ANPC

AfricanNuclearPhysicsConference

AFRICAN NUCLEAR PHYSICS CONFERENCE

Kruger National Park, South Africa
1 - 5 July 2019

E. G. Lanza
INFN - Sezione di Catania
Italy

Five workshop questions:

1. Are the dipole resonances due to collective or single-particle excitations?
2. What is the interplay between isovector and isoscalar contributions?
3. What are the contributions due to E1 and M1?
4. How strongly is the observed strength distribution biased by the method or selected decay channel?
5. What experimental advances are desirable to answer the outstanding questions?

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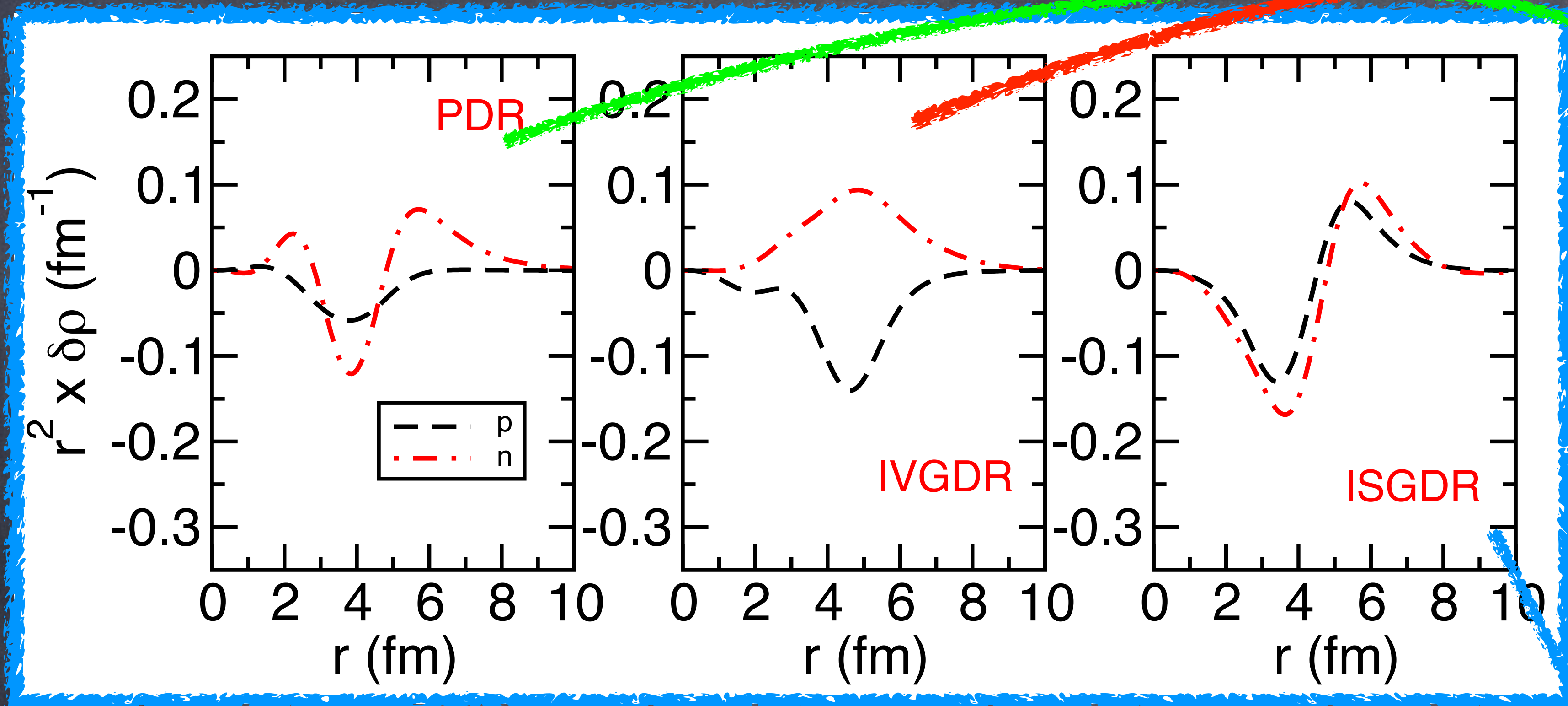
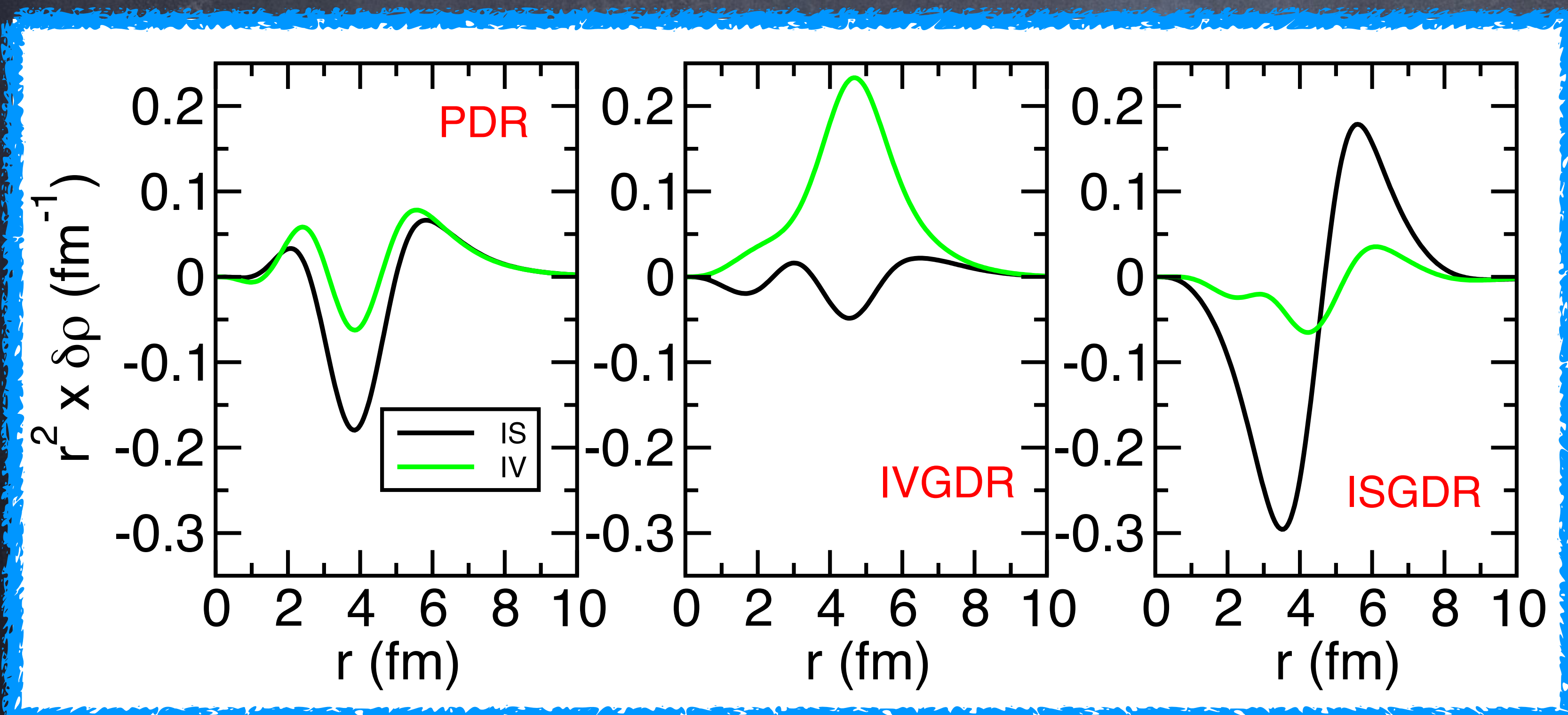
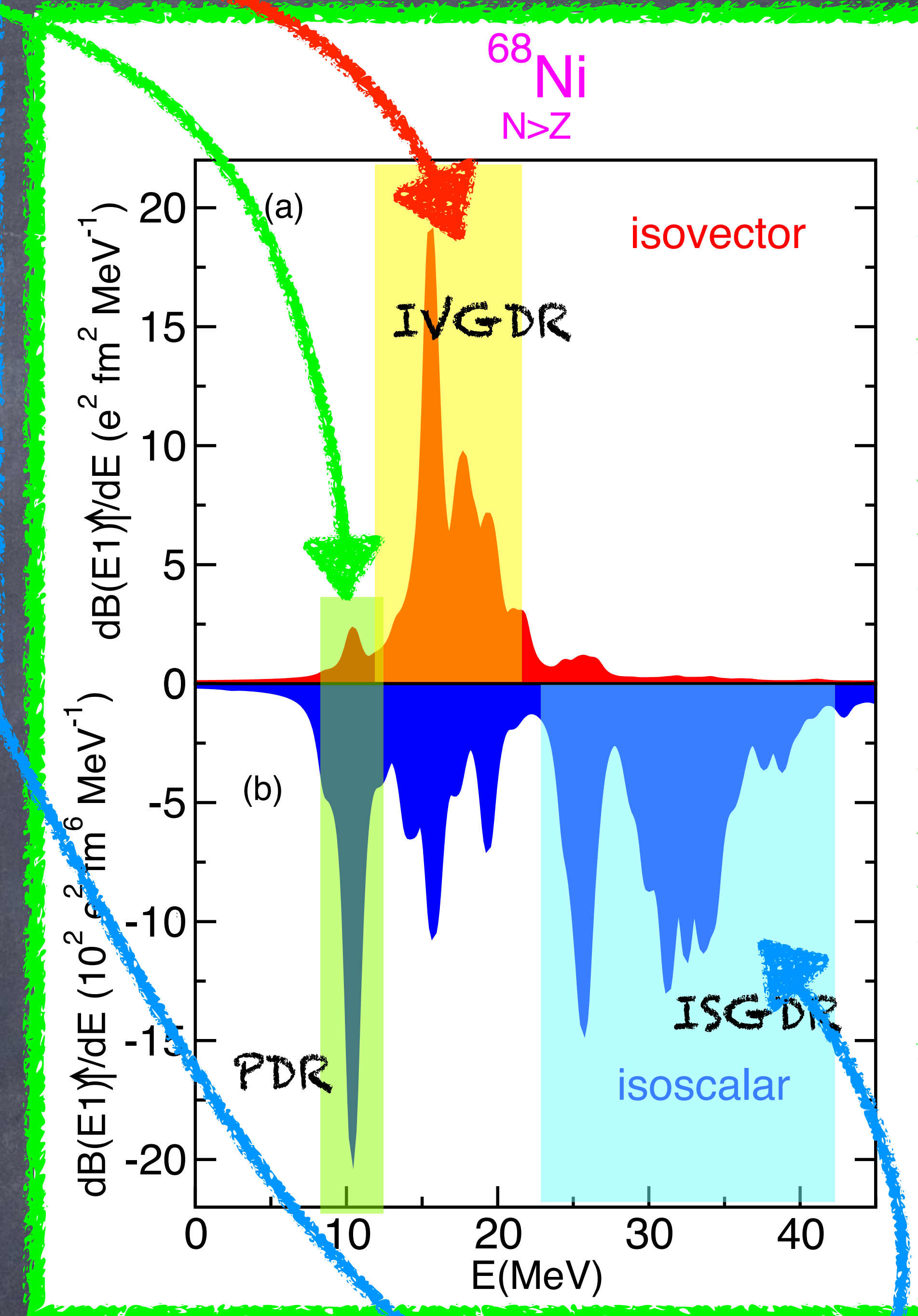
Are the Pygmy Dipole Resonances due to collective or single-particle excitations?



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





RPA calculations with SGII Skyrme interaction

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

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

What is the nature of these dipole states?

Are these low-lying dipole excitations collective?

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Are these low-lying dipole excitations collective?

D. Vretenar, N. Paar, P. Ring, G.A. Lalazissis,
NPA 692 (2001) 496

In RPA calculations, for a state ν, the contribution of a particle-hole configuration can be calculated by defining the amplitude

$$A_{ph}^{\nu} = |X_{ph}^{\nu}|^2 - |Y_{ph}^{\nu}|^2$$

with the normalization condition

$$\sum_{ph} A_{ph}^{\nu} = 1$$

And one can see what is the contribution, in percentage, of a p-h configuration to the formation of the state ν.

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D. Vreten

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^{132}Sn

SGII (E=9.34 MeV)		
p-h conf.	E(MeV)	A_{ph}
$(2p_{3/2}, 2d_{5/2})^{\pi}$	9.62	1.8%
$(1g_{9/2}, 1h_{11/2})^{\pi}$	9.33	2.3%
$(1g_{7/2}, 2f_{7/2})^{\nu}$	9.12	4.5%
$(2d_{5/2}, 2f_{7/2})^{\nu}$	8.85	3.6%
$(2d_{3/2}, 3p_{1/2})^{\nu}$	9.04	14.9%
$(2d_{3/2}, 2f_{5/2})^{\nu}$	9.07	24.0%
$(3s_{1/2}, 3p_{3/2})^{\nu}$	9.09	43.9%
$(3s_{1/2}, 3p_{1/2})^{\nu}$	9.67	1.0%
$(1h_{11/2}, 1i_{13/2})^{\nu}$	9.21	1.7%

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G. Co', V. De Donno, C. Maieron, M. Anguiano, A. M. Lallena, PRC 80 (2009) 014308

Defining an index to measure the degree of collectivity of a specific excited state:

$$D = \frac{N^*}{N_{ph}}$$

where N^* is the number of states with

$$|X^{\nu}_{ph}|^2 - |Y^{\nu}_{ph}|^2 \geq \frac{1}{N_{ph}}$$

N_{ph} is the total number of p-h configurations

$$D = \begin{cases} 1 & \text{if } \textbf{all} \text{ p-h participate} \\ \frac{1}{N_{ph}} & \text{if } \textbf{only one} \text{ participate} \end{cases}$$

SGII (E=9.34 MeV)			
p-h conf.	E(MeV)	A_{ph}	$b_{ph}(E1)$
$(2p_{3/2}, 2d_{5/2})^{\pi}$	9.62	1.8%	-0.42
$(1g_{9/2}, 1h_{11/2})^{\pi}$	9.33	2.3%	0.88
$(1g_{7/2}, 2f_{7/2})^{\nu}$	9.12	4.5%	0.06
$(2d_{5/2}, 2f_{7/2})^{\nu}$	8.85	3.6%	-0.83
$(2d_{3/2}, 3p_{1/2})^{\nu}$	9.04	14.9%	-0.65
$(2d_{3/2}, 2f_{5/2})^{\nu}$	9.07	24.0%	1.79
$(3s_{1/2}, 3p_{3/2})^{\nu}$	9.09	43.9%	1.47
$(3s_{1/2}, 3p_{1/2})^{\nu}$	9.67	1.0%	-0.17
$(1h_{11/2}, 1i_{13/2})^{\nu}$	9.21	1.7%	-0.88

