Pygmy Dipole Resonances: a short overview

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DIPARTIMENTO DI
FISICA E
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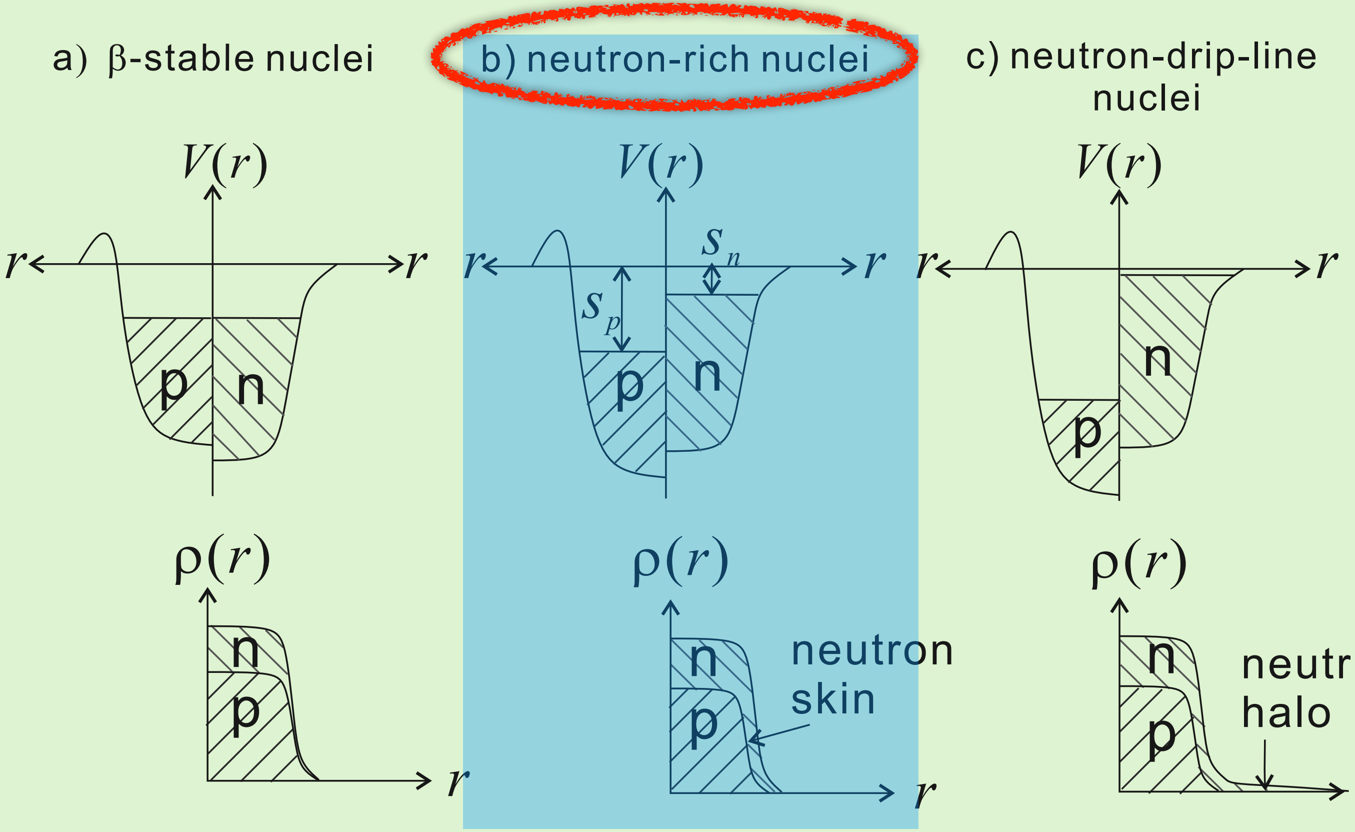
"ETTORE MAJORANA"

T.Aumann and T. Nakamura

Phys. Scr. **T152** (2013) 014012

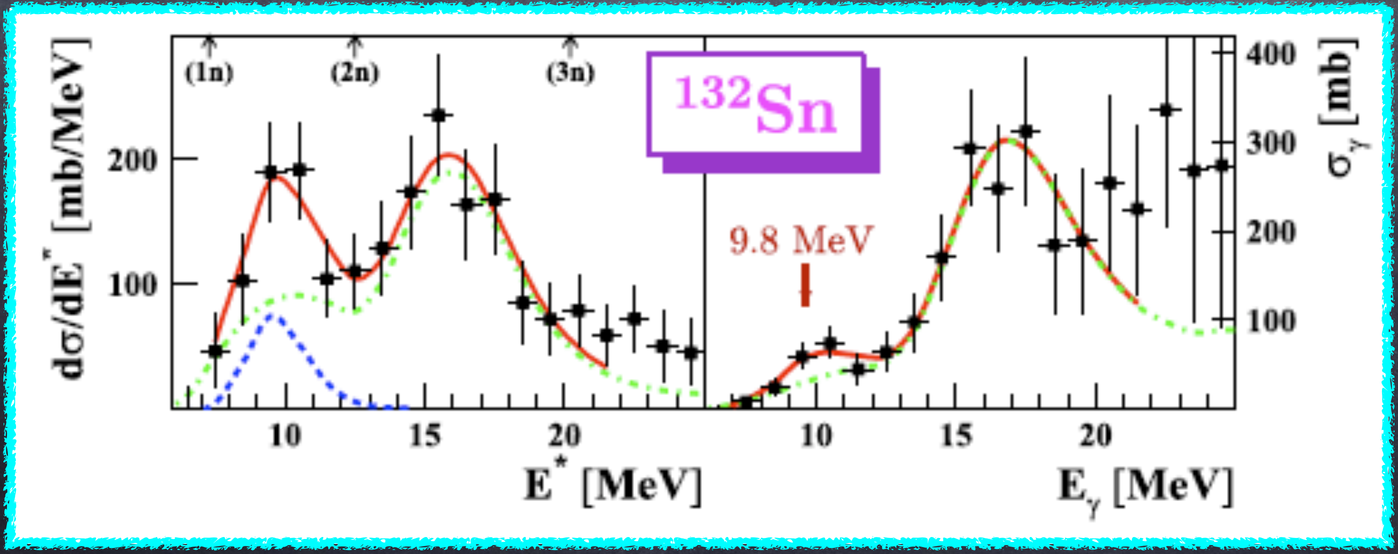


The Pygmy Dipole Resonances (PDR) are dipole states located at much lower energy than the GDR peak.

Called "pygmy" because their strength are much smaller than GDR.
They exhaust only few per cent of the EWSR.

They are present in all the nuclei with neutron excess.
Therefore, more evident in nuclei far from the stability line

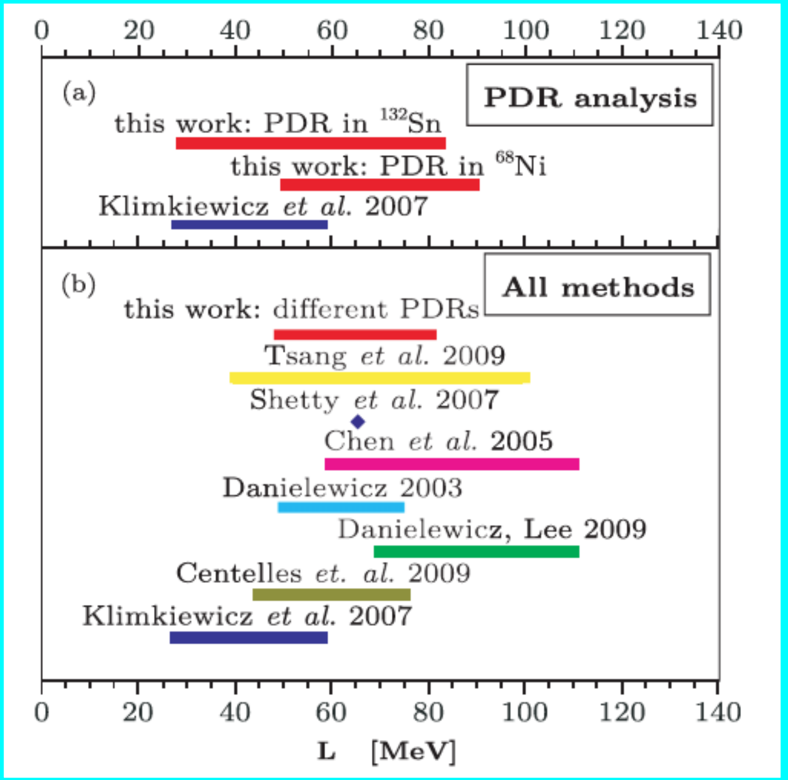
$^{132}Sn + ^{208}Pb$ @ 500 MeV/u
P.Adrich et al., PRL 95 (2005) 132501



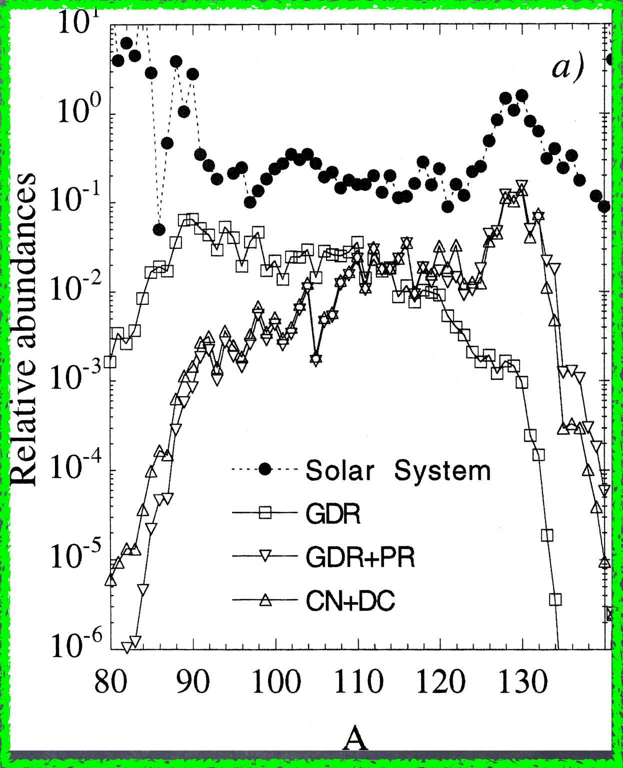
There exist a relationship between the PDR strength and the energy symmetry parameter L of the EoS.

