The pygmy dipole strength, the neutron skin thickness and the symmetry energy

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Motivation

Giant Resonances are collective excitations of atomic nuclei.

The measurement of such excitations has allowed us to constraint many properties of the nuclear equation of state —a basic input for different calculations in nuclear astrophysics,

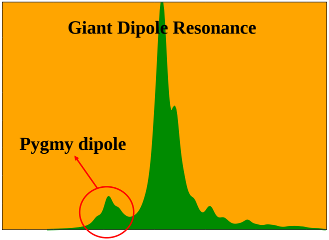
Giant Monopole Resonance $\rightarrow K_0$
Giant Dipole Resonance $\rightarrow c_{\rm sym}(\rho = 0.1 \text{ fm}^{-3})$
Giant Quadrupole Resonance $\rightarrow m^*$

Experiments on Giant Resonances constitute a basic tool for the study of fundamental properties of the nuclear strong interaction.

Motivation

What is the Pygmy Dipole Strength (PDS)?

Low-energy peak in the dipole response of neutron rich nuclei



We know that

- **the PDS is important for the determination of reaction rates in $r-$processes**
- **might be correlated with the slope of the symmetry energy: a basic property of the nuclear EoS that plays a crucial role in a variety of physical systems: from the very big (neutron stars) to the very small (neutron skin)**
- **But, why does the PDS appear in certain models as a coherent excitation (resonance), and not in others (shell effect)?**

Motivation: L versus Pygmy Dipole Strength

It is shown for a large set of successful MF models that the EWSR exhausted by the PDS is correlated with the slope of the symmetry energy

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 041301(R) (2010)

Constraints on the symmetry energy and neutron skins from pygmy resonances in ^{68}Ni and ^{132}Sn

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Correlations between the behavior of the nuclear symmetry energy, the neutron skins, and the percentage of energy-weighted sum rule (EWSR) exhausted by the pygmy dipole resonance (PDR) in ^{68}Ni and ^{132}Sn are investigated by using different random phase approximation (RPA) models for the dipole response, based on a representative set of Skyrme effective forces plus meson-exchange effective Lagrangians. A comparison with the experimental data has allowed us to constrain the value of the derivative of the symmetry energy at saturation. The neutron skin radius is deduced under this constraint.

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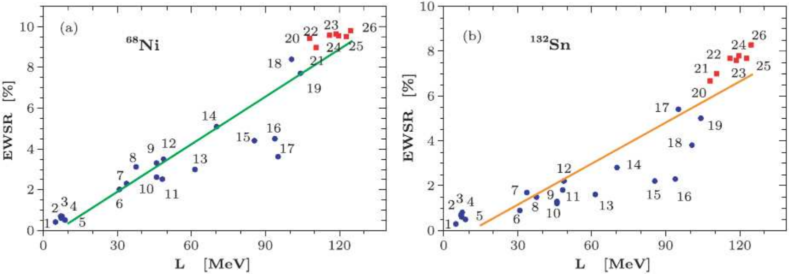
One of the interesting problems presently receiving particular attention is that of the size of the neutron root-mean-square (r.m.s.) radius in neutron-rich nuclei. In fact, this quantity is

PDR) [6], and of the charge-exchange spin-dipole strength [7] were suggested as constraints. In addition, by means of heavy-ion collisions the symmetry energy has also been probed

Motivation: L versus Pygmy Dipole Strength

L **correlated with the PDS** $L = 65 \pm 16$ **MeV**



PDS is understood as a ressonant oscillation of the outermost neutrons against the isospin saturated core

Motivation: L versus Pygmy Dipole Strength

Correlation analysis of SV-min interaction

The curvature of the $\chi^2(p_i)$ around the minimum as a function of the model parameters $\rightarrow$ allows one to determine the correlation between parameters and predicted observables

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **81**, 051303(R) (2010)