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

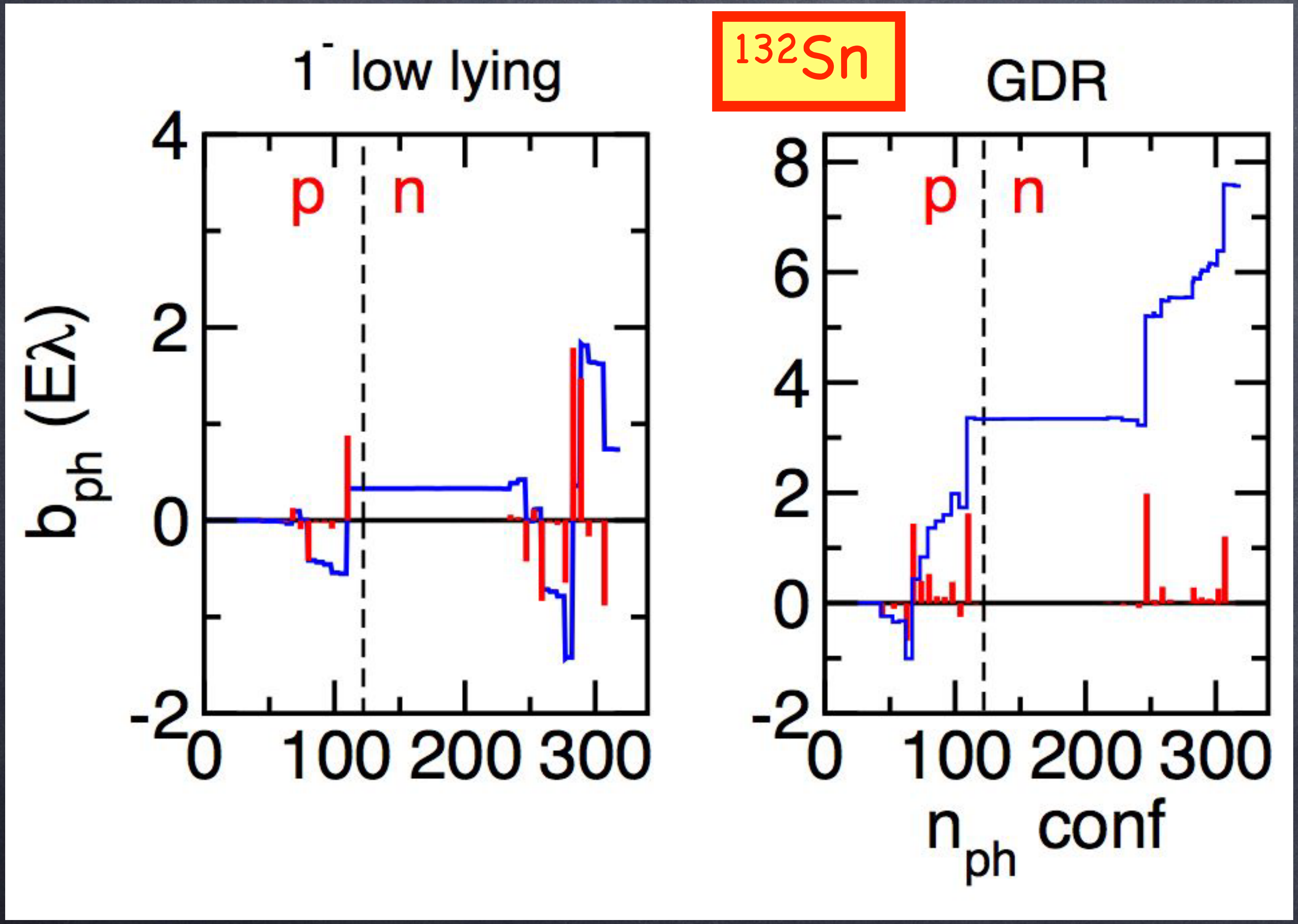
The analysis based on the A_{ph} or D are not exhaustive: they do not take into account the transition amplitude T^{λ}_{ph} associated with the elementary p-h configurations.

Particle-hole configurations with small A_{ph} may have big b_{ph}

E.G. Lanza, F. Catara, D. Gambacurta, M.V. Andrés, Ph. Chomaz
PRC 79 (2009) 054615

Collectivity means also coherence.

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



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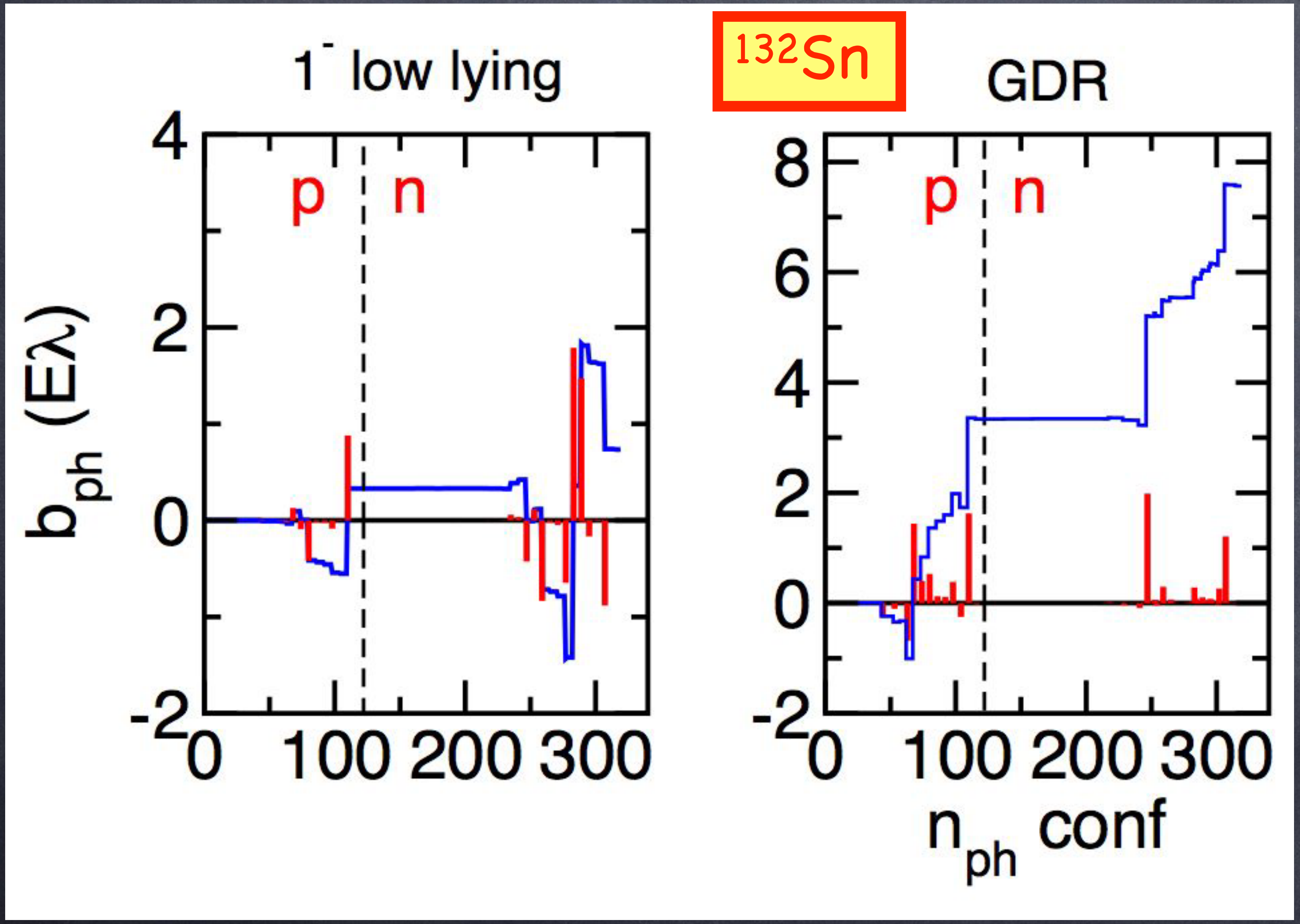
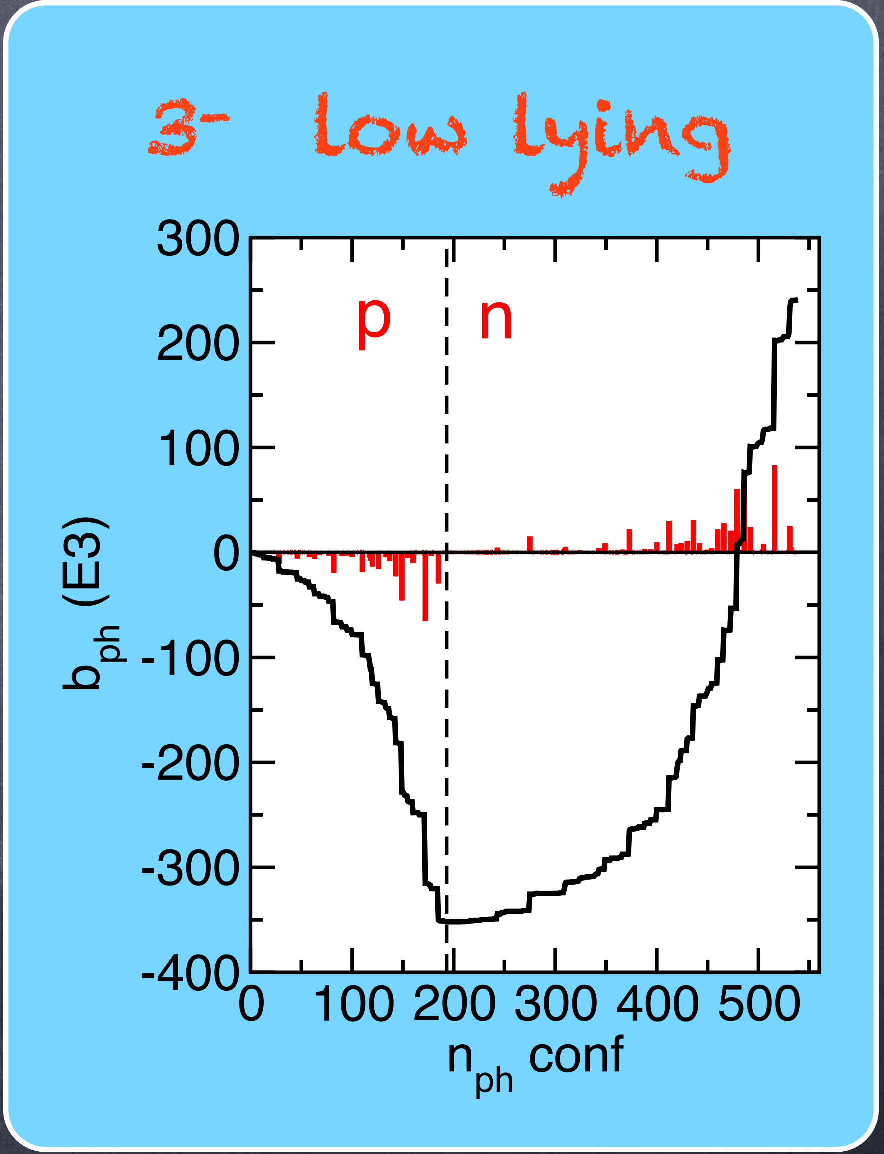
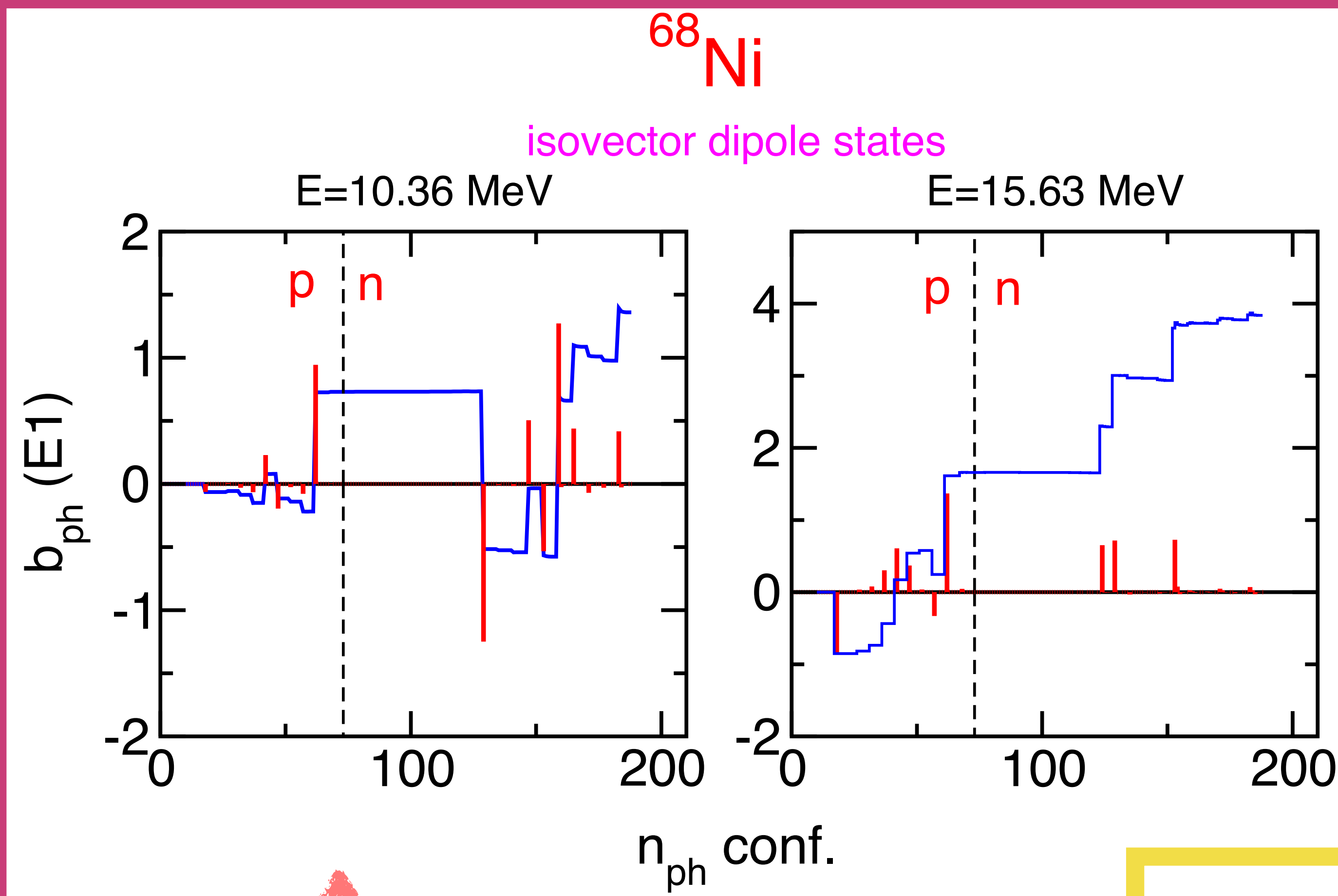


