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SPES exotic beams for science

Nuclear and Coulomb excitations of the pygmy dipole resonances

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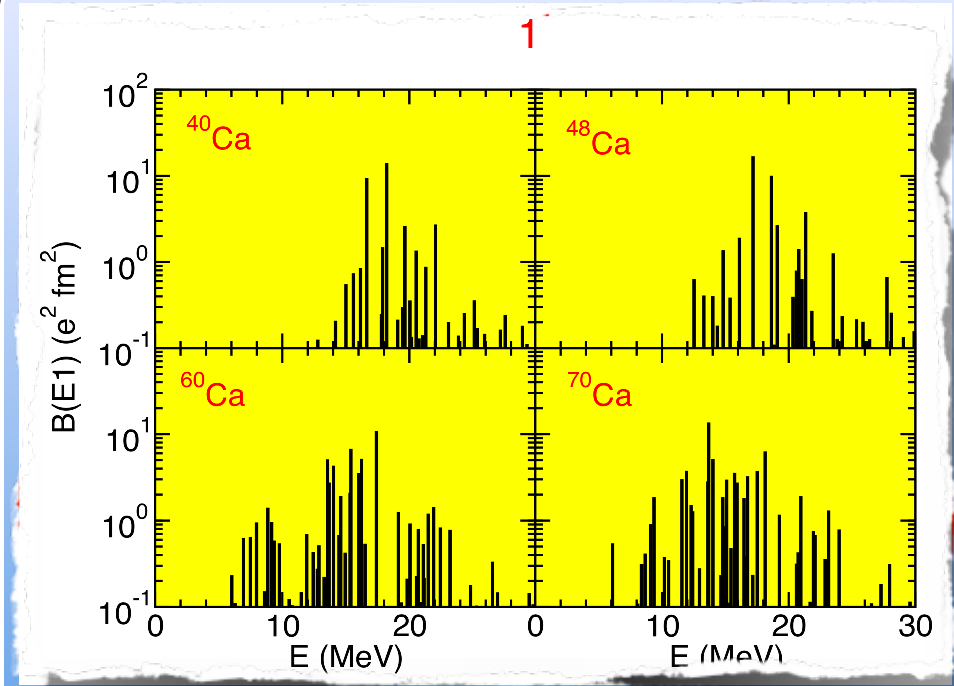


Introduced by **A.M. Lane** (Ann. Phys. 63 (1971) 171). Called "pygmy" because its strength much smaller than GDR. Later there have been several studies , microscopic and macroscopic, to try to relate this strength with the presence of a neutron skin.

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.

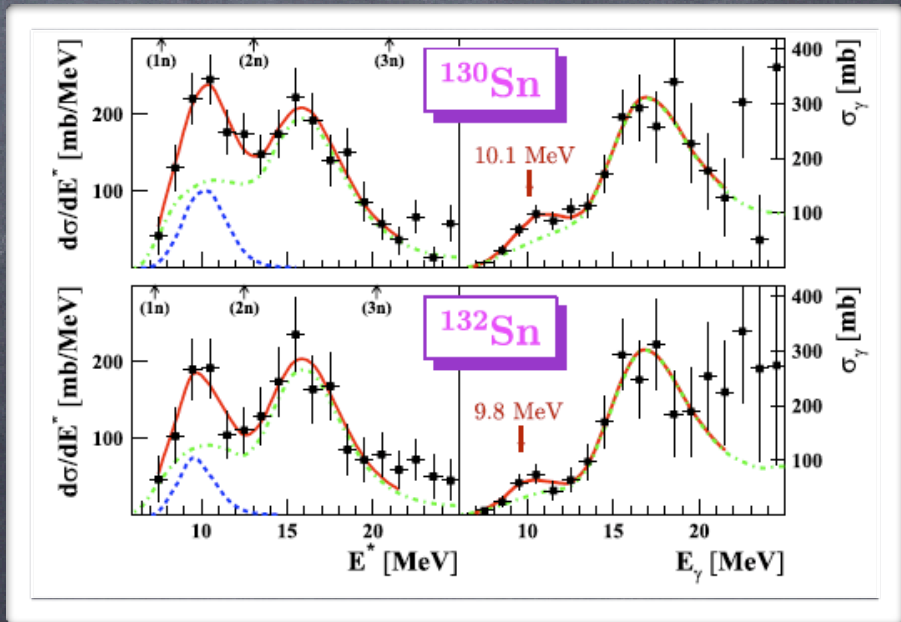
For the dipole mode, additional strength has been found below the normal giant resonance region

