Electric Dipole Response of Nuclei Studied by Proton Inelastic Scattering

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

photos
in Osaka U.
2015.10.31

High Resolution Spectroscopy and Tensor Interactions
November 16-19, 2015
at Nakanoshima Center, Osaka University

1. <u>Electric Dipole Responses</u>

RCNP, TU-Darmstadt, Konan, …

AT et al., PRL**107**, 062502 (2011)
C. Iwamoto et al., PRL**108**, 262501 (2012)
I. Poltoratska et al., PRC**85**, 041304 (2012)
AT et al., EPJA**50**, 28 (2014)
A.M. Krumbholz et al., PLB**744**, 7 (2015)
T. Hashimoto *et al*., PRC**92**, 031305(R)(2015)

Symmetry Energy
Electric Dipole Polarizability
Neutron Skin
Pygmy Dipole Resonance

→ Zr Isotopes: Talk by C. Iwamoto

2. <u>Spin-M1 Responses</u>

RCNP, TU-Darmstadt, …

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

Quenching of IS/IV Spin-M1 Strengths

→ Talk by H. Matsubara

^{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

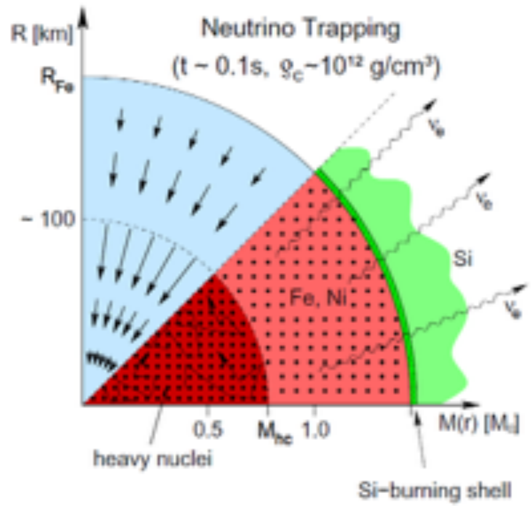
Dep. of Phys., Niigata University

Y. Shimbara

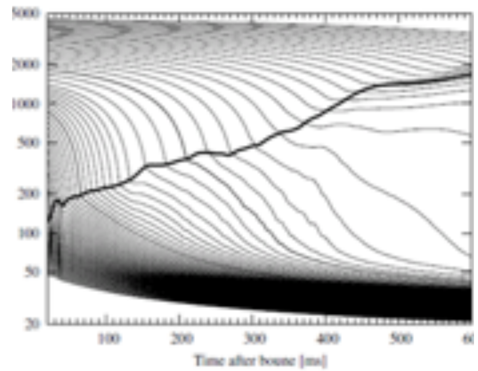
Symmetry Energy of Nuclear EOS

is important in nuclear physics and nuclear-astrophysics

Core-collapse supernova

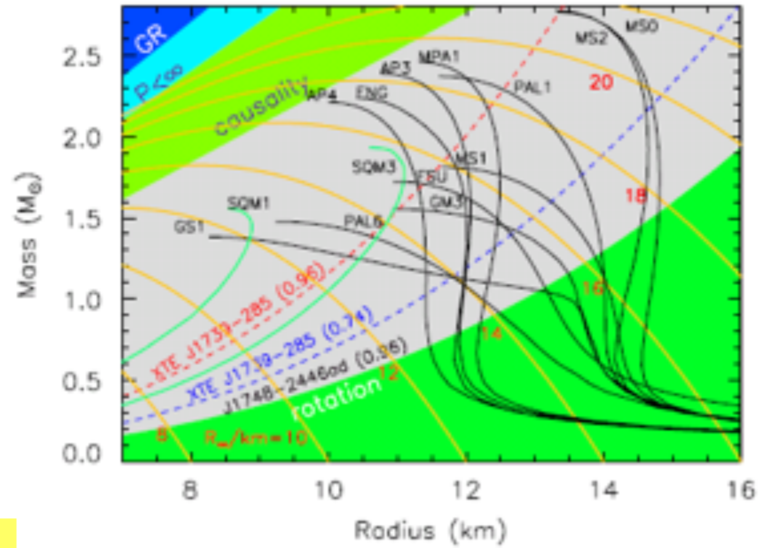


Langanke and Martinez-Pinedo



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

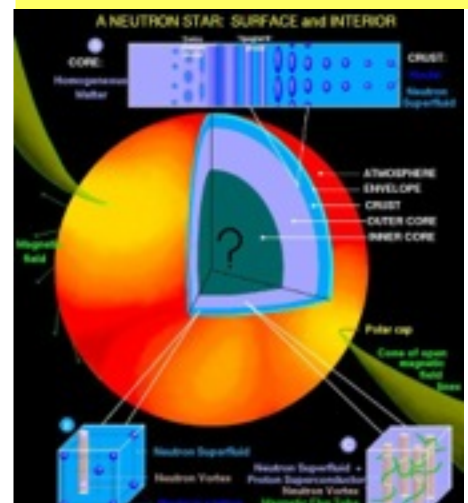
Neutron star mass vs radius



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

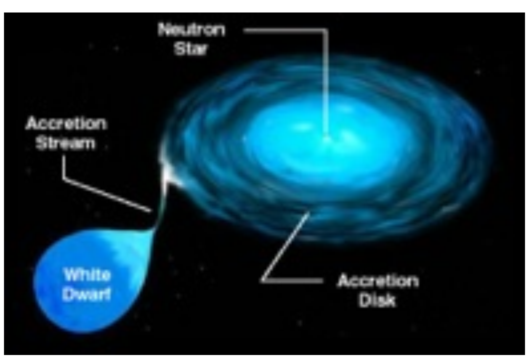
Nucleosynthesis

Neutron star structure

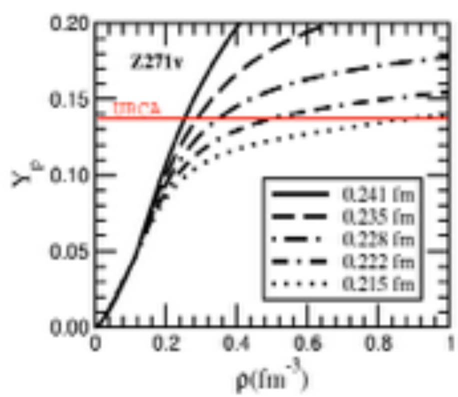


http://www.astro.umd.edu/~miller/nstar.html

Accreting neutron star X-ray burst



Neutron star cooling



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

Nuclear Equation of State (EOS)
at zero temperature

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

EOS for Energy per nucleon

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

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

Symmetry energy

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

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

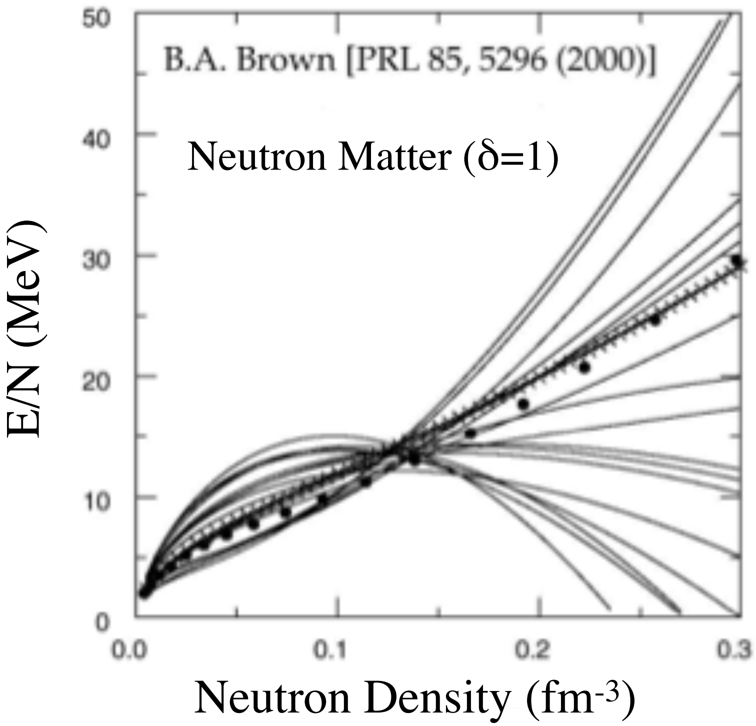
S: symmetry energy at the saturation density
L (slope parameter): density dependence

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

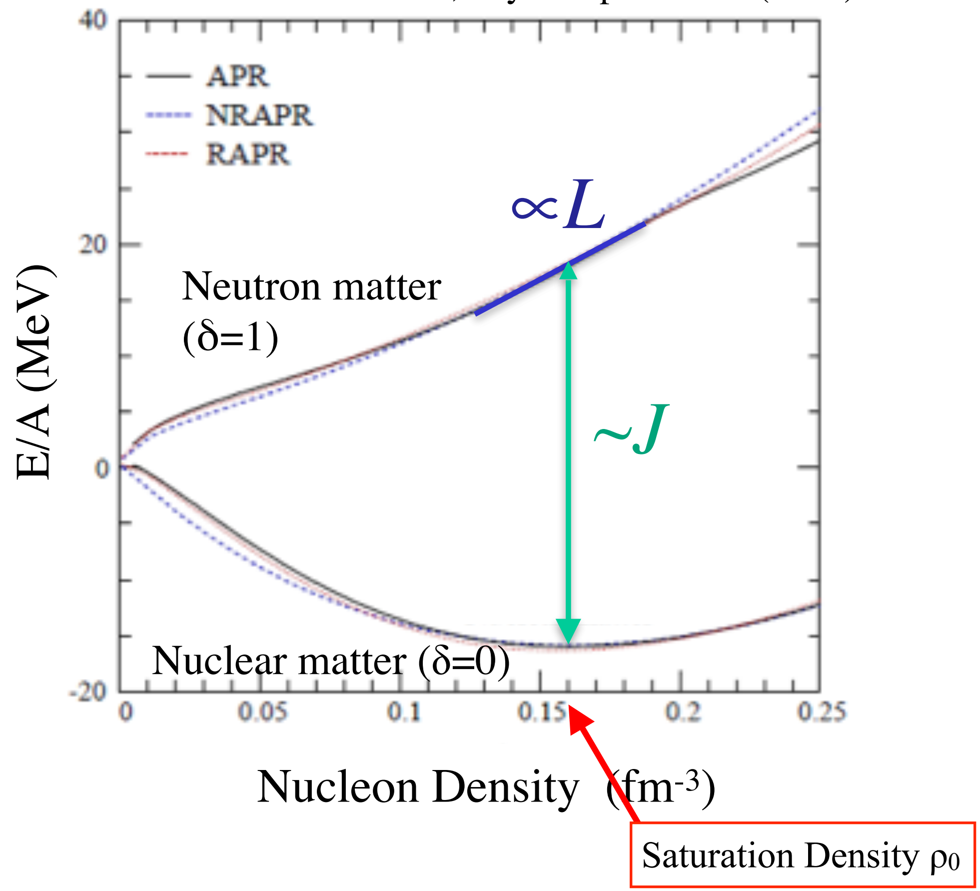
$$L \propto P \propto R^4_{\text{n-star}}$$

(Baryonic Pressure)

Nuclear Equation of State (EOS)



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



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

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

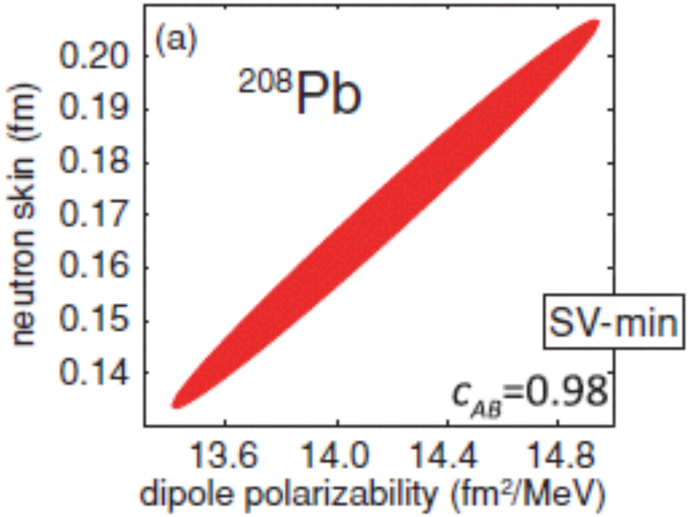
$$\rho(r)=\rho_n(r)+\rho_p(r)$$

$$\delta(r)=\frac{\delta_n(r)-\delta_p(r)}{\delta_n(r)+\delta_p(r)}$$

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

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).

