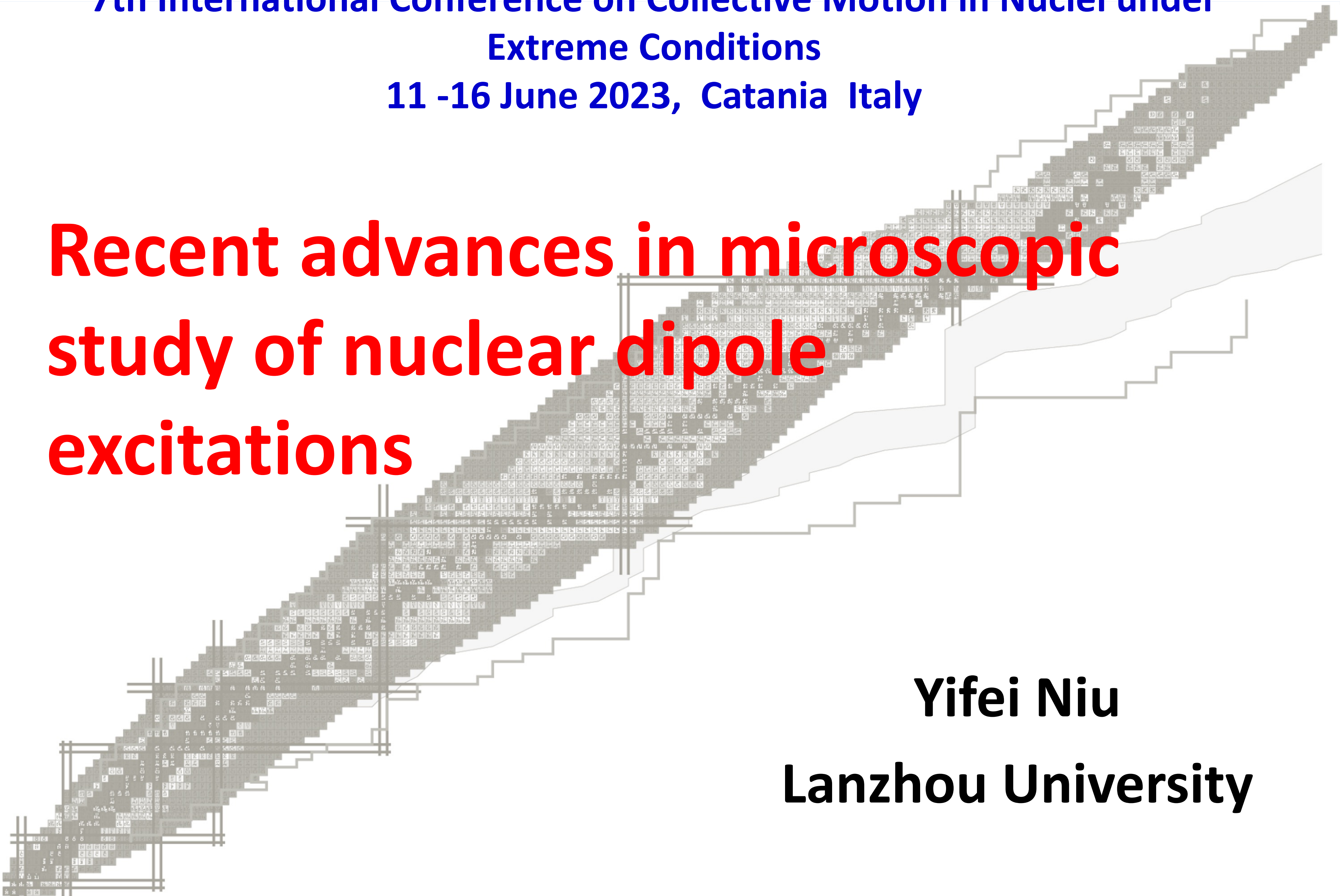
7th International Conference on Collective Motion in Nuclei under Extreme Conditions
11 -16 June 2023, Catania Italy

Recent advances in microscopic study of nuclear dipole excitations



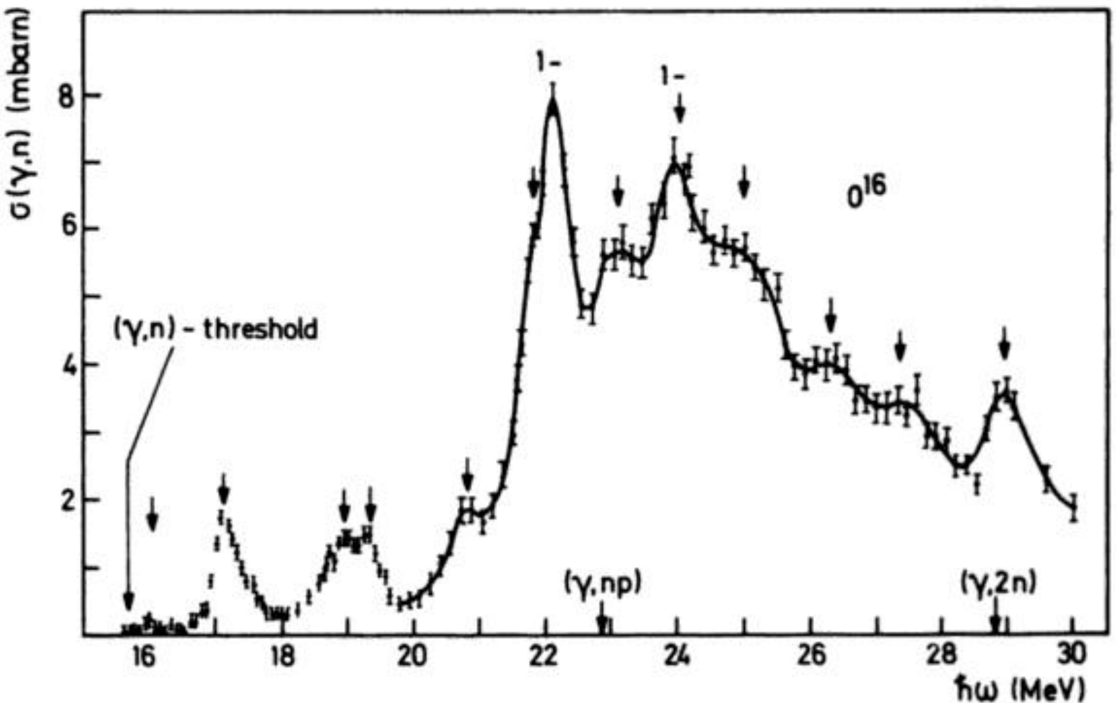
Yifei Niu
Lanzhou University

Outline

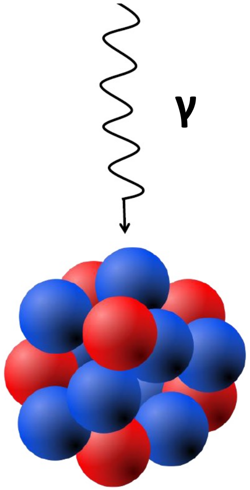
- **Introduction**
- **Learning structure of giant resonances from their γ-decay**
- **Nuclear dipole polarizability and constraints on symmetry energy**
- **Summary**

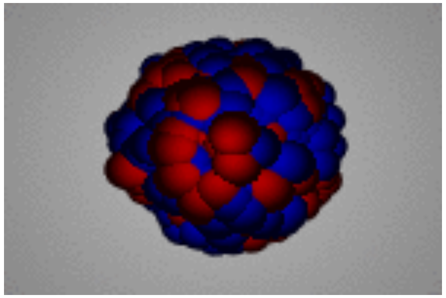
Giant Dipole Resonance

- **Photo-nucleus reaction in ^{16}O**



R. Bramblett, Phys. Rev. 133, B869 (1964)

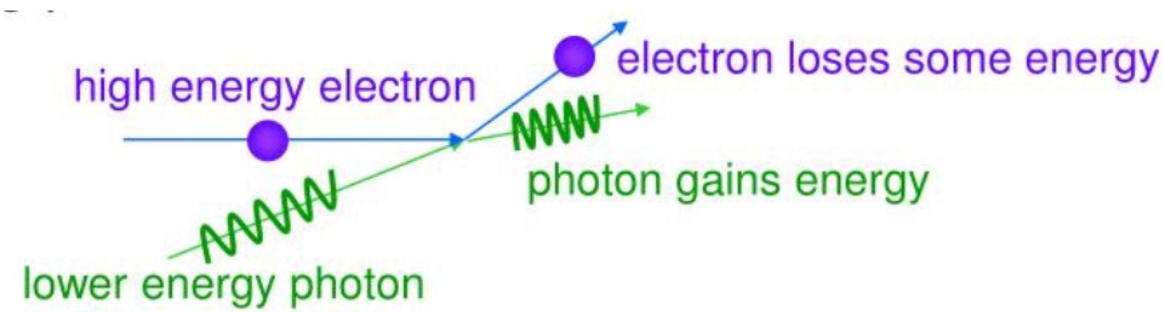




- **Characteristics**
  - Broad resonance width ~ 5 MeV
  - Larger transition probabilities than s.p.
  - Excitation energy varies slowly and smoothly with mass number

