The Nuclear Equation of State

Theoretical models for nuclear structure studies

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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 predictions** (interaction in the medium) are found **depending** on the **approach**

  → EoS and (recently) **few groups** in the world are able to perform calculations for **light and medium mass nuclei**.

  [Not suitable for the description of heavy systems and high-lying excited states yet]

→ Based on effective interactions, **Nuclear Energy Density Functionals** are **successful** in the description of **masses, nuclear sizes, deformations, Giant Resonances,...**

Nuclear Energy Density Functionals:

Nuclear EDFs $E[\rho]$ are derived from an effective $\mathcal{H}/\mathcal{L}$ solved at first order perturbation theory (Hartree-Fock)

Main types of successful EDFs:

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

$$\begin{aligned} \mathcal{L}_{int} &= \bar{\Psi}\Gamma_\sigma \Psi \Phi_\sigma + \bar{\Psi}\Gamma_\delta \boldsymbol{\tau} \Psi \Phi_\delta - \bar{\Psi}\Gamma_\omega \gamma_\mu \Psi A^{(\omega)\mu} \\ &- \bar{\Psi}\Gamma_\rho \gamma_\mu \tau \Psi A^{(\rho)\mu} \end{aligned} \quad (1)$$

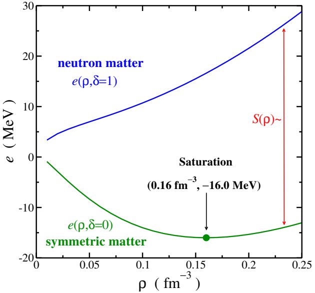
Non-relativistic models, based on Hamiltonians where ef fective interactions are proposed and tested:

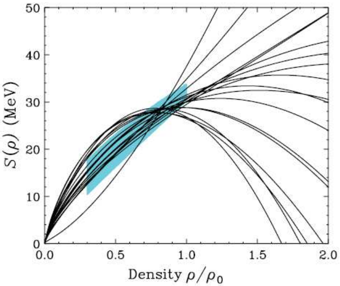
$$V_{\mathrm{Nucl}}^{\mathrm{eff}} = V_{\mathrm{attractive}}^{\mathrm{long-range}} + V_{\mathrm{repulsive}}^{\mathrm{short-range}} + V_{\mathrm{SO}}$$

$\rightarrow$ Fitted **parameters contain** (important) **correlations beyond the Hartree-Fock**

$\rightarrow$ Nuclear energy functionals are **phenomenological** $\rightarrow$ **not directly connected to any NN** (or NNN) **interaction**

The Nuclear Equation of State: Infinite System





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

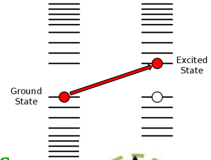
$$= \left(e_0 + \frac{1}{2}Kx^2 + ...\right) + \delta^2\left(J + Lx + \frac{1}{2}K_{sym}x^2 + ...\right)$$

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

Nuclear **EoS** around saturation density have a **crucial impact** on **nuclear structure and reaction** studies, as well as on **astrophysics** or **Standard Model** tests.

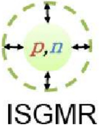
How one can determine the properies of the EoS?

Example: Giant Resonances (GR)

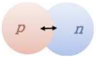


GR are collective and coherent excitations of atomic nuclei (10^1 MeV scale).

