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Parity violating asymmetry and dipole polarizabily: how do they reconcile with each other?

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Nuclear Structure and Dynamics - NSD 2024

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Valencia, Spain

UNIVERSITAT DE BARCELONA

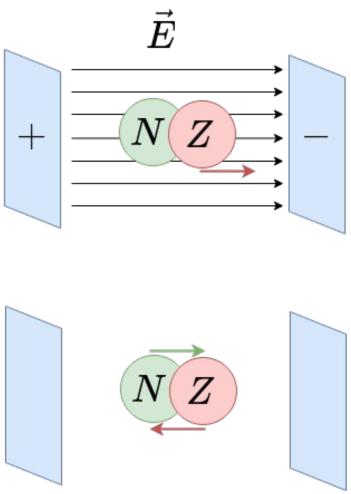
Electric Dipole Polarizability: introduction

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

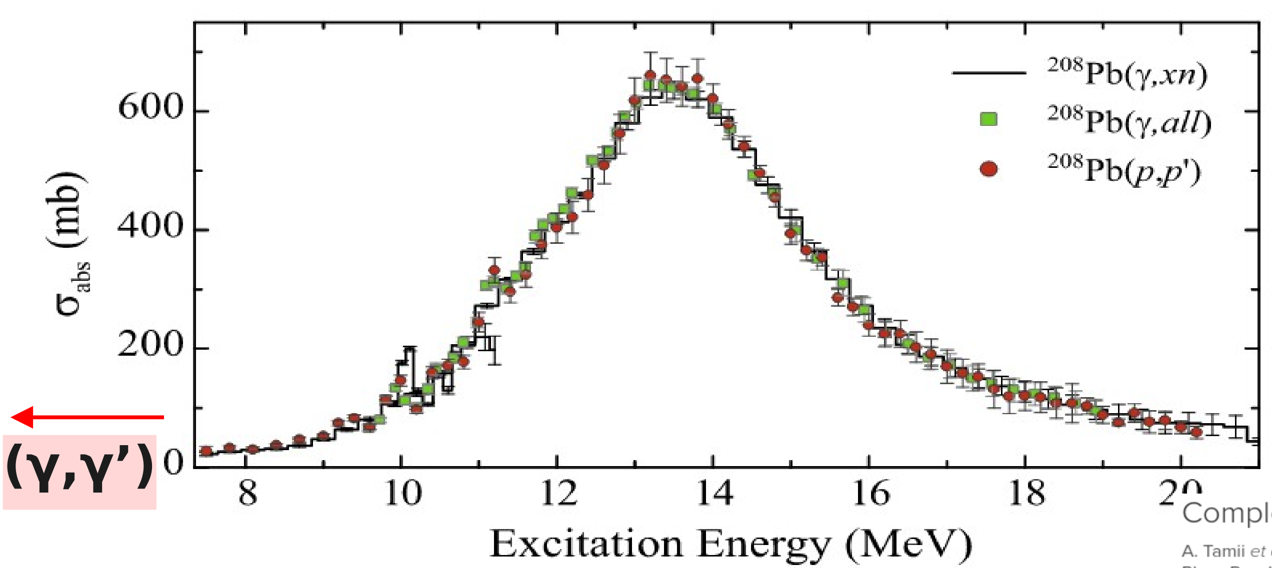
$$\alpha = \frac{\text{electric dipole moment}}{\text{external electric field applied}}$$

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)



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

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb
A. Tamii *et al.*
Phys. Rev. Lett. **107**, 062502 – Published 3 August 2011

Electric Dipole Polarizability: theory

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

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

Dipole operator subtract CM motion

$$\frac{eN}{A}\sum_{i=1}^{Z} r_i Y_{1M}(\hat{r}_i) - \frac{eZ}{A}\sum_{i=1}^{N} r_i Y_{1M}(\hat{r}_i)$$

And, thus,

$$\alpha_D = 2\sum_{\nu\neq 0}\frac{|\langle\nu|F_{\mathrm{dipole}}|0\rangle|^2}{E_\nu - E_0} \equiv 2m_{-1}$$

Considering the G.S. perturbed by an **external field** λF (with λ → 0). <H>=<H_0+λF_{dipole}> can be written as:

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

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

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

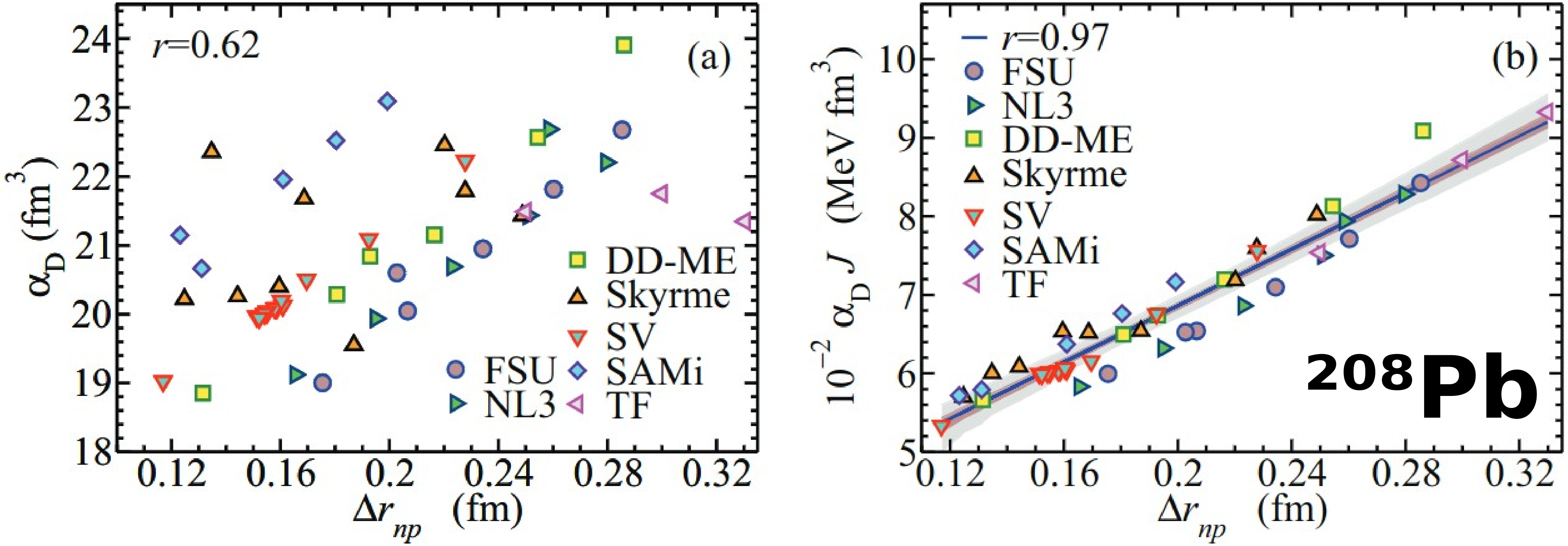
$$\alpha_D \approx \frac{A\langle r^2\rangle}{12J}\left[1+\frac{5}{2}\frac{\Delta r_{np}+\sqrt{\frac{3}{5}\frac{e^2Z}{70J}}-\Delta r_{np}^{\text{surface}}}{\langle r^2\rangle^{1/2}(I-I_C)}\right]$$

J = e(PNM)-e(SNM) → Symmetry energy at ρ_0

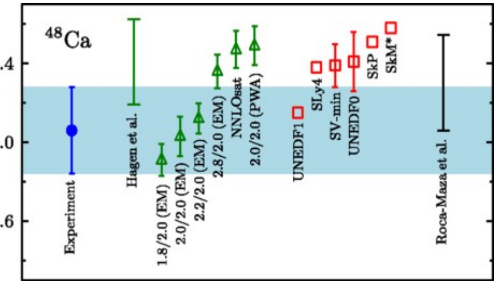
$\Delta r_{np} = \langle r_n^2\rangle^{1/2}-\langle r_p^2\rangle^{1/2}$ → Neutron skin thickness

Using microscopic calculations

(Energy Density Functionals ↔ Hartree-Fock+Random Phase Approximation)

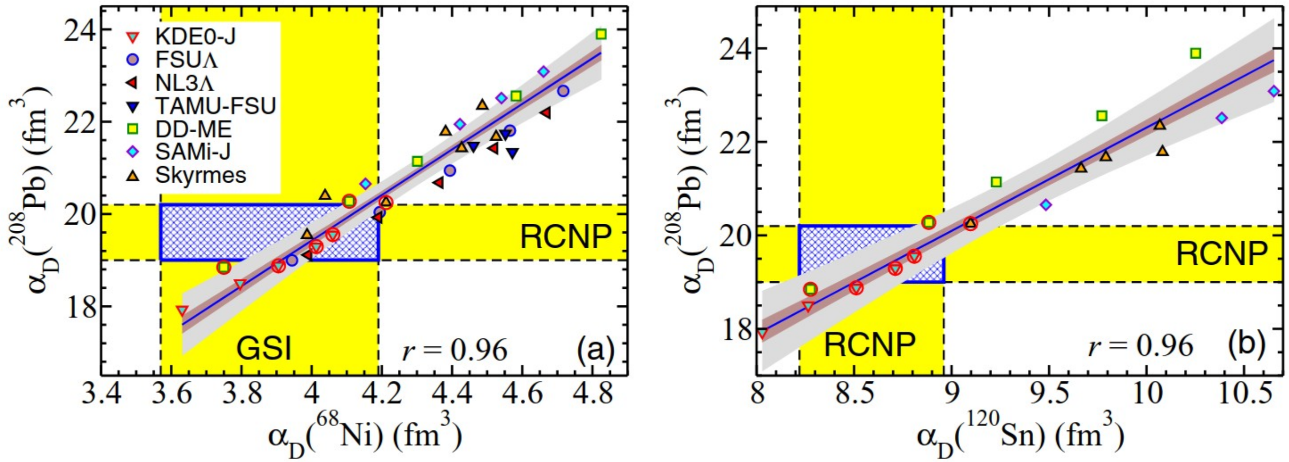


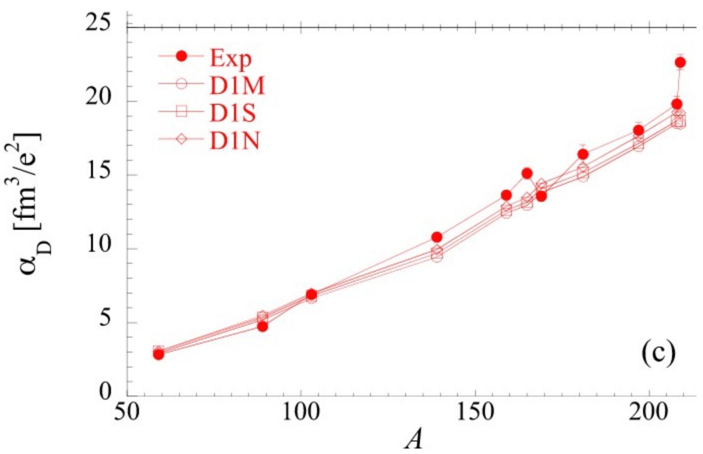
Electric Dipole Polarizability: measurements vs theory