New γ beam facilities

- **Inverse compton scattering**

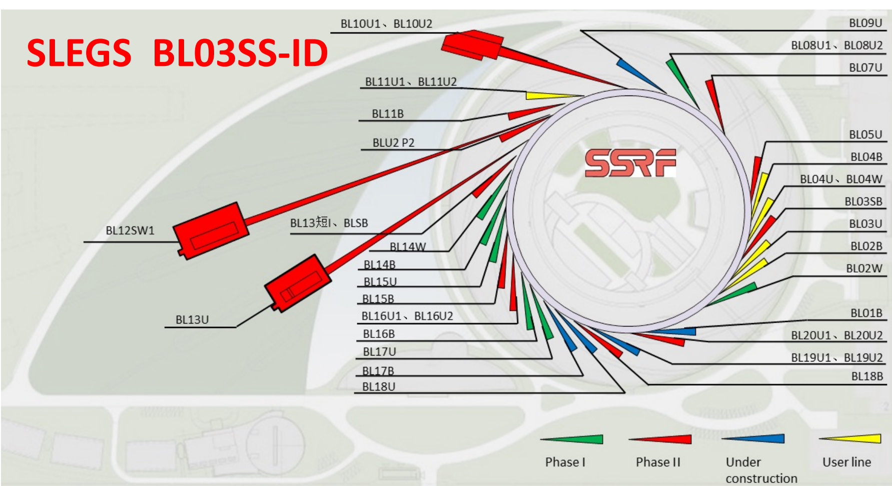


$$E_\gamma^{max} \approx 4\gamma^2 E_l$$

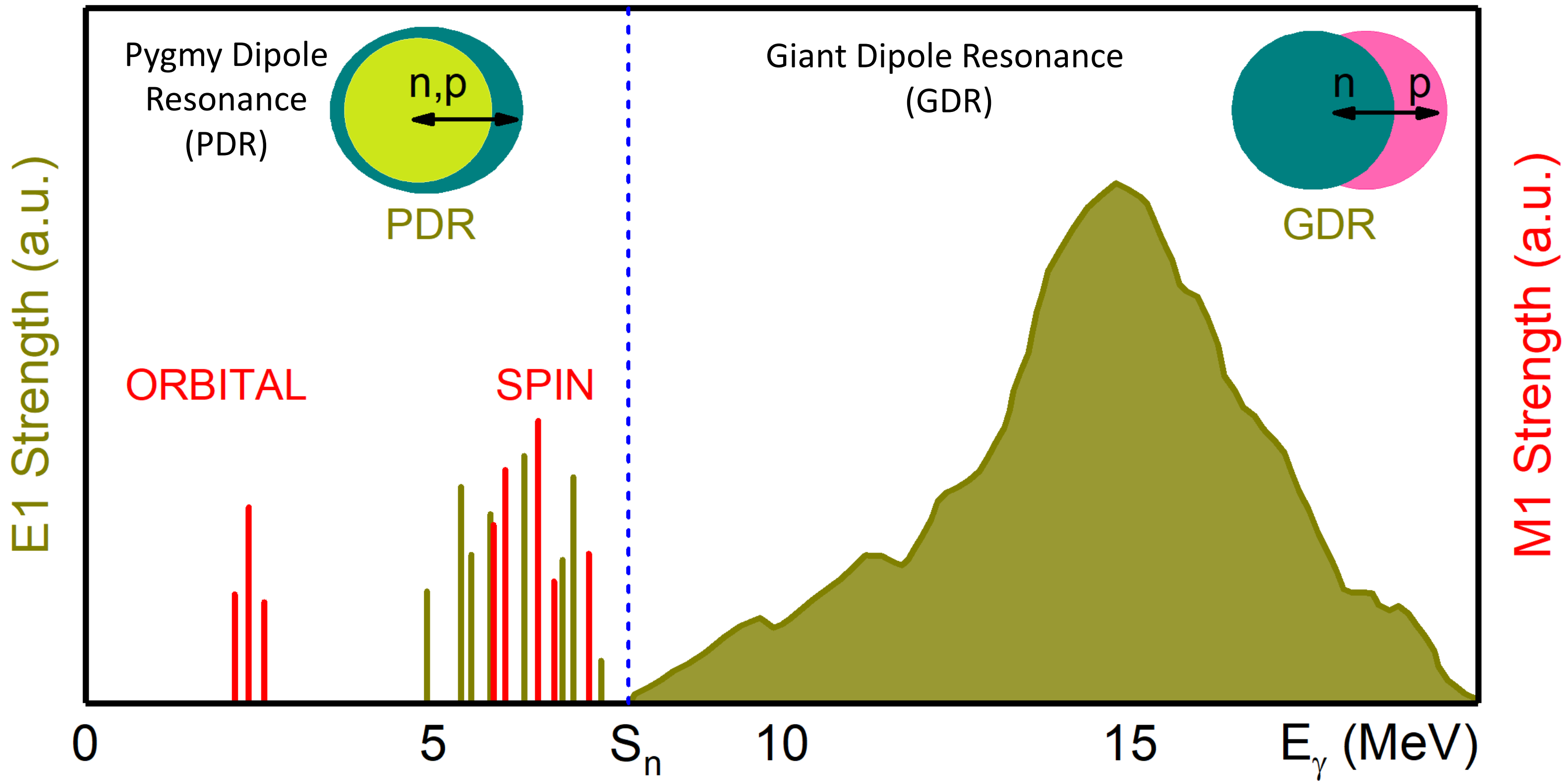
E_e=3.5GeV
E_L=0.116eV(CO_2)
γ = 6849
E_γ =$4\gamma^2 E_L$=21.7MeV

- **High Intensity γ-ray Source (HIγS)** *H. R. Weller et al., Prog. Part. Nucl. Phys. 62, 257 (2009)*
- **Extreme Light Infrastructure – Nuclear Physics (ELI-NP)** *K. A. Tanaka et al., Matter Radiat. Extremes 5, 024402 (2020)*
- **Shanghai Laser Electron Gamma Source (SLEGS)**

H. W. Wang et al., 原子核物理评论 37, 1 (2020); Nucl. Sci. Tech. 33:87 (2022)



Physics in photo-nucleus reaction

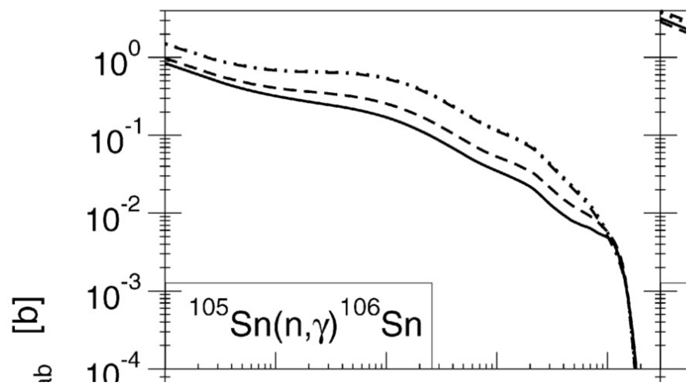


- **What is the microscopic structure and damping mechanism of GDR?**
- **What is the nature of pygmy dipole resonance?**

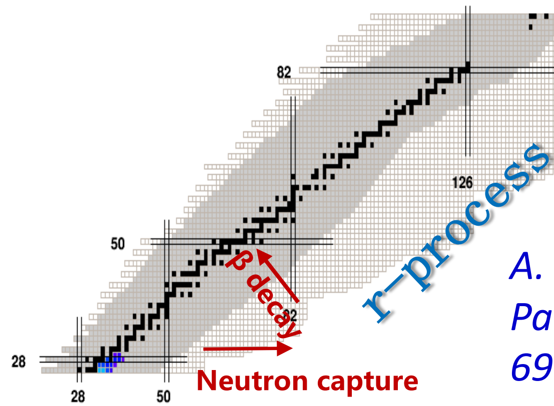
A. Bracco et al., Prog. Part. Nucl. Phys. 106, 360 (2019)
E. Lanza and A. Vitturi, contribution to Handbook of Nuclear Physics (2022)
A. Zilges et al., Prog. Part. Nucl. Phys. 122, 103903 (2022)

Why to study dipole excitation?

- ***How were the heavy elements from iron to uranium made?***

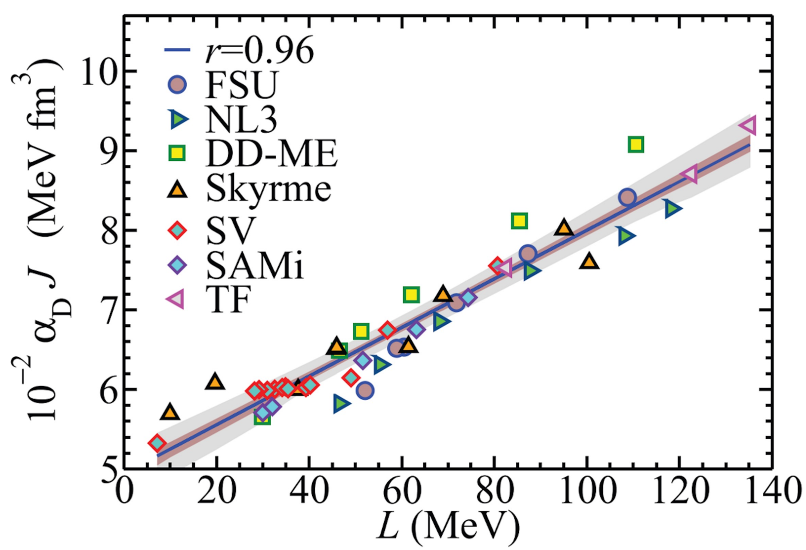


E. Litvinova et al., NPA 823, 26 (2009)

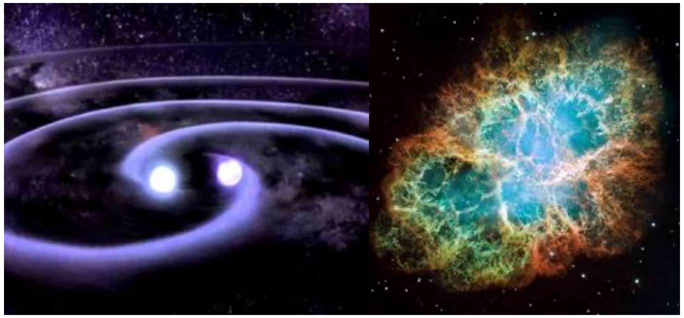


A. C. Larsen et al., Prog. Part. Nucl. Phys. 107, 69 (2019)

- ***What is the equation of state (EOS) of nuclear matter?***



Roca-Maza, Brenna, Colo, et al., PRC 88, 024316 (2013)



Roca-Maza and Paar, Prog. Part. Nucl. Phys. 101, 96 (2018)

