Fenomeni collettivi in nuclei esotici (e non solo…)

Incontro Nazionale di Fisica Nucleare
(LNS, Catania, 12-14 Novembre 2012)

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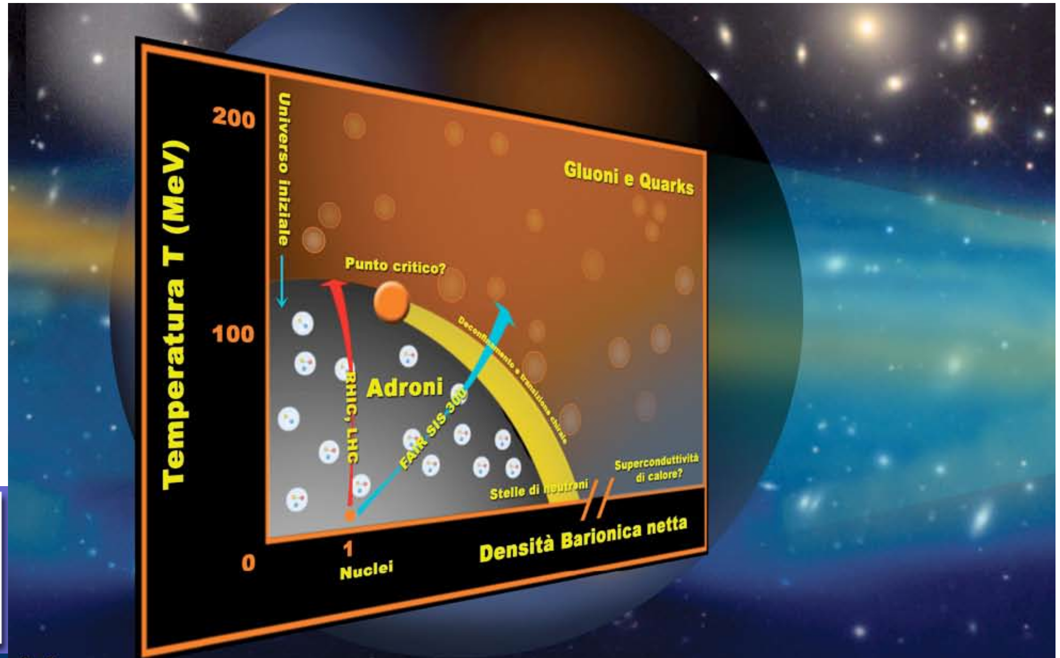
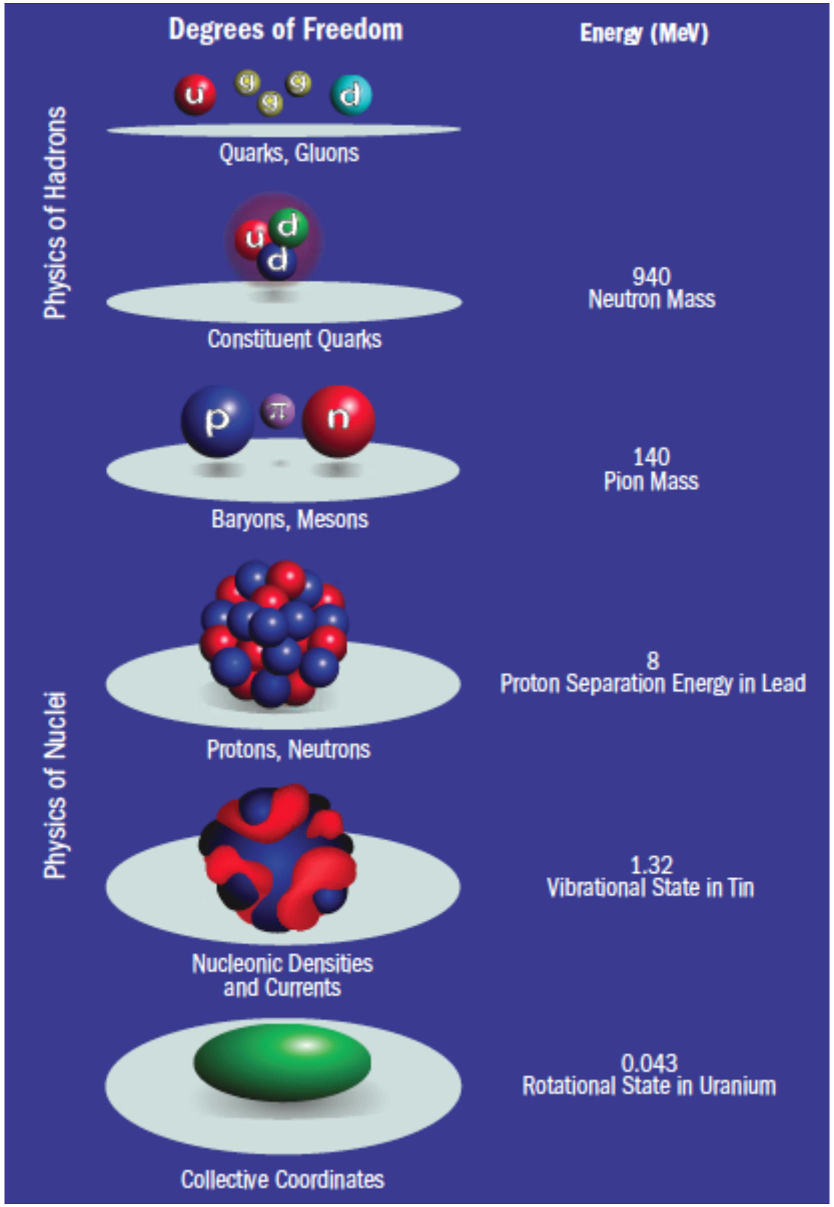


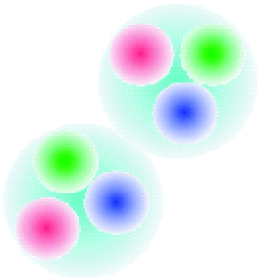
The domain of low-energy nuclear physics



- Clear separation between the nucleon scale and the nuclear scale.
- On the nuclear scale, there exist phenomena associated with **different degrees of freedom** (single-particle or collective).
- Different **densities and shapes** are involved.
- Challenge: a **unified description** or (more realistically) an increase of predictive power through cross-comparison of models.

Figure from: G.F. Bertsch, D. Dean, W. Nazarewicz, SciDAC Review (2007).

One key question: the NN force
(in the effective theory spirit: not unique)



QCD (χPT)

Fit to observables

$$\langle \Psi | H | \Psi \rangle$$
$$\langle \Psi | P^{-1} P H P^{-1} P | \Psi \rangle$$
$$\langle \Phi | H' | \Phi \rangle$$

free or bare NN interaction

Ab-initio (?) approaches
(variational, Montecarlo …)
Shell model

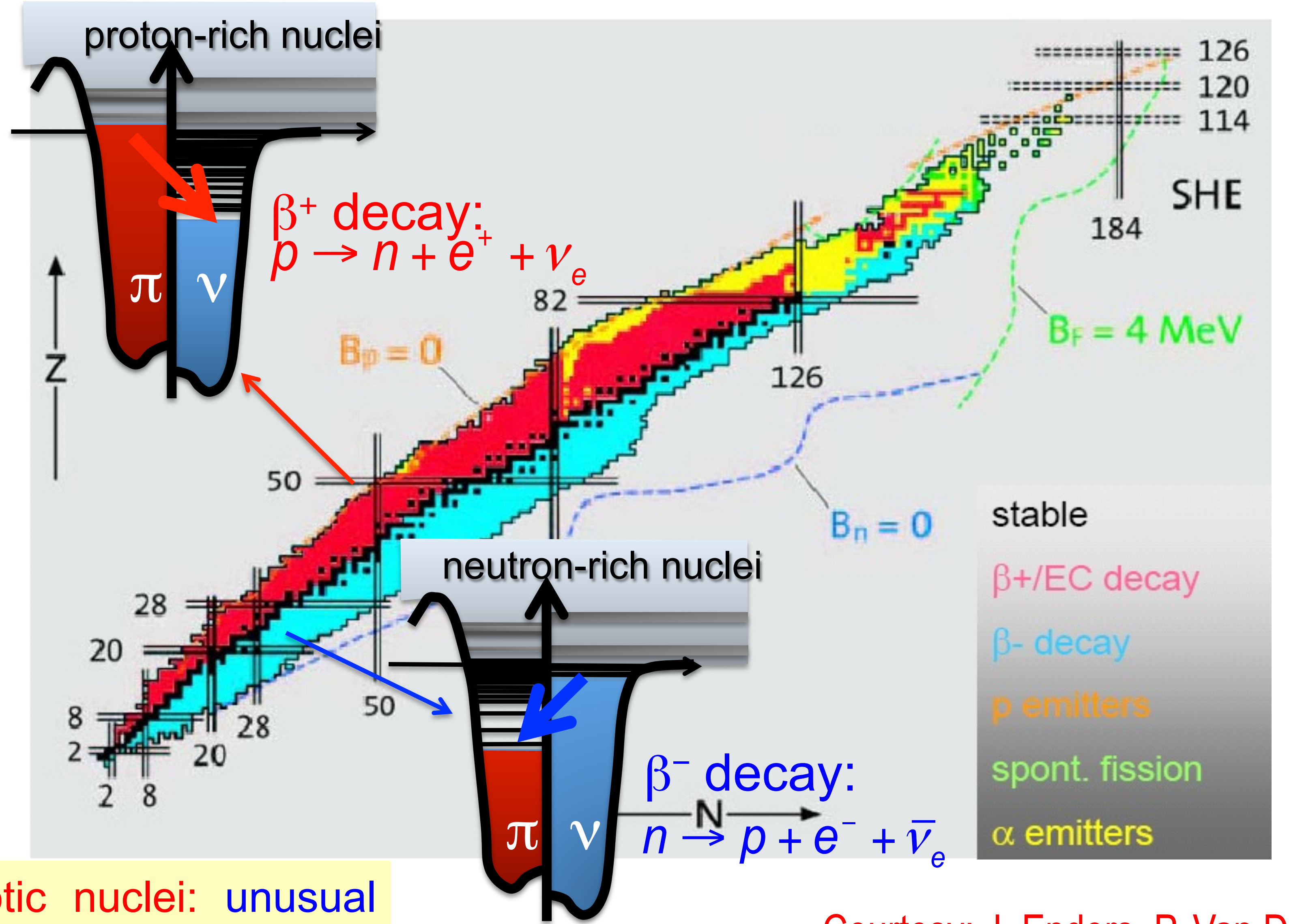
effective NN interaction

relativistic models :

nucleon-meson couplings g(ρ)

non-relativistic models
(Skyrme, Gogny) : V[ρ]

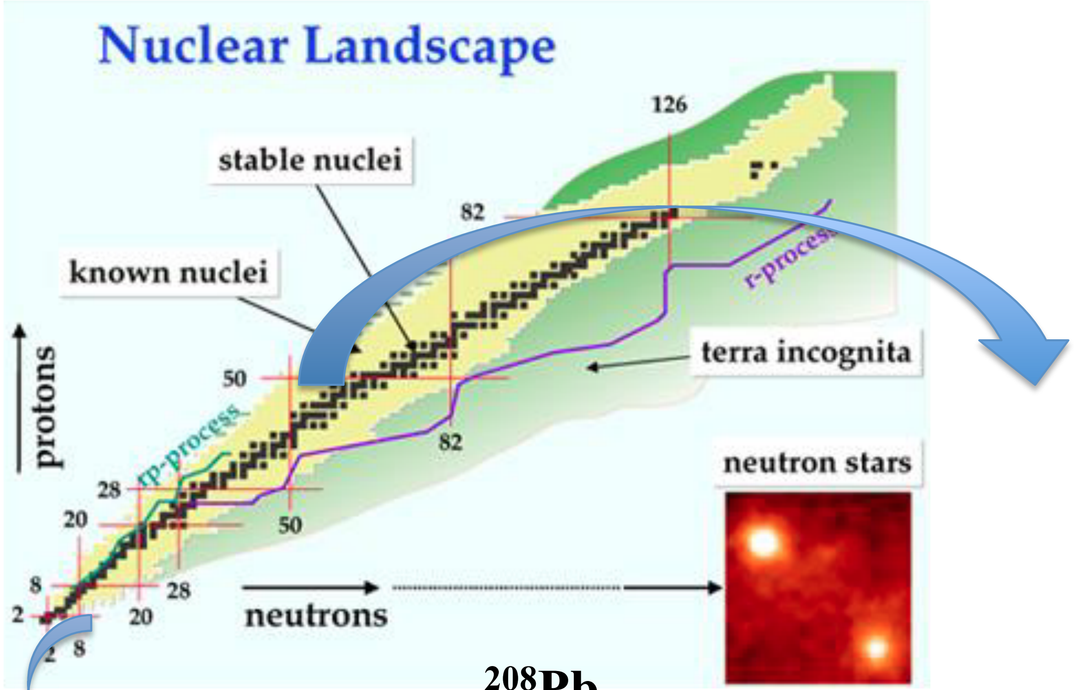
The nuclear chart



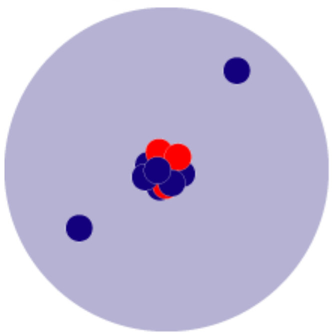
Exotic nuclei: unusual neutron-proton ratios

Courtesy: J. Enders, P. Van Duppen

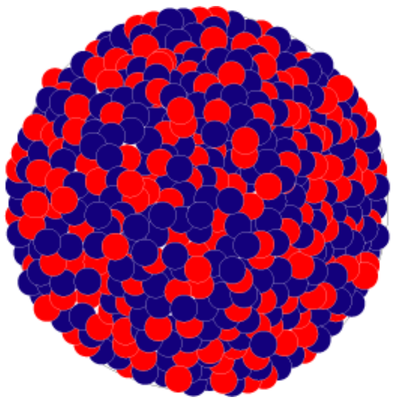
Why exotic nuclei (in pictures…)

