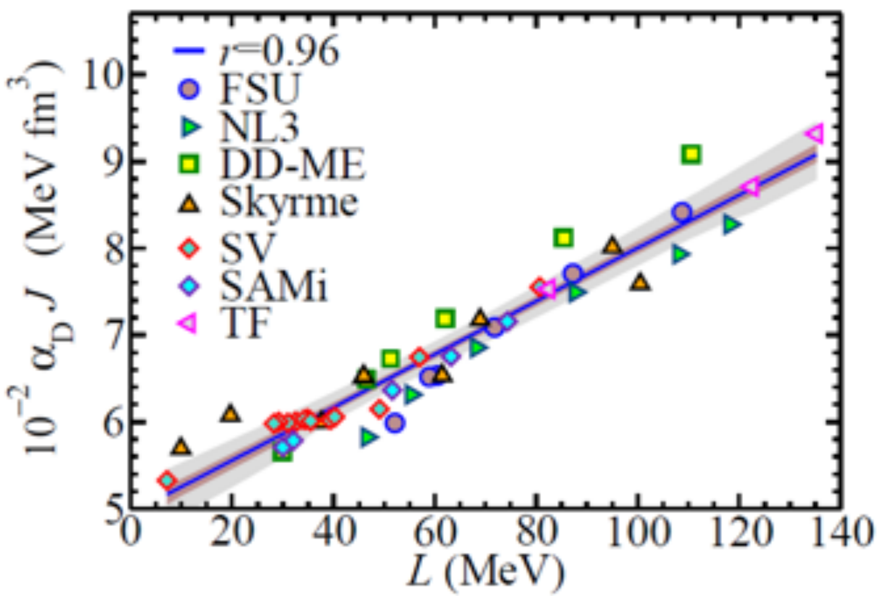
E1 Response of ^{208}Pb and α_D



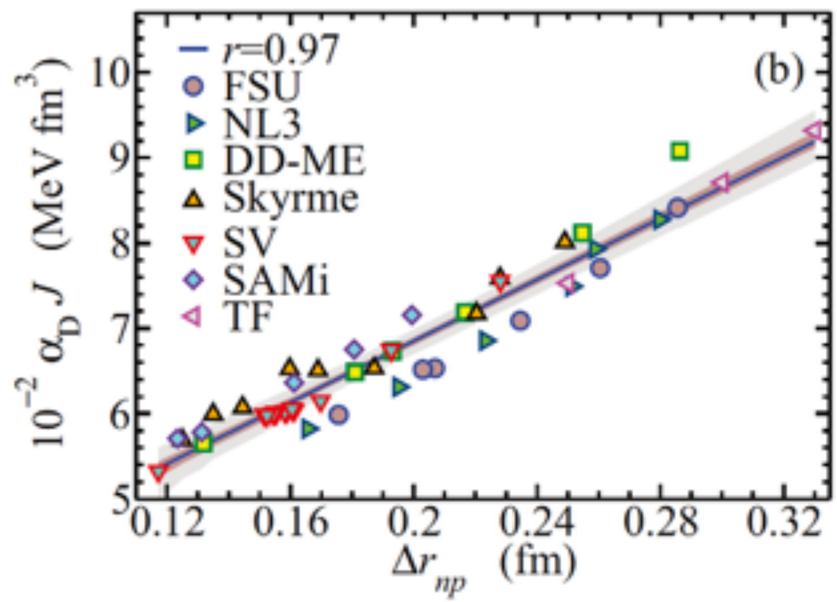
Constraints

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

Symmetry Energy Parameters



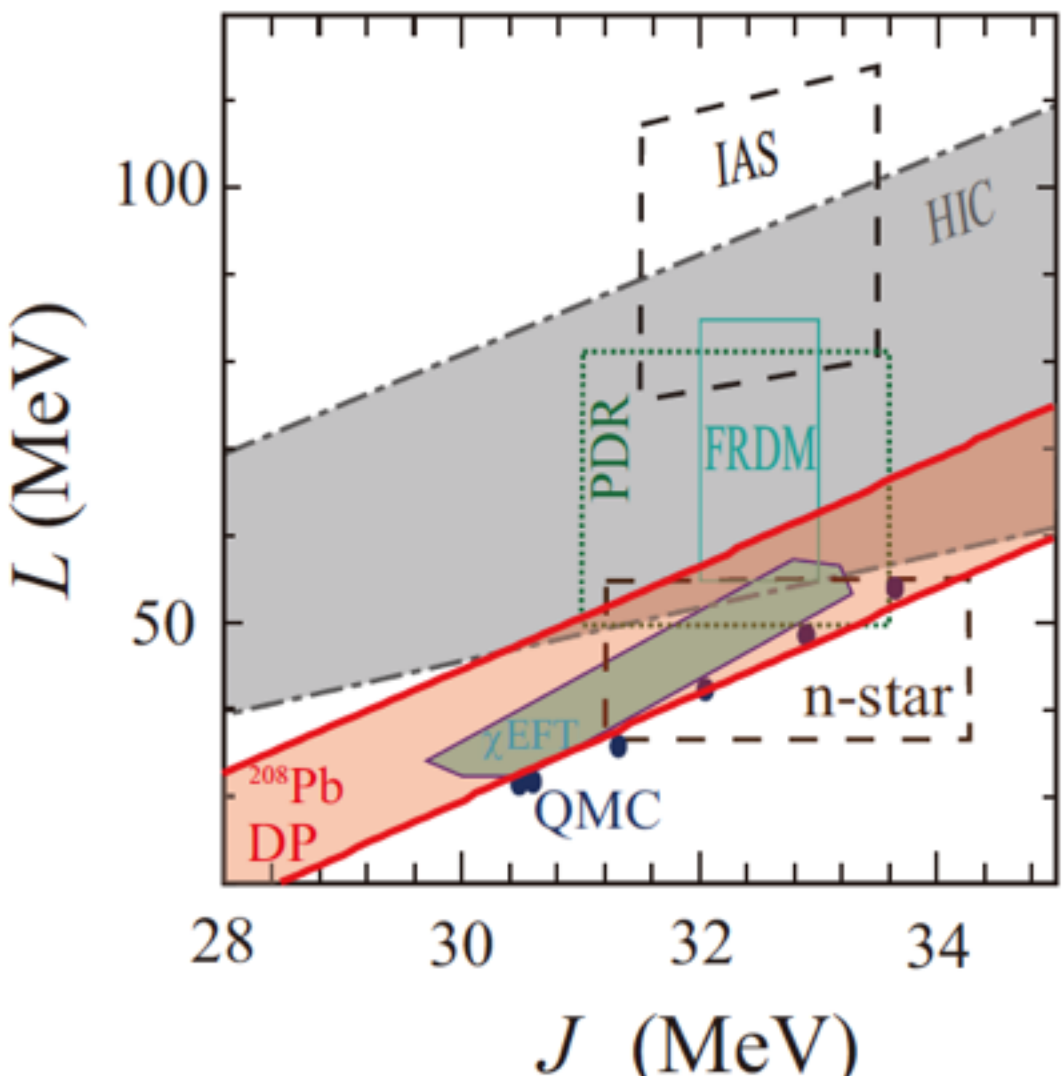
