Gamma spectroscopy as a tool to search for particle–phonon coupled states: status and perspectives

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Nuclear Structure Physics with Advanced Gamma–Detector Arrays (NSP13)

10-12 June 2013 *Palazzo del Bo', Padova, Italy*
Europe/Rome timezone

Collaboration

Milano University and INFN

A. Bracco, S. Bottoni, G. Bocchi, G. Benzoni, N. Blasi, F. Camera, F. Crespi, S. Leoni, B. Million, O. Wieland et al.

P.F. Bortignon, G.Colò, et al.

Legnaro INFN Laboratory

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

Padova University and INFN

D. Bazzacco, E. Farnea, S. Lenzi, S.Lunardi, A. Gottardo, G. Montagnoli, D.Montanari, F.Scarlassara, C.Ur, et al.

IFIN-HH Bucharest

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

IFIC, CSIC-University of Valencia, Spain

A. Gadea, ...

Krakow, Poland

A. Maj, P. Bednarczyk, B. Fornal, M. Kmiecik, M. Ciemala et al.,

Ruder Boskovic Institute, Zagreb

S. Szilner et al.

EXILL Collaboration

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

OUTLINE:

- **INTRODUCTION**

  1. Importance of **Particle-Phonon** correlations in nuclear structure studies

  2. Experimental and Theoretical Approach

  3. The case of ^{49,47}Ca:
     Heavy-Ion Transfer reactions as a tool for complete in-beam γ-spectroscopy

  4. The case of ^{65}Cu:
     Particle-Phonon Coupling around Ni Isotopes

- **WORK in PROGRESS and PERSPECTIVES:**

  1. (n,γ) Data from ILL

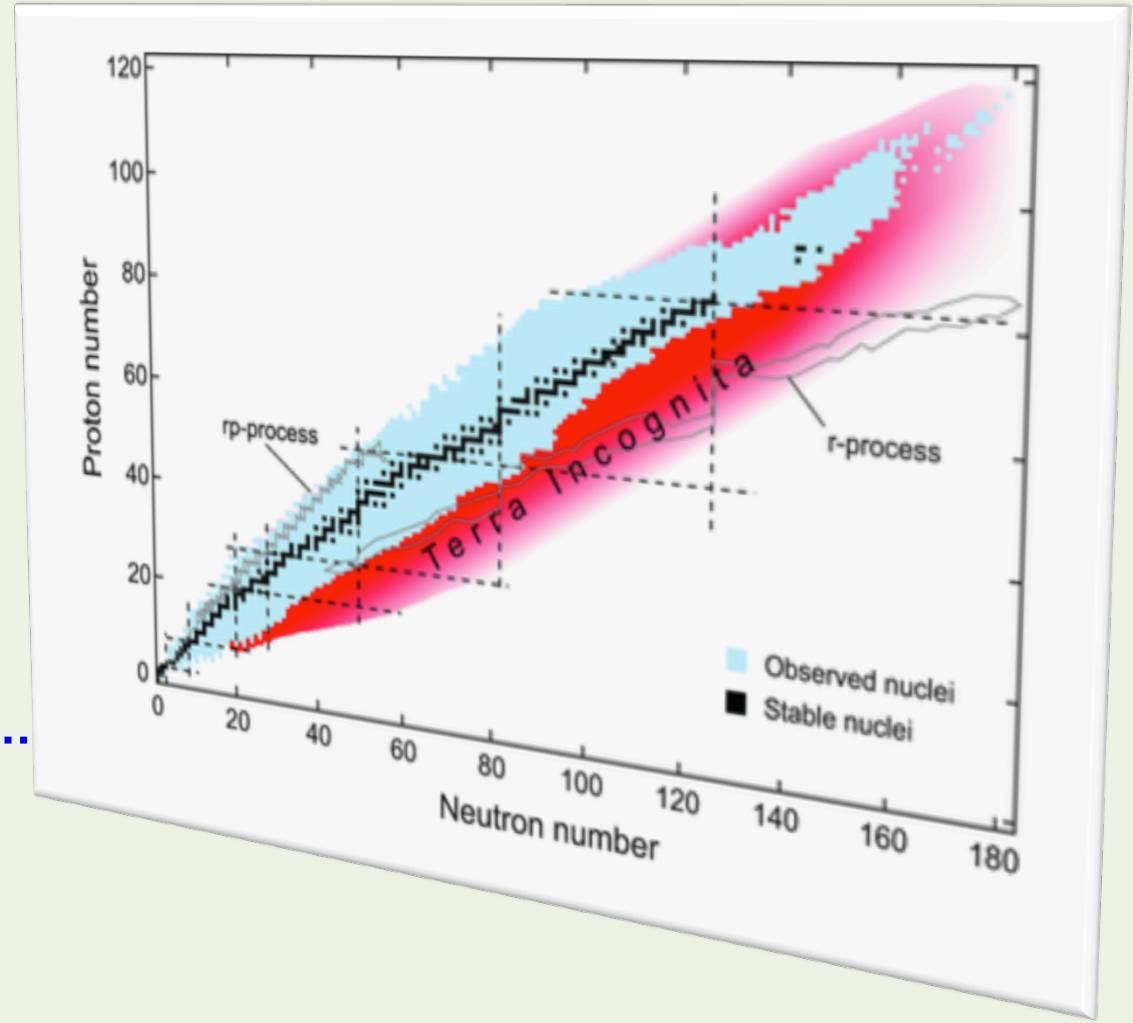
  2. Future studies with RIB around ^{132}Sn

HOT topic in Nuclear Structure

Evolution of Shell Structure with N/Z

Study of Shell closures, Magic Numbers, Effective Nuclear Force, …

- **Doubly Magic Nuclei**
- **Near to Magic Nuclei**
  (1 and 2 nucleons away)



Experimental Tools

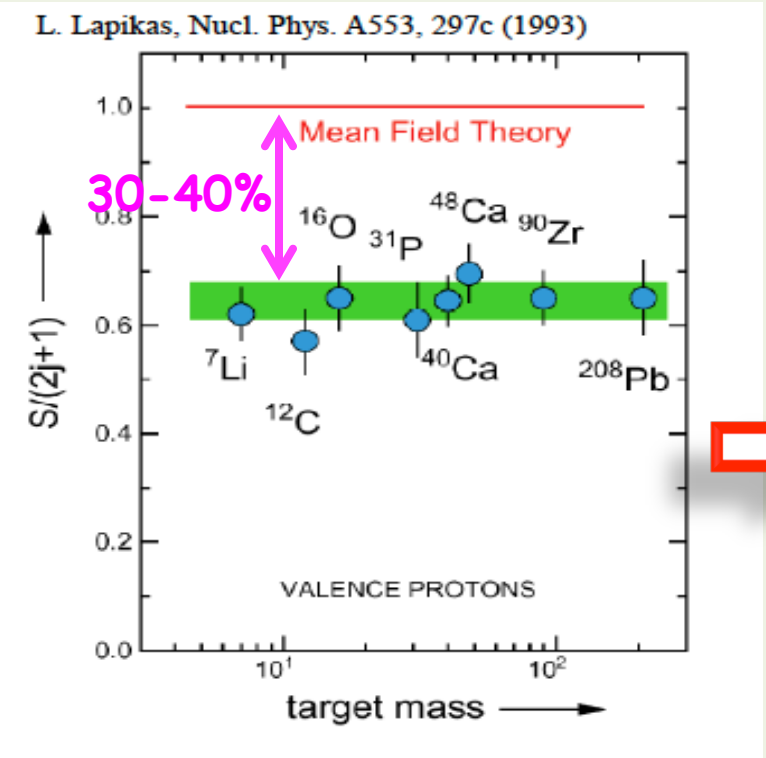
- **Coulex**
  → **Collectivity B(E2), B(E3), …**
- **Knock-out, transfer reactions, …**
  → **Spectroscopic Factors**
  Purity of nuclear states
  Single particle ***(SF ~ 1)***
  Correlations ***(SF < 1)***

Spectroscopic Factors

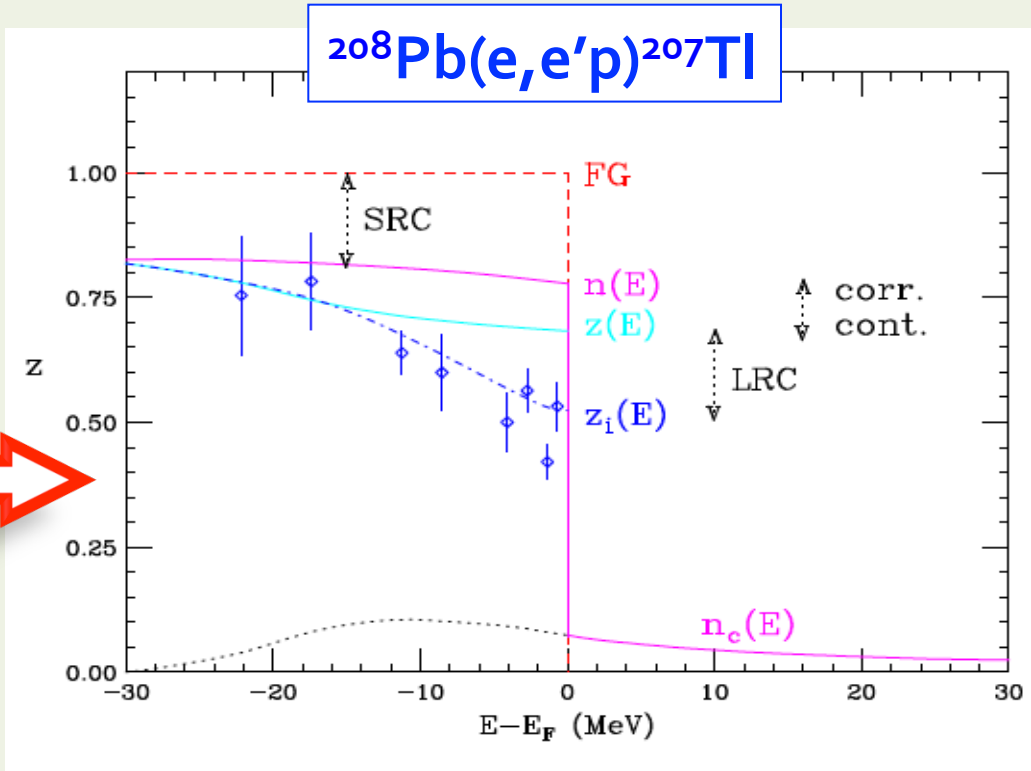
Nature and **Occupancy** of single-particle orbits
→ **Interplay** Single-Particle and Collectivity

$$S_{l,j} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{EX}}{\left(\frac{d\sigma}{d\Omega}\right)_{DWBA}}$$

Crucial test of Shell Model and Interactions



30-40 % reduction of SF
compared to
Independent Particle Model

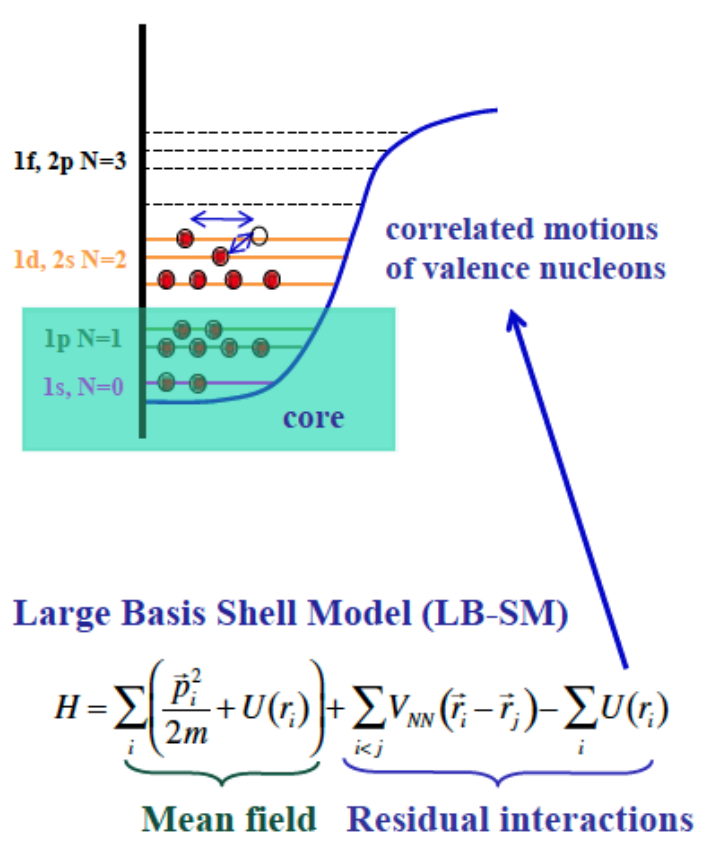


Quenching of SF due to correlations:
SHORT Range: Deeply Bound States
LONG Range (coupling to vibrations): Surface States

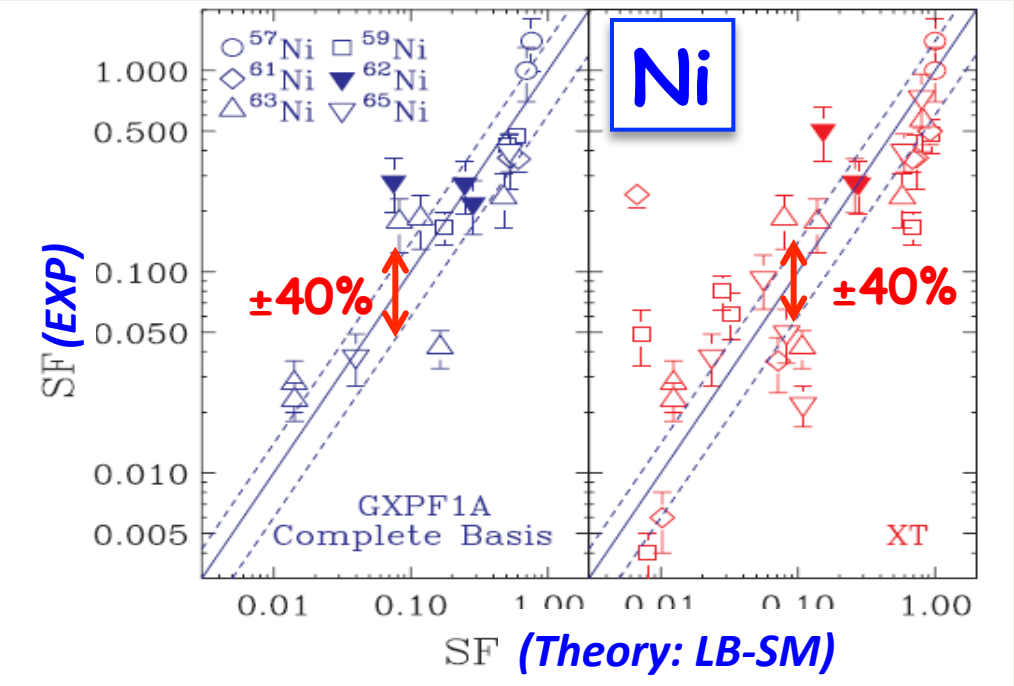
V.R. Pandharipande et al., Rev. Mod. Phys. 89(1997)981

Large Basis Shell Model (LB-SM)

Mainly Correlations among valence nucleons



M.B. Tsang et al. PRL102(2009)062501



Source of discrepancies

- Core excitations
- State fragmentation …

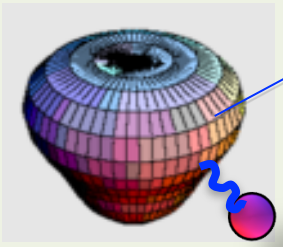
→ ***Coupling between Particle and Vibrations is not FULLY included …***
(LONG RANGE CORRELATION)

V.R. Pandharipande et al., Rev. Mod. Phys. 89(1997)981, C. Barbieri et al. PRL103(2009)20502, …

Focus on Long Range Correlations

→ *only partially included in Shell Model*

Coupling between Particle and Phonon



Key Ingredient for:

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

Research Program in Milano

FOCUS on Particle-Phonon Coupled States

Systematic Study around magic nuclei: Ca, Ni, Sn, …

Experiments:

Transfer with Heavy-Ions @ LNL

(n,γ) and (n,Fission) @ ILL

^{7}Li reactions @ Bucarest

→ ***Preparatory work for SPES, SPIRAL2, HE- ISOLDE, …***

Theory *(Colò, Bortignon)**:***

Coupling with 1 particle

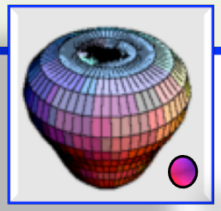
- *effective single particle levels*
- *coupling strength*

Coupling with 2 particles

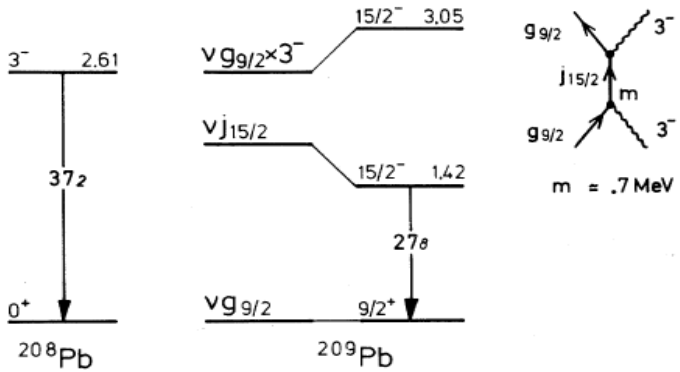
- *core + 2 particles model*
- *physics of pairing*

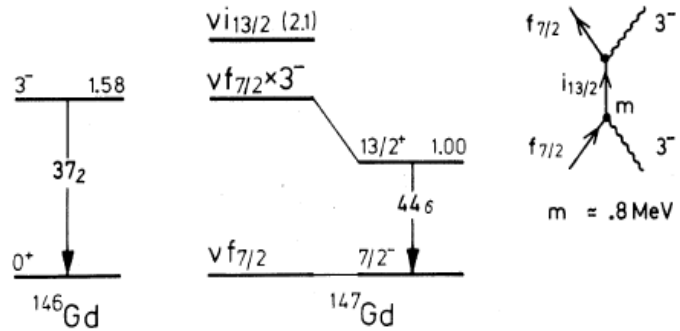
Dependence on Fermi Surface

Experimental STATUS



Up to now: **Scarce Information** Mostly in **Heavy-Masses**





A ~ 200

^{209}**Bi**: Bohr & Mottelson, Vol. II.
^{209}**Pb**: P. Kleinheinz et al.,PRL48(1982)1457
^{207}**Pb**: N. Pietralla et al., PLB681(2009)134

A ~ 150

^{147}**Gd**, ^{147}**Tb**: P. Kleinheinz et al.,PRL48(1982)1457;
P. Kleinheinz, Physica Scripta 24(1981)236.

