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EXCELENCIA
MARÍA
DE MAEZTU
04/2025-03/2031

Electric dipole polarizability and The neutron skin thickness

Xavier Roca-Maza

COMEX 8

Collective Motion in Nuclei under Extreme Conditions

Florida State University, Tallahassee, December 15th - 19th



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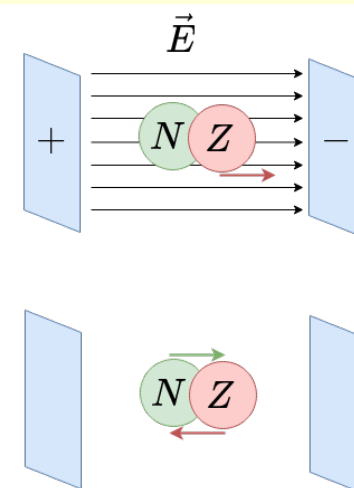
Electric Dipole Polarizability: introduction

The **electric dipole polarizability** measures the **tendency** of the nuclear **charge distribution** to be **distorted**

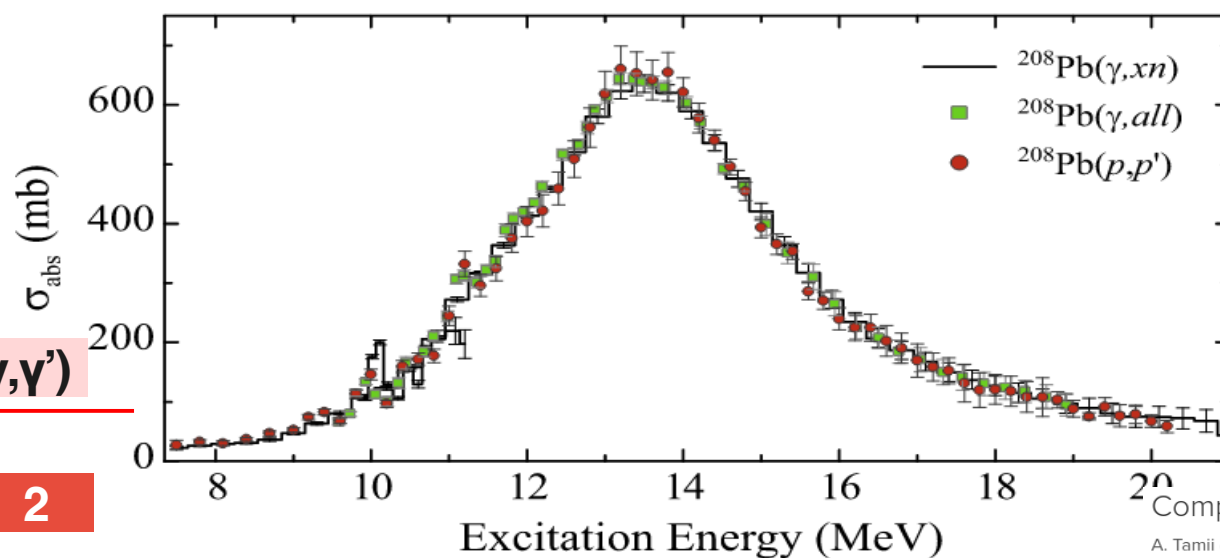
$$\alpha = \frac{\text{electric dipole moment}}{\text{external electric field applied}}$$

Microscopically, it relates with the **photo-absorption cross-section**

$$\alpha_D = \frac{\hbar c}{2\pi^2 e^2} \int \frac{\sigma_{\text{abs}}}{\omega^2} d\omega,$$



Measured using **polarized** proton scattering at **very forward angles** (dominated by **E1** and **M1** well separated)



$$\alpha_D(^{208}\text{Pb}) = 19.6 \pm 0.6 \text{ fm}^3$$

Electric Dipole Polarizability: theory

Theoretically, the total photo-absorption cross section, can be written as

$$\sigma_{\gamma\text{-abs}} = 4\pi^2\alpha \sum_{\nu} (E_{\nu} - E_0) |\langle \nu | F_{\text{dipole}} | 0 \rangle|^2$$

Dipole operator
subtract CM motion

And, thus,

$$\alpha_D = 2 \sum_{\nu \neq 0} \frac{|\langle \nu | F_{\text{dipole}} | 0 \rangle|^2}{E_{\nu} - E_0} \equiv 2m_{-1} \quad \frac{eN}{A} \sum_{i=1}^Z r_i Y_{1M}(\hat{r}_i) - \frac{eZ}{A} \sum_{i=1}^N r_i Y_{1M}(\hat{r}_i)$$

Considering the G.S. perturbed by an external field λF (with $\lambda \rightarrow 0$):

$\langle \mathcal{H} \rangle = \langle \mathcal{H}_0 + \lambda F_{\text{dipole}} \rangle$; The variation in the expectation energy can be written as:

$$\delta \langle \mathcal{H} \rangle = \lambda^2 \sum_{\nu \neq 0} \frac{|\langle \nu | F | 0 \rangle|^2}{E_{\nu} - E_0} + \mathcal{O}(\lambda^3) = \lambda^2 m_{-1} + \mathcal{O}(\lambda^3)$$

$$m_{-1} = \frac{1}{2} \frac{\partial^2 \langle \mathcal{H} \rangle}{\partial \lambda^2} \Big|_{\lambda=0}$$

Dielectric
Theorem

Electric Dipole Polarizability: simple model & correlations

Applying the **dielectric theorem** to the **Droplet Model** Hamiltonian (first Migdal and latter on Meyer et al. NPA385, 269) one can find

