Interplay between collective and single particle excitations around neutron-rich doubly-magic nuclei

Silvia Leoni
Università degli Studi di Milano e INFN sez. Milano

NN2015
12th INTERNATIONAL CONFERENCE ON NUCLEUS-NUCLEUS COLLISIONS
June 21-26, 2015, Catania, Italy

OUTLINE

INTRODUCTION

Models aimed at describing Excited States in Nuclei

SHELL Model and Particle-Phonon Coupling Model

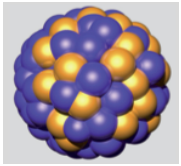
→ *Limitation and Future Perspectives for Unified Picture*

SURVEY of RECENT *γ – spectroscopy* RESULTS around DOUBLY MAGIC NUCLEI

1. ^{48}Ca – *Multinucleon Transfer*
2. ^{132}Sn – *Neutron Induced Fission*
3. ^{208}Pb – (n,γ)

Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei



Many Body
Finite Quantum
System

Proton number Z

Neutron number N

2
8
20
28
50
82
126

terra incognita

248 Stable

~3000 discovered

> 6000 expected

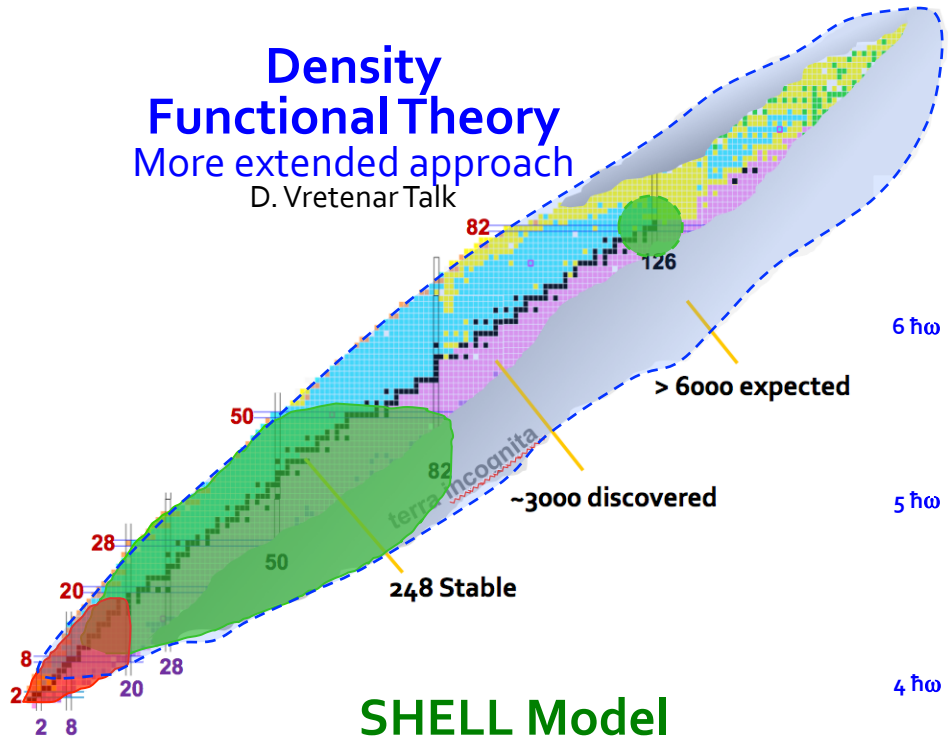
Challenges in MODERN NUCLEAR PHYSICS

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

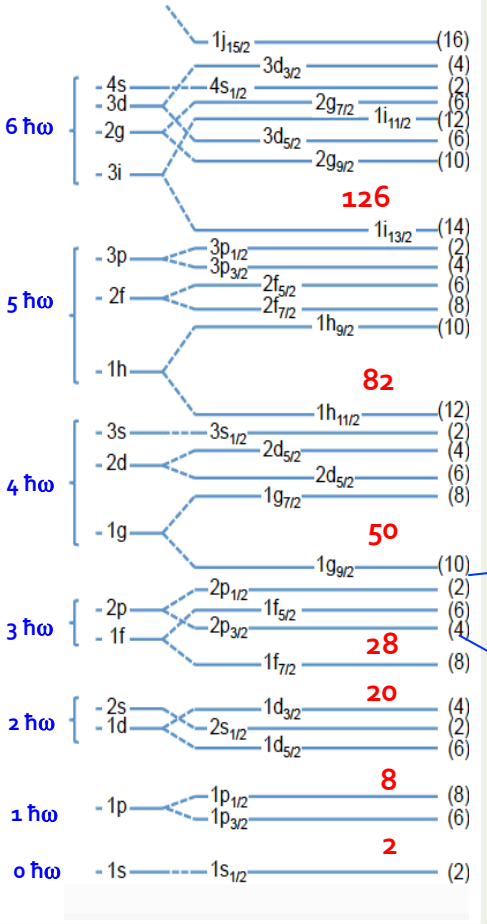
Density Functional Theory

More extended approach

D. Vretenar Talk



Shell Structure for p and n



Configuration Space

$$\binom{K}{A} = \frac{K!}{(K-A)!A!}$$

Number of ways to distribute A nucleons over K orbitals

N=Z		Number of configurations
44	^{88}Ru	≈ 10^{28}
28	^{56}Ni	≈ 10^{10}
24	^{48}Cr	≈ 10^{7}
22	^{44}Ti	≈ 10^{4}

SHELL Model

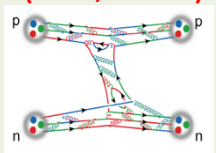
Large Scale Calculations With Frozen CORE

- A up to ≈ 100
- Around Closed shell

T. Otsuka, ...
A.Brown, ...
F. Nowacki, ...
L. Coraggio, ...
...

ab-initio

NN, NNN (EFT, QCD)

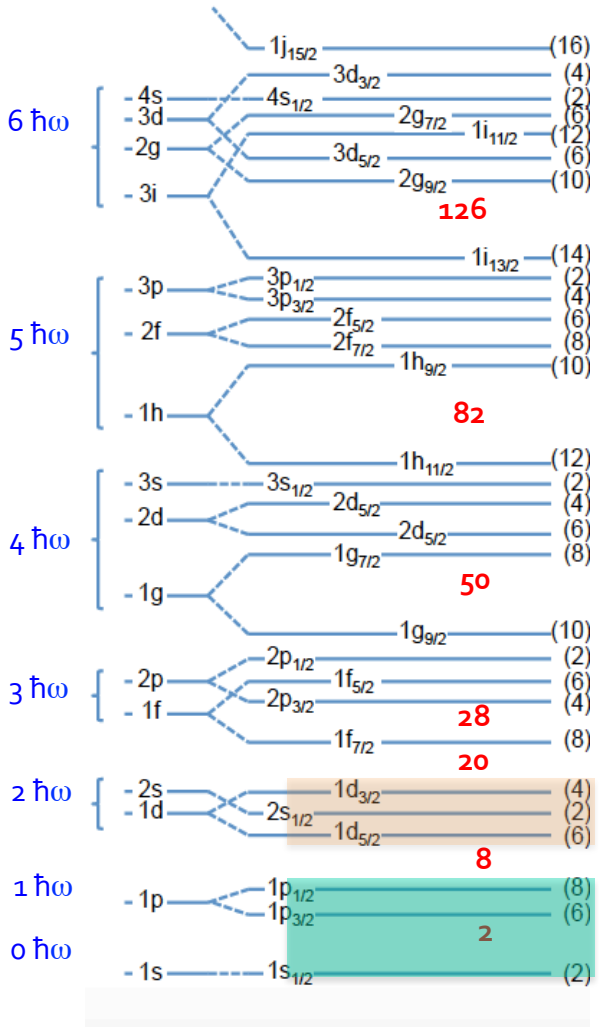


W.Nazarewicz , ...
M. Hjorth-Jensen, ...
G. Hagen, ...
C. Forssen, ...
P. Navratil, ...
A.Schwenk, ...

MICROSCOPIC Structure of Nuclei: a computational challenge ...

SHELL MODEL CALCULATIONS

Shell Structure



MAIN IDEA

Use SHELL GAPS as a TRUNCATION of the model space

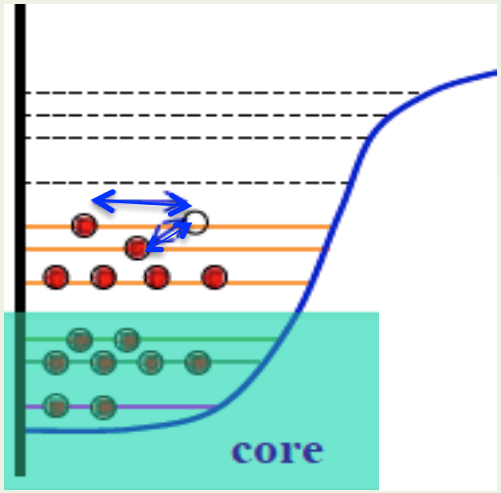
Nucleus (N,Z) =

Frozen CORE + valence nucleons (N-N*, Z-Z*)

Doubly magic nucleus (N*, Z*)

^{4}He, ^{16}O, ^{40}Ca, ^{132}Sn, ^{208}Pb

Excitations restricted to ONE-TWO oscillator SHELLS



LIMITATIONS

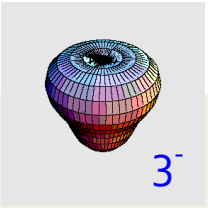
- *interactions among **valence nucleons***
- *CORE excitations are not fully included **(few nucleons only)***

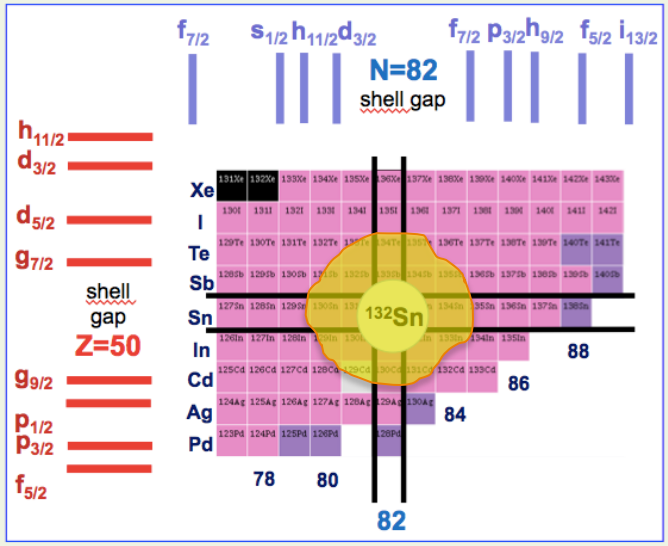
→ *CORE Excitations may be very complex and not doable with SHELL MODEL*

Relevance of CORE Excitations

Low lying excited states in **DOUBLY MAGIC** Nuclei are dominted by complex, collective excitations

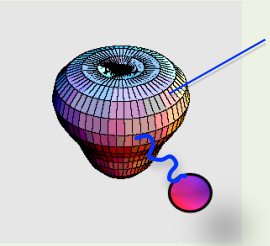
2^+, 3^-, 4^+, … **PHONONS**





The Structure of Nuclei with **one** or **two valence particles** is influenced by

Particle-PHONON couplings



excited core (phonon)

Key Ingredient for:

- Quenching of Spectroscopic Factors,
- Anharmonicity of vibrational spectra
- Damping of Giant Resonances, …

