Electromagnetic Response of Nuclei Studied by Proton Scattering

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Busan, September 10-13, 2018

Outline

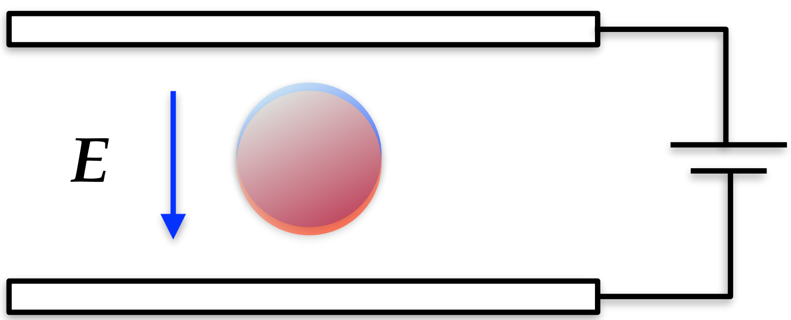
1. Electric dipole responses of atomic nuclei (published works)

   Electric dipole polarizability of ^{208}Pb, ^{120}Sn and ^{48}Ca

   Constraints on the symmetry energy parameters

2. Gamma coincidence measurements (on-going projects)

Electric Dipole Response of Nuclei



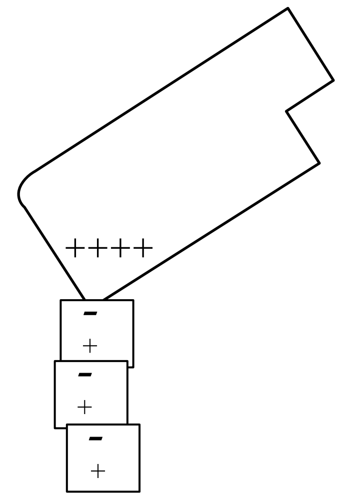
Polarization in Static Electricity

Electrostatic Phenomenon:

Photo from *Fundamentals of Physics, Electricity and Magnetism*, Halliday/Resnick/Walker

Polarization in Static Electricity

Electrostatic Phenomenon:
Electric Polarization



Charge in the comb

⟶ induces polarization in a neutral paper

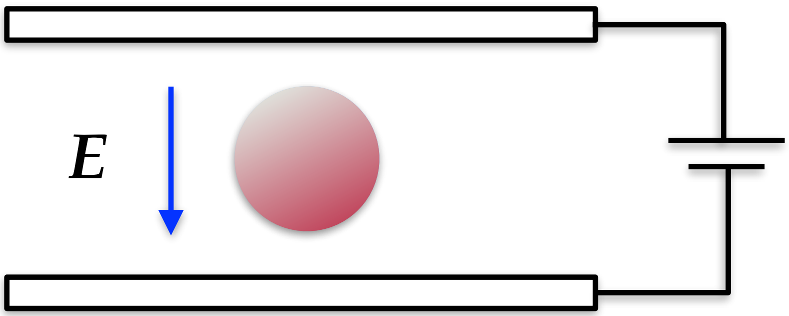
⟶ The paper is attracted by the comb.

⟶ The next paper is polarized and is attracted.

Photo from *Fundamentals of Physics, Electricity and Magnetism*, Halliday/Resnick/Walker

Electric Dipole Polarizability of Atomic Nuclei

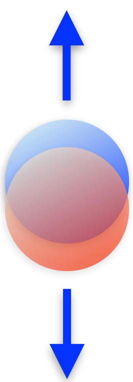
Electric Dipole Polarizability (EDP)



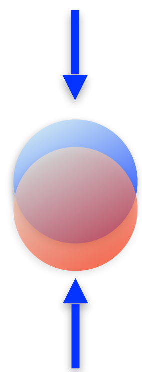
$$p = \alpha_D E$$

p: electric dipole moment

α_D: electric dipole polarizability



Separating force from the electric potential

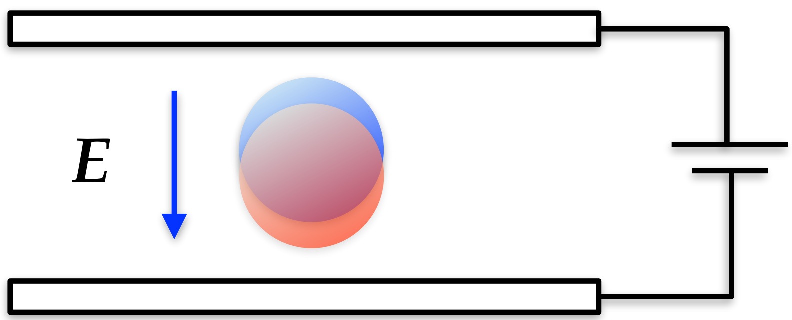


Restoring force is essentially originated from the symmetry energy

Electric dipole polarizability is determined by the balance between the electric potential and the symmetry energy.

Electric Dipole Polarizability of Atomic Nuclei

Electric Dipole Polarizability (EDP)



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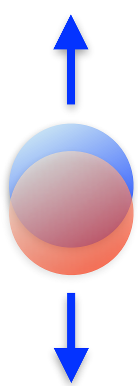


Separating force from the electric potential

Restoring force is essentially originated from the symmetry energy

Electric dipole polarizability is determined by the balance between the electric potential and the symmetry energy.

Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

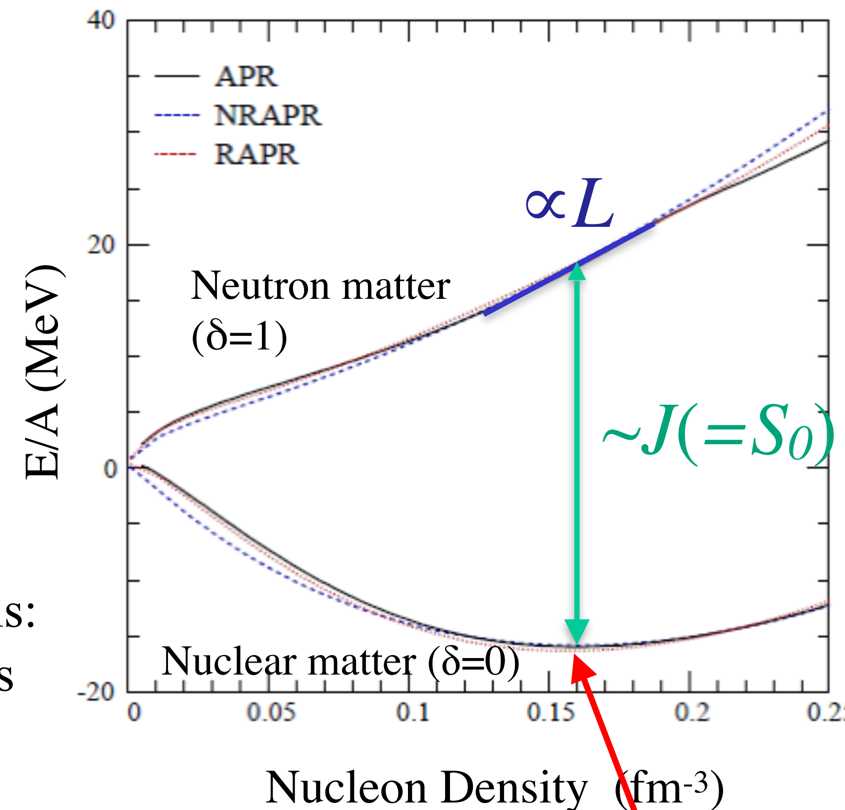
$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\delta^2+\cdots$$

$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

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

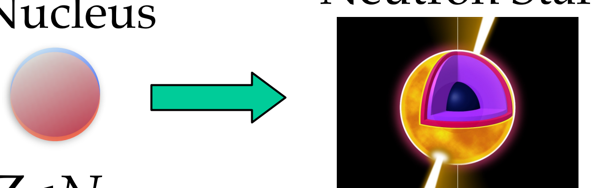
⇔ difference between *p-n* chemical potentials: how the system energy changes when protons are replaced by the neutrons



Saturation Density ρ_0

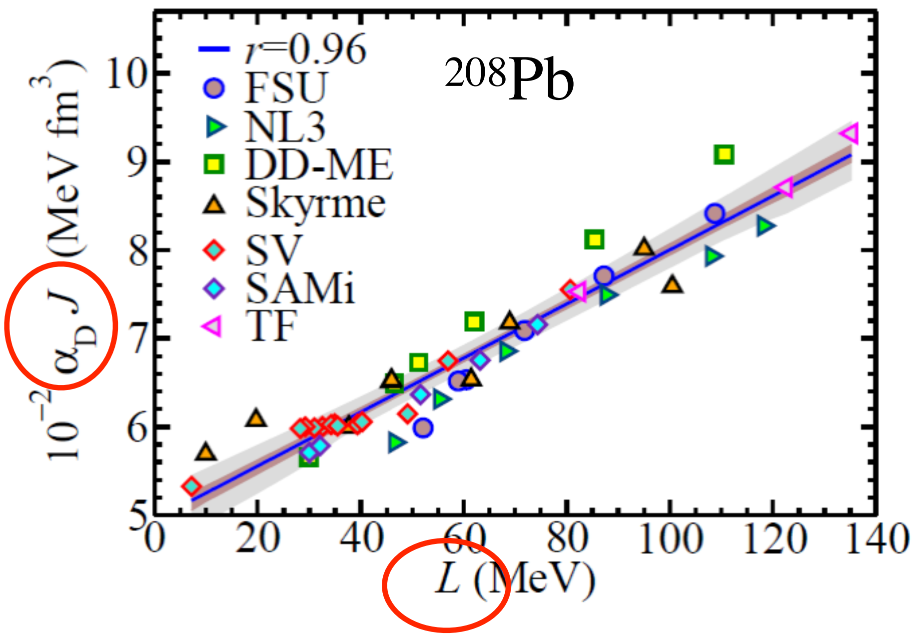
~ 0.16 fm^{-3}

Nucleus
Neutron Star



$Z \lesssim N$ $Z \ll N$

Electric dipole polarizability (α_D) is sensitive to the symmetry energy parameters



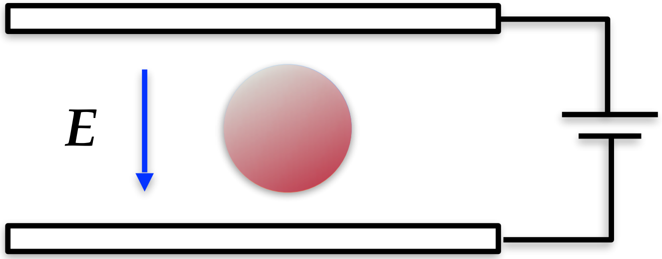
X. Roca-Maza *et al*., PRC**88**, 024316(2013)

Correlations observed in various interaction sets.

