Symmetries in subatomic systems

Les symétries dans les systèmes subatomiques

27 Sept
02 Oct
2010
Lacanau

joliot-curie@cenbg.in2p3.fr

Speakers
John R. Arrington
Richard F. Casten
Guy Chanfray
Vincent Debat
Jerzy Dudek
Héloïse Goutte
Elias Khan
Krishna Kumar
Silvia M. Lenzi
Piet Van Isacker
Giuseppe Verde
Lorenz Willmann

Deadline for registration: 30 June 2010

http://www.cenbg.in2p3.fr/joliot-curie

Giant resonances and isospin asymmetry

E. Khan

IPN Orsay
Institut de Physique Nucléaire

Outline

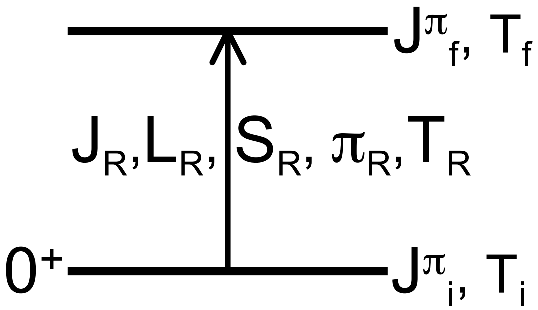
1) Properties and interest of giant resonances

2) How to describe GR ?

3) GR in exotic nuclei: status

1) Properties of giant resonances (L,S,T)

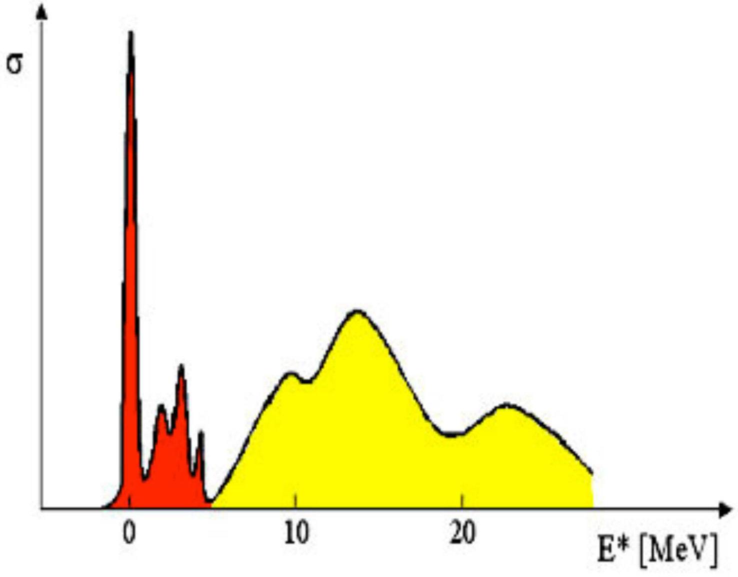
Quantum numbers



$$\vec{J}_f = \vec{J}_i + \vec{J}_R \qquad \vec{T}_f = \vec{T}_i + \vec{T}_R$$

$$\vec{J}_R = \vec{L}_R + \vec{S}_R$$

$$\Pi_f = \Pi_i.(-1)^{L_R}$$



$L_R=2$, $S_R=0$, $T_R=0$

Isoscalar quadrupole response

If the nucleus is even even, $J^{\pi}_{i} = 0^+$

→

$$\vec{J}_f = \vec{L}_R + \vec{S}_R$$

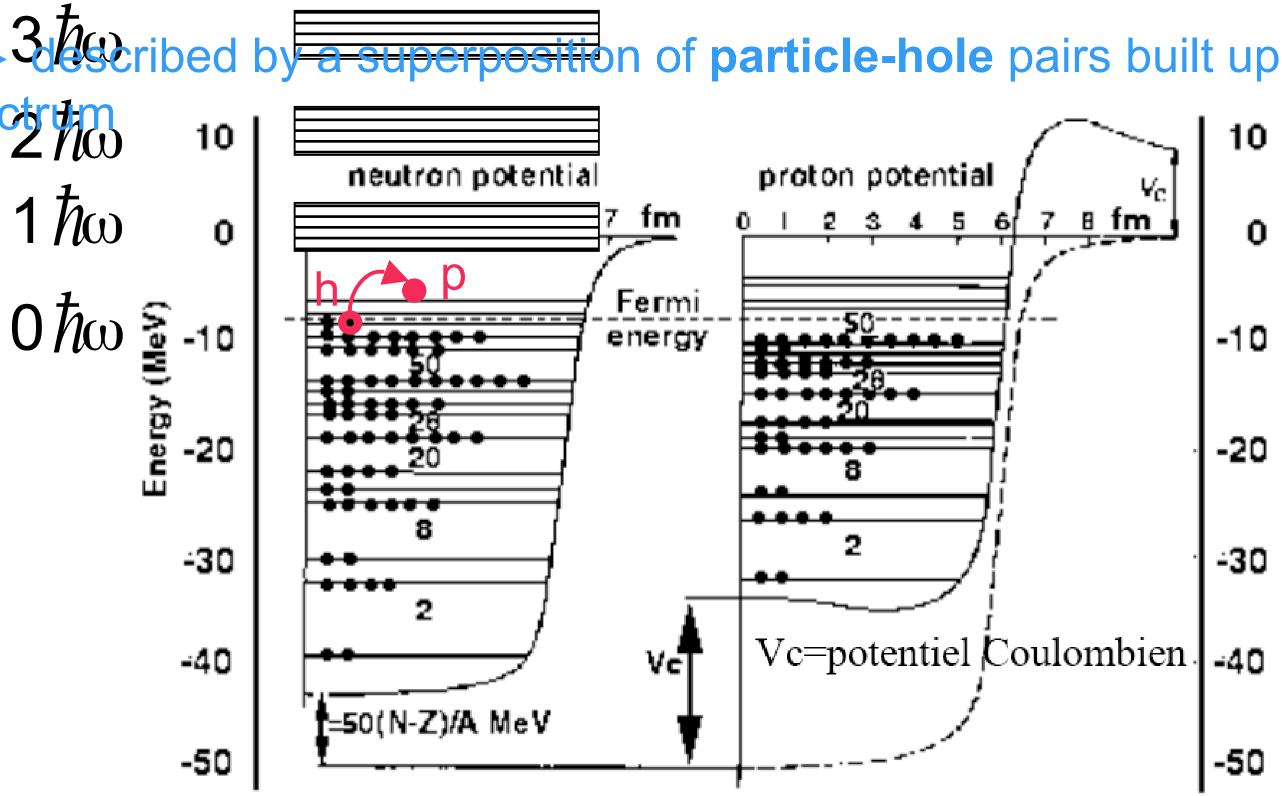
$$\Pi_f = (-1)^{L_R}$$

→ The GR is characterised by L_R, S_R and T_R

Microscopic description of GR

GR = large σ and collective nuclear excitation located at high energy (>10 MeV)

→ described by a superposition of **particle-hole** pairs built upon the mean-field spectrum



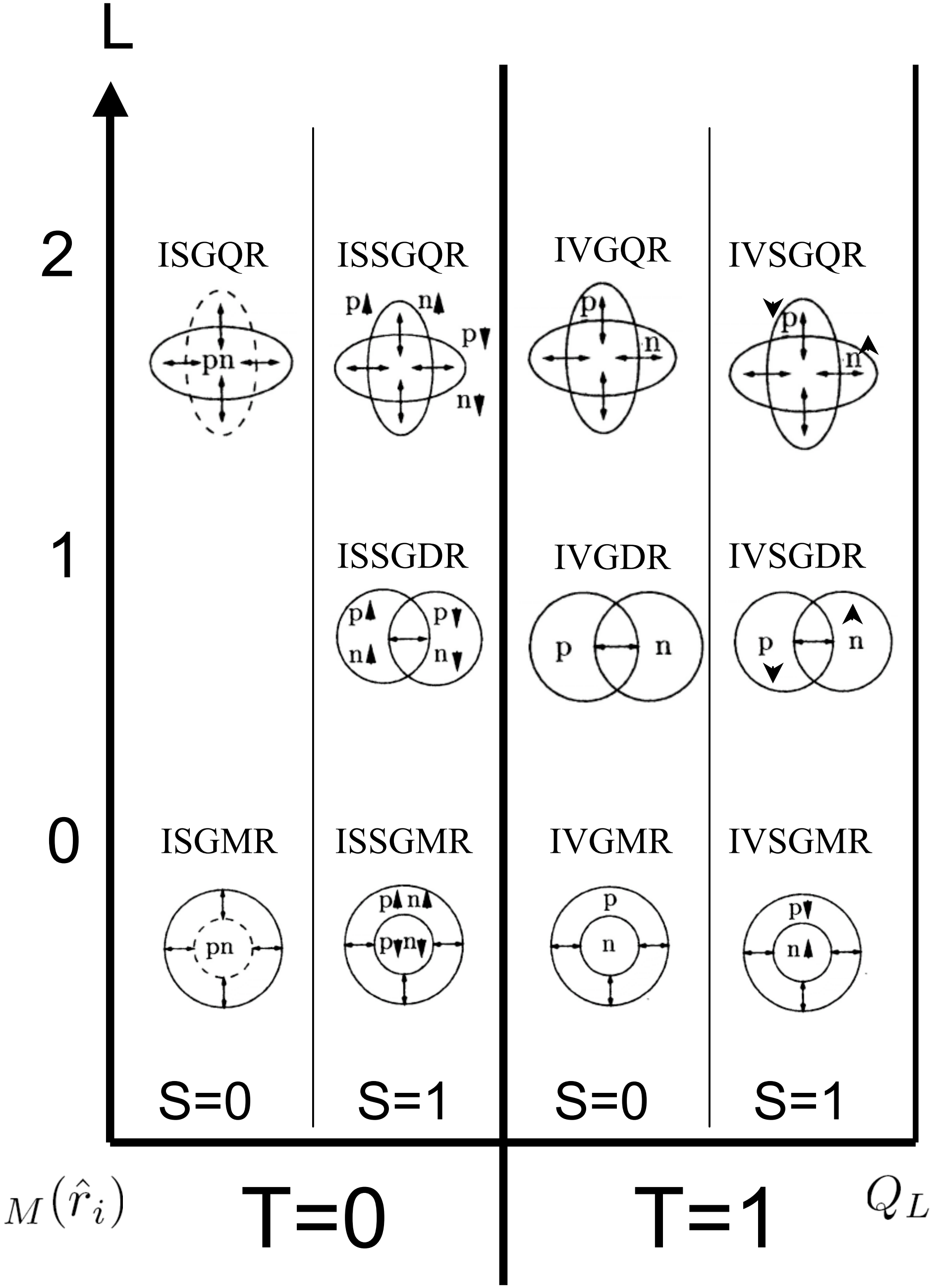
$$\vec{s}_p = \frac{\vec{1}}{2} \quad \vec{s}_h = \frac{\vec{1}}{2}$$

$$\vec{t}_h = \frac{\vec{1}}{2} \quad \vec{t}_p = \frac{\vec{1}}{2}$$

$$\vec{S}_R = \vec{s}_p + \vec{s}_h = \vec{0} \; or \; \vec{1}$$

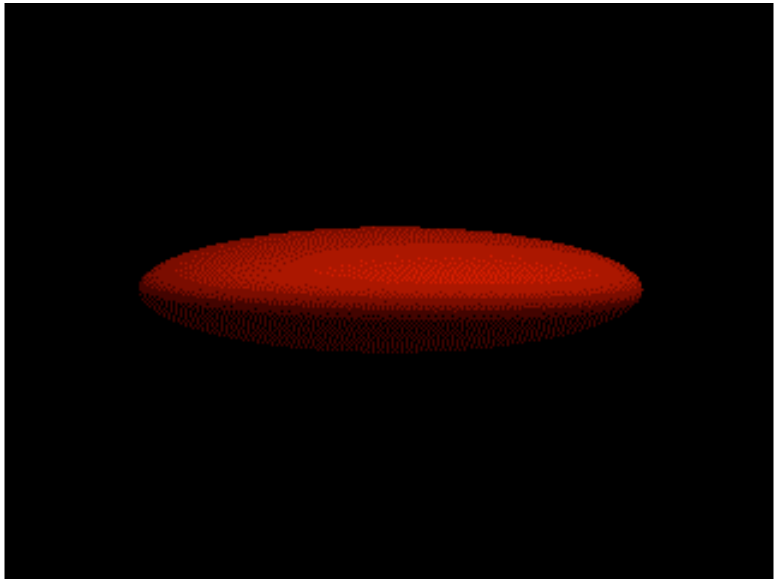
$$\vec{T}_R = \vec{t}_p + \vec{t}_h = \vec{0} \; or \; \vec{1}$$

