Pygmy Dipole States in deformed nuclei

Studied via isoscalar and isovector probes

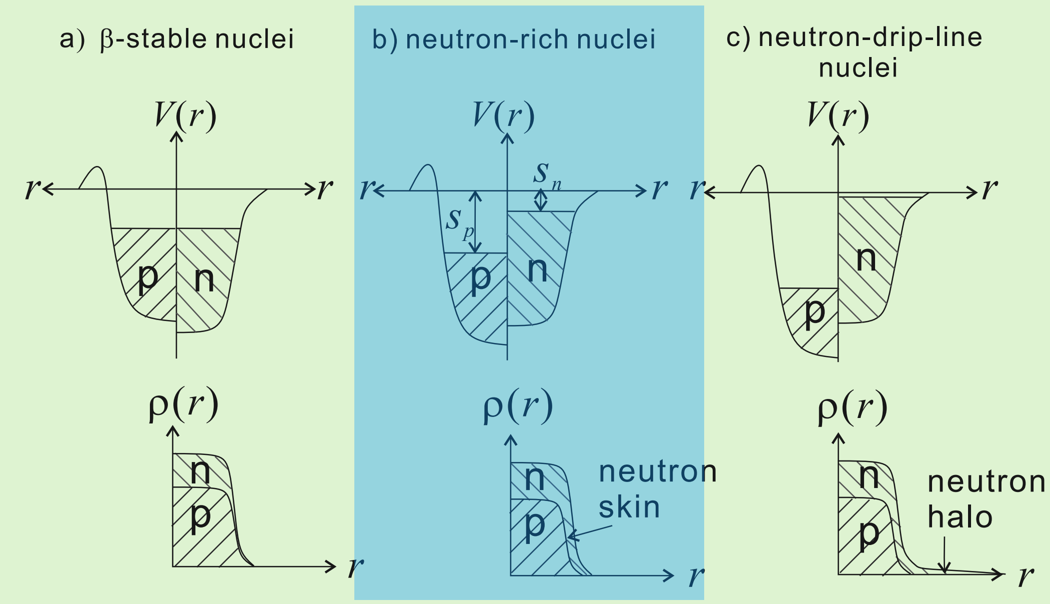


Figure 1. The change of the mean field potential (top) and density profiles (bottom) from β stable (a) to neutron-rich nuclei (b) and to much more neutron-rich nuclei near the neutron-drip line (c) is schematically shown. The upper panels indicate how the change of the ratio of proton/neutron numbers can induce a significant difference of Fermi energies between protons and neutrons as measured by $S_p - S_n$. Such a difference causes the formation of a thick neutron skin as in the bottom panel of (b). When S_n approaches zero, the neutron halo structure appears as a consequence of the quantum tunneling.

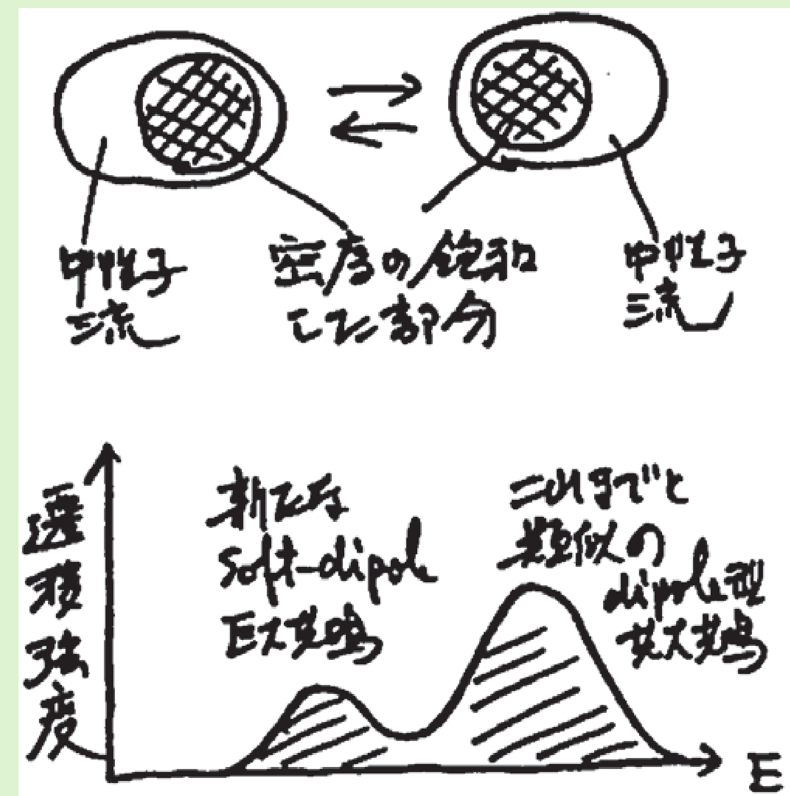


Figure 2. The upper panel shows the vibration of the 'neutron fluid' relative to the 'saturated core'. The bottom panel shows the transition probability as a function of excitation energy. The lower-energy bump corresponds to a 'new soft-dipole giant resonance', whereas the higher-energy bump corresponds to 'GDR analogous to the conventional one'. The figure is reprinted with kind permission from Ikeda [12].

Review papers

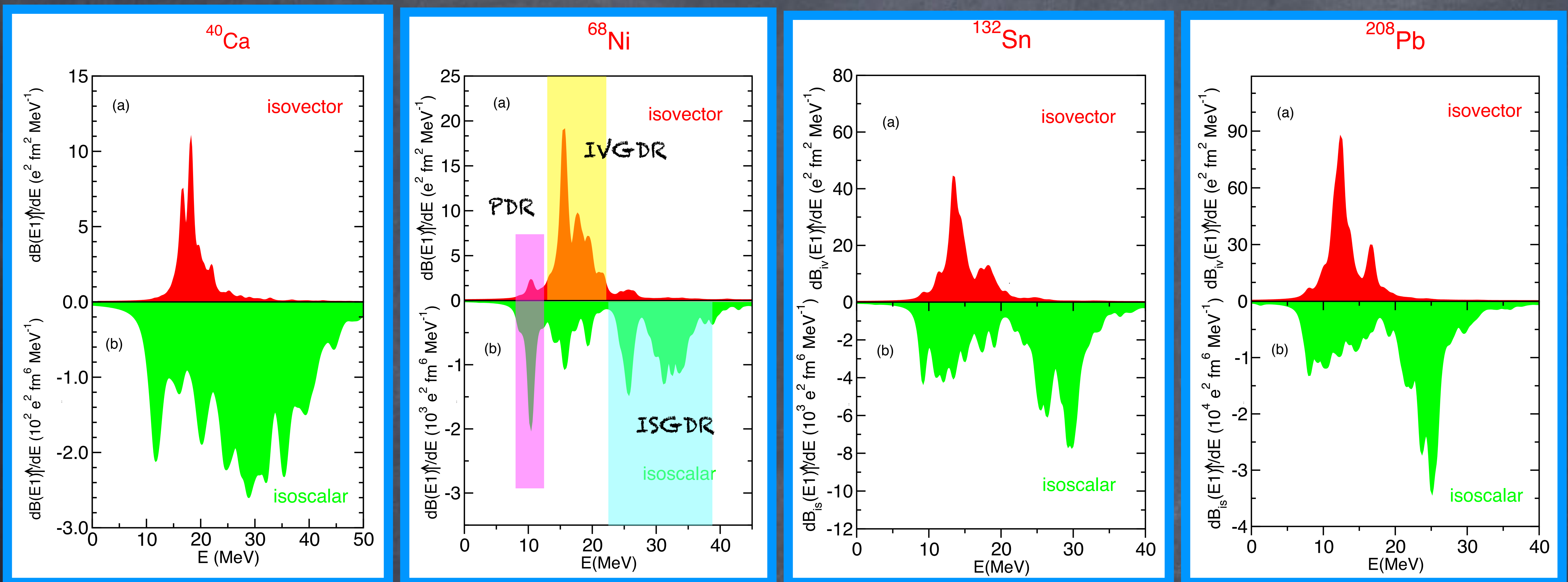
* N. Paar, D. Vretenar, E. Khan and G. Colò,
  Rep. Prog. Phys. 70, 691 (2007).

* 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).

Calculations done with the Hartree-Fock plus RPA with SGII Skyrme effective interactions



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

isovector

isoscalar

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

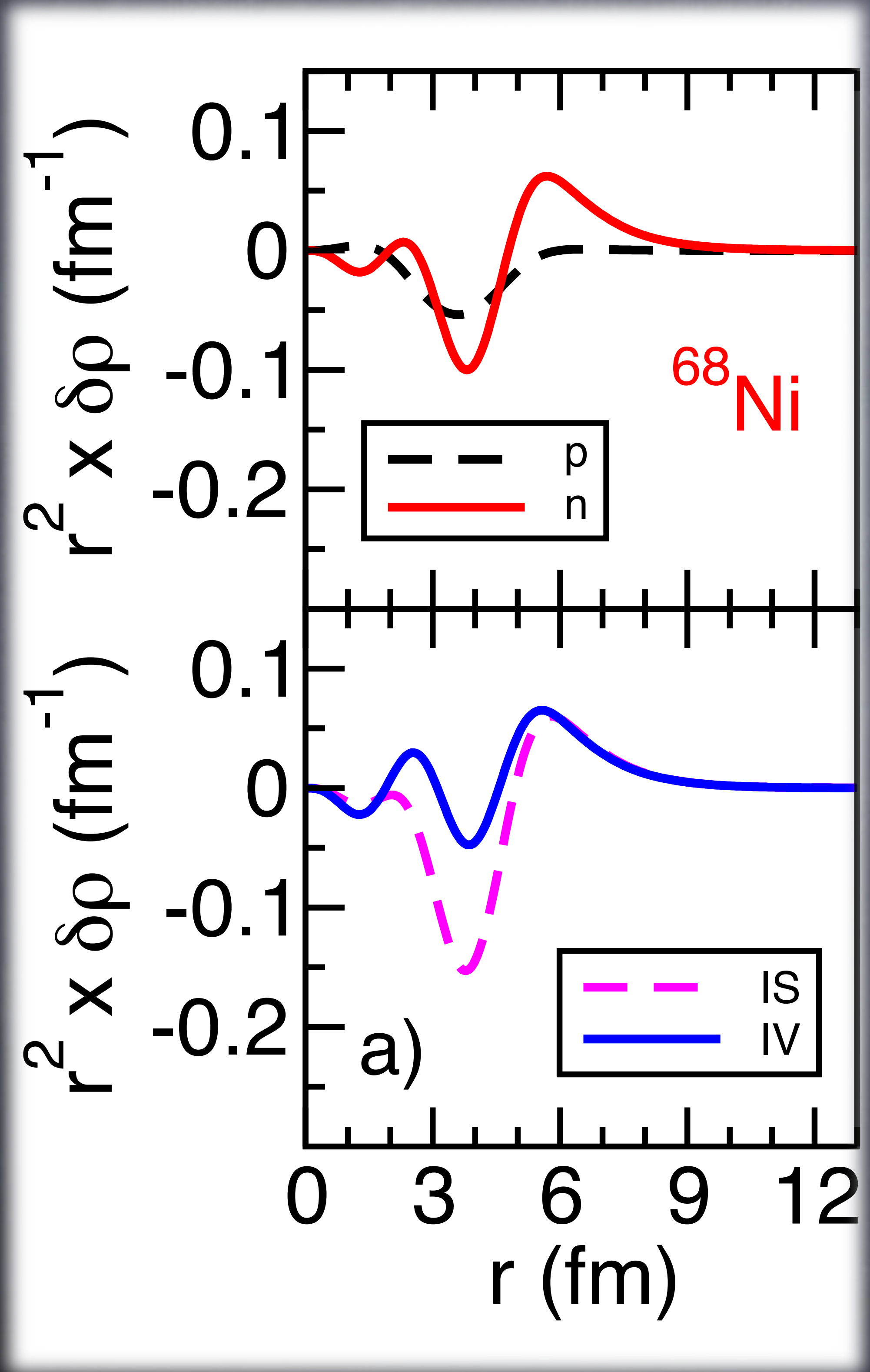
The low-lying dipole states (aka Pygmy Dipole Resonance) carry only few per cent of the EWSR and are located at an energy range below the GDR.

They are present in all the nuclei with N>Z (due to the neutron excess).
They are related to the symmetry energy.

Strong isoscalar component (transition densities)

$$\delta\rho^{\nu} = \frac{1}{\sqrt{4\pi}} \sum_{ph} (-)^{j_p + l_p + \frac{1}{2}} \frac{\hat{j}_p \hat{j}_h}{\hat{\lambda}} < j_h \tfrac{1}{2}\, j_p -\tfrac{1}{2} | \lambda 0 > \delta(\lambda + l_p + l_h, even)$$

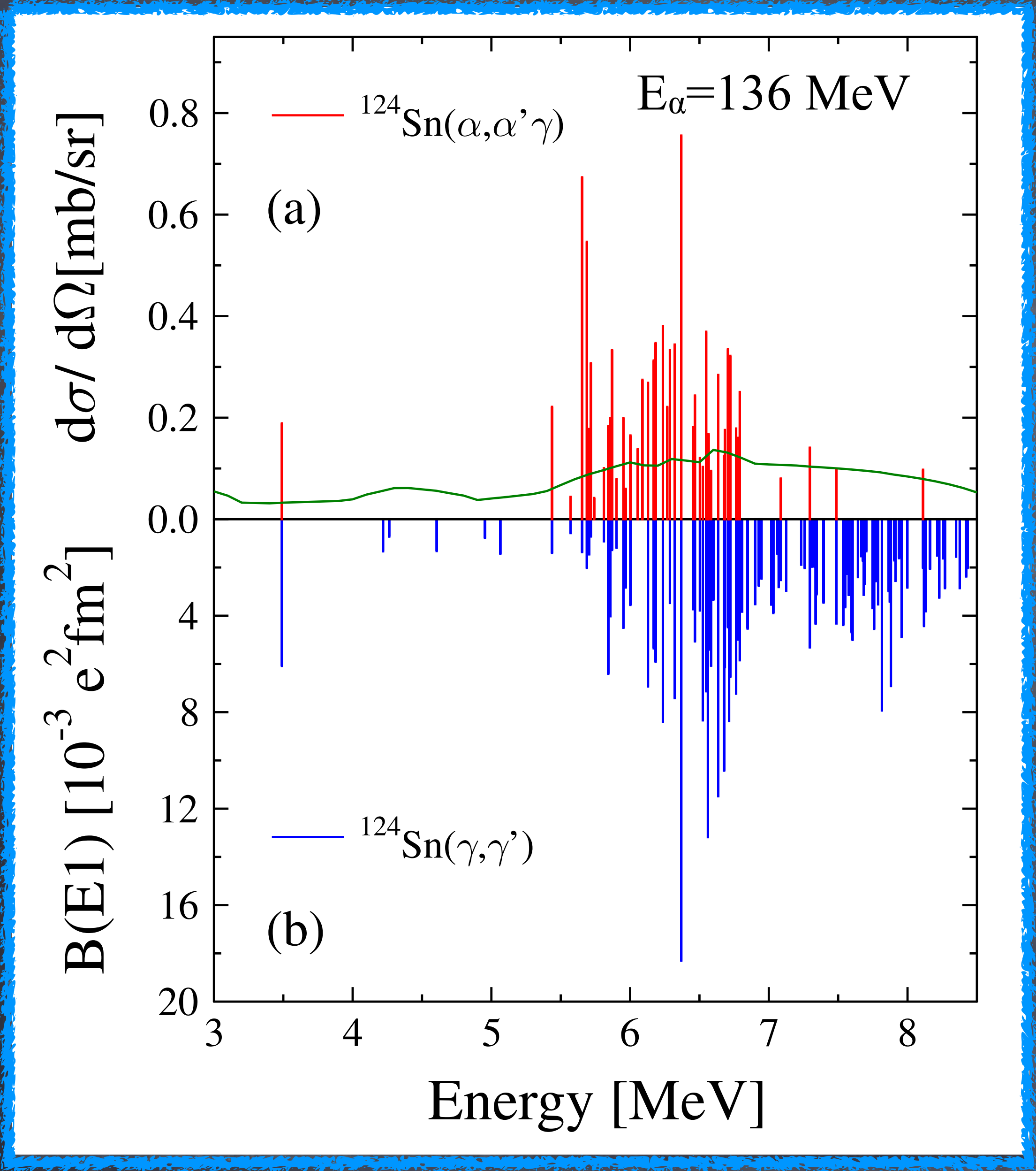
$$\cdot \left[X^{\nu}_{ph} - Y^{\nu}_{ph} \right] R_{l_p j_p}(r) R_{l_h j_h}(r)$$



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

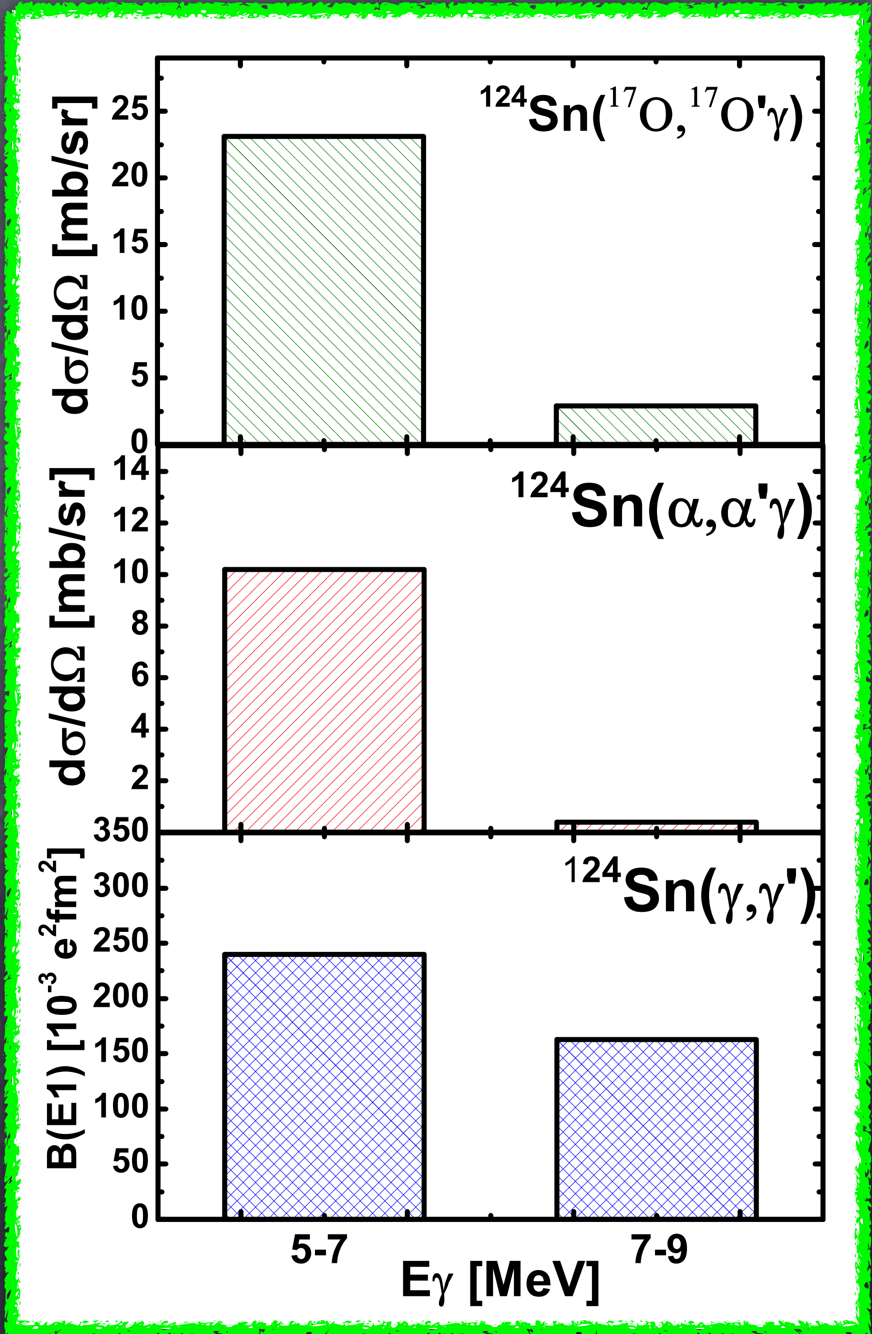
"Theoretical definition" of the PDR

Due to their strong isoscalar component these states can be studied also via an isoscalar probe



Experimental data isoscalar probe

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

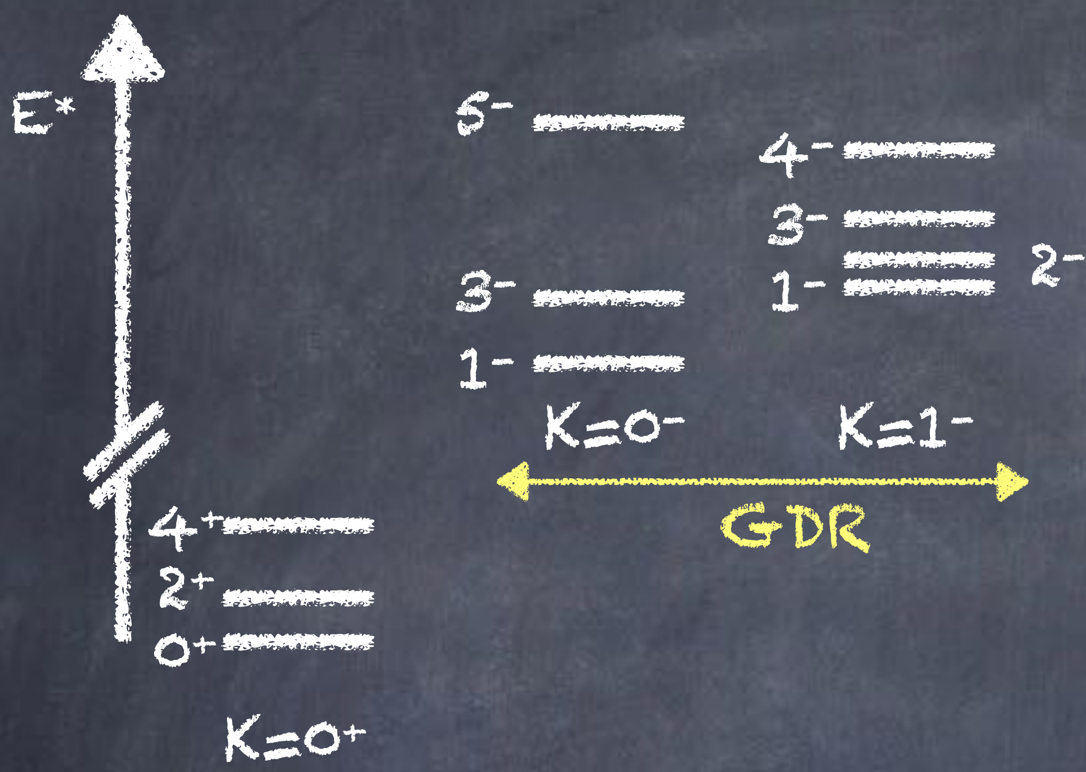
J. Endres et al., PRL 105 (2010) 212503

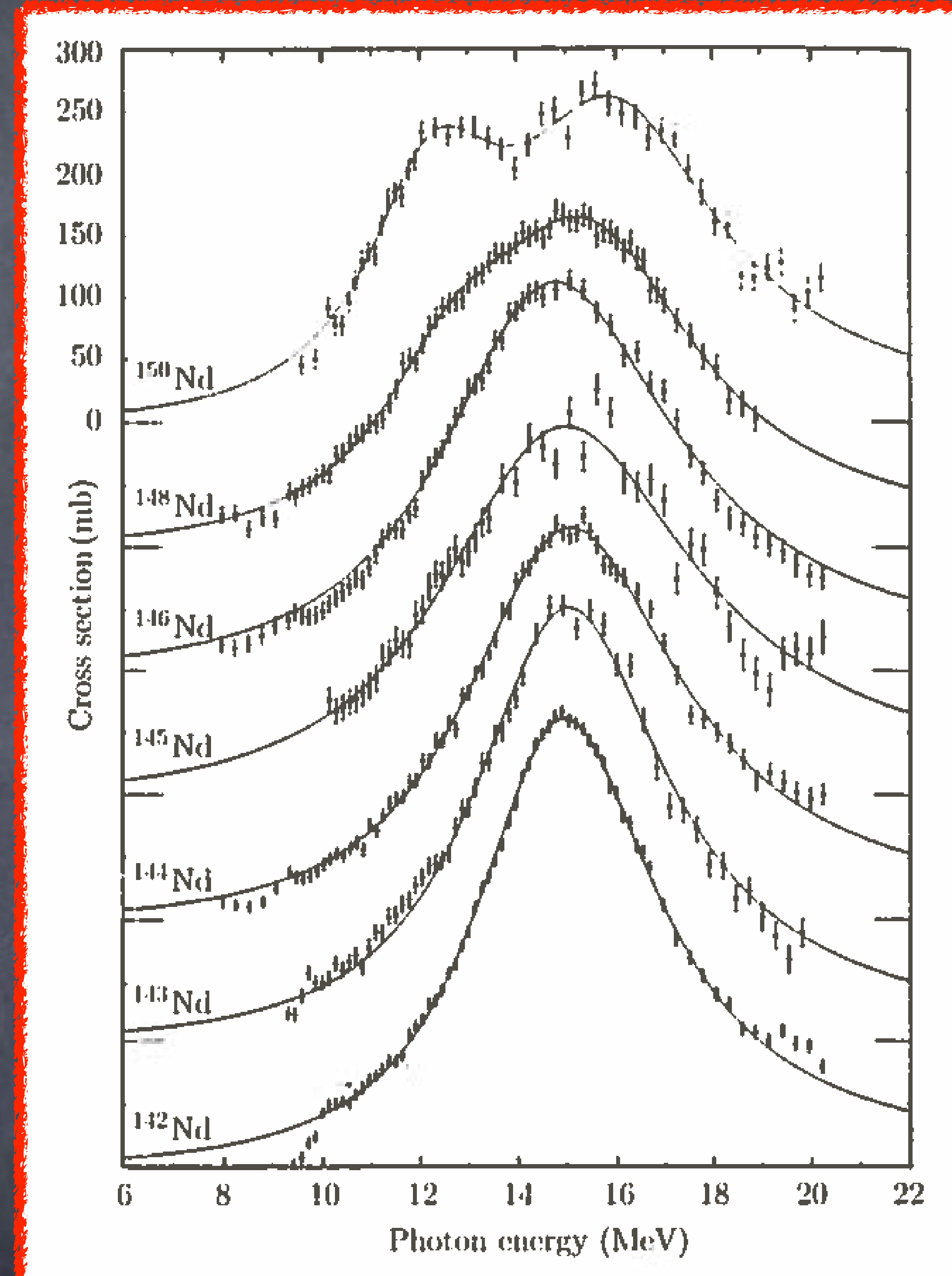
F.C.L. Crespi et al., PRL 113 (2014) 012501

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

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

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





B.L. Berman and S.C. Fultz, Rev. Mod. Phys. 47 (1975) 713

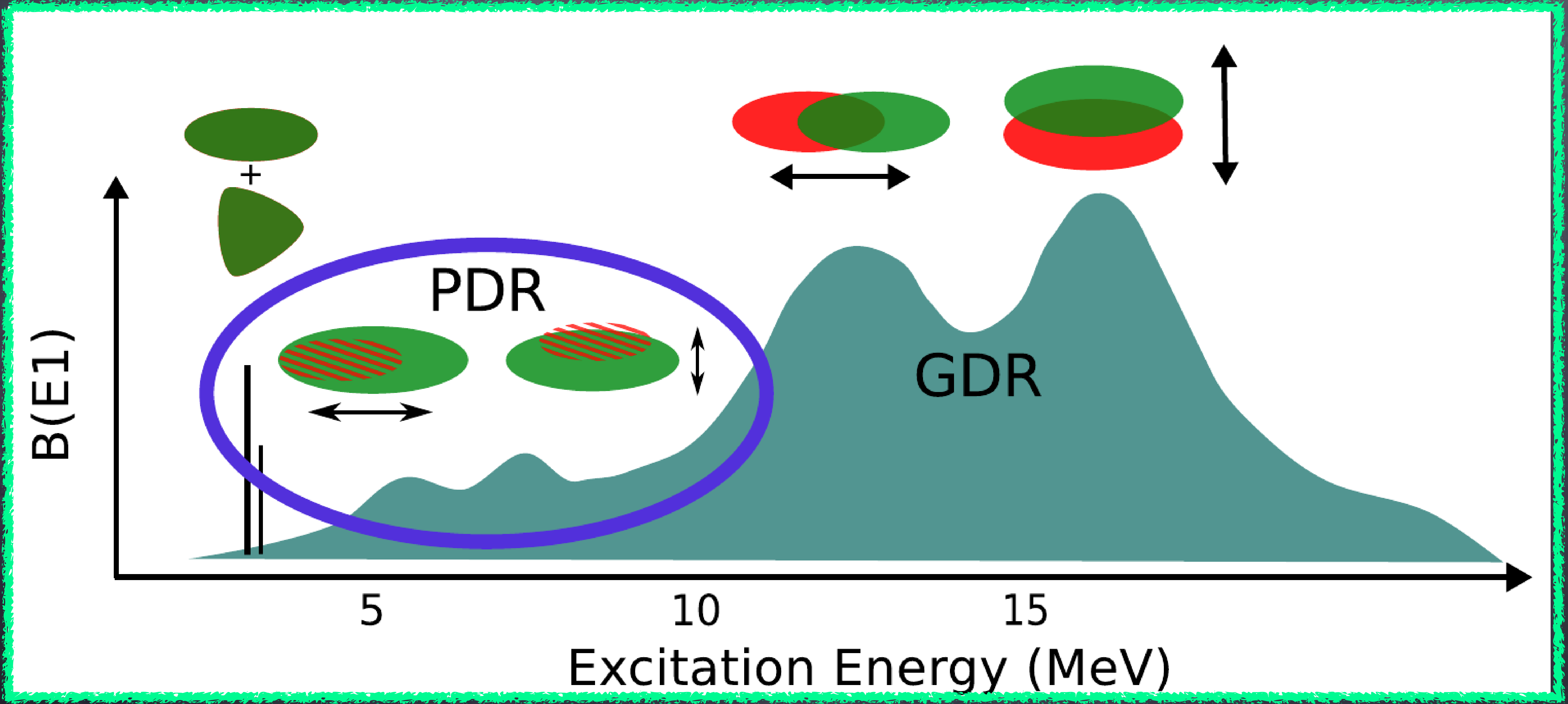
Splitting of the GDR

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

Bohr and Mottelson book

M. Danos, Nucl. Phys. A 5 (1958) 23
K. Okamoto, Phys. Rev. 111 (1958) 143

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



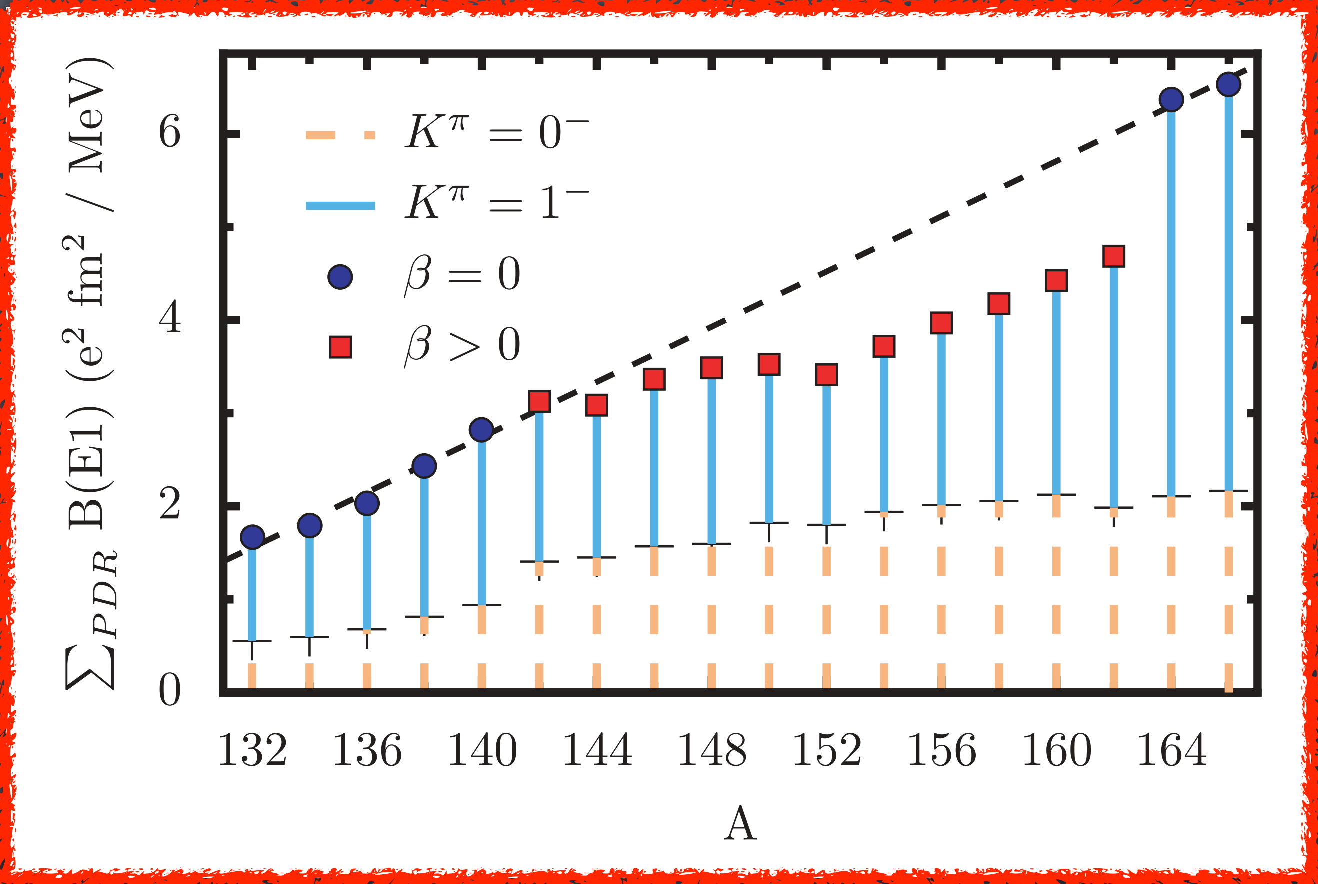
A. Krugmann, Thesis (2014), TU-Darmstadt,

Microscopic description of deformed nuclei with particular attention to the pygmy dipole resonances

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

They study the electric dipole response in the GDR and PDR energy regions for several tin isotopes performing 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.



Very neutron rich deformed nuclei may not be as good candidates as spherical nuclei for the study of PDR states

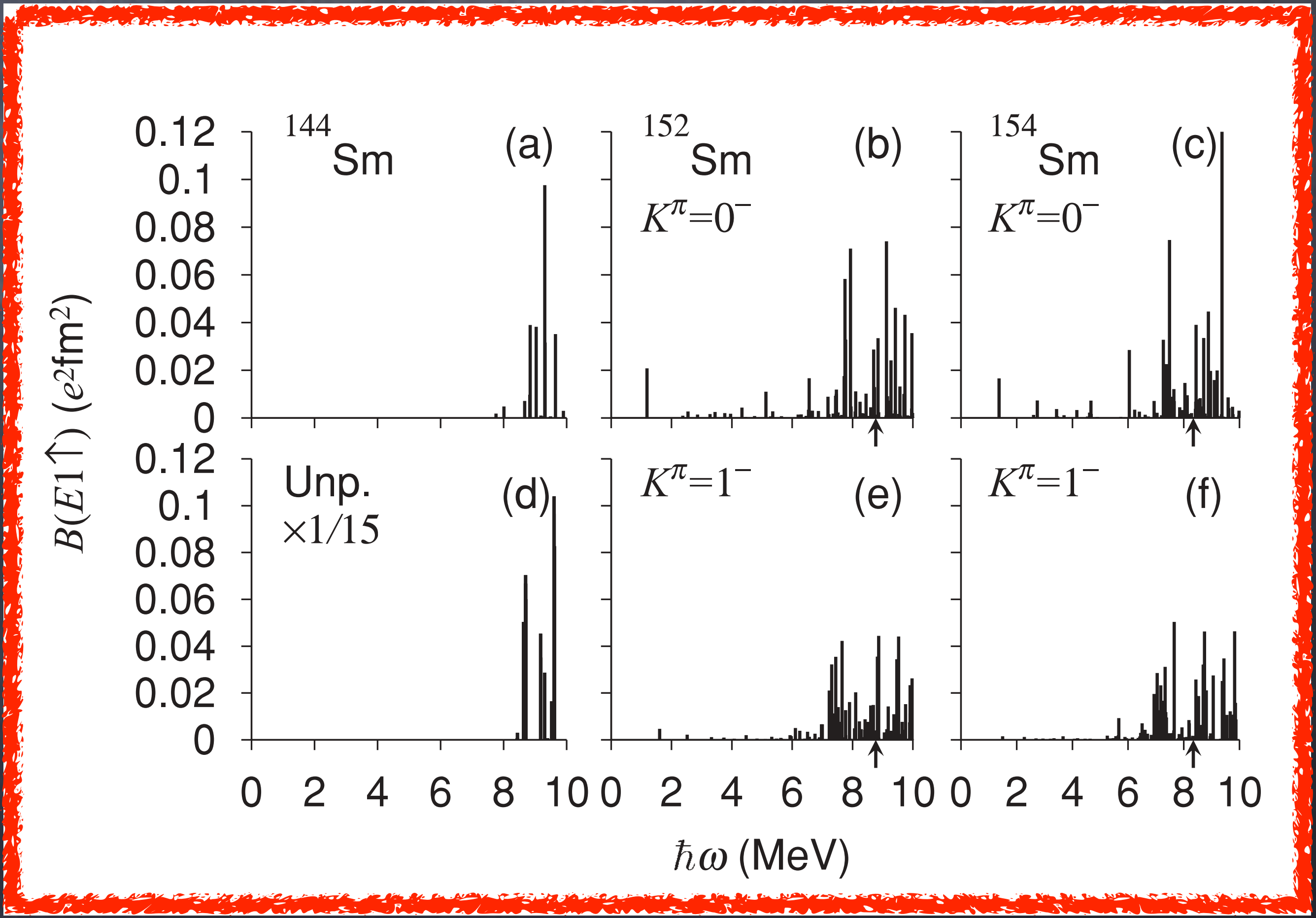
* K. Yoshida and T. Nakatsukasa, PRC 83, 021304(R) (2011).

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. Yoshida et al. adopts the Bogoliubov method and the other the BCS approximation.

The treatment of continuum and weakly bound orbitals are also different.

The calculations of Peña et al. are fully self-consistent, and they do not have the contamination of the spurious center-of-mass motion.

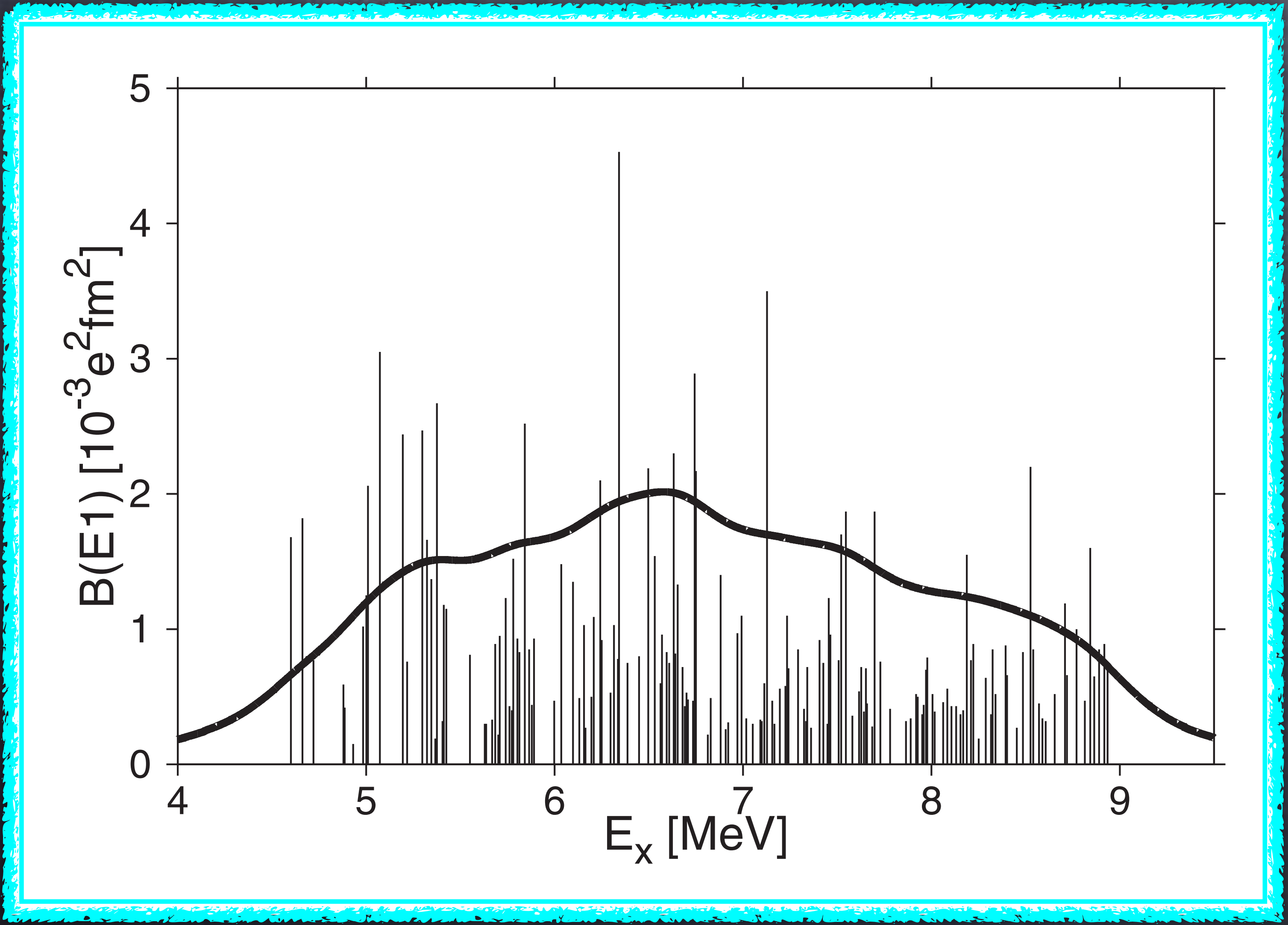


experimental work for pygmy dipole resonances in deformed nuclei

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

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

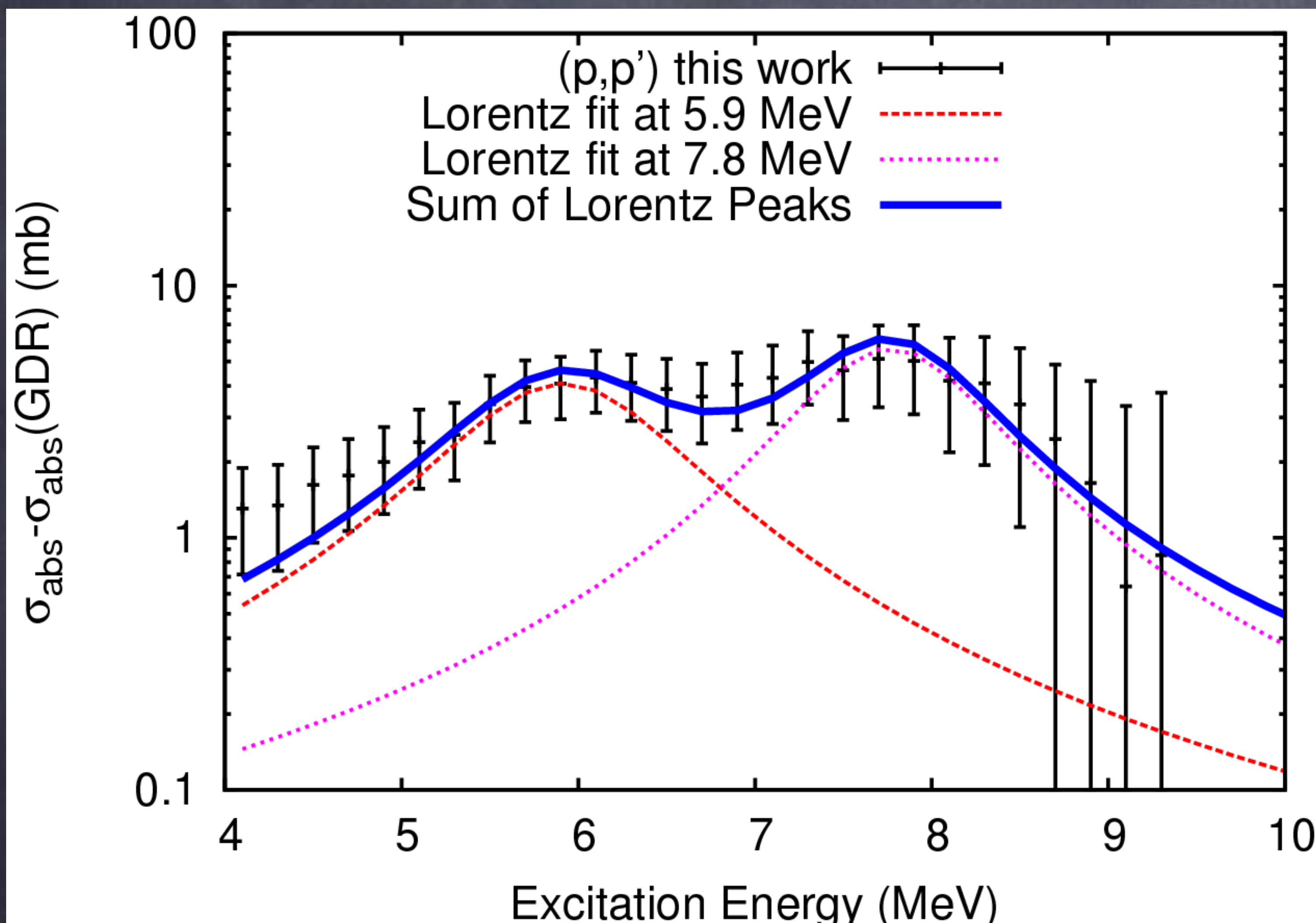
It is known that the GDR is split into two peaks



Observed many 1⁻ states between 4 and 9 MeV.

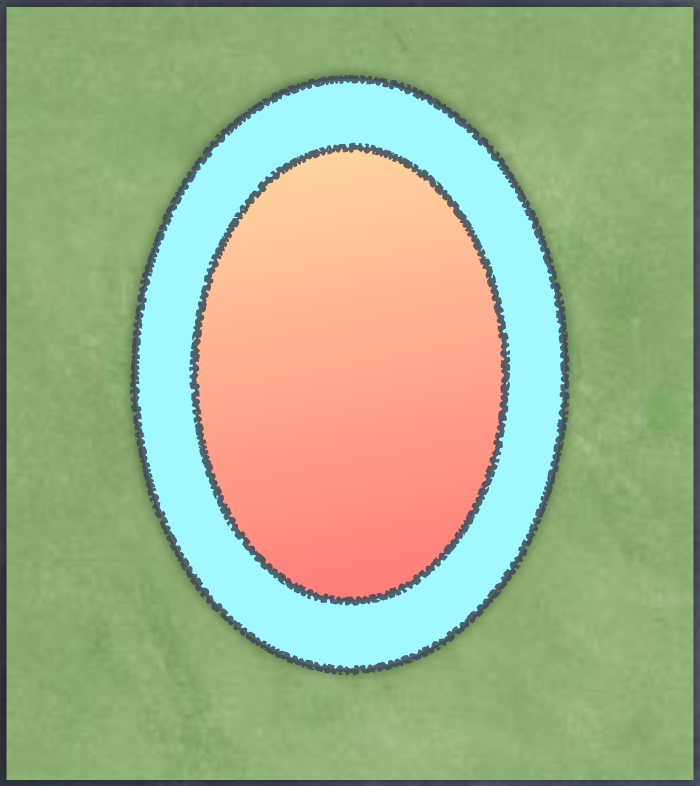
A pronounced splitting, as seen in the GDR ,is not evident

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



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

Pygmy for deformed nuclei



Assume $N = N^c + N^v$

$$\rho(r,\theta) = \rho_p(r,\theta) + \rho_n^c(r,\theta) + \rho_n^v(r,\theta)$$

Assume $N^c = Z$ then $\rho_n^c(r,\theta) = \rho_p(r,\theta)$

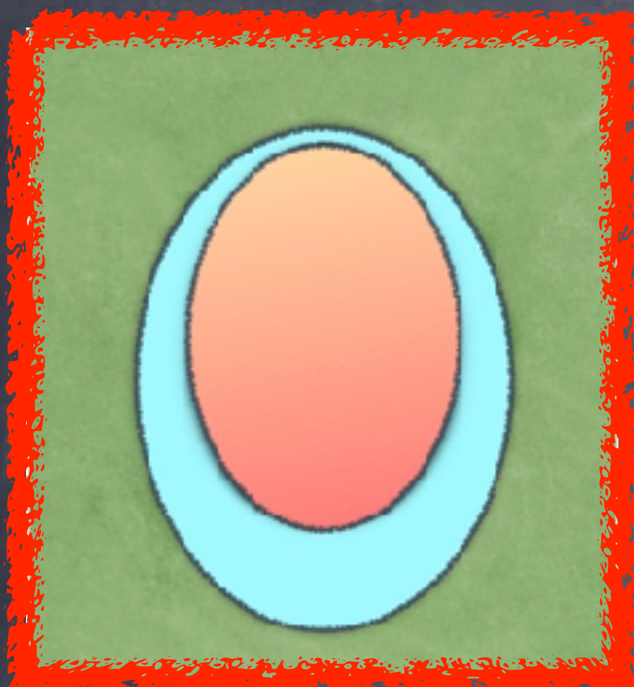
Fermi distribution with axially symmetric deformed surface with different geometries

$$\rho_p(r,\theta) = \frac{\rho_{0p}}{1 + exp\{[r - R_{0p}(1 + \beta_p Y_{20}(\theta)]/a_p\}}$$

$$\rho_n(r,\theta) = \frac{\rho_{0n}}{1 + exp\{[r - R_{0n}(1 + \beta_n Y_{20}(\theta)]/a_n\}}$$

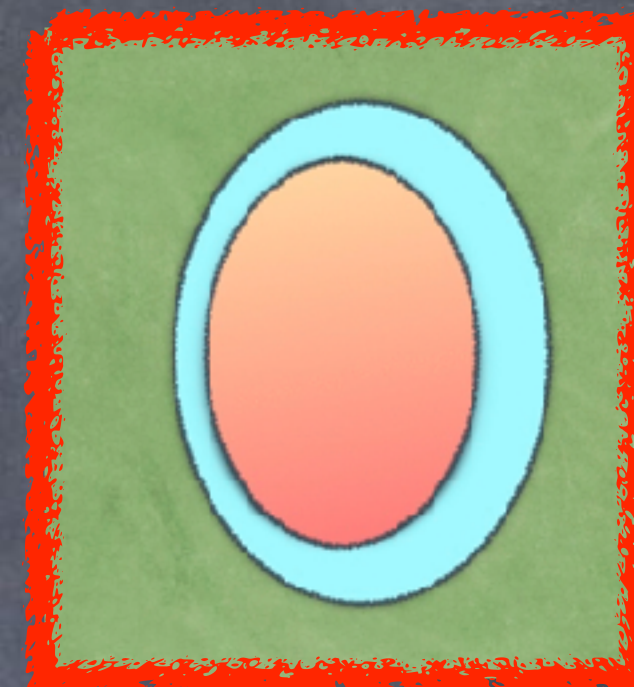
Pygmy for deformed nuclei

$K^{\pi}=0^{-}$



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

$K^{\pi}=1^{-}$

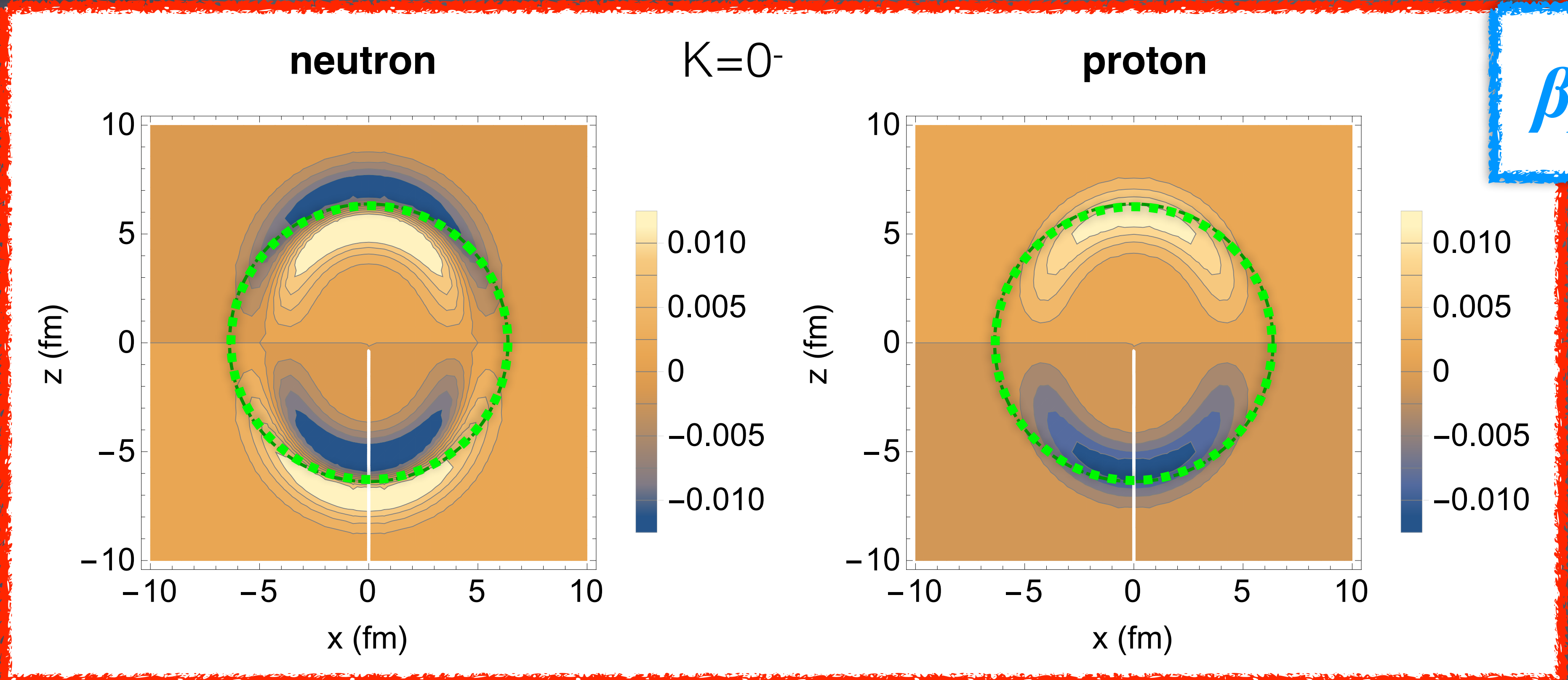


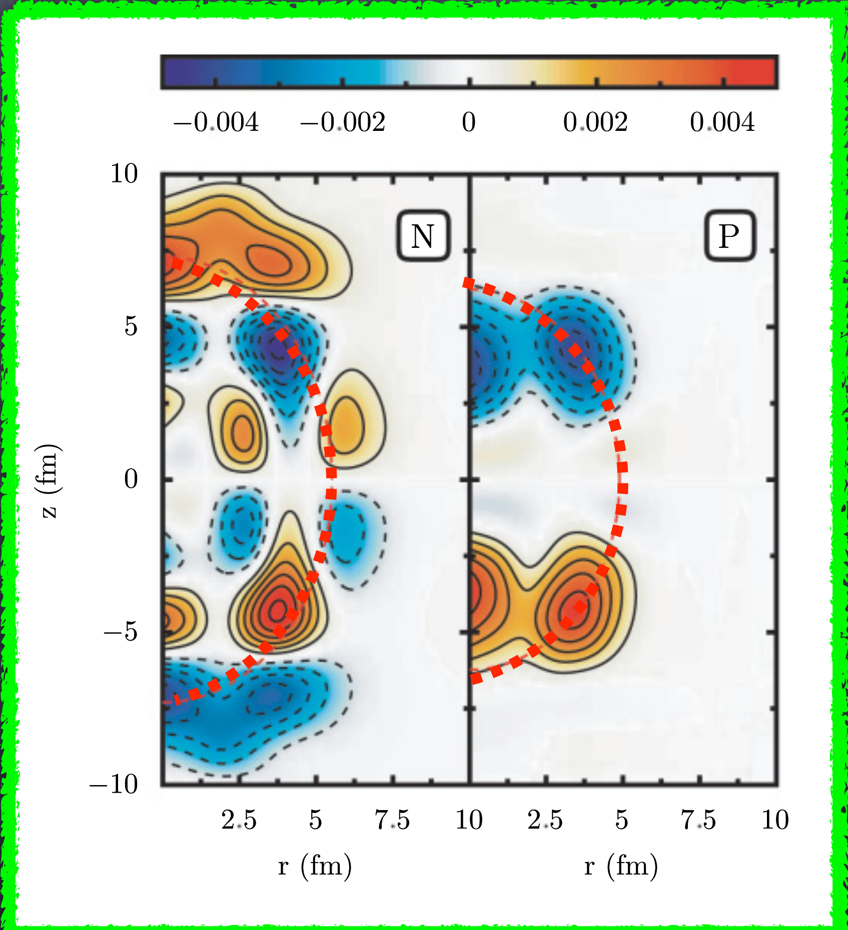
$$\delta\rho_p^{K^\pi}(r,\theta,\phi) = \delta_1\big[-\frac{2N^v}{A}\frac{d}{dr}\rho_p(r,\theta,\phi)\big]Y_{1,K}(\theta,\phi)$$

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

$Z=N^c=50$, $N=100$, $R_{0p}=4.89$ fm, $R_{0n}=5.52$ fm, $a_{0p}=a_{0n}=0.6$ fm,

$\beta_p=\beta_n=0.31$





Calculation done within the relativistic QRPA based on a relativistic HFB basis.

^{150}Sn

$K^{\pi}=0^-$

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

Z=N^c=50, N=100, R_{0p}=4.89 fm, R_{0n}=5.52 fm, a_{0p}=a_{0n}=0.6 fm,

$\beta_p=\beta_n=0.31$

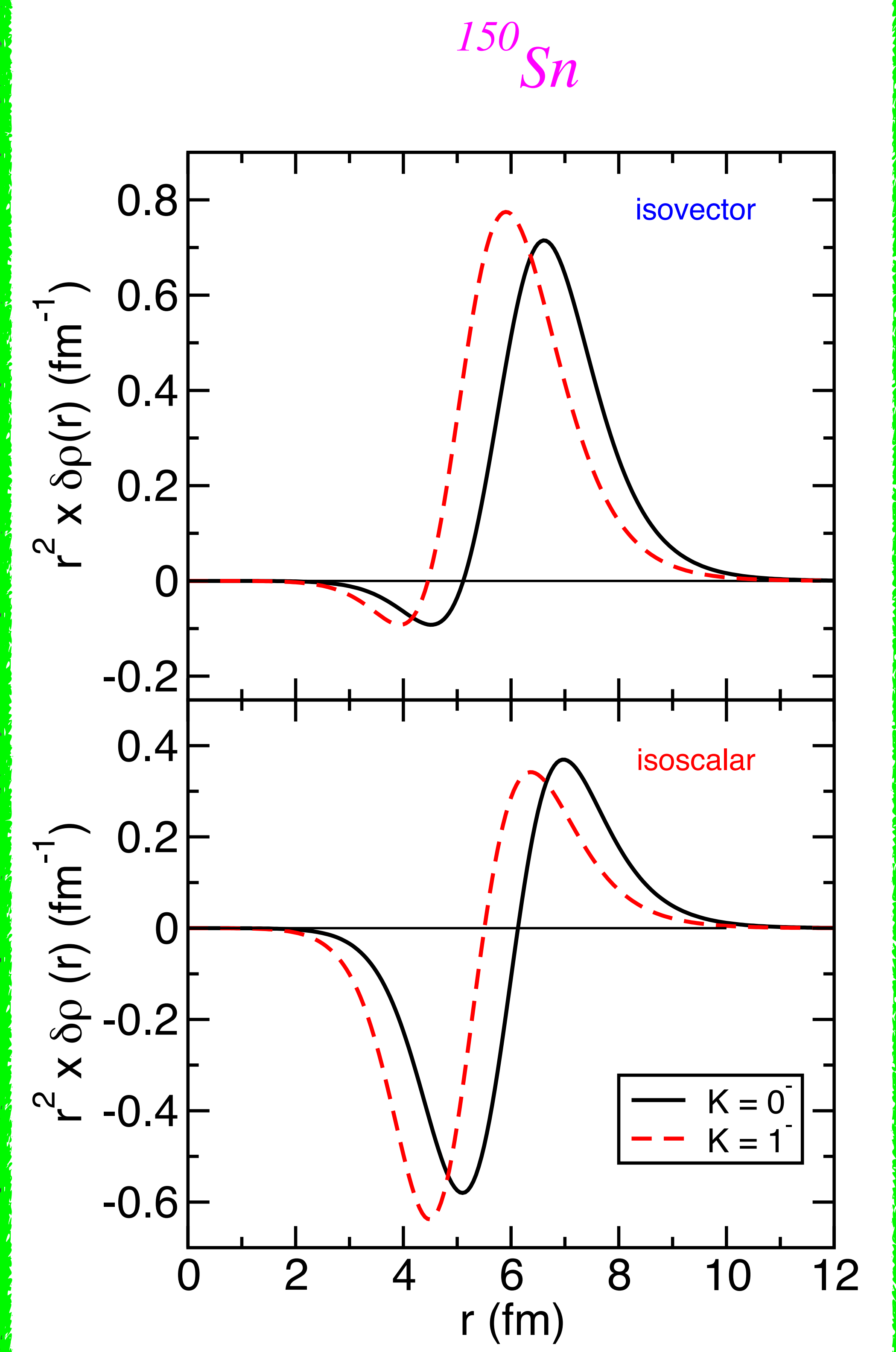
The radial transition densities are obtained by expanding the intrinsic transition densities in spherical harmonics

Like in the spherical case, for the PDR there is a strong contribution of the isoscalar transition density at the nuclear surface

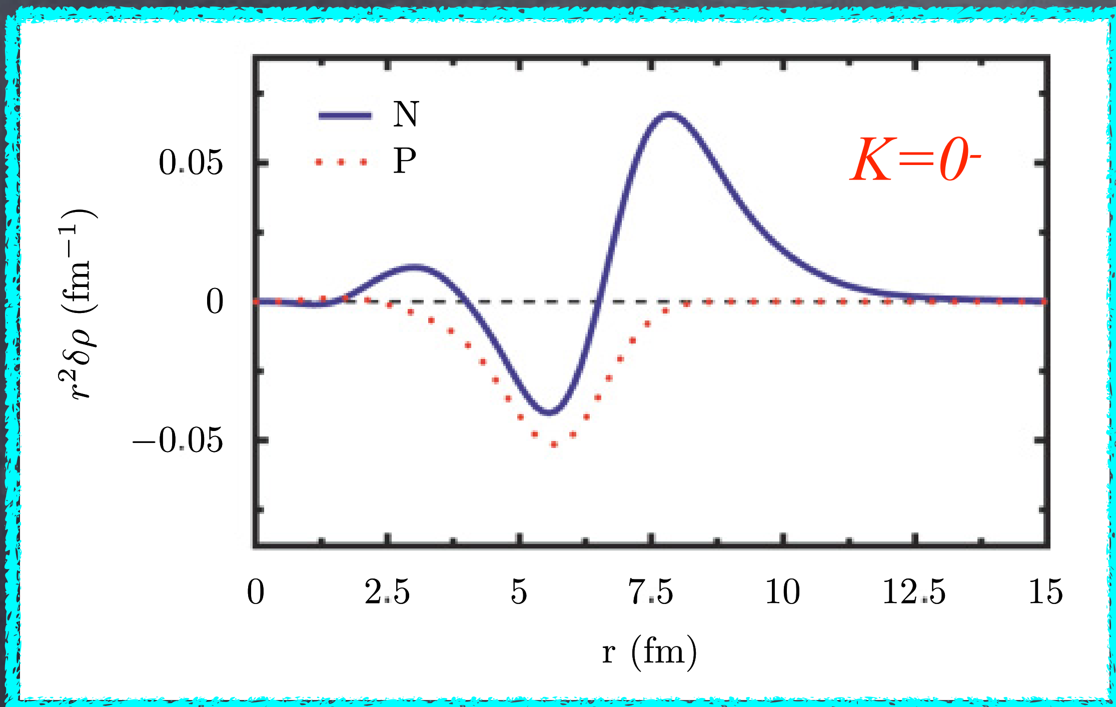
Reduced dipole transition probabilities

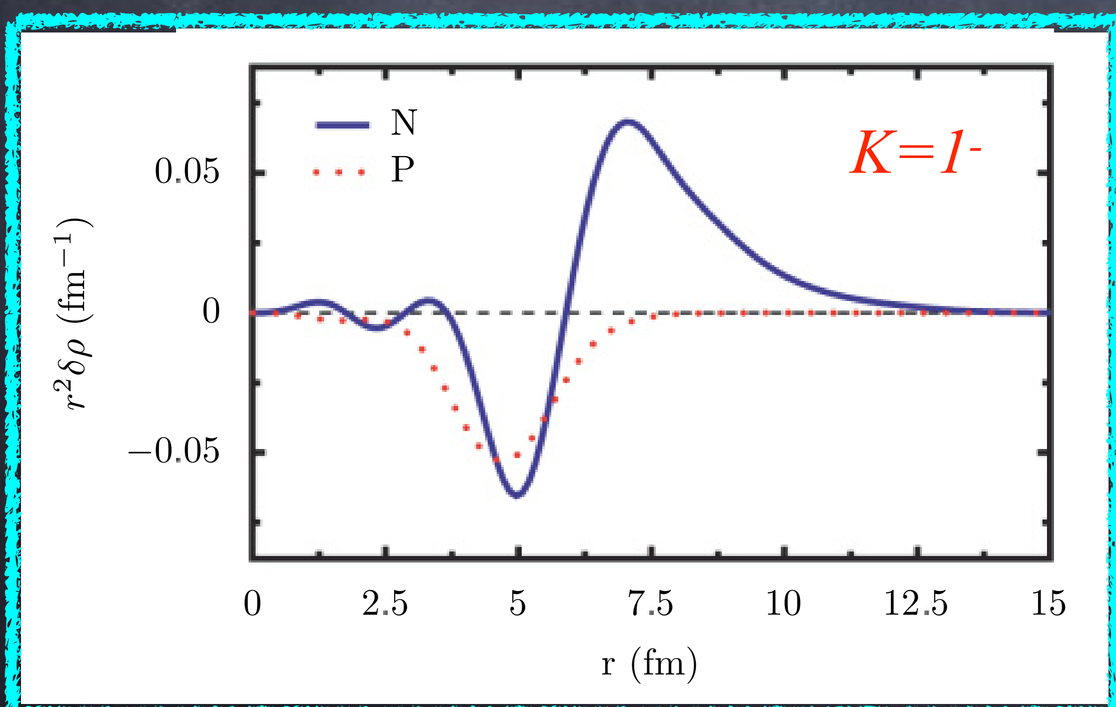
$$B_K^{IS}(E1) \propto \left| \int_0^\infty \delta\rho_{IS}^K(r)\, r^5\, dr \right|^2$$

$$B_K^{IV}(E1) \propto \left| \int_0^\infty \delta\rho_{IV}^K(r)\, r^3\, dr \right|^2$$

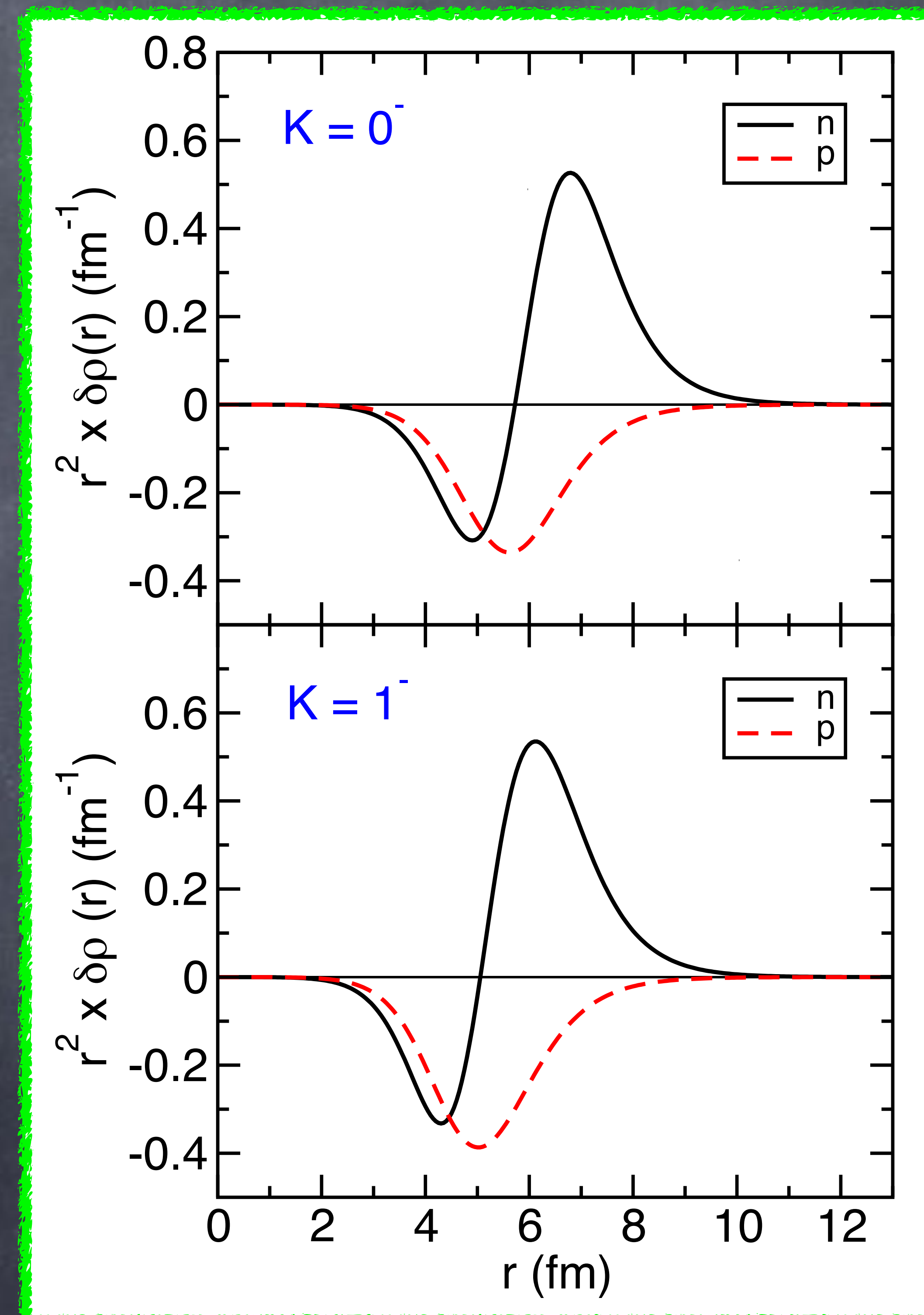


D.Peña Arteaga, E.Khan, P.Ring,
PRC 79 (2009) 034311



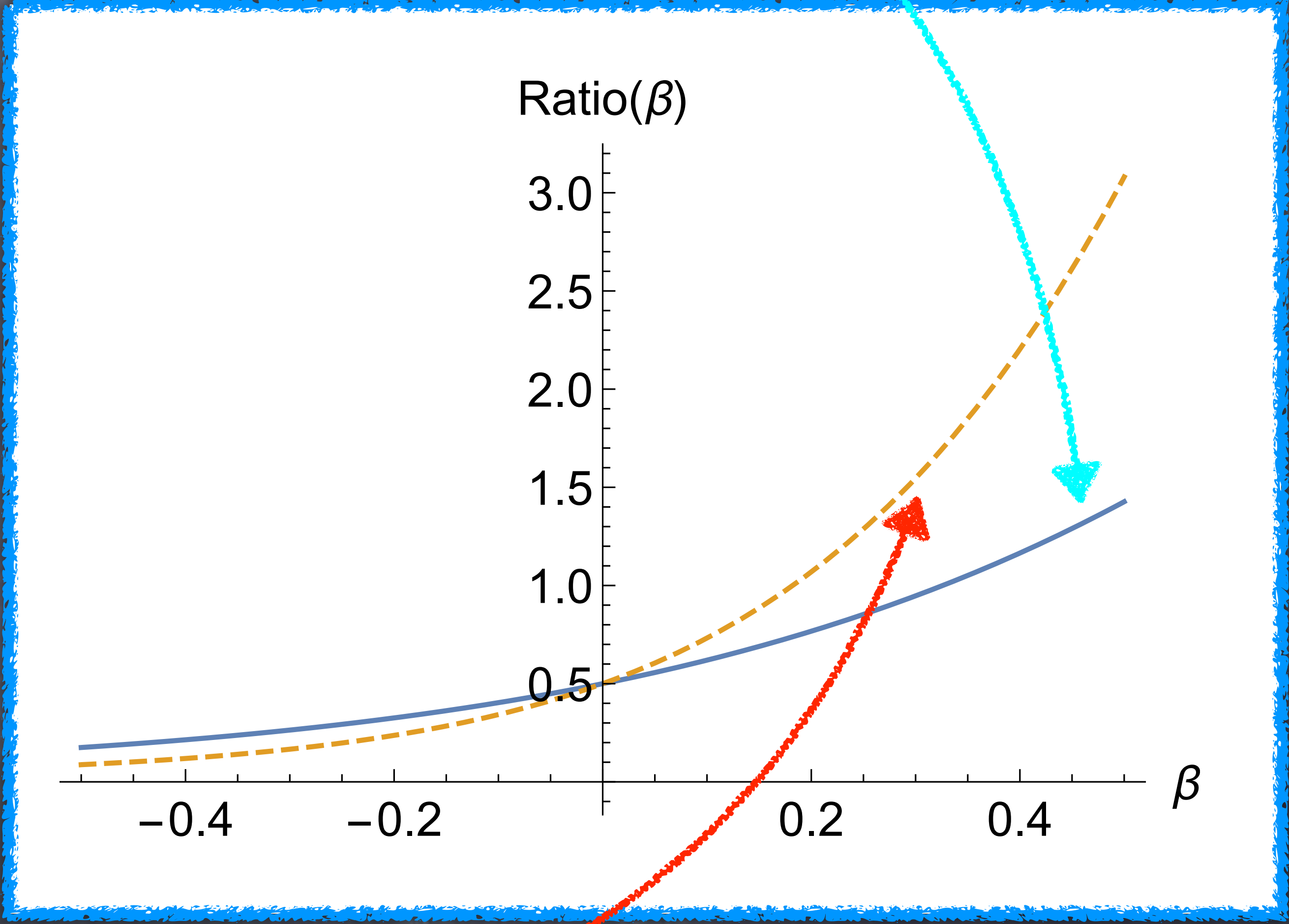


^{150}Sn



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

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



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

The variation of the ratio for the isoscalar case is stronger

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

Project PR251, Research Proposal to the PAC of iThemba LABS, South Africa.

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.

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.

It seems that the low-lying dipole states can be a good laboratory to study the interplay between isoscalar and isovector modes

Pygmy Dipole States in deformed nuclei

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Thank you for your attention