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

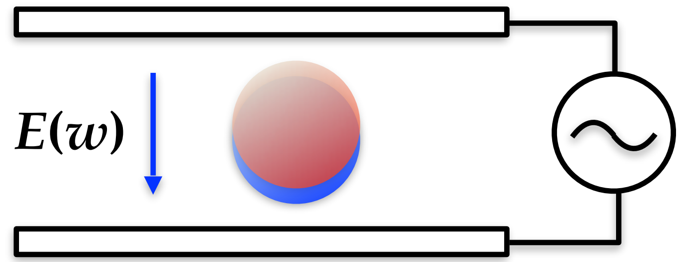
Precise determination of α_D gives a constraint band in the *J*-*L* plane.

EDP is determined from the photo-absorption cross sections



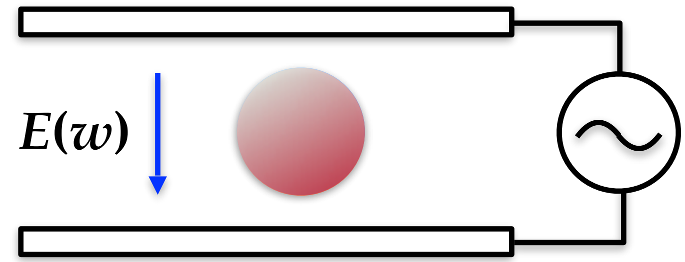
dielectric material
in a static electric field

EDP is determined from the photo-absorption cross sections



dielectric material
in an oscillating electric field

EDP is determined from the photo-absorption cross sections



dielectric material
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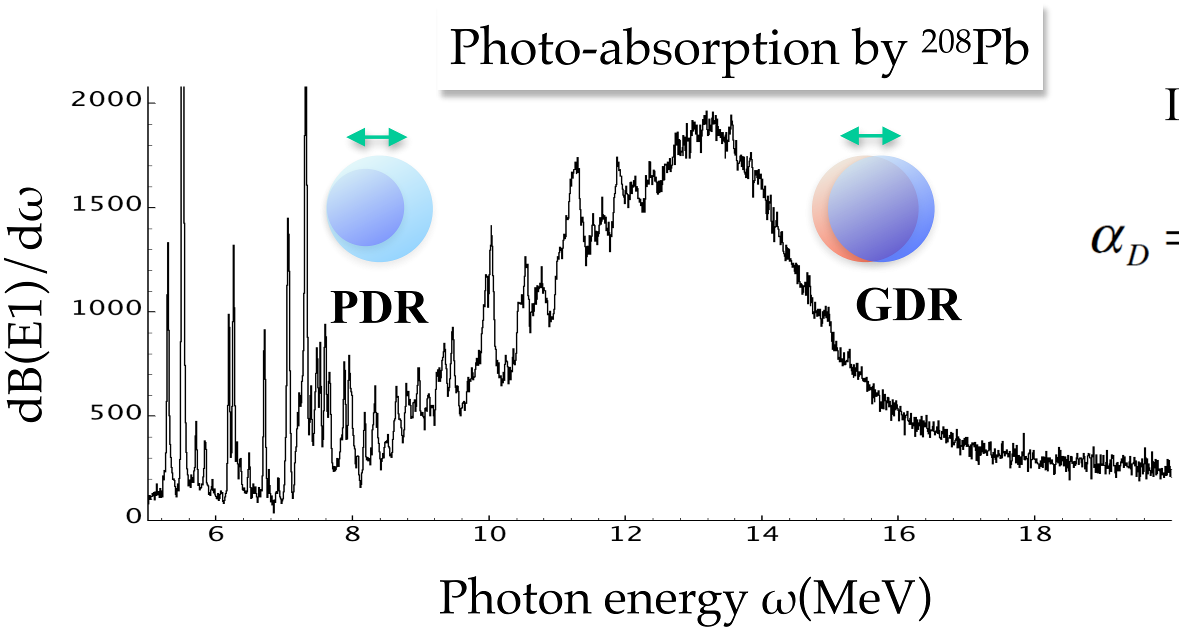


Inversely energy-weighted sum-rule

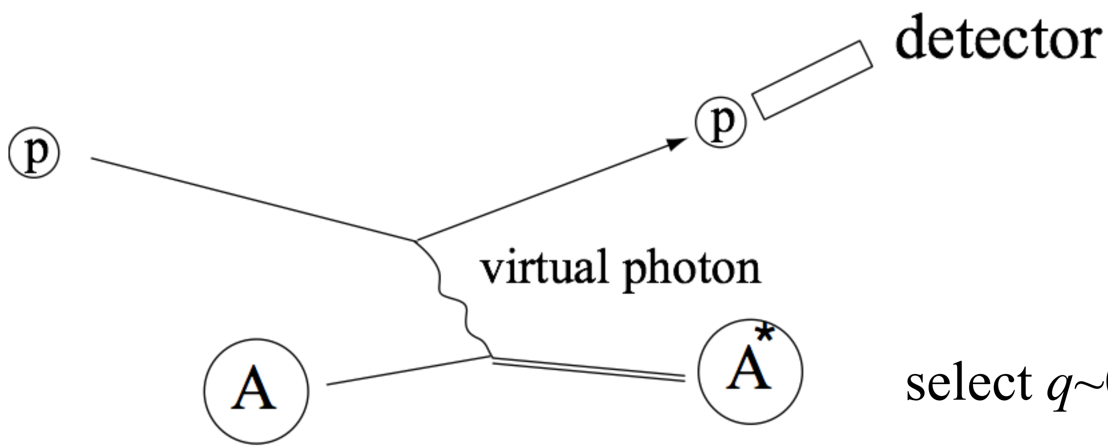
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int \frac{\sigma_{\text{abs}}^{E1}}{\omega^2} d\omega = \frac{8\pi}{9}\int \frac{dB(E1)}{\omega}$$

first order perturbation calc.

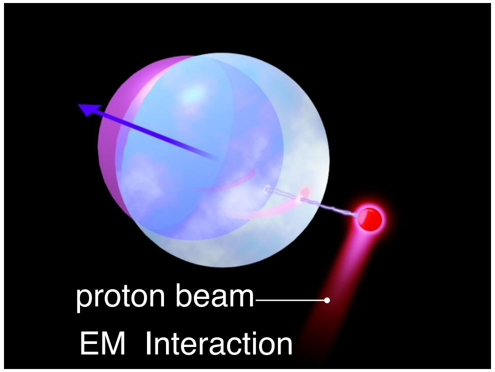
A.B. Migdal: 1944

Probing the E1 Response by Proton Scattering

Missing Mass Spectroscopy by Virtual Photon Excitation

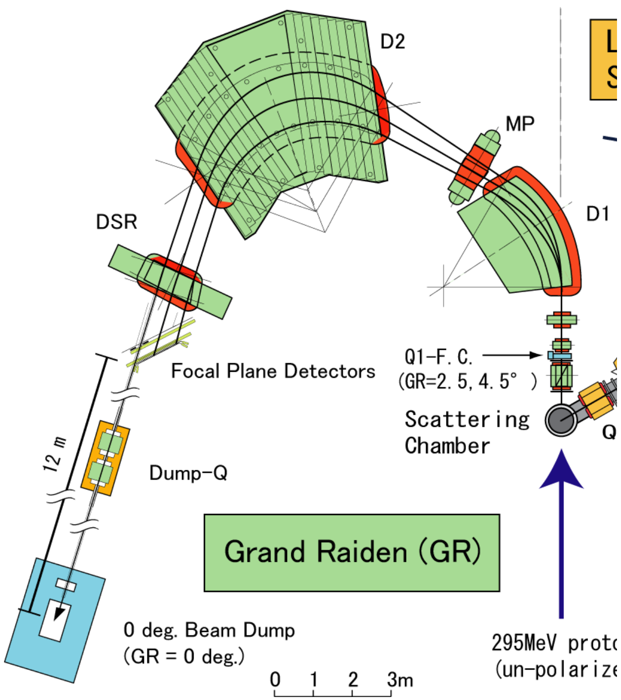


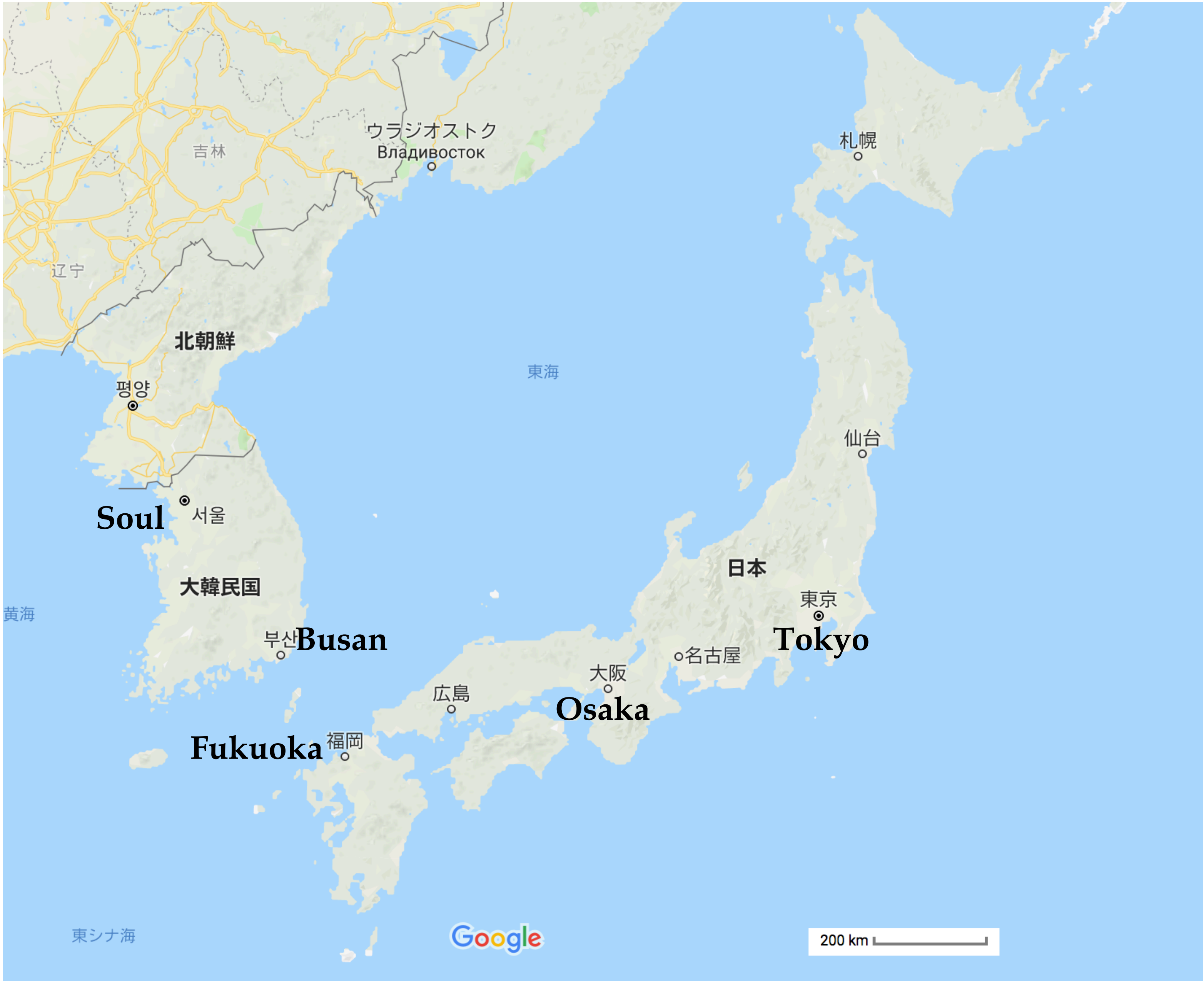
select q~0 (~0 deg.)