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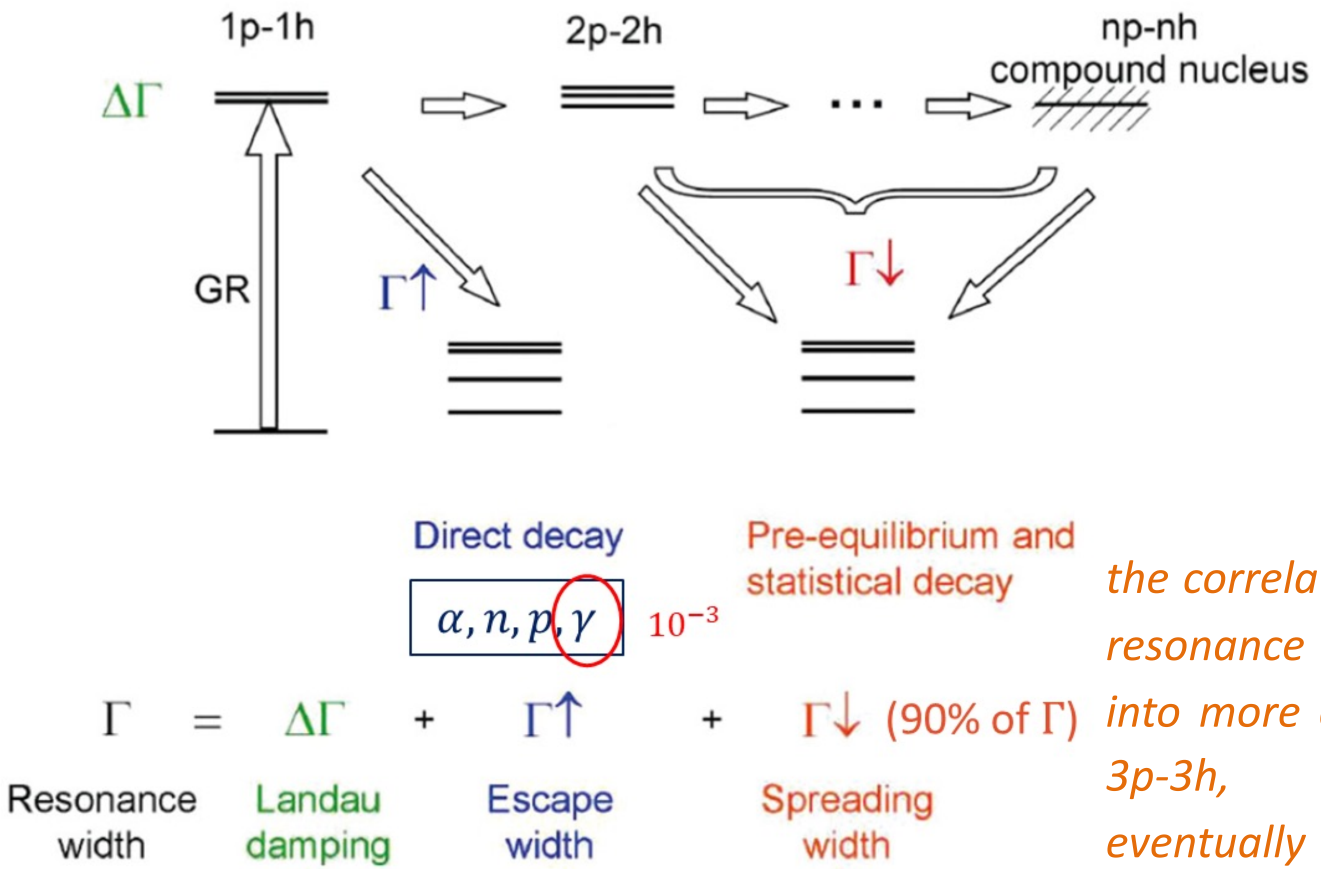
- Introduction
- **Learning structure of giant resonances from their γ-decay**
- Nuclear dipole polarizability and constraints on symmetry energy
- Summary

Damping of giant resonances

- Typical values of the centroid energy: **10-15 MeV**

  FWHM: **3-5 MeV**
- Giant vibrations go only through few periods of oscillation before they relax

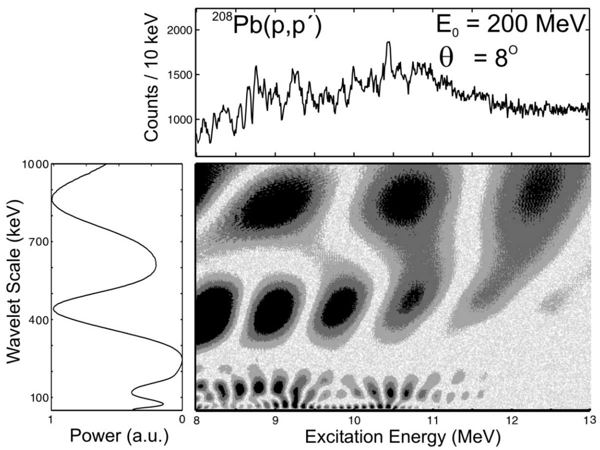


the correlated 1p-1h giant resonance state relaxes into more complex 2p-2h, 3p-3h, etc. states, eventually dissolving into the compound nucleus

P. von Neumann-Cosel and A. Tamii, Eur. Phys. J. A 55, 110 (2019)

How to prove the above picture?

- Isoscalar Giant Quadrupole Resonance (ISGQR)



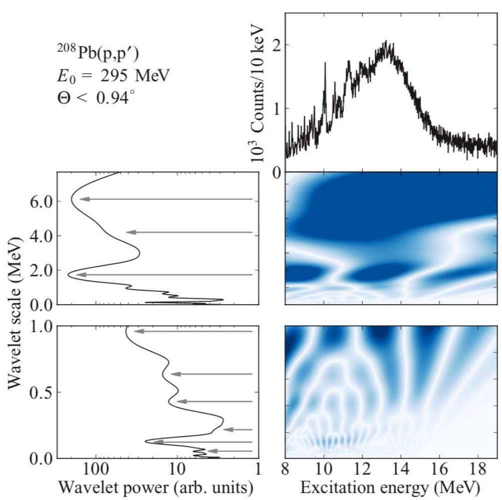
High resolution (p,p') experiment

✓ Damping mechanism:

By comparing with SRPA/QPM (2p-2h) model, the coupling to surface vibrations is the main source of the observed scale.

A. Shevchenko, et al., Phys. Rev. Lett. 93, 122501 (2004)

- Isovector Giant Dipole Resonance (IVGDR)



High resolution (p,p') experiment

✓ Damping mechanism:

In contrast to ISGQR (where fine structure arises from the coupling to low-lying surface vibrations), Landau damping is the main mechanism.

I. Poltoratska, et al., Phys. Rev. C 89, 054322 (2014)

γ decay of giant resonances

Although Γ_γ is a tiny part of Γ, it provides significant information

- ✓ Electromagnetic interaction involved reaction can be clearly interpreted.
- ✓ Sensitive to GR multipolarity
- ✓ Provide isospin character and wavefunction information of GRs

P. F. Bortignon, et al., Phys. Lett. B 148, 20 (1984) *V. Yu. Ponomarev, et al., Nucl. Phys. A 550, 150 (1992)*

- **Experiment Proposals**

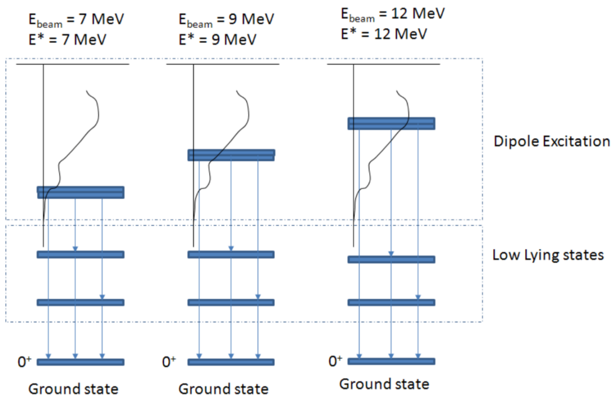
RCNP EXPERIMENT E

PROPOSAL FOR EXPERIMENT AT RCNP

February 9, 2017

TITLE: Gamma decay from giant resonances: a pilot experiment

SPOKESPERSONS: Angela Bracco, Peter von Neumann-Cosel and Atsushi Tamii



ELI-NP TDR *Romanian Reports in Physics, 68, Supplement, S539 (2016)*

It calls for theoretical interpretation for the γ -decay data!

It is important to show how the γ decay of GRs to low-lying states provide microscopic structure information and damping mechanisms of GRs

Formalism of γ decay

- γ-decay width

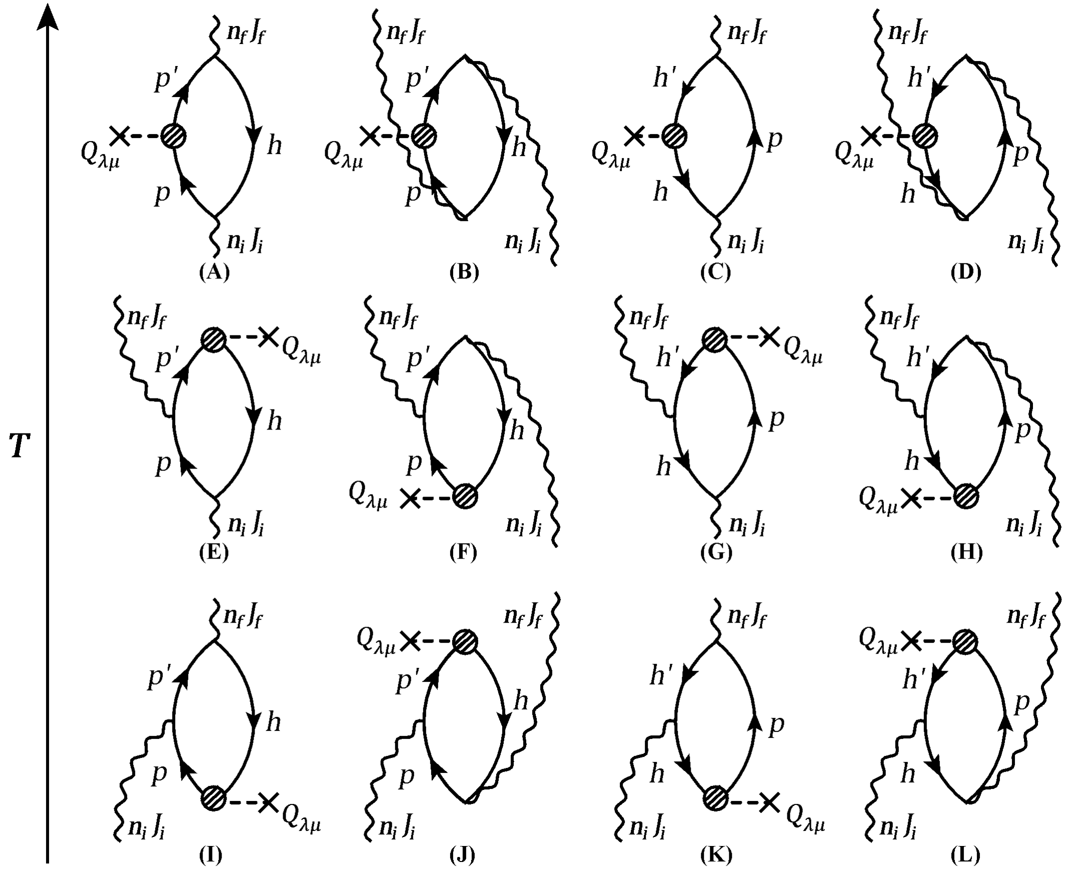
$$\Gamma_\gamma(E\lambda; i \to f) = \frac{8\pi(\lambda+1)}{\lambda\,[(2\lambda+1)!!]}\left(\frac{E}{\hbar c}\right)^{2\lambda+1} B(E\lambda; i \to f)$$