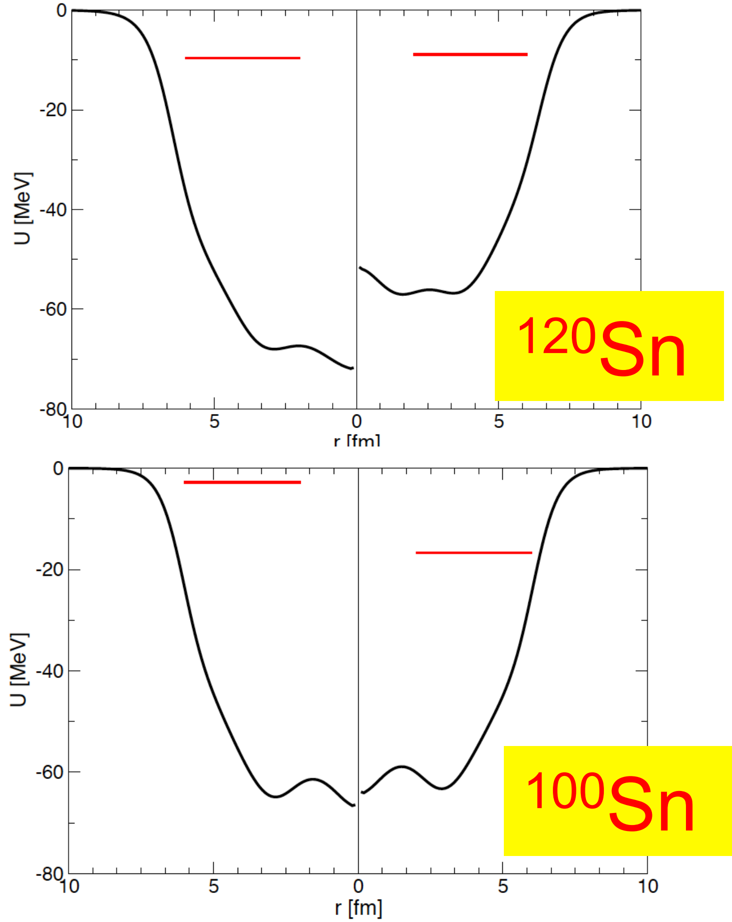


^{11}Li



^{208}Pb





p n

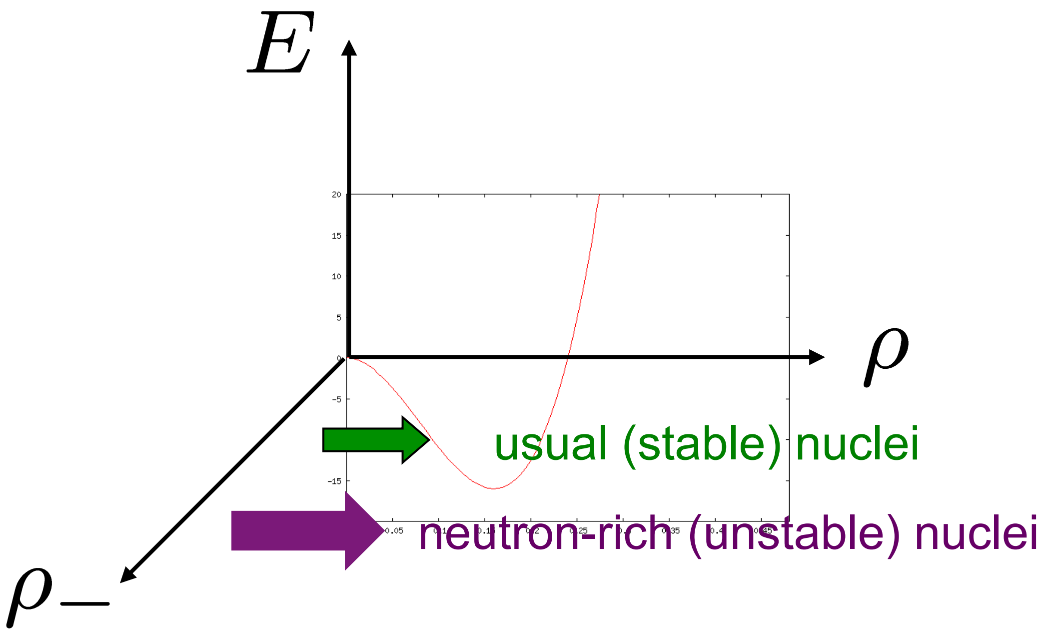
Z = 50

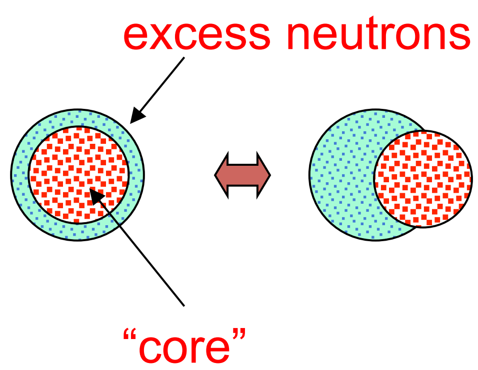
Why exotic nuclei (in words…)

- When the n-p asymmetry is changed one expects changes in effective forces – V [ρ,δ] where $\rho = \rho_n+\rho_p$, and $\rho_- = \delta = (\rho_n-\rho_p)/\rho$.

- The goal is to understand the behaviour of E/A in different conditions. Link with the Equation of State (EoS) – cf. later.

- Do weakly bound systems display new excitation modes ?

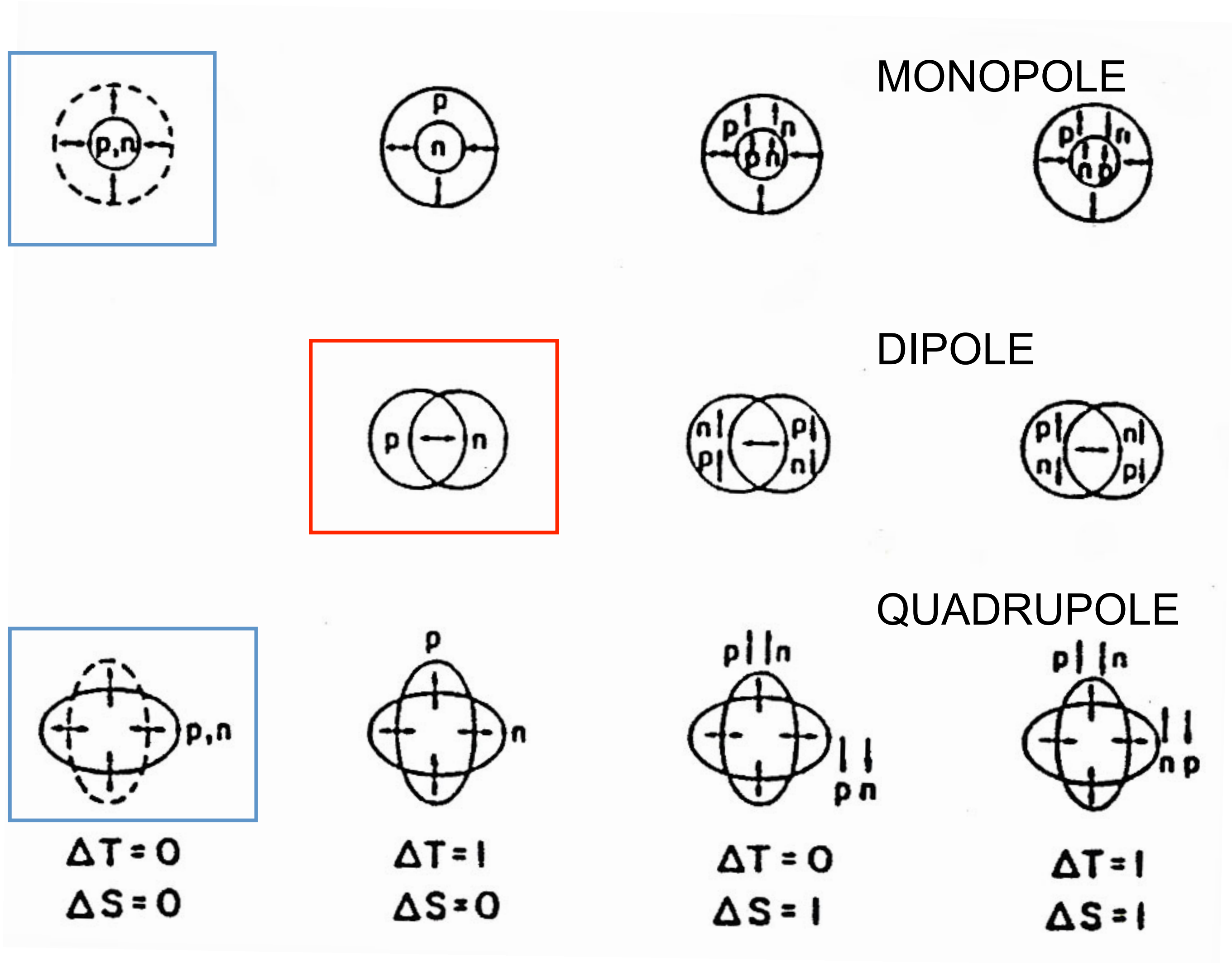




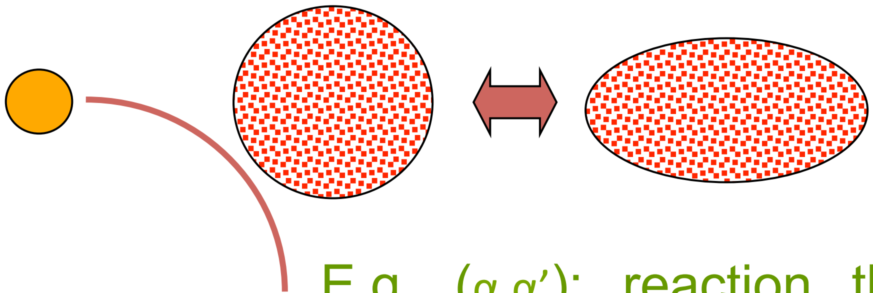
Collective vibrational modes

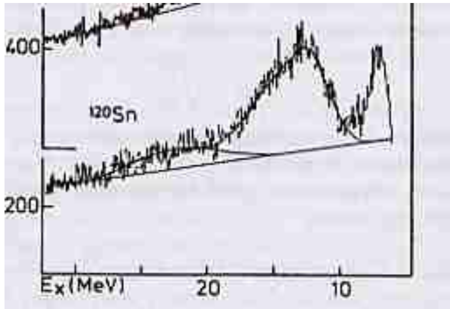
In the isoscalar vibrations, the n and p oscillate in phase

In the isovector case, the n and p oscillate in opposition of phase



Strength of the collective modes





E.g. (α,α′): reaction theory should be used to calculate a cross section associated with the mode.

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2 \quad f(\theta) = -\frac{m}{2\pi\hbar^2} \int d^3R \; \chi_f^*(R) \langle f | V_{Aa} | i \rangle \chi_i(R)$$

When a state *n* is excited, either in the target or projectile, the cross section is, within a simplified picture, proportional to the **strength** of the mode *n*.

$$\hat{F} = \sum_i r_i^L Y_{LM}(\hat{r}_i) \otimes (1, \tau_z(i)) \qquad S_n \equiv |\langle n | \hat{F} | 0 \rangle|^2$$

Collective modes have a strength which is large compared to the typical single-particle one. E.g.: electromagnetic transition probability = B(EL).

A theory for collective states: linear response

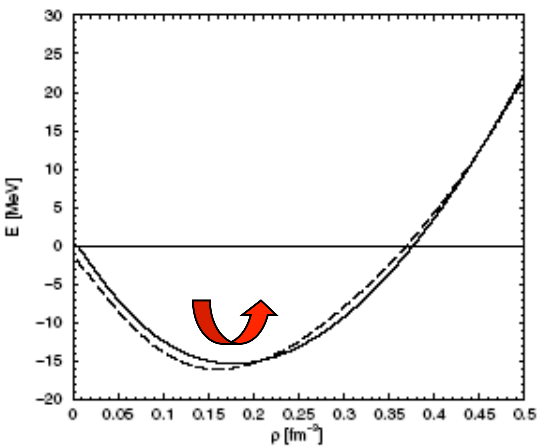
$$E = \langle \Phi | H_{\text{eff}} | \Phi \rangle = E[\rho]$$

Energy Density Functional

$|\Phi\rangle$ ⇨ Slater determinant

(Skyrme, Gogny, RMF)

ρ ⇨ One-body density (densities)



- The ground-state is determined by the minumum of the total energy (HF or HFB equations).

$$\frac{\delta E}{\delta \rho} = 0$$

- The second derivative of the energy is associated with the restoring force when vibrations are excited (RPA or QRPA equations).

$$\frac{\delta^2 E}{\delta \rho \delta \rho}$$

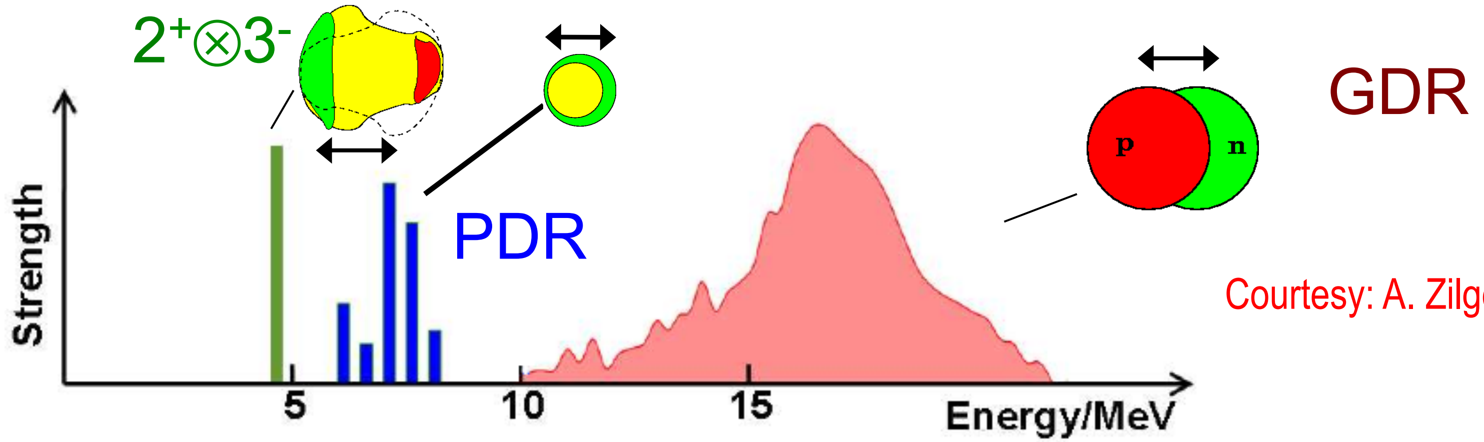
Comp. Phys. Commun. 184, 142 (2013)

Advantage : consistent description of light/(super)heavy nuclei, exotic systems, uniform matter, part of the neutron star interior.