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

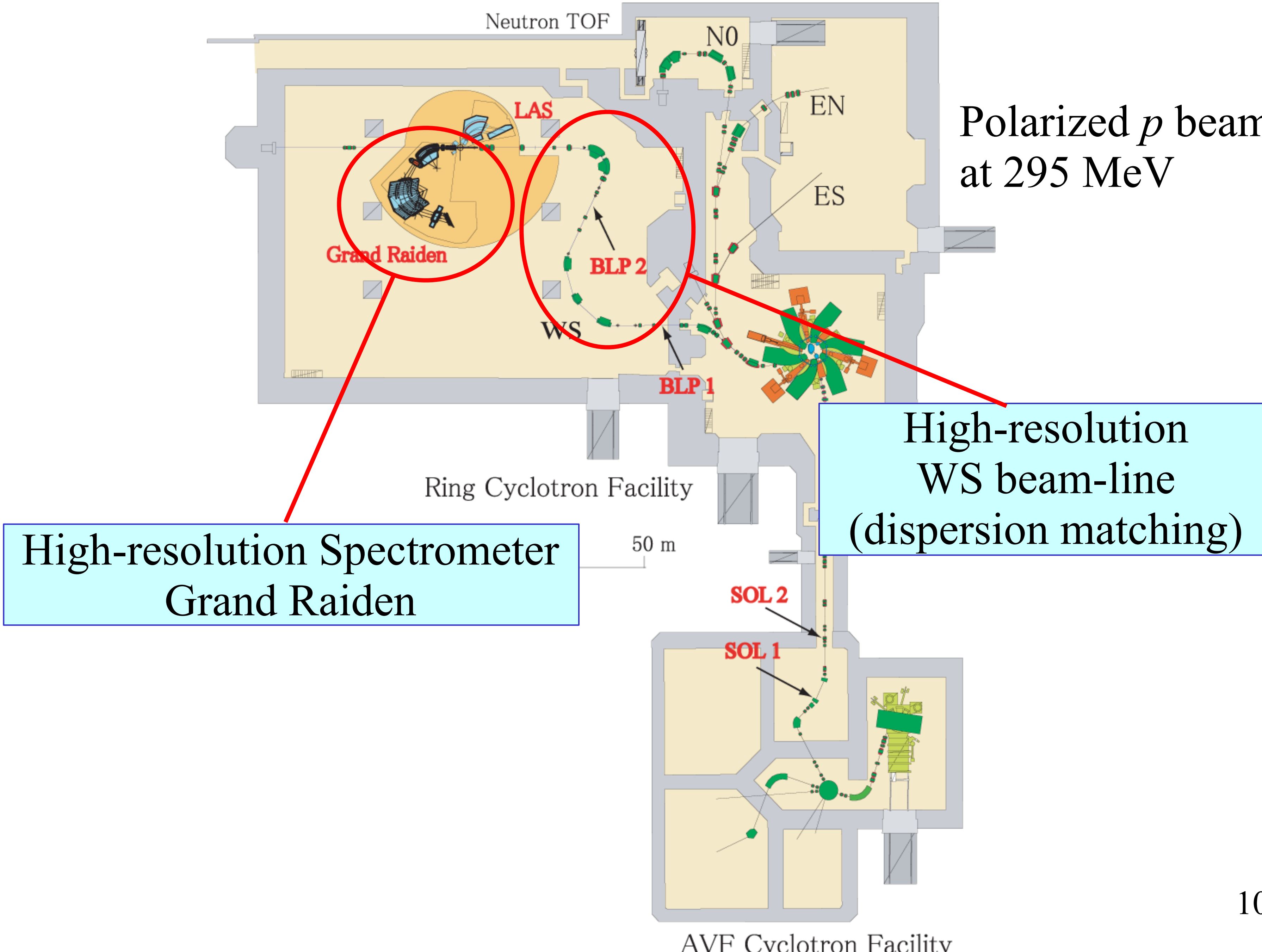
Experimental Methods




ウラジオストク
Владивосток
吉林
札幌
辽宁
北朝鮮
東海
평양
仙台
Soul
서울
日本
大韓民国
東京
黃海
부산
Busan
Tokyo
名古屋
大阪
広島
Osaka
Fukuoka
福岡
東シナ海
Google
200 km

Research Center for Nuclear Physics (RCNP), Osaka University

Polarized p beam at 295 MeV

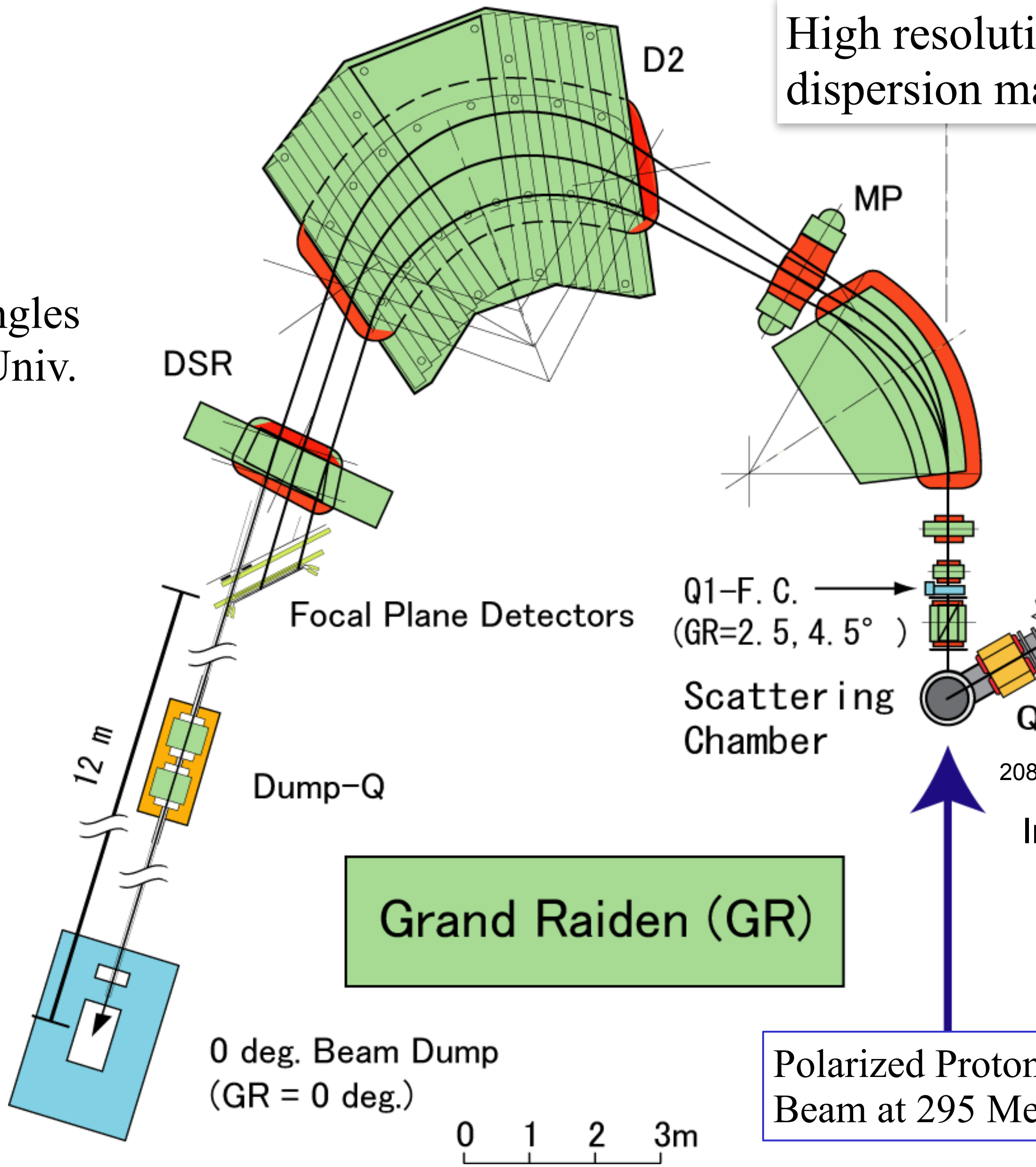


Coulomb Excitation by Proton Scattering

RCNP

High resolution of 20-30 keV:
dispersion matching.