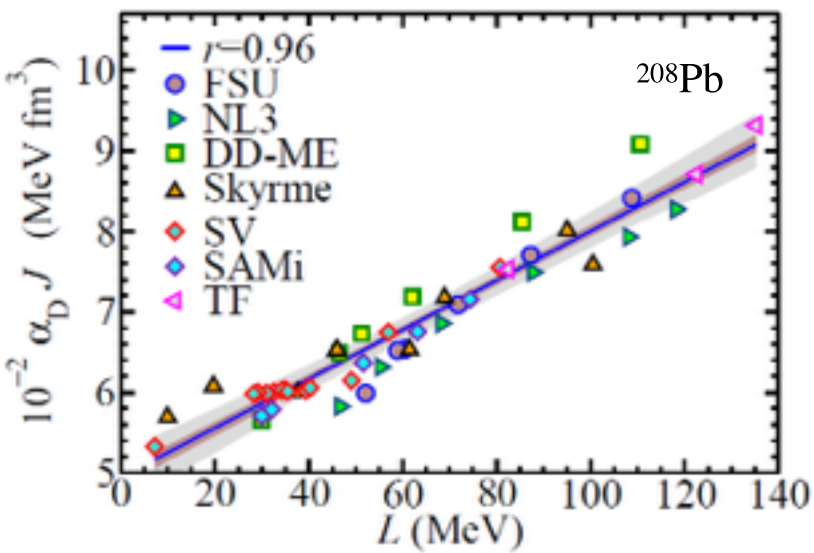


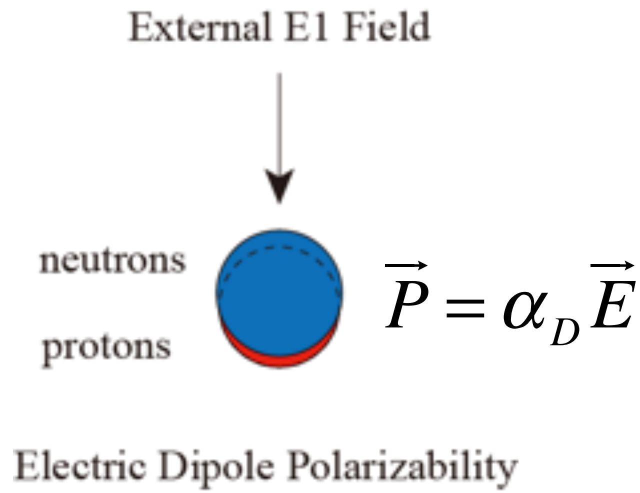
~L

(α_D)

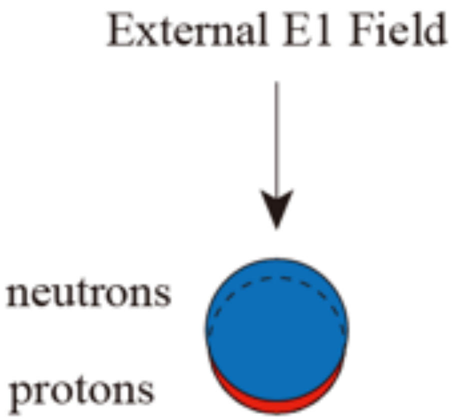
Strong correlation between the dipole polarizability and the neutron skin of ^{208}Pb

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

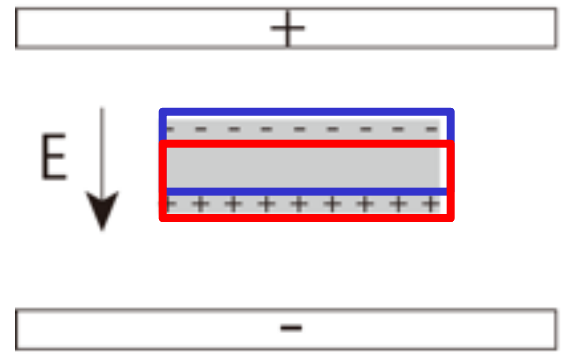




Electric Dipole Polarizability (α_D)



Electric Dipole Polarizability α_D



Electric Dipole Polarization

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

α: dipole polarizability of an atom

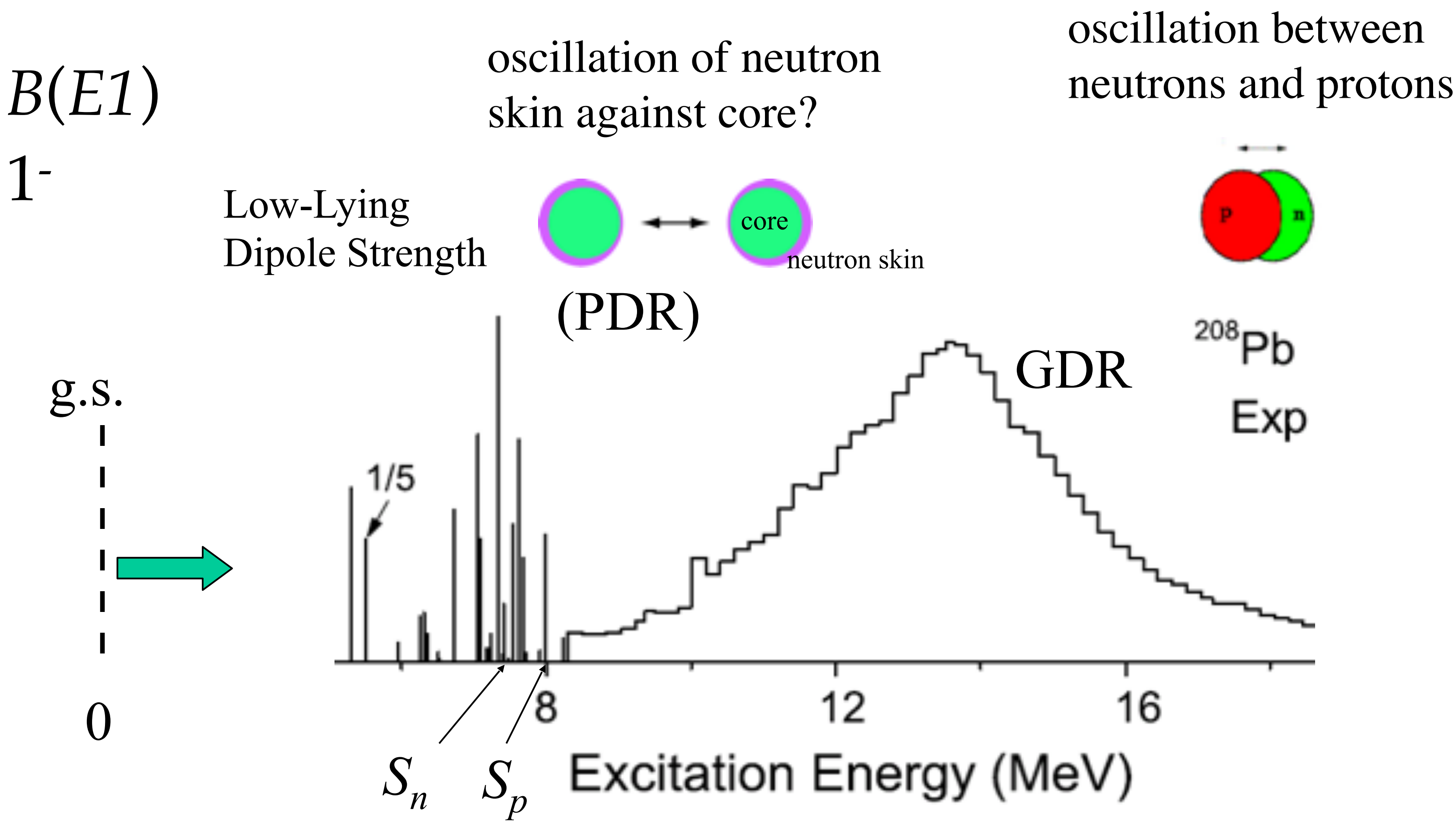
Restoring force ← symmetry energy

Inversely energy weighted sum-rule of B(E1)

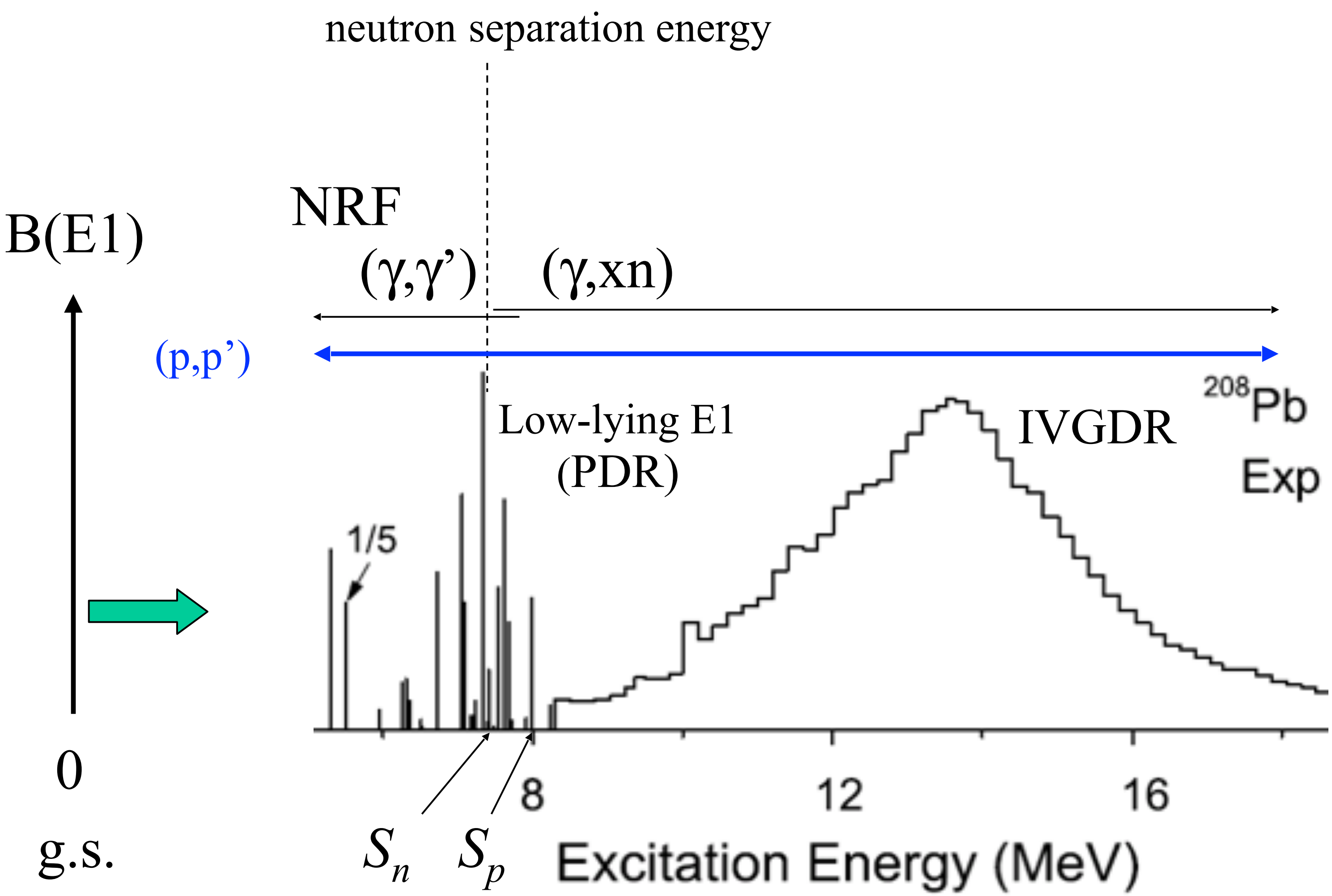
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{\text{abs}}^{E1}}{\omega^2} d\omega = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

→ Requires the $B(E1)$ distribution

Electric Dipole Response of Nuclei

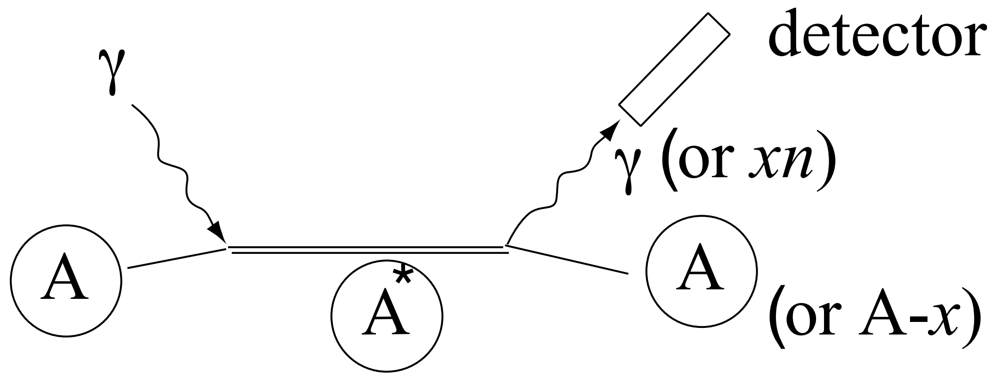


Electric Dipole Response of Nuclei



Probing the EM response of the target nucleus

Real Photon Measurements, NRF or (γ,xn)

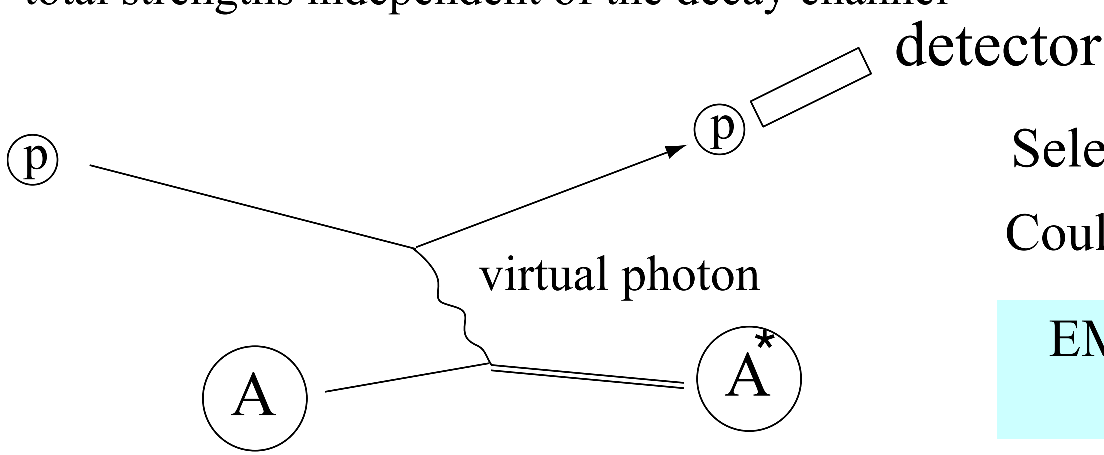


Decay γ or *n* is detected.

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.)