Evidence for **Particle-phonon couplings** in **A~50** Nuclei

^{49}Ca: $9/2^+$ @ 4017 keV $= 3^- \otimes p_{3/2}$
^{47}Ca: $11/2^+$ @ 3999 keV $= 3^- \otimes f^{-1}_{7/2}$

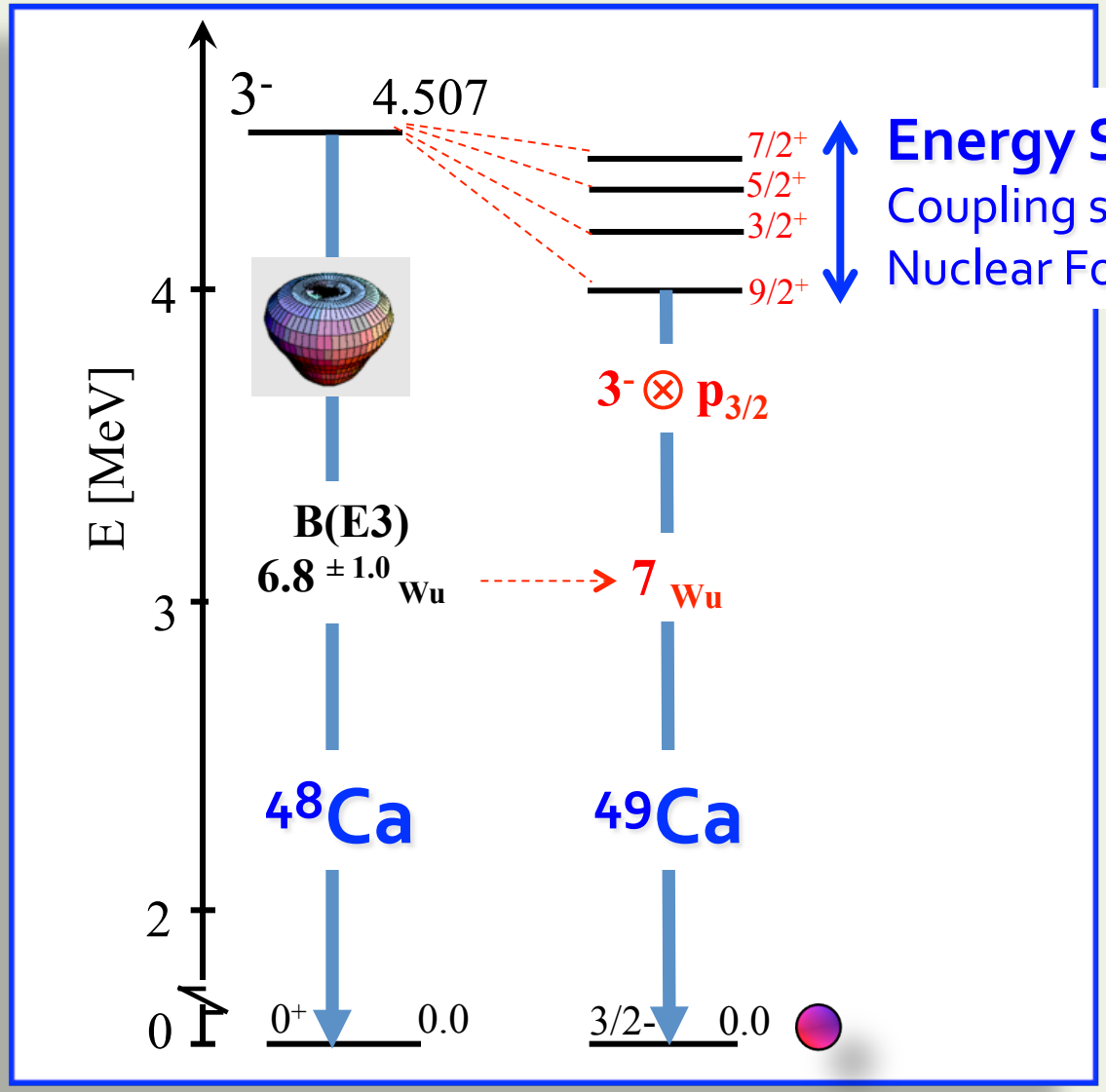
indication also in ^{41,43}Ar: S. Szilner et al., PRC84(2011)014325
^{65}Co: F. Recchia et al., PRC85(2012)064305 *lifetime analysis ??*

→ ***Robustness of Collectivity in rather Light systems***

Experimental Signature

- Multiplet of States: $|l-j| \le I \le l+j$
- B(Eλ) of phonon

^{48}Ca
(Z=20,N=28)

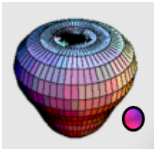


Theoretical Description

PHENOMENOLOGICAL

Particle-phonon
WEAK coupling calculations
(Bohr & Mottelson)

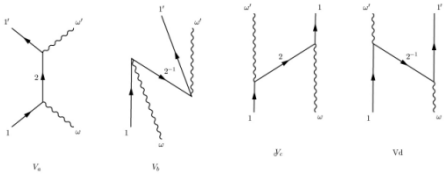
^{49}Ca $3^- \otimes p_{3/2}$
$[\lambda \otimes j_1]_I$



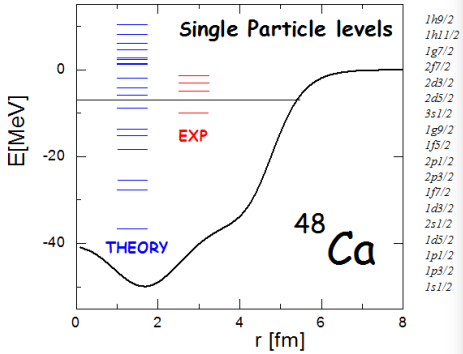
Multiplet of States $9/2^+, 7/2^+, 5/2^+, 3/2^+$

Energy Shift $$\delta E(I)_{a,b,c,d} = \pm \sum_{j_2} \frac{h^2(j_2, j_1, \lambda)}{\varepsilon(j_1) - \varepsilon(j_2) \pm \hbar\omega_\lambda} \times C_{recoupling}$$

Lowest order Perturbative Contributions



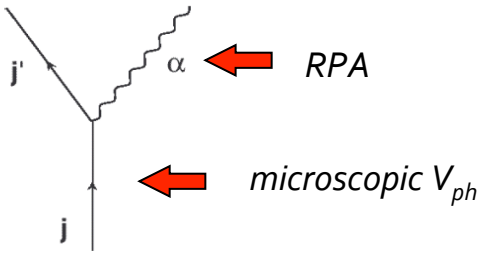
- $\hbar\omega_\lambda$, B(Eλ)
  → Exp. Values/Theory
- s.p. Energies
  $\varepsilon(j_1)$, $\varepsilon(j_2)$
  → HF – SkX
- matrix element
  $h(j_2, j_1, \lambda)$
  → Bohr & Mott.



MICROSCOPIC

Calculations based on

SELF-CONSISTENT Scheme
(Colò, Bortignon, Sagawa, ...)



- **Hartee-Fock with V_{eff}**
  → short-range correlations included
- **Particle-Vibration coupling on top**
  → same Hamiltonian or EDF
- **NO approximation in the vertex**

EXACT treatment of COUPLING

use of WHOLE phonon wave function

Need for More Experimental Input

G. Colò, H. Sagawa, P.F. Bortignon, PRC 82, 064307 (2010).

Best Reaction Mechanism … ?

It has to enhance collective (core)-excitations

- ***Fusion Reactions***
- ***Incomplete Fusion Reactions***

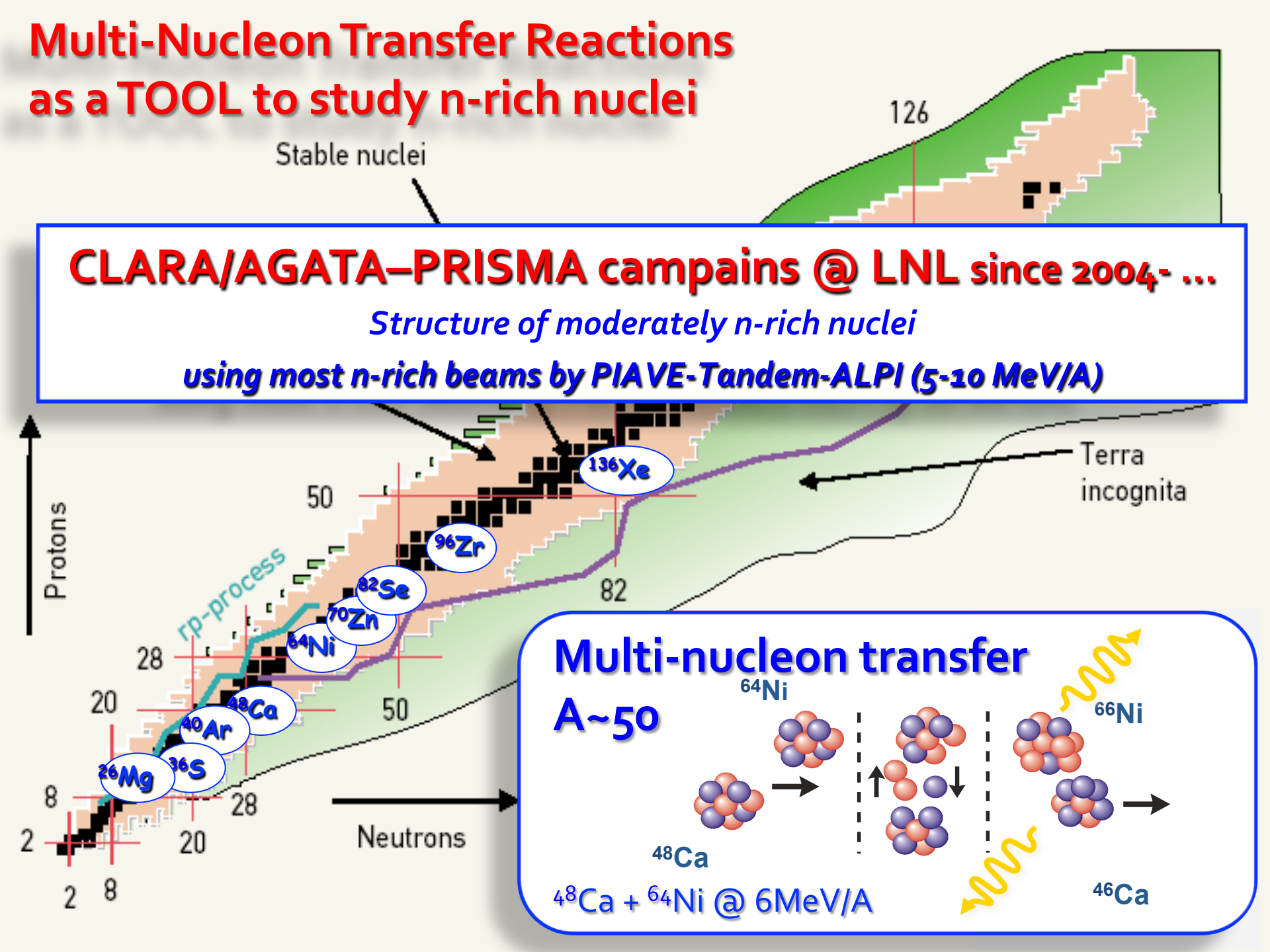
  … need of RIB to reach n-rich systems

- ***Heavy-Ion Transfer Reactions***

  … population of moderately n-rich nuclei even with stable beams

- ***Reactions with ^{7}Li***
- ***(n,γ)***

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



CLARA (ex-EUROBALL)/AGATA – PRISMA setup

Legnaro National Laboratory INFN (Italy)