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



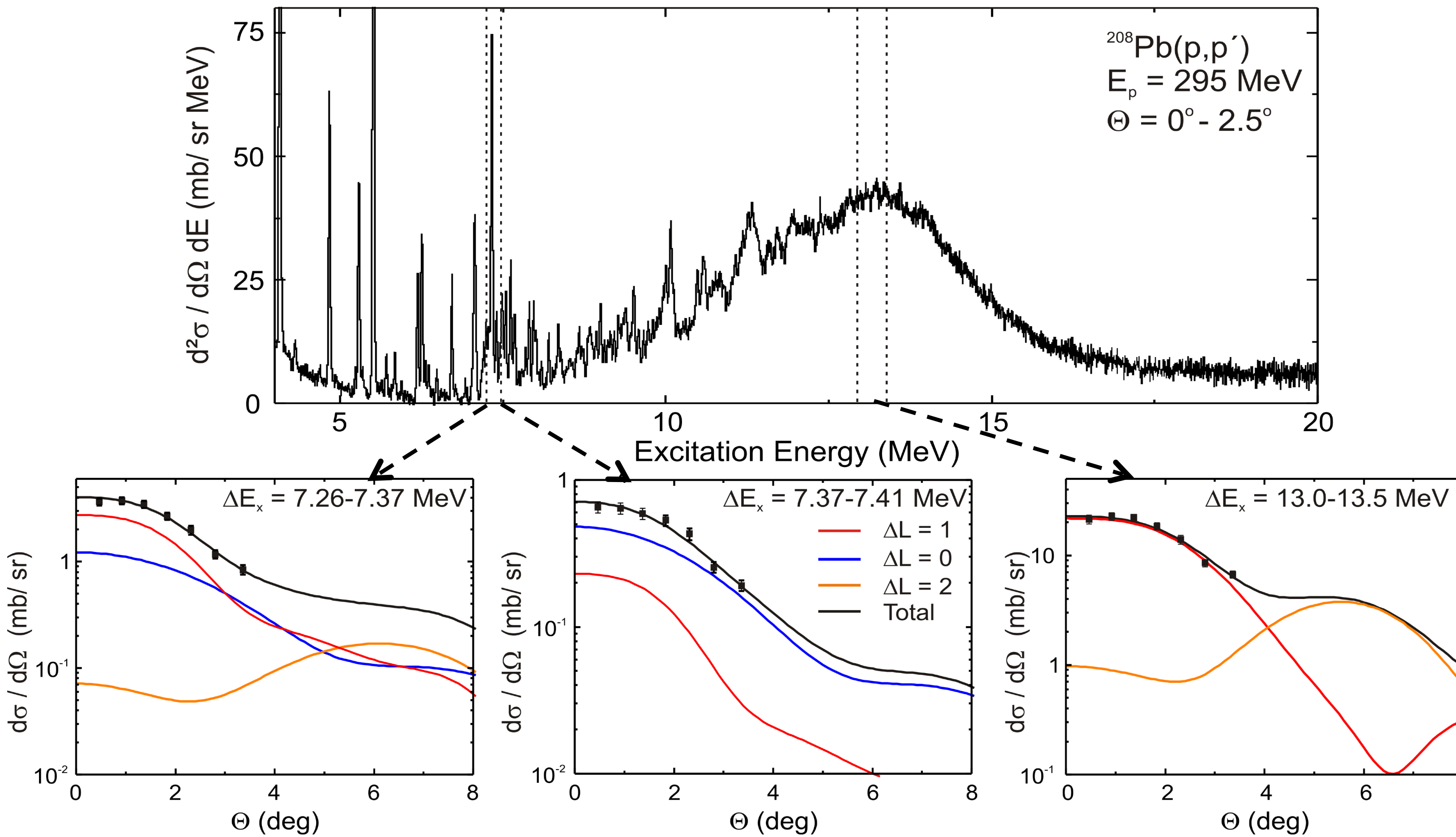
^{208}Pb target: 5.2 mg/cm^2
Intensity : 1-8 nA

Polarized Proton
Beam at 295 MeV

AT et al., NIMA605, 326 (2009)

B(E1): continuum and GDR region

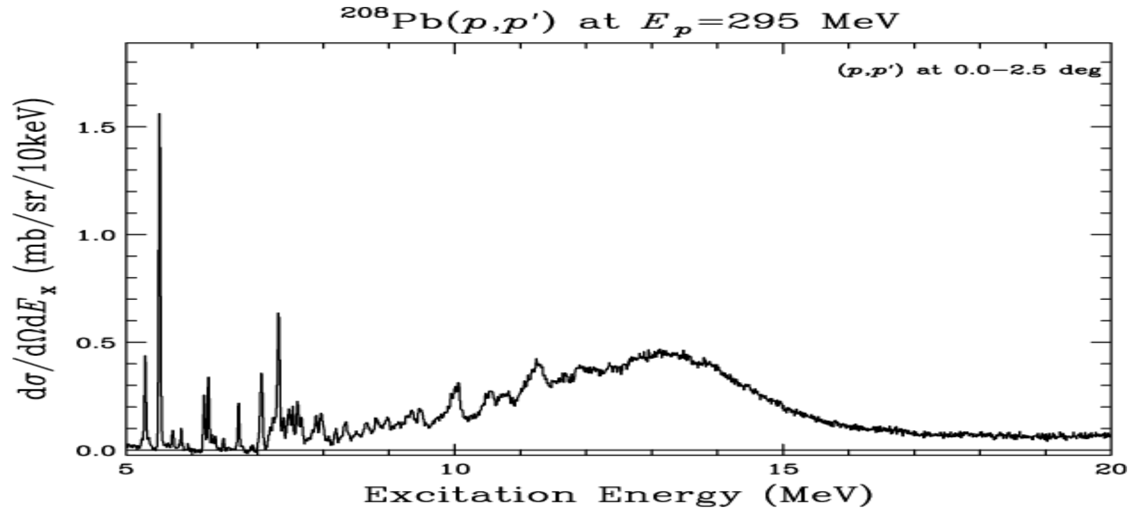
Method 1: Multipole Decomposition

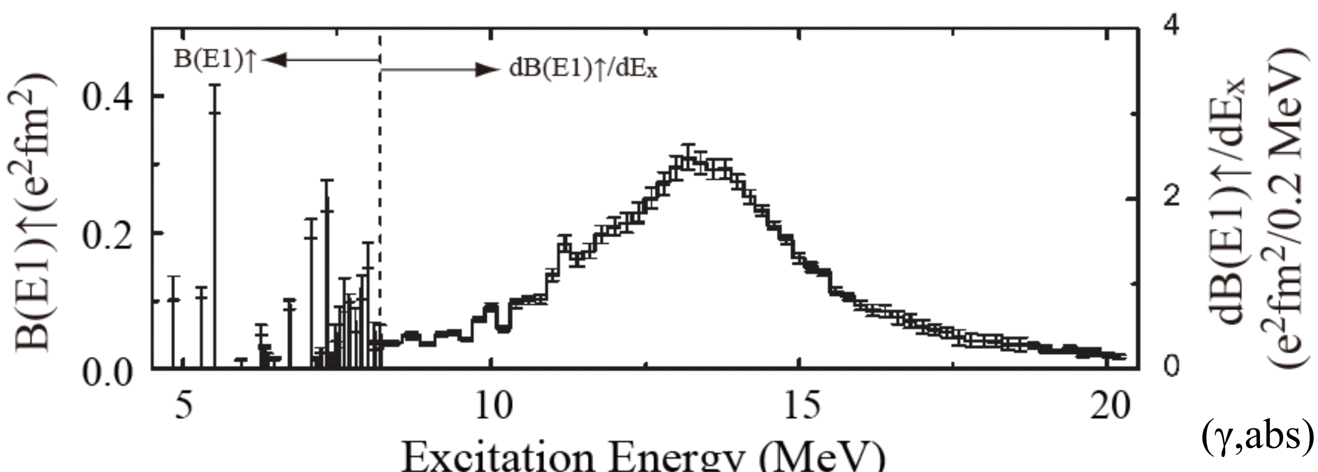


- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

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

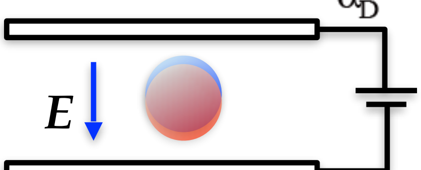




(γ,abs) at Mainz

E_x	0	10	20	130 MeV
α_D	2.7	16.2		1.2 fm³

total 20.1±0.6 fm³



AT et al., PRL107, 062502(2011)

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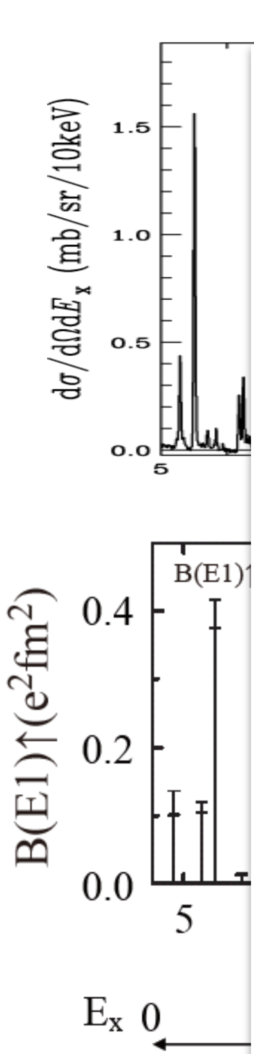
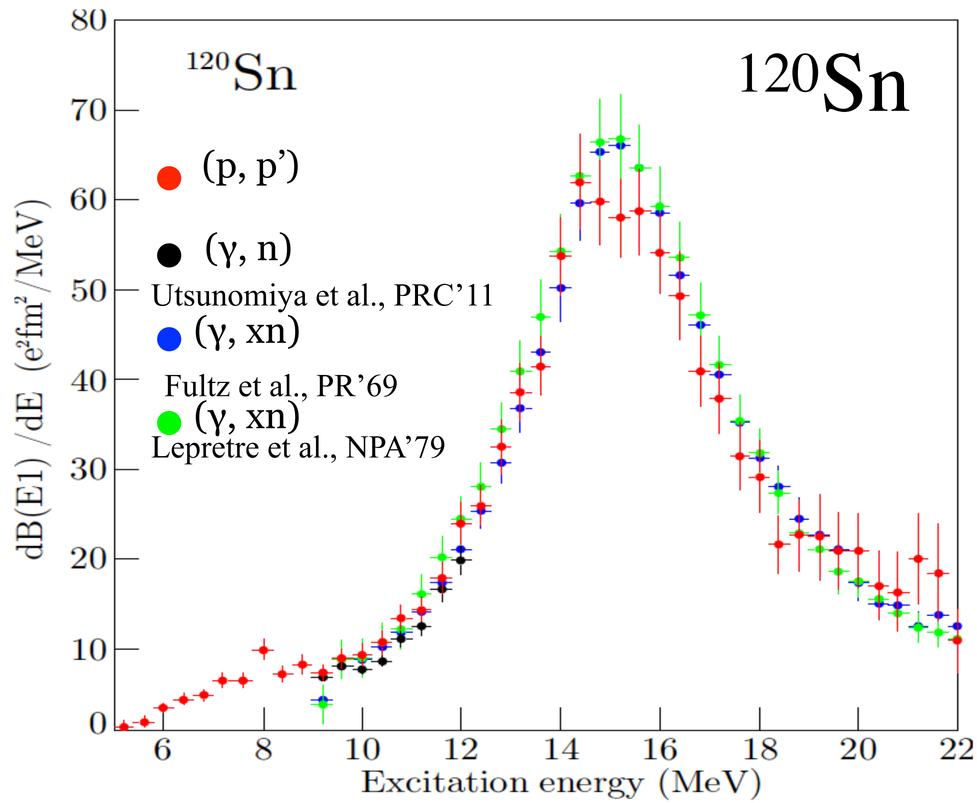


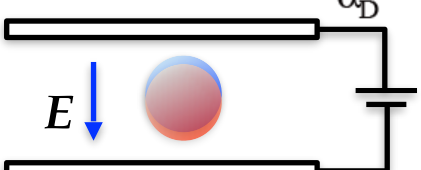
T. Hashimoto *et al.*, PRC**92**, 031305(R)(2015).