F. Catara, E.G. Lanza, M.A. Nagarajan, A. Vitturi,

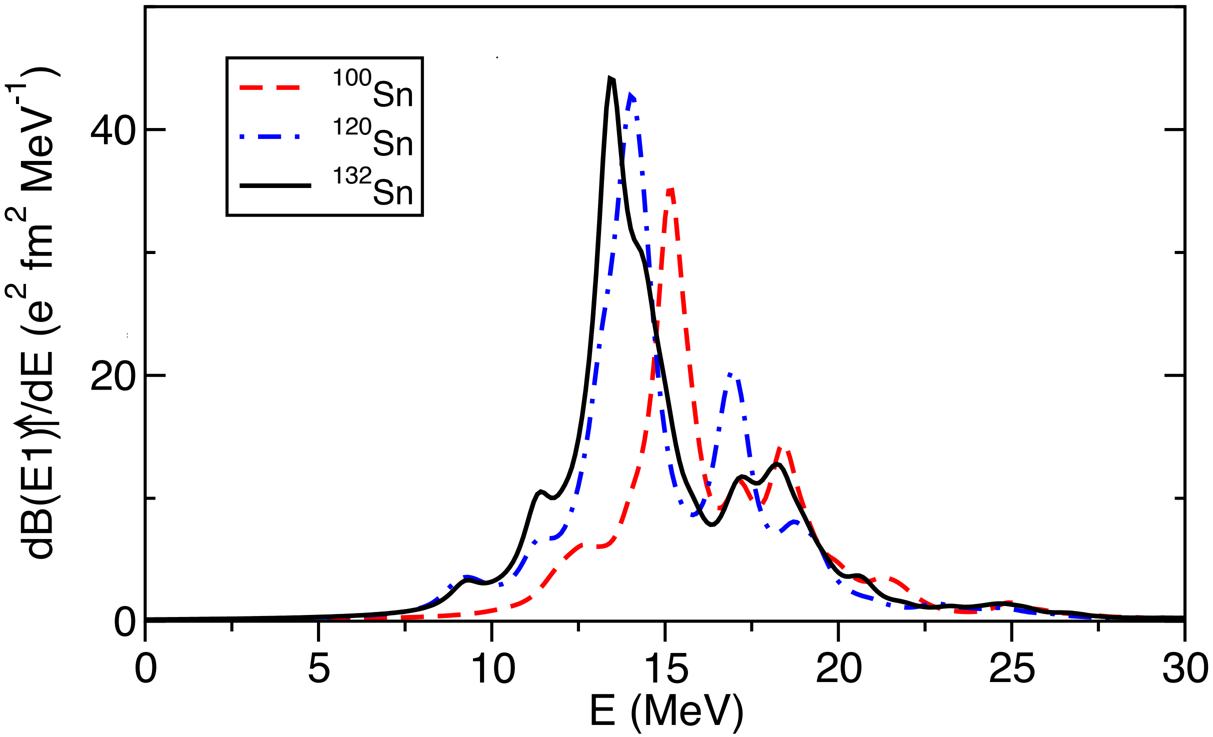
NPA 614 (1997) 86; NPA 624 (1997) 449

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

- using the FRS-LAND setup at GSI →
- using the RISING setup at GSI
- with (γ,γ′) studies below the neutron separation threshold (Darmstadt)
- with (α,α′γ) at KVI.



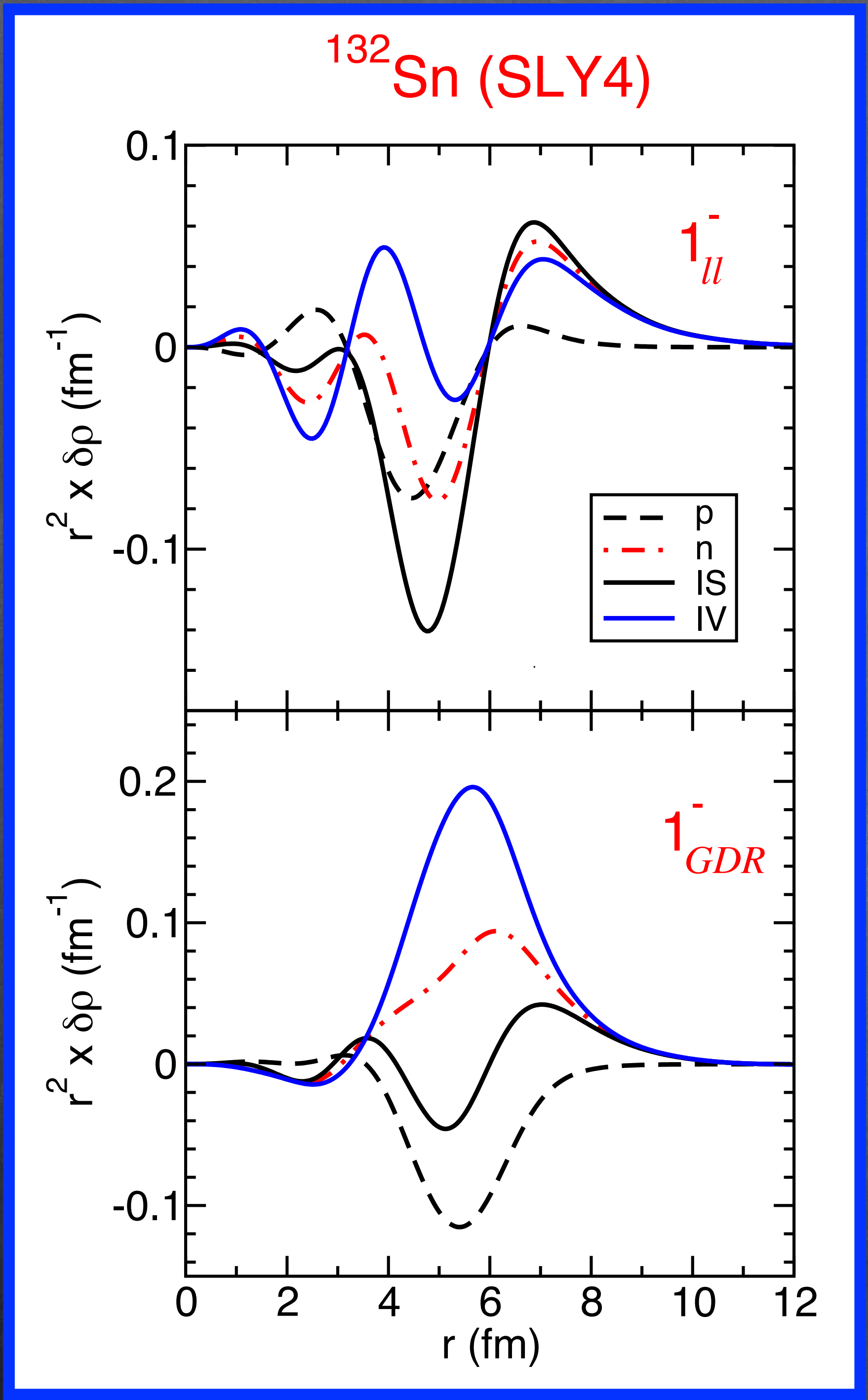
P.Adrich et al. PRL 95 (2005) 132501
O.Wieland et al. PRL 102 (2009) 092502
D.Savran et al. PRL 100 (2008) 232501
J.Endres et al. PRC 80 (2009) 034302



As an example we show some calculations done with the Hartree-Fock plus RPA with SGII Skyrme effective interactions. As far as the neutrons number increases more strength is found at low energy.

Similar calculations have been done before with similar results. See for example:
-D. Sarchi, P. F. Bortignon, G. Colò **(HF+RPA or HF-BCS+QRPA)**, PLB 601 (2007) 27;
-N. Paar, T. Nikšič, D. Vretenar, P. Ring **(RHB+RQRPA)** PLB 606 (2005) 288;
-E. Litvinova, P. Ring, D. Vretenar **(RRPA+PC)** PLB 647 (2007) 111;
-N. Tsoneva and H. Lenske **(QRPA+QPM)** PRC 77 (2008) 024321

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



1^- low lying state

in the interior region, proton and neutron densities are not out of phase; in the interior the isoscalar transition density dominates over the isovector one; in the surface region the contribution comes only from the neutrons. Strong isospin mixing.

