Dipole Polarizability and Parity Violating Asymmetry in ^{208}Pb

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Motivation:

The importance of determining isovector properties in nuclei

- **In the past** (and also in the present), **neutron properties** in stable medium and heavy nuclei have been mainly measured by using **strongly interacting probes**.

  $\Downarrow$

  Limited knowledge of isovector properties

  (X. Roca-Maza, X. Viñas, M. Centelles, P. Ring, and P. Schuck Phys. Rev. C **84**, 054309, 2012)

- **At present**,
  - the use of **rare ion beams** has opened the possibility of measuring properties of **exotic nuclei**.
  - **parity violating elastic electron scattering** (PVES), a **model independent technique**, has allowed to estimate the **neutron radius** of a stable heavy nucleus like ^{208}Pb (PREx@JLab).

  $\Downarrow$

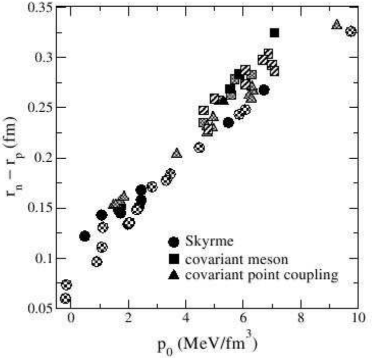
  Promising perspectives for the near future.

Motivation:

It is possible to connect observables with general isovector properties of the nuclear effective interaction?

Example:

Mean-Field predictions show a clear **correlation** between Δr_{np} of a medium and heavy nucleus and the density slope of the symmetry energy ($L = 3\rho_0 \partial_\rho S(\rho)|_{\rho_0} = 3\rho_0 p_0$).

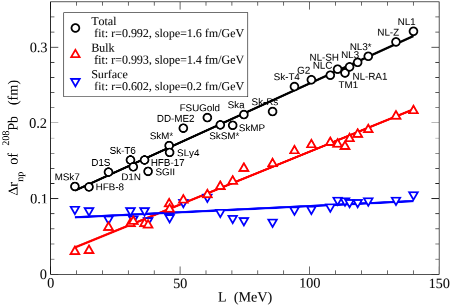


R.J. Furnstahl, NPA, **706**, 85 (2002)

Motivation:

More generally within **MF**, it has been found a semi-empirical law: $a_{\rm sym}(A) \approx S(\rho_A)$ with $\rho_A = \rho_0 - \rho_0/(1 + cA^{1/3}) \Rightarrow$

direct and clear connection of any ground state isospin sensitive **observable** with the parameters of the **EoS**. **Following the same example:** $\Delta r_{np}^{\rm total}(A, I) = \Delta r_{np}^{\rm bulk}(A, I) + \Delta r_{np}^{\rm surface}(A, I)$



$$\Delta r_{np}^{\rm bulk}(A, I) \approx \frac{2r_0}{3J} L \left(1 - \epsilon_A \frac{K_{\rm sym}}{2L}\right) \epsilon_A A^{1/3} (I - I_{\rm C})$$

M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, Phys. Rev. Lett. **102**, 122502 (2009); Phys. Rev. C **80** 024316 (2009); Phys. Rev. C **81** 054309 (2010) and Phys. Rev. C **82**, 054314 (2010)

Motivation:

Observables, processes and observations known to be correlated with the isovector properties of the nuclear effective interaction

- **Binding energies**
- **Neutron distributions** (proton elastic scattering, antiprotonic atoms, parity violating asymmetry,...)
- **Giant Resonances**: Giant Dipole, Gamow-Teller, Isobaric Analog, Spin Dipole and Anti-analog of the Giant Dipole Resonances (inelastic hadron-nucleus, nucleus-nucleus and γ-nucleus scattering).
- **Heavy Ion Collisions** (EoS — transport models)
- **Neutron Star properties**: mass-radius relation, transition density crust-core, composition,... (observational data).
- Low-energy dipole response (?)
- Isovector Giant Quadrupole Resonance (?)
- Isoscalar Giant Resonances along isotopic chains (?)
- ...