AGATA Demonstrator @ LNL

Physics Campaign 2010-2011

AGATA
ADVANCED GAMMA TRACKING ARRAY

PRISMA

ΔΩ = 80 msr

ΔZ/Z ≈ 1/60

ΔA/A ≈ 1/190

Energy acceptance ±20%

Bρ = 1.2 Tm

CLARA

25 EUROBALL HpGe Clover

ε~3 % @ E_γ = 1.3 MeV

2π solid angle

3 rings at 100°, 130°, 150°

High-Efficiency γ-particle coincidence Measurements

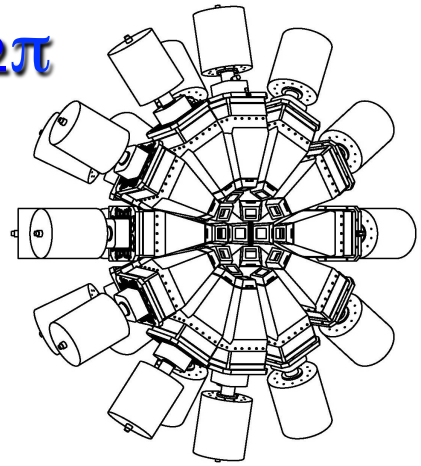
CLARA

25 EUROBALL HpGe Clover

ε~3 % @ E_γ= 1.3 MeV

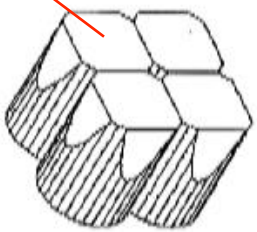
P/T ~45 %

2π

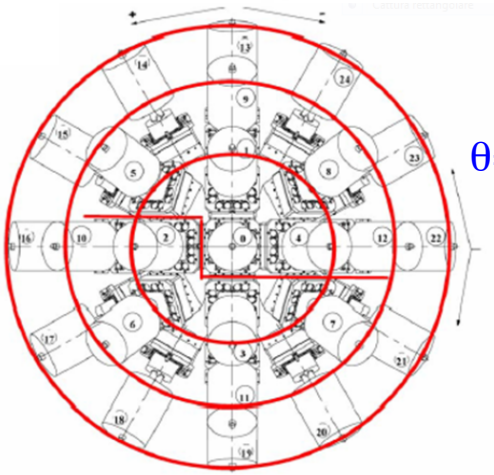


Composite Ge

50mmx70mm



Compton Polarimeters



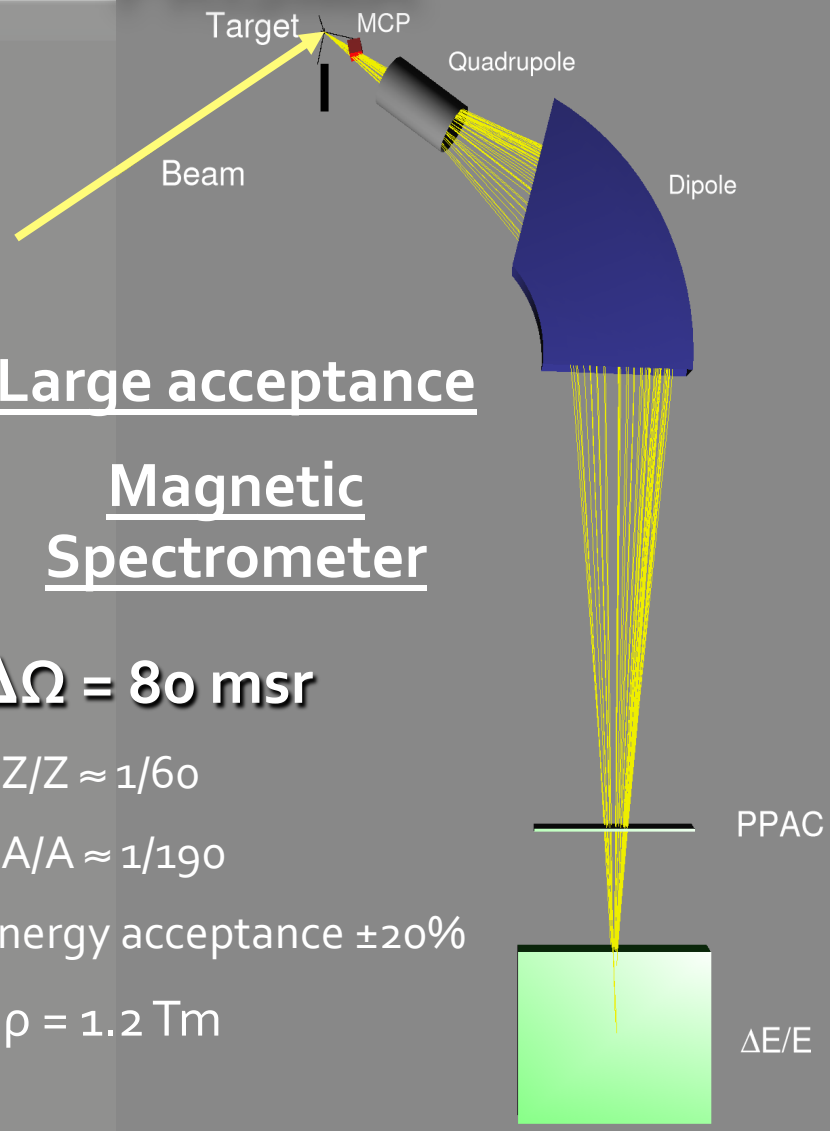
3 RINGS

θ= 100°, 130°, 150°

Angular Distributions γ rays

CLARA always opposite to PRISMA

PRISMA



Large acceptance

Magnetic Spectrometer

ΔΩ = 80 msr

ΔZ/Z ≈ 1/60

ΔA/A ≈ 1/190

Energy acceptance ±20%

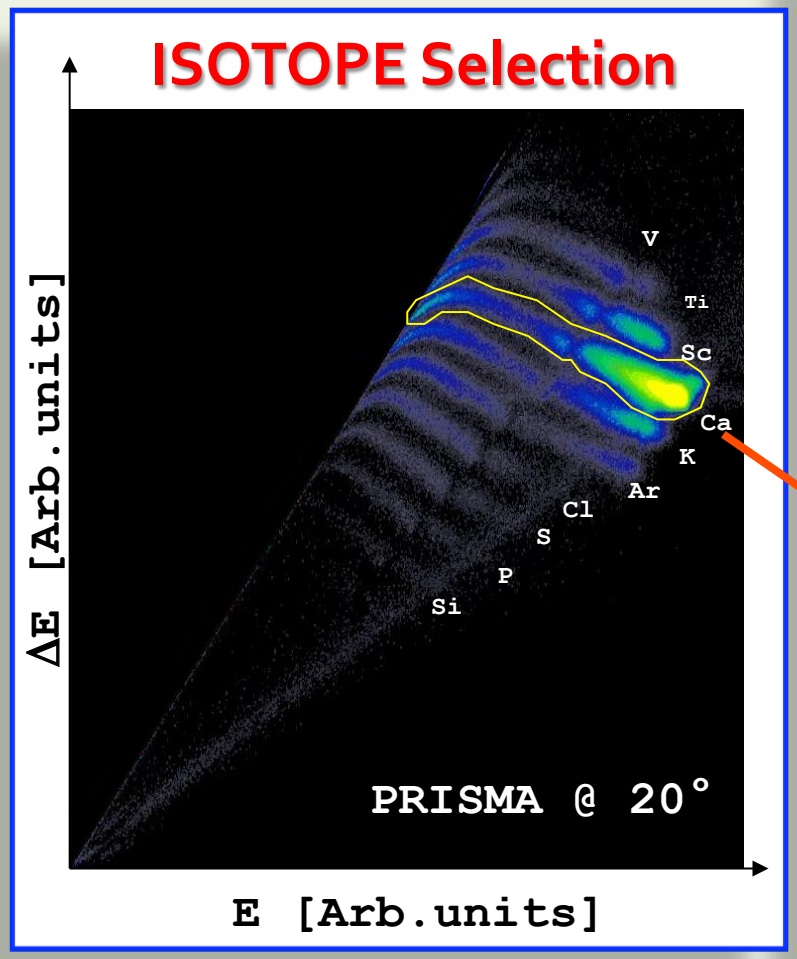
Bρ = 1.2 Tm

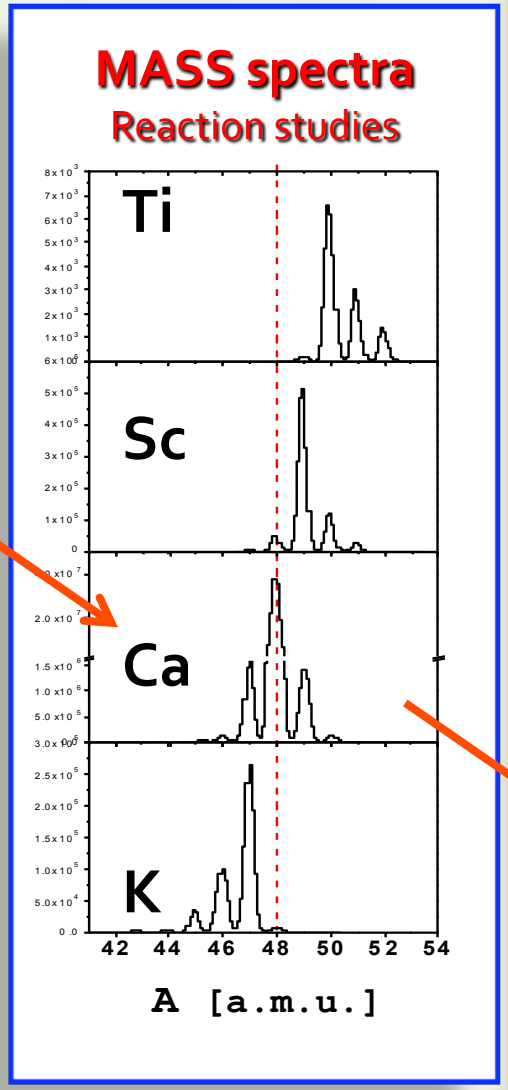
Trajectory Reconstruction - Ion identif.

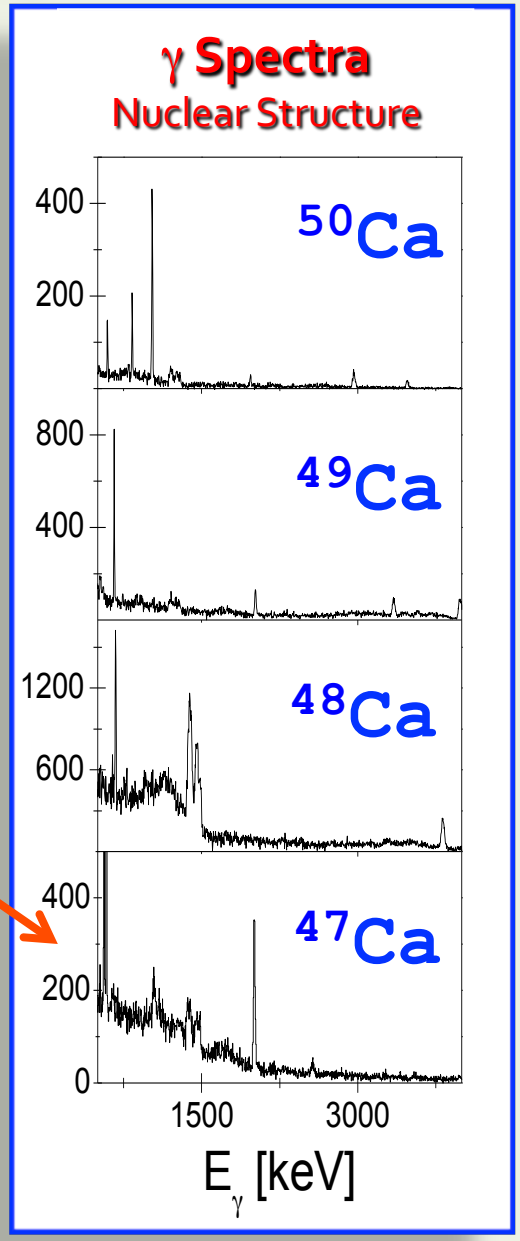
Legnaro National Laboratory INFN (Italy)

$^{48}Ca + ^{64}Ni$ @ 6 MeV/A (v/c ~10%)

CLARA + PRISMA







Daniele Montanari, PhD-Thesis Milano University

γ-particle Coincidence Measurements

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

1 – Reaction Studies

Angular Distributions of ions (Inclusive and γ-gated)

D. Montanari, S. Leoni et al., Phys. Rev. C84(2011)054613
D. Montanari, S. Leoni et al., EPJA47(2011)4

Need for a careful study of spectrometer response

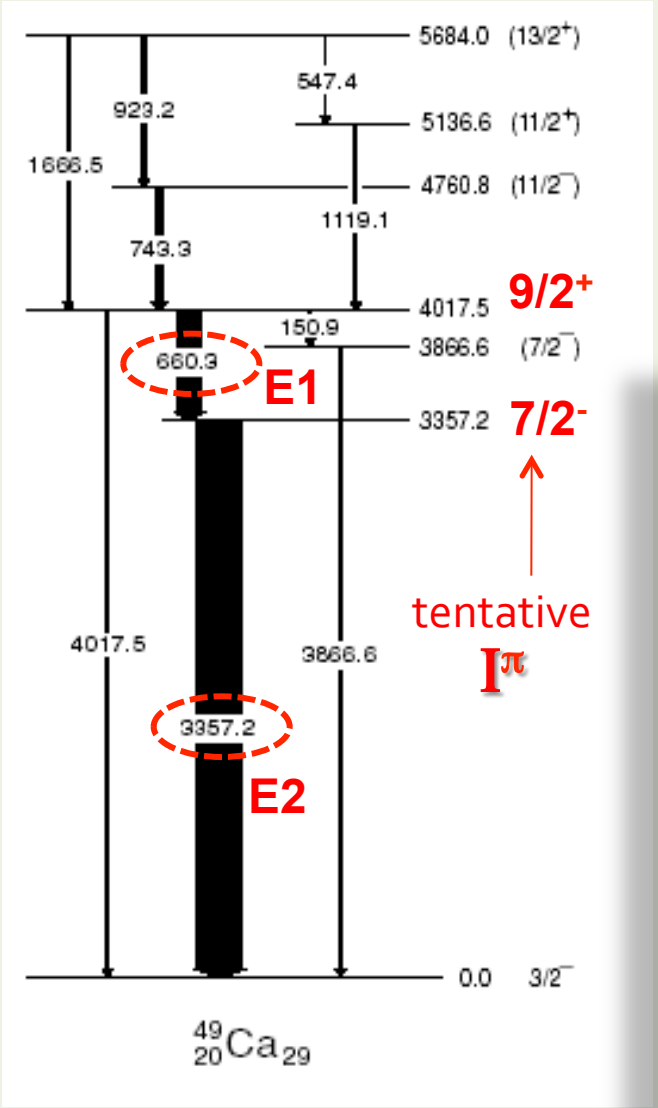
2 – Gamma Spectroscopy

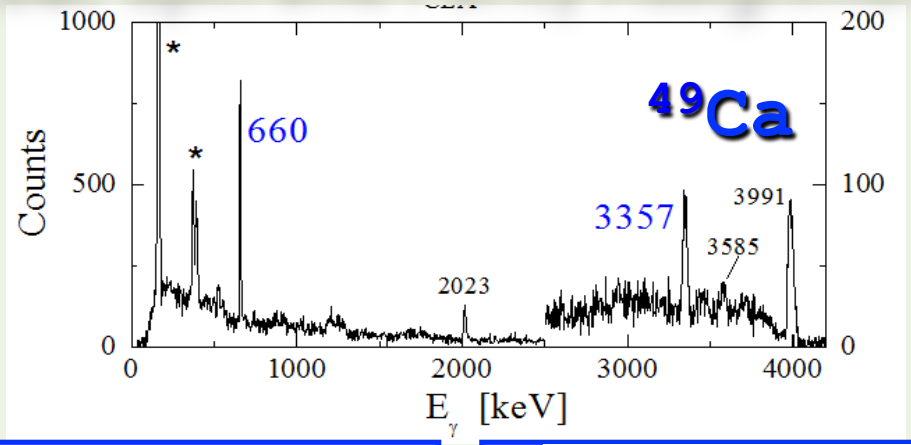
Angular Distributions
Polarizations
Lifetime Analysis

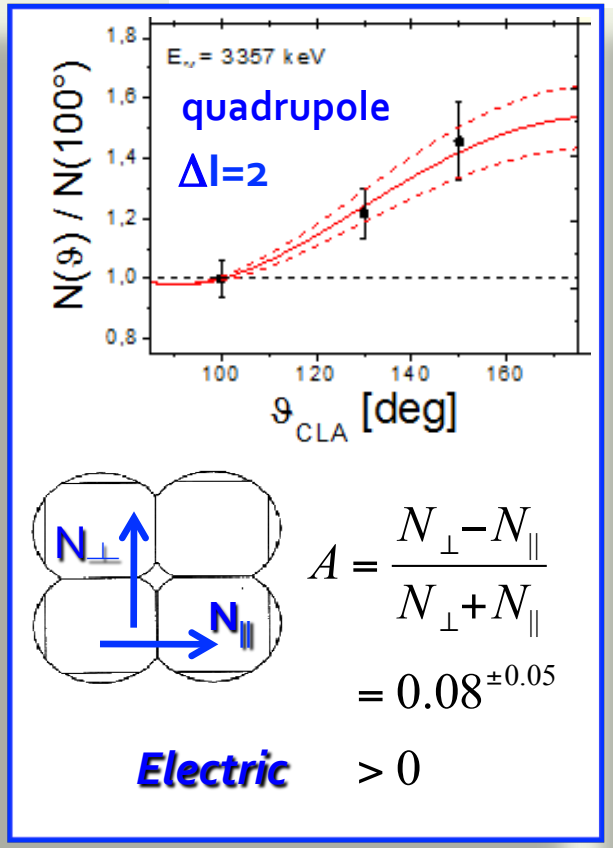
→ *Spin, Parity and Nature of State*

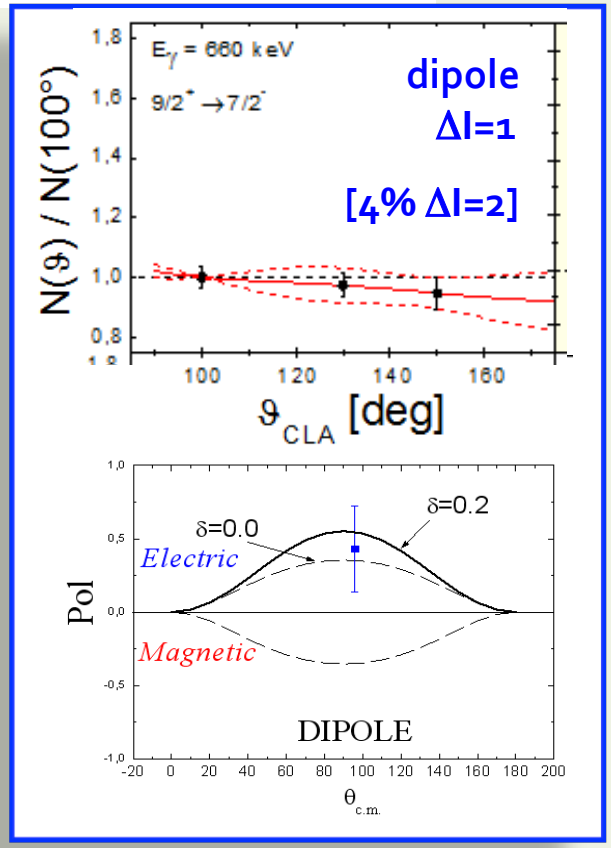
D. Montanari, S. Leoni et al., Phys. Lett. B697(2011)288
D. Montanari, S. Leoni et al., Phys. Rev. C85(2012)044301

