Nature of low-energy dipole states in exotic nuclei

Xavier Roca-Maza
Università degli Studi di Milano, Via Celoria 16, I-20133, Milano

SPES One-day Workshop on "Collective Excitations of Exotic Nuclei"
December 9, 2013, Milano

Motivation

Giant Resonances are collective excitations of atomic nuclei.

The measurement of such (high-energy) excitations has allowed us to constraint many properties of the nuclear equation of state

Giant Monopole Resonance $\rightarrow K_0$

[G. Colò, N. Van Giai, J. Meyer, K. Bennaceur and P. Bonche, Phys. Rev. C 70, 024307 (2004)]

Giant Dipole Resonance $\rightarrow S_2(\rho = 0.1\ \mathbf{fm}^{-3})$

[Luca Trippa, Gianluca Colò, and Enrico Vigezzi, Phys. Rev. C 77, 061304(R) (2008)]

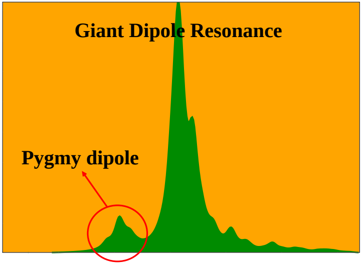
Giant Quadrupole Resonance $\rightarrow m^*$

["Nuclear Structure", Bohr & Mottelson $\rightarrow E_x = \sqrt{2m/m^*}\hbar\omega$]

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 (exotic) nuclei

It might be relevant in ...

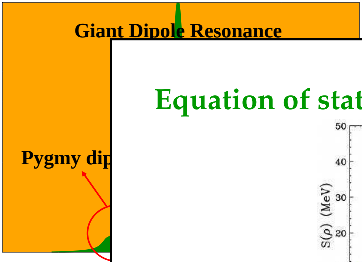
- **neutron-capture rates in the $r-$processes† since the energy window for both observables is similar**
- **if collective, it may be correlated with the slope of the symmetry energy (L): a basic property of the nuclear EoS that impacts on a variety of physical systems: from the very big (neutron stars) to the very small (neutron skin)**

The PDS seems to appear in certain models as a coherent excitation (resonance), and not in others (shell effect)

† $\beta-$decay rates and radiative neutron capture. In the latter, σ may increase due to the low-energy $E1$ enhancement when approaching the neutron drip line. [A. C. Larsen and S. Goriely, PRC 82, 014318 (2010)]

Motivation

What is the Pygmy Dipole Strength (PDS)?



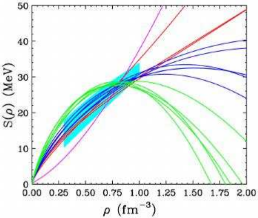
Low-energy peak in the dipole response of neutron rich (exotic)

the
nergy
ables is

▶ i... he
s... EoS
t... the
v... kin)

The I... ent
excita...

Equation of state for uniform nuclear matter



$$e(\rho,\delta) = e(\rho,\delta=0) + S(\rho)\delta^2 + \mathcal{O}\left[\delta^4\right] \text{ with}$$

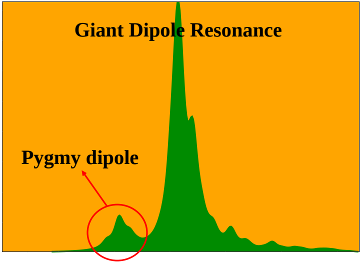
$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

$$S(\rho) = J + L\frac{\rho-\rho_0}{3\rho_0} + K_{sym}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \mathcal{O}\left[(\rho-\rho_0)^3\right]$$

† β−decay rates and radiative neutron capture. In the latter, σ may increase due to the low-energy E1 enhancement when approaching the neutron drip line. [A. C. Larsen and S. Goriely, PRC 82, 014318 (2010)]

Motivation

What is the Pygmy Dipole Strength (PDS)?



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

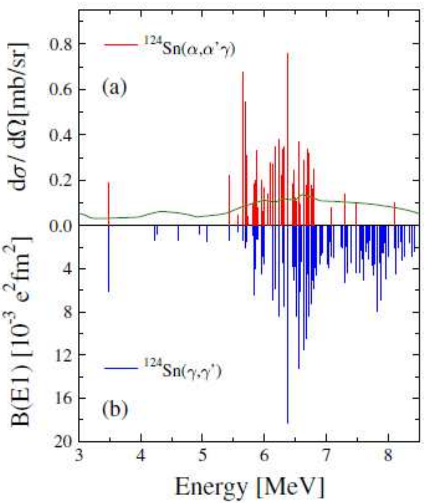
It might be relevant in ...