Isovector static dipole polarizability

Definition: α_D

- The linear response or dynamic polarizability of a nuclear system excited from its g.s., $|0\rangle$, to an excited state, $|\nu\rangle$, due to the action of an external oscillating dipolar field of the form $(Fe^{iwt} + F^{\dagger}e^{-iwt})$:

$$F_D = \frac{Z}{A}\sum_i^N r_n Y_{1M}(\hat{r}_n) - \frac{N}{A}\sum_i^Z r_p Y_{1M}(\hat{r}_p)$$

- is proportional to the **static dipole polarizability, α_D,** for small oscillations

$$\alpha_D = \frac{8\pi}{9}e^2 m_{-1} = \frac{8\pi}{9}e^2 \sum_\nu \frac{|\langle\nu|F_D|0\rangle|^2}{E}$$

where m_{-1} is the inverse energy weighted moment of the strength function,

$$S_D(E) = \sum_\nu |\langle\nu|F_D|0\rangle|^2 \delta(E - E_\nu)$$

Droplet model approach: connection between α_D and the neutron skin

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

- For a heavy nucleus and assuming small variations† of $\langle r^2\rangle$, $e^2Z/70J$ and $\Delta r_{np}^{\mathrm{surface}}$ as compared to that of J and Δr_{np},

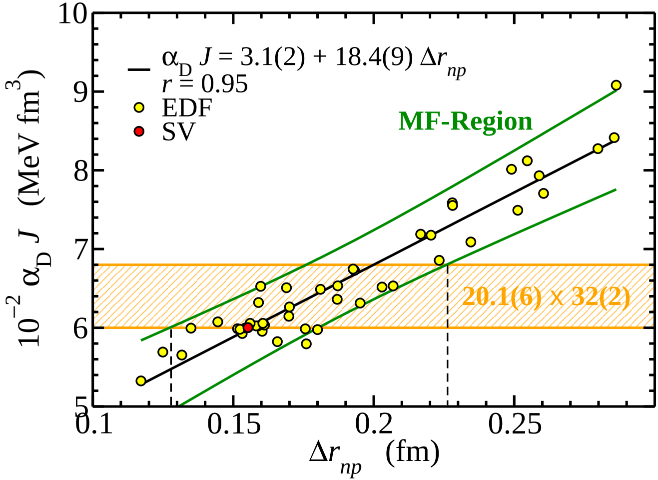
$$\alpha_D J \approx p_1 + p_2\Delta r_{np}$$

†Some numbers: ^{208}Pb and assuming $J = 32 \pm 2$ MeV, $\rho_0 = 0.160 \pm 0.05$ fm^{-3} and

$\Delta r_{np}^{\mathrm{surface}} \approx 0.09 \pm 0.01$ (MF models) $\Rightarrow (e^2Z)/(70J) - \Delta r_{np}^{\mathrm{surface}} \approx -0.04 \pm 0.01$ fm

$\langle r^2\rangle^{1/2} \approx 5.23 \pm 0.55$ fm, $I_c \approx 0.027 \pm 0.003$

Mean-Field + RPA results for ^{208}Pb



Assuming $J = 32 \pm 2$ MeV and α_D from A. Tamii *et al.* Phys. Rev. Lett. **107**, 062502 (2011) $\Delta r_{np} \approx 0.18 \pm 0.05$ fm / $0.156^{+0.025}_{-0.021}$ fm]

Parity violating elastic electron scattering in ^{208}Pb

Theoretical bases of PVES [*Explained yesterday in more detail by Prof. Urciuoli*]:

- **Electrons** interact by exchanging a γ or a Z_0 boson.
- While **protons** couple basically to γ, **neutrons** do it to Z_0.
- **Ultra-relativistic electrons**, depending on their helicity, interact with the nucleons $V_{\pm} = V_{\mathrm{Coulomb}} \pm V_{\mathrm{Weak}}$.
- **Coulomb distortions** should be taken into account: **DWBA** calculations give $\sim$**30%** correction with respect to PWBA.

Refs: C. J. Horowitz, Phys. Rev. C **57** 3430 (1998); C. J. Horowitz, S. J. Pollock, P. A. Souder, and R. Michaels, Phys. Rev. C **63**, 025501 (2001); M. Centelles, X. Roca-Maza, X. Viñas, and M. Warda, Phys. Rev. C **82**, 054314 (2010); X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda, Phys. Rev. Lett. **106** 252501 (2011) and (for the electric proton and neutron form factors) J. Friedrich and Th. Walcher, Eur. Phys. J. A **17**, 607623 (2003)

PREx data analysis:

- **PREx** measures, model-independently, the **parity violating asymmetry** at 1.06 GeV and for a single angle (~ 5 deg.) in ^{208}Pb,

$$\mathbf{A_{pv}} = \left(\frac{d\sigma_+}{d\Omega} - \frac{d\sigma_-}{d\Omega}\right) \Big/ \left(\frac{d\sigma_+}{d\Omega} + \frac{d\sigma_-}{d\Omega}\right)$$