Neutron Skin Thickness



Experimental Value = α_D

→ Constraint in the *J*-*L* plane

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)

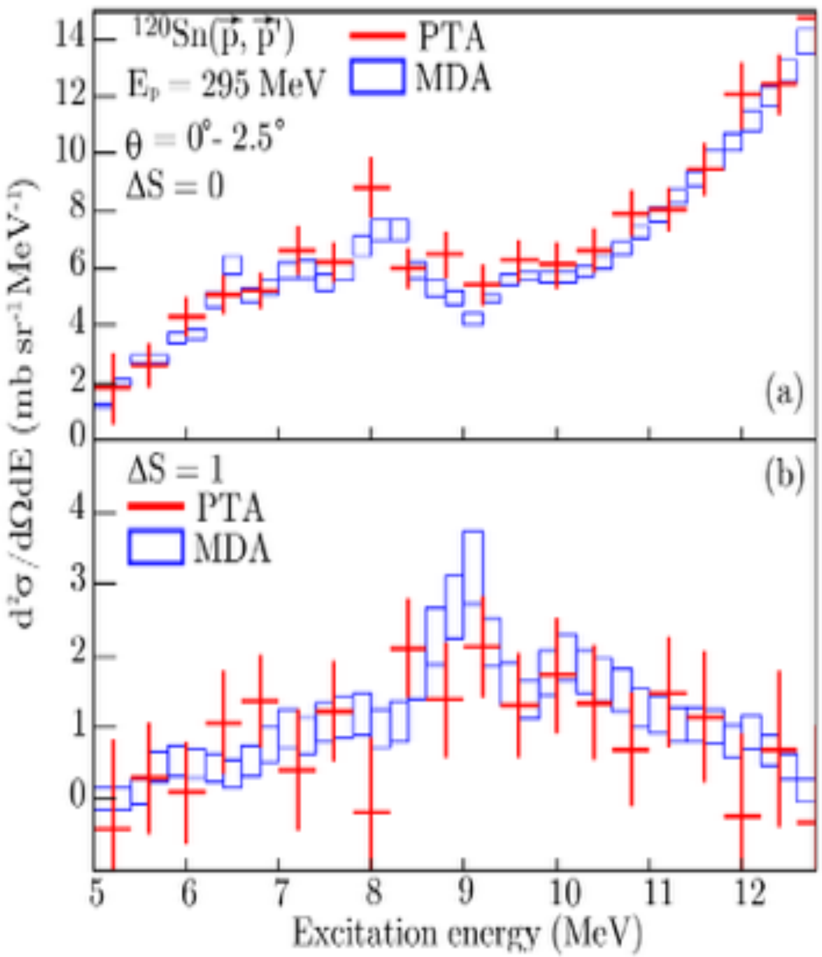
DP: Dipole Polarizability
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