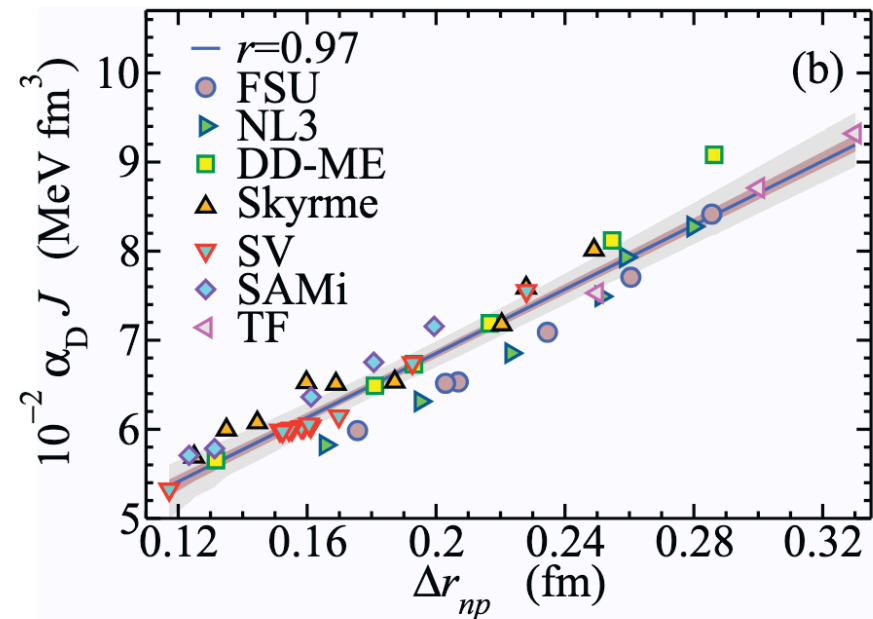
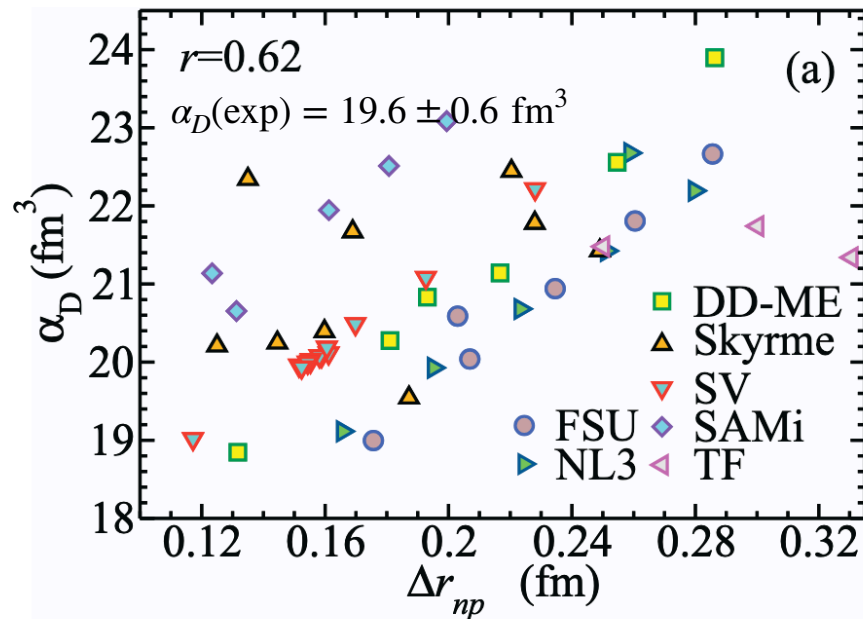
$$\alpha_D \approx \frac{A \langle r^2 \rangle}{12J} \left[1 + \frac{5 \Delta r_{np} + \sqrt{\frac{3}{5} \frac{e^2 Z}{70J}} - \Delta r_{np}^{\text{surface}}}{\langle r^2 \rangle^{1/2} (I - I_C)} \right]$$

$J = e(\text{PNM}) - e(\text{SNM}) \rightarrow$ Symmetry energy at ρ_0

$\Delta r_{np} \equiv \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} \rightarrow$ Neutron skin thickness

Using microscopic calculations (Energy Density Functionals & Ab initio)

PHYSICAL REVIEW C 88, 024316 (2013)

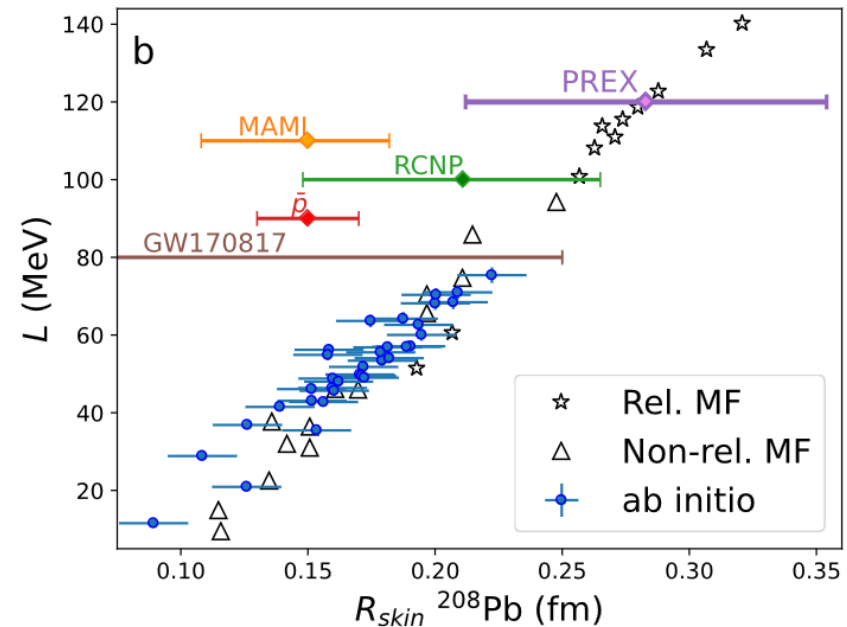
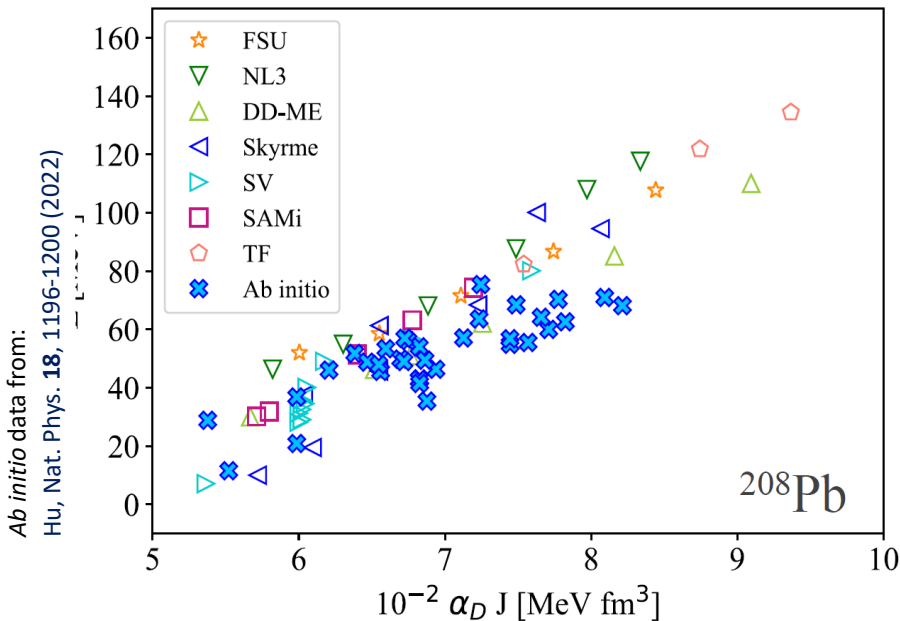