Spectroscopy of ^{49}Ca: Spin and Parity Assignment







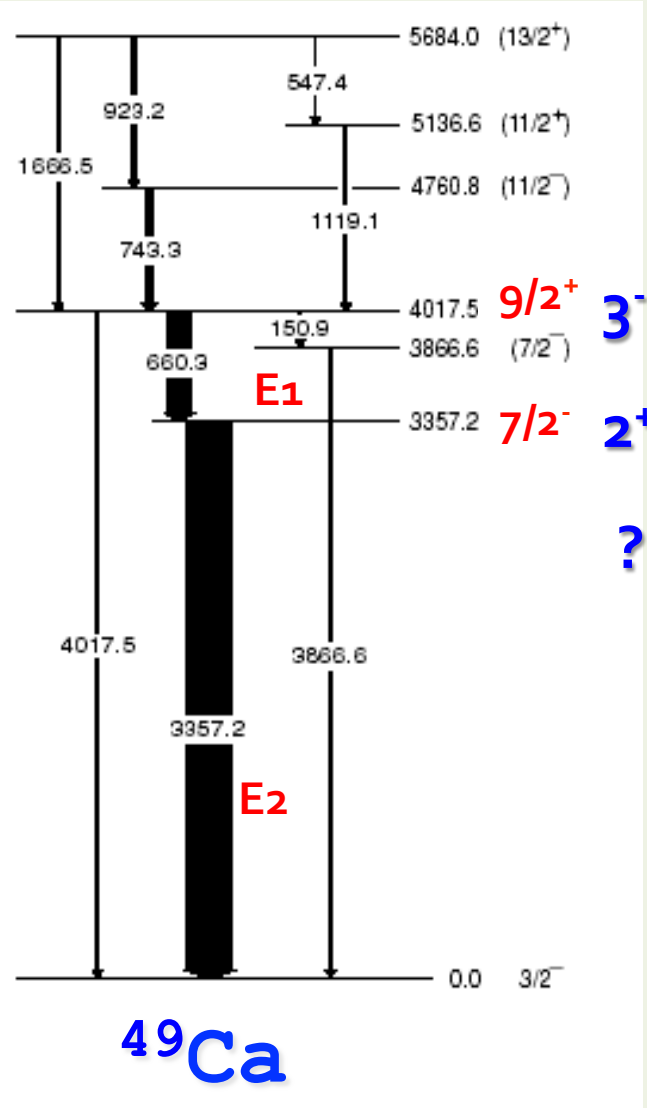


R. Broda, J.Phys.G32(2006)R151

MNT & Thick target data

Interpretation of $7/2^-$ and $9/2^+$

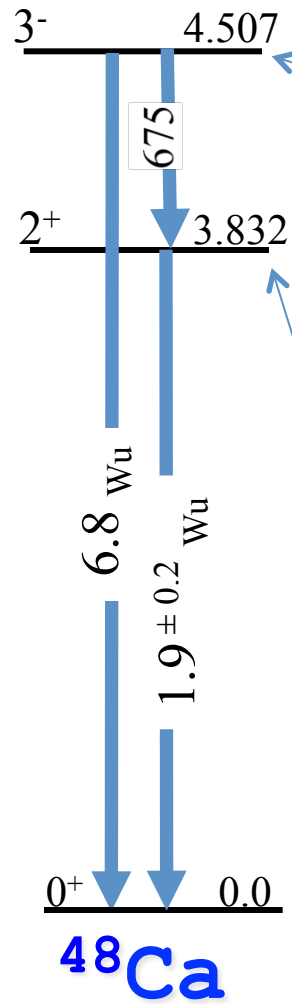
Core(^{48}Ca) - particle ($p_{3/2}$) Couplings ??



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

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

???



Collective Vibration

RPA by Bortignon, Colò:

- **3** components (64, 29, 2%)
- **B(E3) = 7 Wu**

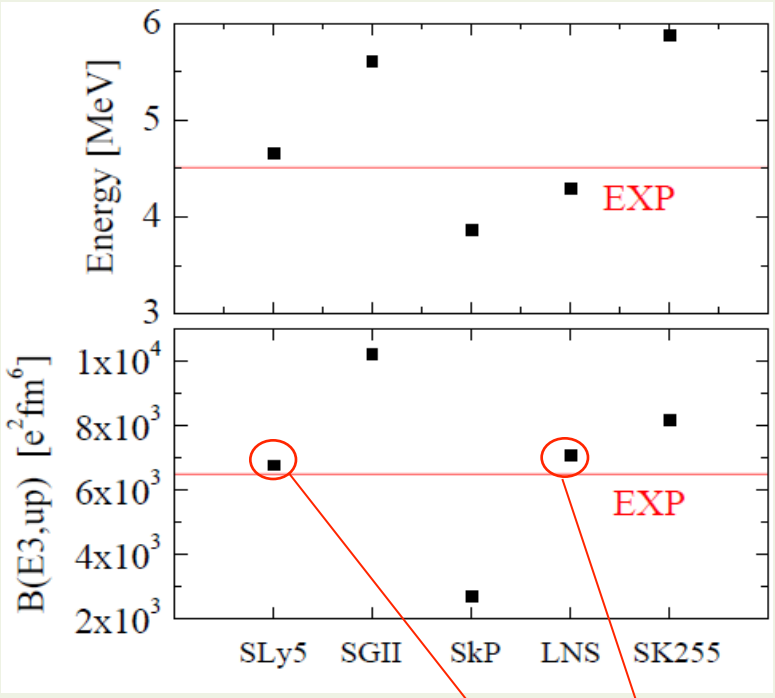
Single Particle State

SHELL model:

97%: $f_{7/2}^{-1}(p_{3/2})$

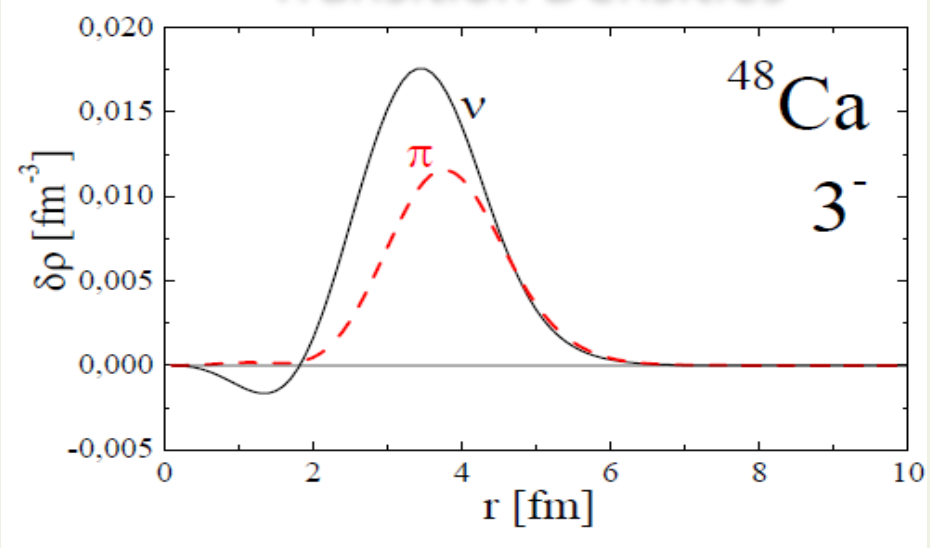
^{48}Ca: 3- RPA calculations

(G. Colò, P.F. Bortignon)



		SLy5	- LNS
π	$1d_{3/2} \rightarrow 1f_{7/2}$	0.82	0.64
	$2s_{1/2} \rightarrow 1f_{7/2}$	0.13	0.29
ν	$1f_{7/2} \rightarrow 1g_{9/2}$	0.01	0.02

Transition Densities



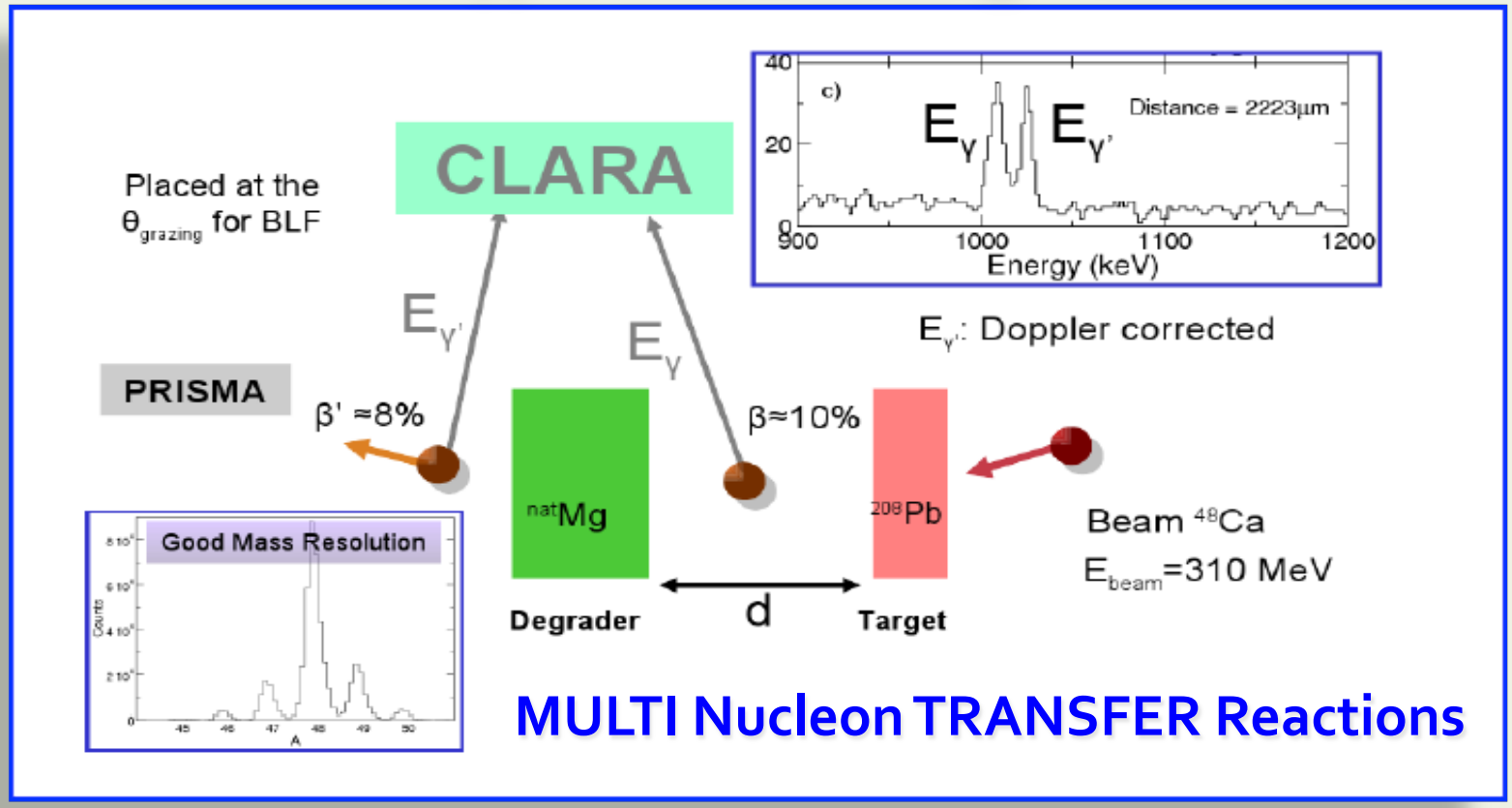
"SIMPLE Structures"

↓

Macroscopic Core Vibration

Lifetimes of ^{49}Ca with Differential PLUNGER

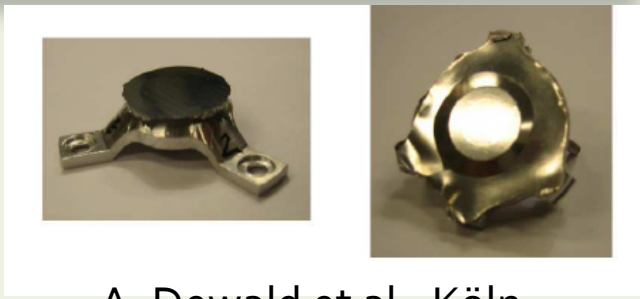
Recoil Distance Doppler Shift Method @ PRISMA-CLARA



D = 30 μm – 2200 μm
τ ~ 0.5 – 75 ps

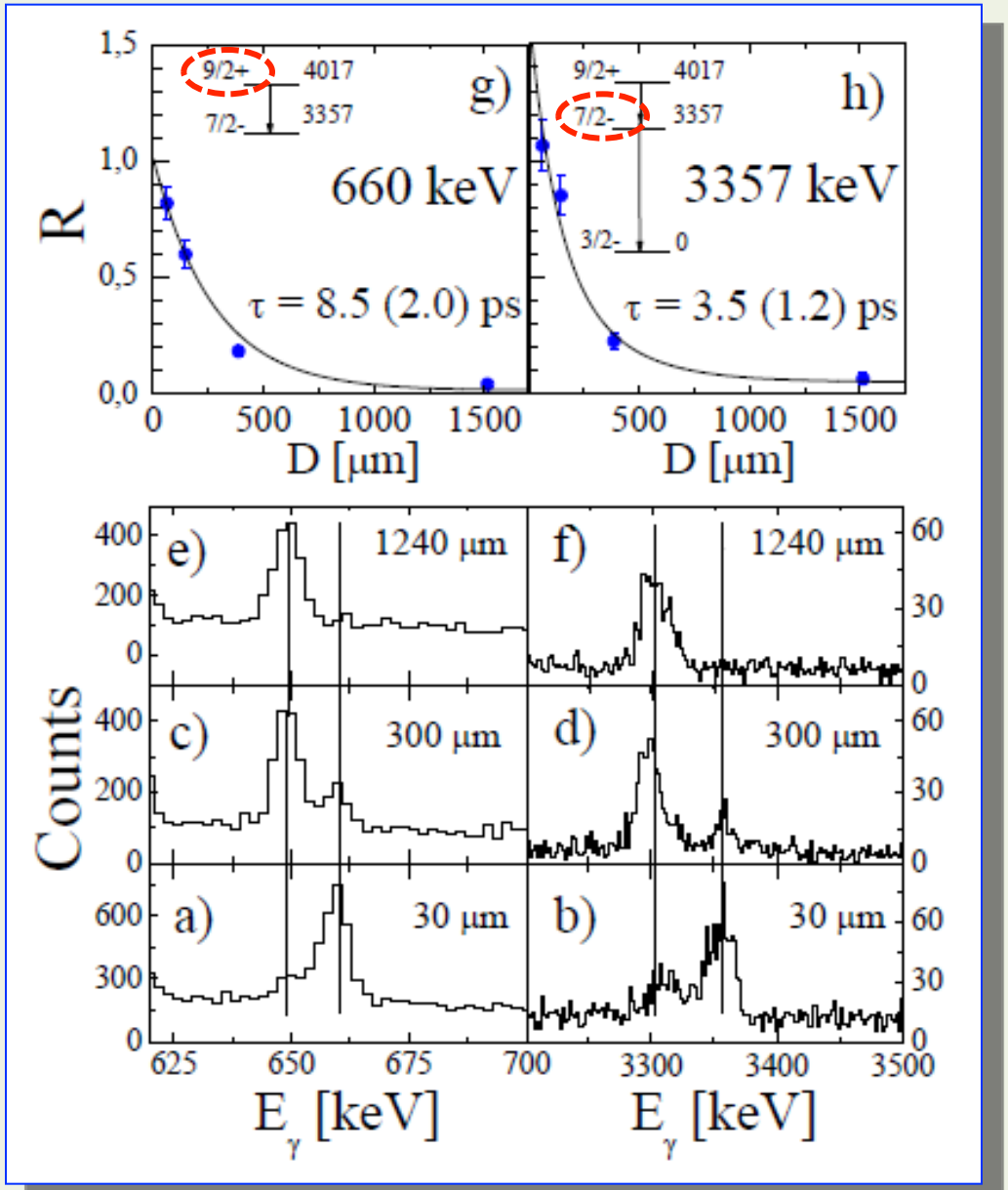
Lifetimes in ^{50}Ca, ^{51}Sc, ^{44,46}Ar

