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University of Milano & INFN

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

19th Nuclear Physics Workshop
September 26-30, 2012
Kazimierz, Poland

Collaboration

Milano University and INFN
A. Bracco, G. Benzoni, N. Blasi, F. Camera, F. Crespi, S. Leoni, B. Million, O. Wieland, S. Bottoni, G. Bocchi et al.
P.F. Bortignon, G.Colò, E. Vigezzi 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.

Torino University and INFN
G. Pollarolo

IFIC, CSIC-University of Valencia, Spain
A. Gadea, ...

IFIN-HH Bucharest
N. Marginean et al.

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

Ruder Boskovic Institute, Zagreb
S. Szilner et al.

AGATA- PRISMA collaborations

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

- WORK in PROGRESS and PERSPECTIVES:

1. Particle-Phonon Coupling around Ni Isotopes

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

HOT topic in Nuclear Structure

Evolution of Shell Structure with N/Z

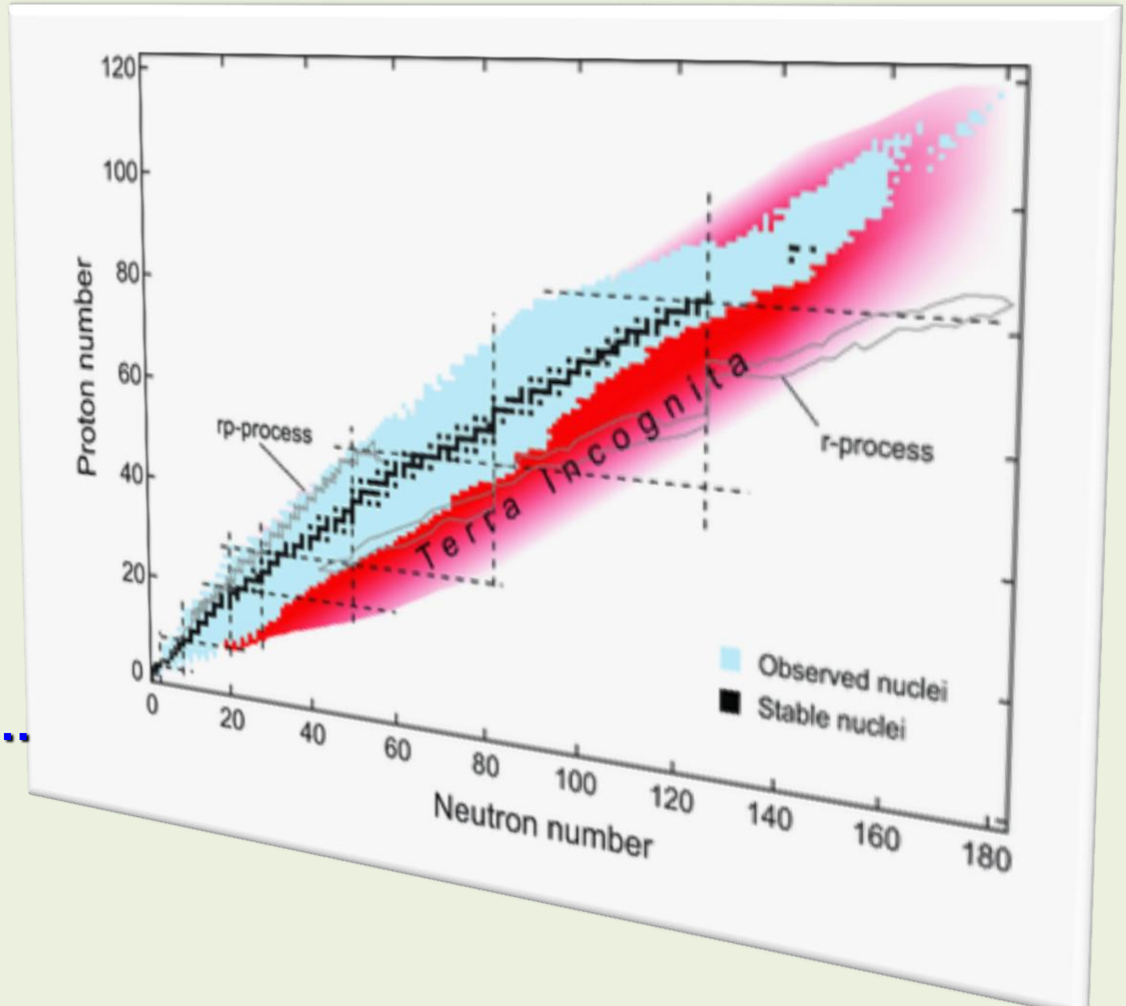
Study of Shell closures, Magic Numbers, Effective Nuclear Force, …

- **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)***

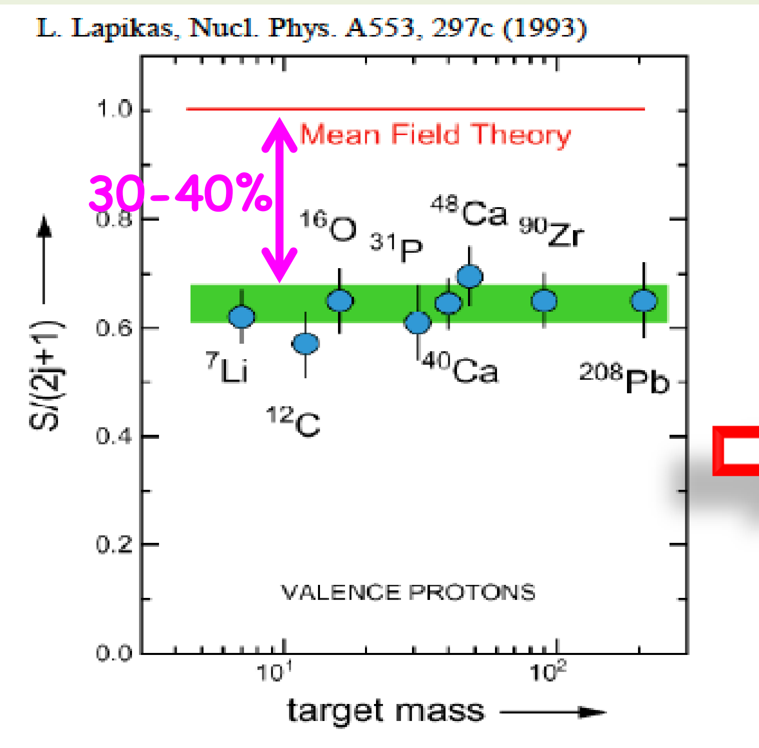


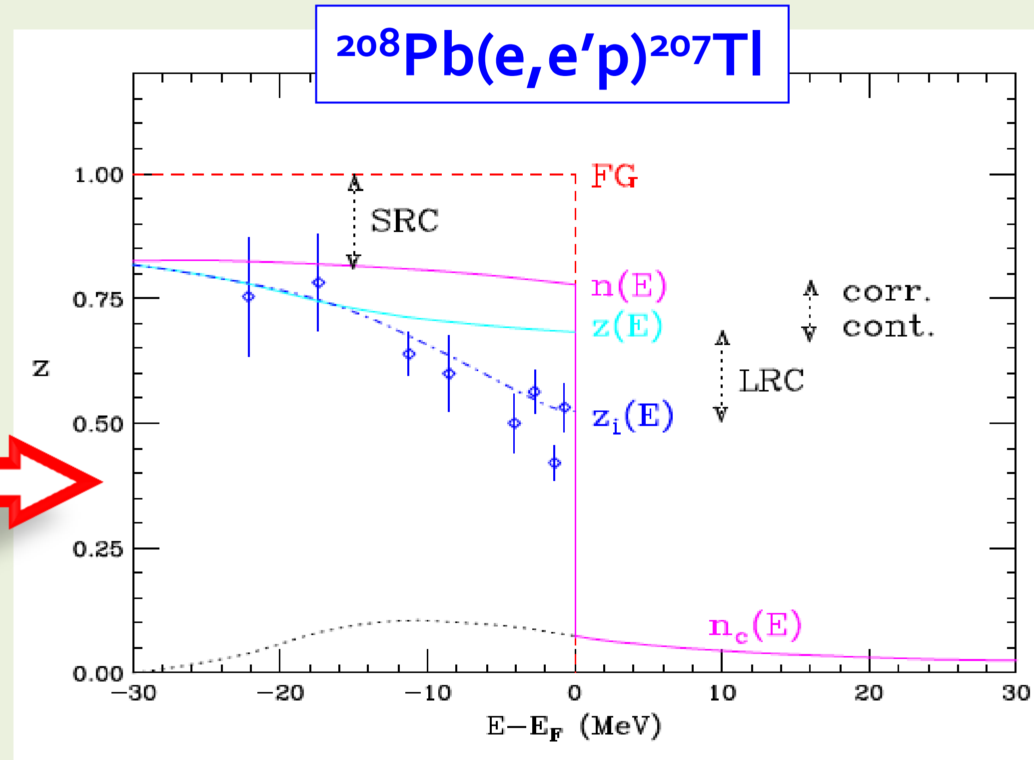
Spectroscopic Factors

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

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

Crucial test of Shell Model and Interactions





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

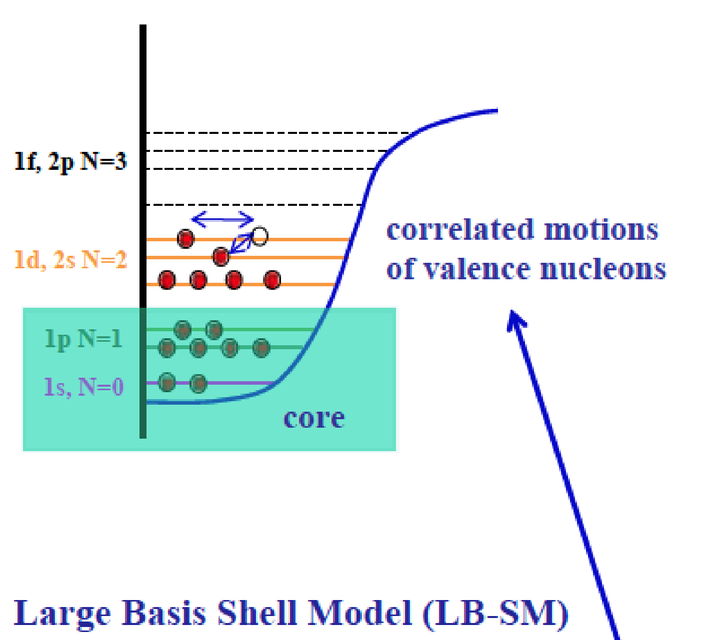
Quenching of SF due to correlations:
SHORT Range: Deeply Bound States
LONG Range (coupling to vibrations): Surface States

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

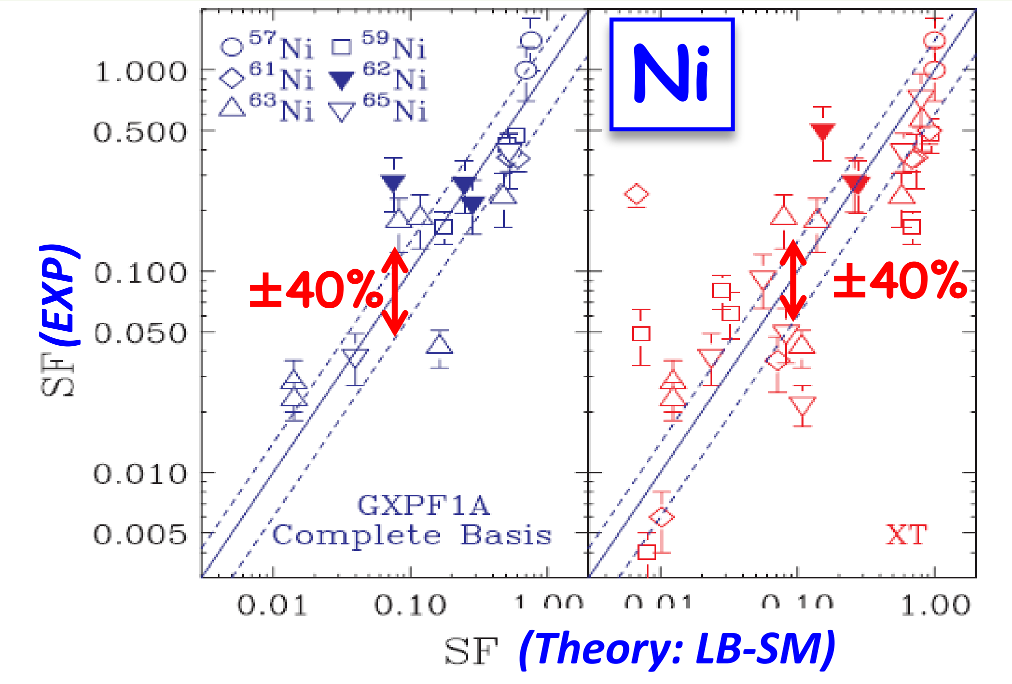
Large Basis Shell Model (LB-SM)

Correlations among valence nucleons

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



$$H = \sum_i \left(\frac{\vec{p}_i^2}{2m} + U(r_i) \right) + \sum_{i<j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(r_i)$$



Source of discrepancies

- Core excitations
- State fragmentation ...

→Coupling between Particle and Vibrations is not included ...