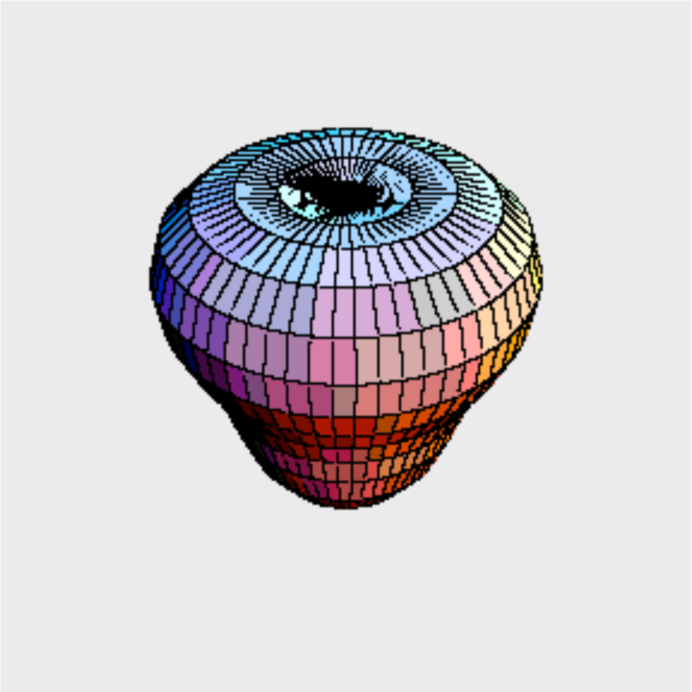
Macroscopic picture of GR



$$Q_{LM} = \sum_{i=1}^{A} r_i^L Y_{LM}(\hat{r}_i)$$

$$Q_{LM} = \sum_{i=1}^{A} t_3(i) r_i^L Y_{LM}(\hat{r}_i)$$

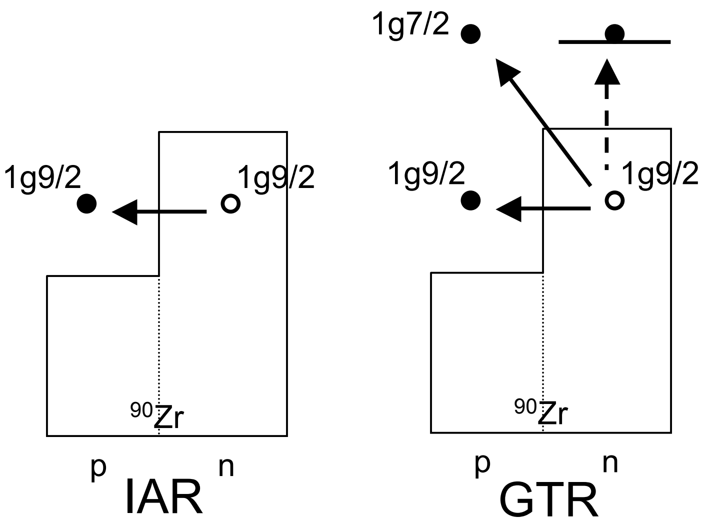


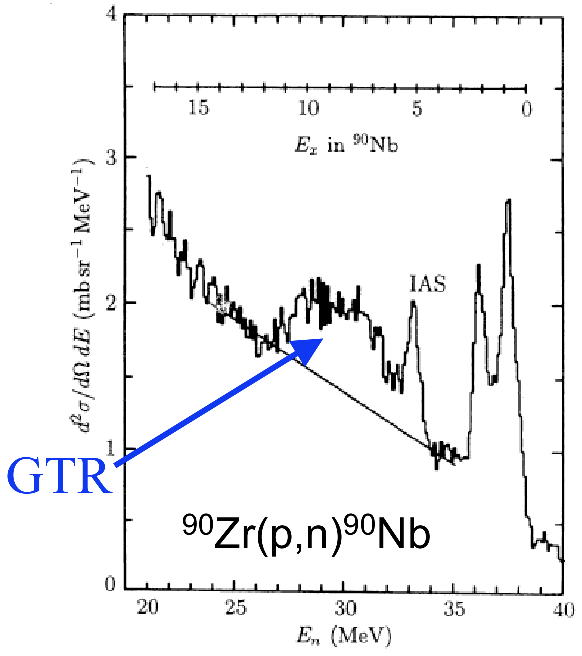


Additionnal GR (micro)

	T=0		T=1	
L	S=0	S=1	S=0	S=1
3	LEOR HEOR			
2	ISGQR		IVGQR ?	IVSGQR
1	ISGDR (2^{d} order)		IVGDR	IVSGDR
0	ISGMR	IS M1	IAR (Fermi) IVGMR	GTR IVSGMR

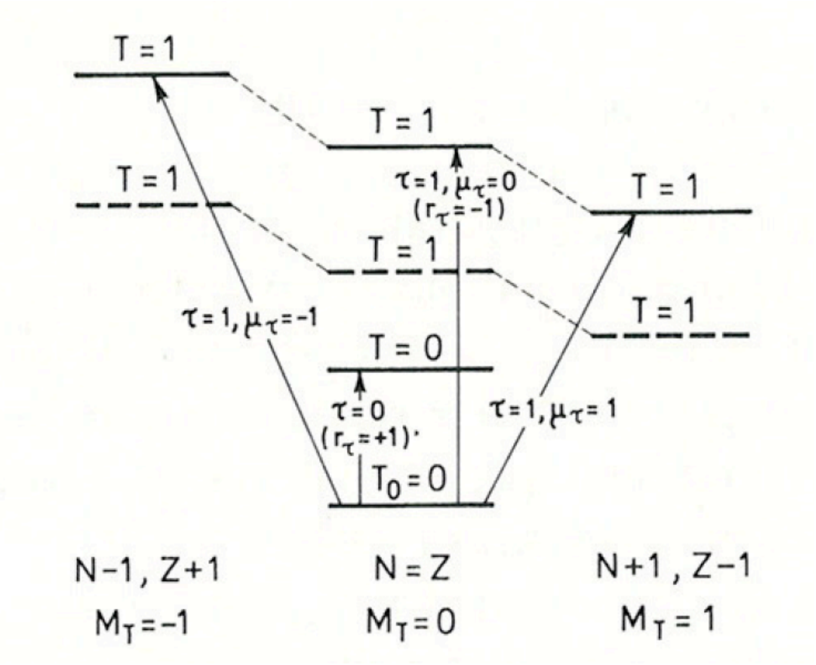
Weak interaction : n ↔ p



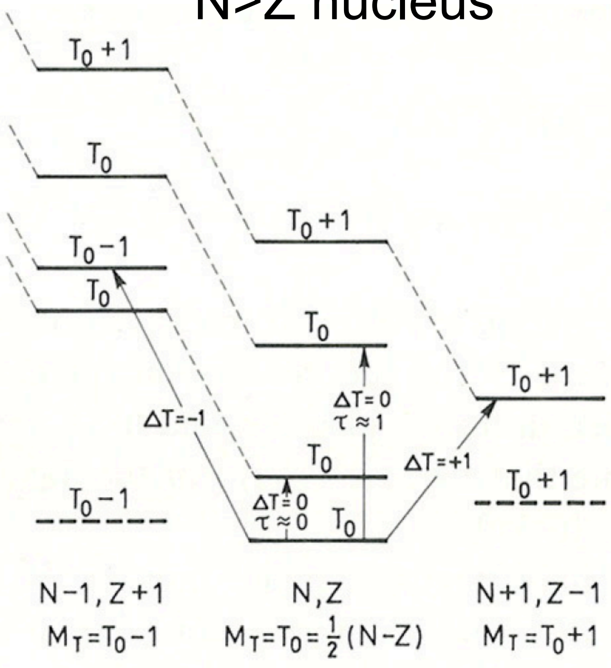


Breaking of isospin symmetry: neutron excess

N=Z nucleus



N>Z nucleus



- **n excess**: IA states no more excited: different T_f value depending on the final nucleus
- **Pauli effect**: transition from (N,Z) towards (Z-1,N+1) hindered (GT+ ≠ GT-)
- NB: in nuclei, no spin up (or down) excess ⟶ no breaking of spin symmetry (deformation not adressed here)
- **Exotic nuclei**: n excess increased

Isospin symmetry broken

T3 degeneracy raised because of

- **Weak interaction** processes (GT resonances)
- **n excess**: $T_i \neq 0$
- **Pauli effect**: transition from (N,Z) towards (N+1,Z-1) hindered

T_3 dependence

L	S=0	S=1	S=0	S=1	S=0	S=1	S=0	S=1
3	LEOR HEOR							
2	ISGQR		IVGQR ?	IVSGQR	IVGQR	IVSGQR: M1,E2,M3	IVGQR ?	IVSGQR
1	ISGDR (2^d order)		IVGDR	IVSGDR	IVGDR	IVSGDR: M0,E1,M2	IVGDR	IVSGDR
0	ISGMR	IS M1	IAR (Fermi) IVGMR	GT^{-}R IVSGMR	IVGMR	GTR IVSGMR	IAR (Fermi) IVGMR	GT^{+}R IVSGMR
	(N,Z)→(N,Z)		(N,Z)→(N-1,Z+1)		(N,Z)→(N,Z)		(N,Z)→(N+1,Z-1)	
	$T_3=0$		$T_3=-1$		$T_3=0$		$T_3=1$	
	T=0				T=1			

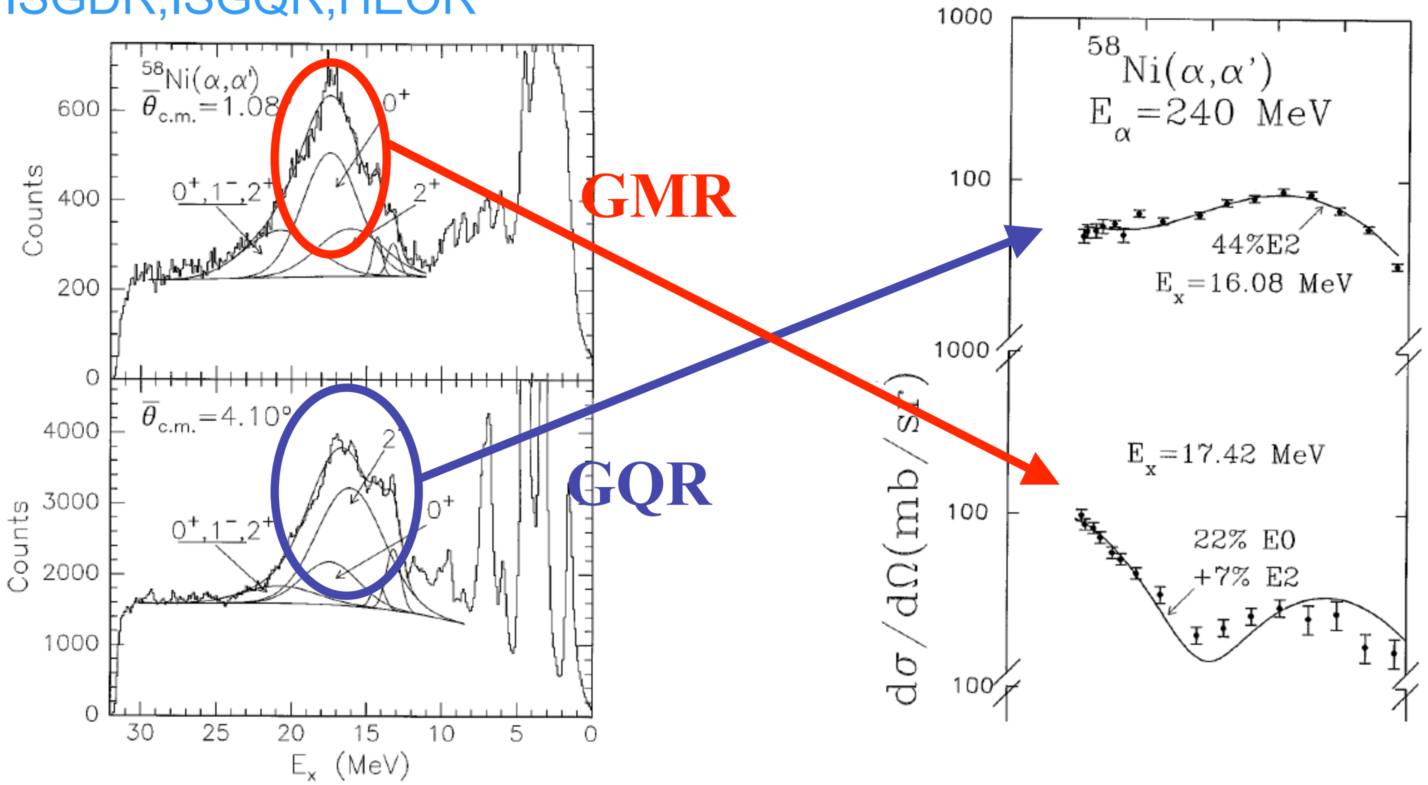
Why and how to study GR ?