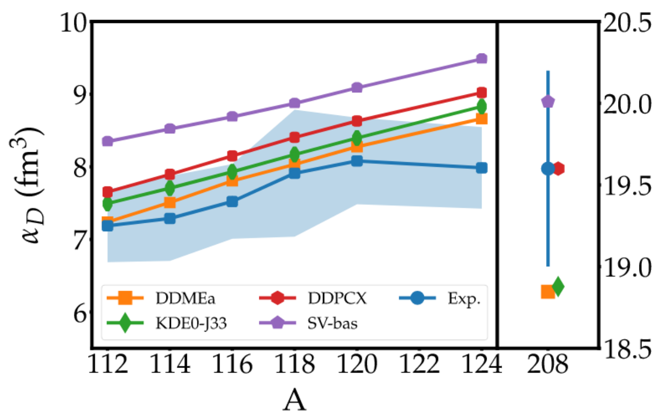
J. Birkhan, M. Miorelli, S. Bacca, S. Bassauer, C. A. Bertulani, G. Hagen, H. Matsubara, P. von Neumann-Cosel, T. Papenbrock, N. Pietralla, V. Yu. Ponomarev, A. Richter, A. Schwenk, and A. Tamii
Phys. Rev. Lett. **118**, 252501 – Published 23 June 2017

X. Roca-Maza, X. Viñas, M. Centelles, B. K. Agrawal, G. Colò, N. Paar, J. Piekarewicz, and D. Vretenar
Phys. Rev. C **92**, 064304 – Published 8 December 2015

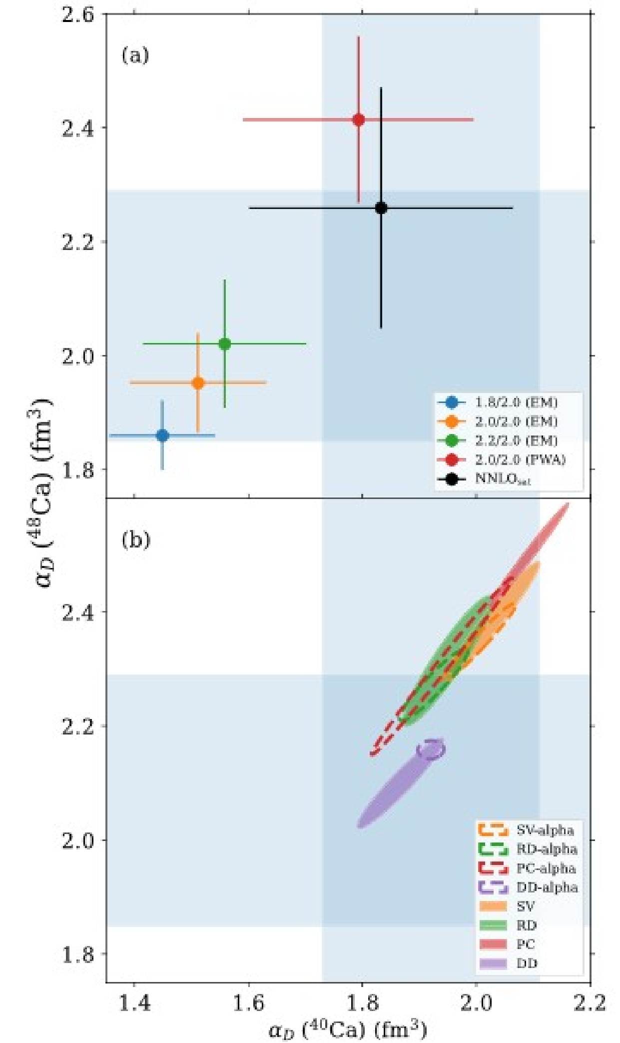




S. Goriely, S. Péru, G. Colò, X. Roca-Maza, I. Gheorghe, D. Filipescu, and H. Utsunomiya
Phys. Rev. C **102**, 064309 – Published 9 December 2020



S. Bassauer, P. von Neumann-Cosel, P.-G. Reinhard et al.
Physics Letters B 810 (2020) 135804



R. W. Fearick, P. von Neumann-Cosel, S. Bacca, J. Birkhan, F. Bonaiti, I. Brandherm, G. Hagen, H. Matsubara, W. Nazarewicz, N. Pietralla, V. Yu. Ponomarev, P.-G. Reinhard, X. Roca-Maza, A. Richter, A. Schwenk, J. Simonis, and A. Tamii
Phys. Rev. Research **5**, L022044 – Published 31 May 2023

Parity Violating Asymmetry: introduction

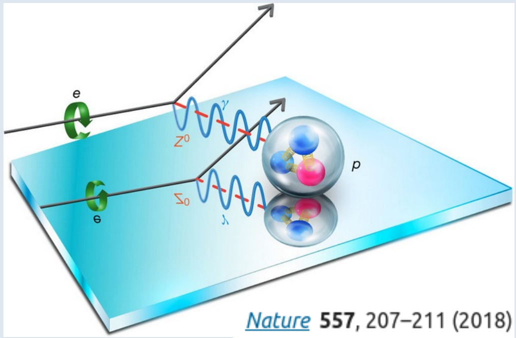
Elastic electron scattering by nuclei:

→ **Parity conserving**

Exchange of **γ** that essentially couples to protons **Q_p^c=1**; **Q_n^c=0**

→ **Parity violating**

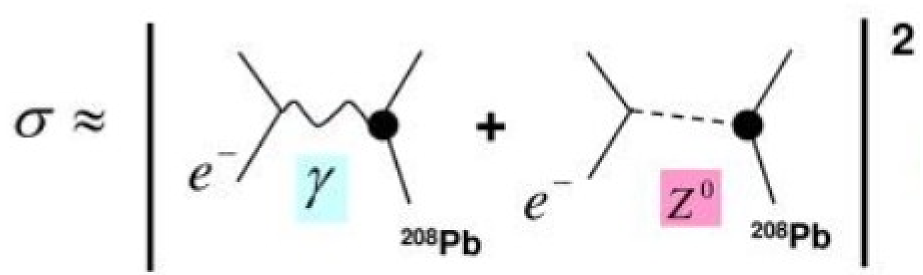
Exchange **Z_0** that essentially couples to neutrons **Q_p^W=0.07**; **Q_n^W=-0.99**



Nature **557**, 207–211 (2018)

Ultra-relativistic electrons (m_e→0) **aligned** (+) or **anti-aligned** (-) to the beam line, in approaching the nucleus:

$$\left[\vec{\alpha}\cdot\vec{p}+V_{\text{Coulomb}}(\vec{r})\pm V_{\text{Weak}}(\vec{r})\right]\Psi_\pm = E\Psi_\pm$$



One can get **advantage** form this **interference pattern** between **electromag.** and **weak** interact.

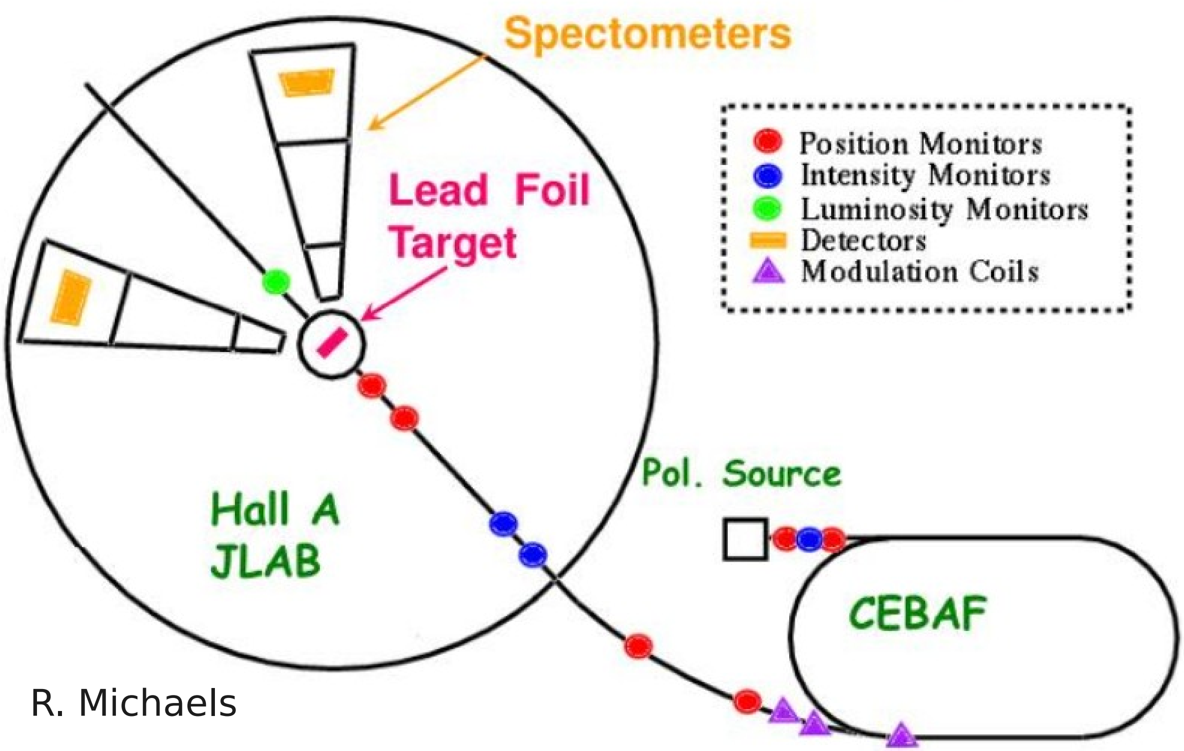
$$A_{PV} = \frac{\frac{d\sigma_+}{d\Omega}-\frac{d\sigma_-}{d\Omega}}{\frac{d\sigma_+}{d\Omega}+\frac{d\sigma_-}{d\Omega}} \approx \frac{\text{Weak}}{\text{Coulomb}}$$

Parity Violating Asymmetry: experiment

Lead and Calcium Radius Experiments

PREx & CREx @ JLab

$$A_{PV} \sim \frac{G_F}{4\sqrt{2}\pi\alpha} Q^2 \sim 10^{-4}(Q[\text{GeV}])^2$$



R. Michaels

→Spectrometers ~ 5⁰

→e⁻ beam E ~ GeV

$$Q^2_{\text{PREx}} = 0.00616\ \text{GeV}^2$$

$$Q^2_{\text{CREx}} = 0.0297\ \text{GeV}^2$$

→ **Demanding experiment:**

For **10^6 electrons** or more only **one** of them **interact weakly** with the nucleus

Proposed new experiment on ^{208}Pb @ Mainz !!!

