Parity violating electron scattering observables, and Dipole Polarizability

Xavier Roca-Maza
Università degli Studi di Milano and INFN

Neutron Skins of Nuclei: from laboratory to stars

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INTRODUCTION

The Nuclear Many-Body Problem:

- **Nucleus:** from few to more than 200 strongly interacting and **self-bound fermions**.
- **Underlying interaction** is **not perturbative** at the (low)energies of interest for the study of masses, radii, deformation, giant resonances,...
- **Complex systems**: **spin, isospin, pairing, deformation,** ...
- **Many-body** calculations based on **NN scattering data** in the vacuum are **not conclusive** yet:
  - **different nuclear interactions in the medium** are found **depending** on the **approach**
  - **EoS** and (only very recently) **few groups** in the world are able to perform extensive calculations for **light and medium mass nuclei**
- Based on effective interactions, **Nuclear Energy Density Functionals** are **successful** in the description of **masses, nuclear sizes, deformations, Giant Resonances,...**

Nuclear Energy Density Functionals:

Main types of successful EDFs for the description of masses, deformations, nuclear distributions, Giant Resonances, ...

Relativistic mean-field models, based on Lagrangians where effective mesons carry the interaction:

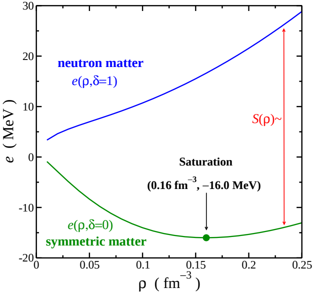
$$\begin{aligned}\mathcal{L}_{int} \quad &= \bar{\Psi}\Gamma_\sigma(\bar{\Psi},\Psi)\Psi\Phi_\sigma \qquad +\bar{\Psi}\Gamma_\delta(\bar{\Psi},\Psi)\boldsymbol{\tau}\Psi\Phi_\delta \\ &-\bar{\Psi}\Gamma_\omega(\bar{\Psi},\Psi)\gamma_\mu\Psi A^{(\omega)\mu} \quad -\bar{\Psi}\Gamma_\rho(\bar{\Psi},\Psi)\gamma_\mu\tau\Psi A^{(\rho)\mu} \\ &-e\bar{\Psi}\hat{Q}\gamma_\mu\Psi A^{(\gamma)\mu}\end{aligned}$$

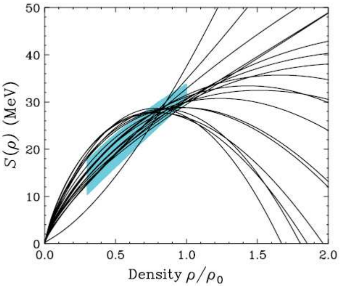
Non-relativistic mean-field models, based on Hamiltonians where effective interactions are proposed and tested:

$$V^{\text{eff}}_{\text{Nucl}} = V^{\text{long-range}}_{\text{attractive}} + V^{\text{short-range}}_{\text{repulsive}} + V_{\text{SO}} + V_{\text{pair}}$$

- Fitted **parameters contain** (important) **correlations beyond the mean-field**
- Nuclear energy functionals are **phenomenological** → **not directly connected to any NN** (or NNN) **interaction**

The Nuclear Equation of State: Infinite System



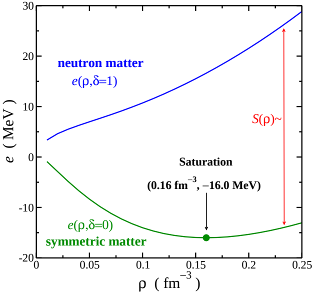


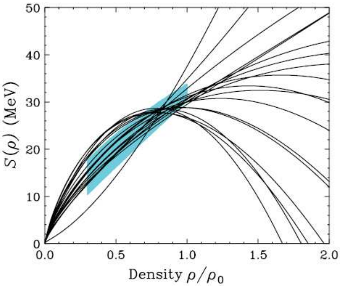
$$\boxed{\frac{E}{A}(\rho,\beta)} = \boxed{\frac{E}{A}(\rho,\beta=0)} + \boxed{S(\rho)\beta^2} + \mathcal{O}(\beta^4)$$

- Nuclear Matter

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



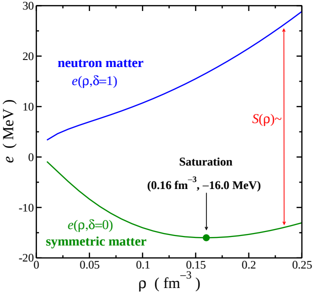


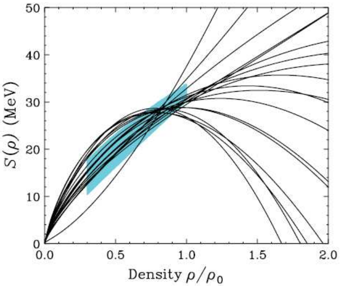
$$\boxed{\frac{E}{A}(\rho,\beta)} = \boxed{\frac{E}{A}(\rho,\beta=0)} + \boxed{S(\rho)\beta^2} + \mathcal{O}(\beta^4)$$

