Isovector and Isoscalar Spin Isospin Responses

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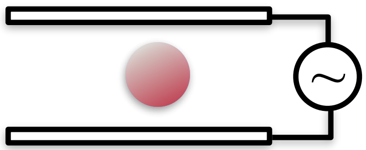
Osaka University, Japan

Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16)

September 29-30, 2016, Osaka

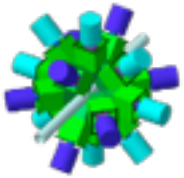
Outline

I. Electric Dipole Response of Nuclei
and the Symmetry Energy of the Nuclear EOS

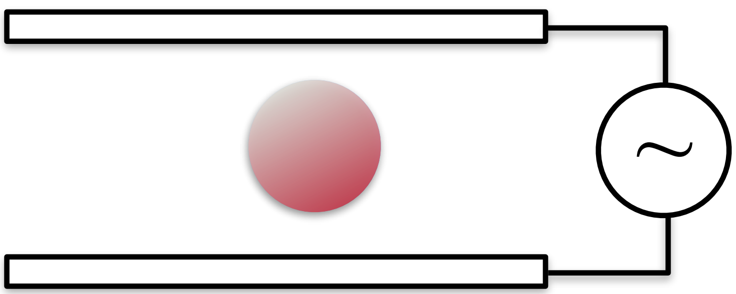


II. Spin-Magnetic Response of Nuclei

III. Summary



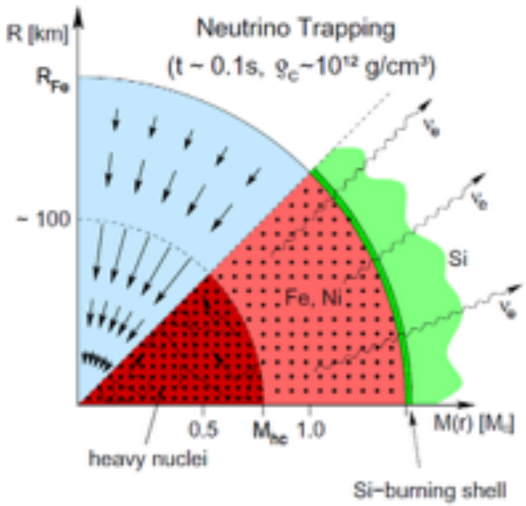
I.
Electric Dipole Response of Nuclei and the Symmetry Energy of the Nuclear EOS



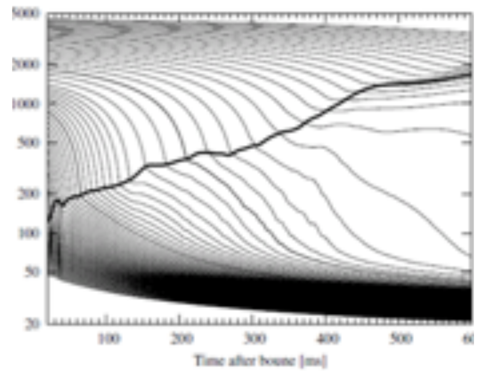
Symmetry Energy of the Nuclear Equation of State

is important for nuclear physics and nuclear-astrophysics

Core-collapse supernova

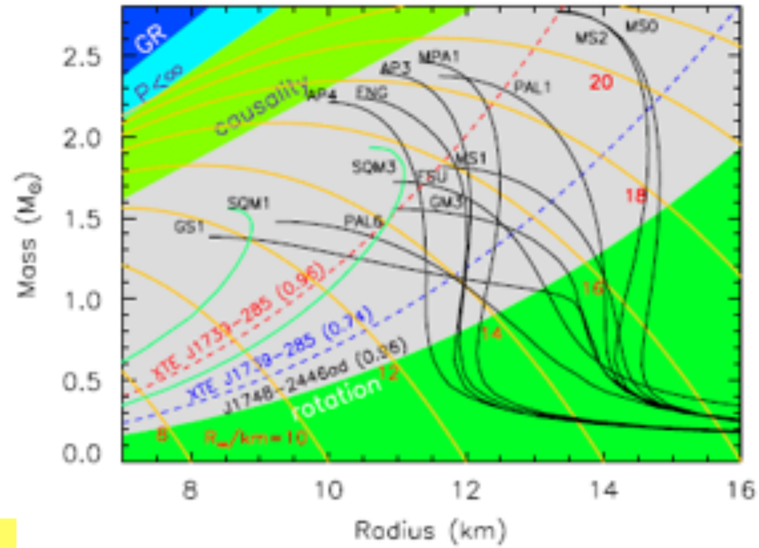


Langanke and Martinez-Pinedo



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

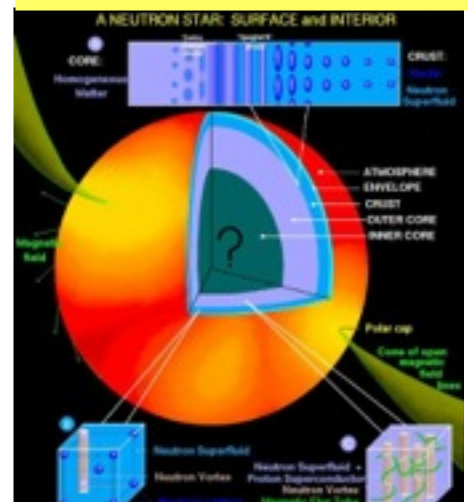
Neutron star mass vs radius



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

Nucleosynthesis

Neutron star structure

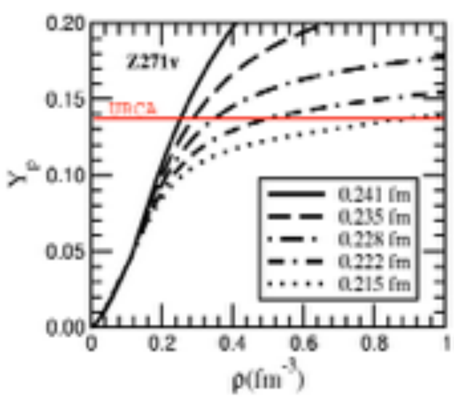


http://www.astro.umd.edu/~miller/nstar.html

Neutron Star Merger Gravitational Wave

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

Neutron star cooling



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

Nuclear Equation of State

How to study the EOS?

Thermodynamics

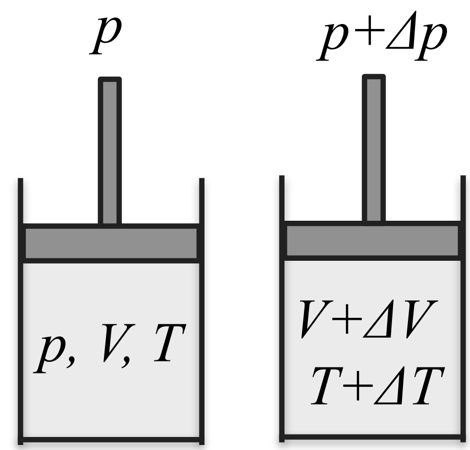
Give a "small perturbation" to the system

then observe how the system changes

→ response

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

adiabatic compressibility



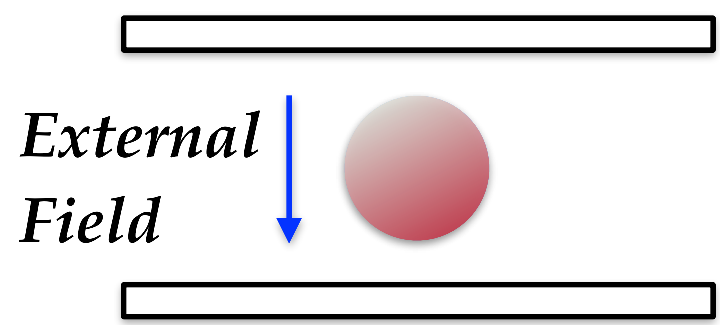
equilibrium

Nuclear EOS

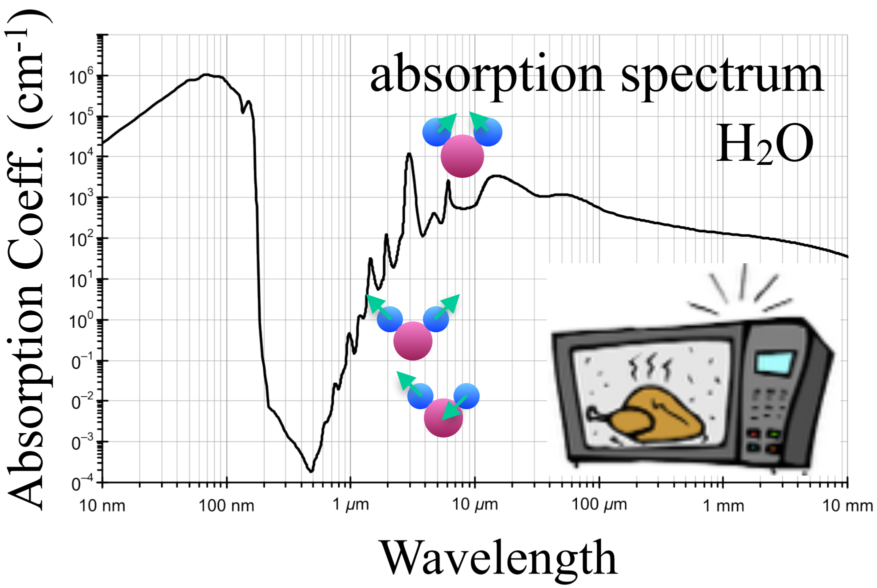
Small perturbation by an external field

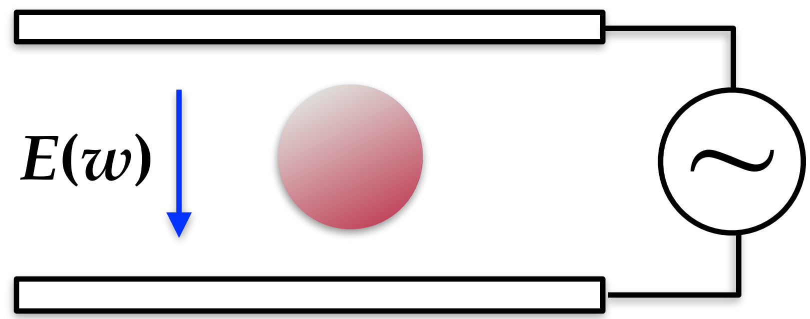
Observe how the system change

→ nuclear response

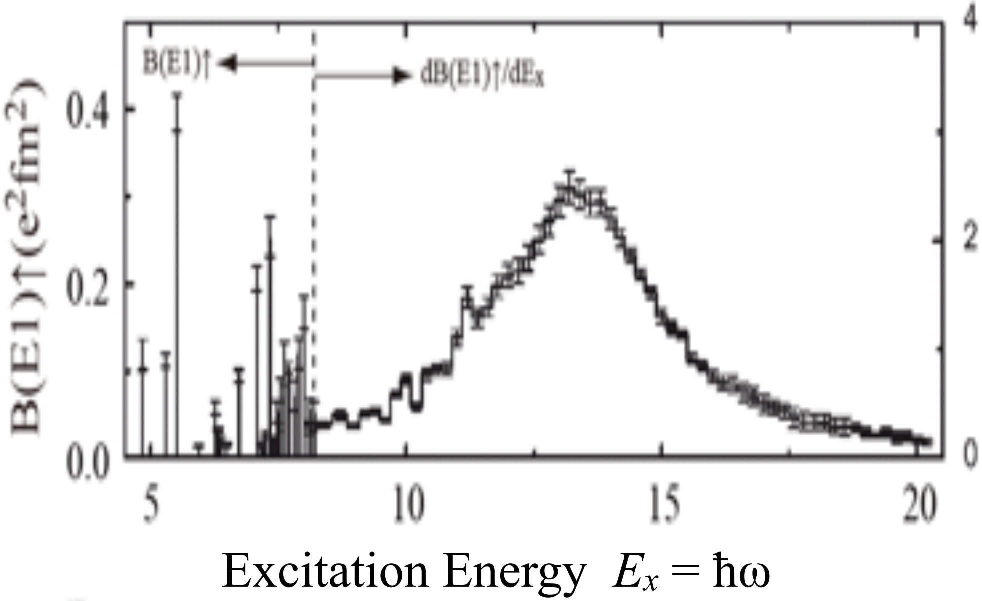


Electric Dipole Response





dielectric material
in an oscillating electric field



Electric Dipole (E1)
Reduced Transition Probability

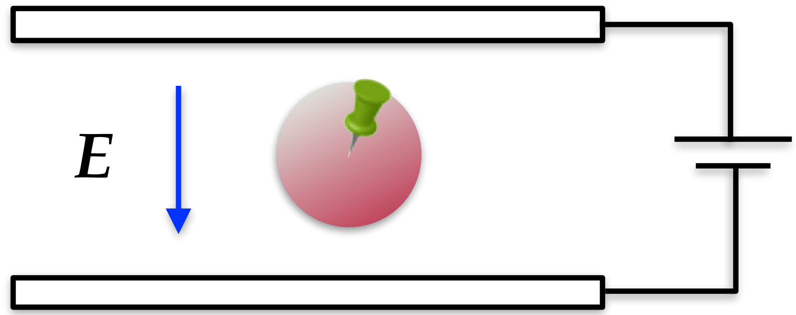
$$\frac{dB(E1)}{dE_x} = \frac{9\hbar c}{16\pi^3 e^2}\frac{\sigma_{\rm abs}^{E1}}{E_x}$$

Electric Dipole Polarizability (α_D)

Electric dipole moment

$$p = \alpha_D \times E$$

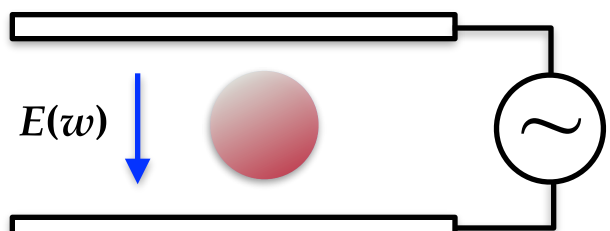
α_D: electric dipole polarizability



nucleus
in a static electric field
with fixing the c.m. position

Inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{1}{E_x} \frac{dB(E1)}{E_x}$$



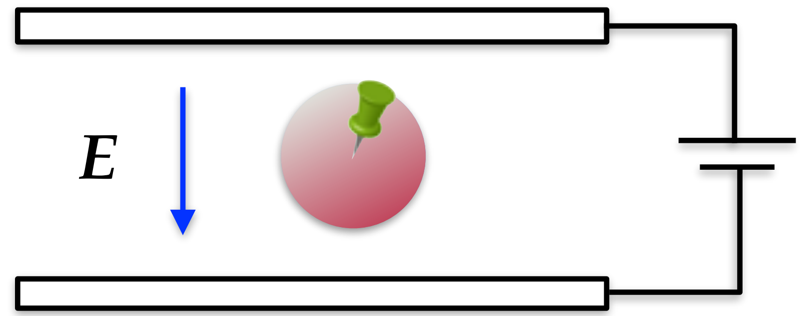
first order perturbation calc. A.B. Migdal: 1944

Electric Dipole Polarizability (α_D)

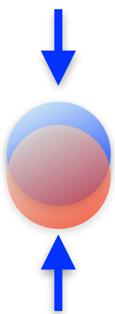
Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability



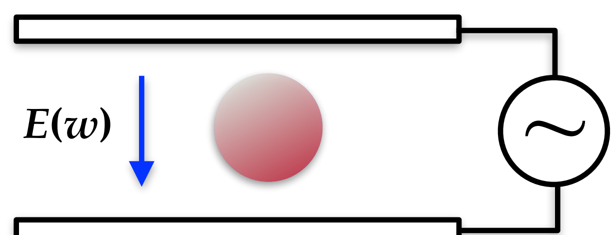
nucleus
in a static electric field
with fixing the c.m. position



The **restoring force** originates from the **symmetry energy**.

Inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{1}{E_x} \frac{dB(E1)}{E_x}$$



first order perturbation calc. A.B. Migdal: 1944

Nuclear Equation of State (EOS)
at zero temperature

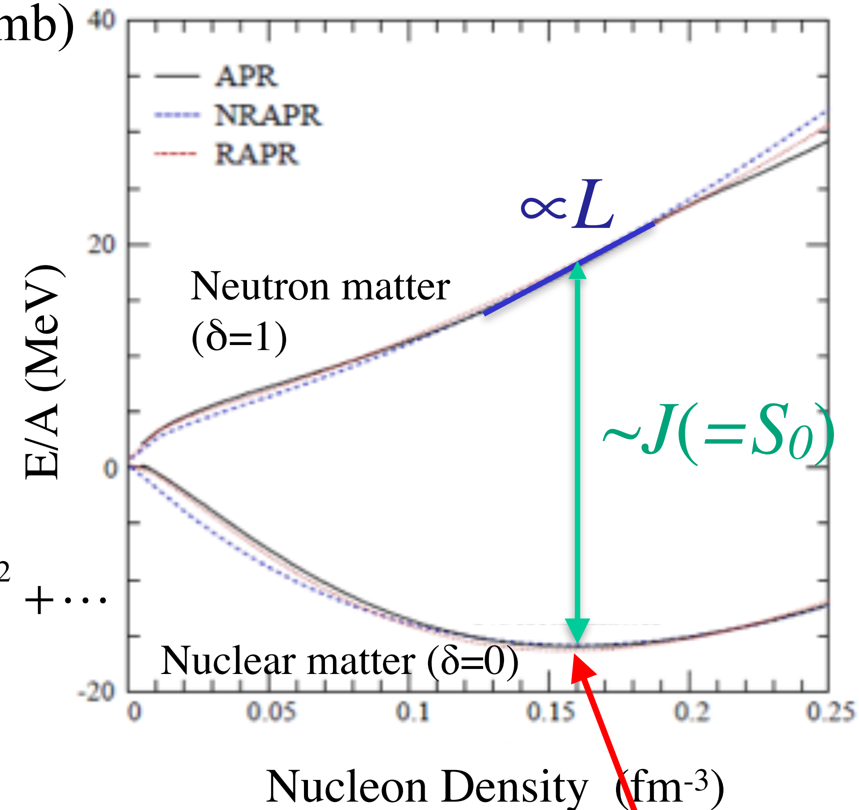
Nuclear equation of state (neglecting Coulomb)

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

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

Symmetry energy

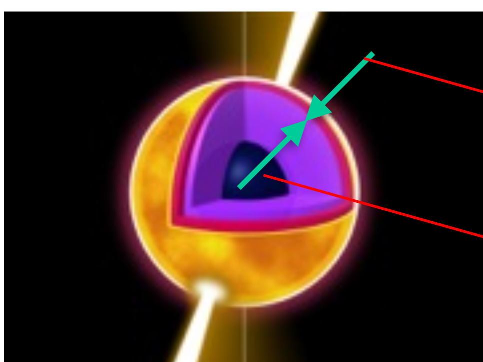
$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho_0)+\frac{K_{sym}}{18\rho_0^2}(\rho-\rho_0)^2+\cdots$$



Saturation Density ρ_0

$\rho_0 \sim 0.16$ fm^{-3}

Neutron Star



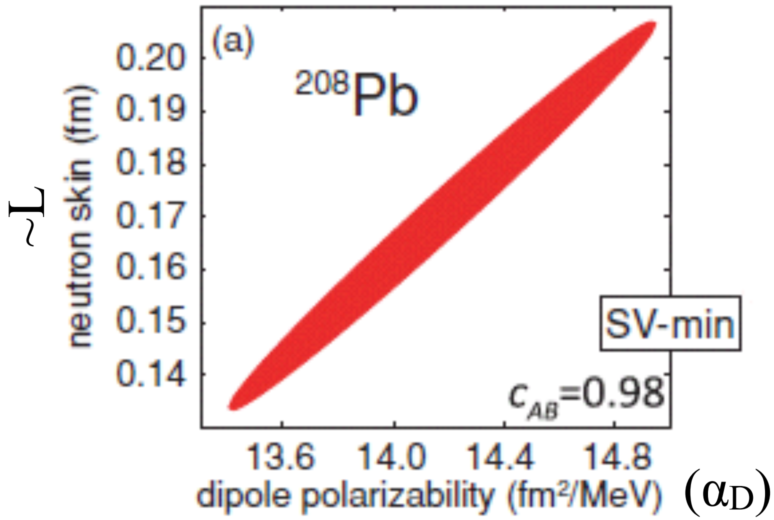
gravitational pressure

baryonic pressure $\propto L$

$\propto R_{nstar}^4$

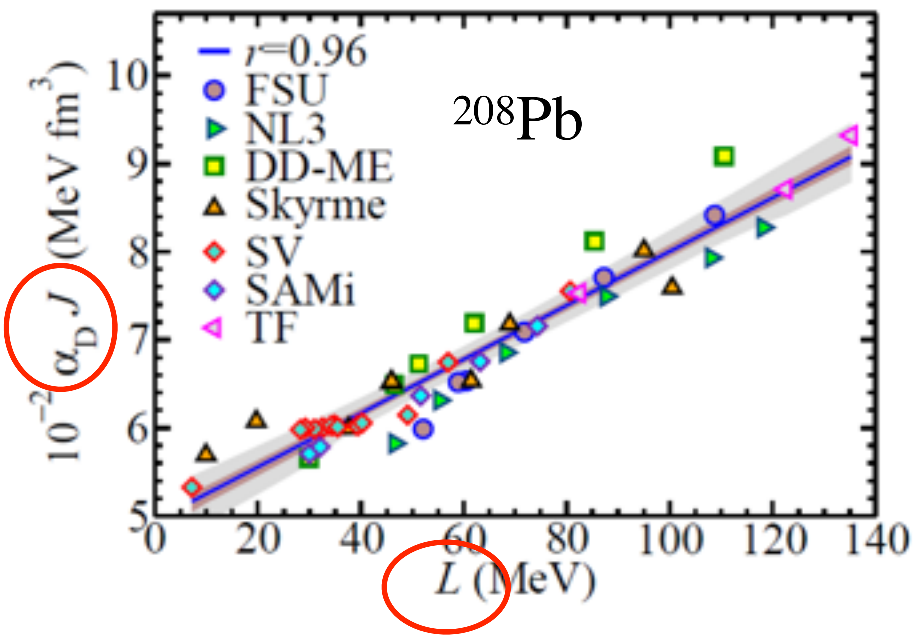
Lattimer&Prakash, PRep442, 109(2007)

Theoretical Models to Connect α_D to the Symmetry Energy



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

Energy Density Functional (EDF) approach using the SV_{min} effective interaction.

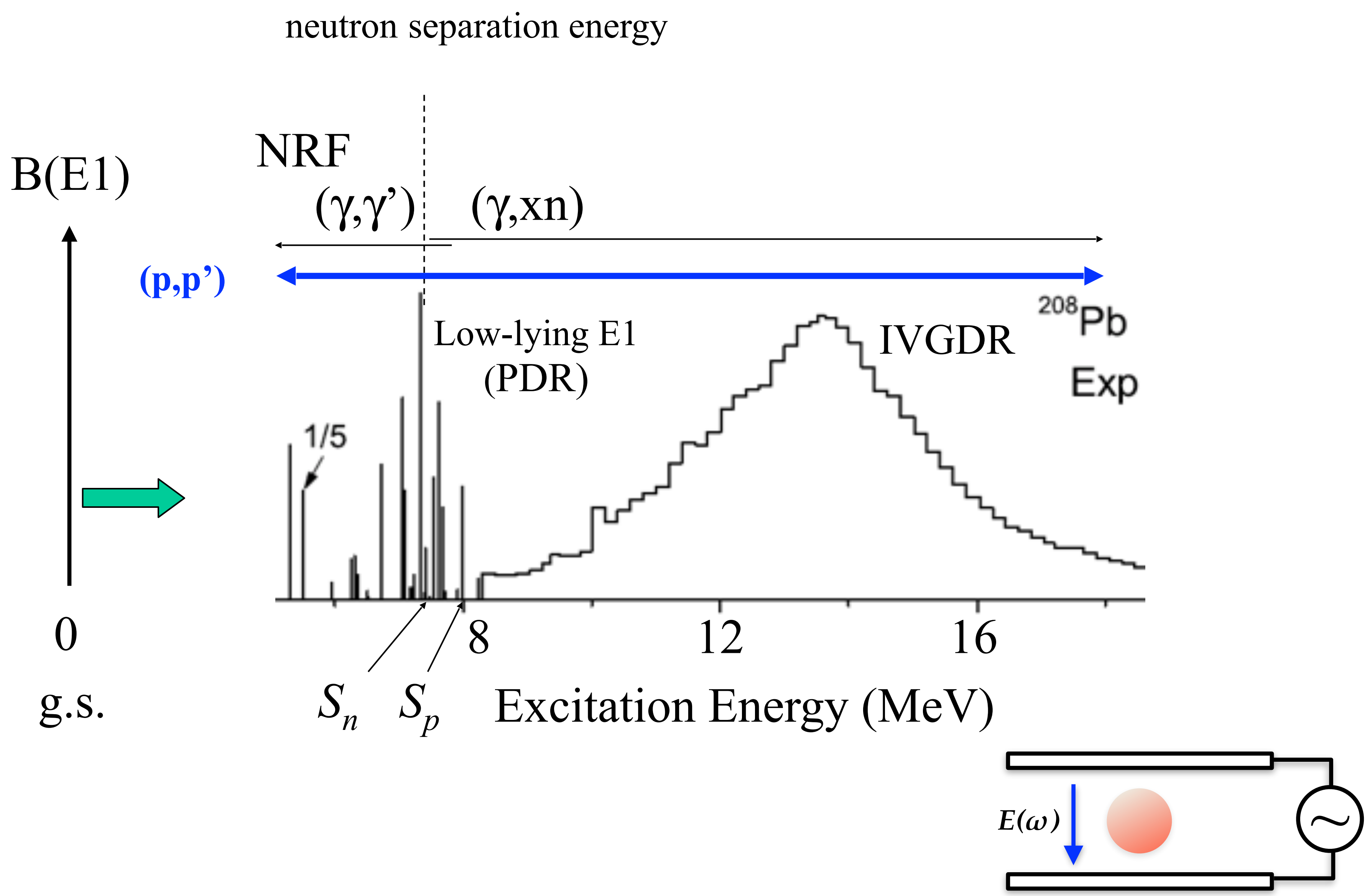


X. Roca-Maza *et al.*, PRC**88**, 024316(2013)

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \dots$$

Precise determination of α_D of ^{208}Pb gives a constraint band in the J-L plane.

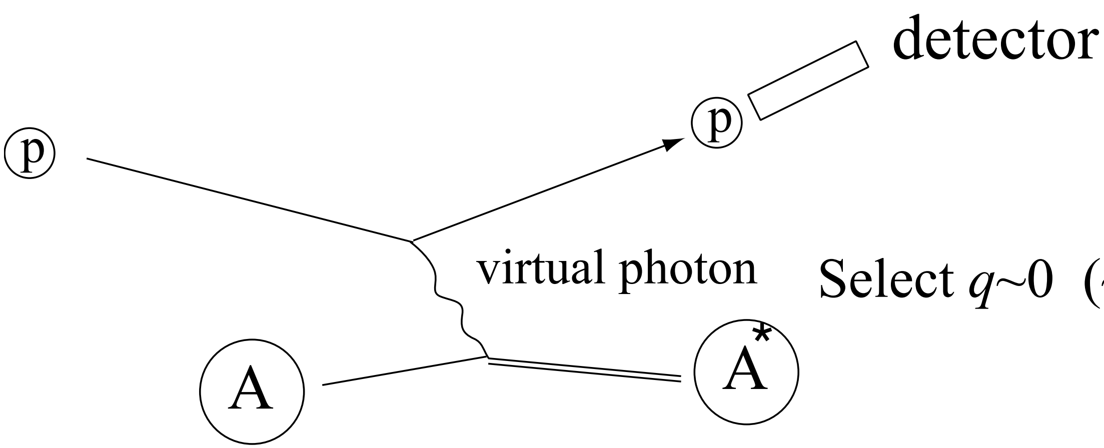
Electric Dipole (*E1*) Response of Nuclei

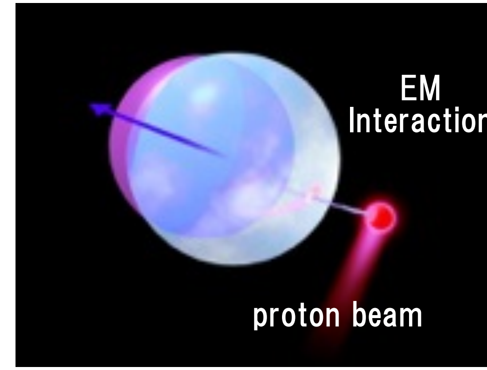


Coulomb Excitation by Proton Scattering

RCNP

Missing Mass Spectroscopy by Virtual Photon Excitation

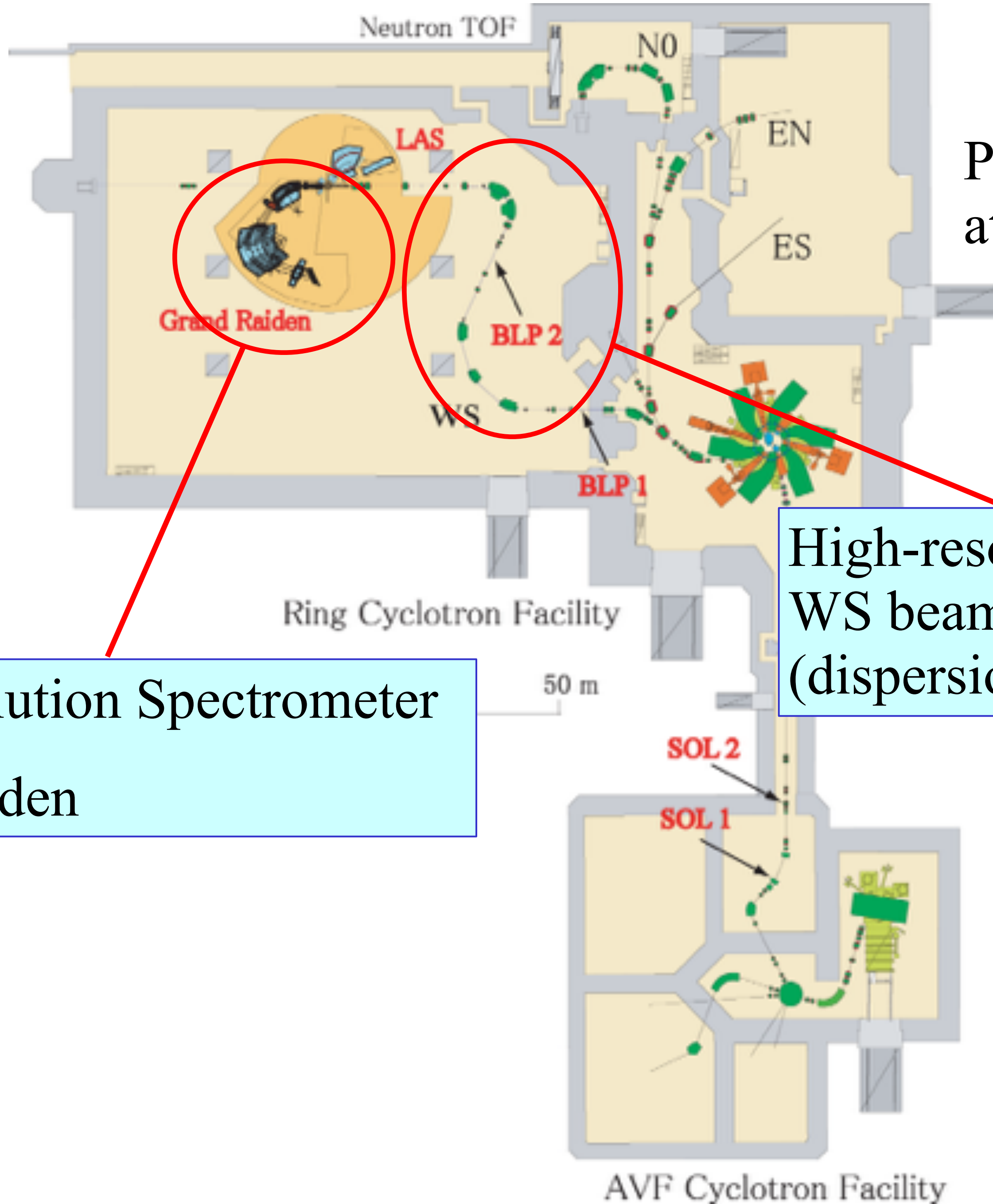




Select $q\sim 0$ (~0 deg.)