- GR have large cross section: dominant excitation mode

- Among the easiest to detect ; provides information on nuclear structure

- (L,S,T,T_3) combinations probe various observables. Ex : (0,0,0,0) probes nuclear matter incompressibility

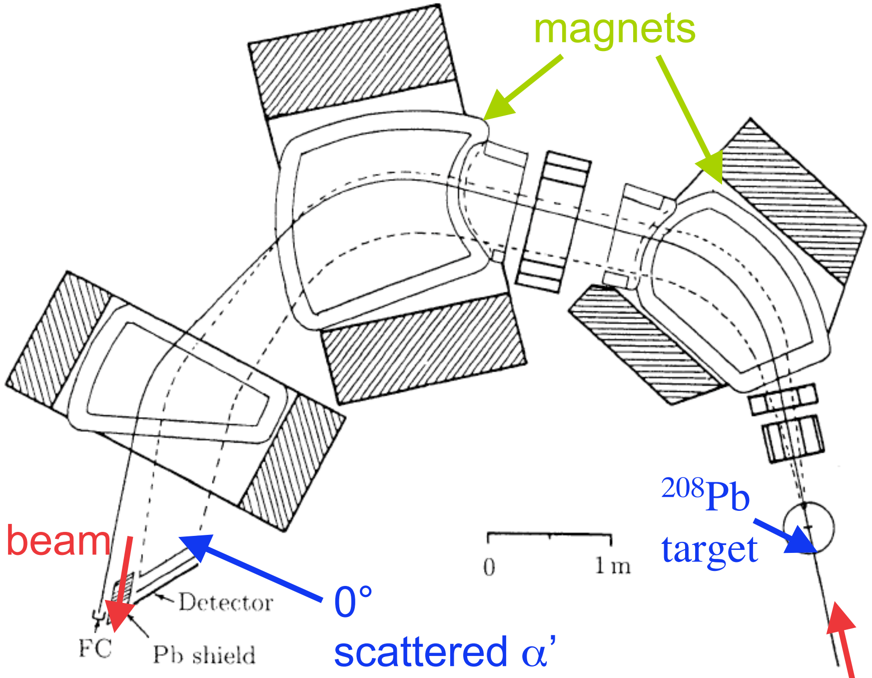
- Experimentaly, a given probe selects a column (T,T_3). The L,S value is selected with the **reaction/excitation energy** and/or **angular distribution**. Ex: (T=0,T_3=0) ISGMR, ISGDR,ISGQR,HEOR



Measurement of GR

- Ex: IS GMR using (α,α')

With stable nuclei



magnets

beam

0°
scattered α'

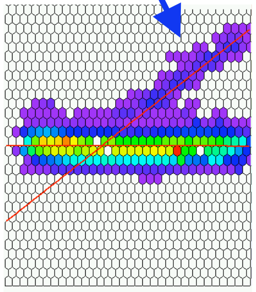
^{208}Pb
target

α beam
(200 MeV)

With exotic nuclei

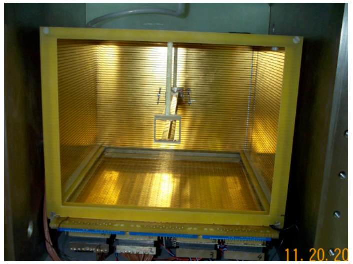
scattered α'

^{68}Ni beam
(50 MeV/A)
+contaminants



Active
Target
(He gas)

Si detectors



Properties under study

L	S=0	S=1	S=0	S=1	S=0	S=1	S=0	S=1	S=0
3	LEOR HEOR								
2	ISGQR Effective mass		IVGQR ?	IVSGQR	IVGQR	IVSGQR: M1,E2,M3	IVGQR ?	IVSGQR	
1	ISGDR (2^d order) squeezing &vortex		IVGDR	IVSGDR n skin	IVGDR n skin	IVSGDR: M0,E1,M2	IVGDR	IVSGDR n skin	
0	ISGMR incompressibility	IS M1 (weak)	IAR (Fermi) IVGMR n skin	GTR IVSGMR n skin	IVGMR	IVSGMR: M1	IAR (Fermi) IVGMR	GTR IVSGMR n skin	GPV pairing
	(N,Z)→(N,Z)		(N,Z)→(N-1,Z+1)		(N,Z)→(N,Z)		(N,Z)→(N+1,Z-1)		(N,Z)→(N+2,Z)
	$T_3=0$		$T_3=-1$		$T_3=0$		$T_3=1$		
	T=0		T=1						

2) How to describe GR ?

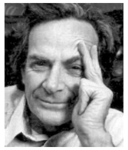
EDF

E[ρ]

HK theorem
Skyrme
Gogny

Action

$$S=\int_{t_1}^{t_2}dt\int d\vec{r}\,(i\hbar\Psi^*(\vec{r},t)\partial_t\Psi(\vec{r},t)-E[\rho])$$



Ind. Particles

$$S=i\hbar\sum_{i=1}^{A}\int_{t_1}^{t_2}dt\int d\vec{r}\,(\varphi_i^*(\vec{r},t)\partial_t\varphi_i(\vec{r},t)-E[\rho])$$

Many-body
problem

Least action pcple

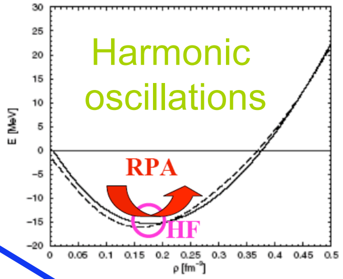
$\delta S=0$

TDHF

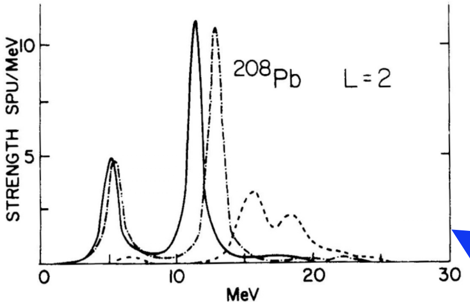
$$i\hbar\partial_t\varphi_i=\frac{\delta E[\rho]}{\delta\rho}\varphi_i\widehat{=}h\varphi_i$$

Linear
response
theory

$$\Pi=\Pi_0+\Pi_0\frac{\delta h}{\delta\rho}\Pi$$

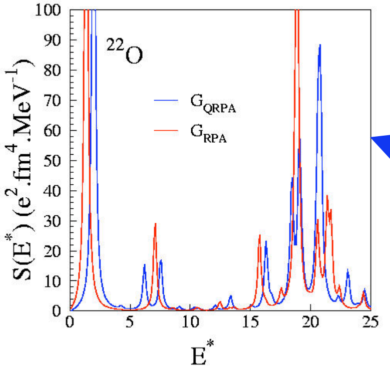

Harmonic
oscillations

Response
function S(E*)



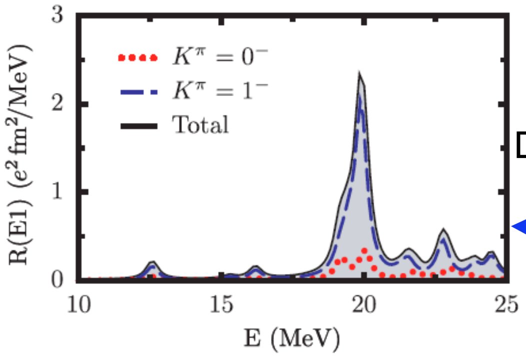
G.F. Bertsch and S.F. Tsai,
Phys. Rev. C18 (**1975**) 125

Magic
nuclei



E. Khan, Nguyen Van Giai,
Phys. Lett. B472 (**2000**) 253

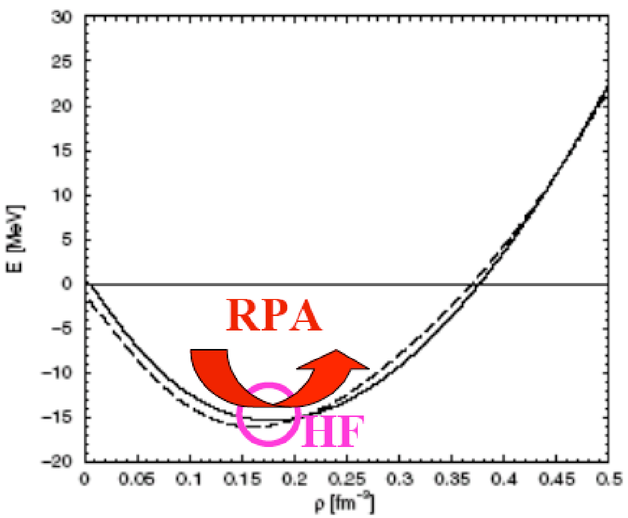
Isotopic
chain



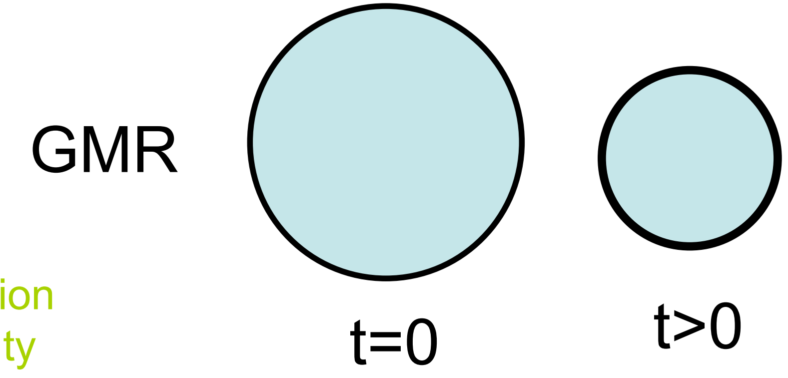
Deformed
nuclei

D. Pena Arteaga, P. Ring Phys.
Rev. C77(**2008**) 034317

Representation of a GR

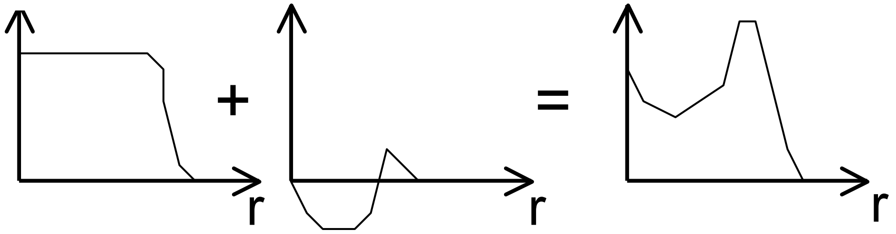


$$\rho(r,t) = \rho(r) + \delta\rho(r)Cos(\omega t)$$



transition density

$$\rho(r) \quad + \quad \delta\rho(r) = \rho(r,0)$$



- GR are collective (many ph pairs involved)
- Small amplitude vibration: $\delta\rho << \rho$

$$\boxed{\delta\rho(r) = \sum_{mi}(X_{mi} - Y_{mi})\phi_i^*(r)\phi_m(r)}$$

The Hohenberg-Kohn (HK) theorem

(Chemistry Nobel 98)

•There exists an energy functionnal **E[ρ]** which depends on the (local) density. It allows to exactly predict ground state observables (solves the many body problem)

- Knowledge of this functional in nuclei ?