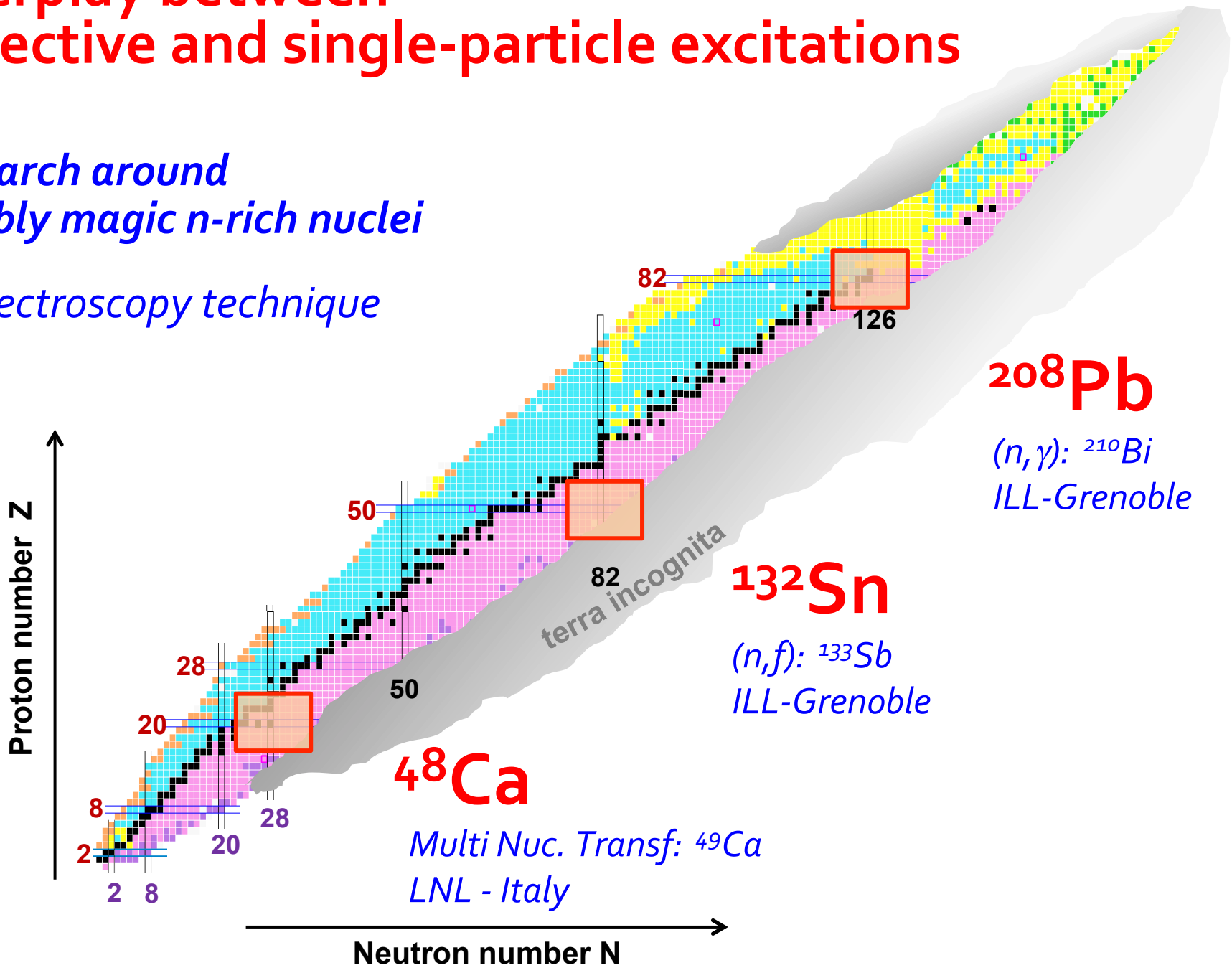
PHENOMENOLOGICAL (Bohr-Mottelson)
MICROSCOPIC (Colò, Bortignon, Sagawa, Dabaczewski, Vretenar, …)

→ *VERY limited EXPERIMENTAL Information on Particle-PHONON Couplings around DOUBLY MAGIC NUCLEI*

Interplay between collective and single-particle excitations

a search around doubly magic n-rich nuclei

γ-spectroscopy technique



^{208}Pb

(n,γ): ^{210}Bi
ILL-Grenoble

^{132}Sn

(n,f): ^{133}Sb
ILL-Grenoble

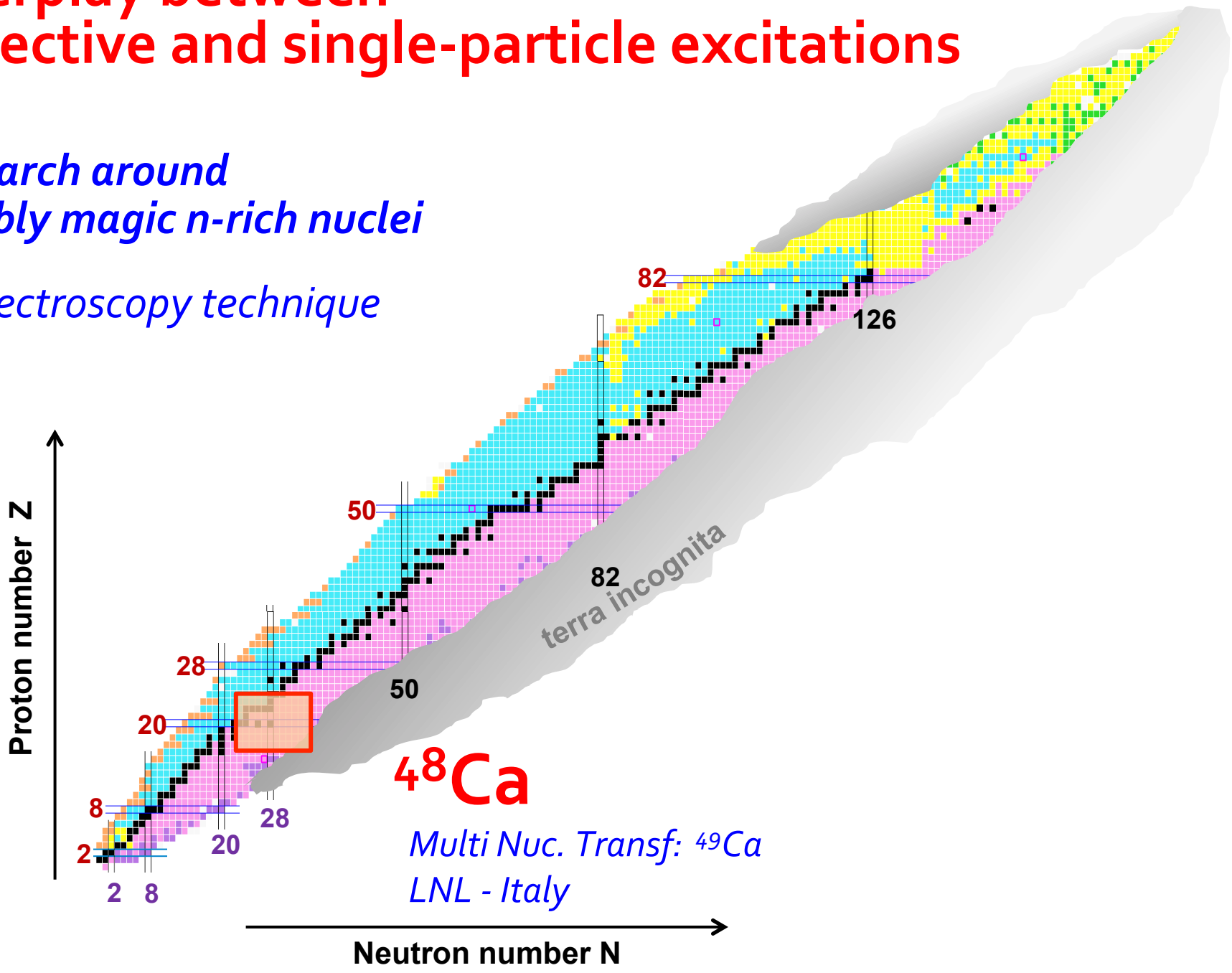
^{48}Ca

Multi Nuc. Transf: ^{49}Ca
LNL - Italy

Interplay between collective and single-particle excitations

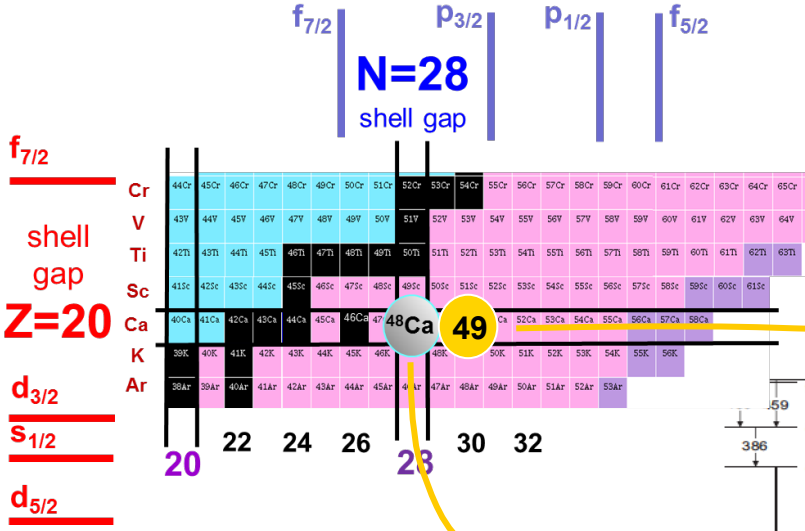
a search around doubly magic n-rich nuclei

γ-spectroscopy technique

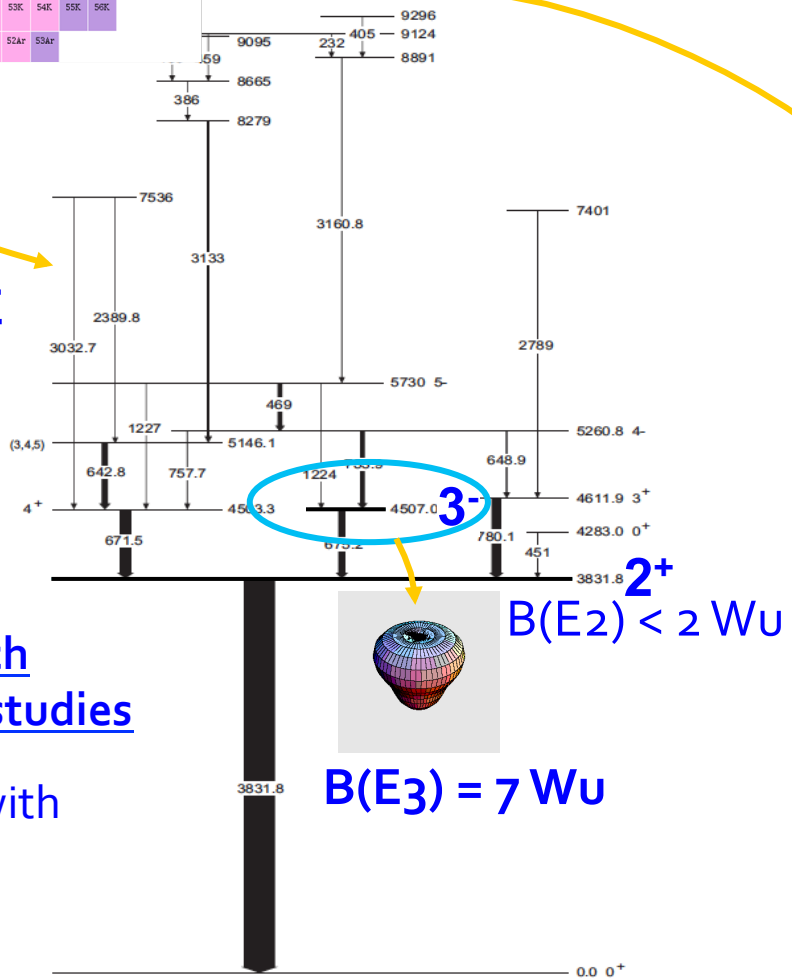


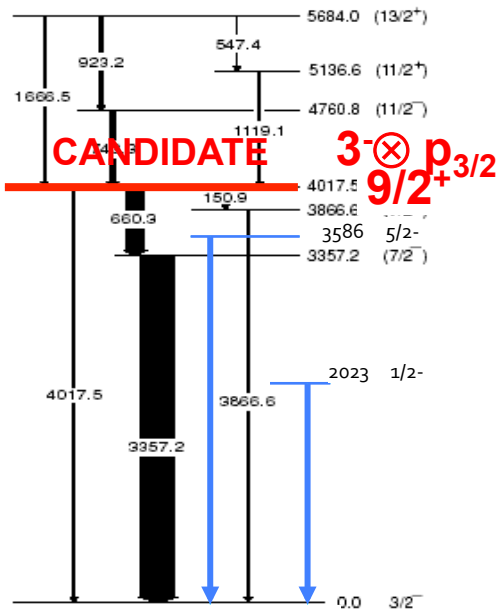
^{49}Ca

- *Single particle levels*
- ***Couplings** between proton and 3$^-$ phonon*



Double SHELL CLOSURE at theValley of Stability





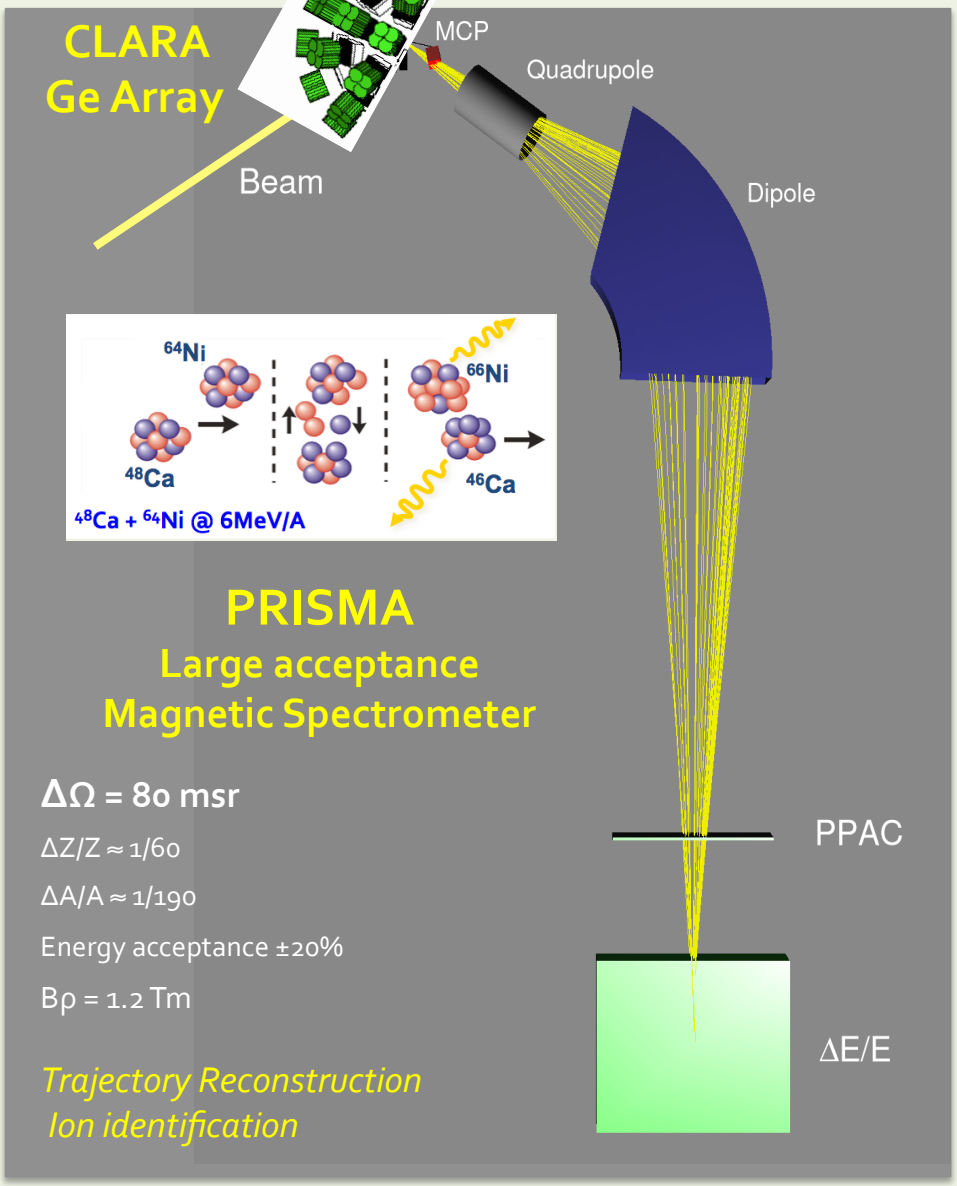
[Nuclei hard-to-reach for yrast spectroscopic studies](#)

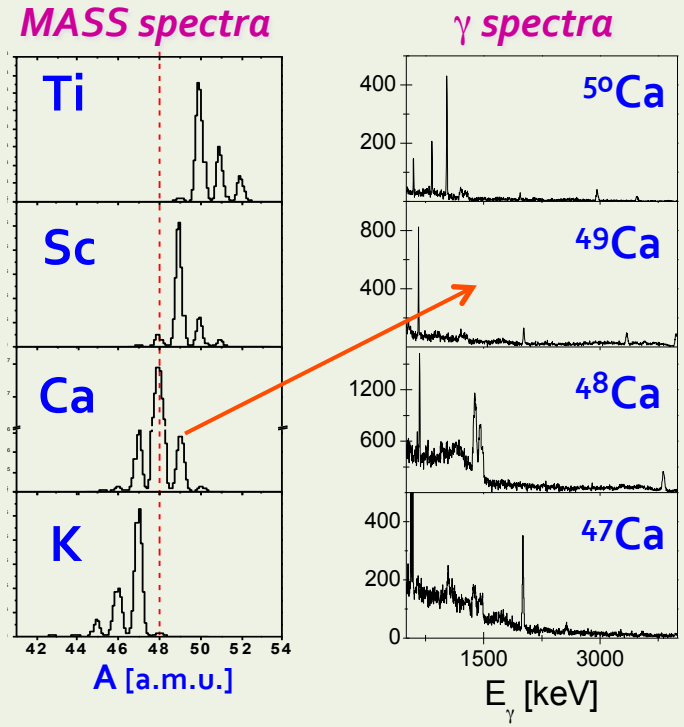
Multi nucl. transfer with **THICK** targets

Krakow group: R. Broda, B. Fornal et al., …

Studies of Moderately N-Rich Nuclei

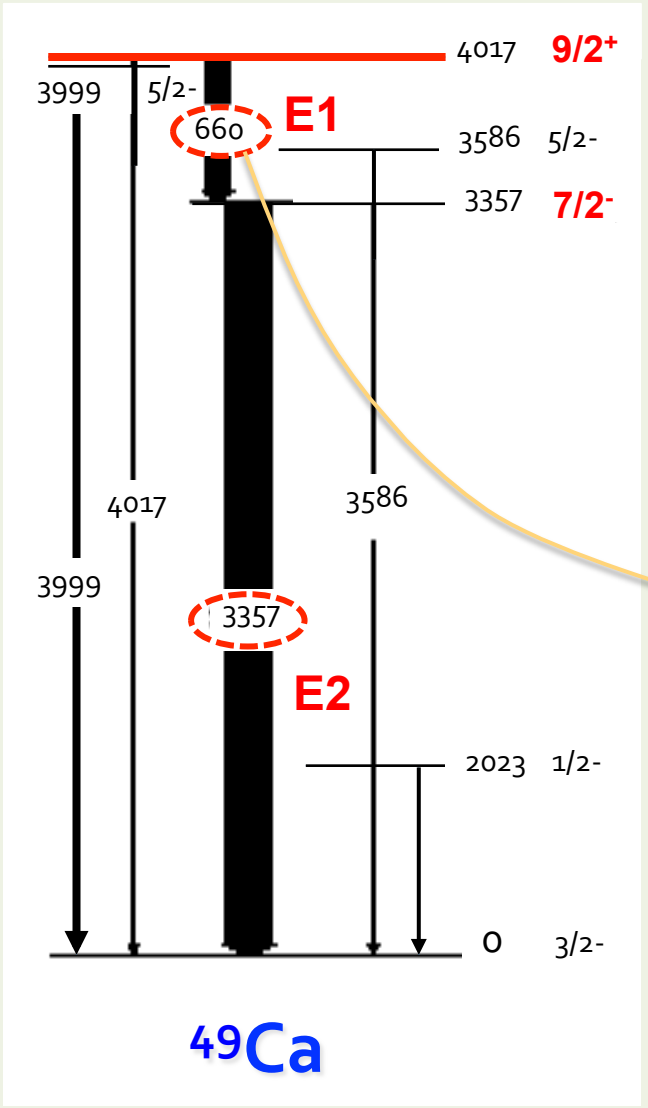
Multi Nucl er with THIN targets: Ge Array coupled to Magnetic Spectrometer





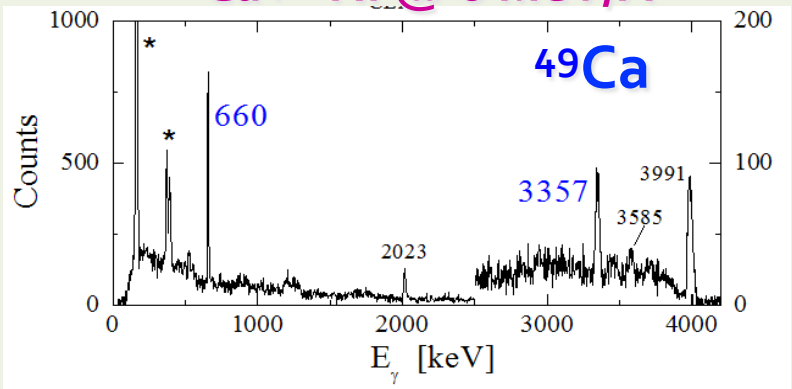
Similar Studies with AGATA-PRISMA (LNL) and EXOGAM/AGATA-VAMOS (GANIL)

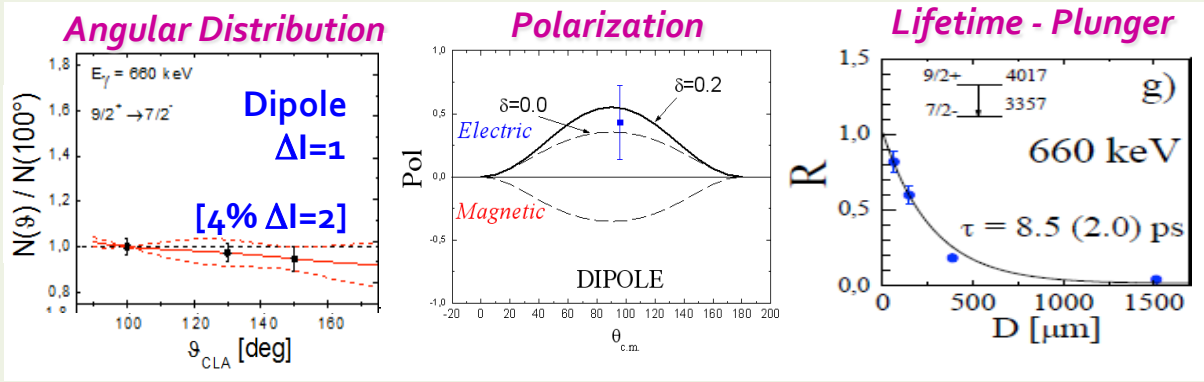
Spectroscopy of ^{49}Ca: Spin, Parity and Lifetimes



