STRENGTH

STructure and REaction Nuclei: towards a Global THeory

TNPI2017 - XVI Conference on Theoretical Nuclear Physics in Italy

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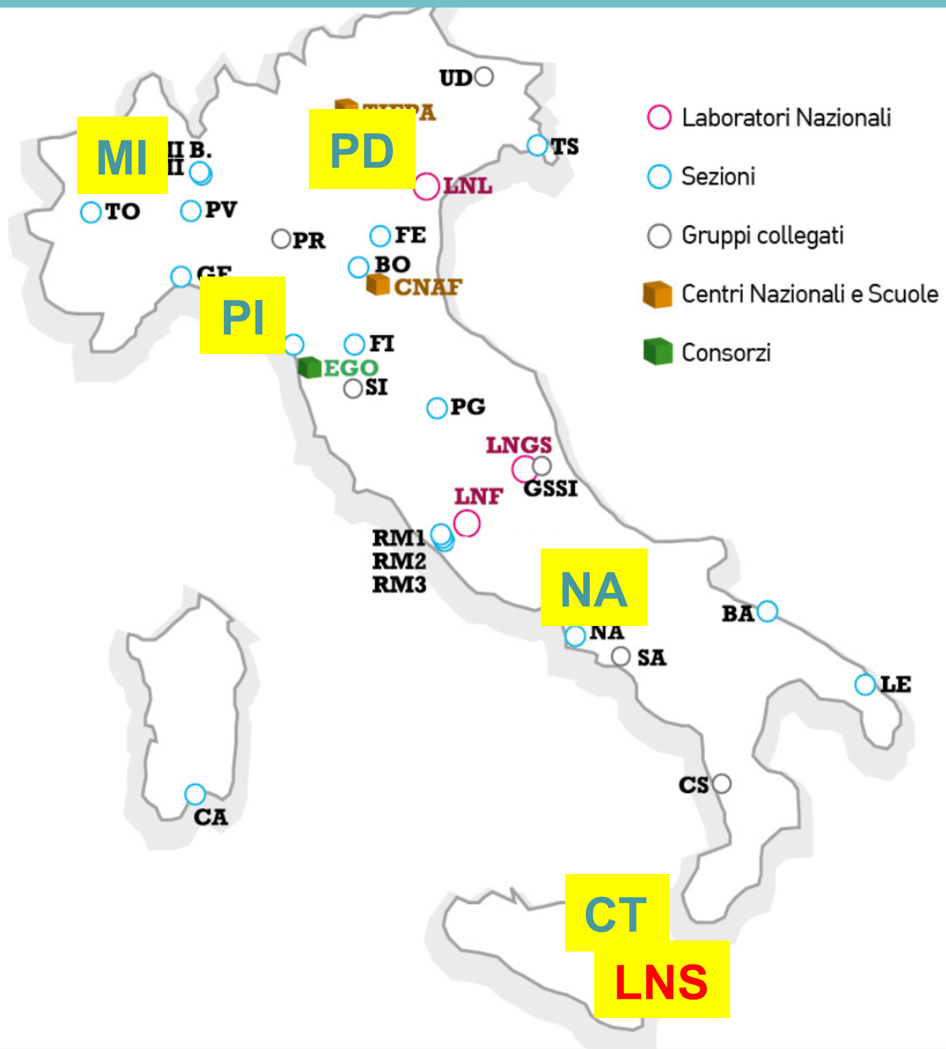
Cortona

Europe/Rome timezone

Angela Gargano
Sezione di Napoli

STRENGTH

Started in 2014 with the aim to combine the diverse and complementary expertise of the main Italian theoretical groups working in the fields of nuclear structure and reaction dynamics with hadronic probes in order to better confront the new challenges arising from the Radioactive Ion Beam Facilities



Sede	Responsabile	FTE
MI	Enrico Vigezzi	2.5
PD	Lorenzo Fortunato	5.2
PI	Angela Bonaccorso	1.0
NA	Angela Gargano	7.2
CT	Edoardo Lanza	2.0
LNS	Maria Colonna	2.8
		20.7

* anno di riferimento 2018

# Ric.	Ass. senior	Non strutturati
26	2	7

1. Development and application of models for nuclear structure studies

- Shell model
- Density functional theory and its extensions
- Microscopic and algebraic cluster models

All based on the use of effective interactions (microscopic or phenomenological) to account for the reduction in the number of degrees of freedom explicitly considered, namely the dimension of the basis spaces or the form of many-body wave functions

1. Construction of effective interactions
2. Assessment and extensions of the models
3. Calculations of bulk/spectroscopic properties, reaction observables and comparison with experiment

The complementary nature of these approaches may be of help to acquire a more comprehensive understanding of the studied phenomena. *Key questions,* as the role of the various components of nuclear force or the interplay of single-particle and collective modes, can be tackled thus providing insights on different aspects of the nuclear problem

2. Dynamics of nuclear excitations and reaction mechanisms

- Heavy ion collisions from the Coulomb barrier up to the Fermi energies involving different reaction mechanisms (fusion-fission, deep-inelastic and charge equilibration, inelastic collisions leading to collective excitations) between neutron-rich systems in the framework of semi-classical or microscopic theories

- Collisions dominated by peripheral, direct mechanisms such as transfer, charge exchange and breakup direct reactions

- Determination of optical potentials for total reaction cross section calculations, elastic scattering and knockout involving light exotic nuclei

In these studies, attention is payed to the underlying structure models and the effective interactions with the aim of reaching **a description as coherent as possible of both nuclear structure and reaction dynamics**

STRENGTH

Strong support to the experimentalists in the analysis of recent experimental data on exotic nuclei as well as in the proposal of new "key" experiments, in particular to the Italian project SPES @ LNL

Topics

1. Many-body correlations and nuclear structure properties

2. Collective modes in neutron rich nuclei

3. Direct reactions

Many-body correlations and nuclear structure properties

Shell model

Reduced number of active nucleons in a truncated space

$$H_{\text{eff}} = \sum_{i=1}^{\mathcal{N}} h_i + \sum_{i<j=1}^{\mathcal{N}} V_{ij}$$

Excluded degrees of freedom taken into account through effective interactions and operators

- J. Bonnard, S.M. Lenzi, A.P. Zuker, PRL **116**, 212501 (2016)
- Talk by L. De Angelis
- Talk by T. Fukui

Beyond the DFT
Particle vibration coupling approaches

Collective vibrations & single particles as relevant building blocks

$$\mathcal{H} = \mathcal{H}'_{sp} + \mathcal{H}_B + h$$

h = interaction between particles and vibrations
→ diagonalized or treated perturbatively

- G. Colò, P. F. Bortignon, G. Bocchi, PRC **95**, 034303 (2017)
- F. Barranco, G. Potel, R.A. Broglia, E. Vigezzi PRL **119**, 082501 (2017)
- Talk by E. Vigezzi

Cluster models

Aggregates of nucleons, and in particular four-body correlated systems, as relevant building blocks

- α-cluster model based on group-theory - G. Stellin, L. Fortunato, A. Vitturi, JPG 43 (2016) 085104
- microscopic quartet model - Talk by M. Sambataro

Hybrid configuration mixing model for odd nuclei

G. Colò, P. F. Bortignon, G. Bocchi, PRC **95**, 034303 (2017)

Excitation energies and electromagnetic transitions of one-valence particle nuclei

^{49}Ca= ν + ^{48}C

^{133}Sb= π + ^{132}Sn

Future developments
extensions to non-magic systems

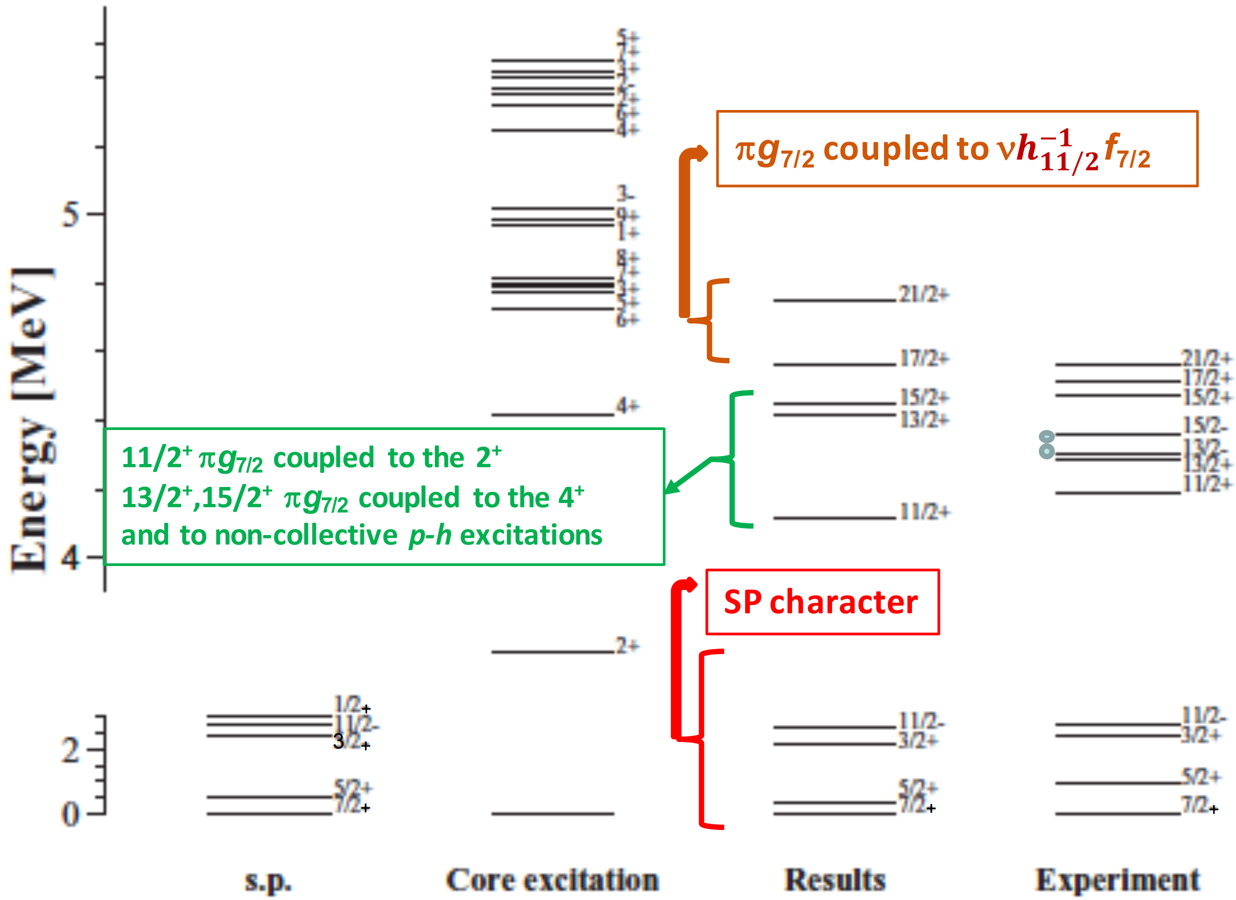
- ✓ Hartree-Fock (HF) description of the particle states in the core $|jm\rangle$
- ✓ Random phase approximation (RPA) calculations for the core excitations $|NJ\rangle$
- ✓ Residual interaction acting among $|[j' \otimes NJ]_{jm}\rangle$*

self-consistent calculation
HF, RPA, and coupling interactions
from a Skyrme force

* $|[j' \otimes NJ]_{jm}\rangle$ basis → nonorthogonal and overcomplete!