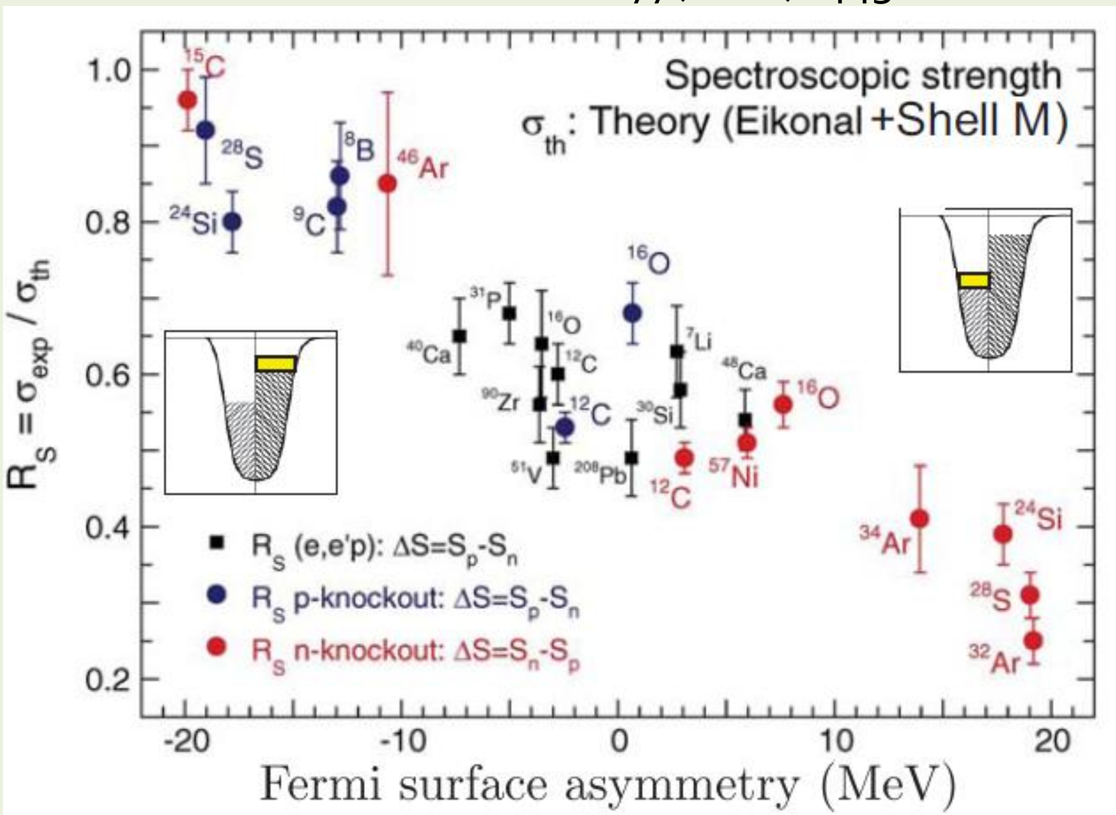
(LONG RANGE CORRELATION)

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

Spectroscopic Factors Information from Exotic Nuclei

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

A. Gade et al. PRC77(2008)044306



Dependence on Fermi Surface

Enhanced *CORRELATIONS* in Strongly bound valence nucleons

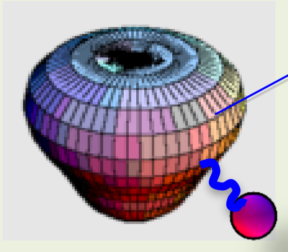
Need for a more profound investigation of correlations

→ Long Range Correlations

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, …

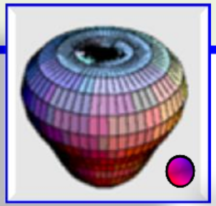
Theory** (Colò, Bortignon)**:

Coupling with 1 particle
- *effective single particle levels*
- *coupling strength*

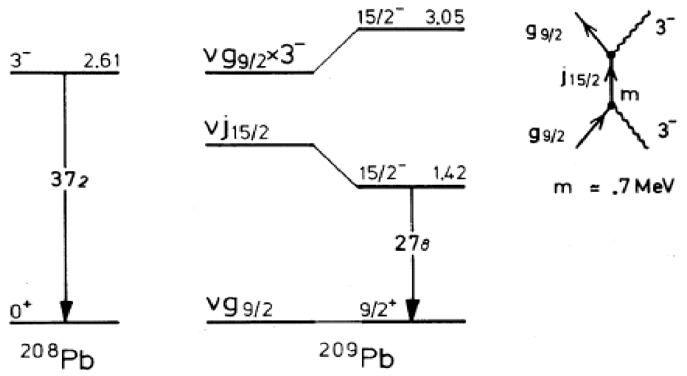
Coupling with 2 particles
- *core + 2 particles model*
- *physics of pairing*

Dependence on Fermi Surface

Experimental STATUS

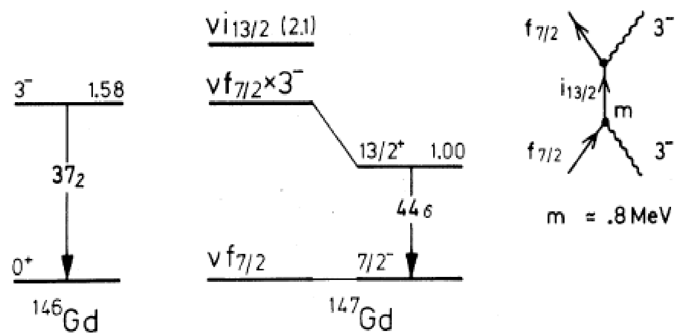


Up to now: **Scarce Information** Mostly in **Heavy-Masses**



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

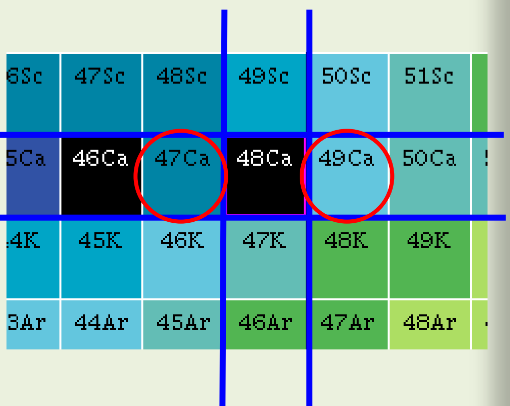
^{49}Ca: $9/2^+$ @ 4017 keV $= 3^- \otimes p_{3/2}$
^{47}Ca: $11/2^+$ @ 3999 keV $= 3^- \otimes f^{-1}_{7/2}$

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

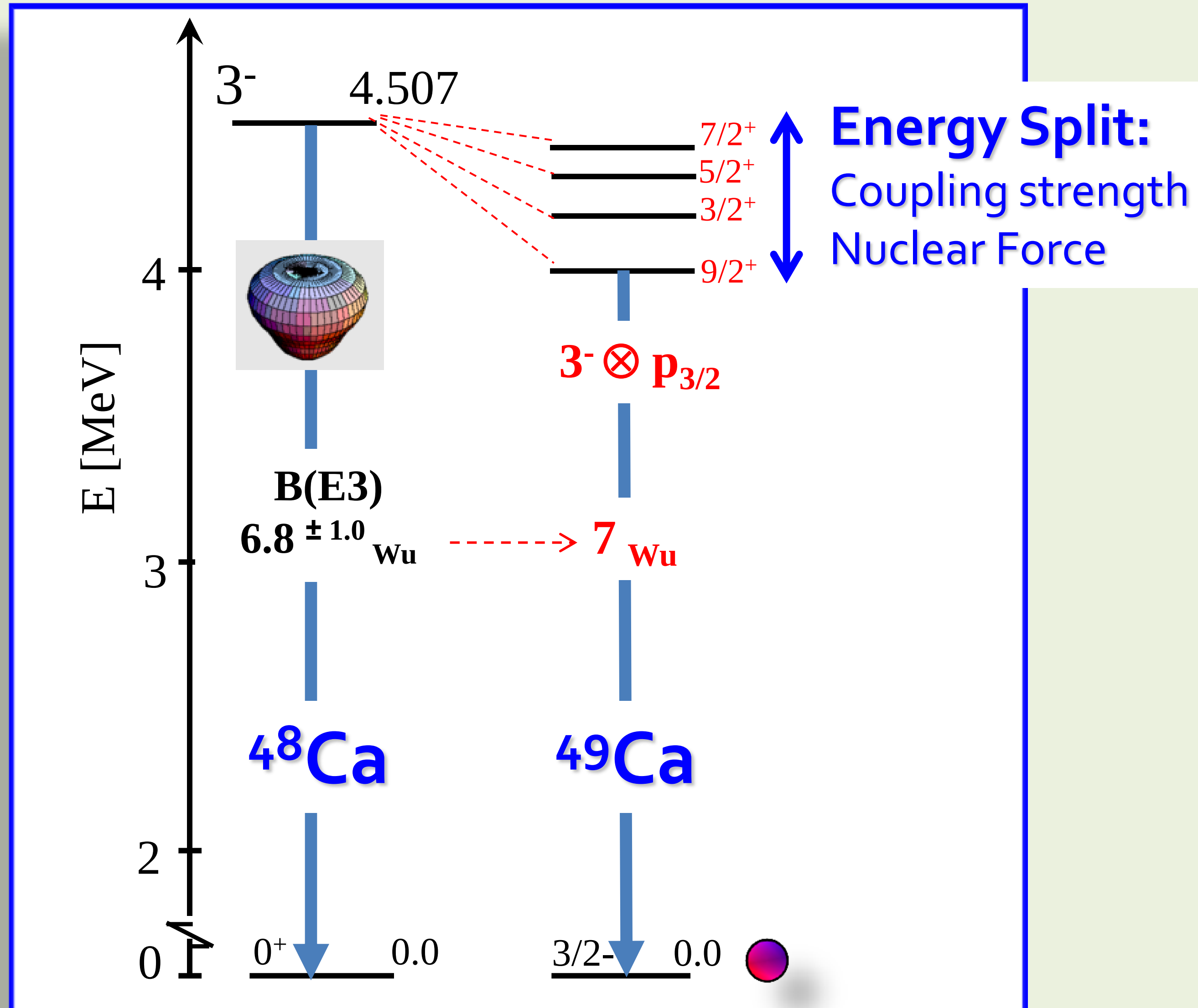
Experimental Signature

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



^{48}Ca

(Z=20,N=28)



Theoretical Description

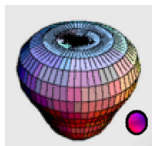
PHENOMENOLOGICAL

Particle-phonon

WEAK coupling calculations

(Bohr & Mottelson)

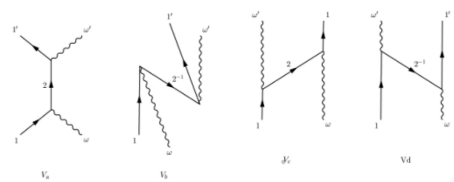
^{49}Ca $3^- \otimes p_{3/2}$ $[\lambda \otimes j_1]_I$



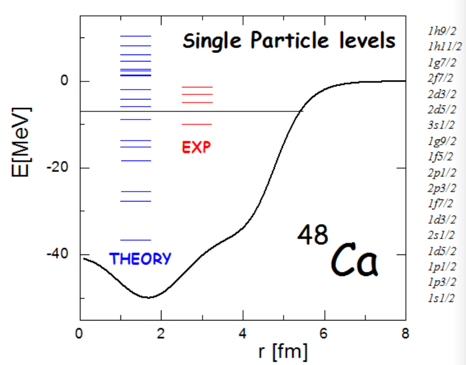
Multiplet of States $9/2^+, 7/2^+, 5/2^+, 3/2^+$

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
- s.p. Energies
  ε(j₁), ε(j₂) → HF – SkX
- matrix element
  $h(j_2, j_1, \lambda)$
  → Bohr & Mott.

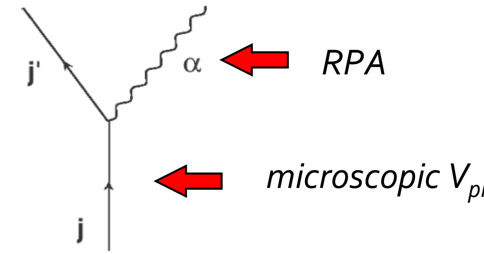


MICROSCOPIC

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 for RIB to reach n-rich systems

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

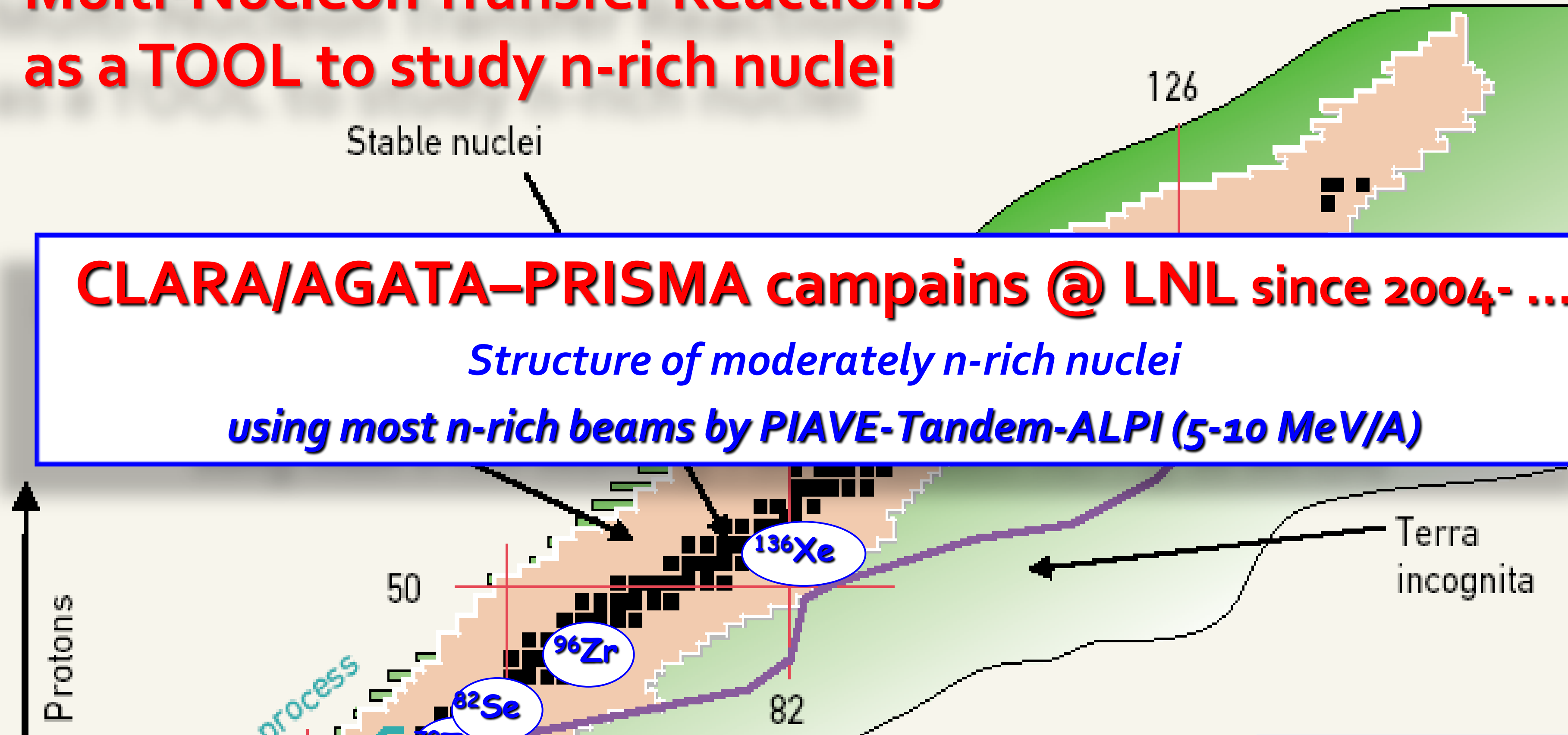
  … population of moderately n-rich nuclei even with stable beams