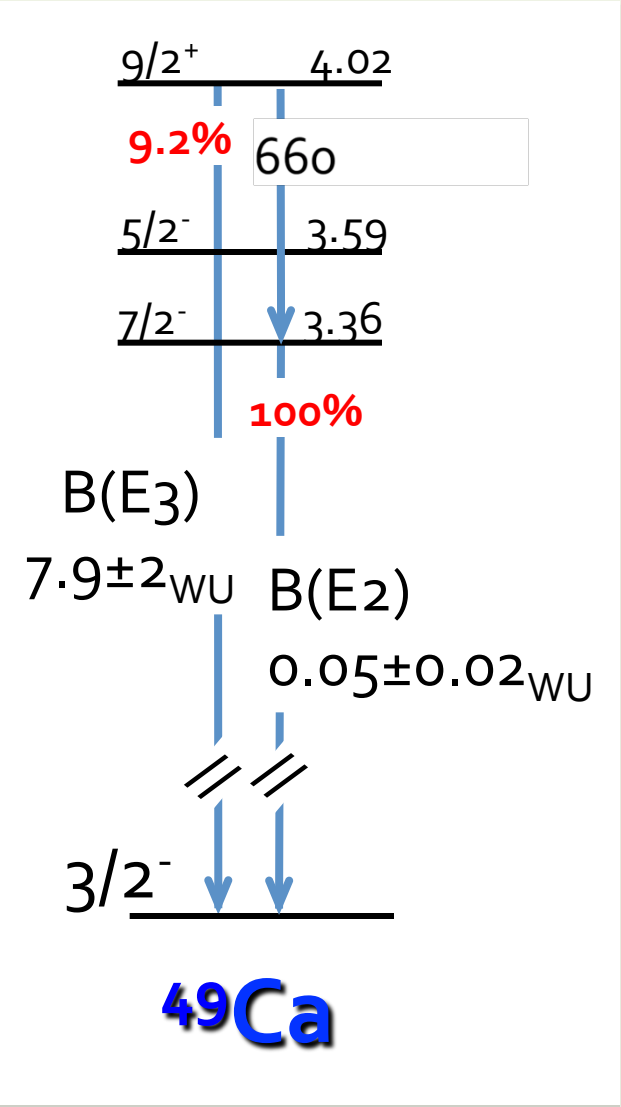
Valiente-Dobon et al.,PRL102(2009)242502
D. Mengoni et al., PRC82(2010)024308



A. Dewald et al., Köln

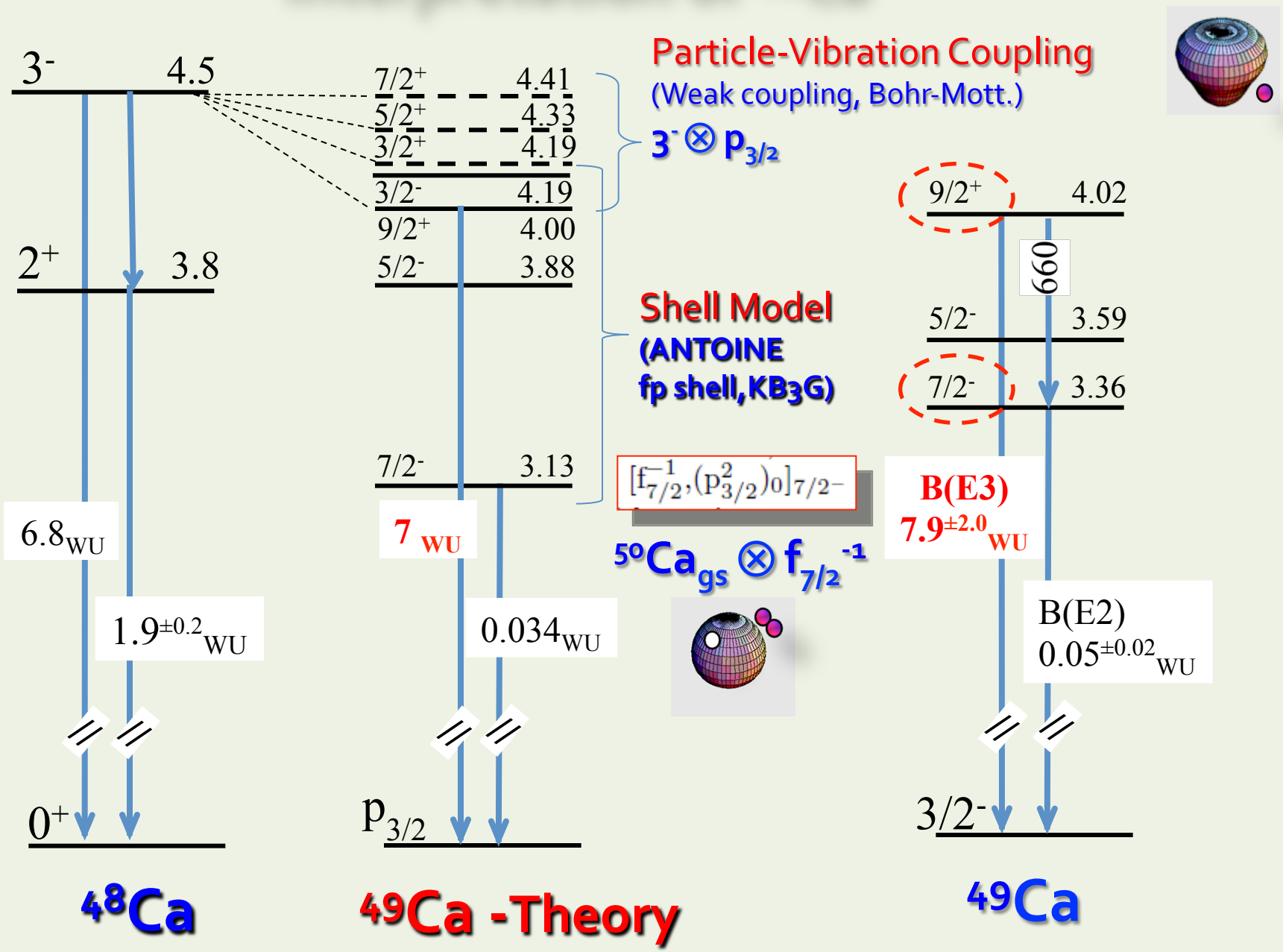
Lifetimes of ^{49}Ca





Branching from
R. Broda thick target exp.

Interpretation of ^{49}Ca

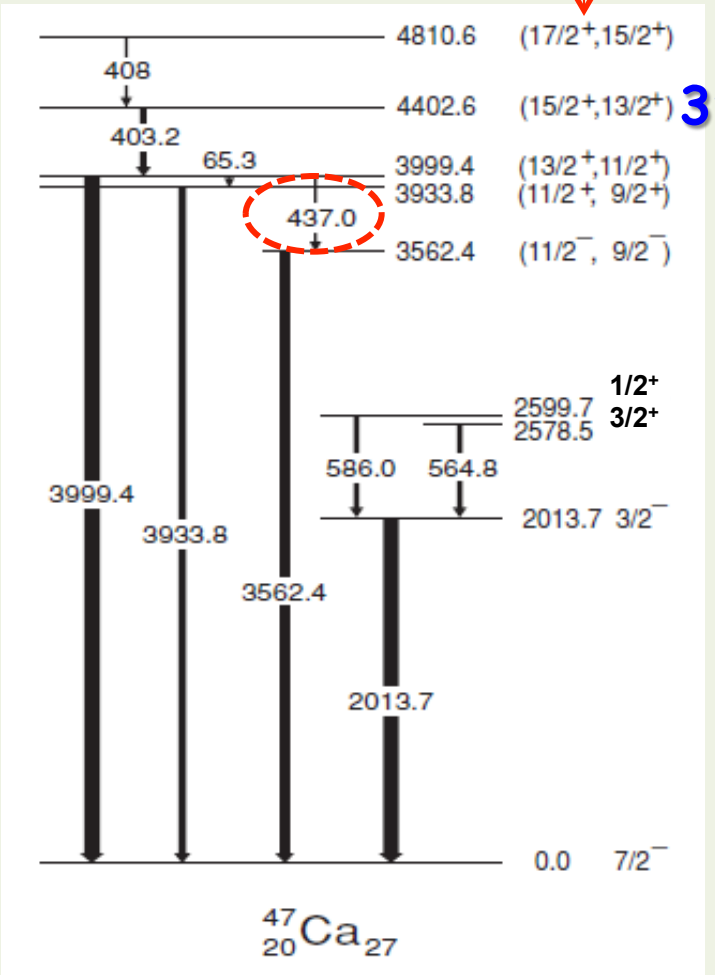


D. Montanari, S. Leoni et al., Phys. Lett. B697(2011)288

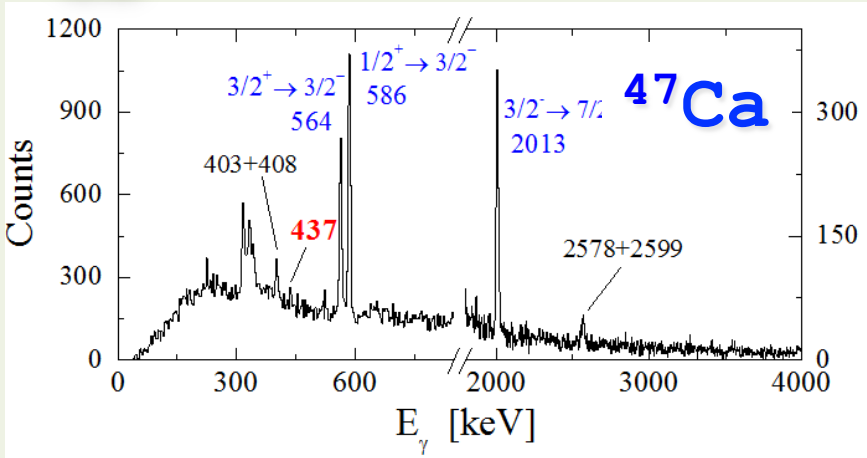
The case of ^{47}Ca

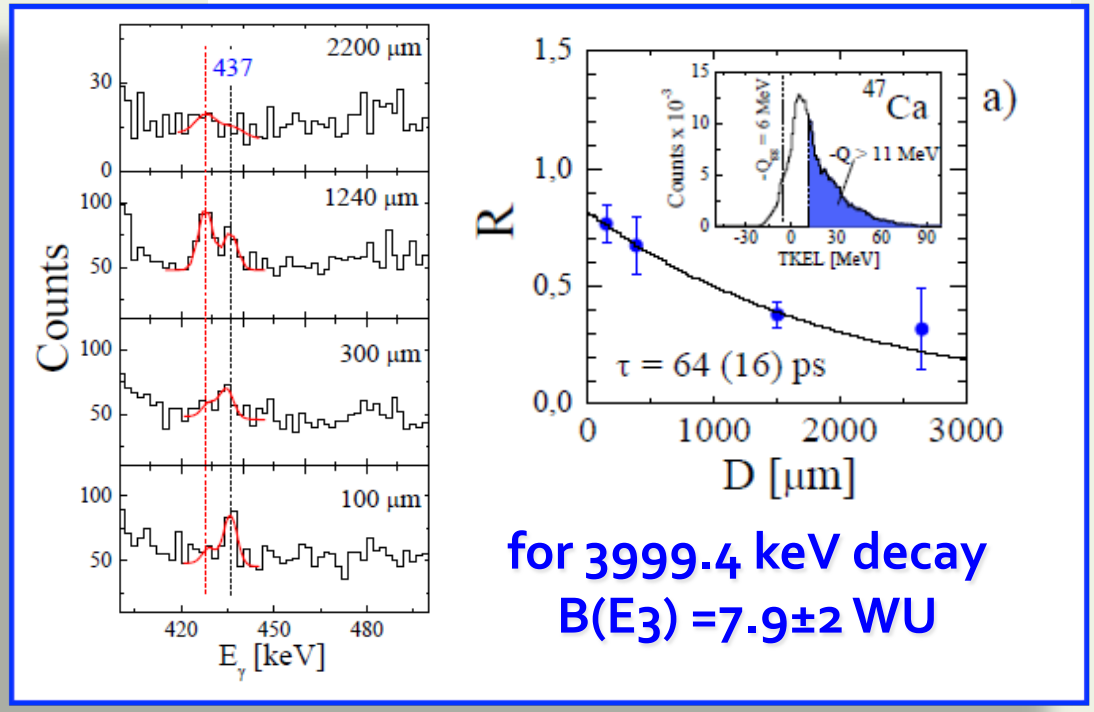
R. Broda, J.Phys.G32(2006)R151
MNT & Thick target data

tentative
I^{π}



$3^- \otimes f_{7/2}^{-1}$
???