- Nuclear Matter
- Symmetric Matter

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



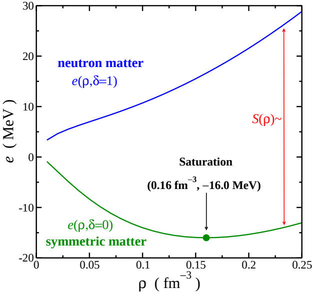


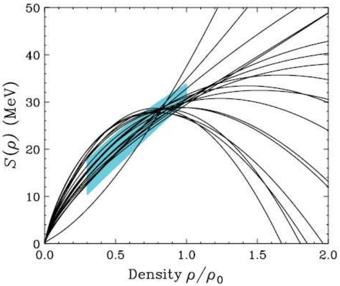
$$\boxed{\frac{E}{A}(\rho,\beta)} = \boxed{\frac{E}{A}(\rho,\beta=0)} + \boxed{S(\rho)\beta^2} + \mathcal{O}(\beta^4)$$

- Nuclear Matter
- Symmetric Matter
- Symmetry energy

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}\right]$$

The Nuclear Equation of State: Infinite System



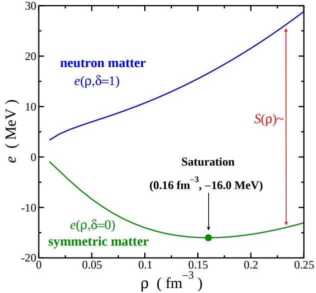


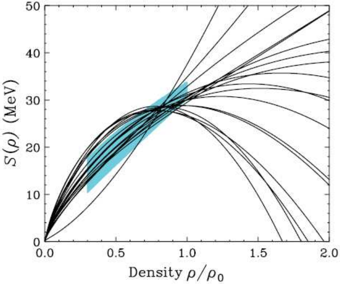
$$\boxed{\frac{E}{A}(\rho,\beta)} = \boxed{\frac{E}{A}(\rho,\beta=0)} + \boxed{S(\rho)\beta^2} + \mathcal{O}(\beta^4)$$

$$= \frac{E}{A}(\rho,\beta=0) + \beta^2\left(J + Lx + \frac{1}{2}K_{sym}x^2 + \mathcal{O}(x^3)\right)$$

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}; \quad x = \frac{\rho - \rho_0}{3\rho_0}\right]$$

The Nuclear Equation of State: Infinite System





$$\frac{E}{A}(\rho,\beta) = \frac{E}{A}(\rho,\beta=0) + \beta^2\left(\boxed{J} + \boxed{L}x + \frac{1}{2}\boxed{K_{sym}}x^2 + \mathcal{O}(x^3)\right)$$

- $S(\rho_0) = J$
- $\left.\frac{d}{d\rho}S(\rho)\right|_{\rho_0} = \frac{L}{3\rho_0} = \frac{P_0}{\rho_0^2}$
- $\left.\frac{d^2}{d\rho^2}S(\rho)\right|_{\rho_0} = \frac{K_{sym}}{9\rho_0^2}$

$$\left[\beta = \frac{\rho_n - \rho_p}{\rho}; \quad x = \frac{\rho - \rho_0}{3\rho_0}\right]$$

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** $\Rightarrow$ **more info**
  - **parity violating elastic electron scattering** (PVES), a **model independent technique**, has allowed to estimate the **weak form factor at low** q of a stable heavy nucleus like ^{208}Pb

  $$\Downarrow$$

  Promising perspectives for the near future

STATISTIC UNCERTAINTIES IN EDFs

Covariance analysis: χ^2 test

- Observables $\mathcal{O}$ used to calibrate the parameters $\mathbf{p}$
$$\chi^2(\mathbf{p}) = \sum_{i=1}^{m} \left(\frac{\mathcal{O}_i^{\text{theo.}} - \mathcal{O}_i^{\text{ref.}}}{\Delta \mathcal{O}_i^{\text{ref.}}} \right)^2$$
- Assuming that the χ^2 can be approximated by an hyper-parabola around the minimum $\mathbf{p}_0$,
$$\chi^2(\mathbf{p}) - \chi^2(\mathbf{p}_0) \approx \frac{1}{2} \sum_{i,j}^{n} (p_i - p_{0i}) \partial_{p_i} \partial_{p_j} \chi^2 (p_j - p_{0j})$$
where $\mathcal{M} \equiv \frac{1}{2} \partial_{p_i} \partial_{p_j} \chi^2$ (curvature m.) and $\mathcal{E} \equiv \mathcal{M}^{-1}$ (error m.).
- errors between predicted observables $\mathcal{A}$
$$\Delta \mathcal{A} = \sqrt{\sum_{i}^{n} \partial_{p_i} A \mathcal{E}_{ii} \partial_{p_i} A}$$
- correlations between predicted observables,
$$c_{AB} \equiv \frac{C_{AB}}{\sqrt{C_{AA} C_{BB}}}$$
where, $C_{AB} = \overline{(A(\mathbf{p}) - \overline{A})(B(\mathbf{p}) - \overline{B})} \approx \sum_{ij}^{n} \partial_{p_i} A \mathcal{E}_{ij} \partial_{p_j} B$