$3^- \otimes p_{3/2}$

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





E = 4017.5 keV **$I^\pi = 9/2^+$**

B(E3) = 7.9 ± 2 Wu similar to B(E3) of 3^- in ^{48}Ca

$3^- \otimes p_{3/2}$ = **9/2+**, 7/2+, 5/2+, 3/2+

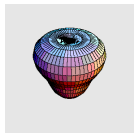
D. Montanari, S. Leoni et al., PLB697 (2011) 288

Interpretation of 9/2+ state of ^{49}Ca

Particle-Vibration Coupling

Weak coupling

Phenom. Model Bohr-Mottelson



3⁻ **Theory** 4.507

7/2⁺ 4.41

5/2⁺ 4.33

3/2⁺ 4.19

9/2⁺ 4.00

RPA Calculation

$B(E3)_{TH} \approx 7$ WU

3 components (64, 29, 2%)

$B(E3)_{EXP} \approx 7$ WU

0^+

^{48}Ca

$3^- \otimes p_{3/2}$

$B(E3)_{TH} \approx 7$ WU

9/2+ 4.017

$B(E3)_{EXP} \approx 7.9\ (2)$ WU

$3/2^-$

5/2⁺, 7/2⁺

3/2⁺

9/2⁺ 3.80

$3^- \otimes p_{3/2}$

$B(E3)_{TH} \approx 6.2$ WU

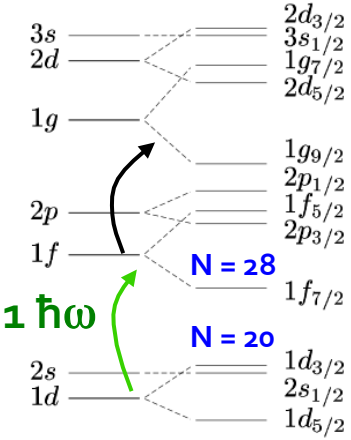
^{49}Ca

G. Colò, P.F. Bortignon, … (Milano)

Large Scale SHELL Model

FULL sd-pf-sdg shell still NOT possible

Truncation scheme sd+pf+sdg (2.515.437 conf) with V_{MU} interaction



SPEC. FACTOR (9/2+)

SHELL MODEL = 0.42

EXP ≈ 0.14

Y. Uozumi et al., NPA 576, 123 (1994)

Y. Utsuno, T. Ostuka, … (Japan)

Lesson Learned from ^{49}Ca

1. ***EXPERIMENT*** *identifies a* ***particle-phonon state 9/2+:***
   a member of $3^- \otimes p_{3/2}$

2. ***PHENOMENOLOGICAL*** *Particle-Phonon Model reproduces the* ***9/2+ state***

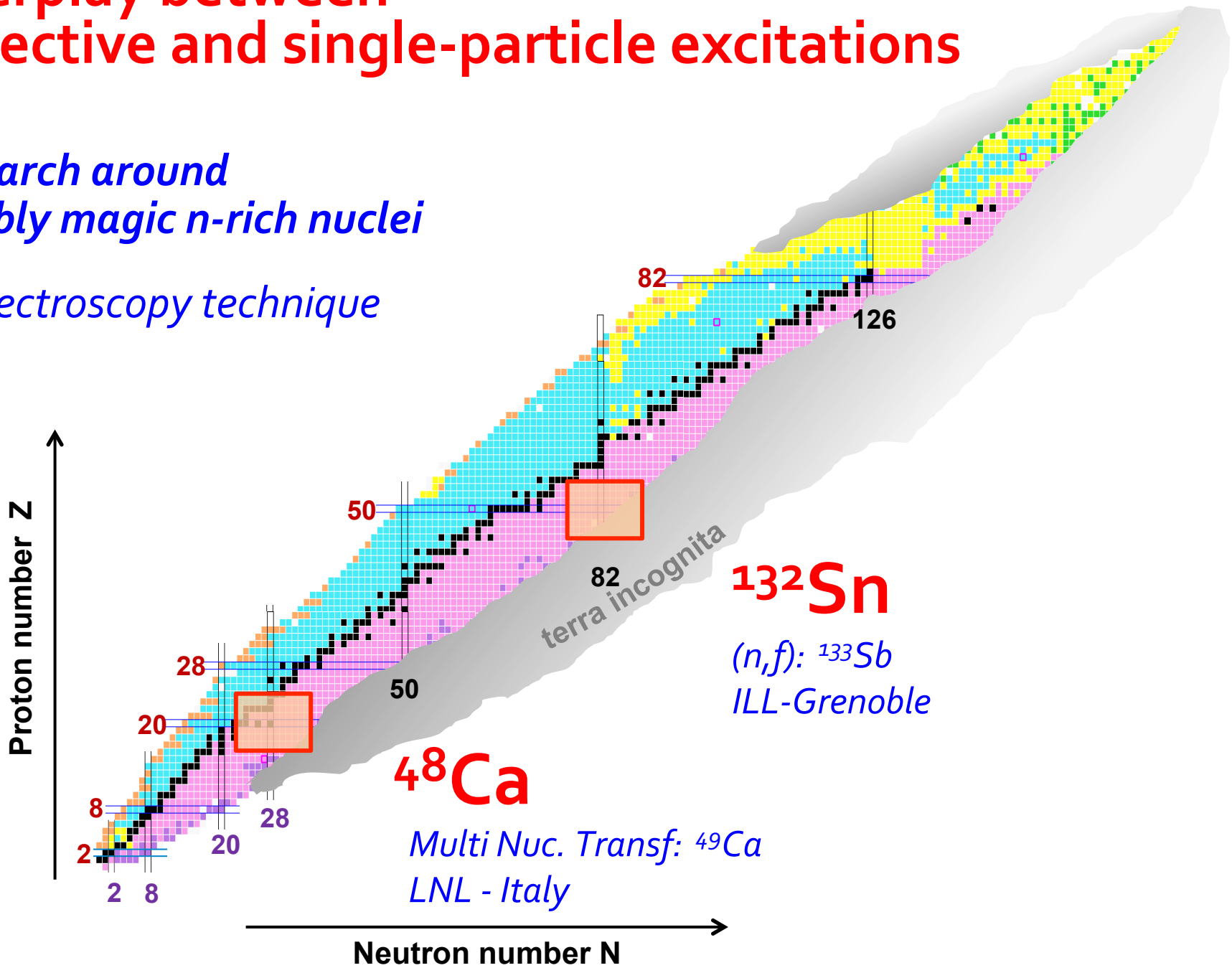
3. ***LARGE SCALE SHELL*** *Model calculations* ***are doable*** *(with space truncation):*

   rather good agreement has been reached,
   but ***single particle component*** *too strong*

Interplay between collective and single-particle excitations

a search around doubly magic n-rich nuclei

γ-spectroscopy technique

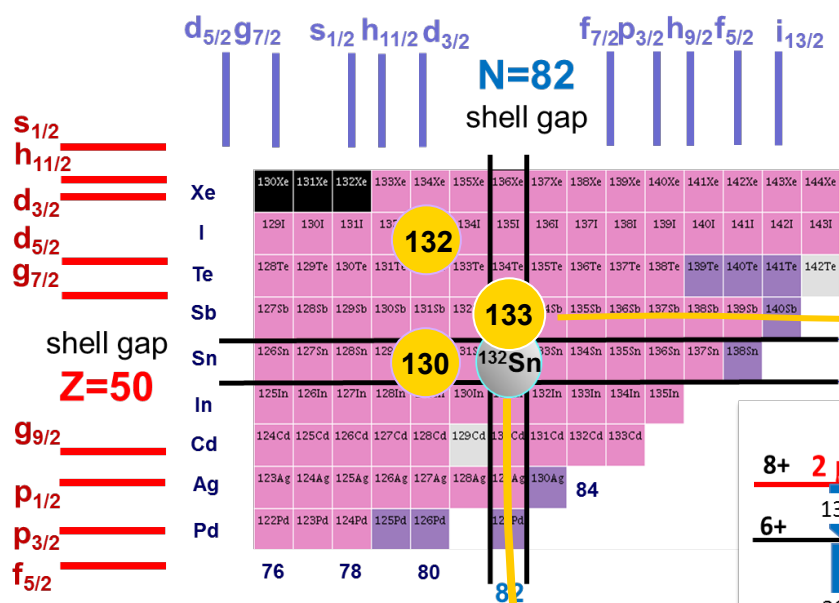


^{132}Sn

(n,f): ^{133}Sb
ILL-Grenoble

^{48}Ca

Multi Nuc. Transf: ^{49}Ca
LNL - Italy



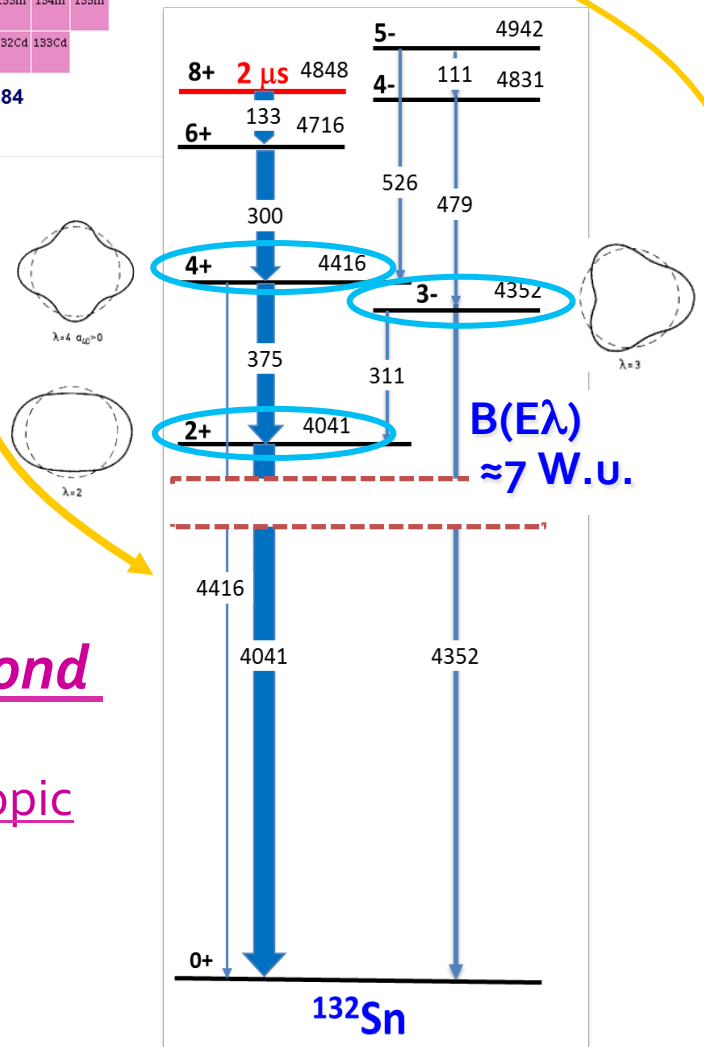
^{133}Sb

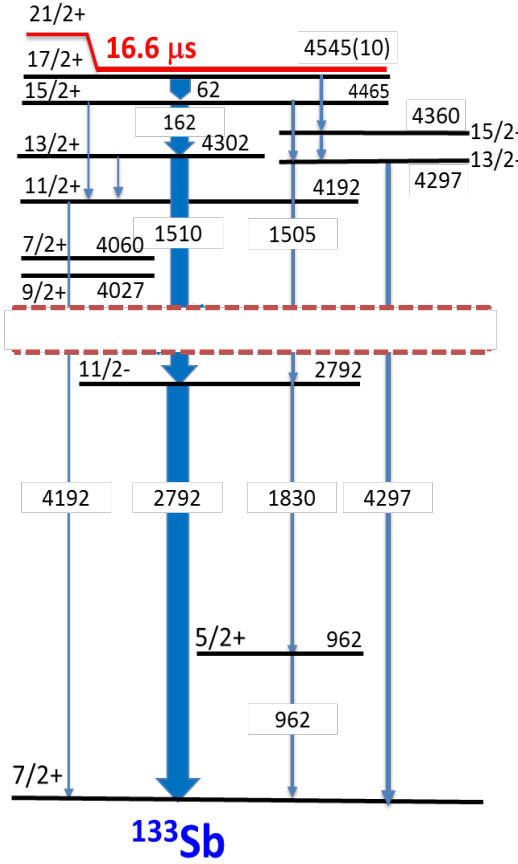
- *Single particle levels*
- ***Couplings** between particle and phonons*