- **neutron-capture rates in the $r-$processes[†] since the energy window for both observables is similar**
- **if collective, it may be correlated with the slope of the symmetry energy: a basic property of the nuclear EoS that impacts on a variety of physical systems: from the very big (neutron stars) to the very small (neutron skin)**

The PDS seems to appear in certain models as a coherent excitation (resonance), and not in others (shell effect)

† $\beta-$decay rates and radiative neutron capture. In the latter, σ may increase due to the low-energy $E1$ enhancement when approaching the neutron drip line. [A. C. Larsen and S. Goriely, PRC 82, 014318 (2010)]

Motivation: experimentally, the PDS splits into two parts ...



J. Endres et al. Phys. Rev. Lett. 105, 212503 (2010)

Alpha-gamma coincidence experiments allow the separation of E1 excitations in ...

- one part excited via **$(\alpha, \alpha'\gamma)$ [dominant isoscalar excitation where the probe mainly interacts with the nuclear surface]** and **(γ, γ')**
- and the other only via **(γ, γ') [dominant isovector excitation where the probe interacts with the whole nucleus]**

Motivation: bibliography (non-exhaustive list)

There is a great interest on the PDS ....

... on experiment

- **Experimental Studies of the Pygmy Dipole Resonance** by D. Savran, T. Aumann and A. Zilges, Prog. Part. Phys. and Nucl. 70 210-245 (2013).
- **Evidence for Pygmy and Giant Dipole Resonances in ^{130}Sn and ^{132}Sn** by P. Adrich et al., Phys. Rev. Lett. 95, 132501 (2005).
- **Concentration of electric dipole strength below the neutron separation energy in N=82 nuclei** by A. Zilges et al., Phys. Lett. B542, 43 (2002).
- **The photoresponse of stable N=82 nuclei below 10 MeV** by S. Volz et al., Nucl. Phys. A779, 1 (2006).
- **Nature of Low-Energy Dipole Strength in Nuclei: The Case of a Resonance at Particle Threshold in 208Pb** by N. Ryezayeva et al., Phys. Rev. Lett. 89, 272502 (2002).
- **Search for the Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon** by O. Wieland et al., Phys. Rev. Lett. 102, 092502 (2009).

... and theory

- **Multiphonon excitations and pygmy resonances in tin isotopes** by E.G. Lanza, F. Catara, D. Gambacurta M.V. Andres and Ph. Chomaz, Phys. Rev. C 79 054615 (2009) and **Pygmy dipole resonances in the tin region** by N. Tsoneva and H. Lenske, Phys. Rev. C 77 024321 (2008).
- **Exotic modes of excitation in atomic nuclei far from stability** by Nils Paar, Dario Vretenar, Elias Khan and Gianluca Colò, Rep. Prog. Phys. 70 691 (2007).
- **Constraints on the symmetry energy and neutron skins from pygmy resonances in ^{68}Ni and ^{132}Sn** by Andrea Carbone, Gianluca Colò, Angela Bracco, Li-Gang Cao, Pier Francesco Bortignon, Franco Camera, and Oliver Wieland, Phys. Rev. C 81, 041301 (2010).
- **Nuclear symmetry energy and neutron skins derived from pygmy dipole resonances** by A. Klimkiewicz et al., Phys. Rev. C 76, 051603(R) (2007).
- **Low-lying dipole response: Isospin character and collectivity in ^{68}Ni, ^{132}Sn, and ^{208}Pb** by X. Roca-Maza, G. Pozzi, M. Brenna, K. Mizuyama, and G. Colò, Phys. Rev. C 85, 024601 (2012).
- **Pygmy resonances and neutron skins** by J. Piekarewicz, Phys. Rev. C 83, 034319 (2011).

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 **exotic** ^{68}Ni and ^{132}Sn and the **stable** ^{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:

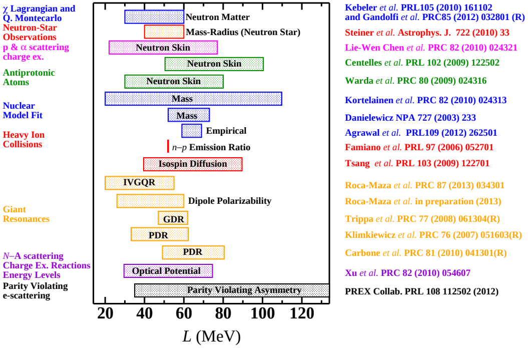
- RPA and unperturbed dipole strength.
- the transition densities.
- the isoscalar or isovector nature.
- the most relevant p-h contributions.