Outline of the physics cases of this talk

- Do we have a clear picture of the dipole response of atomic nuclei ? The nature of the low-energy dipole states.
- The pre-equilibrium dipole emission.
- Beyond the simple vibrational picture: complex spectra understood with geometric or algebraic models.
- The interplay between single-particle and collective degrees of freedom.
- Many interesting issues we shall not discuss: …

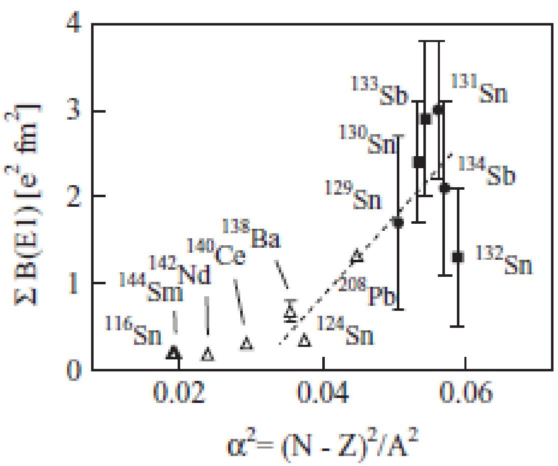
The low-energy, or “pygmy”, dipole resonance



Courtesy: A. Zilges

Dipole strength below the GDR has been recently observed in several nuclei. The very nature of these states has been questioned. Probably only in light nuclei it is a real “skin” mode.

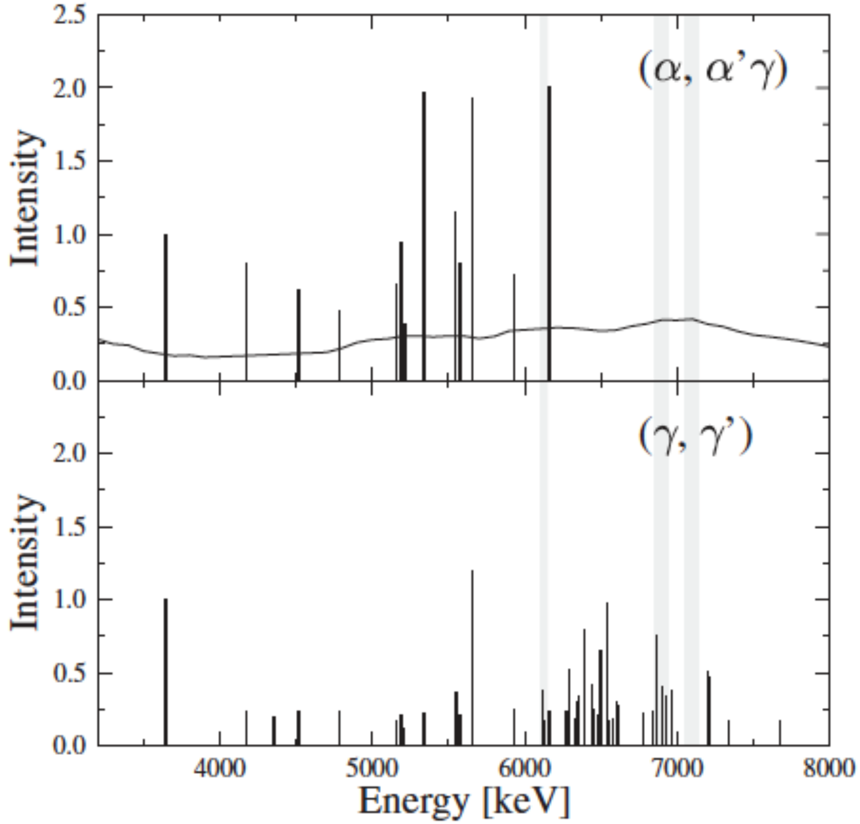
Problem: how to attack the problem experimentally ? Coulex, (γγ’) …



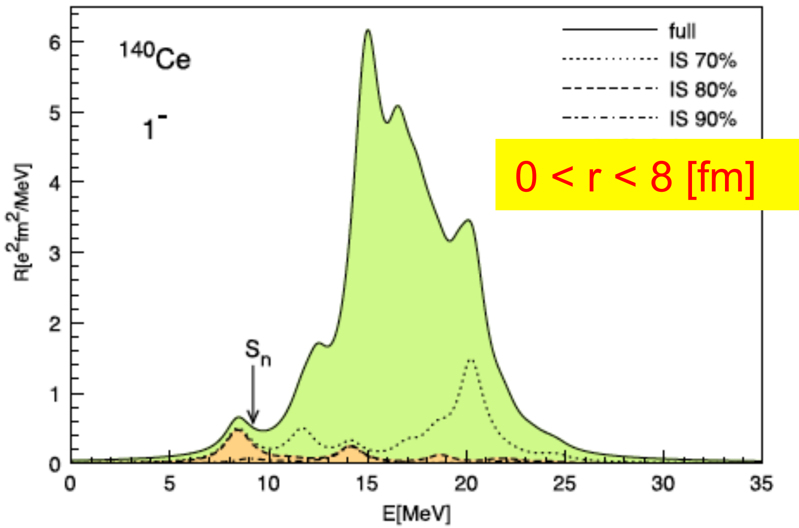
A. Klimkiewicz *et al.*, PRC 76, 051603(R) (2007).

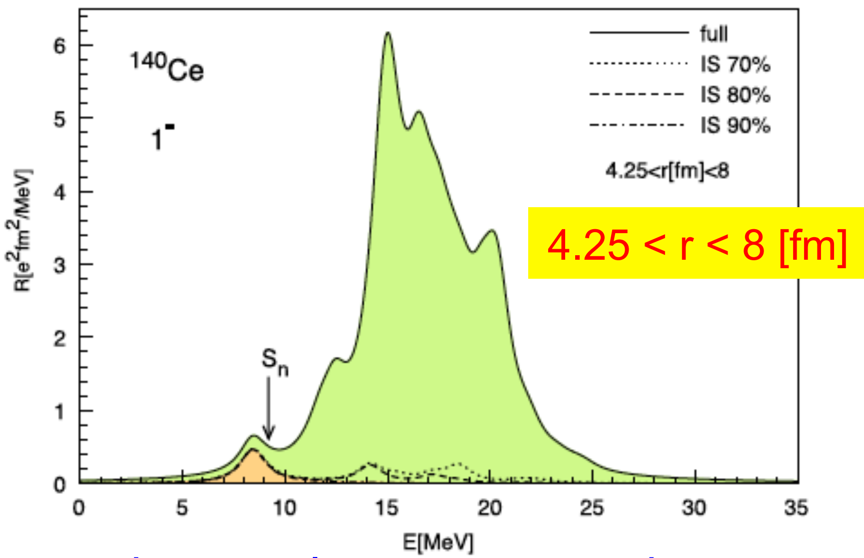
^{140}Ce
Z = 58
N = 82

- Neutron excess
- Broken isospin
- Mixed IS/IV character of the dipole states



D. Savran *et al.*, PRL 97, 172502 (2006).

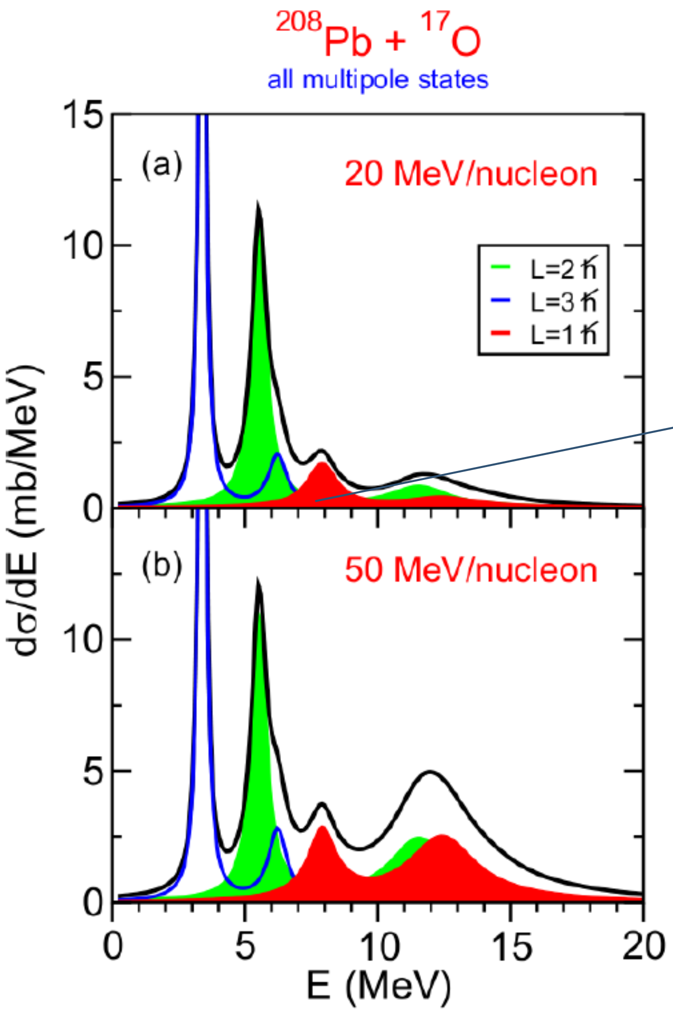


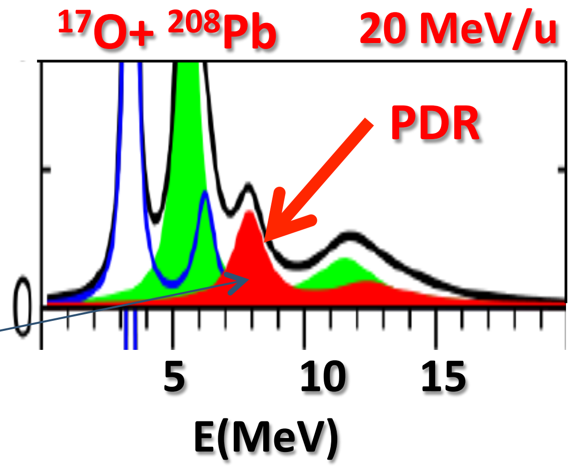


Suggestion: at lower energy there are states that are isoscalar on the surface of the nucleus. **These are created by neutrons.**

N. Paar *et al.*, PRL 103, 032502 (2009).

Complementary probes to excite the PDR





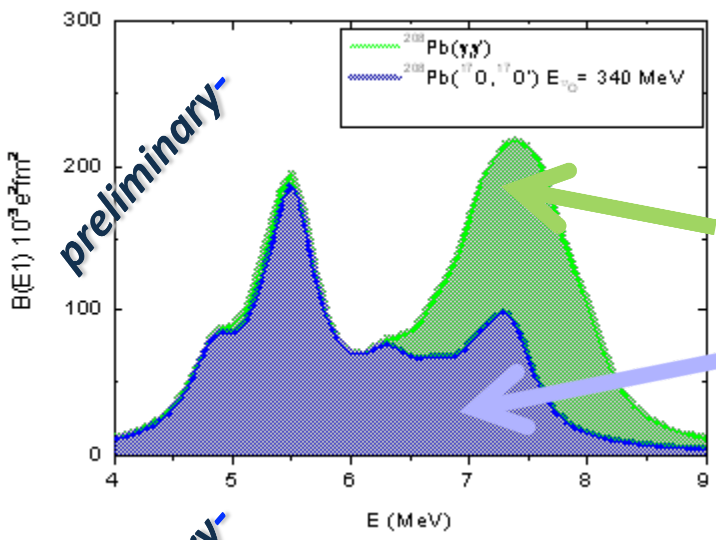
E. Lanza *et al.*
PRC 84, 064602 (2011)

Calculation of excitation functions with the semiclassical reaction model yet with realistic structure input.

The PDR cross section is rather independent of E.

At lower energies, PDR favoured over GDR.

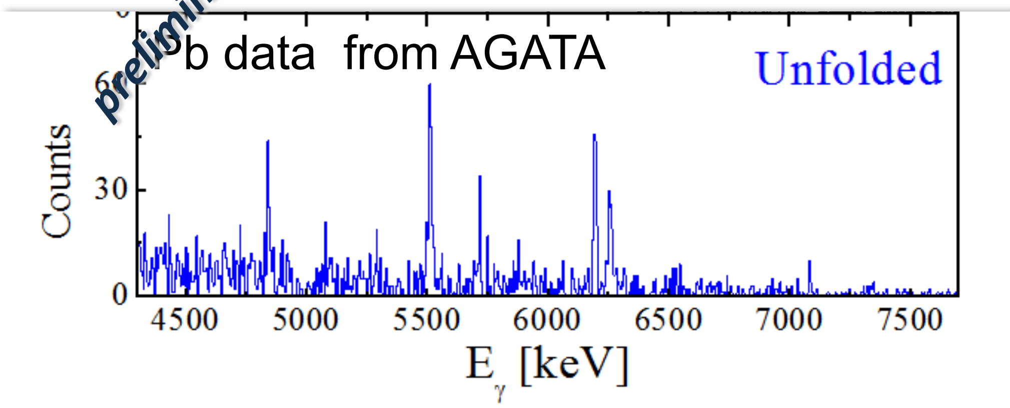
Experiment on ^{208}Pb (AGATA @ LNL)



Comparison of the strength from

(γ, γ') and (^{17}O , ^{17}O' γ) experiments

Some missing strength in case of (^{17}O , ^{17}O' γ) above 7 MeV



Perspectives for more experiments at LNL.

Also, at SPIRAL2 / SPES, exotic nuclei in **inverse kinematics** can be explored.

Work in progress on ^{90}Zr, ^{124}Sn , ^{140}Ce …

Relationship with the symmetry energy

Nuclear matter EOS

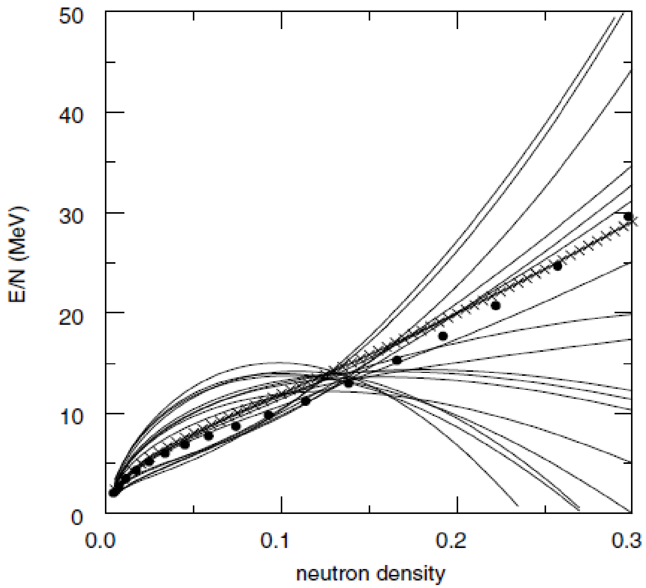
Symmetric matter EOS

Symmetry energy S

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2$$

$$\rho = \rho_n + \rho_p$$
$$\delta = (\rho_n - \rho_p)/\rho$$

Going from E[ρ] to P[ρ] we obtain the EOS (cf. F. Burgio).