- **Input for the calculation: ρ_n and ρ_p**
- ρ_p of ^{208}Pb is well known from other experiments
- ρ_n of ^{208}Pb is the quantity to be determined

Problem: In the analysis, one can only fix one paramter of the adopted neutron distribution to the data on A_{pv}.
Solution: Fix a range for the other parameter/s based on theoretical calculations.
Problem: Model dependence is introduced.
Solution: measurements of A_{pv} at different angles (measuring more nuclei would also help).

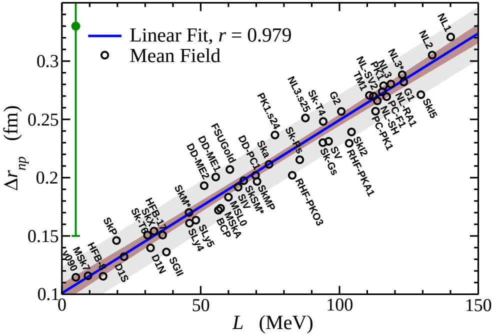
In case in which a measurement of A_{pv} at different angles is not possible/available,

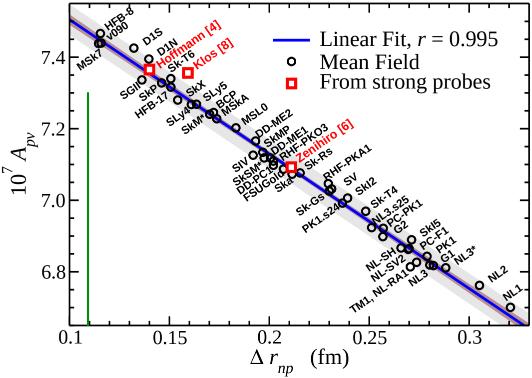
we propose the following analysis:

Direct correlations within MF

X. Roca-Maza, M. Centelles, X. Viñas, and M. Warda, Phys. Rev. Lett. **106** 252501 (2011)

Linear correlation suggested by PWBA is perfect in DWBA

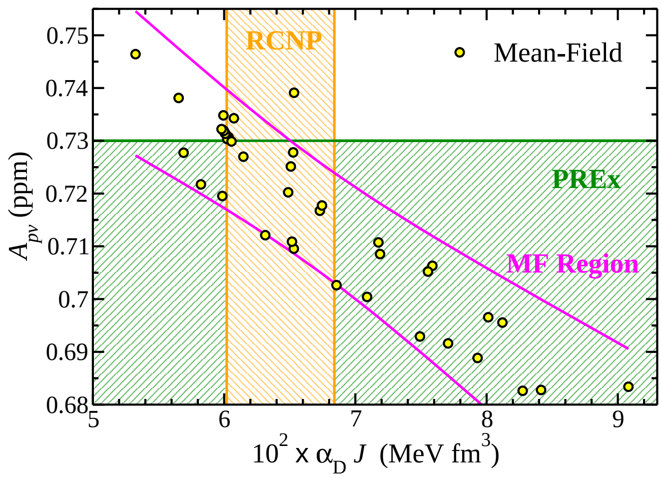




MF correlations allows to determine Δr_{np} and L without direct assumptions on ρ

Different experiments on proton elastic scattering and antirpotonic atoms agrees with the correlation

Constraints set by A_{pv} measured at JLab and α_D measured at RCNP on MF calculations.



Conclusions:

- **MF** models predict a good but not perfect linear **correlation** between $\alpha_D J$ and Δr_{np} in ^{208}Pb
- **Further** experimental and theoretical **studies** are needed in order to better constraint nuclear effective models and **reduce the theoretical uncertainties** in the estimation of Δr_{np} from α_D measurements.

- A **model-independent** determination of Δr_{np} in ^{208}Pb or ^{48}Ca via PVES experiments would need a measurement of A_{pv} at **different scattering angles.**
- We demonstrate a **linear correlation** between A_{pv} and Δr_{np}.
- Other **experiments** fairly **agree** with the **correlation** between A_{pv} and Δr_{np}.
- A_{pv} measured by the PREx collaboration at JLab and α_D measured at RCNP are complementary **observables** that may set tight **constraints** on the **density dependence of the symmetry energy.**

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