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

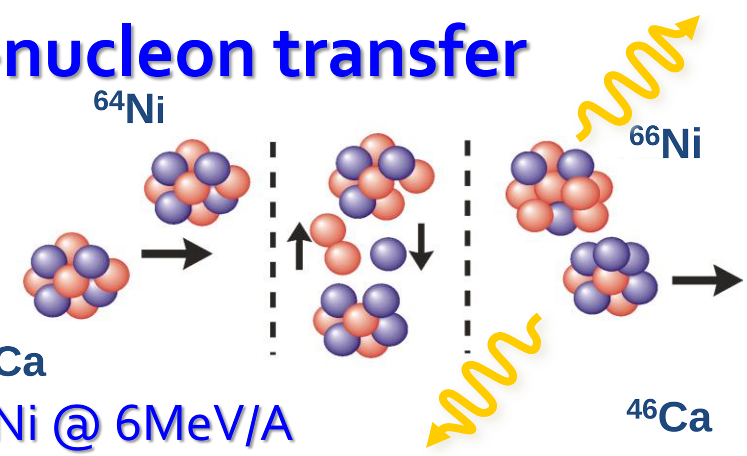
CLARA/AGATA–PRISMA campains @ LNL since 2004- …

Structure of moderately n-rich nuclei

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



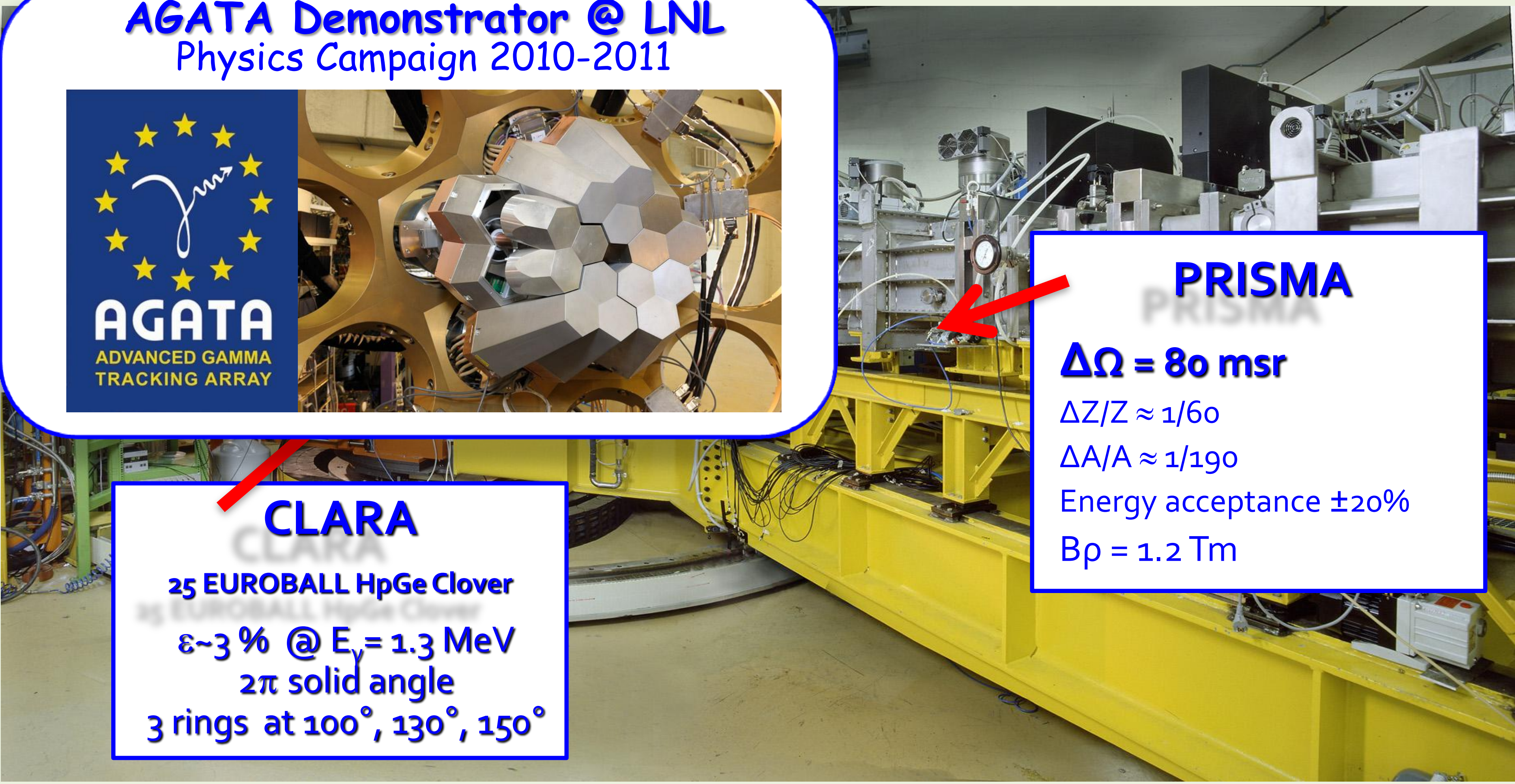
Multi-nucleon transfer A~50



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

CLARA (ex-EUROBALL)/AGATA – PRISMA setup

Legnaro National Laboratory INFN (Italy)



AGATA Demonstrator @ LNL

Physics Campaign 2010-2011

PRISMA

$\Delta\Omega$ = 80 msr

$\Delta Z/Z \approx 1/60$

$\Delta A/A \approx 1/190$

Energy acceptance ±20%

$B\rho$ = 1.2 Tm

CLARA

25 EUROBALL HpGe Clover

$\varepsilon \sim 3$ % @ E_γ = 1.3 MeV

2π solid angle

3 rings at 100°, 130°, 150°

High-Efficiency γ-particle coincidence Measurements

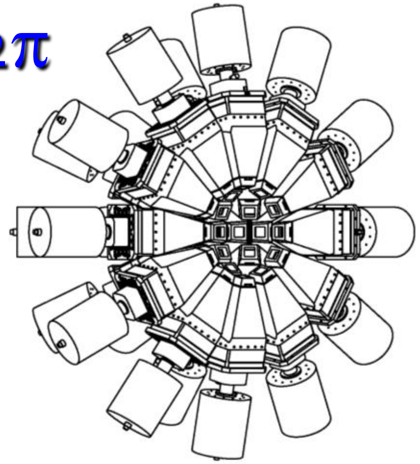
CLARA

25 EUROBALL HpGe Clover

$\varepsilon \sim 3\%$ @ $E_\gamma = 1.3$ MeV

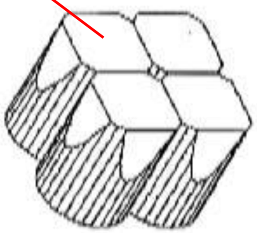
P/T ~45 %

2π

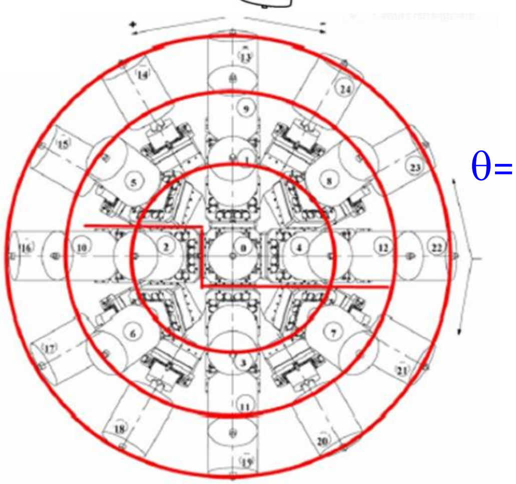


Composite Ge

50mmx70mm



Compton Polarimeters



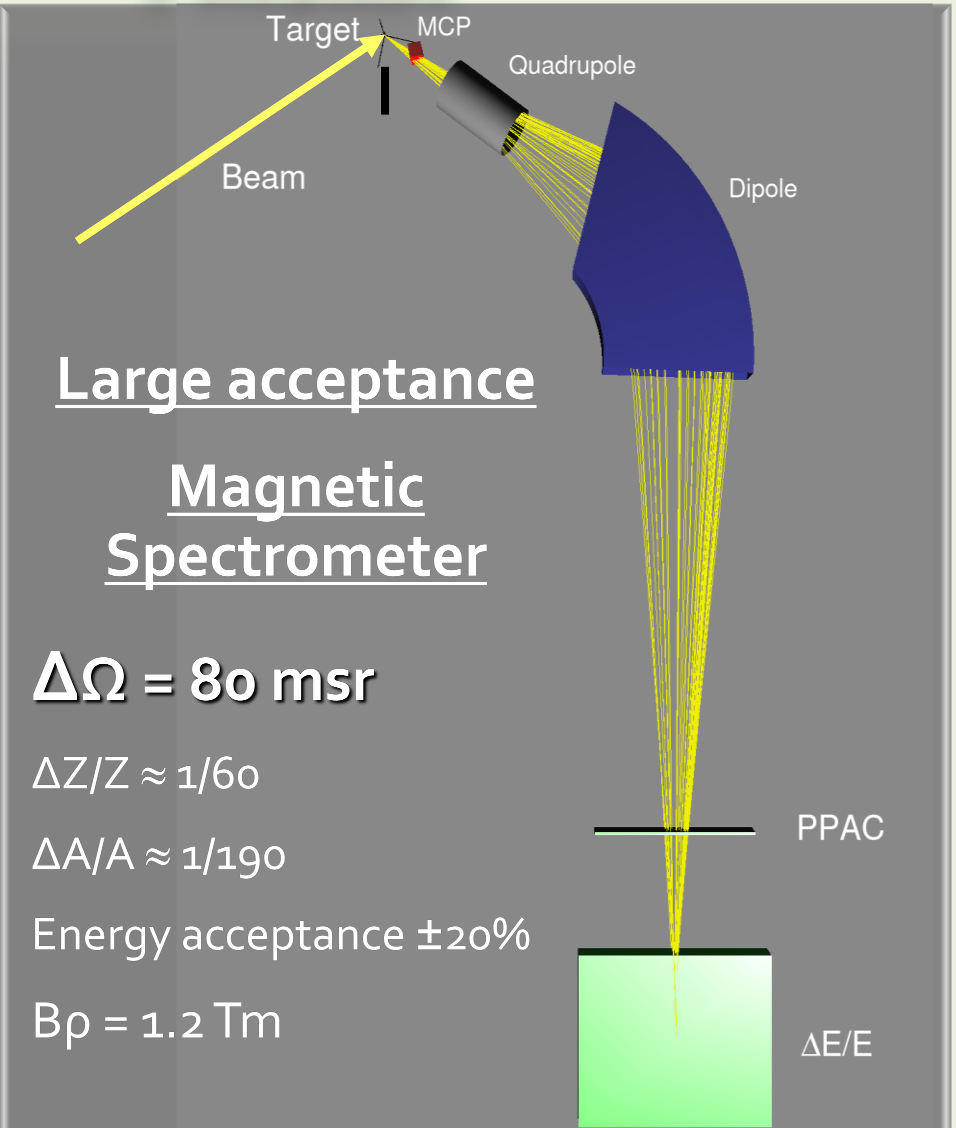
3 RINGS

θ= 100°, 130°, 150°

Angular Distributions γ rays

CLARA always opposite to PRISMA

PRISMA



Large acceptance

Magnetic Spectrometer

ΔΩ = 80 msr

$\Delta Z/Z \approx 1/60$

$\Delta A/A \approx 1/190$

Energy acceptance ±20%

$B\rho = 1.2$ Tm

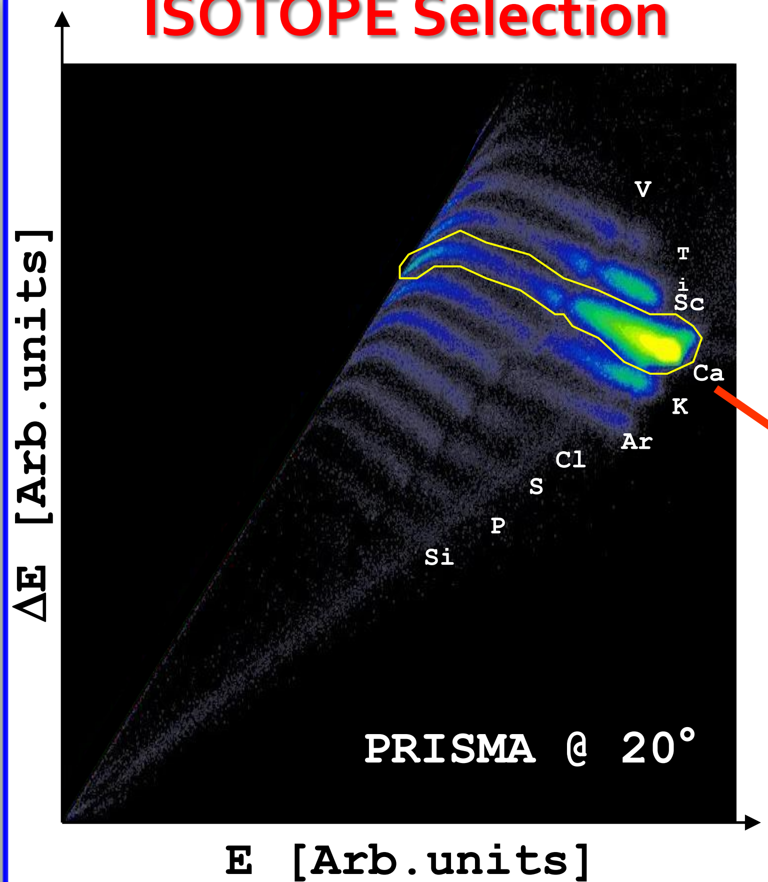
Trajectory Reconstruction - Ion identif.