Electric Dipole Polarizability: simple model & correlations

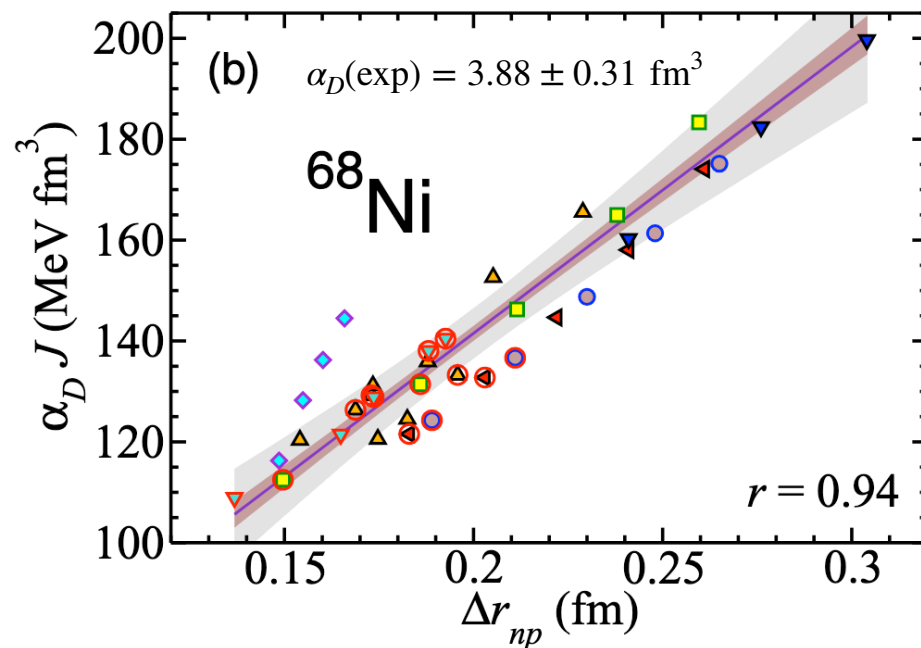
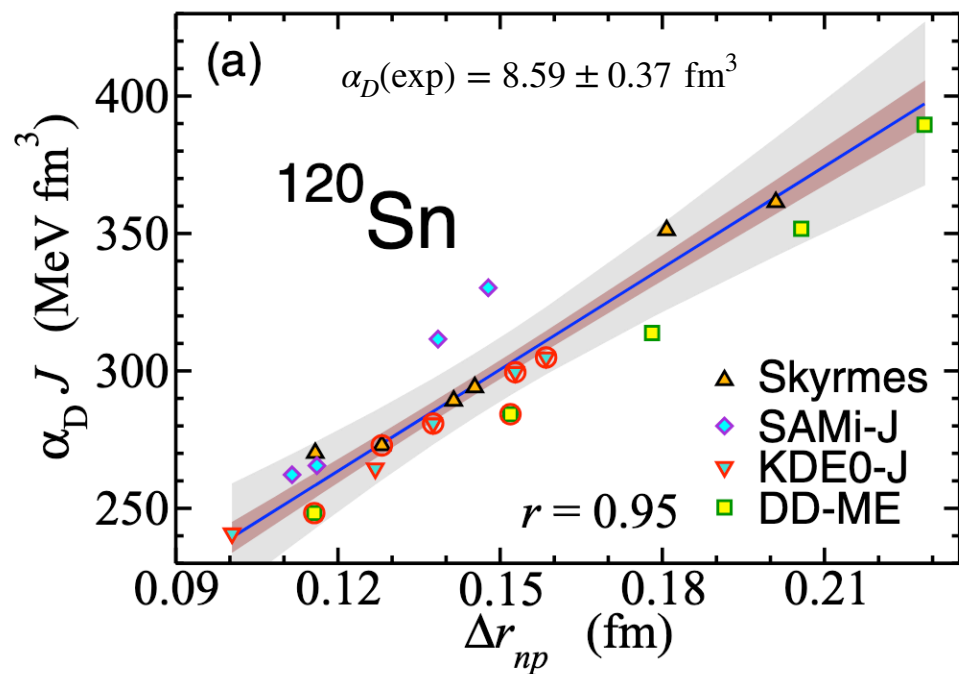
Same as before but **including *ab-initio***, exchanging the axis and using L instead of the neutron skin thickness

$$\Delta r_{np} \approx \frac{1}{12} \frac{N - Z}{A} \frac{R}{J} L$$

Courtesy: Francesca Bonaiti



Electric Dipole Polarizability in ^{120}Sn and ^{68}Ni



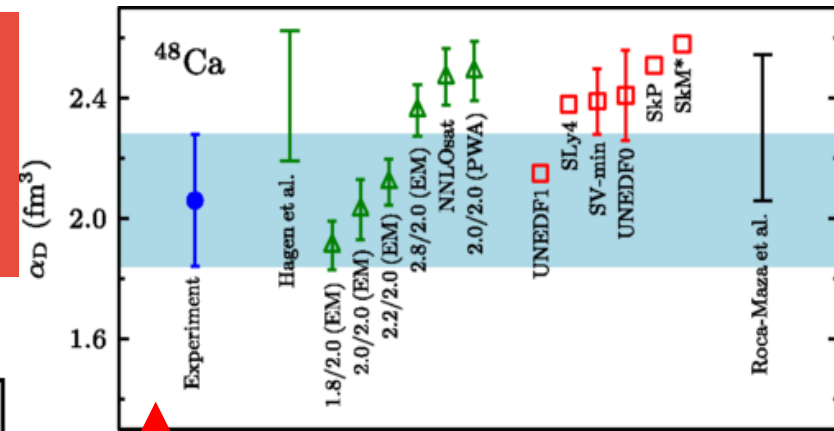
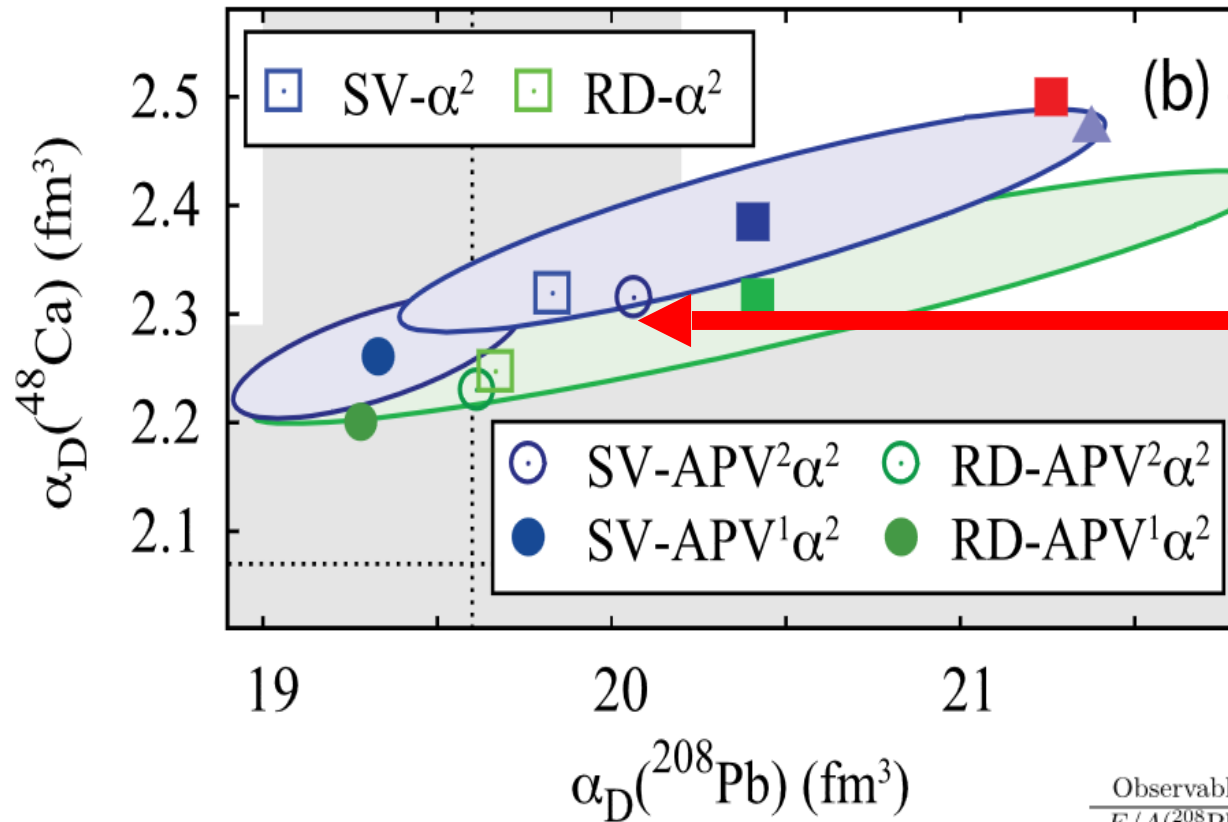
Nucleus	Δr_{np} (a)	Δr_{np} (b)	Δr_{np} (c)
^{68}Ni	0.15–0.19	0.18 ± 0.01	0.16 ± 0.04
^{120}Sn	0.12–0.16	0.14 ± 0.02	0.12 ± 0.04
^{208}Pb	0.13–0.19	0.16 ± 0.02	0.16 ± 0.03