Information content of a new observable: The case of the nuclear neutron skin

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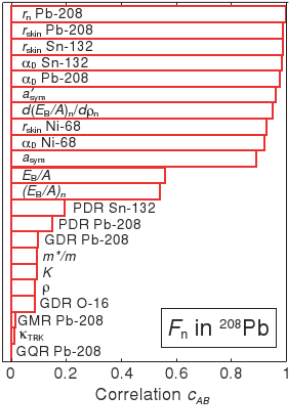
We address two questions pertaining to the uniqueness and usefulness of a new observable: (i) Considering the current theoretical knowledge, what novel information does new measurement bring in? (ii) How can new data reduce uncertainties of current theoretical models? We illustrate these points by studying the radius of the neutron distribution of a heavy nucleus, a quantity related to the equation of state for neutron matter that determines properties of nuclei and neutron stars. By systematically varying the parameters of two theoretical models and studying the resulting confidence ellipsoid, we quantify the relationships between the neutron skin and various properties of finite nuclei and infinite nuclear matter. Using the covariance analysis, we identify observables and pseudo-observables that correlate, and do not correlate, with the neutron skin. By adding the information on the neutron radius to the pool of observables determining the energy functional, we show how precise experimental

Motivation

L UNcorrelated with PDS



PDS is understood as a shell effect particular of the nucleus under study

Motivation

For a better understanding of the PDS we need:

- **a more exhaustive analysis of the microscopic properties of the PDS employing different nuclei and a representative set of nuclear interactions**

  (the main topic of this talk)

- **extend the correlation analysis made by P.-G. Reinhard and W. Nazarewicz to other interactions**

  (work in progress)

Contents

Microscopic analysis of the PDS: model dependence and sensitivity to the symmetry energy

We study the PDS within the self-consistent HF+RPA approach in the measured ^{68}Ni, ^{132}Sn and ^{208}Pb nuclei. For that, we use three Skyrme interactions with very different isovector properties (L ranges from 40 MeV to 100 MeV). We focus on:

- RPA and unperturbed dipole strength.
- the isoscalar or isovector nature.
- the transition densities.
- the most relevant p-h contributions.

Contents

The PDS may be correlated with the neutron skin thickness of neutron rich nuclei: does there exist the possibility of a tighter determination of the neutron skin thickness of a heavy nucleus by using a different experimental investigation?

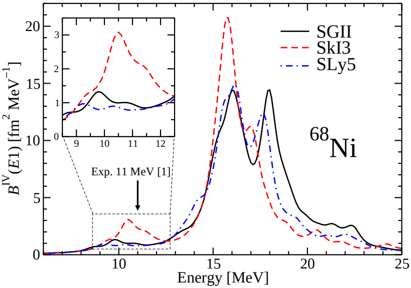
We will show (theoretically) that parity violating elastic electron scattering experiments constitute one of our best (if not the best) means of constraining the neutron rms radius of a nucleus and the symmetry energy.

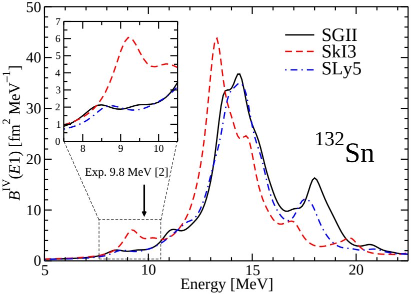
L estimates:

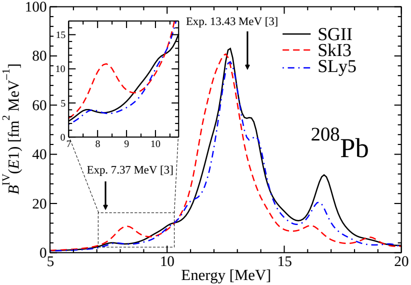
Are the different estimates of the L parameter compatible?

Microscopic analysis of the PDS: model dependence and sensitivity to the symmetry energy

Dipole strength functions







larger $L \rightarrow$ larger PDS peak

A. Carbone *et. al.*, PRC81 (2010) 041301.

Isovector properties of the interactions:

SGII $L = 37.6$ MeV

SLy5 $L = 48.3$ MeV

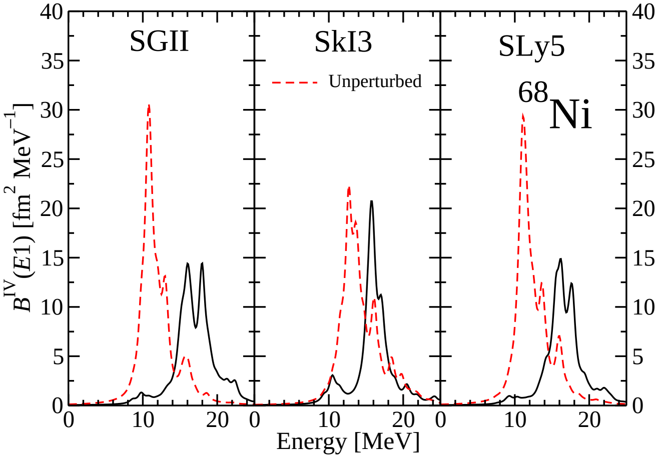
SkI3 $L = 100.5$ MeV

Experiment:

[1] O. Wieland *et. al.*, PRL **102** (2009) 092502.
[2] P. Adrich *et. al.*, PRL **95** (2005) 132501.
[3] N. Ryezayeva *et. al.*, PRL **89** (2002) 272502.

Microscopic analysis of the PDS

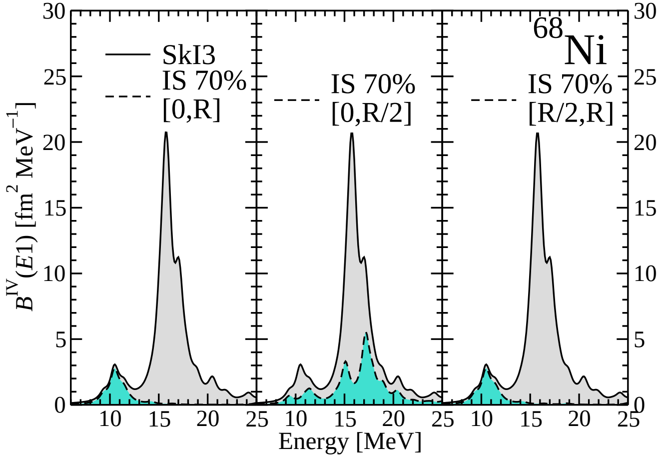
RPA versus unperturbed strength



No low energy peak in the unperturbed response. The low energy peak and the GDR peak of the RPA response does not coincide in energy with the unperturbed peak (SkI3): indications that the PDS may show some coherency depending on the model.

Microscopic analysis of the PDS

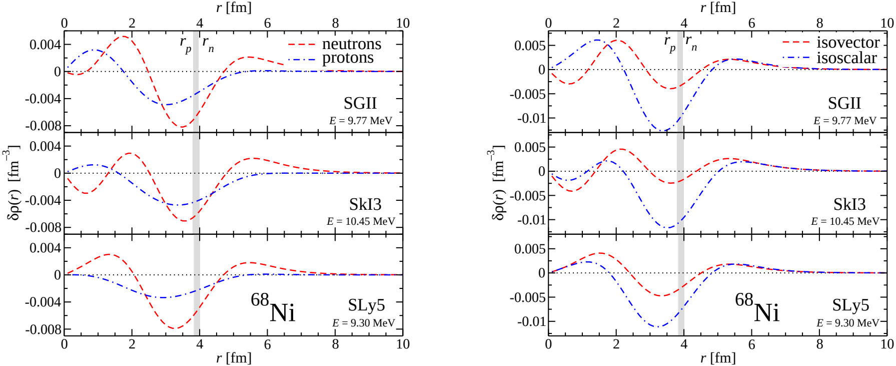
Isoscalar or isovector? $B_{\mathrm{IV}}(E1) = \sum_\nu \left(\frac{Z}{A} \int drr^3 \delta\rho_\nu^n(r) - \frac{N}{A} \int drr^3 \delta\rho_\nu^p(r) \right)$



Isoscalar nature of the PDS is due to outermost neutrons. The nuetron excess is sensitive to the symmetry energy as it is well known from studies on the Δr_{np}. (see also N. Paar *et. al.*, PRL103 (2009) 032502)

Microscopic analysis of the PDS

the transition densities (∼ amplitude of neutron and proton transition probabilities as a function of *r*-coordinate)



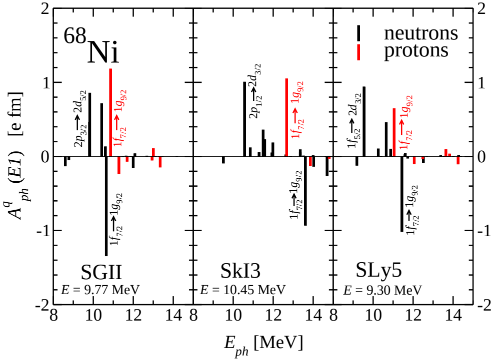
Around the nuclear surface: all models clearly isoscalar.