Double SHELL CLOSURE away from Valley of Stability

long-lived microsecond isomers

limited yrast spectroscopic studies

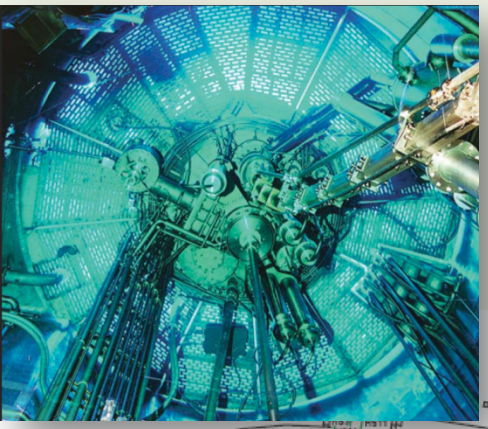




The γ-Spectroscopy Campaign @ ILL-reactor (Grenoble)

2012-2013: 2 Reactor Cycles (100 days, 95% DATA Taking)

58 MW REACTOR



World Brightest Continuum neutron source

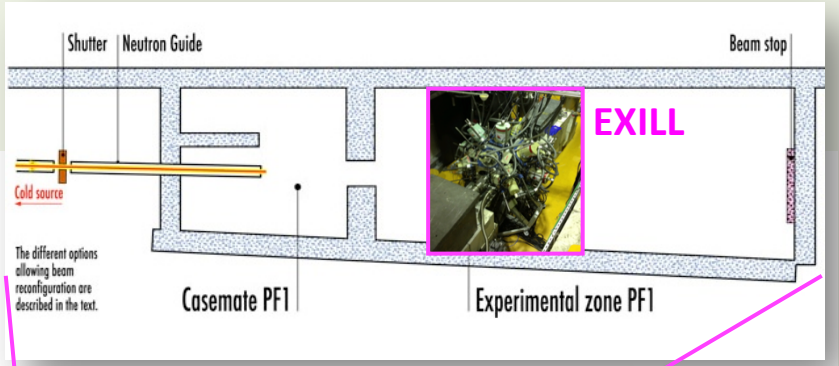
In pile

$\Phi_n = 5\times10^{14}$ n cm^{-2} s^{-1}

Dedicated ballistic neutron guide

Highly collimated beam (1 cm²)
Cold neutrons (meV)

$\Phi_n = 2\times10^{8}$ n cm^{-2} s^{-1}



Reactor hall ILL 5
Experimental level (C)

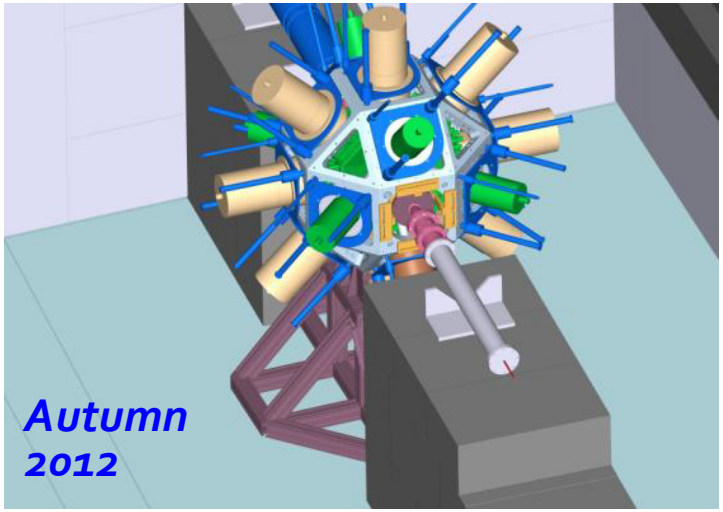
Neutron guide hall - ILL 7
Chartreuse side (EAST)

First time a large HPGe array (52 Ge crystals) installed around a highly collimated cold-neutron beam

SETUP 1

γ – spectroscopy

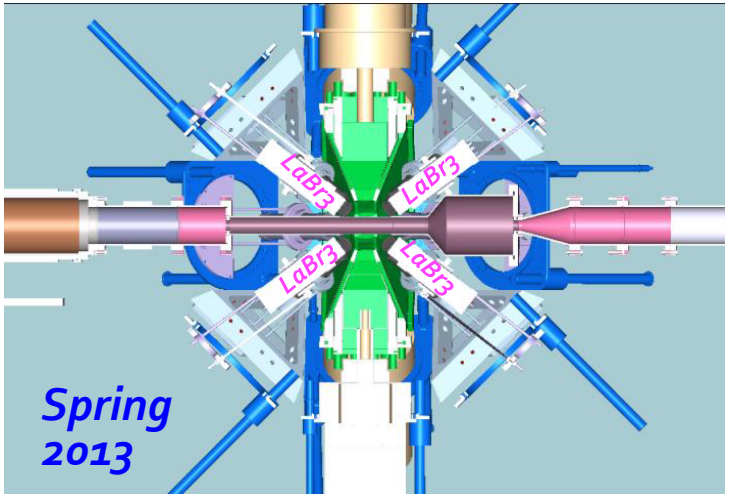
10 EXOGAM – Clovers + 6 Ge GASP
6% efficiency



SETUP 2

Lifetime Measurement

8 EXOGAM – Clovers + 16 LaBr3
Fast Timing



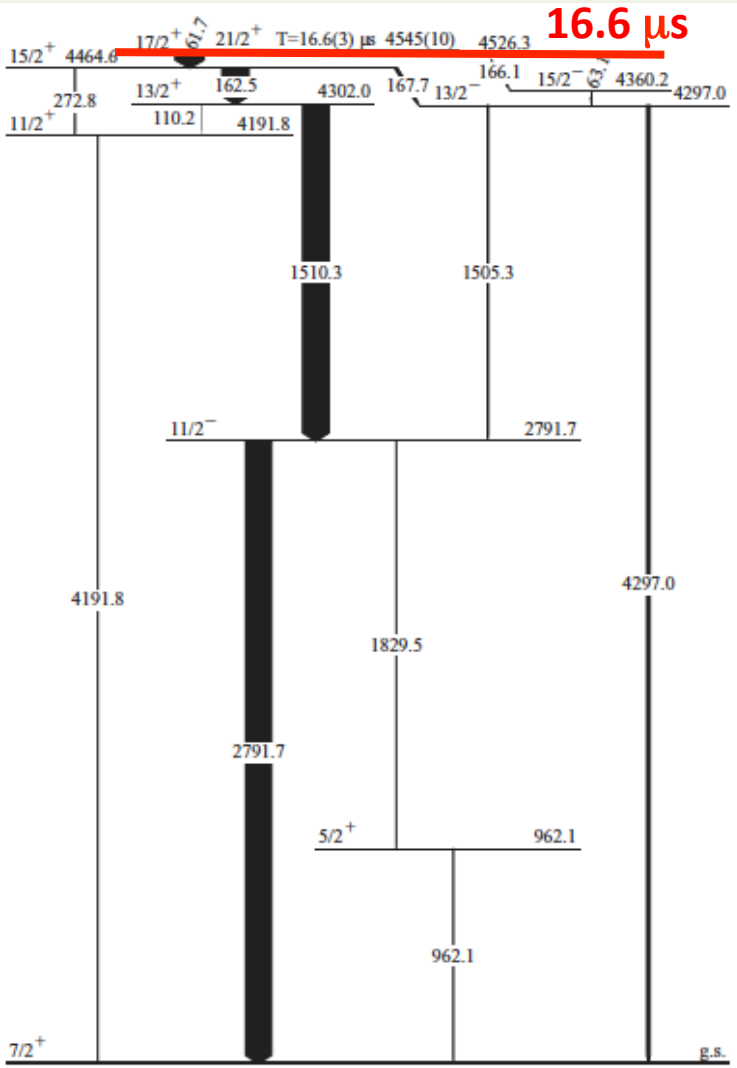
The ACQUISITION SYSTEM

A Fully Digital Approach, TRIGGERLESS

>10 kHz/crystal, **>600 kHz total, 10 ns clock**
*Unique opportunity for **γ-coincidences** over **several μs** time window*

→ ***n-induced fission*** *on ^{235}U and ^{241}Pu and* ***(n,γ)*** *on several targets*

G. DeFrance, A. Blanc, U. Koster, M. Jentschel, P. Mutti, G. Simpson, J.M. Regis, C. Ur et al.



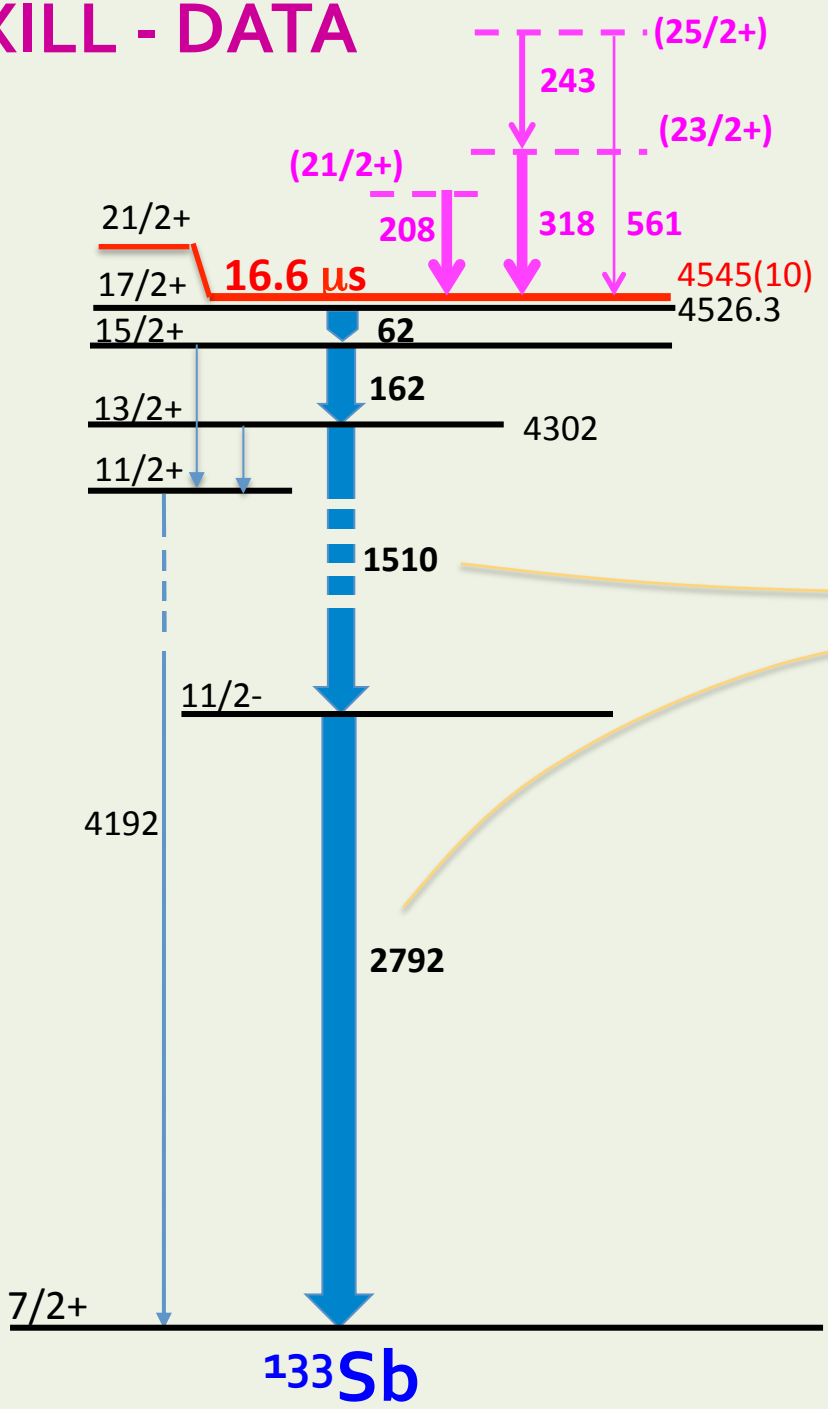
^{133}Sb

FIG. 5. Partial level scheme of ^{133}Sb as obtained in the present work. Excited levels and γ transitions are labeled with energies given in keV.