From correlations among EDFs and plausible $J = 31 \pm 2 \text{ MeV}$

Only from models compatible with data

$$\alpha_D J = \begin{cases} (27 \pm 15) + (570 \pm 33)\Delta r_{np}, & \text{for } ^{68}\text{Ni}; \\ (115 \pm 36) + (1234 \pm 93)\Delta r_{np}, & \text{for } ^{120}\text{Sn}; \\ (301 \pm 32) + (1922 \pm 73)\Delta r_{np}, & \text{for } ^{208}\text{Pb}. \end{cases}$$

Electric Dipole Polarizability in ^{48}Ca and ^{208}Pb



Phys. Rev. Lett. **118**, 252501 – Published 23 June 2017

Ab initio

Combined Theoretical Analysis of the Parity-Violating Asymmetry
for ^{48}Ca and ^{208}Pb

Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz
Phys. Rev. Lett. **129**, 232501 – Published 2 December 2022

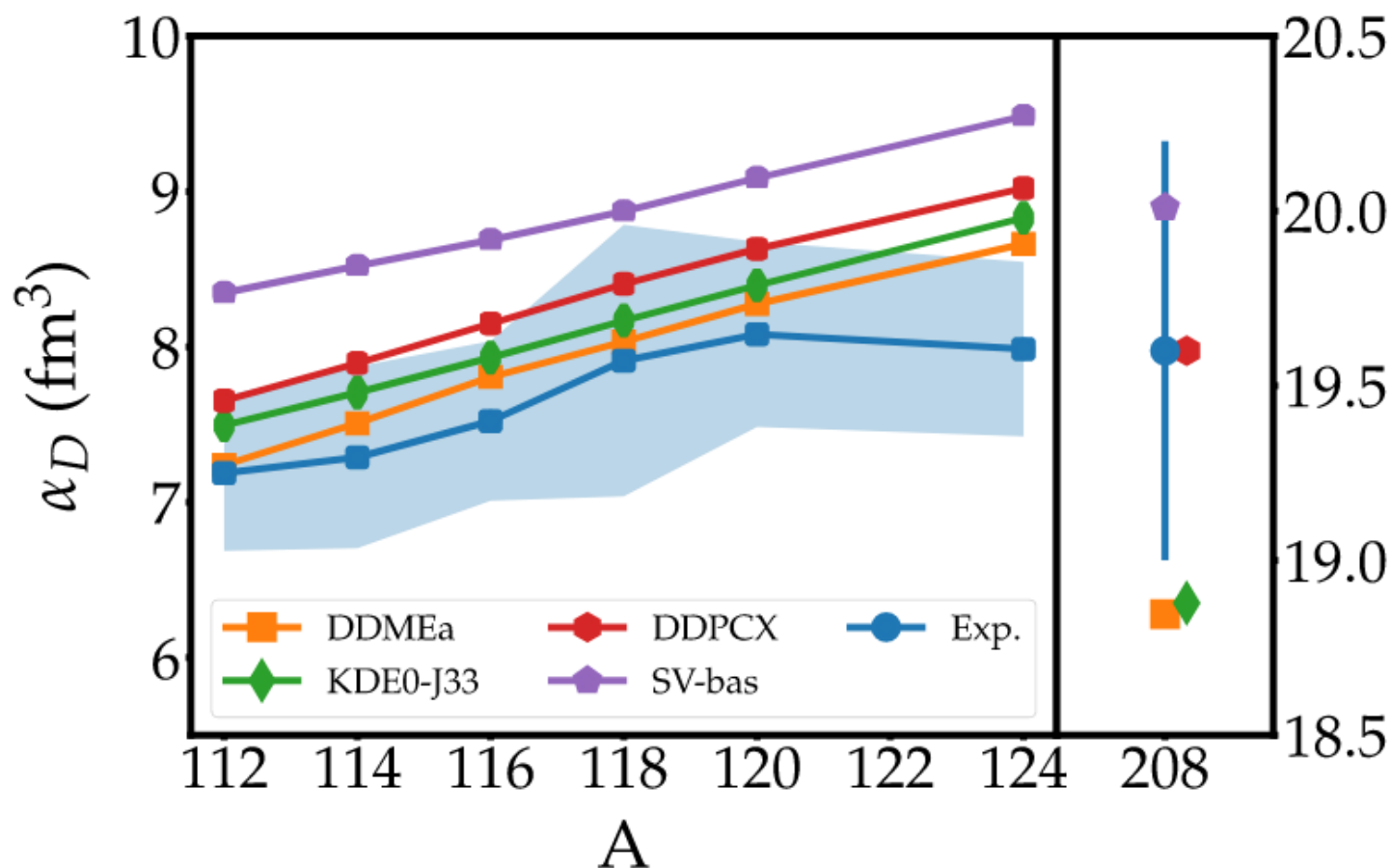
Observable	z	σ_{exp}	σ_{model}	σ_{method}	σ_{em}	PPD
$E/A(^{208}\text{Pb})$	-7.867	0	0.54	0.5	—	$-8.06^{+0.99}_{-0.88}$
$R_p(^{208}\text{Pb})$	5.45	0	0.17	0.05	—	$5.43^{+0.21}_{-0.23}$
$\alpha_D(^{48}\text{Ca})$	2.07	0.22	0.06	0.1	—	$2.30^{+0.31}_{-0.26}$
$\alpha_D(^{208}\text{Pb})$	20.1	0.6	0.59	0.8	—	$22.6^{+2.1}_{-1.8}$

Ab initio predictions link the neutron skin of ^{208}Pb to nuclear forces

Baishan Hu, Weiguang Jiang, Takayuki Miyagi, Zhonghao Sun, Andreas Ekström, Christian Forssén, Gaute Hagen, Jason D. Holt, Thomas Papenbrock, S. Ragnar Stroberg & Ian Vernon

Nature Physics **18**, 1196–1200 (2022) | [Cite this article](#)