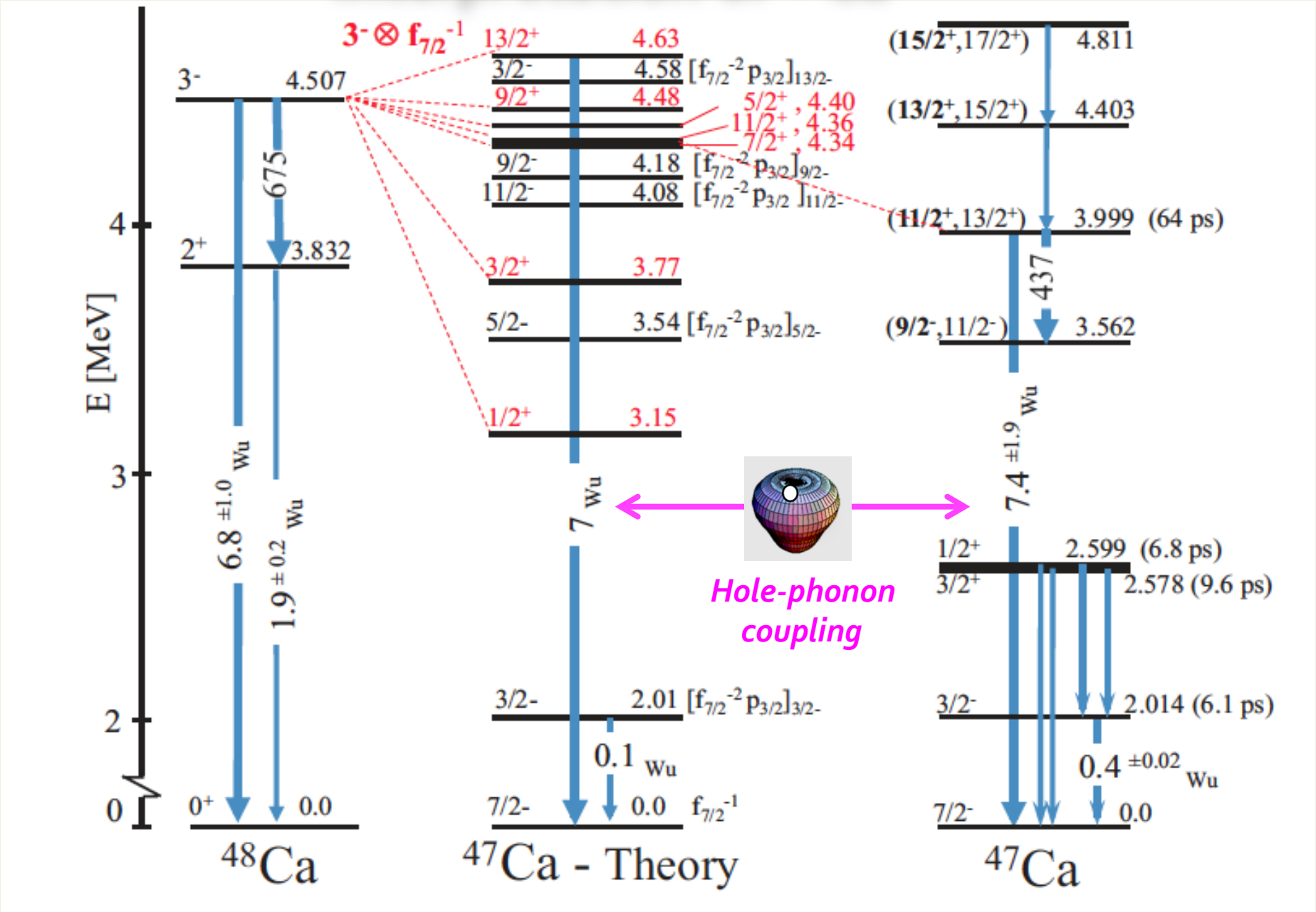




for 3999.4 keV decay
B(E3) =7.9±2 WU

Hole-Vibration Coupling Model : multiplet of states ~ 4 MeV

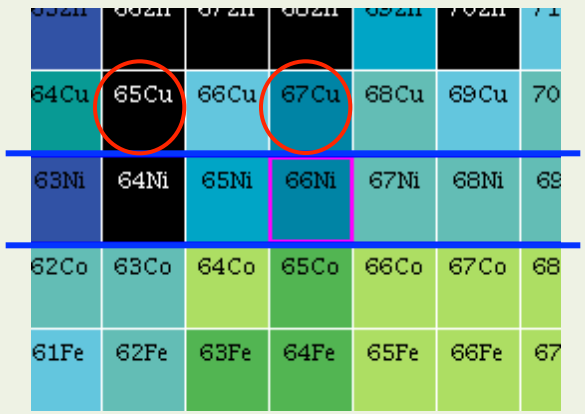
Interpretation of ^{47}Ca



D. Montanari, S. Leoni et al., Phys. Rev. C85(2012)044301

The case of ^{65}Cu

Study of Particle-Phonon states around Ni isotopes



^{64,66}Ni

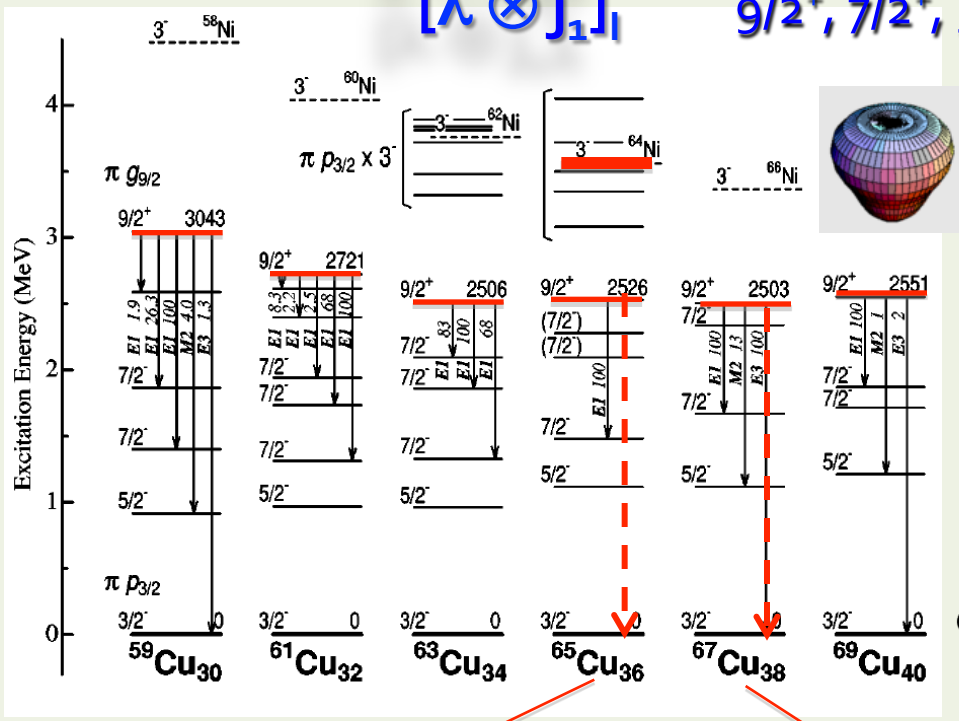
(Z=28,N=36,38)

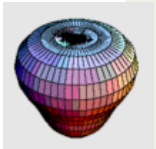
- Superfluid Core in ν
- π coupling

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

$[\lambda \otimes j_1]_I$ → Multiplet of States

$9/2^+, 7/2^+, 5/2^+, 3/2^+$





3-
B(E3)~11 Wu

● $\pi p_{3/2}^-$

August 2012 Experiment

^{64}Ni(^{7}Li,α2n)^{65}Cu

Tandem-Bucarest

S. Leoni et al.

FAST TIMING

B(E3)~??? Wu

Existing Data

^{64}Ni(α,p)^{67}Cu

N. Marginean et al.

FAST TIMING

τ(9/2+)~150 ps

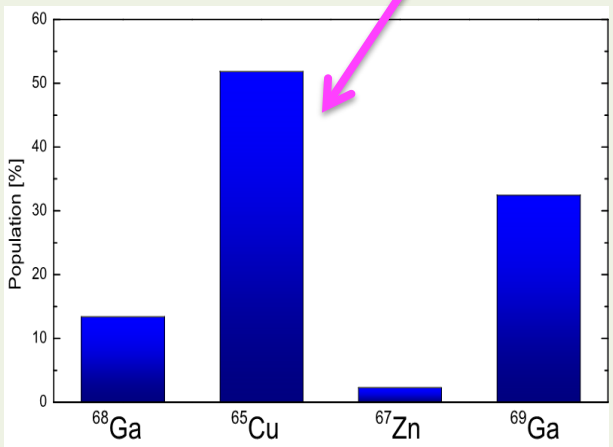
B(E3)~17(2)Wu

Incomplete fusion with ^{7}Li

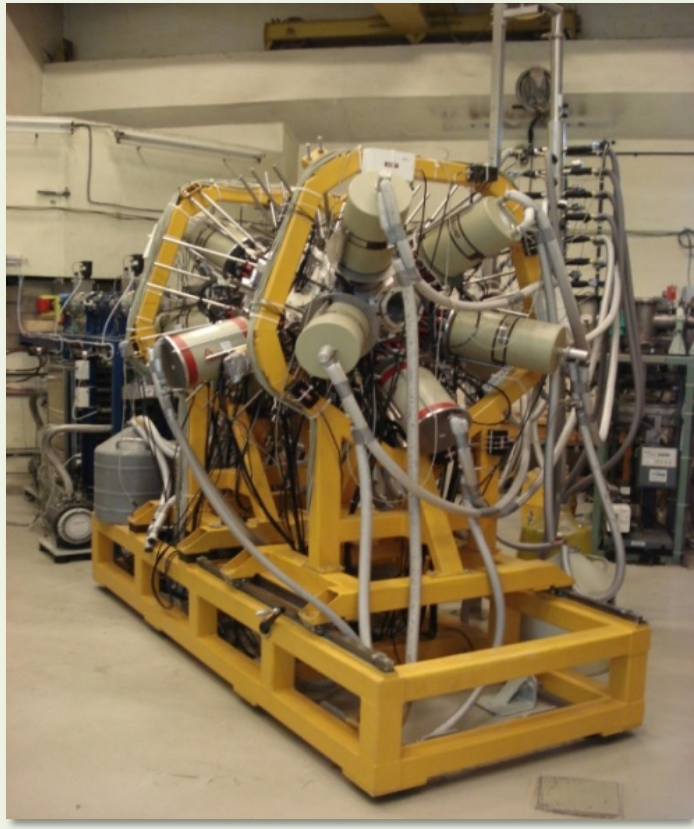
- ***Favorable capture of t and emission of α***
- ***Evaporation of 2n and 1n***
- ***Population of n-rich systems***
  (not possible to reach by fusion)
- ***Population of Off Yrast States***
- ***Intermediate Spins up to 12 ħ***
  (in ^{124}Sn(^{7}Li,a2n)^{125}Sb spins observed up to 23/2 ħ)

G.D. Draculis et al., JPG23(1997)1191
D.S. Judson et al., PRC76(2007) 054306
R.M. Clark et al., PRC72(2005)054605
…

^{7}Li (32 MeV)+ ^{64}Ni → ^{65}Cu + α2n



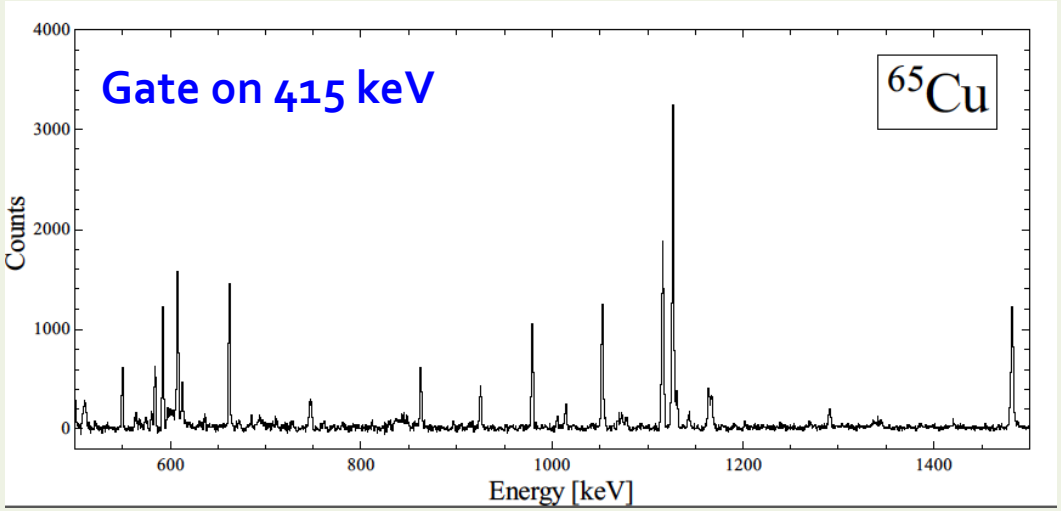
ROSPHERE @ NIPNE (Bucharest)

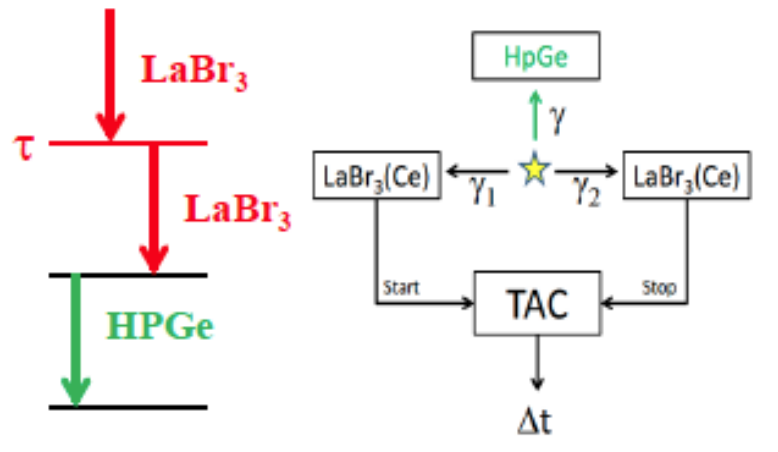


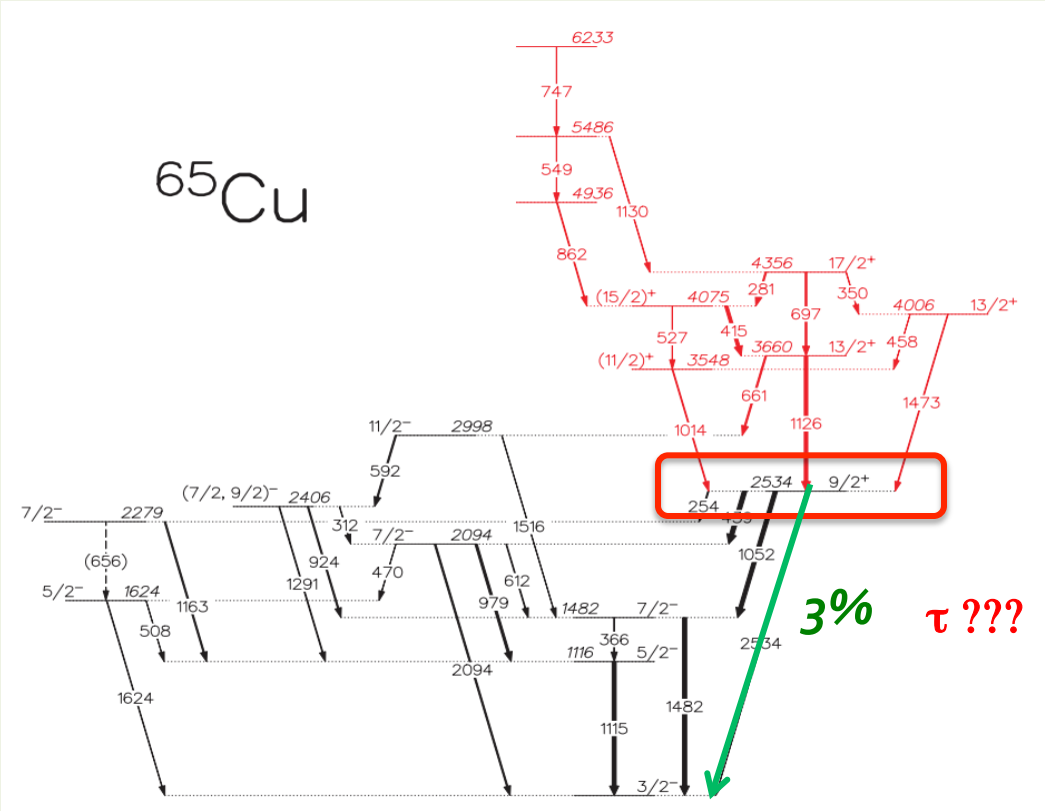
14 HPGe
11 $LaBr_3$(Ce)

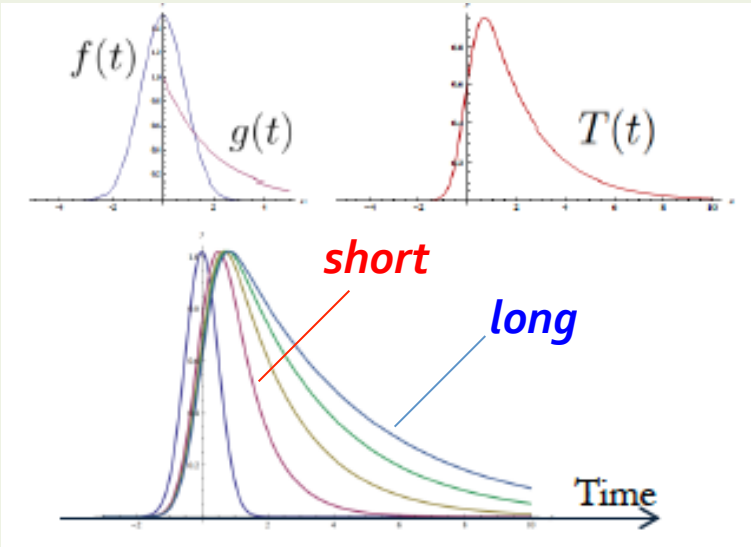
γ-spectroscopy and Lifetimes with Fast-timing techniques