X. Roca-Maza, G. Pozzi, M.Brenna, K. Mizuyama and G. Colò, Phys. Rev. C 85 024601 (2012)

Contents

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

L estimates



X. Viñas et al. EPJA special volume on the symmetry energy

W … A
appr … ^{208}Pb
nucl … very
diffe … 100

- R
- th
- th
- th

X. Roca-Maza, G. Pozzi, M.Brenna, K. Mizuyama and G. Colò, Phys. Rev. C 85 024601 (2012)

Contents

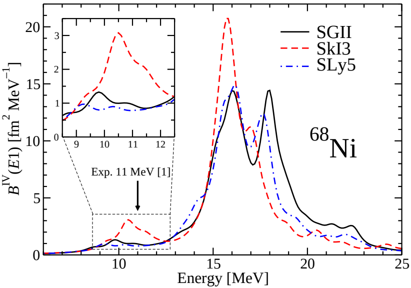
Microscopic analysis of the PDS: model dependence and sensitivity to the symmetry energy

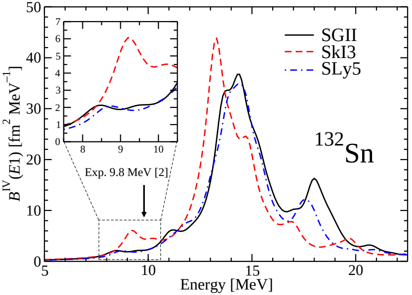
We study the PDS within the self-consistent HF+RPA approach in the **exotic** ^{68}Ni and ^{132}Sn and the **stable** ^{208}Pb nuclei. For that, we use three Skyrme interactions with very different isovector properties **(L ranges from 40 MeV to 100 MeV)**. We focus on:

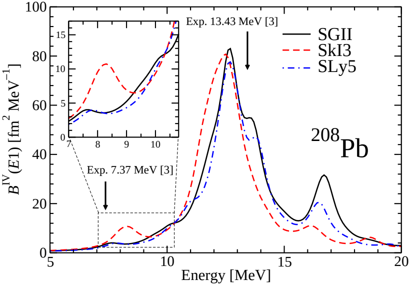
- RPA and unperturbed dipole strength.
- the transition densities.
- the isoscalar or isovector nature.
- the most relevant p-h contributions.

X. Roca-Maza, G. Pozzi, M.Brenna, K. Mizuyama and G. Colò, Phys. Rev. C 85 024601 (2012)

Dipole strength functions (IV)







larger L → 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

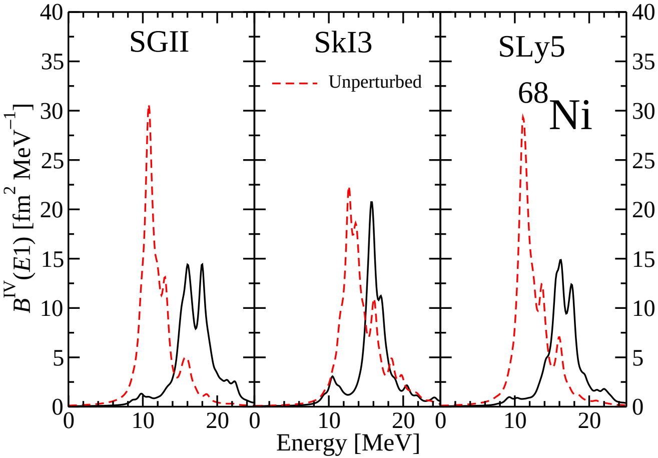
SkI3 L = 100.5 MeV

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

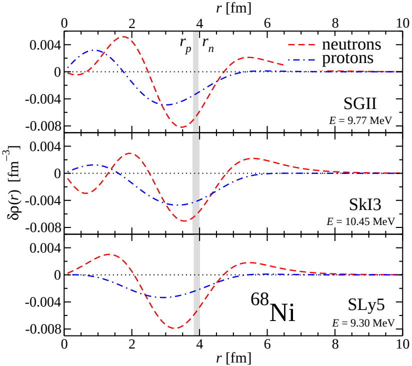


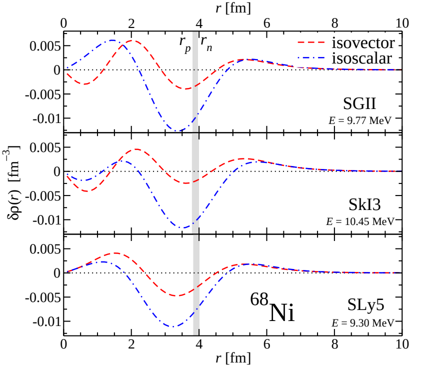
- No low energy peak in the unperturbed response.