Electric Dipole Polarizability: Sn isotopes



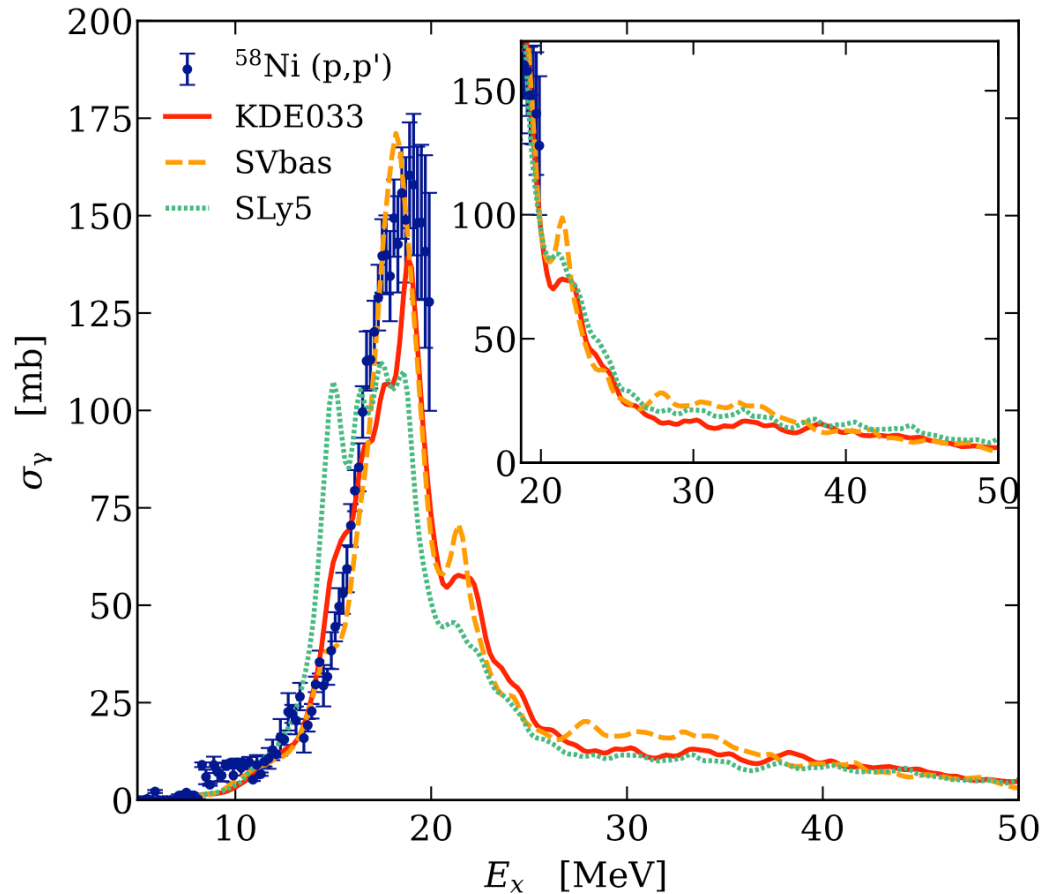
Electric Dipole Polarizability in ^{40}Ca and ^{58}Ni

Electric dipole polarizability of ^{40}Ca

R. W. Fearick¹, P. von Neumann-Cosel^{2,*}, S. Bacca^{3,4}, J. Birkhan², F. Bonaiti³, I. Brandherm², G. Hagen^{5,6}, H. Matsubara^{7,8}, W. Nazarewicz⁹ et al.

Show more

Phys. Rev. Research 5, L022044 – Published 31 May, 2023



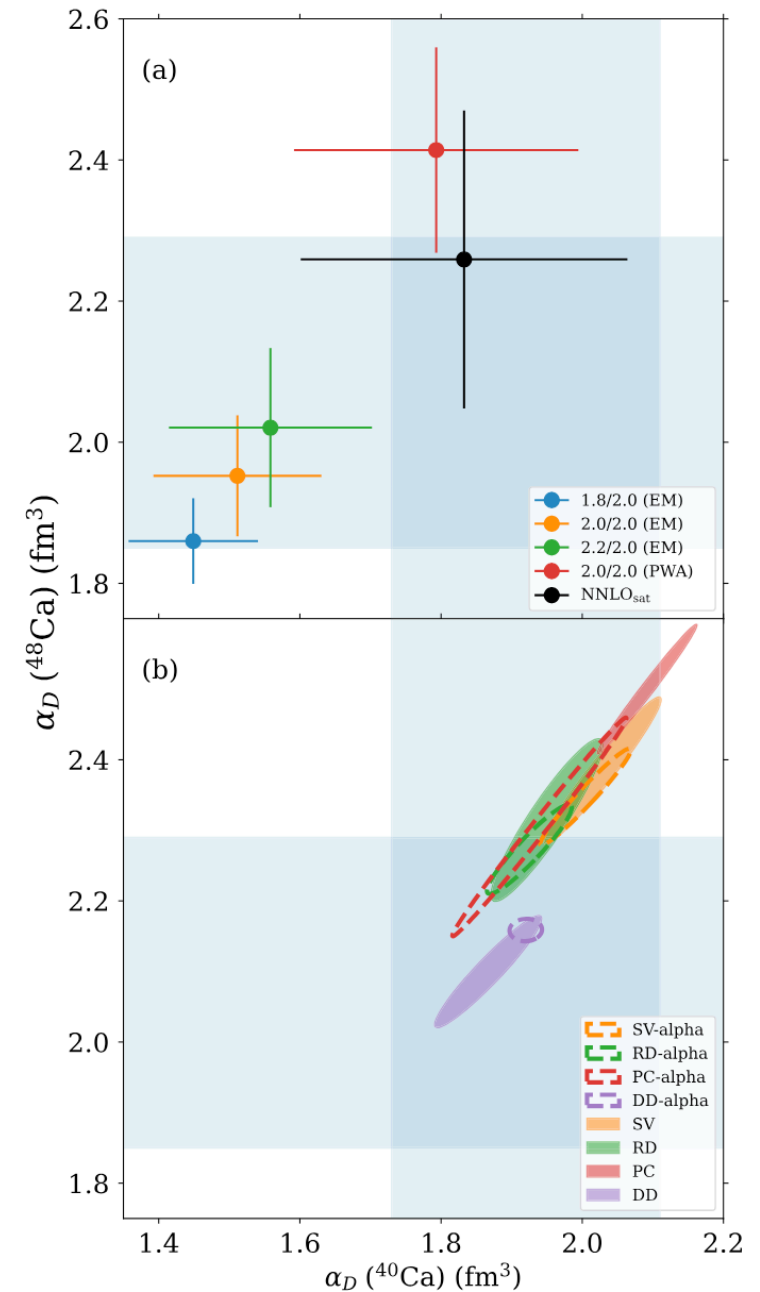
Electric dipole polarizability of ^{58}Ni

I. Brandherm¹, F. Bonaiti^{2,3,4}, P. von Neumann-Cosel^{1,*}, S. Bacca², G. Colò^{5,6}, G. R. Jansen^{7,4}, Z. Z. Li (李征征)^{8,9,10}, H. Matsubara^{11,12}, Y. F. Niu (牛一斐)^{9,10} et al.