135 MeV

1.12 ± 0.07 7.00 ± 0.29 0.82 ± 0.12

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



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

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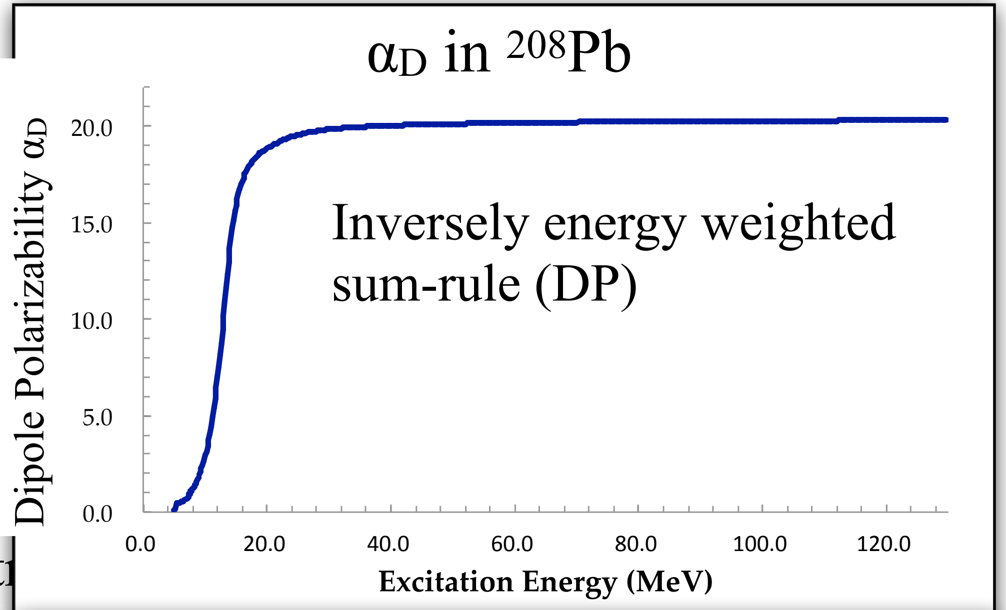

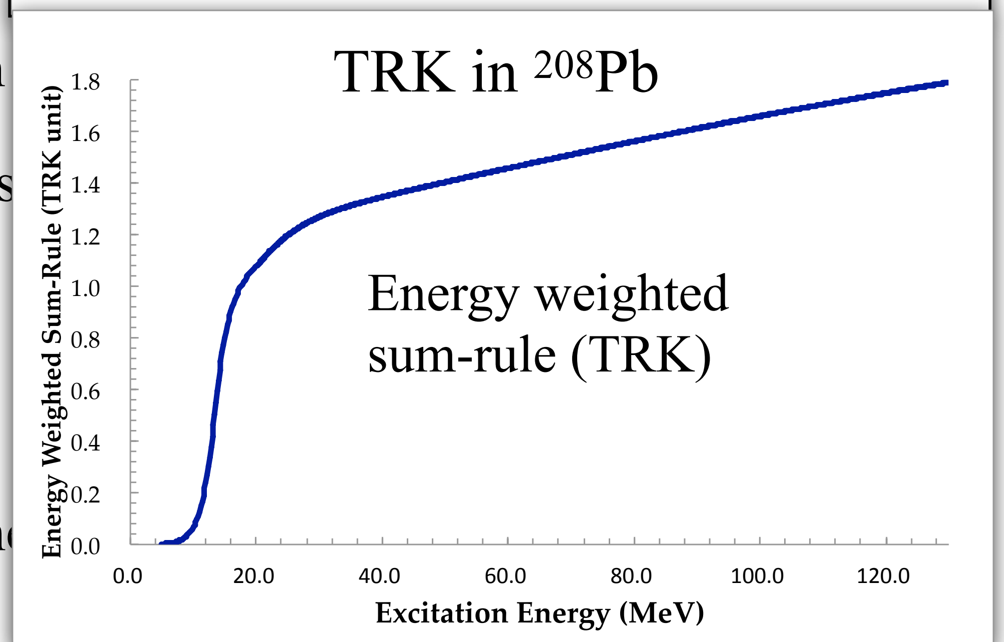

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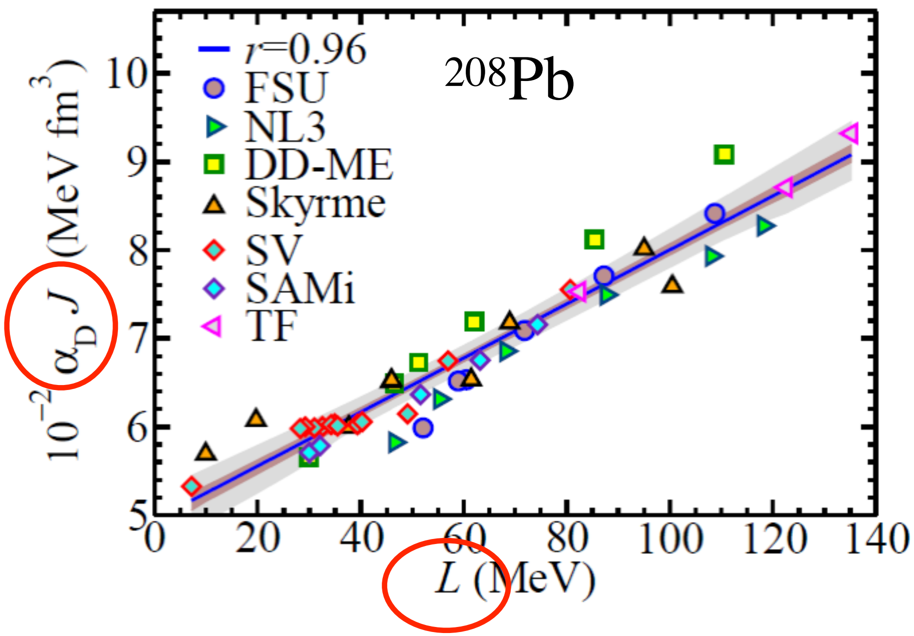
- Measurements in a broad E_x range is required.

Electric dipole polarizability (α_D) is sensitive to the symmetry energy parameters



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

Correlations observed in various interaction sets.

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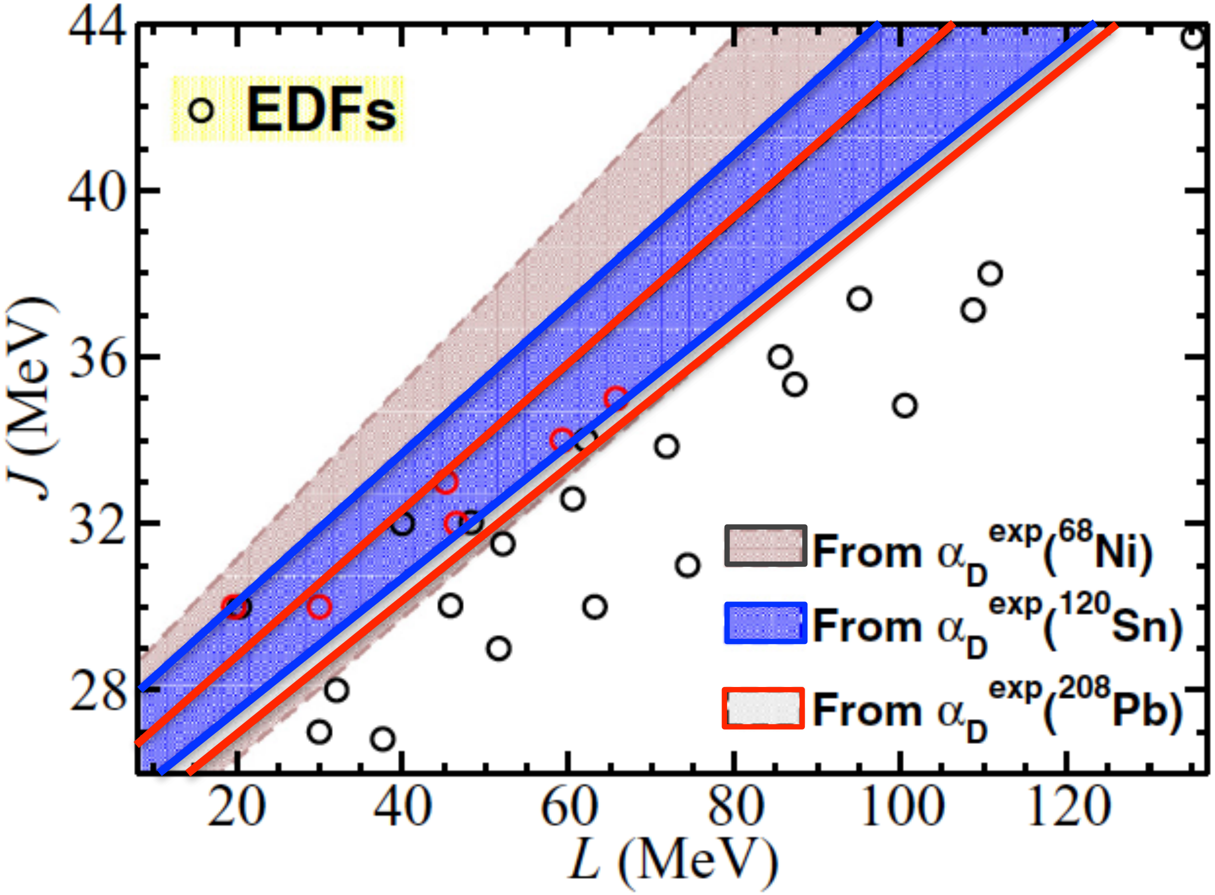
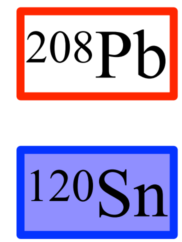
Precise determination of α_D gives a constraint band in the *J*-*L* plane.