- HK states the existence of a functional for a given state, not an universal functional for the nuclear chart

- In nuclear physics coefficients in **E[**ρ] are adjusted on radii, masses, … : takes into account correlations beyond mean field.

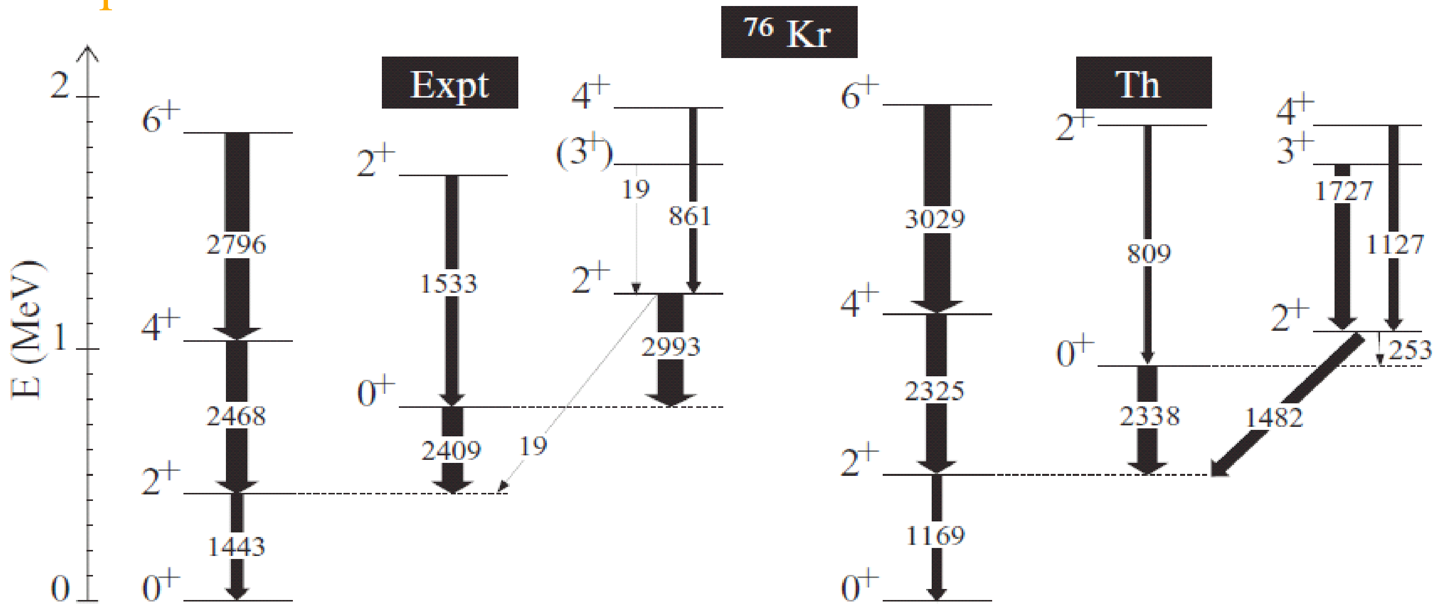
- Nuclei: symmetry restoration (broken in self-bound systems)

- Kohn-Sham = method to calculate **ρ,** knowing **E[**ρ]

Excited states in the DFT:
GCM or RPA ?

- **GCM** (~5DCH): mixes the HF solutions with **various** deformation to obtain the lowest energy states.

Adapted for **low E** and **low J** states (does not take into account 1p-1h configurations) and for quadrupolar correlations



J. -P. Delaroche, M. Girod, J. Libert, H. Goutte, S. Hilaire, S. Péru, N. Pillet, and G. F. Bertsch
Phys. Rev. C **81**, 014303 (2010)

- **RPA**: Mixes the 1p-1h configuration on a **single** HF solution.

Adapted for **collective** states, at **low or high E** (giant resonances)

RPA/shell model

Advantages of the RPA:

- simplicity, also from the computational point of view;
- relates easily the interaction to the observable
- there is no "core" (that is, no need of effective charges);
- it is possible to study highly excited states.
- Provides densities and transition densities

Disadvantages:

- not all the many-body correlations are taken into account.
- weak predictive power for low energy part of the spectrum

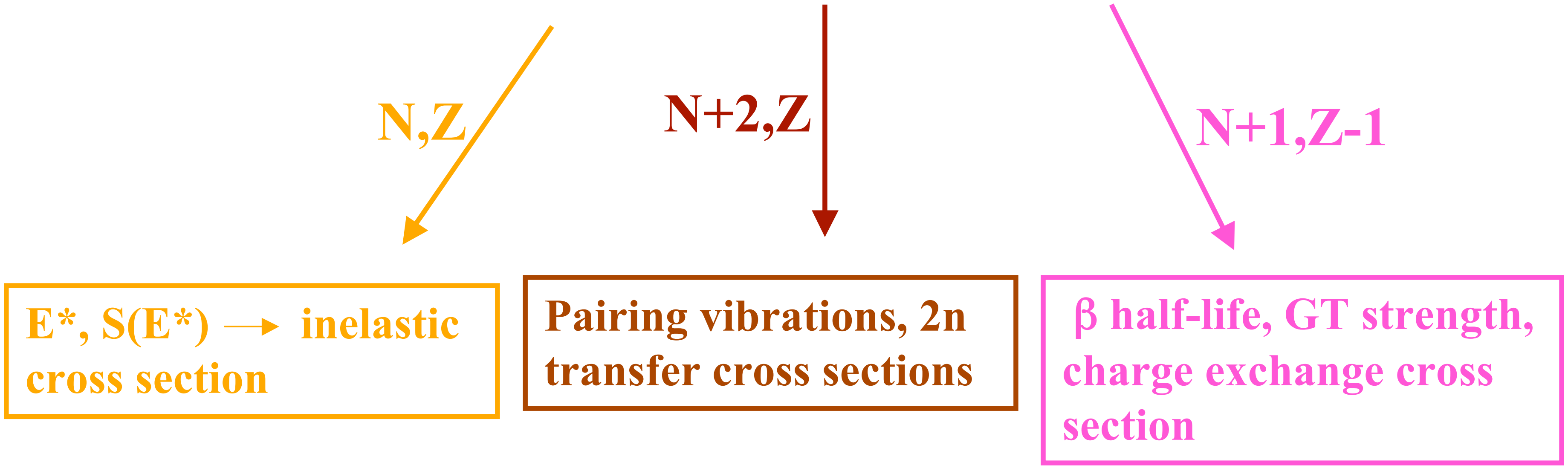
The Quasiparticle-RPA (QRPA)

- Excitation and pairing
- Method known since ~40 years in nuclear physics
- Strong peak of activity since year **2000**. Why ?

- QRPA : excited states are a superposition of 2 quasiparticles states
- A quasiparticle is a superposition of a particle and a hole

Study of nuclear transition of the whole nuclear chart

(isotopic chain, open shell, drip-line, …)



N,Z

N+2,Z

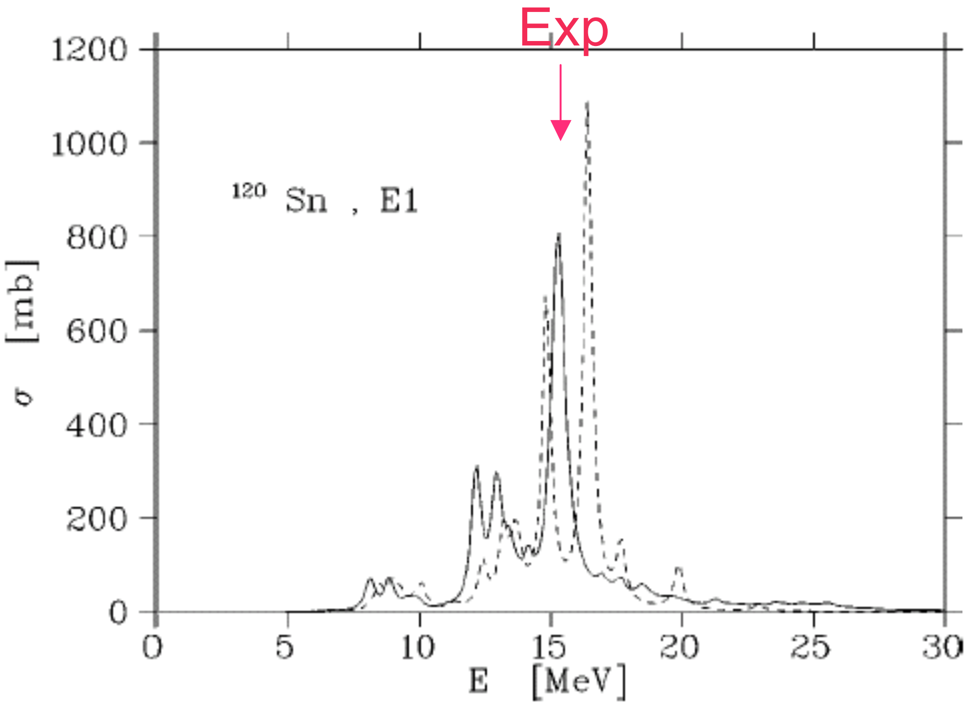
N+1,Z-1

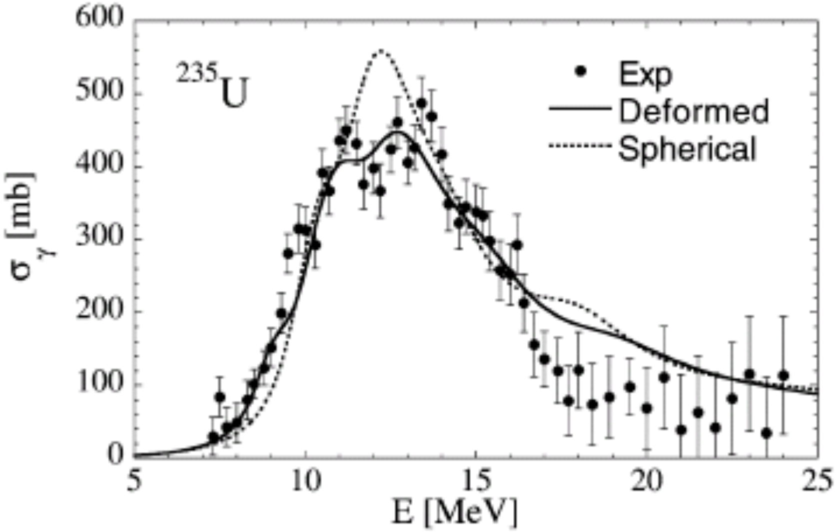
E*, S(E*) → inelastic cross section

Pairing vibrations, 2n transfer cross sections

β half-life, GT strength, charge exchange cross section

Illustrative results





3) GR in exotic nuclei

Issues of GR in exotic nuclei

- Provides a general description of GR

- Observable test: n skin effect, incompressibility in n rich matter, …

- Low energy (soft) mode: around separation energy
  → detection, pairing, temperature