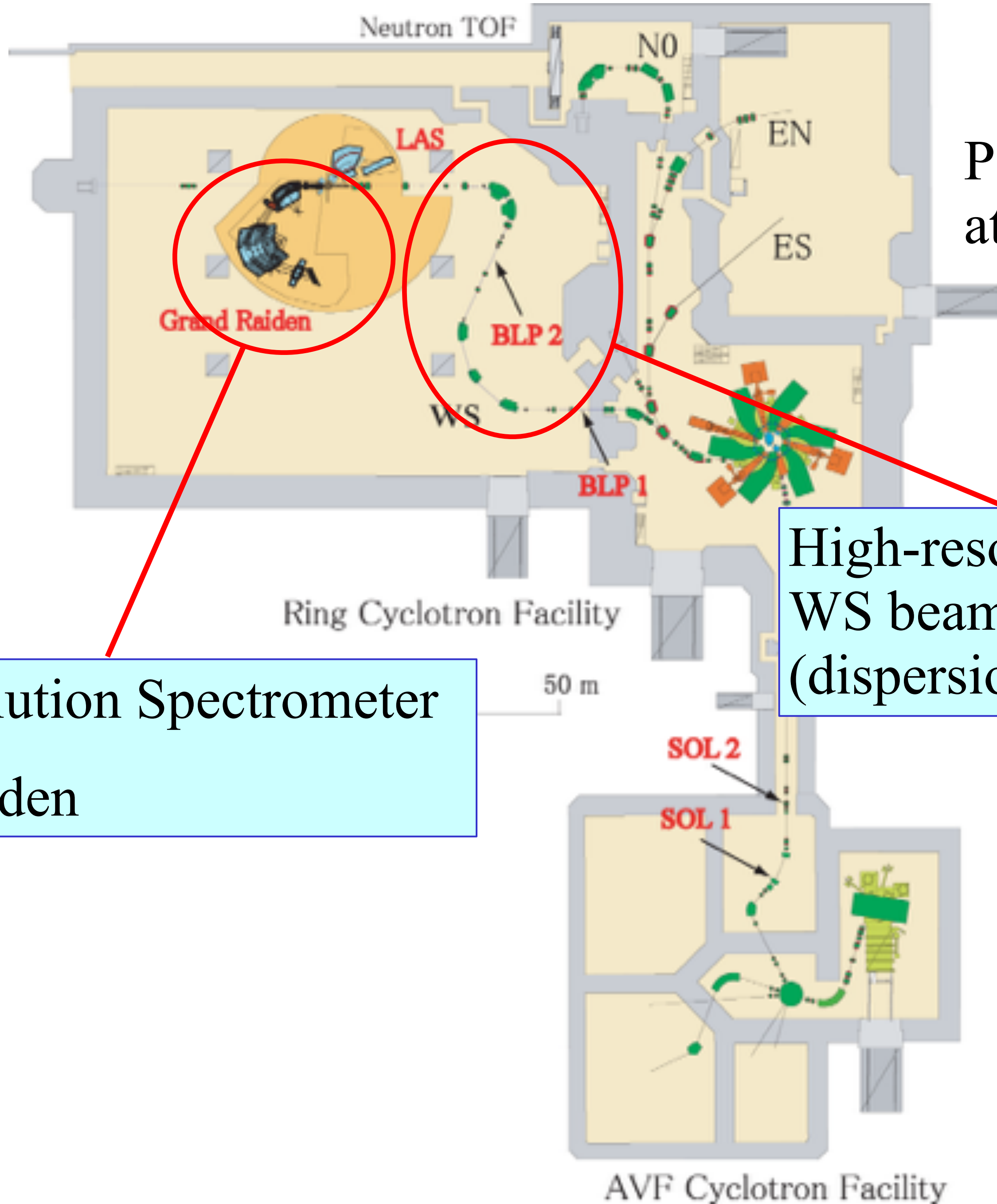
Coulomb excitation dominates

EM Interaction is well known
(model independent)

Experimental Method

High-resolution measurements of proton inelastic scattering at zero degrees and forward angles

Research Center for Nuclear Physics (RCNP), Osaka University



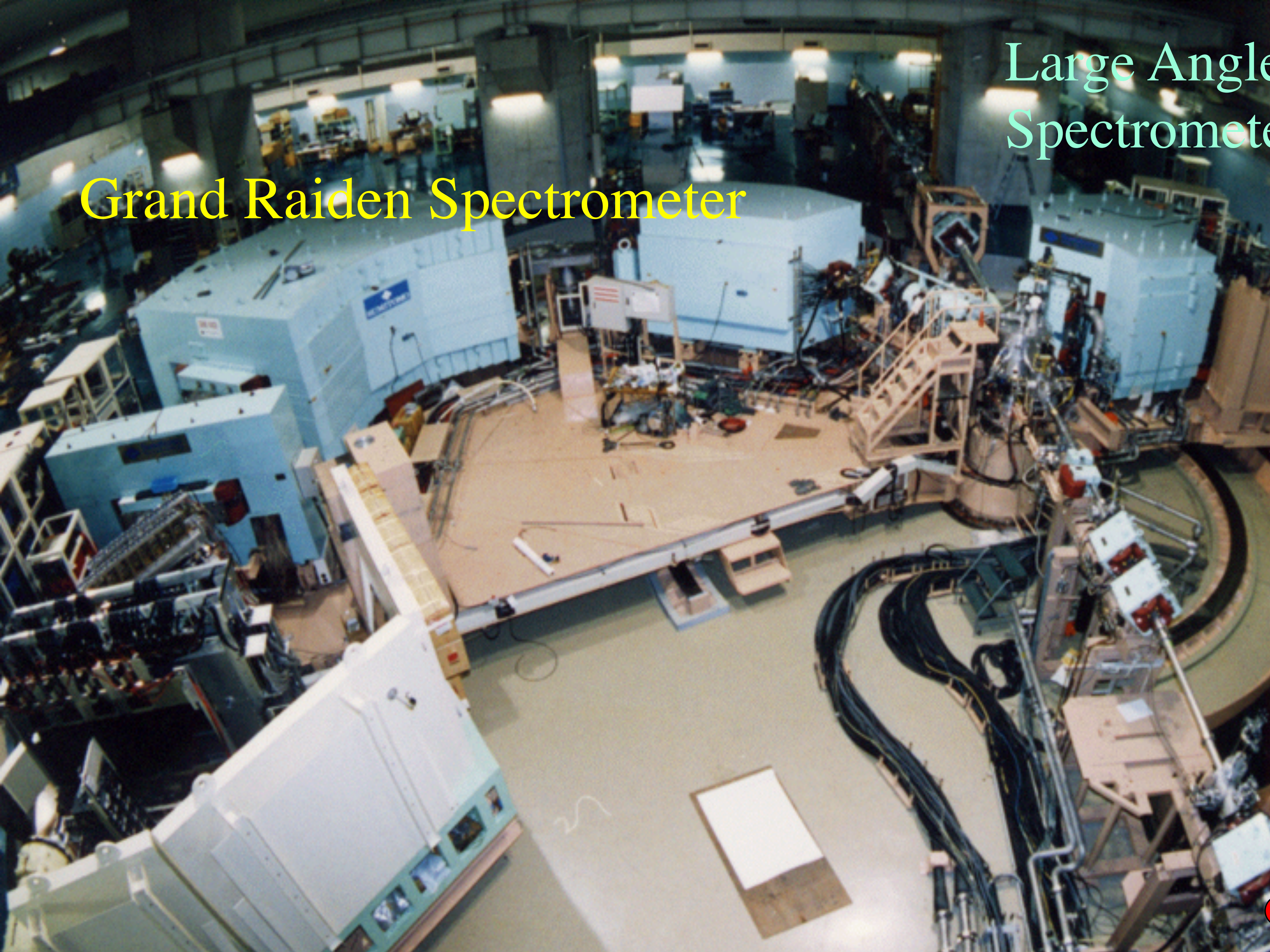
Polarized p beam at 295 MeV

High-resolution Spectrometer

Grand Raiden

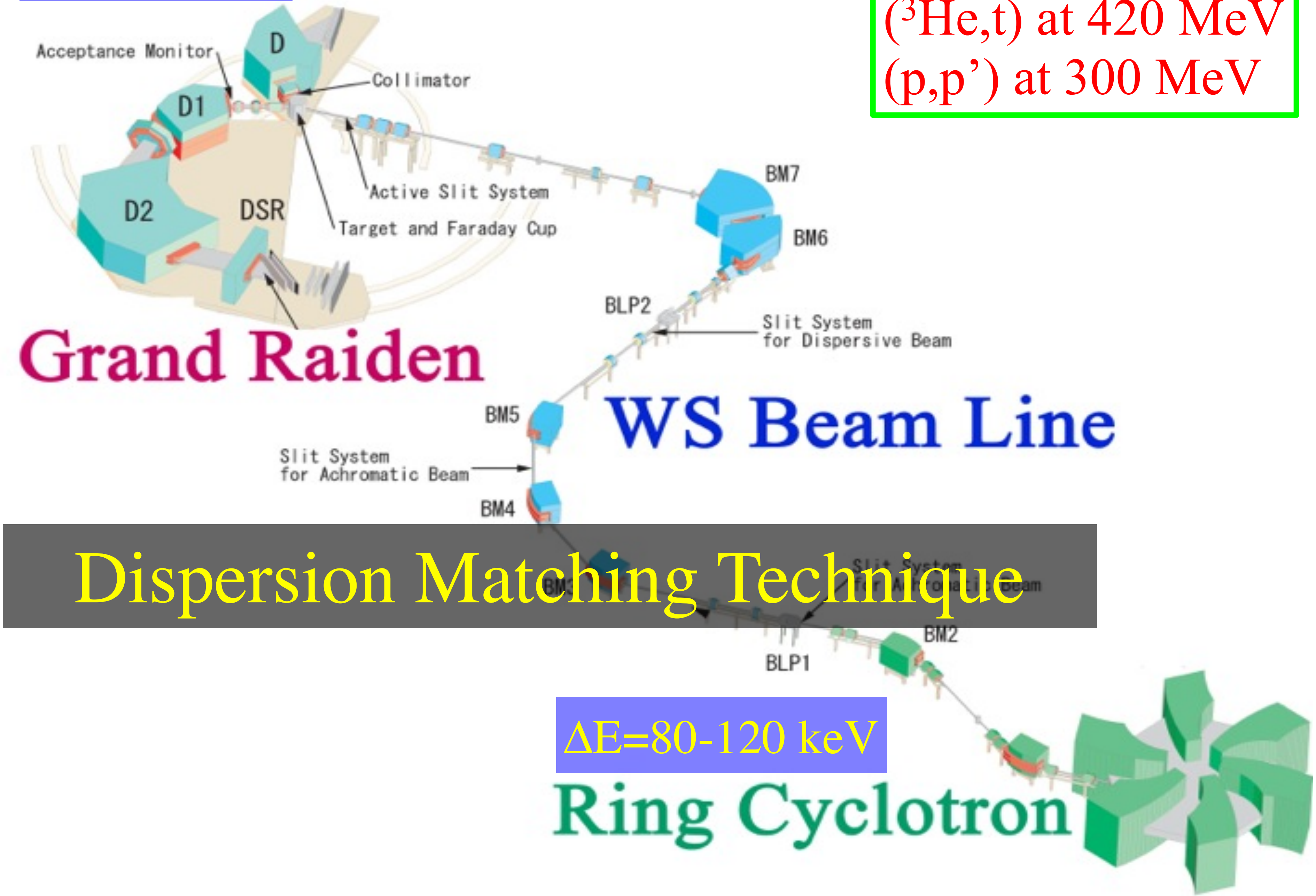
High-resolution WS beam-line (dispersion matching)


RCNP Ring Cyclotron
SUMITOMO
High quality beams at 100-400 MeV/A


Large Angle
Spectromete
Grand Raiden Spectrometer

ΔE=20-30 keV

(^{3}He,t) at 420 MeV
(p,p') at 300 MeV

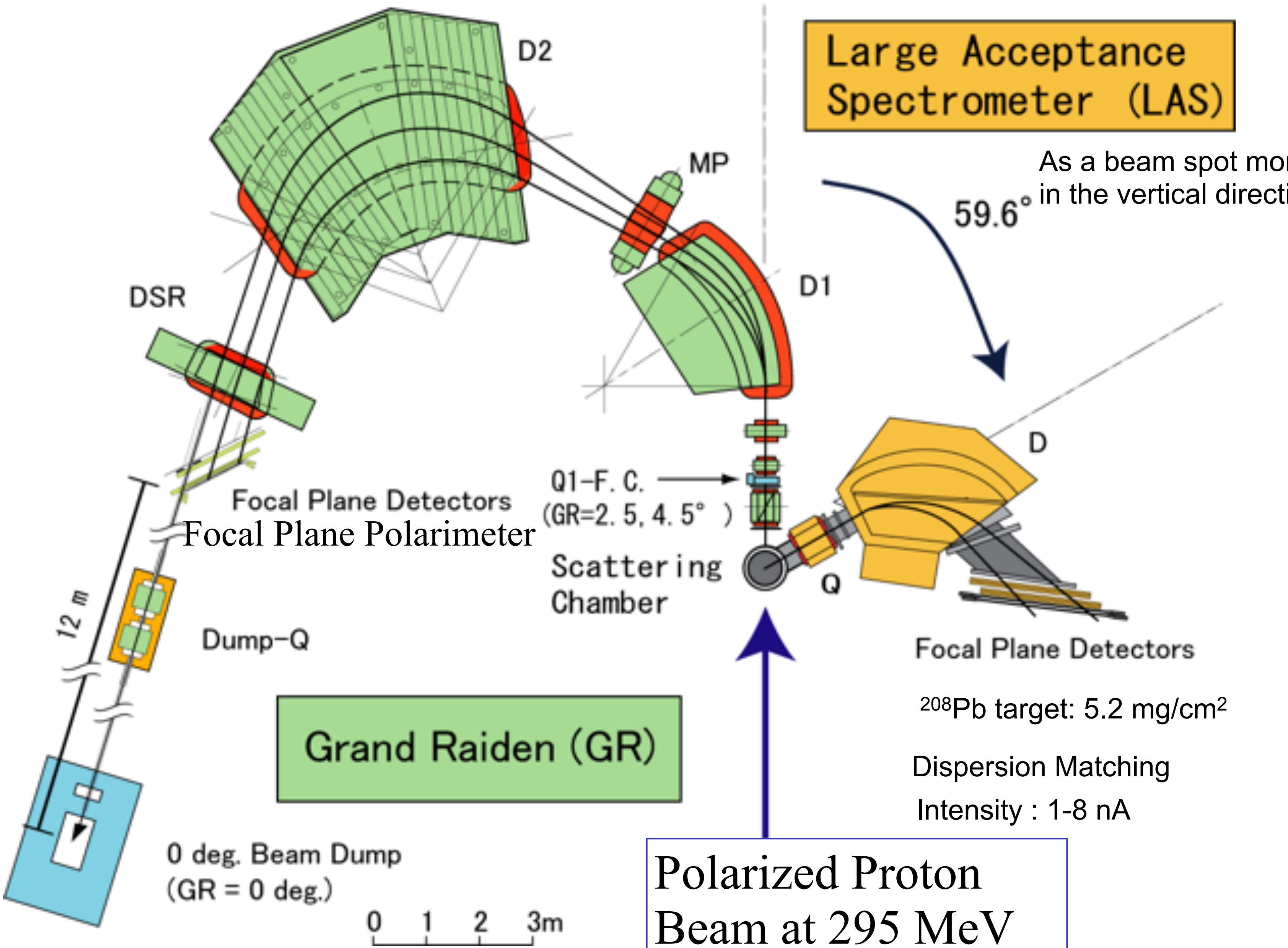


Dispersion Matching Technique

ΔE=80-120 keV

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

AT et al., NIMA605, 326 (2009)