New Mode

Strong isoscalar component at the surface region. Therefore, the mode can be excited by an isoscalar probe.

GDR

the proton and neutron densities oscillate with opposite phases; isovector transition density much larger than the isoscalar one.

From an experimental point of view, the evidence for these states comes almost from Coulomb excitation processes. As known, these can only provide values of the multipole $B(E\lambda)$ transition rates:

$$F_\lambda^C \approx \frac{[B(E\lambda)]}{r^{\lambda+1}}$$

To our opinion, if we want to understand their nature we should explore these states with reactions where the nuclear part of the interaction is involved. This can be done because of the strong isoscalar component of the PDR state.

By tuning the projectile mass, charge, bombarding energy and scattering angle one can alter the relative role of the nuclear and Coulomb components, as well as the isoscalar and isovector contributions.

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

$$H = H_A + H_B \quad \text{where} \quad H_A = H_A^0 + W_A(t)$$

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

t-dependence through R(t)

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

coupled channel equations

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

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

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. This implies

$$v_{nn} = v_{pp} = v_0 + v_1 \;; \quad v_{np} = v_0 - v_1 \,.$$

The double folding potential has two terms

$$U_0(\vec{r}_\alpha) = \iint \rho_A(\vec{r}_1)\, v_0(r_{12})\, \rho_a(\vec{r}_2)\, d\vec{r}_1\, d\vec{r}_2$$

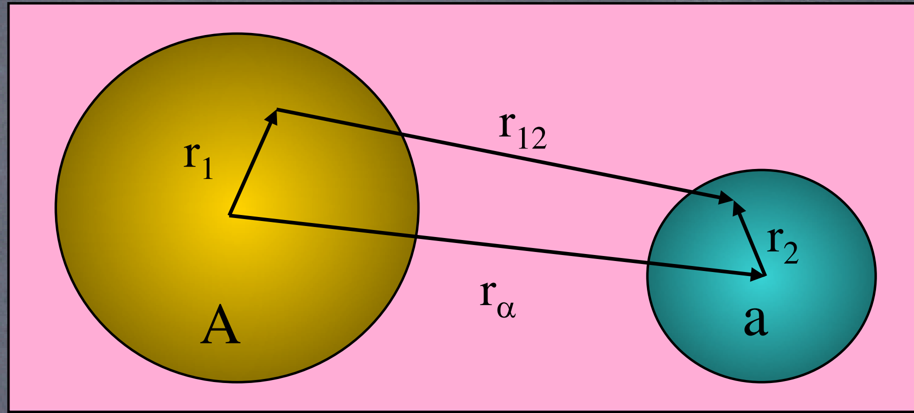
$$U_1(\vec{r}_\alpha) = \iint \left[\rho_{An}(\vec{r}_1) - \rho_{Ap}(\vec{r}_1)\right] \times \times v_1(r_{12}) \left[\rho_{an}(\vec{r}_2) - \rho_{ap}(\vec{r}_2)\right] d\vec{r}_1\, d\vec{r}_2$$

where

$$r_{12} = \left|\vec{r}_\alpha + \vec{r}_2 - \vec{r}_1\right|$$

In the case $\rho_n = N/Z\,\rho$; $\rho_p = N/A\,\rho$

$$U_1(\vec{r}_\alpha) = \left(\frac{N_a - Z_a}{a}\right)\left(\frac{N_A - Z_A}{A}\right) \times \int\!\!\int \rho_A(\vec{r}_1) v_1(r_{12}) \rho_a(\vec{r}_2) \quad d\vec{r}_1 d\vec{r}_2.$$

