Nuclear and Coulomb excitations of low lying dipole states in exotic and stable nuclei

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Introduced by A.M. Lane (Ann. Phys. 63 (1971) 171).

Called "pygmy" because its strength is much smaller than GDR.
Later there have been several studies , microscopic and macroscopic, to try to relate this strength with the presence of a neutron skin.

Partial Width Correlations and Common Doorway States

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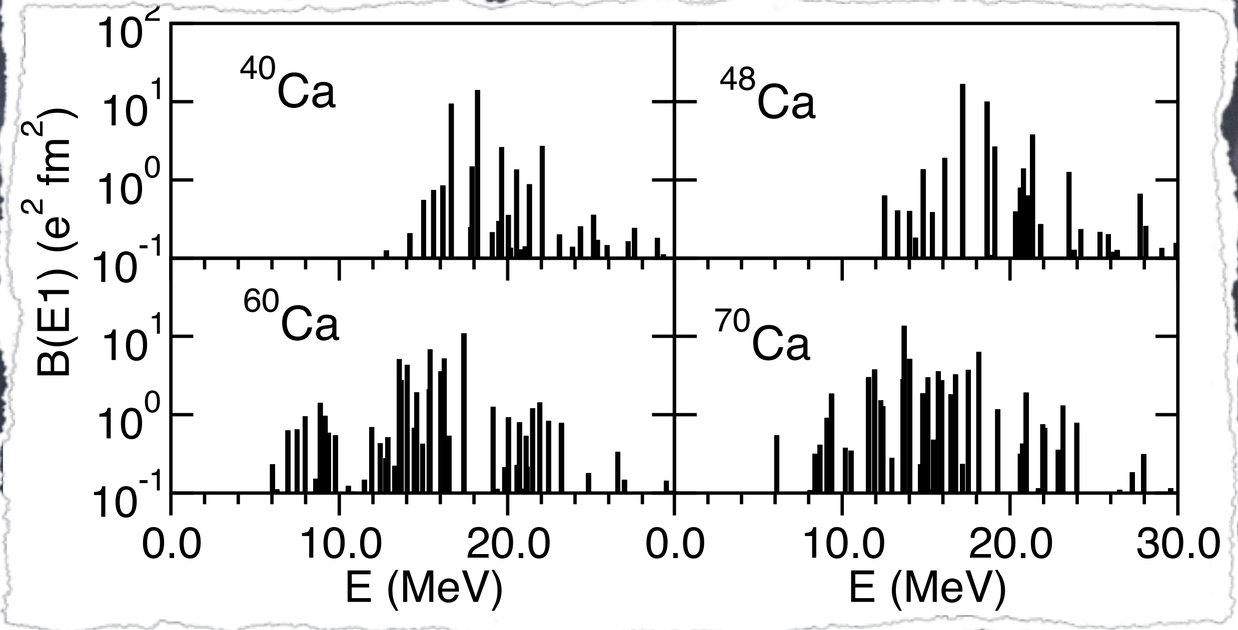
on whether or not such common doorways are expected to occur in practice. A detailed calculation of the 1^- states of ^{208}Pb and ^{60}Ni shows how such states can occur. In ^{208}Pb, they are three states having large components of the $3p^{-1}4s$ configuration, which is associated with most of the neutron and photon strength in the vicinity of 6 MeV. A by-product of this study is an explanation of the "pygmy" dipole resonance.

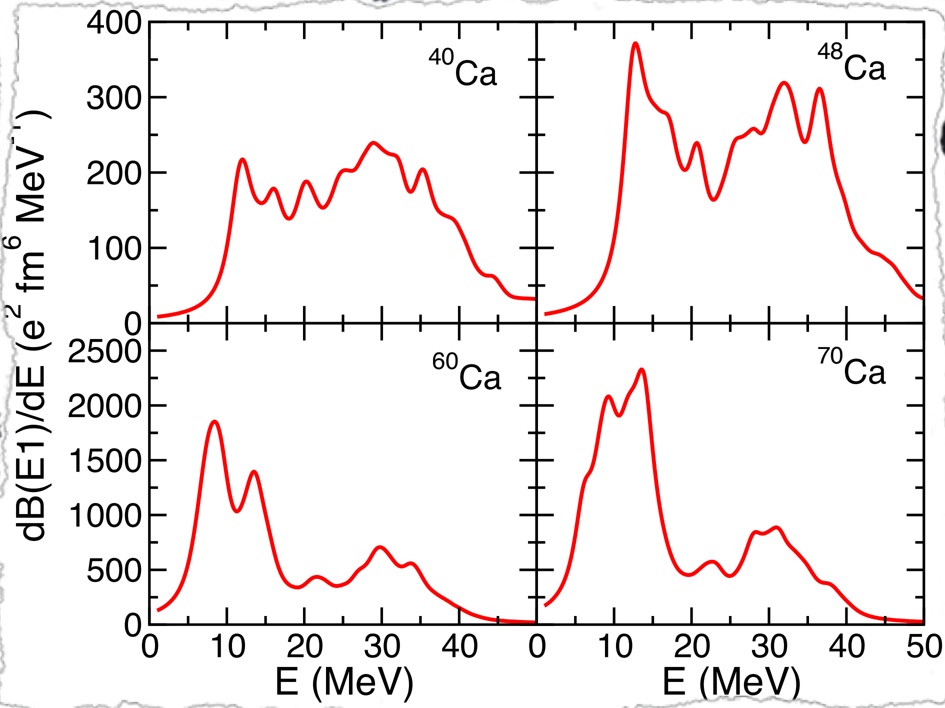
In the course of developing the theory, the relevant experimental data on correlations is presented and discussed.

Isovector response



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



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

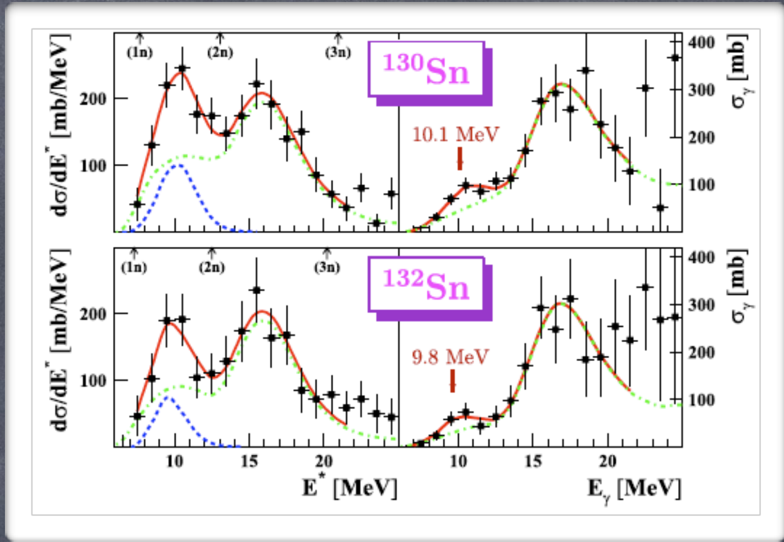
Experimentally they have been measured mainly by mean of Coulomb excitation by various groups

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

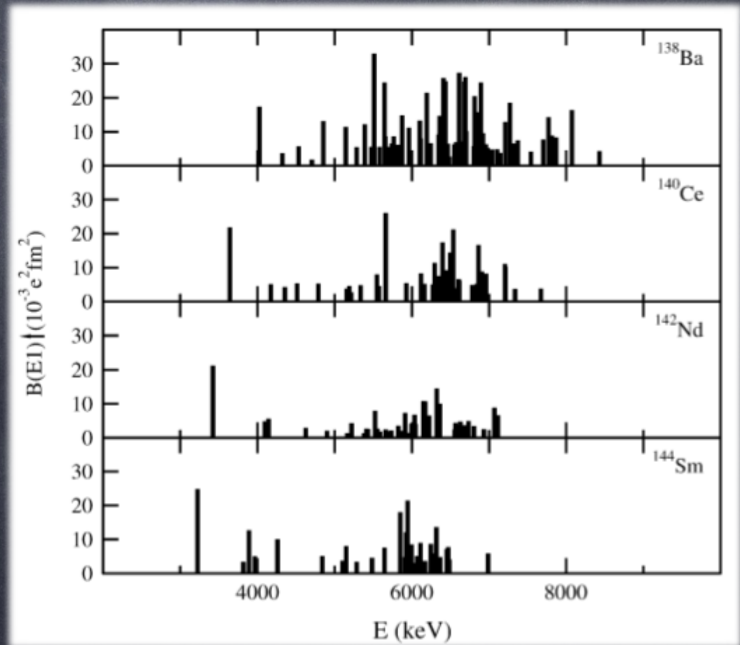


BELOW NEUTRON SEPARATION THRESHOLD

stable nuclei

- with (γ,γ') studies (Darmstadt University) →
- with $(\alpha,\alpha'\gamma)$ at KVI.

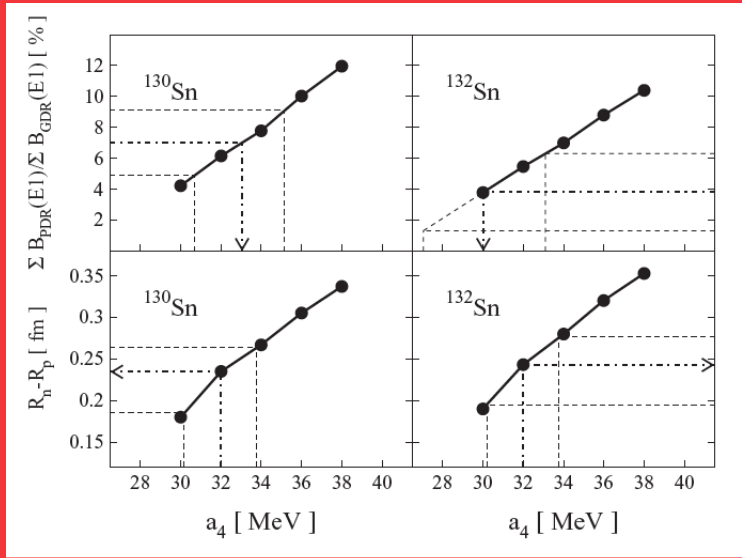
D.Savran et al. PRL 100 (2008) 232501
J.Endres et al. PRC 80 (2009) 034302



Although is controversial discussed, it seems there exist a strong relationship between the PDR strength and the neutron skin.

The neutron skin can be related to the energy symmetry parameter a_4.

Consequences on neutron stars and r-process

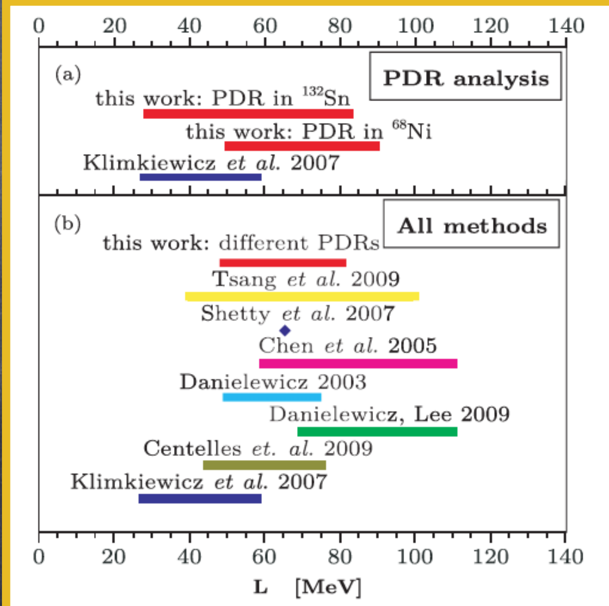


A. Klimkiewicz et al. (LAND Collaboration), PRC 76 (2007) 051603(R)

Relativistic Hartree-Bogoliubov (RHB) plus the quasi particle relativistic RPA (RQRPA) calculations

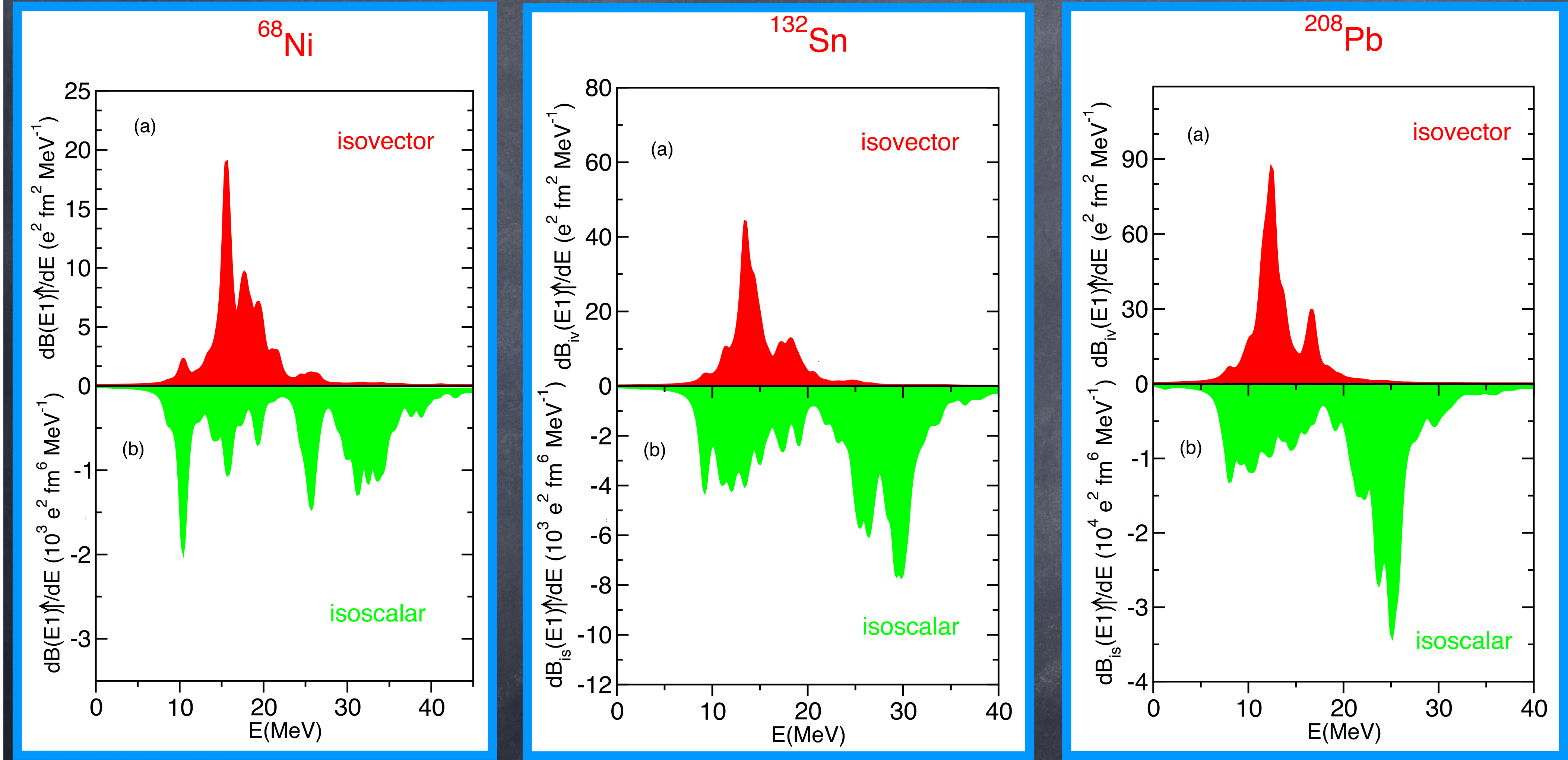
Carbone et al., PRC 81 (2010) 041301(R)

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



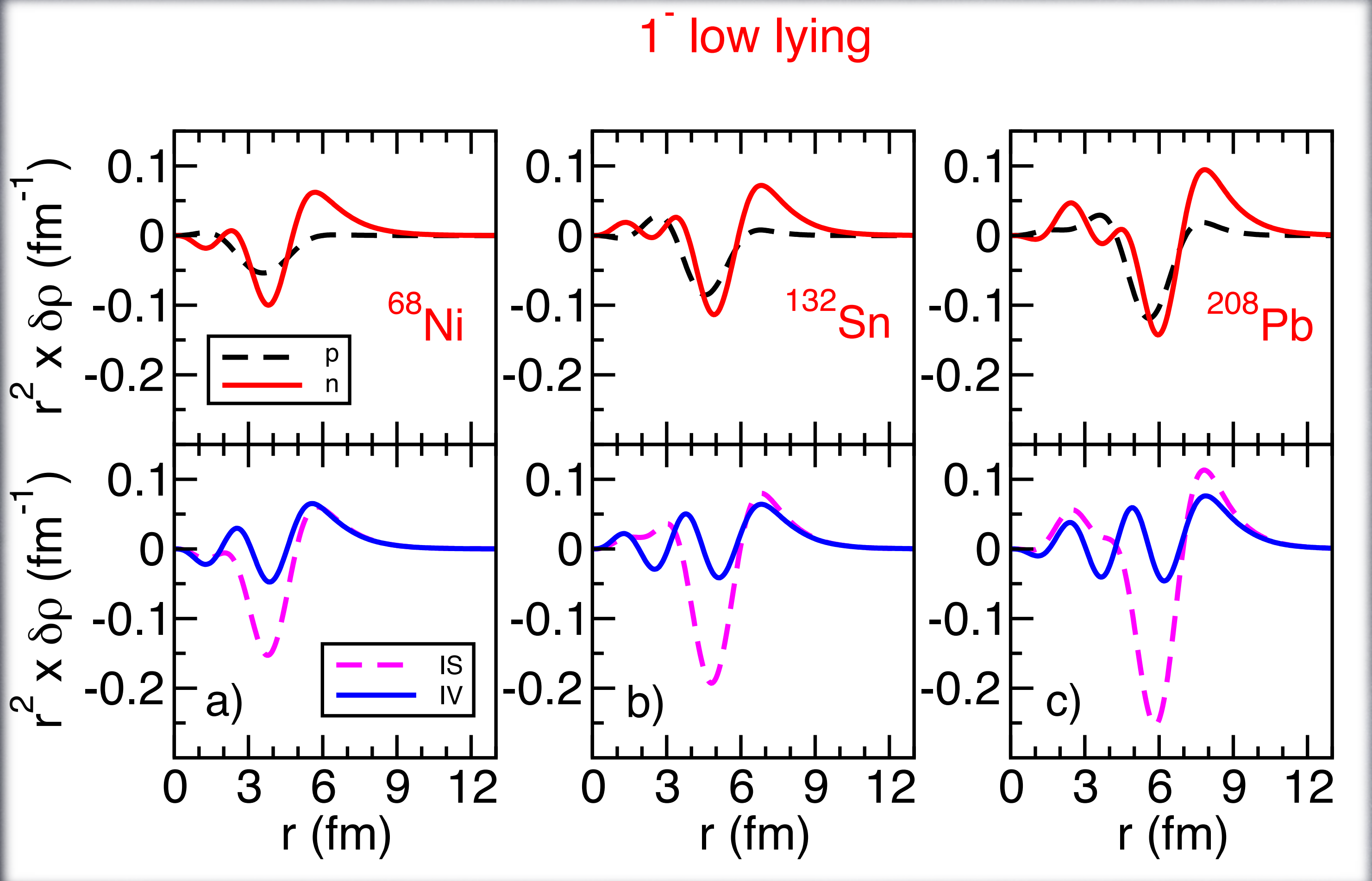
To be compared with the values deduced from PREX and polarizability experiments.

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



$$O_{1M}^{(IV)} = \sum_{i=1}^{A} r_1 Y_{1M}(\hat{r}_1)\tau_z(i)$$

$$O_{1M}^{(IS)} = \sum_{i=1}^{A} r_1^3 Y_{1M}(\hat{r}_1)$$

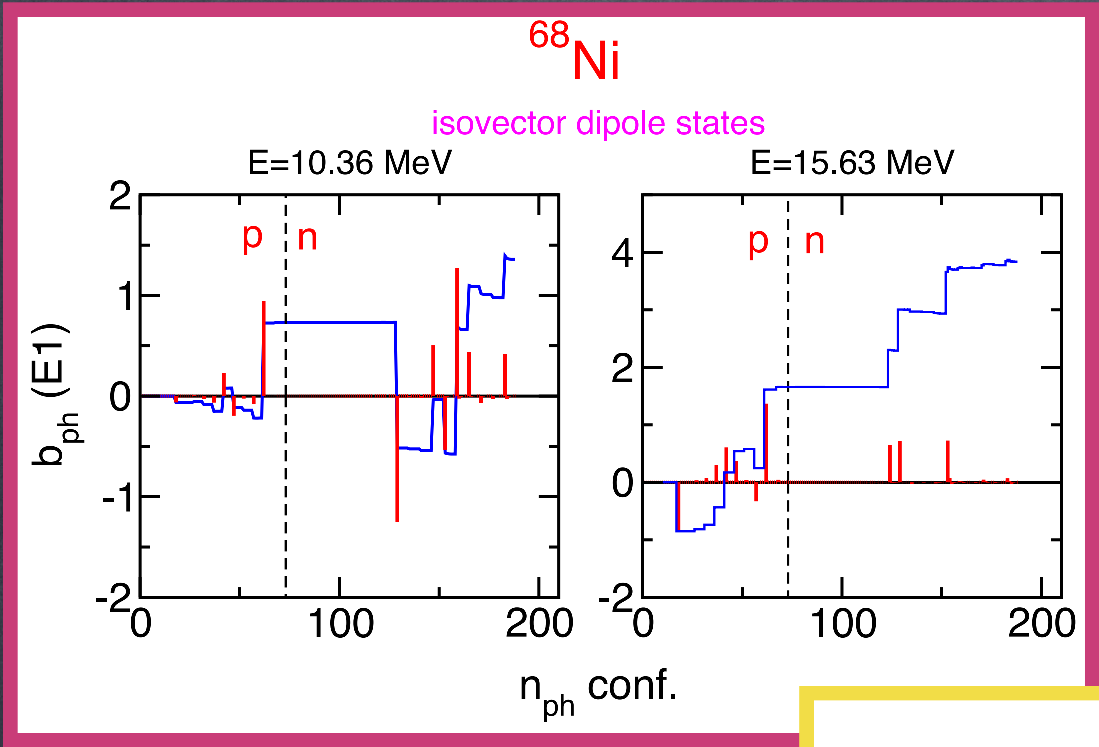


The low lying peaks have the same features: n and p transition densities are in phase inside the nucleus; at the surface only the neutron part survive.

"Theoretical definition" of the PDR

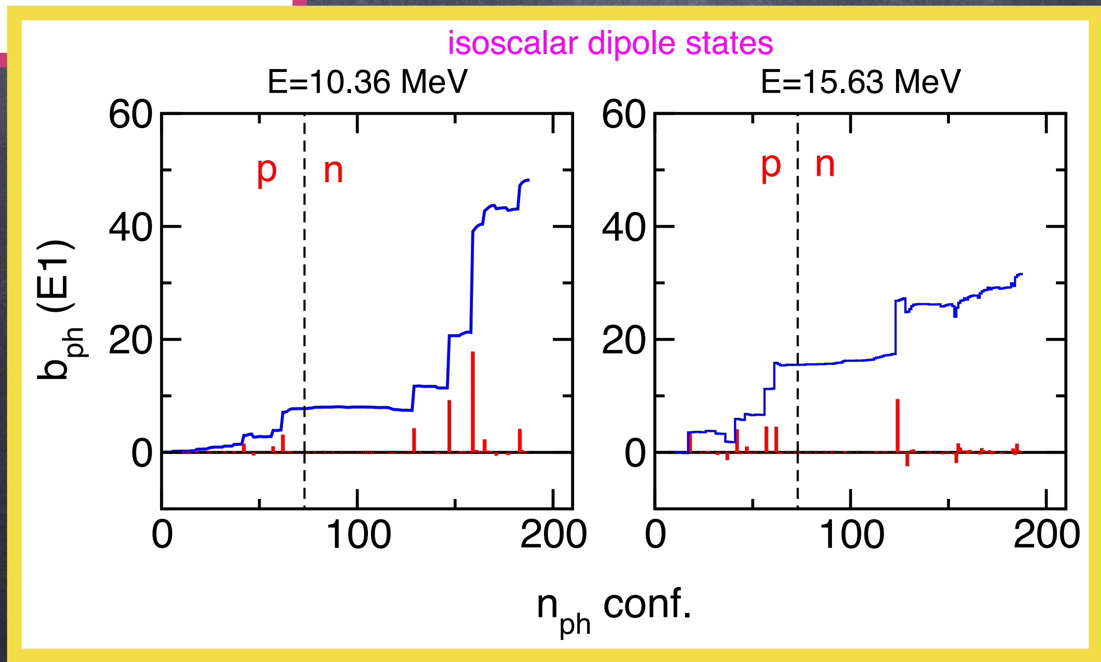
The isovector parts have more nodes as we increase the nucleons number. This may be related to the different major shell of the nuclei and may be a first indication of the non collective character of these states.

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



collective

non collective



From an experimental point of view, the evidence for these states comes almost from Coulomb excitation processes.

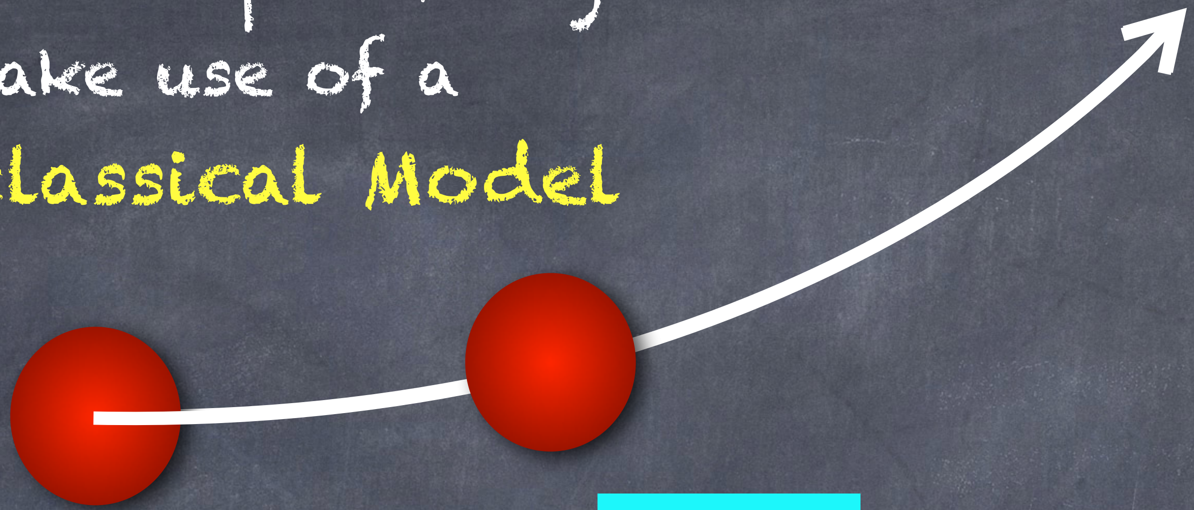
One should explore these states also with reactions where the nuclear part of the interaction is involved.

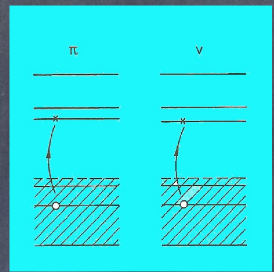
This can be done because of the strong isoscalar component of the low-lying dipole states.

By varying the projectile mass, charge, bombarding energy and scattering angle one can alter the relative role of the nuclear and Coulomb components.

To explore this possibility we make use of a

Semiclassical Model





The two nuclei move according to a classical trajectory while quantum mechanics is used to describe the internal degrees of freedom

$$H = H_A + H_B$$

where

$$H_A = H_A^0 + W_A(t)$$

$$W_A(t) = \sum_{ij} < i | U_B(\vec{R}(t)) | j > a_i^{+} \, a_j + h.c.$$

t-dependence through R(t)

The time dependent state is

$$|\Psi,t>=\sum_{\alpha} A_{\alpha}(t)e^{-iE_{\alpha}t}|\Phi_{\alpha}>$$

The Schrödinger equation can be cast into a set of linear differential equations

$$\dot{A}_{\alpha}(t) = -i\sum_{\alpha'} e^{i(E_{\alpha}-E_{\alpha'})t} < \Phi_{\alpha}|W(t)|\Phi_{\alpha'} > A_{\alpha'}(t)$$

COUPLED CHANNEL EQUATIONS

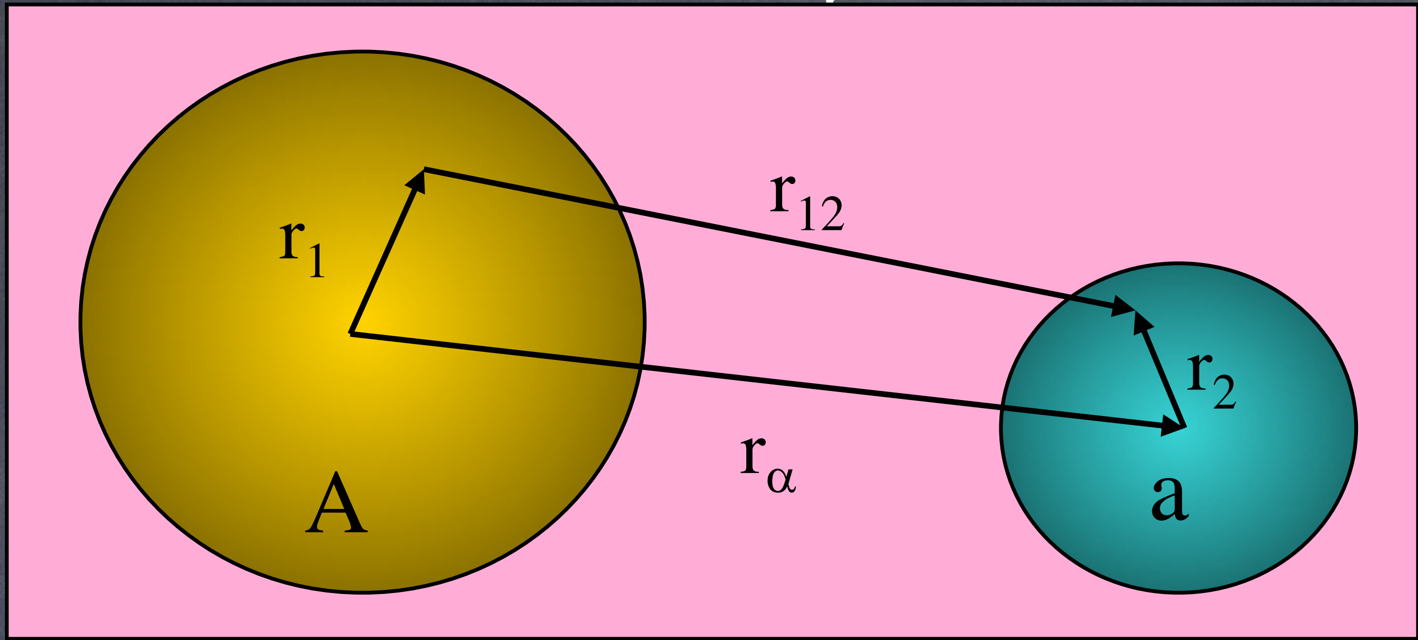
Probability to excite the state $P_{\alpha}(b)=|A_{\alpha}(t=\infty)|^2$ b impact parameter

its cross section is

$$\sigma_{\alpha} = 2\pi\int_0^{+\infty} P_{\alpha}(b)T(b)b\,db.$$

$T(b)$: transmission coefficient taking into account process not explicitly included in the space model

Double Folding procedure



The nucleon nucleon interaction depends on the isospin

$$v_{12} = v_0(r_{12}) + v_1(r_{12})\tau_1 \cdot \tau_2$$

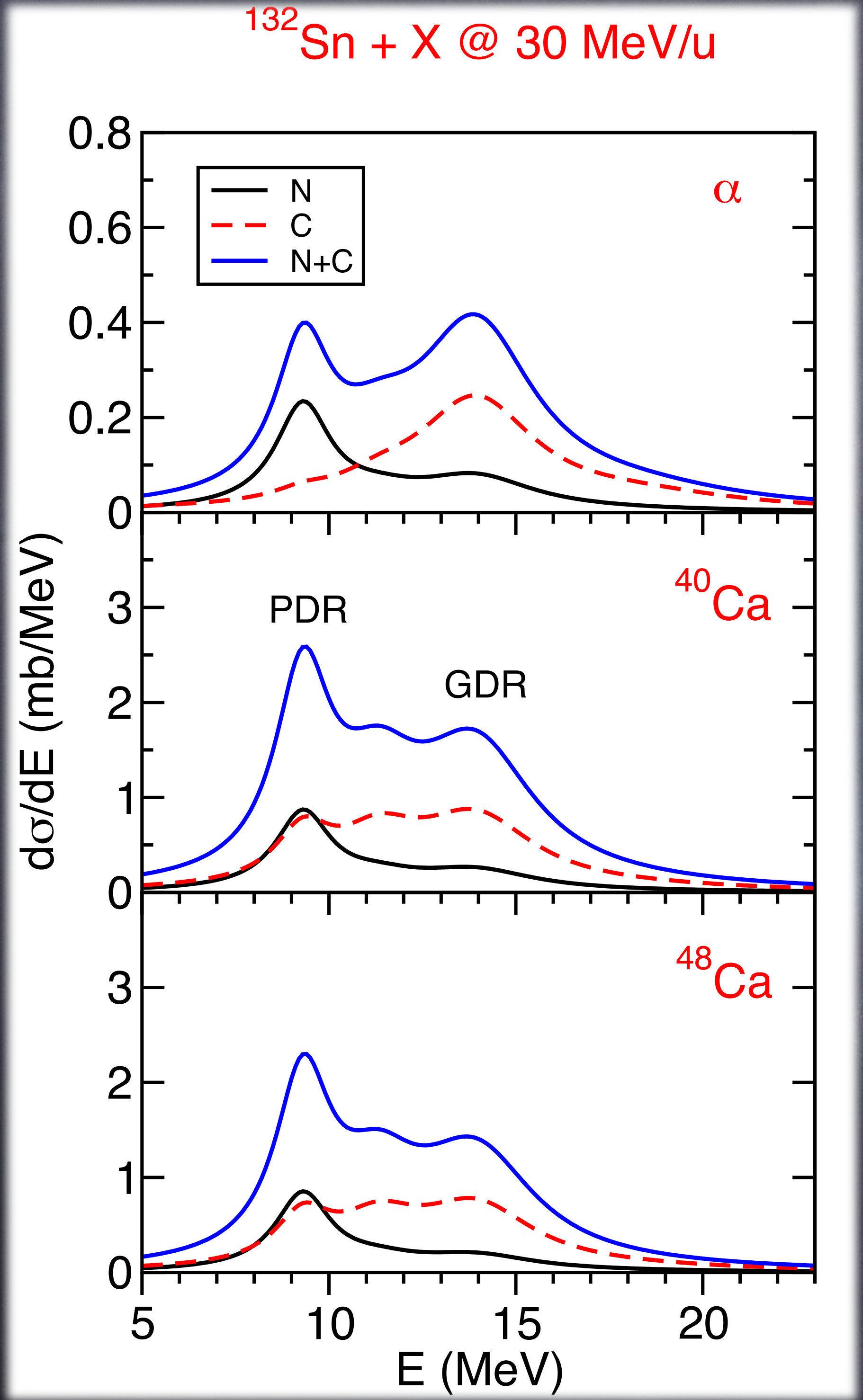
where τ_i are the isospin of the nucleons.

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

Therefore the nuclear form factors are

$$F_0(r_\alpha) = \iint \left[\delta\rho_{An}(\vec{r}_1) + \delta\rho_{Ap}(\vec{r}_1)\right] \times$$
$$\times v_0(r_{12}) \left[\rho_{an}(\vec{r}_2) + \rho_{ap}(\vec{r}_2)\right] r_1^2 dr_1 r_2^2 dr_2$$

$$F_1(r_\alpha) = \iint \left[\delta\rho_{An}(\vec{r}_1) - \delta\rho_{Ap}(\vec{r}_1)\right] \times$$
$$\times v_1(r_{12}) \left[\rho_{an}(\vec{r}_2) - \rho_{ap}(\vec{r}_2)\right] r_1^2 dr_1 r_2^2 dr_2$$



Phys. Rev C 84 (2011) 064602

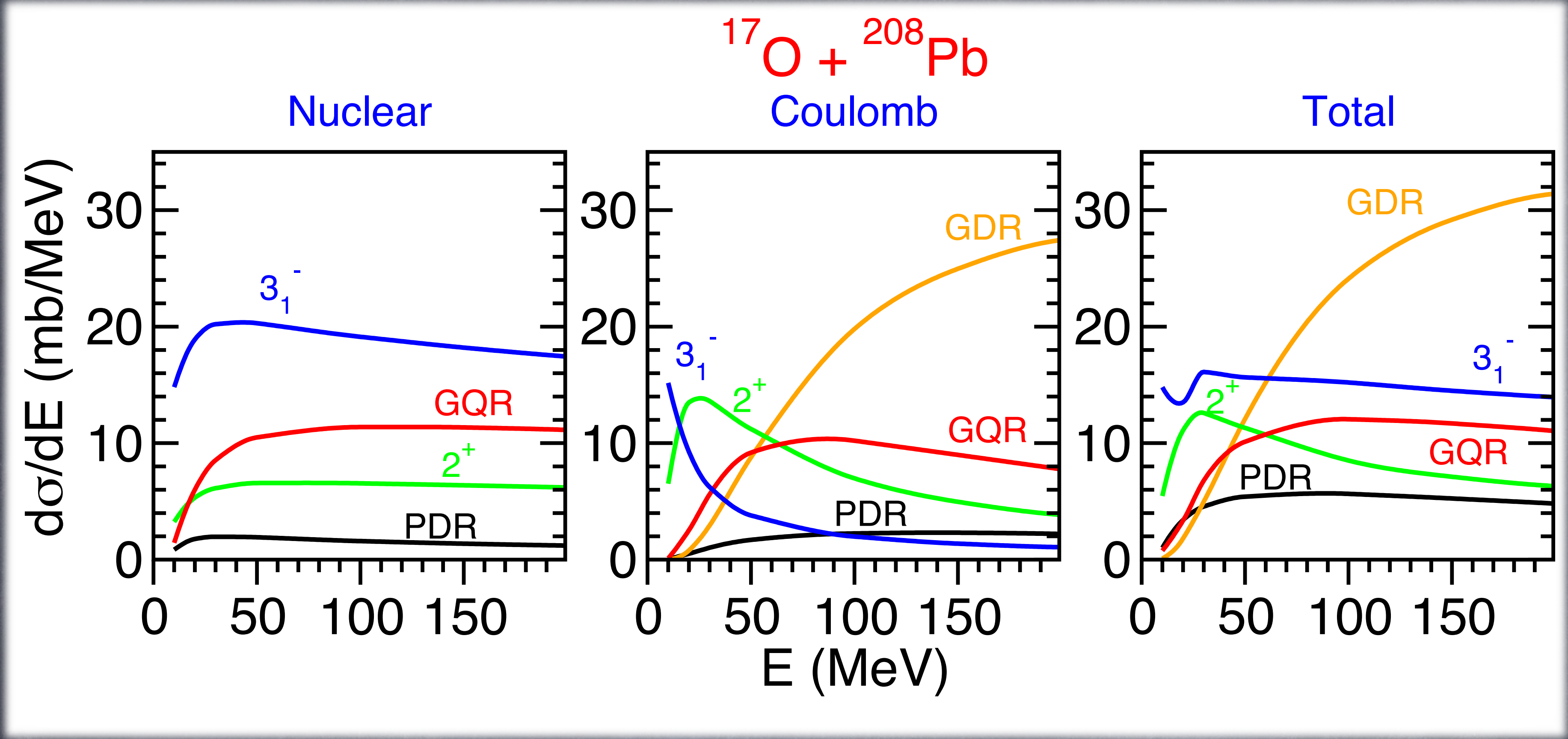
Only 1⁻ states

The continuous lines are obtained by a smoothing folding procedure with Lorentzians whose widths vary with the energy like $\Gamma = 0.026\ E^{1.9}$

(P.Carlos et al. NPA 219 (1974) 61)

The balance between PDR and GDR changes by changing the partners of the reactions because of the relative role of nuclear and Coulomb contributions.

The peak at the GDR energy region is dominated by the Coulomb field.
For the PDR the nuclear is stronger for the α case, while for the isotope of the Ca Coulomb and nuclear contribution are of the same magnitude



The pure isoscalar states are more excited by the nuclear field.

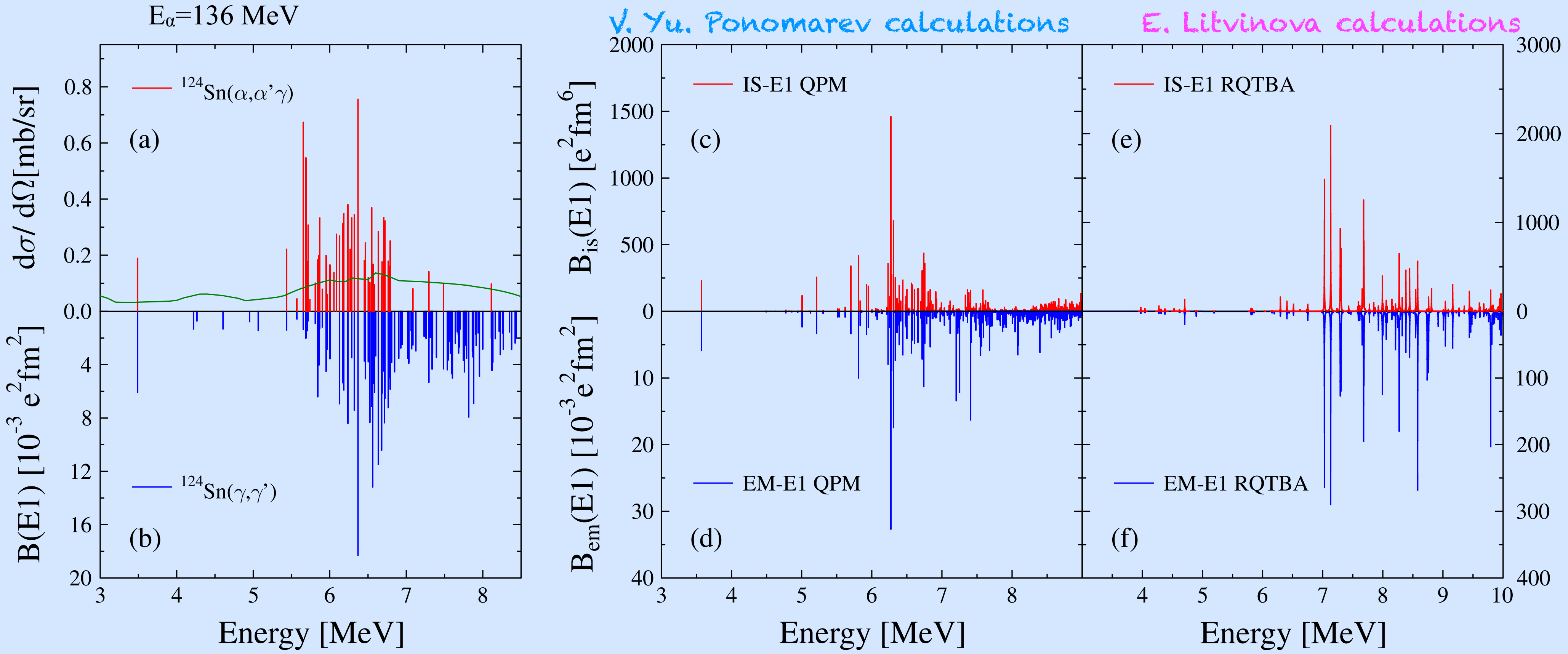
The low lying states get more excited by the Coulomb field at low incident energies and then the excitation decreases with the increase of the energy.
The giant resonances excitation increases with the energy.

The Coulomb and nuclear contribution interfere positively for the PDR.

The investigation of the Pygmy state can be better carried out at low incident energy (below 50 MeV/u). Also because of the different widths of the low lying states and the giant resonances.

Splitting of the low-lying dipole strength

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

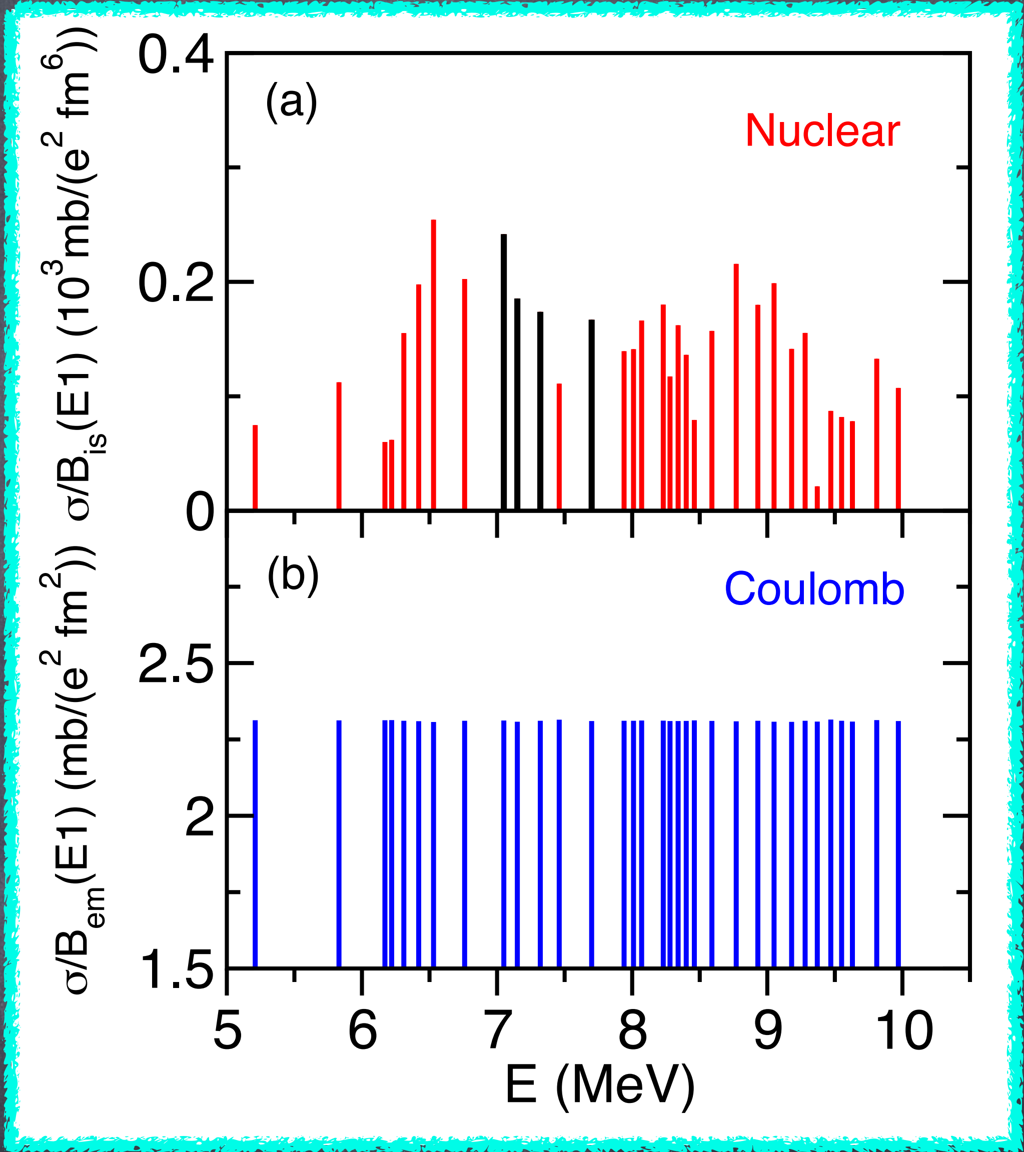


The lower lying group of states is excited by both isoscalar and isovector probes while the states at higher energy are excited by photons only.

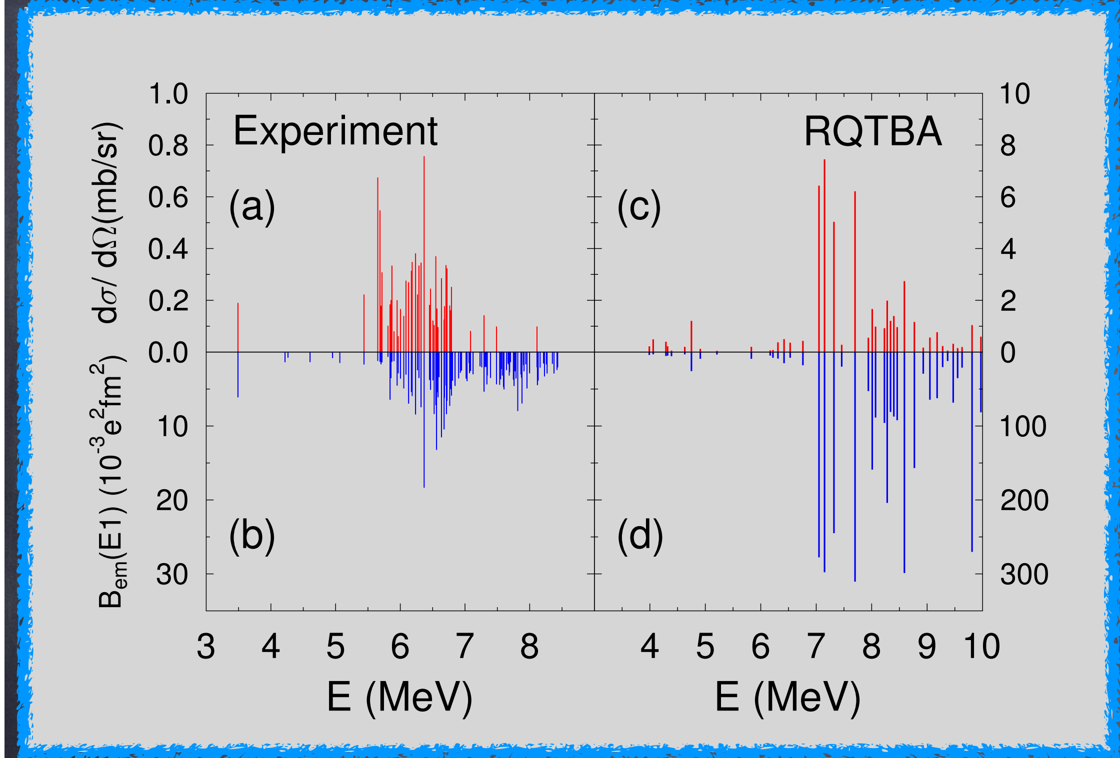
For the isoscalar case they are comparing cross section with $B_{is}(E1)$

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

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



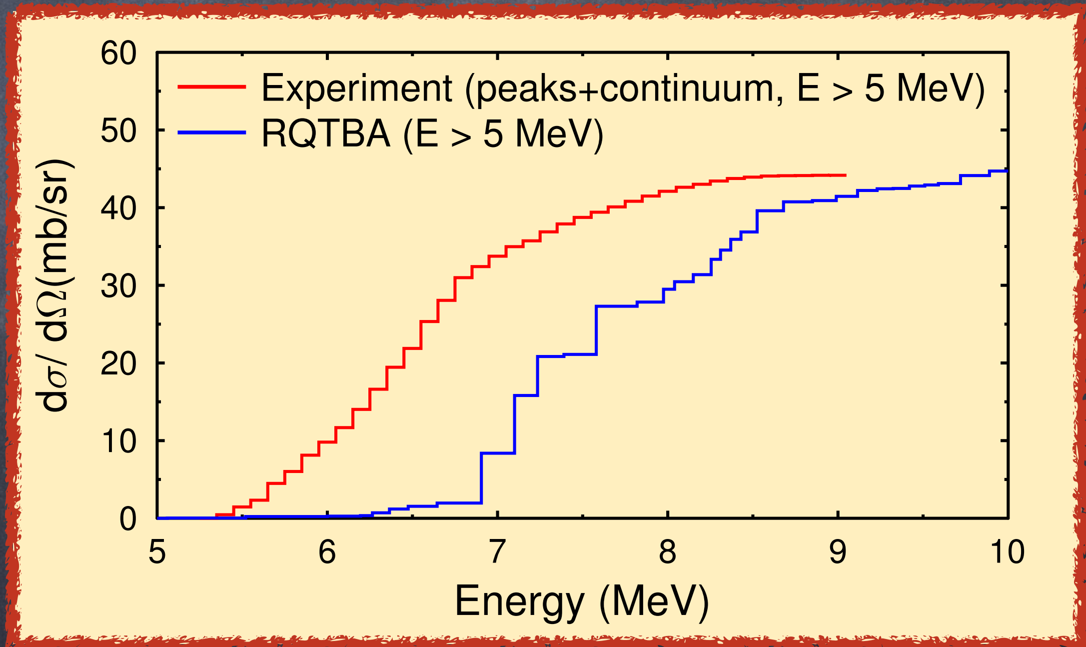
Calculations done using the transition densities of the RQTBA and by putting by hand the energies of all the states to zero in order to eliminate the contributions due to the dynamic of the reaction, such as the Q-value effect.



Comparison between our cross section calculations (with the transition densities of RQTBA) and the experimental data.

This calculation provides the missing link to directly compare the results from the microscopic RQTBA calculations to experimental data measured via the $(\alpha, \alpha' \gamma)$ reaction,

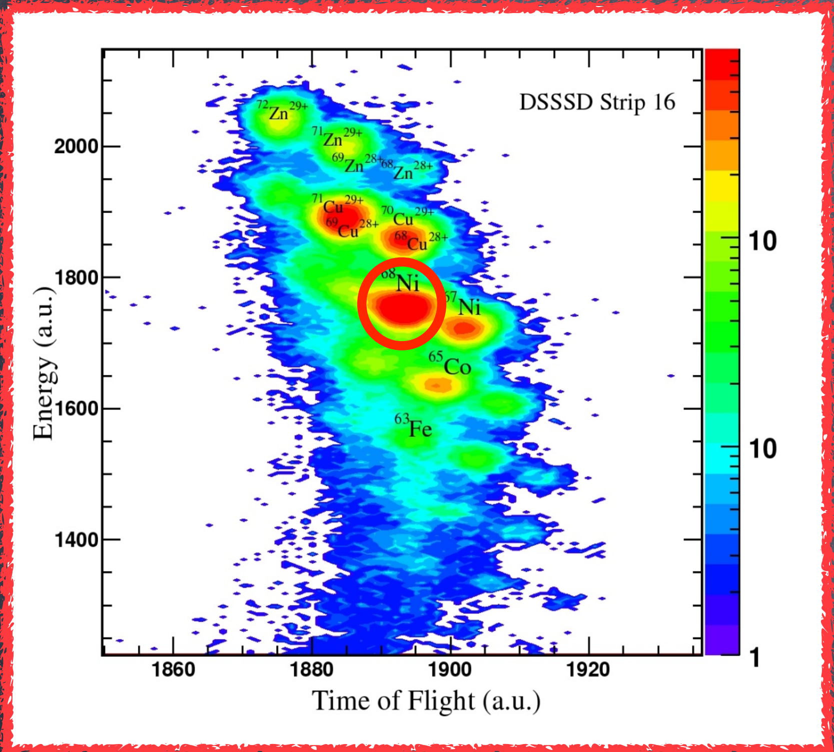
confirming the structural splitting of the low-lying E1 strength.

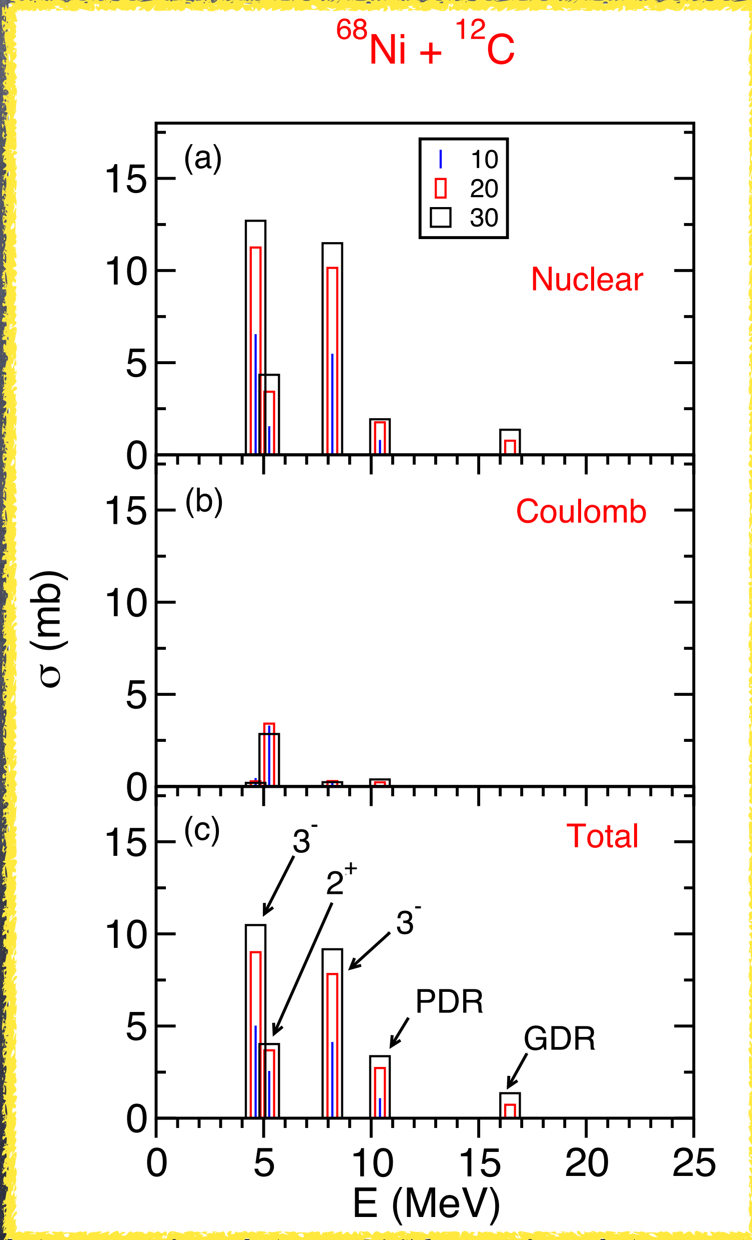


Comparison in terms of the cross section cumulative sum.

Experiment with CHIMERA at LNS next fall

At 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. A yield of 20kHz was measured for this beam.





We propose to use this beam at energy around 30 A·MeV on a thick ^{12}C target to excite the pigmy resonance. The γ-decay of the resonance can be measured using the CsI of the CHIMERA detector.

Summary

Nuclei with neutron excess show a low-lying dipole strength with a strong isoscalar component.

Combined reactions processes involving the Coulomb and nuclear interactions can provide a clue to reveal characteristic features of these states.

The splitting of the low-lying E1 strength is confirmed by our calculations.