Accurate Determination of the Neutron Skin Thickness of ^{208}Pb through Parity-Violation in Electron Scattering
D. Adhikari *et al.* (PREX Collaboration)
Phys. Rev. Lett. **126**, 172502 – Published 27 April 2021

Precision Determination of the Neutral Weak Form Factor of ^{48}Ca
D. Adhikari *et al.* (CREX Collaboration)
Phys. Rev. Lett. **129**, 042501 – Published 20 July 2022

Parity Violating Asymmetry: theory

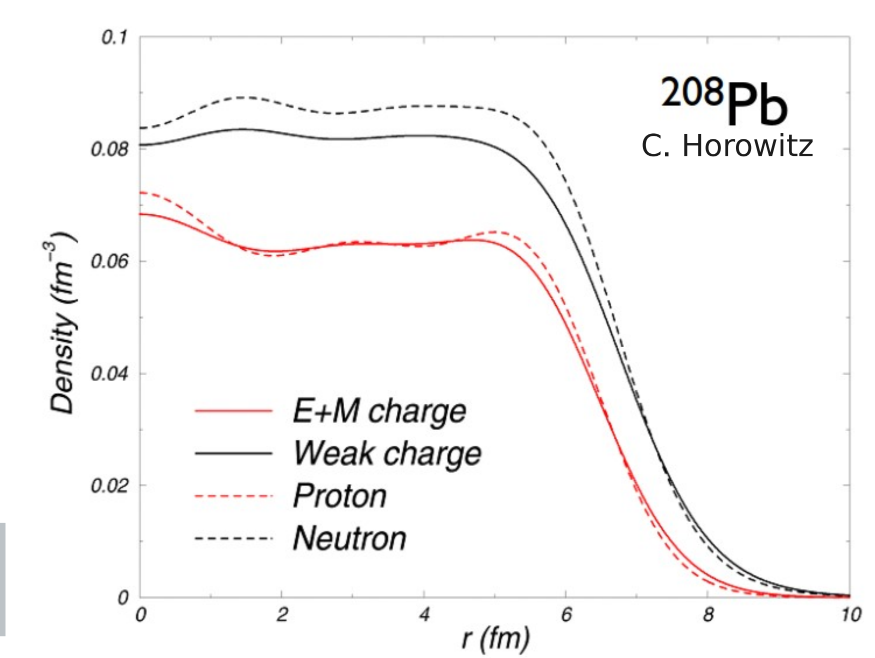
To solve the **Dirac equation**

$$\left[\vec{\alpha}\cdot\vec{p} + V_{\mathrm{Coulomb}}(\vec{r}) \pm V_{\mathrm{Weak}}(\vec{r})\right]\Psi_{\pm} = E\Psi_{\pm}$$

The main inputs are the **electromagnetic ρ_{ch}** and **weak charge ρ_{W}** distributions

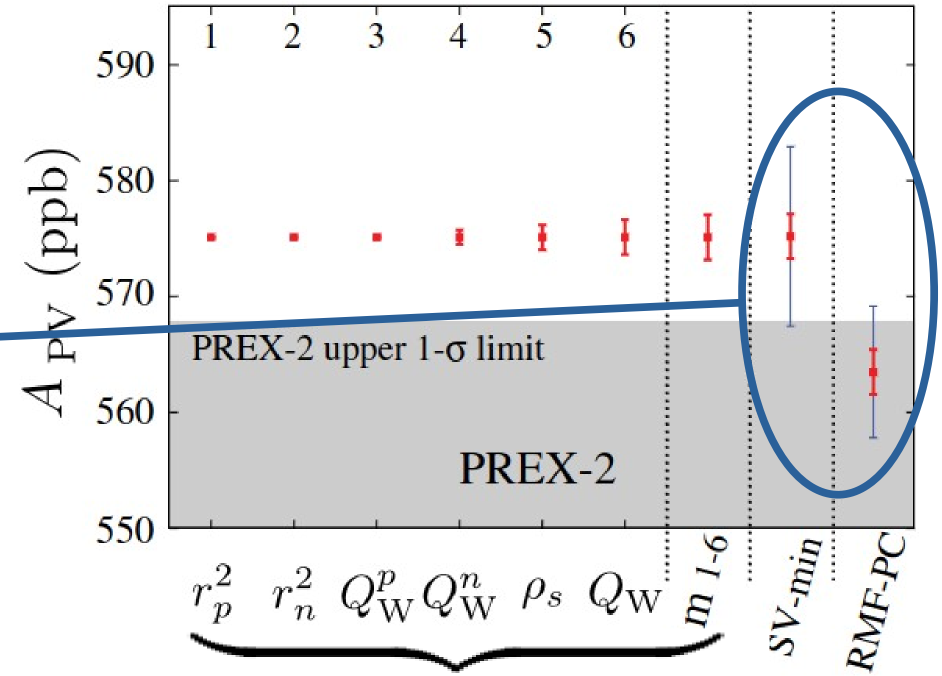
$$V_{\mathrm{Coulomb}}(\vec{r}) = Z\alpha \int \frac{\rho_{\mathrm{ch}}(\vec{r}')}{|\vec{r}-\vec{r}'|}d\vec{r}' \qquad V_{\mathrm{Weak}}(\vec{r}) = \frac{G_F}{2\sqrt{2}}\rho_{\mathrm{W}}(\vec{r})$$

We need to know the **neutron and proton distributions** in nuclei and the **electromagnetic and weak** charge **form factors** of the **neutron** and the **proton**