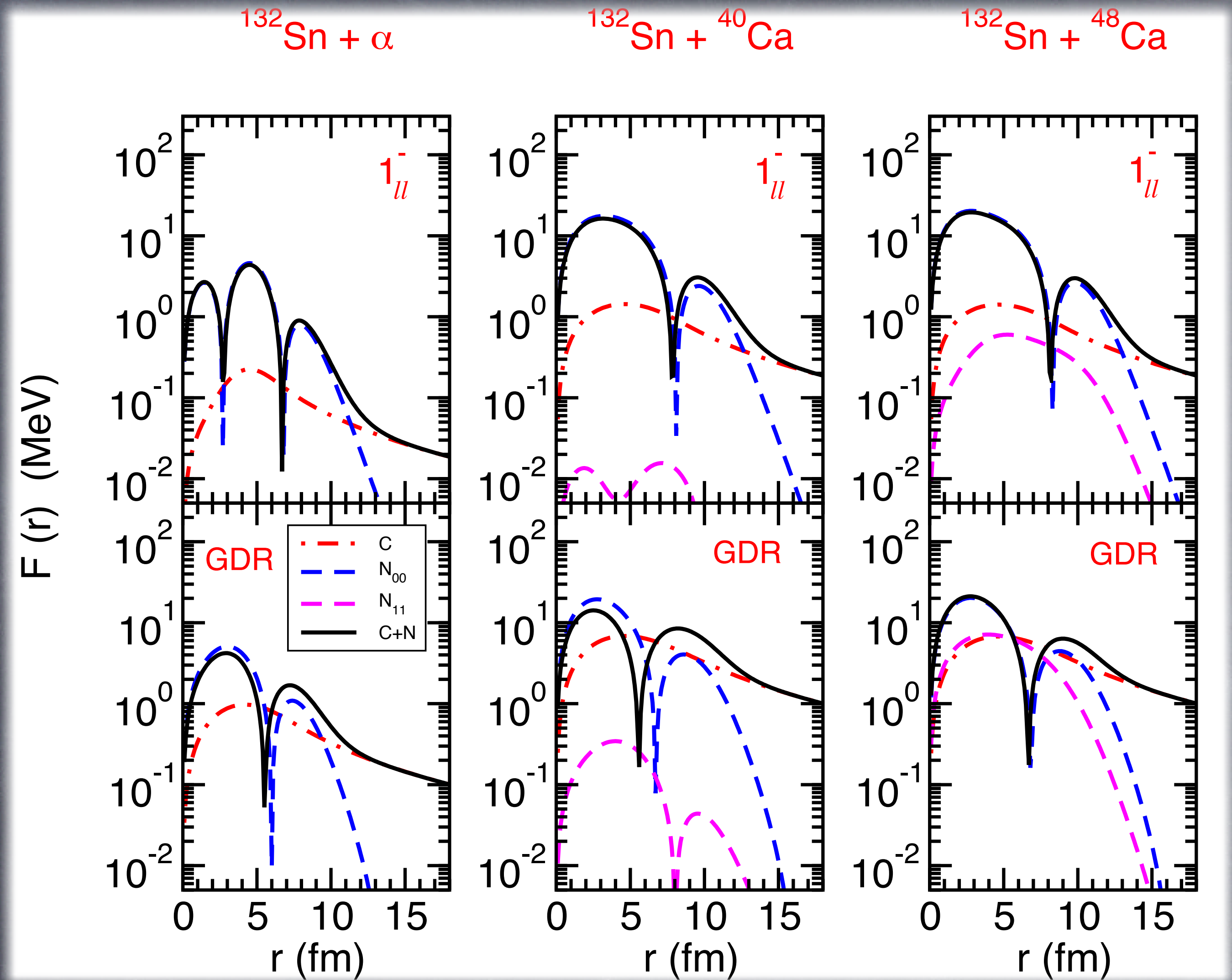


Therefore the nuclear form factors are

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

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

As before, in the case one of the two nuclei has $N=Z$ then F_1 is zero.



The Coulomb contribution is very different for the two states, while the nuclear one is of the same order of magnitude.

The isospin part is important only for ^{48}Ca

$$v_0(r) = \left[7999\frac{e^{-4r}}{4r} - 2134\frac{e^{-2.5r}}{2.5r}\right] - 262\delta(r)$$

$$v_1(r) = -\left[4886\frac{e^{-4r}}{4r} - 1176\frac{e^{-2.5r}}{2.5r}\right] + 217\delta(r)$$

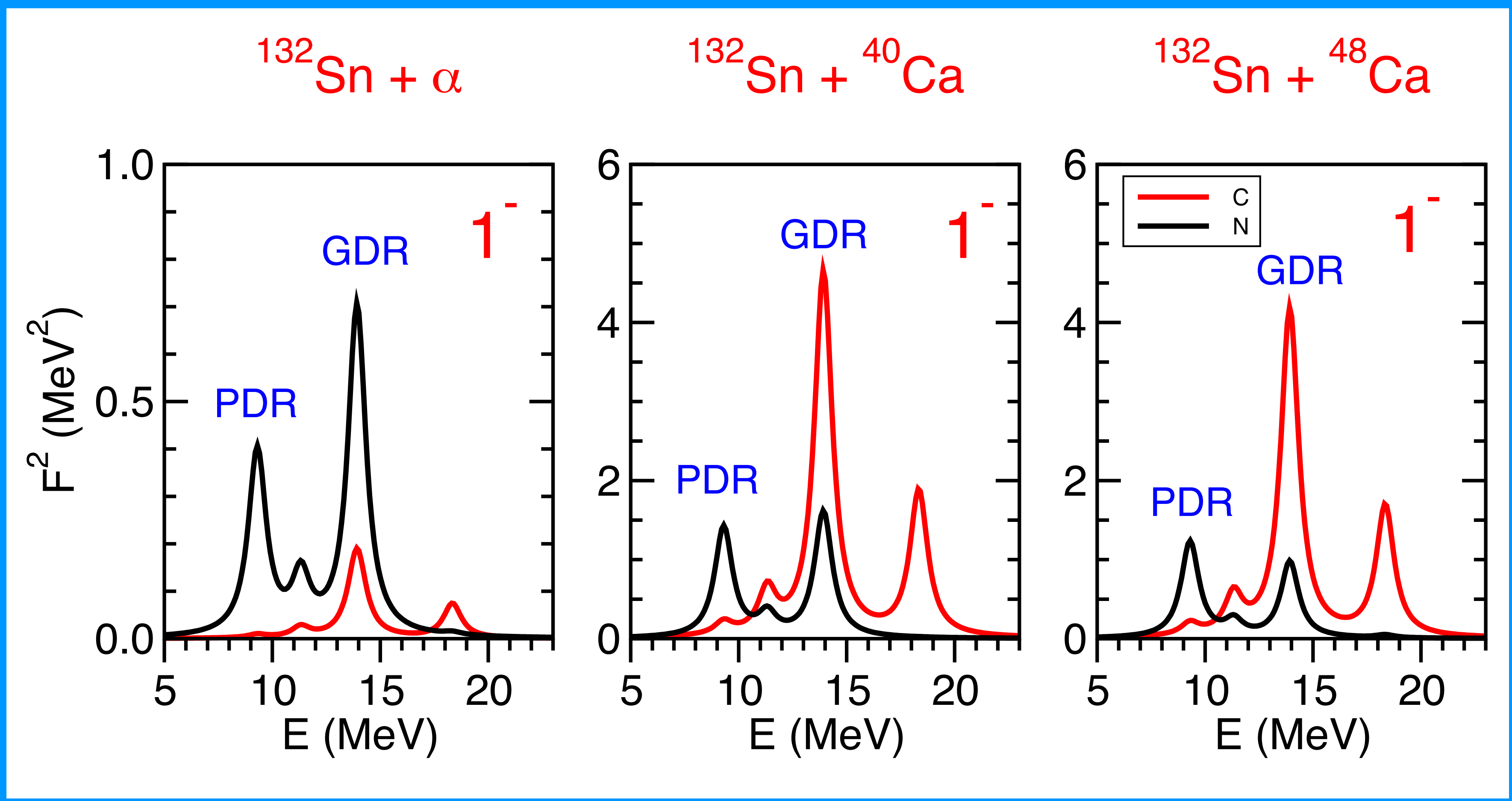
folding done with the effective nucleon-nucleon M3Y interaction