Carbone et al., PRC 81 (2010) 041301(R)

Hartree-Fock + RPA (RHB) and relativistic mean field plus relativistic RQRPA calculations using several Skyrme interactions and effective Lagrangians



The presence of the PDR has consequences on rapid neutron capture process



A strong effect on the formation of the heavy element during the r-process.

S. Goriely,

PLB 436 (1998) 10

Review papers

- N. Paar, D. Vretenar, E. Khan and G. Colo`, Rep. Prog. Phys. 70, 691 (2007).
- T. Aumann and T. Nakamura, Phys. Scr. T152, 014012 (2013).
- D. Savran, T. Aumann and A. Zilges, Prog. Part. Nucl. Phys. 70, 210 (2013).
- A. Bracco, F. C. L. Crespi and E. G. Lanza, Eur. Phys. J. A 51, 99 (2015).
- A. Bracco, E. G. Lanza and A. Tamii, Prog. Part. Nucl. Phys. 106 (2019) 360.
- E. G. Lanza, L. Pellegri, A. Vitturi and M. V. Andrés, Prog. Part. Nuc. Phys. to be published

From the theoretical point of view they are studied with

Macroscopic model

- Incompressible three fluid model: Steinwedel-Jensen
- Inert core oscillating against a neutron skin: Goldhaber-Teller

Microscopic model

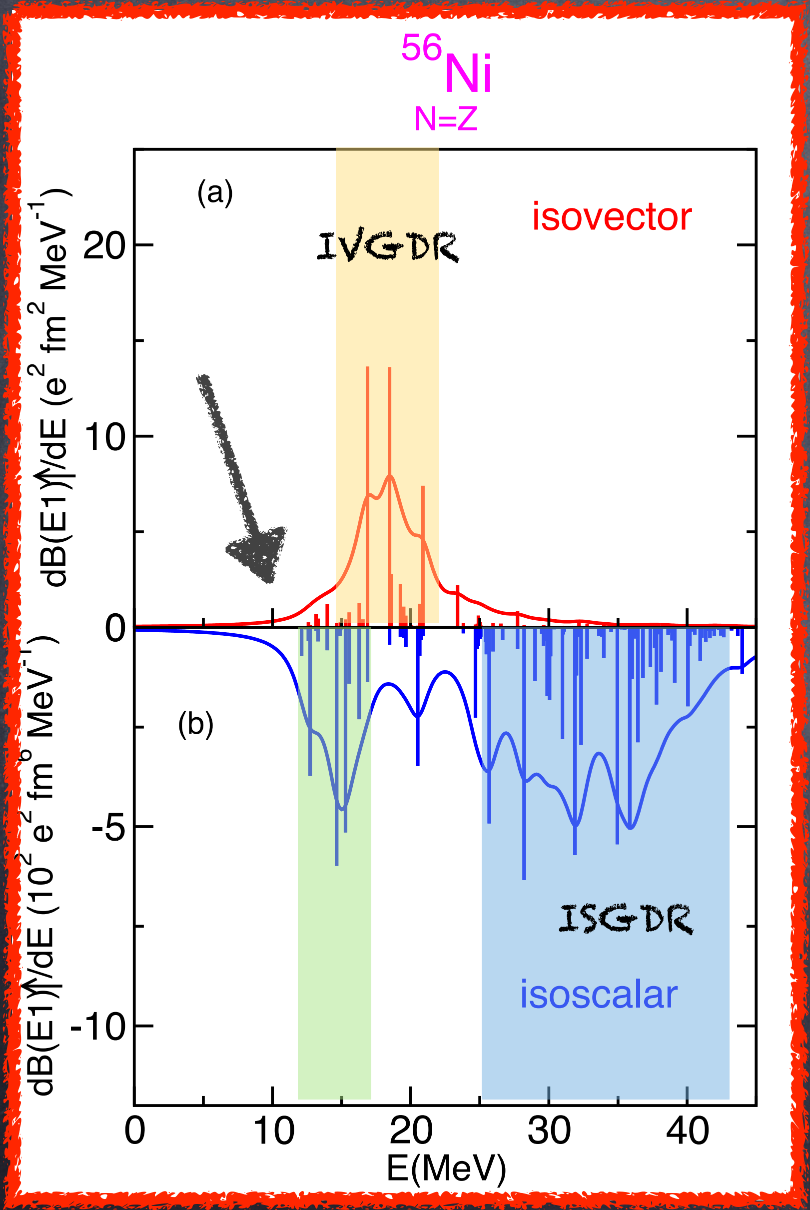
- HF + RPA with Skyrme interaction
- Relativistic RPA and relativistic QRPA
- HFB + QRPA with Skyrme or Gogny interactions
- Second RPA (SRPA) and Subtracted SRPA (SSRPA)
- Quasi particle phonon model (QPM)
- Relativistic Quasi-particle Time Blocking Approximation (RQTBA)
- ……