Example: Fitting protocol of SLy5-min (NON-Rel) and DD-ME-min1 (Rel)

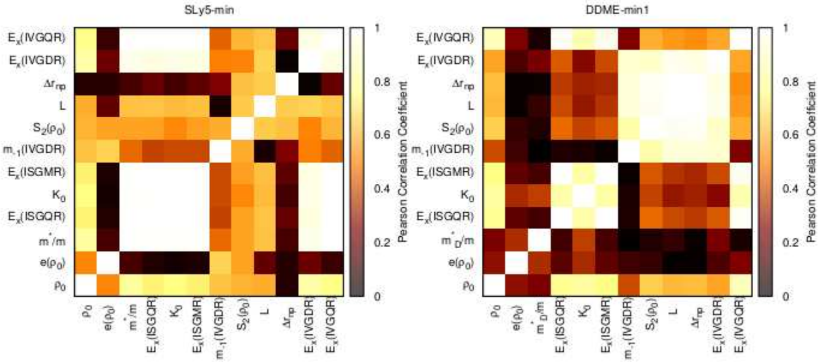
SLy5-min:

- Binding energies of ^{40,48}Ca, ^{56}Ni, ^{130,132}Sn and ^{208}Pb with a fixed adopted error of 2 MeV
- the charge radius of ^{40,48}Ca, ^{56}Ni and ^{208}Pb with a fixed adopted error of 0.02 fm
- the neutron matter Equation of State calculated by Wiringa *et al.* (1988) for densities between 0.07 and 0.40 fm^{-3} with an adopted error of 10%
- the saturation energy ($e(\rho_0) = -16.0 \pm 0.2$ MeV) and density ($\rho_0 = 0.160 \pm 0.005$ fm^{-3}) of symmetric nuclear matter.

DD-ME-min1:

- binding energies, charge radii, diffraction radii and surface thicknesses of 17 even-even spherical nuclei, ^{16}O, ^{40,48}Ca, ^{56,58}Ni, ^{88}Sr, ^{90}Zr, ^{100,112,120,124,132}Sn, ^{136}Xe, ^{144}Sm and ^{202,208,214}Pb. The assumed errors of these observables are 0.2%, 0.5%, 0.5%, and 1.5%, respectively.

Covariance analysis: SLy5-min (NON-Rel) and DD-ME-min1 (Rel)



J. Phys. G: Nucl. Part. Phys. 42 034033 (2015).

The **neutron skin** is **strongly correlated** with **J** and **L** in both models but **NOT** with α_D. **(I will discuss on that latter)**

Covariance analysis: SLy5-min (NON-Rel) and DD-ME-min1 (Rel)

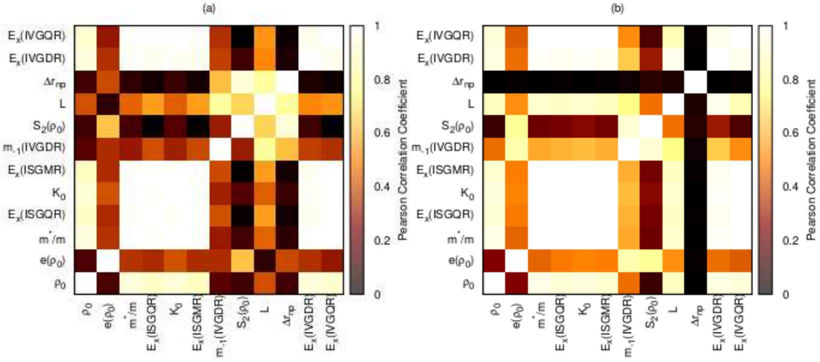
A	SLy5-min A_0		$\sigma(A_0)$	DDME-min1 A_0		$\sigma(A_0)$	units
SNM							
ρ_0	0.162	$\pm$	0.002	0.150	$\pm$	0.001	fm^{-3}
$e(\rho_0)$	-16.02	$\pm$	0.06	-16.18	$\pm$	0.03	MeV
m^*/m	0.698	$\pm$	0.070	0.573	$\pm$	0.008	
J	32.60	$\pm$	0.71	33.0	$\pm$	1.7	MeV
K_0	230.5	$\pm$	9.0	261	$\pm$	23	MeV
L	47.5	$\pm$	4.5	55	$\pm$	16	MeV
^{208}Pb							
E_x^{ISGMR}	14.00	$\pm$	0.36	13.87	$\pm$	0.49	MeV
E_x^{ISGQR}	12.58	$\pm$	0.62	12.01	$\pm$	1.76	MeV
Δr_{np}	0.1655	$\pm$	0.0069	0.20	$\pm$	0.03	fm
E_x^{IVGDR}	13.9	$\pm$	1.8	14.64	$\pm$	0.38	MeV
m_{-1}^{IVGDR}	4.85	$\pm$	0.11	5.18	$\pm$	0.28	MeV^{-1} fm^2
E_x^{IVGQR}	21.6	$\pm$	2.6	25.19	$\pm$	2.05	MeV