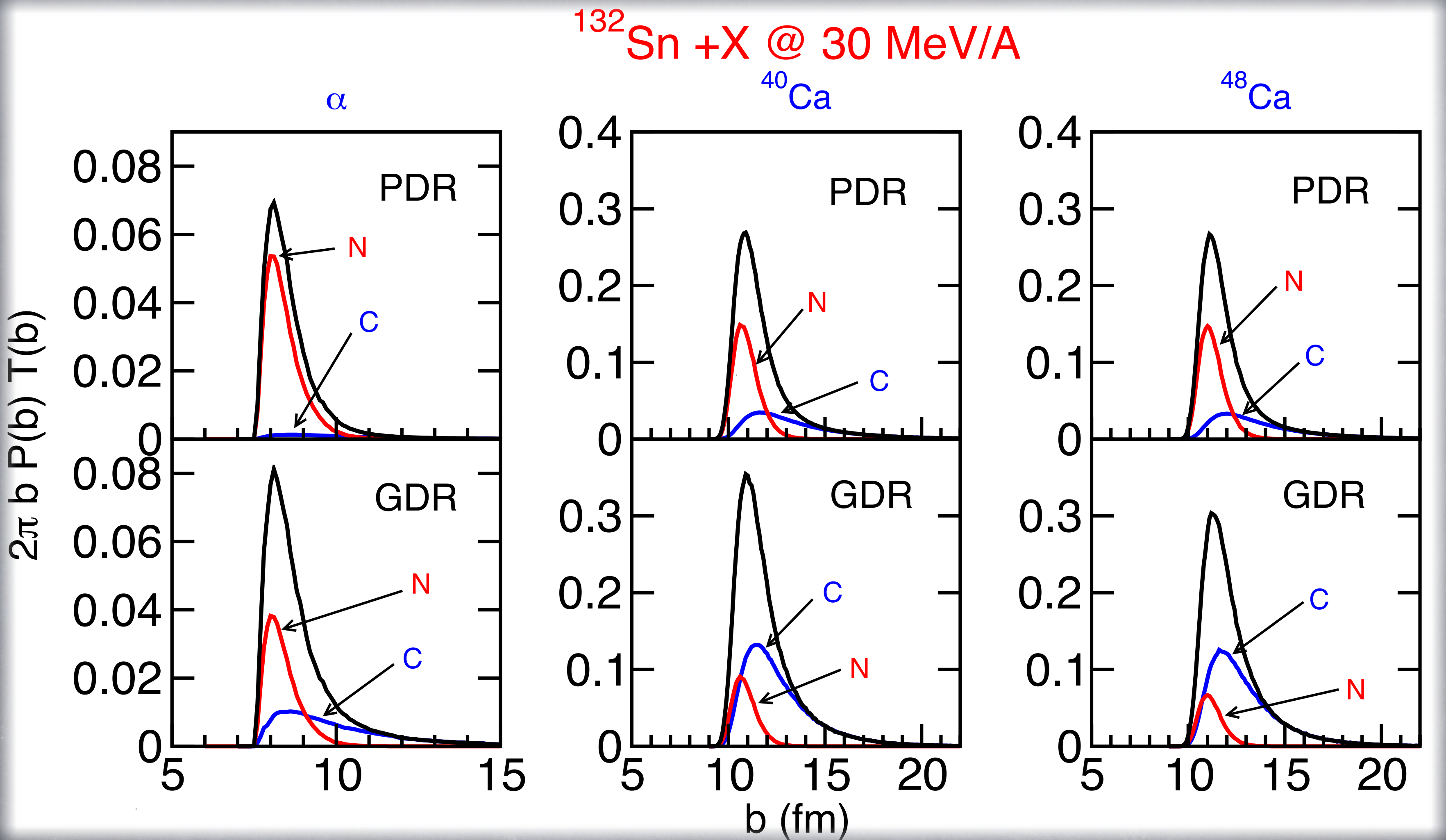
G. R. Satchler, Direct Nuclear Reactions, Oxford University Press 1983.

Square of the formfactors at the surface.

Different reactions alter the relative "intensity" of the PDR and GDR states. This is due also to the different interplay of isoscalar and isovector contributions.

State	E_{harm} (MeV)	EWSR(%)
1^-_{ll} (PDR)	9.3	1.1
1^-_{ll2}	11.3	4.4
GDR	13.9	56
1^-_{hl}	18.3	25

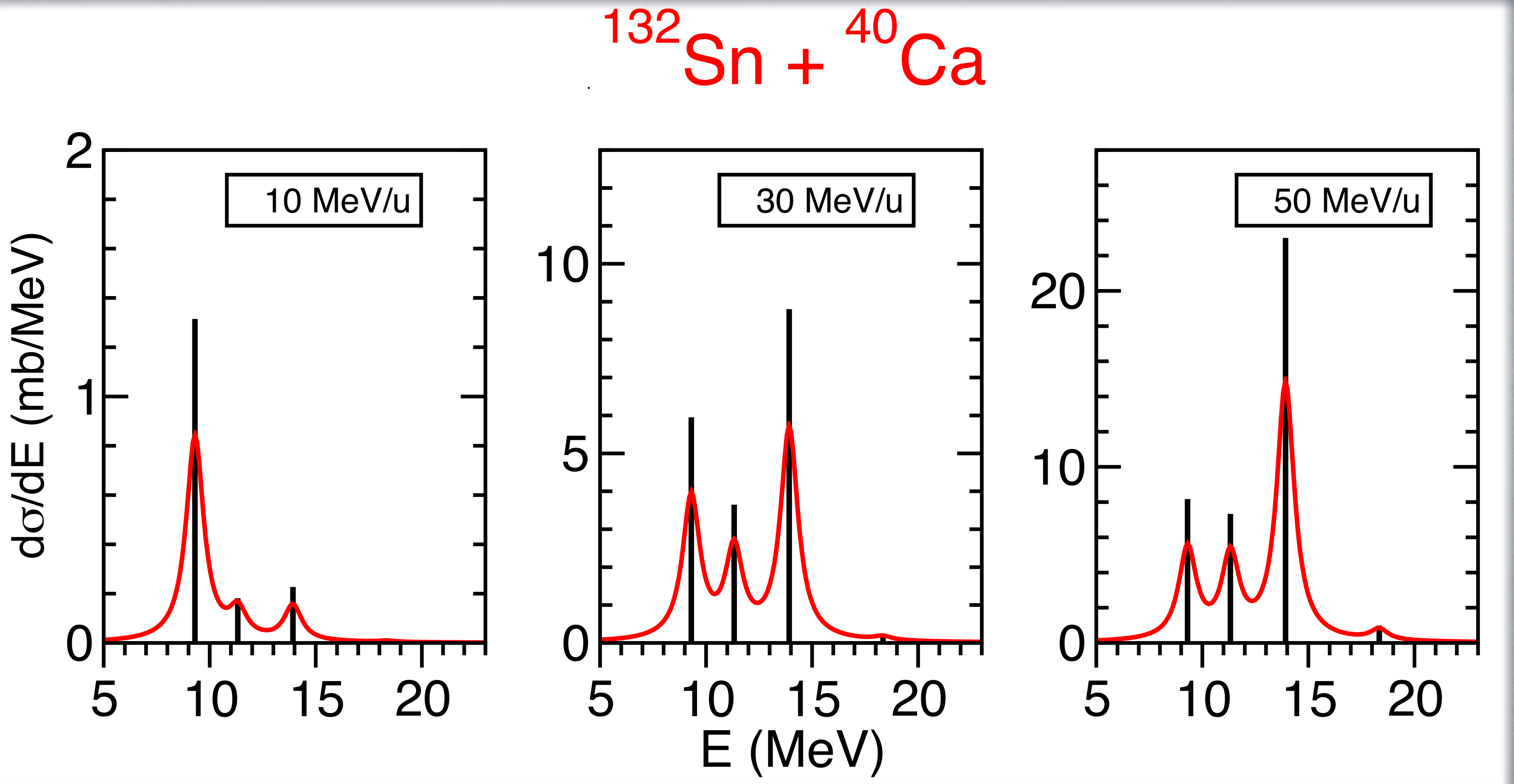




"Partial wave cross section"