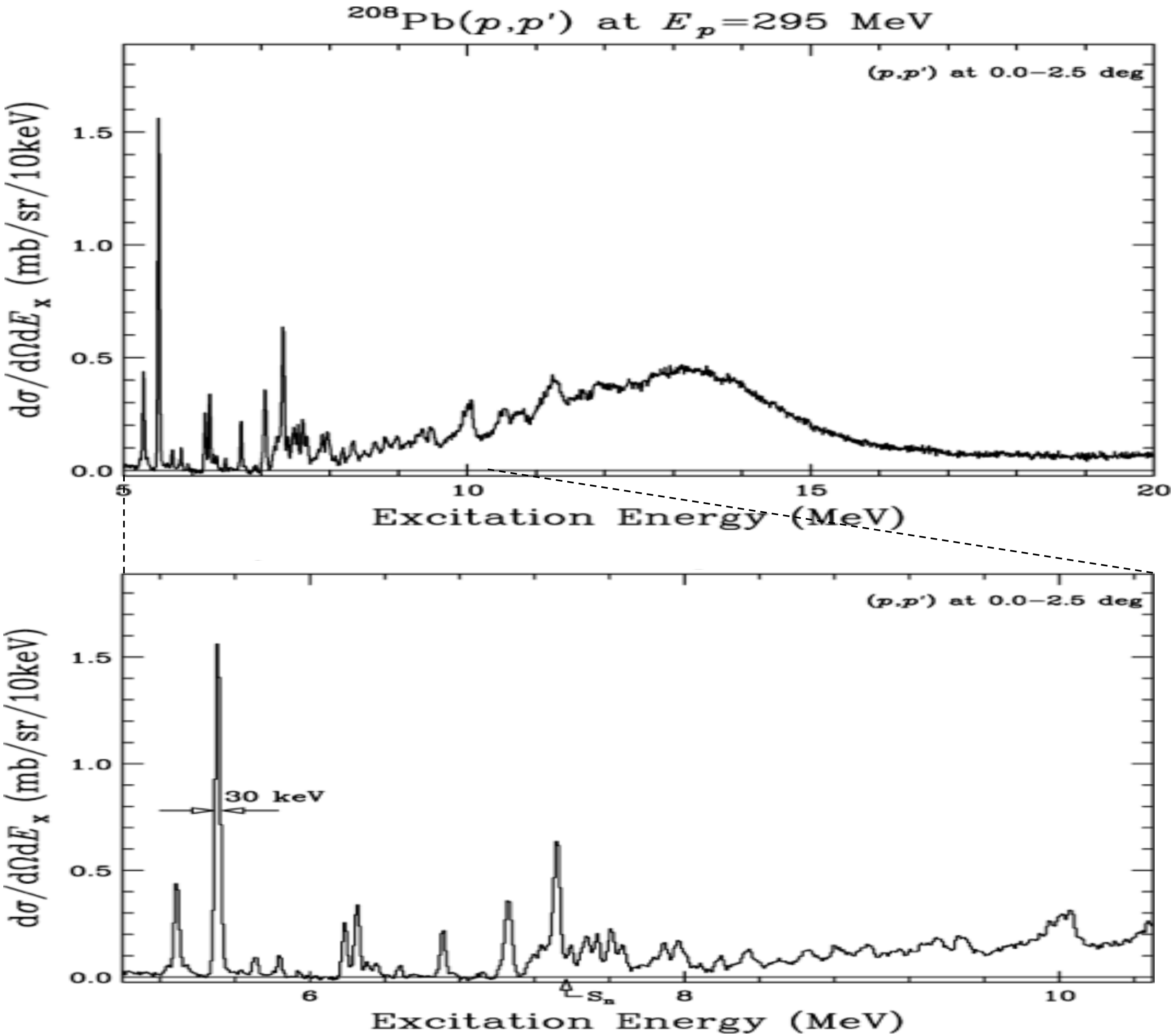


^{208}Pb target: 5.2 mg/cm^2

Dispersion Matching

Intensity : 1-8 nA

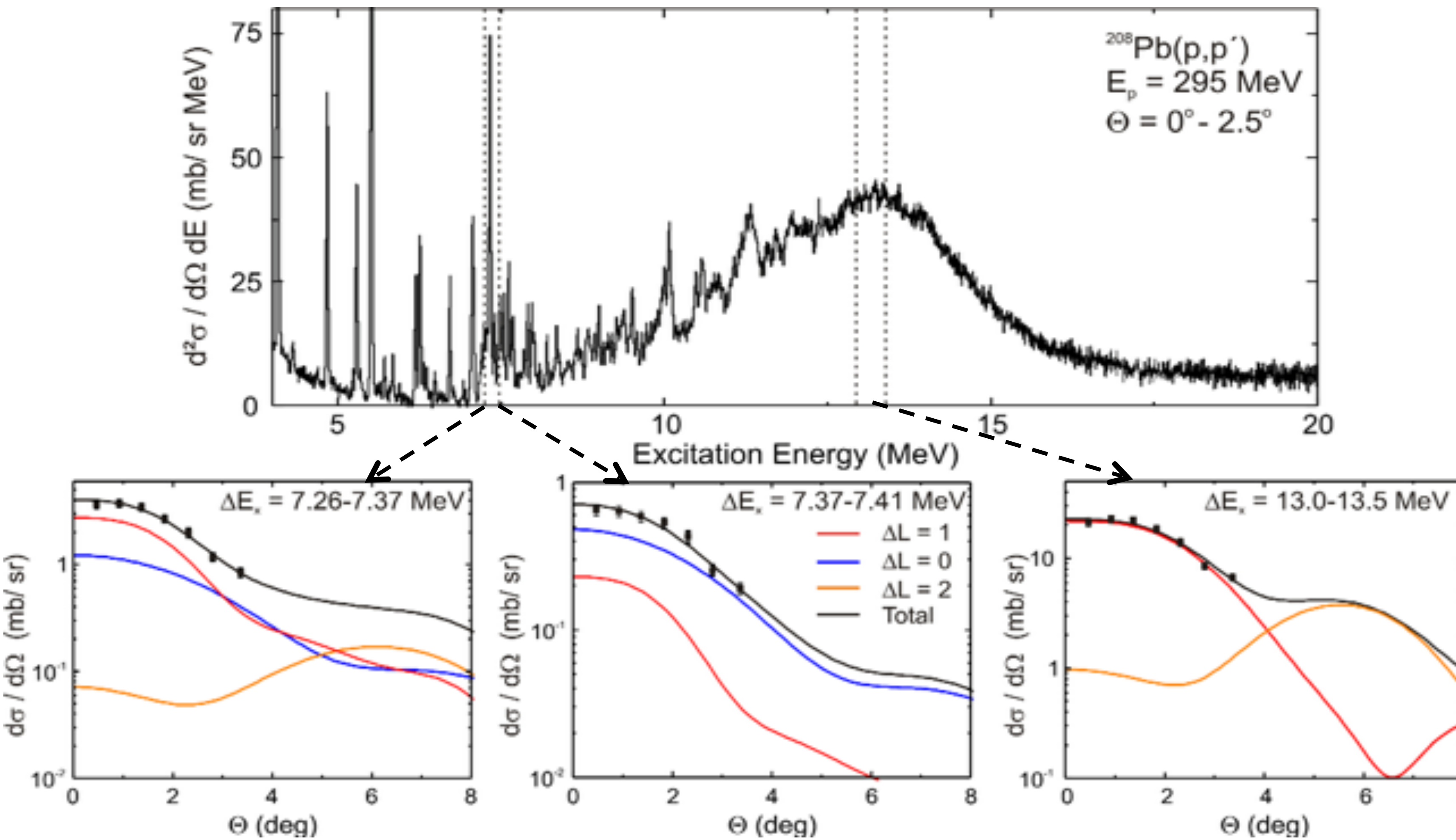
Polarized Proton Beam at 295 MeV



$^{208}Pb(p,p')$ 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
dσ/dΩdE_x (mb/sr/10keV)
6
8
10
S_n
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

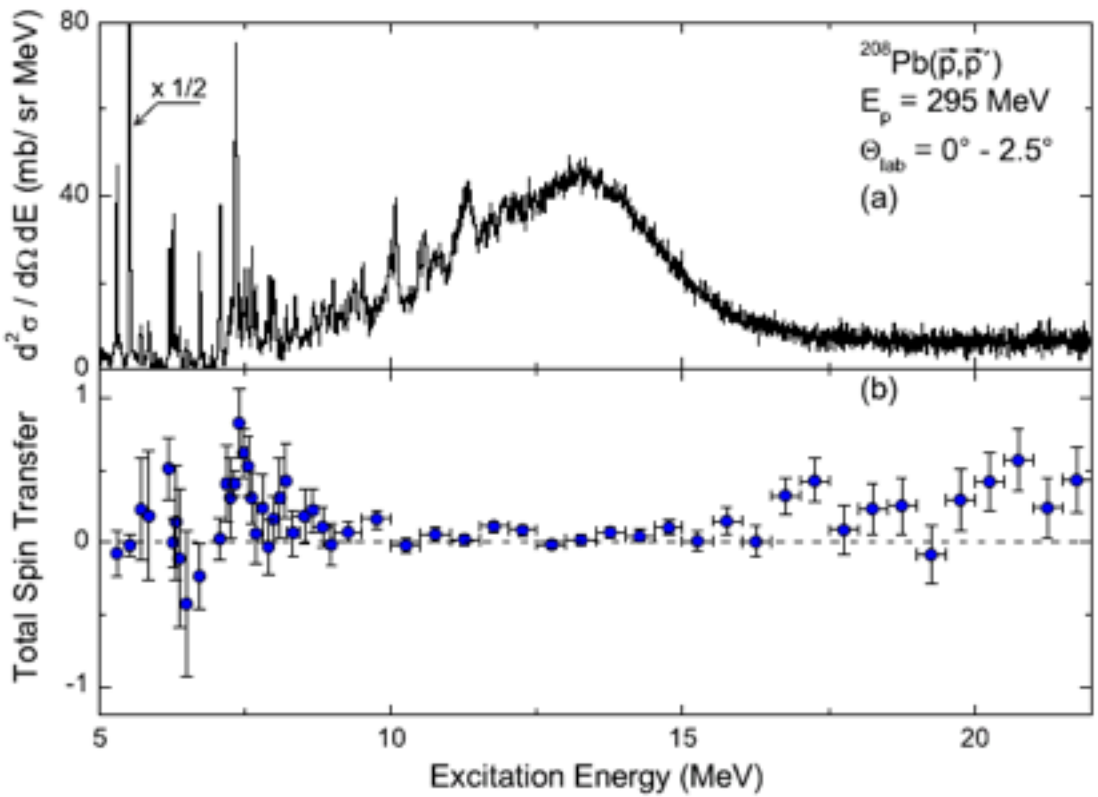
- Polarization observables at 0° → spinflip / non-spinflip separation