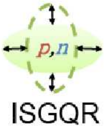
→ **How compressible is a nucleus (depends on K) is determined by the E_x of the (IS) Giant Monopole Resonance**



→ **How intense is the neutron-proton interaction in the nuclear medium (depends on J, L, ...) can be disentangled by the E_x of the (IV) Giant Dipole and Quadrupole Resonances**



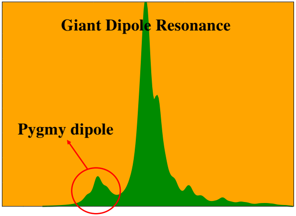
→ **How dense is the s.p. level distribution around the Fermi surface (related to the effective mass) is correlated with the E_x of the (IS) Giant Quadrupole resonance**



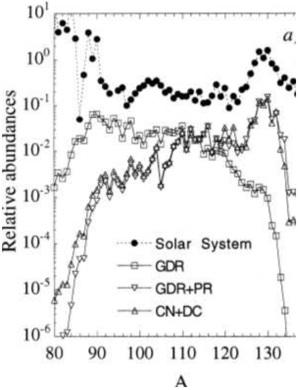
Experiments on GR constitute a basic tool for the study of fundamental properties of the nuclear EoS.

Let us have a look to an specific case of current interest

The Pygmy Dipole Strength (PDS)



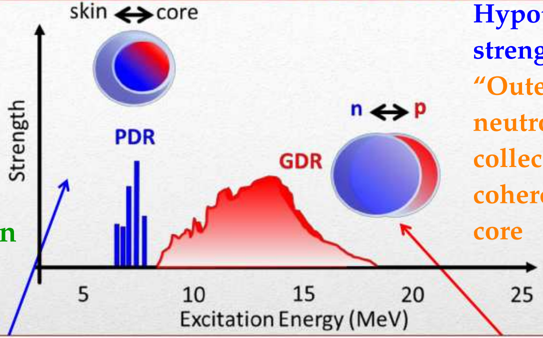
Low-energy peak in the dipole response of neutron rich (exotic) nuclei



S.Goriely, Phys. Lett. B436 10 (1998)

Nucleosynthesis: **radiative neutron captures by exotic nuclei are fundamental in the rapid neutron-capture process (r-process) that explains the origin of 1/2 of the nuclides heavier than iron observed in nature.** **Low-energy dipole strength influences capture cross section**

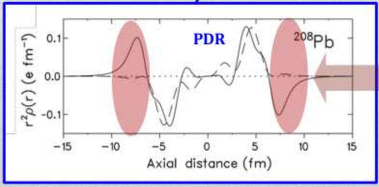
Nuclear Structure information from the E1 response in Nuclei



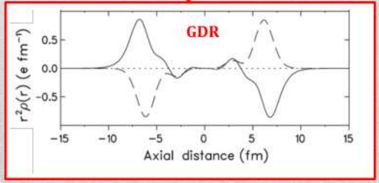
Hypothesis pygmy strength: "Outermost" neutrons oscillate collectively and coherently against core

ρ ~ amplitude of neutron/proton transition probability

States of different nature → Average Transition charge densities



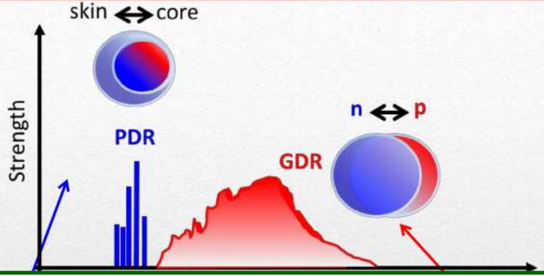
Neutron skin oscillation



Figures from: N. Ryezayeva el. al Phys. Rev. Lett. 89 (2002) 272502

➢ Interesting to use a probe interacting mainly at the surface...

Nuclear Structure information from the E1 response in Nuclei



if low-energy peak is composed by coherent oscillations of the outermost neutrons, the macroscopic dynamics of the PDS might be understood and, hence, the restoring force in this type of oscillations may be correlated with the parameters characterizing the nuclear EoS (e.g. the slope of the symmetry energy $L \propto p_{neut}(\rho_0)$)