coupling to more complex configurations

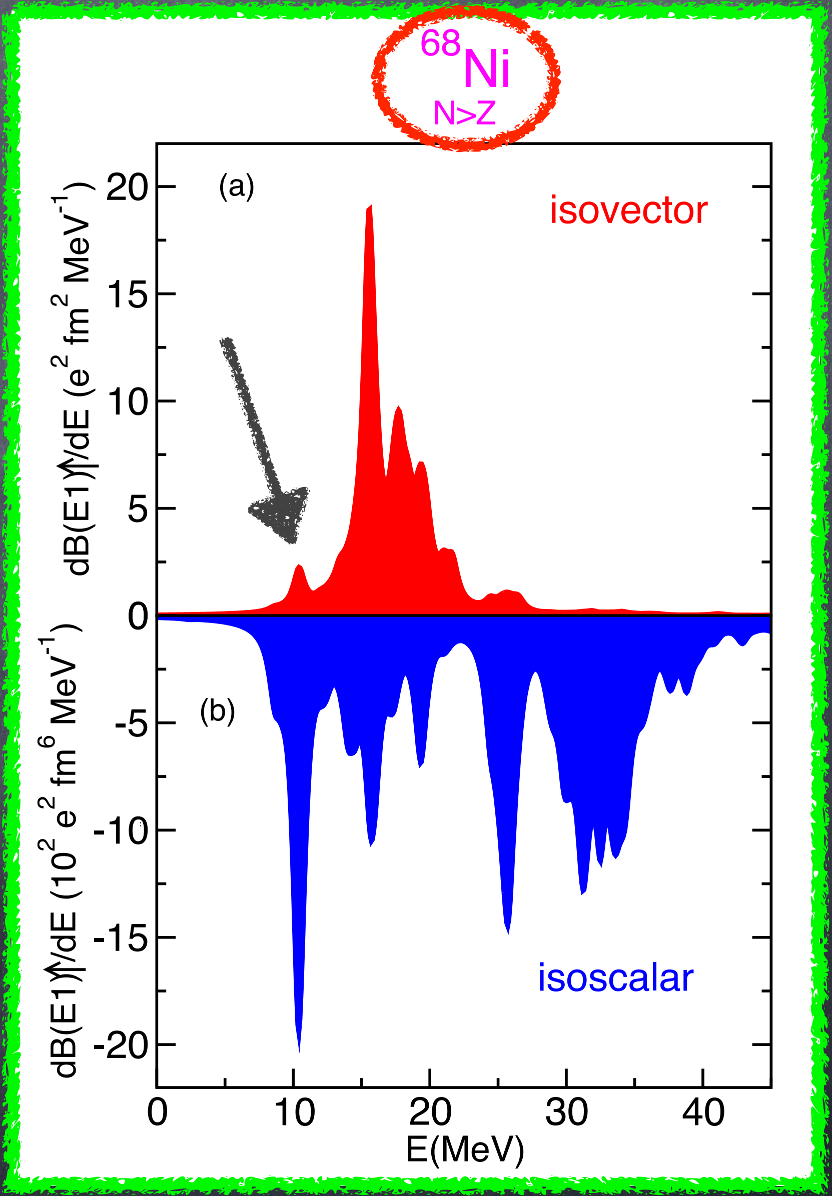
RPA calculations with SGII interaction

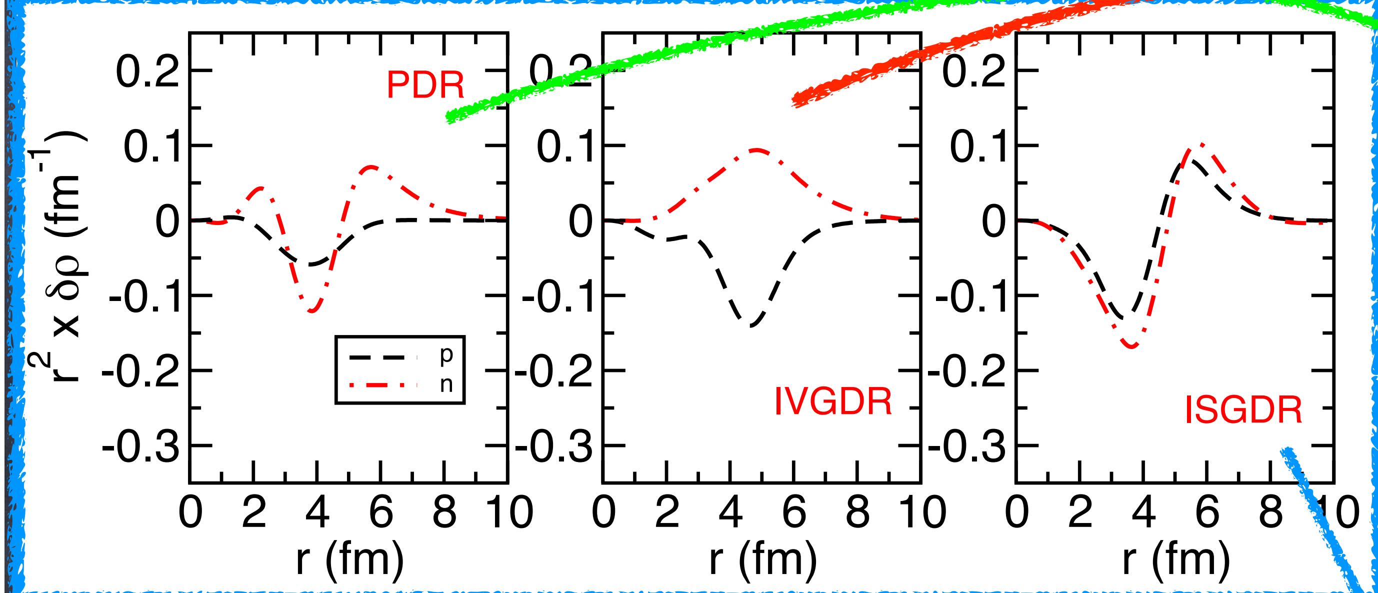
$$O_{1M}^{(IV)} = 2\frac{Z}{A}\sum_{n=1}^{N} r_n Y_{1M}(\hat{r}_n) - 2\frac{N}{A}\sum_{p=1}^{Z} r_p Y_{1M}(\hat{r}_p)$$

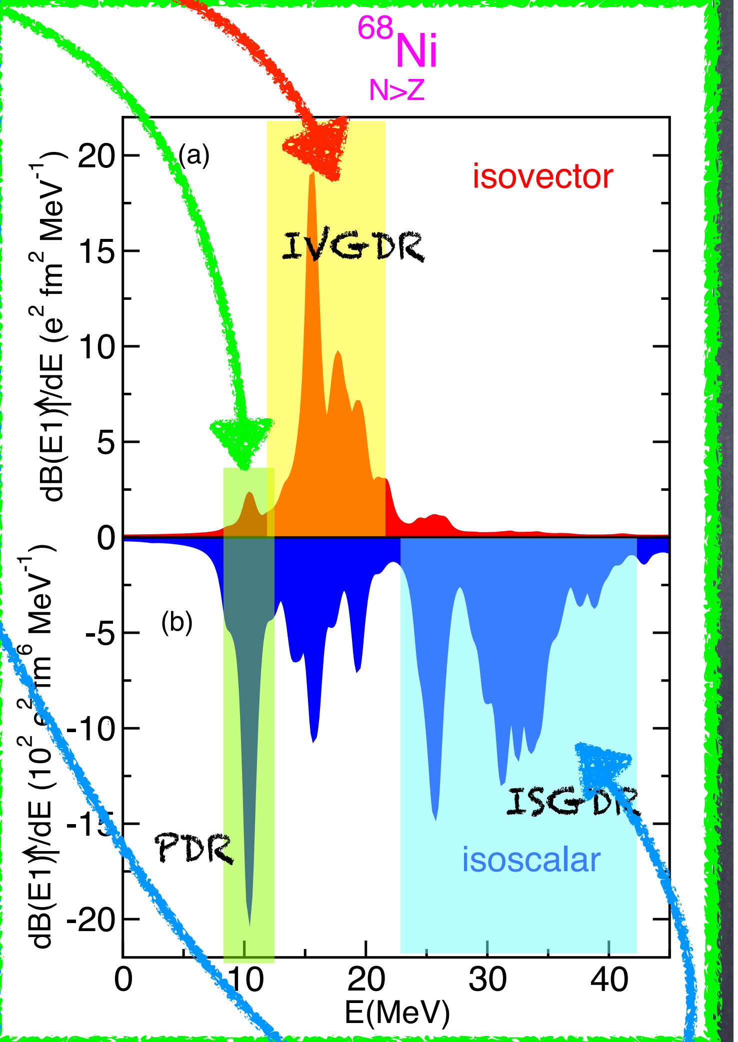
$$O_{1M}^{(IS)} = \sum_{i=1}^{A}(r_i^3 - \frac{5}{3} < r^2 > r_i) Y_{1M}(\hat{r}_i)$$



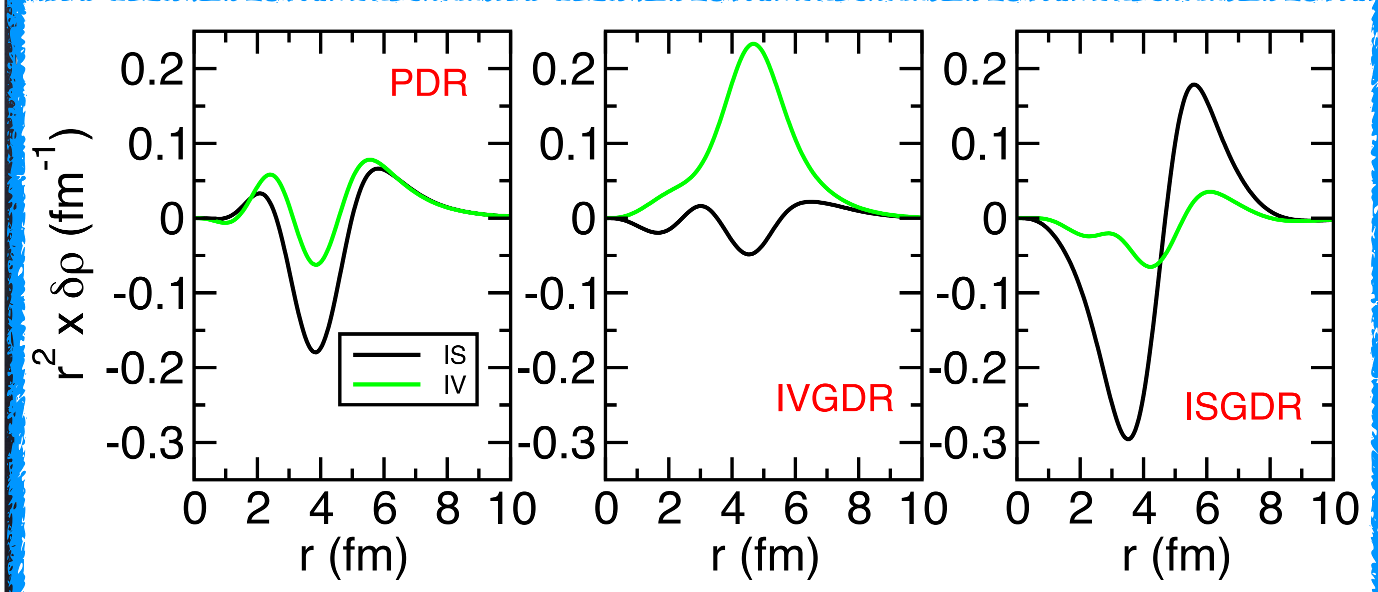
Dipole states





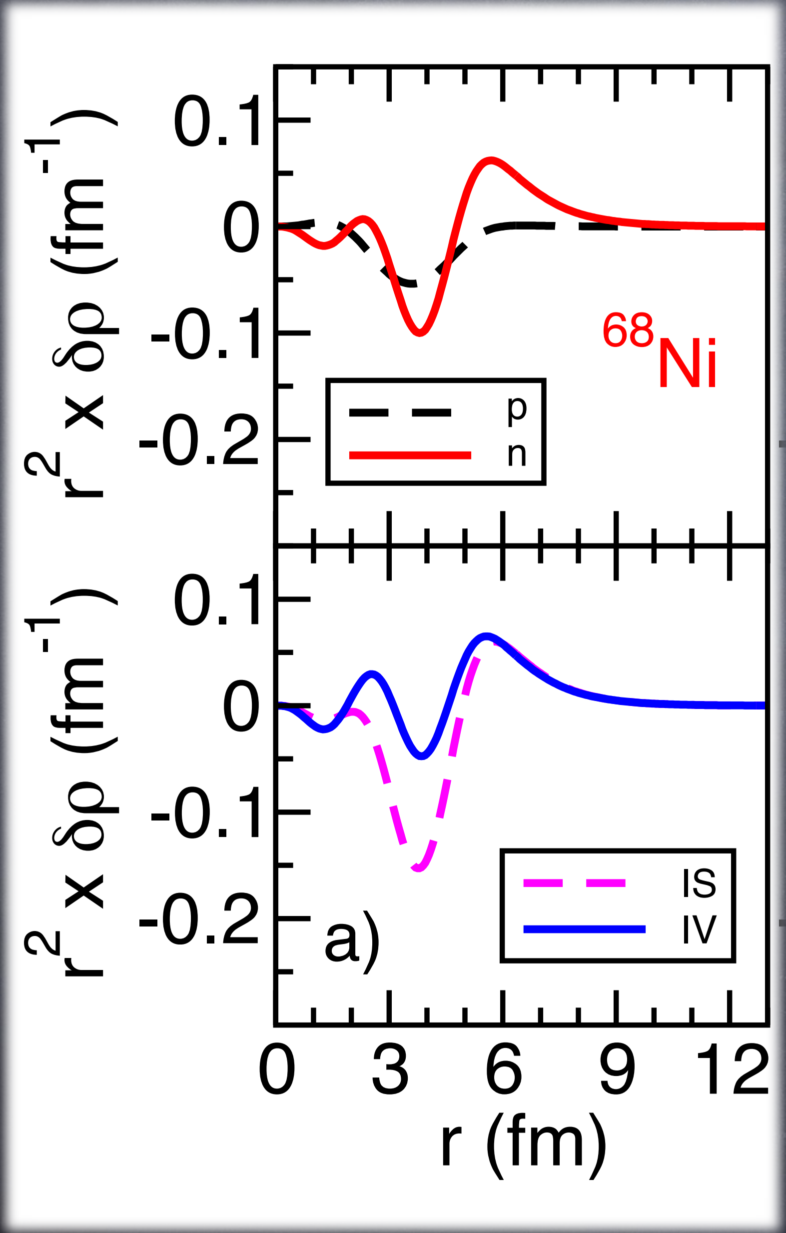


$$\delta\rho^{\nu} = \frac{1}{\sqrt{4\pi}}\sum_{ph}(-)^{j_p+l_p+\frac{1}{2}}\frac{\hat{j}_p\hat{j}_h}{\hat{\lambda}} < j_h\,\tfrac{1}{2}\,j_p\,-\tfrac{1}{2}\,|\,\lambda 0 > \delta(\lambda+l_p+l_h,even) \cdot\left[X^{\nu}_{ph}-Y^{\nu}_{ph}\right]R_{l_p j_p}(r)R_{l_h j_h}(r)$$