model-independent

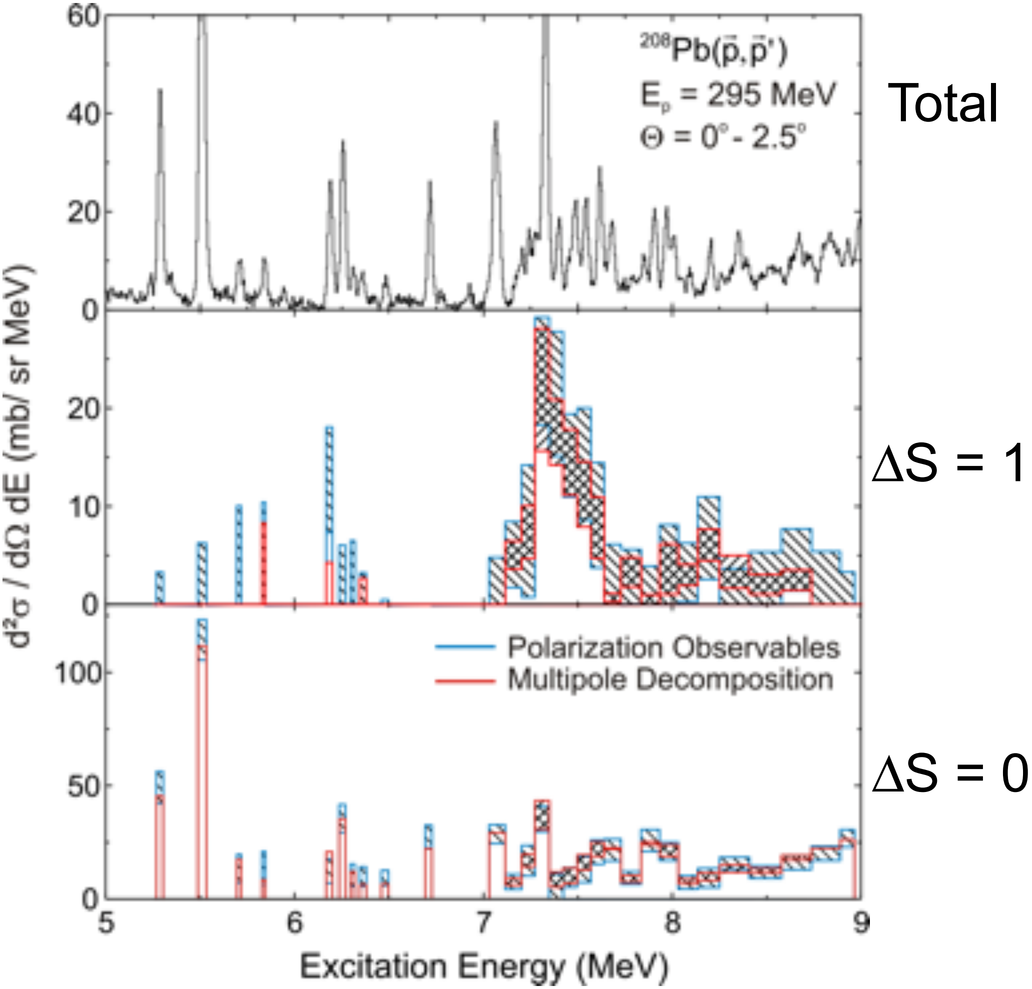
E1 / spin-M1 decomposition

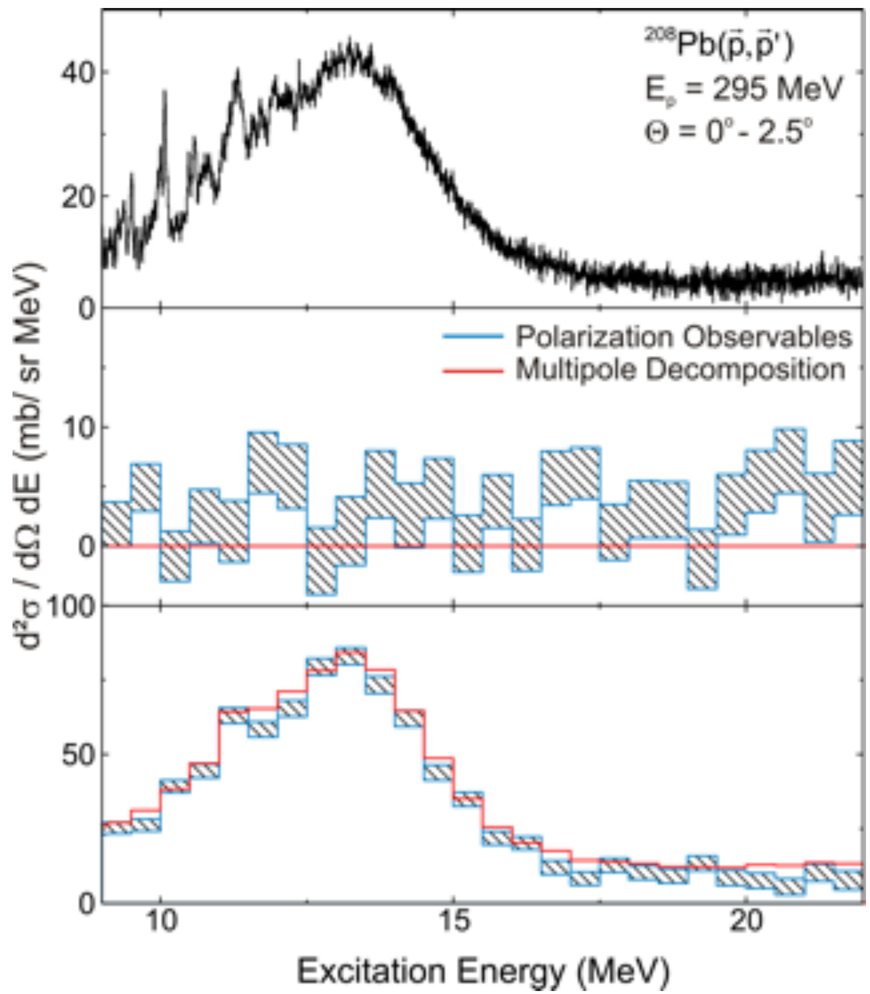
T. Suzuki, PTP 103 (2000) 859

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



Comparison between the two methods

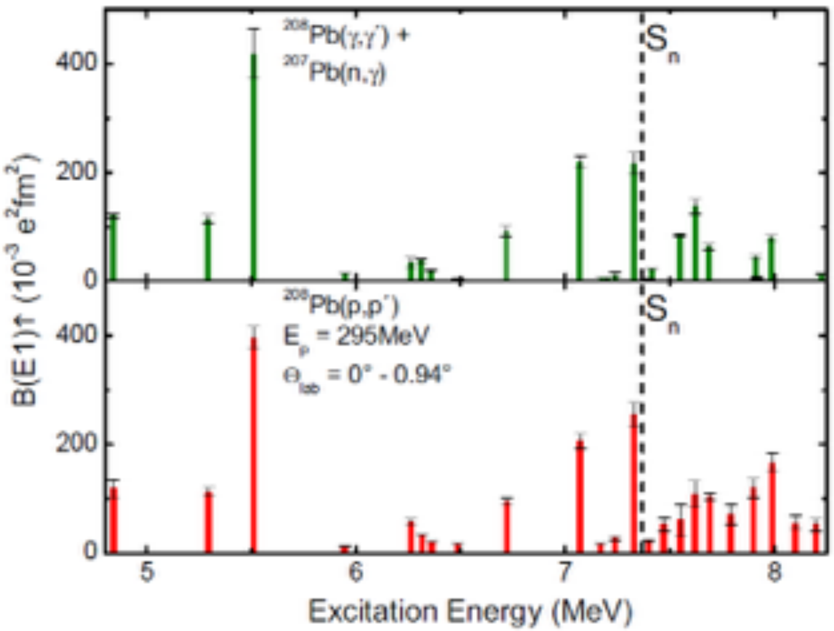




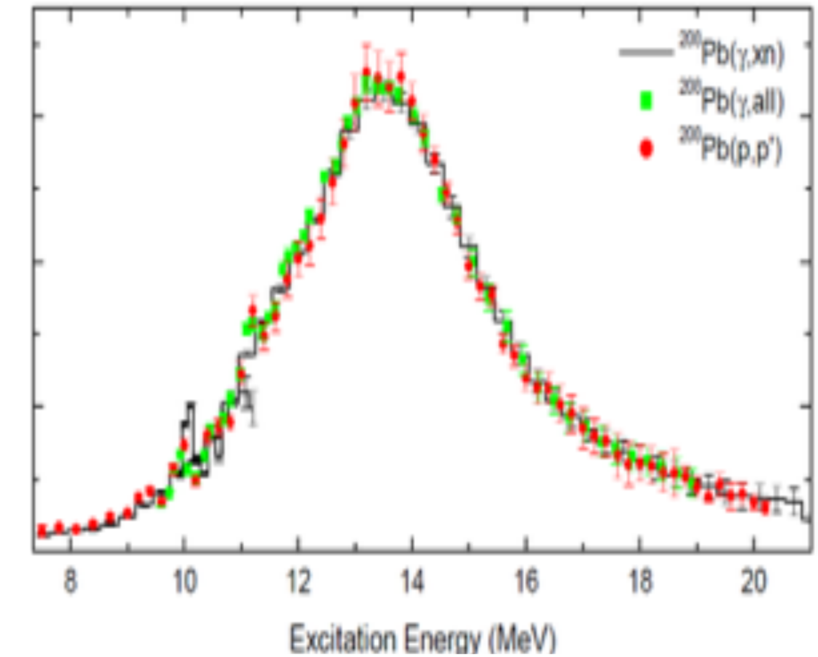
Distribution of B(E1)