- **Missing mass spectroscopy**:
  Total strength is measured independently of the decay channels.
- **Electromagnetic Probe:** the interaction is well known
- **Single shot measurement** across S_n in $E_x = 5\text{-}22$ MeV.
- **High energy resolution** (20-30 keV)
- **Spin observable** & angular distribution → extraction of E1

Research Center for Nuclear Physics (RCNP), Osaka University



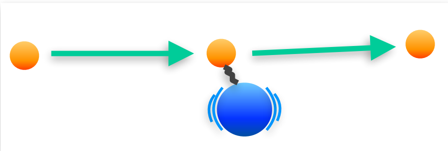
Polarized p beam at 295 MeV

High-resolution WS beam-line (dispersion matching)

High-resolution Spectrometer

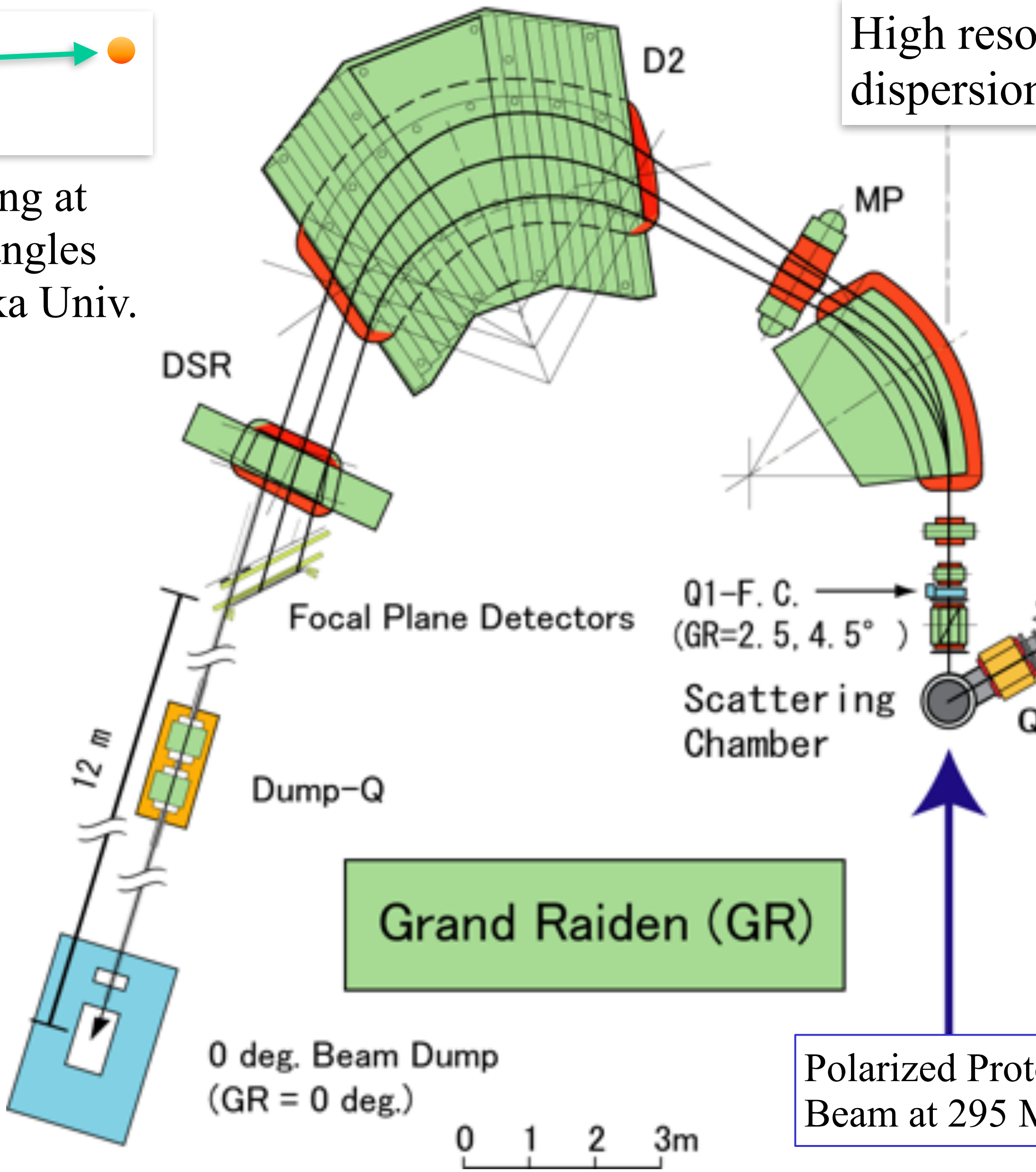
Grand Raiden

Missing mass spectroscopy by Coulomb Excitation



Proton scattering at very forward angles at RCNP, Osaka Univ.

High resolution of 20-30 keV: dispersion matching.

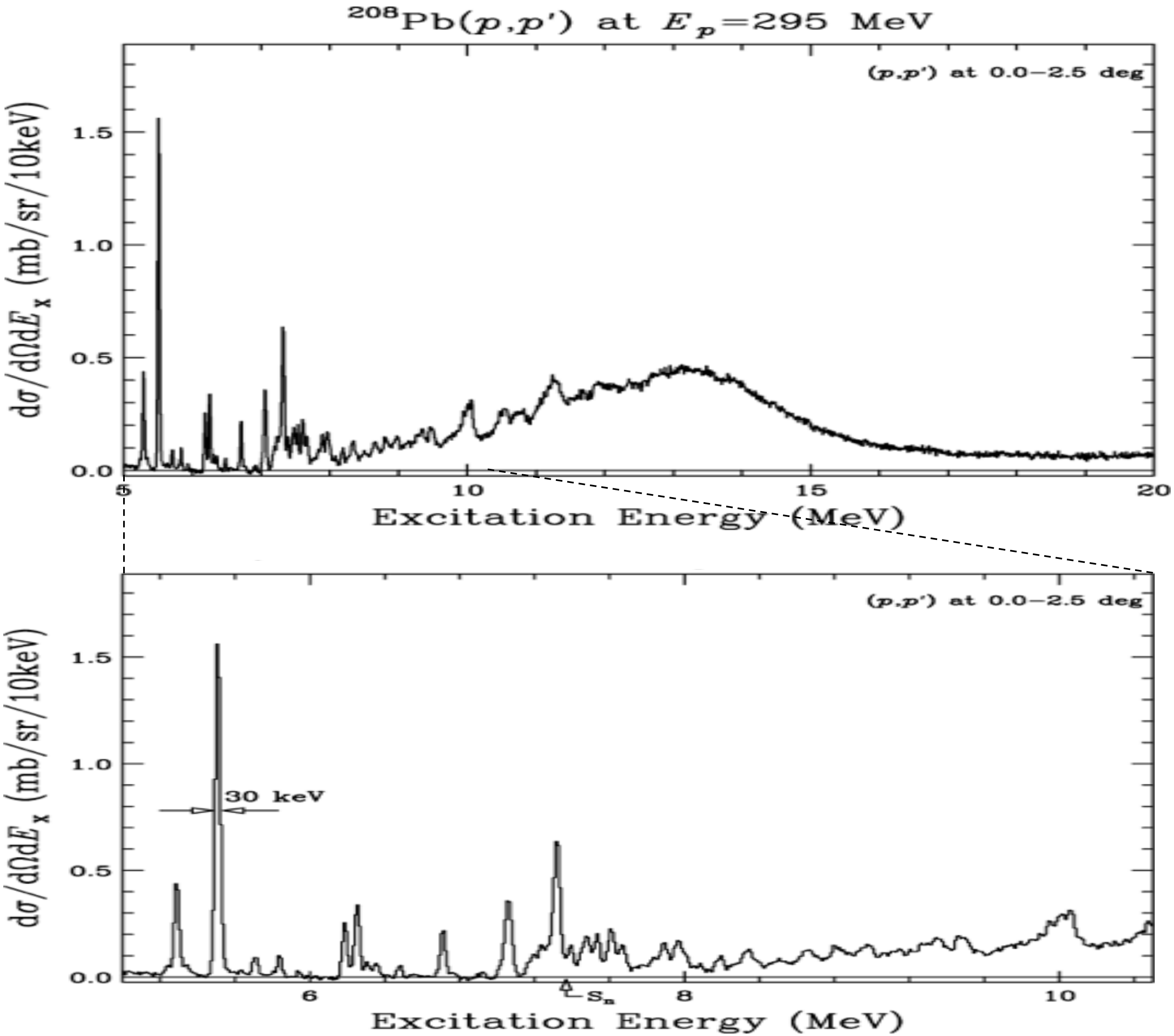


^{208}Pb target: 5.2 mg/cm^2

Intensity : 1-8 nA

Polarized Proton Beam at 295 MeV

AT et al., NIMA 605, 326 (2009)



^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE_x (mb/sr/10keV)
Excitation Energy (MeV)
(p,p') at 0.0–2.5 deg
30 keV
S_n
dσ/dΩdE_x (mb/sr/10keV)
Excitation Energy (MeV)

B(E1): continuum and GDR region

Method 2: Decomposition by Spin Observables

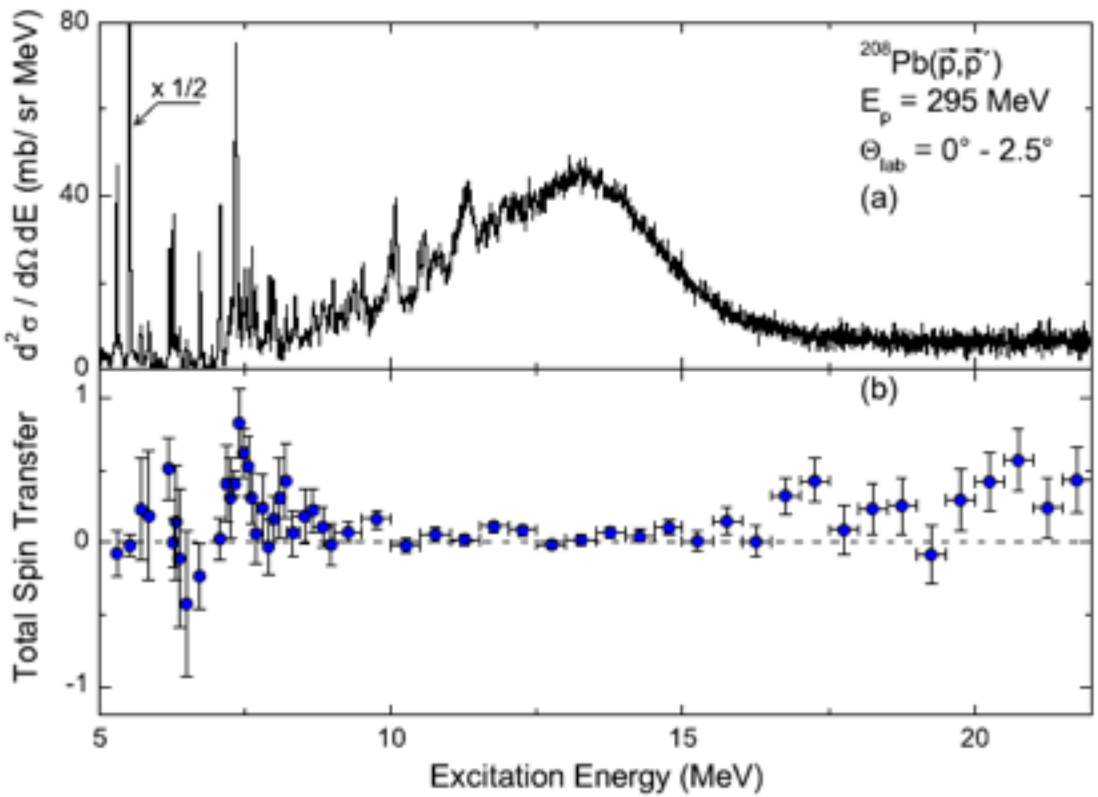
- Polarization observables at 0° → spinflip / non-spinflip separation