Results for ^{133}Sb

13/2⁻ @ 5.6 MeV
15/2⁻ @ 6.7 MeV
too high!



J^π	Main components Theory
2_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.56), $\pi g^{-1}_{9/2} d_{5/2}$ (0.19), $\pi g^{-1}_{9/2} g_{7/2}$ (0.14)
3_1^-	$\nu s^{-1}_{1/2} f_{7/2}$ (0.40), $\nu d^{-1}_{3/2} f_{7/2}$ (0.12), $\pi p^{-1}_{1/2} g_{7/2}$ (0.12)
4_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.63), $\pi g^{-1}_{9/2} g_{7/2}$ (0.21)
6_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.86), $\pi g^{-1}_{9/2} g_{7/2}$ (0.11)
8_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.98)
5_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.99)
7_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.98)
(9_1^+)	$\nu h^{-1}_{11/2} f_{7/2}$ (0.99)
1_1^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.76), $\nu h^{-1}_{11/2} h_{9/2}$ (0.24)
2_2^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.72), $\nu h^{-1}_{11/2} f_{7/2}$ (0.18)
2_1^-	$\nu d^{-1}_{3/2} f_{7/2}$ (0.79)
3_1^+	$\nu h^{-1}_{11/2} f_{7/2}$ (0.96)
3_2^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.96)
4_2^+	$\pi g^{-1}_{9/2} d_{3/2}$ (0.56), $\nu h^{-1}_{11/2} f_{7/2}$ (0.32)
5_2^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.99)
6_2^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.74), $\nu h^{-1}_{11/2} f_{7/2}$ (0.13)
7_2^+	$\pi g^{-1}_{9/2} g_{7/2}$ (0.99)

Structure and Reactions of ^{11}Be: Many-Body Basis for Single-Neutron Halo

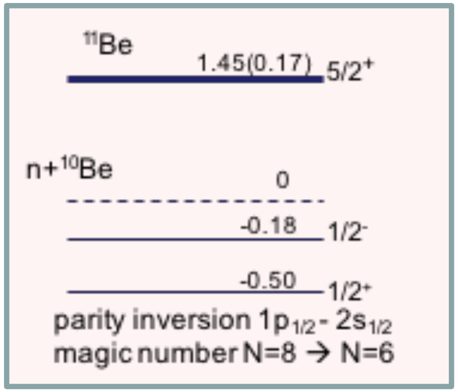
F. Barranco, G. Potel, R.A. Broglia, E. Vigezzi PRL **119**, 082501 (2017)

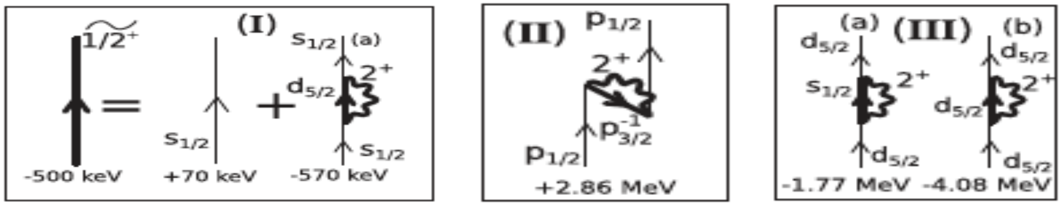
Many body correlations

- ✓ Renormalized nuclear field theory
- $p_{3/2}$, $p_{1/2}$, $s_{1/2}$, $d_{5/2}$ single-particle states up E_{cut}=25 MeV
- Coupling to quadrupole collective vibrations of ^{10}Be
- Mixing between bound and continuum states

→ 3 parameters for the 2^+ vibration (exp) + 4 for the bare mean field (fit)

Effects due to octupole and pair removal modes of ^{10}Be are marginal





Diagrams describing the main self-consistent renormalization processes of the SP energies

Bold lines describe dressed particle/hole states

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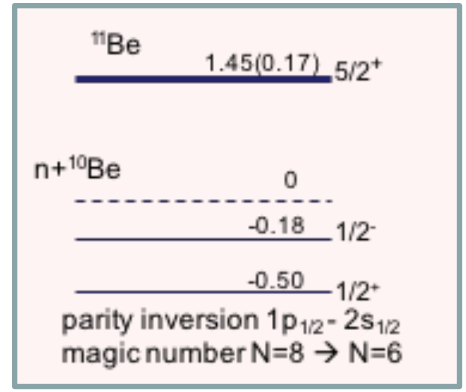

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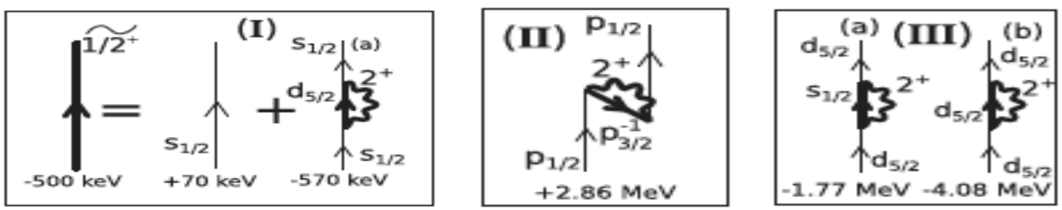

Diagrams describing the main self-consistent renormalization processes of the SP energies

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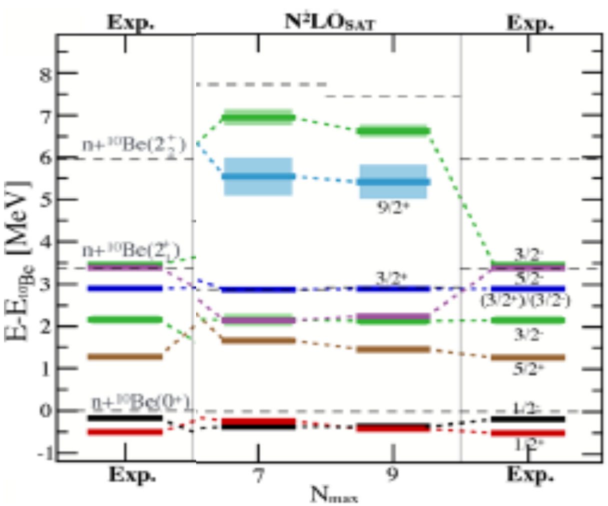
Why a NFT calculation? when ^{11}Be can be studied with *ab initio* approaches.



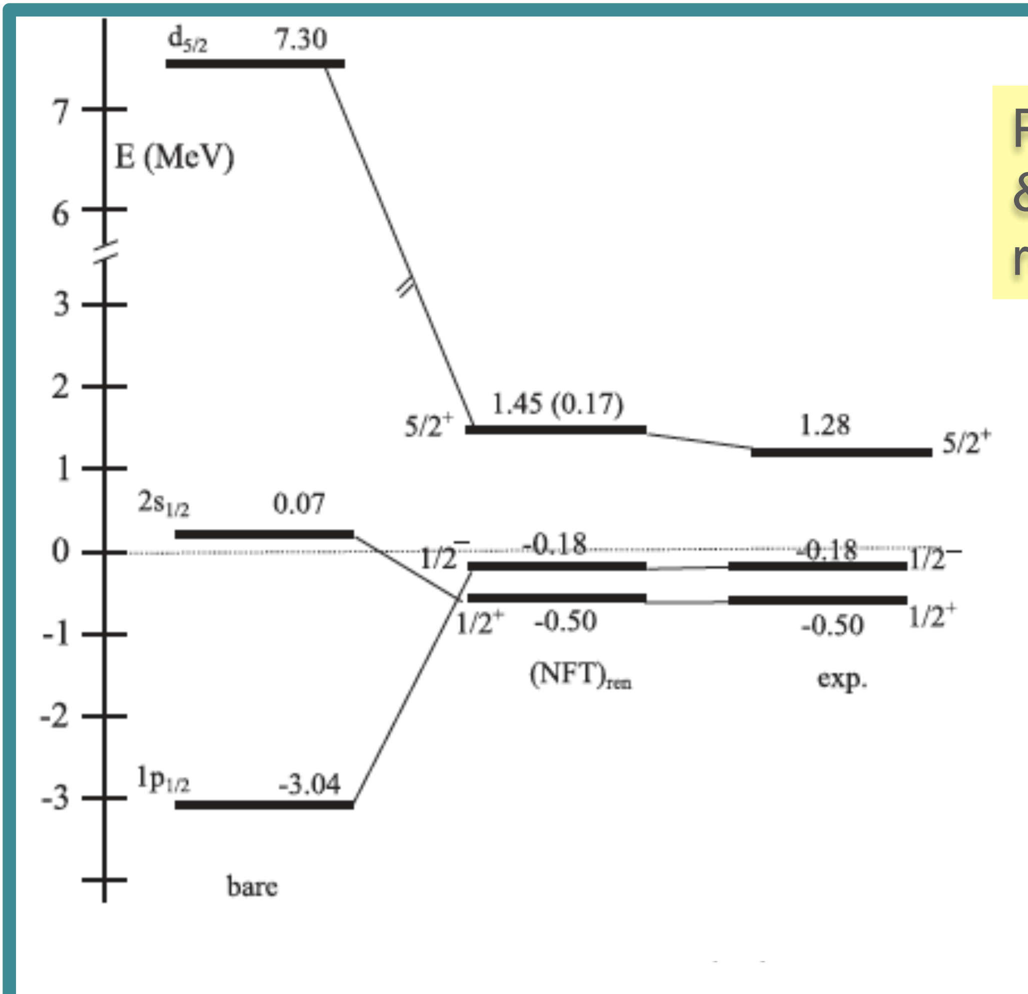
No-core shell model with continuum - A. Calci, et al., PRL **117**, 242501 (2016)

Better framework to clarify

- Role of the mean field
- Mechanism behind the parity inversion
- Role of the continuum states

in **exotic nuclei**

Results



Parity inversion between the $1p_{1/2}$ and $2s_{1/2}$ & position/width of $5/2^+$ resonance → reproduced!

$$|\widetilde{1/2^+}\rangle = \sqrt{0.80}|s_{1/2}\rangle + \sqrt{0.20}|(d_{5/2}\otimes 2^+)_{1/2^+}\rangle,$$