Constraints on *J*-*L* from the EDP data

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



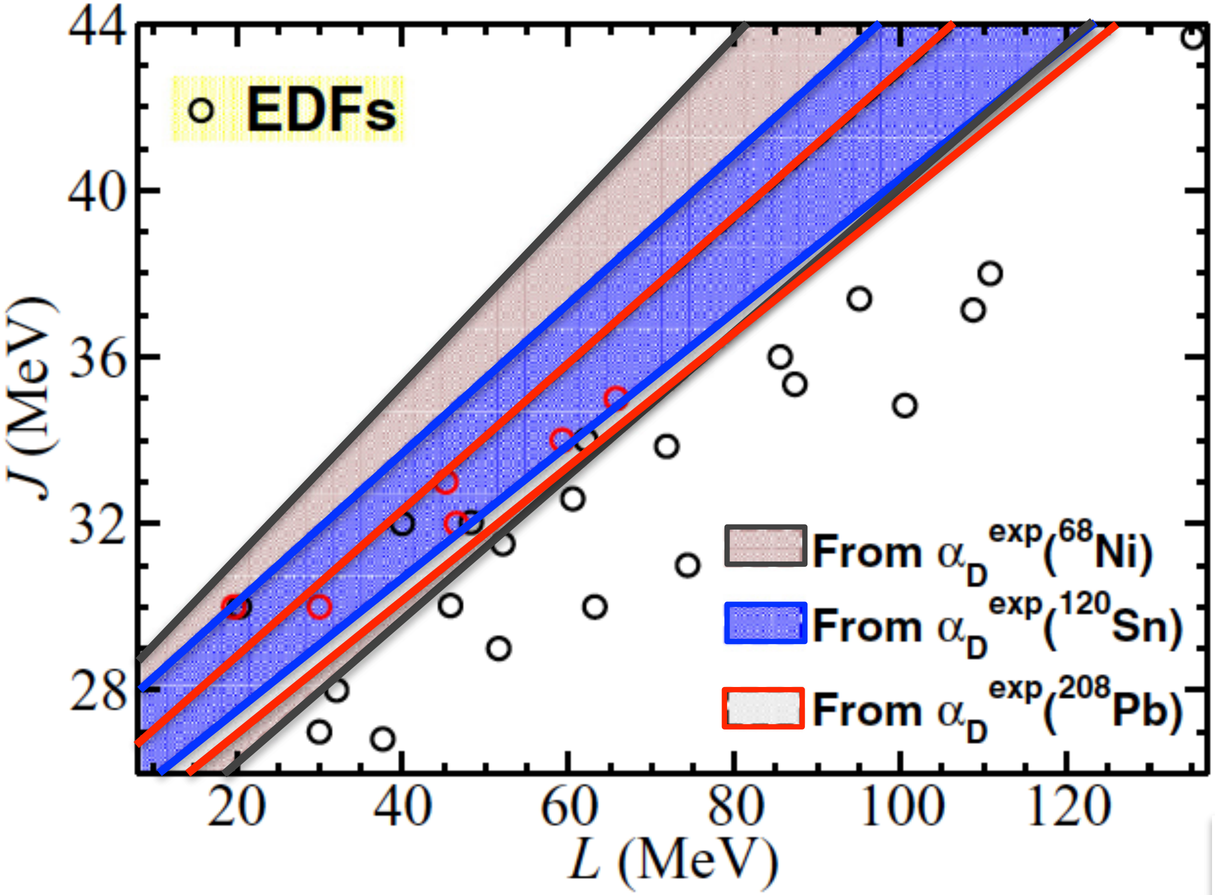


RCNP ^{208}Pb: AT *et al*., PRL**107**, 062502 (2011).

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

Constraints on *J*-*L* from the EDP data

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



^{208}Pb

^{120}Sn

^{68}Ni

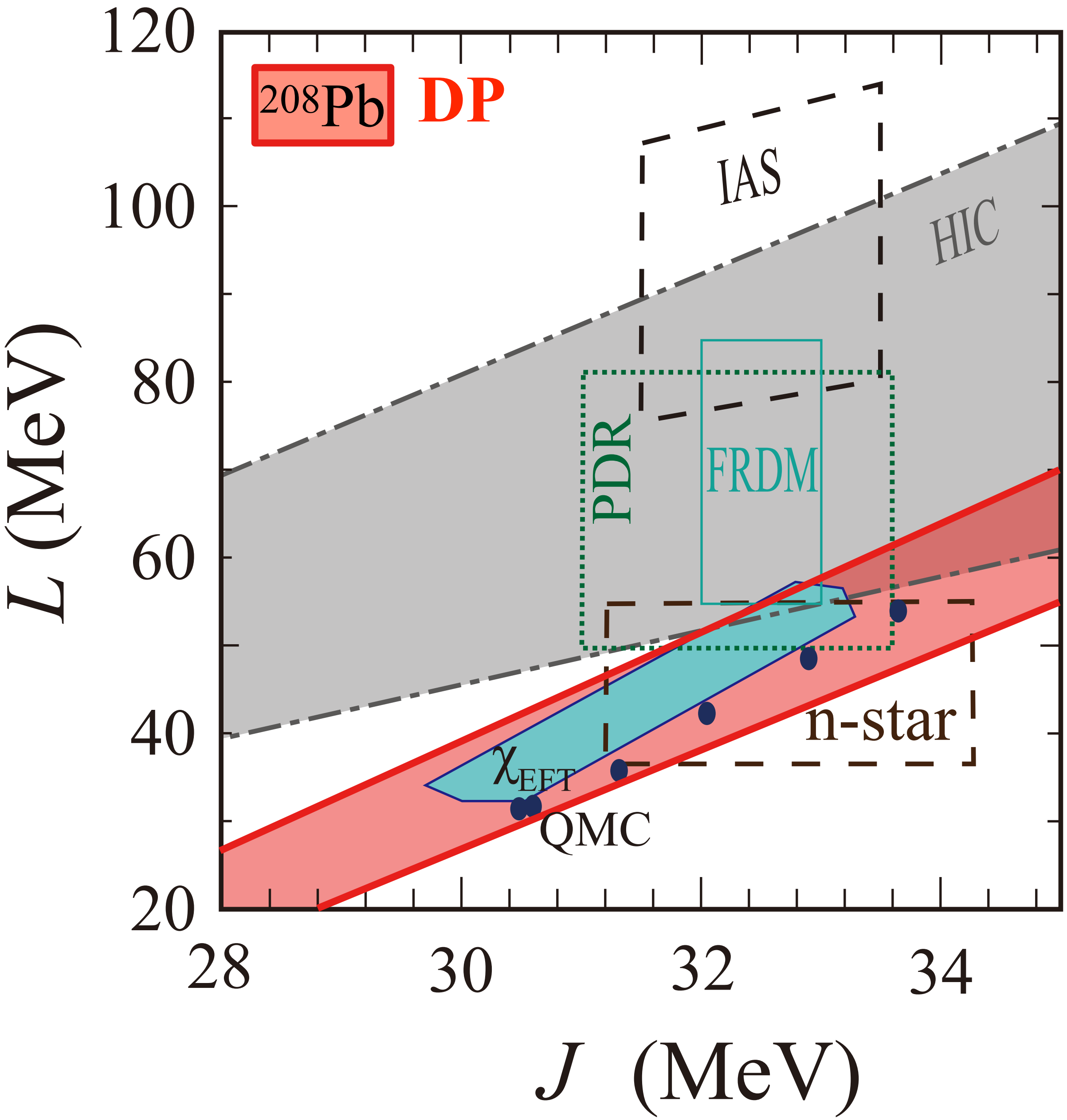
These α_D data give essentially one constraint on the symmetry energy in the *J*-*L* plane.

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*



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

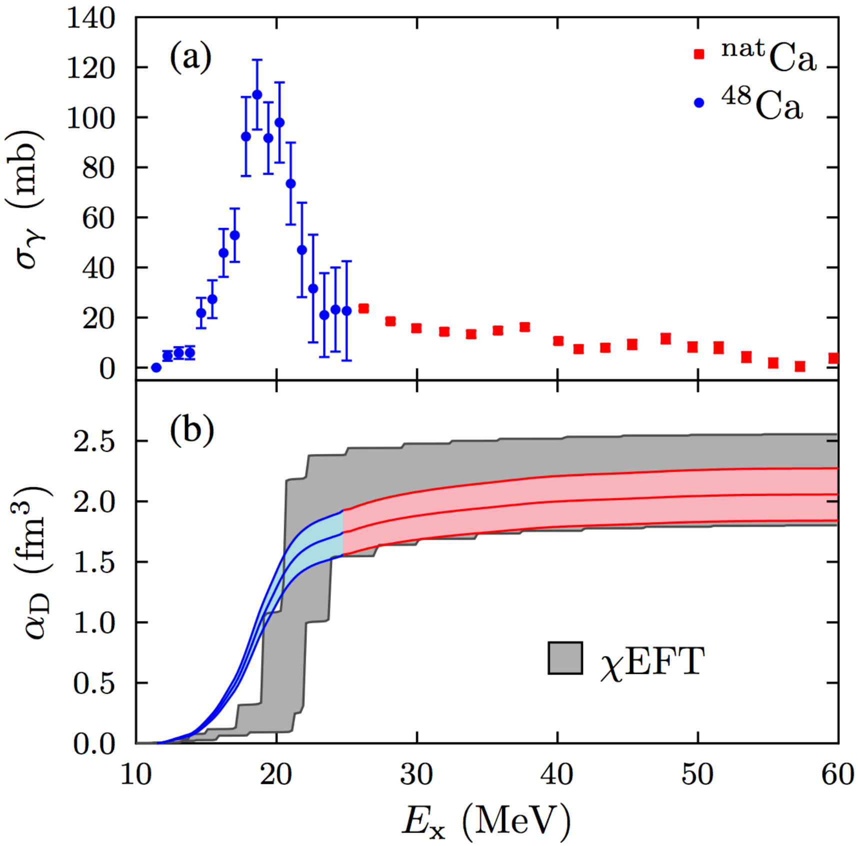
χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