I. Poltoratska, PhD thesis

low-lying discrete states

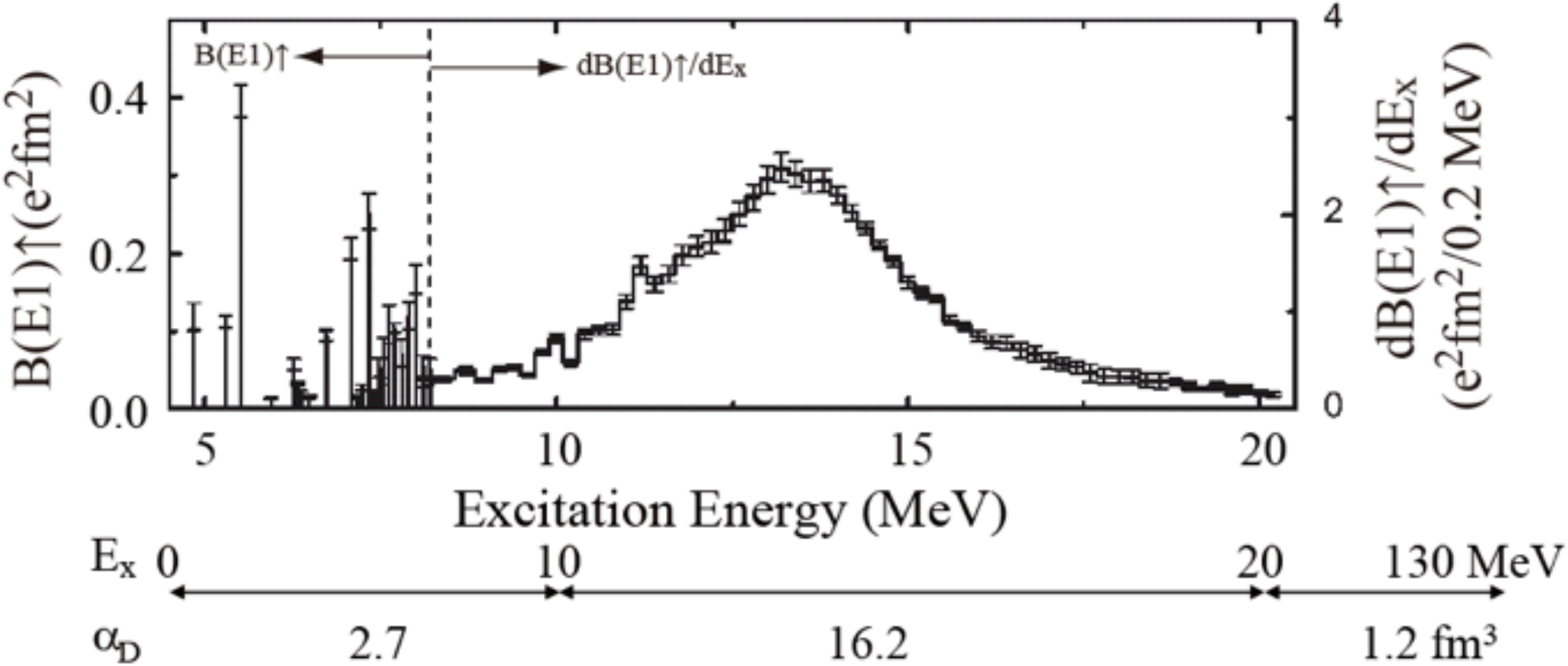


GDR region



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

E1 Response of ^{208}Pb and α_D

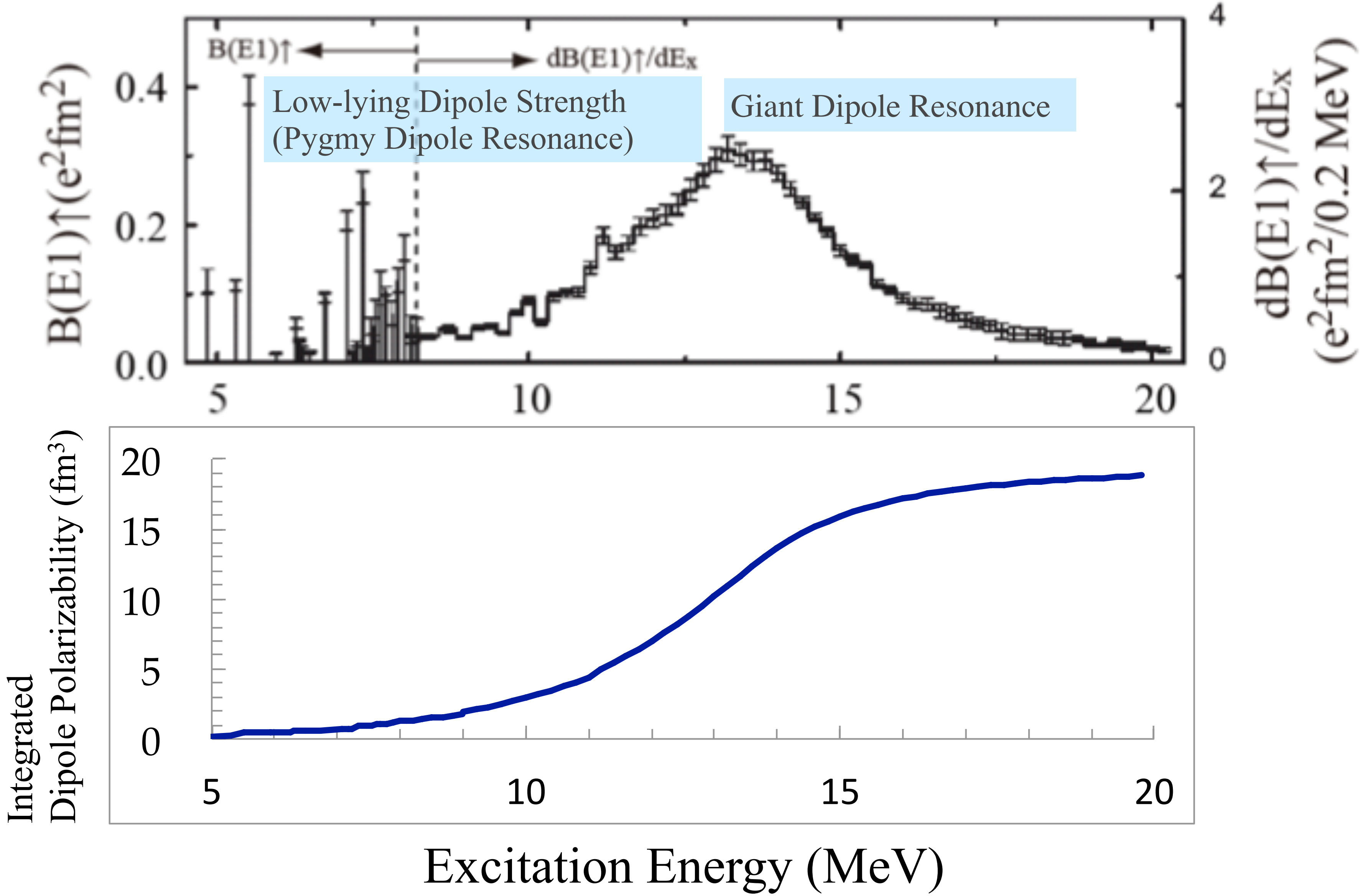


combined data

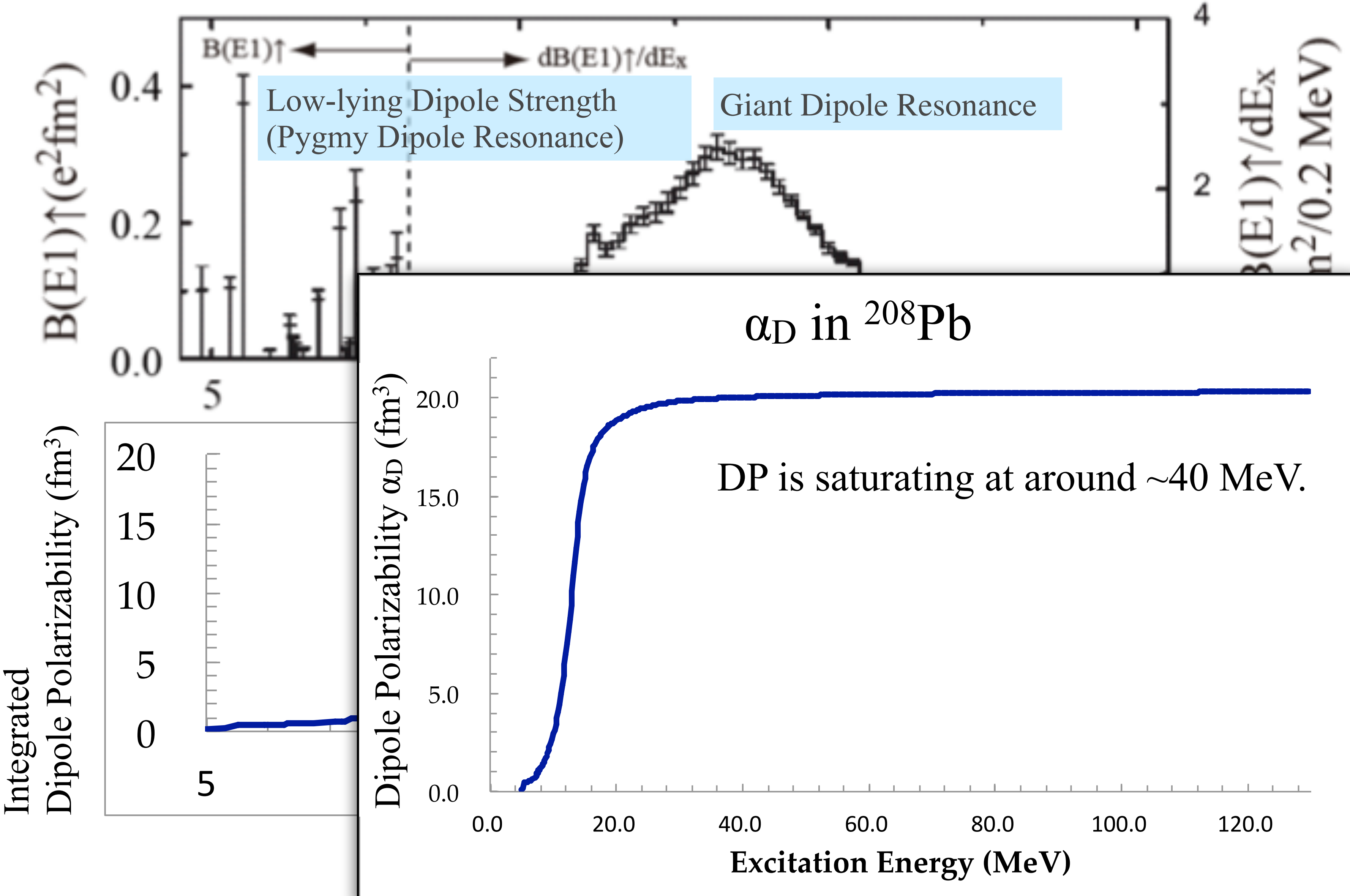
The dipole polarizability of ^{208}Pb has been precisely determined.

AT et al., PRL107, 062502(2011)

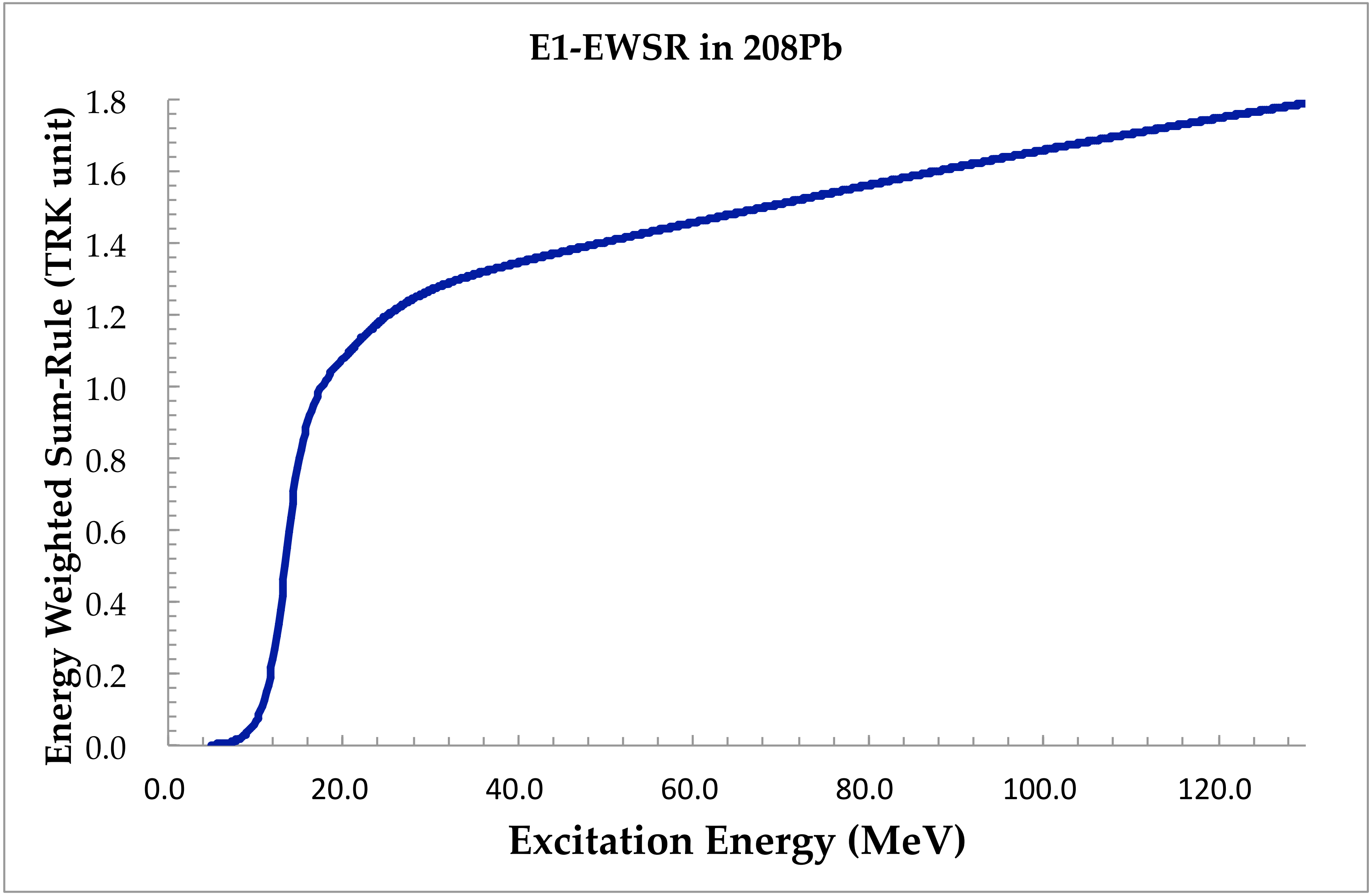
Electric Dipole Response of ^{208}Pb



Electric Dipole Response of ^{208}Pb



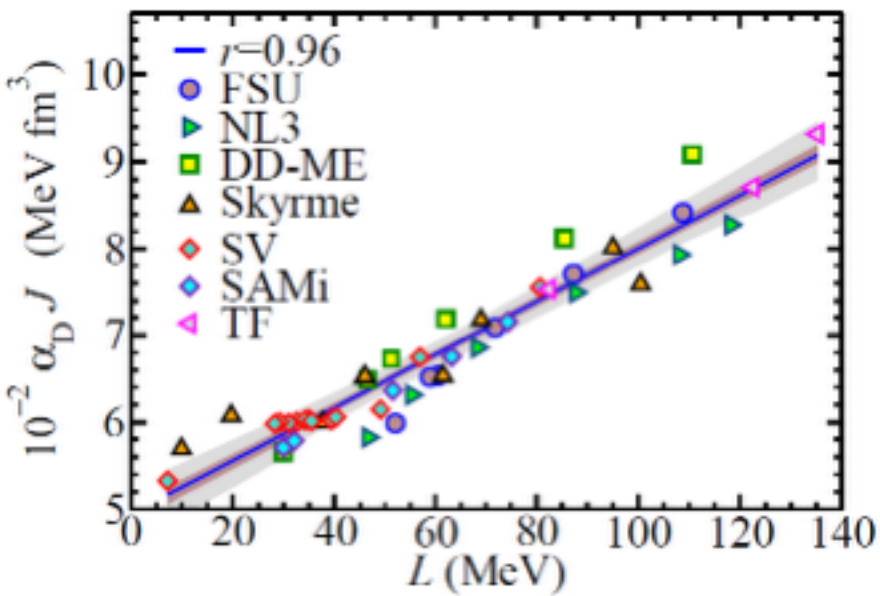
Energy Weighted (TRK) Sum-Rule of ^{208}Pb



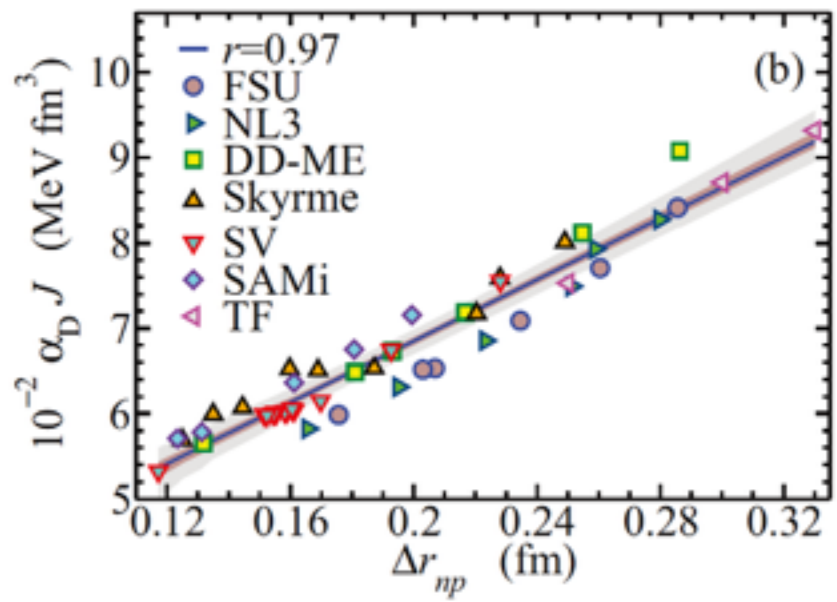
Constraints

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

Symmetry Energy Parameters



Neutron Skin Thickness

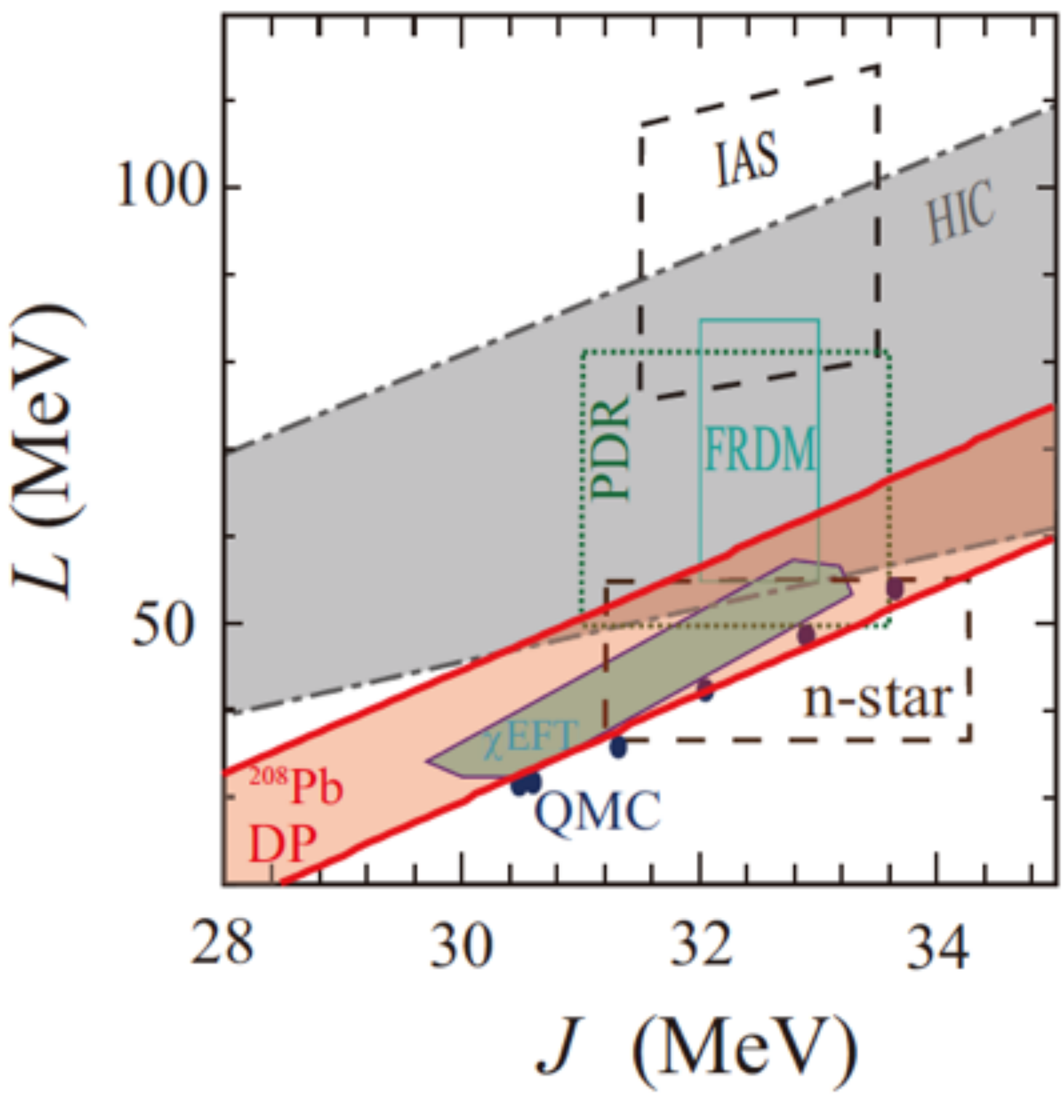


Experimental Value = α_D

➔ 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)