This is a $3\hbar\omega$ nuclear transitions generated by the second order $\Delta L=1$ transition operator and it can be seen as a compressional mode.

$$\delta\rho^{\nu}=\frac{1}{\sqrt{4\pi}}\sum_{ph}(-)^{j_p+l_p+\frac{1}{2}}\frac{\hat{j}_p\hat{j}_h}{\hat{\lambda}}<j_h\,\tfrac{1}{2}\,j_p\,-\tfrac{1}{2}\,|\,\lambda\,0>\delta(\lambda+l_p+l_h,even)$$
$$\cdot\left[X^{\nu}_{ph}-Y^{\nu}_{ph}\right]R_{l_p j_p}(r)\,R_{l_h j_h}(r)$$



Neutron and proton transition densities are in phase inside the nucleus; at the surface only the neutron part survive.

"Theoretical definition" of the PDR

The strong mixing of isoscalar and isovector character at the nuclear surface allows the experimental study with both isoscalar and isovector probes.

Experimentally they are studied with

Isovector probes

- Relativistic Coulomb excitation at GSI
- Nuclear resonance fluorescence (NRF) technique: (γ, γ') at Darmstadt
- Coulomb excitation by proton scattering: (p, p') in Osaka and iThemba LABS

Isoscalar probes

- $(\alpha, \alpha' \gamma)$ At KVI
- $(^{17}O, ^{17}O' \gamma)$ on various target ^{208}Pb, ^{90}Zr, ^{140}Ce at Legnaro lab (LNL-INFN)
- $(^{68}Ni, ^{68}Ni' \gamma)$ on ^{12}C at INFN-LNS, Catania

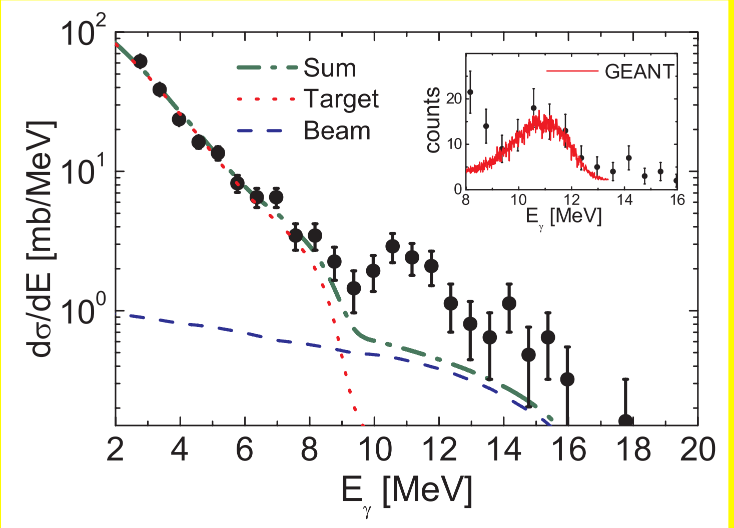
Experimental data
isovector probe

ABOVE NEUTRON SEPARATION THRESHOLD

exotic nuclei

- using the FRS-LAND setup at GSI
- using the RISING setup at GSI (for ^{68}Ni) →

P.Adrich et al. PRL 95 (2005) 132501
O.Wieland et al. PRL 102 (2009) 092502

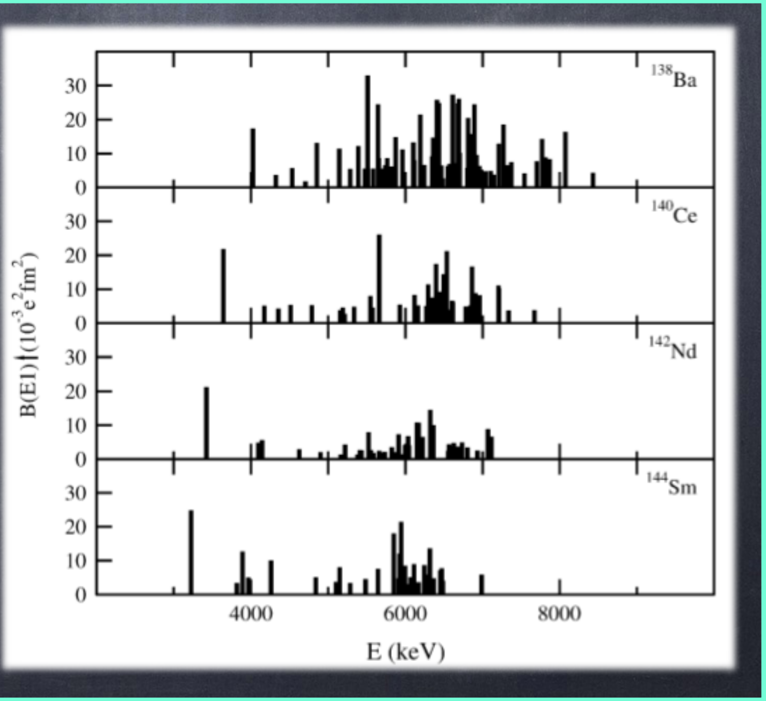


BELOW NEUTRON SEPARATION THRESHOLD

stable nuclei

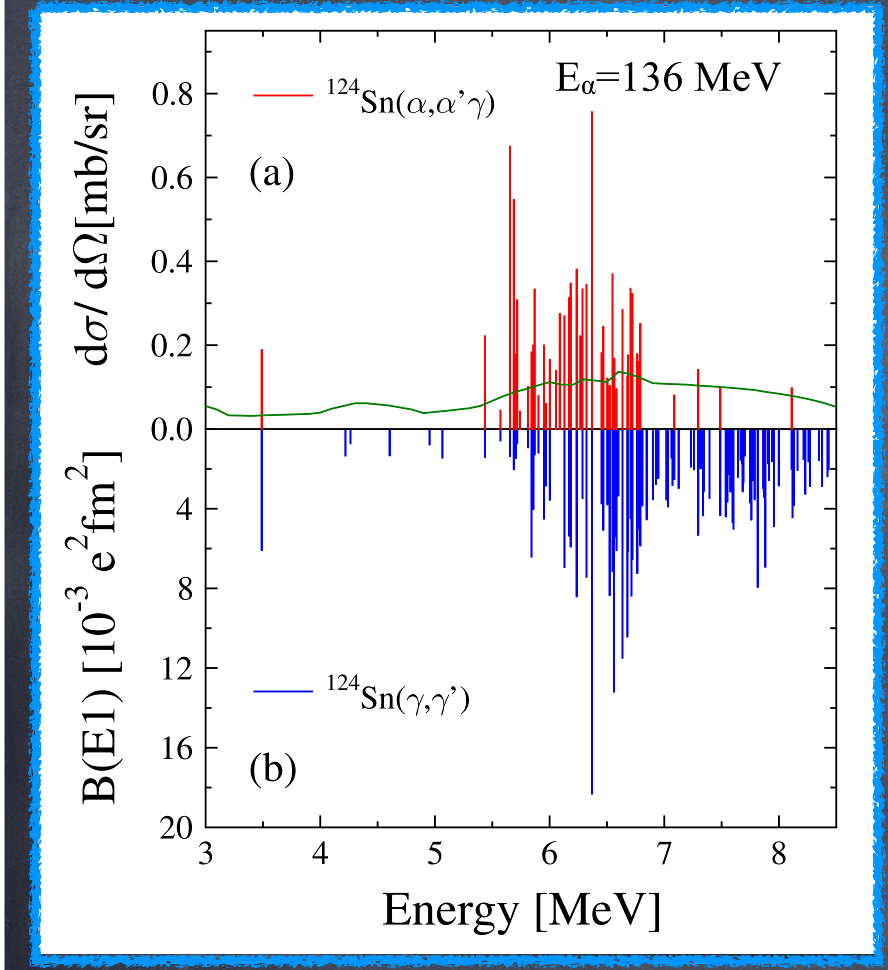
- with (γ,γ') studies (Darmstadt University) →