FAST Timing technique
γγγ coincidences







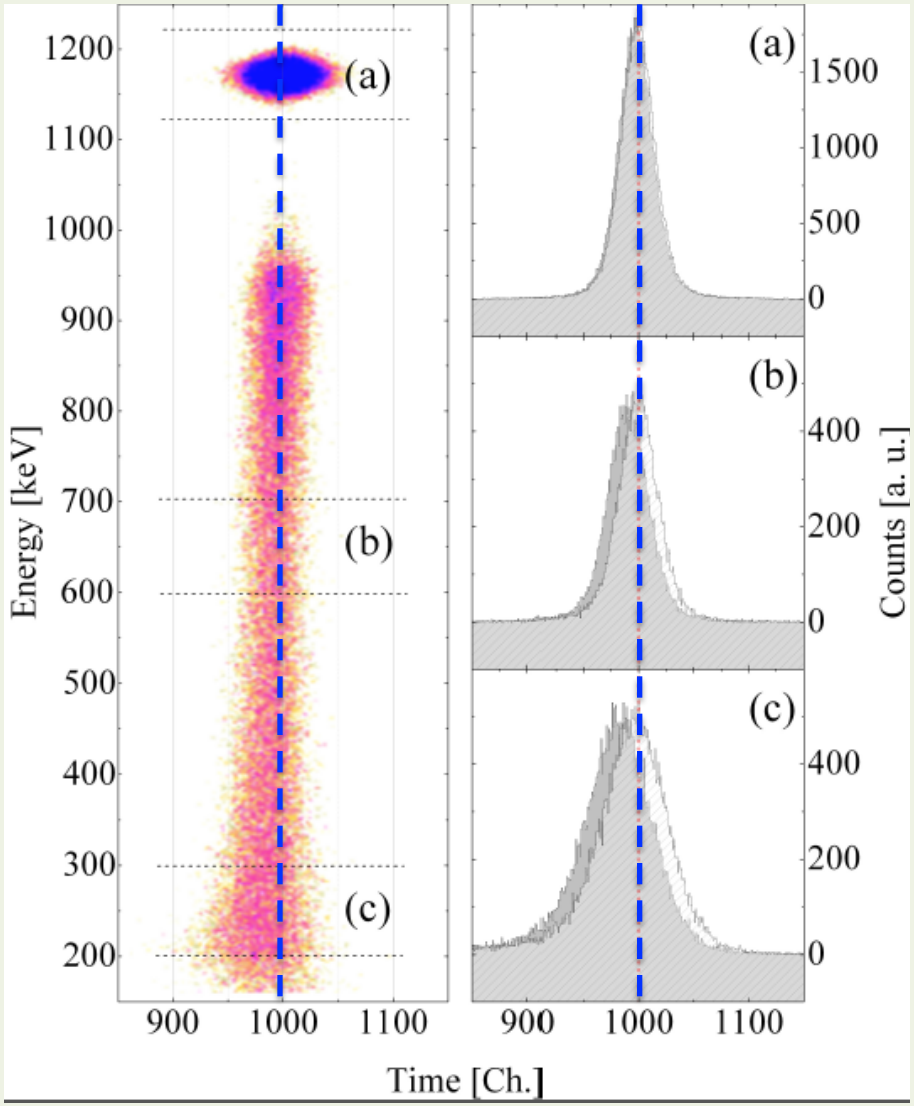


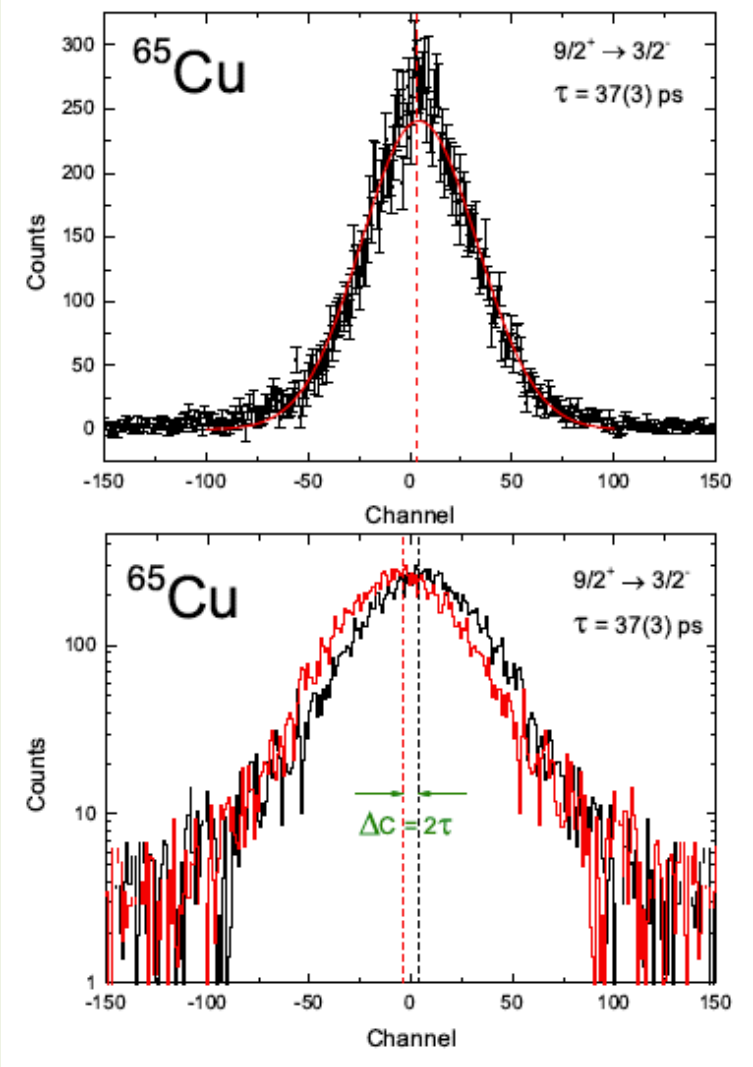
For short lifetimes: Centroid shift

C.J. Chiara et al., PRC85(2012) 024309

Carefull time walk correction
With ^{60}Co source

τ = 37(3)ps
B(E3)=8.89 ± 1.65 W.u.





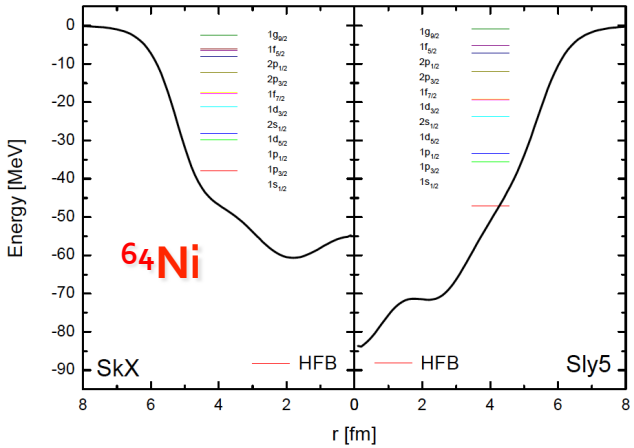
Theoretical Interpretation: $3^- \otimes p_{3/2}$ Weak Coupling

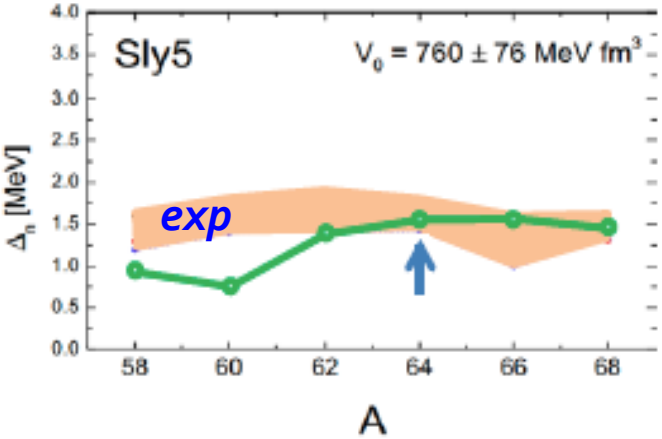
(S. Bottoni, G. Bocchi, G. Colò, PF. Bortignon)

Single Particle π Levels

^{64}Ni (Z=28,N=36,38)

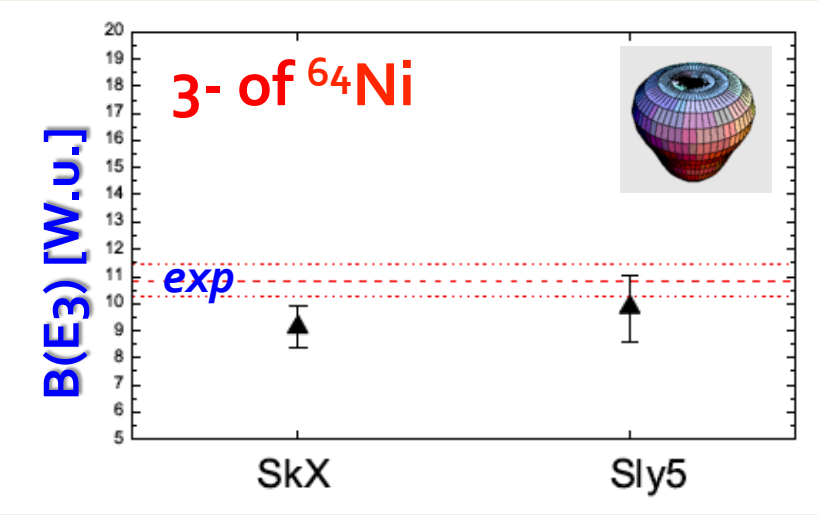
Superfluid Core

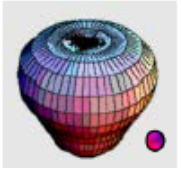




SkX : $V_0 = 680 \pm 68$ MeV fm^3

Sly5 : $V_0 = 760 \pm 76$ MeV fm^3

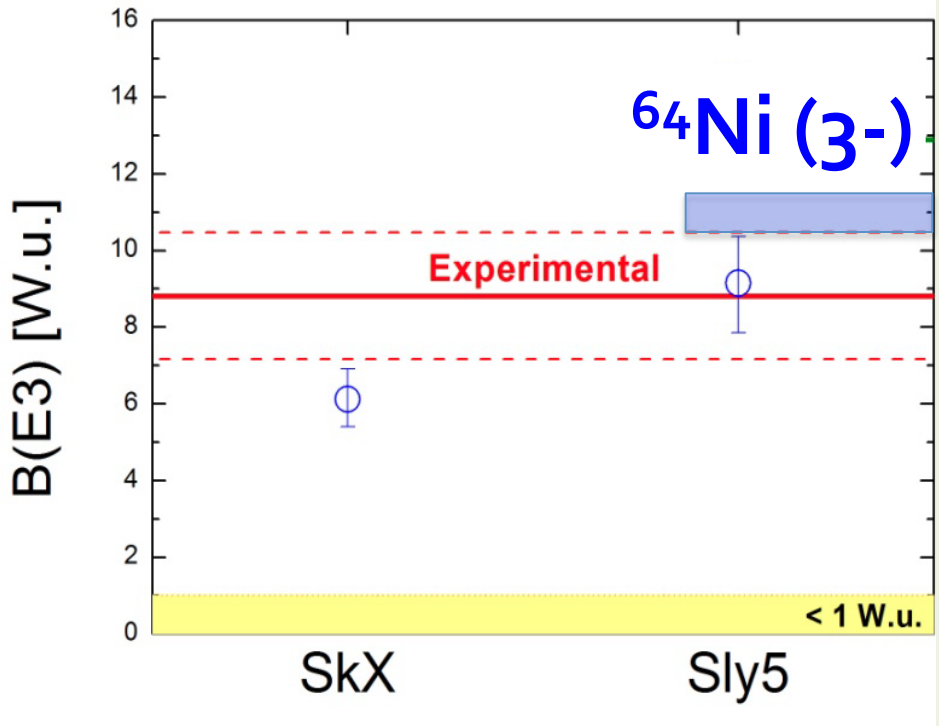


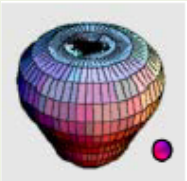


$$3^- \otimes p_{3/2} = [\lambda \otimes j_1]_I$$

multiplet → $9/2^+$, $7/2^+$, $5/2^+$, $3/2^+$

9/2+ state of ^{65}Cu





$\boxed{9/2^+}$, $7/2^+$, $5/2^+$, $3/2^+$

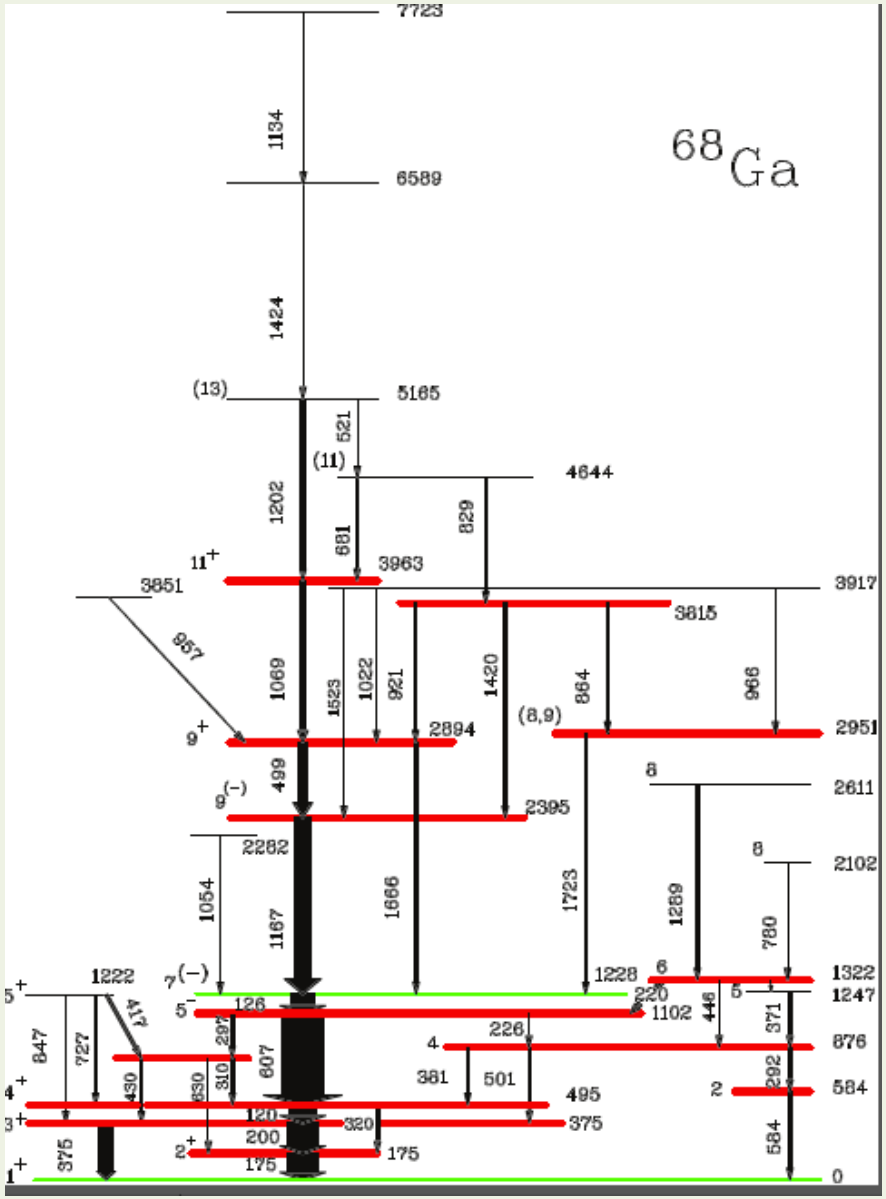
9/2+ of ^{65}Cu is a particle-phonon coupled state

			E [MeV]	B(E3) [W.u]
^{66}Ni core	3^-	Exp.	3.370	??
		Theory (SkX)	4.4	7.9
		Theory (Sly5)	5.2	7.5
^{67}Cu	$9/2^+$	Exp.	2.503	17.0 ± 2.0
		Theory (SkX)	2.9	5.4
		Theory (Sly5)	2.9	5.2

*Very Different Situation for **9/2+** of **^{67}Cu**: particle-phonon calculations do not agree with data !*

Significant Structural changes from ^{65}Cu to ^{67}Cu ??

By-product: Lifetimes in ^{68}Ga (odd-odd !!)