  model-independent

  E1 / spin-M1 decomposition

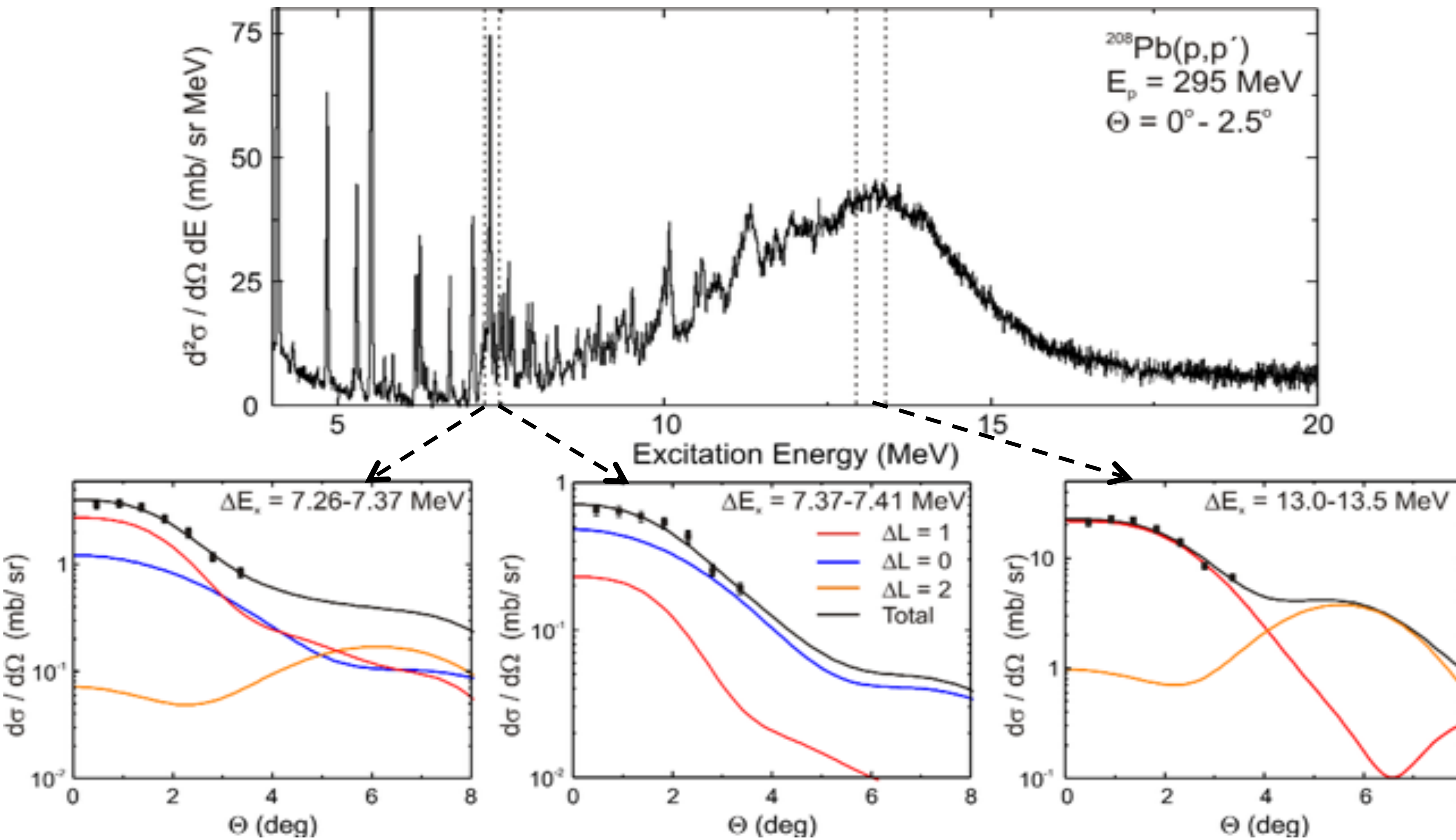
  T. Suzuki, PTP 103 (2000) 859

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



B(E1): continuum and GDR region

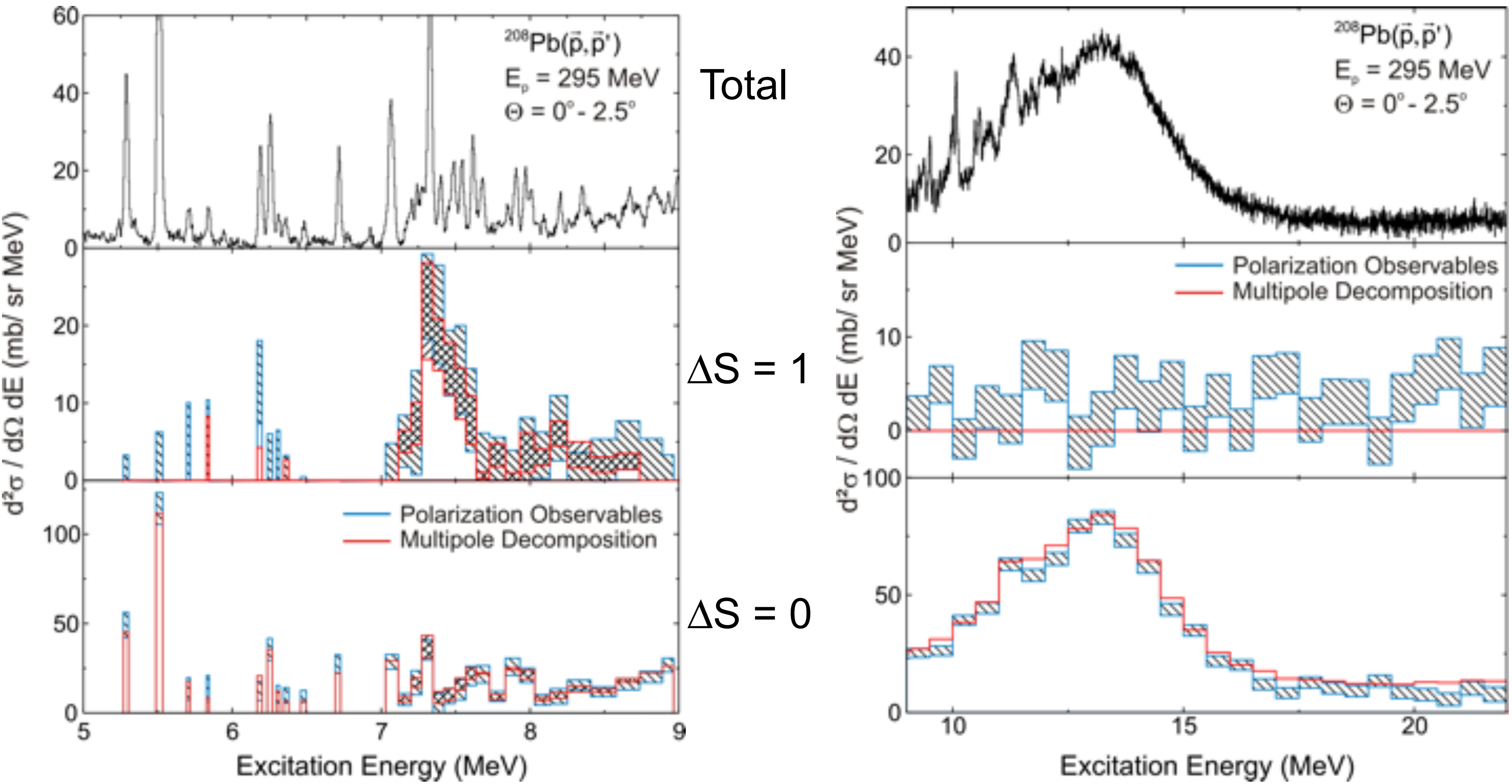
Method 1: Multipole Decomposition



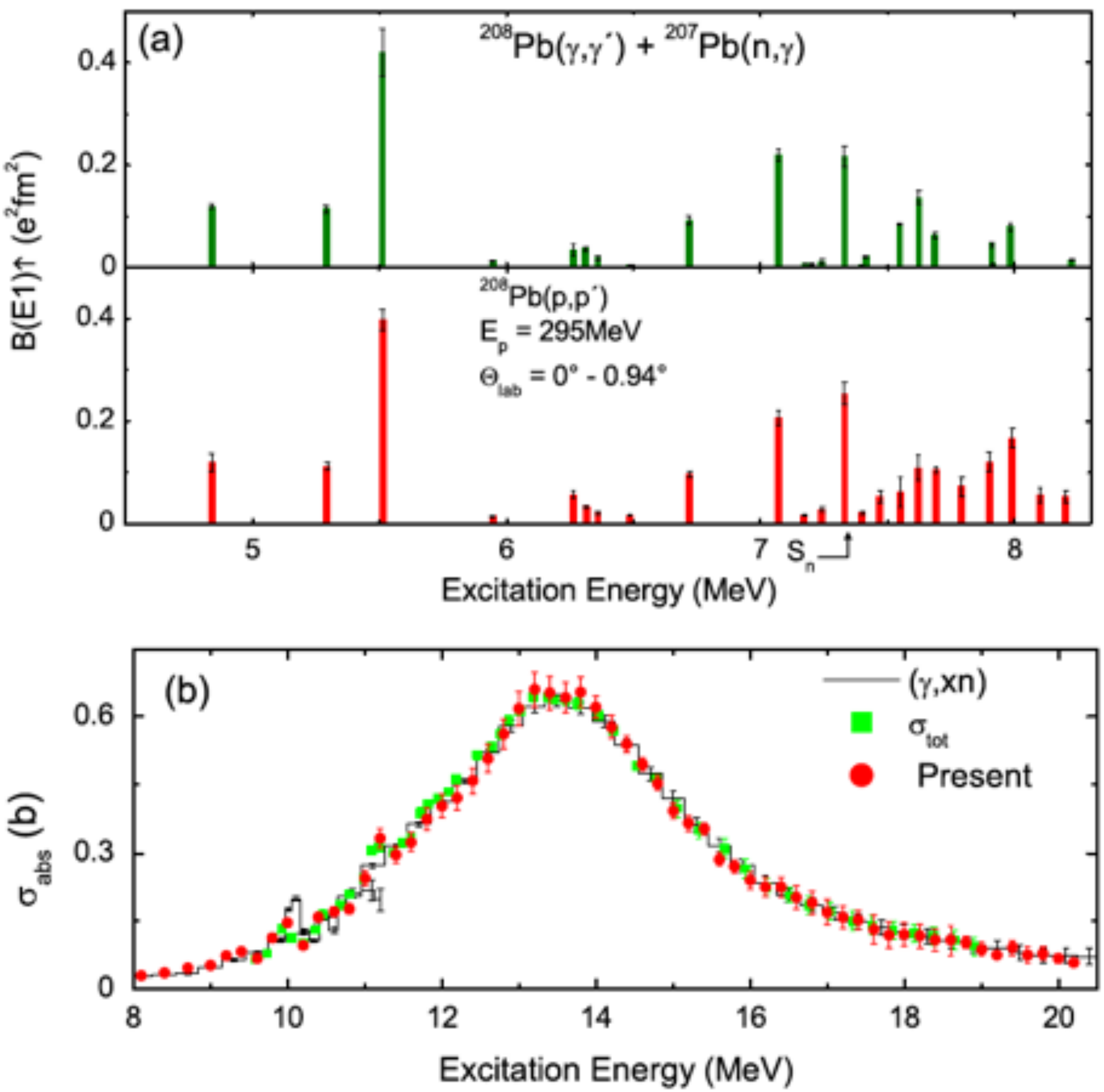
- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

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



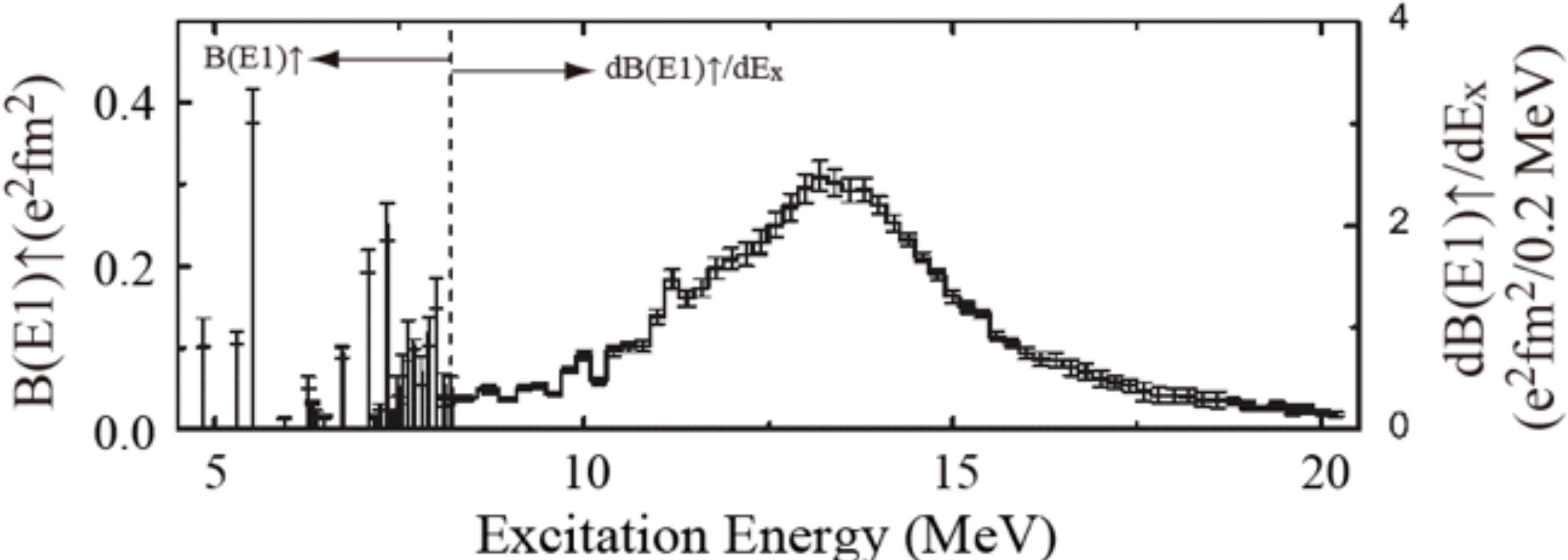
Comparison with (γ,γ’) and (γ,xn)



low-lying discrete states

GDR region

E1 Response of ^{208}Pb and α_D



E_x	0	10	20	130 MeV
α_D	2.7	16.2		1.2 fm³

total 20.1±0.6 fm³

combined data

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

AT et al., PRL107, 062502(2011)

Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn

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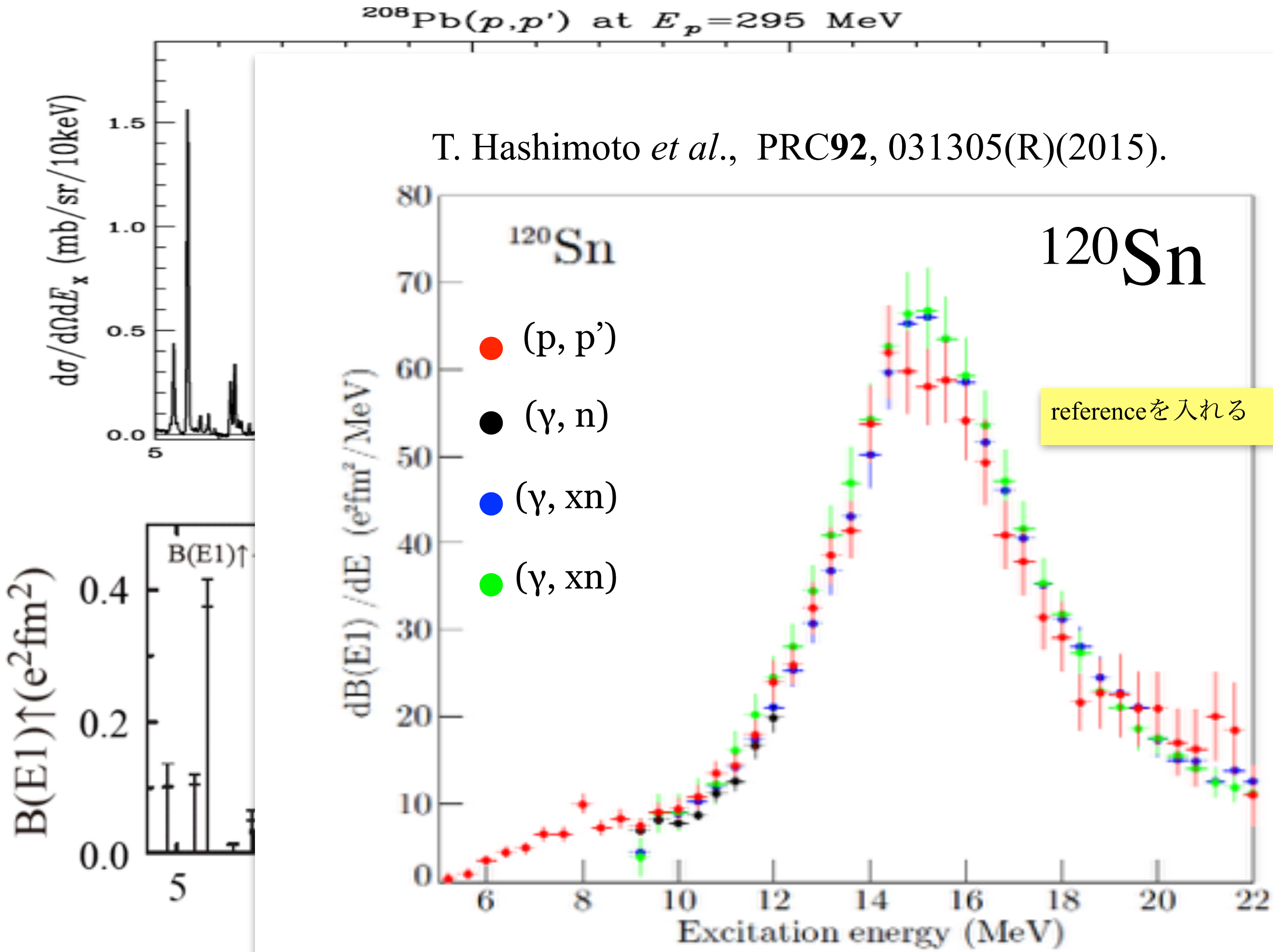
TECHNISCHE UNIVERSITÄT DARMSTADT