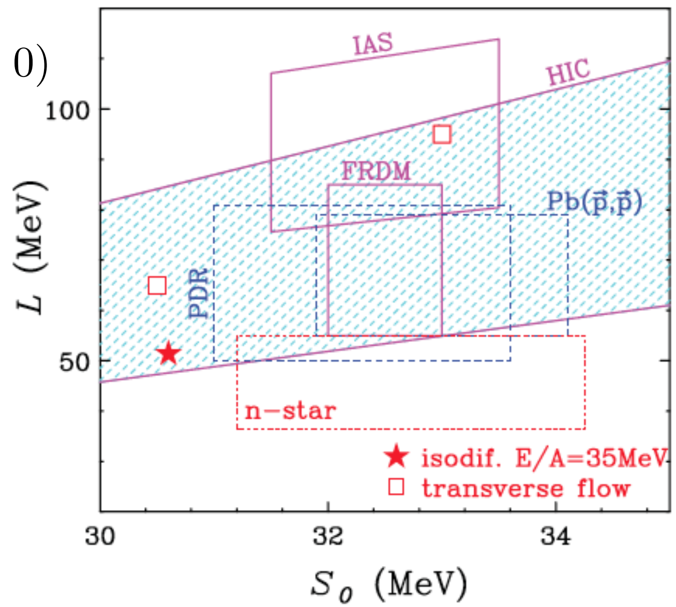
B.A. Brown, PRL 85, 5296 (2000)

$$S = \frac{E}{A}(\rho,\delta=1) - \frac{E}{A}(\rho,\delta=0)$$

$$\frac{\partial}{\partial\rho}\frac{E}{A} = \frac{\partial}{\partial\rho}\frac{E}{A}(\rho,\delta=0) + \frac{\partial S}{\partial\rho}\delta^2$$

$$\left.\frac{\partial}{\partial\rho}\frac{E}{A}\right|_{\rho=\rho_0,\delta=1} = \frac{L}{3\rho_0} \equiv p_0$$

The PDR is also related to the pressure, which create the neutron excess.



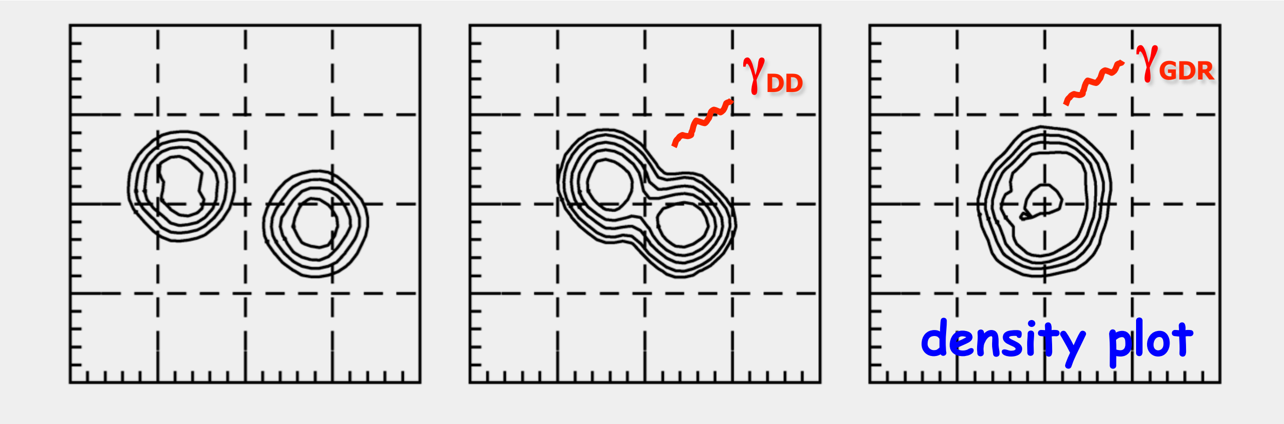
B. Tsang *et al.*, Phys. Rev. C 86, 015803 (2012)

PDR - A. Carbone *et al.*, Phys. Rev. C 81, 041301(R) (2010)

GDR vs "dynamical" or "pre-equilibrium" dipole (I)

In heavy-ion collisions, if a n-p asymmetric compound system is formed this has an **initial dipole moment** D(t=0).
Due to the restoring n-p force a **dipole oscillation** can be expected.

The restoring force is expected to be sensitive to the **symmetry energy below ρ_0**.

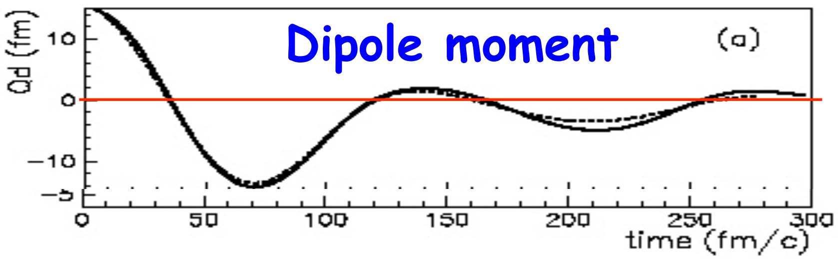


Giant Dipole Resonance (GDR) → out-of-phase collective oscillation of neutrons and protons in the nucleus: neutron and γ-ray emission.
Dynamical Dipole (DD) → excitation of a pre-equilibrium GDR in the charge-asymmetric aforementioned system: prompt dipole γ−ray emission.

GDR vs "dynamical" or "pre-equilibrium" dipole (II)

The energy of the DD is expected to be **lower than that of the GDR** in the compound system due to the strong **deformation**.

$$D(t) = \frac{NZ}{A}\left(R_Z(t) - R_N(t)\right)$$



Thermal Equilibrium
$3 \cdot 10^{-21}$ s

Simenel *et al.*, PRL86 (2001) 2971

The **intensity** of the emitted dipole radiation ("gamma yield") can be expected to be quite **sensitive** on many properties of the system under study: mass and charge, mass and charge asymmetry, E_{lab}, centrality of the collision.
BNV simulations have been performed by the Catania group.

PHYSICAL REVIEW C **79**, 021603(R) (2009)

Dynamical dipole mode in fusion reactions with exotic nuclear beams

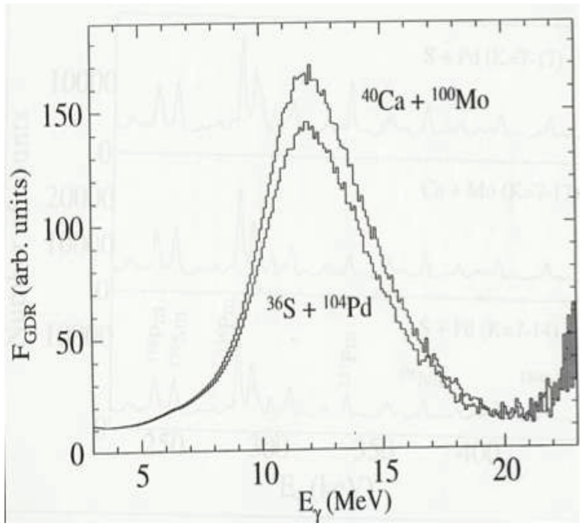
V. Baran,[1] C. Rizzo,[2,3] M. Colonna,[2,3] M. Di Toro,[2,3,*] and D. Pierroutsakou[4]

Experimental observation in fusion reactions

Experimental method: Comparison of the energy spectra and the angular distributions of the γ-rays from two reactions with different charge asymmetry that populate the same compound nucleus.

Evidence of the dynamical dipole mode:

1) Extra γ yield (prompt dipole radiation) for the charge asymmetric case.
2) Anisotropic γ-ray excess angular distribution (depends on the DD excitation mechanism and lifetime, and on the rotational angular velocity of the composite system during the DD γ emission).



Flibotte et al., PRL 77 (1996) 1448.

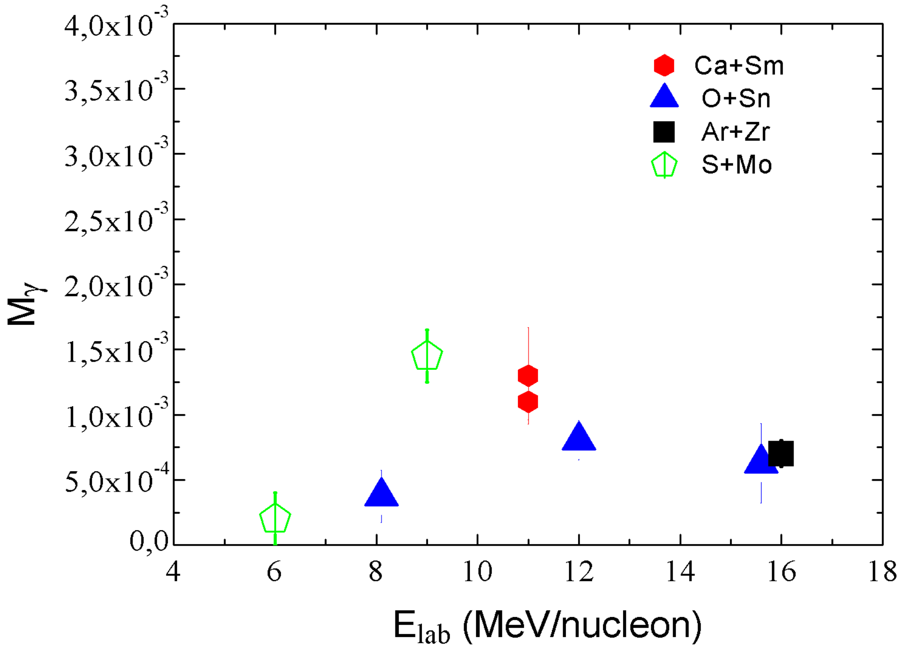
D. Pierroutsakou et al., EPJA 17 (2003) 71; PRC 71 (2005) 054605; PRC 80 (2009) 024612.

B. Martin et al., PLB 664 (2008) 47.

A.Corsi et al. PLB 679 (2009) 197.

C. Parascandolo et al., Acta Physica Polonica B 42 (2011) 629; D. Pierroutsakou et al., AIP Conf. Proc. 1423 (2012) 59.

DD yield : comparison between available data and theory



- The dependence of the γ-yield on the initial dipole moment is not very clear.
- The dependence on E_{lab} has been studied in few cases, and a "rise-and-fall" trend seems to appear.

CN: ^{132}Ce

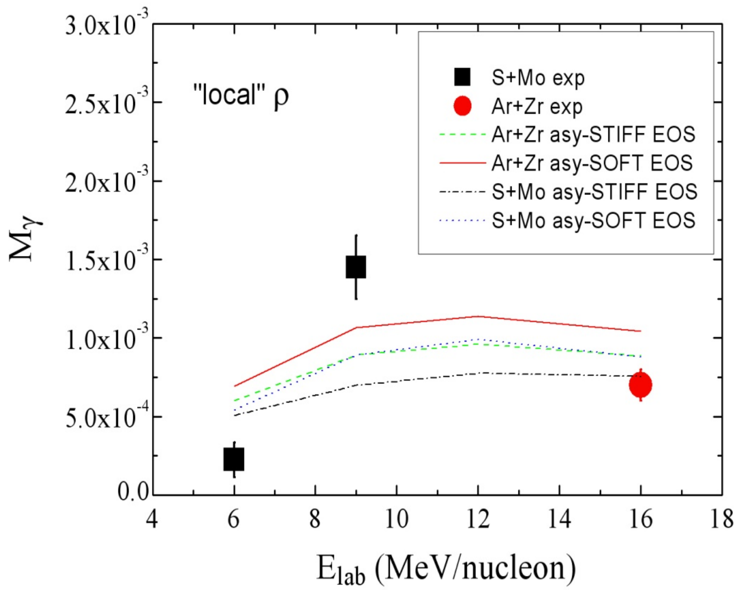
^{36,40}Ar+^{96,92}Zr D(t=0) = (20.6 - 4) fm

^{32,36}S+^{100,96}Mo D(t=0)= (18.2 - 1.7) fm

^{16}O+^{116}Sn D(t=0) = 8.6 fm

CN: ^{192}Pb

^{40,48}Ca+^{152,144}Sm: D(t=0) = (30.6 - 5) fm



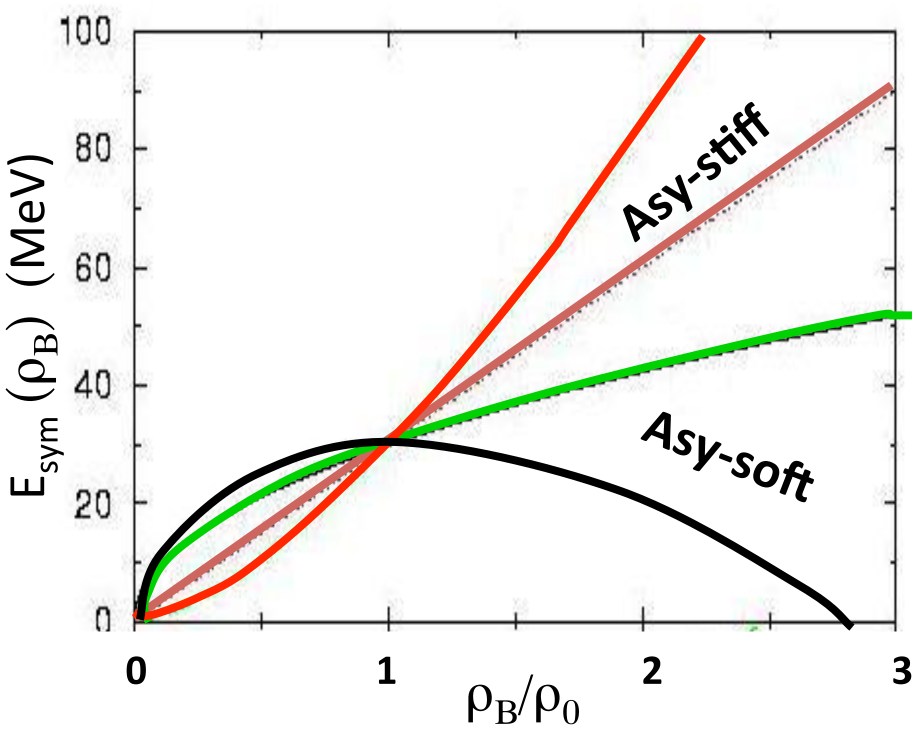
Sensitivity to S(ρ) at sub-saturation density

Larger values of S at $\rho < \rho_0$ imply a larger isovector restoring force.

Asy-soft with respect to Asy-stiff EoS:
higher DD centroid energy and larger yield.