Energy Level [keV]	$\tau \pm \sigma$
175	3.37 ± 0.11 ns
375	2.87 ± 0.04 ns
495	< 30 ps
584	< 30 ps
806	< 30 ps
876	527.42 ± 22.63 ps
1102	214.46 ± 2.80 ps
1322	187.21 ± 17.21 ps
2395	298.90 ± 5.76 ps
2894	226.00 ± 8.27 ps
2951	< 30 ps
3815	103.15 ± 17.40 ps
3963	< 30 ps

Previously reported < 5 ns

On Going Analysis: the EXILL Campaign @ ILL

(n,γ) DATA

^{49,47}Ca → ^{48,46}Ca + 1n

Cold n + ^{46,48}Ca (Reactor ILL, Grenoble)
Exogam/GASP Ge Array + $LaBr_3$
*Search for **low-spin members** of the Particle-phonon multiplet with 3- of ^{48}Ca*

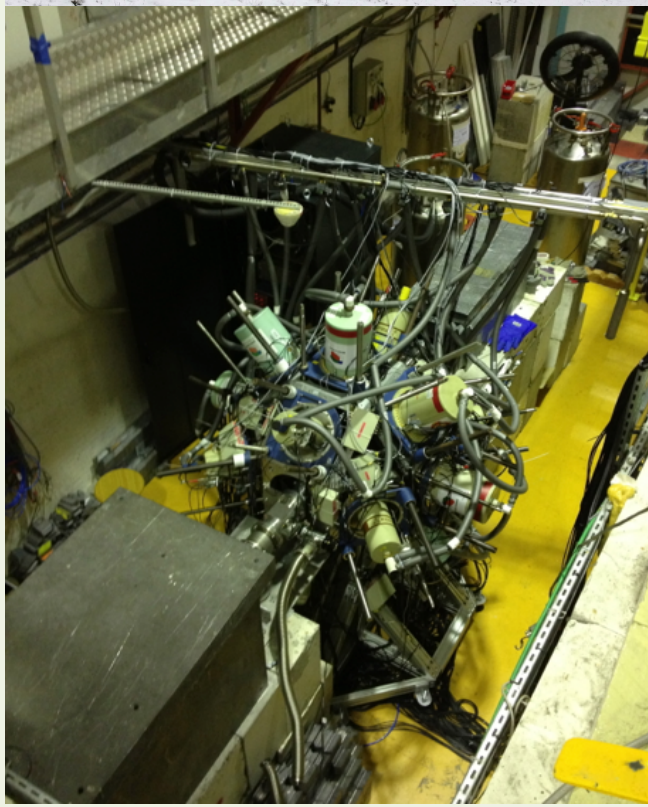
^{210}Bi → ^{209}Bi + 1n

Cold n + ^{209}Bi (Reactor ILL, Grenoble)
Exogam/GASP Ge Array + $LaBr_3$
*Search for **proton-neutron multiplet** with 3- in ^{208}Pb (34 Wu !!!)*

FISSION DATA

1 and 2 nucleons around ^{132}Sn

Cold n + ^{235}U and ^{241}Pu (Reactor ILL, Grenoble)
Exogam/GASP Ge Array + $LaBr_3$

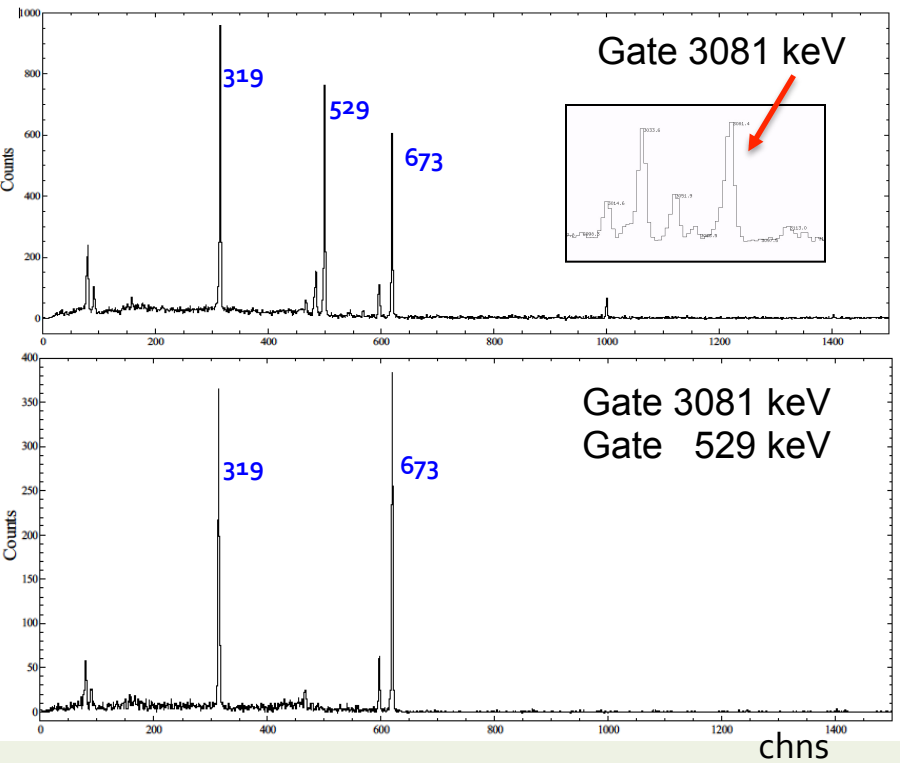


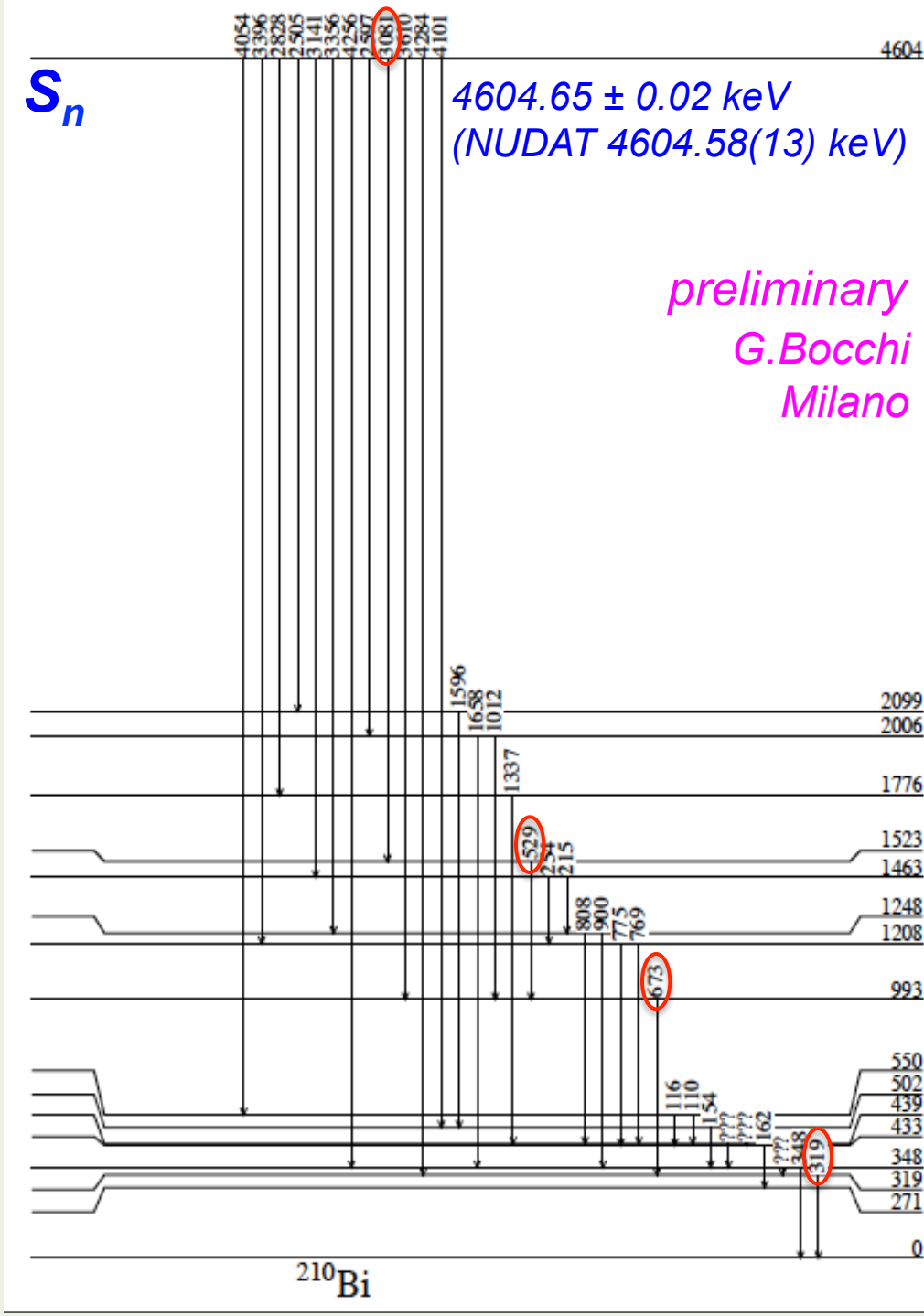
γ spectroscopy and Lifetimes (Fast Timing)

^{210}Bi

EXOGAM only
< 1 day

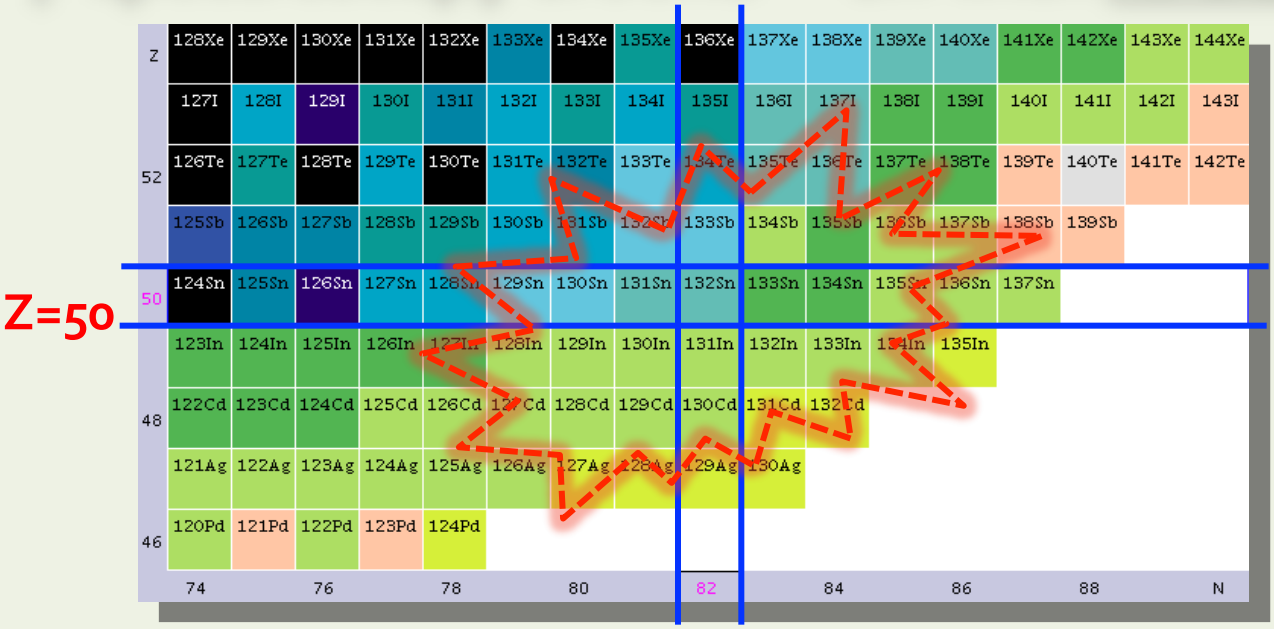
28 10^6 events single γ





Perspectives with RIB

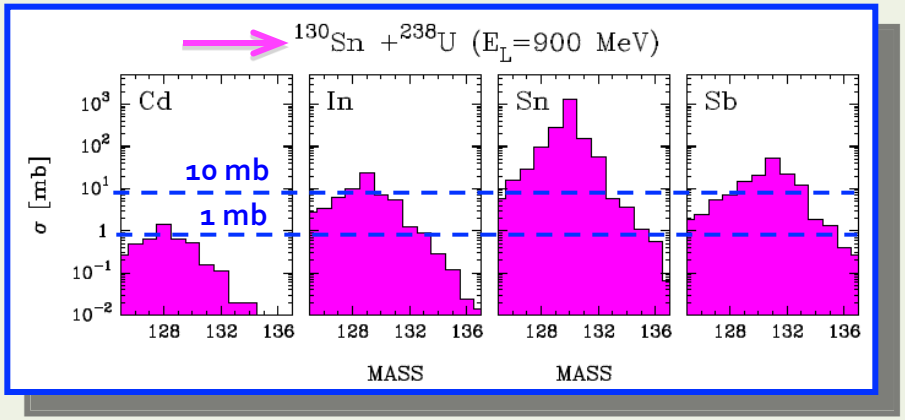
γ spectroscopy around ^{132}Sn with HI transfer reactions



STUDY OF

- Single particle states
- particle-phonon couplings
- high spins

I^{π}, $B(E\lambda)$



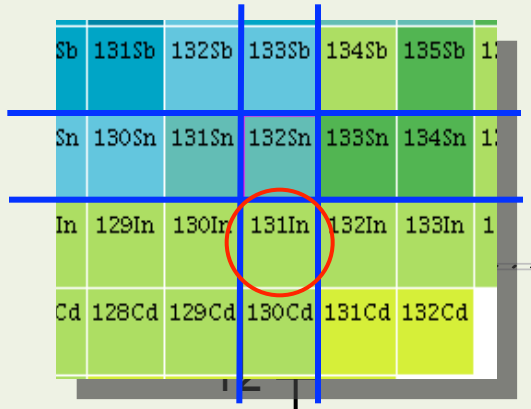
Hard to directly produce by RIB with high intensities

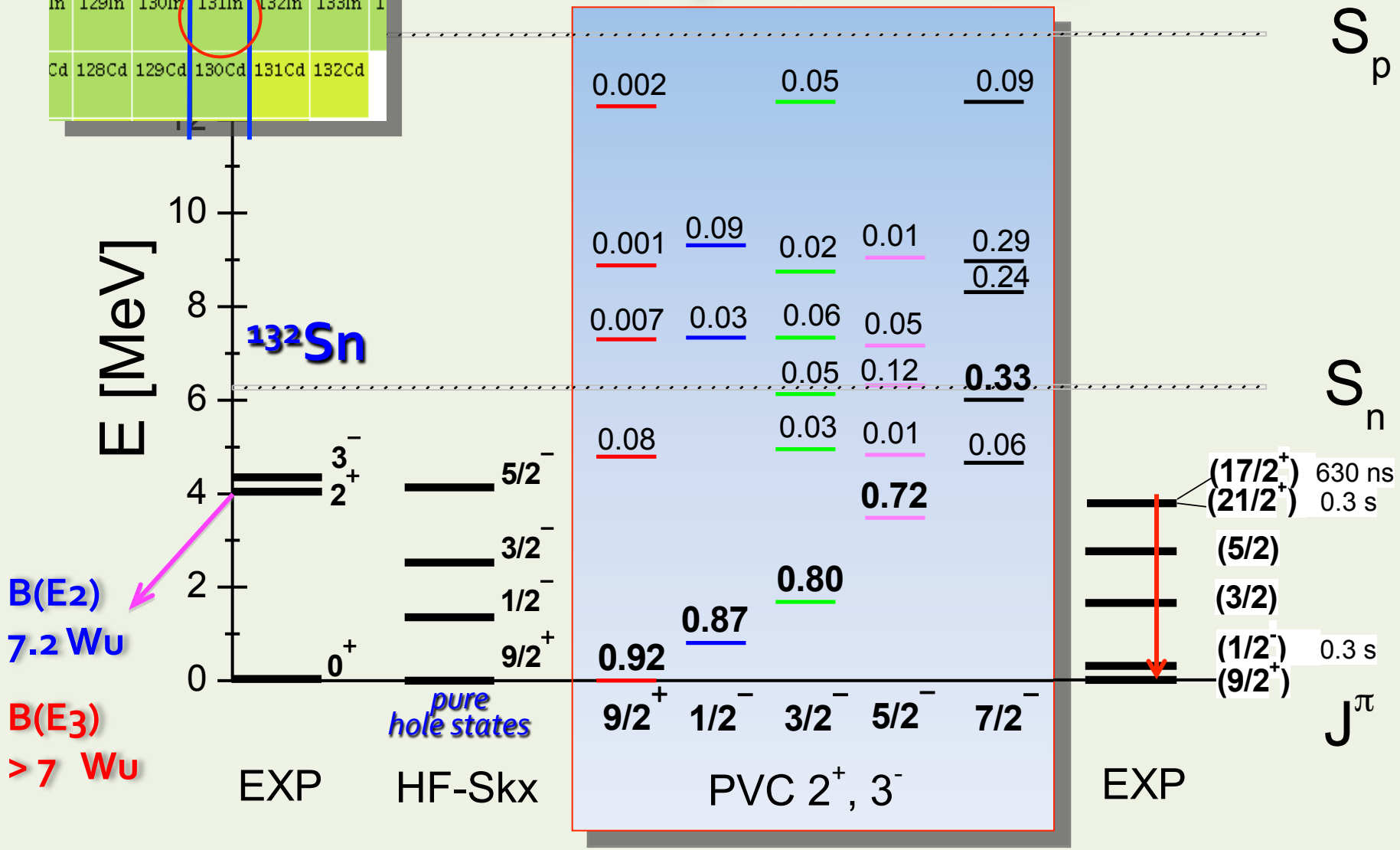
(as for example 131In, 130Cd, ...)

GRAZING calculations

Conservative estimates for more than 1 nucleon transfer

^{131}In – proton hole states





G.Colò and P.F.Bortignon

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

Conclusions

+ ***FOCUS on Particle-Phonon Coupled States:***

  Building block of anarmonicity of vibrational spectra
  Quenching of Spectroscopic Factors, …

  → ***Research Program in Milano in Exp. and Theory:***
  Systematic study in different mass regions to obtain information on Interaction strength, N/Z dependence…

+ ***γ-spectroscopy of n-rich nuclei with HEAVY-ION Transfer, Incomplete Fusion Reactions, …***

  Angular Distribution, Polarization, Lifetime Analysis
  → *Spin, Parity and Nature of Nuclear State*
  → ***Evidence for particle-phonon states in $^{47,49}Ca$***
  → ***Evidence In ^{65}Cu***

+ ***EXILL Campaign, … very good data…***

+ ***Preparatory Work for Radioactive Beam Physics …***

Thank You for the Attention