Show more

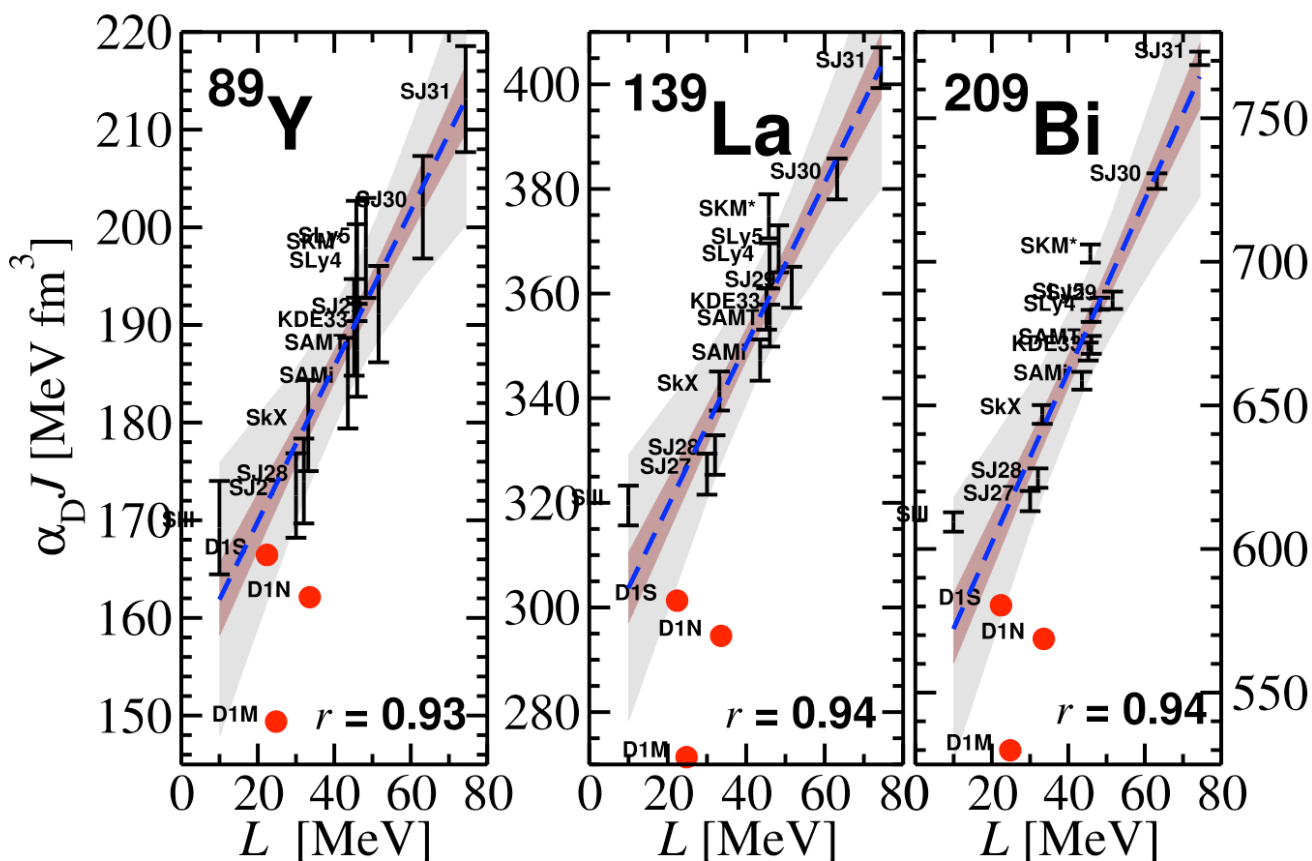
9

Phys. Rev. C 111, 024312 – Published 13 February, 2025



E

Electric Dipole Polarizability in odd-even nuclei



$$\begin{aligned}
 J &= 32.5(1.0) + 0.17(0.02)L && \text{for } ^{89}\text{Y}, \\
 J &= 26.7(6) + 0.14(0.02)L && \text{for } ^{139}\text{La}, \\
 J &= 24.0(6) + 0.13(0.01)L && \text{for } ^{209}\text{Bi}. \\
 \\
 J &= 25.0(2) + 0.19(2)L && \text{for } ^{68}\text{Ni}, \\
 J &= 25.4(1.1) + 0.17(1)L && \text{for } ^{120}\text{Sn}, \\
 J &= 24.5(8) + 0.17(1)L && \text{for } ^{208}\text{Pb}.
 \end{aligned}$$

E1 moments from a coherent set of measured photoneutron cross sections

S. Goriely¹, S. Péru^{2,3}, G. Colò⁴, X. Roca-Maza⁴, I. Gheorghe⁵, D. Filipescu⁵, and H. Utsunomiya⁶

Show more

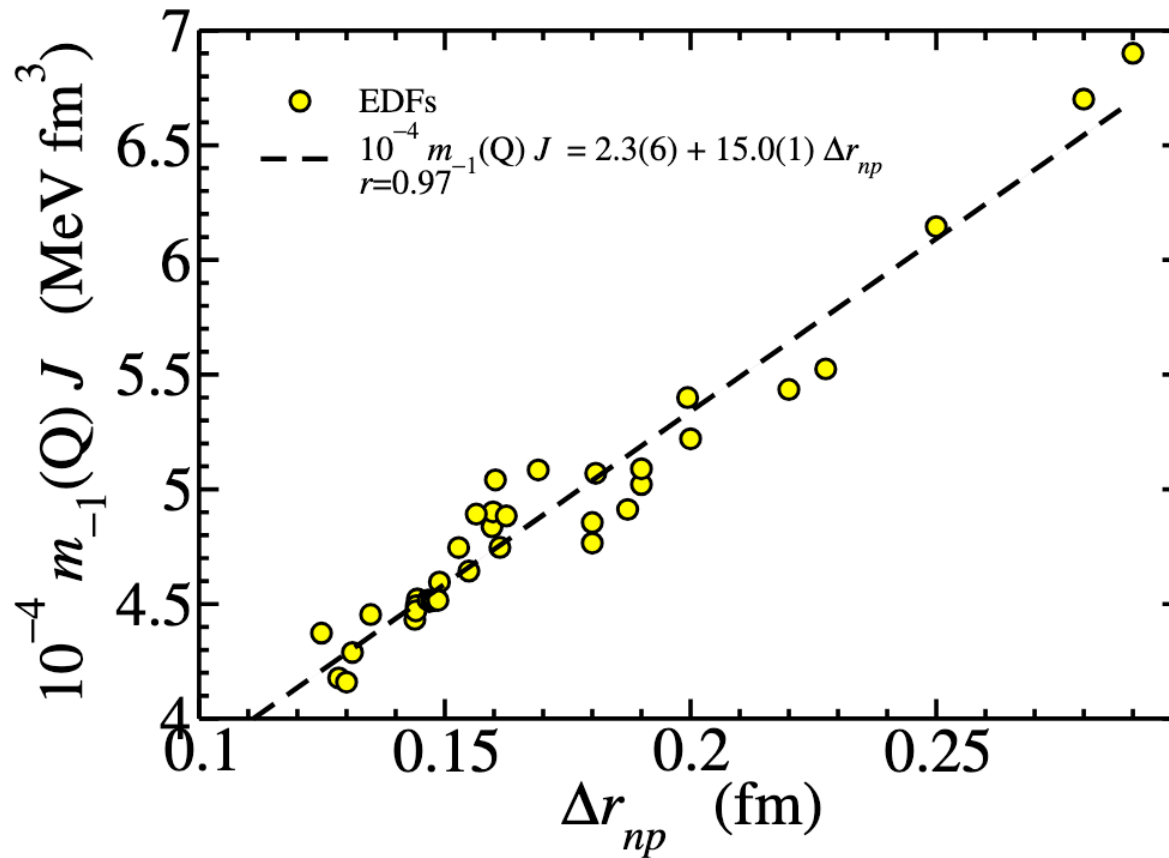
Is the **polarizability** of other **isovector modes** related to the **symmetry energy** and **neutron skin thickness** (in a heavy nucleus)?

$$\frac{1}{\alpha_L} = \left. \frac{\partial^2 \langle \mathcal{H} \rangle}{\partial \langle \mathcal{O}_L \rangle^2} \right|_{\lambda=0}$$

We **should expect** so from the **dielectric theorem**.