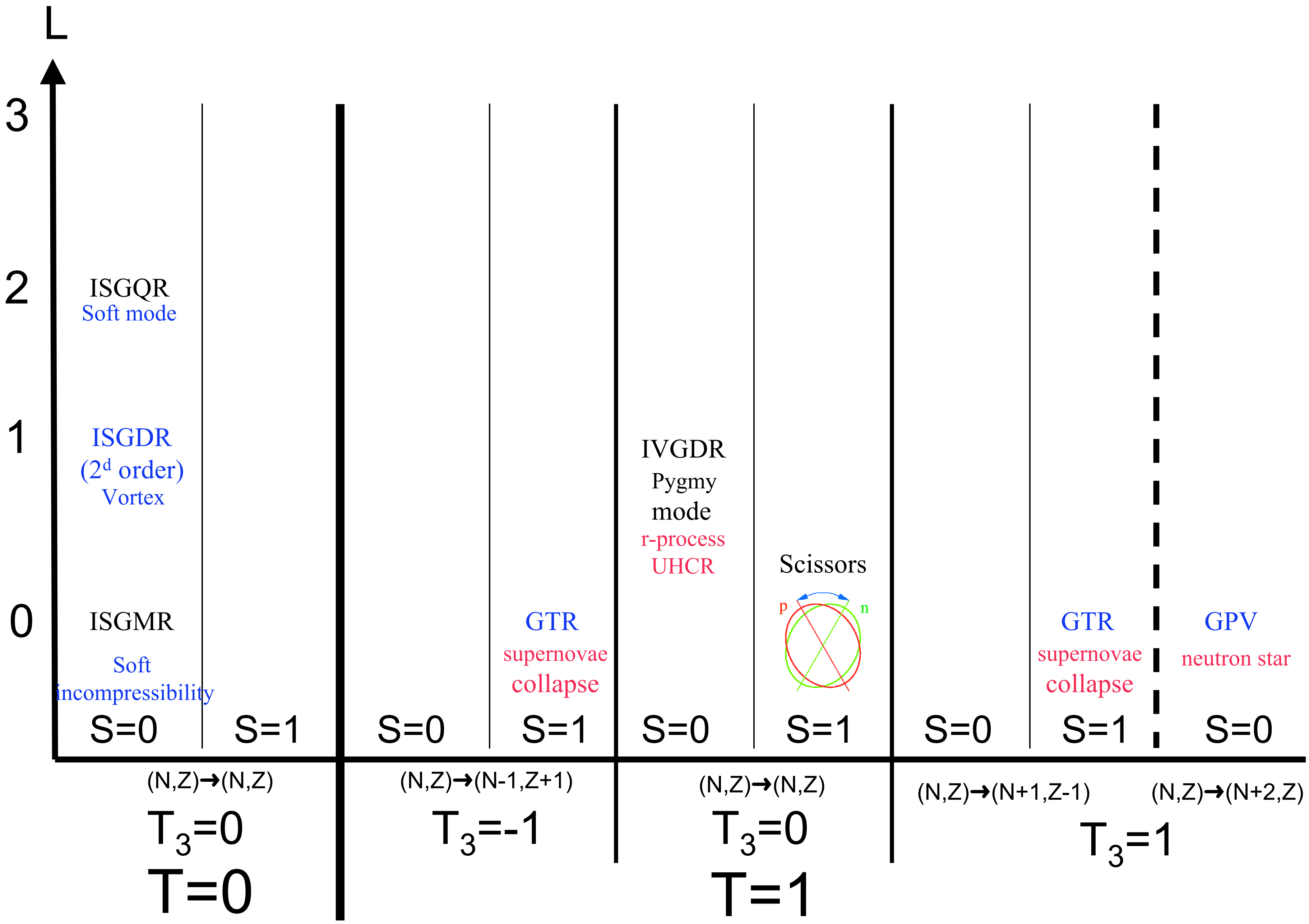
- Collective (pygmy) or only low-lying strength ?

- Continuum for drip-line

- Neutron excess: IS & IV components

- Exp status (since 2000): IV GDR in $^{20-22}$**O** (GSI), ^{132}**Sn** (GSI),
  ^{26}**Ne** (Riken/Orsay), ^{68}**Ni**(Milano)
  IS GMR & GQR in ^{56}**Ni** (GANIL/Orsay**)**

Exotic GR



L

3

2

1

0

ISGQR
Soft mode

ISGDR
(2^d order)
Vortex

ISGMR

Soft
incompressibility

S=0

S=1

(N,Z)→(N,Z)

$T_3=0$

T=0

S=0

GTR
supernovae
collapse

S=1

(N,Z)→(N-1,Z+1)

$T_3=-1$

IVGDR
Pygmy
mode
r-process
UHCR

S=0

Scissors

p

n

S=1

(N,Z)→(N,Z)

$T_3=0$

T=1

S=0

GTR
supernovae
collapse

S=1

(N,Z)→(N+1,Z-1)

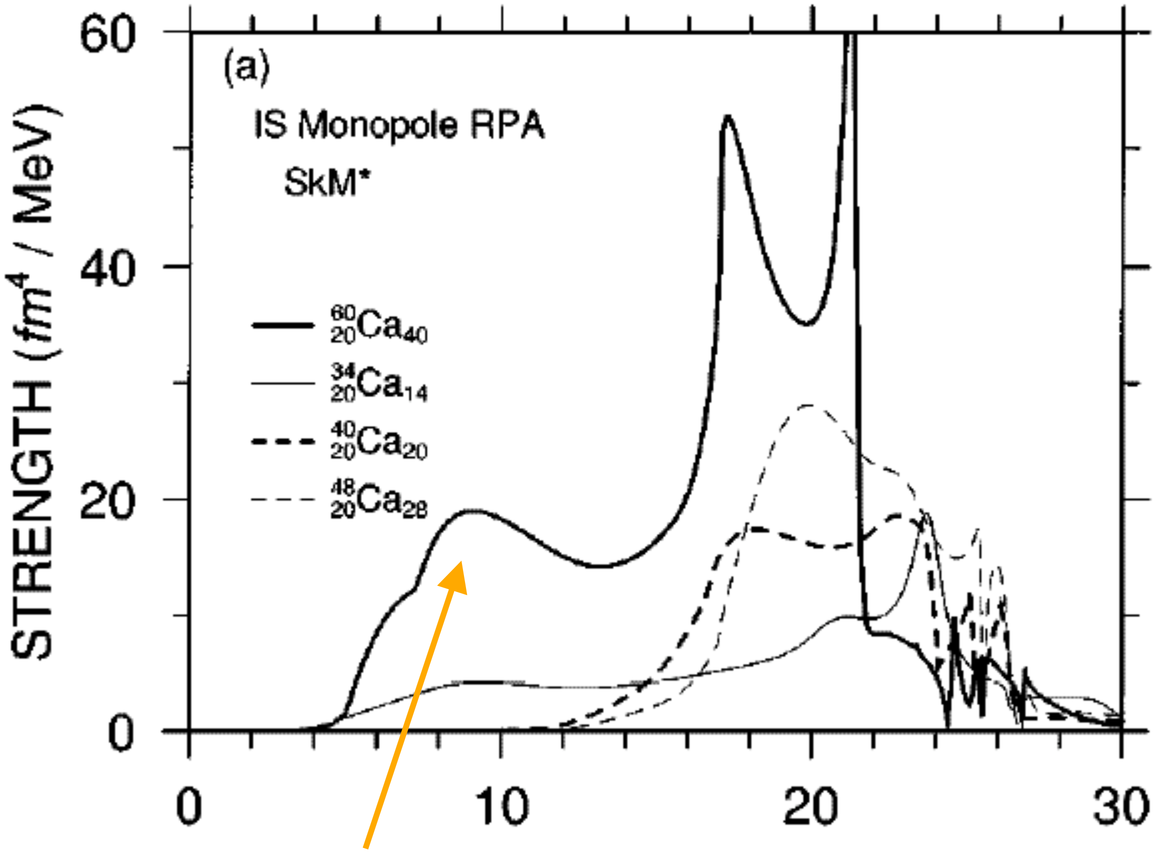
GPV
neutron star

S=0

(N,Z)→(N+2,Z)