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



135 MeV

E_x 0

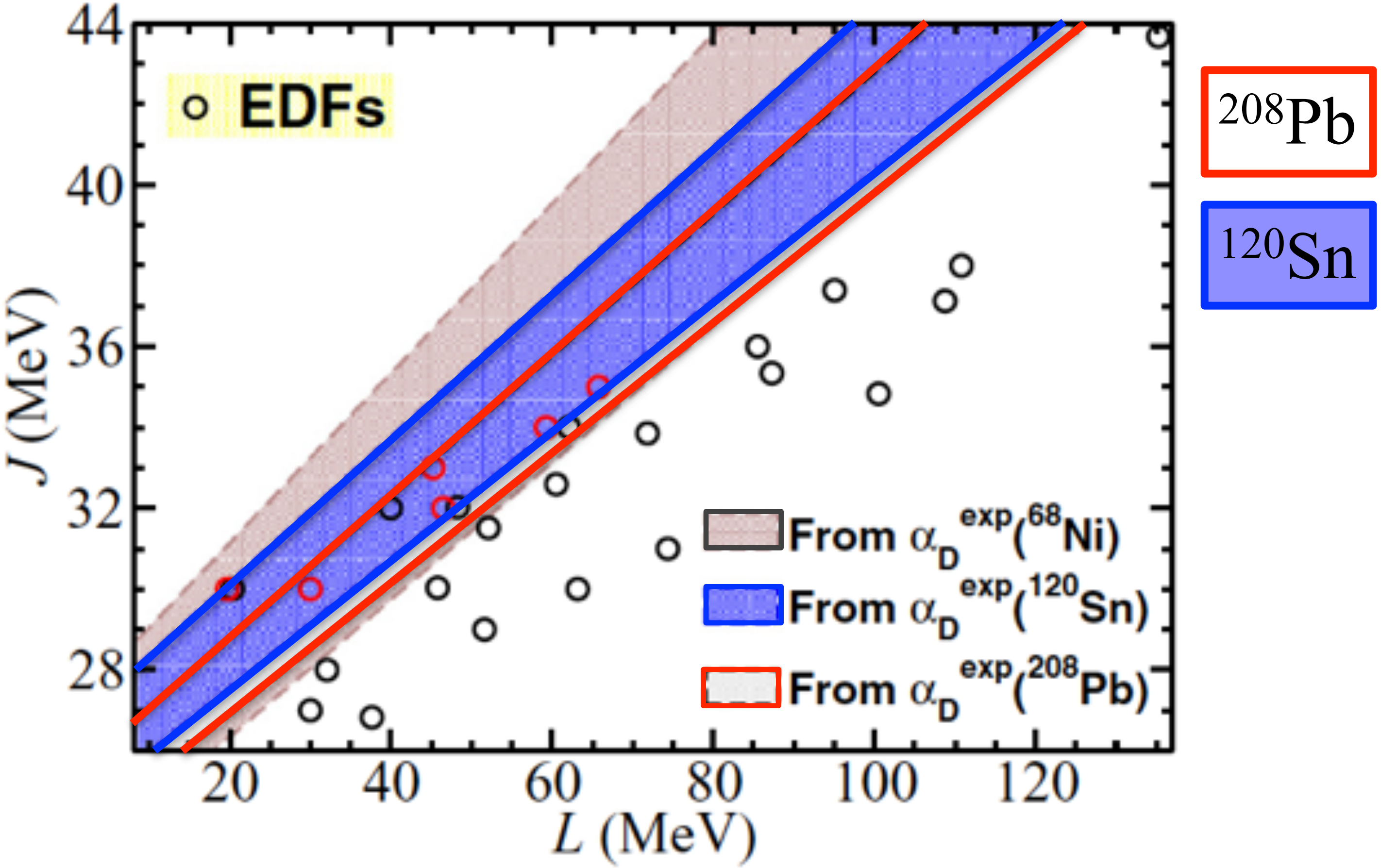
α_D

1.12 ± 0.07 | 7.00 ± 0.29 | 0.82 ± 0.12

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

Constraints on J-L and the n-skin thickness

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



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

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

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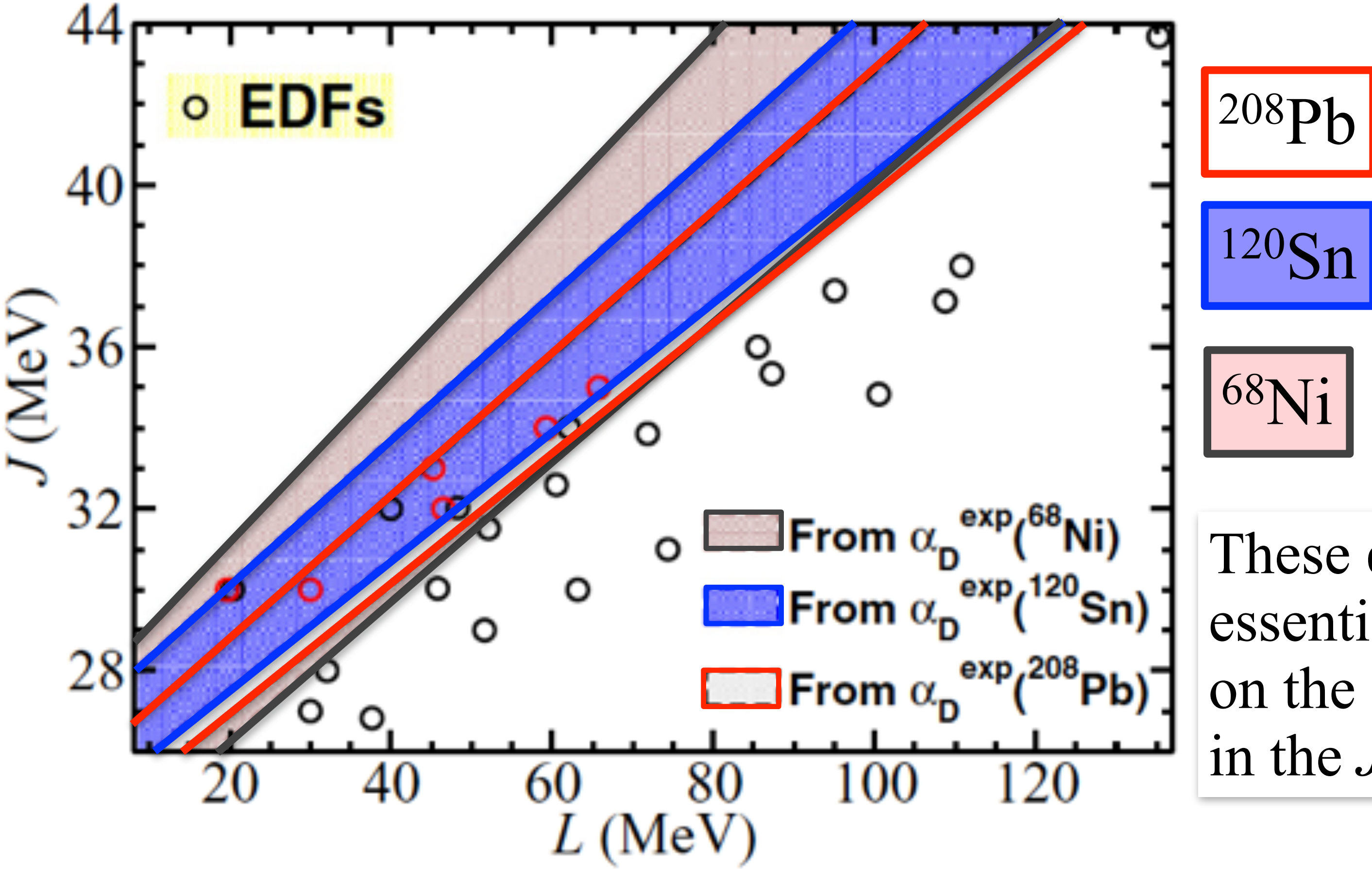


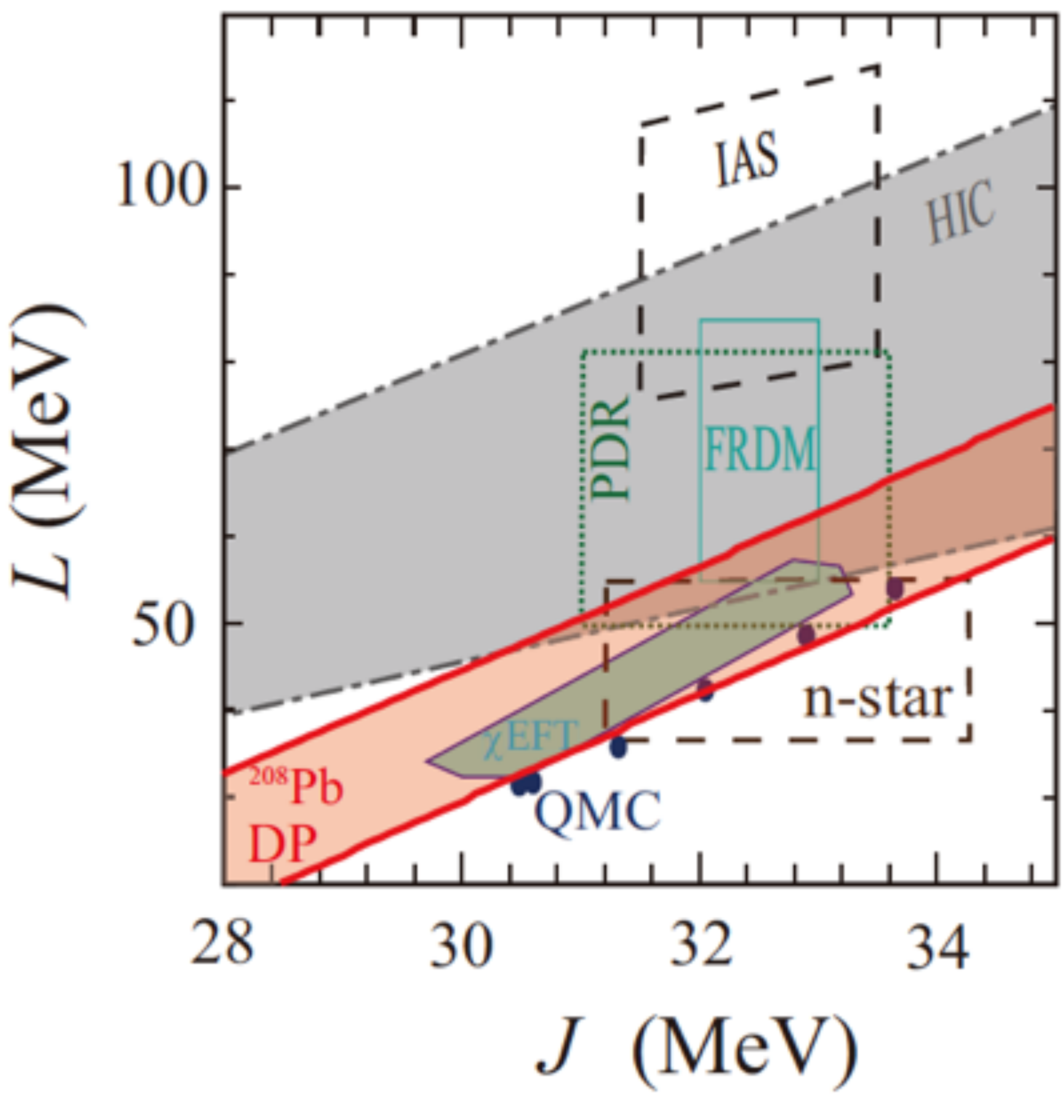
These α_D data give essentially one constraint on the symmetry energy in the *J*-*L* plane.

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

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

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

Constraints on J and L



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

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

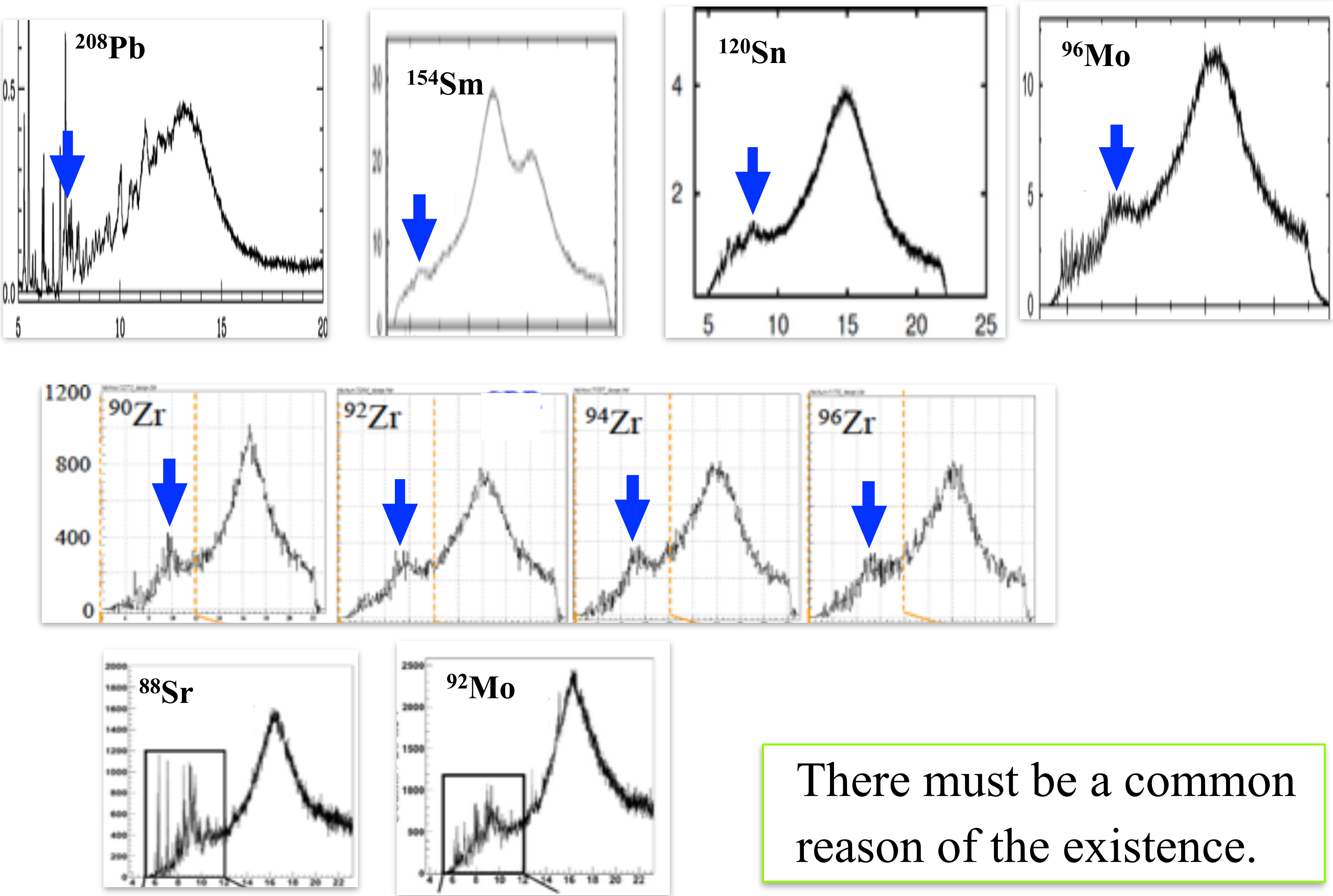
C.J. Horowitz et al., JPG41, 093001 (2014)

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)

Universal Existence of PDR in Nuclei with A > ~90 ?