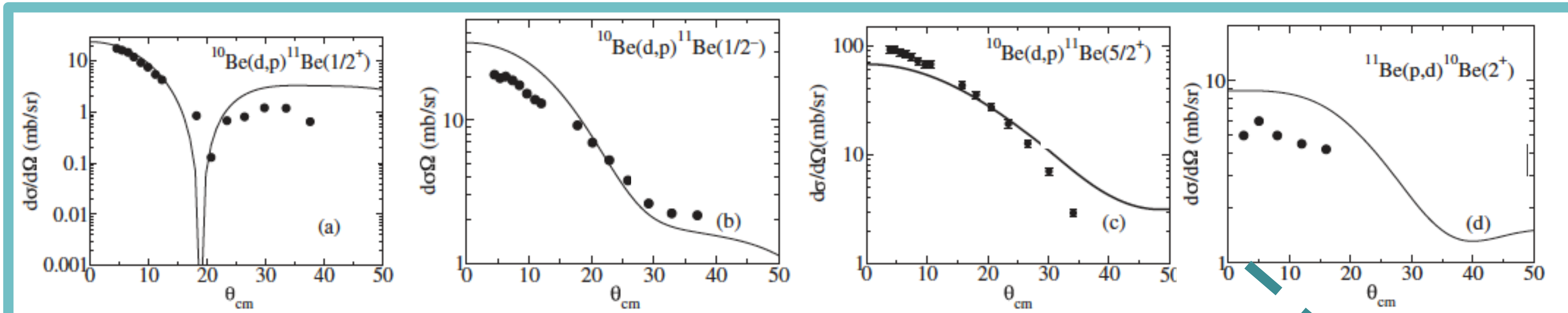
$$|\widetilde{1/2^-}\rangle = \sqrt{0.84}|p_{1/2}\rangle + \sqrt{0.16}|(p_{1/2}, p_{3/2}^{-1})_{2^+}\otimes 2^+)_{0^+}, p_{1/2}\rangle,$$

$$|\widetilde{5/2^+}\rangle = \sqrt{0.49}|d_{5/2}\rangle + \sqrt{0.23}|(s_{1/2}\otimes 2^+)_{5/2^+}\rangle + \sqrt{0.28}|(d_{5/2}\otimes 2^+)_{5/2^+}\rangle.$$

- **strong coupling of $d_{5/2}$ to 2^+ → $s_{1/2}$ and $d_{5/2}$ BE increasing (0.6 and 5.9 MeV)**
- **smaller phase space of the clothed $\widetilde{1/2^-}$ state with respect to the bare $p_{1/2}$ due to the antisymmetry between the valence nucleon and those participating in 2^+ → $p_{1/2}$ BE decreasing (2.9 MeV)**

Results

The radial dependence of the many-body wave functions and the phonon admixture in single-neutron states can be probed by one-nucleon transfer reactions



Absolute differential cross sections

(*p*, *d*) field acts on

$$|\widetilde{1/2^+}\rangle = \sqrt{0.80}|s_{1/2}\rangle + \sqrt{0.20}|(d_{5/2} \otimes 2^+)_{1/2^+}\rangle$$

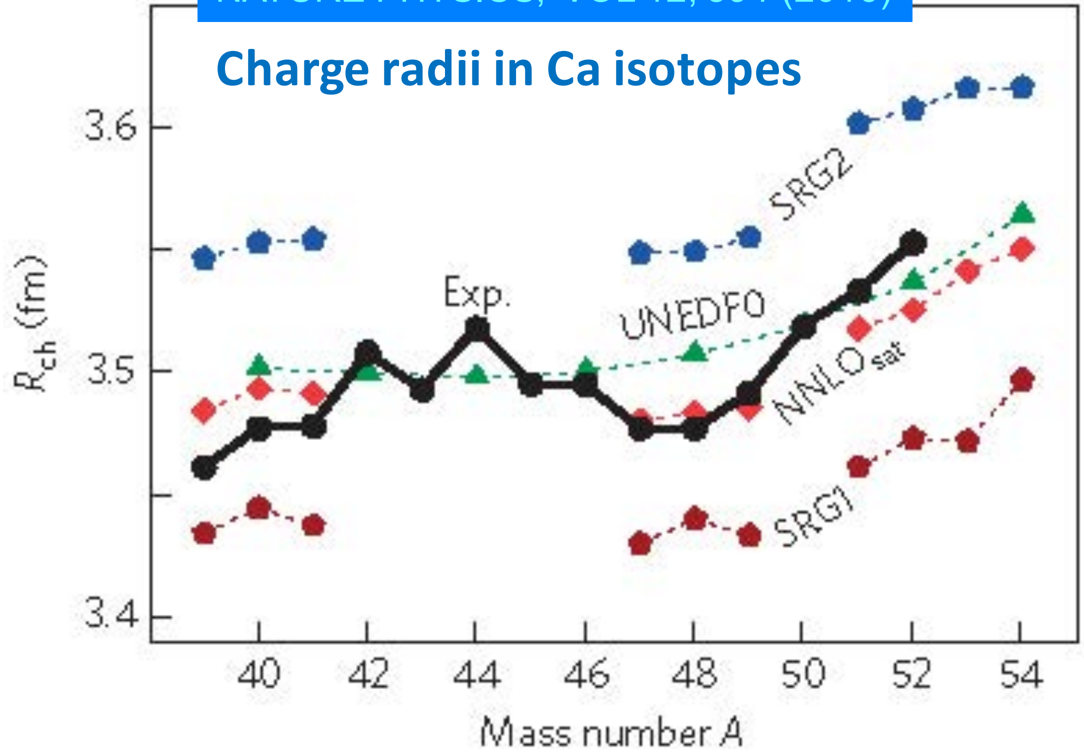
Overall account of the experimental findings!

renormalization of the radial dependence of the single-particle states due to the many-body processes involving the continuum states plays an important role in the absolute one-nucleon transfer differential cross sections

Neutron skin and charge radii in *sd* and *fp* nuclei

J. Bonnard, S.M. Lenzi, A.P. Zuker, PRL **116**, 212501 (2016)

R. F. Garcia Ruiz et al.,
NATURE PHYSICS, VOL 12, 594 (2016)



For neutron-rich calcium isotopes, beyond N=28

no even-odd staggering

large and unexpected increase of the size

very large charge radius for ^{52}Ca, with an increase relative to ^{48}Ca of $\delta\langle r^2\rangle^{48,52} = 0.530(5)\ \mathrm{fm}^2$

1. Try a fit of radii for Z<30

J. Duflo and A.P. Zuker, PRC 66, 051304 (2002)

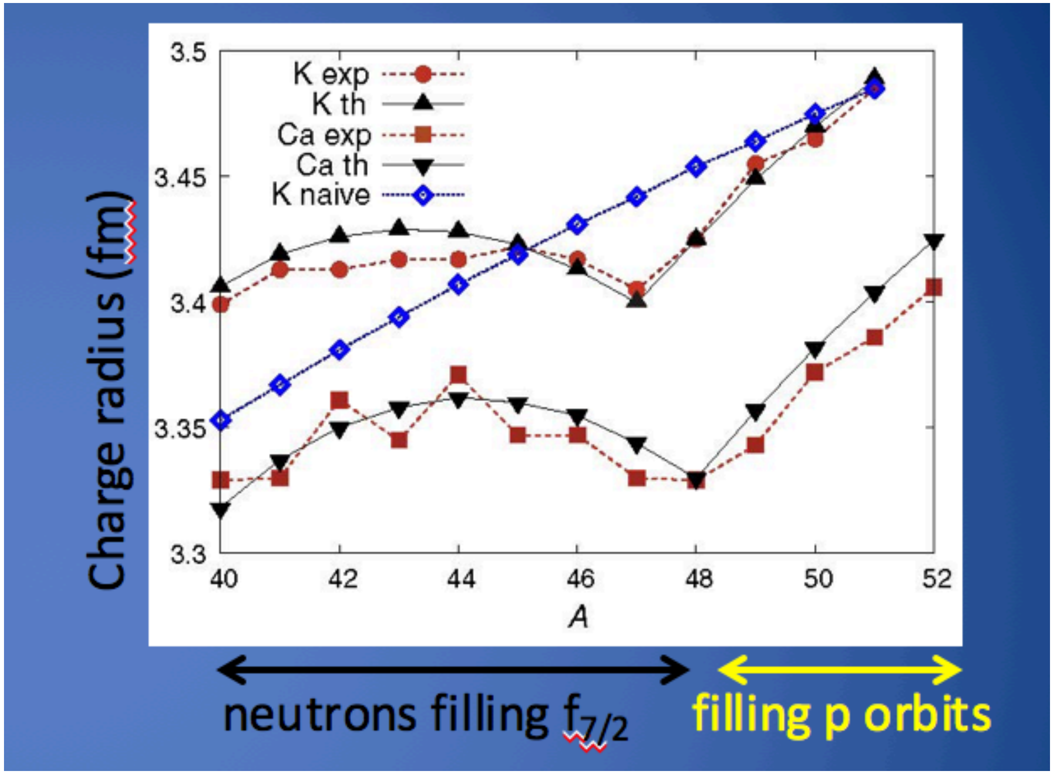
$$\sqrt{\langle r_\pi^2 \rangle} = \rho_\pi = A^{1/3}\left(\rho_0 - \frac{\zeta}{2}\frac{t}{A^{4/3}} - \frac{\upsilon}{2}\left(\frac{t}{A}\right)^2\right)e^{(g/A)}$$

$$+\lambda[z(D_\pi - z)/D_\pi^2 \times n(D_\nu - n)/D_\nu^2]A^{-1/3}$$

term accounting for correlations

t = (N-Z)

ρ_0, ζ, *v*, *g* = parameters



→ ***Suggestion***: ***p* orbits are LARGER than *f* orbits**

Effect that can be simulated in shell-model calculations by using different values for neutrons and protons and for different orbits

2. Semi-microscopic SM calculation for single-particle states built on ^{40}Ca

- V_{low-k} (Λ=2 fm^{-1}) from N3LO
- $$\hbar\omega_{\nu} = \frac{41.47}{\langle r_{\nu}^2 \rangle} \sum_i n_i \left(N_i + \frac{3}{2}\right) / N \ ; \ \hbar\omega_{\pi} = \frac{41.47}{\langle r_{\pi}^2 \rangle} \sum_i z_i \left(N_i + \frac{3}{2}\right) / Z$$

$\langle r_{\pi}^2 \rangle$ & $\langle r_{\nu}^2 \rangle$ from DZ formula and fit of the mirror energies differences (MED) for T=1/2 mirror nuclei with ζ treated as a free parameter

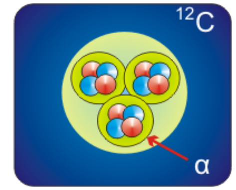
A	J^{π}	MED(MeV)	$\hbar\omega_{\nu}$(MeV)	$\hbar\omega_{\pi}$ (MeV)	ζ(fm)	$\Delta r_{\nu\pi}$(fm)	r_{π}(fm)	r_{ν}(fm)
41	$7/2^-$	7.278	10.78	10.63	0.610	0.015	3.422	3.437
	$3/2^-$	7.052	10.61	10.59	1.513	0.038	3.427	3.465
	$1/2^-$	7.129	10.61	10.59	1.482	0.037	3.428	3.465
	$5/2^-$	7.351	10.75	10.61	0.702	0.018	3.424	3.442
	$5/2^-$	7.338	10.75	10.61	0.725	0.018	3.427	3.442