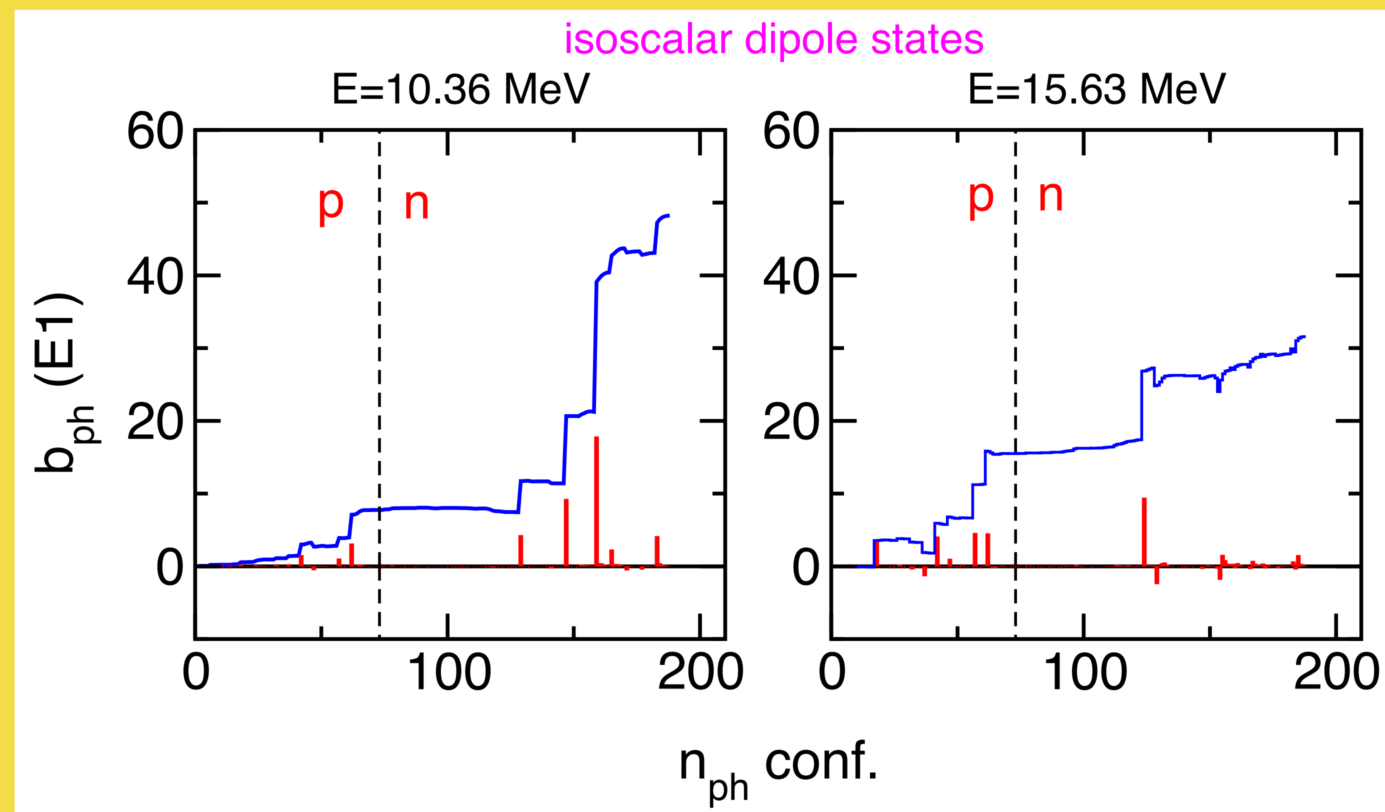


The low lying structures dipole states are related to the co-operative, although not coherent, effects of several p-h excitations.

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



Collective



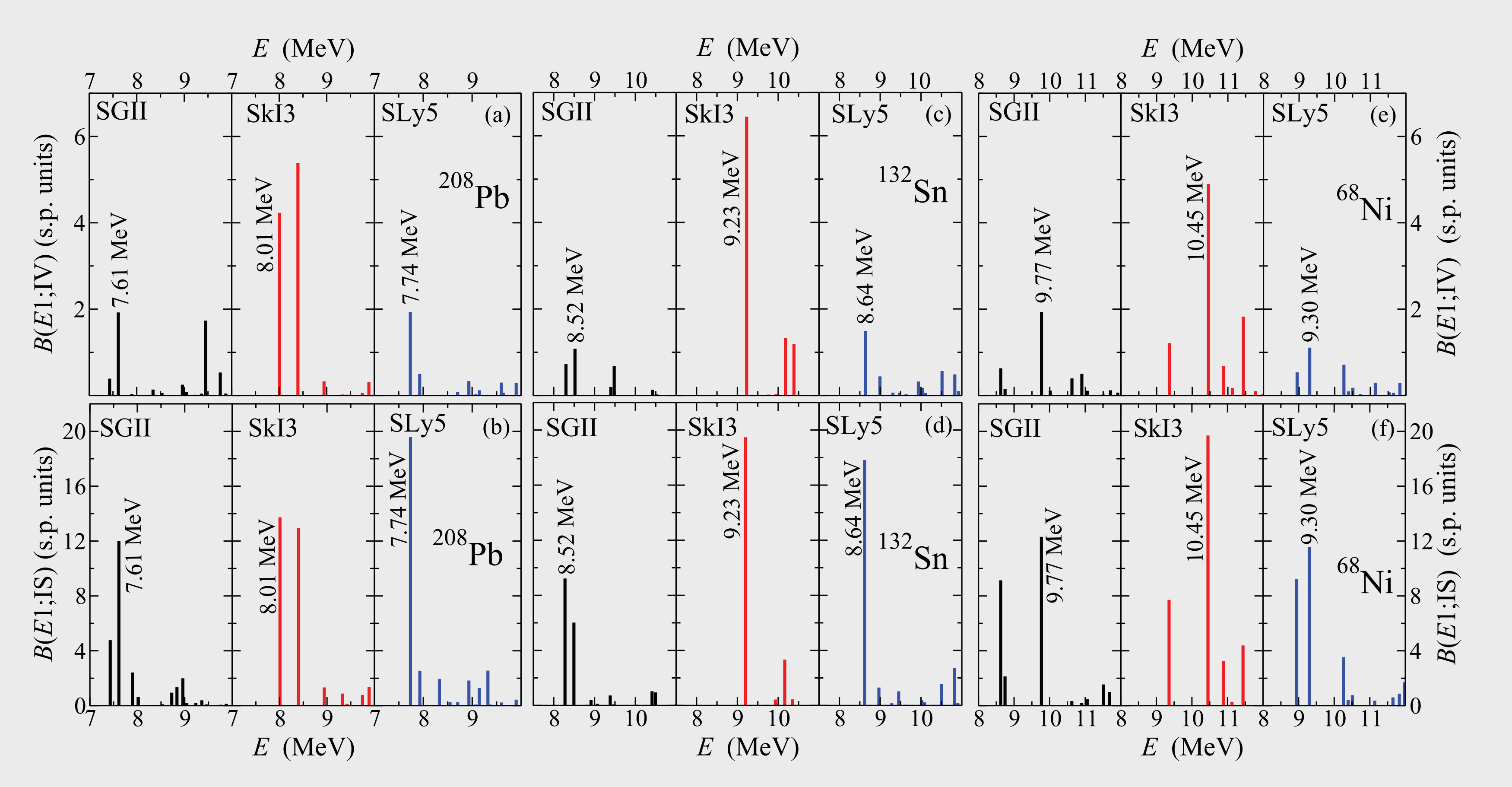
Non Collective

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

A simple estimate for the collectivity can be obtained by the reduced transition probabilities in Weisskopf units

$$B_W^{(IV)}(E1) = \frac{3^3 R^2}{4^3 \pi} \times \begin{cases} (\frac{N}{A})^2 & \text{protons} \\ (-\frac{Z}{A})^2 & \text{neutrons} \end{cases}$$

$$B_W^{(IS)}(E1) = \frac{3R^6}{4^3 \pi}$$



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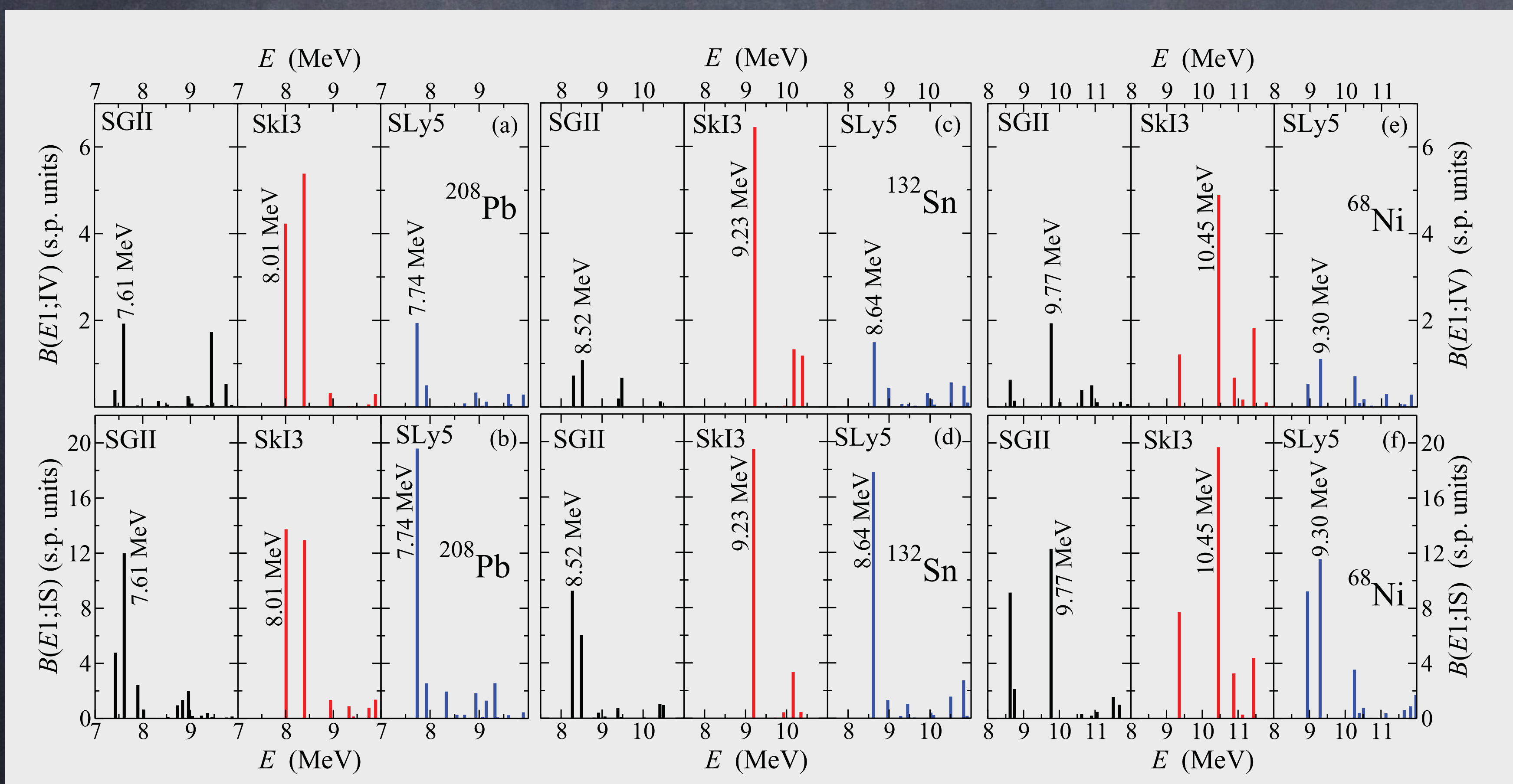
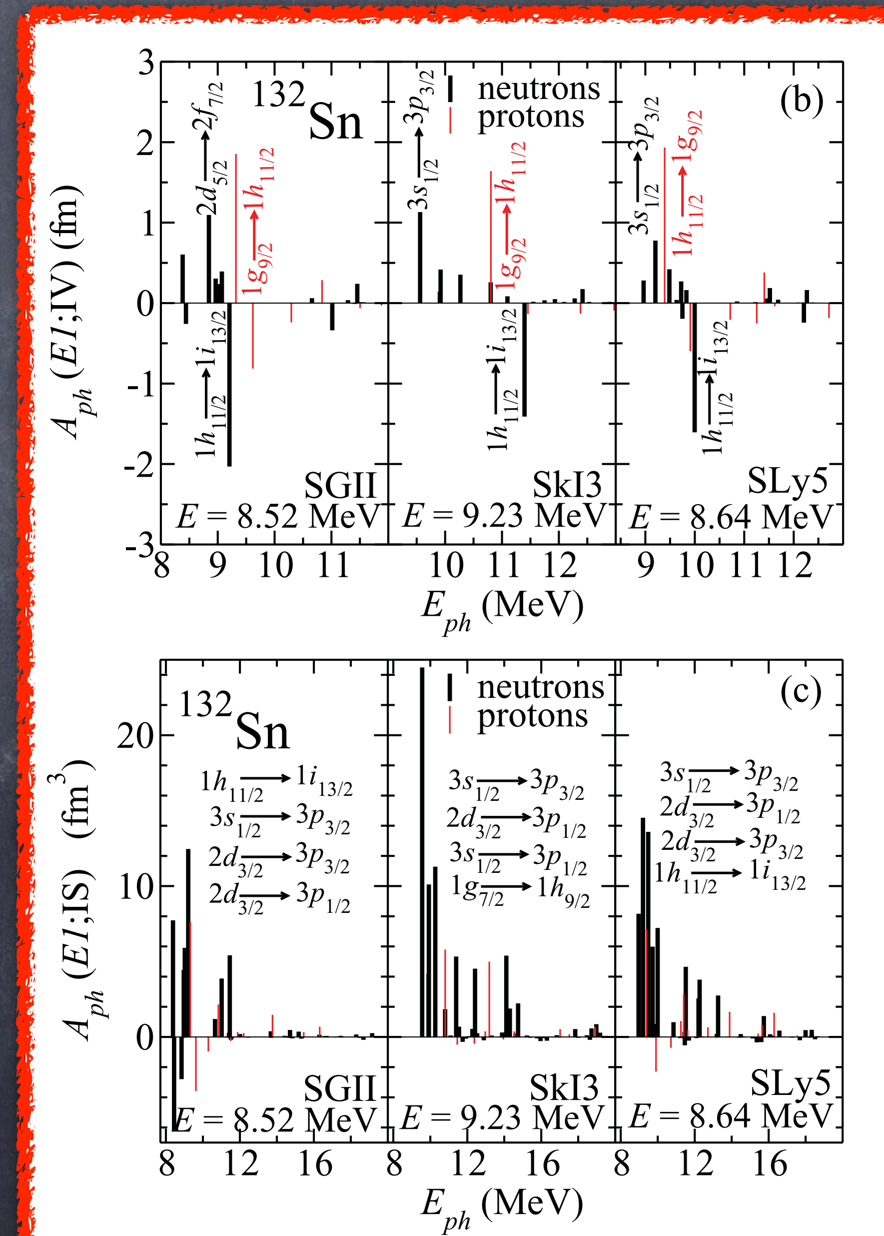




A more precise estimate come from the plot of the A_{ph} (which are the same that the b_{ph} shown before)

V. Baran, D.I. Palade, M. Colonna, M. Di Toro, A. Croitoru and A. I. Nicolin, PRC 91 (2015) 054303

Schematic TDA and RPA models (generalisation of Brown-Bolsterli) with separable p-h interaction $A_{ij}=\lambda\, Q_i Q_j^*$

In the standard case for $\lambda>0$ ($\lambda<0$) one solution is pushed up (down). In both cases the corresponding state, in the degenerate case, is collective in the sense that it exhaust all the energy independent sum rule.

By relaxing the condition of a unique coupling constant

$$A_{ij} = \lambda_1\, Q_i Q_j^* \ for\ \rho > \rho_0\,;\ A_{ij} = \lambda_3\, Q_i Q_j^* \ for\ \rho < \rho_0\,;$$

$$A_{ij} = \lambda_2\, Q_i Q_j^* \ for\ intermediate\ cases$$

Two states are found, n_1 and n_2, one with energy pushed up and the other one with energy close to the unperturbed one.