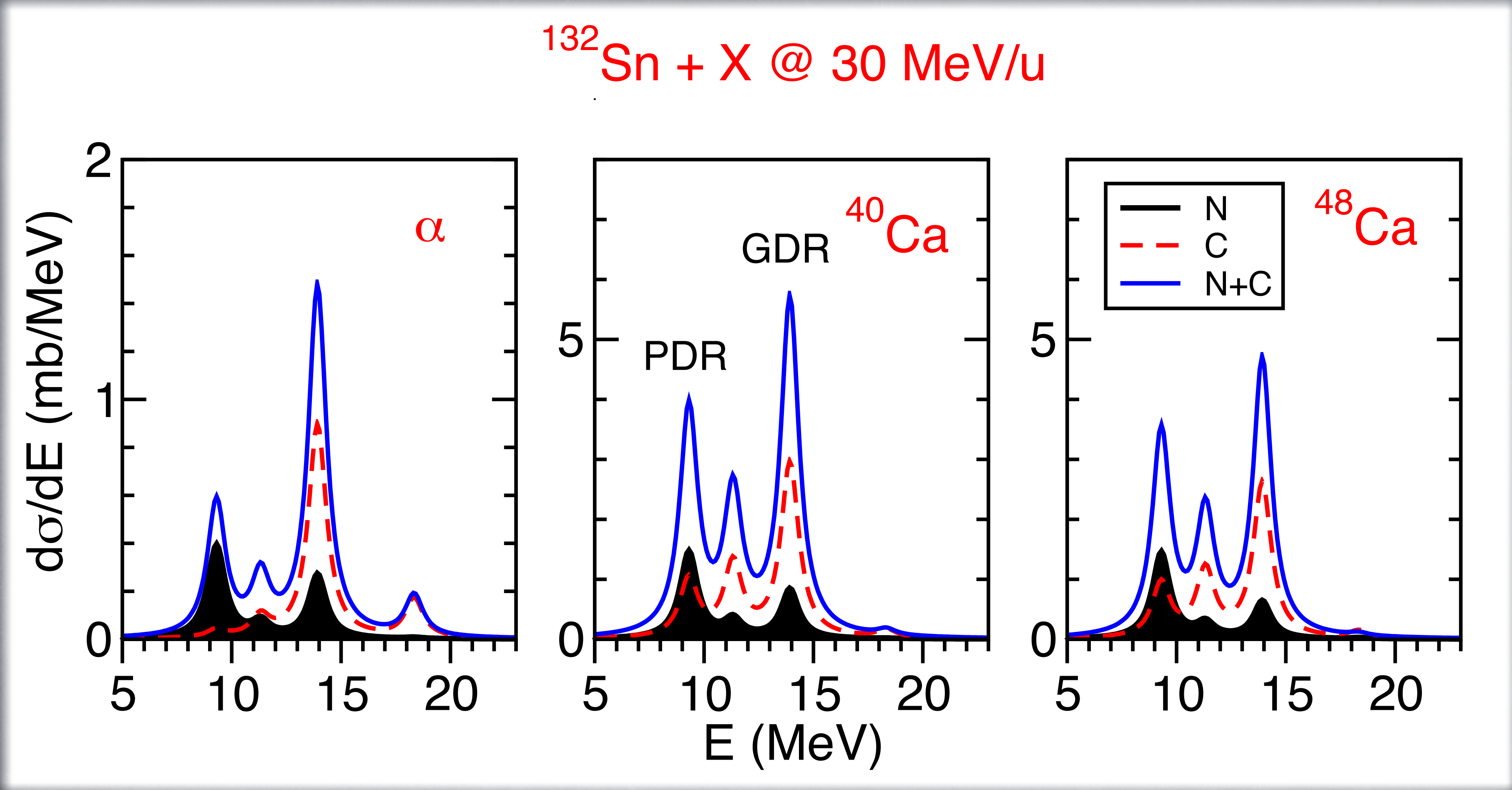
For the PDR, the nuclear part is much more important than the Coulomb one.

Only a limited range of impact parameters give contribution to the nuclear part (nuclear contribution are enhanced at grazing angles); for the Coulomb part the range of b is much larger.