Legnaro National Laboratory INFN (Italy)

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

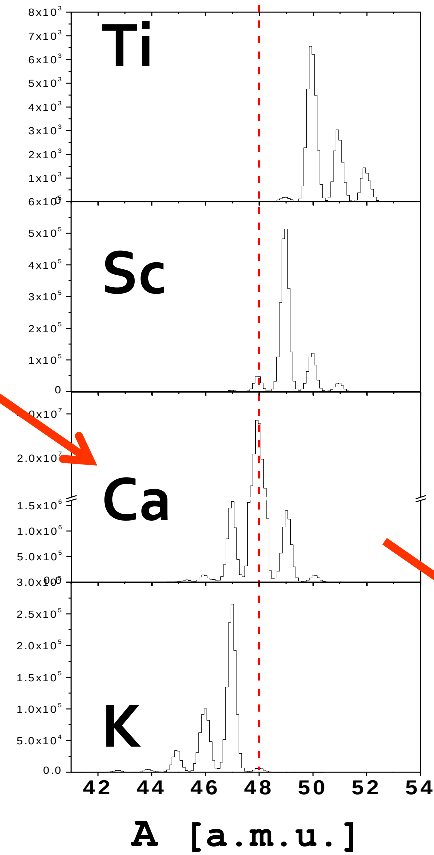
CLARA + PRISMA

ISOTOPE Selection



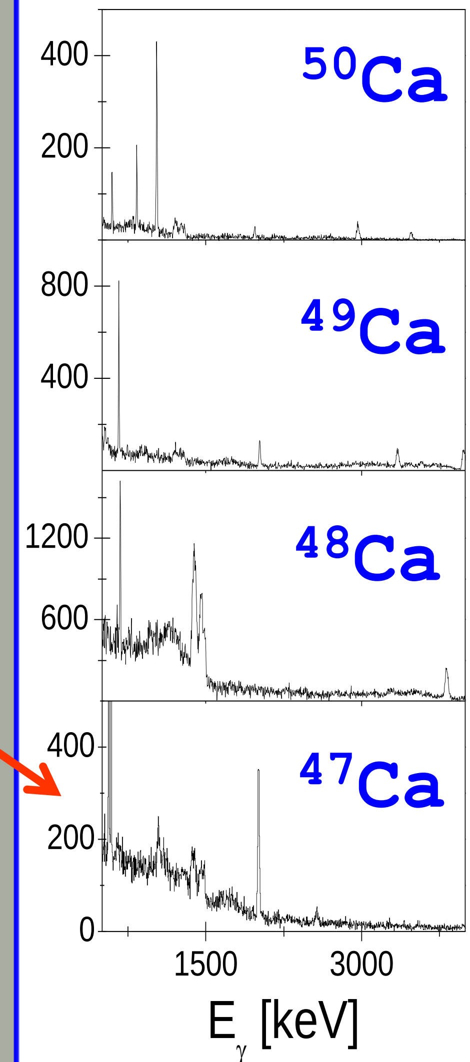
MASS spectra

Reaction studies



γ Spectra

Nuclear Structure



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

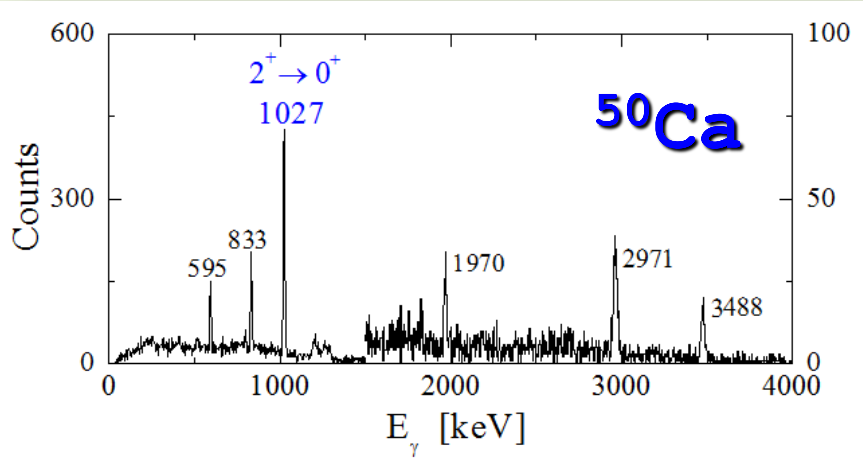
2 – Gamma Spectroscopy

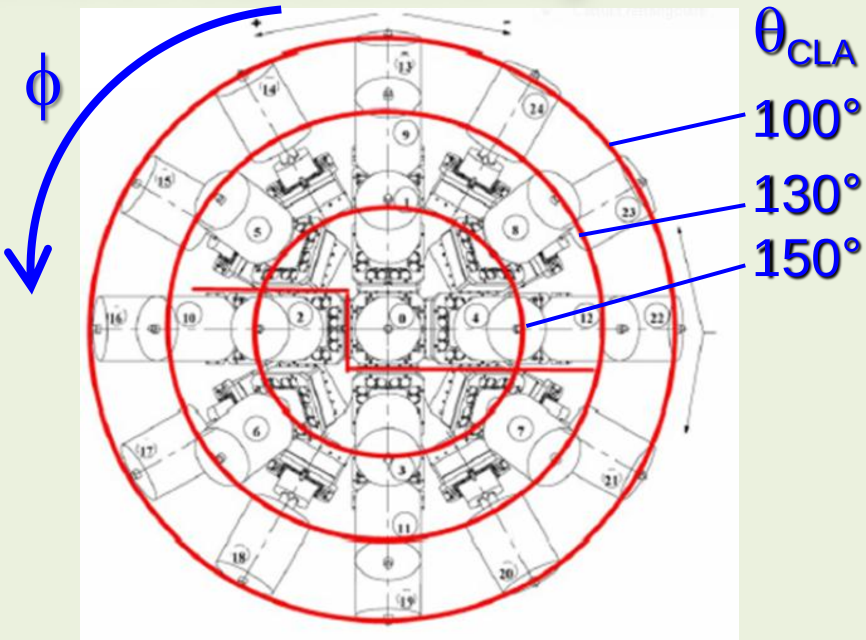
Angular Distributions
Polarizations
Lifetime Analysis

→ Spin, Parity and Nature of State

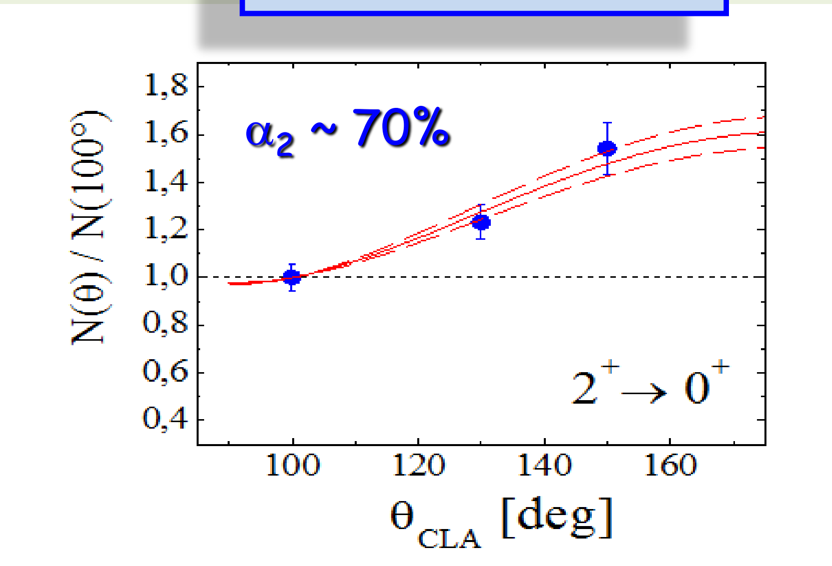
D. Montanari, S. Leoni et al., Phys. Lett. B697(2011)288
D. Montanari, S. Leoni et al., Phys. Rev. C85(2012)044301

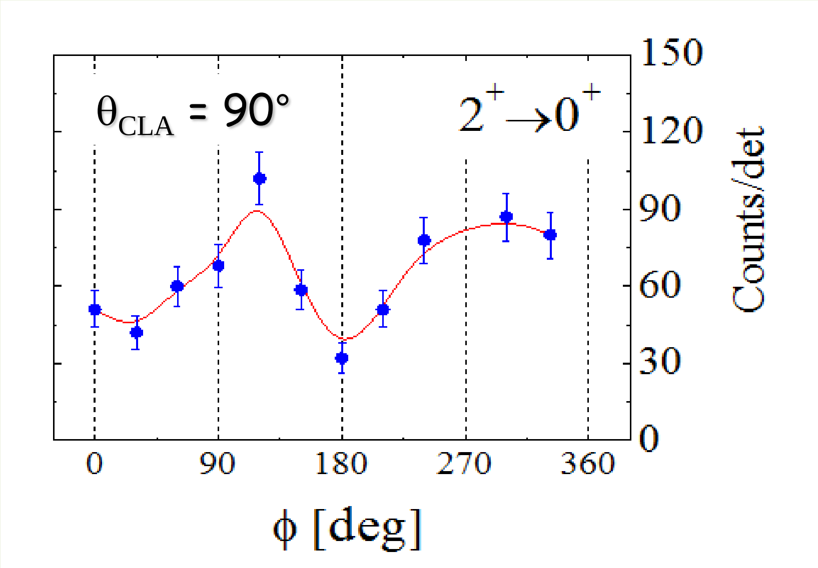
γ-Ray Angular Distributions in CLARA Array





$$W(\theta) = 1 + \alpha_2 A_2 P_2(\cos\theta)$$

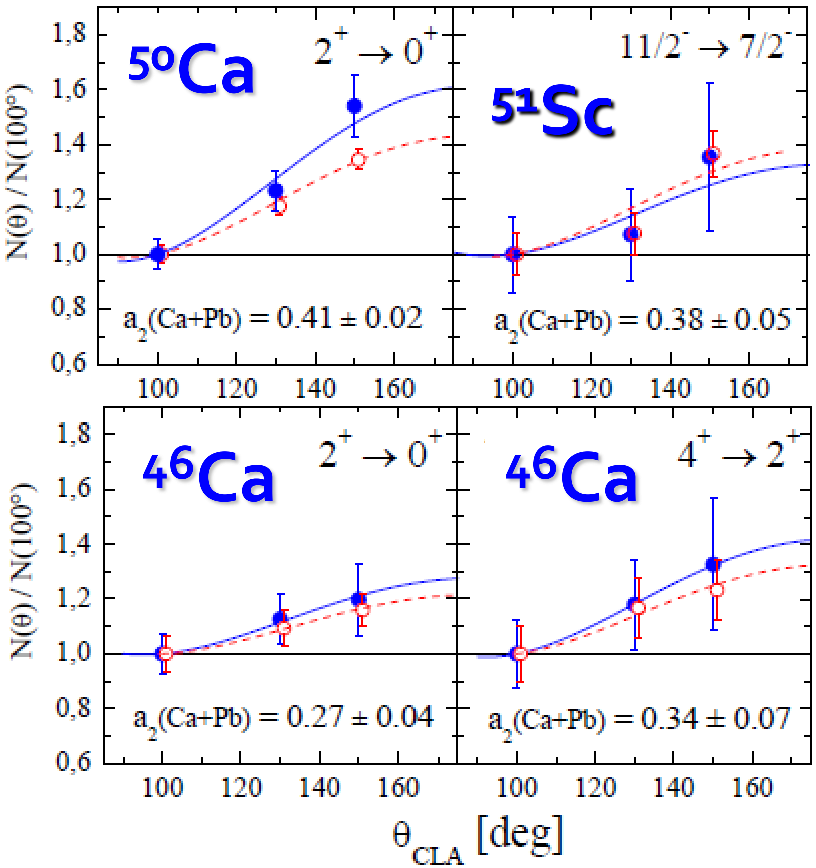




Oblate SPIN Alignment perpendicular to reaction plane

Similar Anisotropy

for known ΔI = 2 transitions

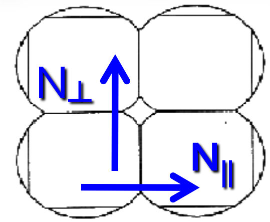


^{48}Ca + ^{64}Ni @ 282 MeV

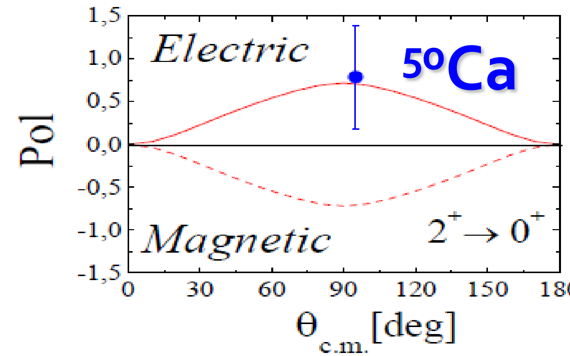
^{48}Ca + ^{208}Pb @ 310 MeV

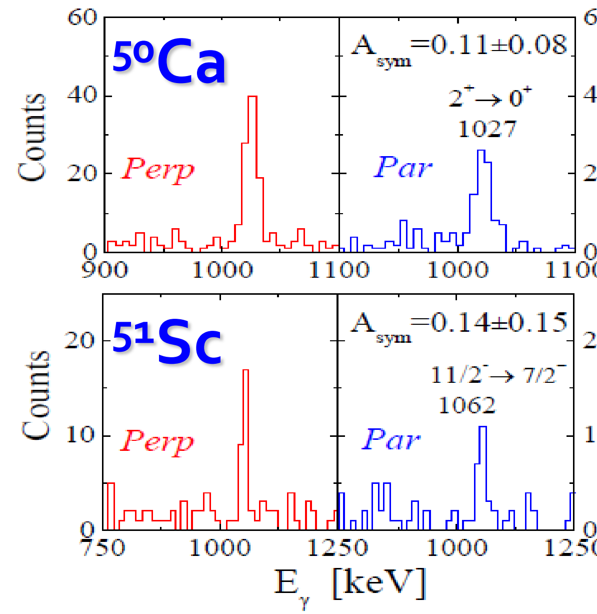
Asymmetry of

Compton Scattering in CLOVERs@90°

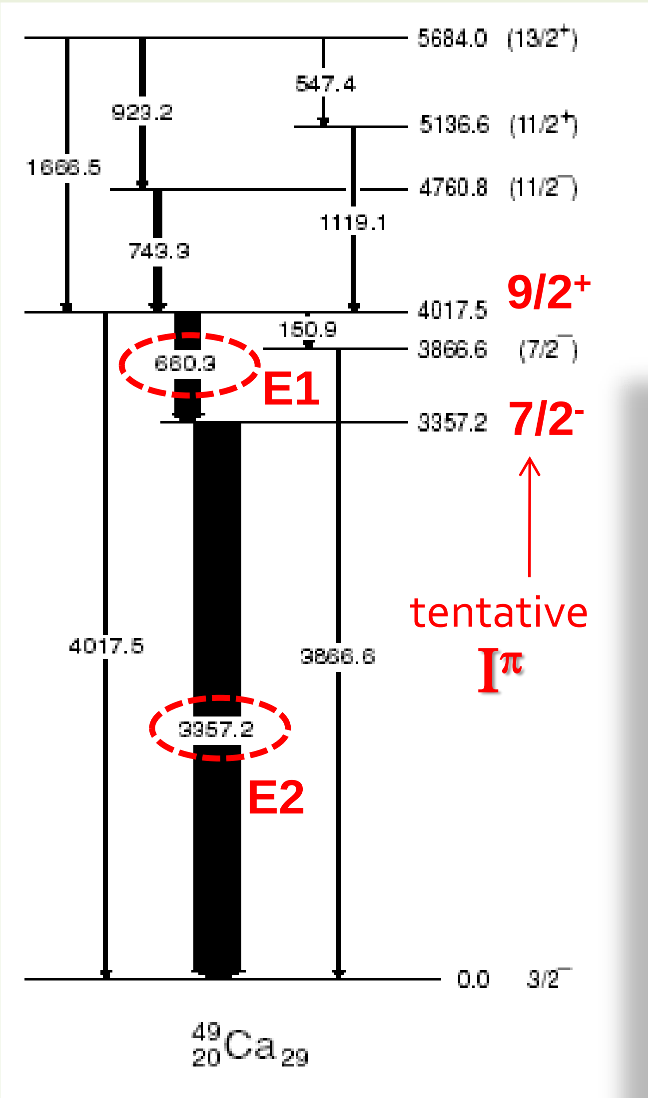


$$A_{sym} = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \quad \begin{matrix} > 0 \;\; \textbf{E} \\ < 0 \;\; \textbf{M} \end{matrix}$$