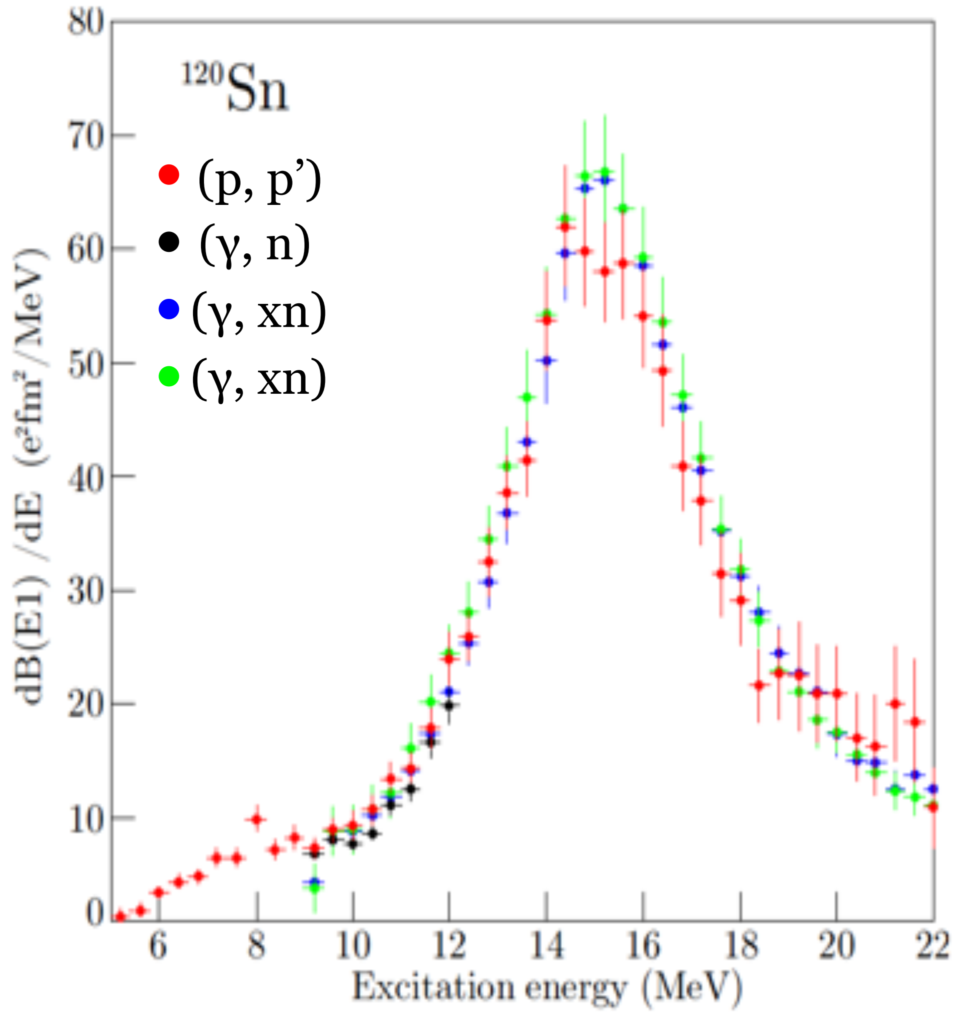
QMC: S. Gandolfi, EPJA50, 10(2014).