The energy independent sum rule is distributed only between these two states

$$|<n_1|Q|0>|^2 + |<n_2|Q|0>|^2 = \sum_i |Q_i|^2$$

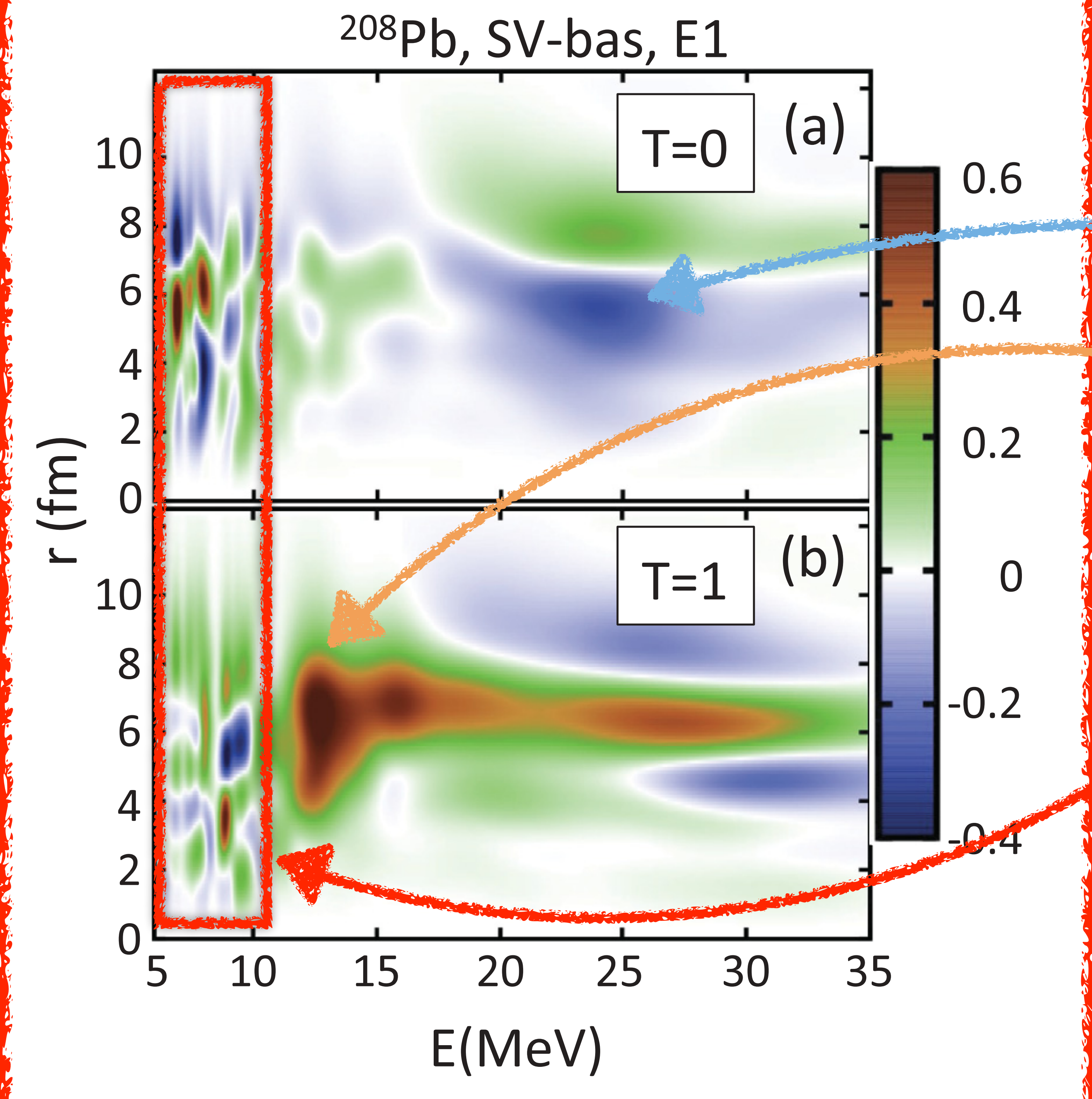
This is taken as an indication of a collective behaviour of both states.

Similar results are obtained for the schematic RPA model.

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

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

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?

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

Luna Pellegri proposal at LNS:

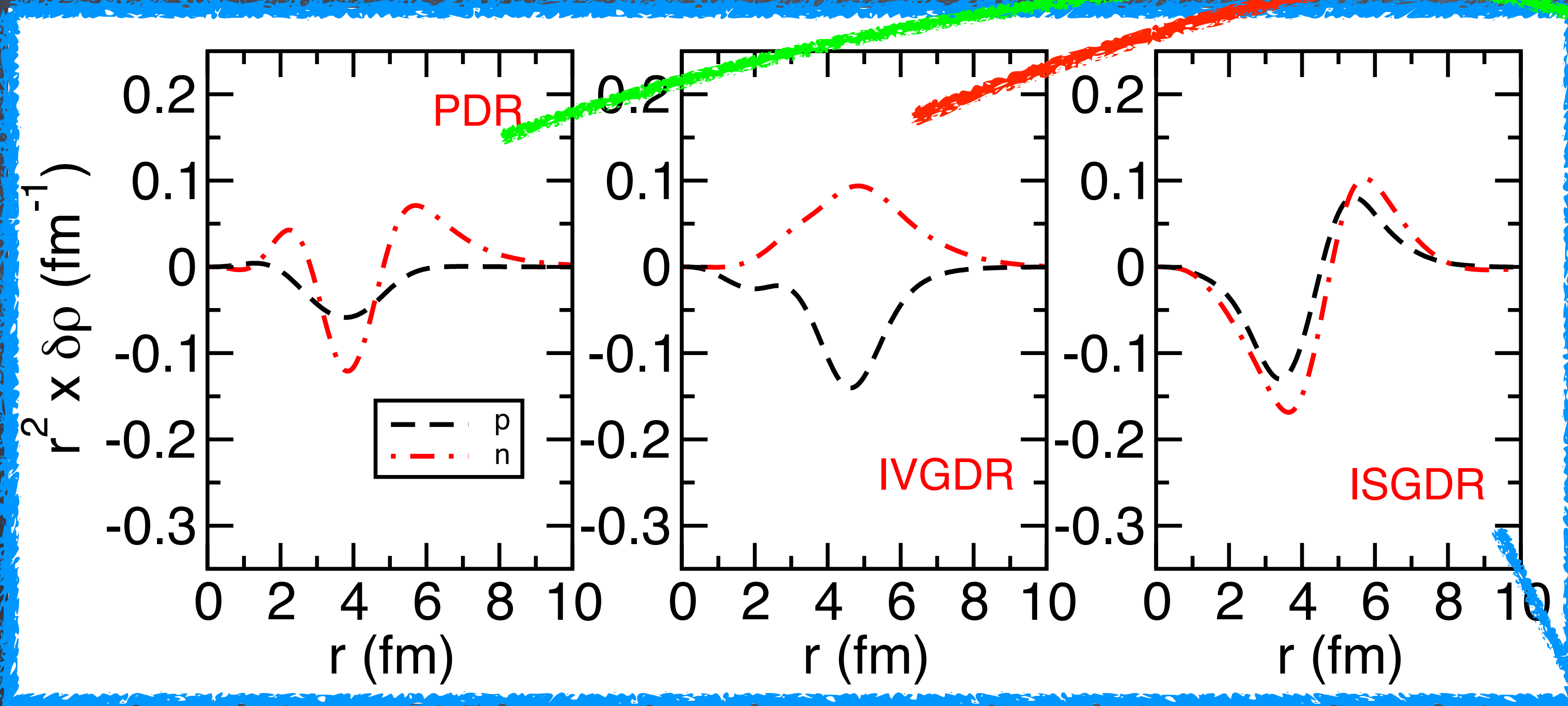
Transfer reactions to populate the Pygmy Dipole Resonance in ^{96}Mo

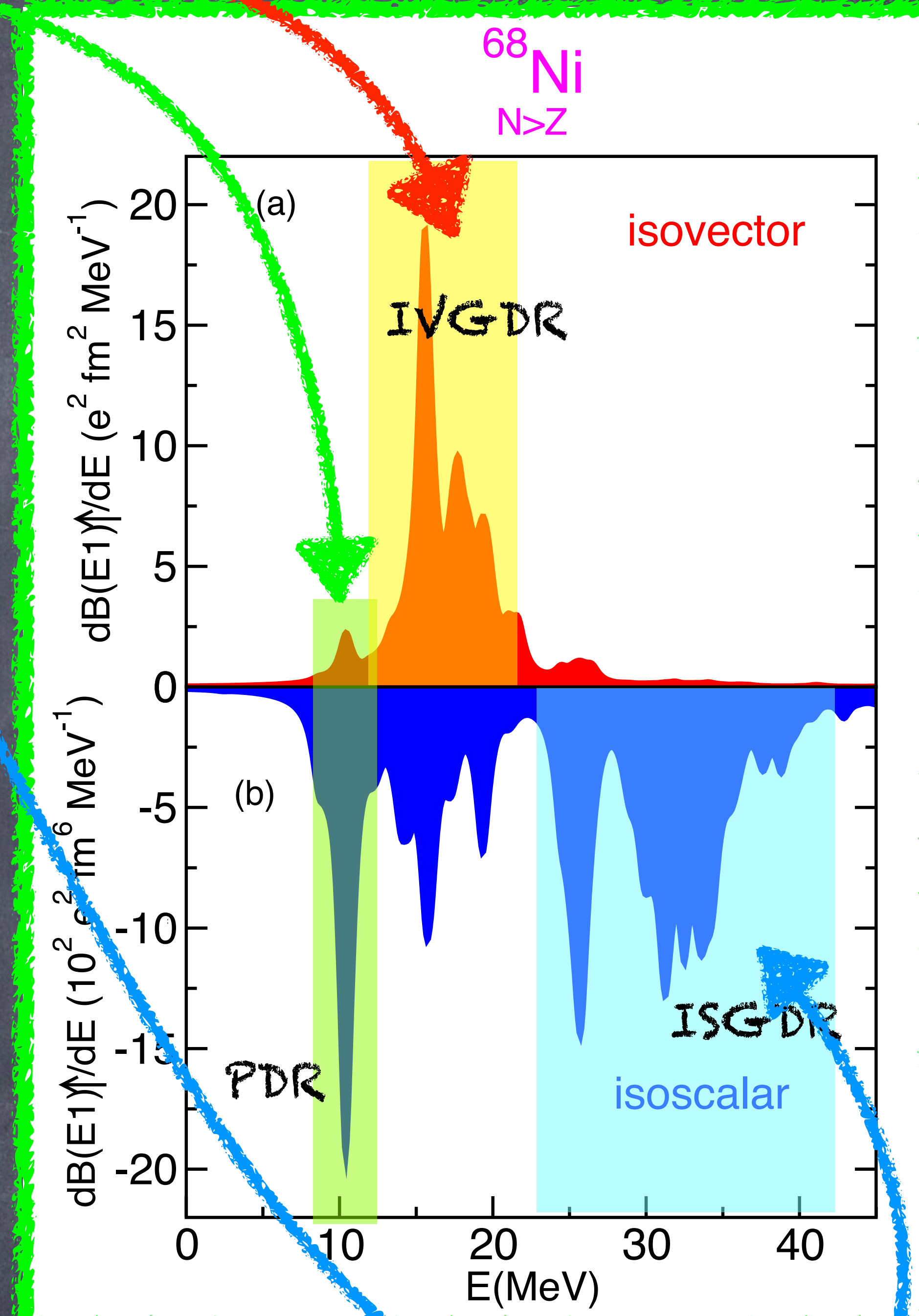
To study a possible single-particle character of low-lying excited states via transfer reactions:

$^{95}Mo(d,p)^{96}Mo^*$ at E_d=10 MeV,
$^{97}Mo(p,d)^{96}Mo^*$ at E_p=26 MeV
$^{96}Mo(\alpha, \alpha'\gamma)^{96}Mo^*$ at iThemba.

The beam will be provided by the Tandem at LNS and the reaction products measured by the MAGNEX spectrometer

What is the interplay between isovector and isoscalar contributions?





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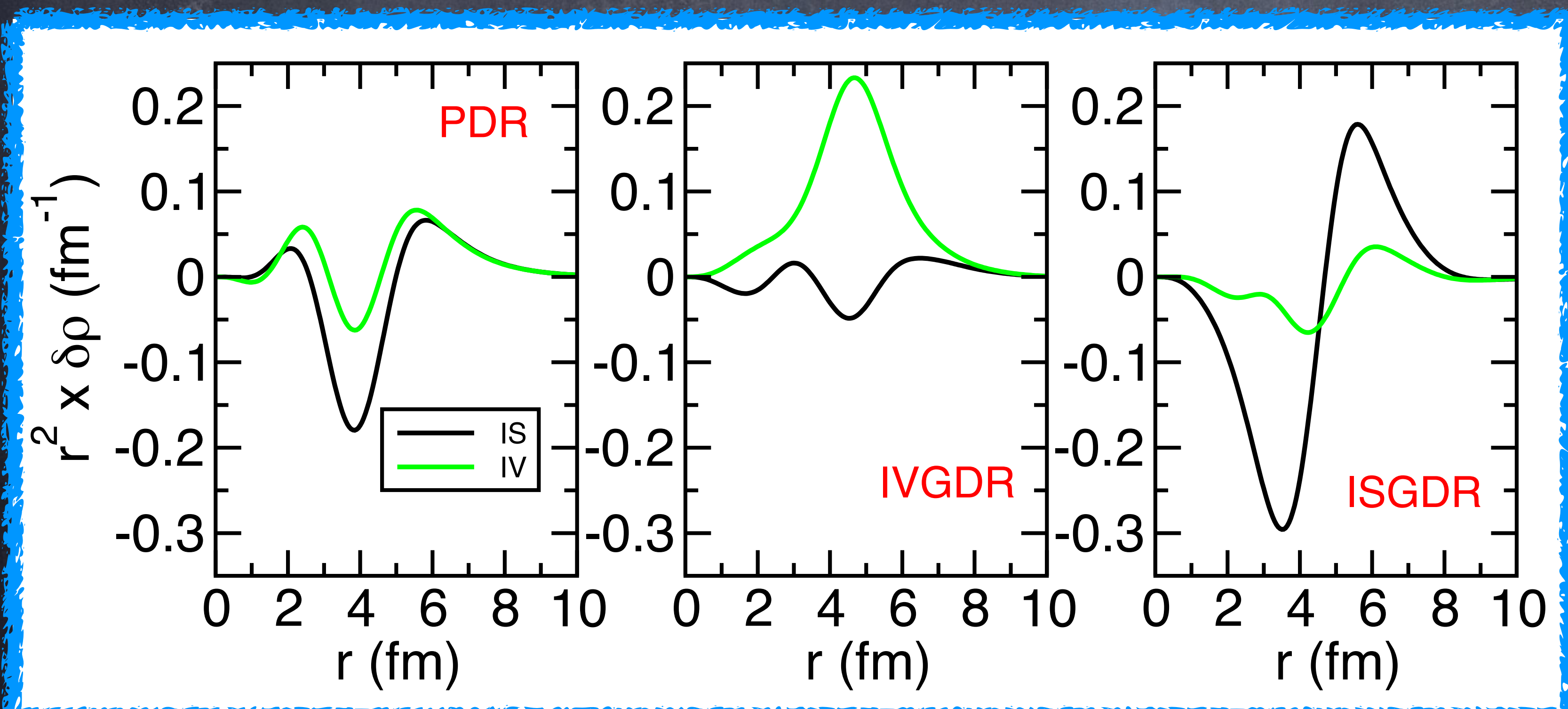
$$\cdot\left[X^{\nu}_{ph} - Y^{\nu}_{ph}\right] R_{l_p j_p}(r) R_{l_h j_h}(r)$$