Statistical uncertainties depend on the fitting protocol, that is on the **data (or pseudo-data) and associated errors used for the fits: Let us see an example...**

Covariance analysis: modifying the χ^2

→ **SLy5-a:** χ^2 as in SLy5-min except for the neutron EoS (relaxed the required accuracy = increasing associated error).

→ **SLy5-b:** χ^2 as in SLy5-min except the neutron EoS (not employed) and used instead a tight constraint on the Δr_{np} in ^{208}Pb



J. Phys. G: Nucl. Part. Phys. 42 034033 (2015).

- When a **constraint** on a property is **relaxed**, **correlations** of other observables with such a property should become **larger** → **SLy5-a: α_D is now better correlated with Δr_{np}**
- When a **constraint** on a property is **enhanced** —artificially or by an accurate experimental measurement— **correlations** of other observables with such a property should become **small** → **SLy5-b: Δr_{np} is not correlated with any other observable**

PARITY VIOLATING ASYMMETRY

Some basics ...

- **Electrons** interact by exchanging a γ or a Z_0 boson.
- While **protons** couple basically to γ, **neutrons** do it to Z_0.
- Electron motion governed by the Dirac equation:
$$[\vec{\alpha} \cdot \vec{p} + \beta m_e + V(r)]\psi = E\psi$$
where $V(r) = V_C(r) + \gamma^5 V_W(r)$
- Dirac equation for helicity states ($m_e \approx 0$)
$$[\vec{\alpha} \cdot \vec{p} + (V_C(r) \pm V_W(r))]\psi_\pm = E\psi_\pm$$
- **Ultra-relativistic electrons, depending on their helicity,** will interact with the nucleus seeing a slightly different potential "αZ" $\pm$ "G_F".

Refs: Phys. Rev. C **57** 3430 (1998); Phys. Rev. C **63**, 025501 (2001); Phys. Rev. C **78**, 044332 (2008); Phys. Rev. C **82**, 054314 (2010); Phys. Rev. Lett. **106** 252501 (2011)

Some basics ...

- The **interference** between the DCS of electrons with $+$ and $-$ helicity states,

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

- **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 of $V_\pm$ are the ρ_n **and** ρ_p **(main uncertainty in** ρ_n**)** and **nucleon form factors** for the e-m and the weak neutral current.

Qualitative considerations ...

Within the Plane Wave Born Approximation,

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

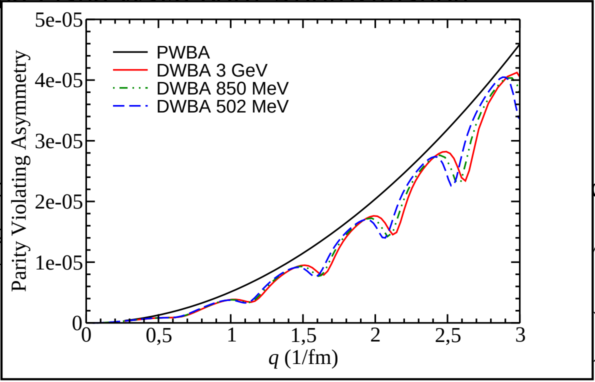
... which depends on $F_n(q) - F_p(q)$. For $q \to 0$, it is approximately,

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

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

Qualitative considerations ...

Within the Plane Wave Born Approximation



... which ... oximately,

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

Qualitative considerations ...

Within the Plane Wave Born Approximation,

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

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

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

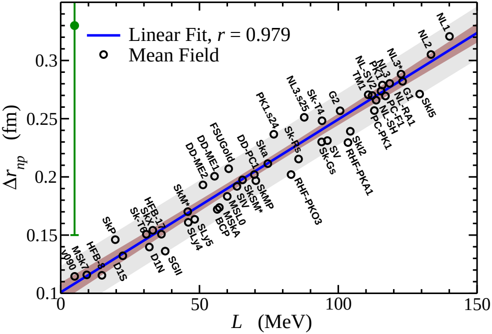
variation of $A_{p\nu}$ at a fixed q dominated by the variation of Δr_{np}. $F_p(q)$ well fixed by experiment

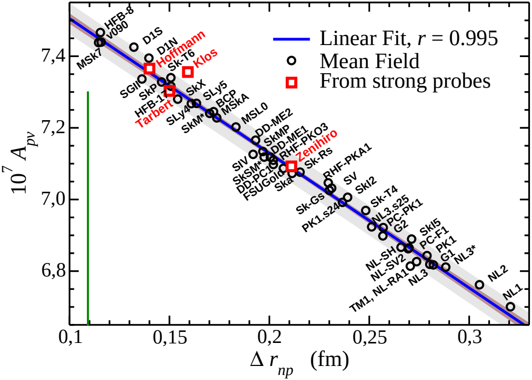
So, let us check DWBA results...