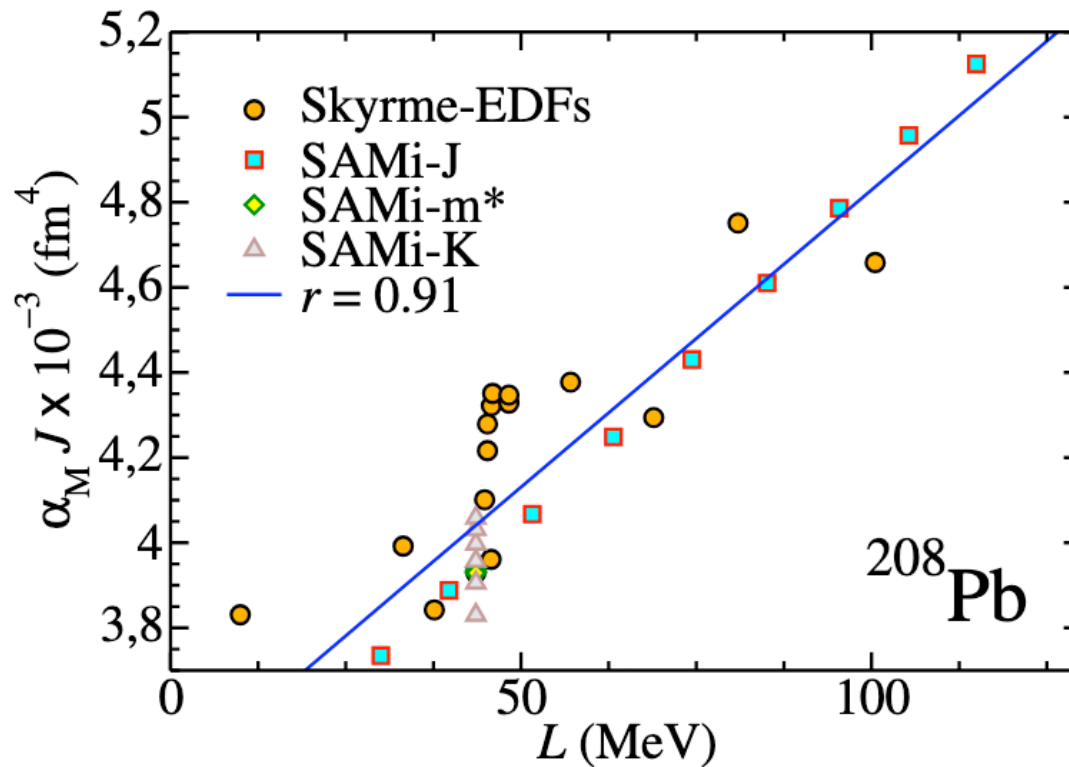
Example 1: Isovector Quadrupole Polarizability in ^{208}Pb

$$\alpha_Q \approx \frac{A \langle r^4 \rangle}{16\pi J} \left[1 + \frac{7 \Delta r_{np} + \sqrt{\frac{3}{5}} \frac{e^2 Z}{70J} - \Delta r_{np}^{\text{surface}}}{\langle r^2 \rangle^{1/2} (I - I_C)} \right]$$



Example 2: Isovector Monopole Polarizability in ^{208}Pb

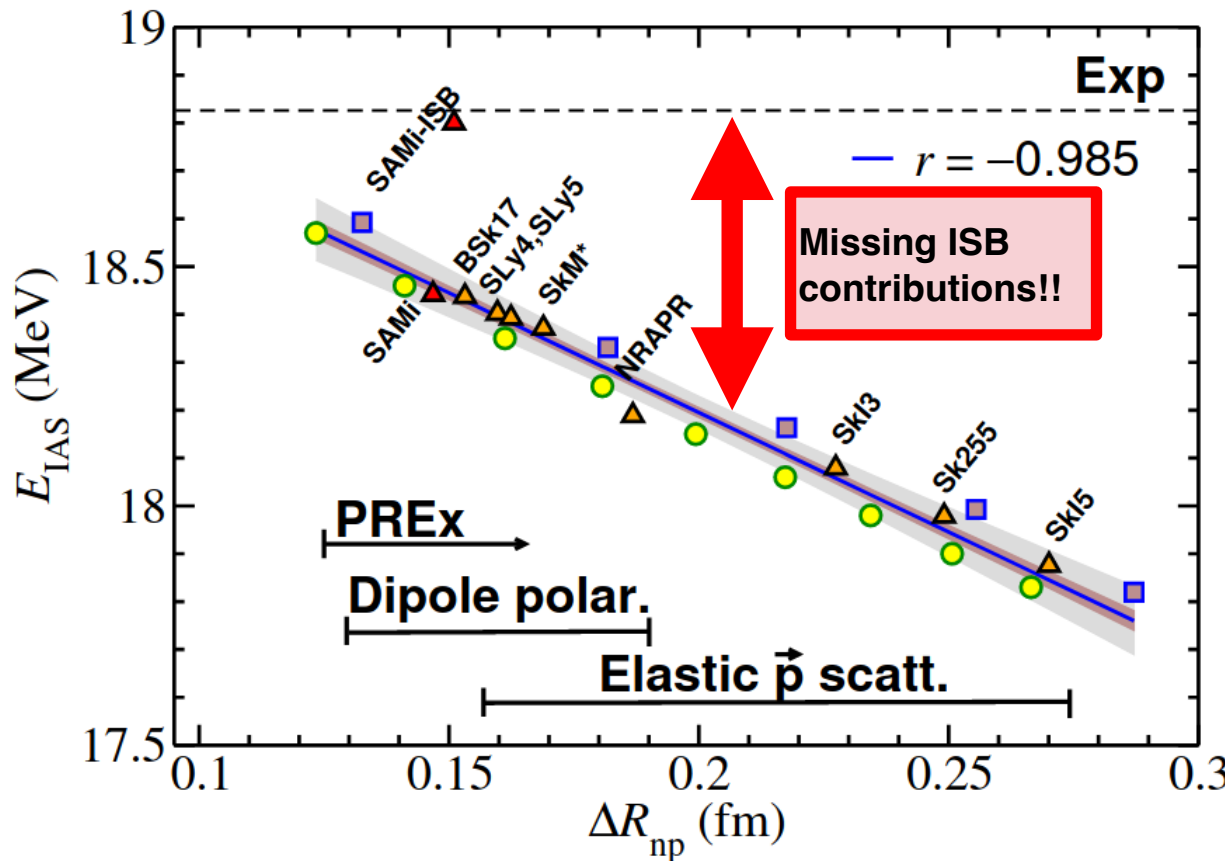
$$\alpha_M \approx \frac{e^2}{4\pi} A \frac{\langle r^4 \rangle - \langle r^2 \rangle^2}{J} \left[1 + \frac{7}{3} \frac{L}{J} A^{-1/3} \right]$$



And since we are @ COMEX: IAS and Δr_{np}

Let me remind you other relevant observable

$$E_{IAS} = E_A - E_0 = \langle A | \mathcal{H} | A \rangle - \langle 0 | \mathcal{H} | 0 \rangle = \frac{\langle 0 | T_+ [\mathcal{H}, T_-] | 0 \rangle}{\langle 0 | T_+ T_- | 0 \rangle}$$



Simple model:

$$E_{IAS}^{C,direct} = \frac{1}{N-Z} \int [\rho_n(\vec{r}) - \rho_p(\vec{r})] U_C^{direct}(\vec{r}) d\vec{r}$$

$$U_C^{direct}(\vec{r}) = \int \frac{e^2}{|\vec{r}_1 - \vec{r}|} \rho_{ch}(\vec{r}_1) d\vec{r}_1$$

$$\begin{aligned} E_{IAS} &\approx E_{IAS}^{C,direct} \\ &\approx \frac{6 Ze^2}{5 R_p} \left(1 - \frac{1}{2} \frac{N}{N-Z} \frac{R_n - R_p}{R_p} \right) \\ &\approx \frac{6 Ze^2}{5 r_0 A^{1/3}} \left(1 - \sqrt{\frac{5}{12}} \frac{N}{N-Z} \frac{\Delta R_{np}}{r_0 A^{1/3}} \right) \end{aligned}$$

Summary

Electric dipole polarizability is sensitive to the **neutron distribution** in atomic nuclei and **models** seem to be **compatible** with **experimental data**

Extraction of the **neutron skin** from models describing the **dipole polarizability** or **other observables** is **model dependent** (in some cases, more than in others)

From Theory:

→ An effort to better understand the **systematics** on the **dipole polarizability** would be of interest [see e.g. Sn chain in Bassauer et al. PLB 810, 135804 (2020)].