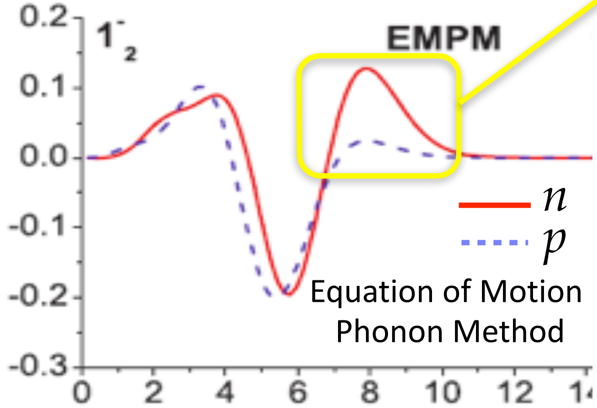
There must be a common reason of the existence.

Excess Neutron Oscillation of the PDR

Theoretical predictions of the transition densities.

^{208}Pb

PDR region

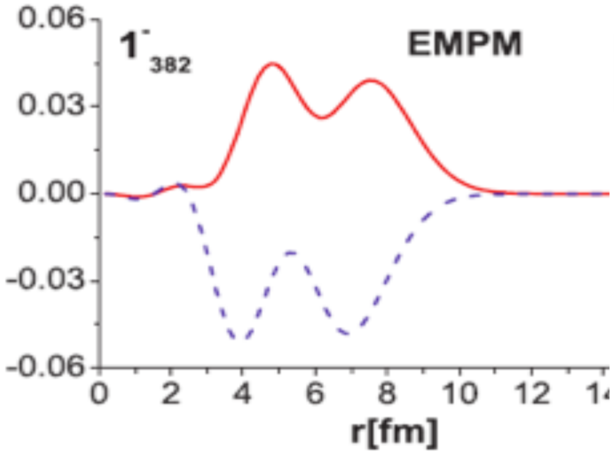


Dipole oscillation of the excess neutron on surface against the isospin saturated core?

In both the IS and IV response

Signature of the neutron excess oscillation
- surface sensitivity
- IS excitation
- characteristic q-dependence

GDR region



Out of phase *n*-*p* oscillation

Only in the IS response

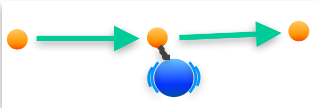
*D. Bianco et al., PRC **86** (2012) 044327*

Courtesy of A. Zilges

Experimental hints on the structure of the PDR

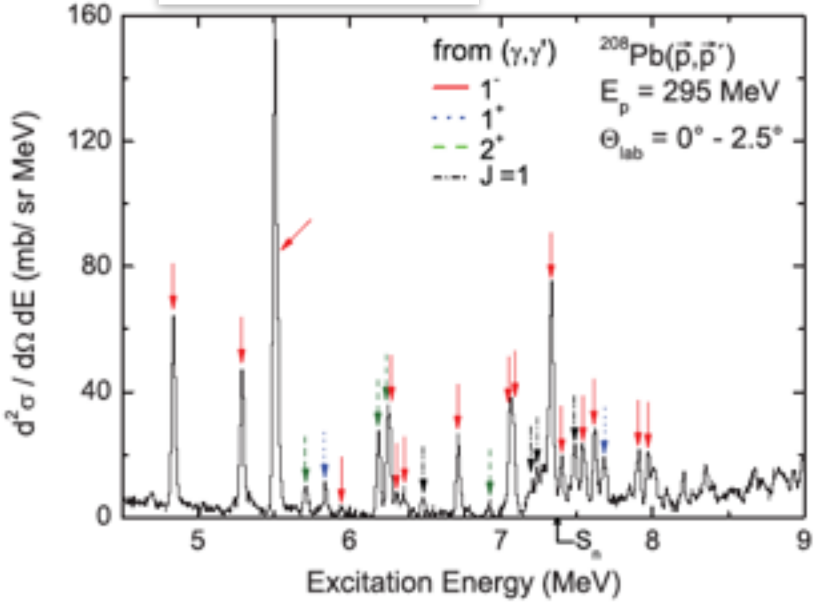
- Universal existence for nuclei with A~90?
- Splitting of the PDR strengths (α,α')⇔(γ,γ')
- Large cross section for surface sensitive probes
- Different angular distribution in (p,p') at forward angle?
- Splitting of PDR in deformed nuclei?
- Larger strength (in TRK) in neutron rich nuclei

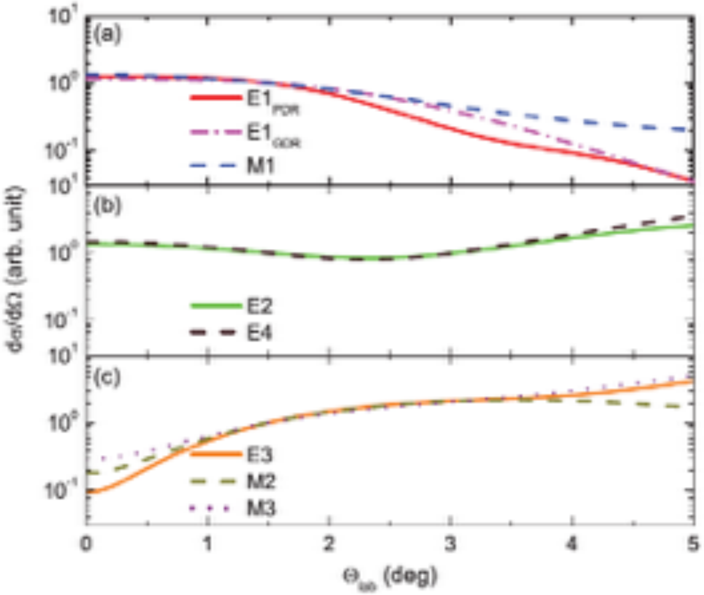
MDA of the E1 excitations

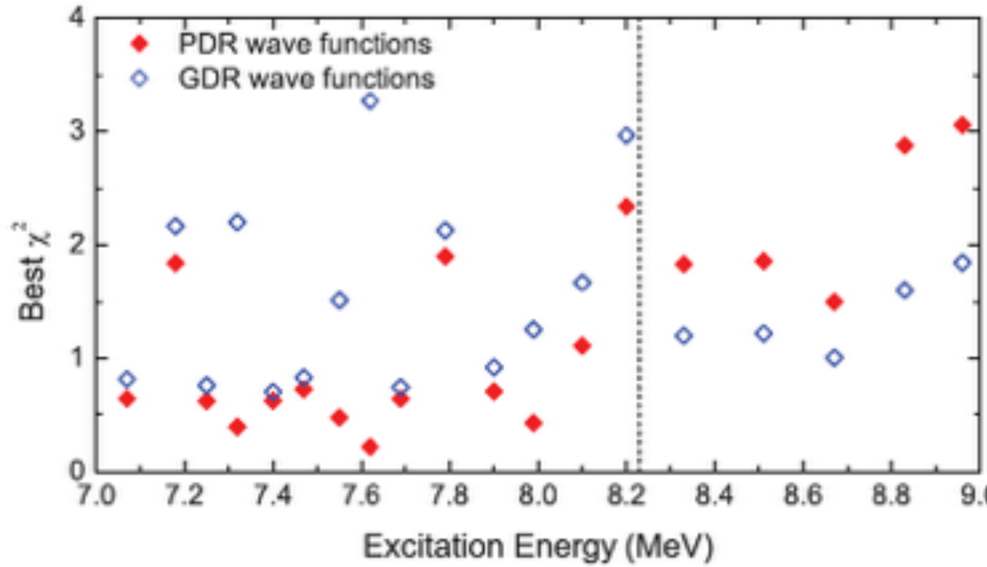


Proton scattering

^{208}Pb   I. Poltoratska et al., PRC85, 041304 (2012)







II.
Spin Magnetic Response of Nuclei

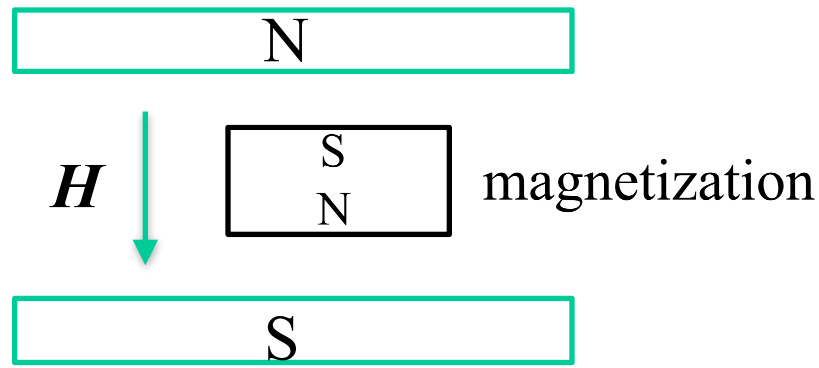
Spin Susceptibility

Magnetic dipole (*M1*) operator

$$O(M1) = g_\ell^{IS}\ell + \underline{g_s^{IS}\boldsymbol{\sigma}} + g_\ell^{IV}\ell\cdot\boldsymbol{\tau} + \underline{g_s^{IV}\boldsymbol{\sigma}\cdot\boldsymbol{\tau}}$$

IS(1) and IV(τ) terms

→ <u>**Magnetic Susceptibility**</u>



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

χ_σ: magnetic susceptibility

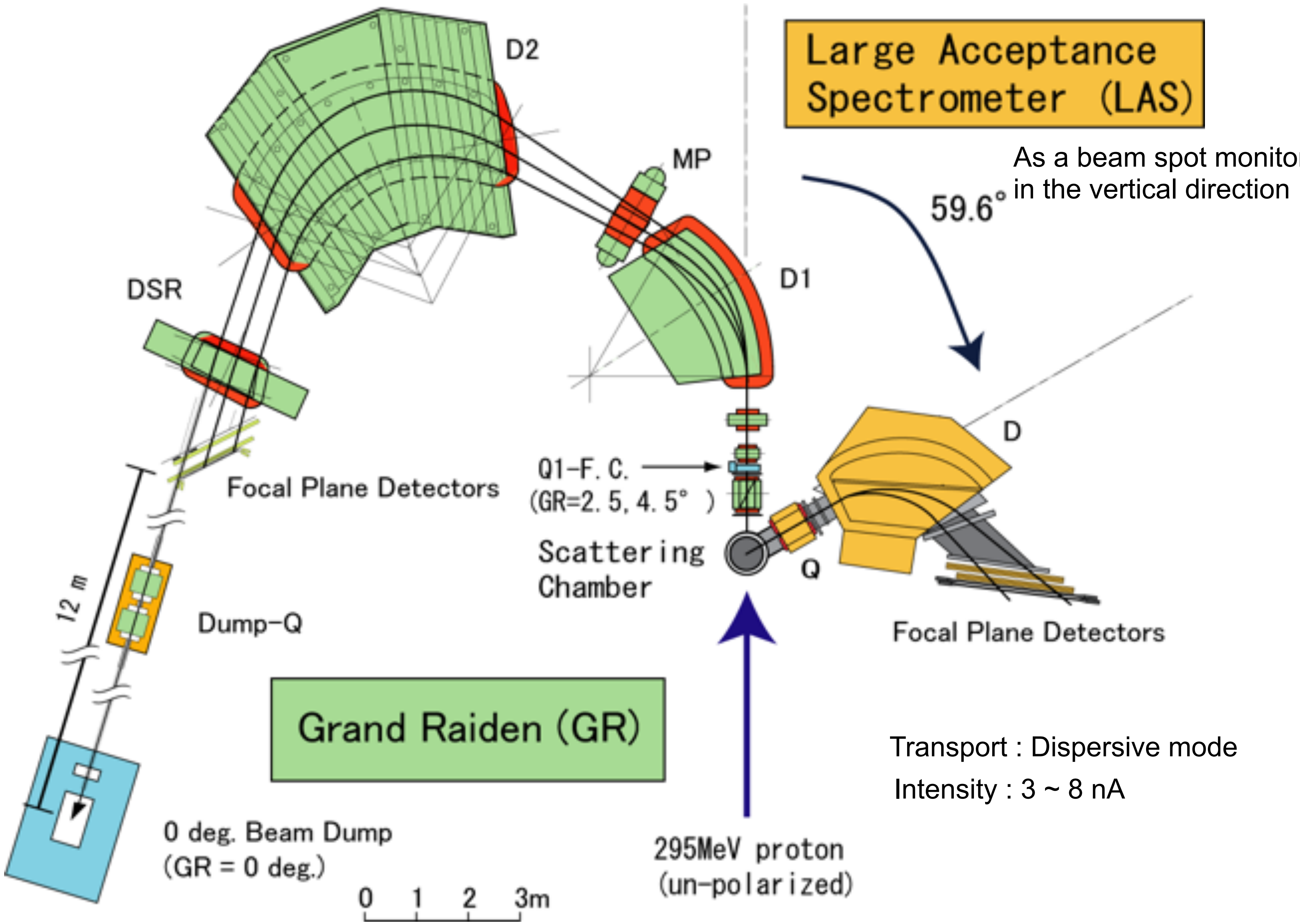
Inversely energy-weighted sum rule of the spin-M1 strengths

→ <u>**Spin Susceptibility**</u>

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

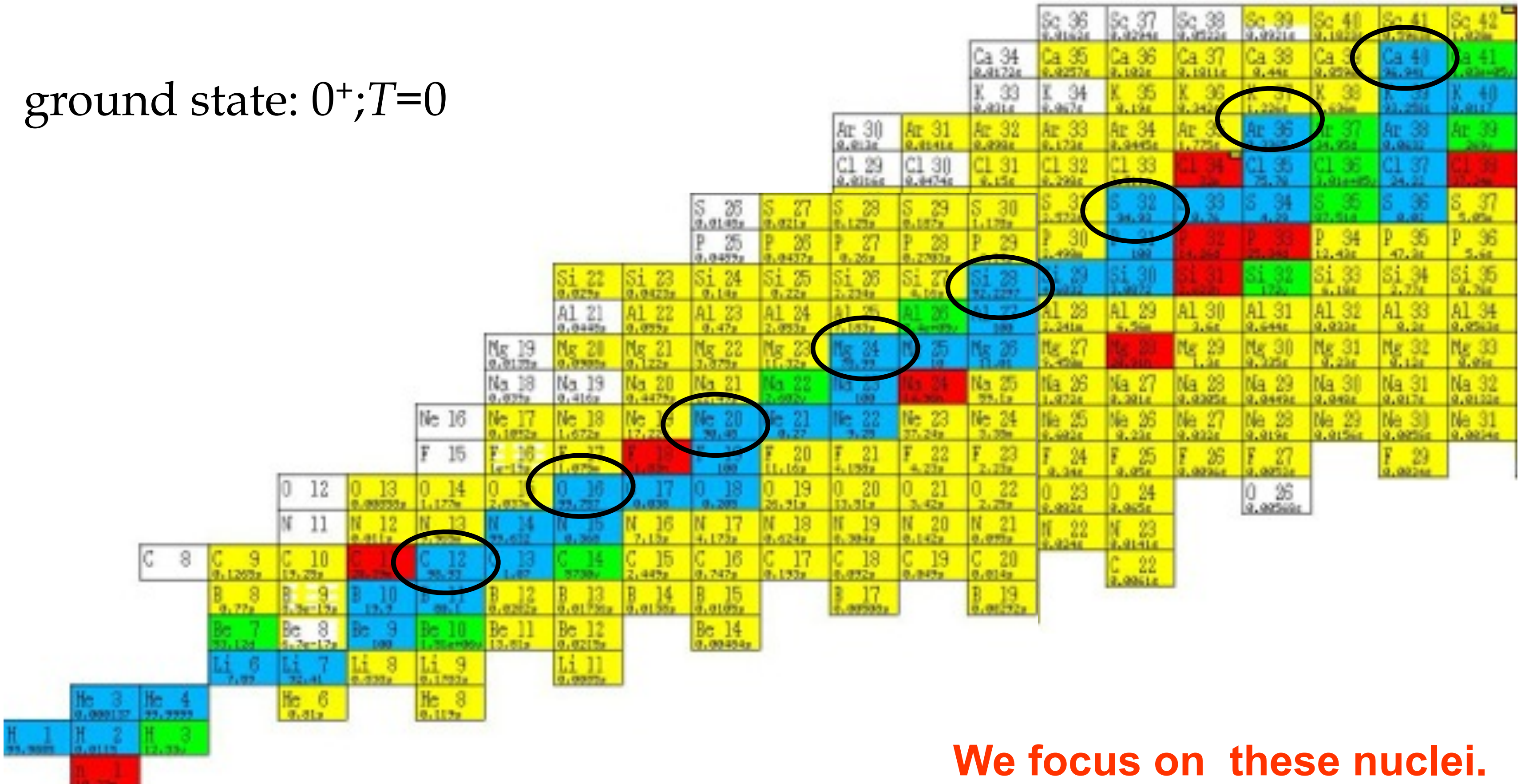
- magnetic response of nuclear matter (e.g. in a magnetar)
- ν-emissivity
- ν-transportation