D.Savran et al. PRL 100 (2008) 232501
J.Endres et al. PRC 80 (2009) 034302



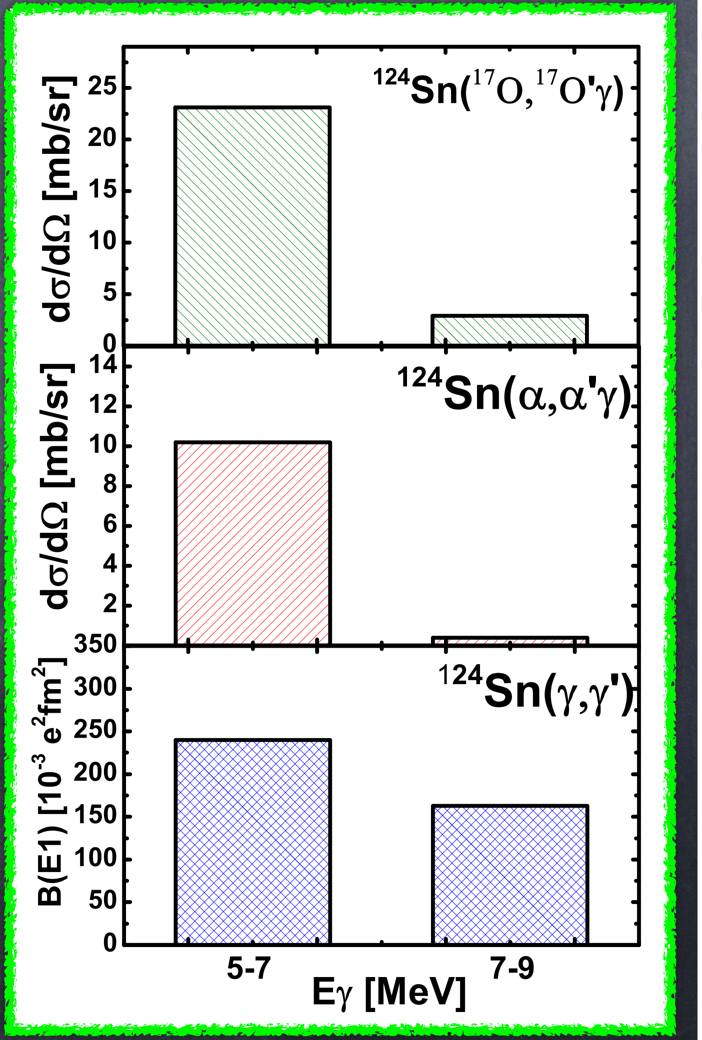
Experimental data isoscalar probe

(below neutron emission threshold)



The use of isoscalar probes has brought to light a new feature of this new mode

The splitting of the PDR



D. Savran et al., PRL 97 (2006) 172502

J. Endres et al., PRL 80(2009) 034302

J. Endres et al., PRL 105 (2010) 212503

F.C.L. Crespi et al., PRL 113 (2014) 012501

L. Pellegri et al., PLB 738 (2014) 519

F.C.L. Crespi et al., PRC 91 (2015) 024323

Some Open Problems:

1. Are the dipole resonances due to collective or single-particle excitations?
2. Spherical and Deformed nuclei
3. What is the interplay between isovector and isoscalar contributions?

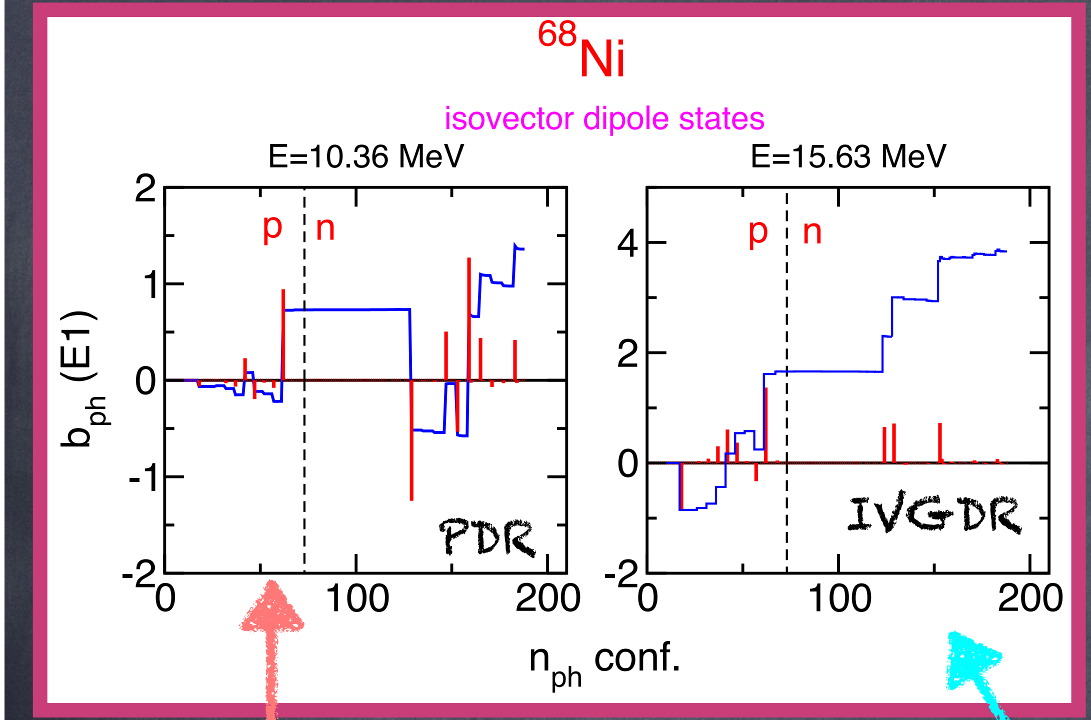
Are the Pygmy Dipole Resonances due to collective or single-particle excitations?

In a macroscopic models the collectivity is implicitly assumed in the models.

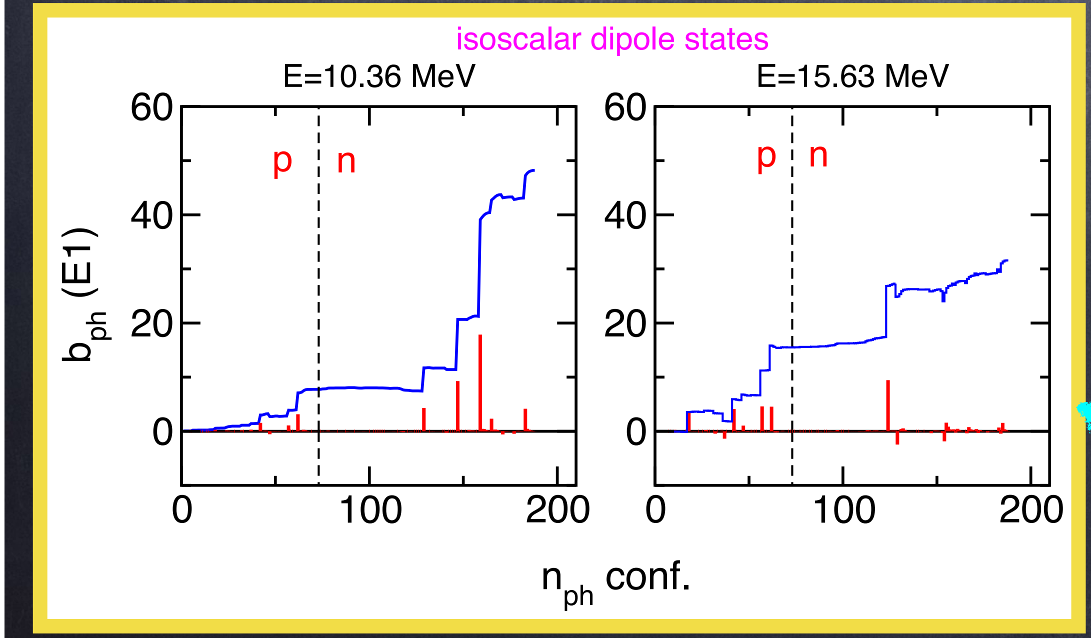
For the microscopic model (for instance in RPA) one has to investigate the number of p-h configurations and their coherence property

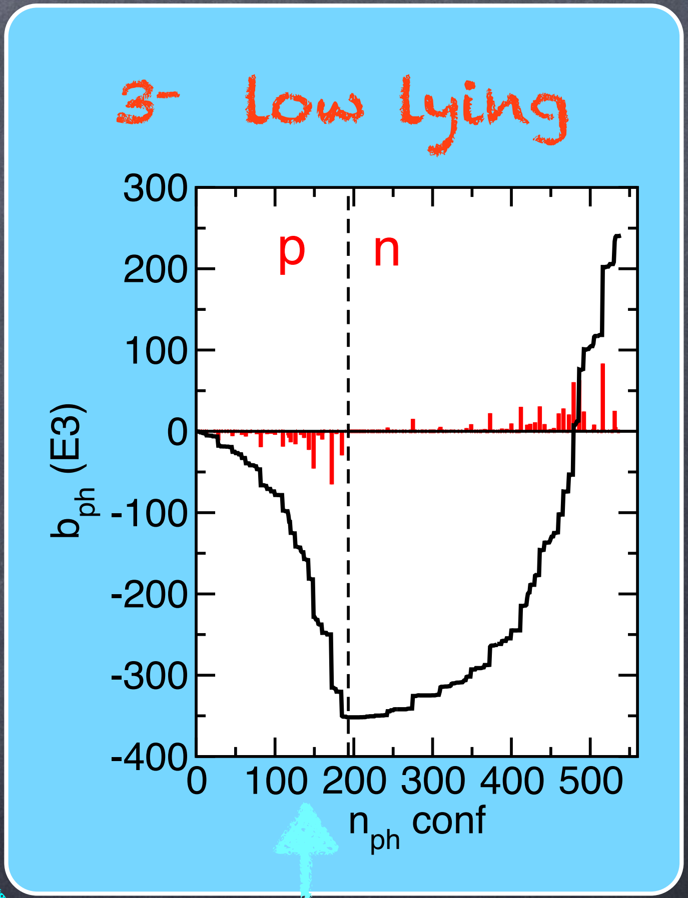
Collectivity means also coherence.

$$B(E\lambda;0\rightarrow\nu)=\left|\sum_{ph} b_{ph}(E\lambda)\right|^{2}=\left|\sum_{ph}\left(X^{\nu}_{ph}-Y^{\nu}_{ph}\right)T^{\lambda}_{ph}\right|^{2}$$