^{208}Pb: direct correlations

$\delta A_{pv} \sim$ **1%;**
$\delta \Delta r_{np} \sim 0.02$ **fm;**
$\delta L \sim$ **10 MeV (systematic)**

X. Roca-Maza, *et al.*, PRL **106** 252501 (2011)





EDF correlations allows to determine Δr_{np} and L without direct assumpt. on ρ, JLab and Mainz forthcoming experiments

Different experiments on proton elastic scattering, antirpotonic atoms and pion-photoproduction agrees with the correlation

Some considerations on parity conserving elastic electron scattering

Analyzing power for polarimetry

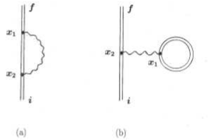
it gives the **degree of spin polarization** of the electrons from an initially unpolarized beam that are scattered in the **direction** θ

- **Accurate theoretical calculations** are very useful for a precise **calibartion** of the polarimeters used in parity violating experiments
- **We usually neglect Bremsstrahlung, kinematic and dynamical recoil (can be accounted for in e.g. GEANT4 simulations).**
- **Different codes** (mine and Doris Jakubassa-Amundsen) with same input **agree numerically within the 0.1%** at the kinematics of interest.

Analyzing power for polarimetry

- For few MeV e^- and nucleus of interest for calibrations:
  - different **theoretical nuclear charge distributions** produce an error of the order of **0.1 % (or samller)**.
  - **electron screening important small angles** [CPC 9 (1975) 31]
  - rearrangement collisions in which the projectile exchanges places with an atomic electron (small effect) [J. Phys. B: At. Mol. Phys. 6 (1973) 2280.]

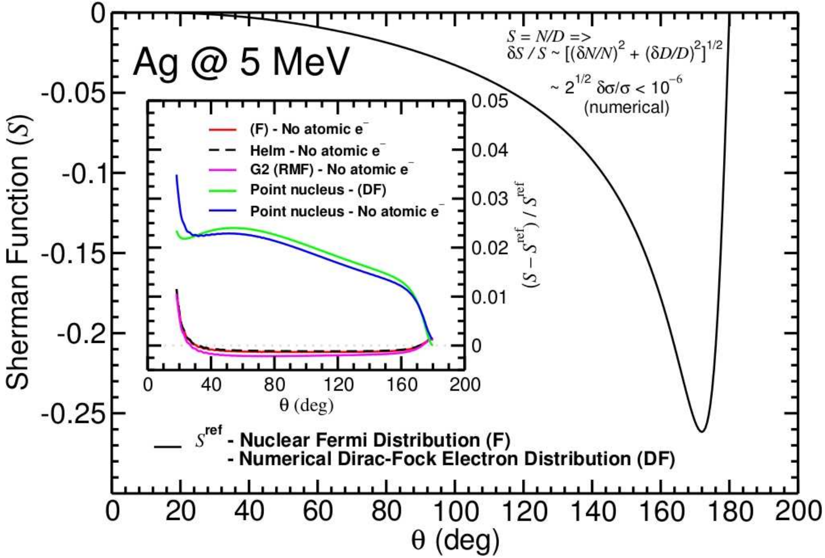
- **QED (radiative) corrections** can be partially included (a) self-energy (b) vacuum polarization corrections.



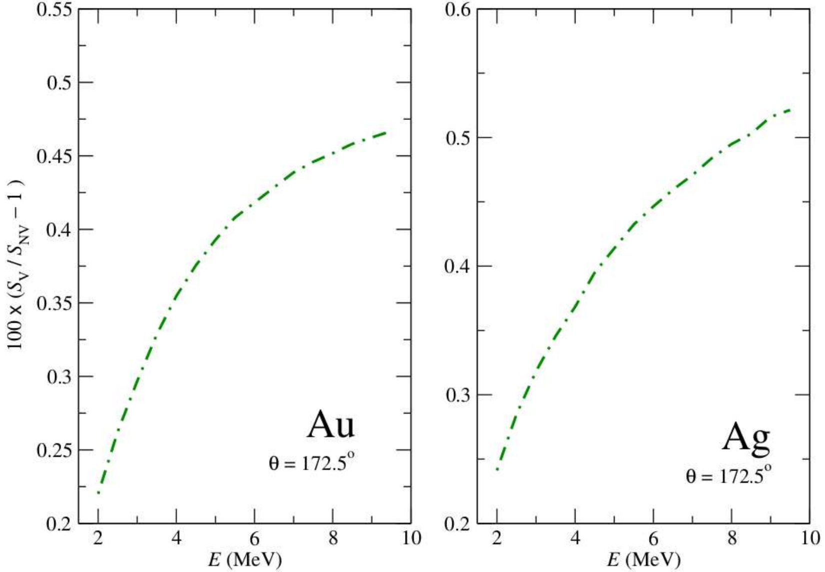
(b) error ~ 0.5% in analyzing power and (a) *believed* same order and opposite sign [Phys. Rev. A 61 (2000) 052112]