- Transition probability

$$B(E\lambda; i \to f) = \frac{1}{2J_i+1}\,|\langle J_f||Q_\lambda||J_i\rangle|^2$$

A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. II, 1975

- Reduced transition matrix element



Random phase approximation

RPA level

1p-1h

Particle vibration coupling

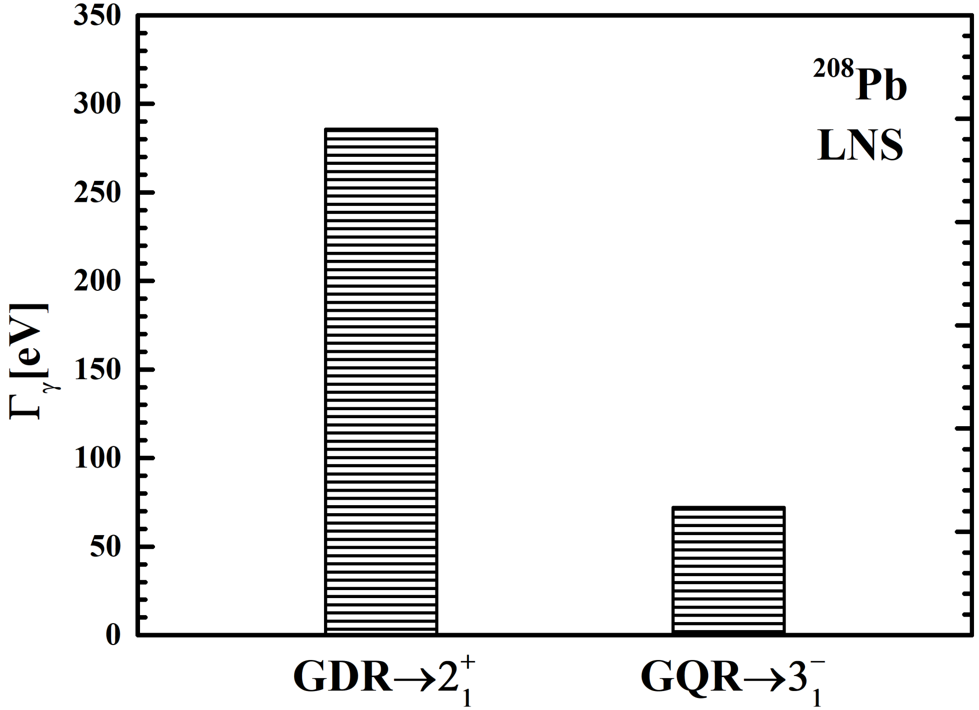
PVC level

2p-2h

M. Brenna et al., PRC 85, 014305 (2012)

γ-decay widths of ^{208}Pb

- γ decay widths of GRs to low-lying states in ^{208}Pb



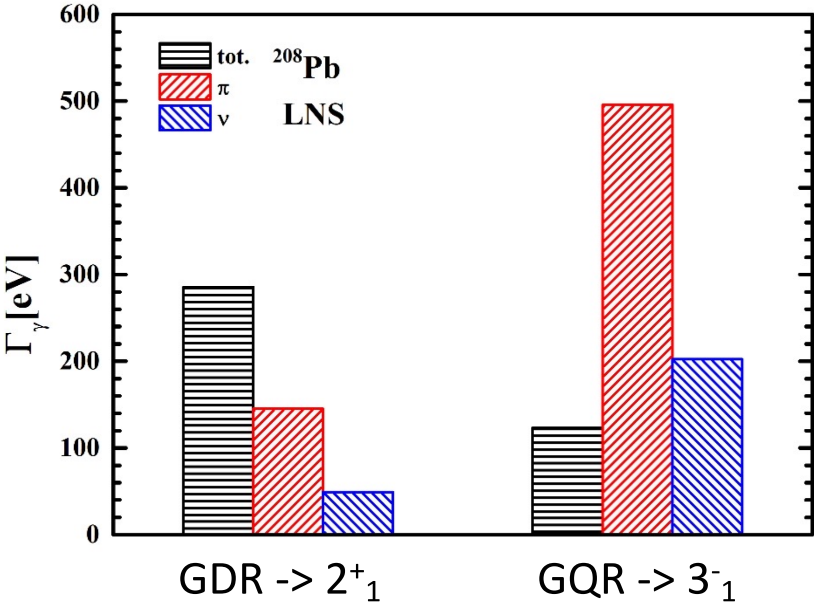
$$\Gamma_\gamma(\mathrm{GDR} \to 2_1^+) > \Gamma_\gamma(\mathrm{GQR} \to 3_1^-)$$

Why?

different isospin properties between GDR and GQR?

Sensitivity to isospin of GRs

- $\boldsymbol{\gamma}$-decay widths contributed by protons and neutrons



✓ Constructive interference:

GDR: $\Gamma_\gamma^{tot} > \Gamma_\gamma^{\pi(\nu)}$

GDR (IV) $\xrightarrow{E1(IV)}$ 2_1^+ (IS)

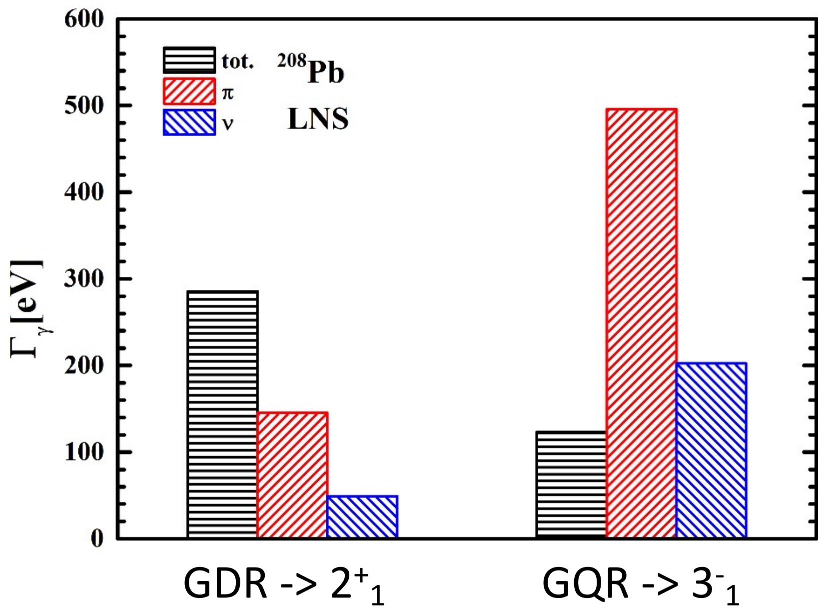
✓ destructive interference:

GQR: $\Gamma_\gamma^{tot} < \Gamma_\gamma^{\pi(\nu)}$

GQR (IS) $\xrightarrow{E1(IV)}$ 3_1^- (IS)

Sensitivity to isospin of GRs

- $\boldsymbol{\gamma}$-decay widths contributed by protons and neutrons



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✓ destructive interference:

GQR: $\Gamma_\gamma^{tot} < \Gamma_\gamma^{\pi(\nu)}$

GQR (IS) $\xrightarrow{\text{E1(IV)}}$ 3_1^- (IS)

- *N=Z* nucleus ^{56}Ni without Coulomb: Isospin symmetry limit

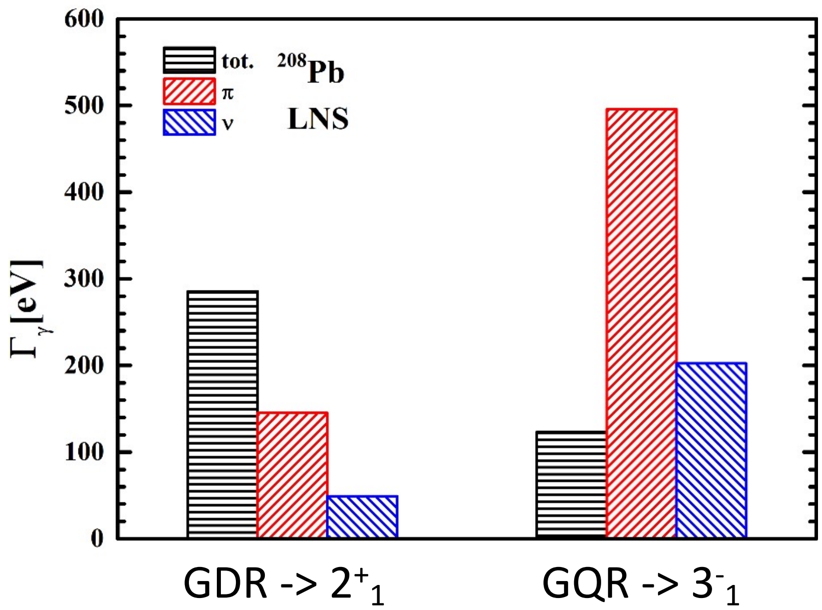
^{56}Ni	Γ_γ	Γ_γ^π	Γ_γ^ν
$\mathrm{GDR} \to 2_1^+$	3877.72	969.43	969.43
$\mathrm{GQR} \to 3_1^-$	0.00	84.95	84.95

↔

$$\begin{aligned}\Gamma(\mathrm{GDR} \to 2_1^+) &= 4 \cdot \Gamma^{\pi(\nu)}(\mathrm{GDR} \to 2_1^+),\\ \Gamma(\mathrm{GQR} \to 3_1^-) &= \Gamma^\pi(\mathrm{GQR} \to 3_1^-) - \Gamma^\nu(\mathrm{GQR} \to 3_1^-)\\ &= 0.\end{aligned}$$

Sensitivity to isospin of GRs

- $\boldsymbol{\gamma}$-decay widths contributed by protons and neutrons



✓ Constructive interference:

GDR: $\Gamma_\gamma^{tot} > \Gamma_\gamma^{\pi(\nu)}$

GDR (IV) $\xrightarrow{\text{E1(IV)}}$ 2_1^+ (IS)

✓ destructive interference:

GQR: $\Gamma_\gamma^{tot} < \Gamma_\gamma^{\pi(\nu)}$

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- *N*=*Z* nucleus ^{56}Ni without Coulomb: Isospin symmetry limit