- Indications that the PDS may show some coherency depending on the model. (RPA peaks do not coincide in energy with the unperturbed peak)

Microscopic analysis of the PDS

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



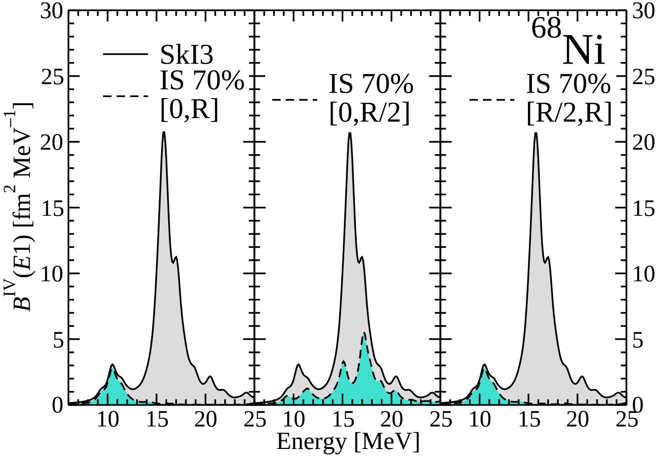


Around the nuclear surface: all models clearly isoscalar.
In the interior: not clear nor definite trends in the studied models.

Microscopic analysis of the PDS

Isoscalar or isovector?

$$B_{IV}(E1) = \sum_{\nu} \left(\frac{Z}{A} \int d r r^3 \delta\rho_{\nu}^{n}(r) - \frac{N}{A} \int d r r^3 \delta\rho_{\nu}^{p}(r) \right)$$



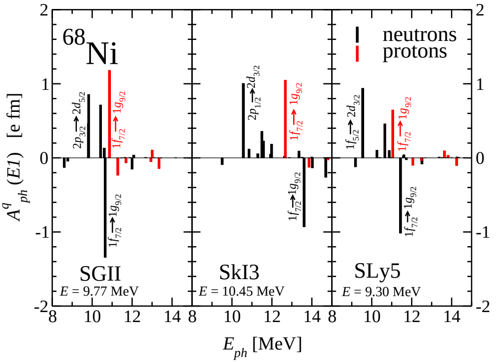
[N. Paar *et. al.*, PRL103 (2009) 032502]

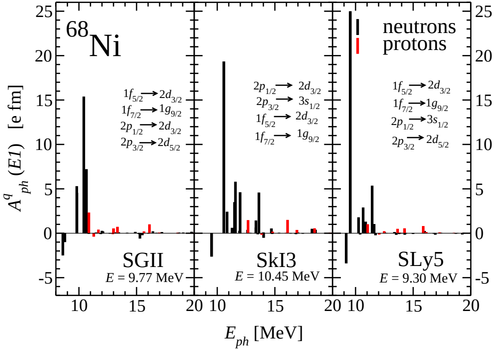
IS nature of the PDS due to outermost nucleons (neutrons in a neutron-rich nucleus). The Δr_{np} is correlated with I and L.

Microscopic analysis of the PDS

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

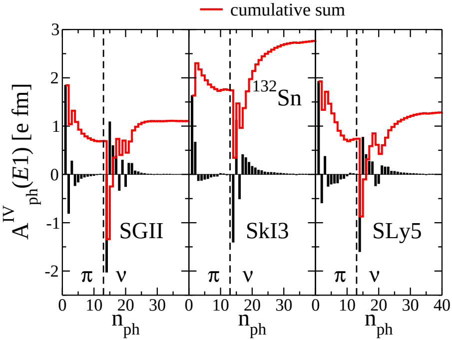
$$B(E1) \equiv \left| \sum_{ph,q} A^q_{ph}(E1) \right|^2$$

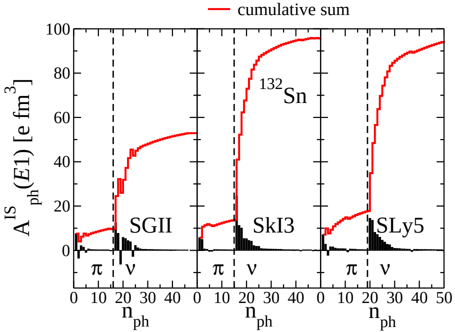




The largest neutron p-h contributions (around 8 with $B_{IS} > 1$) are coherent and all of them (except one) correspond to transitions of the outermost neutrons $\rightarrow$ **indicates that the ISPDS is a collective mode that may be correlated with N − Z.**