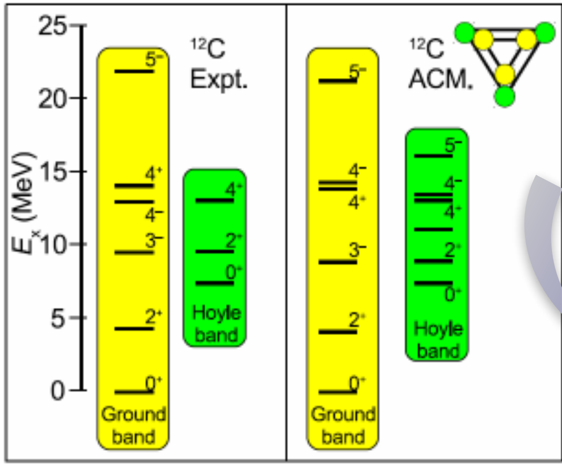
rms radii of *p* orbits exceed those of the *f* orbits by ~0.7 fm

Electromagnetic selection rules for ^{12}C in the 3 α cluster model

G.Stellin, L.Fortunato, A. Vitturi, JPG **43** (2016) 085104

α particle as building block





The Hoyle band intepreted as a first vibrational breathing excitation of the triangular configuration

Bijker and Iachello, PRC **61** 067305 (2000)

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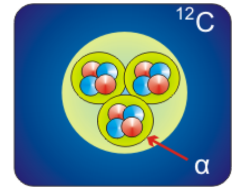

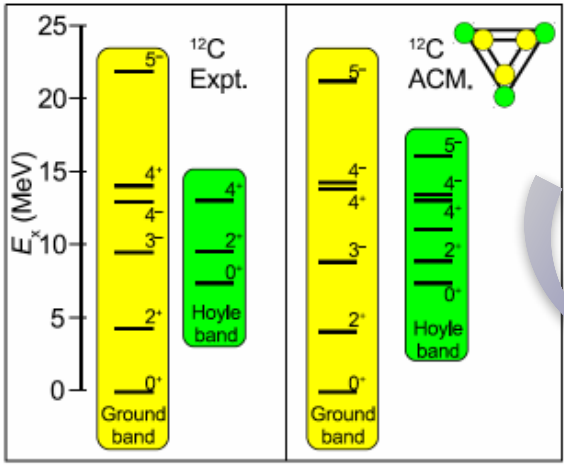

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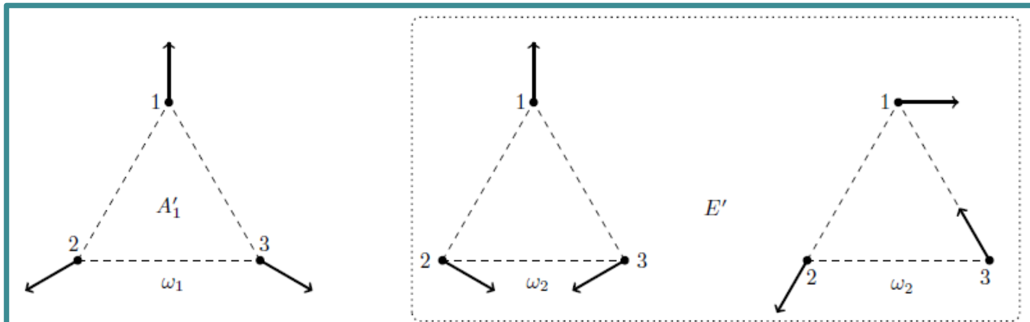
Normal modes of vibrations



3 α particles perform *normal harmonic vibrations* about their equilibrium positions at the vertexes of an equilateral triangle, which is expected to rotate as a rigid symmetric top

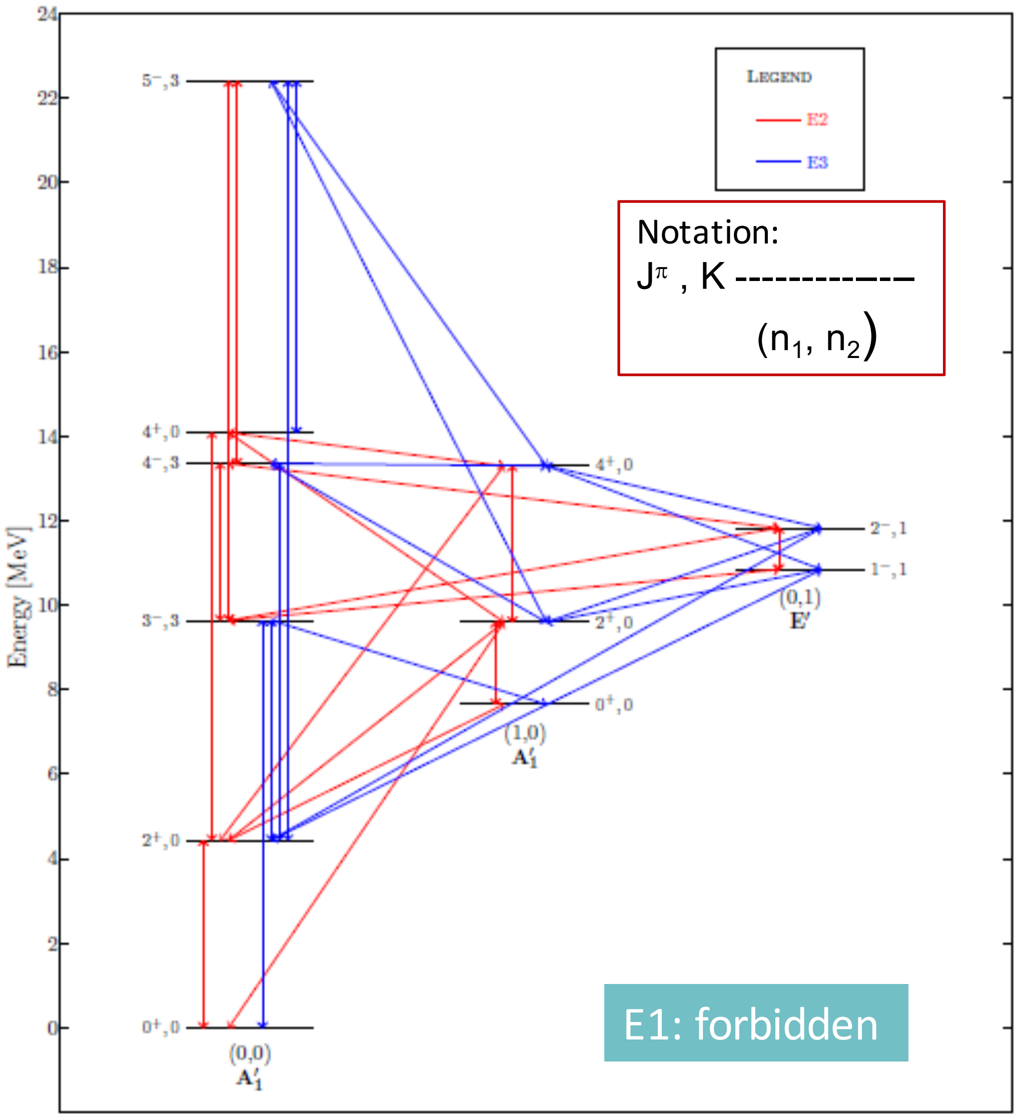
Assuming decoupled vibrational for each mode

$$\Psi^{n_1,n_2}_{J,K,M} = \Phi^{A}_{n_1}(Q_1)\Phi^{E}_{n_2}(Q_2,\,Q_3)\psi_{JKM}$$

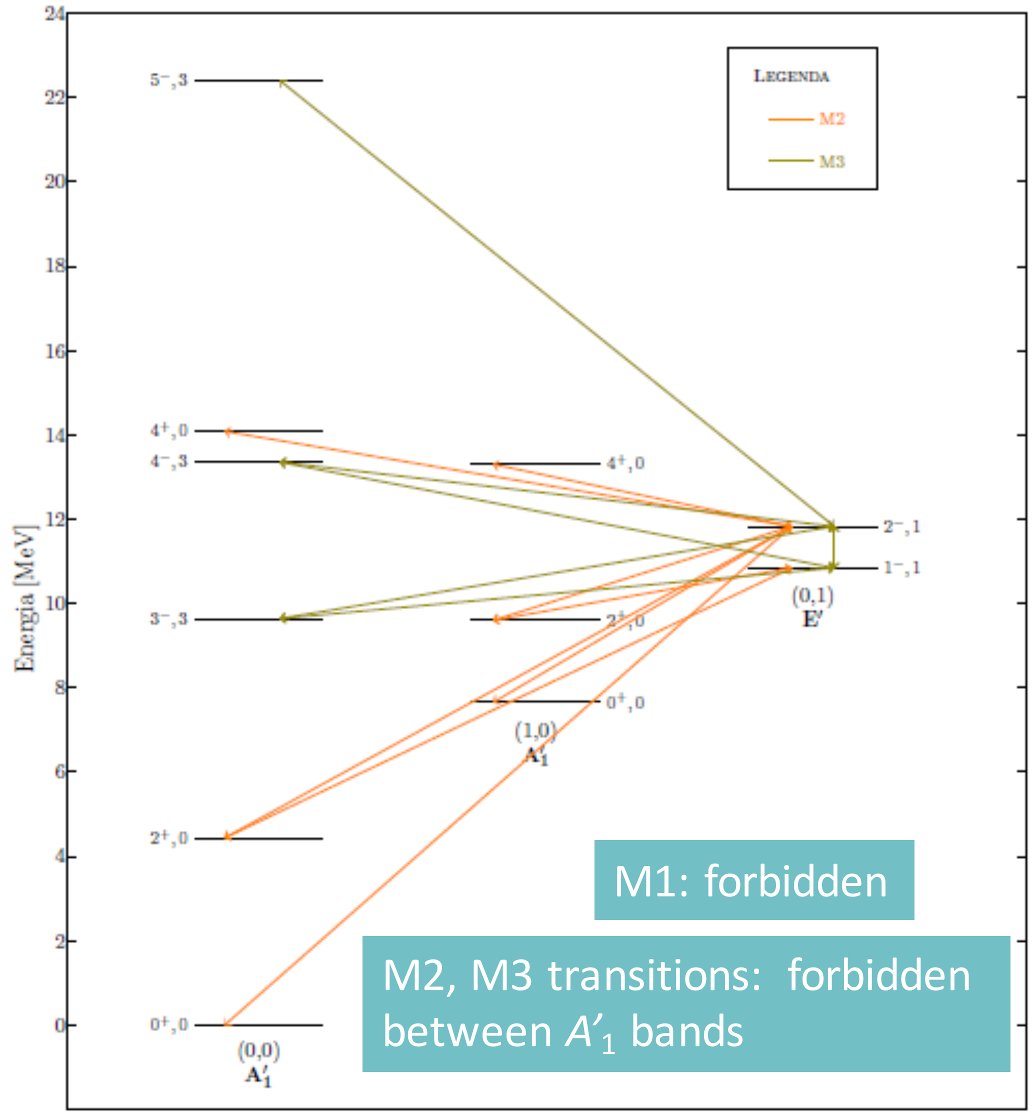
n_1, n_2 = phonon numbers in the A'_1 and E'' vibrations; ψ_{JKM} =rotational wave function