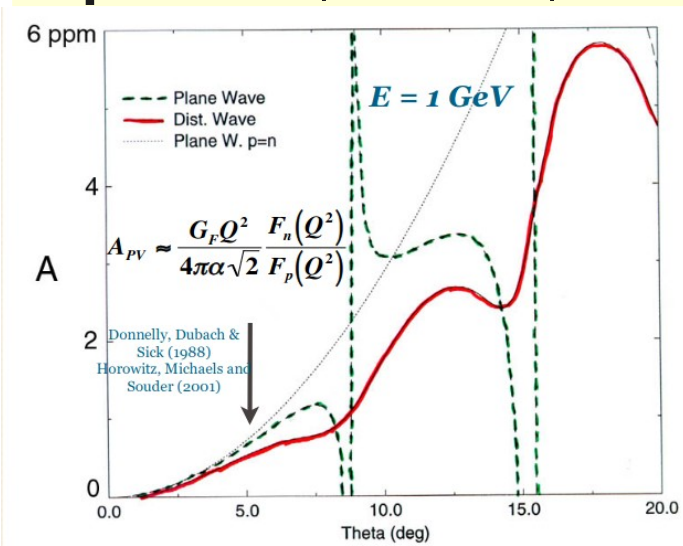
Parity Violating Asimmetry: theory

The **main uncertainties** come from **nuclear model errors** on the description of the **neutron distribution (blue error bars)**

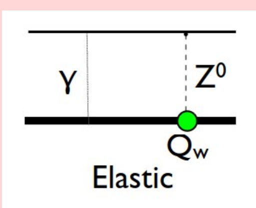


Hadronic uncertainties less relevant

→ **Coulomb distortions are important** (order αZ)



Are **γZ₀ box** corrections **important**? not included



Parameter	Value
$\langle r_p^2 \rangle$ (fm^2)	0.726 ± 0.019
$\langle r_n^2 \rangle$ (fm^2)	-0.1161 ± 0.0022
μ_p	2.792 847
μ_n	-1.9130
$Q_p^{(W)}$	0.0713 ± 0.0001
$Q_n^{(W)}$	-0.9888 ± 0.0011
ρ_s	-0.24 ± 0.70
κ_s	-0.017 ± 0.004
$Q_{126,82}^{(W)}$	-117.9 ± 0.3

Information Content of the Parity-Violating Asymmetry in ^{208}Pb

Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz
Phys. Rev. Lett. **127**, 232501 – Published 29 November 2021

Parity Violating Asimmetry: simple model & correlations

The **parity violating asymmetry** within the **PWBA:**

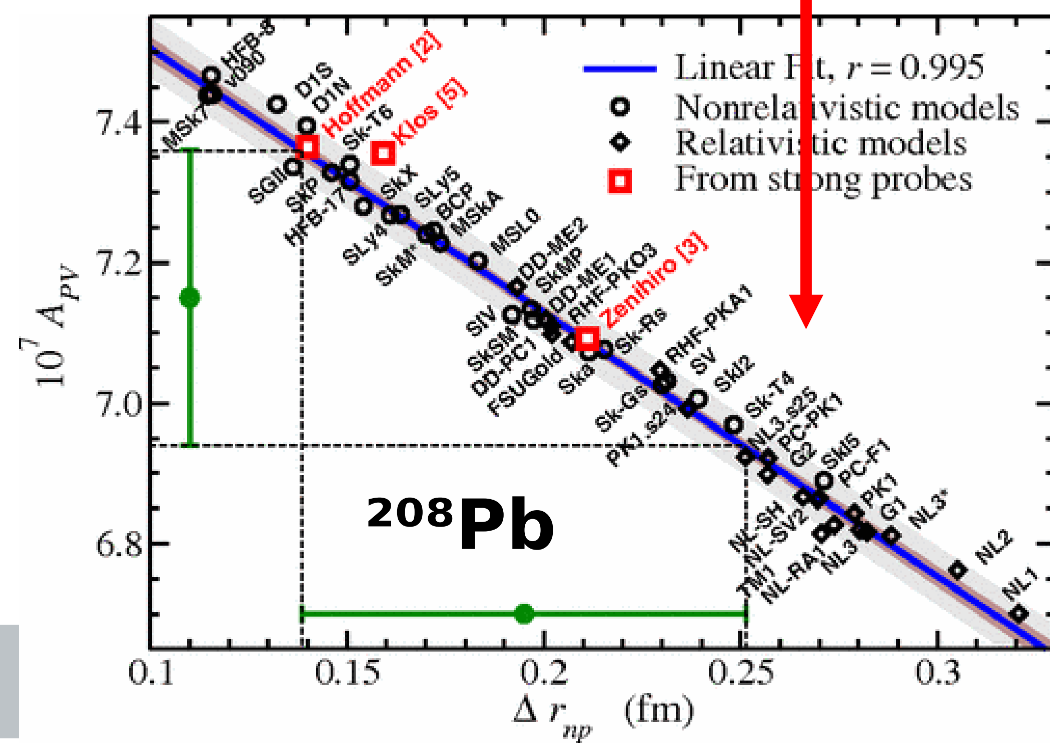
$$A_{PV}^{\mathrm{PWBA}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[\underbrace{4\sin^2\theta_W}_{\approx 1} + \frac{F_n(Q)-F_p(Q)}{F_p(Q)}\right]$$

$$\xrightarrow{Q\to 0} \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[1-\frac{Q^2\langle r_p^2\rangle}{3}\frac{\Delta r_{np}}{\langle r_p^2\rangle^{1/2}}\right]$$

30% error (for PREx) due to Coulomb distortions does not blur **the main physics**

The **parity violating asymmetry** within the **DWBA:**

- → Energy Density Functionals
- → Expeirmental ρ_n form hadronic probes + ρ_p from e^- scattering