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

PHYSICAL REVIEW C **96**, 064312 (2017)

Interplay between isoscalar and isovector correlations in neutron-rich nuclei

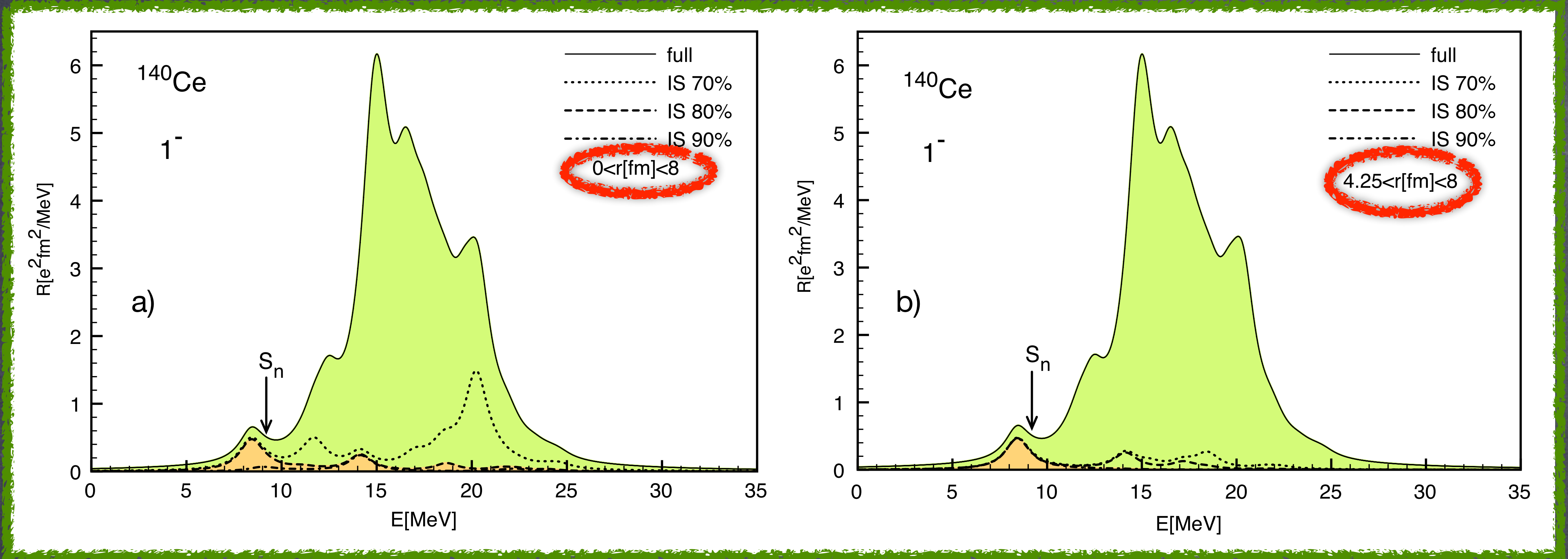
Ikuko Hamamoto[1,2] and Hiroyuki Sagawa[1,3]
[1] *Riken Nishina Center, Wako, Saitama 351-0198, Japan*
[2] *Division of Mathematical Physics, Lund Institute of Technology at the University of Lund, Lund 22362, Sweden*
[3] *Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8580, Japan*

PHYSICAL REVIEW C **99**, 054314 (2019)

Interplay between low-lying isoscalar and isovector dipole modes: A comparative analysis between semiclassical and quantum approaches

S. Burrello,[1] M. Colonna,[1] G. Colò,[2,3] D. Lacroix,[4] X. Roca-Maza,[2,3] G. Scamps,[5,6] and H. Zheng[1,7]
[1] *Laboratori Nazionali del Sud, INFN, I-95123 Catania, Italy*
[2] *Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, Milano 20133, Italy*
[3] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Milano, via Celoria 16, Milano 20133, Italy*
[4] *Institut de Physique Nucléaire, IN2P3-CNRS, Université Paris-Sud, Université Paris-Saclay, F-91406 Orsay Cedex, France*
[5] *Institute of Astronomy and Astrophysics (IAA), Université libre de Bruxelles (ULB), CP 226, Boulevard du Triomphe, B-1050 Bruxelles, Belgium*
[6] *Center for Computational Sciences, University of Tsukuba, Tsukuba 305-8571, Japan*
[7] *School of Physics and Information Technology, Shaanxi Normal University, Xi'an 710119, China*

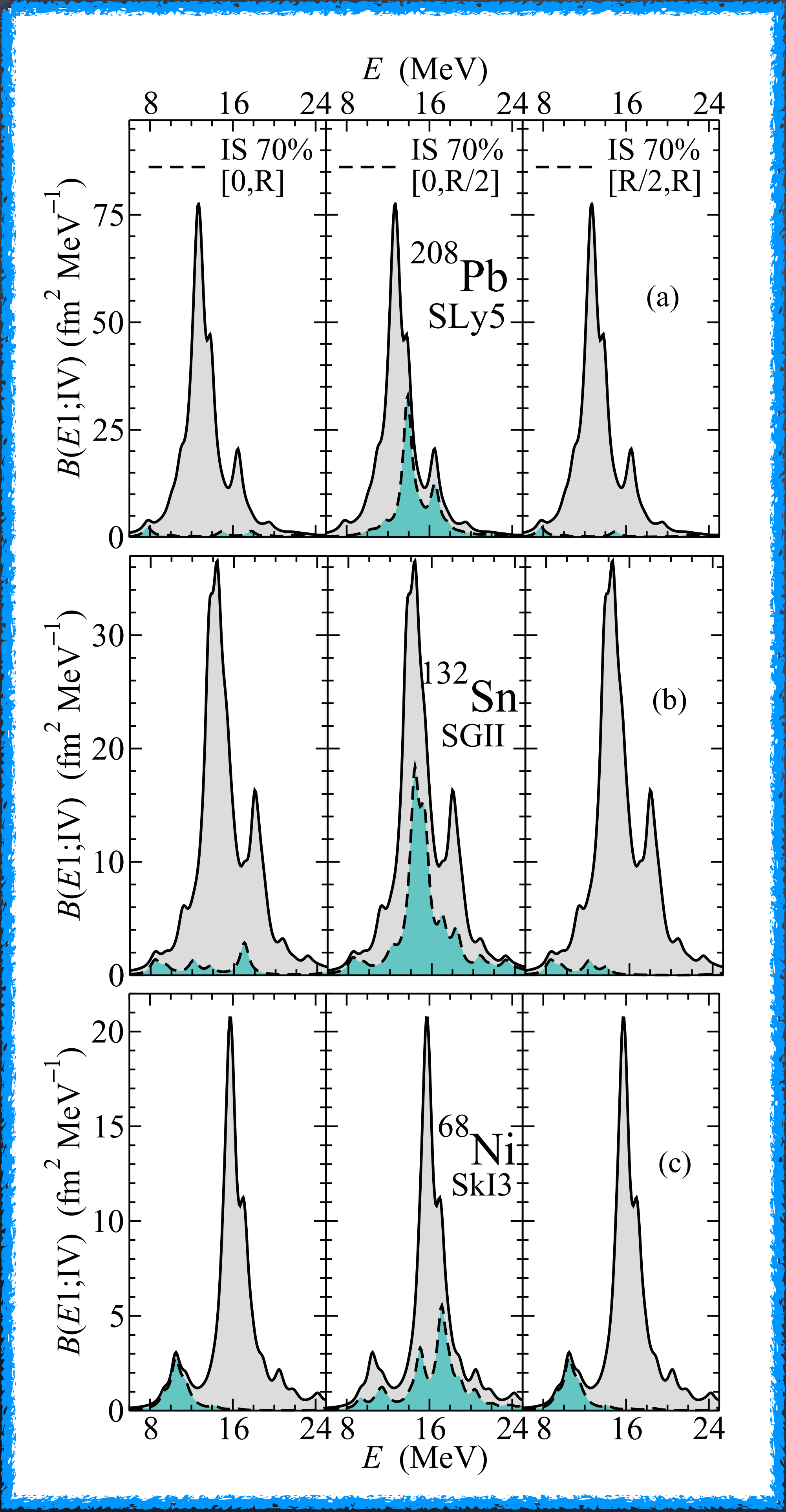
N. Paar, Y.F. Niu, D. Vretenar, J. Meng, PRL 103 (2009) 032502



Calculations done with a fully self-consistent relativistic quasi-particle random phase approximation based on the relativistic Hartree-Bogoliubov model (RHB + RQRPA).

Whenever the proton and neutron transition densities, for each particular state, are found in phase over more than 70% (80%) within the radial interval between 0 and 8 fm (4.5 to 8 fm) the state is denoted IS 70% (IS 80%).

For the surface region between 4.25 fm and 8 fm, transitions with predominant isoscalar character are located mainly in the low energy region giving rise to the peak at 8.4 MeV.



X. Roca-Maza, G. Pozzi, M. Brenna, K. Mizuyama, G. Colò, PRC 85 (2012) 024601

Fully self-consistent non relativistic mean field approach based on Skyrme Hartree-Fock plus random phase approximation.

For each radial distance, at which the neutron and proton transition densities were calculated, the state ν is defined 70% isoscalar if the 70% of the points satisfy the following condition:

$$|\delta\rho^{IS}(r)| \geq |\delta\rho^{IV}(r)| \,.$$

This analysis shows that most of the states that are 70% isoscalar belong to the PDR peak at low energy for all the three nuclei studied.

The strong isoscalar component of the low-lying dipole states consent to considered these states as a good laboratory for the study of various aspects of the interplay between isoscalar and isovector modes.

This is also important in the experimental analysis where a fundamental role is played by the radial form factors used.

The description of inelastic cross section with isoscalar probes

- DWBA, first order theory
- Coupled Channel, high order effect important
- Semiclassical approximations

Example: the transition amplitude for the DWBA

$$T^{DWBA} = \int \chi^{(-)}(k_\beta, r) F(r) \chi^{(+)}(k_\alpha, r) dr$$

the radial form factor $F(r)$ contains all the structure effects, they can be derived in macroscopic or microscopic approaches

$$F^C(r) \approx \frac{\sqrt{B(EL)}}{r^{L+1}}$$

$$F^N(r) \approx \beta_N \frac{dU^N(r)}{dr}$$

Dipole radial form factors calculation

- Goldhaber-Teller for the IVGDR

$$\delta\rho^{GT}(r) = \beta_1\Big[\frac{2N}{A}\frac{d}{dr}\rho_p(r) - \frac{2Z}{A}\frac{d}{dr}\rho_n(r)\Big]$$

- Harakeh-Dieperink for the ISGDR

- Microscopic form factor (double folding)
(with microscopic transition densities)

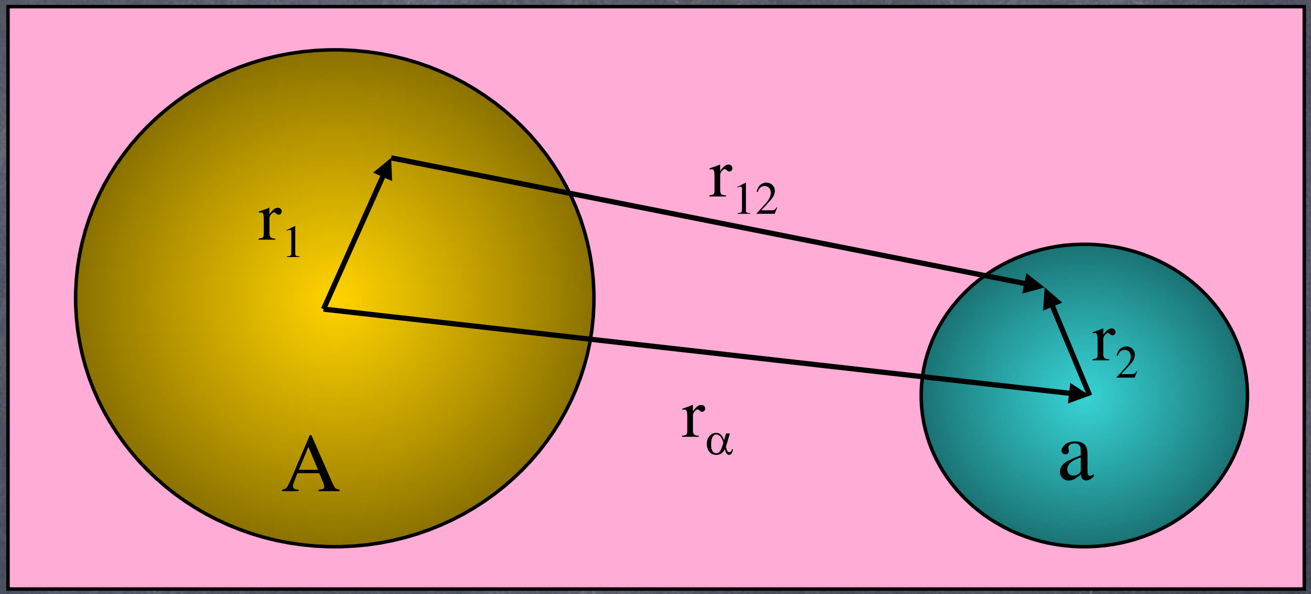
The nucleon nucleon interaction depends on the isospin

$$\nu_{12} = \nu_0(r_{12}) + \nu_1(r_{12})\tau_1 \cdot \tau_2$$

where τ_i are the isospin of the nucleons.

In the case $\rho_n = N/Z\, \rho$; $\rho_p = N/A\, \rho$, F_1 is zero when one of the two nuclei has $N=Z$.