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

Dipole Polarizability of ^{120}Sn

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

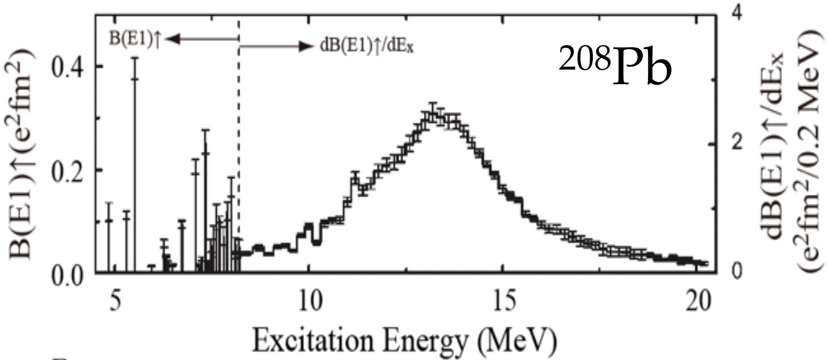




Dipole Polarizability of ^{120}Sn and ^{208}Pb

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

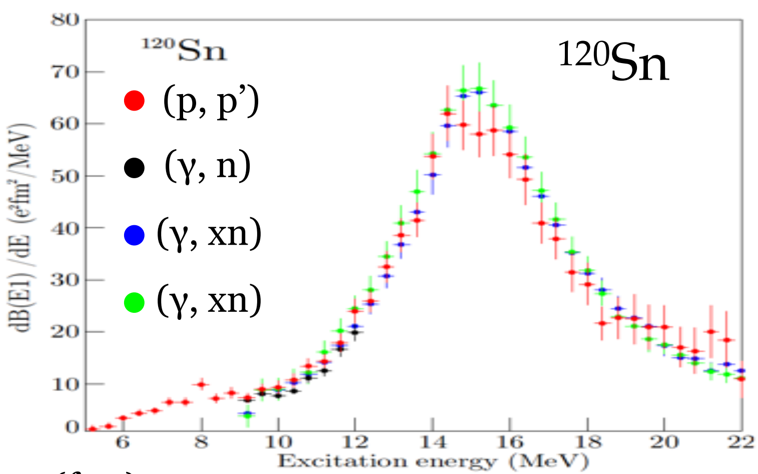
calc. by P.-G. Reinhard



E_x: 0 — 10 — 20 — 130 MeV

α_D: 2.7 | 16.2 | 1.2 fm^3

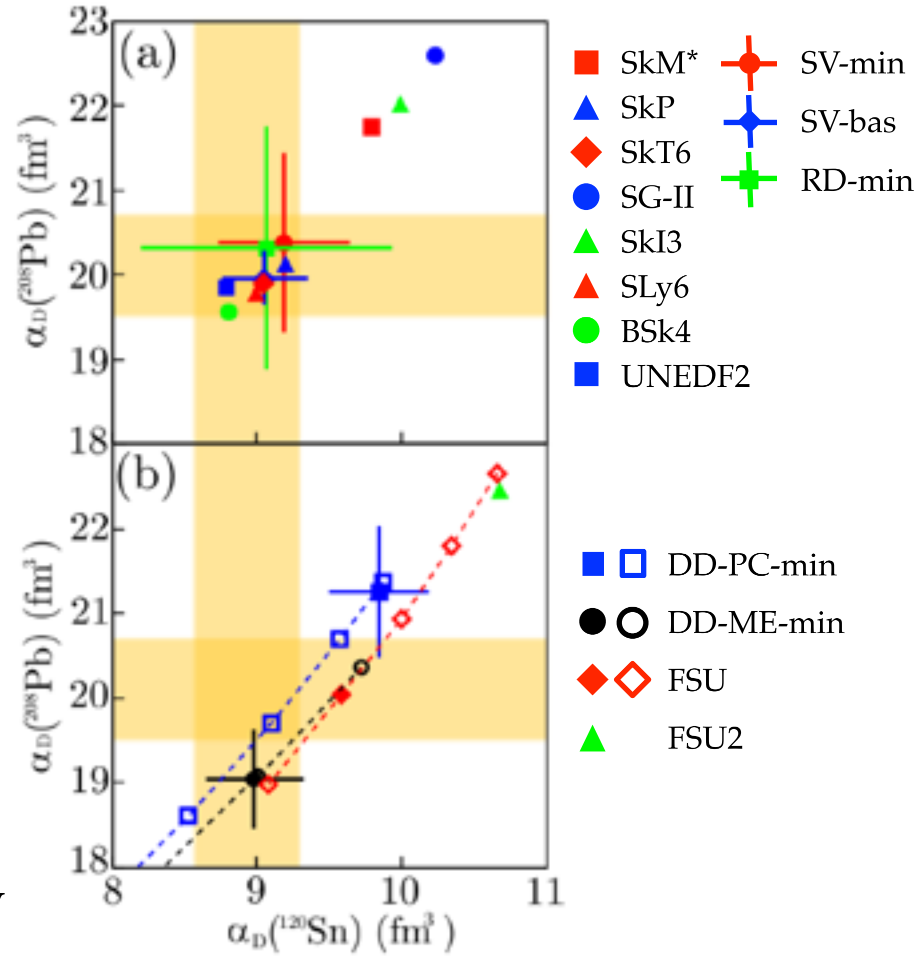
Total: $\alpha_D = 20.1 \pm 0.6$ fm^3



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



Quasi-Deuteron Excitation Contribution

Photon absorption by a virtual deuteron in the nucleus

Needs to be subtracted for comparison with EDF calculations.