Results

lowest allowed electric transitions



lowest allowed magnetic transitions



The predicted selection rules are robust signatures of α-cluster model

Electromagnetic measurements in ^{12}C are highly desirable to test the validity of the model

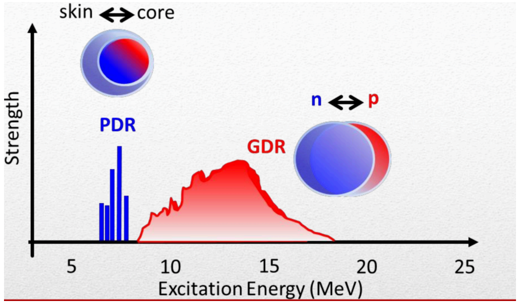
Collective modes in n-rich nuclei

Pigmy dipole resonance (PDR)

PDR → reaction rates in the astrophysical r – process

PDR → neutron skin → symmetry energy of the Equation of state(EoS)→ neutron-rich nuclear matter

E1 strength for $5 \lesssim E \lesssim 10$ MeV - observed in different mass regions, in particular in neutron-rich nuclei



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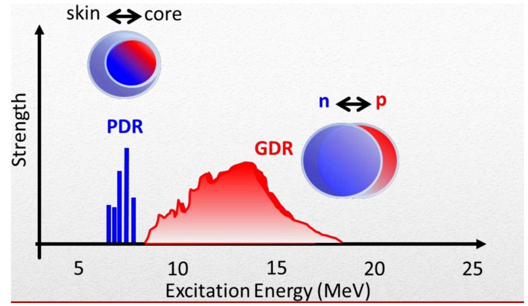
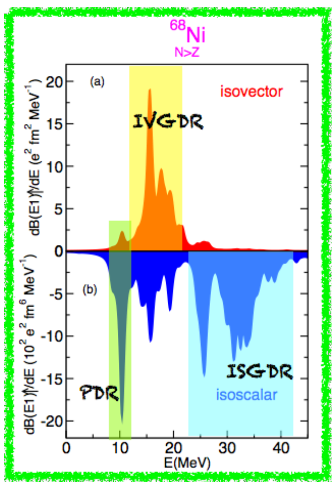
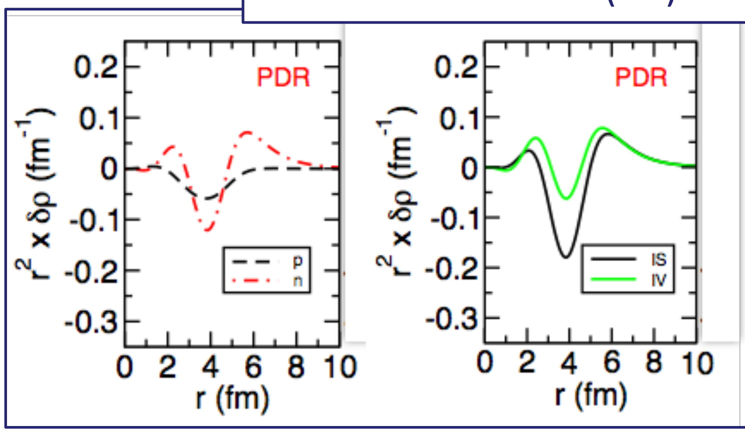


From HF +RPA calculations



Transition densities (TD)



neutrons and protons are in phase inside the nucleus and at the surface only neutrons survive (isoscalar (IS) and isovector (IV) TD have the same magnitude) → IS/IV mixing → PDR populated by IS and IV probes

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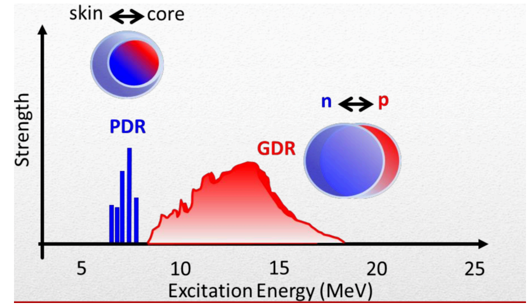

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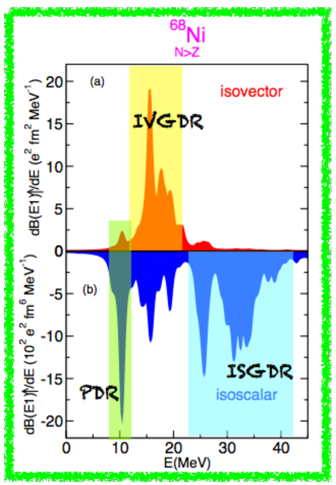

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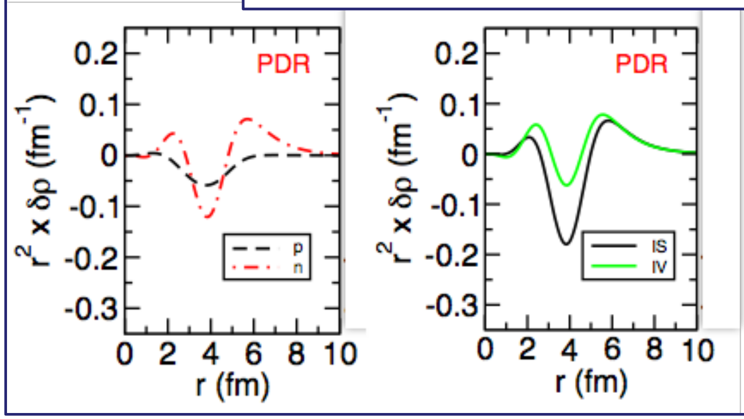

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Open questions

- ✓ Nature of the PDR, single-particle/collective?
- ✓ Mixing among the IS and IV components
- ✓ Its evolution with respect to mass, deformation and neutron excess

- A. Bracco, F.C.L. Crespi, and E.G. Lanza, EPJA A **5**, 99 (2015)
- H. Zheng, S. Burrello, M. Colonna, V. Baran, PRC **94**, 014313 (2016)
- X. Roca-Maza, … G. Colò, *et al*, PRC **92**, 064304 (2015)
- E. Lanza *et al.* , work in progress

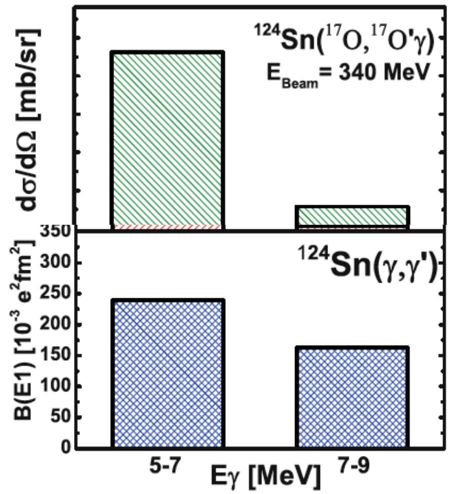
Strong collaboration between CT-PD, LNS-MI

Gamma decay of pygmy states from inelastic scattering of ions

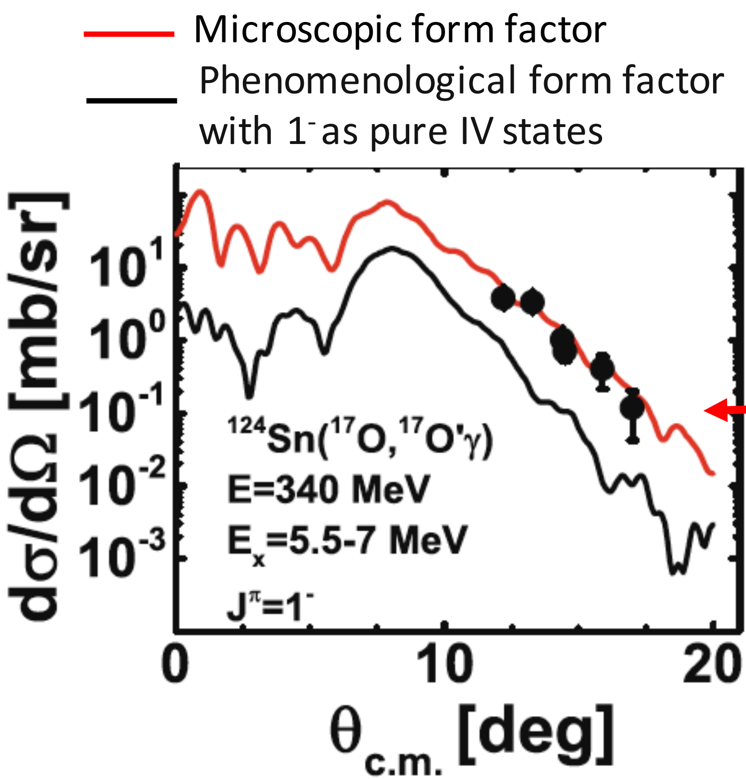
A. Bracco, F.C.L. Crespi, and E.G. Lanza, EPJA A **5**, 99 (2015)

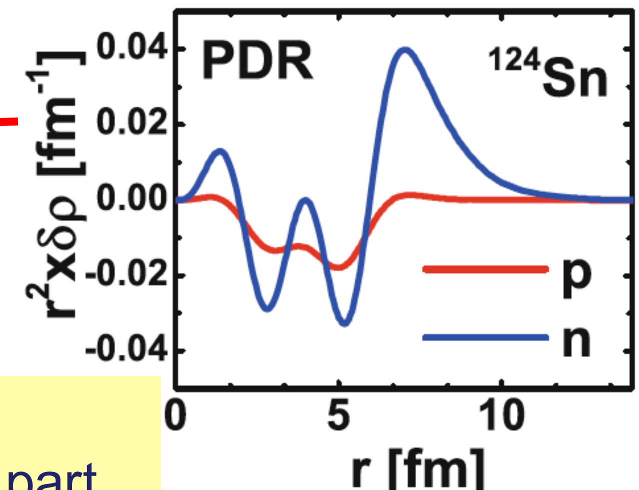
Analysis of exp PDR excitations for several (^{17}O,$^{17}O\gamma'$) reactions (@LNL) with microscopic form factors from RPA transition densities to investigate isospin mixing

$^{124}Sn(^{17}O,^{17}O\gamma)^{124}Sn$ at 340 MeV



Are higher-lying states dominantly of IV type ? Or do they contain a IS component with transition density peaked well inside the nuclear surface?