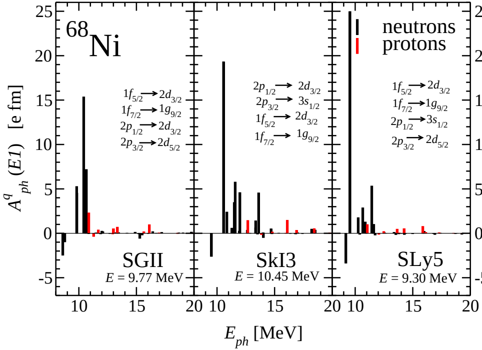
In the interior: neither clear nor definite trends for the studied models.

Microscopic analysis of the PDS

The most relevant p-h excitations in the IS and IV dipole response

$B^{\mathrm{IS/IV}}(E1) \equiv \left| \sum_{ph,q} A^{q}_{ph}(E1;\mathrm{IS/IV}) \right|^2$





The largest neutron p-h contributions (around 8 with $B_{\mathrm{IS}} > 1$) are coherent and all of them (except one) correspond to transitions of the outermost neutrons $\rightarrow$ **indicates that the ISPDS is a collective mode that may be correlated with $N - Z$.**

Conclusions:

PDS in ^{68}Ni, ^{132}Sn, ^{208}Pb:

1. The larger the value of L, the larger in strength we find the IV peak in the PDS region.
2. The isoscalar character of the PDS is qualitatively supported by all models and it is basically due to the outermost neutrons. ($\sim$ neutron skin)
3. The IV dipole response in neutron rich nuclei DOES NOT display a clear collectivity in all studied models.
4. The IS dipole response in neutron rich nuclei display a clear collectivity in all studied models. If systematically confirmed, it would provide a reasonable explanation to the correlation of the PDS with the neutron excess, hence, with the neutron skin thickness and, therefore, with the slope of the symmetry energy.
5. The isoscalarity displayed by the states giving rise to the PDS may probe also properties like the nuclear compressibility at subsaturation densities.

- **The isovector channel of the nuclear EoS (symmetry energy) is not very well known. Specially the density dependence (L)**
- **Nuclear EoS is not accurate at very large densities (no data only Brueckner calculations)**
- **Experiments on the PDS and neutron skins may help in setting tighter constraints to the slope of the symmetry energy and, therefore, improve the predictability of nuclear astrophysical calculations**
- **Observational data and nuclear astrophysical calculations may help in constraining some properties of the nuclear EoS**

The PDS may be correlated with the neutron skin thickness of neutron rich nuclei: does there exist the possibility of a tighter determination of the neutron skin thickness of a heavy nucleus by using a different experimental investigation?

Yes, there exists:
PREX-like experiments are essentially model independent!
They may allow us to further constrain the symmetry energy and substantially improve our understanding of the neutron distribution in nuclei, the PDS, the structure and composition of a neutron star crust,...

PREX

Parity violating electron elastic scattering is a model indepedent probe of neutrons in nuclei:

1. Electrons interact by exchanging a γ or a Z_0 boson.
2. While protons couple basically to γ, neutrons do it with Z_0.
3. Ultra-relativistic electrons, depending on their helicity, interact with the nucleons $V_\pm = V_{\mathrm{Coulomb}} \pm V_{\mathrm{Weak}}$.
4. PREX measures the parity violating asymmetry,

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

   at a single angle.
5. For solving the problem of an ultra-relativistic e^- moving under the effect of $V_\pm$, we solve the Dirac equation via the exact phase-shift analysis (DWBA). Input: ρ_n and ρ_p

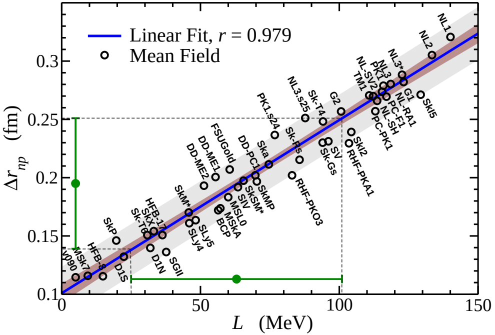
We propose a way to analyze the data which minimize the assumptions and do not compormise the accuracy of such kind of experiments