^{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

~2.5%

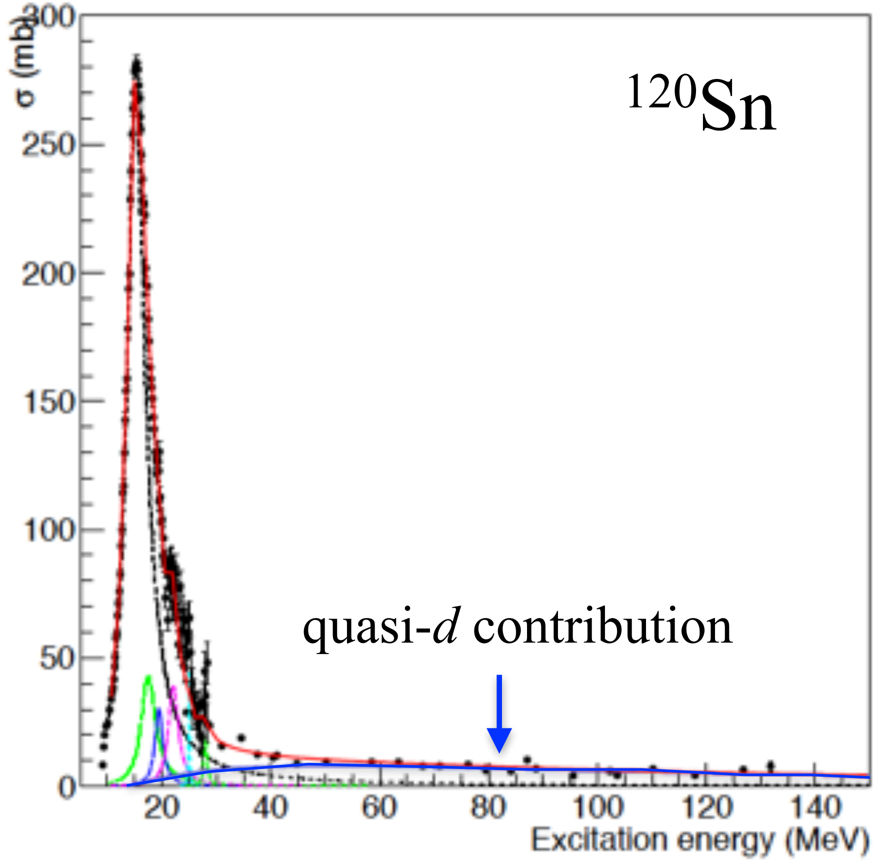
^{120}Sn

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

quasi-*d*: 0.34 ± 0.08 fm^3

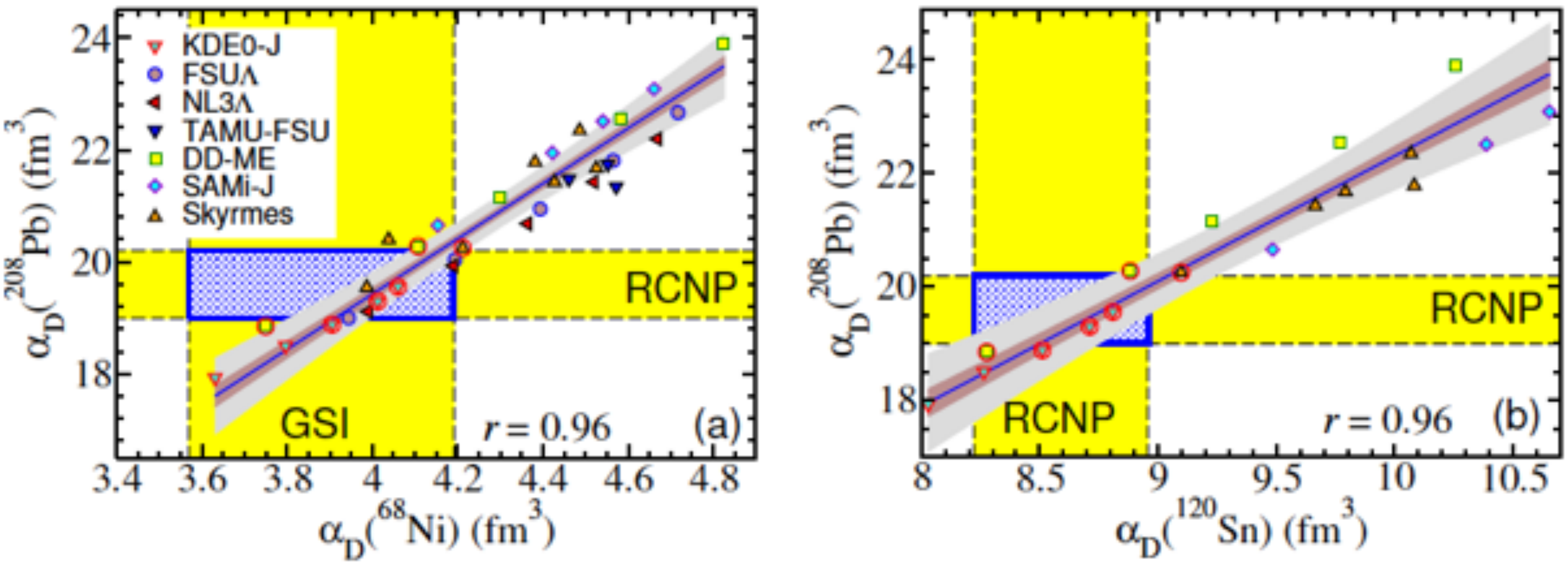
w/o quasi-*d*: 8.59 ± 0.37 fm^3

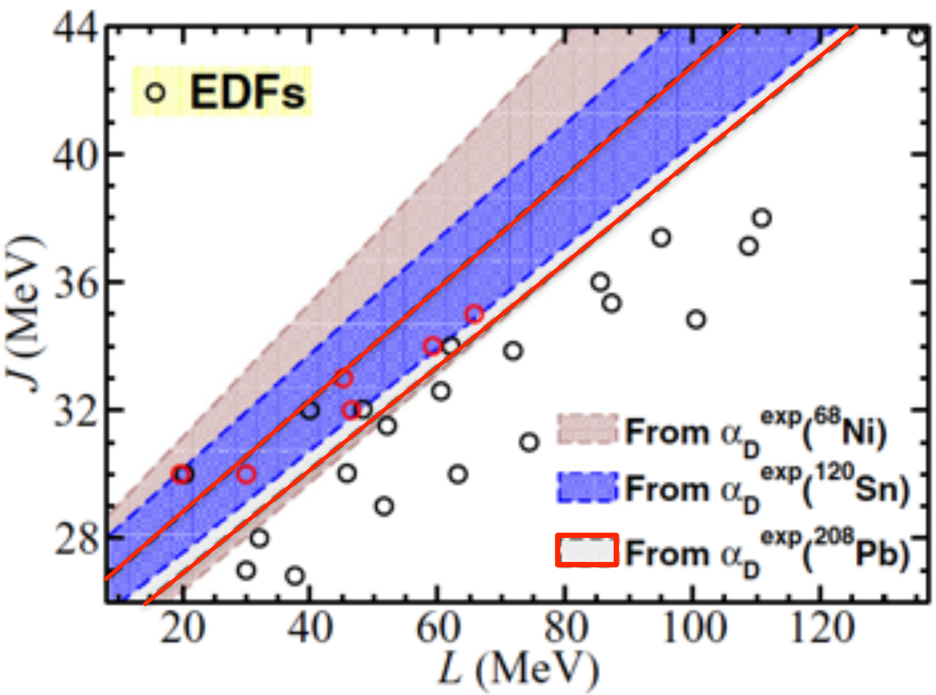