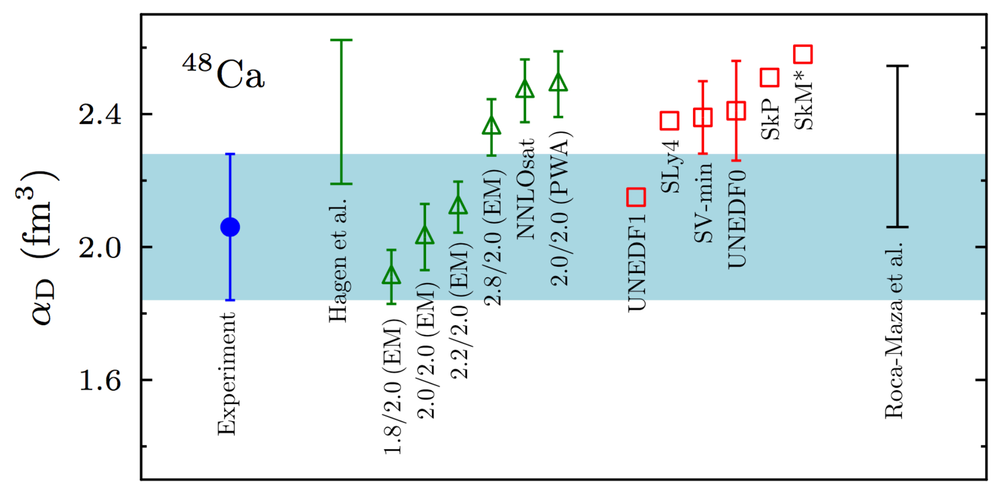
Electric Dipole Polarizability of ^{48}Ca

where the EDF and ab-initio calculations meet each other



J. Birkhan et al., PRL118, 252501(2017)

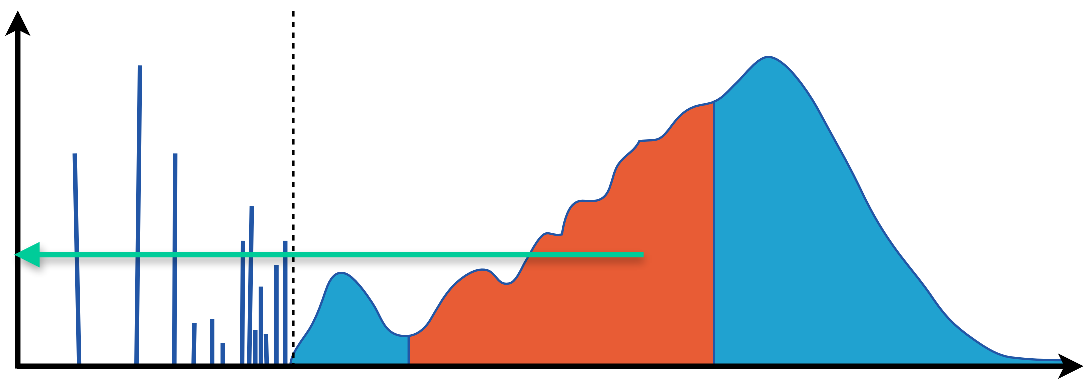
Theory: Darmstadt-Tennessee-TRIUMF



A dedicated new measurement is planned in 2020 for smaller uncertainty.

RCNP will have one-year shutdown in 2019

Gamma-Decay
of
Electric Dipole Excitations



CAGRA+GR Campaign Exp. Oct-Dec 2016

1. Structure of the PDR *1 (α,α'γ) and (p,p'γ) on ^{64}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb
2. Inelastic ν-nucleus response
3. Super-deformed states, high-spin states

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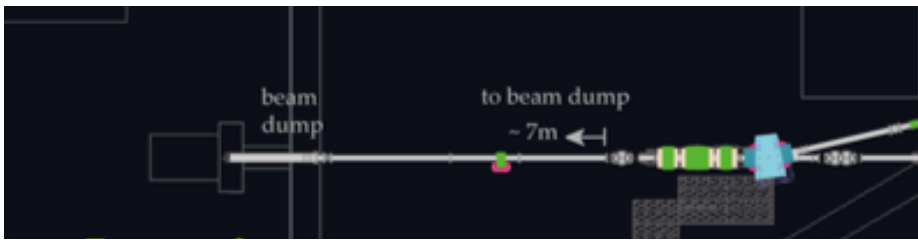
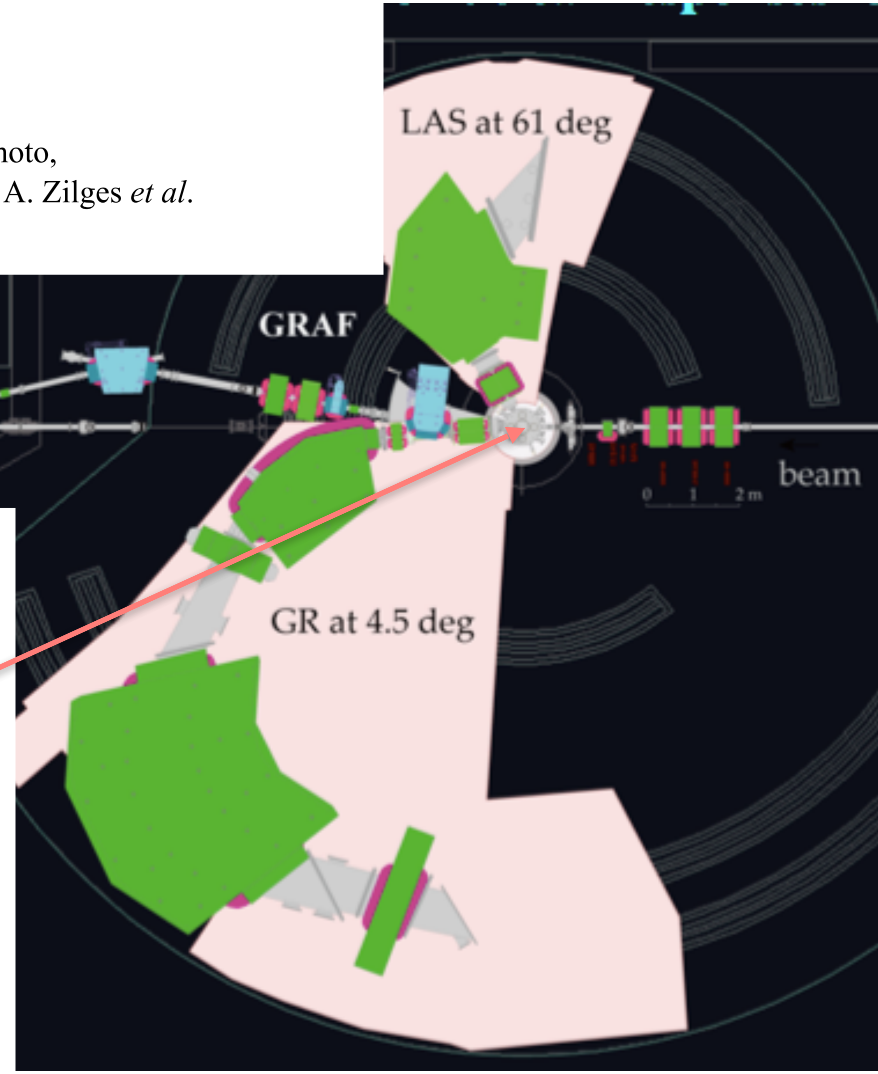
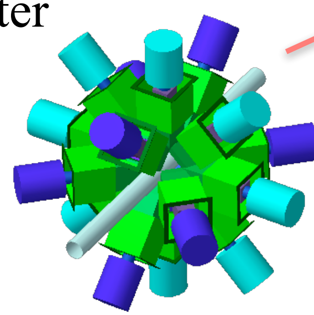




CAGRA(Clover Ge Array)
E. Ideguchi and M. Carpenter
Clovers: ANL+Tohoku+IMP



***1 Collaboration**
RCNP, Tohoku, ANL, LBNL, Milano, TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN, IMP, …

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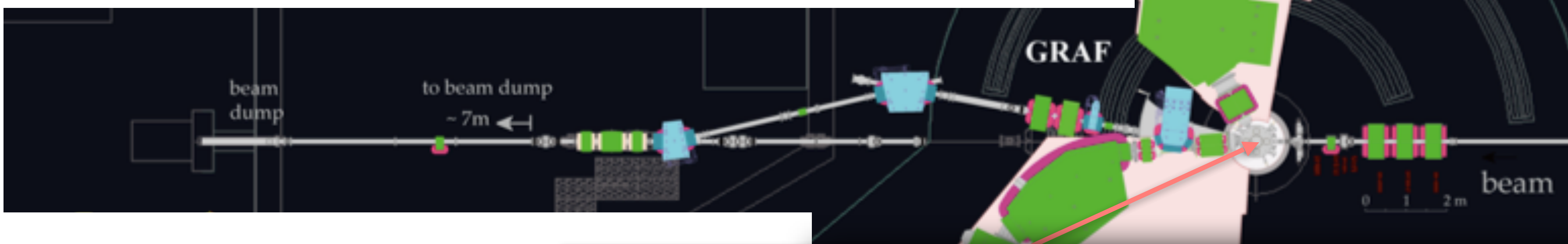

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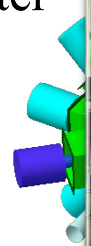

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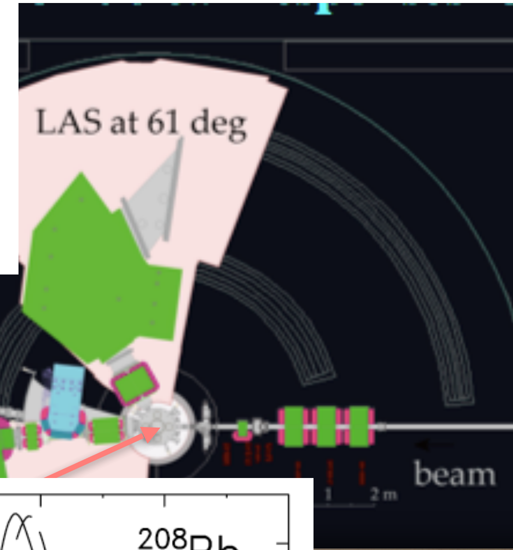
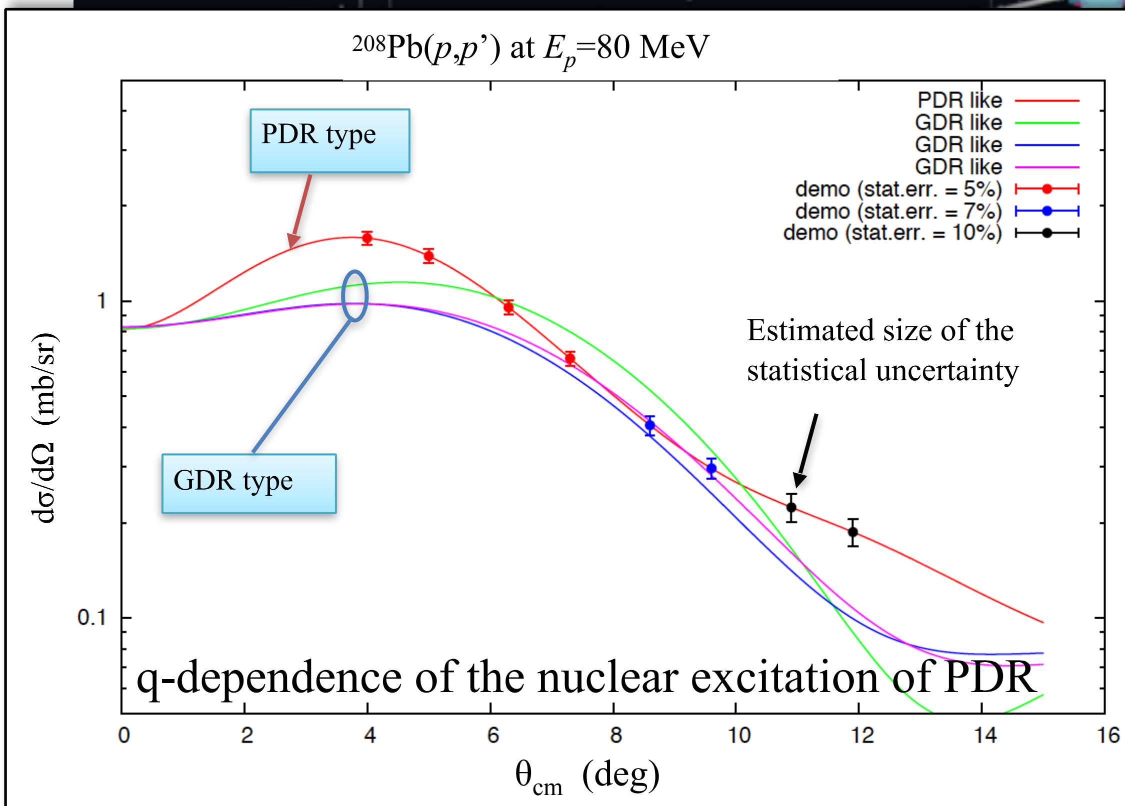
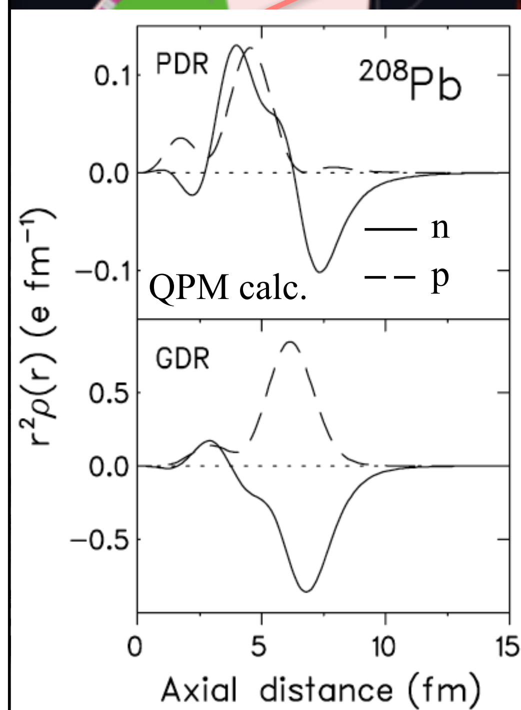