$T_3=1$

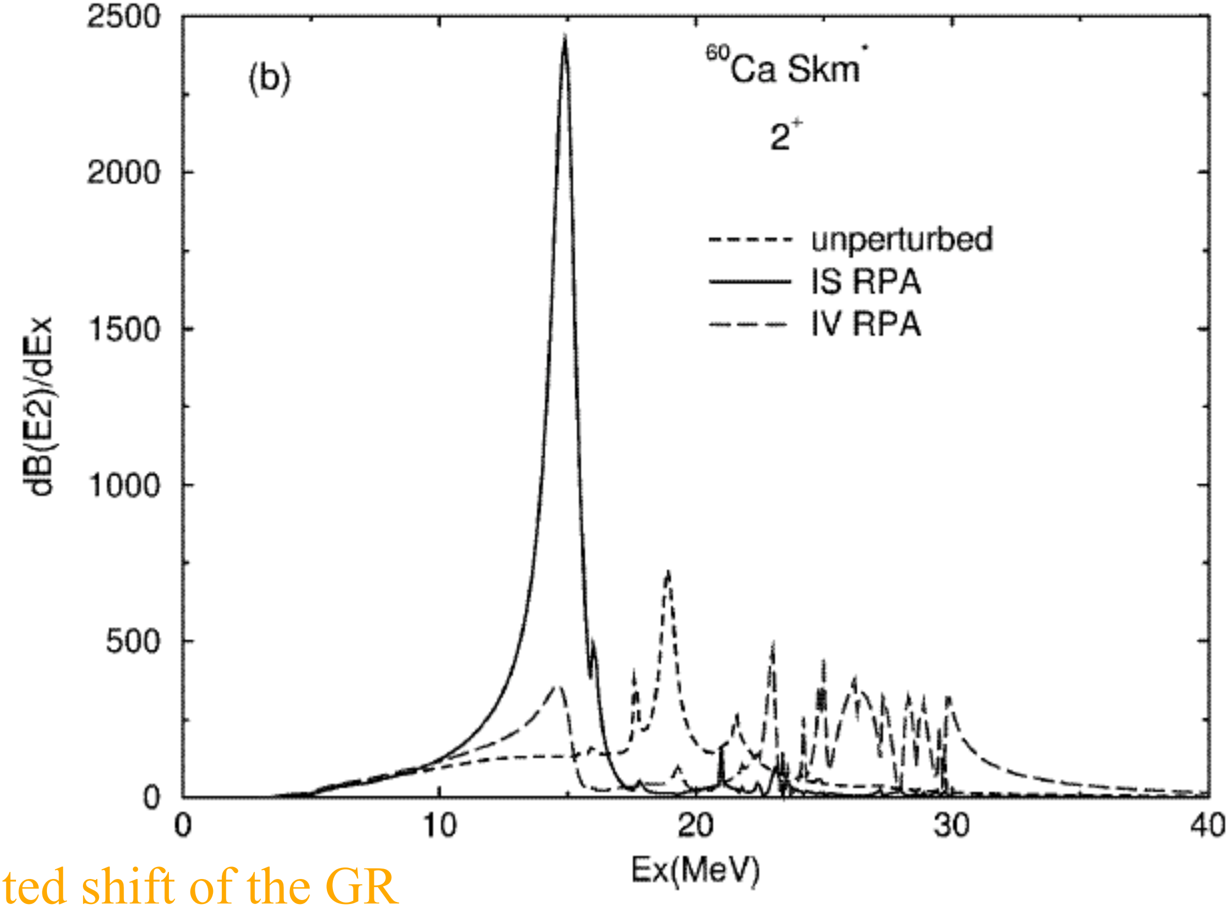
Soft GMR



Compression of low-density nuclear matter

H. Sagawa and H. Esbensen, Nucl. Phys. A **693**, 448 (2001)

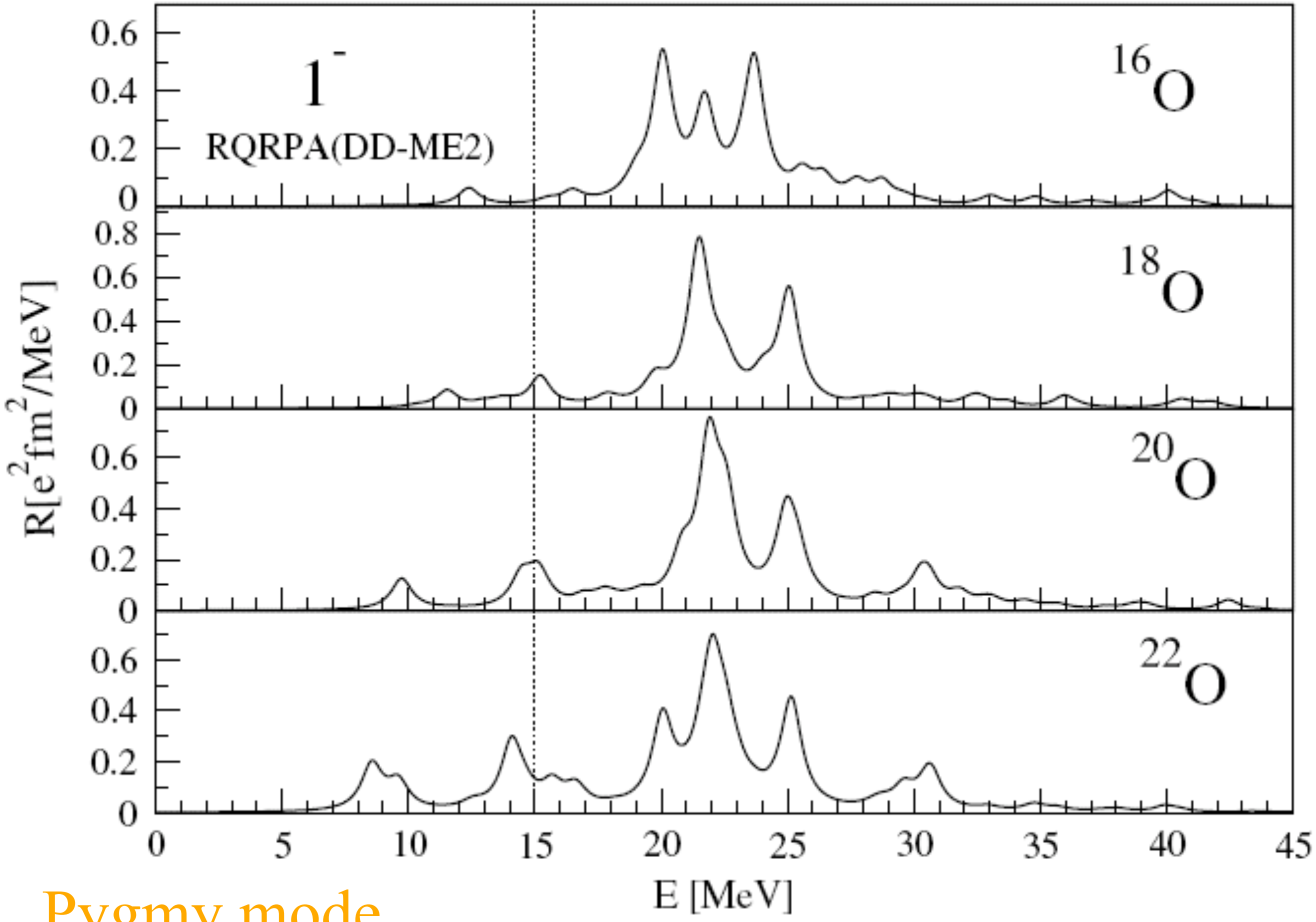
Soft GQR



Unexpected shift of the GR

H. Sagawa and H. Esbensen, Nucl. Phys. A **693**, 448 (2001)

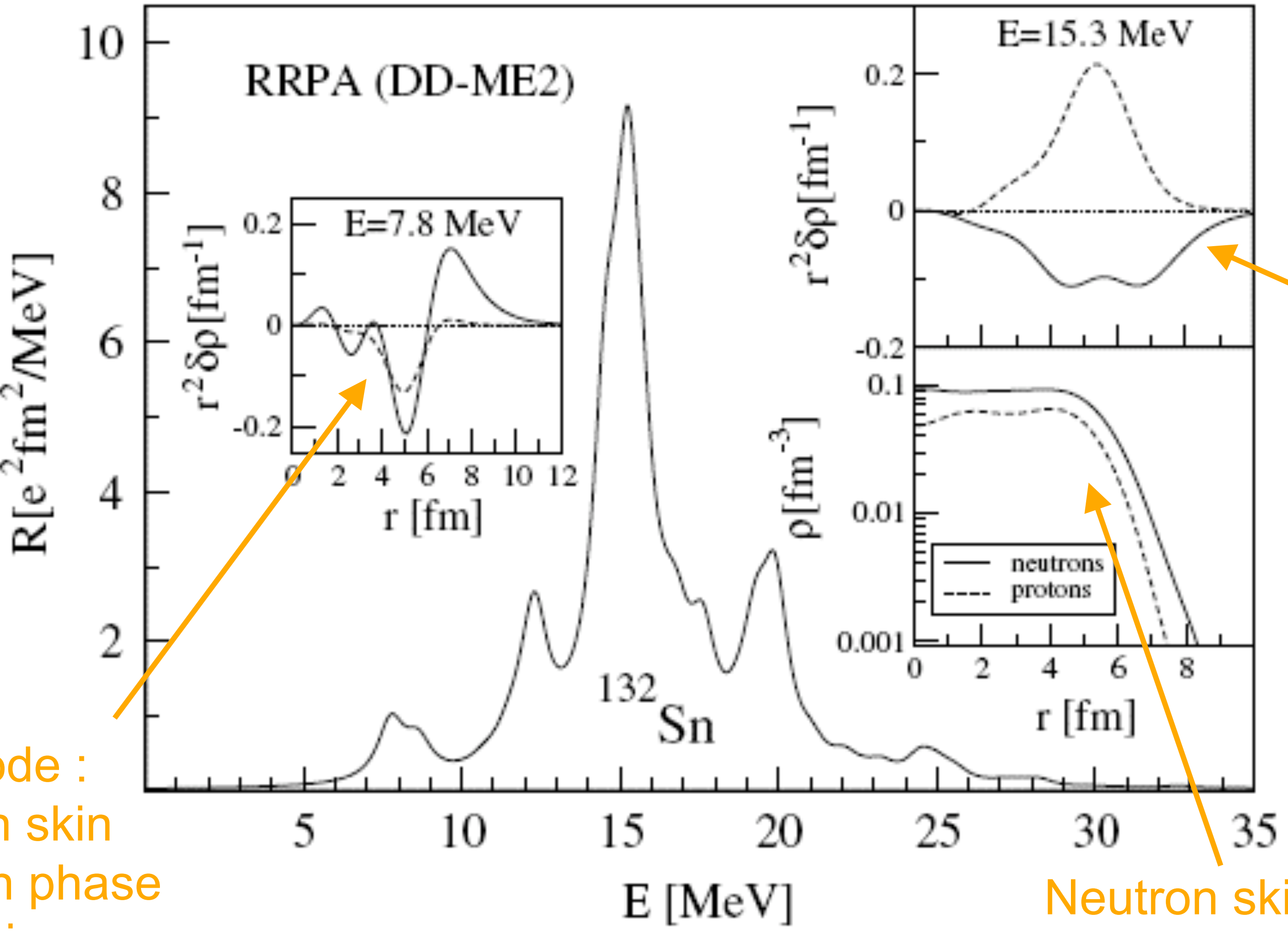
Soft GDR predictions



Pygmy mode

N. Paar, P. Ring, T. Niksic, D. Vretenar, Phys. Rev. C **67**, 034312 (2003)

Soft GDR predictions

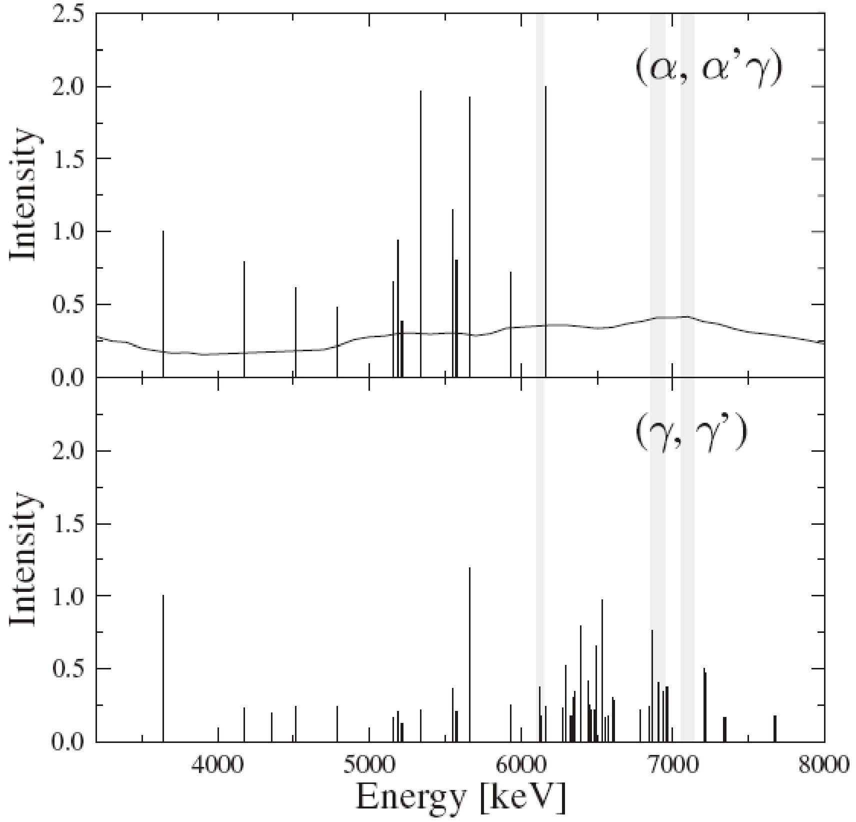


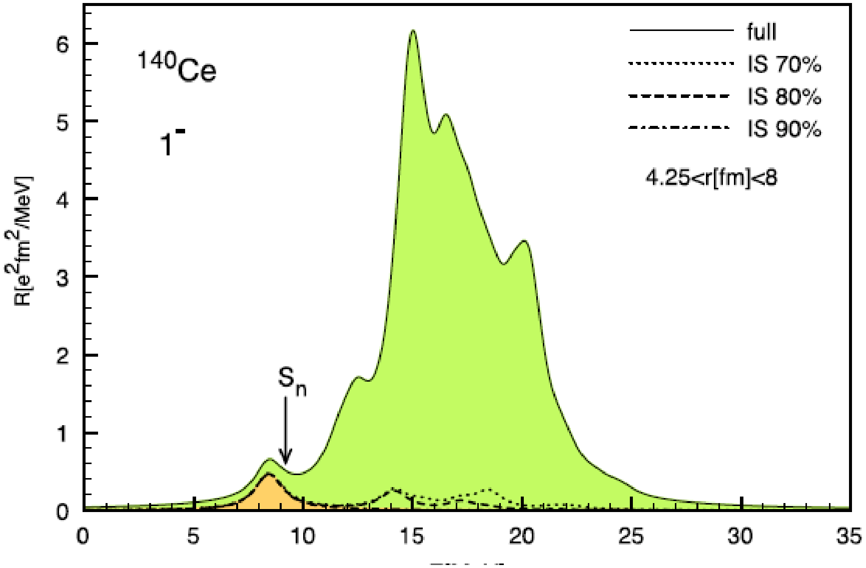
Soft mode :
Neutron skin
+core in phase
+collective