~4%



Constraints on J-L and n-skin thickness from DP Data

X. Roca-Maza et al., PRC92, 064304(2015)





Talk by Roca-Maza

Data

^{208}Pb: AT *et al.*, PRL**107**, 062502 (2011).
RCNP

^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).
RCNP

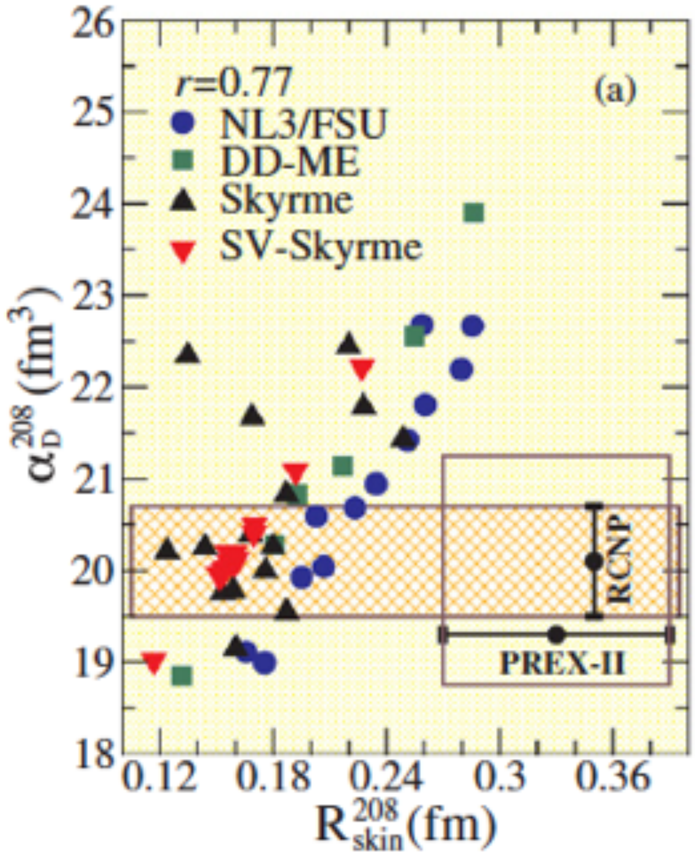