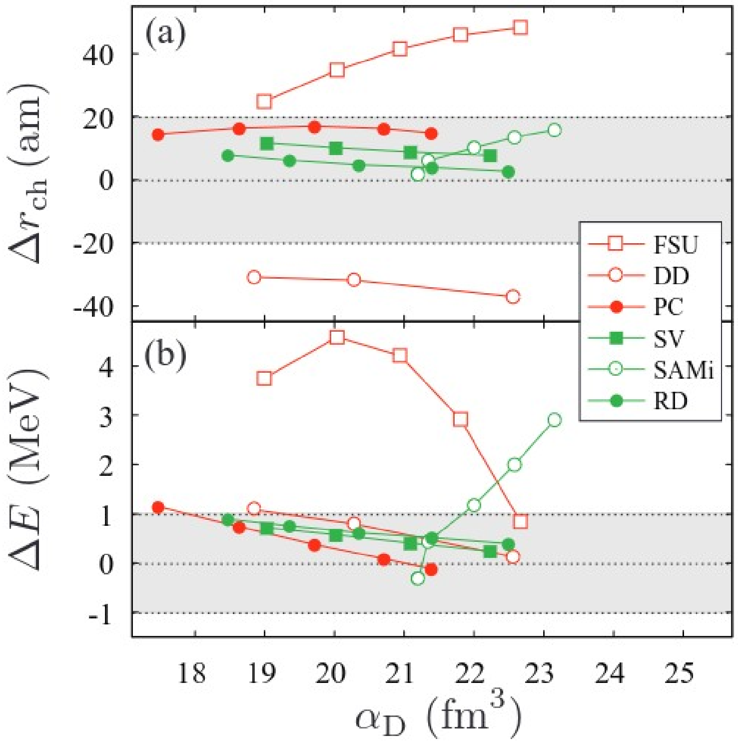


Neutron Skin of ^{208}Pb, Nuclear Symmetry Energy, and the Parity Radius Experiment
X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda
Phys. Rev. Lett. **106**, 252501 – Published 21 June 2011

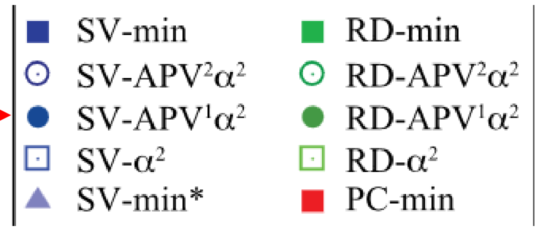
Parity Violating Asymmetry: measurements vs. theory

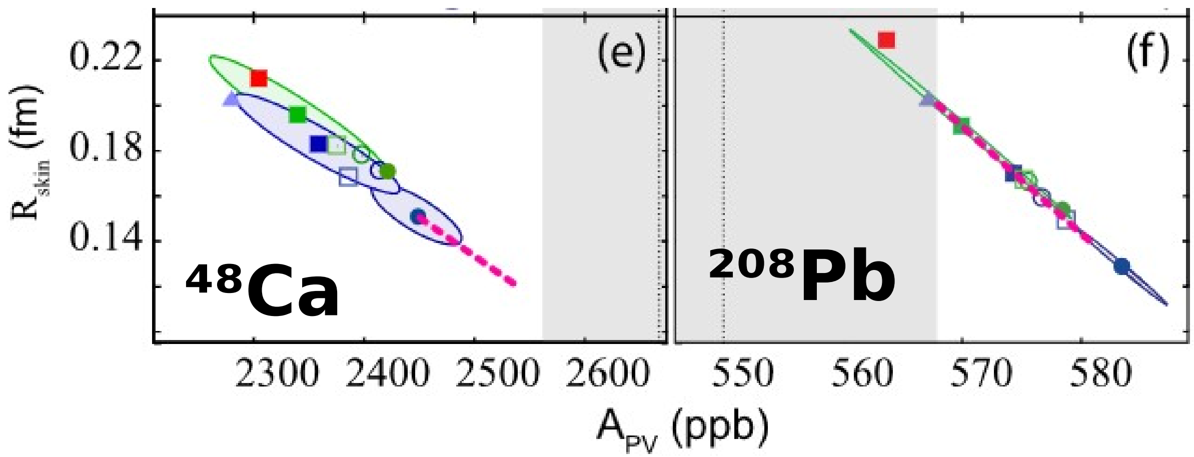
Selecting those **models** we consider **well calibrated** to **masses** and **radii**

Theoretical (**EDFs** and **ab initio**) and experimental 1σ errors overlap in ^{208}Pb but not in ^{48}Ca → **No simultaneous description**