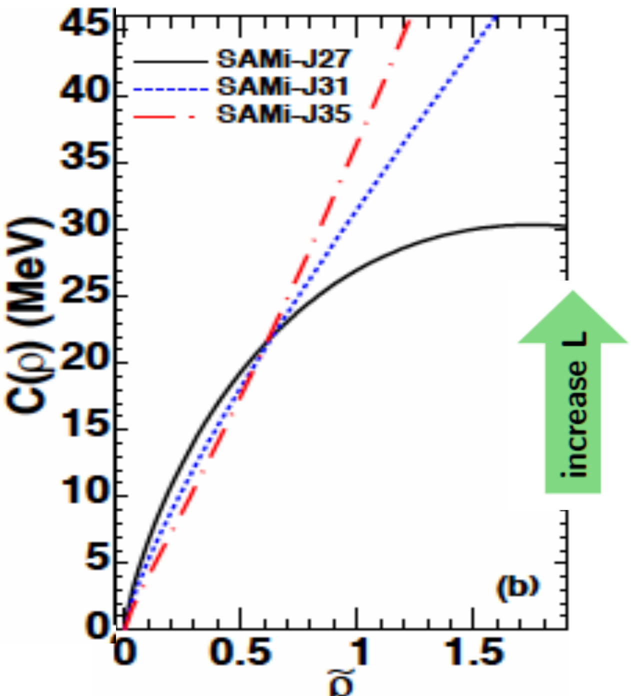
- A relevant contribution comes from the scalar part
- Nuclear interaction is important

Dipole response in neutron-rich nuclei with new Skyrme interactions

H. Zheng, S. Burrello, M. Colonna, V. Baran, PRC **94**, 014313 (2016)

How the mixed IS/IV character of the E1 response in neutron-rich depends on the symmetry energy - ^{68}Ni ^{132}Sn ^{208}Pb

- **semiclassical model (no single-particle structure is included)**
- **SAMi-J interactions (from MI group); J=symmetry energy coefficient at saturation density**



Symmetry energy versus reduced density $\tilde{\rho} = \rho/\rho_0$

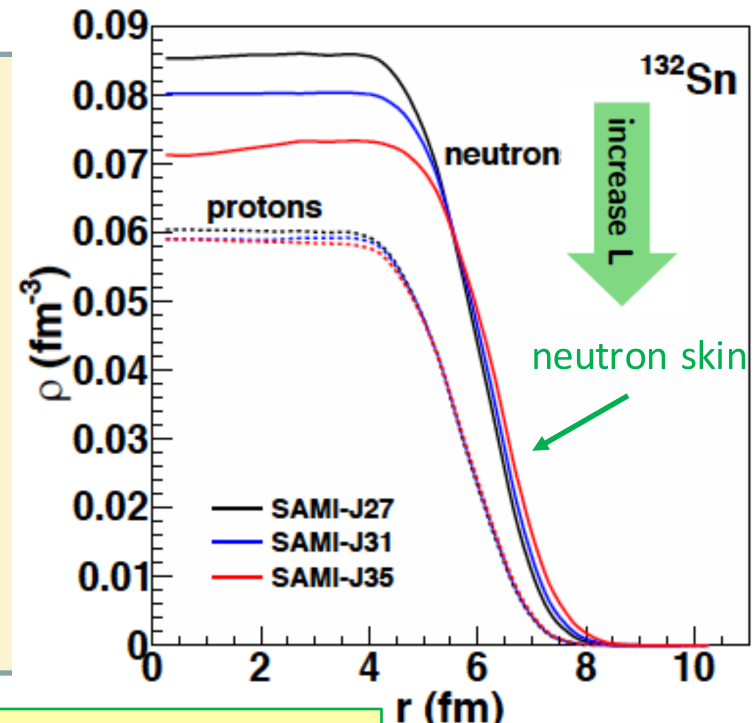
J= C(ρ$_0$) from 27 to 35 MeV

$$E_{sym}/A = C(\rho) I^2$$

$$I = (N-Z)/A$$

$$\rho_0 = 0.159 \ \text{fm}^{-3}$$

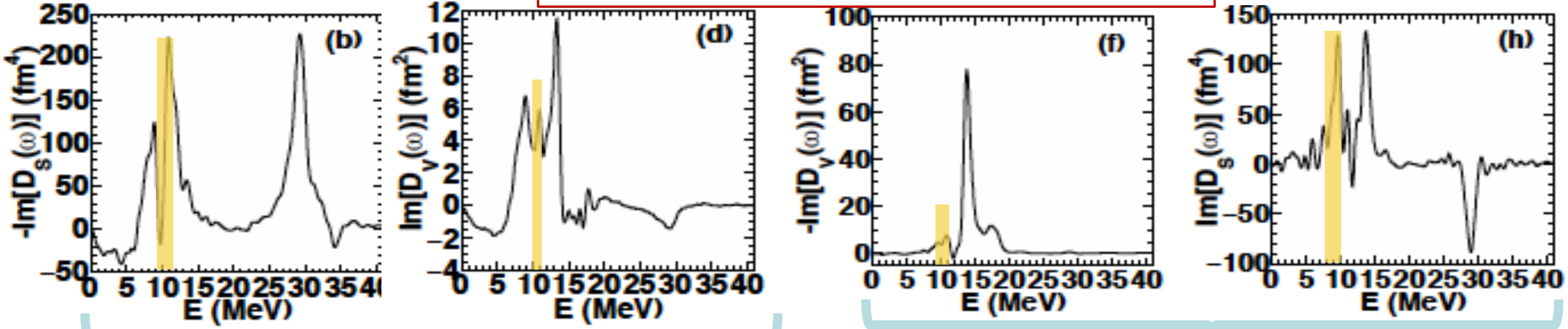
$$L = 3\,\rho_0 \frac{dC(\rho)}{d\rho}\bigg|_{\rho=\rho_0}$$



Indirect measure of neutron skin

Coupling of isoscalar and isovector excitations confirmed: an initial IS perturbation of the system → IV response and viceversa

IS and IV strength functions for ^{132}Sn

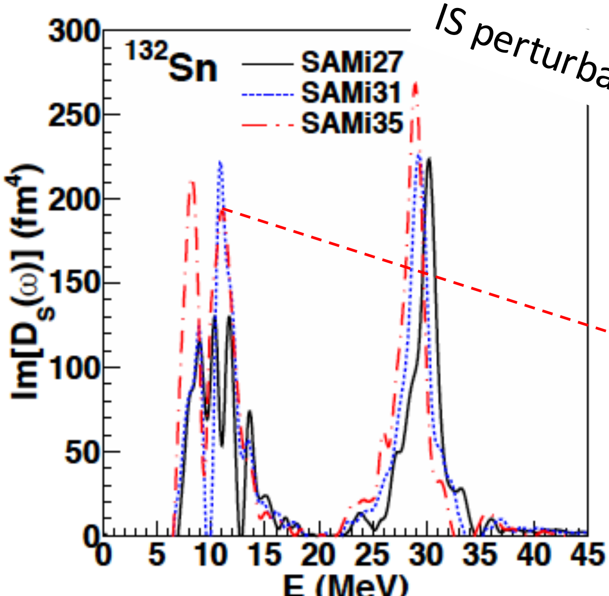


IS perturbation

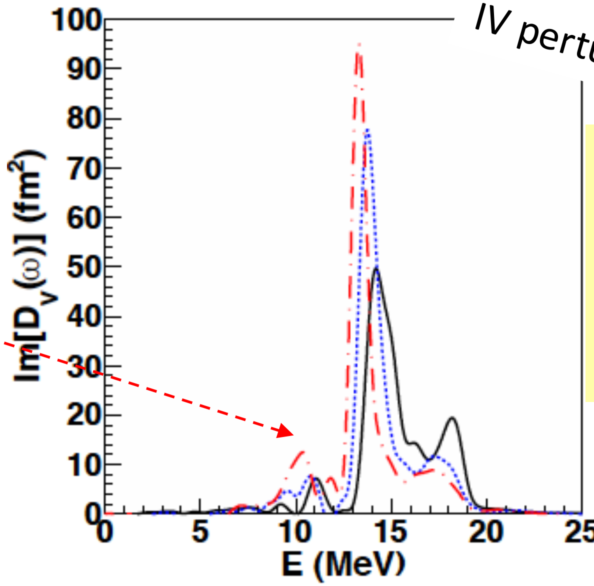
IV perturbation

Strength functions for ^{132}Sn

IS perturbation



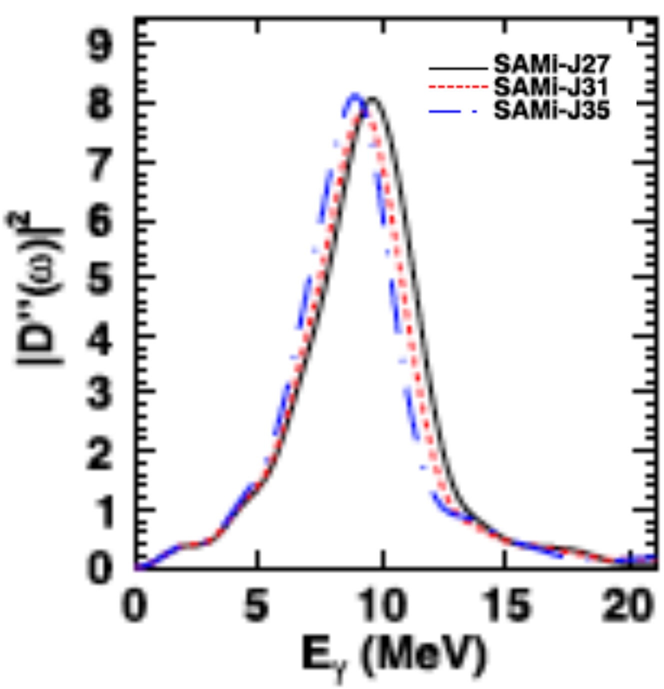
IV perturbation



Larger neutron/proton asymmetry (larger *L*=>more extended neutron skin)→increase of the IS/IV coupling

The same analysis can be performed for *pre-equilibrium dipole strength:* dipole oscillations in compound systems originating from reactions with strong isospin asymmetry between target and projectile

Pre-equilibrium dipole response in the charge-asymmetric reaction $^{132}Sn + ^{58}Ni$ @ E_{lab} = 10 MeV/A



H. Zheng, S. Burrello, M. Colonna, PLB **769**, 424 (2017)

The neutron skin thickness from the measured electric dipole polarizability in ^{68}Ni, ^{120}Sn, and ^{208}Pb

X. Roca-Maza, … G. Colò, *et al*, PRC **92**, 064304 (2015)

How to get information on the symmetry energy and its density dependence from the electric dipole polarizability α_D

- **RPA or QRPA approaches**
- **EDF (Skyrmes, …)**

From Droplet model (DM)

$$\alpha_D^{DM} \approx \frac{\pi e^2}{54} \frac{A \langle r^2 \rangle}{J} \left[1 + \frac{5}{2} \frac{\Delta r_{np}^{DM}}{I \langle r^2 \rangle^{1/2}} \right]$$