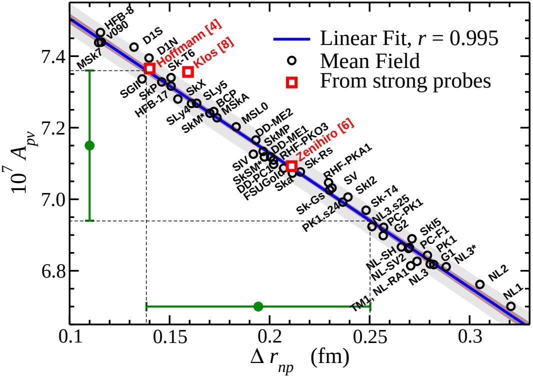
(basically, we do not assume a neutron density shape usually dependent in two or more parameters)

PREX data analysis:

How we can extract from PREX the value of *L*?

Figures from X. R-M *et al.* Phys. Rev. Lett. **106** (2011) 252501





Almost perfect linear correlation in MF models

Different experiments also in agreement

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

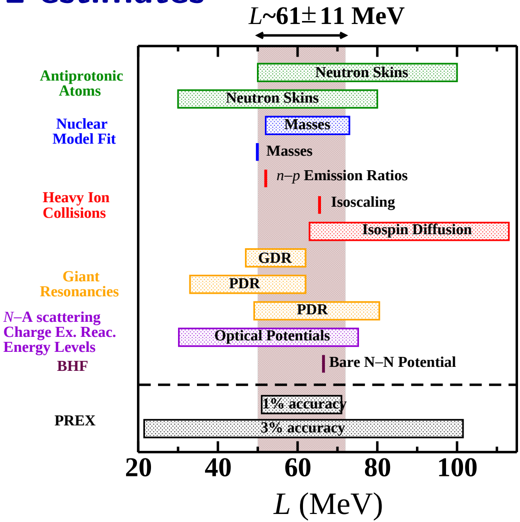
Conclusions:

Δr_{np} of ^{208}Pb and L from PREX:

- Careful and exhaustive analysis of mean field predictions.
- Analysis free from model dependent assumptions on the nucleon distributions.
- We demonstrate a close linear correlation between the parity violating asymmetry and the neutron skin thickness within the same framework in which the latter is correlated with L.
- Other experiments fairly agree with the shown correlations.
- The quality of the correlation supports the commissioning of an improved PREX run to measure the parity violating asymmetry more accurately.

Which is the constrain PREX can set on the density slope of the nuclear symmetry energy? And, how does it compares with other estimates?

L estimates



Centelles *et al.* PRL 102 (2009) 122502
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Myers *et al.* PRC 57 (1998) 3020
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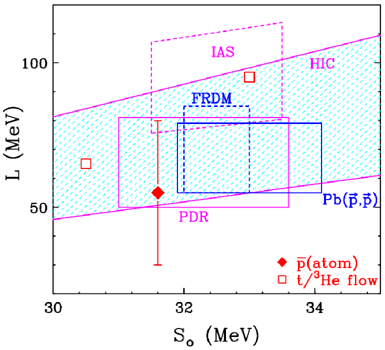
Li *et al.* Phys. Rep. 464 (2008) 113
Trippa *et al.* PRC 77 (2008) 061304(R)
Klimkiewicz *et al.* PRC 76 (2007) 051603(R)
Carbone *et al.* PRC 81 (2010) 041301(R)
Xu *et al.* PRC 82 (2010) 054607.
Vidaña *et al.* PRC 80 (2009) 045806

X. Roca-Maza *et. al.* PRL 106 (2011) 252501
(estimated error from PREX data centered
at L=61 MeV: average of all other estimates)

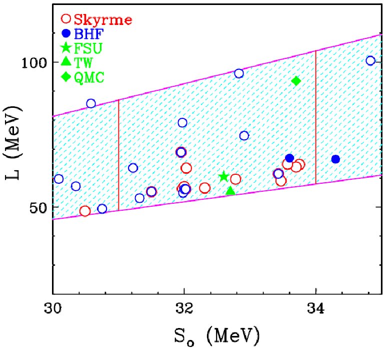
J-L correlation: NuSYM collaboration

Current Status

Experimental Measurements



Results from models



Thank you for your attention!