Calculations reliable up to the 0.5-0.6% accuracy

Example 1: effects of different contributions



Example 2: effects of vavuum polarization corrections



DIPOLE POLARIZABILITY

Polarizability, Strength distribution and its moments

- 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 isovector oscillating field** (dipolar in our case) of the form $(Fe^{iwt} + F^{\dagger}e^{-iwt})$:

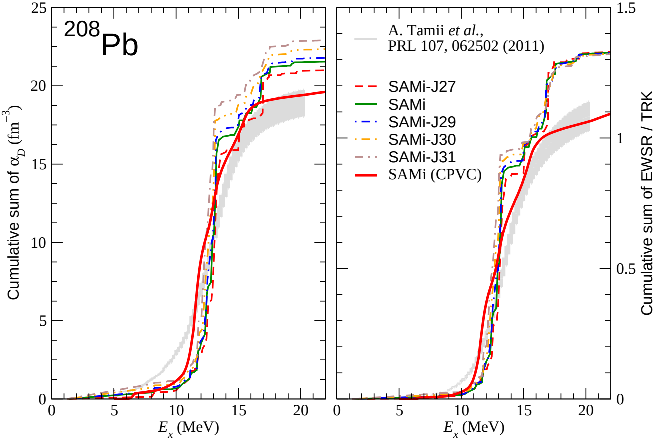
  $$F_{JM} = \sum_{i}^{A} r^J Y_{JM}(\hat{r})\tau_z(i) \; (\Delta L = 1 \rightarrow Dipole)$$

- is proportional to the **static polarizability** for small oscillations

  $\alpha = (8\pi/9)e^2 m_{-1} = (8\pi/9)e^2 \sum_{\nu} |\langle\nu|F|0\rangle|^2/E$ where m_{-1} **is the inverse energy weighted moment** of the **strength function**, defined as, $S(E) = \sum_{\nu} |\langle\nu|F|0\rangle|^2 \delta(E - E_{\nu})$

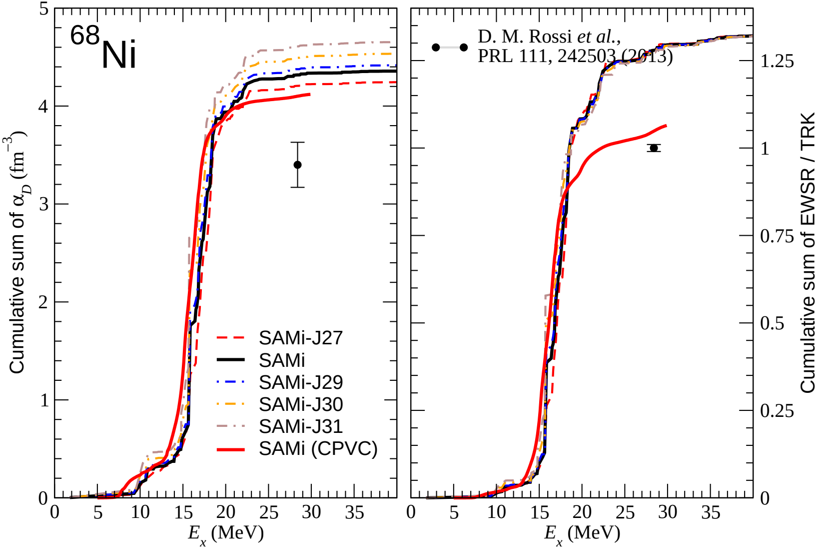
Let us compare some experiment with theory within the measured energy range...

Example 1: Cumulative sum of α_D and EWSR



The correction in the RPA predictions for the α_D^{RPA} due to the fact that not all possible correlations have been included in the model (α_D^{corr}) that lead to a fair reproduction of the experimental resonance width can be estimated to be $\frac{\alpha_D^{RPA} - \alpha_D^{corr}}{\alpha_D^{RPA}} \lesssim -\frac{\Gamma^2}{4E_x^2}$ **This correction might not be negligible**

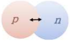
Example 2: Cumulative sum of α_D and EWSR



Theory versus experiment

- **RPA** strength concentrated at a ~ single peak: **EWSR and α_D "saturate" earlier in** E
- **PVC** strength follow **reasonable** trends with E, thought **no** calculations exist for the Δr_{np} **and refitting** of the interaction would be needed at the **PVC** level.
- **RPA** has been proben to be successful in describing experimental E_x and sum rules
- **Experimental data** on the α_D analysed via RPA need to include the **full dipole response** with low and high-energy parts:
  - **Data** within a given energy range, better if it is **extrapolated**: low energy part is more important than high energy part
  - **Data** in the high energy range, should be taken carefully due to quasi-deuteron excitations contaminations (small but sizeble correction to α_D)

Isovector Giant Dipole Resonance:



Dipole polarizability: a macroscopic approach

electric polarizability measures tendency of the nuclear charge distribution to be distorted $\left(\alpha \sim \frac{\text{electric dipole moment}}{\text{external electric field}}\right)$

- The dielectric theorem establishes that the m_{-1} moment can be computed from the expectation value of the Hamiltonian in the constrained ground state $\mathcal{H}' = \mathcal{H} + \lambda\mathcal{D}$.