Strong correlation $\alpha_D J - \Delta r_{np}$

J=symmetry energy coefficient at saturation density

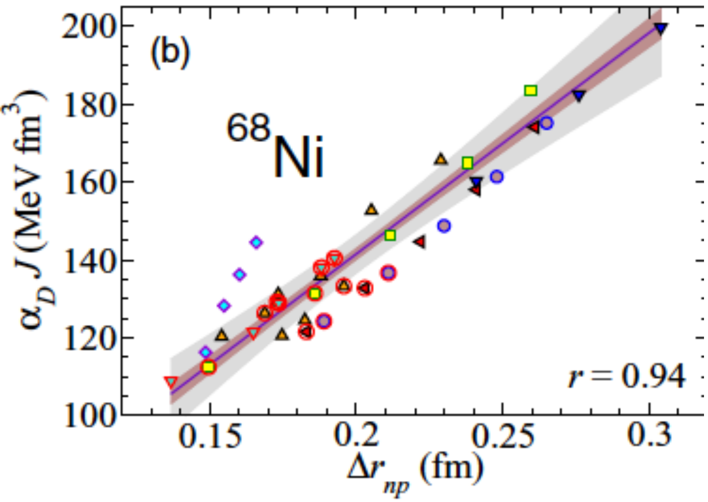
$$\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$$

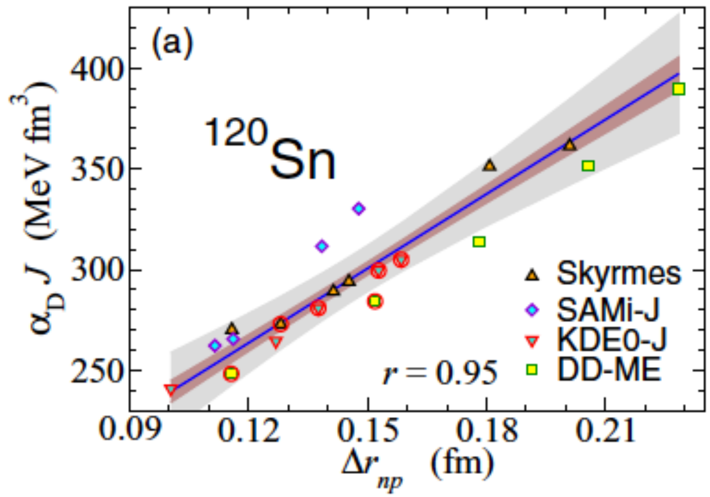
high-precision measurements of α_D - if J is known - may be used to constrain the neutron skin thickness Δr_{np}

→

providing important constraints on the density dependence of the symmetry energy

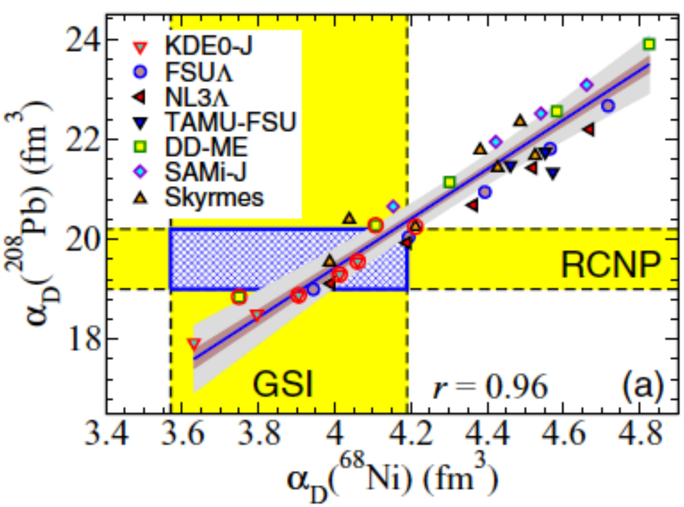
➢ Assessment of the validity of correlations suggested by the DM

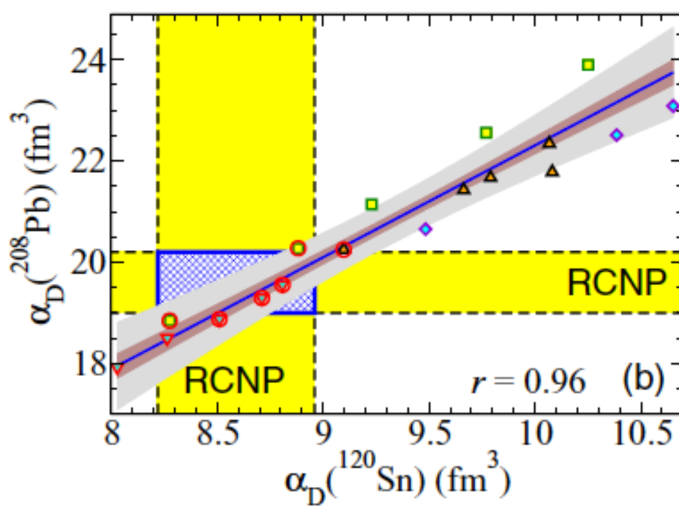




When α_D is scaled by *J* the spread is small
[large correlation coefficient *r*]

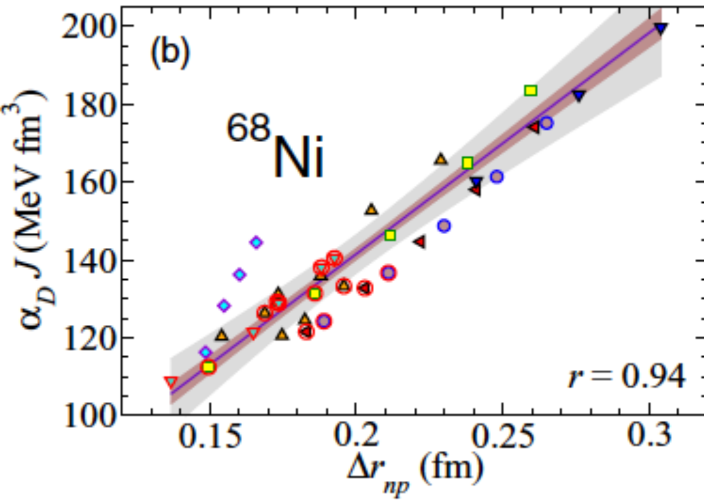
➢ Identification of a subset of EDFs that simultaneously reproduces the measured electric dipole polarizability in ^{68}Ni, ^{120}Sn, and ^{208}Pb

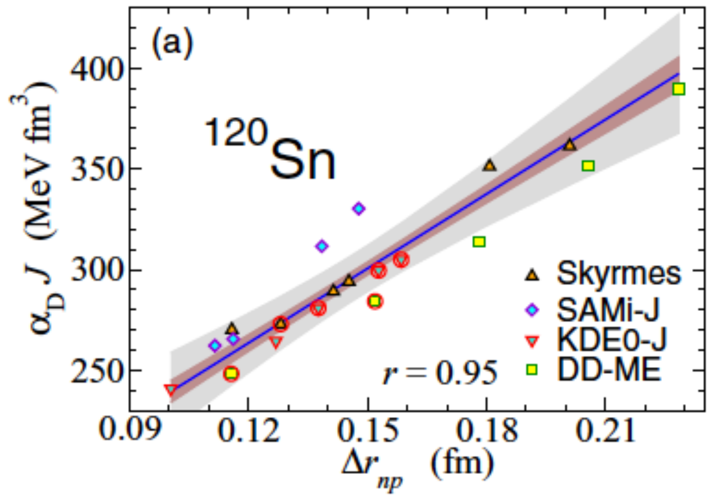




electric dipole polarizability of ^{208}Pb versus those of ^{68}Ni and ^{120}Sn

➢ Assessment of the validity of correlations suggested by the DM





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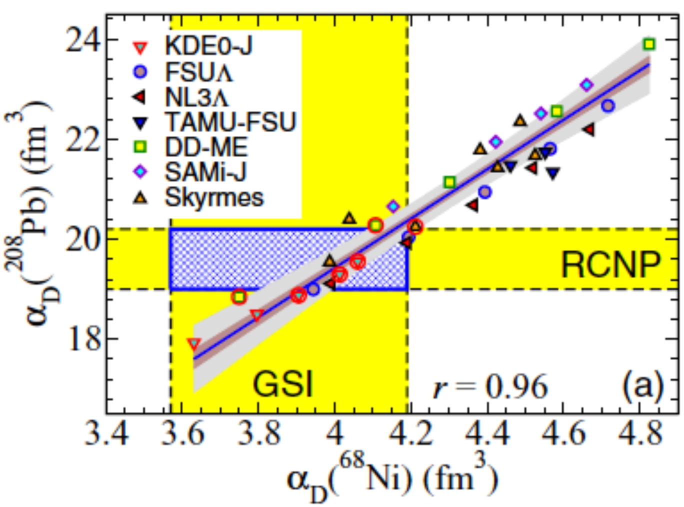


Strong correlation between α_D of two nuclei is instrumental to predict the values of α_D in other nuclei

➢ **The subset of EDFs is used to estimate isovector-sensitive observables: such as the neutron skin (Δr_{np}), the coefficient (J), and the slope (L) of the symmetry energy at the saturation density**

Δr_{np} (in fm)
(a) from the subset of EDFs
(b) from DM

	^{68}Ni	^{120}Sn	^{208}Pb
(a)	0.15 – 0.19	0.12 – 0.16	0.13 – 0.19
(b)	0.16 $\pm$ 0.04	0.12 $\pm$ 0.04	0.16 $\pm$ 0.03

J and L values (in MeV)

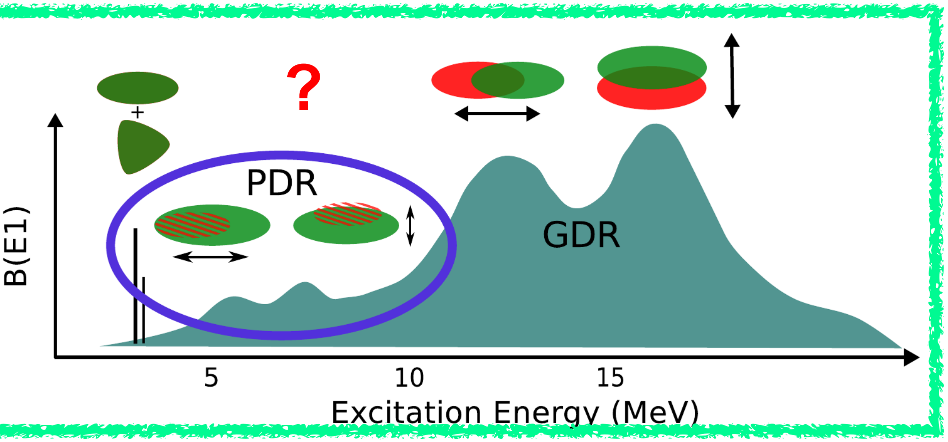
J	30 – 35
L	20 – 66

These estimates are consistent with predictions extracted in heavy ion reaction [M.Colonna *et al*, EPJA 50, 30 92014)] and suggest a fairly soft symmetry energy