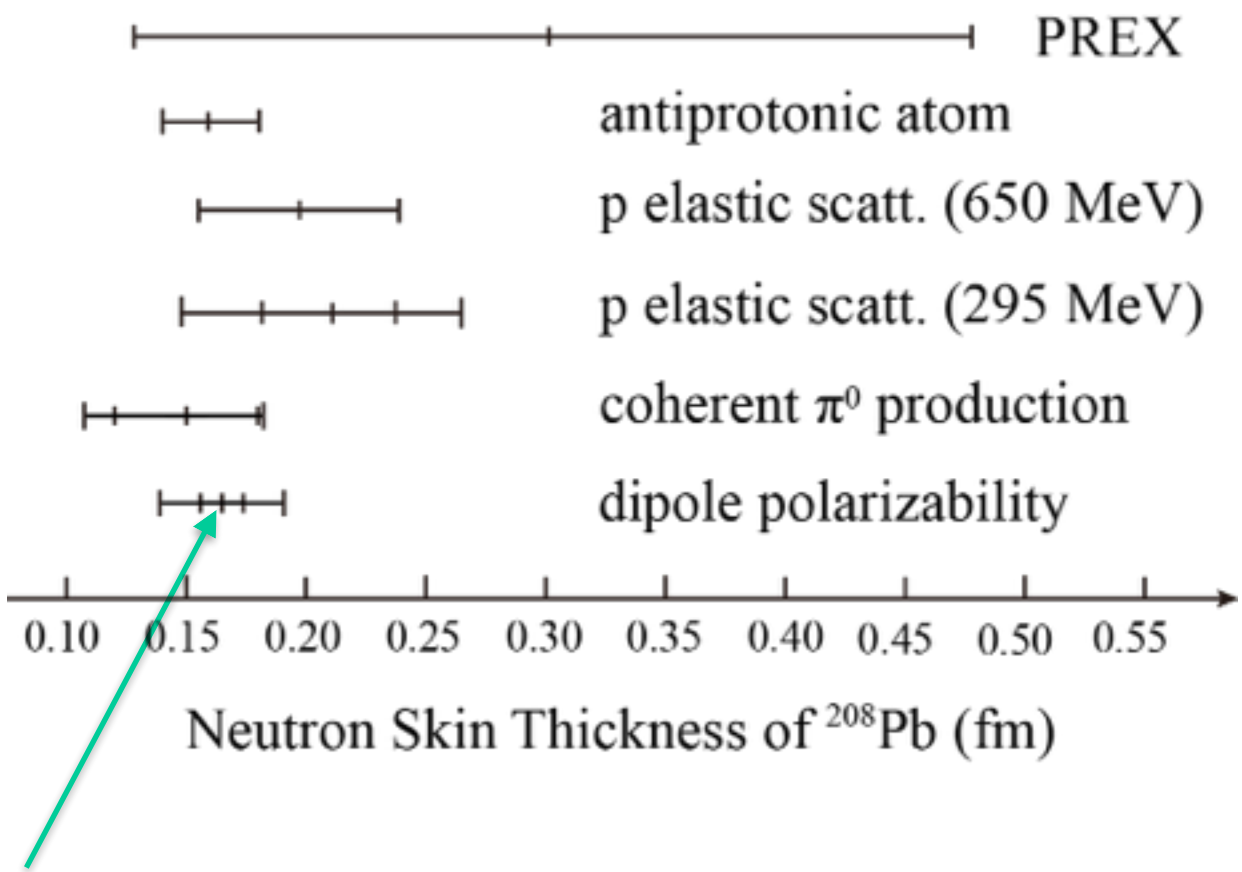
C.J. Horowitz et al., JPG41, 093001 (2014)

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)

Neutron Skin Thickness of ^{208}Pb



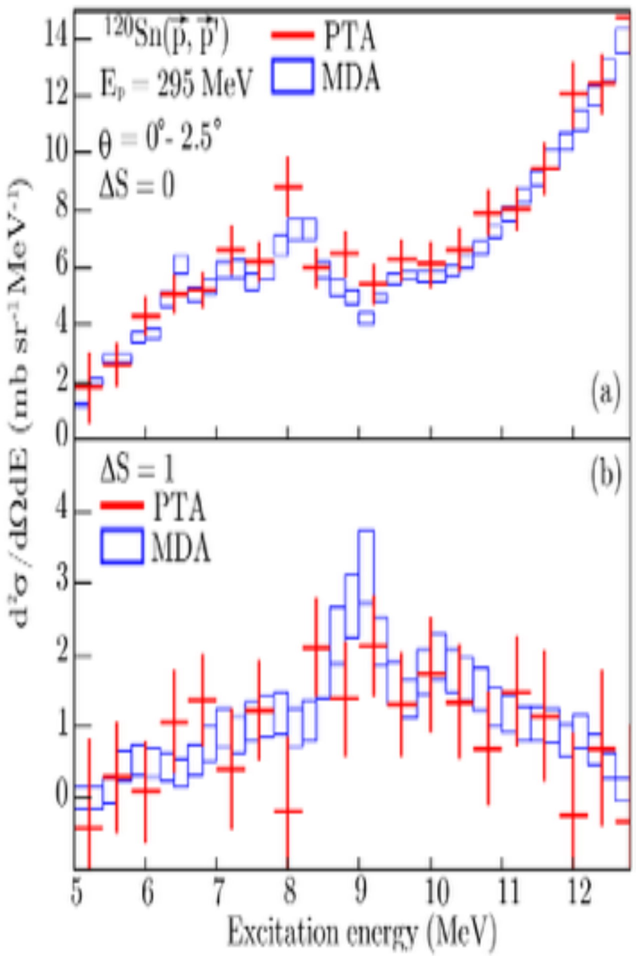
$\Delta R_{np} = 0.165 \pm (0.009)_{\mathrm{expt}} \pm (0.013)_{\mathrm{theor}} \pm (0.021)_{\mathrm{est}}$ fm

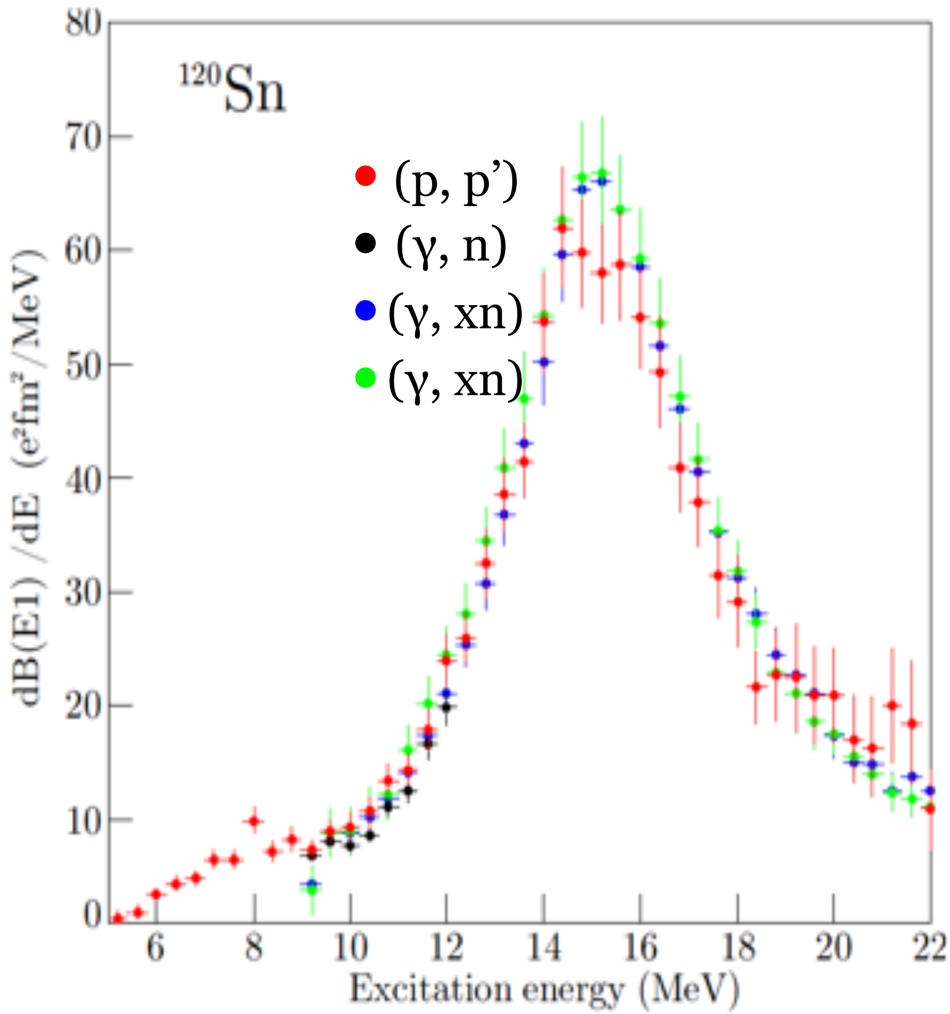
for the estimated J=31 ± $(2)_{\mathrm{est}}$

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

Dipole Polarizability of ^{120}Sn

T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).





135 MeV

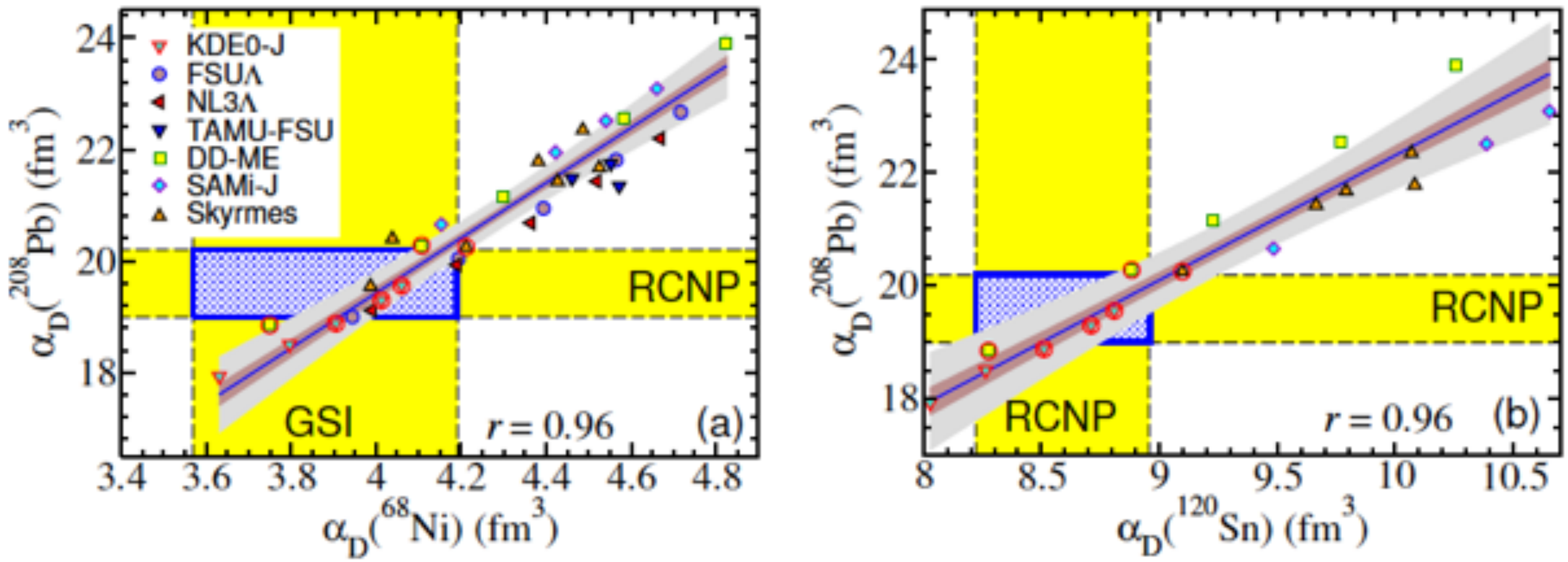
α_D (fm³)