Spectrometer Setup for 0-deg (p,p′) at RCNP



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

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

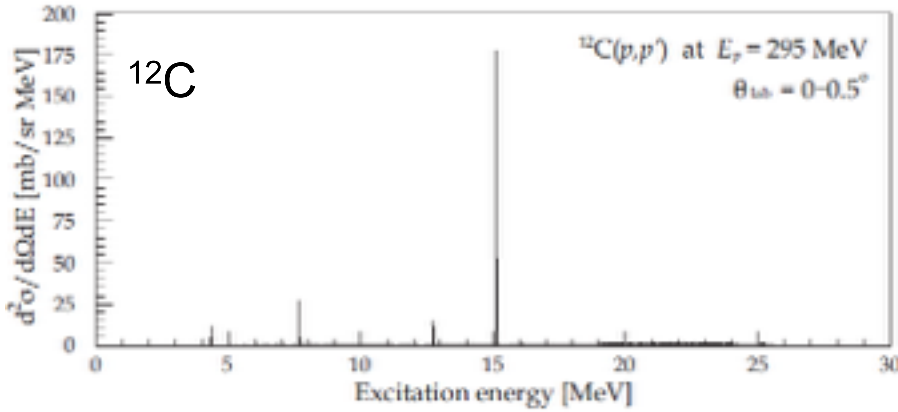


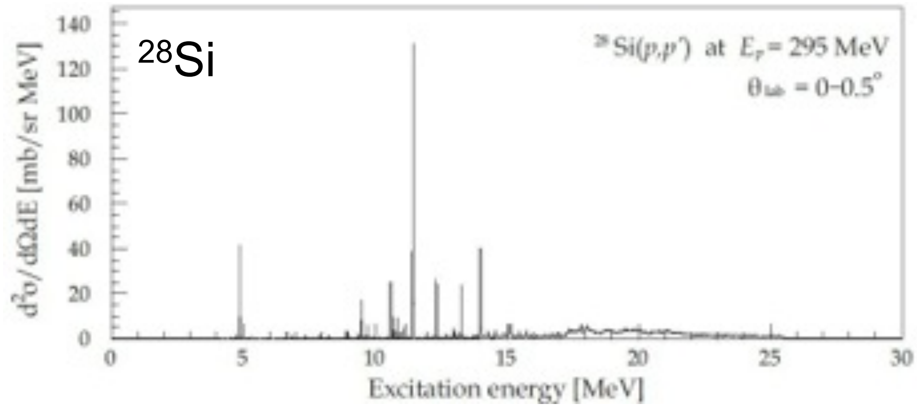
We focus on these nuclei.

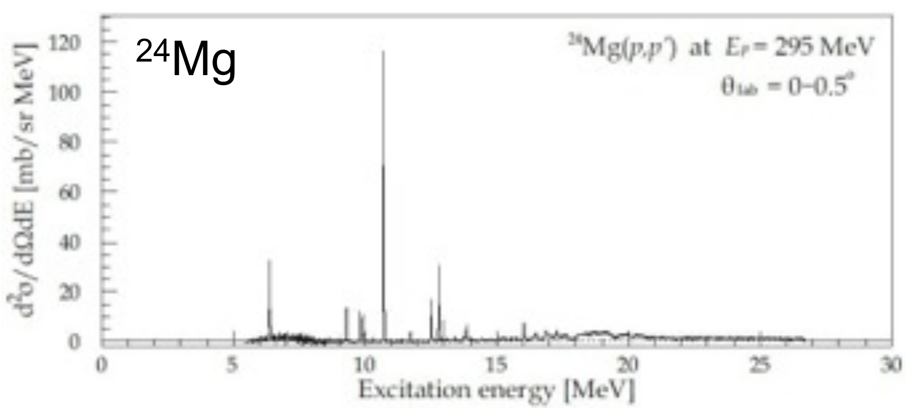
Stable self-conjugate even-even nuclei:

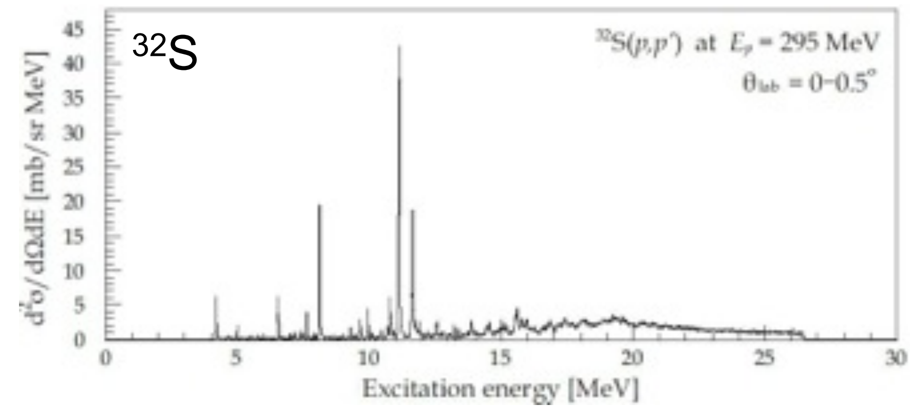
(^{4}He), ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca

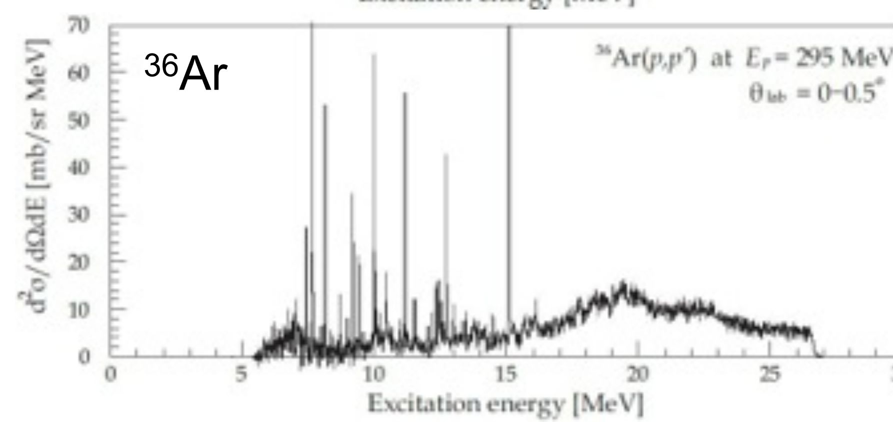
Energy spectra at 0-degrees



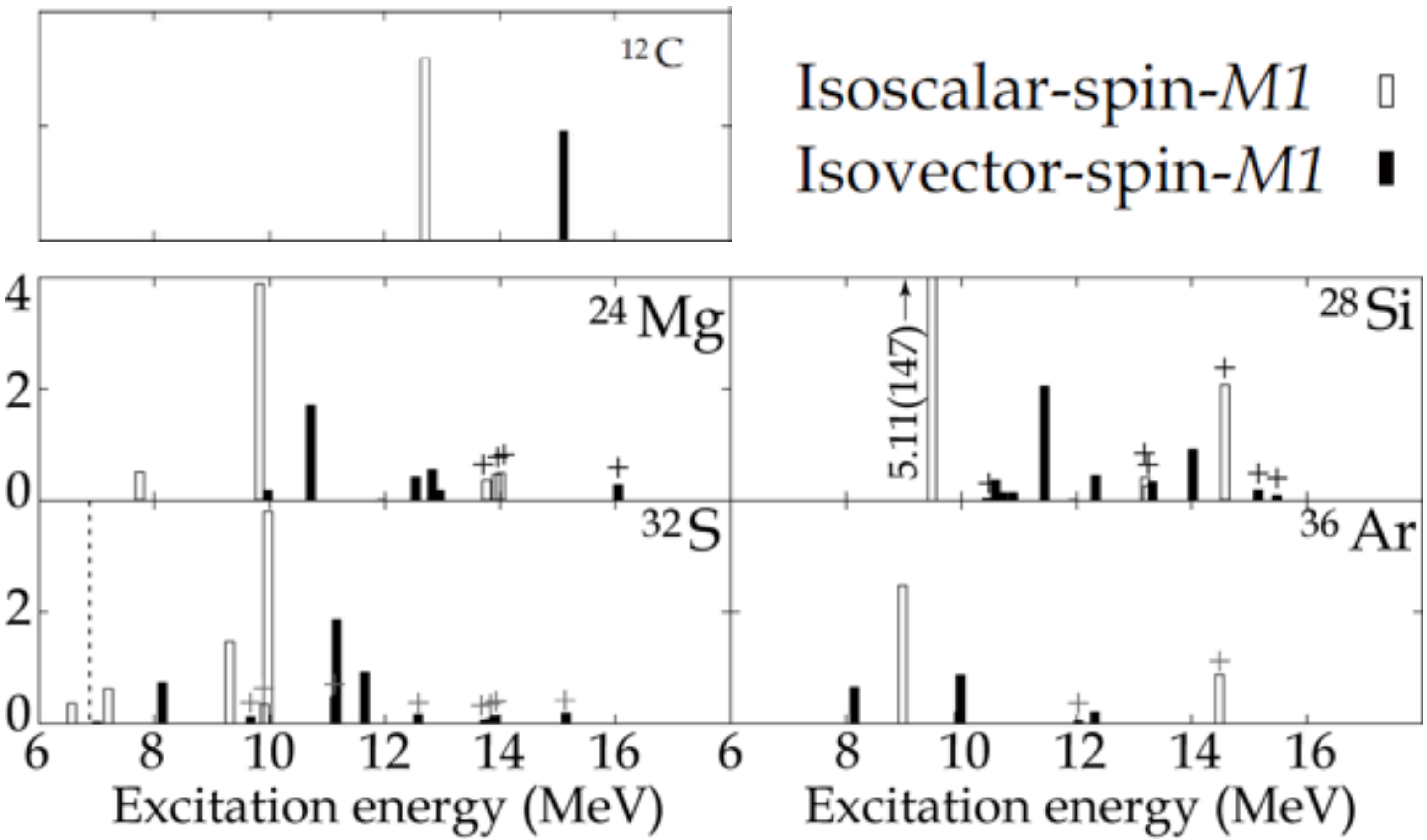








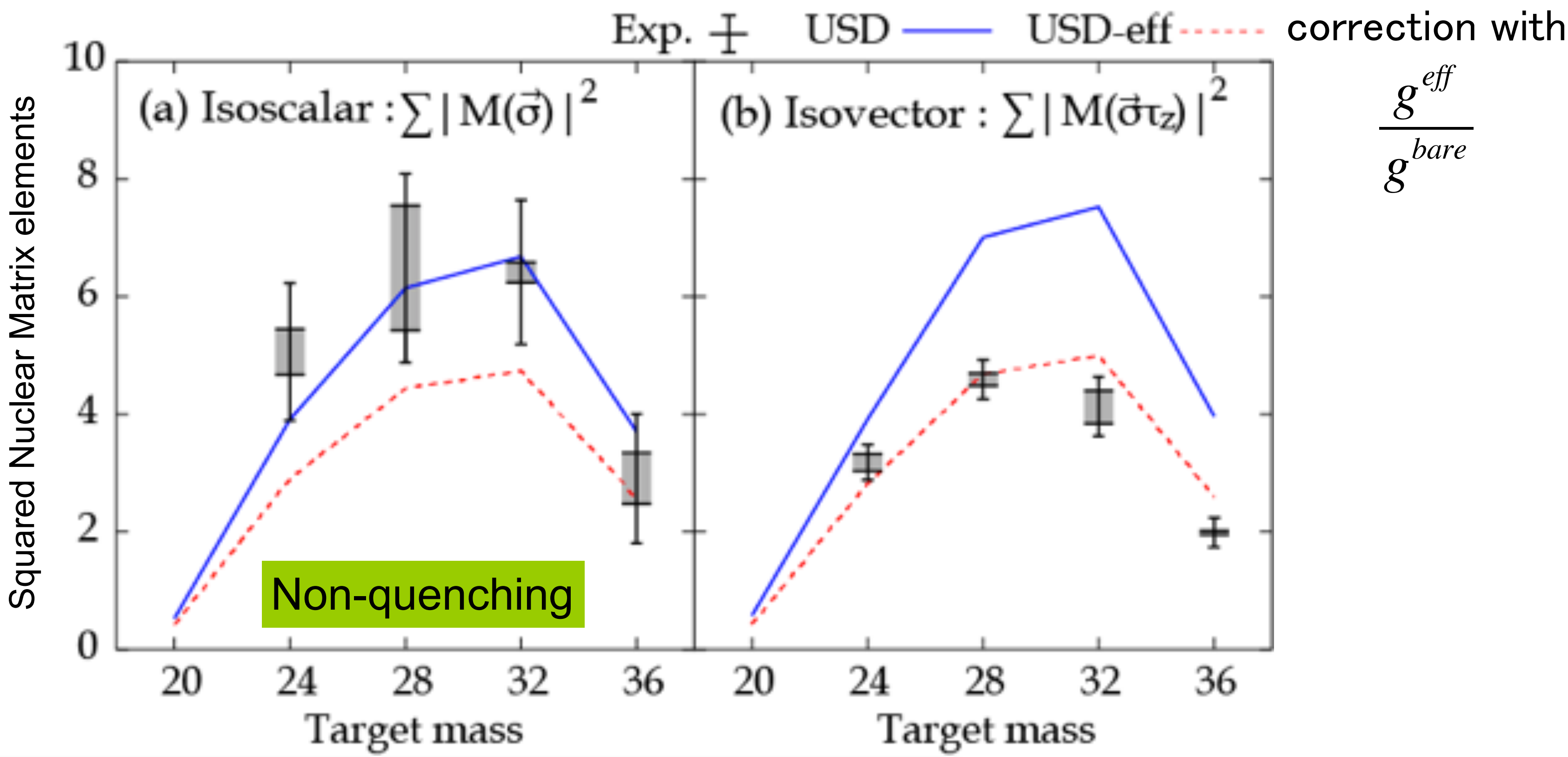
IS/IV-spin-M1 distribution



Spin-M1 SNME

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

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

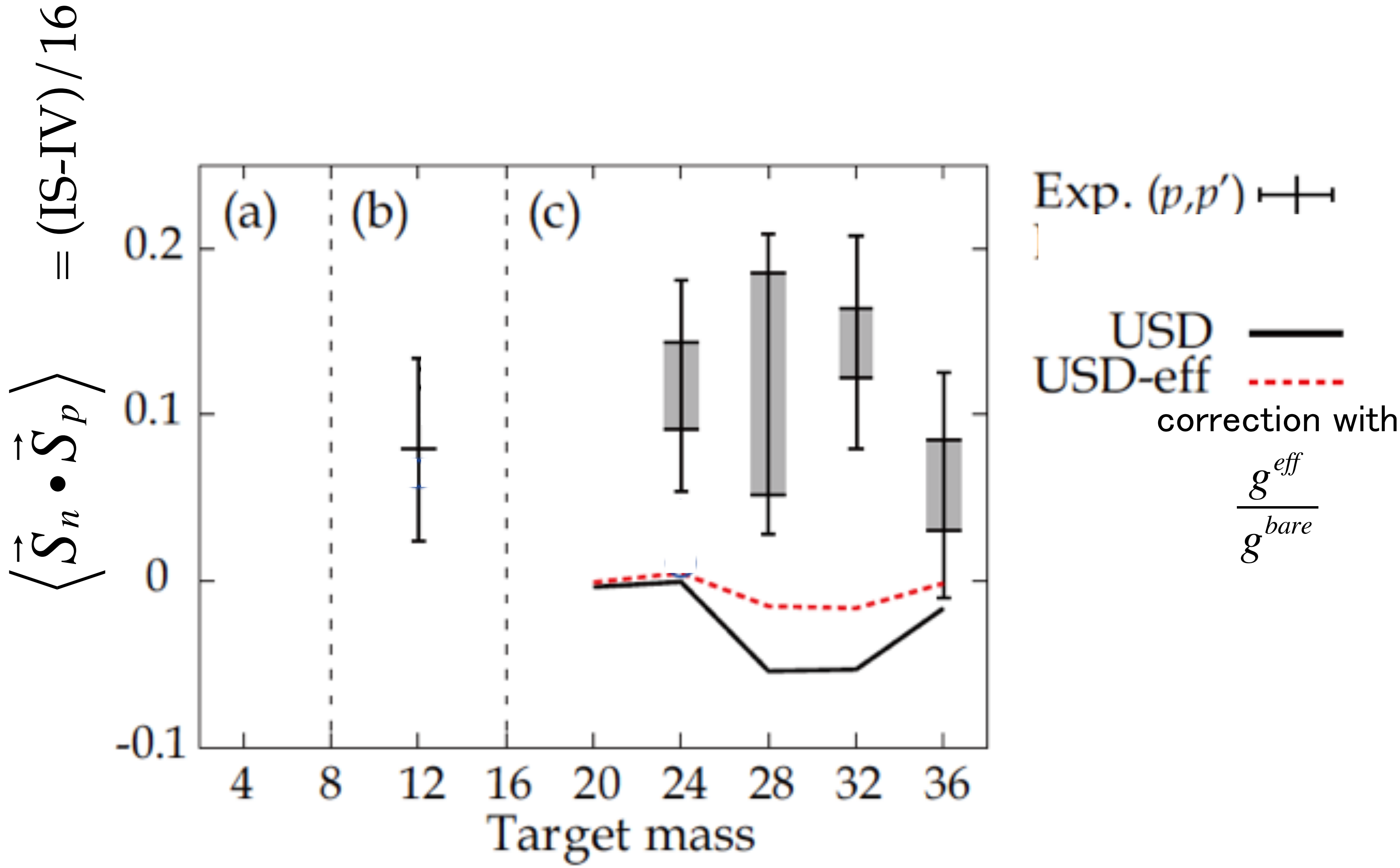


Isoscalar spin-M1 SNME is NOT quenching.

np Spin Correlation Function

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

Shell-Model: USD interaction



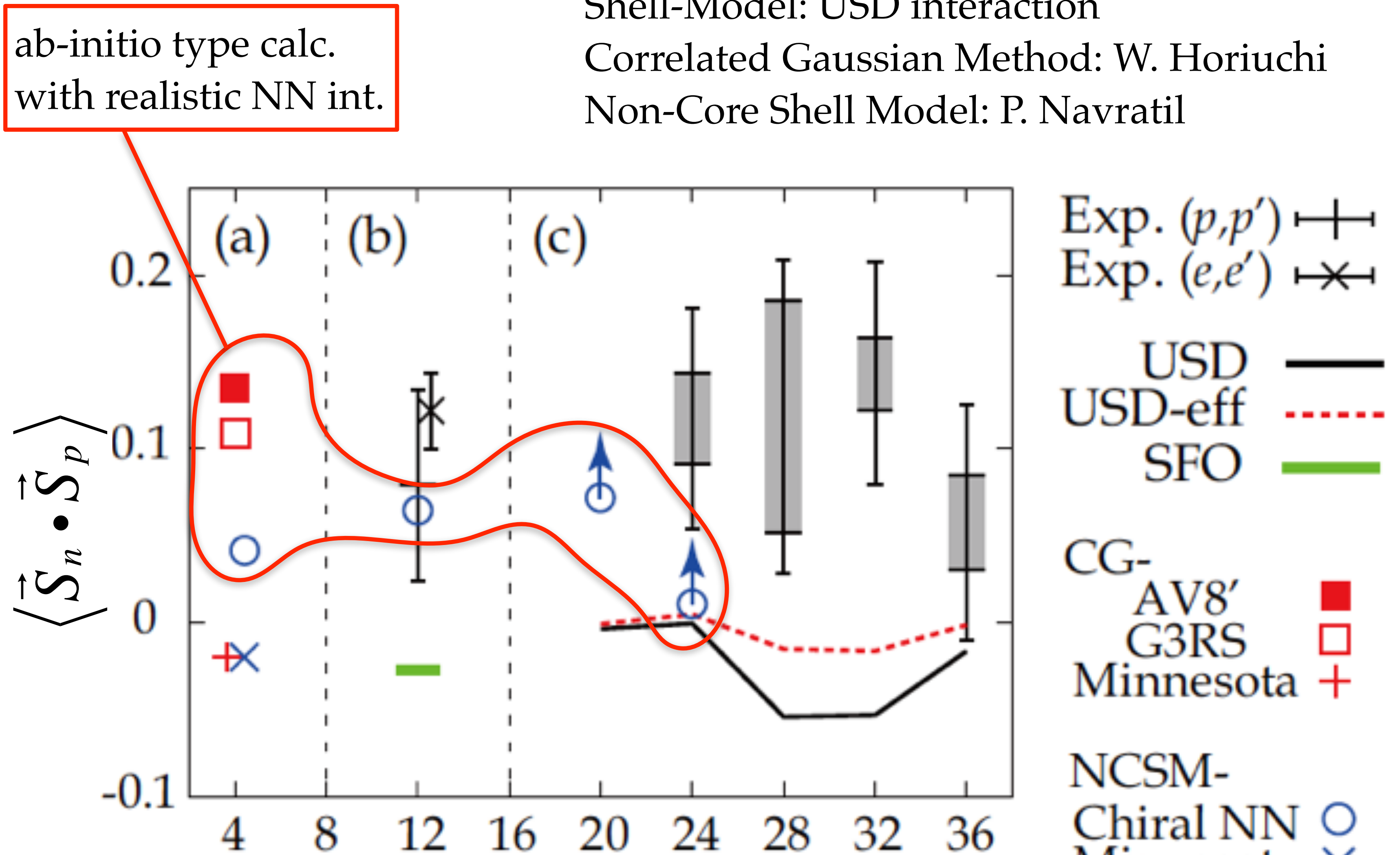
np Spin Correlation Function

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

Shell-Model: USD interaction

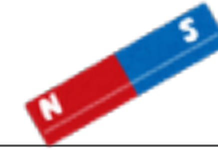
Correlated Gaussian Method: W. Horiuchi

Non-Core Shell Model: P. Navratil



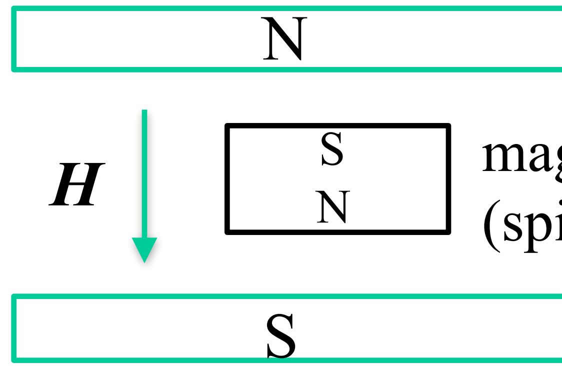
Relevance to tensor correlation and *np*-paring in nuclear ground states

Spin Susceptibility



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

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

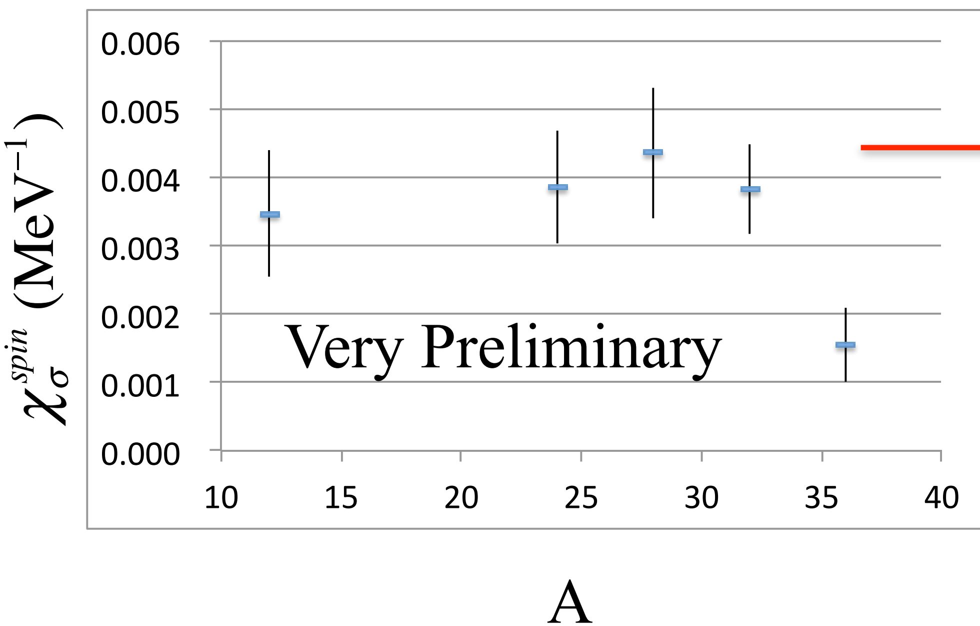


magnetization (spin part)

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

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

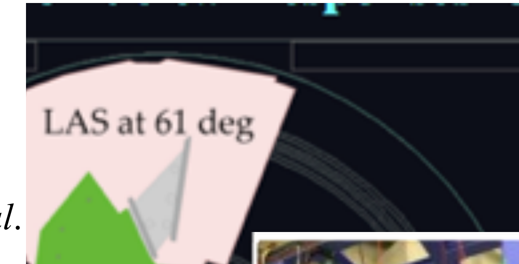
G. Shen et al., PRC**87**, 025802 (2013)

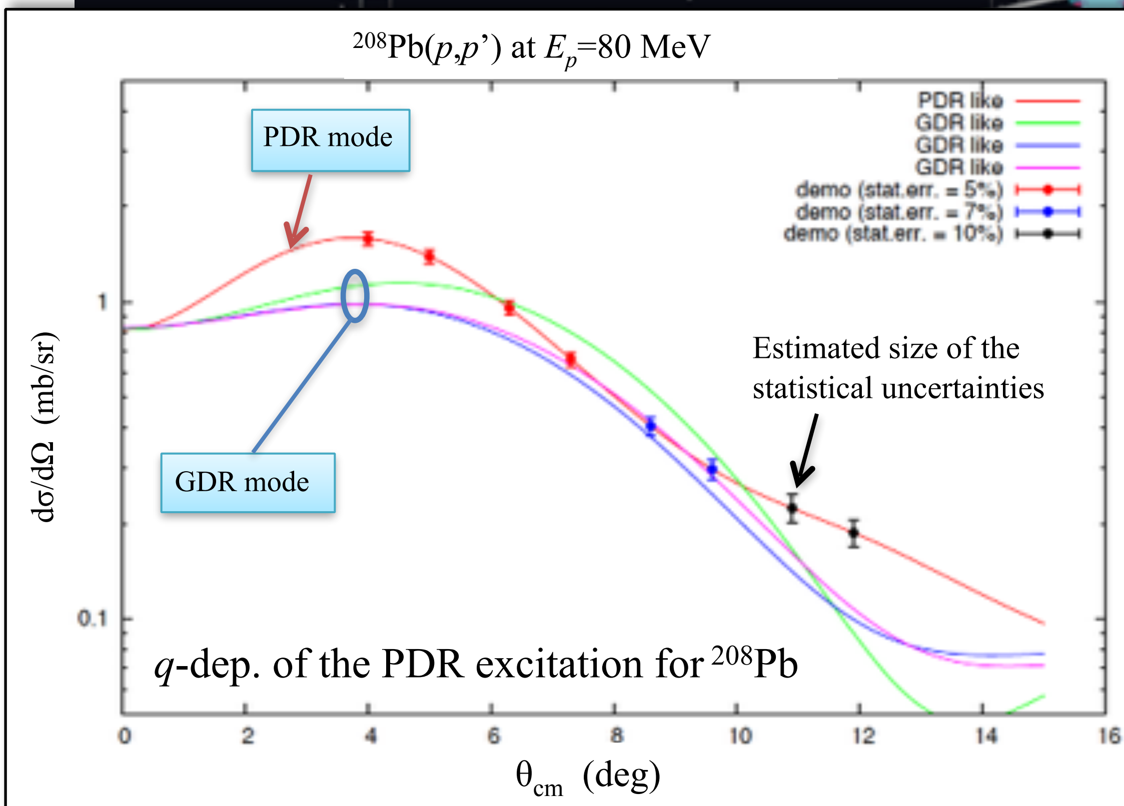
Further theoretical analysis is required.

CAGRA+GR Campaign Exp. From Oct. 2016

1. **Structure of the PDR *1** (α,α'γ) and (p,p'γ) on ^{58}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb
2. Inelastic ν-nucleus response, S. Noji et al.,
3. Super-deformed states, high-spin states, D. Jenkins et al.,

*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.*





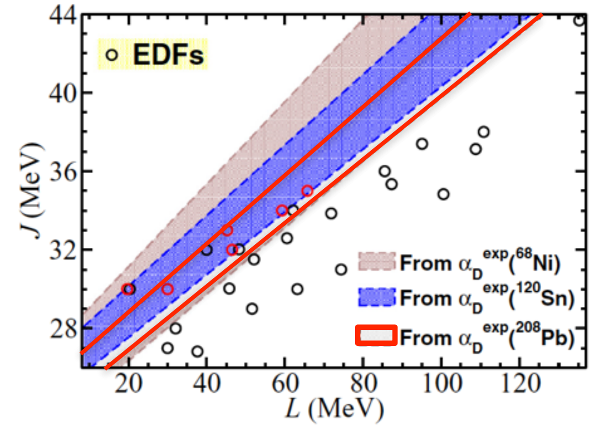
q-dep. of the PDR excitation for ^{208}Pb

Talk by M. Carpenter tomorrow

Summary

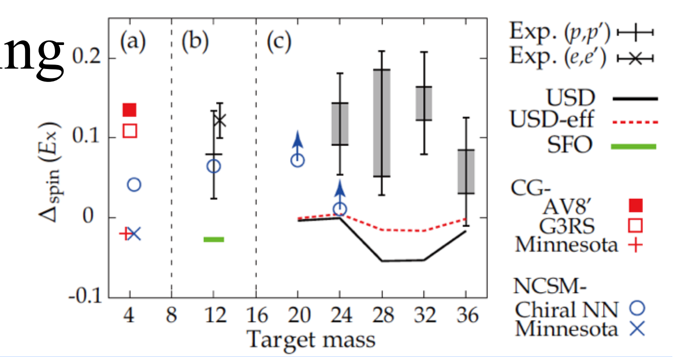
- The electric dipole response of nuclei is one of the fundamental properties nuclei.

  A constraint band has been obtained for the symmetry energy parameters from the measured electric dipole polarizability.



- Spin magnetic response of nuclei has been measured for N=Z even even nuclei in the sd-shell.

  The IS spin excitation strength is not quenching while the IV spin excitation strength is quenching as the Gamow-Teller strength.



Thank you

for your attention