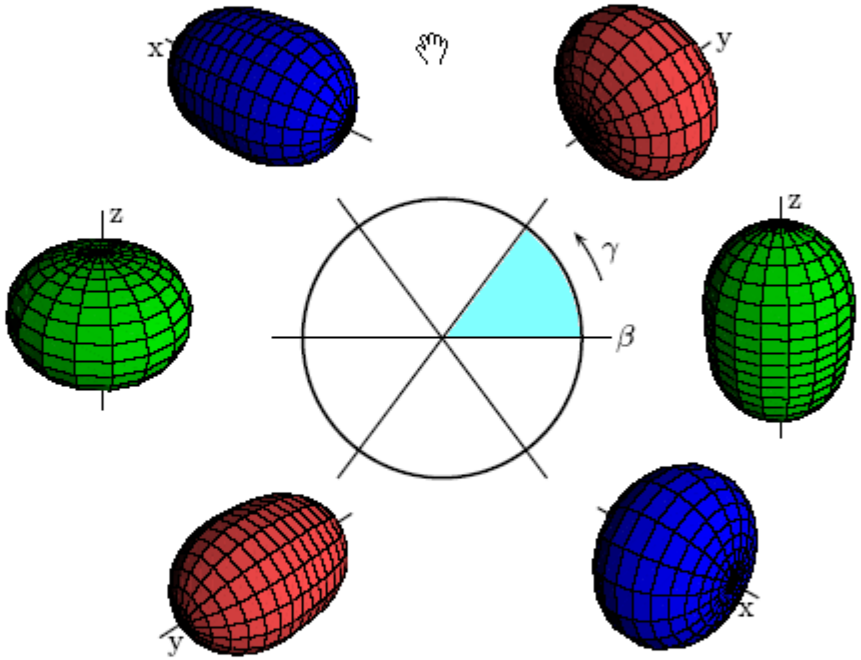
This sensitivity is much enhanced in the case of the exotic system $^{132}Sn + ^{58}Ni$ at 10 MeV/nucleon.

The DD strength is expected to be larger by 25% in the case of the Asy-soft EOS.



Cf. LoI for SPES.

The variety of nuclear shapes



Along the nuclear chart, one encounters quadrupole deformations (we do not discuss octupole deformations, cf. W. Nazarewicz *et al.*).

The coordinates β, γ identify the shape.

The spherical nuclei treated so far, are associated to $\beta = 0$.

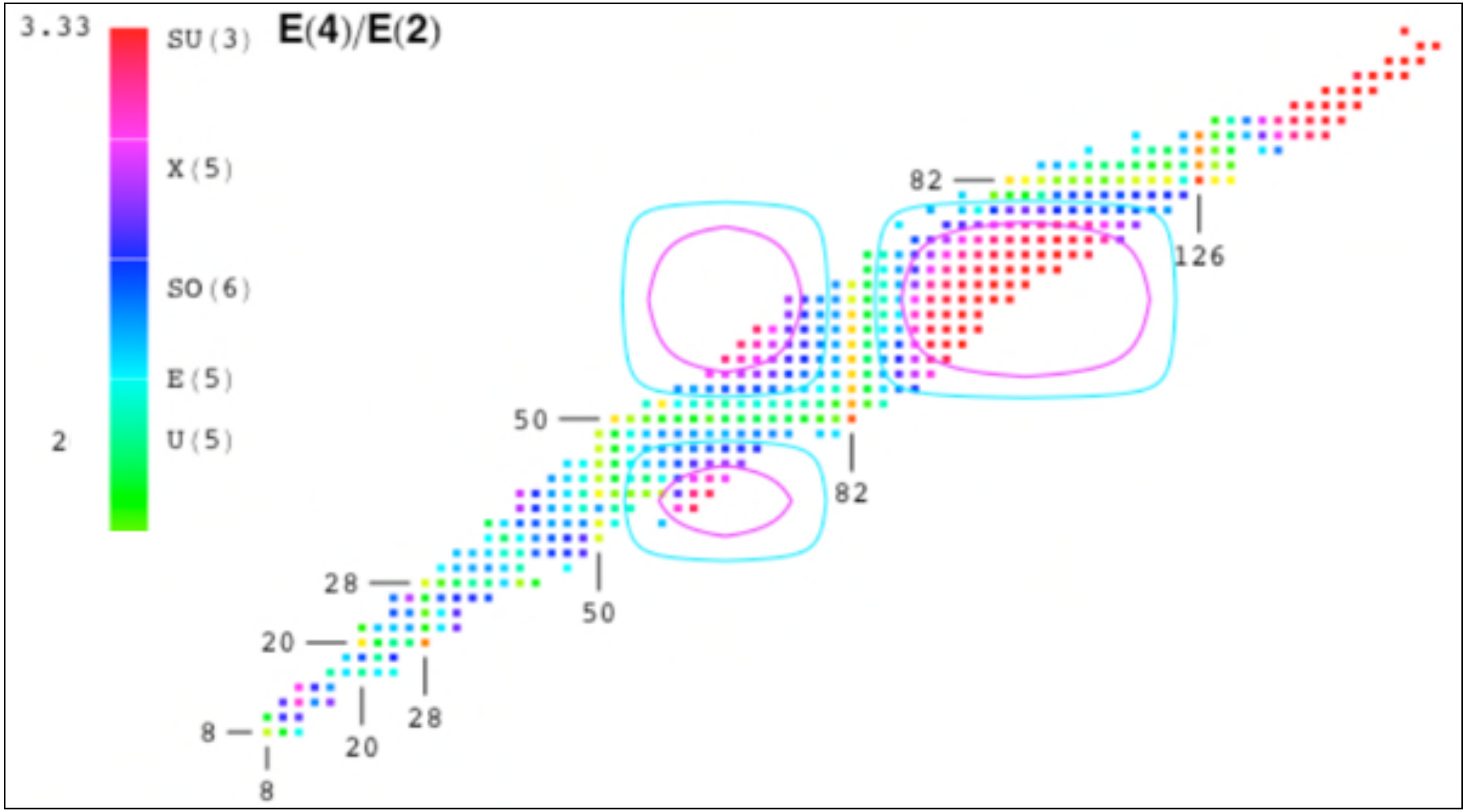
Spherical vibrator (HO)

2	0^+, 2^+, 4+
1	2^+
0	0^+

Well-deformed rotator $$E = \frac{\hbar^2}{2\mathcal{I}} I(I+1)$$

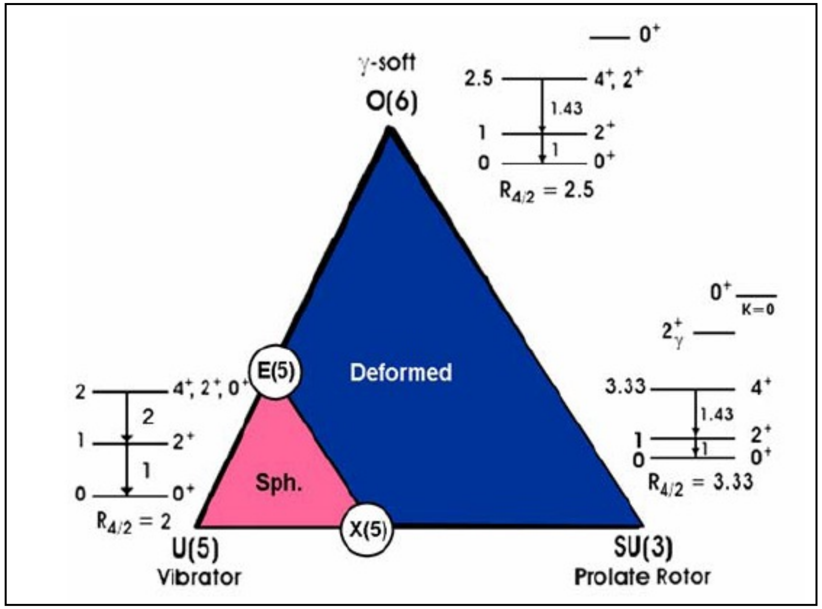
3.33	4+
1	2^+
0	0^+

R = E(4^+)/E(2^+)



Courtesy: P. Van Isacker

Algebraic and geometrical models



Algebraic models are very instrumental in tracing the origin of regularities in the low-lying spectra and associating them to group symmetries.

They are based on group theory and have a longstanding tradition in nuclear physics.

Recently, some transition point has been proposed.

$$H_B = T_{vib} + T_{rot} + V.$$

$$T_{vib} = -\frac{\hbar^2}{2B_m}\left\{\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\beta^4\frac{\partial}{\partial\beta} + \frac{1}{\beta^2}\frac{1}{\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma}\right\}$$

$$T_{rot} = \frac{\hbar^2}{2B_m}\frac{1}{4\beta^2}\sum_{k=1}^{3}\frac{Q_k^2}{\left[\sin\left(\gamma - \frac{2\pi}{3}k\right)\right]^2}$$

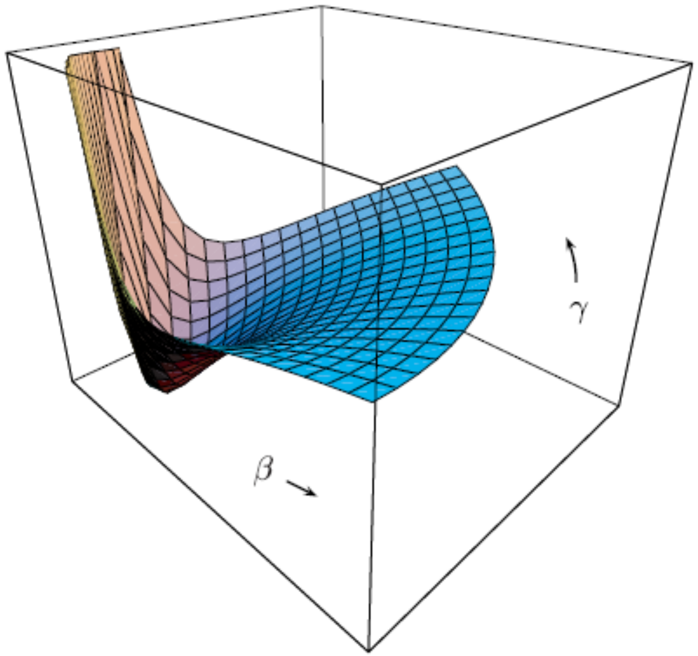
The collective model (Bohr-Mottelson) treats vibrations and rotations of an ellipsoidal shape given a potential V(β,γ). The spectrum can be compared with the experimental findings.

L.F. EPJA26 s01 (2005) 1

A (far from trivial) example

Bohr Hamiltonian with:

$$V(\beta,\gamma) = A\beta^2 + \frac{B}{\beta^2} + C\left(\gamma - \gamma_0\right)^2$$



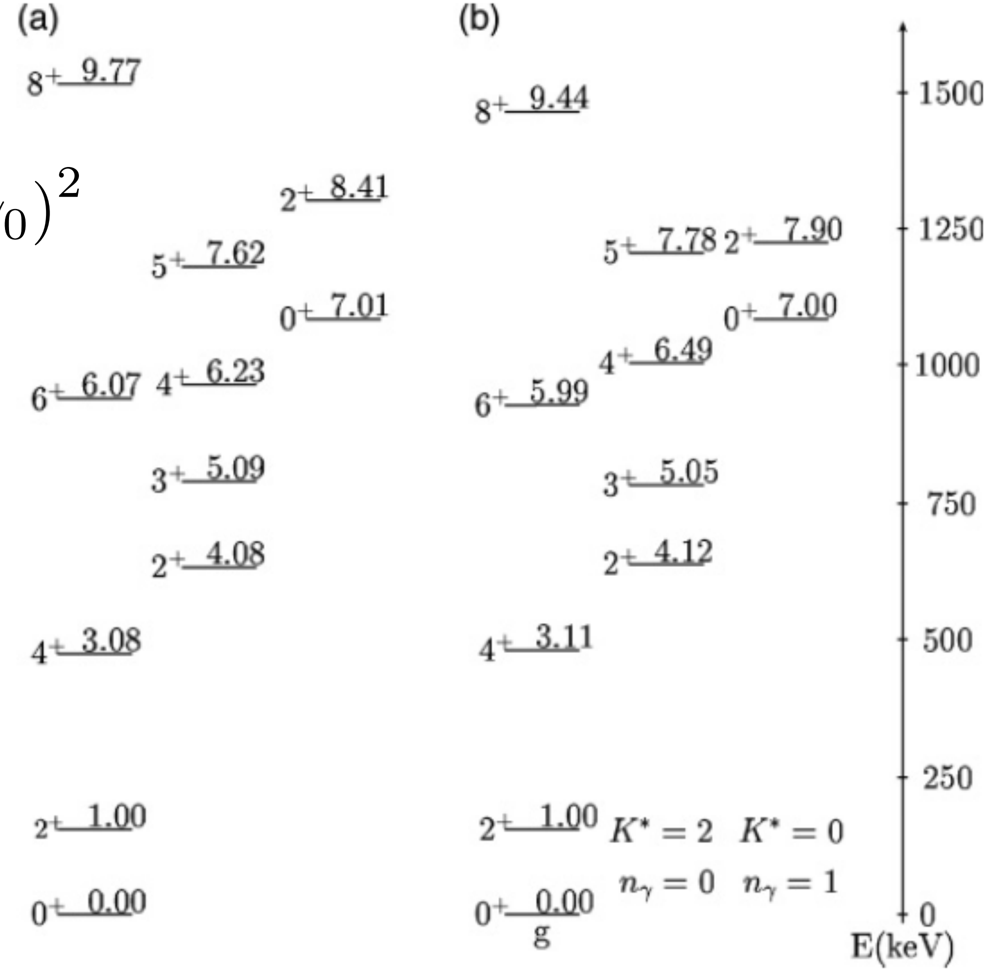
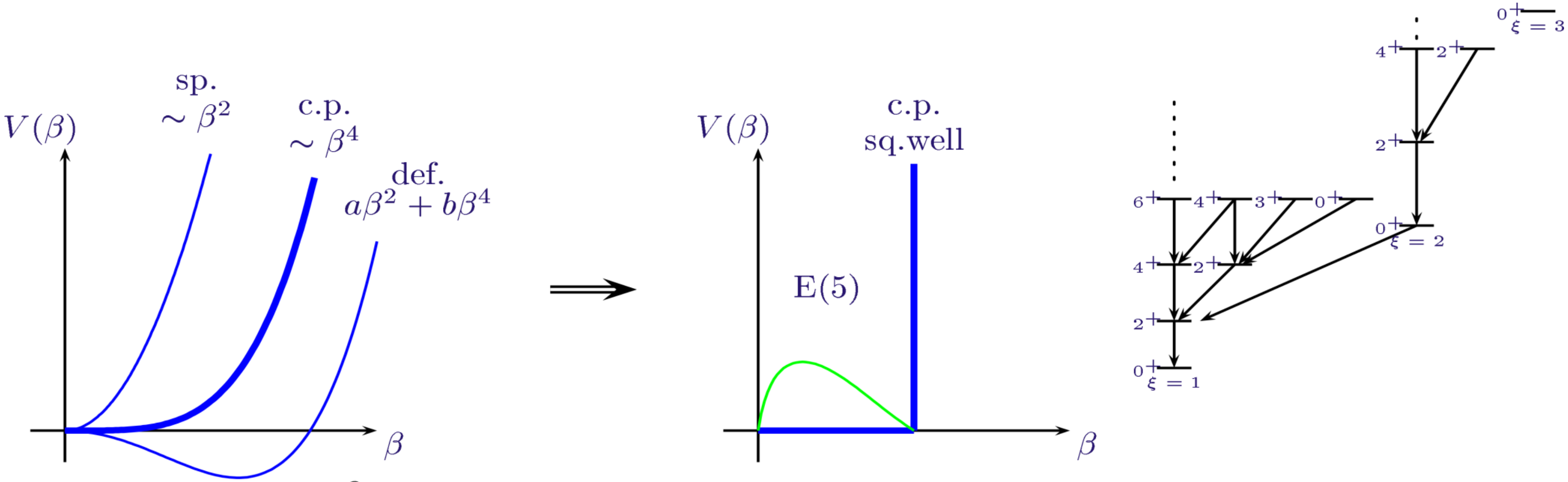
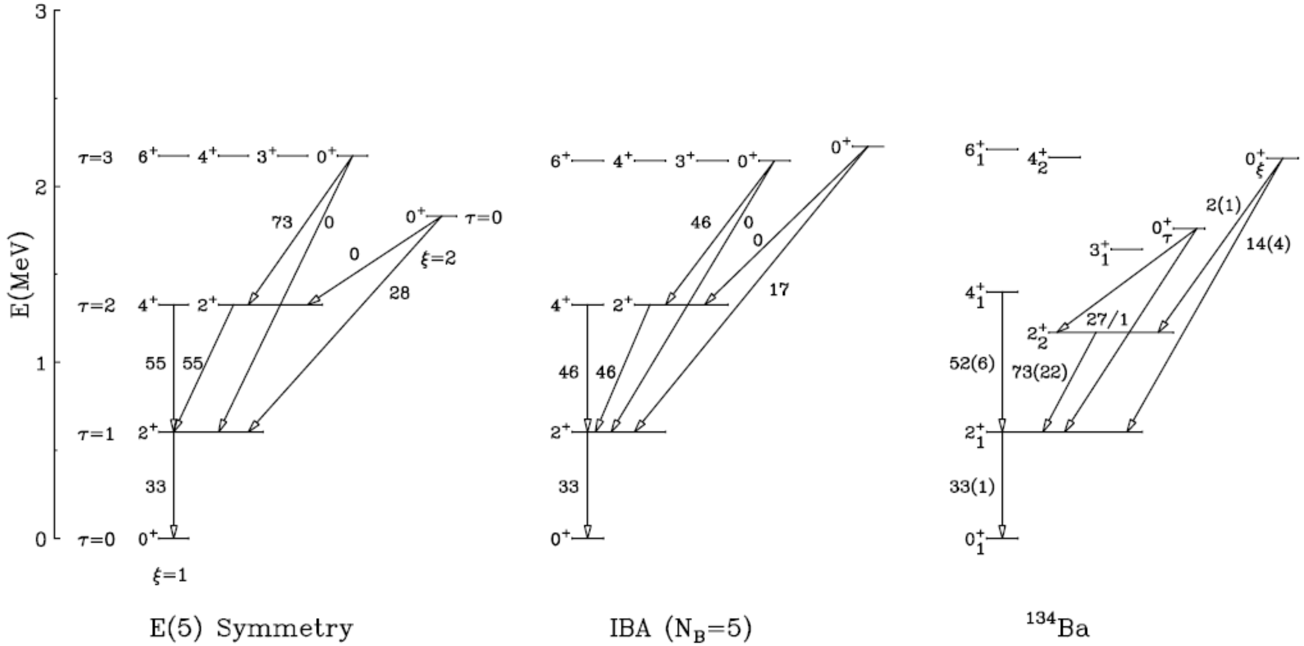
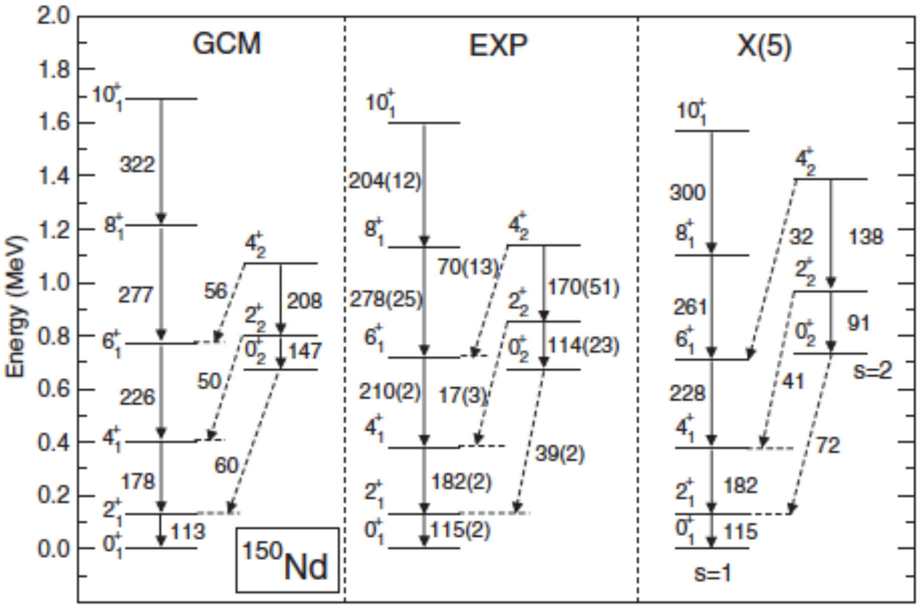