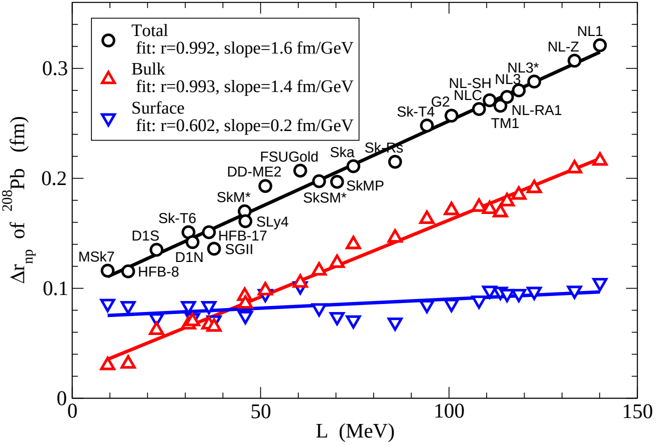
Adopting the Droplet Model:

$$m_{-1} \approx \frac{A\langle r^2\rangle^{1/2}}{48J}\left(1 + \frac{15}{4}\frac{J}{Q}A^{-1/3}\right)$$

within the same model, connection with the neutron skin thickness:

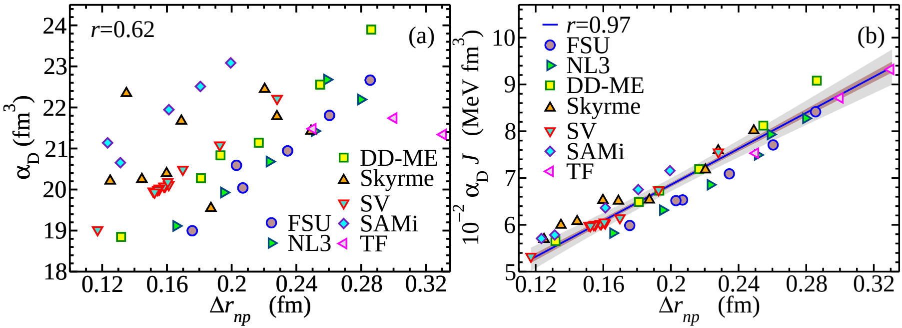
$$\alpha_D \approx \frac{A\langle r^2\rangle}{12J}\left[1 + \frac{5}{2}\frac{\Delta r_{np} + \sqrt{\frac{3}{5}}\frac{e^2 Z}{70J} - \Delta r_{np}^{\text{surface}}}{\langle r^2\rangle^{1/2}(I - I_C)}\right]$$

Δr_{np} in ^{208}Pb:



Isovector Giant Dipole Resonance in ^{208}Pb:

Dipole polarizability: microscopic results HF+RPA



X. Roca-Maza, *et al.*, Phys. Rev. C 88, 024316 (2013).

Experimental dipole polarizability $\alpha_D = 20.1 \pm 0.6$ fm^3; A. Tamii *et al.*, PRL 107, 062502 (RCNP) [No quasi-deuteron $\alpha_D = 19.6 \pm 0.6$ fm^3].

$\alpha_D J$ is linearly correlated with Δr_{np} and no α_D alone within EDFs

Isovector Giant Dipole Resonance in ^{68}Ni:

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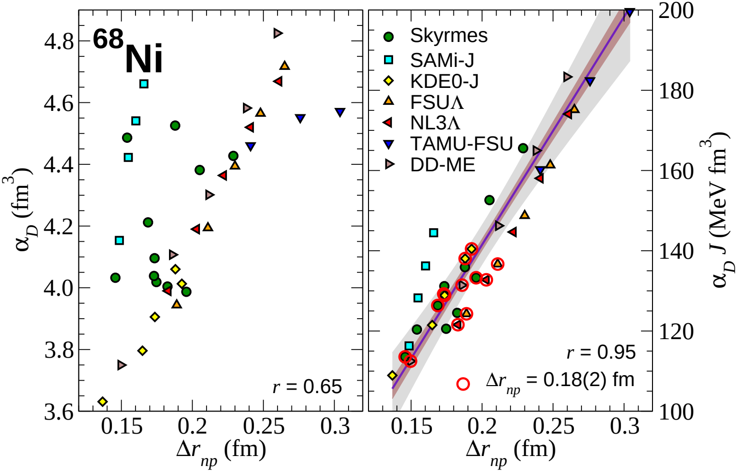
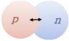


Experimental dipole polarizability $\alpha_D = 3.40 \pm 0.23$ fm^3 D. M. Rossi *et al.*, PRL 111, 242503 (GSI). $\alpha_D = 3.88 \pm 0.31$ fm^3 "full" response D. M. Rossi, T. Aumann, and K. Boretzky.