Non Collective





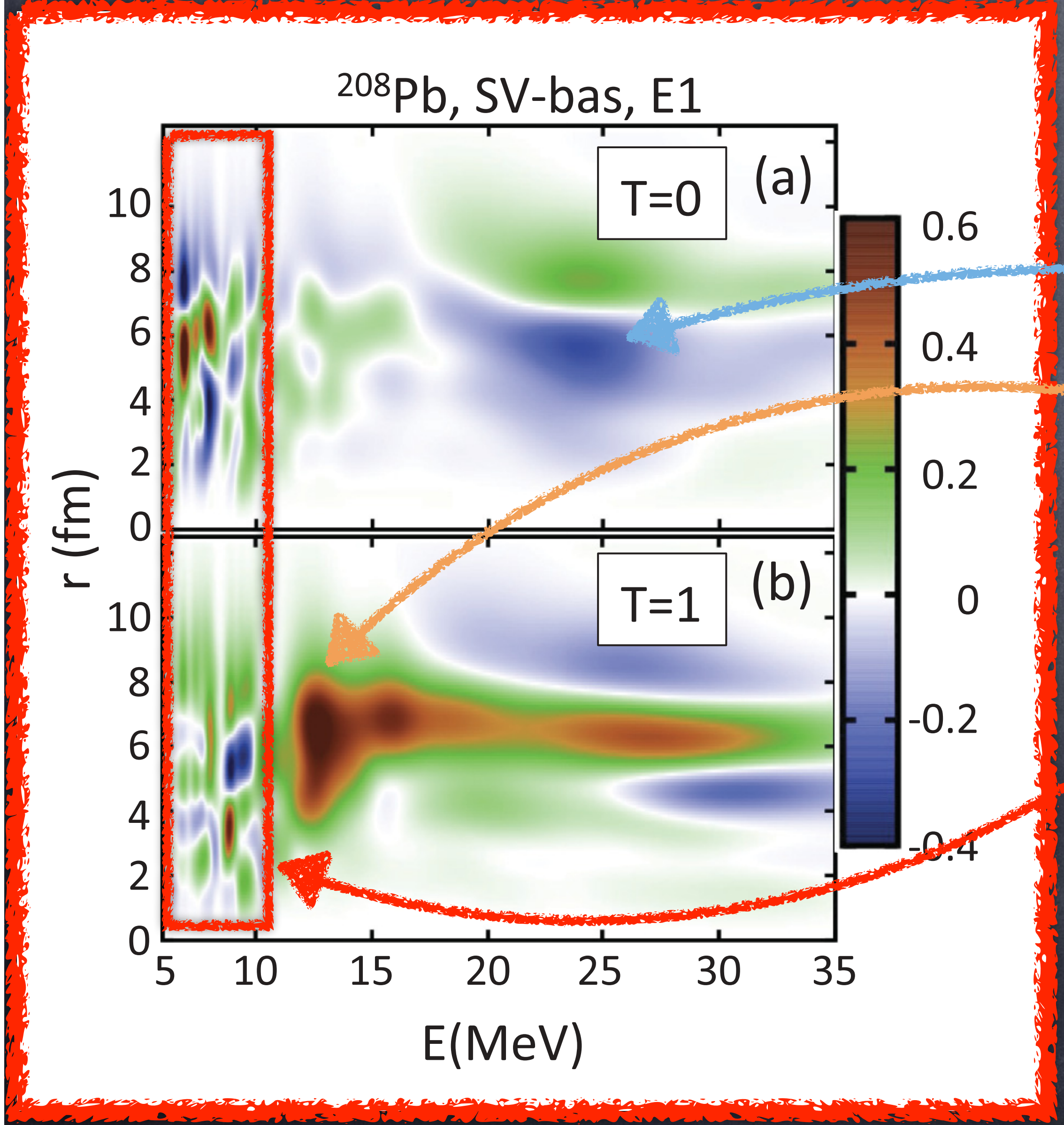
Collective

P.-G. Reinhard and W. Nazarewicz, PRC 87 (2013) 014324

Correlation analysis based on data analysis methods

$$\rho^{(T)}(E,r) = 4\pi \sum_{\nu} \int_0^{\infty} dq\, q^2\, j_1(qr)\, F_\nu^{(T)}(q) \times G_\Gamma(E-E_\nu)$$

Energy-averaged radial transition densities



$F_\nu^{(T)}(q)$ Dipole transition form factor

$G_\Gamma(E-E_\nu)$ Gaussian folding function

IVGDR collective

ISGDR collective

A complex multinodal behaviour in both isospin channels and a strong state dependence suggest a <u>weak collectivity</u>

Collectivity: is it only a theoretical problem?
What about the experimental data?

Is there a way to look at it in a clear way?

What has to be measured to determine the degree of collectivity of a state?

One way could be to determine whether they are single particle level.

M. Weinart et al. PRL 127 (2021) 242501

$^{119}\mathrm{Sn}\ (d, p'\ \gamma)\ ^{120}\mathrm{Sn}$ at 8.5 MeV

SONIC@HORUS at Cologne University

Results analysed within an EDF plus Quasiparticle Phonon Model

Two dominant configurations were identify to contribute mainly to the states between 6 and 7 MeV while for the high-energy part is predicted to have more complicated 2ph+3ph configurations.

Proposed experiment by Luna Pellegri

Transfer reactions to populate the PDR in $^{96}\mathrm{Mo}$

$^{95}\mathrm{Mo}(d,p)^{96}\mathrm{Mo}^*$ at $E_d = 10$ MeV,

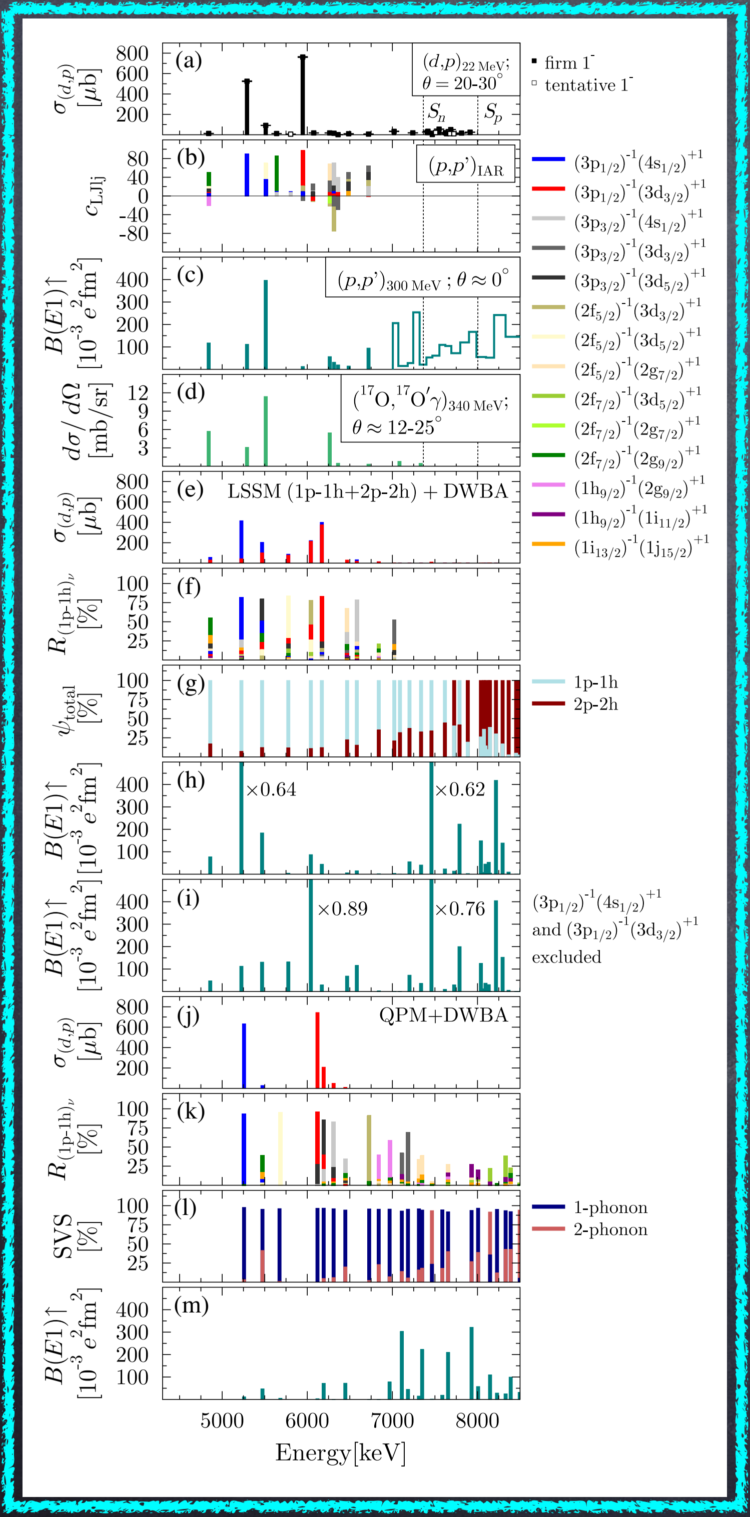
$^{97}\mathrm{Mo}(p,d)^{96}\mathrm{Mo}^*$ at $E_p = 26$ MeV

Beam provided by the Tandem at and the reaction products measured by the MAGNEX spectrometer. at INFN-LNS, Catania

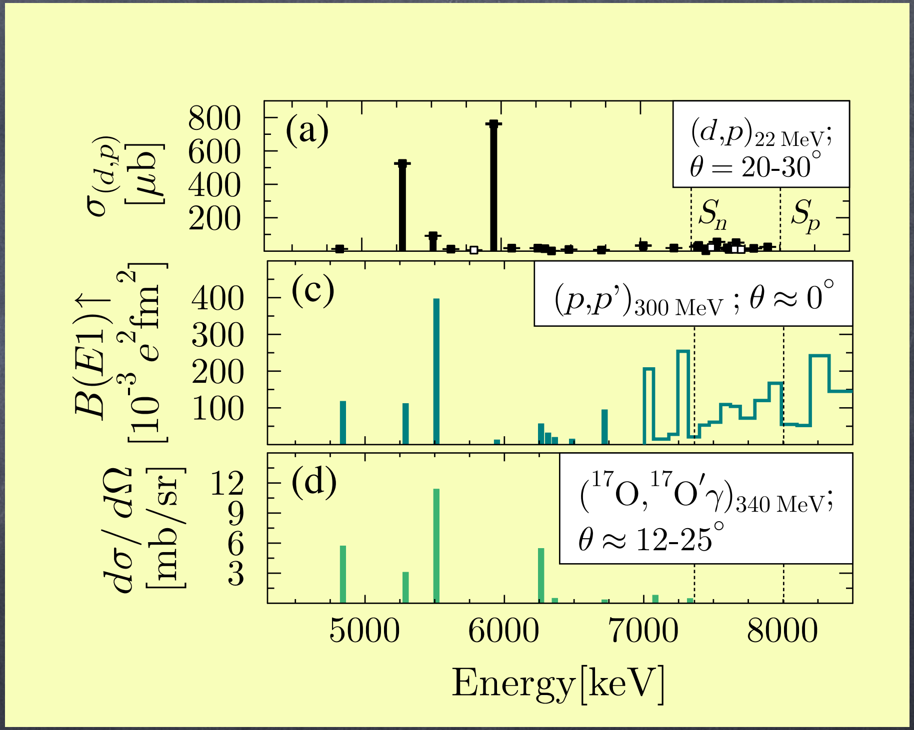
It will be compared with
$^{96}\mathrm{Mo}(\alpha, \alpha'\gamma)^{96}\mathrm{Mo}^*$ at iThemba.