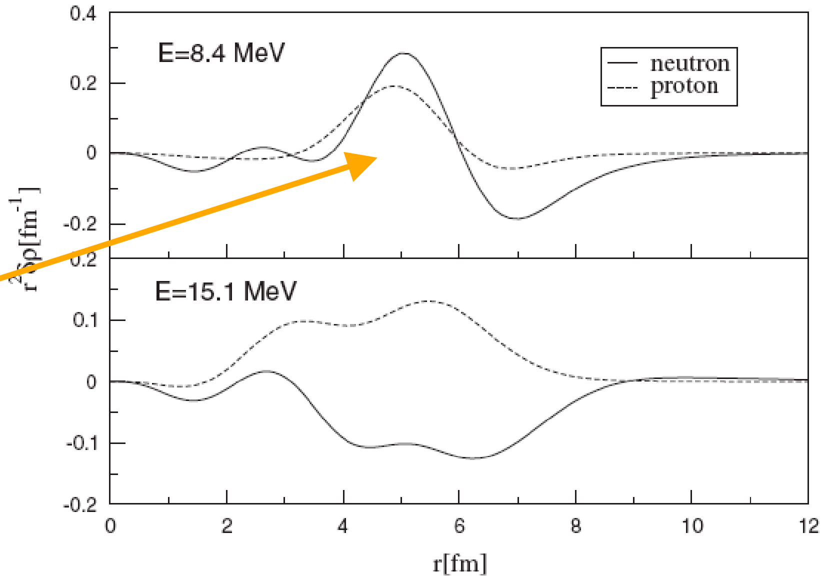
IVGDR

Neutron skin

IS/IV nature of the pygmy mode







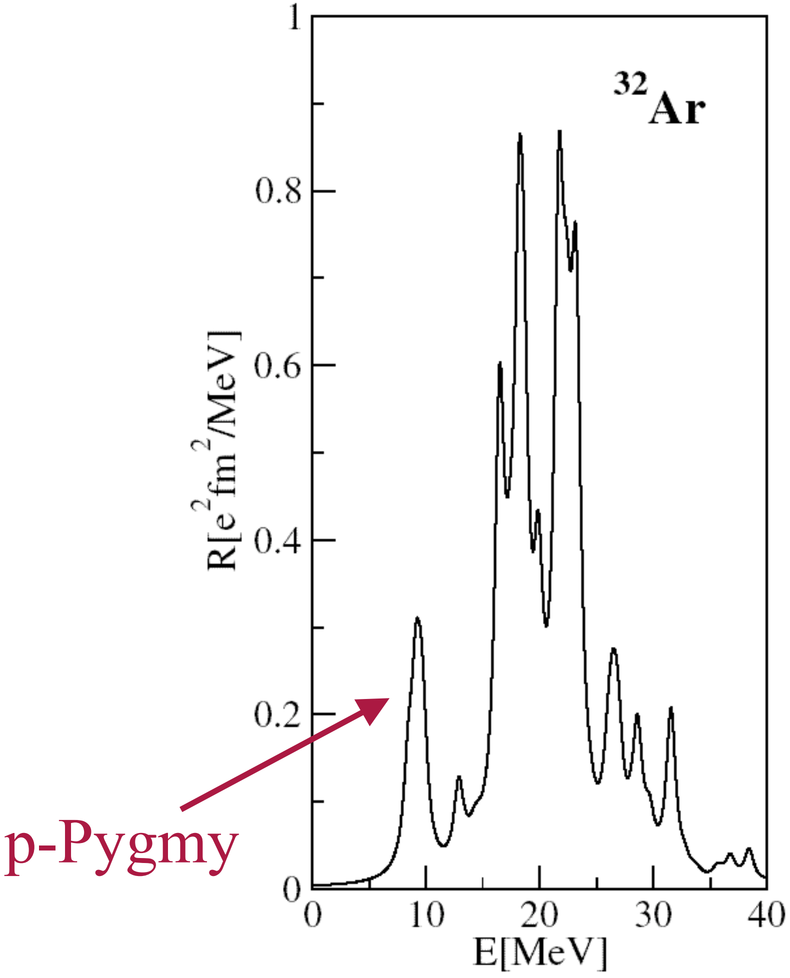
Translation of an IV n skin
around an IS np core

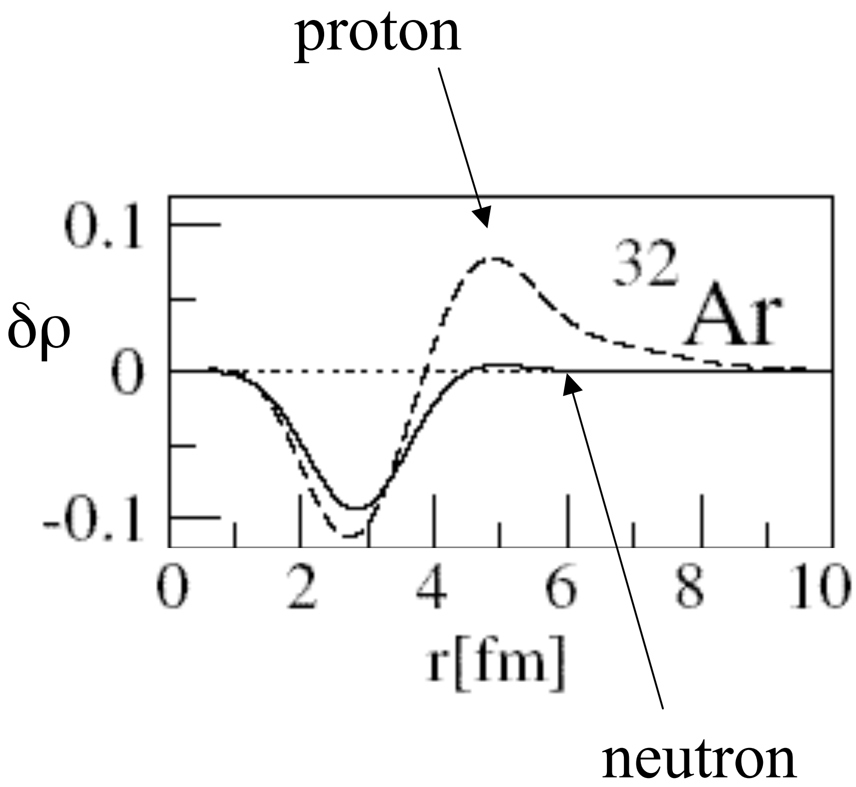
^{140}Ce is stable

Same pattern in exotic nuclei ?

N. Paar, Y.F. Niu, D. Vretenar, J. Meng, Phys. Rev. Lett. **103**, 032502 (2009)

Proton pygmy dipole

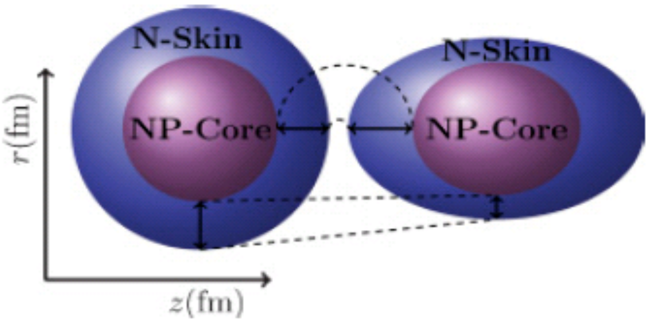


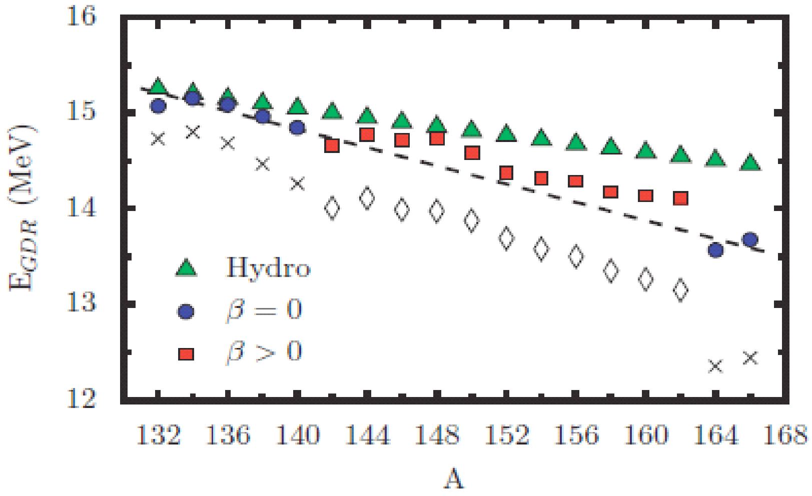


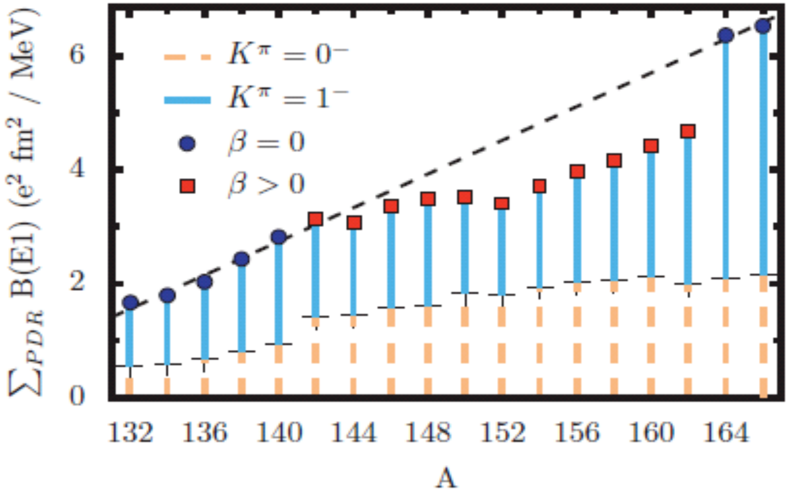
N. Paar, D. Vretenar, P. Ring, Phys. Rev. Lett. **94**, 182501 (2005)

GR in nuclei with extreme n excess

Large neutron skin → weakening of the LS → disappearance of magic numbers (Z=50) → deformation





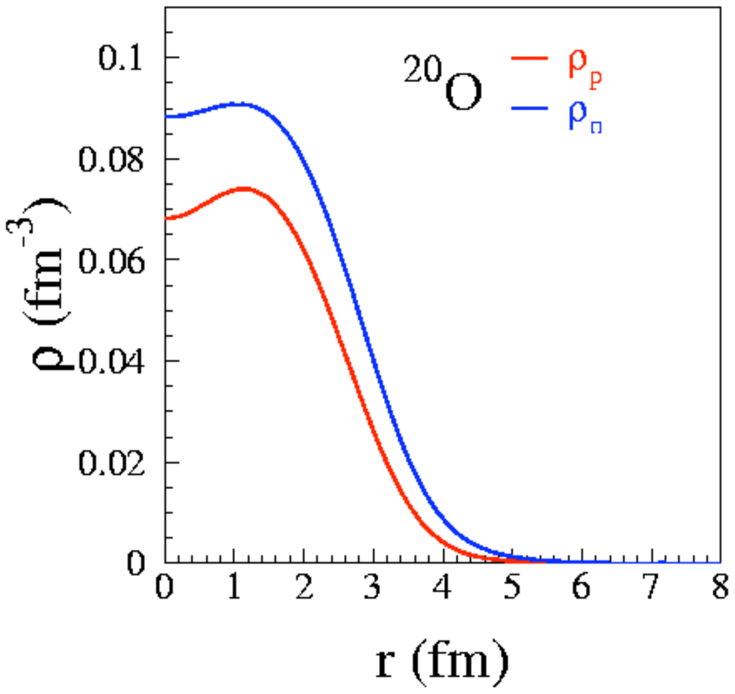


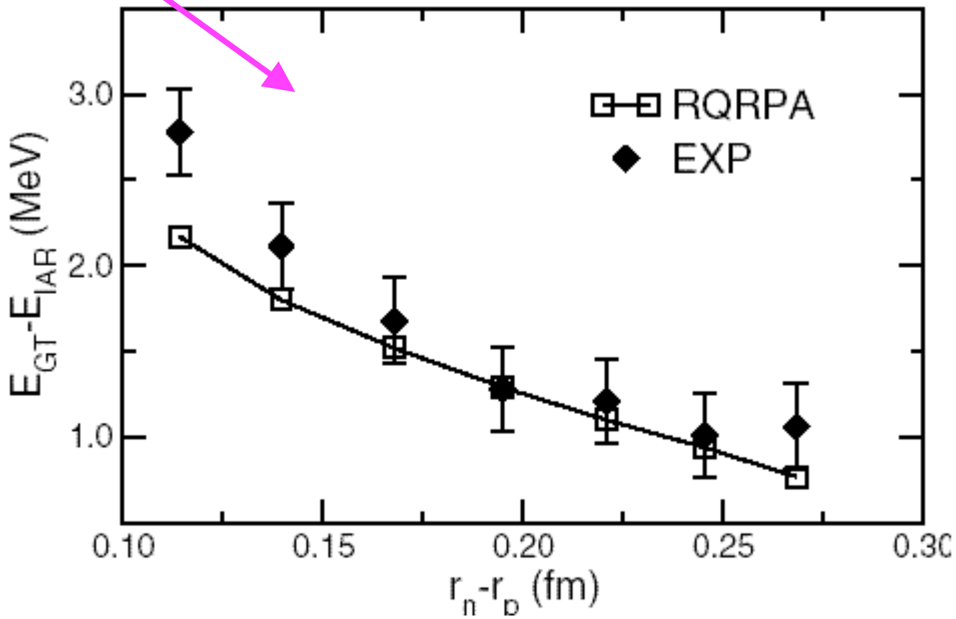
The pygmy mode is quenched by the deformation because of the reduction of the n skin

D. Peña Arteaga, E. Khan, and P. Ring, Phys. Rev. C **79**, 034311 (2009)

How to measure a neutron skin with GR ?