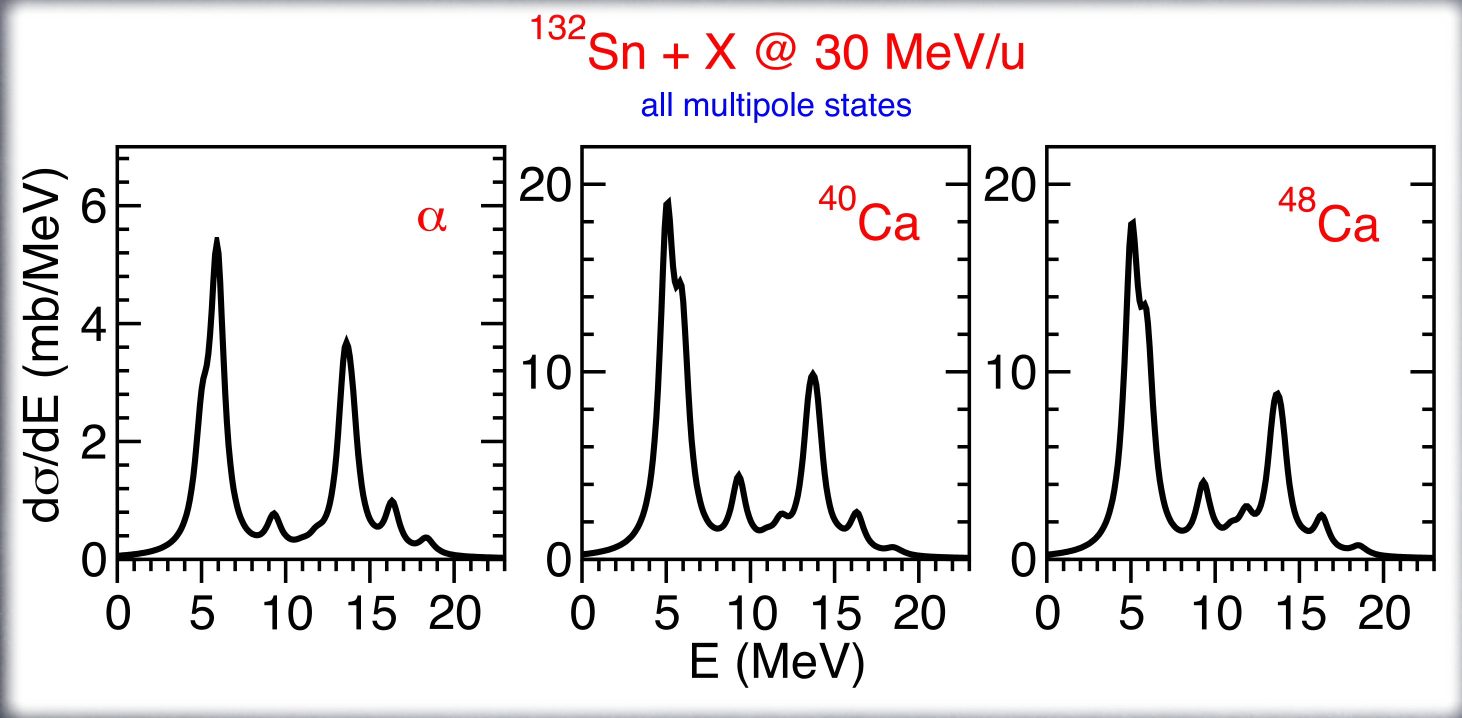
The continuous red lines are obtained by a smoothing folding procedure with Lorentzian of 1 MeV width.

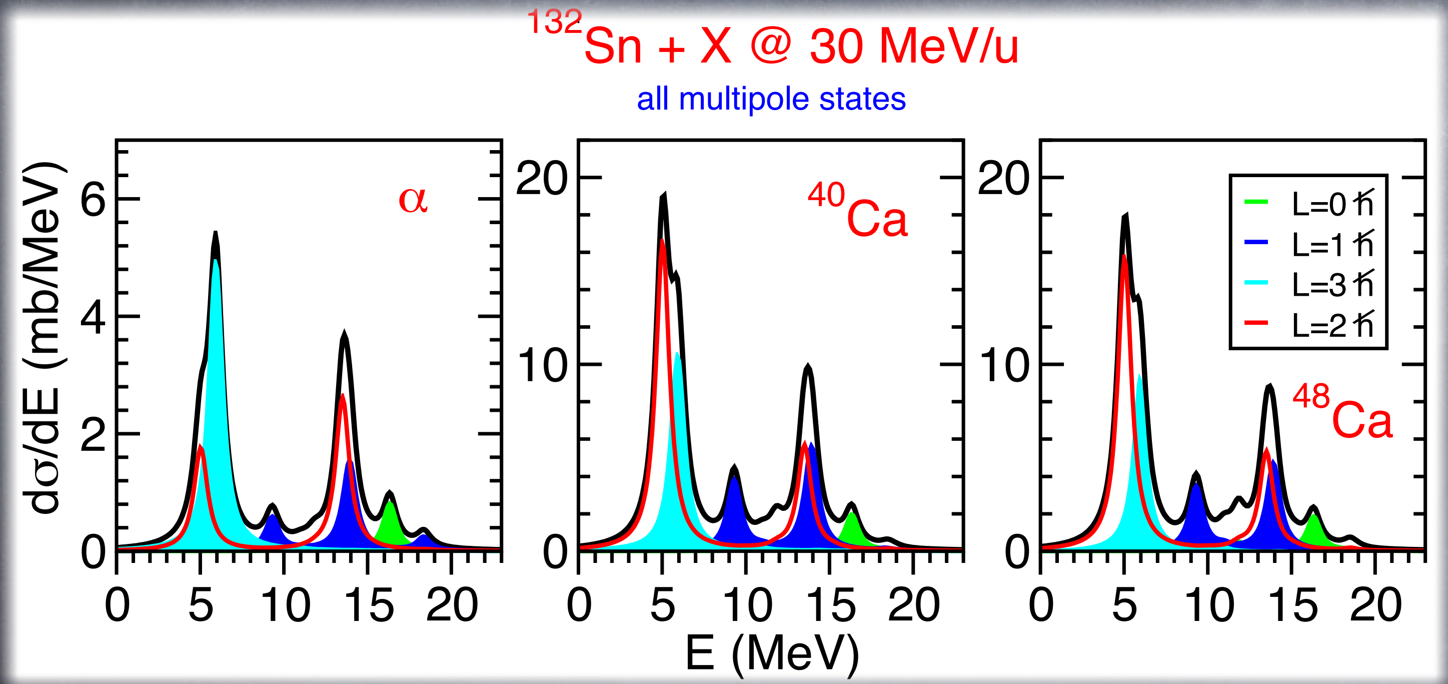
The balance between PDR and GDR changes at different incident energies, because of the relative role of nuclear and Coulomb contributions.



Predictions for the excitation of the dipole states by different projectiles (α, ^{40}Ca, ^{48}Ca).