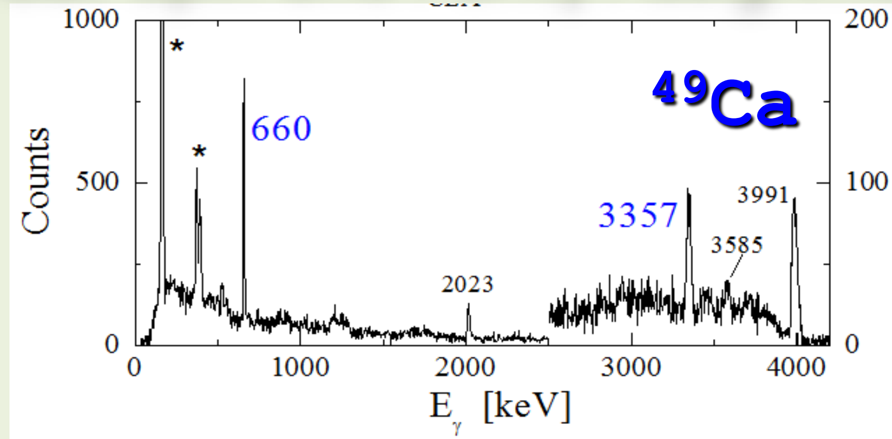


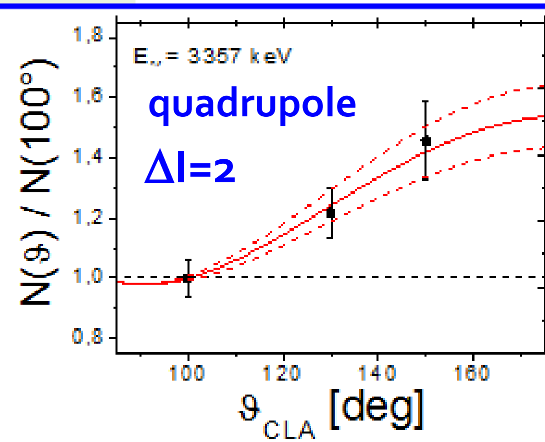
Spectroscopy of ^{49}Ca: Spin and Parity Assignment

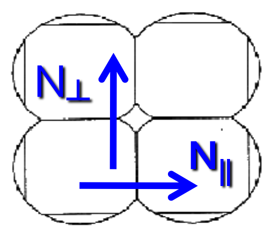


R. Broda, J.Phys.G32(2006)R151

MNT & Thick target data

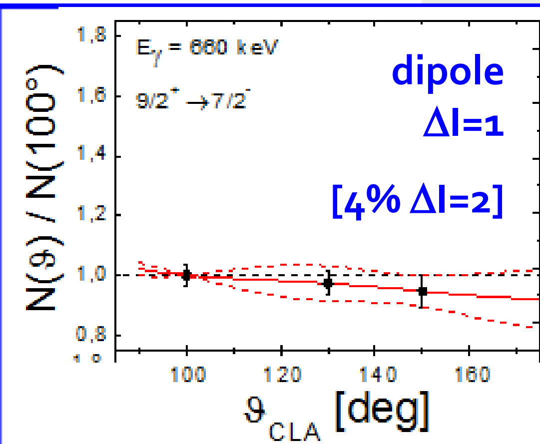


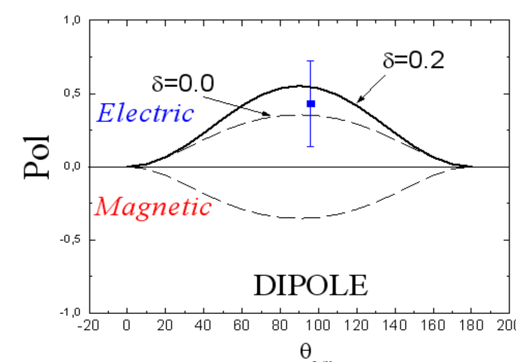




$$A = \frac{N_{\perp} - N_{\|}}{N_{\perp} + N_{\|}} = 0.08^{\pm 0.05} > 0$$

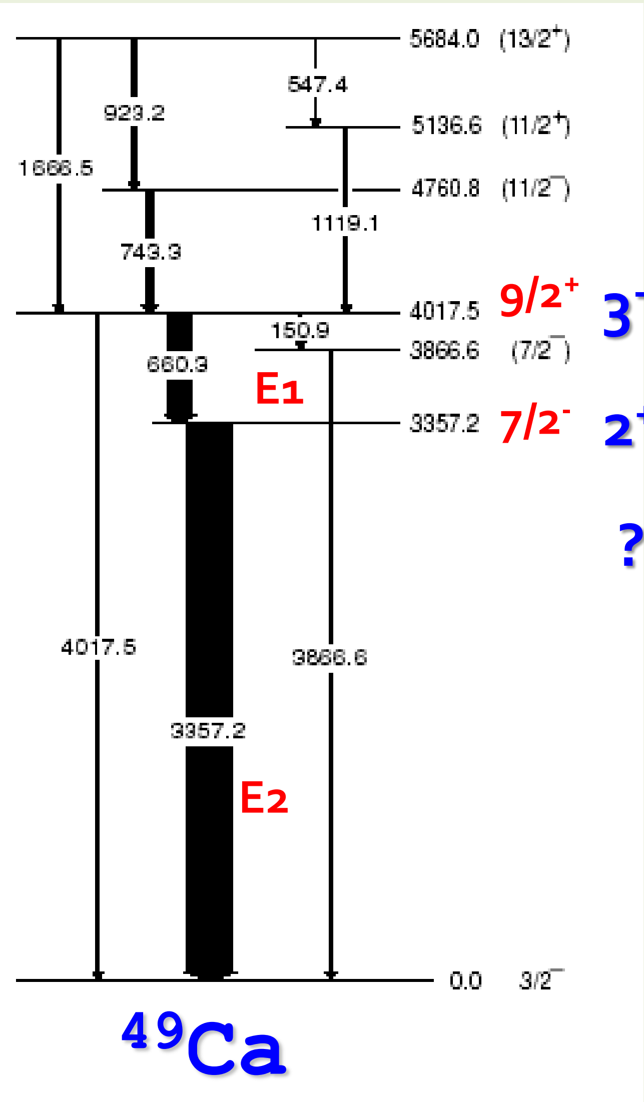
Electric





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

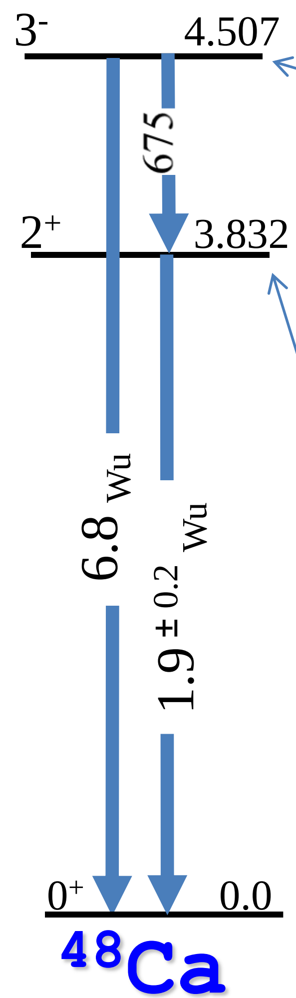
Core(^{48}Ca) - particle ($p_{3/2}$) Couplings ??



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

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

???



Collective Vibration

RPA by Bortignon, Colò:

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

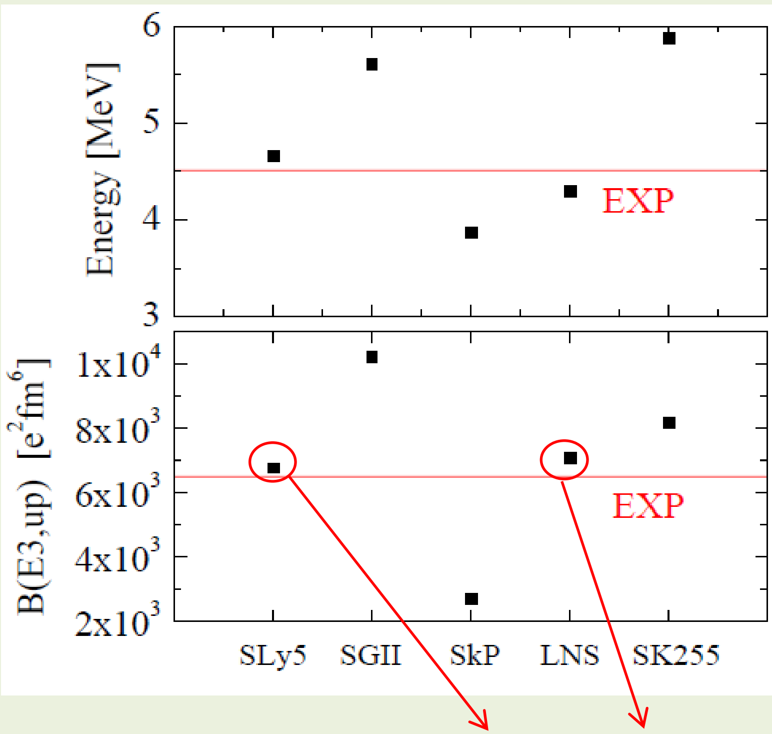
Single Particle State

SHELL model:

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

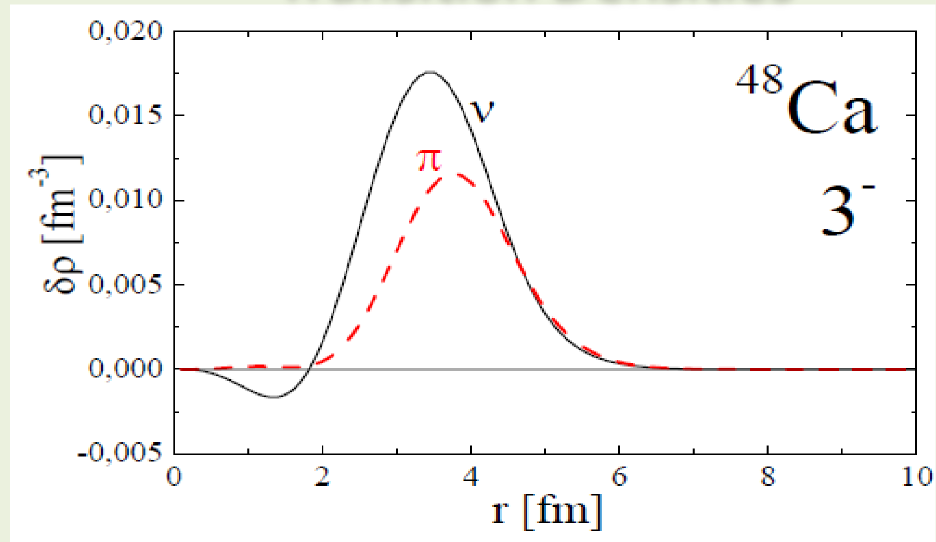
^{48}Ca: 3- RPA calculations

(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



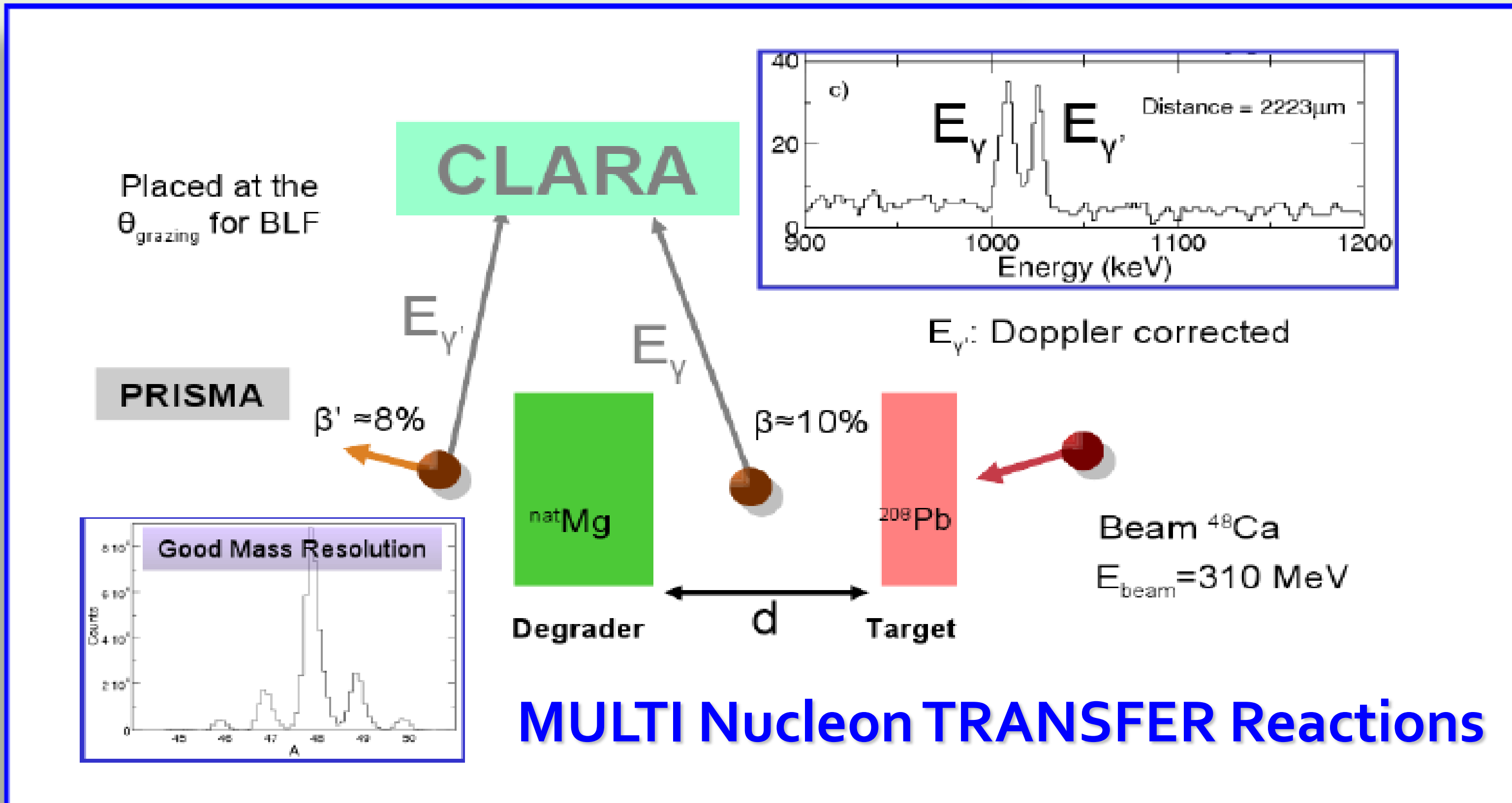
"SIMPLE Structures"