FIG. 4. Experimental spectrum of ^{188}Os (a) and irrotational fit (b) obtained with $B_D = 62.301$, $C = 82.66$, $A_3 = 2.3917$. Experimental data are taken from Ref. [39].

An example: E(5) and ^{134}Ba







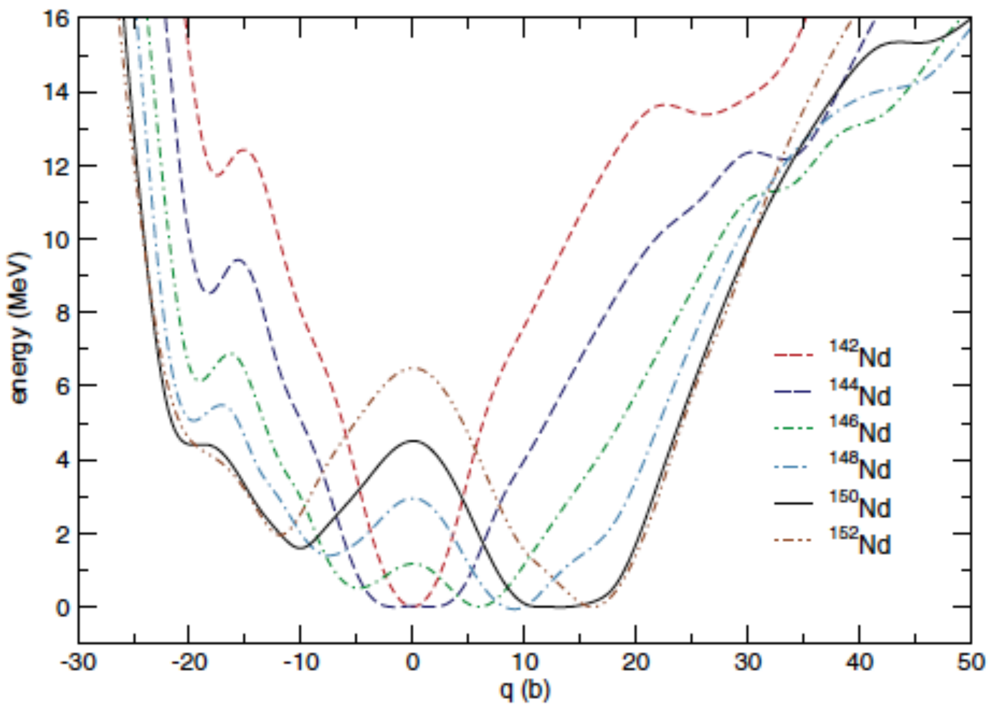
T. Nikšić et al., PRL 99, 092502 (2007)

"Microscopic" description of the critical point – through extension beyond mean field of the conventional RMF.

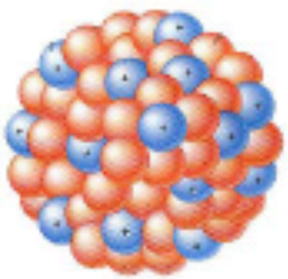
$$|\Psi\rangle = \int dq\ f(q)|\Phi(q)\rangle$$

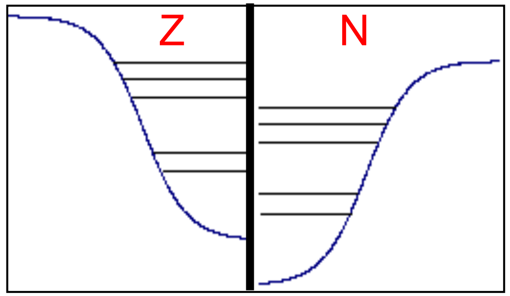
$$E = \frac{\langle\Psi|H|\Psi\rangle}{\langle\Psi|\Psi\rangle}$$

Energy minimization ⇔ Hill-Wheeler



The problem of single-particle states





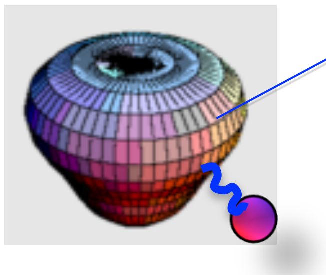
The description in terms of indipendent nucleons lies at the basis of our understanding of the nucleus, but in many models the s.p. states are not considered (e.g., liquid drop, geometrical, or collective models).

There is increasing effort to try to describe the s.p. spectroscopy. The shell model can describe well the *n*p-*n*h couplings, less well the coupling with shape fluctuations.

There is an open debate to which extent density-functional methods can describe the s.p. spectroscopy. They may miss the fact that **single-particle states and collective states are coupled.**

Spherical nuclei

Particle-vibration coupling



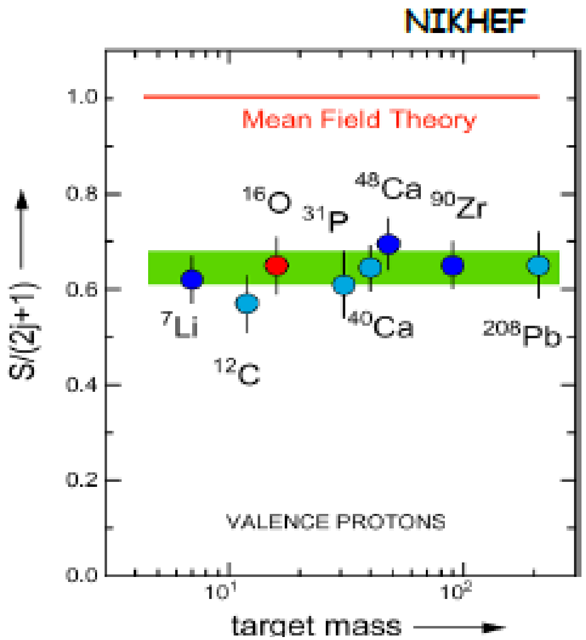
Deformed nuclei

Particle-rotation coupling

Experiment: (e,e'p), as well as (hadronic) transfer or knock-out reactions, show the fragmentation of the s.p. peaks.

$$\left(\frac{d\sigma}{d\Omega}\right)_{\rm exp} = S^2 \left(\frac{d\sigma}{d\Omega}\right)_{\rm DWBA}$$

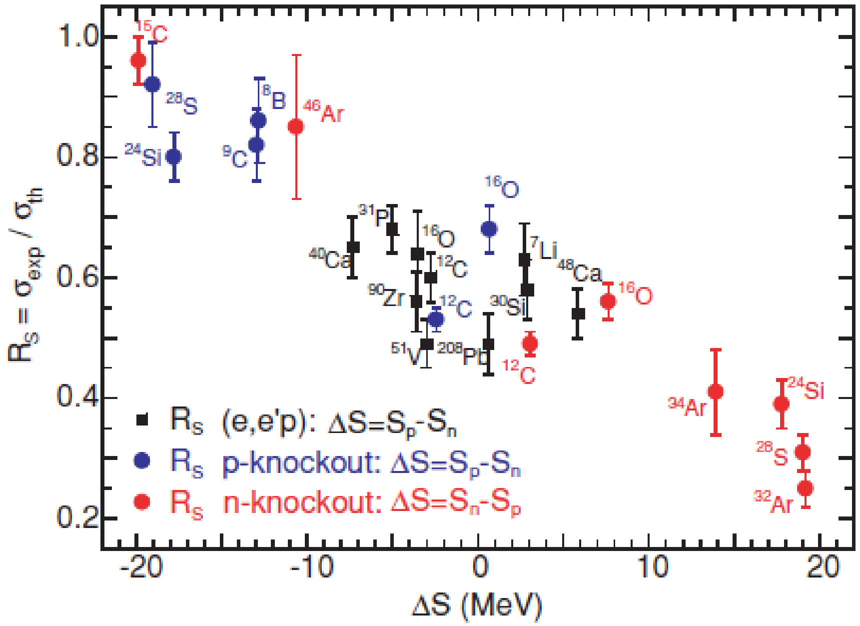
S ≡ Spectroscopic factor



NPA 553, 297c (1993)

Problems:

- Ambiguities in the definition: use of DWBA ? Theoretical cross section have ≈ 30% error.
- Consistency among exp.'s.
- Dependence on sep. energy ?