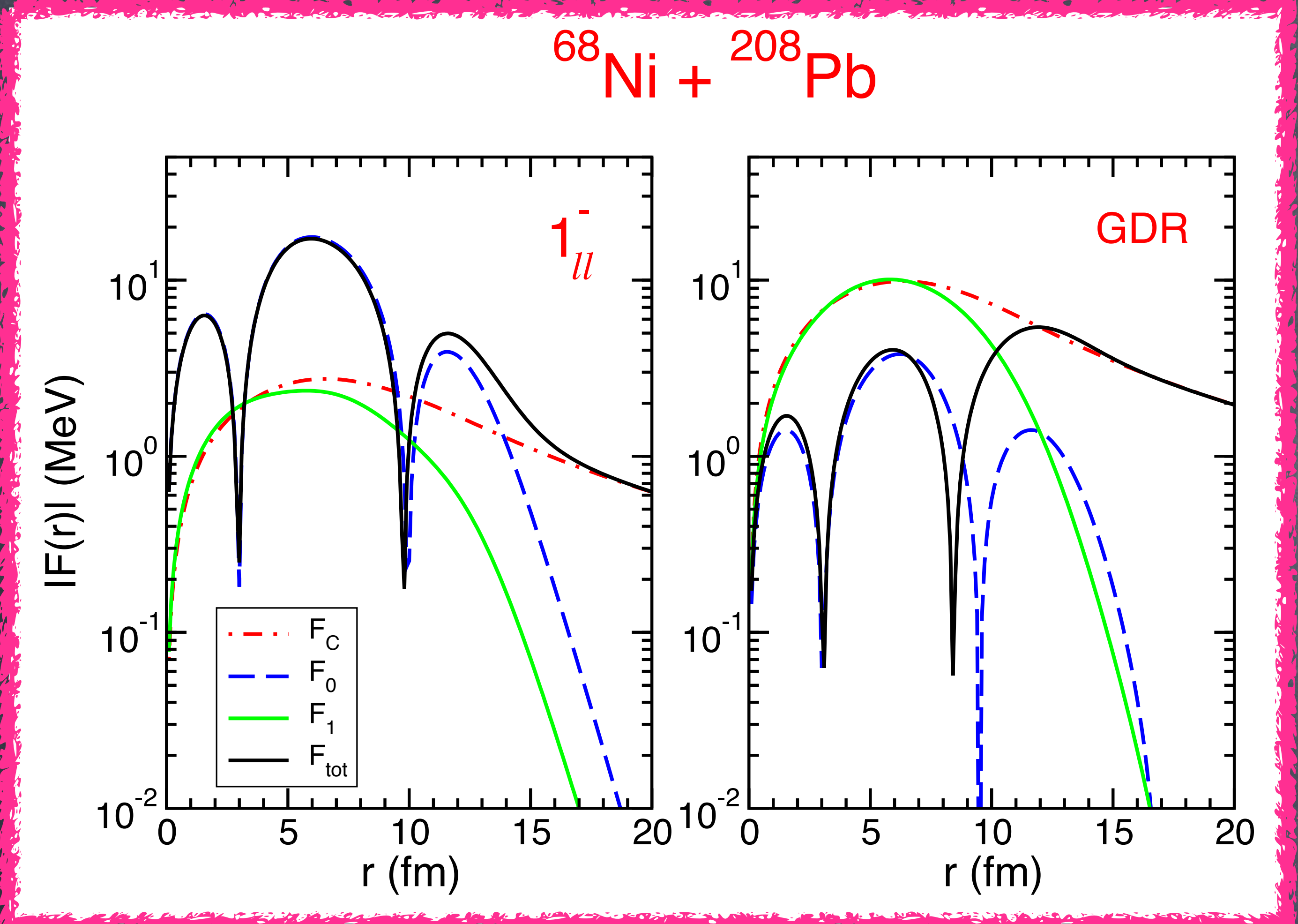
Double Folding procedure



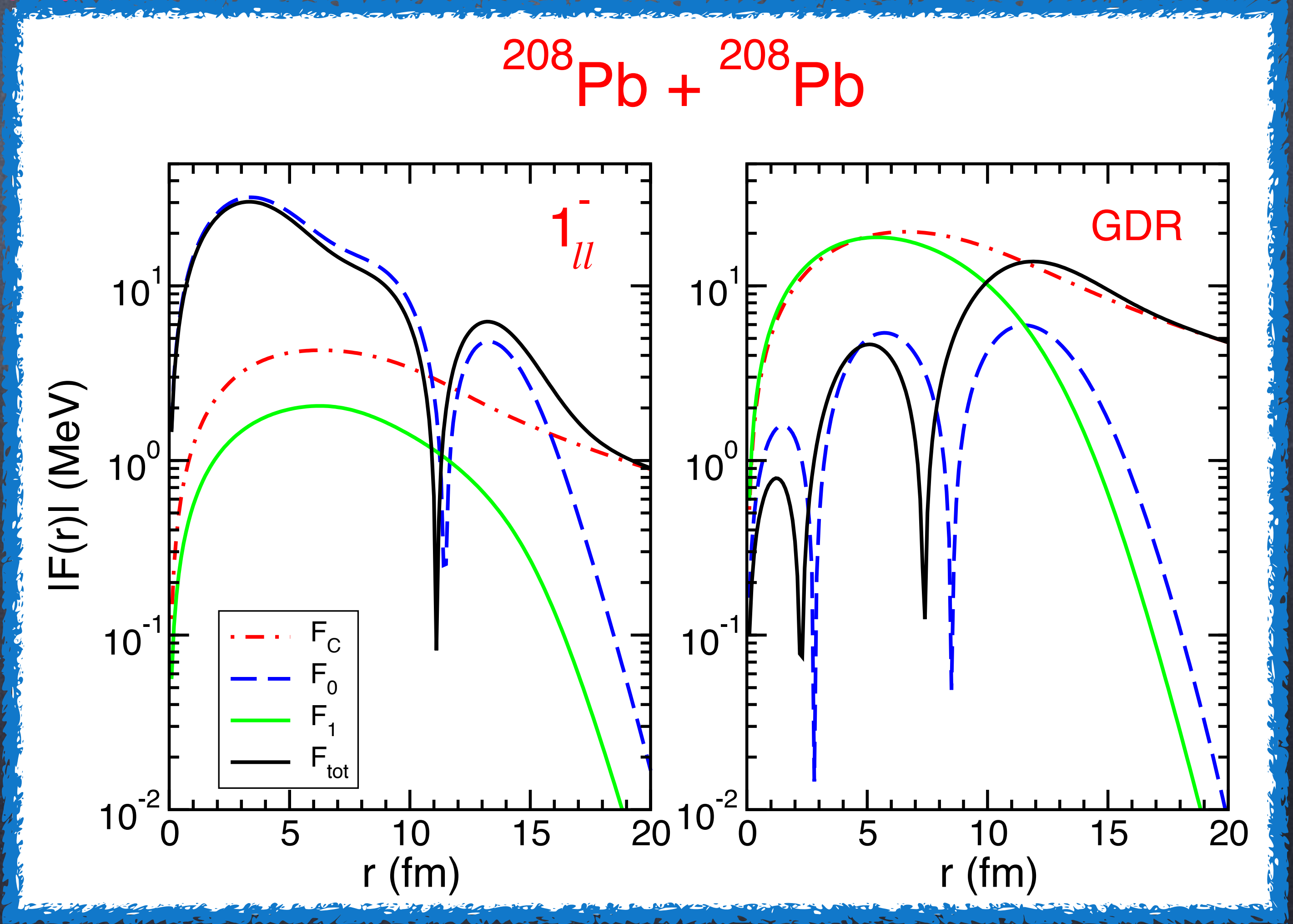
Therefore the nuclear form factors are

$$F_0(r_\alpha) = \int\!\!\int [\delta\rho_{A_n}(\vec{r}_1) + \delta\rho_{A_p}(\vec{r}_1)]\, \nu_0(r_{12})\, [\rho_{a_n}(\vec{r}_2) + \rho_{a_p}(\vec{r}_2)]\, r_1^2 dr_1 r_2^2 dr_2$$

$$F_1(r_\alpha) = \int\!\!\int [\delta\rho_{A_n}(\vec{r}_1) - \delta\rho_{A_p}(\vec{r}_1)]\, \nu_1(r_{12})\, [\rho_{a_n}(\vec{r}_2) - \rho_{a_p}(\vec{r}_2)]\, r_1^2 dr_1 r_2^2 dr_2$$



68Ni + 208Pb
1-ll
GDR
F_C
F_0
F_1
F_tot
|F(r)| (MeV)
r (fm)



208Pb + 208Pb
1-ll
GDR
F_C
F_0
F_1
F_tot
|F(r)| (MeV)
r (fm)

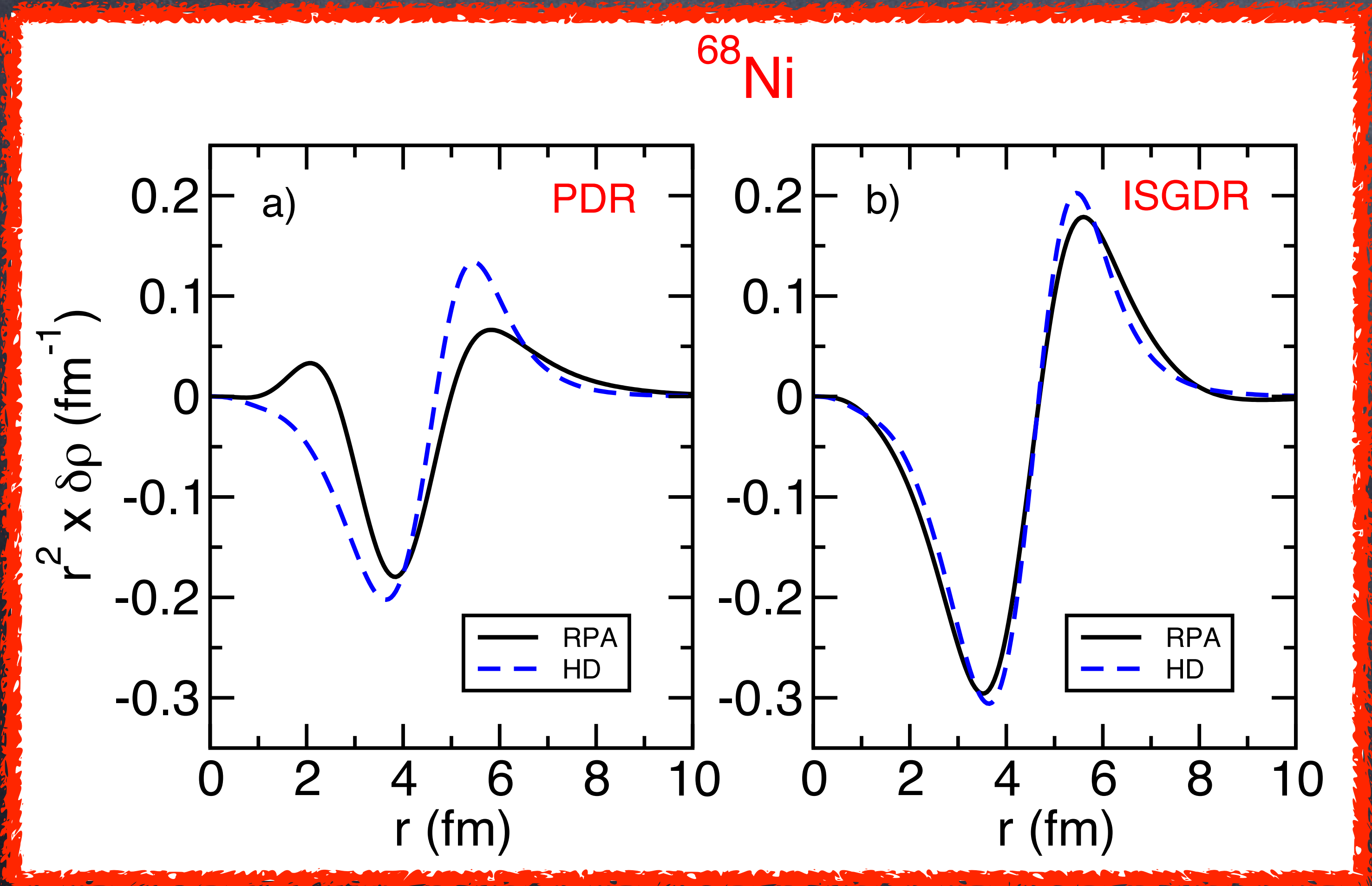
T. J. Deal, NPA 217 (1973) 210;
M. N. Harakeh and A. E. L. Dieperink PRC 23 (1981) 2329

Macroscopic transition density for the ISGDR

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

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

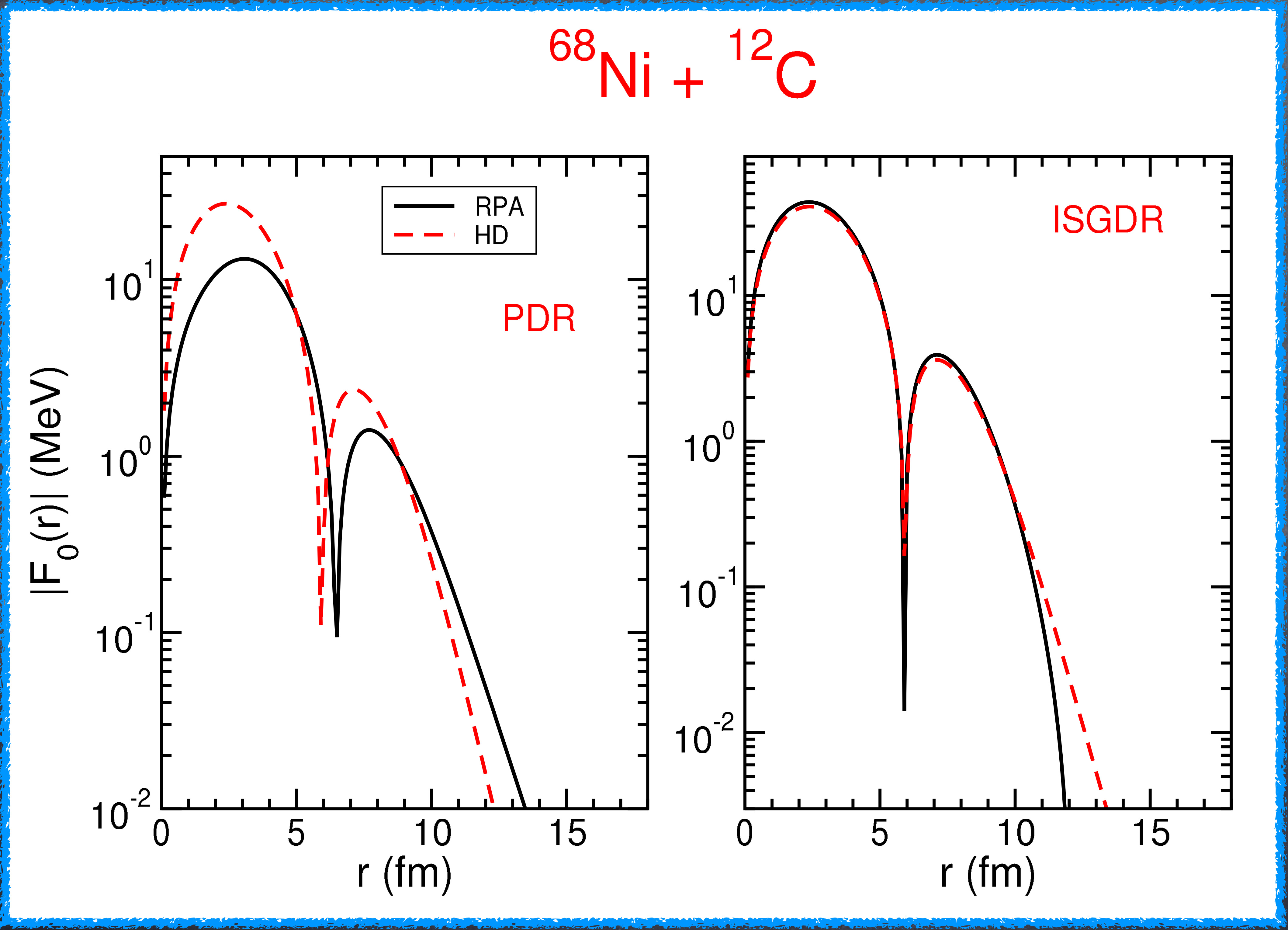
R is the half-density radius of the mass distribution.