M. Spieker et al. PRL 125 (2020) 102503

(d,p) reaction on ^{207}Pb at 22 MeV



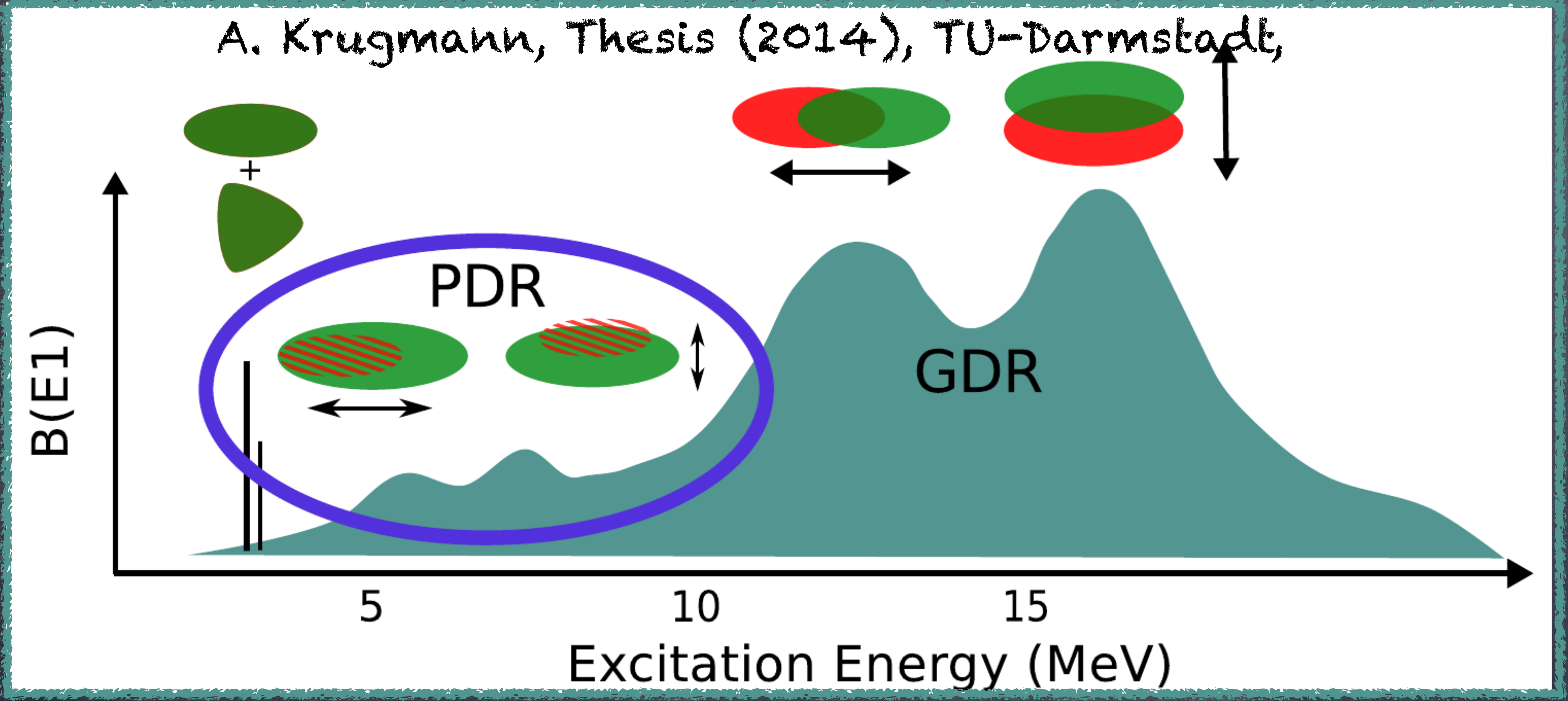
Large Scale Shell Model (LSSM) and Quasiparticle Phonon Coupling calculations have been performed



Most of the 1^- states cannot be considered as single 1p-1h states, since many 1p-1h states contribute to their wave function.

The different response to isoscalar and isovector probes is important also in the study of the pygmy dipole states in the deformed nuclei.

One may wonder whether we can see a separation of the pygmy peak as it occurs in the case of the GDR one.


A. Krugmann, Thesis (2014), TU-Darmstadt,

Bohr and Mottelson book

Splitting of the GDR

$$\frac{E_1^{\perp} - E_1^{\parallel}}{E_1} = \frac{R^{\parallel} - R^{\perp}}{R_0} = 0.95\,\beta$$

Microscopic description of deformed nuclei

Self-consistent HFB-QRPA to describe simultaneously the effects of nuclear deformation and pairing correlations:

* S. Péru and H. Goutte, Phys. Rev. C 77, 044313 (2008)

with the D1S Gogny effective force

* K. Yoshida and N. Van Giai, Phys. Rev. C 78, 064316 (2008)

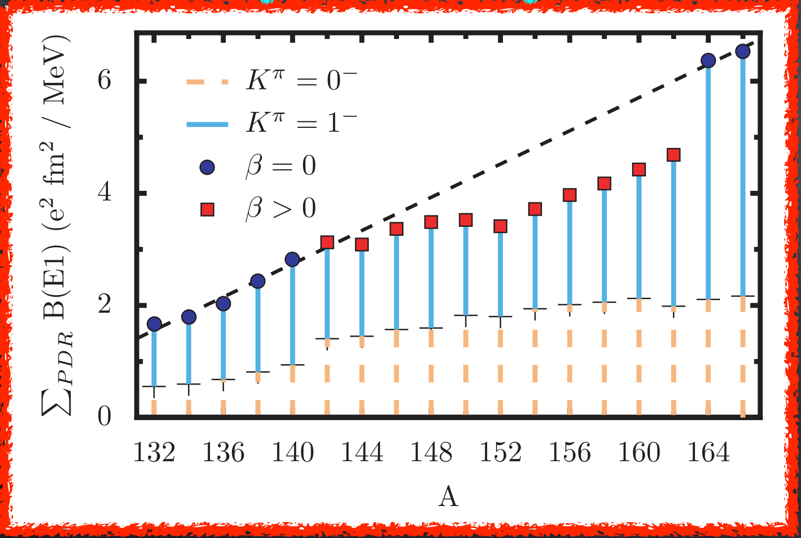
with Skyrme interaction

Microscopic description of PDR in deformed nuclei

D. Peña Arteaga, E. Khan and P. Ring,
PRC 79, 034311 (2009).

Systematic study of the PDR for several tin isotopes within a relativistic Hartree-Bogoliubov (RHB) mean field plus a relativistic QRPA microscopic calculations.

They conclude that the deformation quenches the isovector dipole response in the low-lying energy region.



Neutron rich deformed nuclei may not be good candidates for the study of PDR states

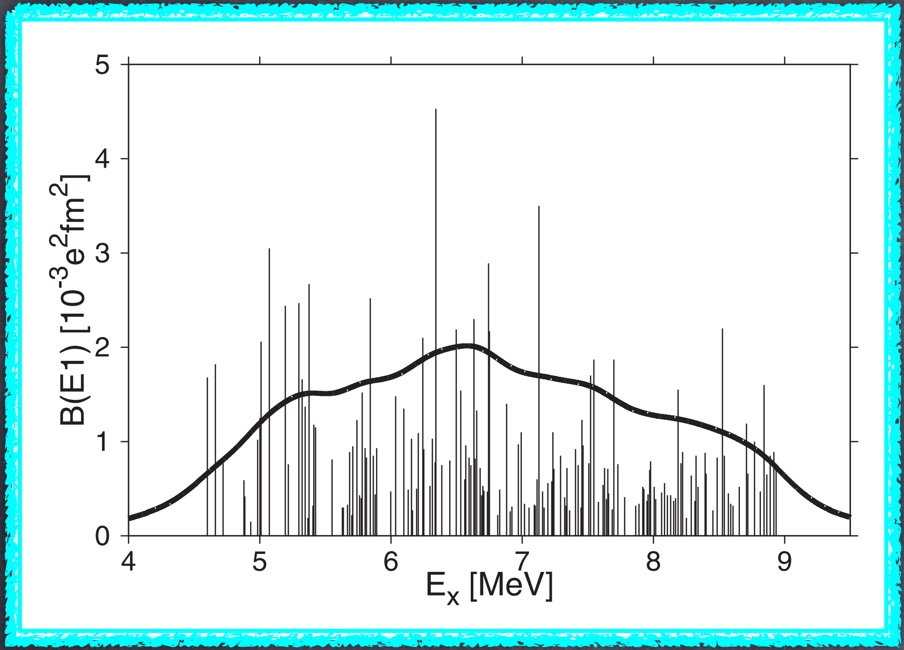
K. Yoshida and T. Nakatsukasa,
PRC 83, 021304(R) (2011).