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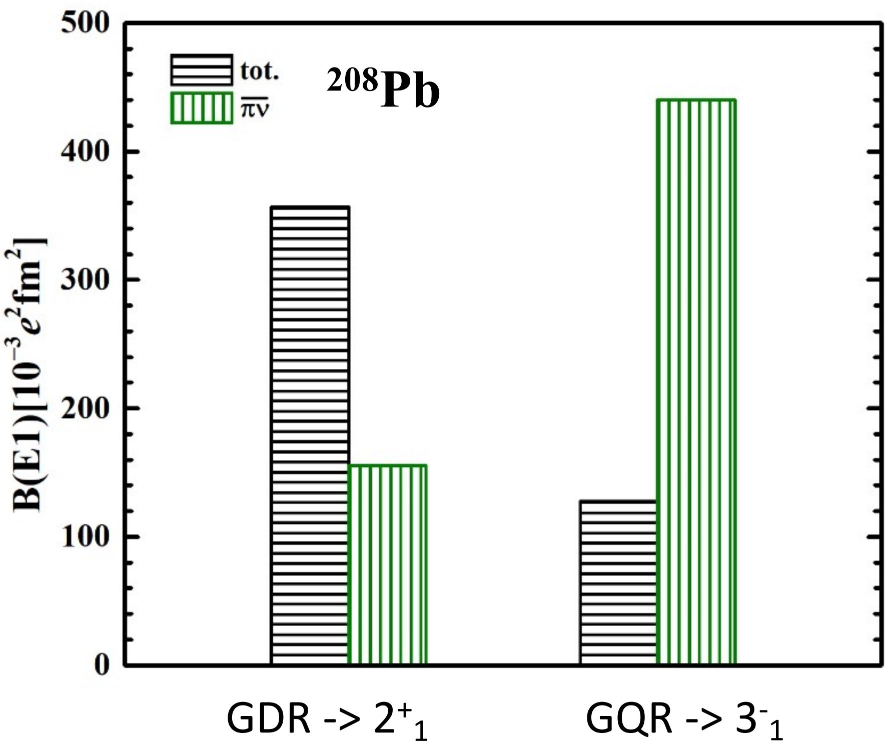
$$\begin{aligned}\Gamma(\mathrm{GDR} \to 2_1^+) =& 4 \cdot \Gamma^{\pi(\nu)}(\mathrm{GDR} \to 2_1^+),\\ \Gamma(\mathrm{GQR} \to 3_1^-) =& \Gamma^\pi(\mathrm{GQR} \to 3_1^-) - \Gamma^\nu(\mathrm{GQR} \to 3_1^-)\\ =& 0.\end{aligned}$$

- *$\boldsymbol{\gamma}$ -decay data can be used to determine the isospin properties of involved states, e.g. pygmy dipole states*

Compare $\boldsymbol{\gamma}$ decay between GDR and GQR

- $\Gamma_\gamma(E\lambda; i \to f) = \frac{8\pi(\lambda+1)}{\lambda\left[(2\lambda+1)!!\right]}\left(\frac{E}{\hbar c}\right)^{2\lambda+1} B(E\lambda; i \to f)$

Exclude the influence of different transition energies

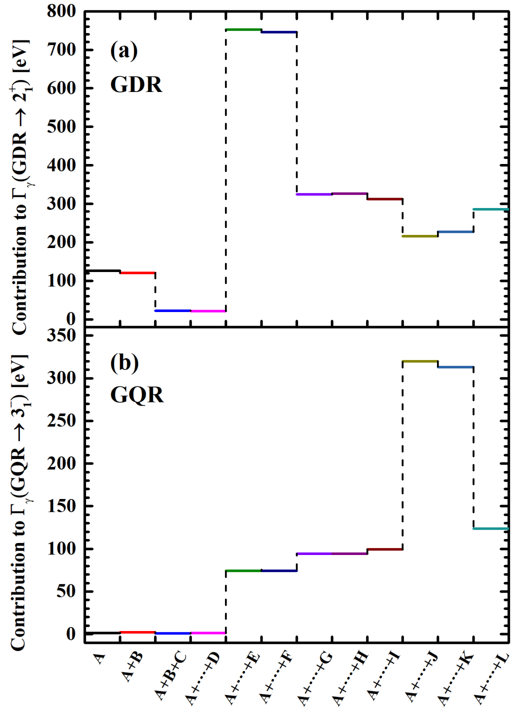


- Exclude the isospin effect: compare averaged contribution of protons and neutrons

$$B^{\overline{\pi\nu}}(\mathrm{GDR} \to 2_1^+) < \frac{1}{2} \cdot B^{\overline{\pi\nu}}(\mathrm{GQR} \to 3_1^-)$$

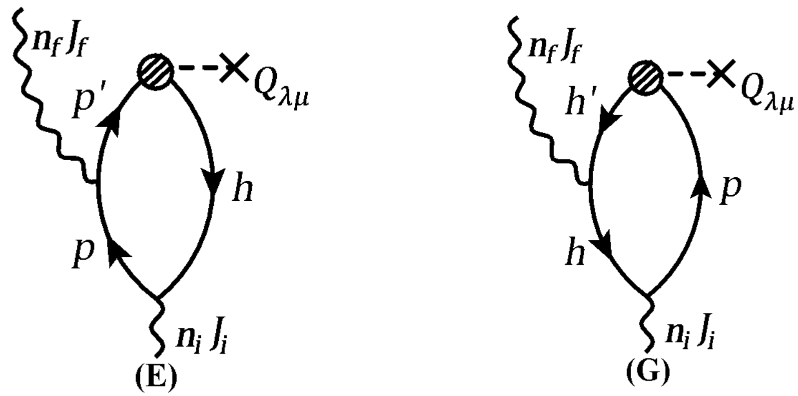
Wave functions of GRs

- Contributions to γ-decay width from different diagrams



✓ Diagrams E and G - PVC level

$\Gamma_\gamma(\mathrm{GDR} \to 2_1^+)$ 76% $\Gamma_\gamma(\mathrm{GQR} \to 3_1^-)$ 95%



$$|J_i\rangle \sim |((1p1h) \otimes J_f)_{J_i}\rangle$$

W. L. Lv, Y. F. Niu, and G. Colo, Phys. Rev. C 103, 064321 (2021)

$$B^{\overline{\pi\nu}}(\mathrm{GDR} \to 2_1^+) < \frac{1}{2} \cdot B^{\overline{\pi\nu}}(\mathrm{GQR} \to 3_1^-)$$

⬇

$\left|[(ph)_J \otimes 2_1^+]_{\mathrm{GDR}}\right\rangle$ component in $|\mathrm{GDR}\rangle$ < $\left|[(ph)_J \otimes 3_1^-]_{\mathrm{GQR}}\right\rangle$ component in $|\mathrm{GQR}\rangle$

- In agreement with damping mechanism from wavelet analysis:

  GDR: 1p-1h configurations (Landau damping)

  GQR: 1p-1h coupled with phonons (spreading width)

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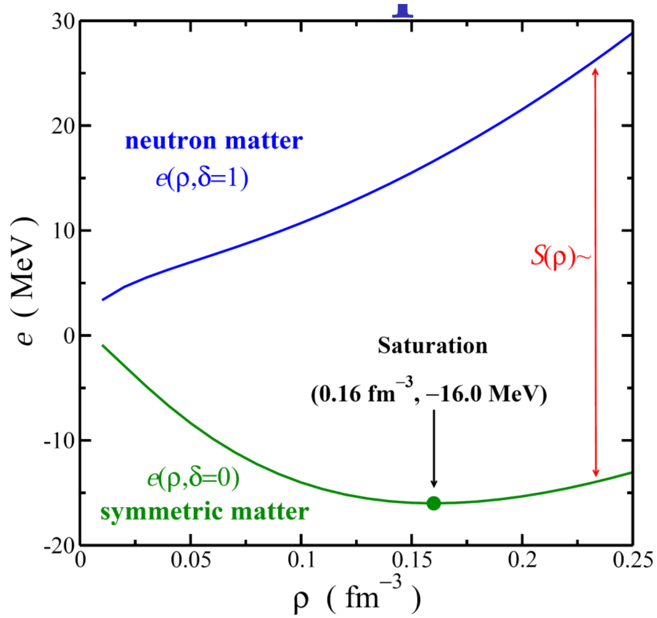
EOS and Symmetry Energy

- **Nuclear Equation of State (EOS)**



- **Importance of EOS**
  - ✓ Mass, radius of neutron star
  - ✓ Tidal deformability of neutron star mergers
  - ✓ Dynamics of core-collapse supernova

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2 \qquad \delta \equiv (\rho_n - \rho_p)/\rho$$

nuclear matter **Symmetric matter** **Symmetry energy**

Electric Dipole Polarizability

- **Microscopic definition:**

$$\alpha_D = \frac{8\pi}{9} e^2 m_{-1} \qquad m_{-1} = \sum_{\nu} \frac{|\langle \nu | \hat{F} | 0 \rangle|^2}{E_\nu}$$

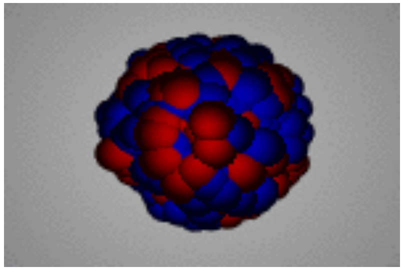
where F is the isovector dipole excitation operator

$$\hat{F} = \frac{Z}{A} \sum_{i=1}^{N} r_i Y_{1M} - \frac{N}{A} \sum_{i=1}^{Z} r_i Y_{1M}$$

How difficult the nuclear charge distribution to be displaced

- **constraints on symmetry energy**

Isovector resonances depend on ρ_n-ρ_p
driven by $S(\rho)$ **restoring force**

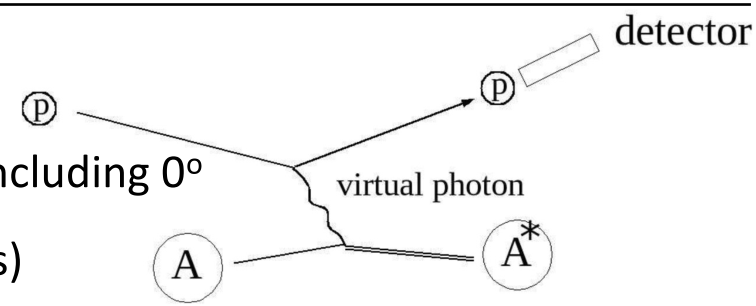


Measurements of dipole polarizability

(p,p') reaction

✓ polarized proton scattering at angles close to and including 0°

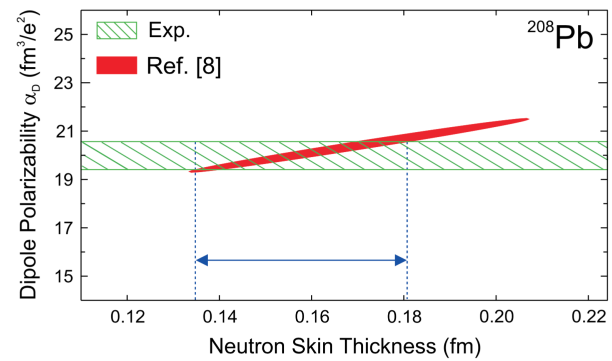
✓ excitations via virtual photons (Coulomb excitations)