Collectivity: Coherence of the different contributions

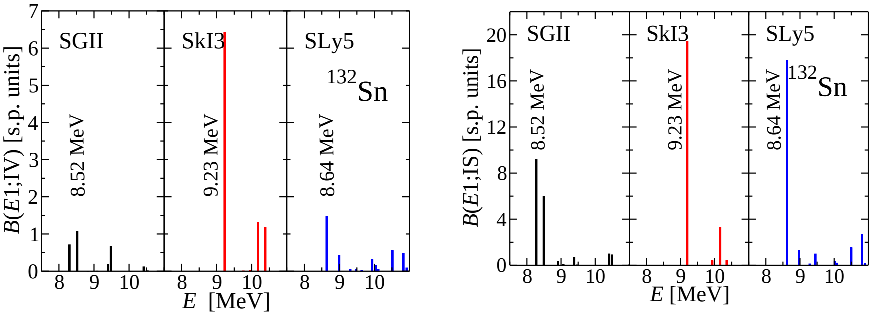




The largest p-h contributions are:

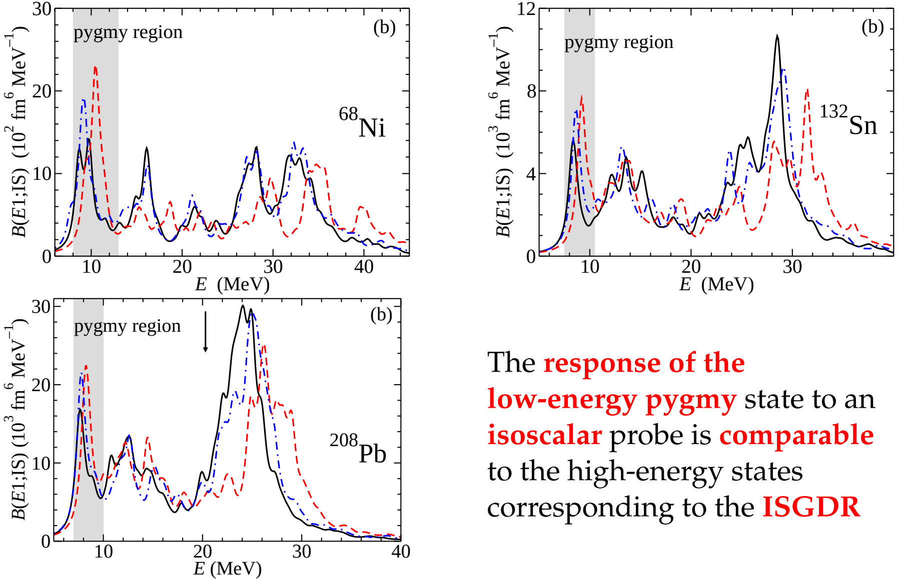
- coherent in the **IS** channel,
- less coherent in the **IV** channel.

Single particle units: qualitative indications



If different p-h states are contributing coherently to the PDS, B(E1) in single-particle units should be clearly larger than 1.

Dipole strength functions (IS)



The **response of the low-energy pygmy** state to an **isoscalar** probe is **comparable** to the high-energy states corresponding to the **ISGDR**

Conclusions:

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

1. The IV (and IS) dipole response show a **low-energy peak** in the strength function **for all studied nuclei and models**.
2. Such an IV **peak** (and also IS) **increases** in magnitude with increasing values of L [in agreement with other works].
3. The **collectivity** associated with the RPA states giving rise to the PDS **show up depending on** the nature of the **probe** used for exciting the nucleus: **there is systematically more collectivity in the IS than in the IV transitions**.
4. The low-energy **IV** and **IS** responses are basically due to the **outermost neutrons**.
5. The **isoscalarity** displayed by the RPA states giving rise to the PDS **may probe isoscalar properties**.

Conclusions:

Therefore,

- **IS probes interacting with the surface of the nucleus** seem to be more **suitable** for the study of the **low-energy dipole response** in nuclei far from the stability valley.
- The properties of **the PDS** may display an **involved correlation** with the parameters of the **nuclear EoS** that it is **not clear enough yet**
- This **puzzle** may be solved by performing **more studies on neutron-rich systems**
- For that, we miss some **systematic scattering experiments** (in inverse kinematics) that can **excite predominantly IS states** like (α,α') or (^{16}O,^{16}O$'$)
  [See next talk from Prof. Lanza]

I would like to kindly thank my collaborators:

Giacomo Pozzi, Marco Brenna, Kazhuito Mizuyama and Gianluca Colò

Thank you for your attention!