On the contrary, calculations performed within an HFB plus QRPA with Skyrme interactions for Nd and Sm isotopes, show an enhancement of the summed low lying dipole strength of about five times larger than those corresponding to spherical nuclei.

The two calculations use:

- different treatments for the pairing.
- Different use of the treatment of continuum and weakly bound orbitals.
- The calculations of Peña et al. are fully self-consistent, and they do not have the contamination of the spurious center-of-mass motion.

experimental work for
pygmy dipole resonances in deformed nuclei

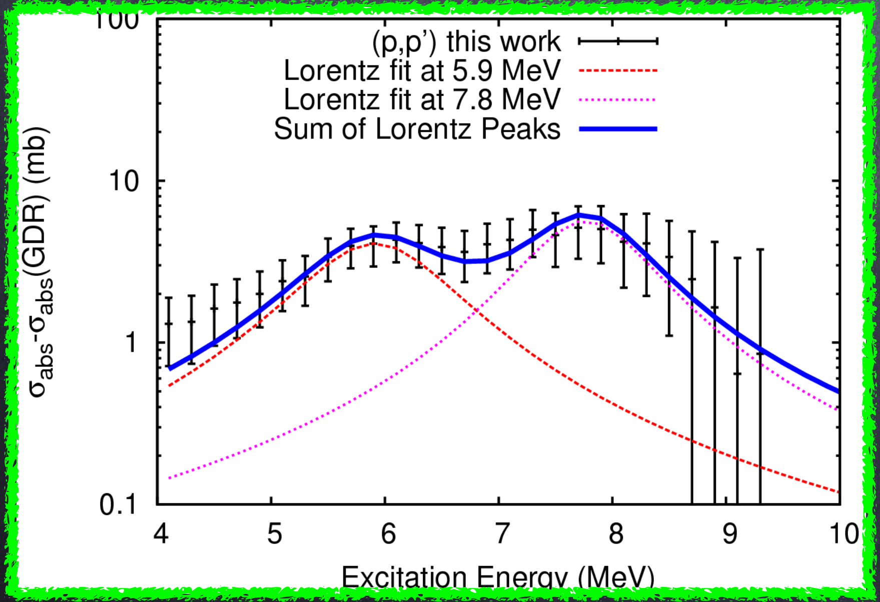


P. M. Goddard et al.,
PRC 88, 064308 (2013).

Polarised ($\vec{\gamma}$, γ') on ^{76}Se (relatively small neutron excess)

Observed many 1^- states between 4 and 9 MeV.

A pronounced splitting, as seen in the GDR, is not evident



A. Krugmann, Thesis (2014),
TU-Darmstadt

Experiment done at RNCP, Osaka, with polarized proton on a deformed nucleus ^{154}Sm at very forward angles

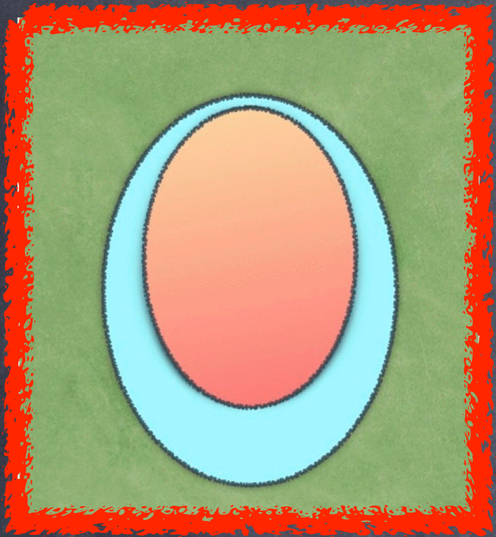
An experiment to measure the PDR in deformed nucleus with isoscalar probes has been performed at the iThemba LABS

Spokeperson: Luna Pellegri

Study of the low-lying 1^- states in the deformed ^{154}Sm nucleus via inelastic scattering of α particles at 120 MeV.

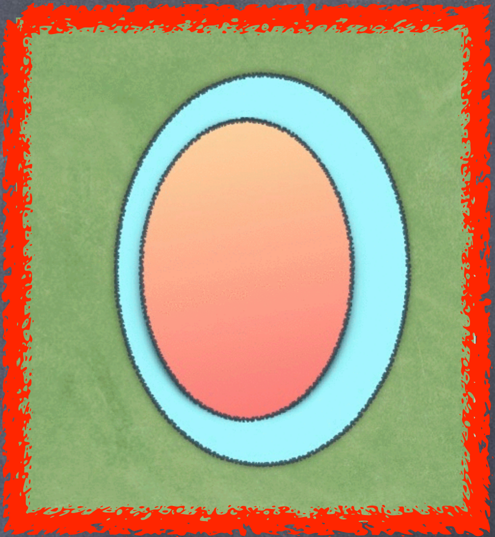
Pygmy for deformed nuclei

K^π=0-



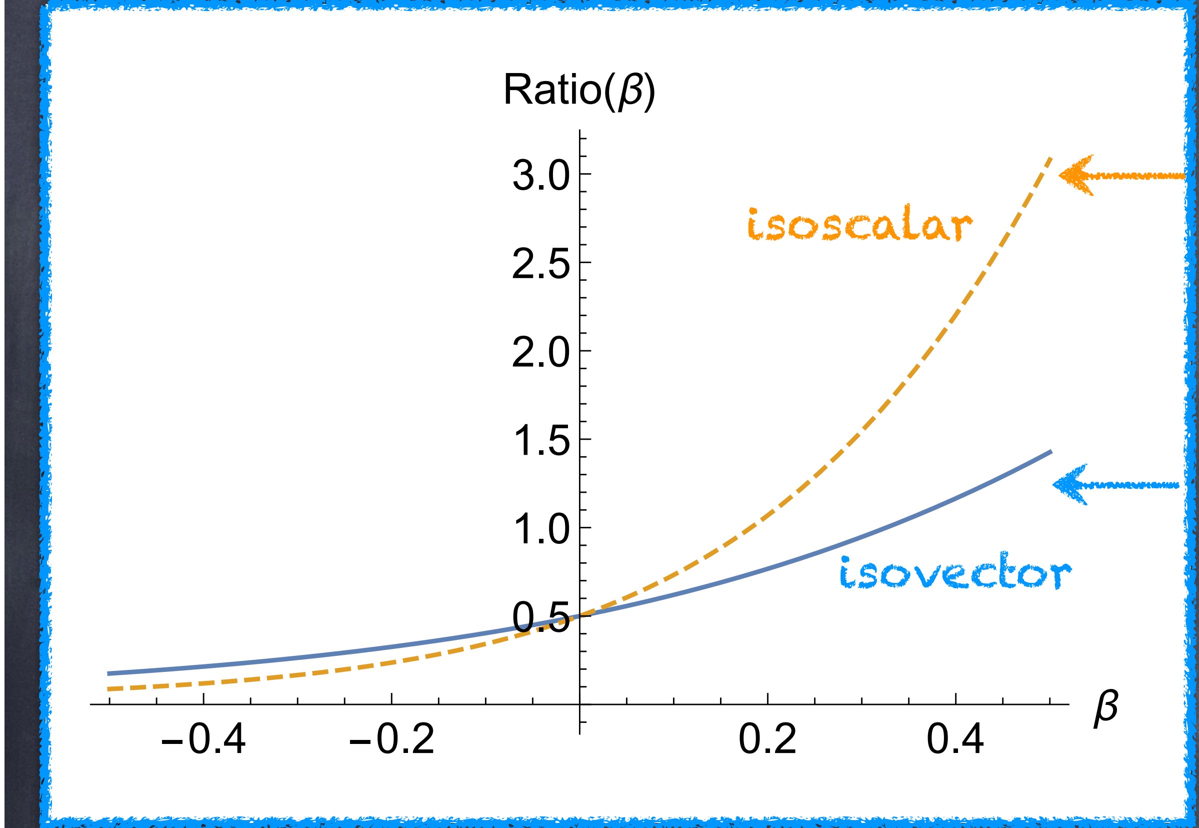
The "intrinsic" isovector transition densities to the intrinsic K^π=0$^-$ and K^π=1$^-$ states will be given within the Goldhaber-Teller model

K^π=1-



$$\delta\rho_p^{K^\pi}(r,\theta,\phi)=\delta_1\big[-\frac{2N^v}{A}\frac{d}{dr}\rho_p(r,\theta,\phi)\big]Y_{1,K}(\theta,\phi)$$

$$\delta\rho_n^{K^\pi}(r,\theta,\phi)=\delta_1\big[-\frac{2N^v}{A}\frac{d}{dr}\rho_n^c(r,\theta,\phi)+\frac{2(Z+N^c)}{A}\frac{d}{dr}\rho_n^v(r,\theta,\phi)\big]Y_{1,K}(\theta,\phi)$$



$$D = \frac{B(E1)^{is}_{K=0^-}}{B(E1)^{is}_{K=1^-} + B(E1)^{is}_{K=-1^-}}$$

$$C = \frac{B(E1)^{iv}_{K=0^-}}{B(E1)^{iv}_{K=1^-} + B(E1)^{iv}_{K=-1^-}}$$

As far as the deformation increases the sharing between the two component is more favourable to the oscillation along the longer axis

The variation of the ratio for the isoscalar case is stronger

Summary

It is well established that the low-lying dipole states (the Pygmy Dipole Resonance) have a strong isoscalar component.

The use of an isoscalar probe is important for both spherical and deformed nuclei.

Open problems - like collectivity, isoscalar and isovector mixing, role of deformation - are a challenge for theoretical and experimental investigations.

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A. Vitturi - Dipartimento di Fisica, Università di Padova and INFN-Padova, Italy

E. G. L.- INFN-Sezione di Catania, Italy