- Dipole Polarizability of **^{208}Pb**

  α_D = 20.1 (6) fm^3

  A. Tamii, et al., Phys. Rev. Lett. 107, 062502 (2011)

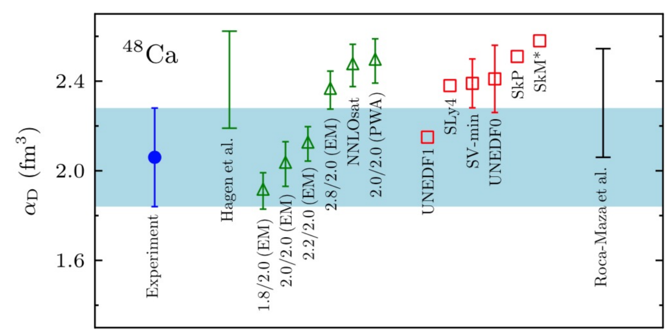


$$r_{\text{skin}} = 0.156^{+0.025}_{-0.021}\ \text{fm}$$

- Dipole Polarizability of **^{48}Ca, ^{40}Ca**

  α_D = 2.07(22) fm^3 1.92(17) fm^3

  J. Birkhan, et al., Phys. Rev. Lett. 118, 252501 (2017)
  R. W. Fearick et al., Phys. Rev. Res. 5, L022044 (2023)



- Dipole Polarizability of **^{120}Sn**

  α_D = 8.93(36) fm^3

  T. Hashimoto, et al., Phys. Rev. C 92, 031305(R) (2015)

r_{skin} = 0.14-0.20 fm

Calculation of dipole polarizability: PVC effect

- Second RPA or Particle-vibration coupling (PVC) with subtraction method

$$R(\omega = 0) = R_{\mathrm{KS}}^{\mathrm{RPA}}$$

The static properties are well adjusted at the mean-field level

Tselyaev, PRC 88, 054301(2013)

D. Gambacurta, et al., Phys. Rev. C 92, 034303 (2015)

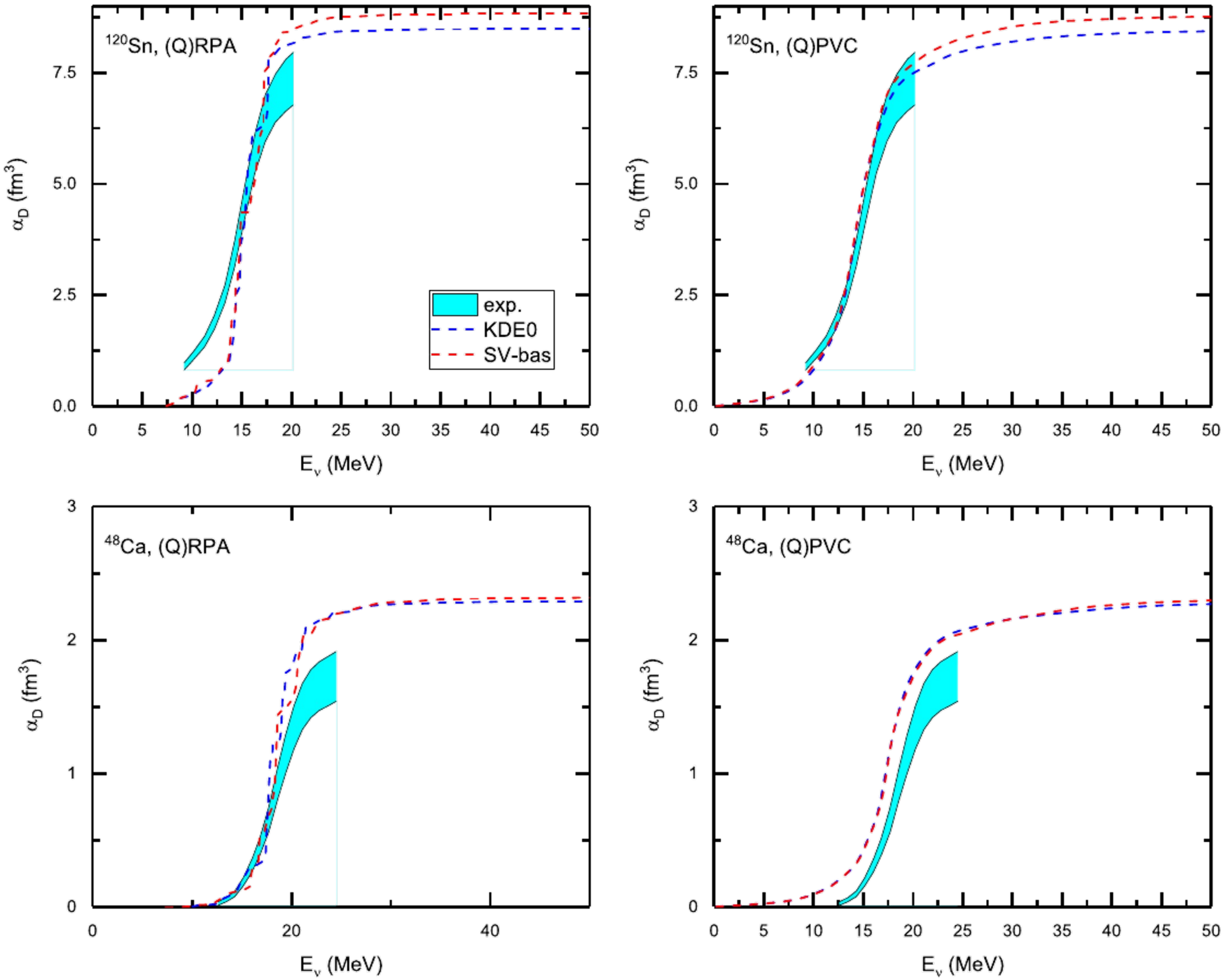
✓ Quasiparticle PVC (QPVC): m_{-1} of dipole excitation

m_{-1}	QRPA	QPVC w.o. subt.	(%)	QPVC w.i. subt.	(%)
^{44}Ca					
SV-k226	2.0989	2.2188	105.7	2.0941	99.8
SV-bas	2.1140	2.2324	105.6	2.1096	99.8
^{120}Sn					
SV-k226	8.7960	9.5213	108.2	8.7681	99.7
SV-bas	8.7798	9.3447	106.4	8.7481	99.6

$$\alpha_D = \frac{8\pi}{9} e^2 m_{-1}$$

- With subtraction, dipole polarizability is kept the same as RPA level

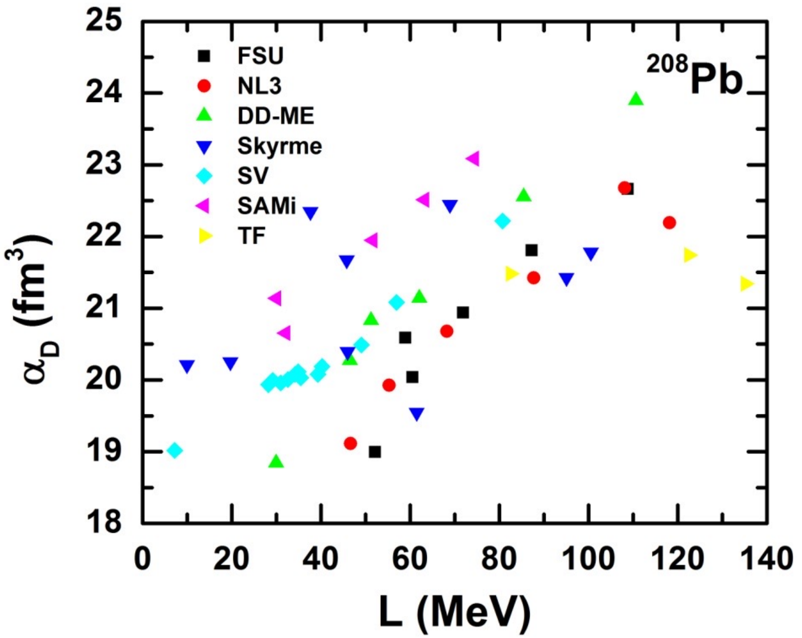
Calculation of dipole polarizability: PVC effect

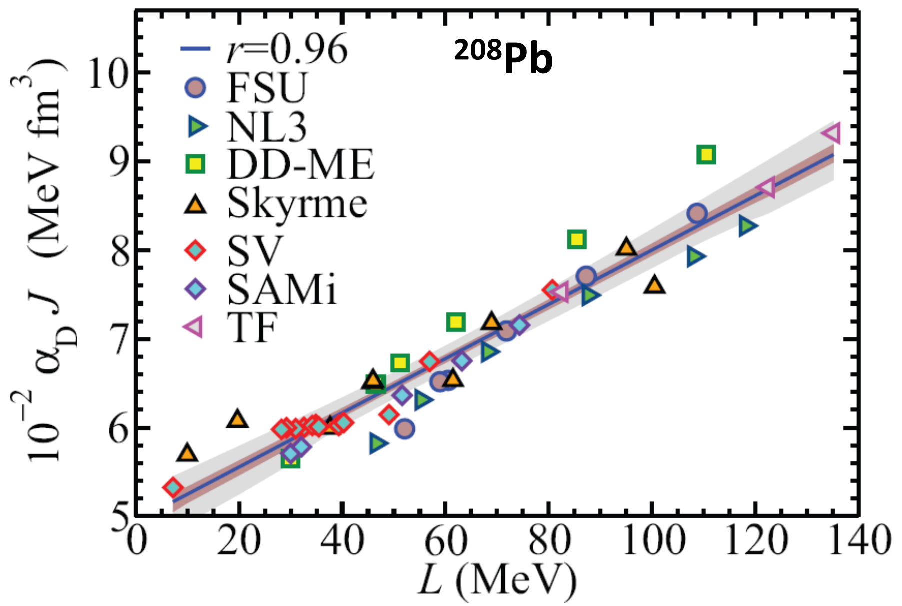


Exp:
Bassauer, et al., PRC 102, 034327 (2020);
Birkhan, et al., PRL 118, 252501 (2017).

