Parity violating asymmetry, dipole polarizability, and the neutron skin thickness in ^{48}Ca and ^{208}Pb

Xavier Roca-Maza
Università degli Studi di Milano and INFN
Via Celoria 16, I-20133, Milano (Italy)

Calcium Radius Experiment workshop, 17-19 March 2013,
Newport News, USA.

Table of contents:

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

- **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

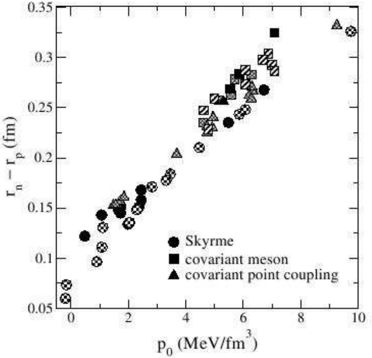
  $\Downarrow$

  Promising perspectives for the near future

Motivation:

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

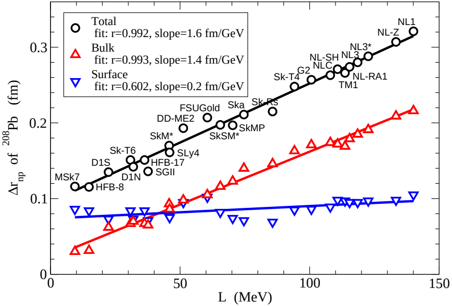
Example:
Mean-Field predictions show a clear **correlation** between Δr_{np} of a medium and heavy nucleus and the density slope of the symmetry energy ($L = 3\rho_0 \partial_\rho S(\rho)|_{\rho_0} = 3\rho_0 p_0$).



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 GQR **[see PRC 87, 034301 (2013)!]**
- Isoscalar Giant Resonances along isotopic chains (?)
- ...

Parity violating elastic electron scattering in ^{48}Ca and ^{208}Pb

From previous talks, we have seen that,

- **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 $V_{\pm} = V_{\mathrm{Coulomb}} \pm V_{\mathrm{Weak}}$.
- **Ultra-relativistic electrons** moving under the effect of $V_{\pm}$ where **Coulomb distortions** are important $\Rightarrow$ solution of the Dirac equation via the Distorted Wave Born Approximation (**DWBA**).
- **Input for the calculation:** ρ_n **and** ρ_p **...** and nucleon form factors for the e-m and the weak neutral current...

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 and CREx measure: model-independently the **parity violating asymmetry**,

$$\mathbf{A_{pv}} = \frac{\frac{d\sigma_+}{d\Omega} - \frac{d\sigma_-}{d\Omega}}{\frac{d\sigma_+}{d\Omega} + \frac{d\sigma_-}{d\Omega}}$$

at 1.06 GeV and for a single angle ($\sim$ 5 deg.) in ^{208}Pb and at 2.20 GeV and for a single angle ($\sim$ 4 deg.) in ^{48}Ca

ρ_n **of ^{208}Pb and ^{48}Ca are the quantities to be determined**, a precise determination of Δr_{np} would constrain the density dependence of the symmetry energy around saturation.

Qualitatively,

- A_{pv} within the Plane Wave Born Approximation,

$$A_{pv} = \frac{G_F q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W + \frac{\mathbf{F_n(q) - F_p(q)}}{F_p(q)}\right]$$

- ... which depends on $\mathbf{F_n(q) - F_p(q)}$. For $q \to 0$, it is approximately,

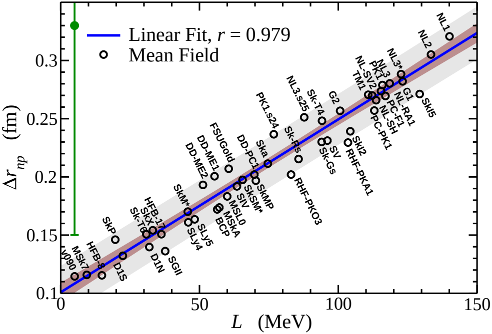
$$\begin{aligned} -\frac{q^2}{6}\left(\langle r_n^2\rangle - \langle r_p^2\rangle\right) &= -\frac{q^2}{6}\left[\mathbf{\Delta r_{np}}(\langle r_n^2\rangle^{1/2} + \langle r_p^2\rangle^{1/2})\right] \\ &= -\frac{q^2}{6}\left(2\langle r_p^2\rangle^{1/2}\mathbf{\Delta r_{np}} + \Delta r_{np}^2\right) \end{aligned}$$