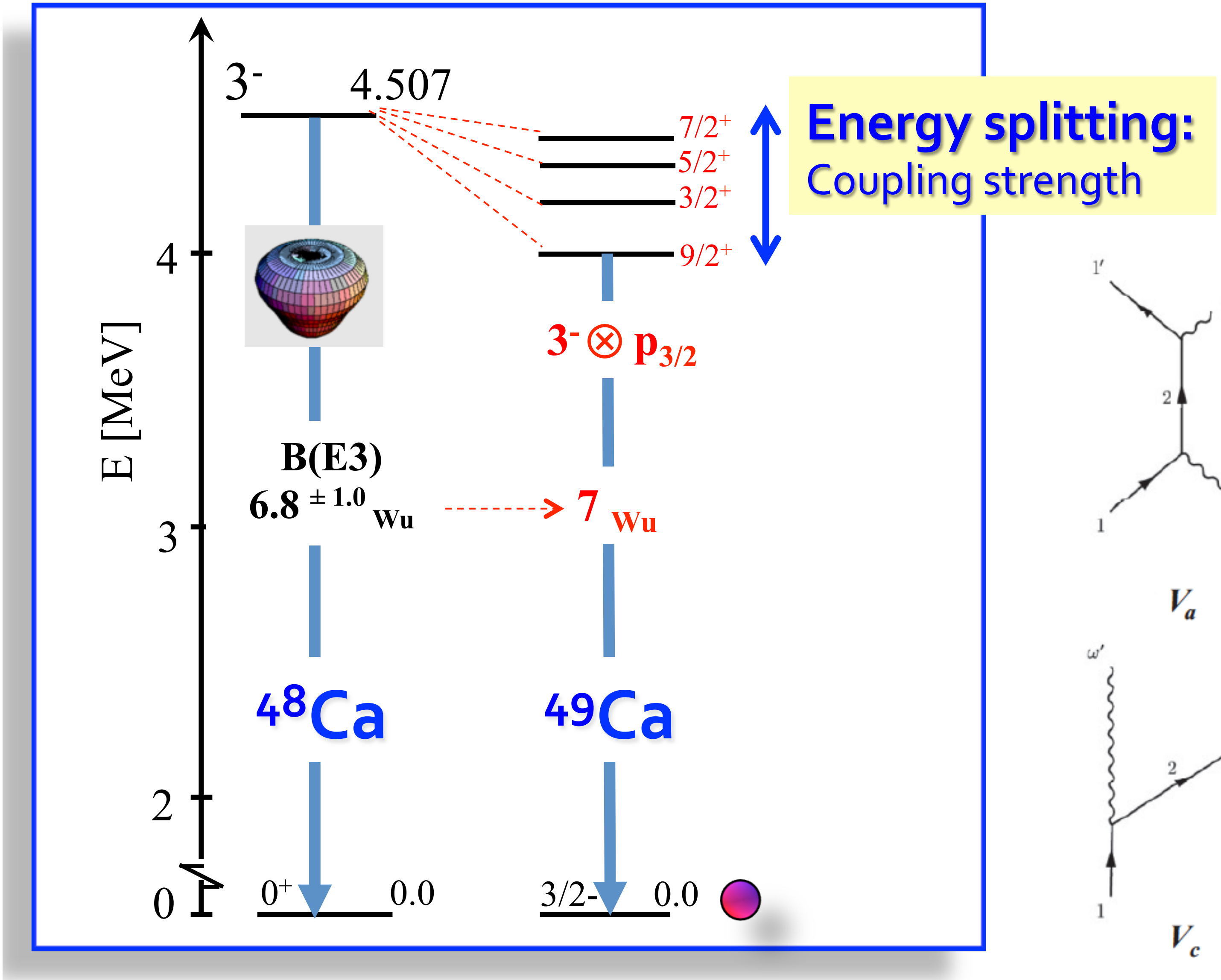


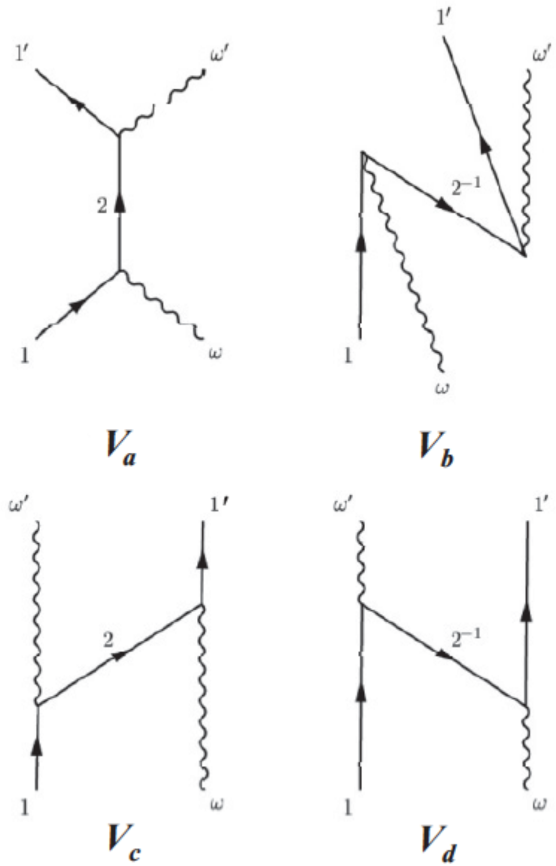
A. Gade et al., PRC 77 (2008) 044306

A possible experimental signature

- **Multiplet of states: $|l-j| \leq I \leq l+j$**
- **B(Eλ) of phonon**

$$H = H_{\text{s.p.}} + H_{\text{coll}} + H_{\text{coupling}}$$





Multi-Nucleon Transfer Reactions as a TOOL to study n-rich nuclei

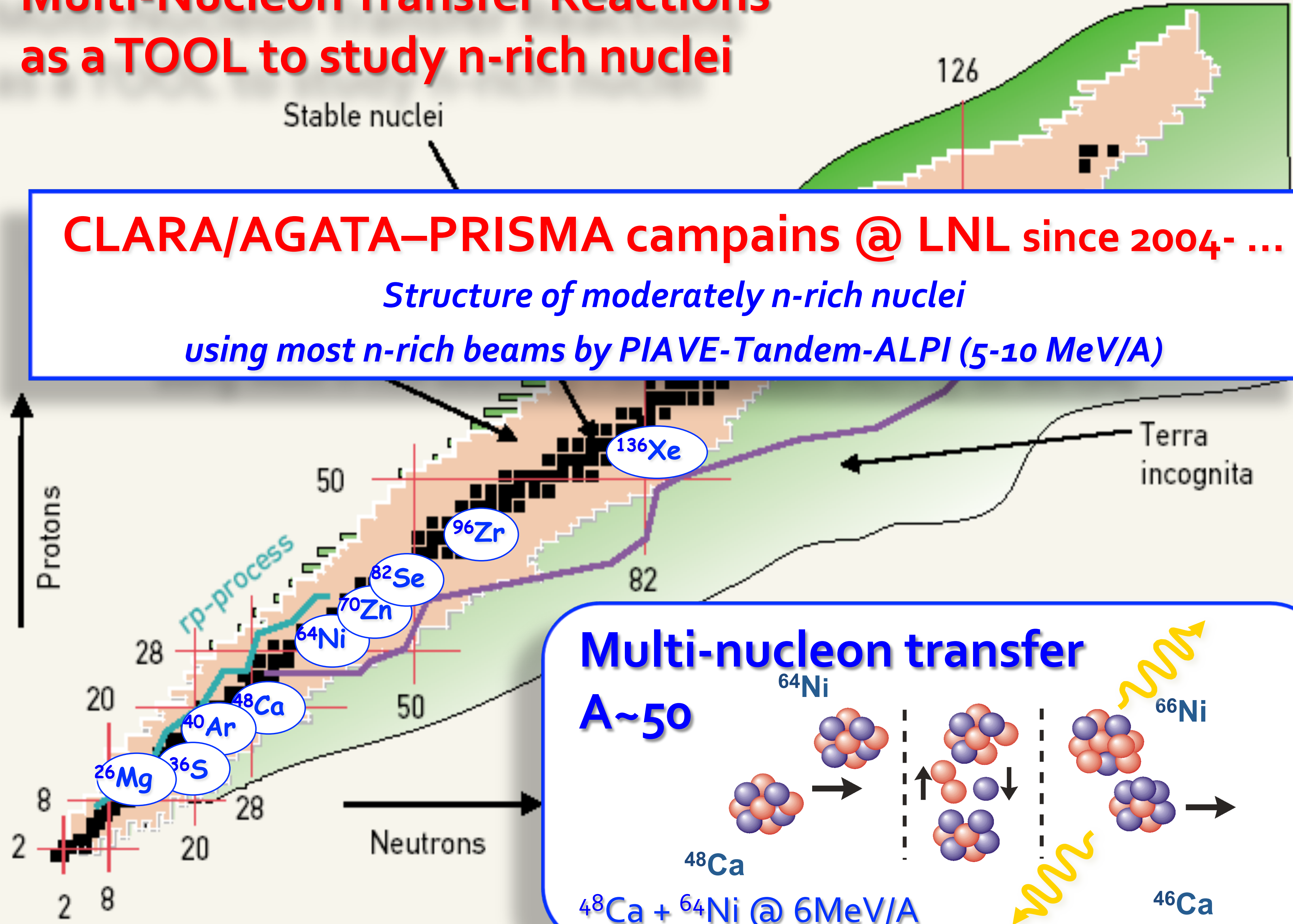
CLARA/AGATA–PRISMA campains @ LNL since 2004- ...

Structure of moderately n-rich nuclei

using most n-rich beams by PIAVE-Tandem-ALPI (5-10 MeV/A)

Multi-nucleon transfer A~50

$^{48}Ca + ^{64}Ni$ @ 6MeV/A



A first benchmark for the method

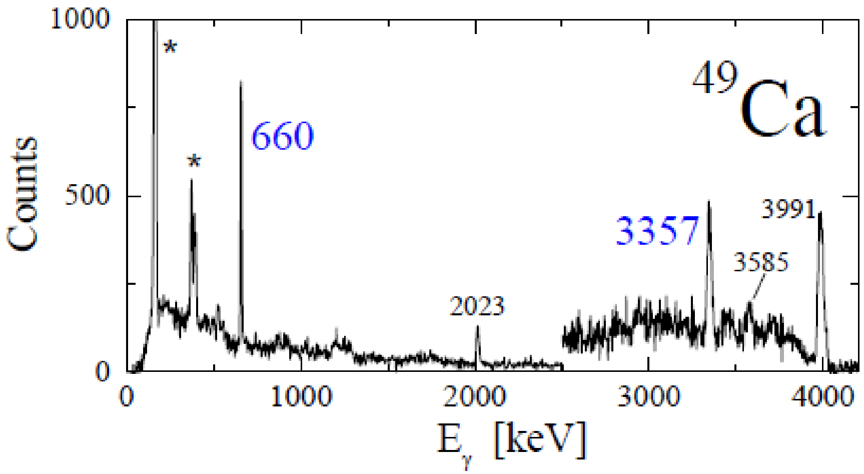
Probing the nature of particle-core couplings in ^{49}Ca
with gamma spectroscopy and heavy-ion transfer reactions

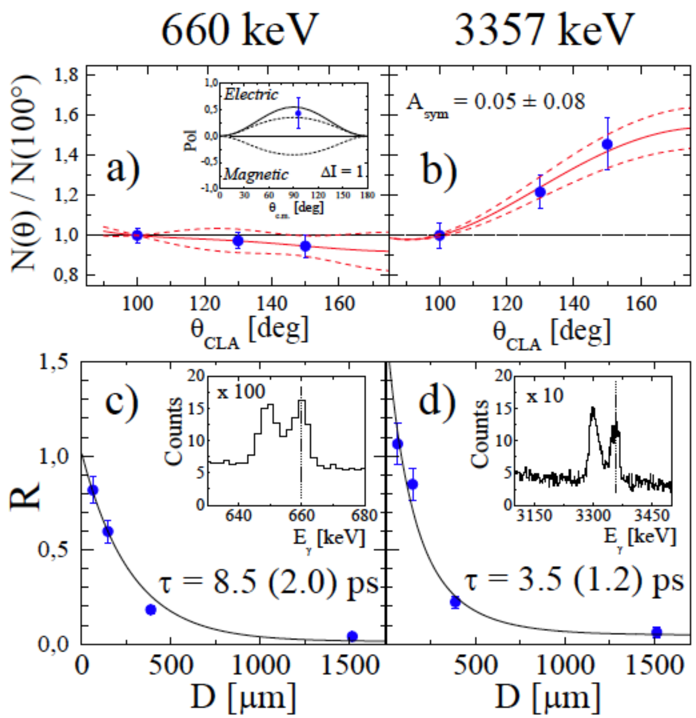
Exp: ^{64}Ni + ^{48}Ca @ 5.7 MeV/A

- Nuclei around ^{48}Ca populated by transfer reactions.

- Angular momentum alignment perpendicular to the reaction plane → γ-spectroscopy allows determining the multipolarity (through angular distribution). Lifetime and polarization measurements have also been performed.

- ^{49}Ca: a first case analyzed in detail !



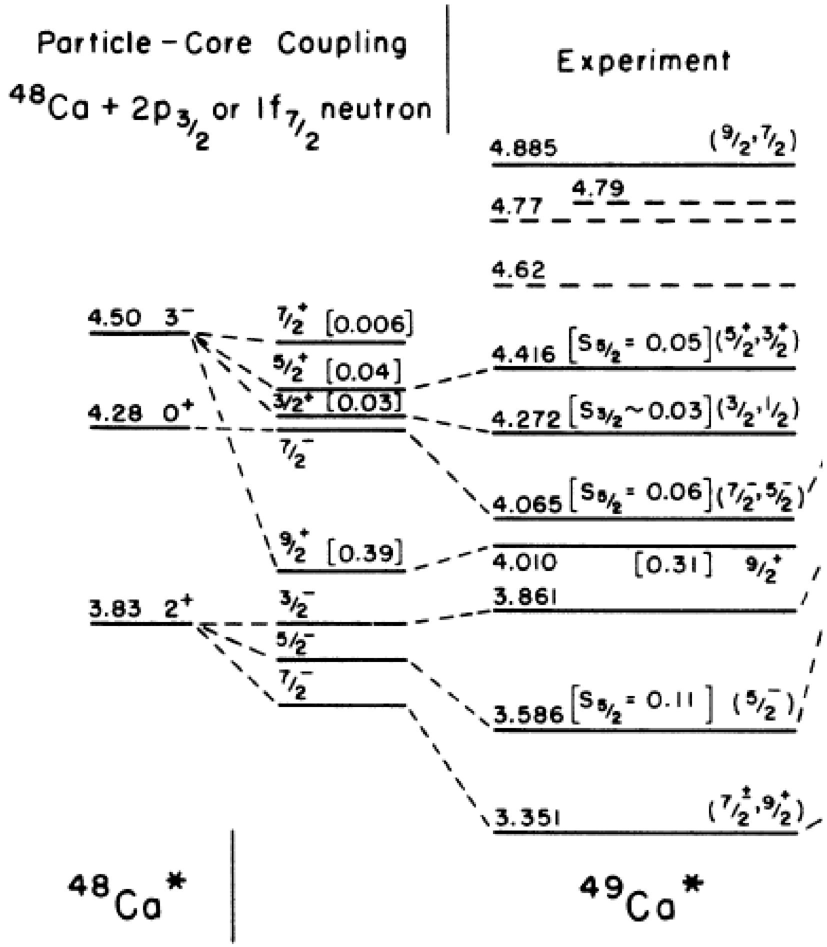


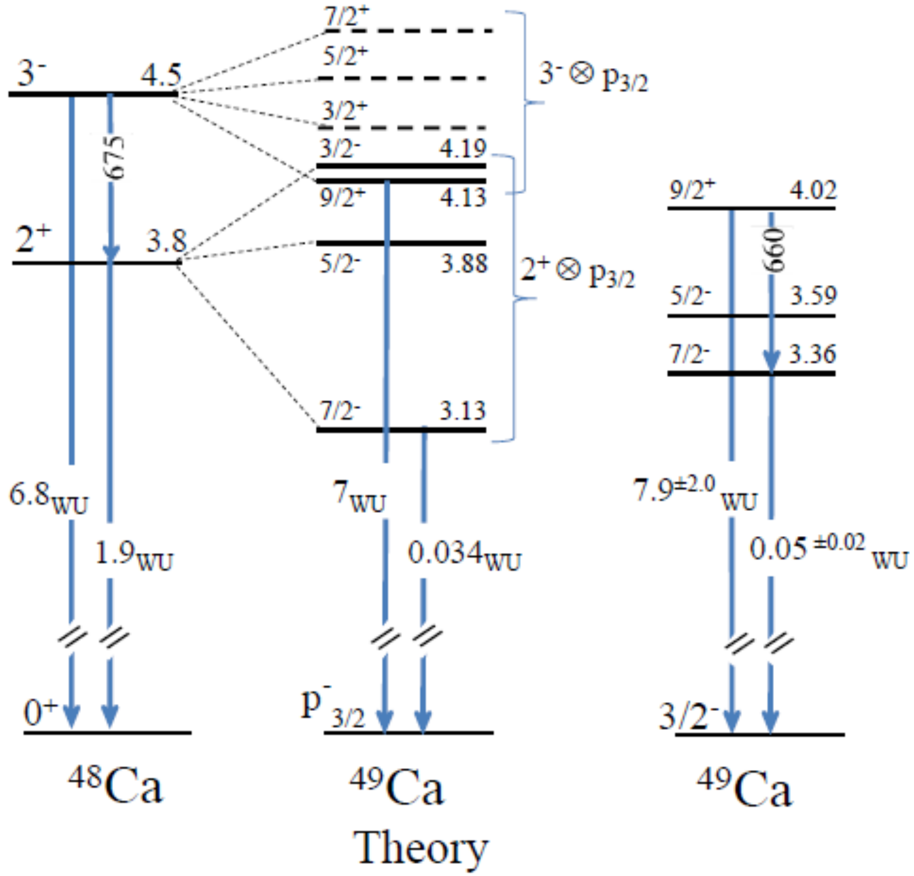
D. Montanari, S. Leoni et al., PLB697(2011)288

Old (d,p) experiment.