- Although the total dipole polarizability is the same from QRPA to QPVC, the evolution trend with energy is much improved

Constraints on Symmetry Energy Slope from α_D





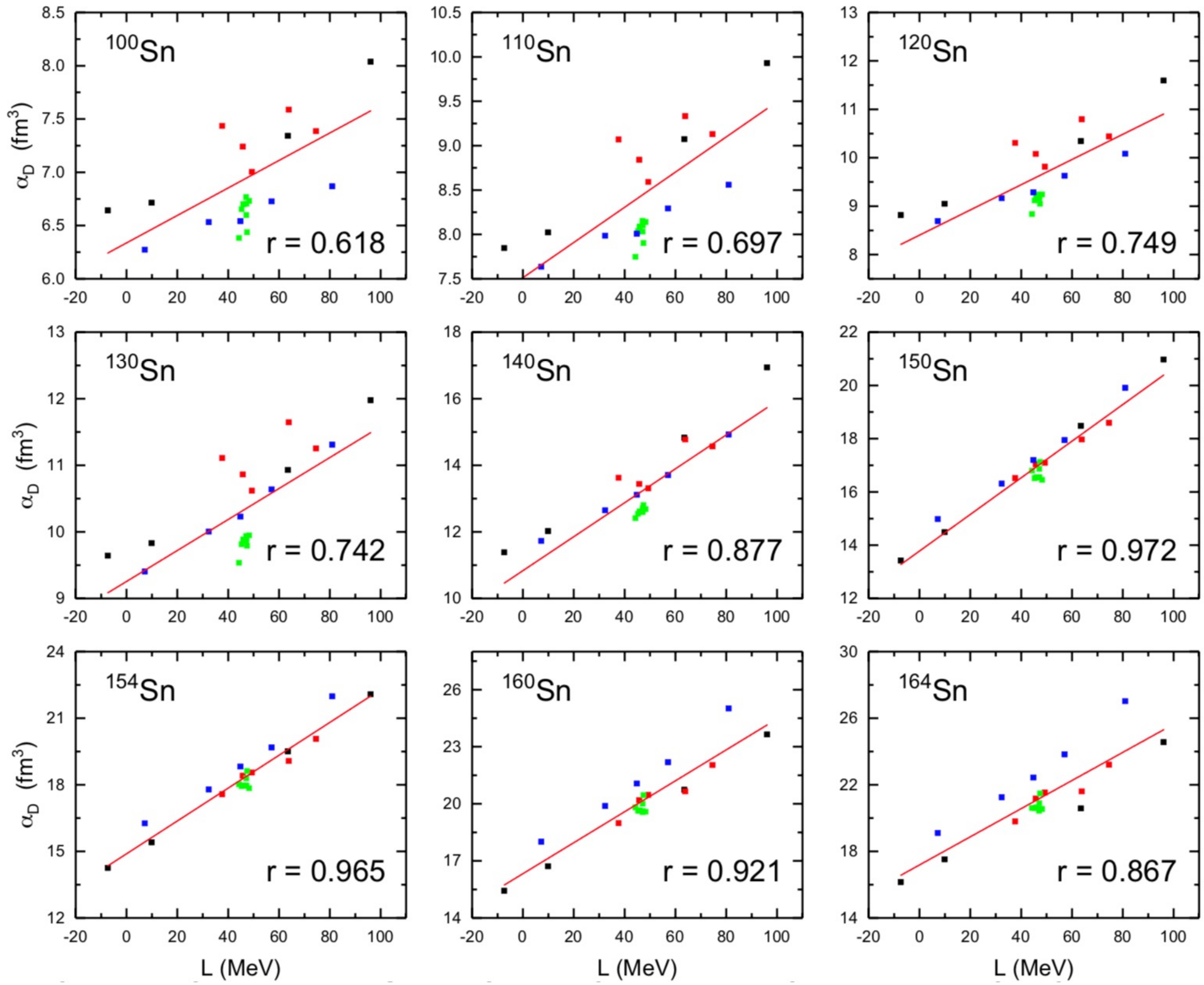
Linear fits give $$10^{-2}\alpha_D J = (4.80 \pm 0.04) + (0.033 \pm 0.001)L$$

If $J = [31 \pm (2)_{\rm est}]$ MeV, $\alpha_D = 20.1 \pm 0.6$ fm^3 then $L = 43 \pm (6)_{\rm expt} \pm (8)_{\rm theor} \pm (12)_{\rm est}$ MeV

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

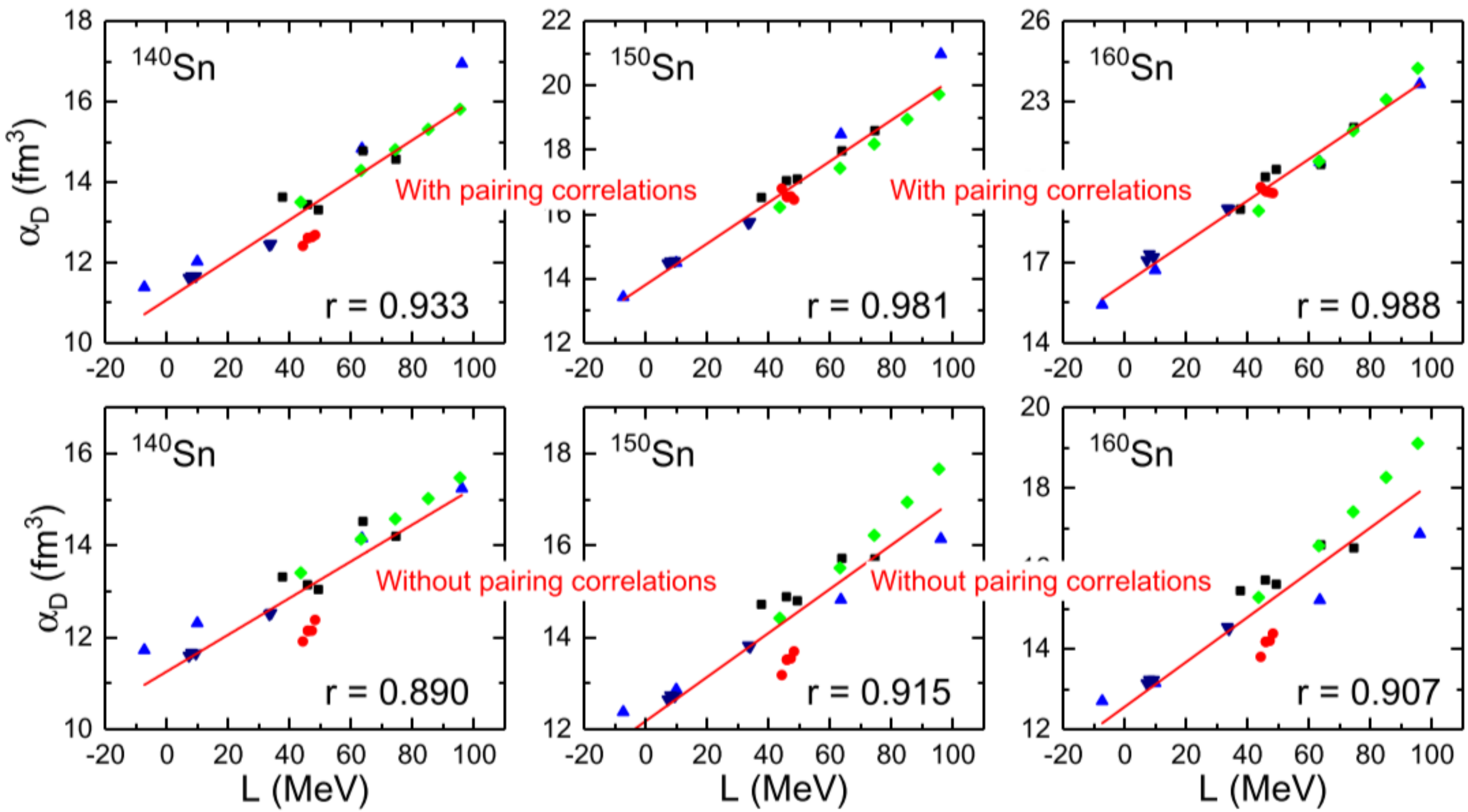
- Could we obtain a better constraint on L from α_D?

Correlations between α_D and L in Sn isotopes



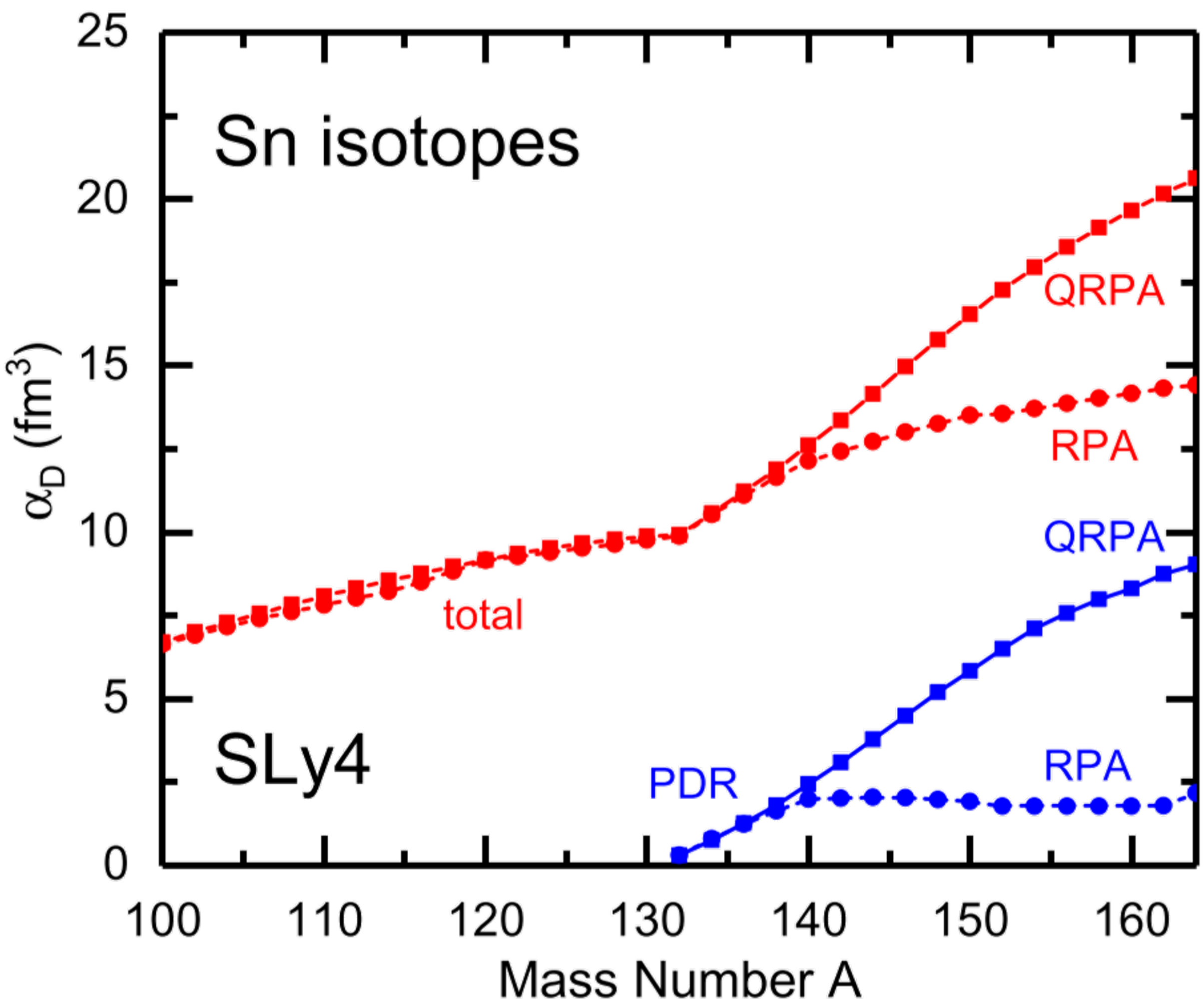
- ✓ The linear correlation between α_D and L becomes better in neutron-rich nuclei
- ✓ It shows strong correlations around ^{150}Sn