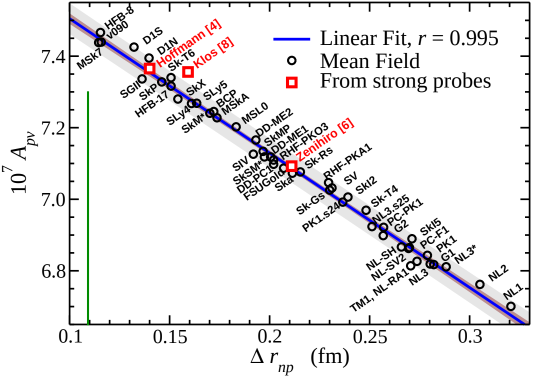
- variation of A_{pv} at a fixed q dominated by the variation of Δr_{np}. $F_p(q)$ well fixed by experiment

^{208}Pb: direct correlations

DWBA; no radiative corrections or strange quark effects included

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

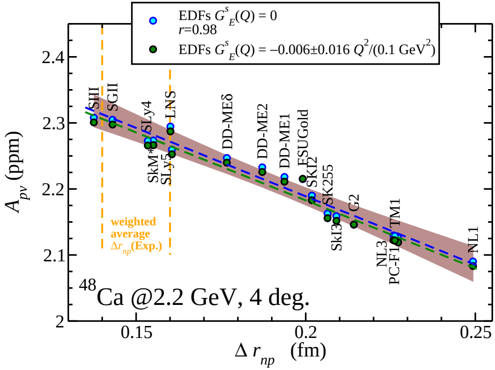




MF correlations allows to determine Δr_{np} and L without direct assumptions on ρ, PREx-II and PV-RAPTOR expected accuracy $\rightarrow$ constrain on L

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

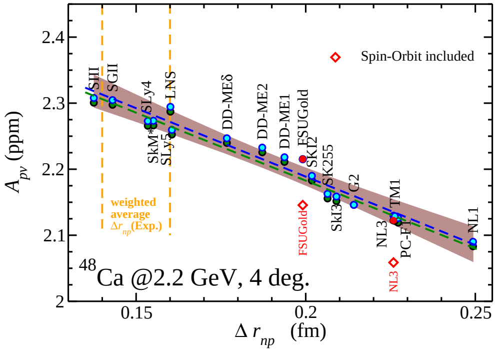
^{48}Ca: direct correlations within MF including radiative corrections and strange quark effects



A_{pv} decreases by around 0.005 ppm with an error of about 0.01 - 0.02 ppm when $G^s_E(Q^2)$ is included.

Used $G^s_E(Q^2)$ from PRC 76, 025202 (2007) by Liu, McKeown, and Ramsey-Musolf Average Δr_{np} from hadronic probes: PRC12, 778 1978; PRL87, 08250113, 343 (2004); Phys. Rev. 174, 1380 (1968); Physics Letters 57B 47 (1975); PRC 67, 054605 (2003) and PRC33 1624 (1986).

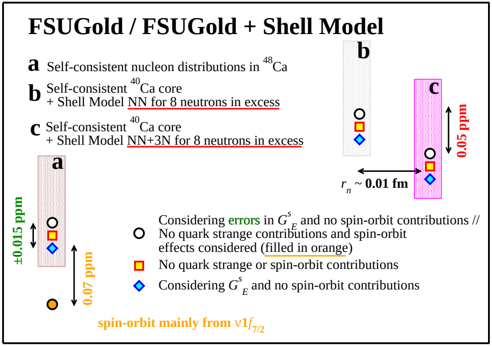
^{48}Ca: estimation of spin-orbit effects



In the two tested models, spin-orbit effects shifts to lower values the A_{pv} consistently by about 0.07 ppm. This predicts a reduction of Δr_{np} of about 0.05 fm.

Charge density distributions including spin orbit effects provided by J. Piekarewicz (FSU).

^{48}Ca: Estimation of three-neutron forces effects in comparison with other corrections



Shell Model calculations based on χEFT with NN to N3LO (fixed to scattering data) and 3N to N2LO (fixed to B tritium and R of alpha particle) **provided by J. Menendez (TU Darmstadt)**.