↓

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

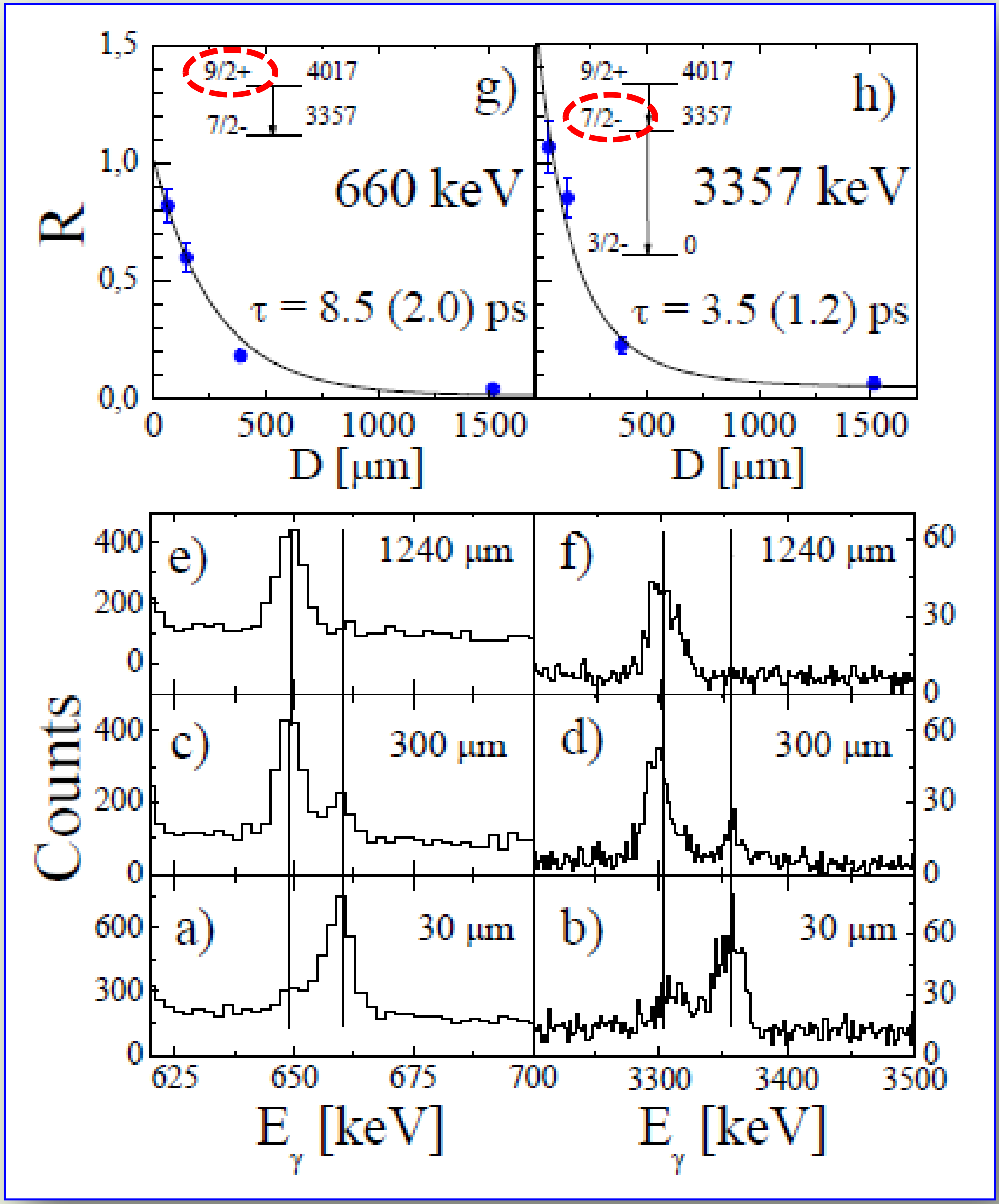
A. Dewald et al., Köln

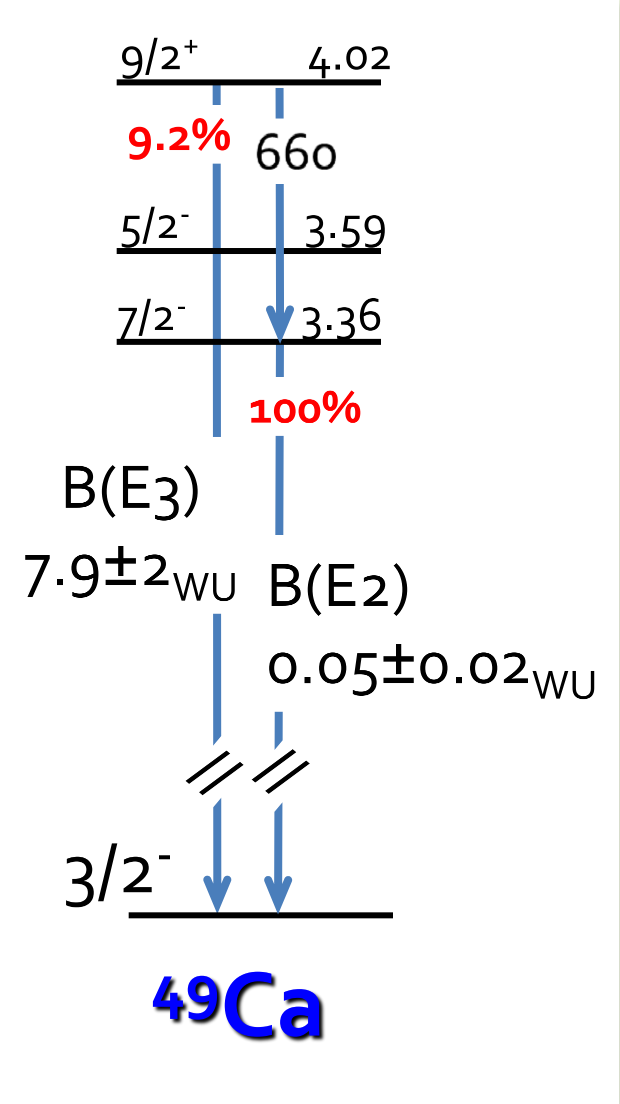
Lifetimes in ^{50}Ca, ^{51}Sc, ^{44,46}Ar

Valiente-Dobon et al.,PRL102(2009)242502

D. Mengoni et al., PRC82(2010)024308

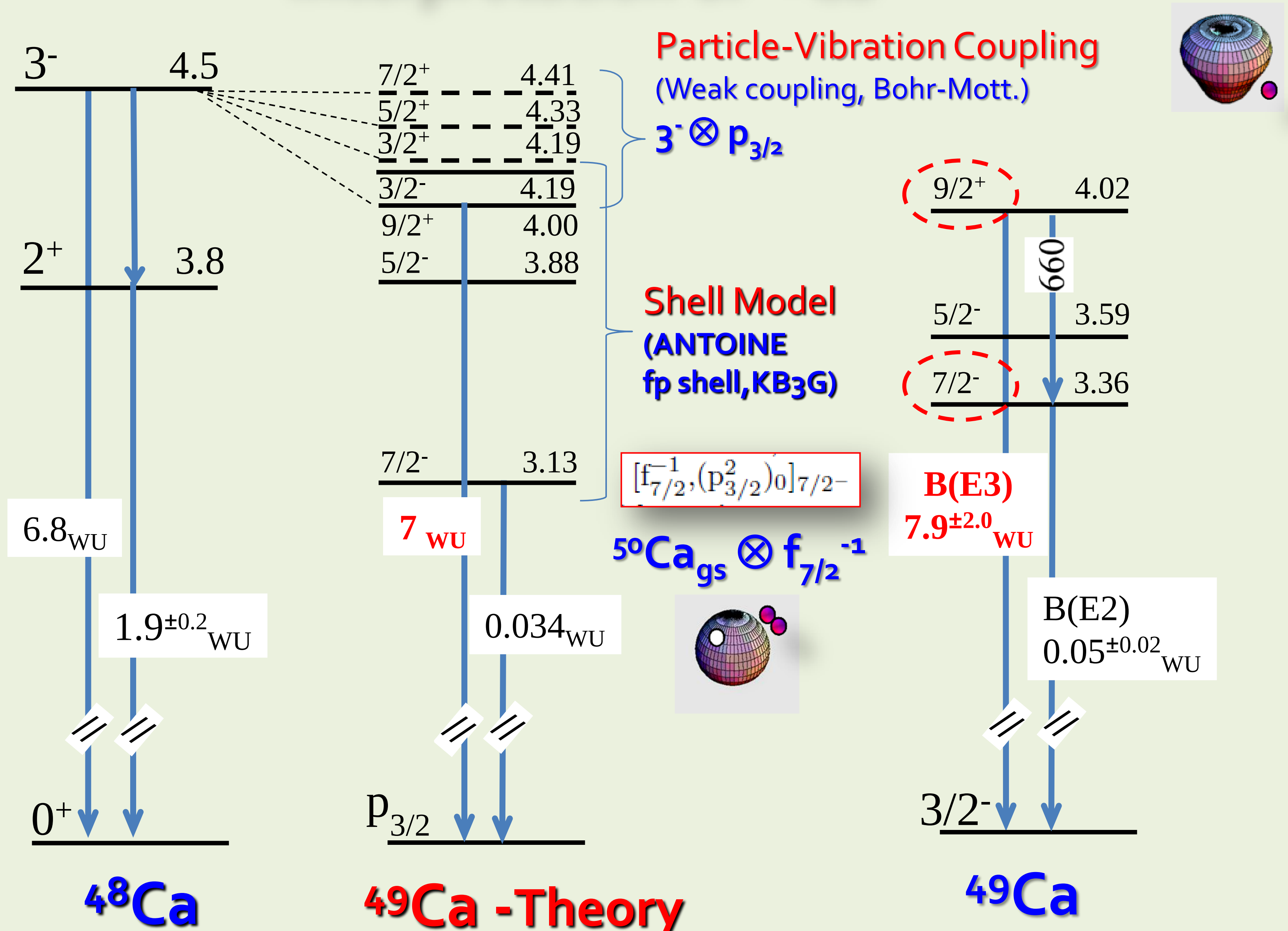
Lifetimes of ^{49}Ca





Branching from
R. Broda thick target exp.