Predictions of Δr_{np} in ^{48}Ca (0.15 – 0.18 fm)
in ^{90}Zr (0.06 – 0.08 fm)

Pigmy dipole response in deformed nuclei

E. Lanza *et al.* , work in progress

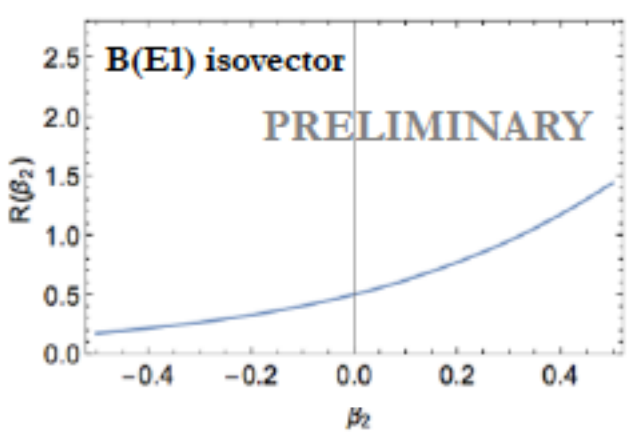


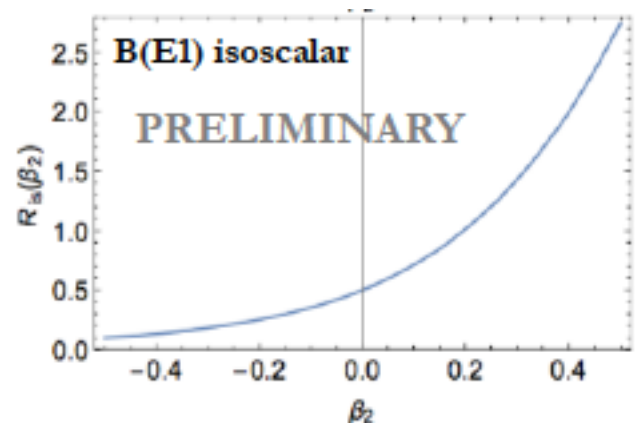
Presence of a double-bump structure of PDR similar to the one observed in the GDR?
Two peaks corresponding to oscillations of the neutron excess against the core along the symmetry axes ($K=0^-$) and the perpendicular one ($K=1^-$)

From calculations within a simple macroscopic model

$$R(\beta) = \frac{B(E1)^{IV}_{K=0^-}}{B(E1)^{IV}_{K=1^-}}$$

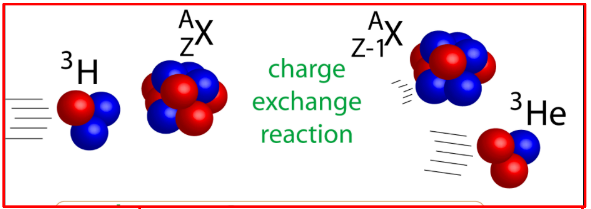
$$R(\beta) = \frac{B(E1)^{IS}_{K=0^-}}{B(E1)^{IS}_{K=1^-}}$$

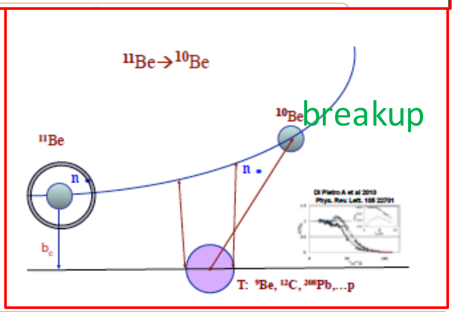


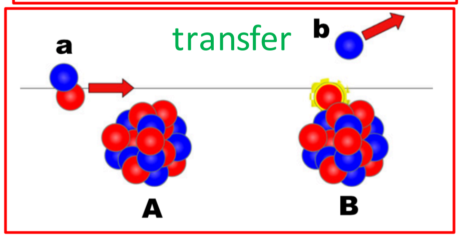


The variation of the ratio for the IS case is stronger → different population of the PDR for different probes

Direct reactions







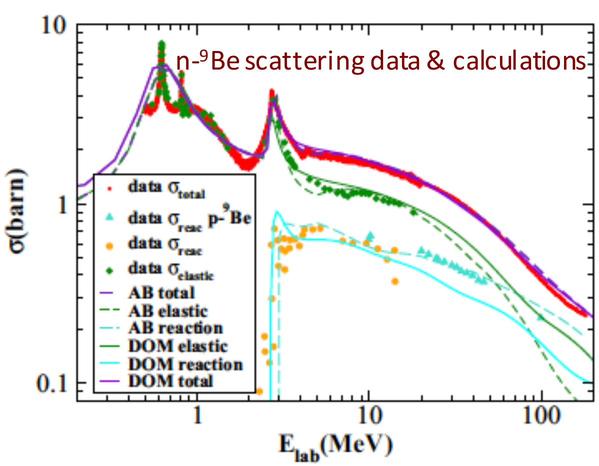
✓ Ion-ion charge exchange dynamics and connections to nuclear beta decay spectroscopy

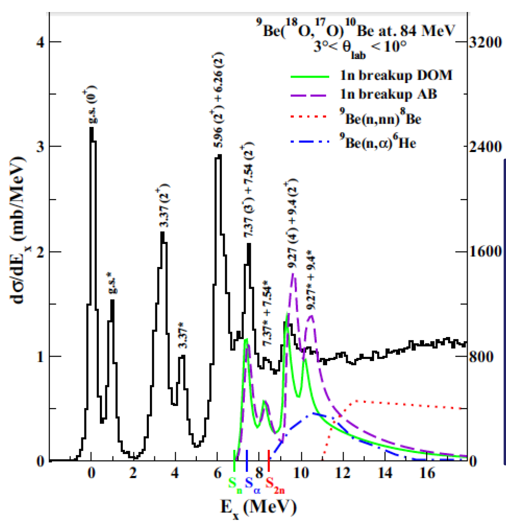
- H. Lenske, I. J. Bellone, M. Colonna, J. A. Lay, to be submitted to PRC
- Talk by J. Bellone

✓ Optical potentials and properties of quasi-bound states

- Talk by A. Bonaccorso

Reaction mechanisms, transfer and fragmentation, that can populate resonance states of exotic nuclei



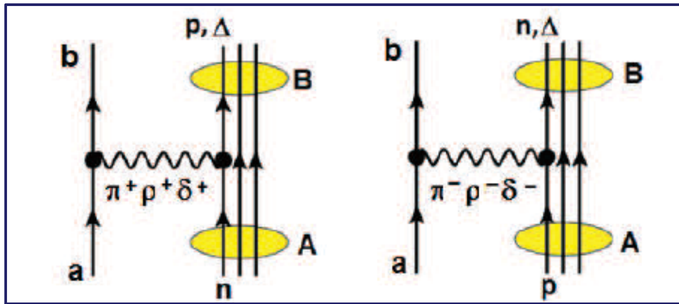


n-^{9}Be optical potentials from A. Bonaccorso, J. Charity, PRC 89 024619 (2014) → study of the continuum states in ^{10}Be populated in the $^9Be(^{18}O,^{17}O)^{10}Be$ reaction [@LNS with MAGNEX, PRC 90 064621 (2014)]

Heavy Ion Single Charge Exchange Reactions and Beta Decay Matrix Elements

H. Lenske, I. J. Bellone, M. Colonna, J. A. Lay, to be submitted to PRC

Direct reactions



$$ {}^{a}_{z}a + {}^{A}_{Z}A \rightarrow {}^{a}_{z\pm1}b + {}^{A}_{Z\mp1}B $$

- **DWBA - Unified structure and reaction description**

$^{18}O+^{40}Ca \rightarrow ^{18}F+^{40}K$

T_{lab} = 15 MeV/A @LNS

For low momentum transfer → factorization of the charge exchange cross section into reaction and structure parts

$$ d\sigma_{\alpha\beta} = F(q_{\alpha\beta},\omega)\sigma_U \left|b^{(ab)}_{0SS}\right|^2 \left|b^{(AB)}_{0SS}\right|^2 $$

β decay strengths

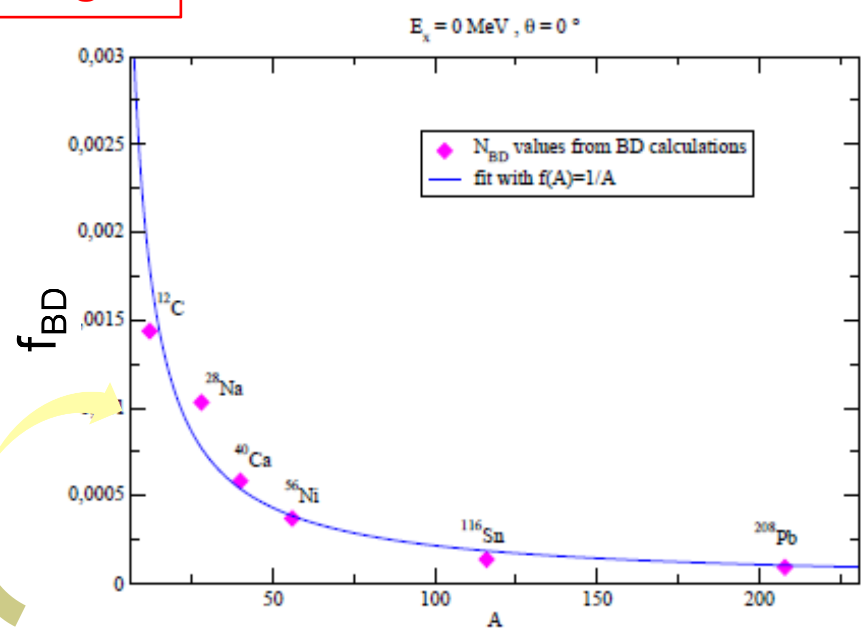
Nuclear interaction

$$ \sigma_U = K(E_{lab},0)|V^{(C)}_{ST}(0)|^2 f_{BD}(R_{abs},R,\sigma) $$

Kinematical factor

Distortion factor

f_{BD} as a function of the target mass A with ^{18}O projectile



To end

From 2014 until now	
papers	**~280***
talks	**~220**
thesis (PhD, triennale, magistrale)	**~25**

* many of them in collaboration with experimental groups

The STRENGTH Units have given an important contribution to the nuclear community through the organization of meetings, workshops and schools

In particular,

- GGI lectures on *Frontiers in Nuclear and Hadronic Physics*, Florence
- Summer school *Rewriting nuclear physics textbooks*, Pisa
- Incontri Nazionali di Fisica Nucleare
- SPES One Day Workshops
- International SPES Workshops