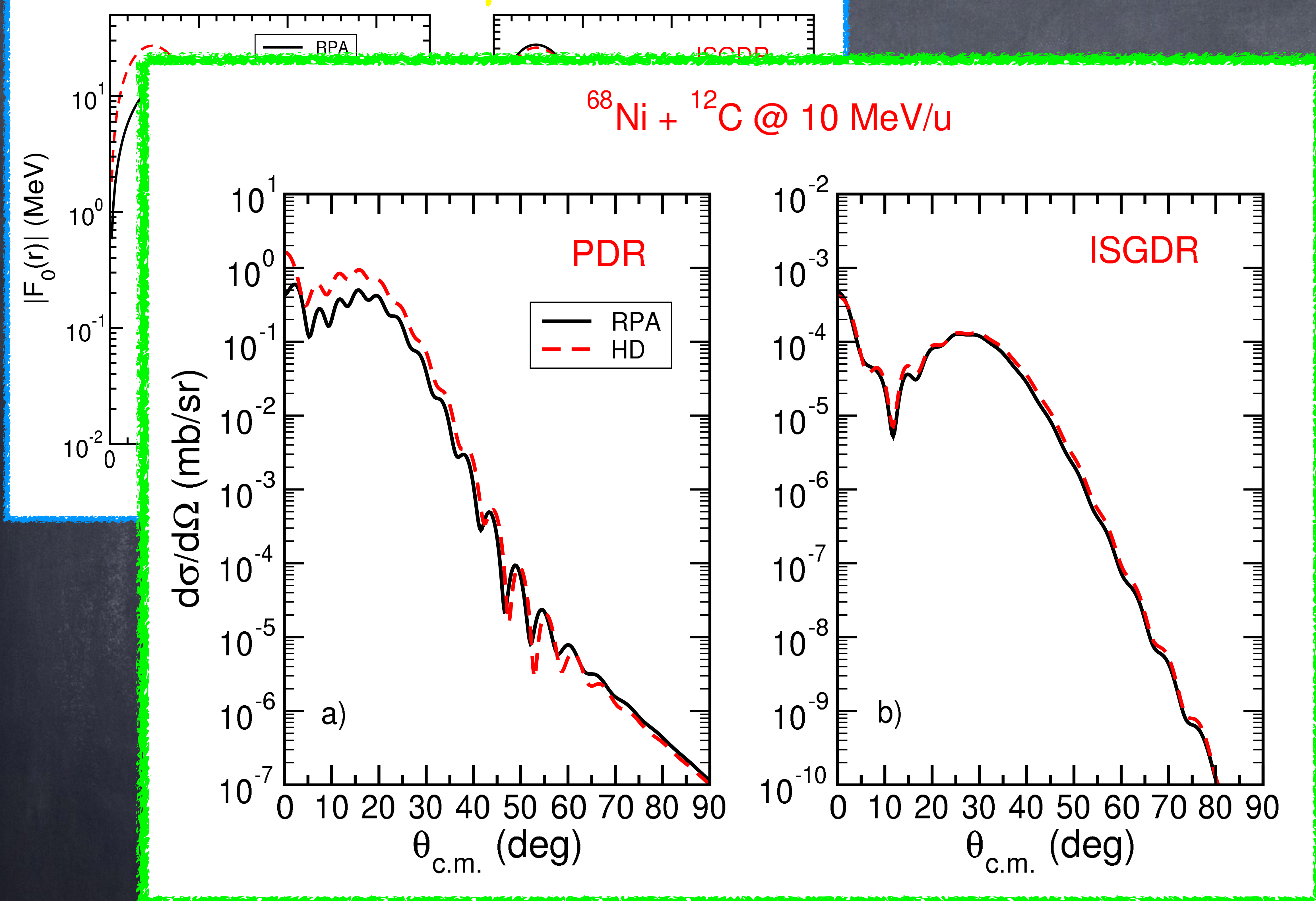
For both states, the macroscopic transition density has been scaled according to the following condition

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

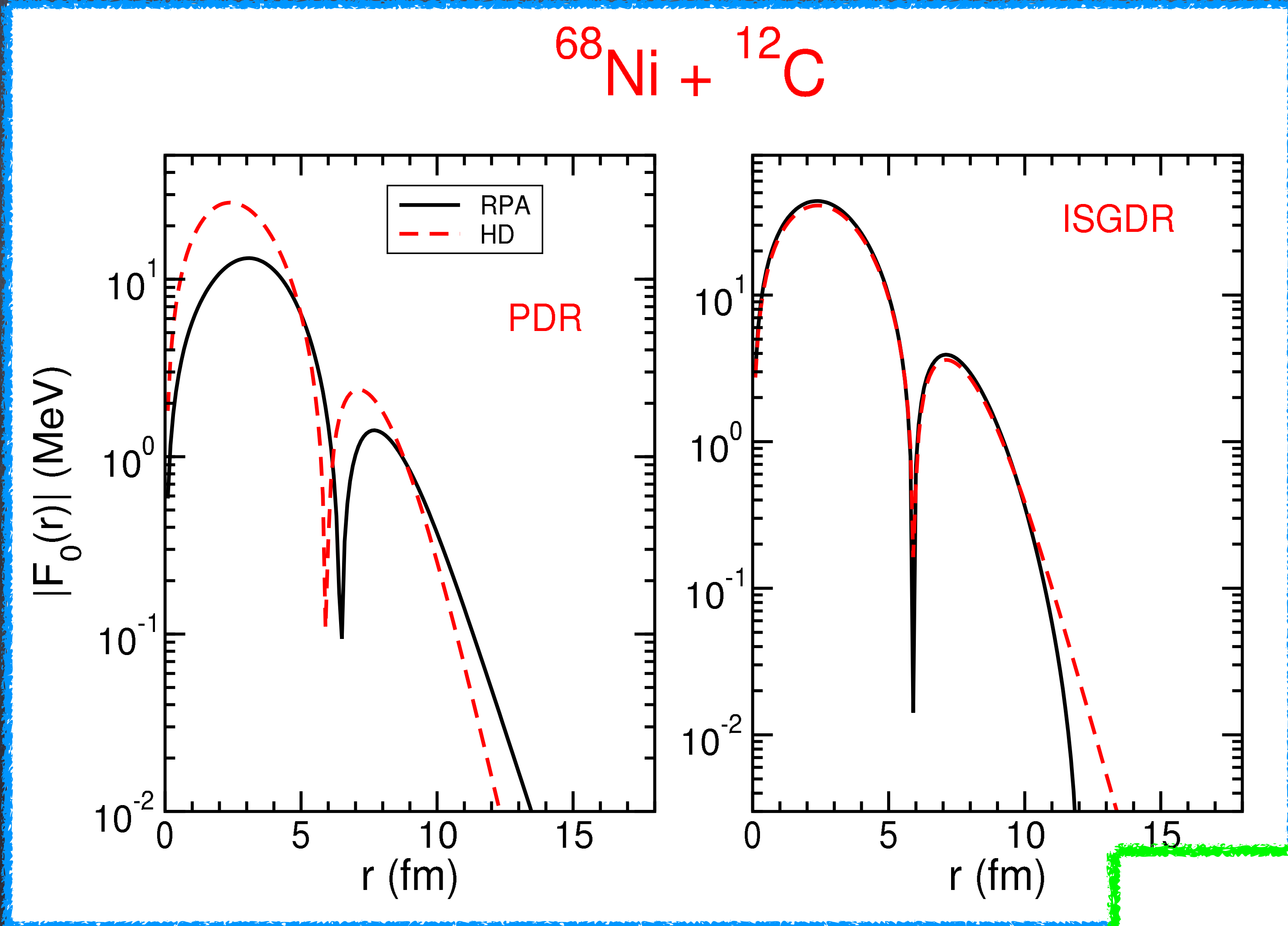
Double folding procedure



Double folding procedure

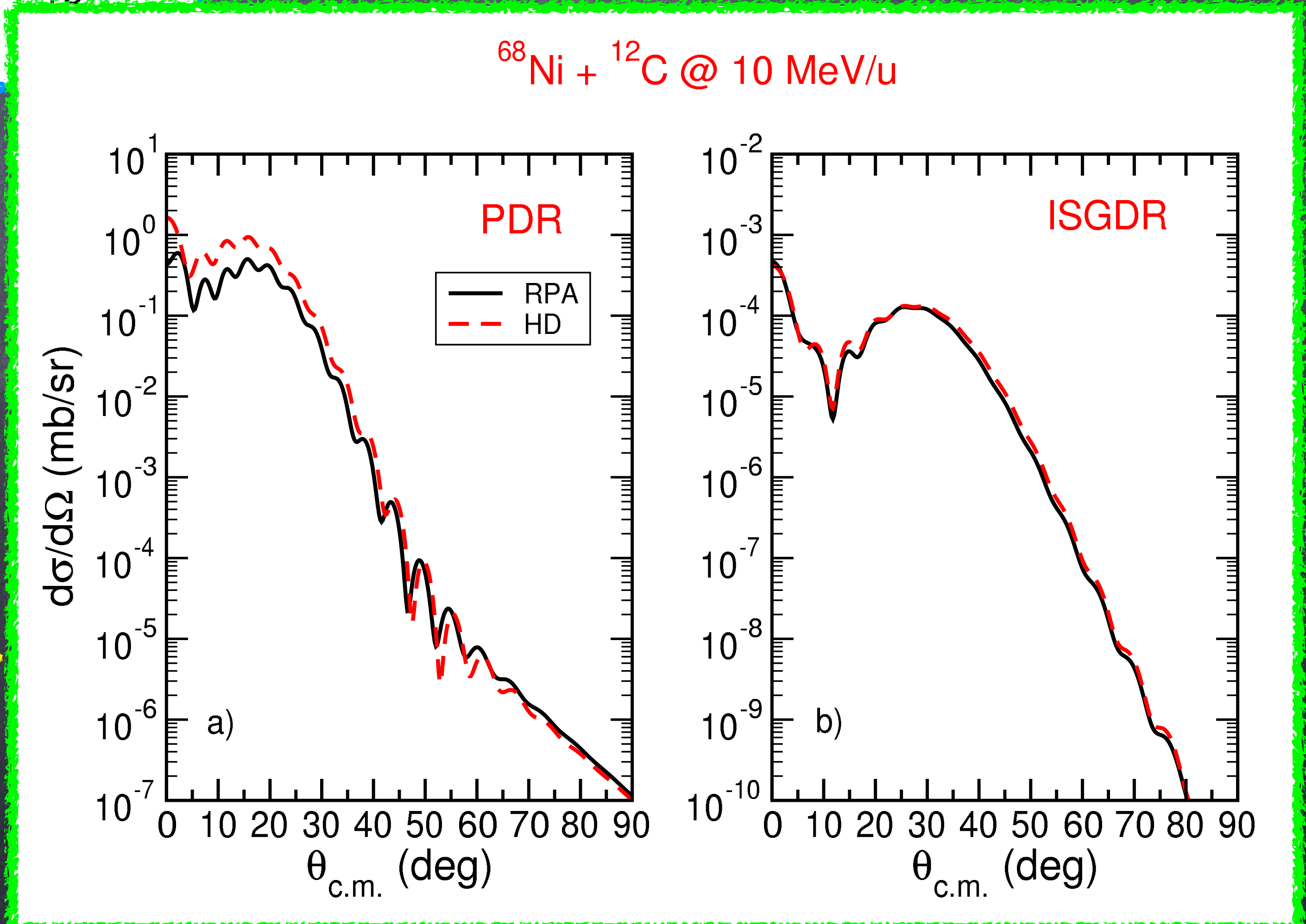


DWBA calculations done with the DWUCK4 code



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

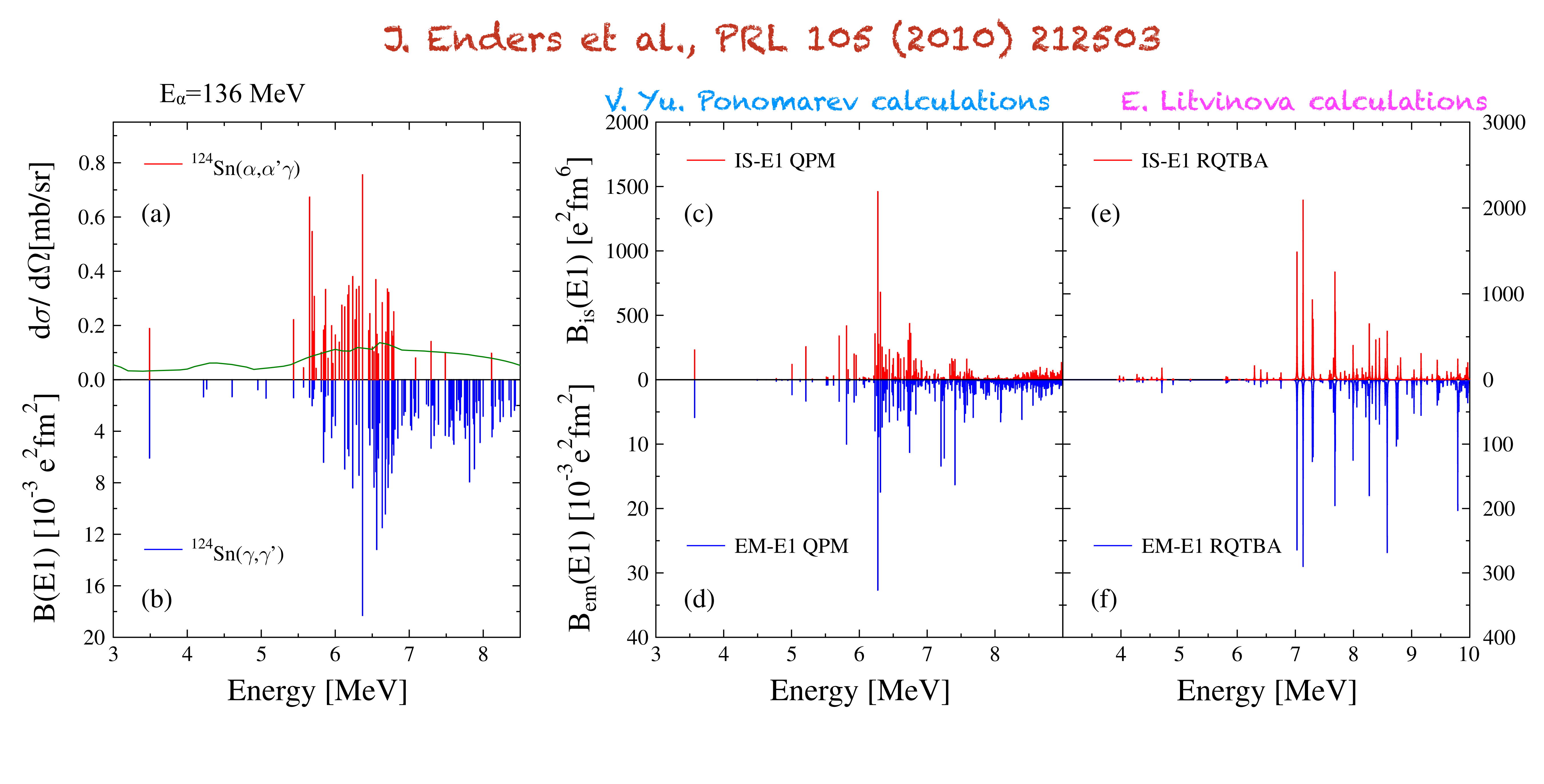
The form factors have been obtained with the double folding procedure with the M3Y nucleon-nucleon potential and with the micro (RPA) and macro transition densities