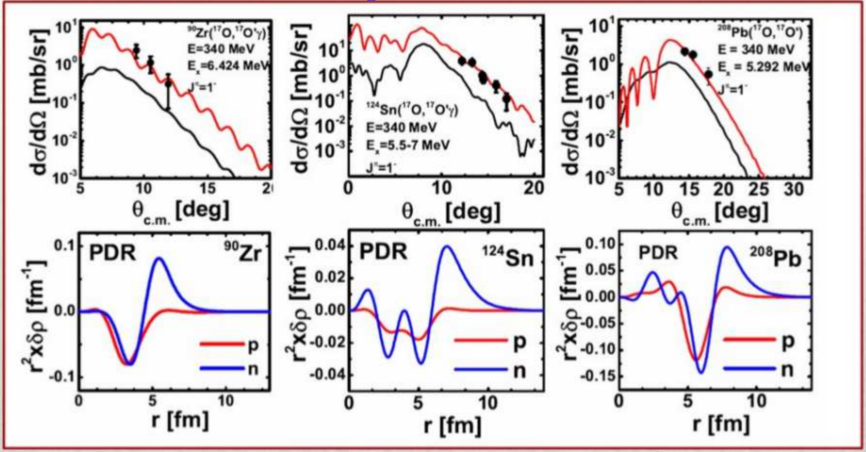
Figures from: N. Ryezayeva el. al Phys. Rev. Lett. 89 (2002) 272502

➢ **Interesting to use a probe interacting mainly at the surface…**

Results on the Low-Lying E1 Strength

- DWBA calculation were performed (red solid lines) using microscopic form factors based on the transition density associated to the E1 PDR states*

Realistic δρ descibe the experiment

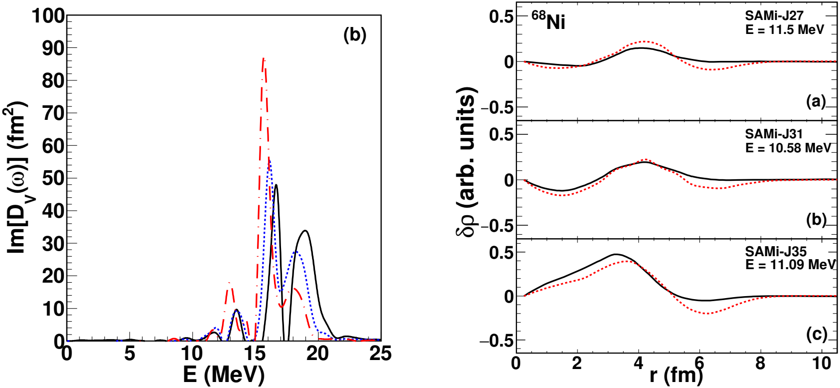


Milano and Catania groups Eur. Phys. J. A, 51 8 (2015) 99

Calculated transition densities:

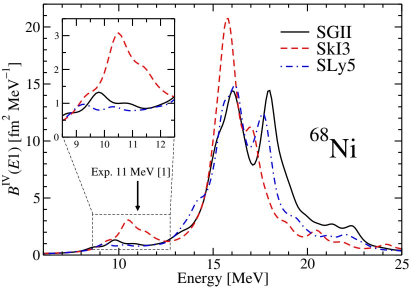
*(for 124Sn)E. Litvinova, et al., PRC 78 (2008)014312, **E.G. Lanza, et al.,PRC 89 (2014) 041601

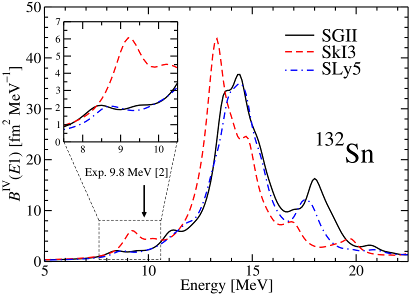
Dipole response: semi-classical transport model (^{68}Ni)

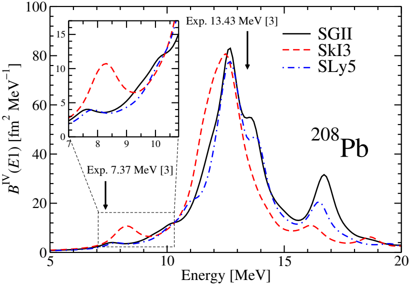


Catania group Phys. Rev. C 94, 014313 (2016)

Isovector dipole response function: RPA







larger L → larger PDS peak

Milano group PRC81 (2010) 041301.