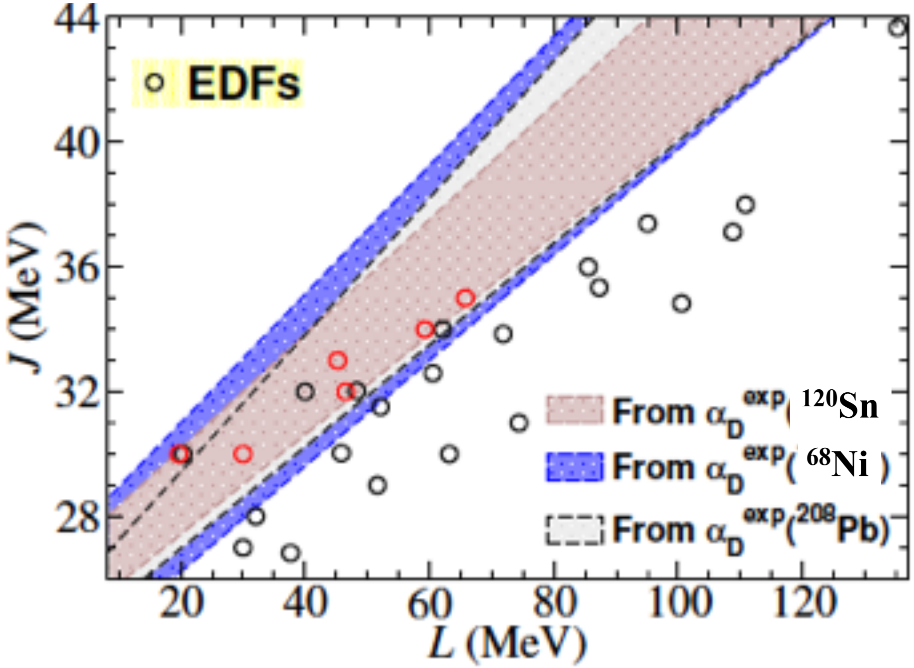
1.12 ± 0.07	7.00 ± 0.29	0.82 ± 0.12

Total: $\alpha_D = 8.93 \pm 0.36$ fm³

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

X. Roca-Maza et al., submitted to PRC





Data

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

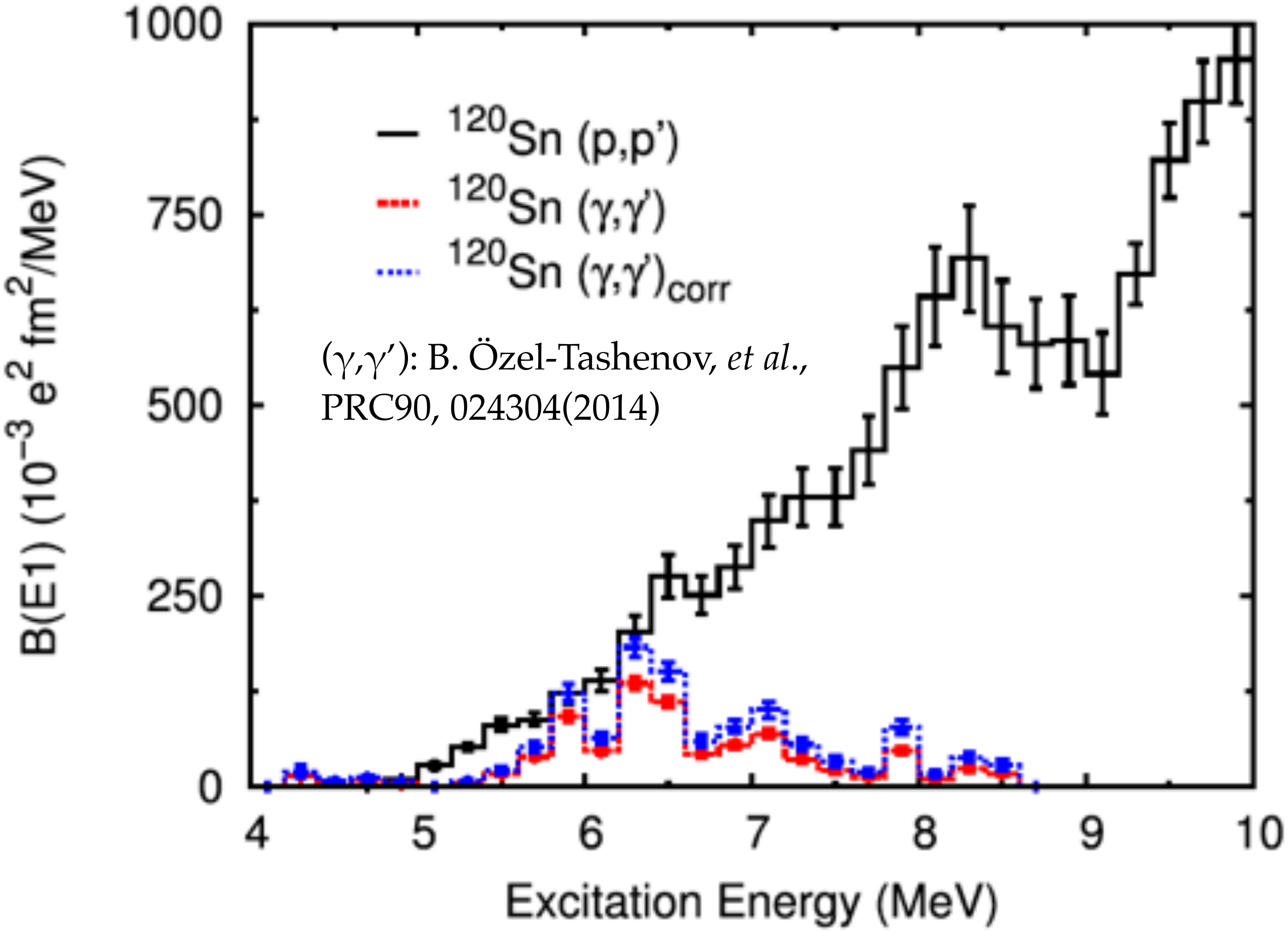
^{120}Sn: T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).
RCNP

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

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

PDR in ^{120}Sn

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



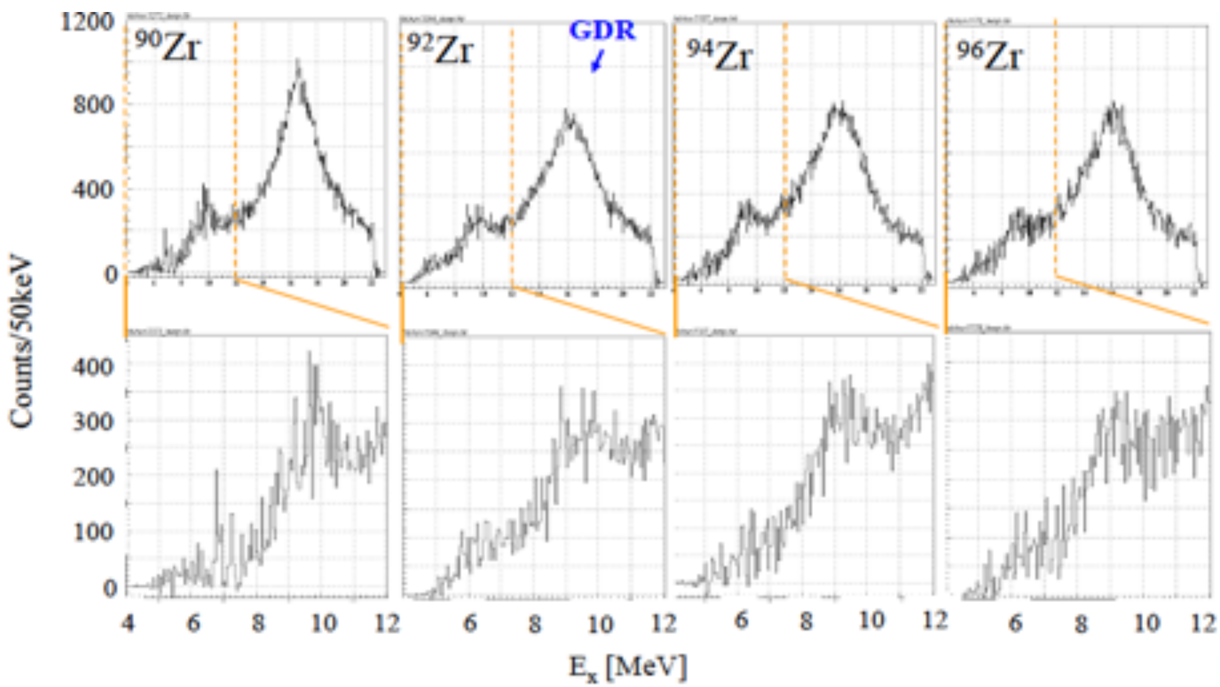
The observed strength by (γ,γ') is significantly smaller than the present (p,p') data.

Work In Progress

- 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

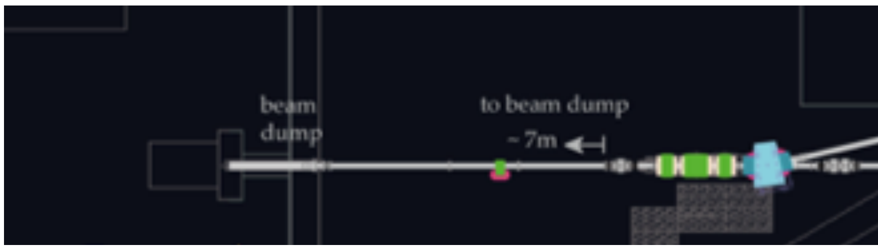
Zr isotopes: presentation by C. Iwamoto on Thursday

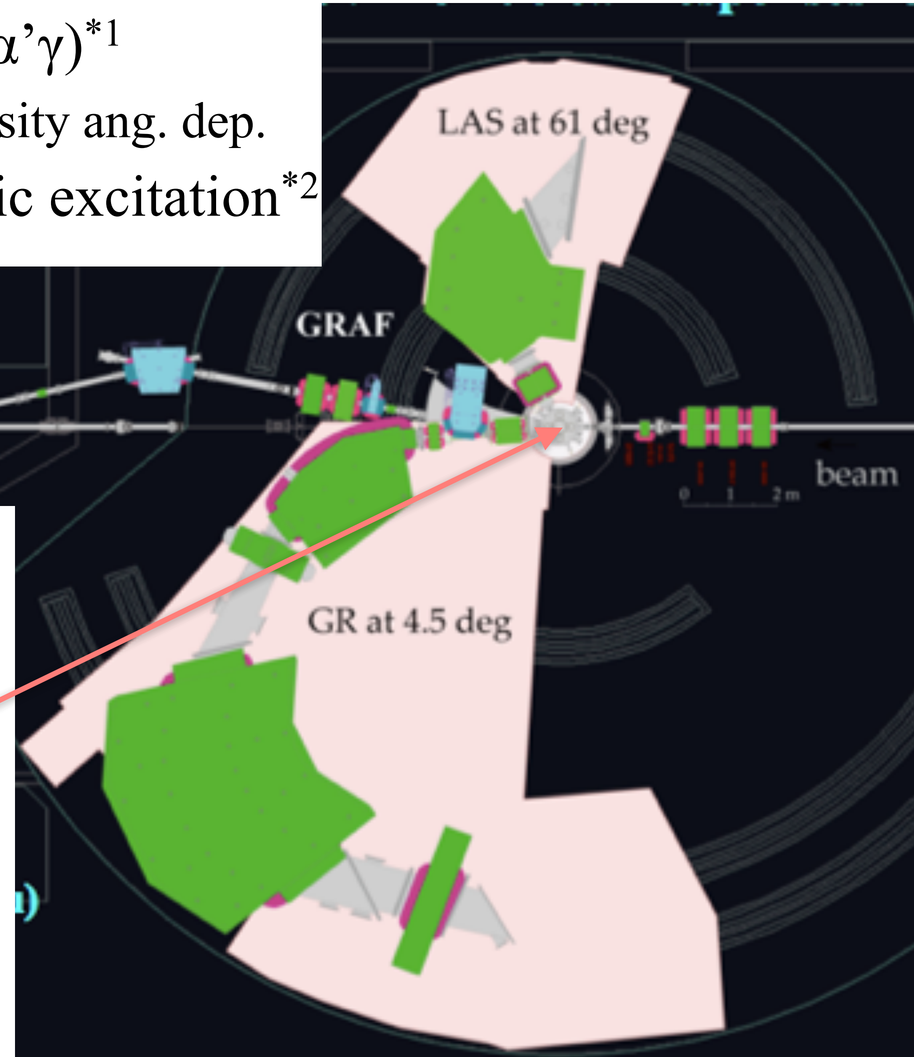


Plan in the Next Year

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 excitation*2

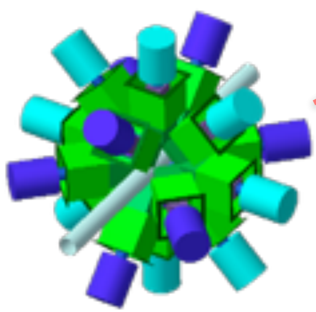




CAGRA(Clover Ge Array)

E. Ideguchi and M. Carpenter

for γ-coincidence measurements



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

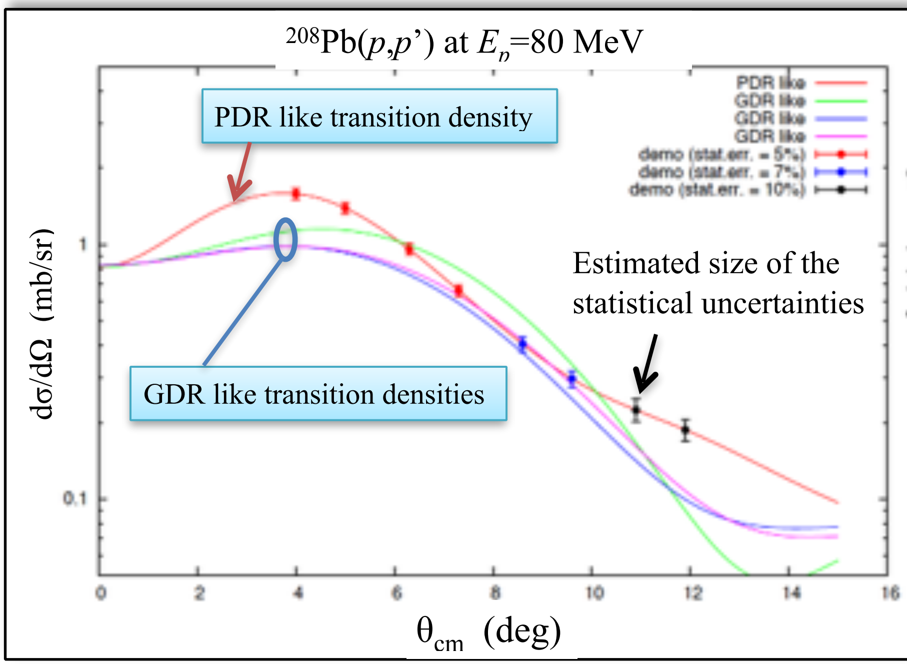
*2 S. Noji, R.G.T. Zegers *et al.*,

Plan in the Next Year

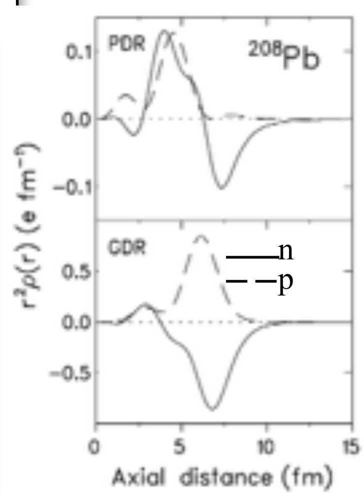
CAGRA+GR Campaign Exp. in 2016

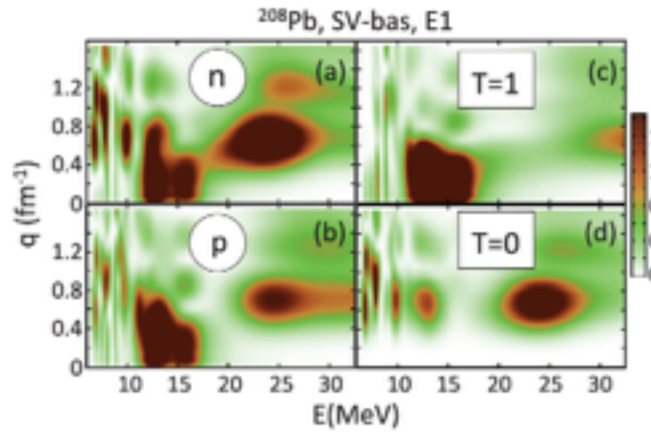
E441 5.0 days (^{6}Li,^{6}Li'γ) for IV spin-flip inelastic excitation
E450 25.0 days (p,p'γ) and (α,α'γ) for PDR
E454 6.0 days (p,p'γ) at 300 MeV and (α,α'γ) for PDR
Total 36.0 days.

(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)

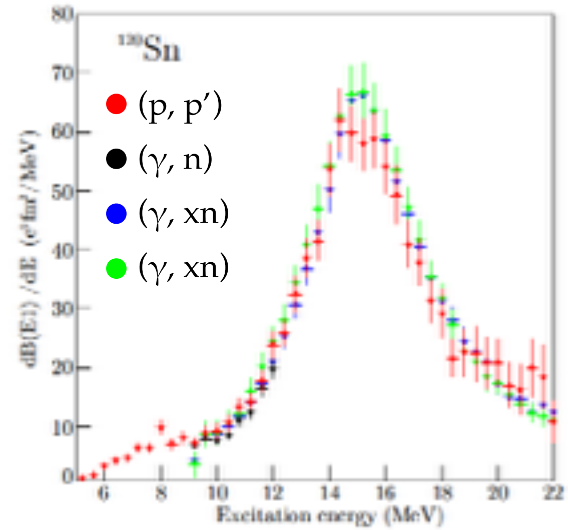
Conclusion

- 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.