From Experiment:

→ **Systematic** measurements of the **dipole polarizability** along **neutron rich** isotopic chains could help testing models and improve our understanding of this observable. [see e.g. Ayangeakaa's talk on Monday]

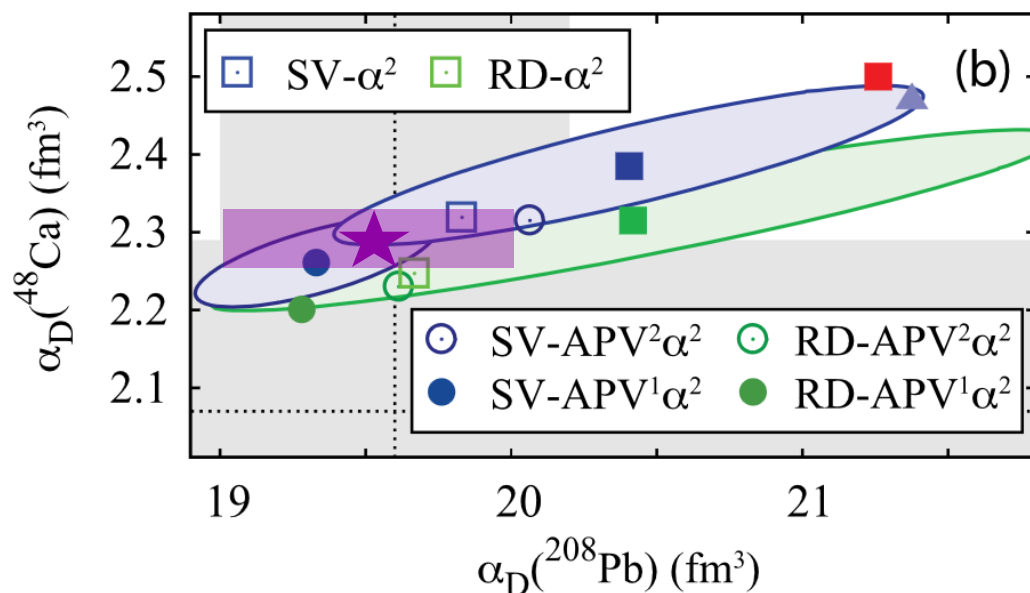
Collaborators

- Gianluca **Colò** (University of Milan)
- Pietro **Klausner** (University of Milan)
- Shihang **Shen** (Beihang University)
- Xavier **Vinyes** & Mario **Centelles** (University of Barcelona)
- Jorge **Piekarewicz** (Florida State University)
- Nils **Paar** & Dario **Vretenar** (University of Zagreb)
- Bijay K. **Agrawal** (Saha Institute of Nuclear Physics)
- P.-G. **Reinhard** (University of Erlangen-Nürnberg)
- Witold **Nazarewicz** (FRIB and Michigan State University)
- Doris H. **Jakubassa-Amunsden** (Ludwig-Maximilians-Universität München)

Bayesian inference Skyrme EDF: can we accommodate α_D and A_{PV} without compromising other observables?

Pietro Klausner, Gianluca Colò, Xavier Roca-Maza, and Enrico Vigezzi
Phys. Rev. C 111 014311 (2025)

By P. Klausner

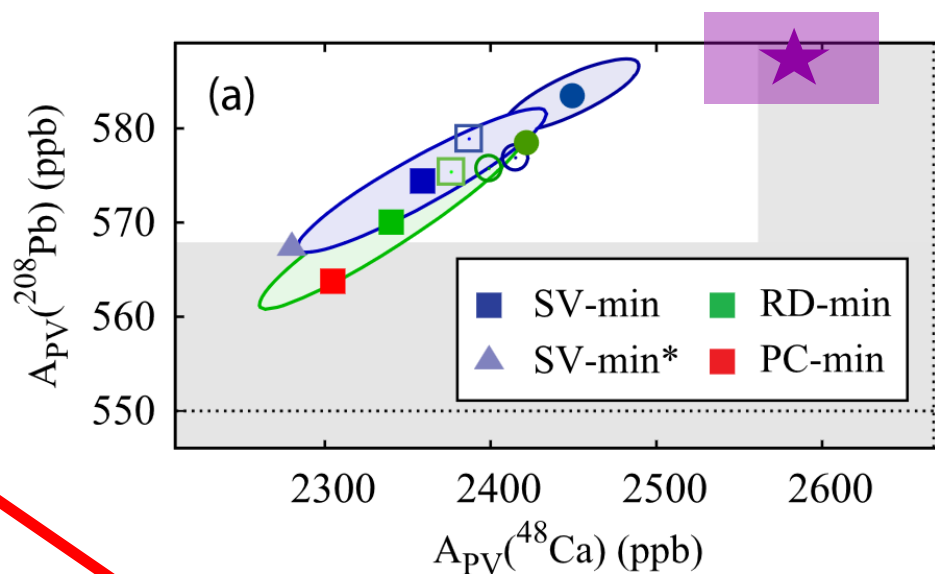


	B.E. (MeV)	R_{ch} (fm)	ΔE_{SO} (MeV)
^{208}Pb	1636 ± 1.8	5.49 ± 0.03	2.34 ± 0.16
^{48}Ca	417 ± 1.2	3.51 ± 0.02	1.92 ± 0.20
^{40}Ca	342 ± 1.6	3.50 ± 0.02	—
^{56}Ni	482 ± 1.4	—	—
^{68}Ni	590 ± 1.0	—	—
^{100}Sn	826 ± 1.6	—	—
^{132}Sn	1103 ± 1.7	4.71 ± 0.03	—
^{90}Zr	784 ± 1.3	4.27 ± 0.02	—

Isoscalar resonances

	E_{GMR}^{IS} (MeV)	E_{GQR}^{IS} (MeV)
^{208}Pb	13.5 ± 0.3	10.8 ± 0.4
^{90}Zr	17.8 ± 0.4	—

	α_D (fm ³)	$m(1)$ (MeV fm ²)	A_{PV} (ppb)
^{208}Pb	19.5 ± 0.5	958 ± 22	589 ± 5
^{48}Ca	2.30 ± 0.08	—	2591 ± 54



Keeping ground and excited state properties within typical Skyrme-EDF accuracy

Bayesian inference Skyrme EDF: can we accommodate α_D and A_{PV} without compromising other observables?

By P. Klausner