Isomer Decay
Measured
at the focal plane of
LOHENGRIN separator (ILL)

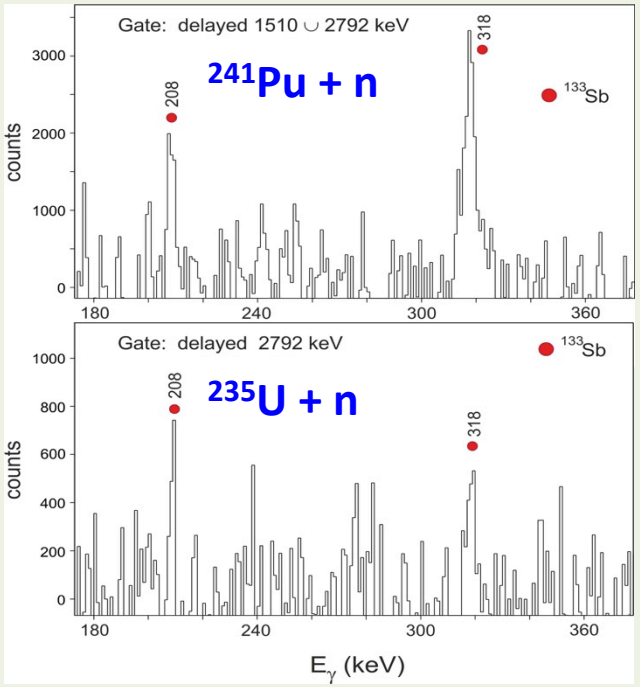
W. Urban et al., PRC79(2009)037304

EXILL - DATA



Prompt-Delayed Coincidences

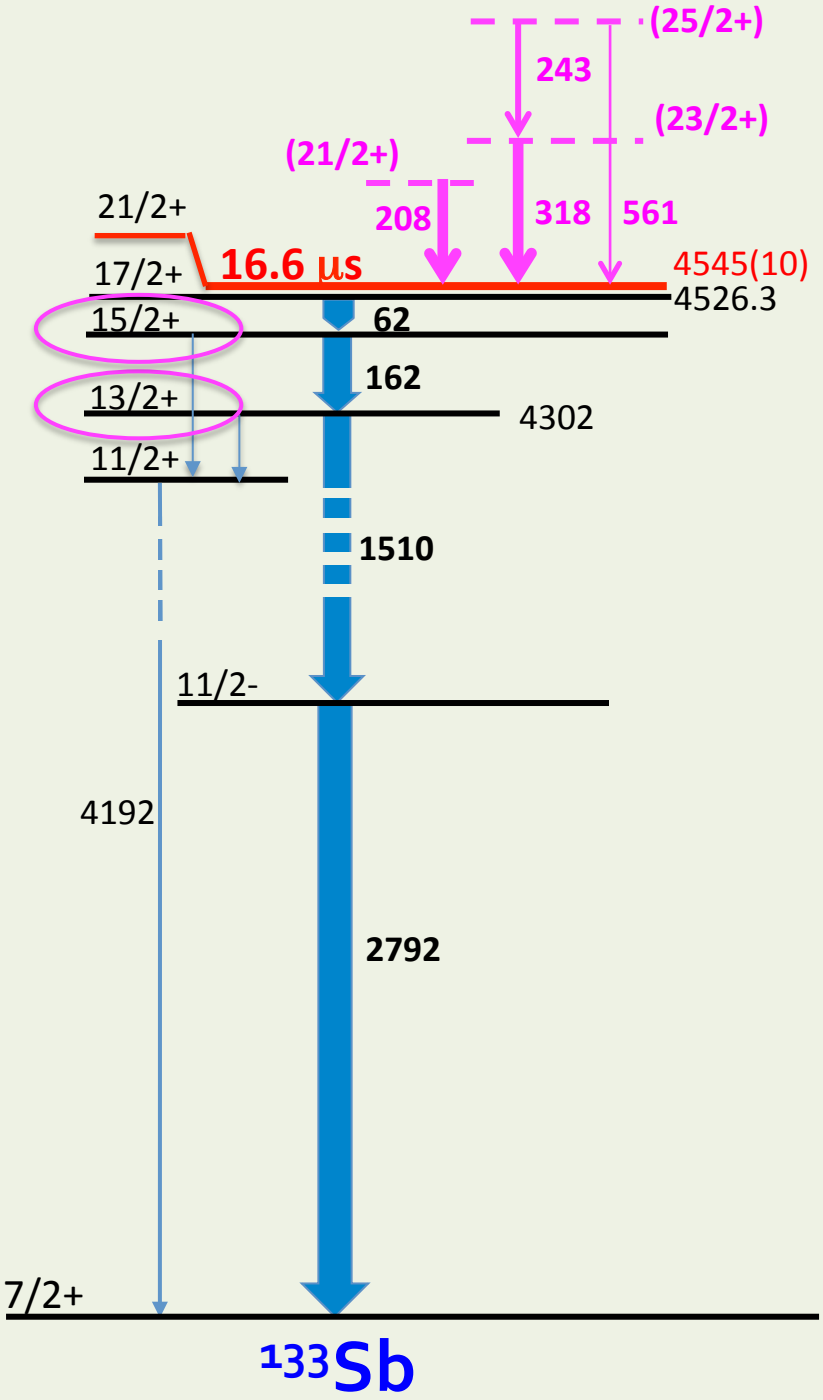
over μs time range



Feeding of the ISOMER

Spins up to 25/2+

G. Bocchi – PhD Thesis, Milano



INTERPRETATION

Multiplet of states

$11/2^+, 13/2^+, \ldots 25/2^+$

Lifetimes Analysis with Scintillators

	τ_{EXP}	B(M1,I→I-1)
15/2+	≈10 ps	0.7 W.u.
13/2+	≈40 ps	0.005 W.u.

> 100

Not Simple Configurations !

Interpretation of ^{133}Sb DATA ?

For systems with A ≈ 100

LARGE SHELL Model *Calculations*
Involving complex ***CORE-excitations are NOT possible !***

→ 3p – 3h excitations take weeks with 10^6 processors
→ More Complex Configurations are impossible

A New Approach

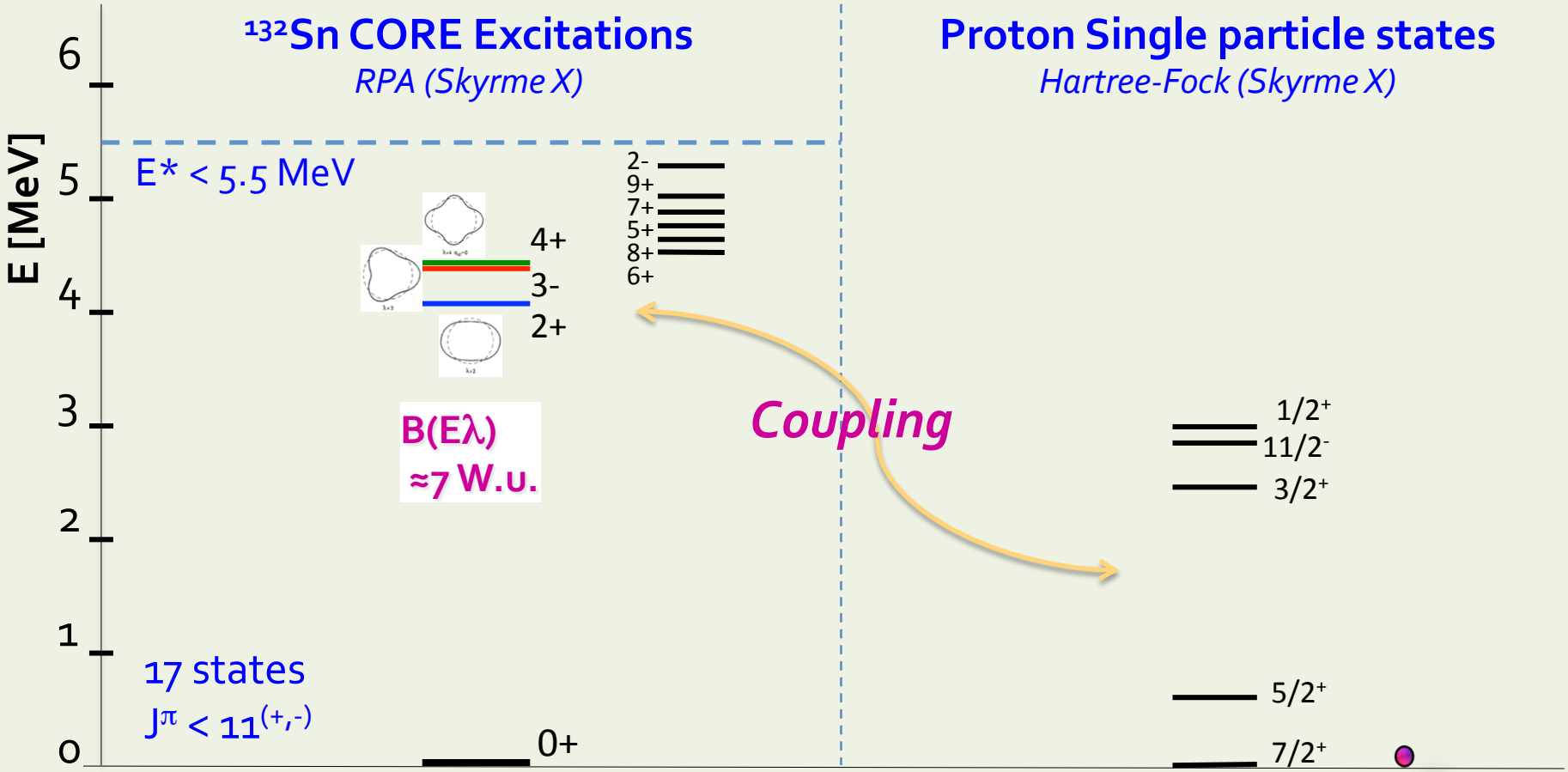
HYBRID Model:

Extended Microscopic Particle-Vibration Coupling Model

G. Colò, P.F. Bortignon (Milano)

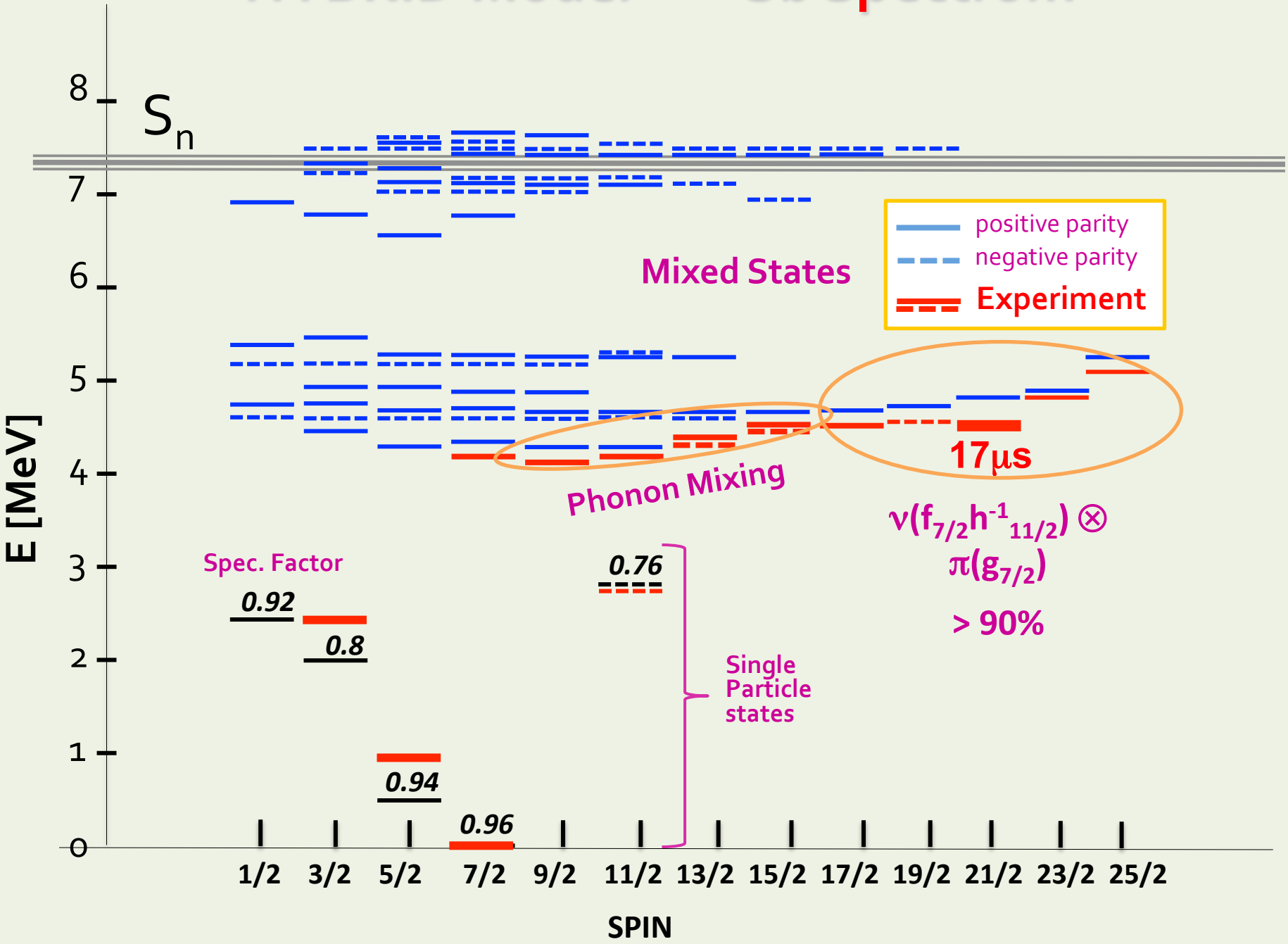
HYBRID Model – Main ingredients

^{133}Sb: ^{132}Sn + 1π



→ ***Coupling matrix elements*** *between* ***single particle*** *and* ***CORE excitations*** *are consistently calculated with the* ***same SkX interaction***

HYBRID Model – ^{133}Sb Spectrum



Lesson Learned from ^{133}Sb

1. ***EXPERIMENT*** *gives evidence for* ***HIGH spin*** *and* ***MIXED*** *configurations*
2. ***LARGE SHELL*** *Model Calculations* ***are NOT doable***
3. ***New HYBRID Model:***

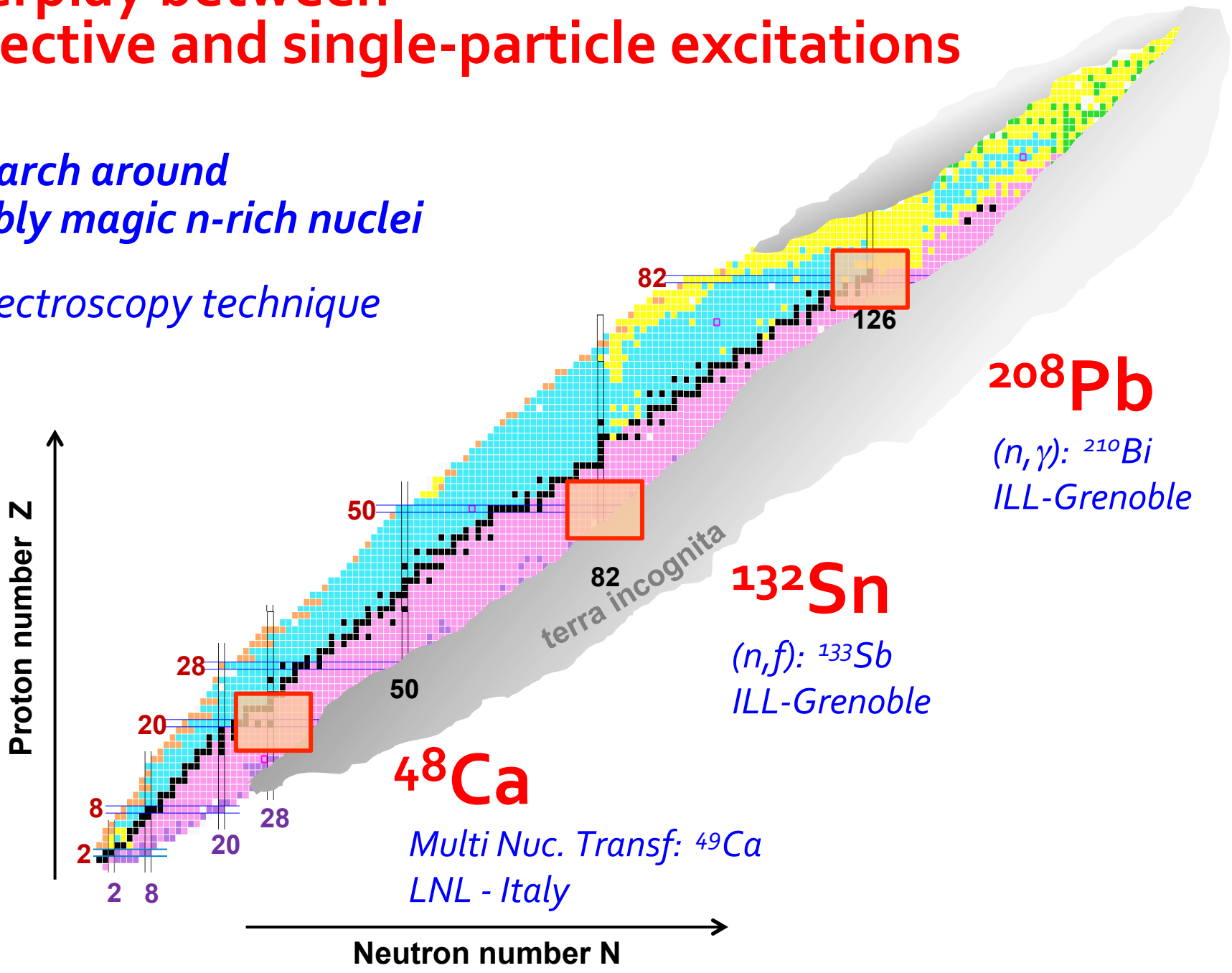
   Coupling of different type of CORE excitations (few nucleons, phonons) to valence particles

→ ***SATISFACTORY Agreement with Experiment***

Interplay between collective and single-particle excitations

a search around doubly magic n-rich nuclei

γ-spectroscopy technique



^{208}Pb

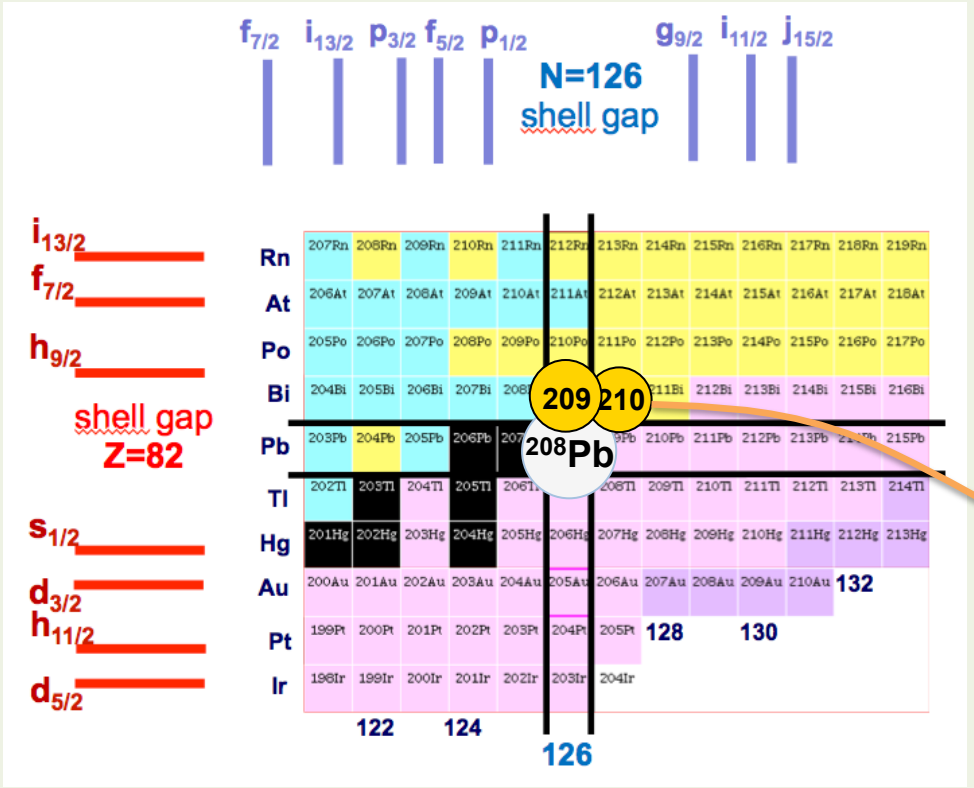
(n,γ): ^{210}Bi
ILL-Grenoble

^{132}Sn

(n,f): ^{133}Sb
ILL-Grenoble

^{48}Ca

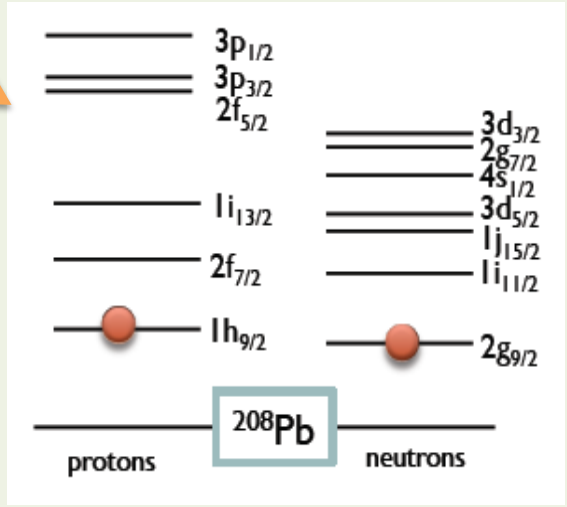
Multi Nuc. Transf: ^{49}Ca
LNL - Italy

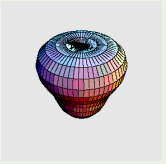


^{210}Bi

- ***Couplings*** *between valence proton and neutron*
- ***Couplings*** *between phonons and pn - pair*