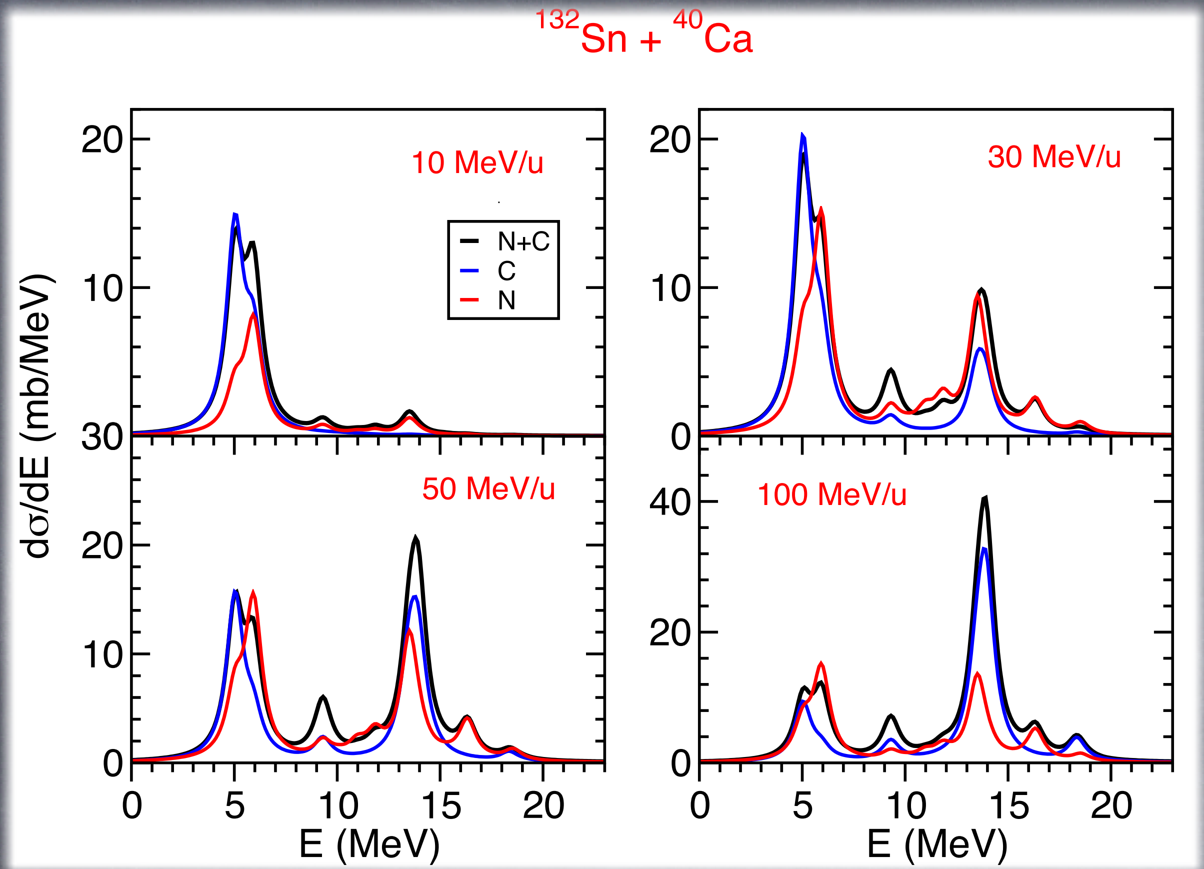
For ^{48}Ca and ^{40}Ca the excitation cross section for the PDR is of the same order of magnitude that the one for the GDR.





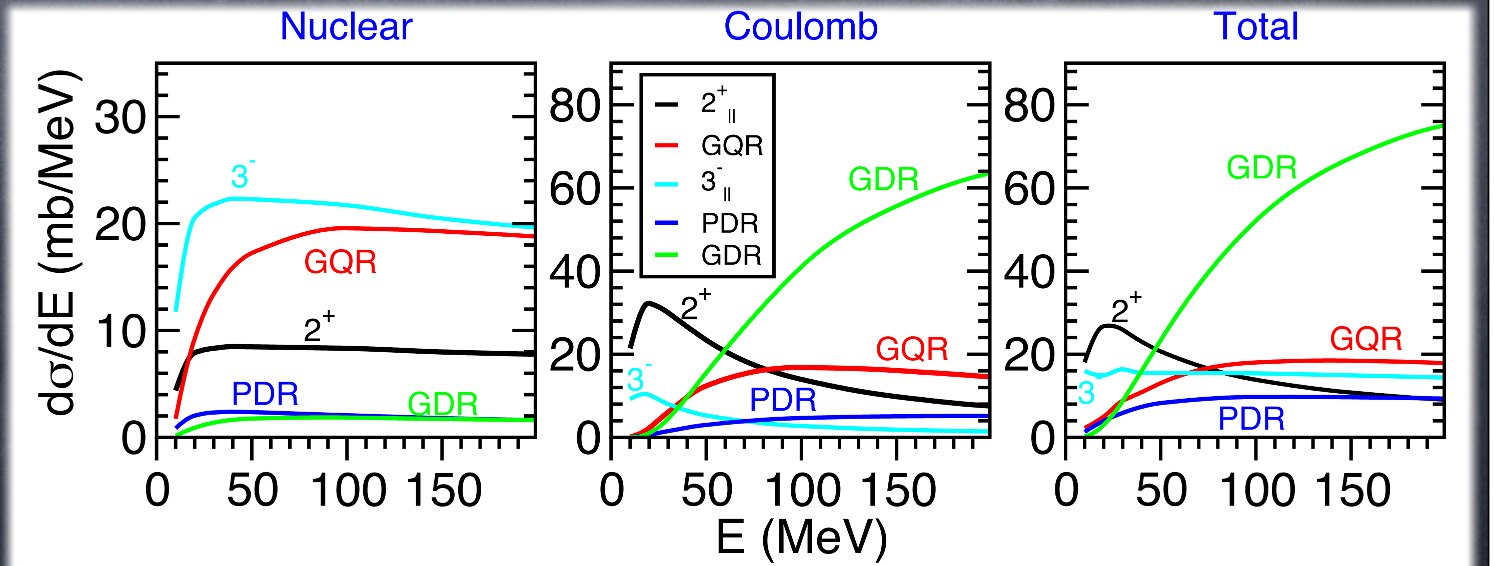
Predictions for the excitation of the states of different multipolarity by different projectiles (α, ^{40}Ca, ^{48}Ca).

State	E (MeV)	EWSR %
GMR	16.3	85
PDR	9.3	1.1
GDR	13.9	56
1^-_{hl}	18.3	25
2+	5.0	11
GQR	13.5	77
3^-	5.9	27



Variation of Coulomb and Nuclear contributions as function of the incident energy.

Variation of multipoles states excitations as function of the incident energy.



Summary

We studied the nature of the low-lying dipole strength in neutron-rich nuclei, often associated to the Pygmy Dipole Resonance. The states are described within the Hartree-Fock plus RPA formalism, using the Skyrme interactions.

We show how the information from combined reactions processes involving the Coulomb and different mixtures of isoscalar and isovector nuclear interactions can provide a clue to reveal the characteristic features of these states.