Isovector properties of the interactions:

SGII L = 37.6 MeV

SLy5 L = 48.3 MeV

SkI3 L = 100.5 MeV

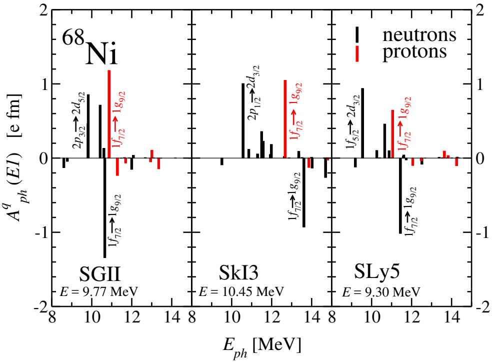
Experiment:

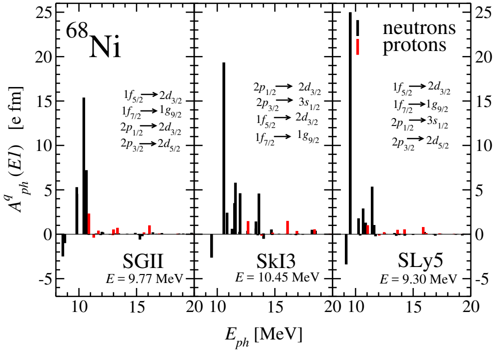
[1] O. Wieland *et. al.*, PRL **102** (2009) 092502.
D. M. Rossi, *et al.* PRL 111, 242503 (2013).
[2] P. Adrich *et. al.*, PRL **95** (2005) 132501.
[3] N. Ryezayeva *et. al.*, PRL **89** (2002) 272502.

Microscopic analysis of the PDS

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

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





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

Conclusions:

- EDFs currently constitute a unique tool for a systematic study of ground and excited state properties of nuclei along the whole nuclear chart and to connect them to the nuclear EoS.

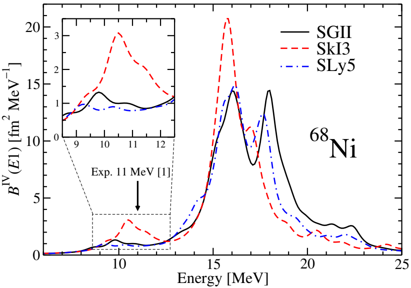
Pygmy dipole strength:

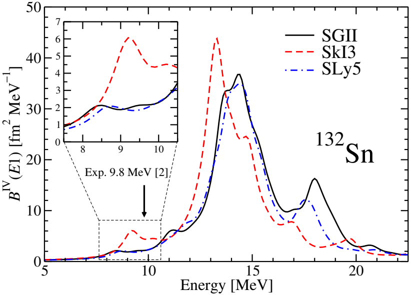
- Relevant not only for **nuclear structure** studies but also in **astrophysics** applications.
- The IV (and IS) dipole response show a **low-energy peak** in the strength function in **neutron-rich nuclei**.
- Such an IV **peak** (and also IS) **increases** in magnitude with increasing values of L.
- **Probes** interacting mainly at the nuclear surface better **suited** for the study of the **low-energy dipole response** (and also other multipoles) in exotic nuclei such as the ones planned to be studied at the LNL (SPES progect).

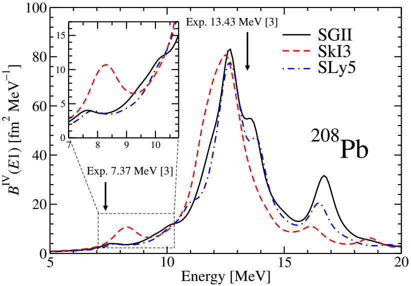
Thank you for your attention!