Damping Mechanism of the GDR

γ_0: gamma-decay to the ground state

viscosity between the *n/p* fluids

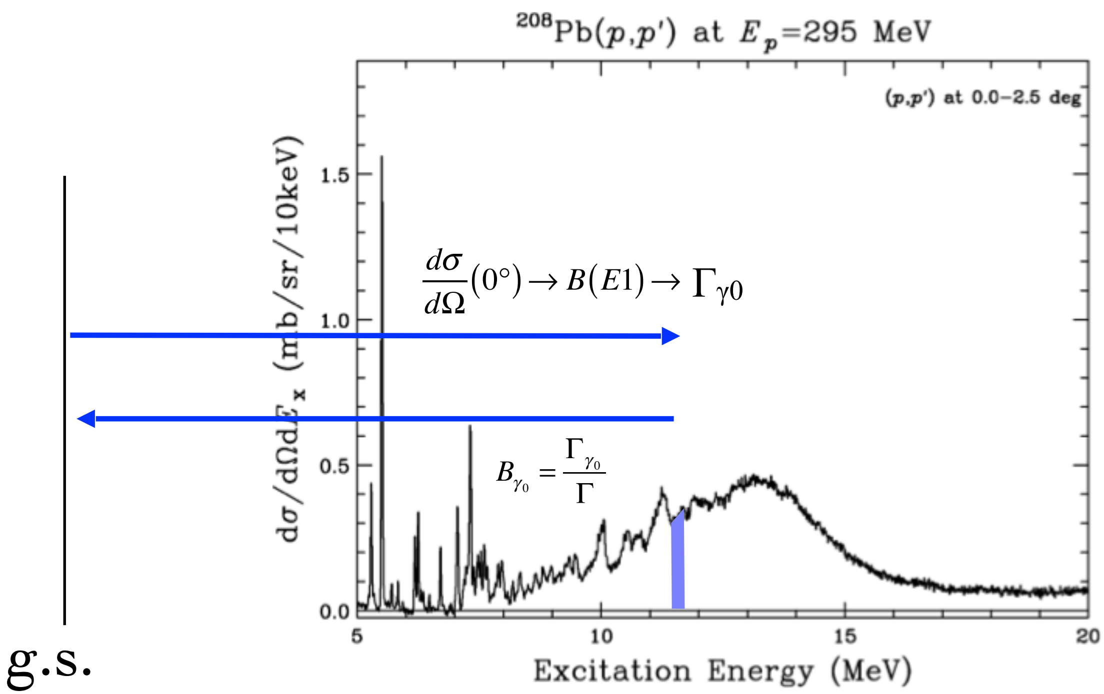
$$B_{\gamma_0} = \frac{\Gamma_{\gamma_0}}{\Gamma}$$

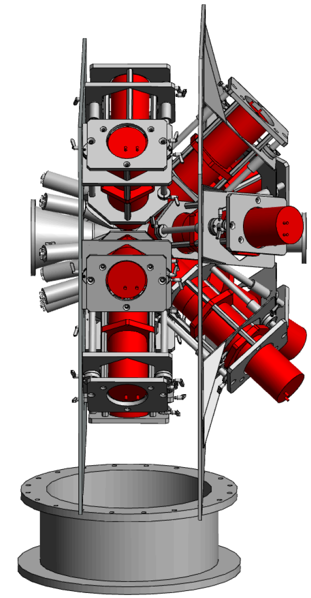
$$\Gamma_{\gamma_0} = \frac{2J_0+1}{2J+1} E_x^3 B(E1)\uparrow$$

measured by γ-decay

measured by (Coulomb) excitation

Characteristic width Γ can be studied across the IVGDR





S. Nakamura

RCNP-E498 in July 2018

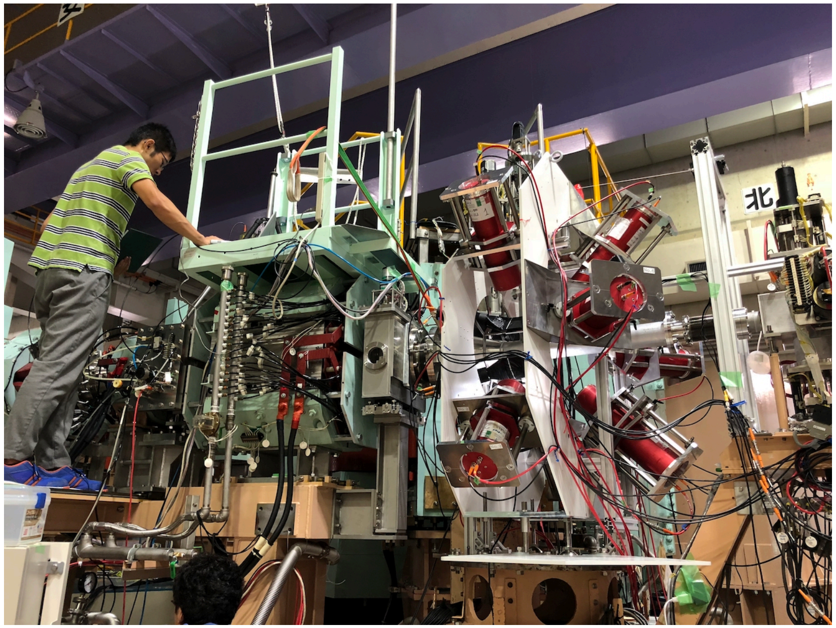
measurement for ^{90}Zr

LaBr3 scintillator array (Scylla)

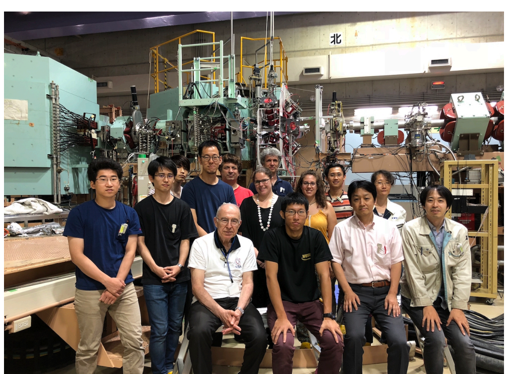
Damping Mechanism of the GDR in ^{90}Zr

(July 2018 at RCNP)

RCNP/Milano/TU-Darmstadt Collaboration



S. Nakamura working on the $LaBr_3$ gamma-detector array (Scylla)

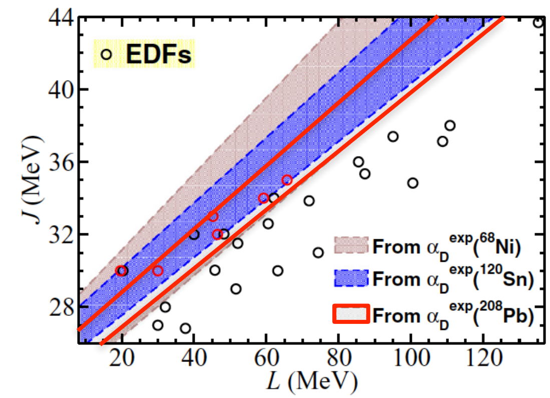


A part of the E498 collaborators

Summary

- The electric dipole polarizability (EDP) is sensitive to the symmetry energy parameters of the nuclear EOS at the saturation density.

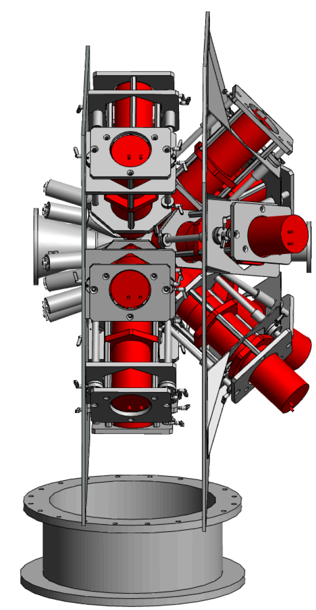
- EDP is a well defined quantity, saturating quickly at ~30 MeV in ^{208}Pb.



- The EDPs have been experimentally determined precisely for ^{208}Pb and ^{120}Sn (and for ^{68}Ni at GSI). Constraint bands on the symmetry energy parameters, *J* and *L*, has been extracted.

- The EDP of 48Ca has been extracted. A dedicated experiment for smaller exp. uncertainty is planned in 2020.

- Gamma-coincidence projects are on going.



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E498 GR+LaBr3 in July 2018

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Thank you

for your attention