Interpretation of ^{49}Ca

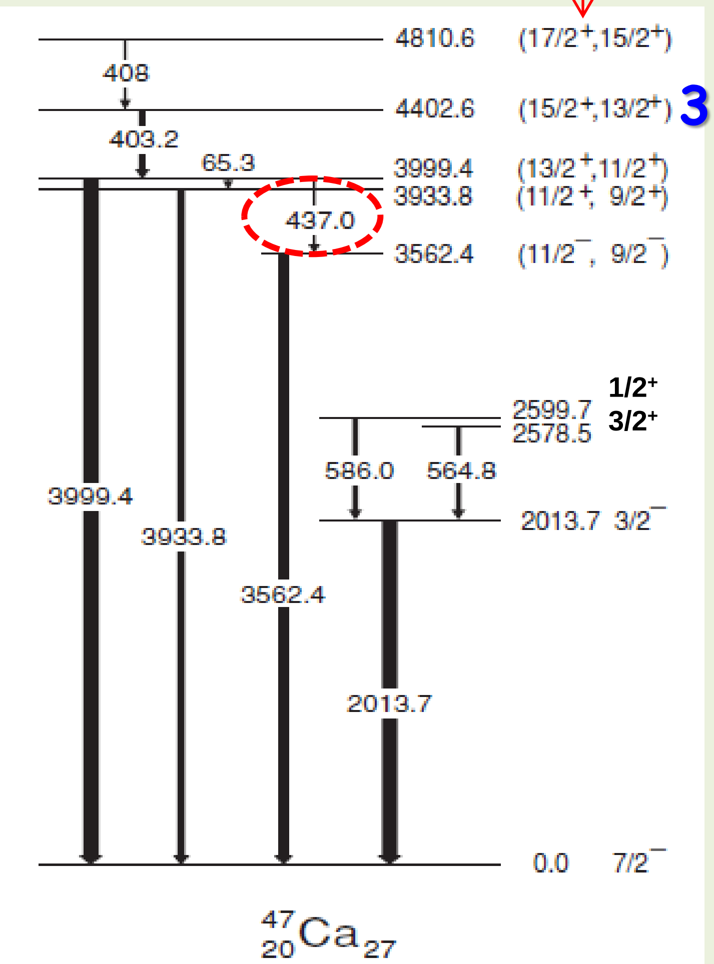


D. Montanari, S. Leoni et al., Phys. Lett. B697(2011)288

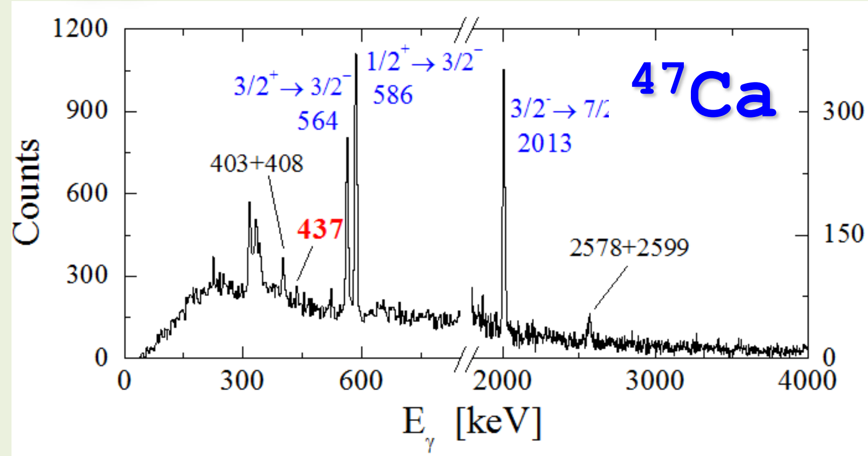
The case of ^{47}Ca

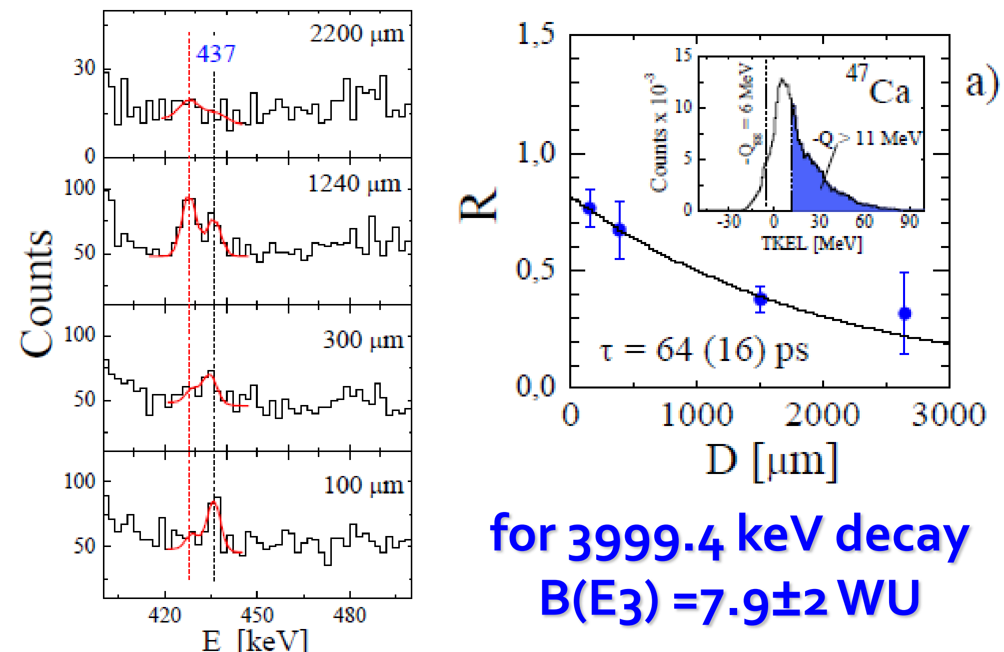
R. Broda, J.Phys.G32(2006)R151
MNT & Thick target data

tentative I^{π}



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

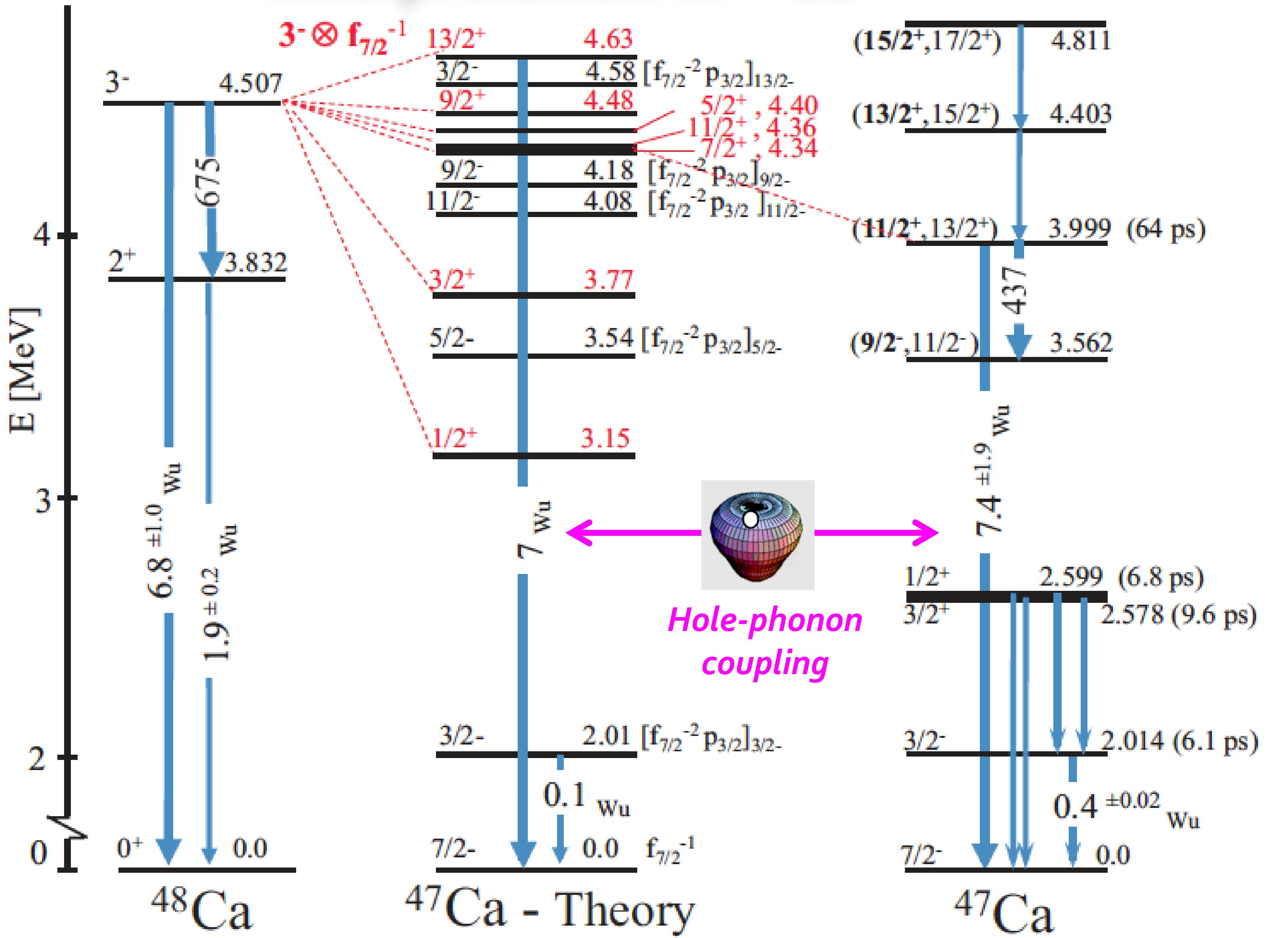




for 3999.4 keV decay
B(E3) =7.9±2 WU

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

Interpretation of ^{47}Ca



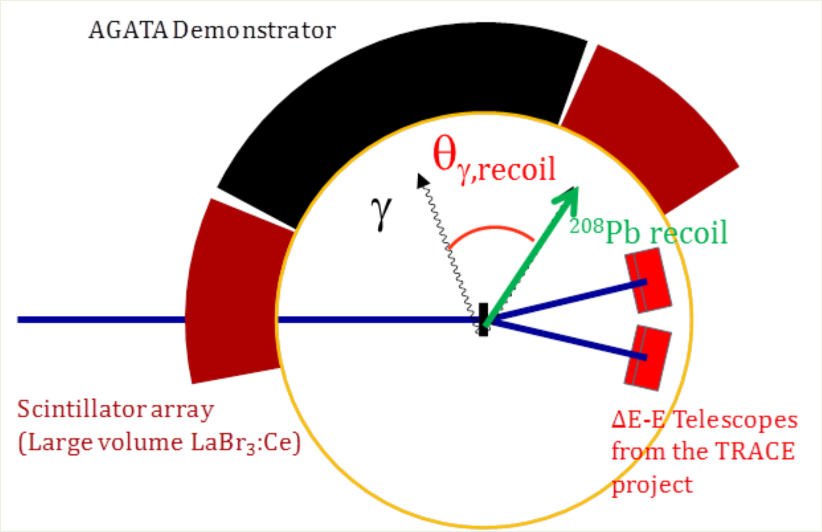
D. Montanari, S. Leoni et al., Phys. Rev. C85(2012)044301

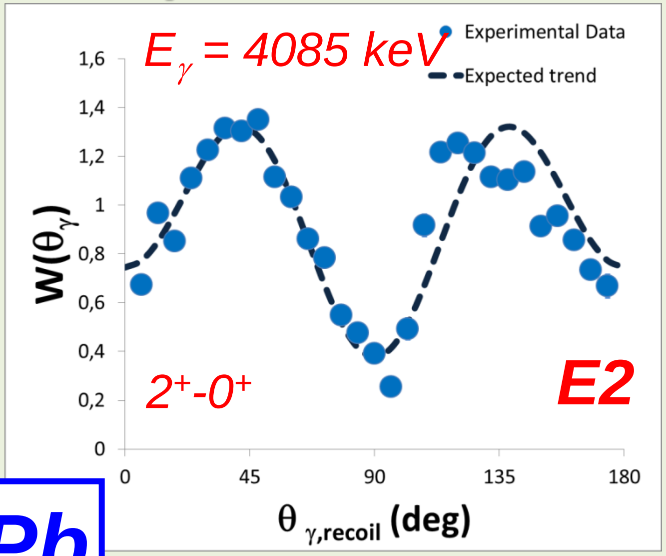
Remark for future Analysis:

High-Precision W(θ) and Pol Measurements with AGATA

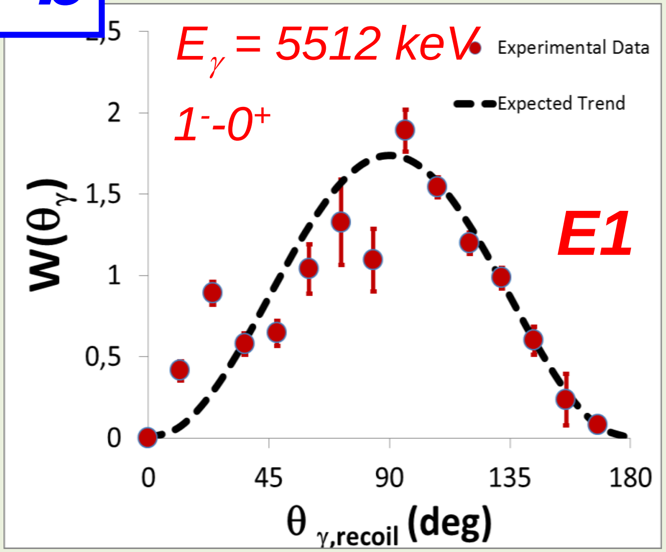
inelastic scattering of light ion beams + γ-decay

^{17}O @ 20 MeV/A on ^{208}Pb





208Pb



Angular Distribution of γ's obtained exploiting ***position sensitivity*** of **AGATA** and **E-ΔE Si** telescopes (pixel type)

PRELIMINARY

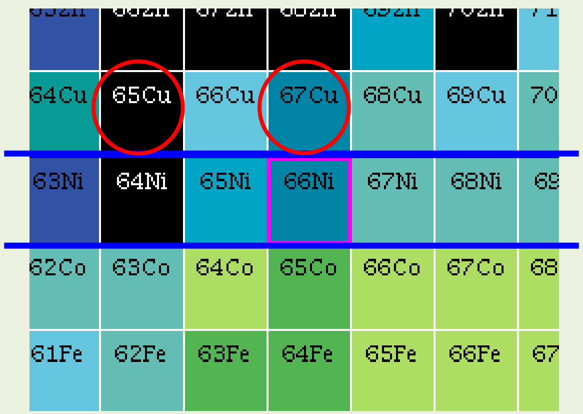
F. Crespi, A. Bracco, et al.
(Milano University)

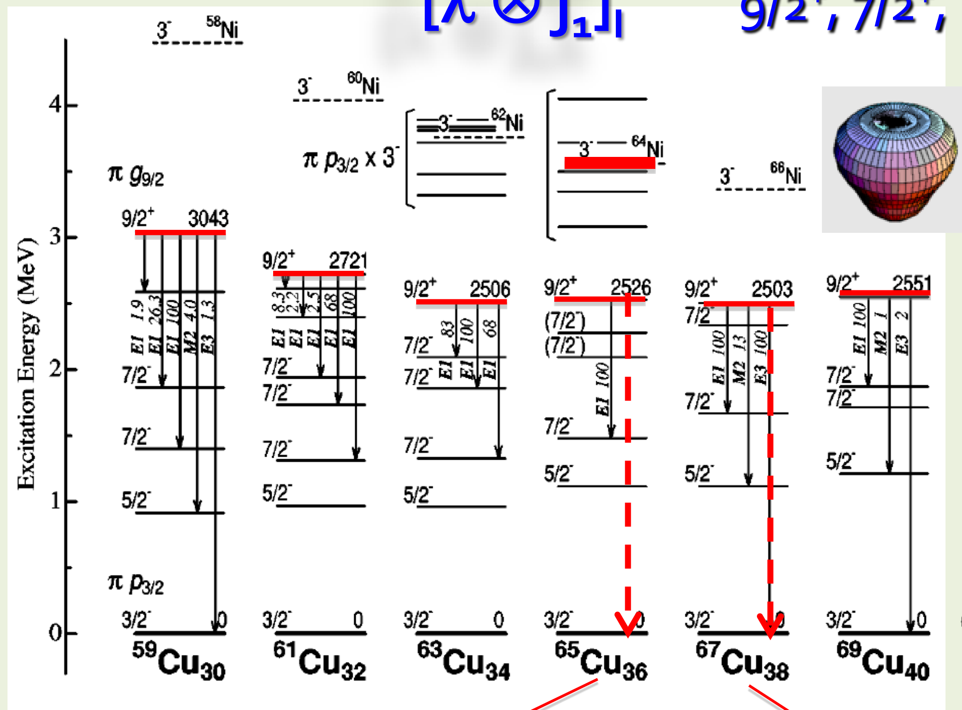
Work in Progress: ^{65,67}Cu

Study of Particle-Phonon states around Ni isotopes

$3^- \otimes p_{3/2}$ → Multiplet of States

$[\lambda \otimes j_1]_I$ $9/2^+, 7/2^+, 5/2^+, 3/2^+$





3-
B(E3)~17Wu

πp$_{3/2}$$^-$

^{64,66}Ni

(Z=28,N=36,38)