Double folding procedure

DWBA calculations done with the DWUCK4 code

Splitting of the low-lying dipole strength

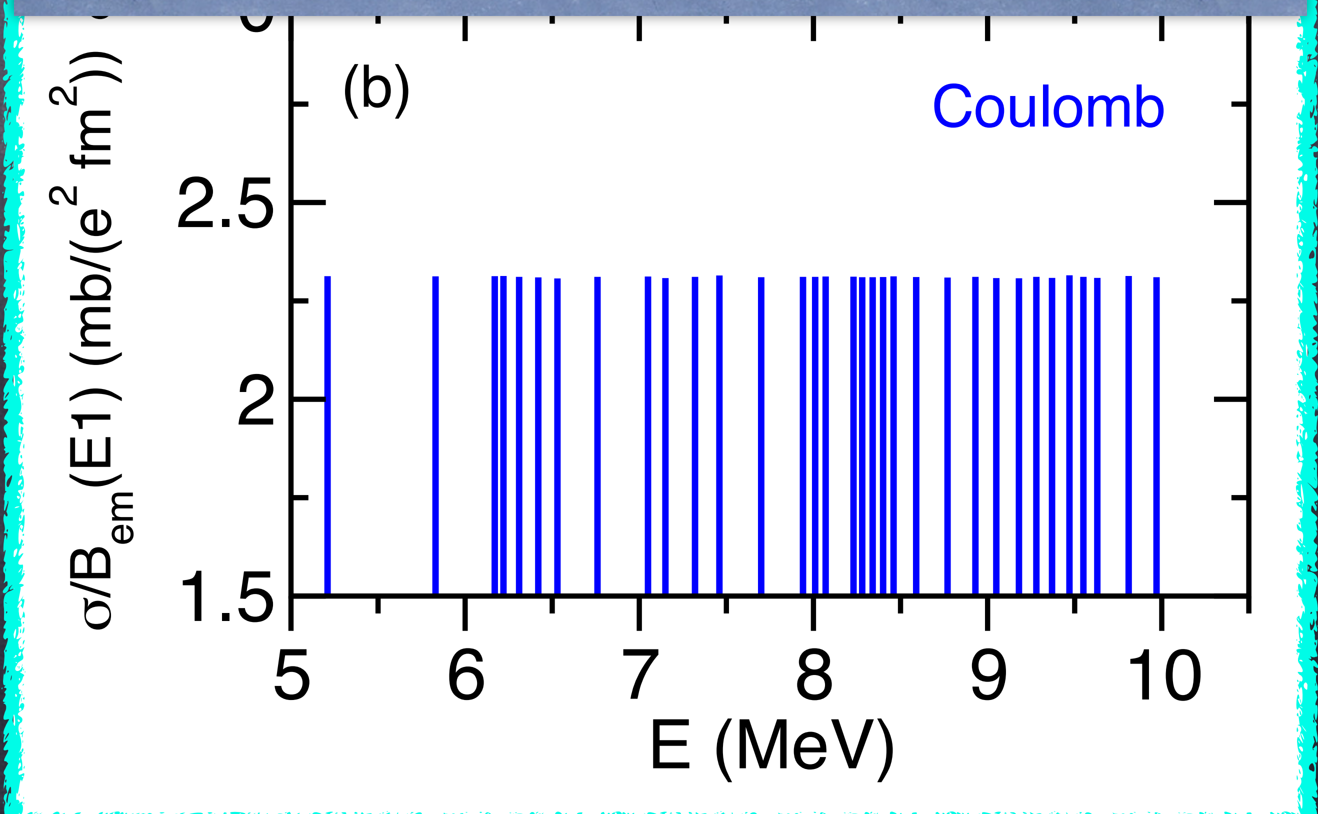


The lower lying group of states is excited by both isoscalar and isovector probes while the states at higher energy are excited by photons only.

For the isoscalar case they are comparing cross section with $B_{is}(E1)$

Calculations done using the transition densities of the RQTBA (E. Litvinova) and by putting by hand the energies of all the states to zero in order to eliminate the contributions due to the dynamic of the reaction, such as the Q-value effect.

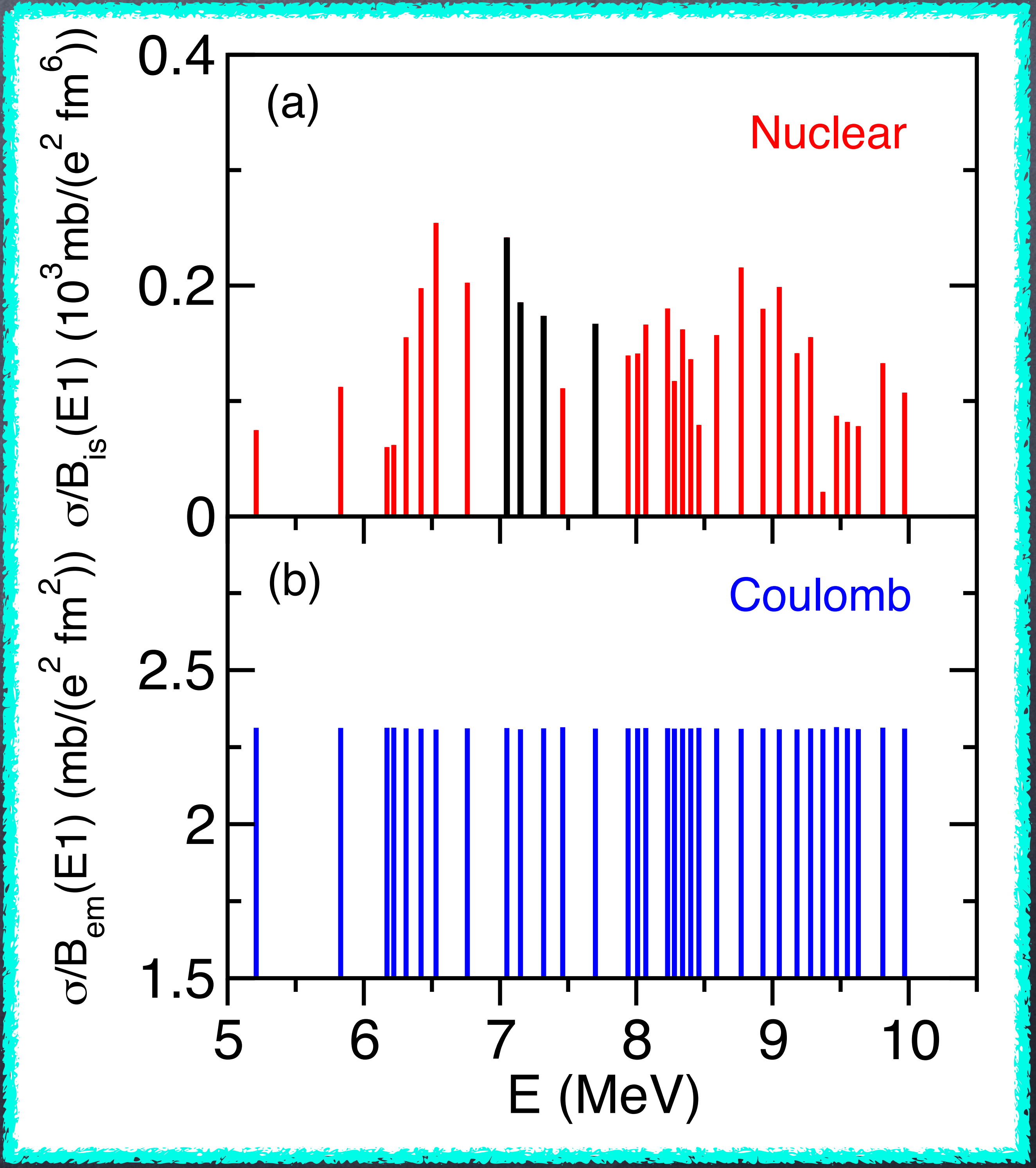
$$\frac{\sigma_x^i(E_i = 0)}{B_x^i(E1)},$$ *i* dipole states, $x = em, is$



For pure Coulomb excitation the relation between the inelastic cross section and the B_{em}(E1) is clear: they are proportional.

Calculations done using the transition densities of the RQTBA (E. Litvinova) and by putting by hand the energies of all the states to zero in order to eliminate the contributions due to the dynamic of the reaction, such as the Q-value effect.

$$\frac{\sigma_x^i(E_i = 0)}{B_x^i(E1)}, \quad i \text{ dipole states, } x = em, is$$

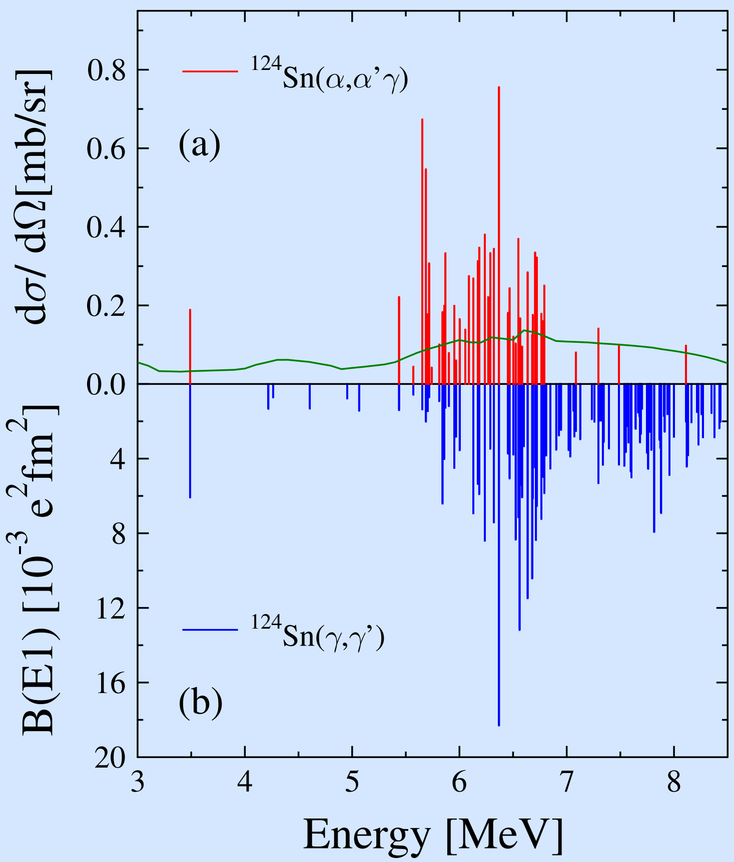


The relation between the isoscalar response and the inelastic excitation cross section due to an isoscalar probe it is not so evident.

For pure Coulomb excitation the relation between the inelastic cross section and the $B_{em}(E1)$ is clear: they are proportional.

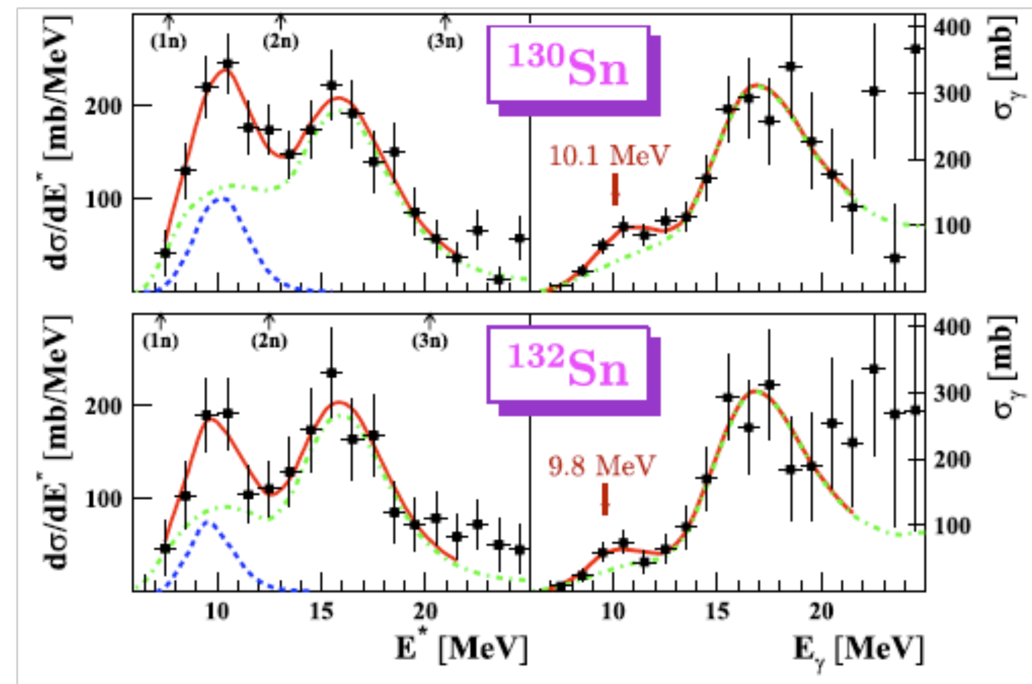
J. Enders et al.,

PRL 105 (2010) 212503



P.Adrich et al., PRL 95 (2005) 132501

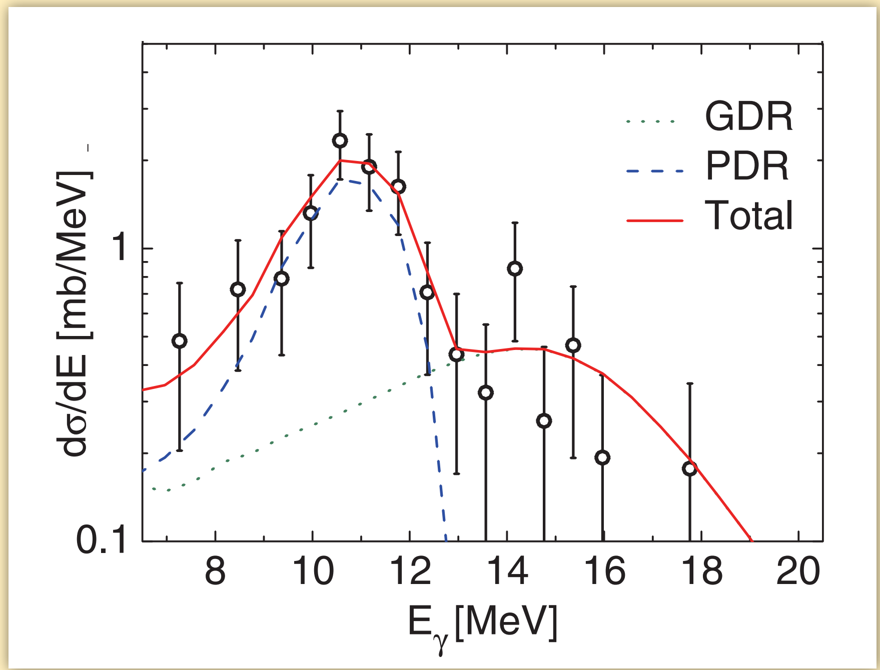
$^{132}Sn + ^{208}Pb$ @ 500 A MeV



O. Wieland et al. ,

PRL 102 (2009) 092502

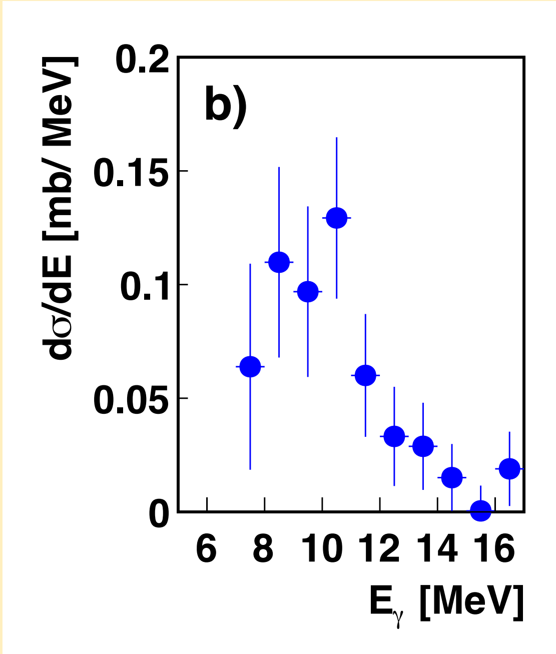
^{68}Ni + Au @ 600 A MeV



N. S. Martorana et al.,

PLB 782 (2018) 112

$^{68}Ni + ^{12}C$ @ 28 A MeV



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Thank you for your attention