^{208}Pb + 1π + 1ν





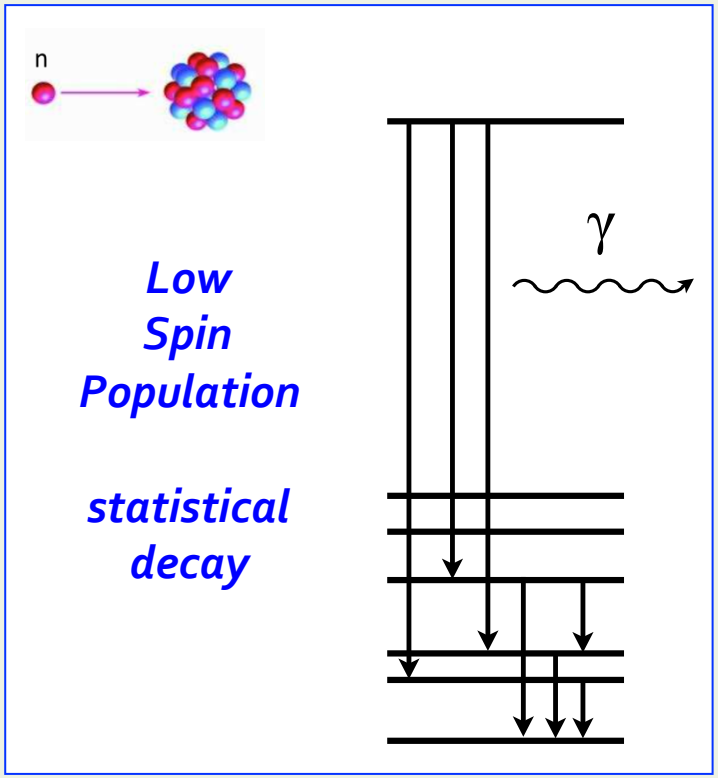
3- in ^{208}Pb (34 Wu)

Doubly-magic SHELL CLOSURE At the Valley of Stability

The nuclei around ^{208}Pb are ***strongly influenced*** by the very collective ***3$^-$ octupole phonon*** of ^{208}Pb, E_x = 2.6 MeV, B(E3) = 34 W.u

Particle-Phonon Multiplet in **^{209}Bi**: ^{209}Bi(d,d'), ^{209}Bi(α,α'), …, Bohr-Mottelson Model (1970)

$^{209}Bi(n,\gamma)^{210}Bi$ – ILL Grenoble



$^{209}Bi(n,\gamma)^{210}Bi$ – ILL Grenoble

54 primary transitions (31 new)

3081

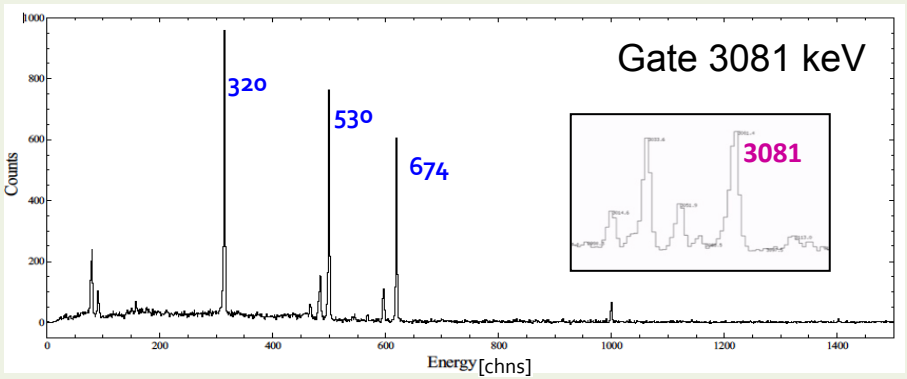
4605.2(1) keV S_n
4⁻,5⁻

61 excited states (24 new)

530

674

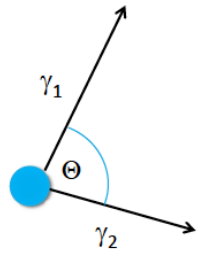
320



Angular Correlations

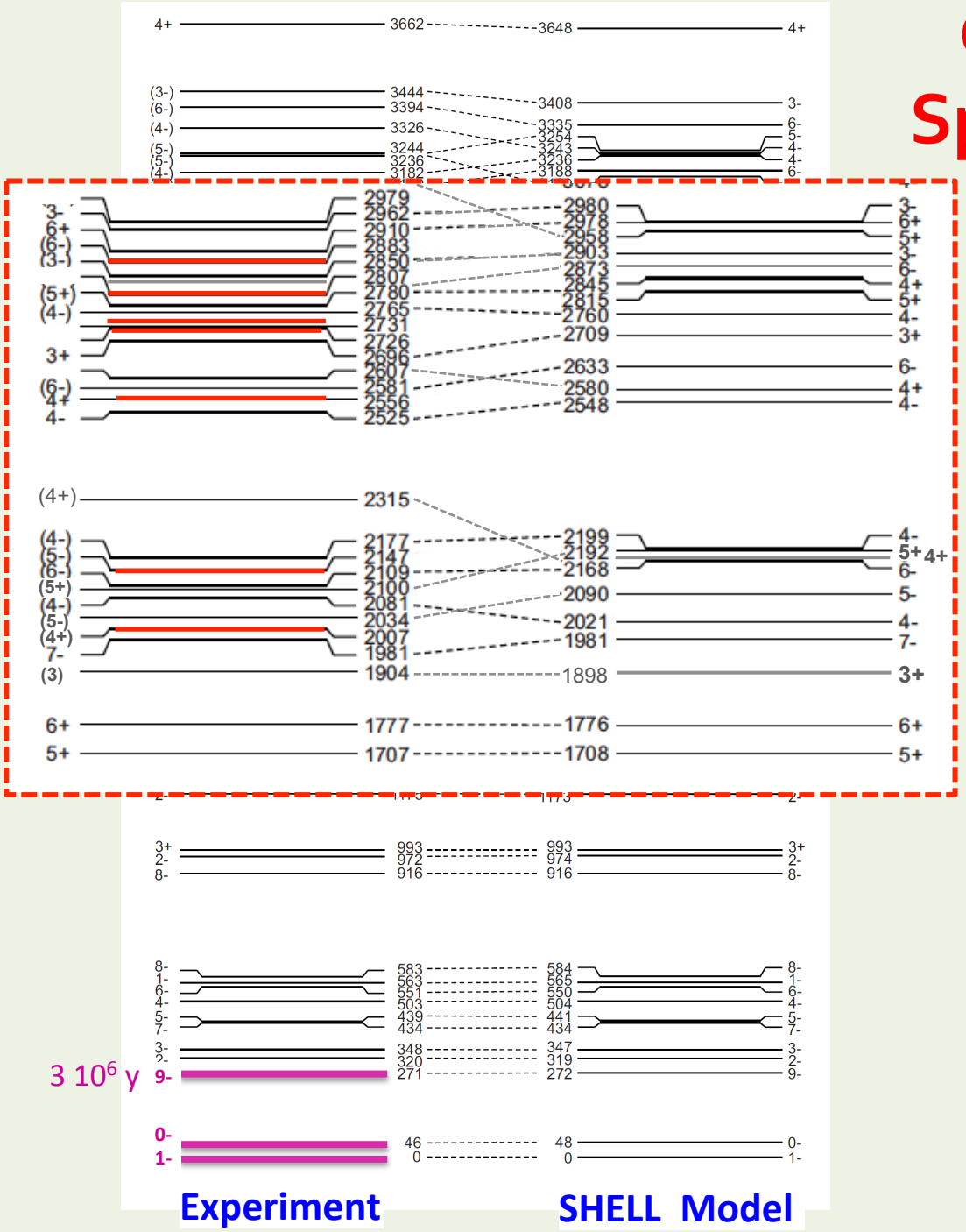
$$W(\Theta) = 1 + A_2 P_2(\cos\Theta) + A_4 P_4(\cos\Theta)$$

Multipolarities of γ-decay
Spin (Parity) of States



N.Cieplicka, PhD-Thesis, Krakow

Complete Low Spin Spectroscopy of ^{210}Bi

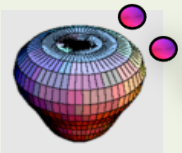


Comparison with SHELL Model

considering
one valence proton and
one valence neutron
outside ^{208}Pb frozen CORE

*Only **few** Low-Spin States*
*in the interval **2-3 MeV***
***NOT** described by*
SHELL Model

Possible
$3^- \otimes (\pi h_{9/2} \nu g_{9/2})$
configuration ?



$E_x(3^-)$ = 2.6 MeV

Lesson Learned from ^{210}Bi

1. ***EXPERIMENT*** *gives* ***COMPLETE*** *spectroscopy of* ***LOW spin*** *states*
2. ***SHELL*** *Model Calculations (with frozen CORE)* ***reproduce almost ALL states*** *originated from the couplings between valence particles*
3. *Above 2 MeV, states from* ***particles-phonon coupling appear***

Testing ground for the New HYBRID Model – CORE + 1 p + 1 n

Conclusions

✧ **Studies of COUPLINGS between PARTICLE and CORE excitations around DOUBLE SHELL CLOSURES**

→ ***Key ingredients for***

quenching of Spectroscopic factors,
damping phenomena,
hanarmonicity of vibrational spectra, …

Impossible to describe by SHELL MODEL Calculations for A > 50
Up to now Mainly interpreted Phenomenologically

✧ **SURVEY of RECENT γ-spectroscopy DATA on excited structures near doubly magic nuclei (hard to reach)**

^{49}Ca – *Multinucleon Transfer*

^{133}Sb – *Neutron Induced Fission*

^{210}Bi – (n,γ)

from Legnaro-INFN Laboratory and ILL (Grenoble)

→ ***Experimental evidence for particle-phonon states***

✧ **New Microscopic Approach: The Hybrid Model**

→ ***Possible Basis for Future Theoretical Description of Complex excitations in Heavy Nuclei***

The Collaboration

Milano University and INFN

A. Bracco, G. Benzoni, N. Blasi, F. Camera, **F**. Crespi, S. Leoni, B. Million, O. Wieland,
R. Avigo, **S. Bottoni**, **G. Bocchi**, S. Ceruti, A. Giaz, **D. Montanari**, R. Nicolini, L. Pellegri,
P.F. Bortignon, G.Colò, et al.

IFJ-PAN, Krakow, Poland

B. Fornal, A. Maj, P. Bednarczyk,, M. Ciemala, **N. Cieplicka**, M. Kmiecik, M. Krzysiek, B. Szpak et al.,

Legnaro INFN Laboratory

G. DeAngelis, D. Napoli, J.J. Valiente-Dobon, L. Corradi, E. Fioretto, A. Stefanini et al.

Padova University and INFN

D. Bazzacco, E. Farnea, S. Lenzi, S.Lunardi, D. Mengoni, G. Montagnoli, F. Recchia, F. Scarlassara, C.Ur, et al.

IFIN-HH Bucharest

N. Marginean, D. Bucurescu, C. Mihai, C. Nita et al.

CSIC-University of Valencia

A. Gadea

EXILL Collaboration

G. DeFrance, A. Blanc, U. Koster, M. Jentschel, **C. Michelagnoli**, P. Mutti, G. Simpson, J.M. Regis et al.

Thank You for the Attention