^{208}Pb vs ^{68}Ni:



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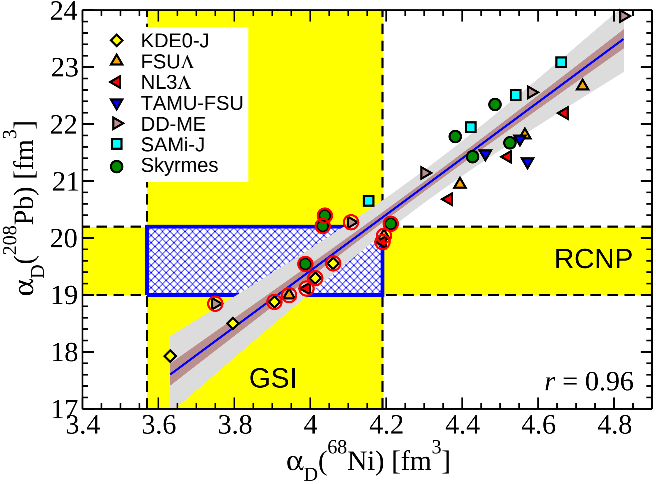
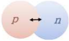
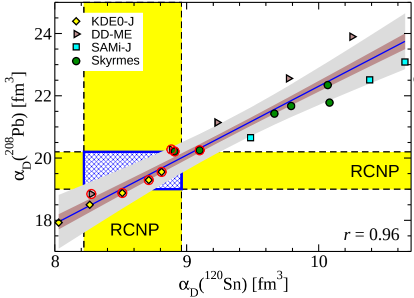


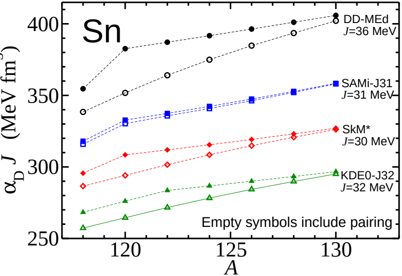
Just as an indication: $\alpha_D(A = 208)/\alpha_D(A = 68) \sim (208/68)^{5/3}$;
Cercled models predict $\Delta r_{np}(^{208}\mathrm{Pb}) = 0.125 - 0.207$ fm and $\Delta r_{np}(^{68}\mathrm{Ni}) = 0.146 - 0.211$ fm; $J = 30 - 35$ MeV; $L = 30 - 65$ MeV.

^{120}Sn vs ^{208}Pb:



Dipole polarizability: microscopic results HF+RPA





FOR THE USED MODELS **Including pairing correlations, Δr_{np} tend to be smaller by a 2.4% on average with a maximum discrepancy of a 5% and the polarizability tends to be smaller by a 4.5% on average with a maximum value of a 8%**

CONCLUSIONS

Conclusions:

- A precise and **model-independent** determination of Δr_{np} in ^{208}Pb via PVES experiments **probes** the **symmetry energy**.
- We demonstrate a close **linear correlation** between $A_{p\nu}$ and Δr_{np} within the same framework in which the Δr_{np} is correlated with L (expected to be better as heavier the nucleus).
- Other **experiments** fairly **agree** with the **correlation** between $A_{p\nu}$ and Δr_{np} in ^{208}Pb.
- EDFs (RPA) show a linear correlation between $\alpha_D J$ and Δr_{np}
- $A_{p\nu}$ and α_D are complementary **observables** that may set **tight constraints** on the **density dependence of the symmetry energy around saturation density, if precisely and/or systematically measured.**

Collaborators:

B. K. Agrawal[1]
P. F. Bortignon, M. Brenna, G. Colò[2,3]
W. Nazarewicz[4,5,6]
N. Paar, D. Vretenar[7]
J. Piekarewicz[8]
P.-G. Reinhard[9]
Michal Warda[10]
Mario Centelles, Xavier Viñas[11]
Misha Gorchtein[12]
Chuck Horowitz[13]

[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 HoÅija 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 für Theoretische Physik II, UniversitÃd't Erlangen-Nürnberg, Staudtstrasse 7, D-91058 Erlangen, Germany
[10] Katedra Fizyki Teoretycznej, Uniwersytet Marii Curie-Sklodowskiej, ul. Radziszewskiego 10, PL-20-031 Lublin, Poland
[11] Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Facultat de Física, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain
[12] PRISMA Cluster of Excellence, Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz, Germany
[13] Department of Physics and Nuclear Theory Center, Indiana University, Bloomington, IN 47405, USA