Pairing effects



Without pairing correlations, the linear correlations become weaker in neutron rich nuclei

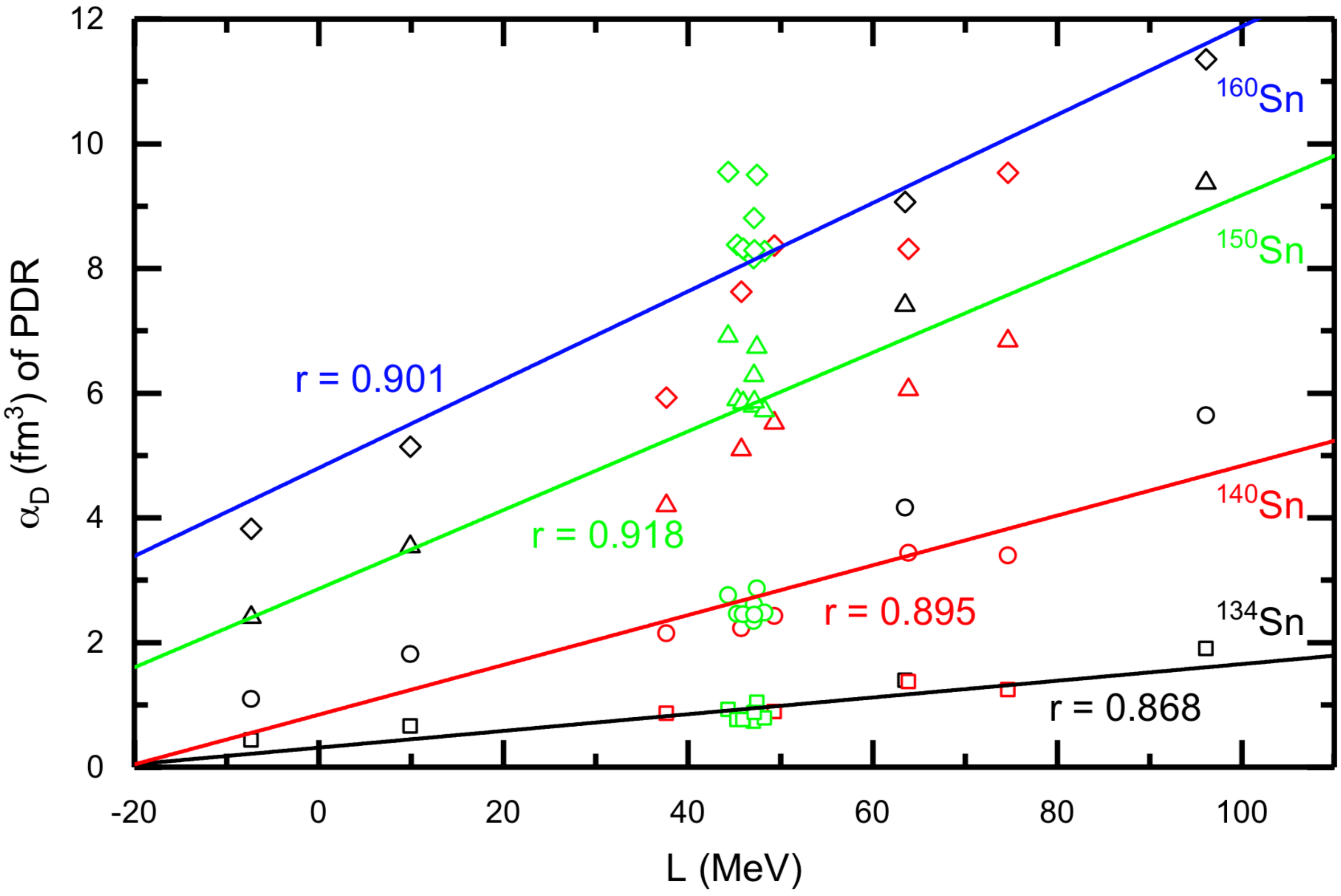
Pairing effects



- ✓ Pairing correlations have important contributions to α_D in neutron rich nuclei
- ✓ Pairing correlations play their roles through pygmy dipole resonance (PDR)

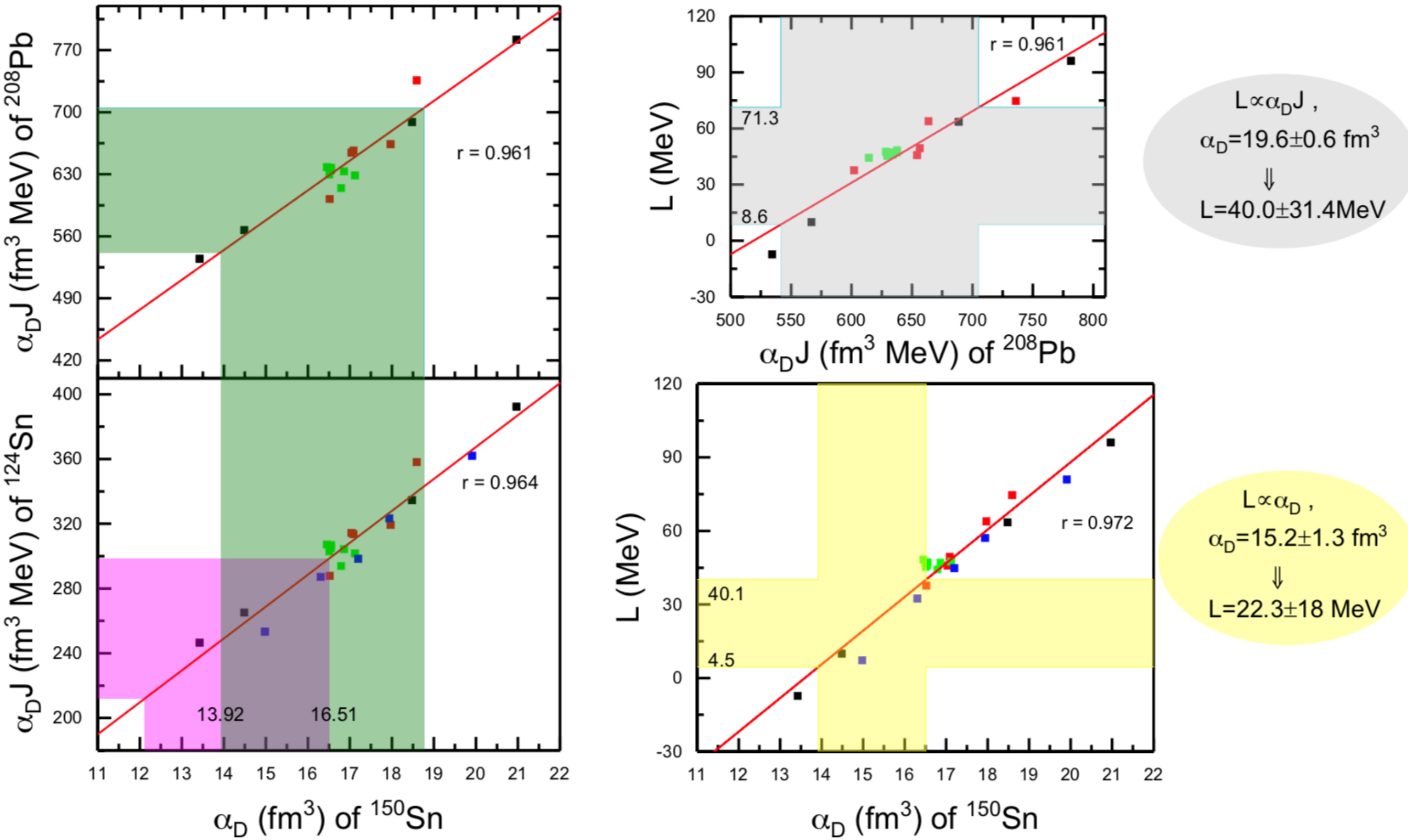
Z. Z. Li et al., PRC 103, 064301 (2021)

Correlations between α_D and L in PDR



✓ When the PDR strength increases, good linear correlations are found between α_D of PDR and L, which enhances the linear correlations between total α_D and L in neutron-rich nuclei.

Predictions of $\alpha_D(^{150}Sn)$ and constraints on L



- ✓ α_D in ^{150}Sn is not measured yet. It can be deduced from $\alpha_D J$ of stable nuclei like ^{208}Pb and ^{120}Sn.
- ✓ Making use of strong linear correlation between α_D and L in ^{150}Sn, L can be better constrained without the introduction of uncertainties in J.

Summary

- γ-decay between GRs and low-lying states
  - ✓ The sensitivity of γ-decay to the isospin of involved states is proven.
  - ✓ A larger 3^- component in GQR wavefunction than the 2^+ component in GDR is found.
  - ➢ A unique probe of the resonance wavefunctions

- Dipole polarizability and nuclear EOS
  - ✓ QPVC improves the evolution trend of dipole polarizability
  - ✓ Linear correlation between electric dipole polarizability and slope parameter of symmetry energy in neutron rich Sn isotopes is found

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Thank you!