Fitting protocol also including **A_{PV}** and **α_D**

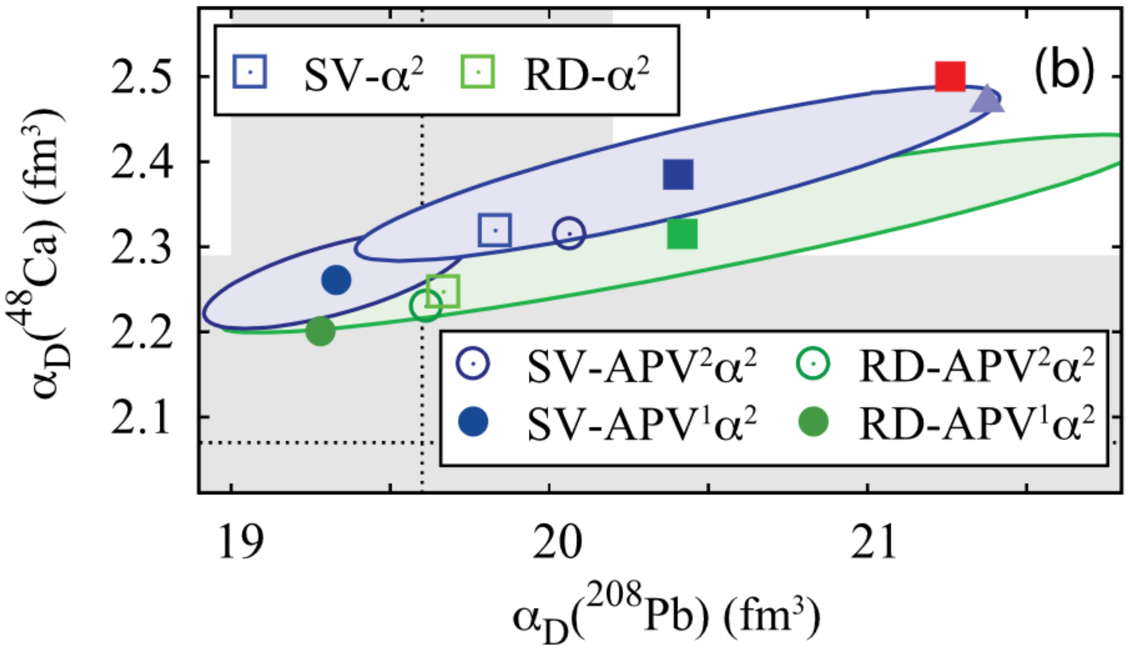




Combined Theoretical Analysis of the Parity-Violating Asymmetry for ^{48}Ca and ^{208}Pb
Paul-Gerhard Reinhard, Xavier Roca-Maza, and Witold Nazarewicz
Phys. Rev. Lett. **129**, 232501 – Published 2 December 2022

Magenta dashed lines from extrapolated Δr_{np} given in G. Hagen et al. Nature Physics 12, 186–190 (2016) and H. Bu et al. Nature Physics (2022)

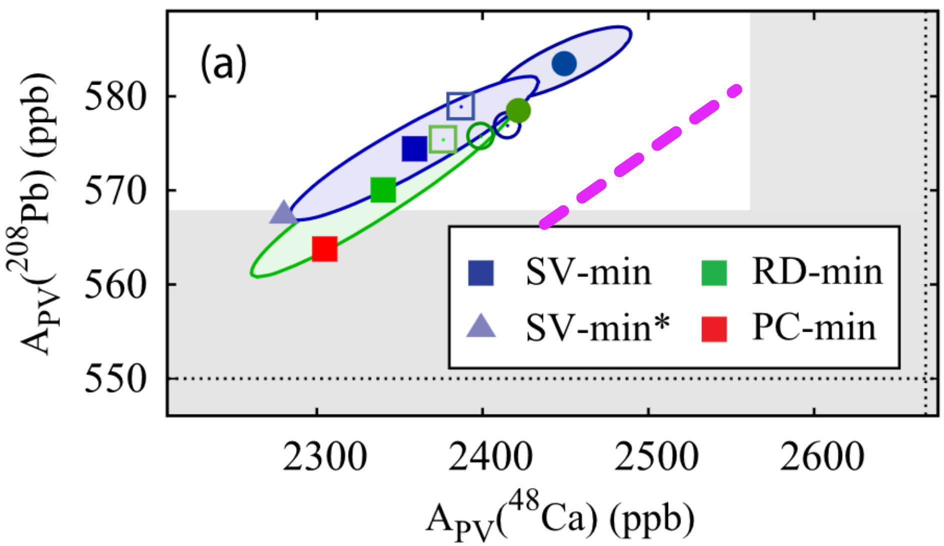
Summary: model performance A_{PV} (sensitive to Δr_{np}) and α_D (sensitive to J and Δr_{np}) in ^{48}Ca and ^{208}Pb



Simultaneous description of **dipole polarizabilities →** point to a **good understanding** of **symmetry energy (J)** and **neutron skins (Δr_{np})**

Ab-initio (B. Hu) Nature Physics (2022)

$$\alpha_D(^{48}\mathrm{Ca}) \quad 2.30^{+0.31}_{-0.26}$$
$$\alpha_D(^{208}\mathrm{Pb}) \quad 22.6^{+2.1}_{-1.8}$$



No simultaneous description of **parity violating asymmetries** (ground state observable) **→** point to a **deficient understanding** of **neutron skins**

Magenta dashed lines from extrapolated Δr_{np} given in G. Hagen et al. Nature Physics 12, 186–190 (2016) and H. Bu et al. Nature Physics (2022)

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

How do A_{PV} and α_D reconcile with each other?

Different ways to learn about the **neutron distribution** in atomic nuclei using **different observables** provide **different answers**

However, within **1.5σ all looks fine**, both from phenomenologic **Energy Density Functionals** and from **Ab Initio**

From Theory:

→ An effort to better understand the **parity violating asymmetry** and the **beam normal spin asymmetry** in ^{208}**Pb** is needed.

→ An effort to better understand the **systematics** on the **dipole polarizability** is needed (e.g. along the Sn isotopic chain; ^{209}Bi ?).

From Experiment:

→ An effort to improve the accuracy in the **parity violating asymmetry in** ^{208}**Pb** (and/or measure other Q values) and to confirm the measured values for the **beam normal spin asymmetry** is needed

→ **Systematic** measurements of the **dipole polarizability** along **neutron rich** isotopic chains (such as for N>74 Sn isotopes)

Collaborators

→ Gianluca **Colò** (University of Milan)

→ Hiroyuki **Sagawa** (University of Aizu & RIKEN)

→ Tomoya **Naito** (University of Tokyo & RIKEN)

→ Shihang **Shen** (Forschungszentrum Jülich)

→ 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)