Three-neutron forces used here shifts downwards the A_{pv} by about **0.05 ppm (very similar to spin-orbit effect)**

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 $(Fe^{iwt} + F^\dagger e^{-iwt})$:

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

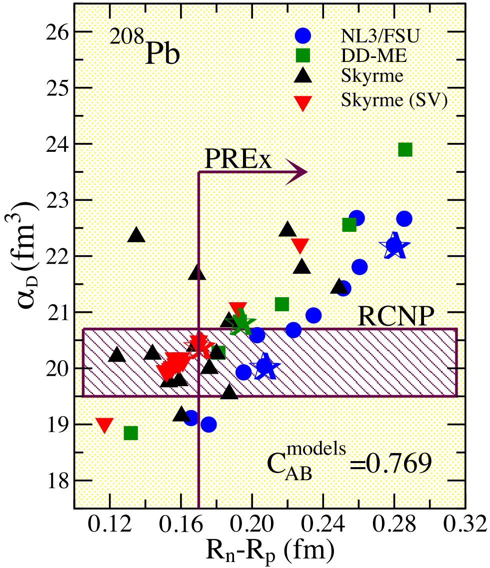
- is proportional to the **static dipole polarizability, α_D,** for small oscillations

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

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

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

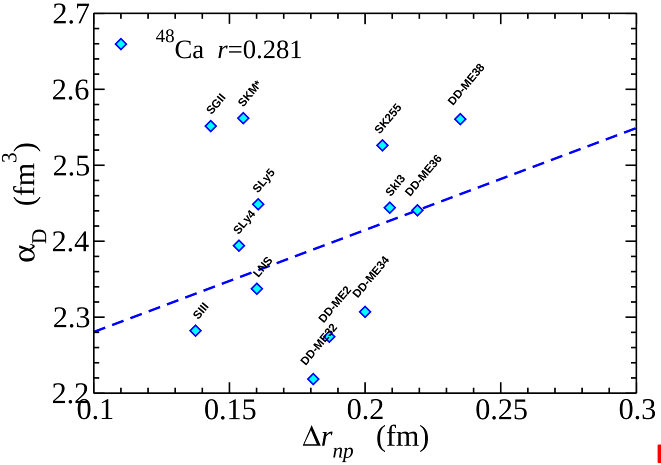
Mean-Field + RPA results for ^{208}Pb



J. Piekarewicz, B. K. Agrawal, G. Colò, W. Nazarewicz, N. Paar, P.-G. Reinhard, X. Roca-Maza and D. Vretenar,

Phys. Rev. C **85** 041302 (2012) (R).

Mean-Field + RPA results for ^{48}Ca



Data on relativistic models provided by N. Paar and D. Vretenar

Conclusions:

- A precise and **model-independent** determination of Δr_{np} in ^{48}Ca and ^{208}Pb via PVES experiments would **probe** at the same time the density dependence of the nuclear **symmetry energy** and the relevance of **three neutron-forces** in ^{48}Ca. Eventually, it can also provide indirect indications on the impact of 3N in ^{208}Pb.
- We demonstrate a close **linear correlation** between A_{pv} and Δr_{np} within the same framework in which the Δr_{np} is correlated with L.
- Other **experiments** fairly **agree** with the **correlation** between A_{pv} and Δr_{np}.

Conclusions:

- **The estimated corrections to the** $A_{pv} \approx A^0_{pv} \times [1 - 0.005(\mathrm{strange}) - 0.03(\mathrm{s-o})]$ where A^0_{pv} is the result from DWBA calculations with a given neutron and proton density distributions convoluted with experimental electromagnetic form factors and weak neutral current form factors including radiative corrections, **indicate a reduction of about the 3%**.
- In addition, the inclusion of **3N-forces** would change the neutron density producing a **reduction in** A^0_{pv} of a few %.

Conclusions:

- Families of modern energy density functionals show an almost linear correlation between α_D and Δr_{np} while the correlation gets worst when models based on different grounds are also taken into account.
- A_{pv} and α_D are complementary **observables** that may set tight **constraints** on the **density dependence of the symmetry energy.**

Collaborators:

B. K. Agrawal[1]
G. Colò[2,3]
W. Nazarewicz[4,5,6]
N. Paar[7]
J. Piekarewicz[8]
P.-G. Reinhard[9]
D. Vretenar[7]
Michal Warda[10]
Mario Centelles[11]
Xavier Viñas[11]

[1] Saha Institute of Nuclear Physics, Kolkata 700064, India
[2] Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy
[3] INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy
[4] Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA
[5] Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[6] Institute of Theoretical Physics, University of Warsaw, ulitsa Hoa 69, PL-00-681 Warsaw, Poland
[7] Physics Department, Faculty of Science, University of Zagreb, Zagreb, Croatia
[8] Department of Physics, Florida State University, Tallahassee, Florida 32306, USA
[9] Institut fr Theoretische Physik II, Universitt Erlangen-Nrnberg, Staudtstrasse 7, D-91058 Erlangen, Germany
[10] Katedra Fizyki Teoretycznej, Uniwersytet Marii CurieSklodowskiej, ul. Radziszewskiego 10, PL-20-031 Lublin, Poland
[11] Departament dEstructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Facultat de Física, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain