Isoscalar and isovector probes to investigate the Pygmy Dipole Resonances

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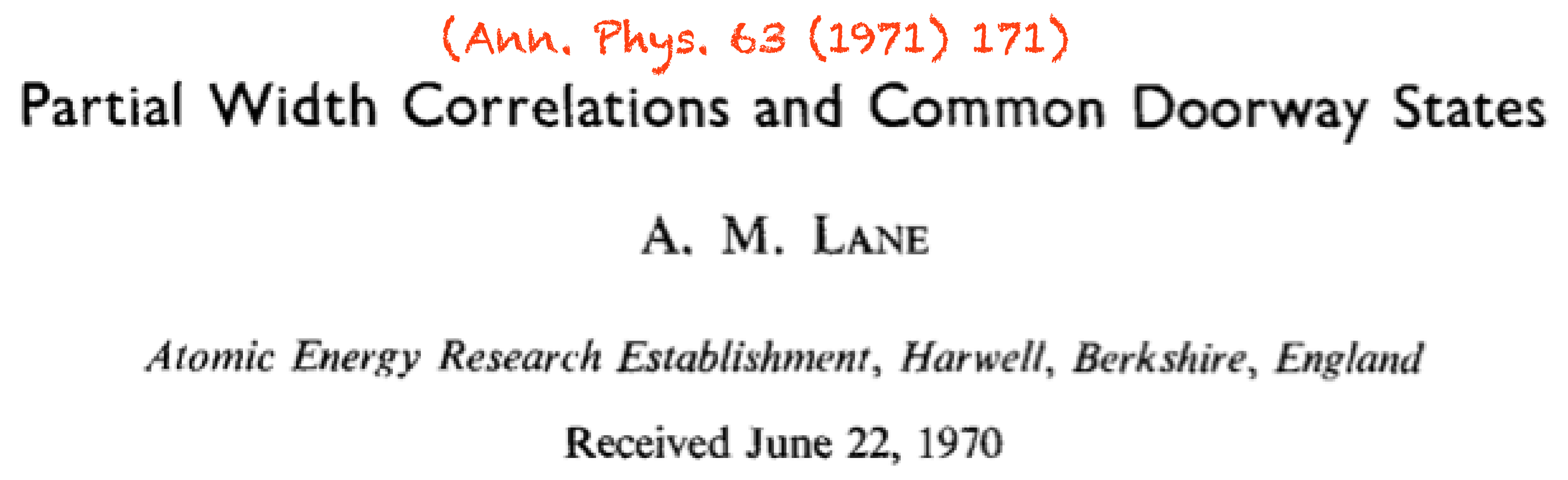
Effect of the pigmy resonance on the calculations of the neutron capture cross section

J. S. Brzosko, E. Gierlik, A. Soltan Jr., Z. Wilhelmi

Canadian Journal of Physics, 1969, 47(24): 2849-2857, 10.1139/p69-348



(Ann. Phys. 63 (1971) 171)

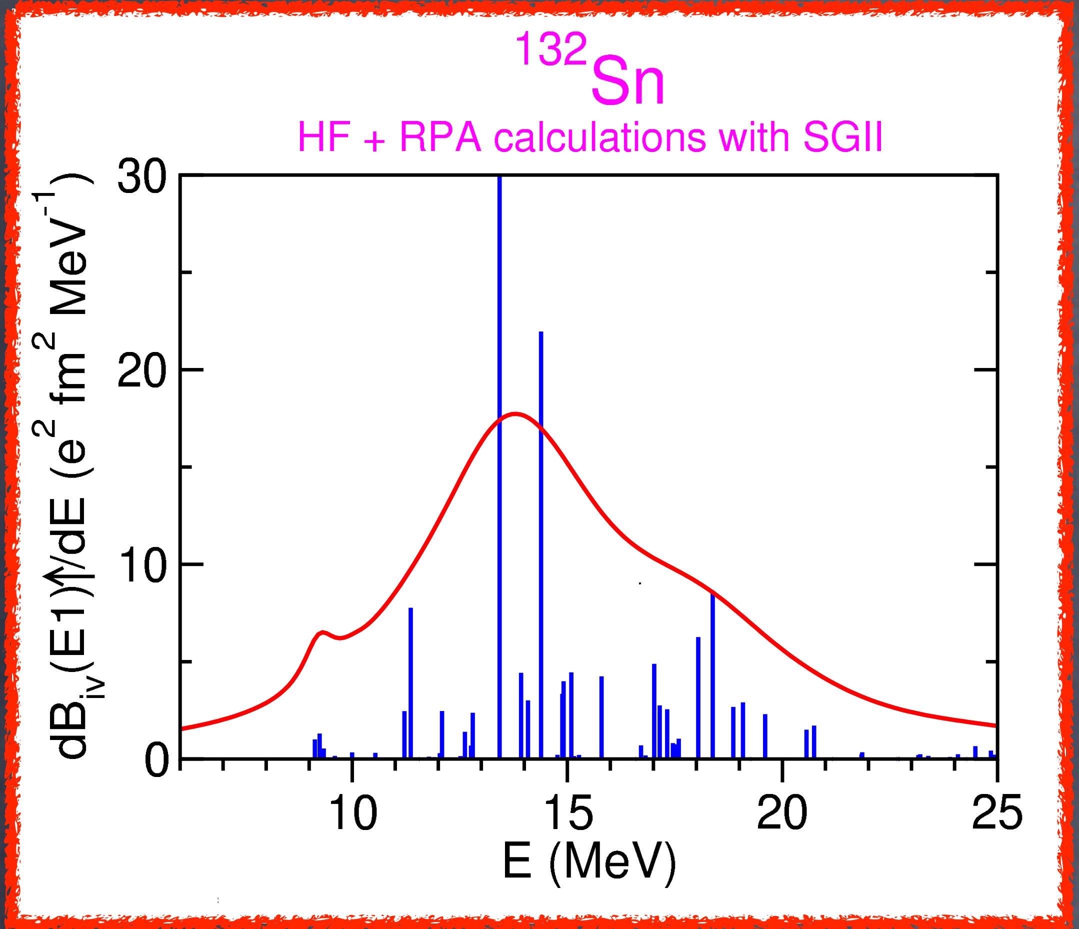
Partial Width Correlations and Common Doorway States

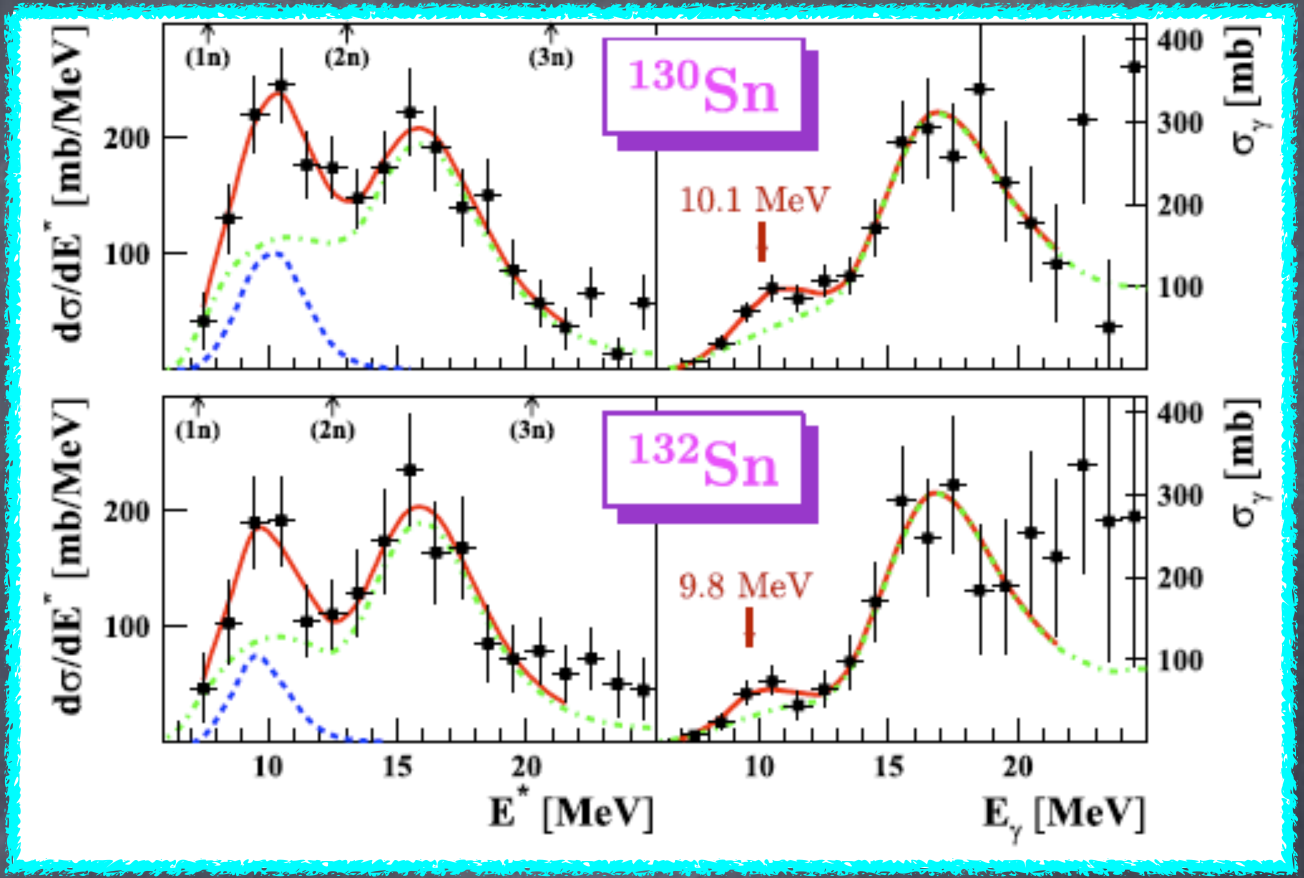
A. M. LANE

Atomic Energy Research Establishment, Harwell, Berkshire, England

Received June 22, 1970

It is a dipole state located at much lower energy than the GDR peak.





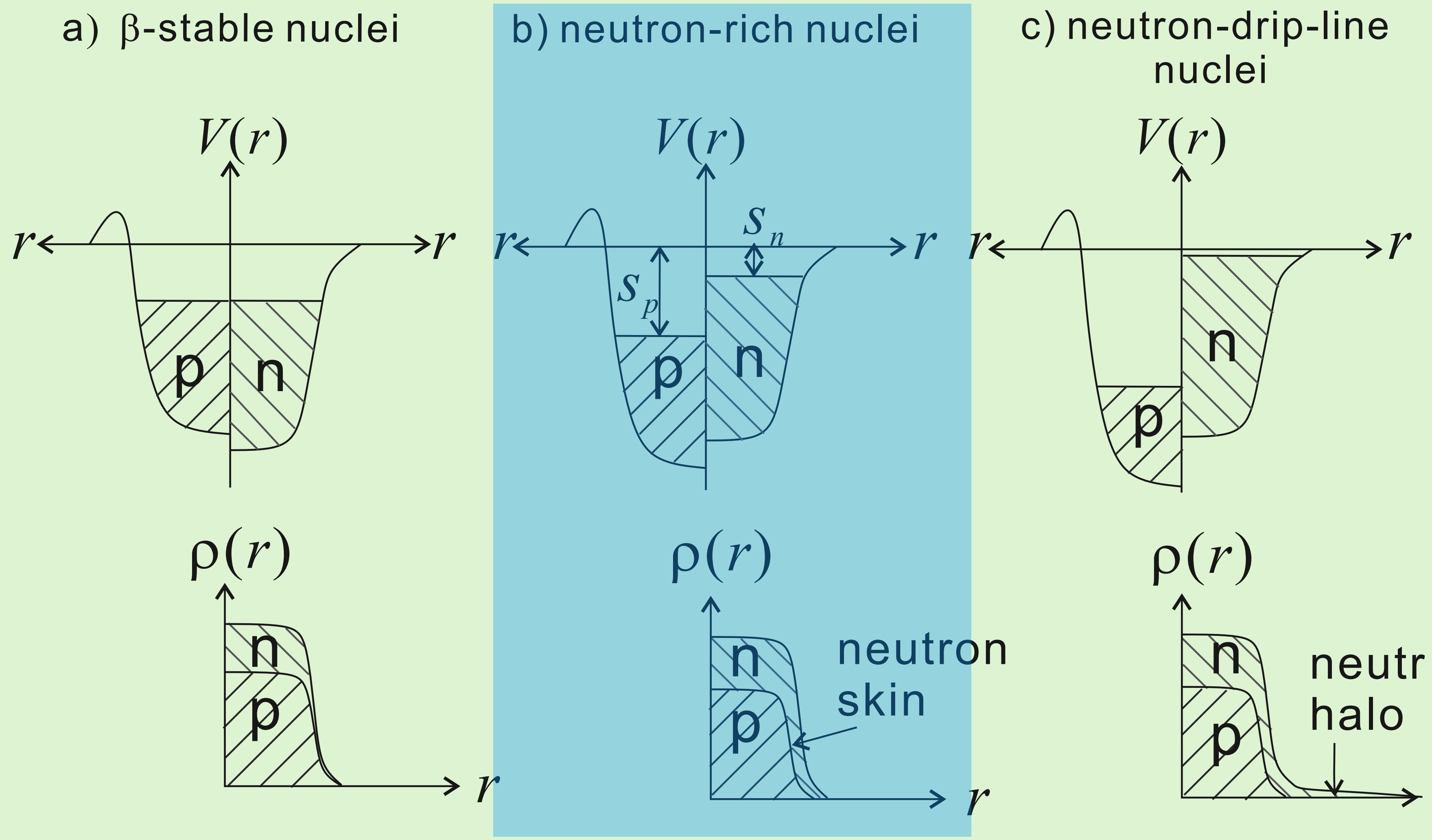
Called "pygmy" because its strength is much smaller than GDR. It exhausts only few per cent of the EWSR.

Many experimental data are now available both for stable and unstable nuclei.

There have been several theoretical studies which relate this strength with the presence of a neutron skin.

T.Aumann and T. Nakamura

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



Review papers

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

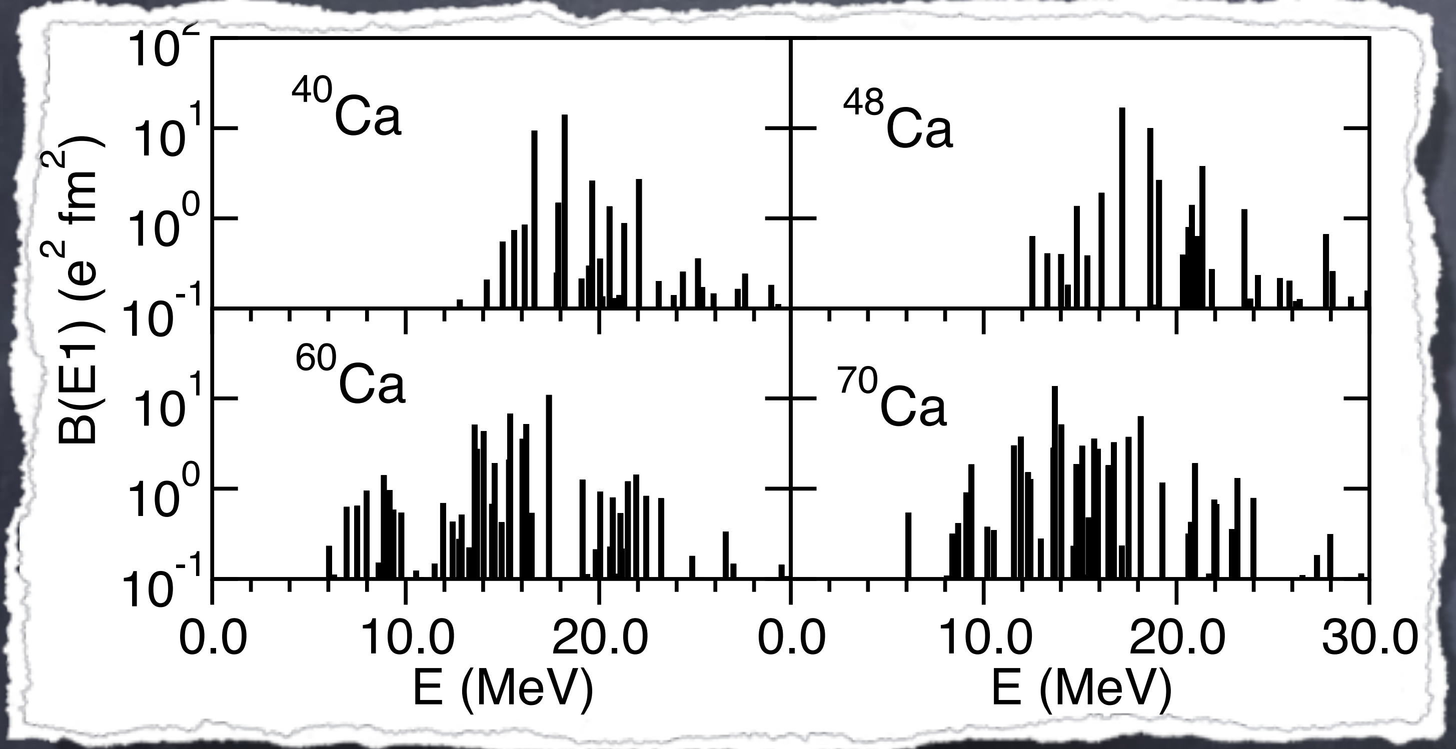
- T. Aumann and T. Nakamura,
  Phys. Scr. T152, 014012 (2013)

- 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).

Isovector response

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



Additional strength below the normal giant resonance region

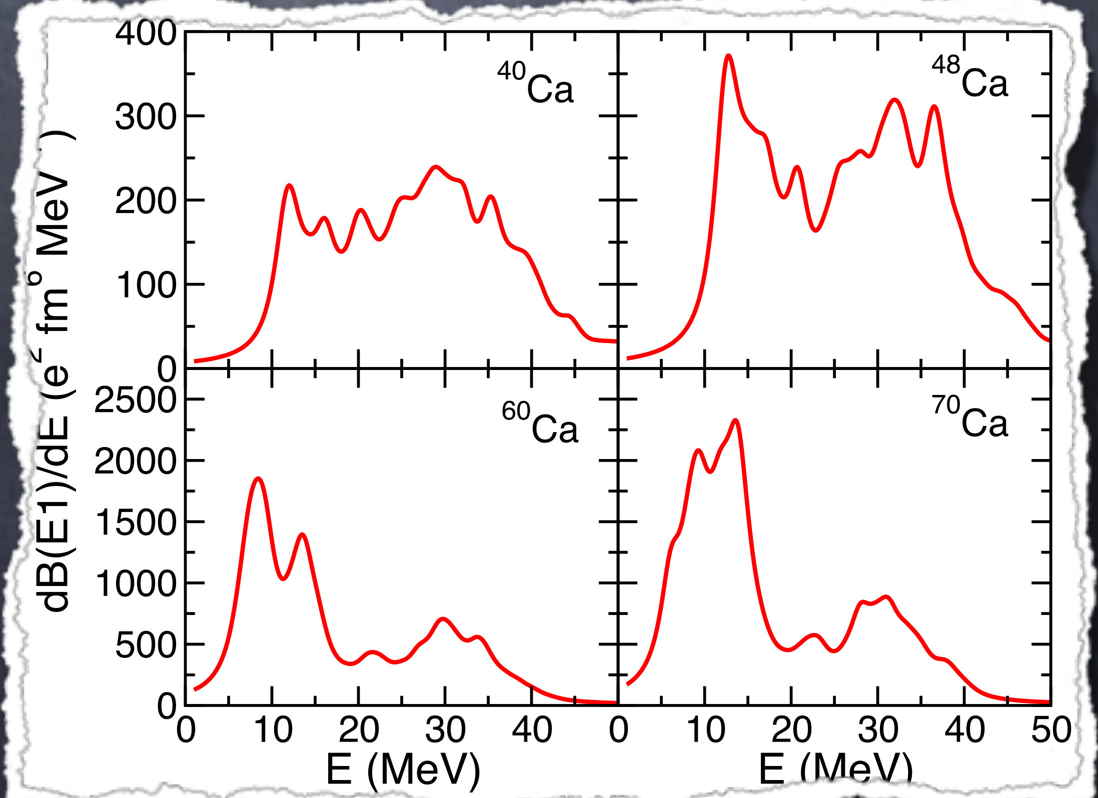
F. Catara, E.G. Lanza, M.A. Nagarajan, A. Vitturi,
NPA 614 (1997) 86;
NPA 624 (1997) 449

Neutron excess

RPA calculations with Skyrme interaction were employed to study the multipole response in neutron rich nuclei. The spectral distributions of such nuclei are much more fragmented than those for well bound systems.

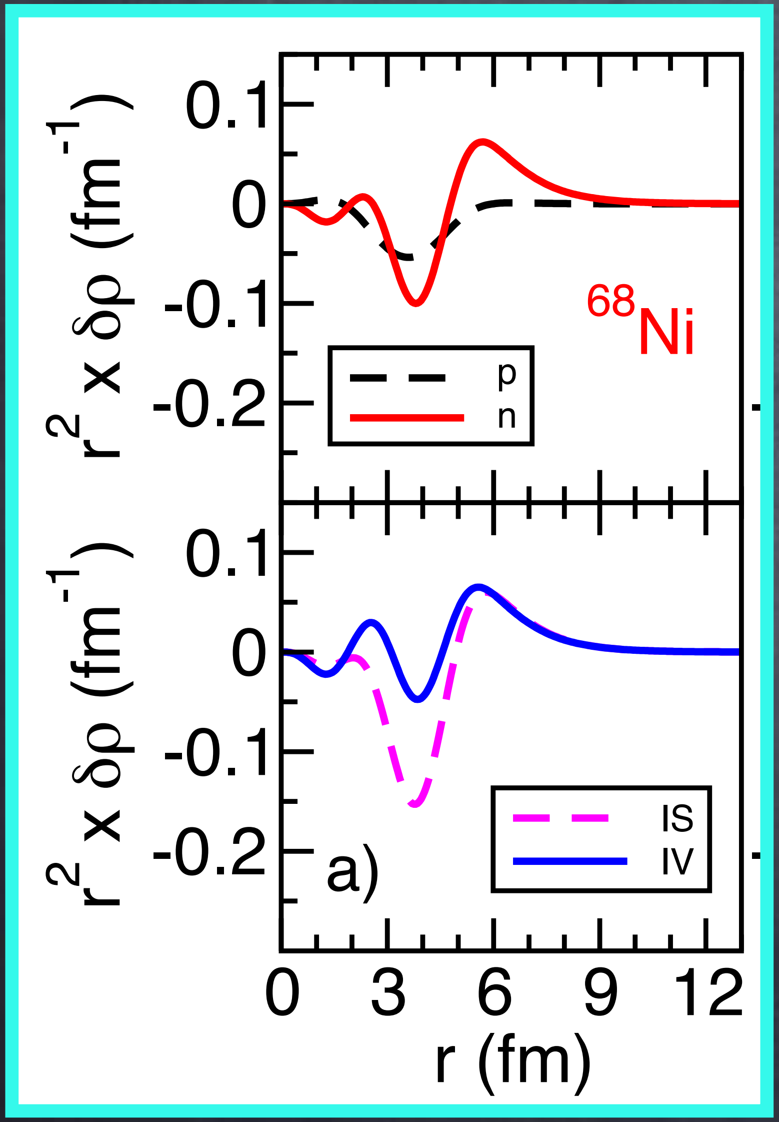
Isoscalar response

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

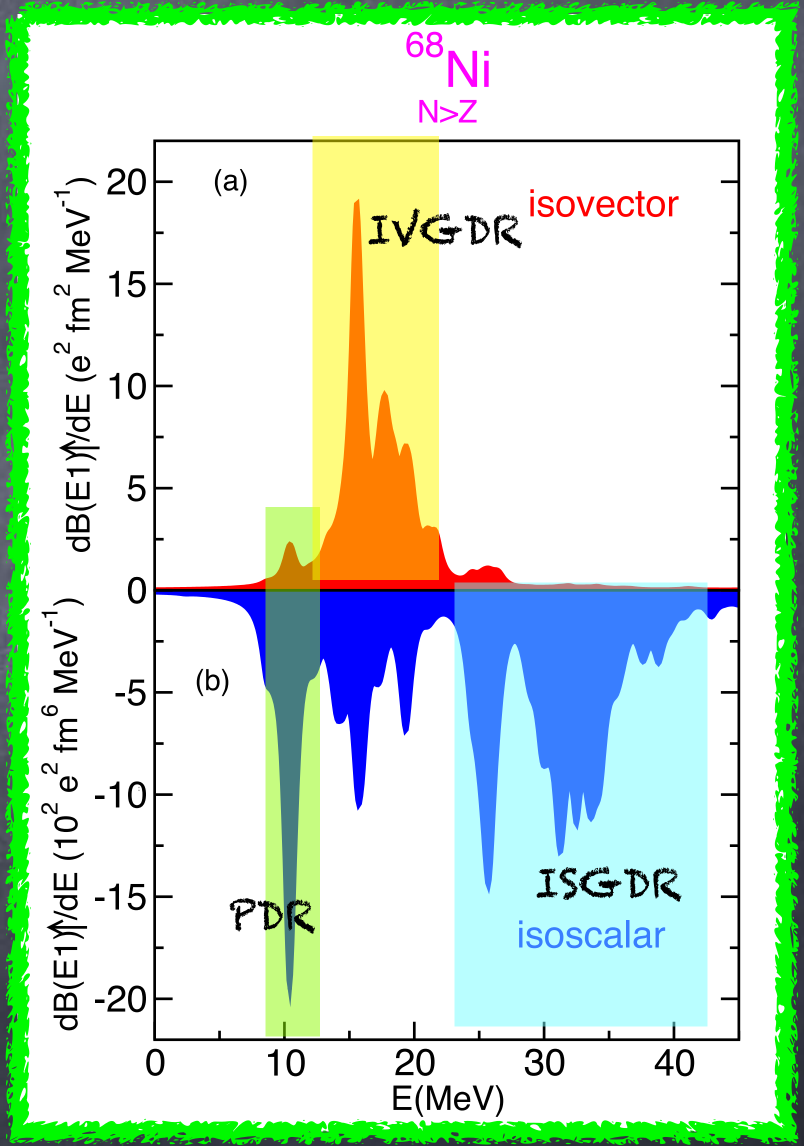


All the theoretical calculations agree on the structure of the transition densities for the PDR.

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

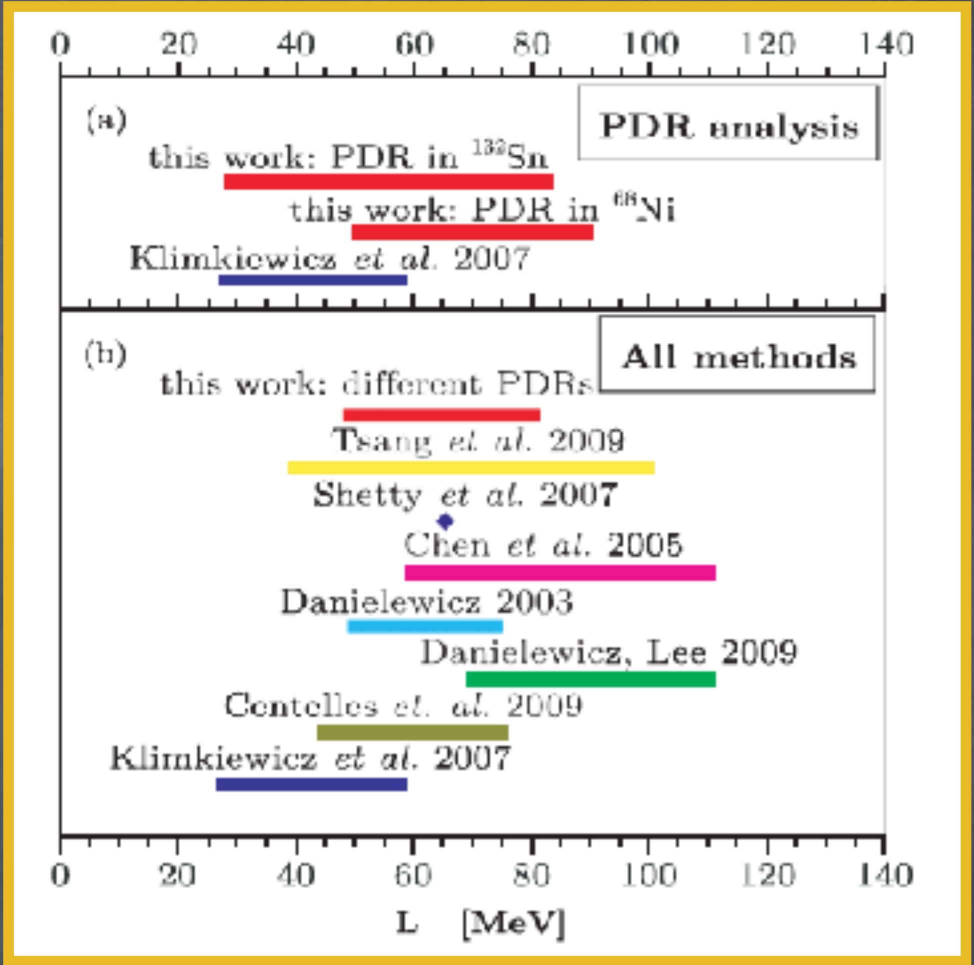


At the nuclear surface the contribution comes only from the neutrons, therefore the isoscalar and isovector transition densities have the same magnitude.



As a consequence this mode can be exited both with isoscalar and isovector probes

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

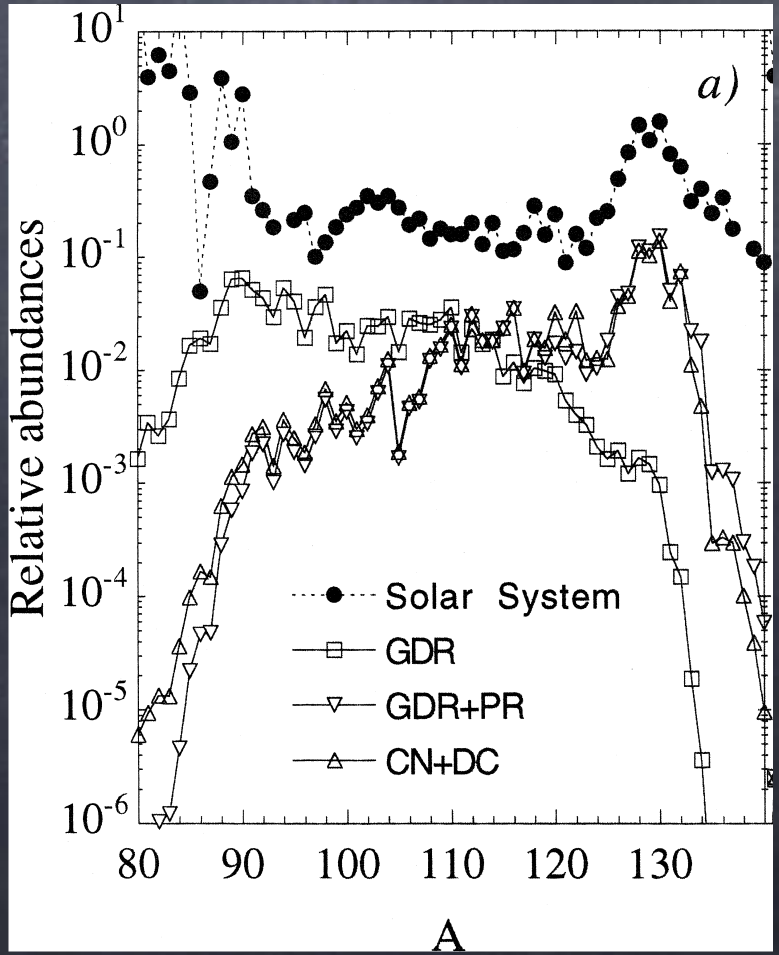


Carbone et al., PRC 81 (2010) 041301(R)

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

The presence of the PDR has consequences on rapid neutron capture process (r-process)

S. Goriely, PLB 436 (1998) 10



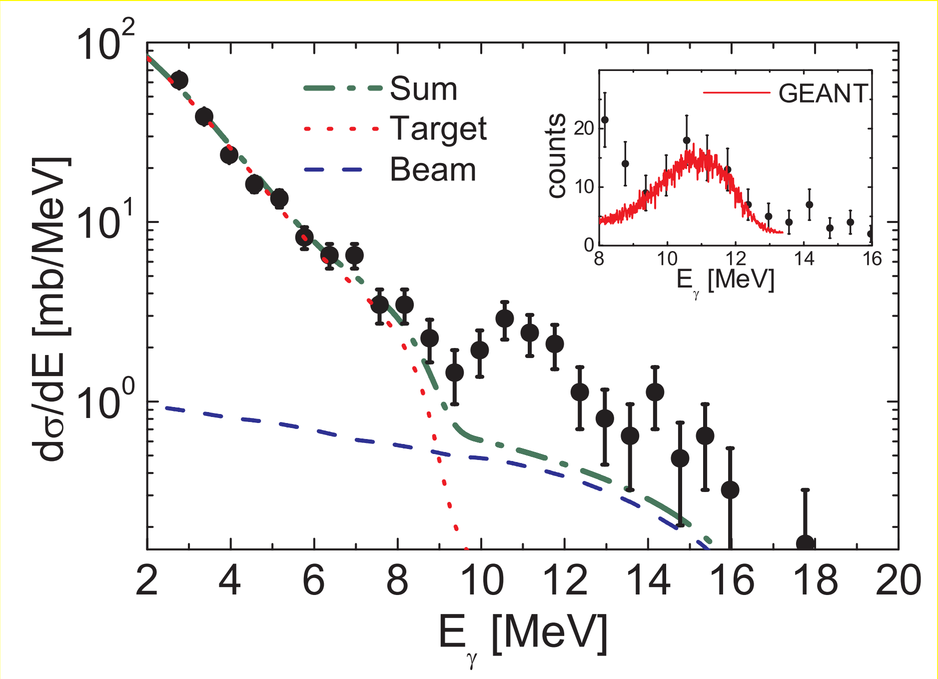
Experimental data
isovector probe

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

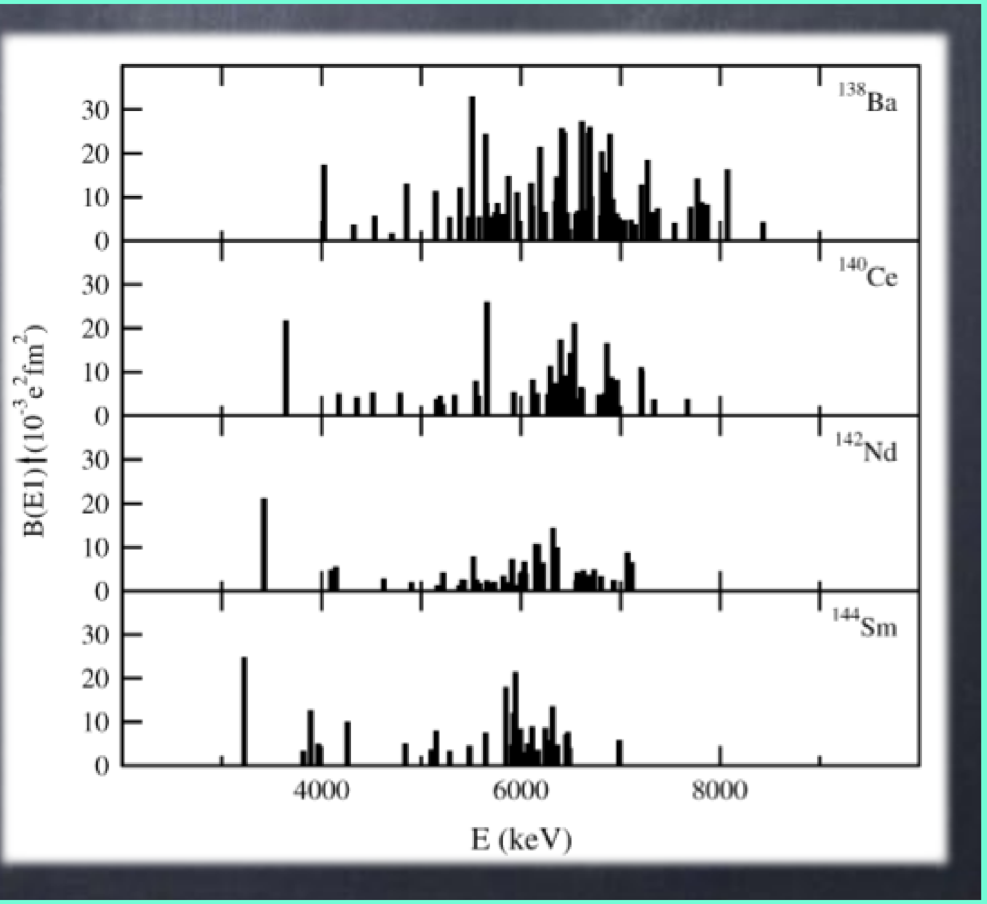


BELOW NEUTRON SEPARATION THRESHOLD

stable nuclei

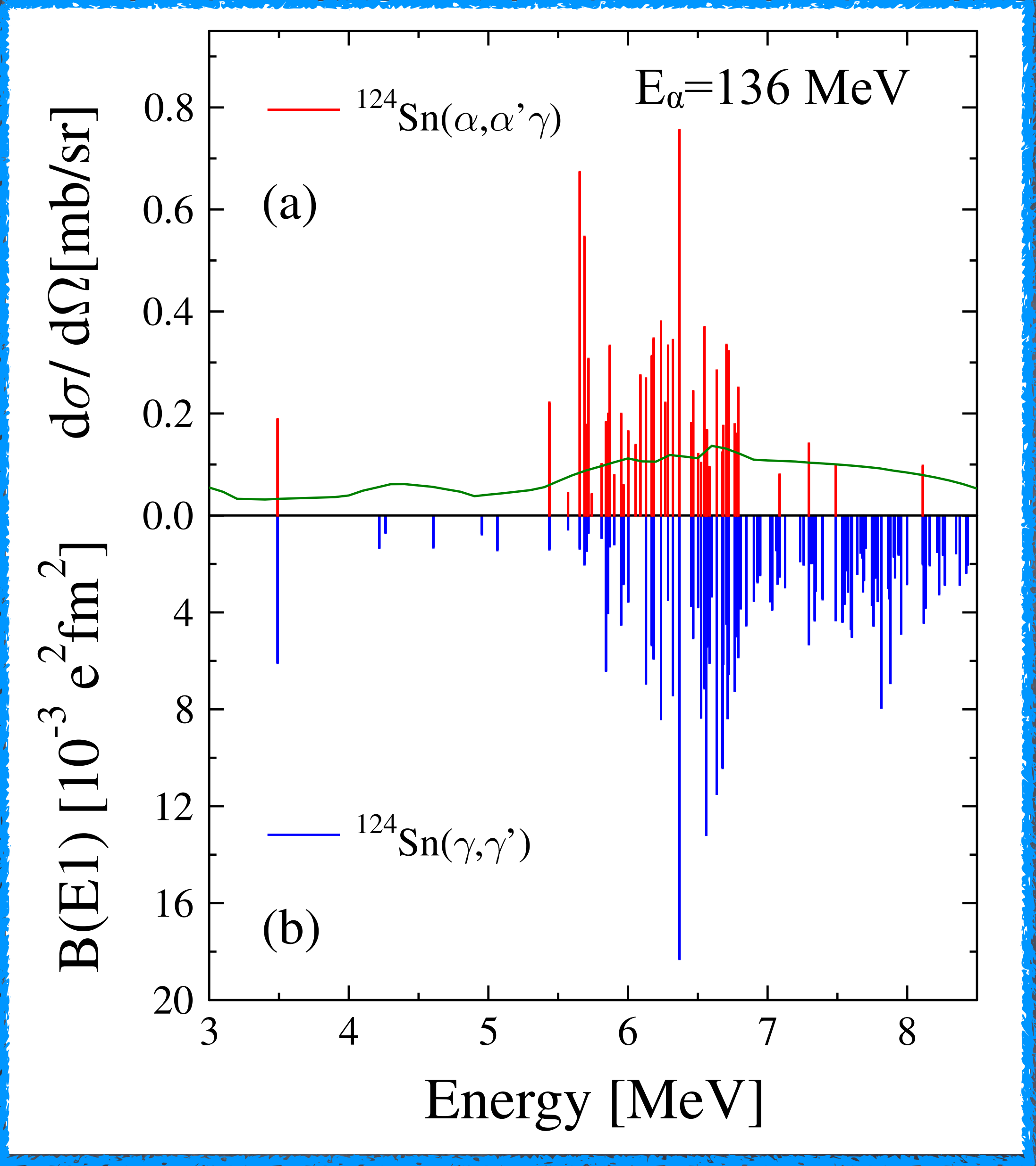
- ◉ with (γ,γ') studies (Darmstadt University) →

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

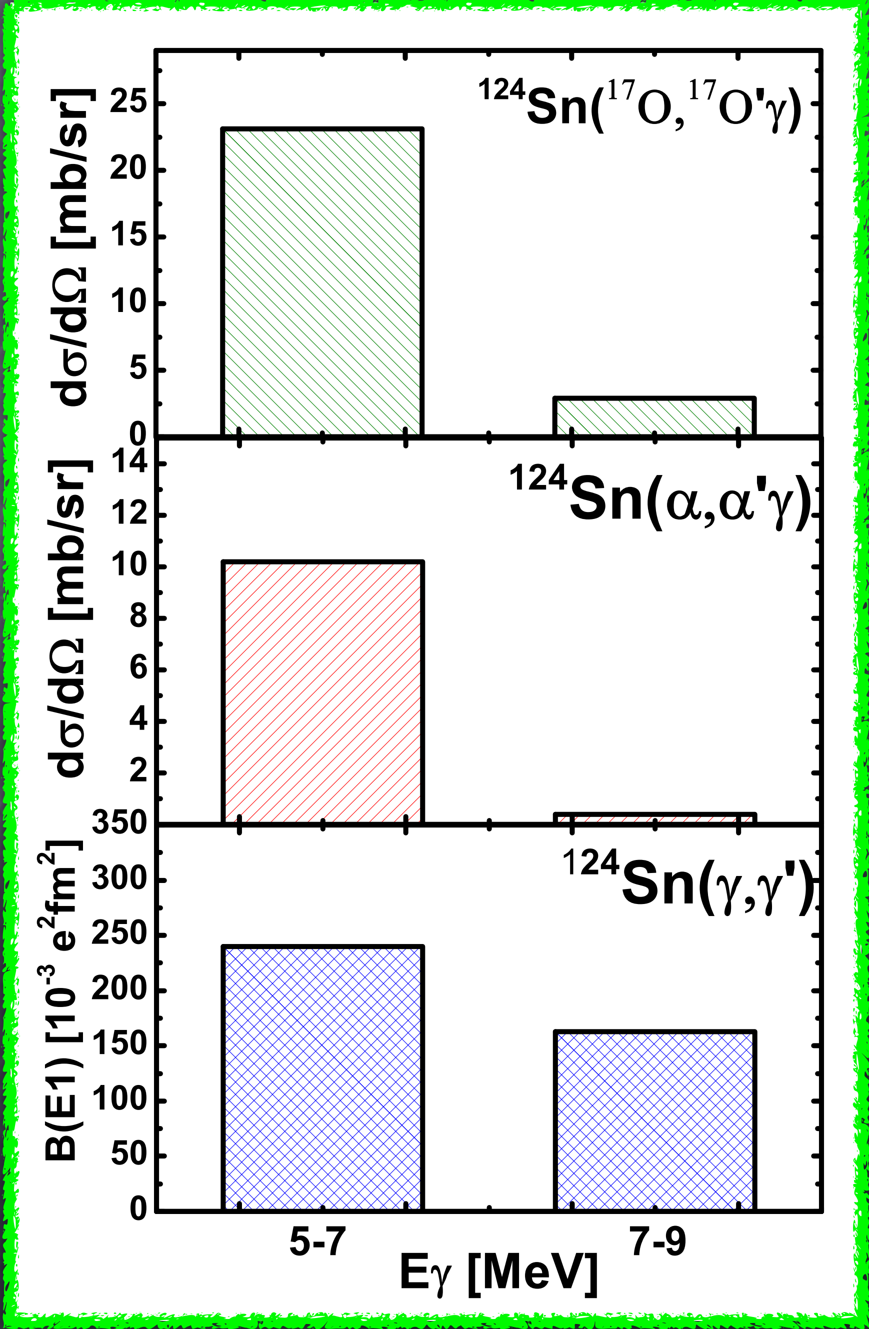


Experimental data isoscalar probe

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



The splitting of the PDR

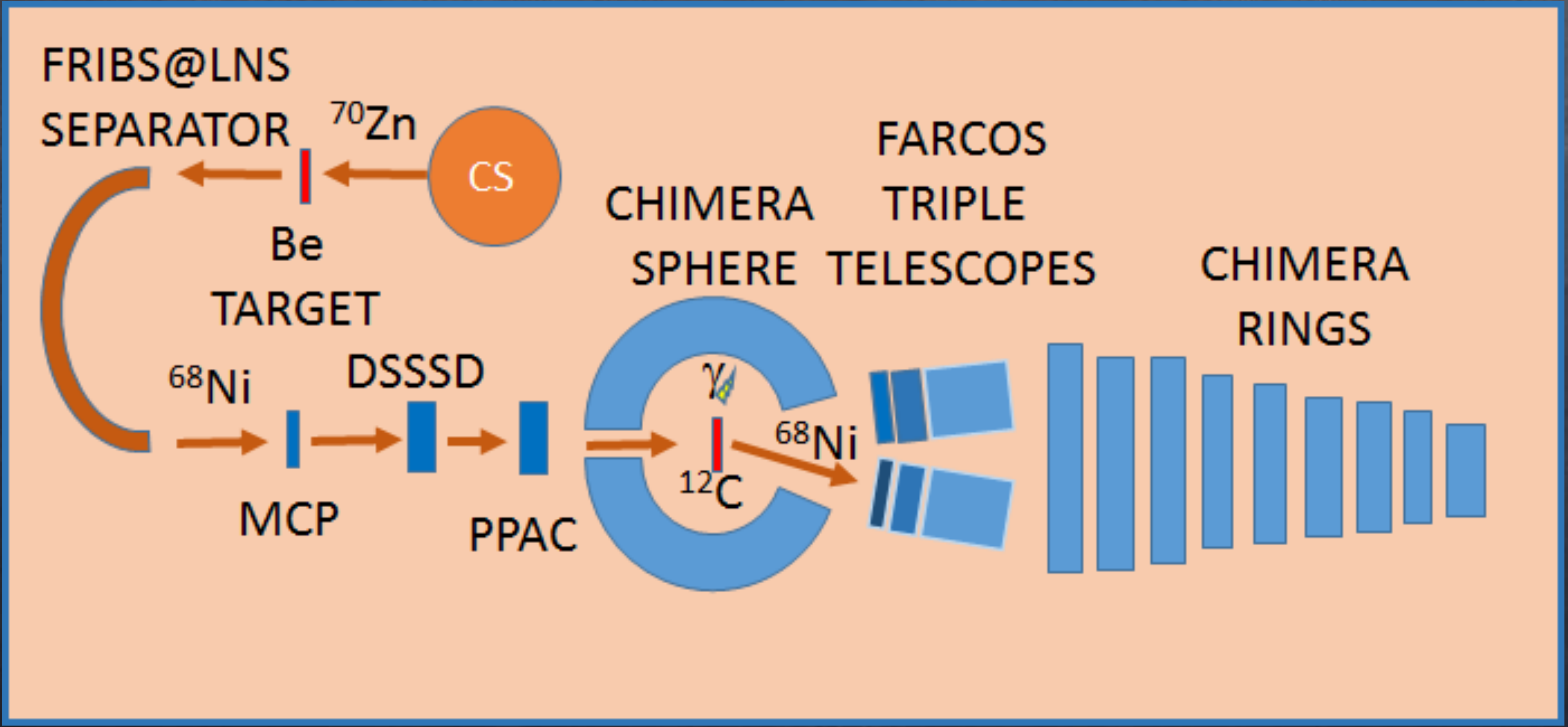


D. Savran et al., PRL 97 (2006) 172502
J. Endres et al., PRL 80(2009) 034302
J. Endres et al., PRL 105 (2010) 212503
F.C.L. Crespi et al., PRL 113 (2014) 012501
L. Pellegri et al., PLB 738 (2014) 519
F.C.L. Crespi et al., PRC 91 (2015) 024323

Measurement of PDR in unstable nucleus (^{68}Ni) via isoscalar probe at LNS Catania

^{68}Ni + ^{12}C @ 28 A•MeV

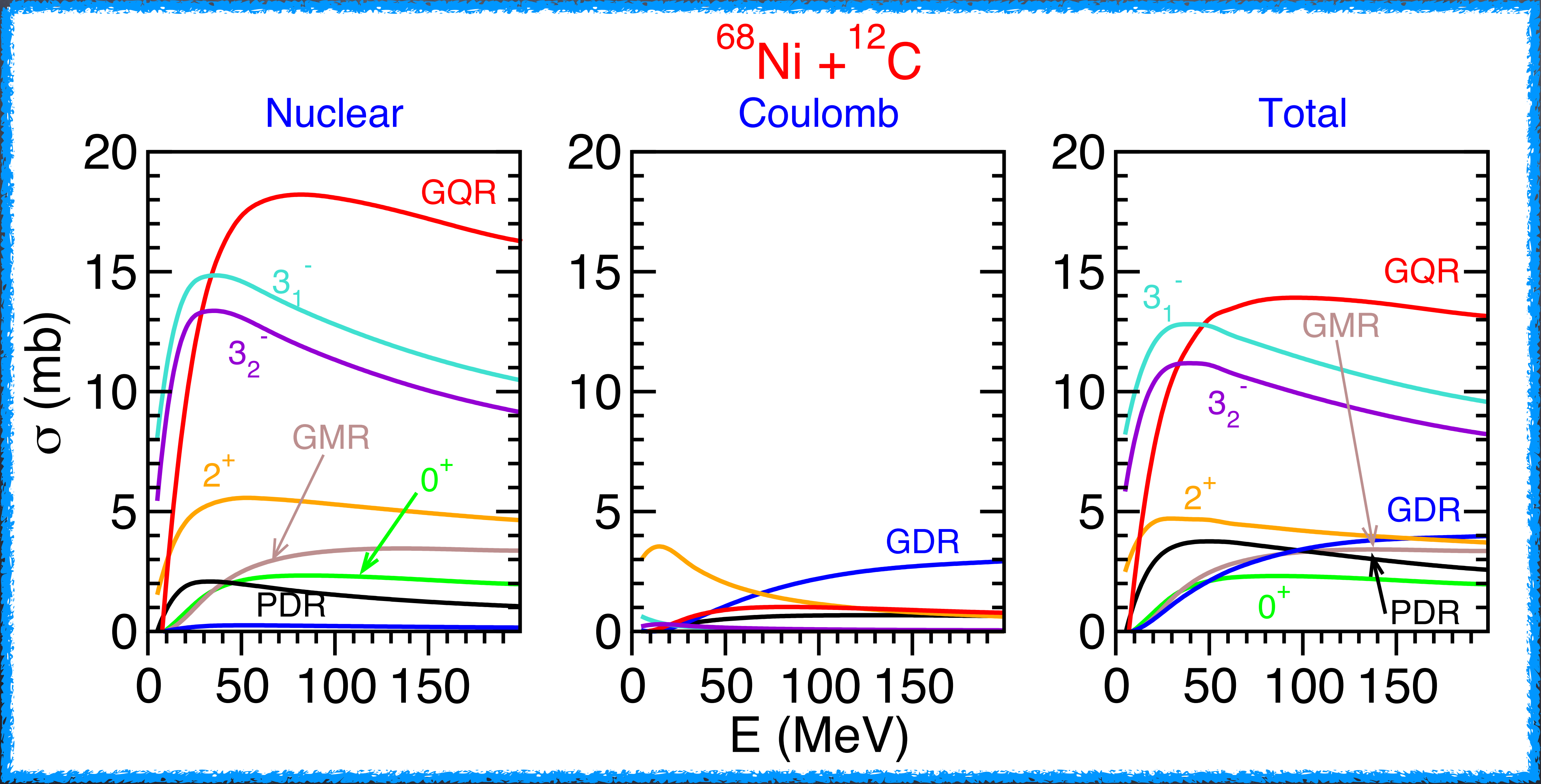
At INFN-LNS a primary ^{70}Zn beam of 40 MeV/A on a ^{9}Be target produce a secondary ^{68}Ni beam in the CHIMERA hall at 28 A•MeV which is sent on a ^{12}C target.



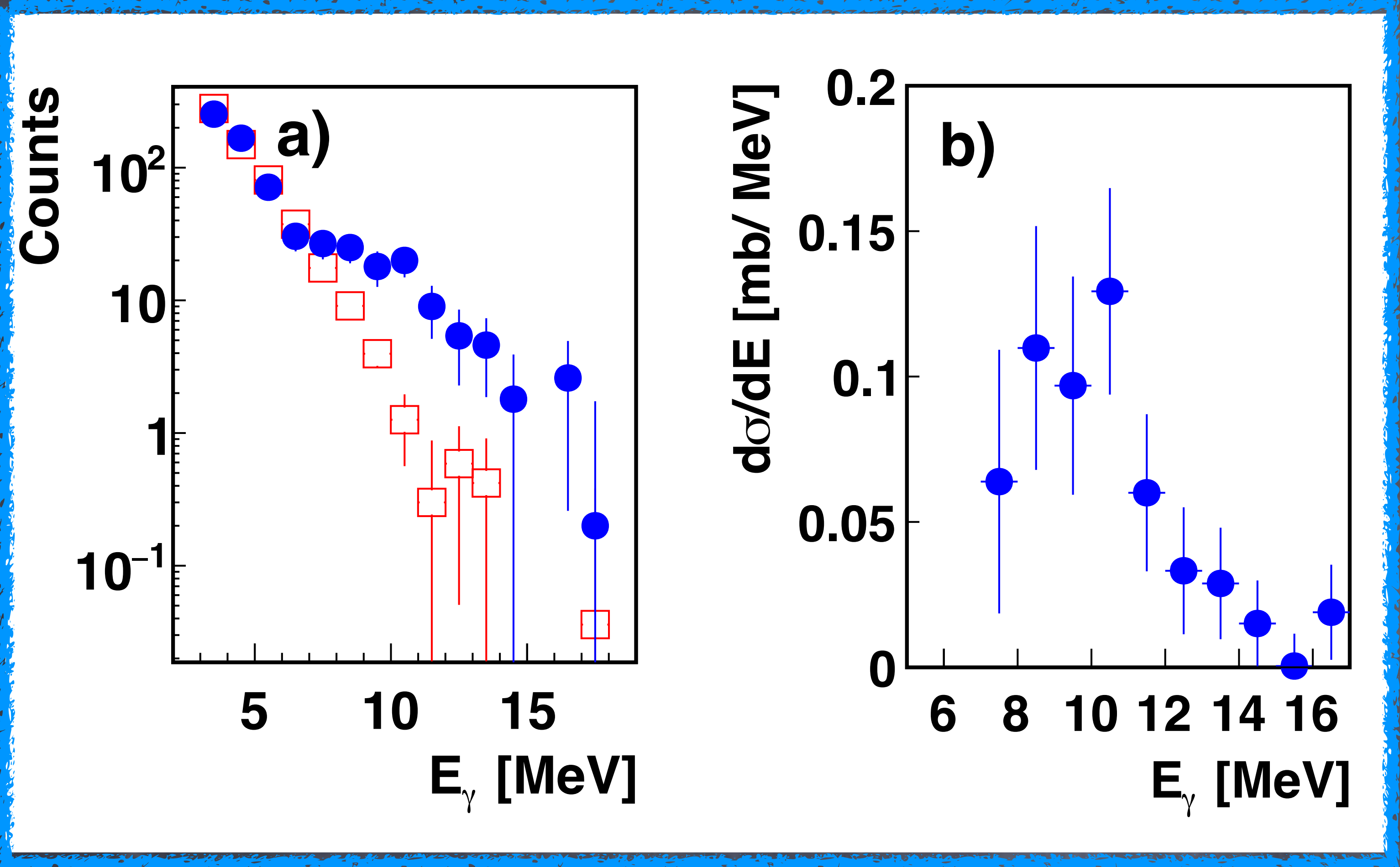
Measurement of PDR in unstable nucleus (^{68}Ni) via isoscalar probe at LNS Catania

^{68}Ni + ^{12}C @ 28 A•MeV

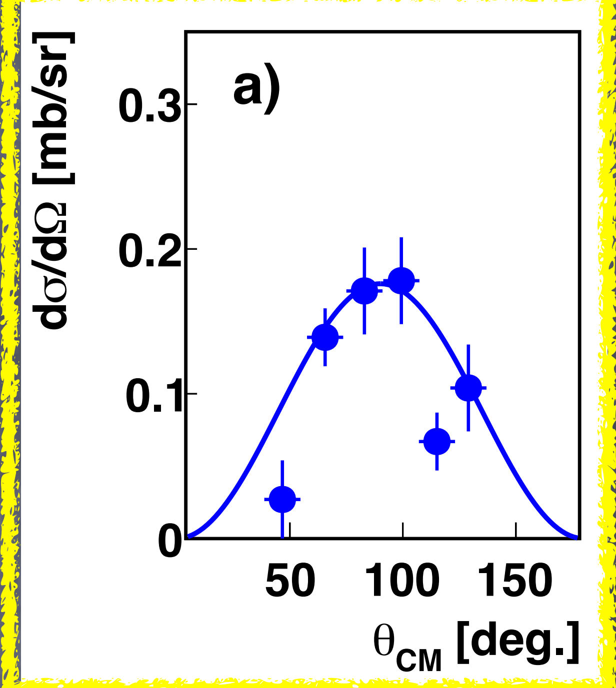
Semiclassical calculations: RPA transition densities, form factors build up with the double folding procedure



The γ-decay of the pygmy resonance, in coincidence with the ^{68}Ni isotope, has been measured using the CsI of the CHIMERA detector.

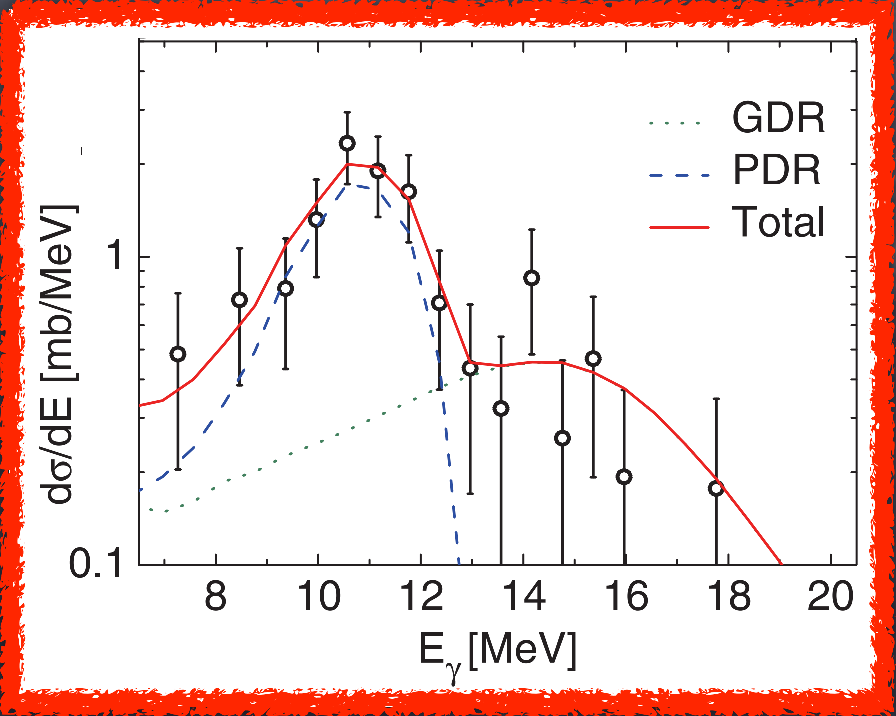


γ-ray angular distribution for E1



^{68}Ni + Au @ 600 A MeV

O. Wieland et al.
PRL 102 (2009) 092502



Apparently there is no splitting for the PDR above the neutron threshold emission

For the study of the Pygmy Dipole Resonance the use of an isoscalar probe has brought to light novel aspects of this mode.

These low-lying dipole states can be considered as a good laboratory for the study of various aspects of the interplay between isoscalar and isovector modes.

(I.Hamamoto and H.Sagawa PRC 96, 064312 (2017))

The mixing of the isoscalar and isovector modes is relevant in the measurement done with isoscalar probes

In the experimental analysis for these cases it is of paramount importance the radial form factors used.

T. J. Deal, NPA 217 (1973) 210;

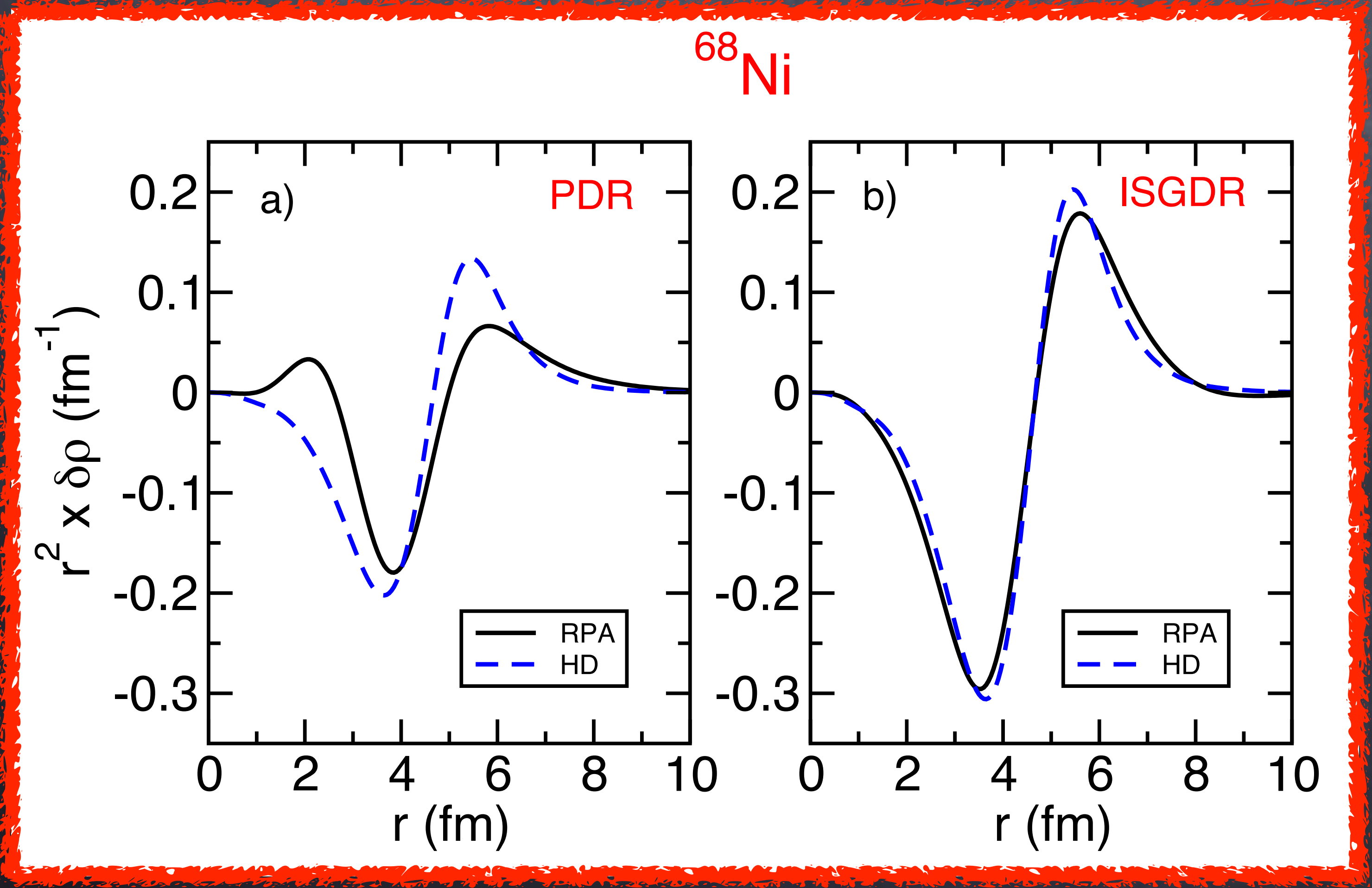
M. N. Harakeh and A. E. L. Dieperink PRC 23 (1981) 2329

Macroscopic transition density for the ISGDR which is also used for the PDR

$$\rho^1(r) = -\frac{\beta_1}{R\sqrt{3}}\left[10r + (3r^2 - \frac{5}{3} < r^2 >)\frac{d}{dr})\right]\rho_0(r)$$

$$\beta_1^2 = -\left(\frac{6\pi\hbar^2}{mAE_x}\right)\frac{R^2}{11 < r^4 > -\frac{25}{3} < r^2 >^2}$$

R is the half-density radius of the mass distribution.

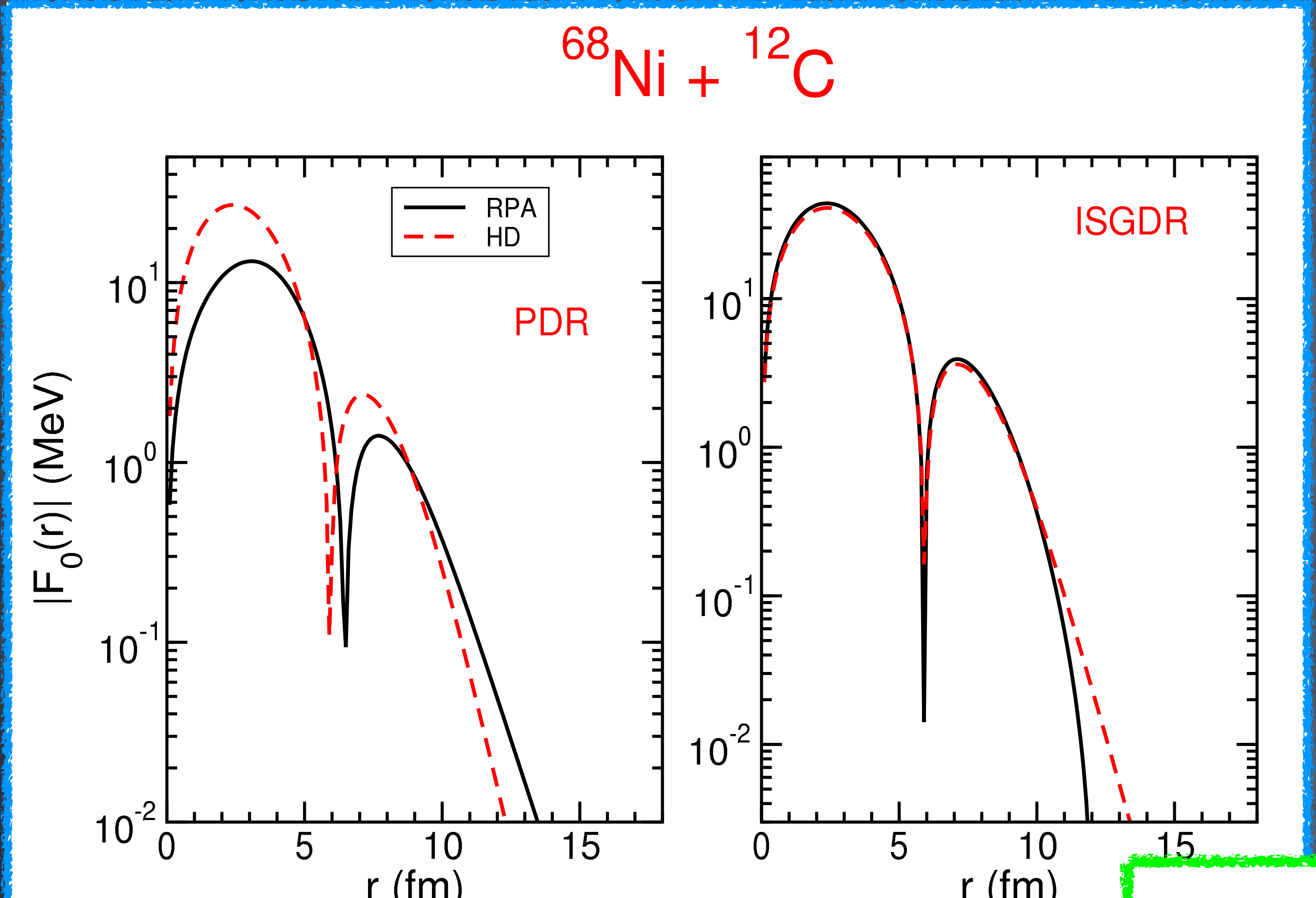


For both states, the macroscopic transition density has been scaled according to the following condition

$$\int_0^\infty \rho^1_{RPA}(r)\, r^5\, dr =$$

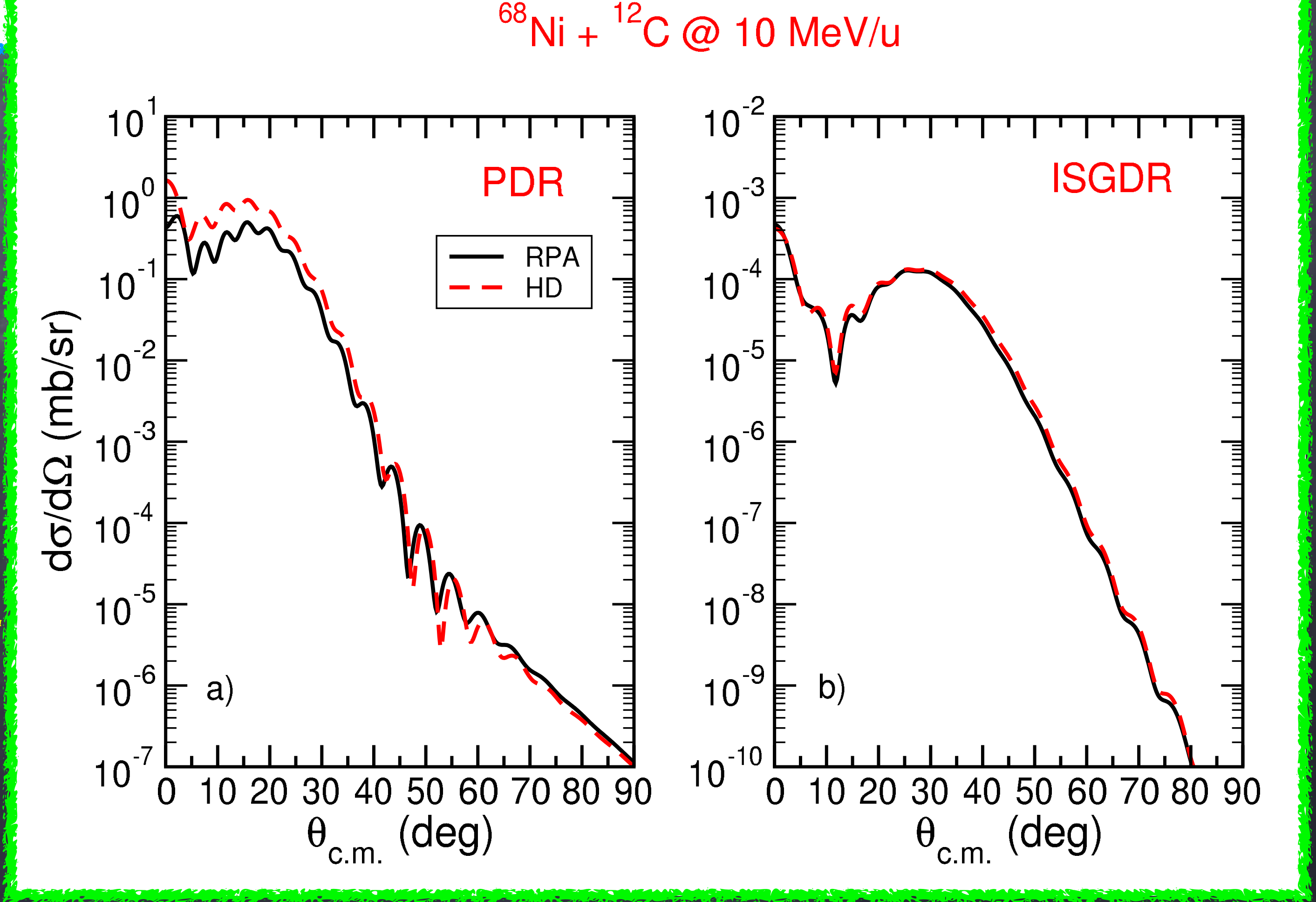
$$\int_0^\infty \rho^1_{macro}(r)\, r^5\, dr$$

Double folding procedure



E.G. Lanza, A. Vitturi and M.V. Andrés, PRC 91, 054607 (2015)

The form factors have been obtained with the double folding procedure with the M3Y nucleon-nucleon potential and with the micro (RPA) and macro transition densities



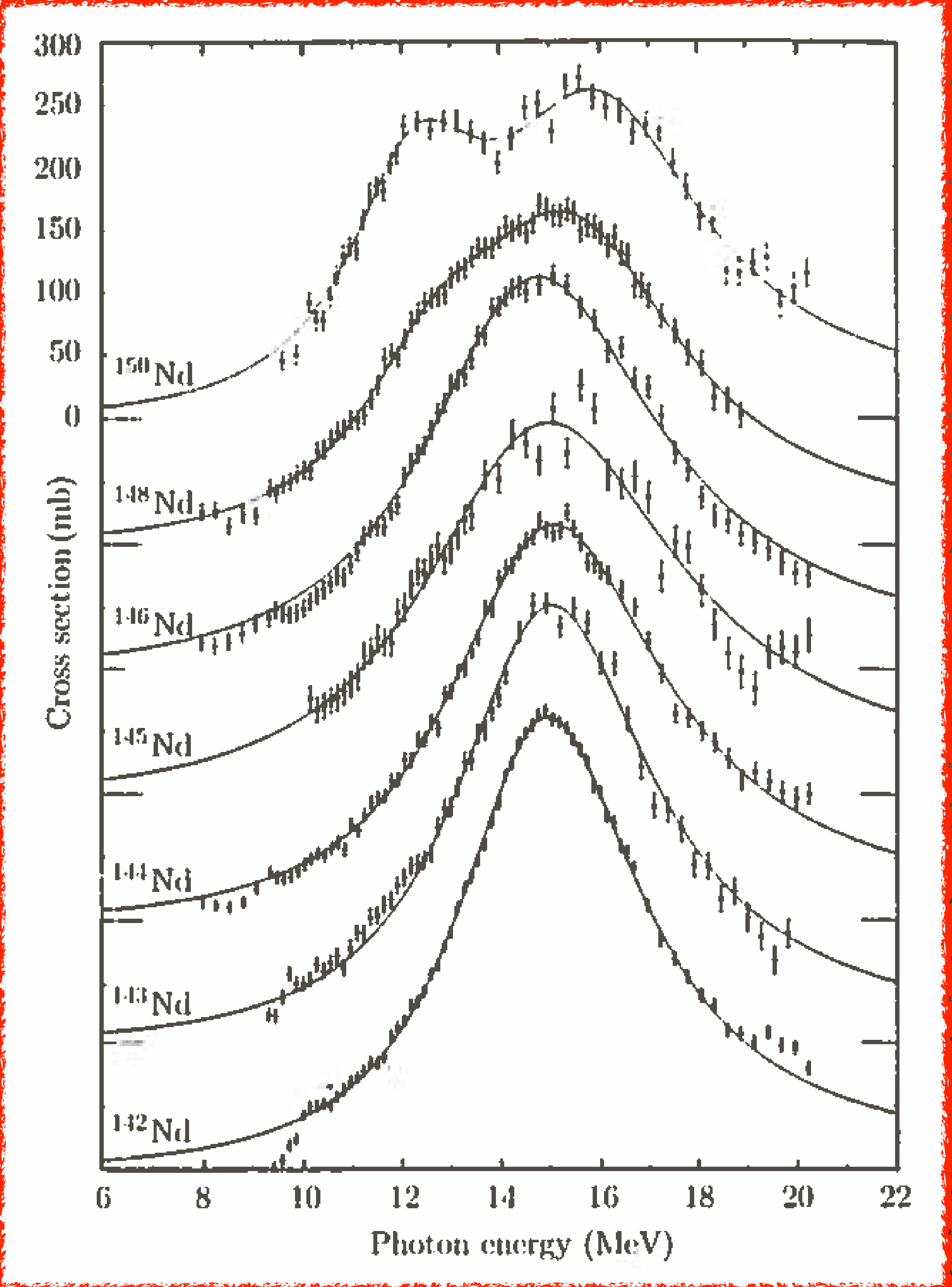
DWBA calculations done with the DWUCK4 code

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

Splitting of the GDR

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

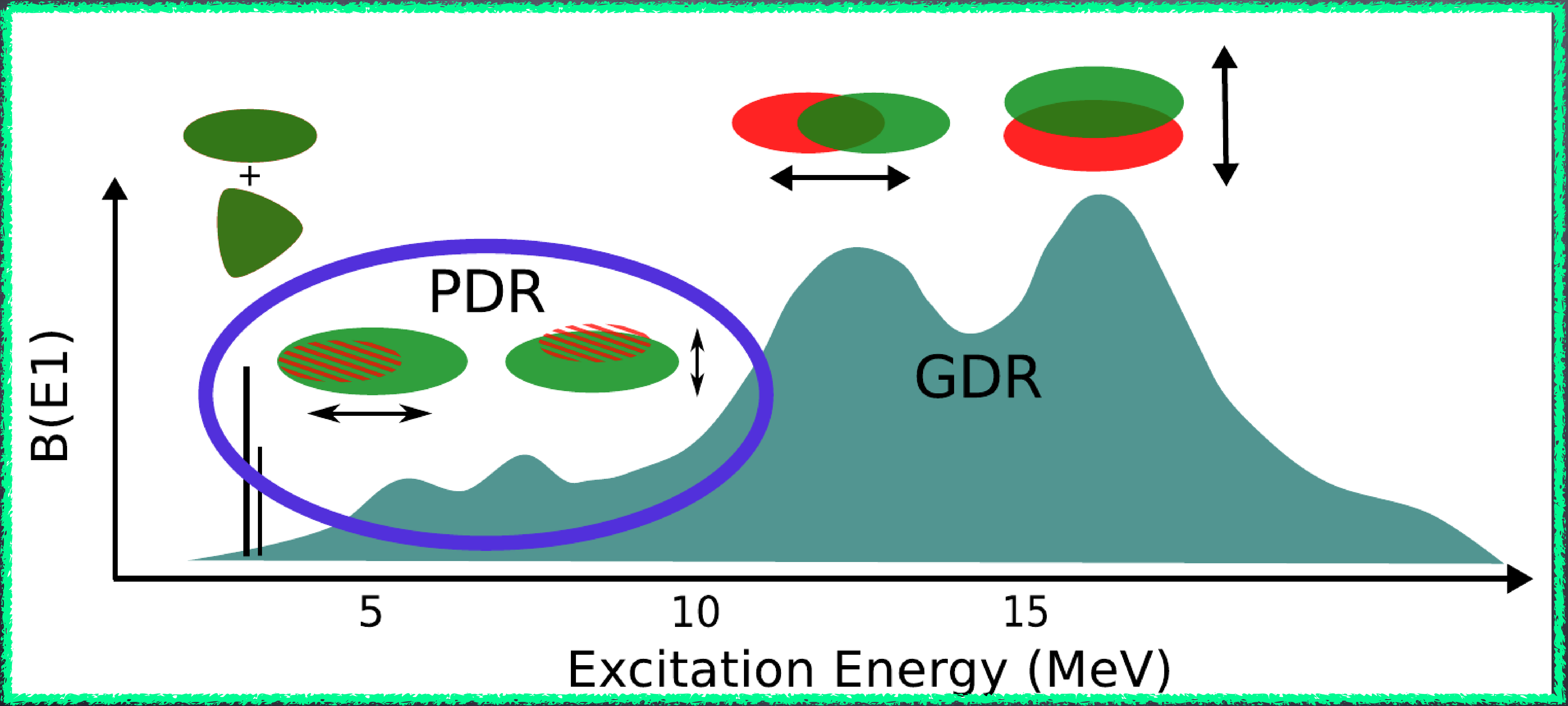
Bohr and Mottelson book



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

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

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



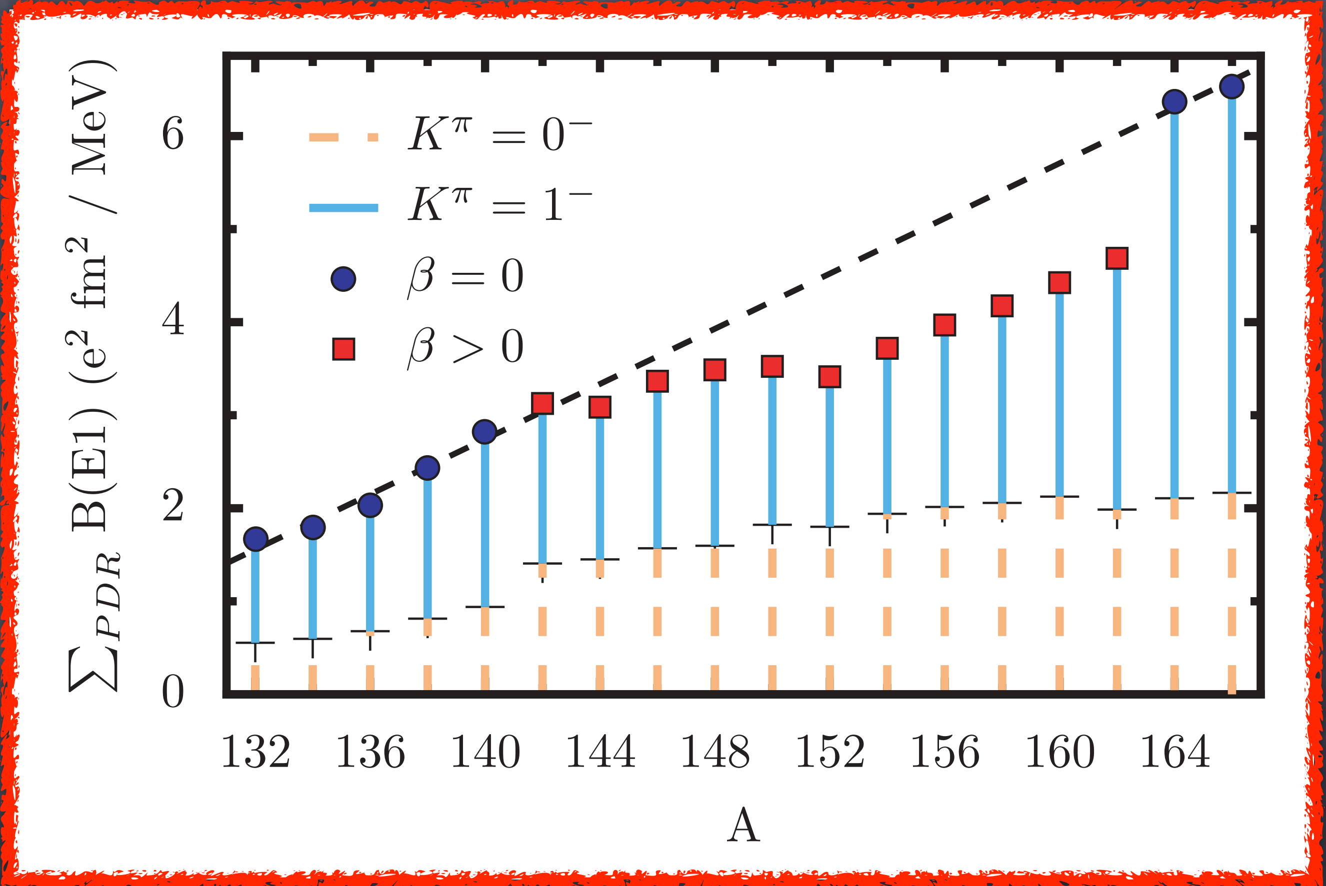
A. Krugmann, Thesis (2014), TU-Darmstadt,

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.

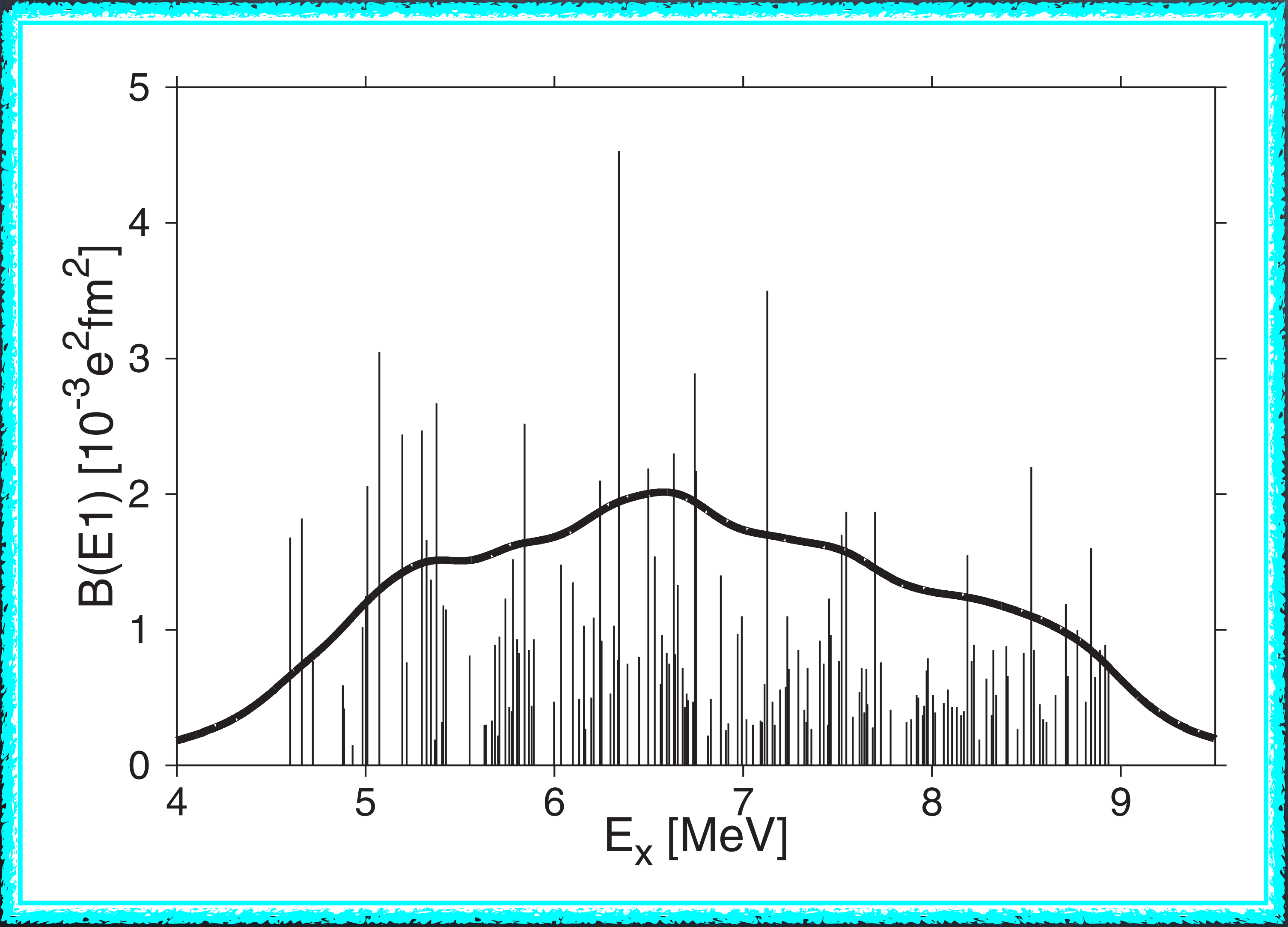
The two calculations use different treatments for the pairing. Yoshida et al. adopts the Bogoliubov method and the other the BCS approximation. The treatment of continuum and weakly bound orbitals is also different: The wave functions are expanded in the harmonic oscillator basis in Peña et al. while the other express them in the coordinate space. 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)

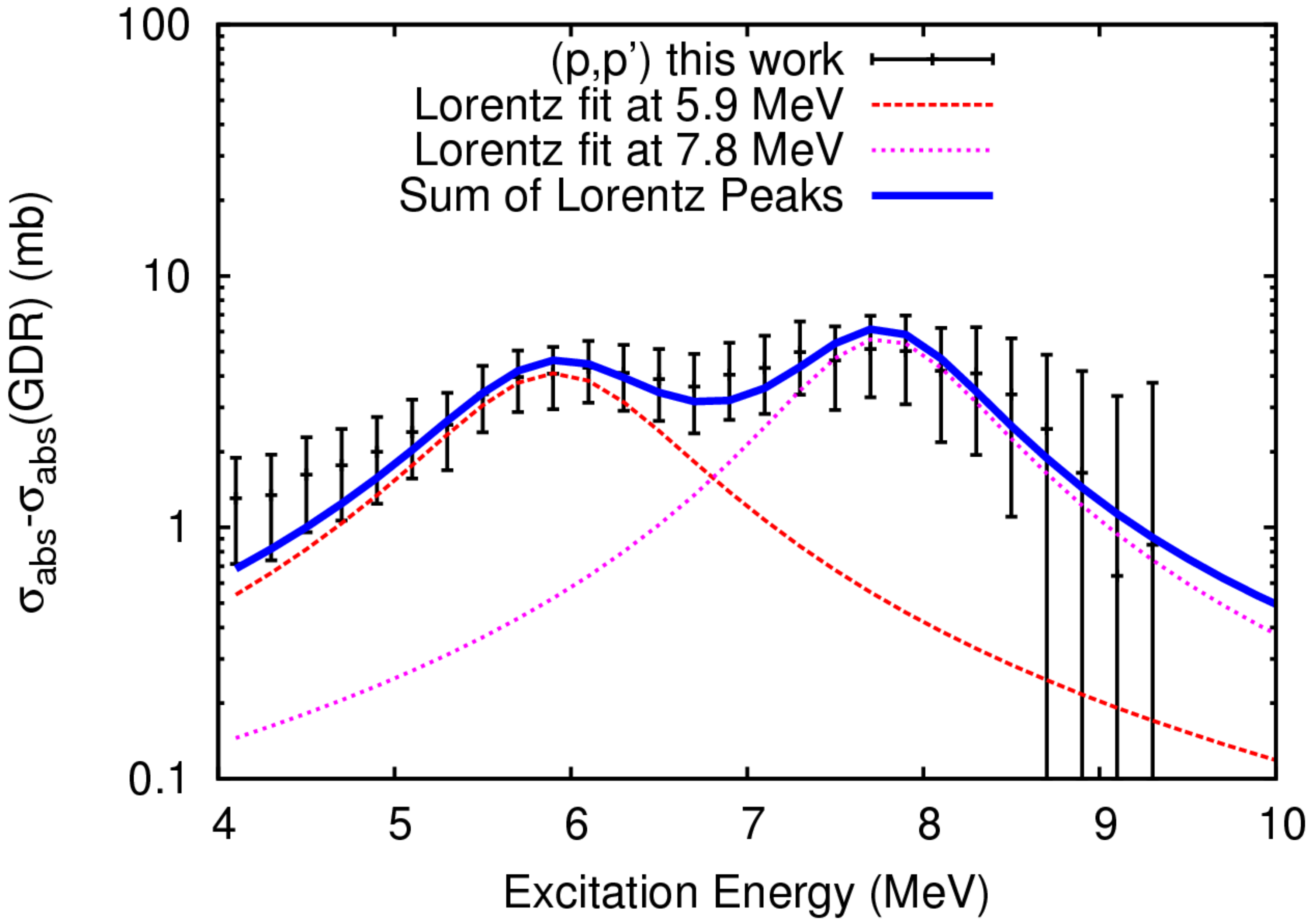
It is known that the GDR is split into two peaks



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

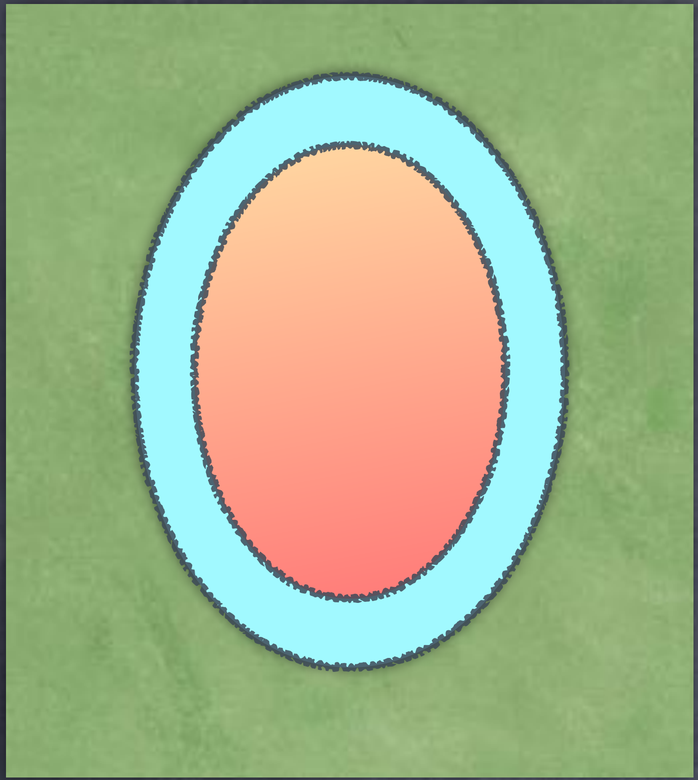
A pronounced splitting, as seen in the GDR ,is not evident

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

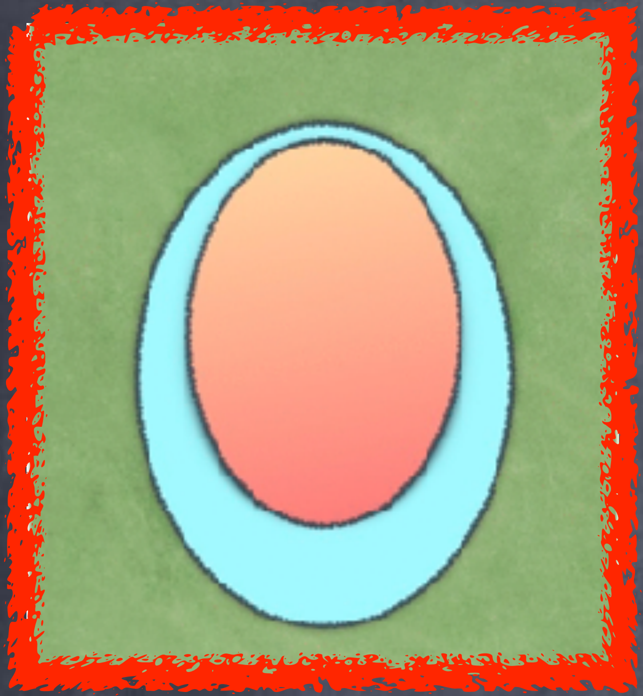
Fermi distribution with axially symmetric deformed surface with different geometries

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

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

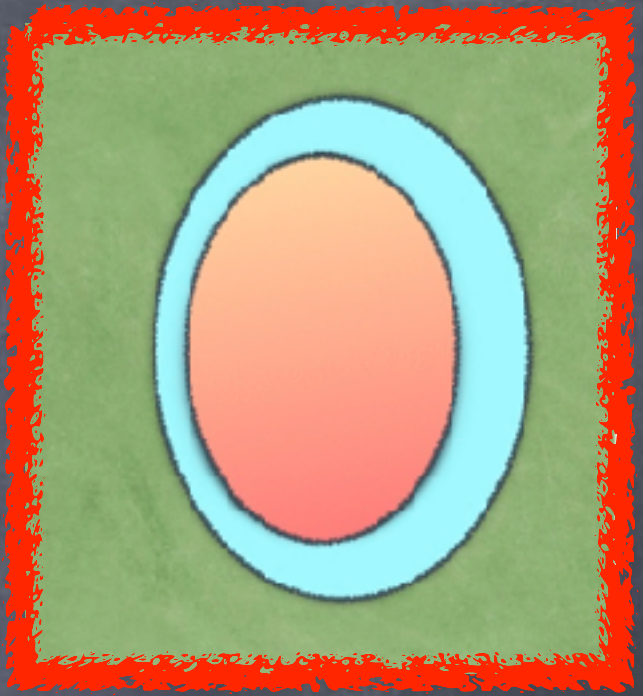
Pygmy for deformed nuclei

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



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

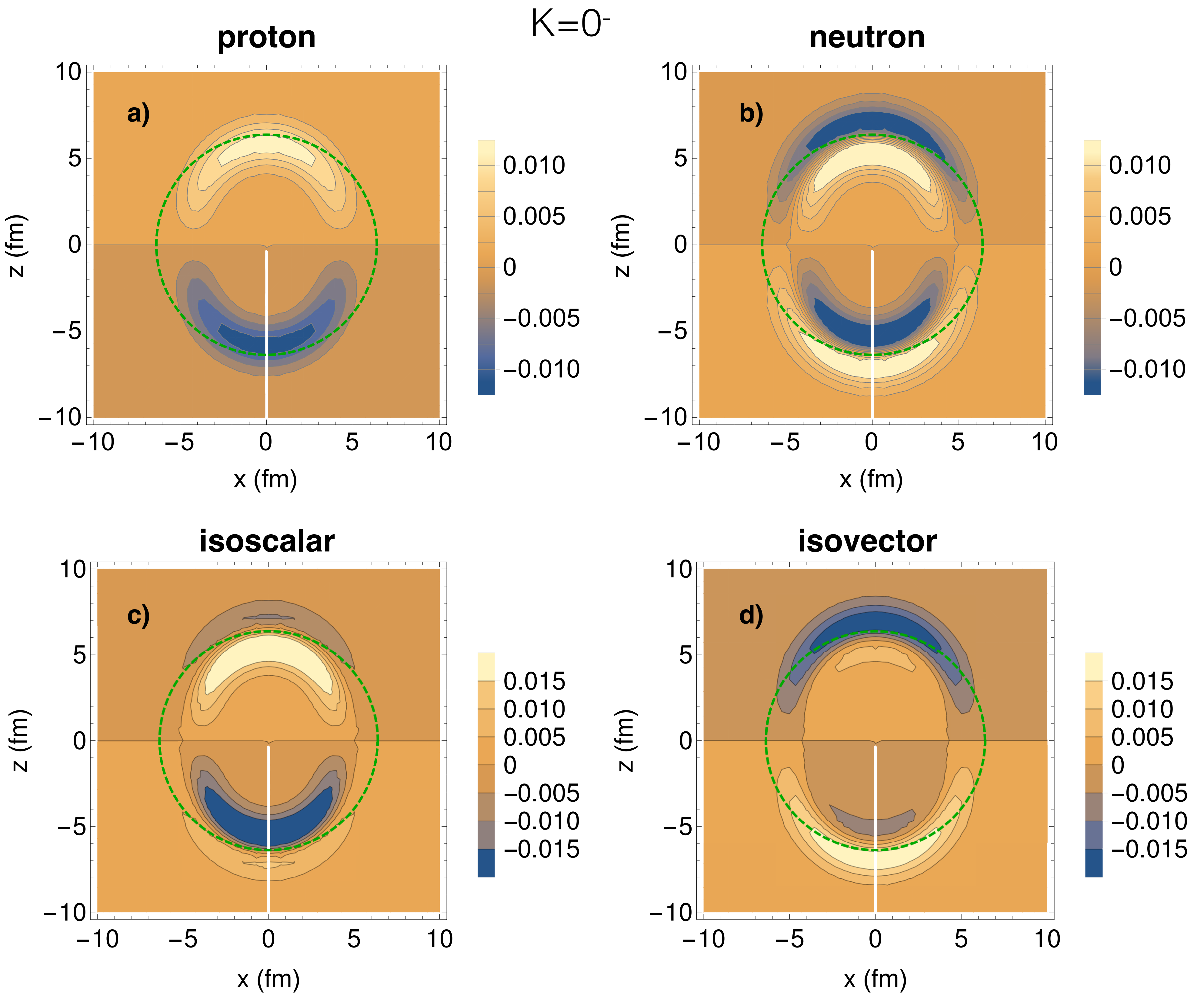
$K^{\pi}=1^{-}$



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

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

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

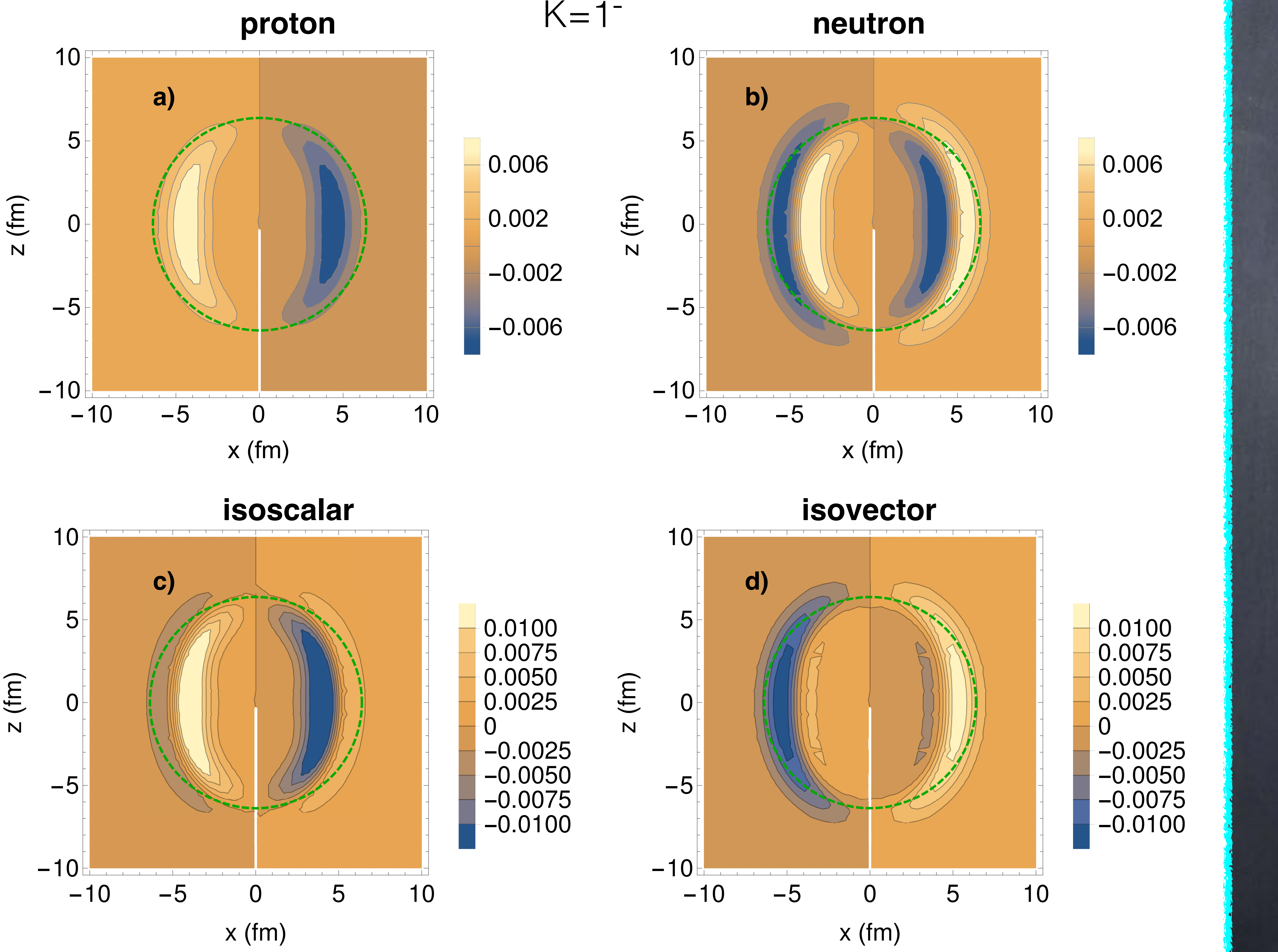


$\beta_p=\beta_n=0.31$

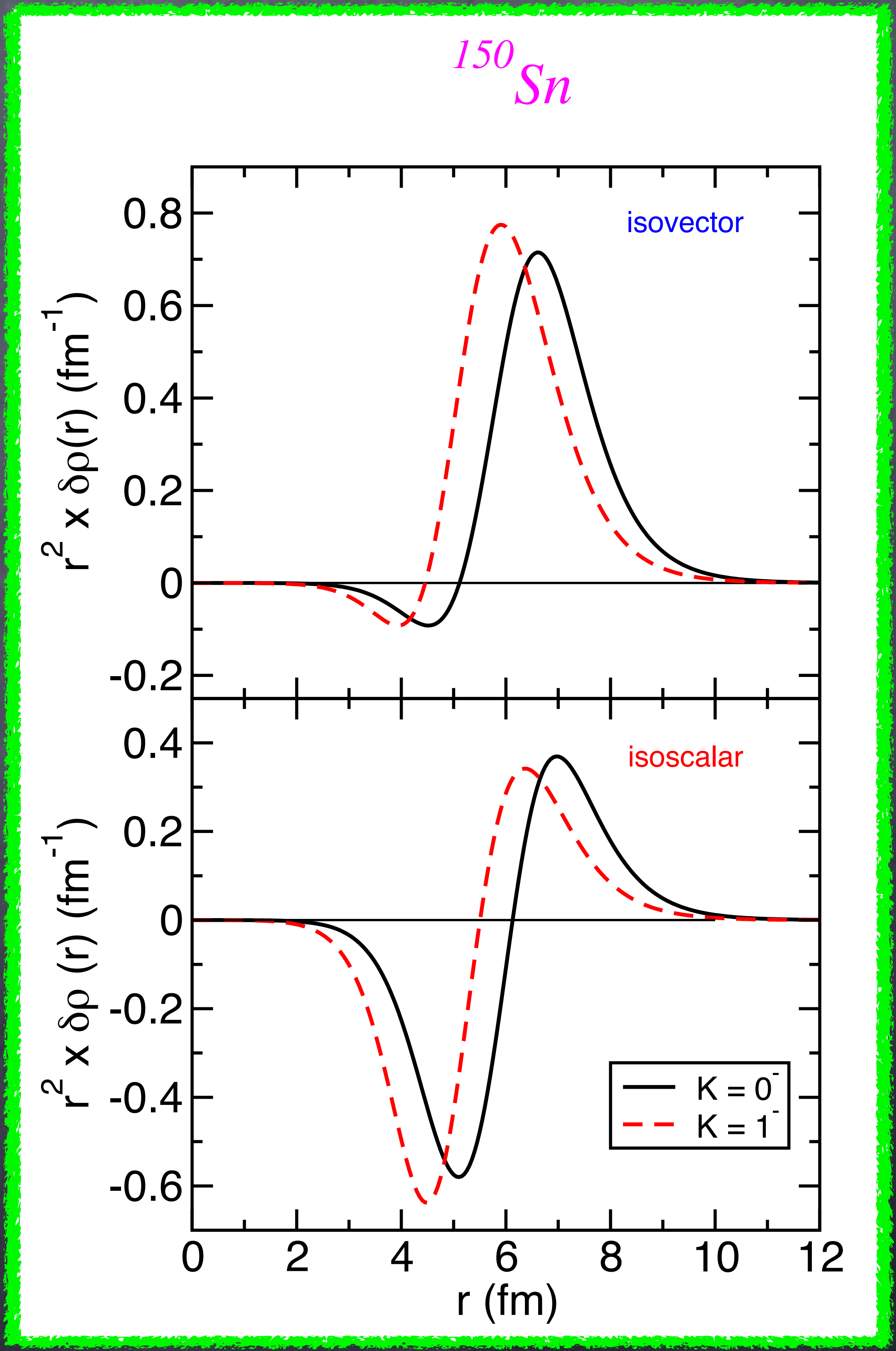
$K^\pi=0^-$

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

$K=1^-$

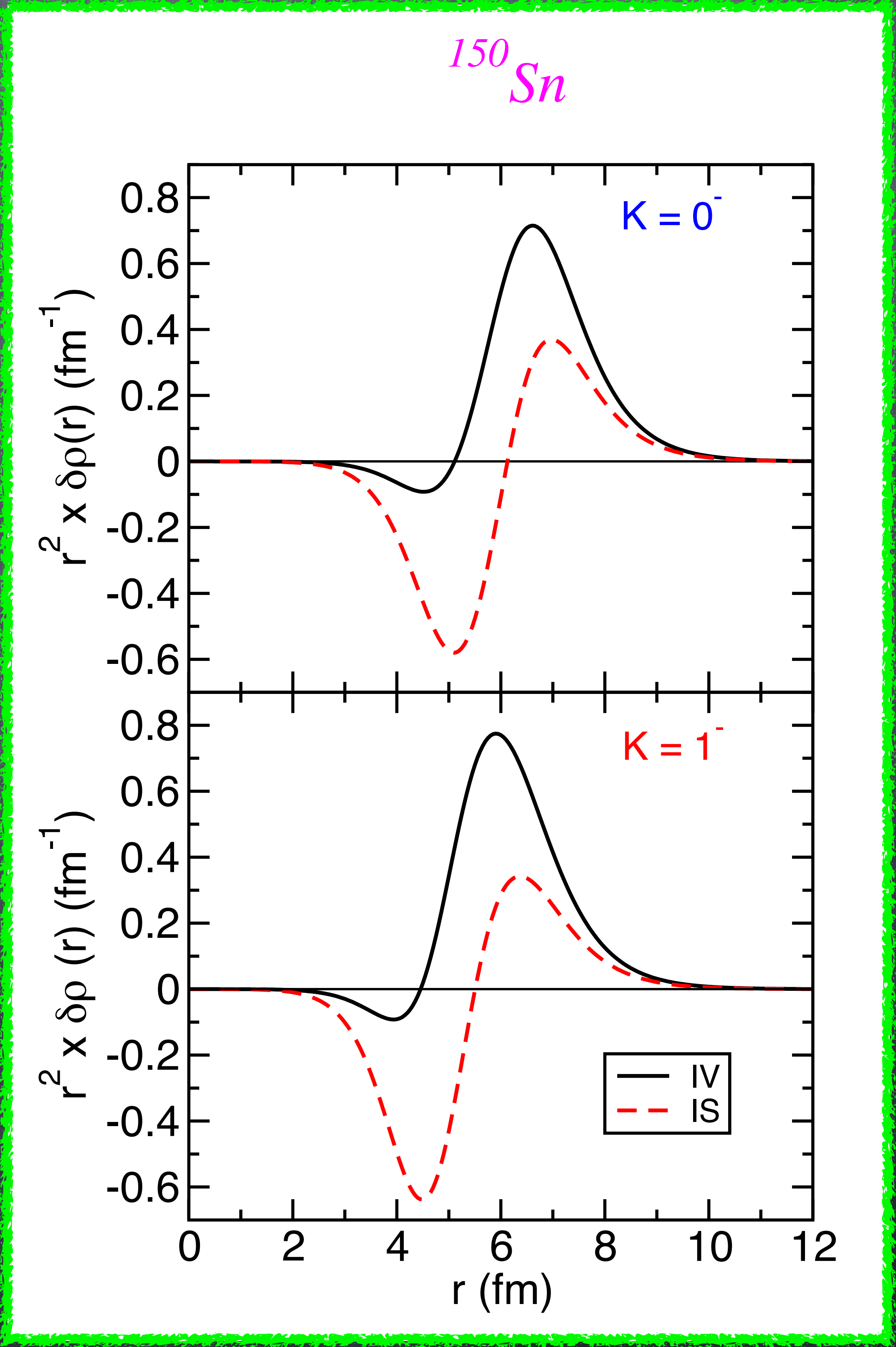

proton
a)
neutron
b)
isoscalar
c)
isovector
d)
z (fm)
x (fm)
10
5
0
−5
−10
0.006
0.002
−0.002
−0.006
0.0100
0.0075
0.0050
0.0025
0
−0.0025
−0.0050
−0.0075
−0.0100

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



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

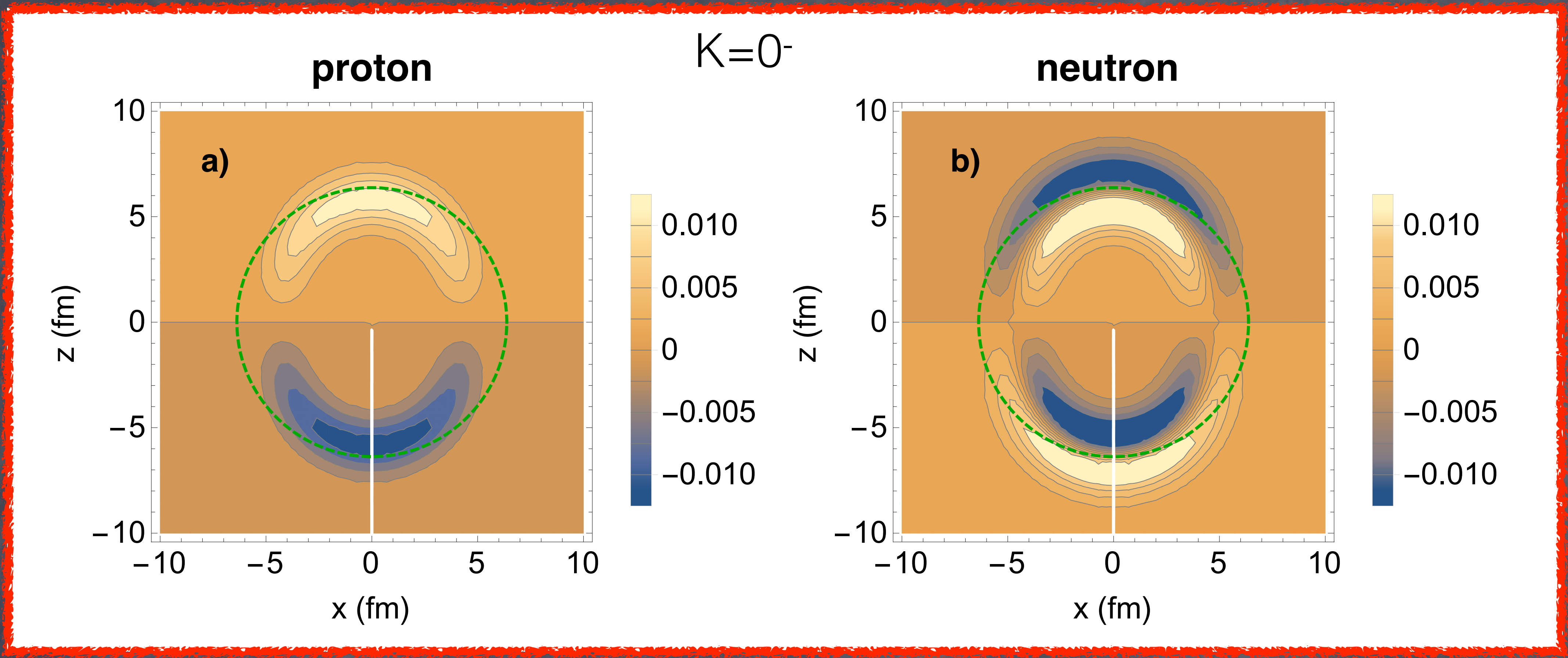
Like in the spherical case, for the PDR there is a strong contribution of the isoscalar transition density at the nuclear surface

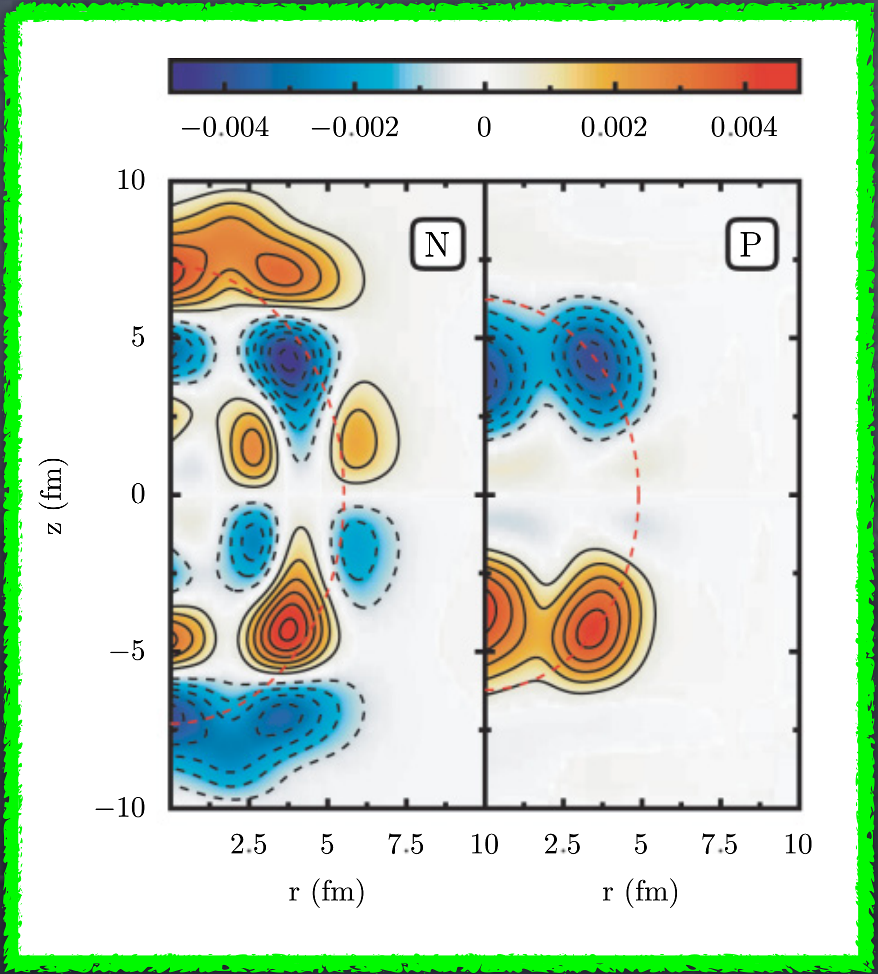


Isoscalar and isovector reduced dipole transition probabilities

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

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





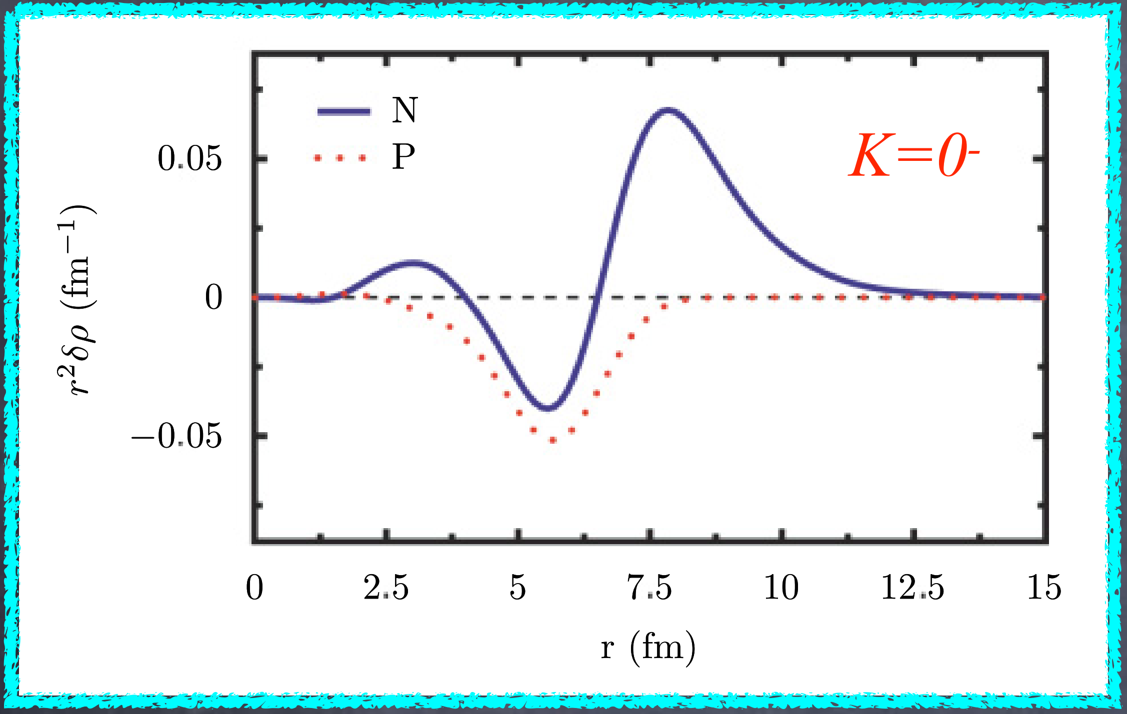
Calculation done within the relativistic QRPA based on a relativistic HFB basis.

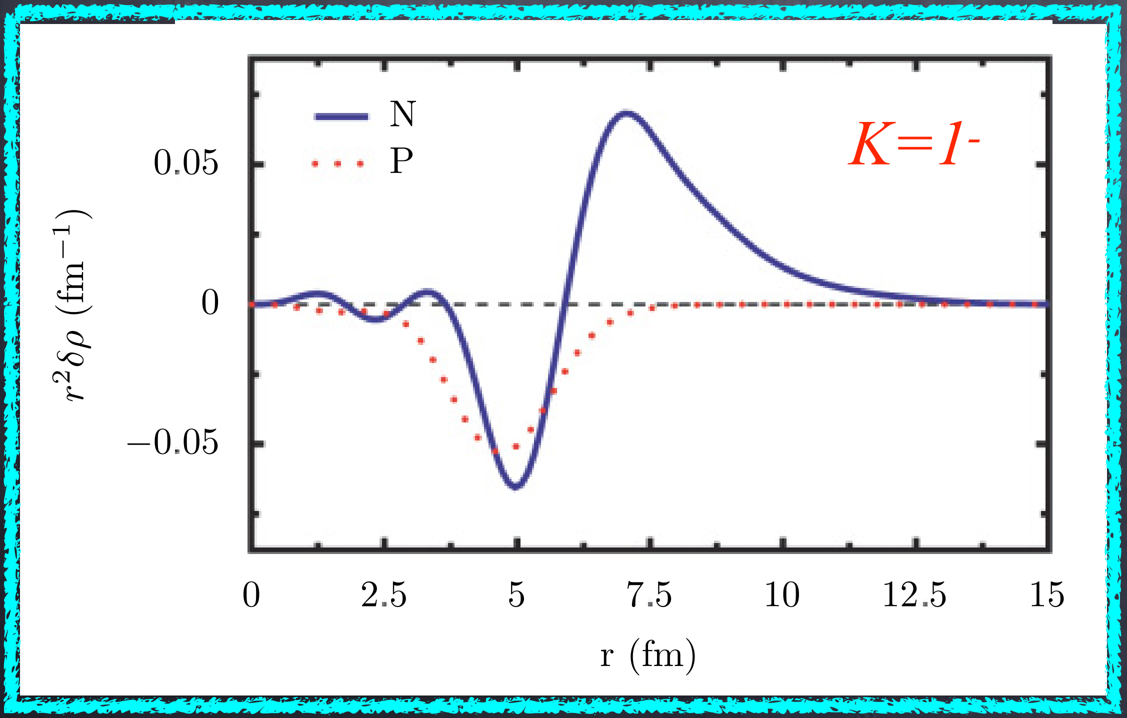
^{150}Sn

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

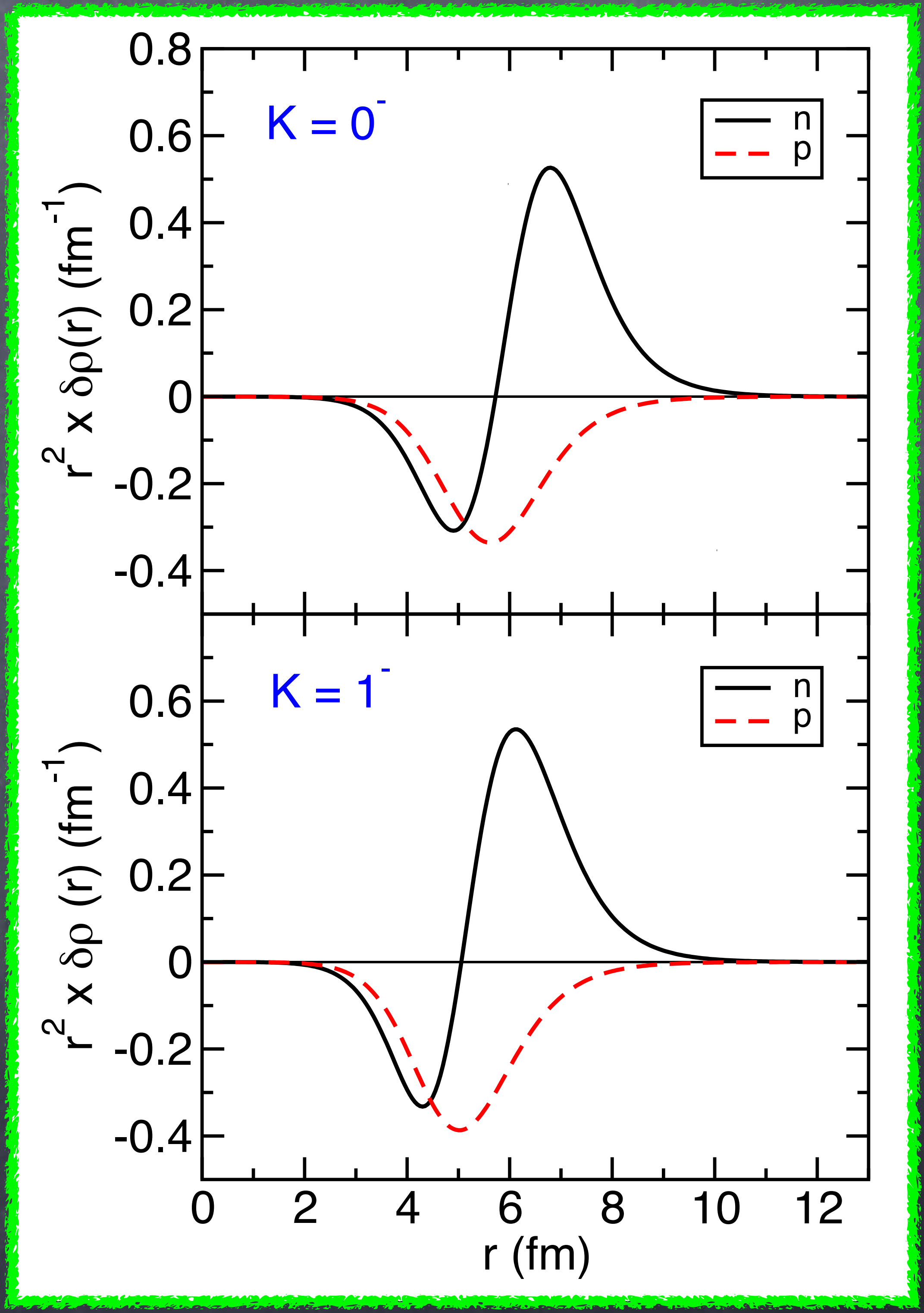
D.Peña Arteaga, E.Khan, P.Ring, PRC 79 (2009) 034311

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





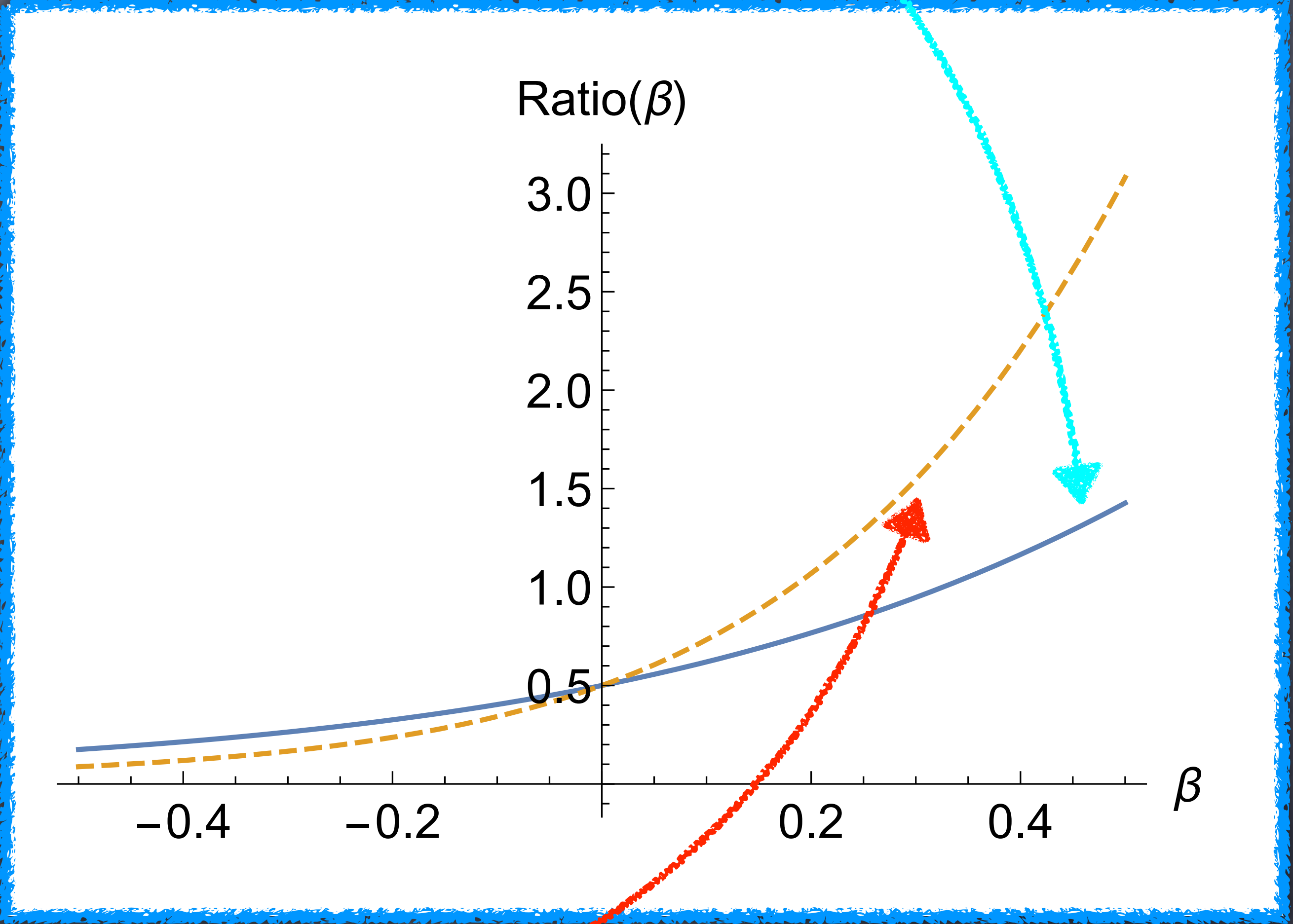
^{150}Sn



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

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