Extra material:

Isovector dipole response function







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

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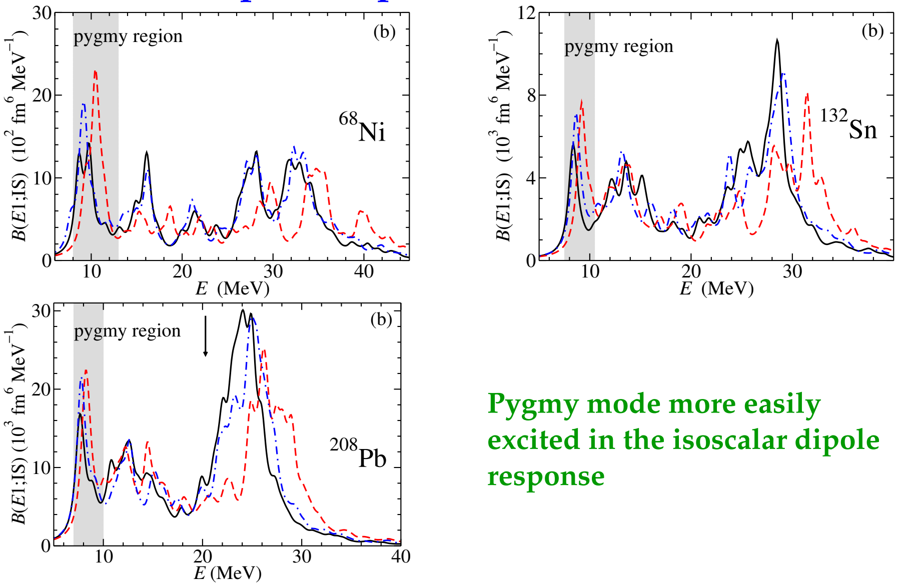
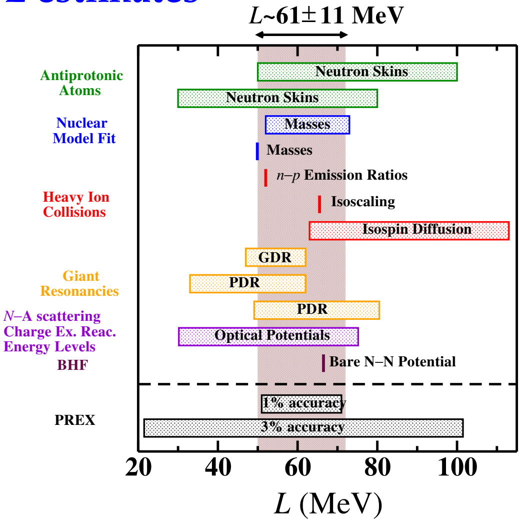
[3] N. Ryezayeva *et. al.*, PRL **89** (2002) 272502.

Isoscalar dipole response function



Pygmy mode more easily excited in the isoscalar dipole response

L estimates



Centelles *et al.* PRL 102 (2009) 122502

Warda *et al.* PRC 80 (2009) 024316

Danielewicz NPA 727 (2003) 233

Myers *et al.* PRC 57 (1998) 3020

Famiano *et al.* PRL 97 (2006) 052701

Shetty *et al.* PRC 76 (2007) 024606

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.

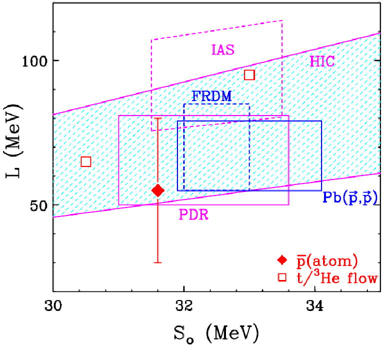
Vidaña *et al.* PRC 80 (2009) 045806

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