- **GDR** : S=0, T=1, L=1 ; DWBA analysis
- **Spin-dipole** : S=1, T=1,L=1 ; Sum rule
- **GTR** : S=1, T=1, L=0 and **IAR** : S=0, T=1, L=0 ; Energy shift

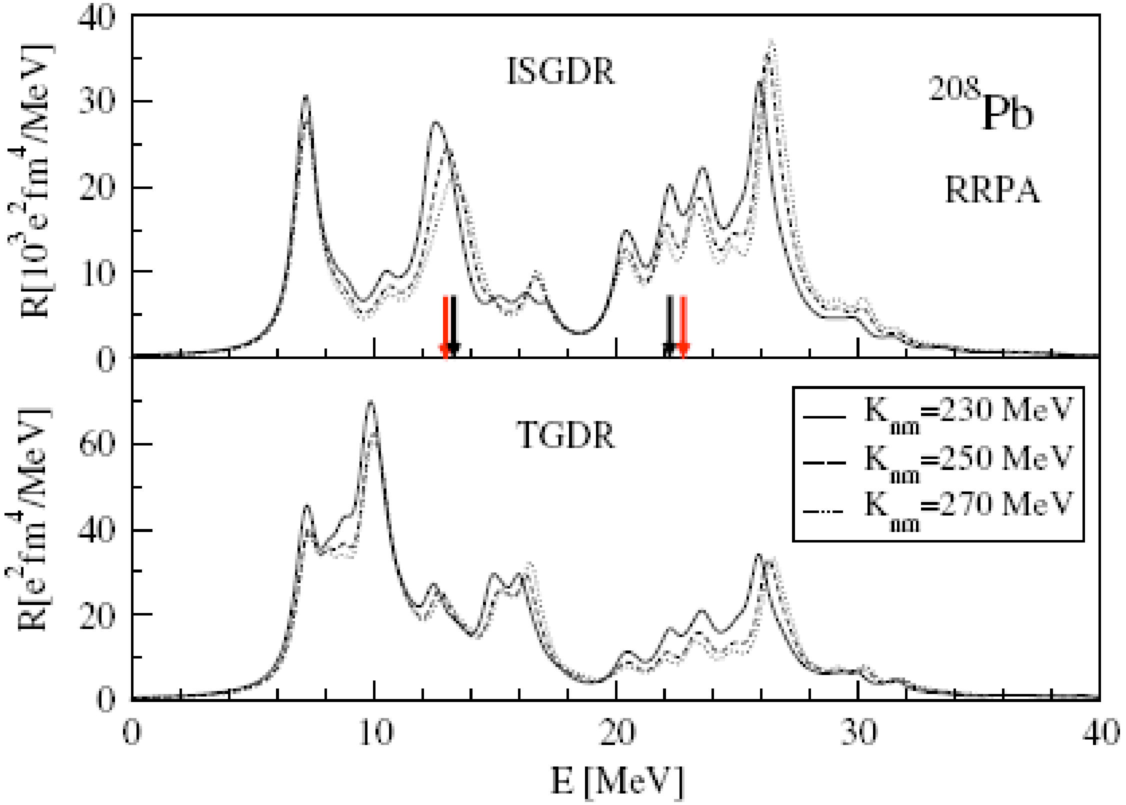




Spin-orbit term
raises the degeneracy

D. Vretenar, N. Paar, T. Niksic, P. Ring, Phys. Rev. Lett. **91**, 262502 (2003)

Isoscalar GDR



D. Vretenar, N. Paar, P. Ring, T. Niksic, Phys. Rev. C **65**, 021301(R) (2002)

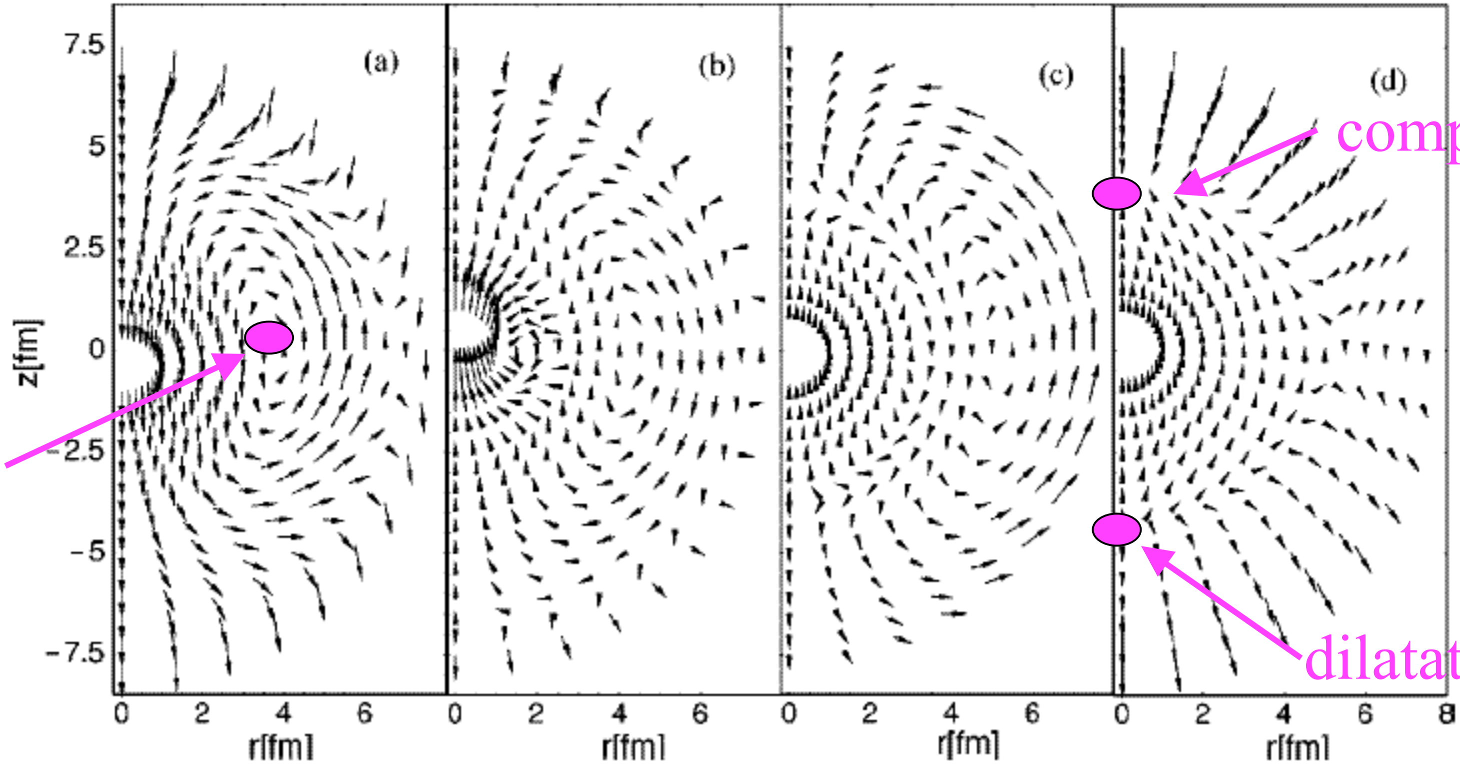
Exotic modes : low energy ISGDR

8 MeV

30 MeV

E*

^{116}Sn



vortex

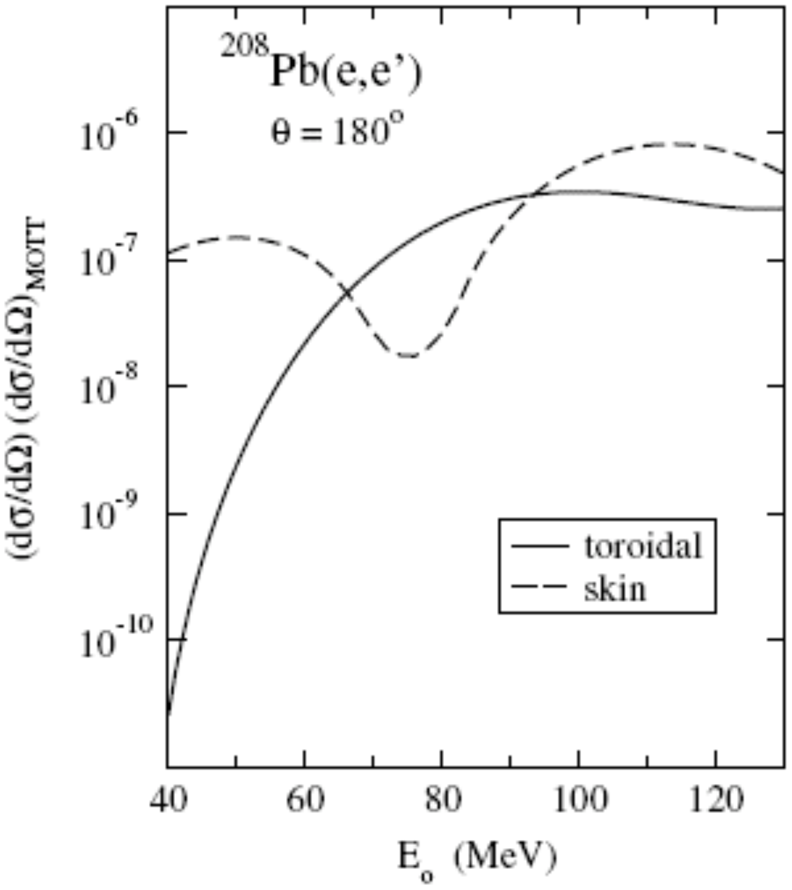
compression

dilatation

Torroidal

Squeezing

Detecting the vortex mode



A. Richter, Nucl. Phys. A **731**, 59 (2004)

Conclusion

- GR are collective high E modes with large cross section
- n excess breaks isospin symmetry: $(L;S,T,T_3)$ ordering of GR
- Easiest (!) to detect and provide various information on nuclear structure: K_∞, n skin, probe the functionnal (see next point)
- Derived as harmonic oscillations from TDHF, based on a single functionnal
- In exotic nuclei, new modes of excitation: soft modes, pygmy.
- Exotic nuclei useful as isotopic chain (Ex: K_∞): analog to magic number evolution

•Not mentionned: GPV, GR and astrophysics, deformation on GR, fine structure, width, decay, hot GR, multiphonon, tools (macrocopic models, sumrule), measurement of GR (exotic nuclei)

Bibliography

- **Giant Resonances**, M. Harakeh and A. Van der Woude (2000)
Status on stable nuclei

- **The nuclear many body problem**, P. Ring and P. Schuck (1980)
Introduction to the theoretical description of GR

- **Exotic modes of excitation in atomic nuclei far from stability**,
N. Paar, D. Vretenar, E. Khan, G. Colo, Rep Prog. Phys. 70 (2007) 691
Status of GR in exotic nuclei