^{68}Ni: D.M. Rossi *et al.*, PRL**111**, 242503 (2013).
GSI

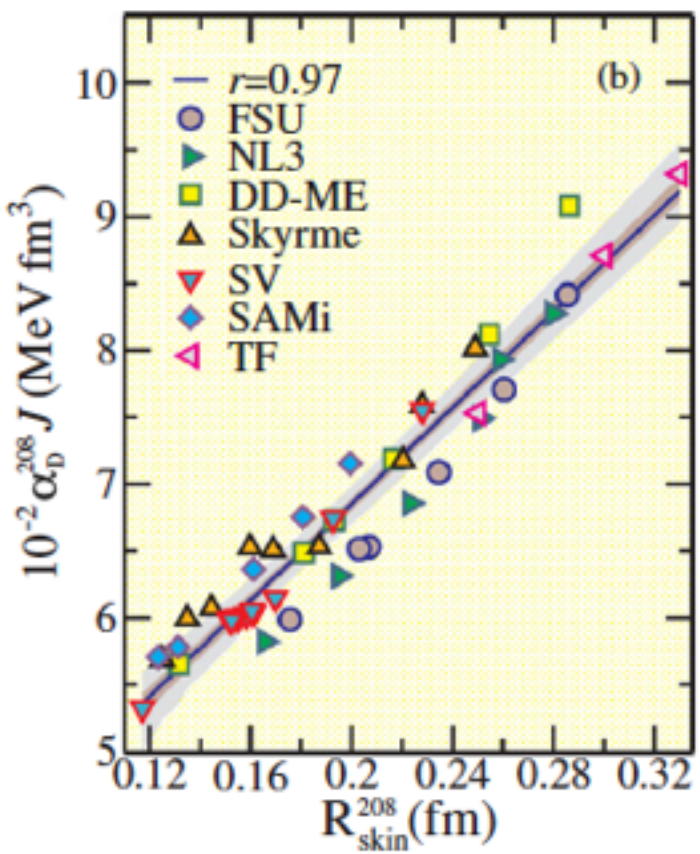
Talk by T. Aumann

Nucleus	Δr_{np} (a)	Δr_{np} (b)	Δr_{np} (c)
^{68}Ni	0.15–0.19	0.18 ± 0.01	0.16 ± 0.04
^{120}Sn	0.12–0.16	0.14 ± 0.02	0.12 ± 0.04
^{208}Pb	0.13–0.19	0.16 ± 0.02	0.16 ± 0.03