Hypothesis: states built with a $f_{7/2}$ or $p_{3/2}$ neutron coupled with a ^{48}Ca phonon.

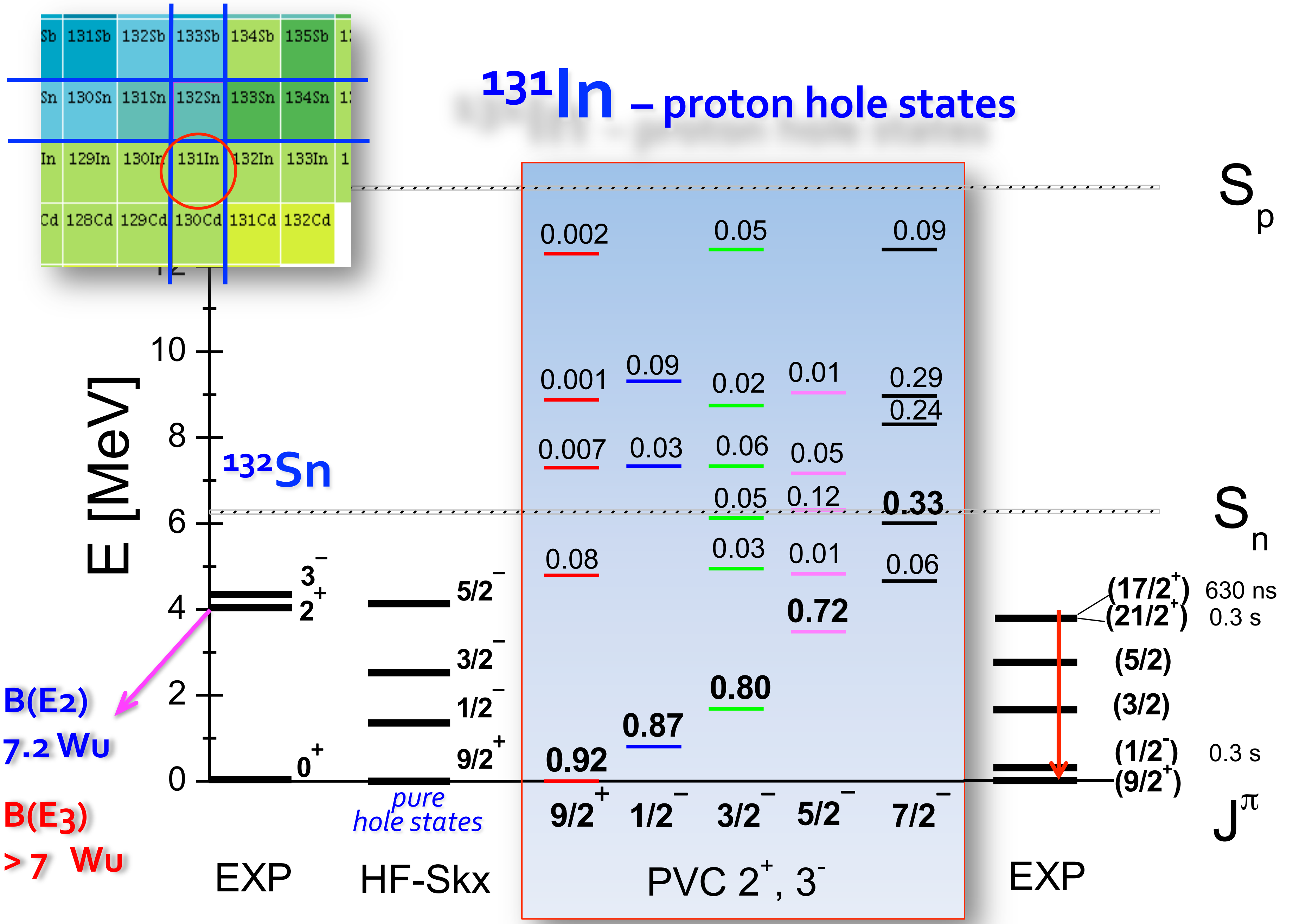
New experiment: confirmation of the PVC hypothesis by means of the electromagnetic transition probabilities





T.R. Canada *et al.*, Phys. Rev. C4, 471 (1971)

^{131}In – proton hole states

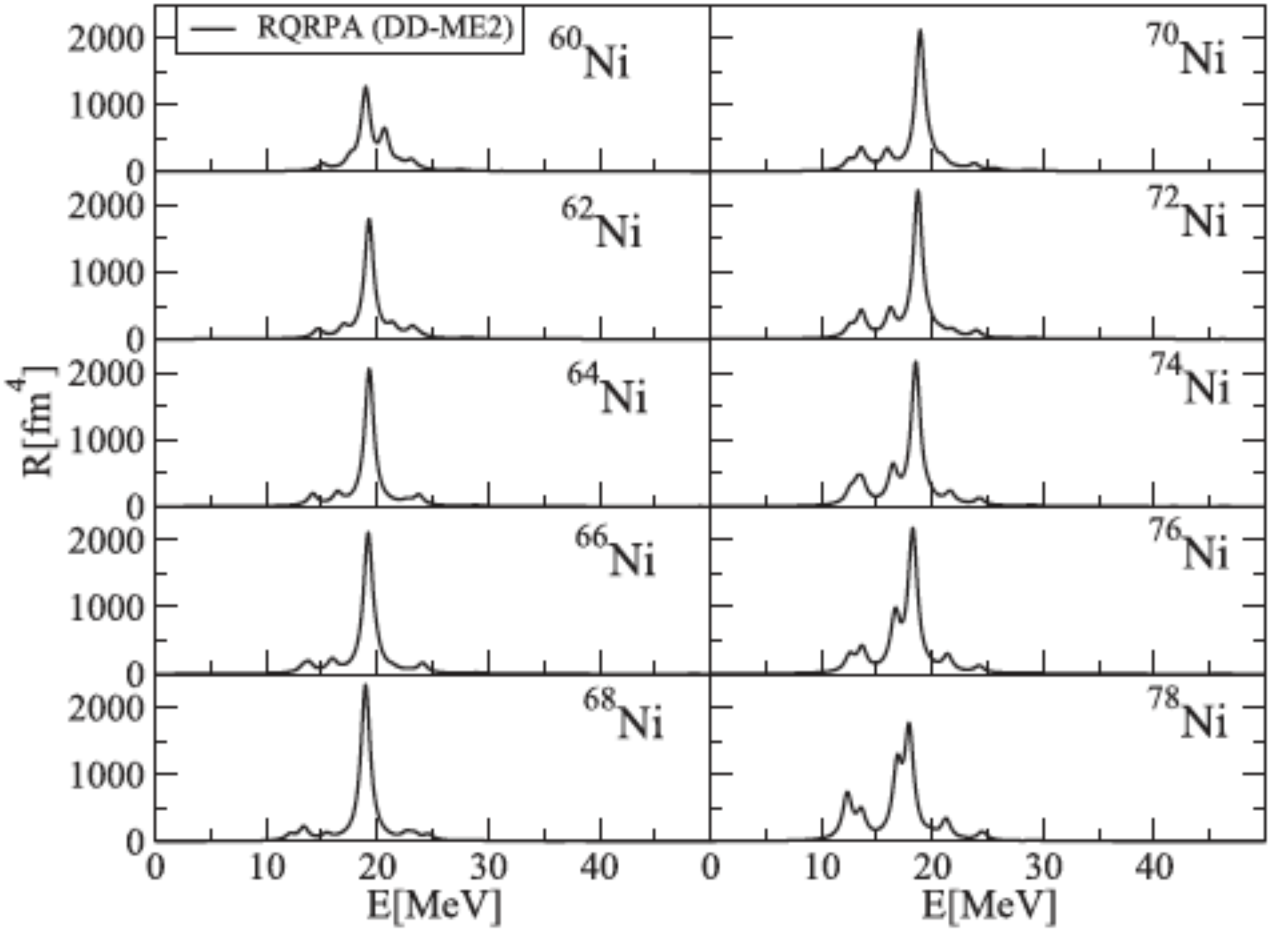


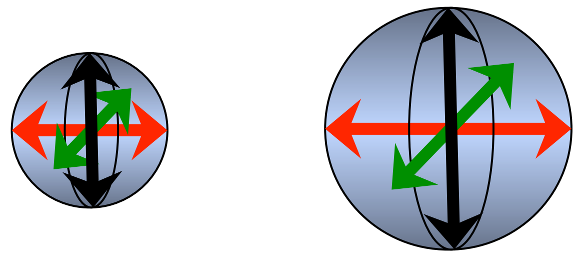
M.Gorska et al., PLB672(2009)313

Conclusions

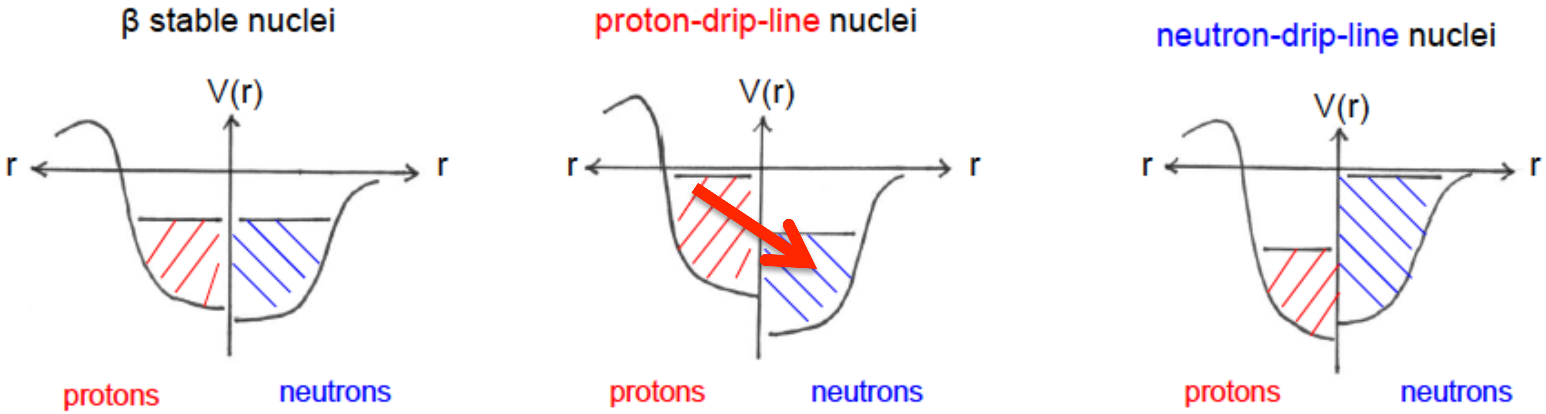
- Exotic nuclei offer a unique possibility to explore the phenomena associated with unusual neutron-proton ratio and/or unusual densities.
- The formalism of Energy Density Functional allows to express the challenge of understanding exotic systems in terms of definining a universal E[ρ,δ].
- We have explored four physics cases.
- In exotic nuclei the isospin is more and more broken, and low-energy (mainly surface neutron) dipole modes constitute a peculiar excitation mode. This provides information on the symmetry energy.
- At even lower density, a dipole mode that challenges even more is the so-called dynamical dipole
- Theories in which the density plays a crucial role, can be complemented by geometrical/algebraic models.
- Density/shape oscillations do have a feedback on s.p. states (e.g., particle-vibration coupling.

Monopole transitions in exotic nuclei



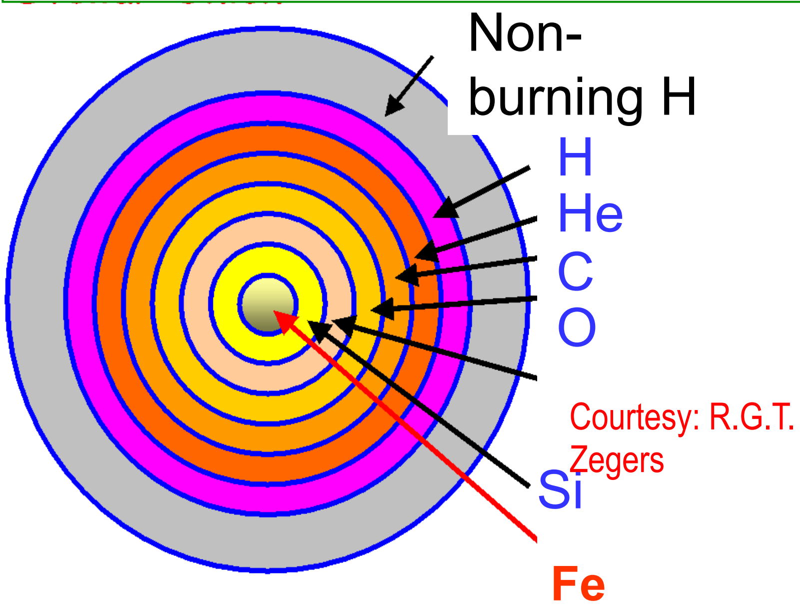


Charge-exchange transitions in exotic nuclei



Courtesy: I. Hamamoto

INTEREST : In, e.g., proton-drip-line nuclei the most collective charge-exchange states (Gamow-Teller) can be inside the β-decay window superallowed β-decay



Courtesy: R.G.T. Zegers

INTEREST : Gamow-Teller σt+ transitions play a role in the electron-capure processes. In turn, these processes are relevant for the evolution of type II (core-collapse) supernovae.

CHEX reaction in inverse kinematics: experimental program at MSU