Neutron Skin Thickness of ^{208}Pb

J. Piekarewicz et al., PRC85, 041302(R) (2012)
C.J. Horowitz et al., JPG41, 093001 (2014)





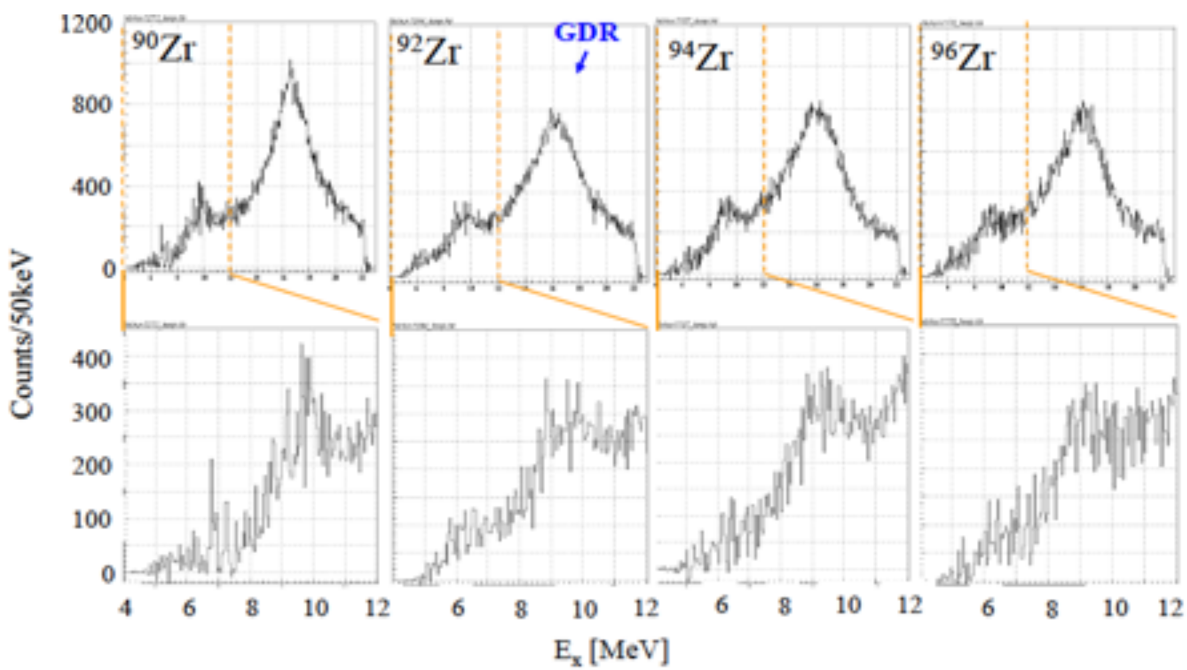
The DP data give **a constraint on the symmetry energy** that is complementary information with neutron skin thickness measurements.

If J (S_0) is determined from other data, the ^{208}Pb DP gives a constant on the ^{208}Pb neutron skin thickness.

Plans in Near Future

- Result on ^{48}Ca (talk by P. von Neumann-Cosel)
- ^{112}Sn, ^{124}Sn and on ^{92}Zr, ^{94}Zr, ^{96}Zr, have been measured in May-June, 2015.
- Data analysis on ^{90}Zr, ^{96}Mo, and ^{154}Sm

Zr isotopes:

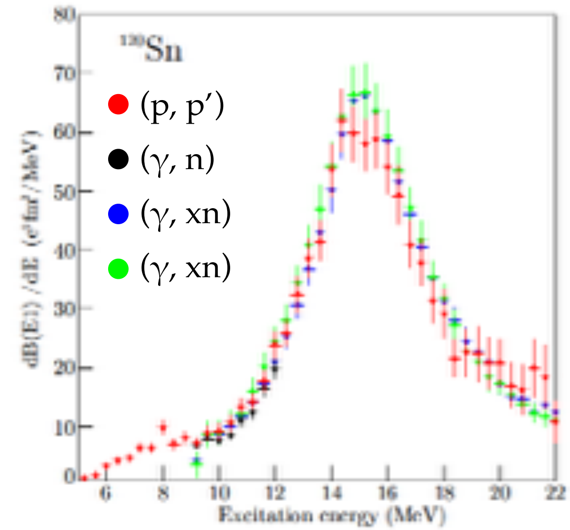


Summary

- The **electric dipole polarizability** (DP) is a well-defined observable which is **sensitive to the isovector property of the nuclear EOS**.

- **Proton inelastic scattering** at very forward angles is an **electromagnetic probe** which is suitable for the study of the **full electric dipole response** of nuclei.

  Measured: ^{208}Pb and ^{120}Sn:



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

- **Theoretical models are indispensable** for extracting a constraint on the EOS from the measured DPs.

- The DP data give **a constraint on the symmetry energy** that is complementary information with neutron skin thickness measurements.
  If J (S_0) is determined from other data, the ^{208}Pb DP data give a constant on the ^{208}Pb neutron skin thickness.

^{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

Thank you