- Superfluid Core in ν
- π coupling

August 2012 Experiment

^{64}Ni(^{7}Li,□)^{65}Cu

Tandem-Bucarest

S. Leoni et al.

FAST TIMING

B(E3)~**???** Wu

Existing Data

^{64}Ni(□,p)^{67}Cu

N. Marginean et al.

FAST TIMING

τ(9/2+)~150 ps

B(E3)~17(2)Wu

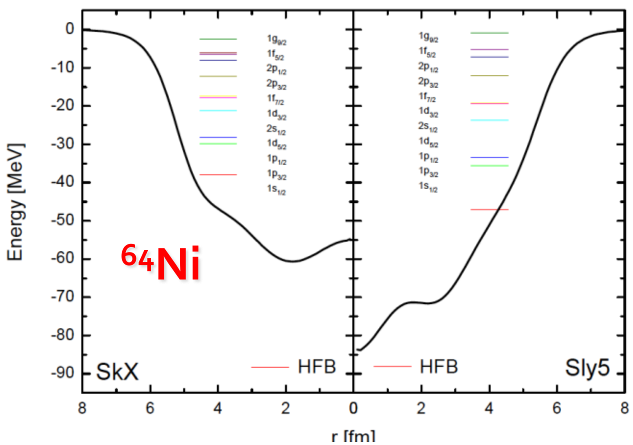
Theoretical Interpretation

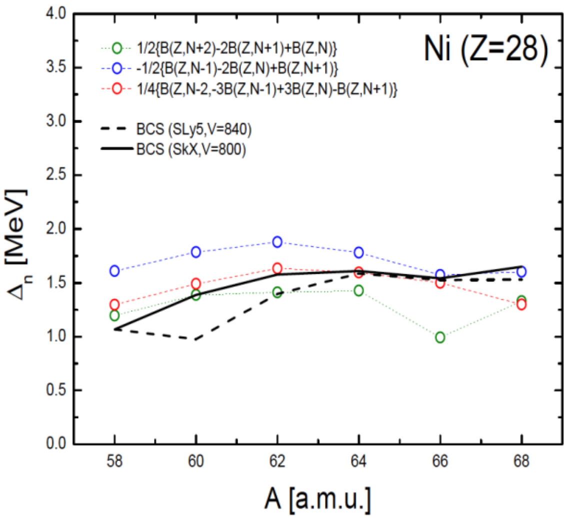
(S. Bottoni, G. Bocchi, G. Colò, PF. Bortignon)

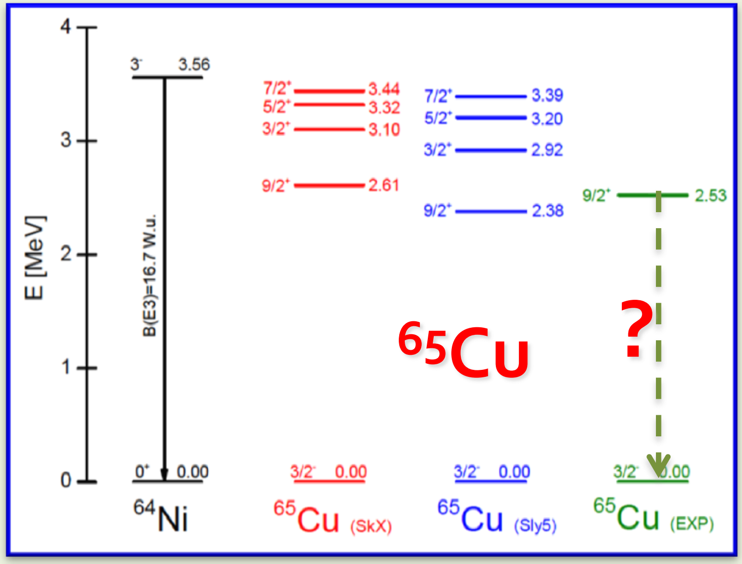
Single Particle π Levels

^{64,66}Ni (Z=28,N=36,38)

Superfluid Core

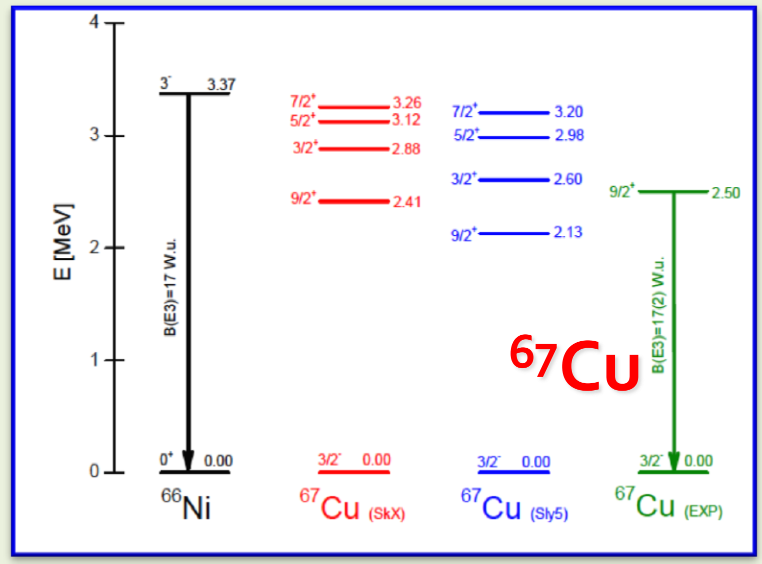






Coupling with proton

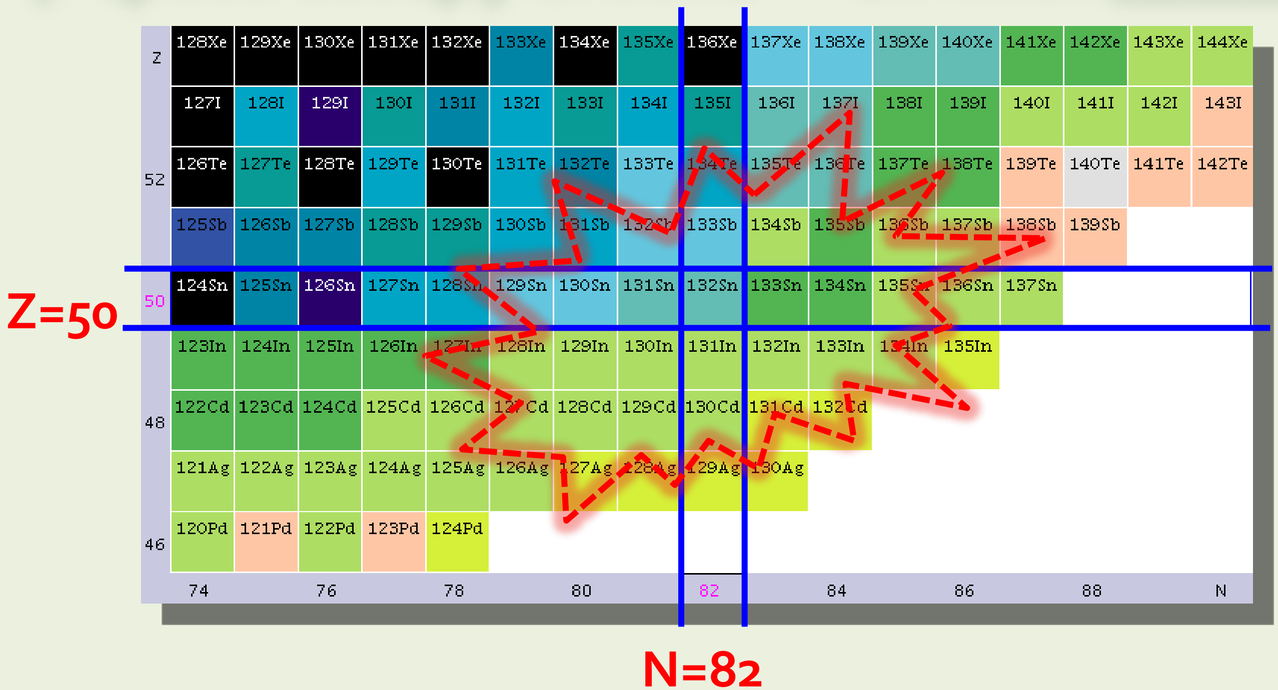
$3^- \otimes p_{3/2}$



→ Good Candidates for Particle-Phonon Coupled states

Perspectives with RIB

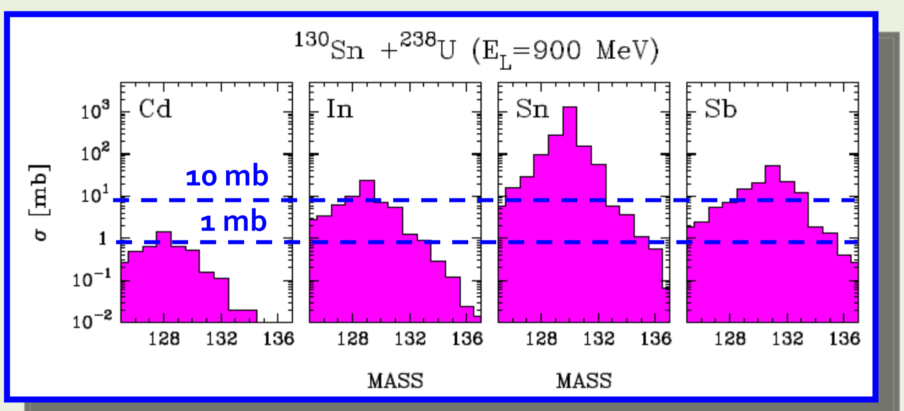
γ spectroscopy around ^{132}Sn with HI transfer reactions



STUDY OF

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

I^{π}, B(Eλ)

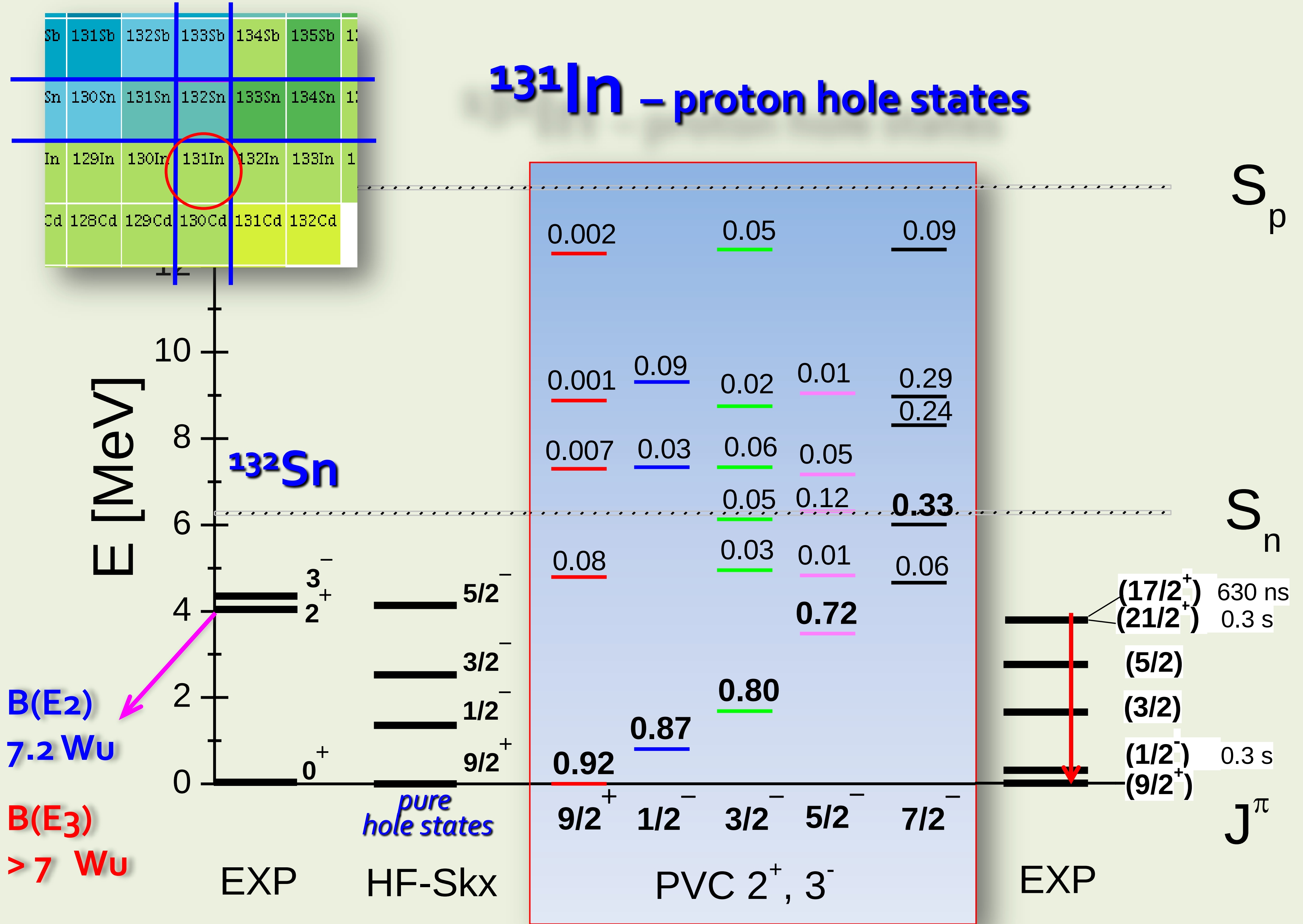


GRAZING calculations
Conservative estimates for more than 1 nucleon transfer

SPES Beams Legnaro-RIB

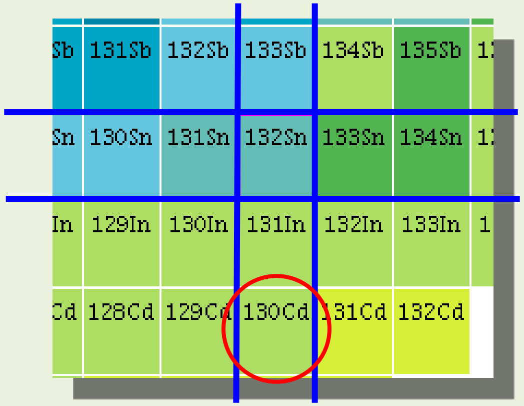
^{130}Sn 1.6 10^8	^{131}Sn 6.8 10^7	^{132}Sn 3.1 10^7	^{133}Sn 2.8 10^6	^{134}Sn 5 10^5
^{129}In 1.1 10^5	^{130}In 1.5 10^4	^{131}In 2.8 10^3	^{132}In 1.9 10^3	^{133}In -
^{128}Cd 2.9 10^3	^{129}Cd 2.5 10^2	^{130}Cd -		

^{131}In – proton hole states



G.Colò and P.F.Bortignon

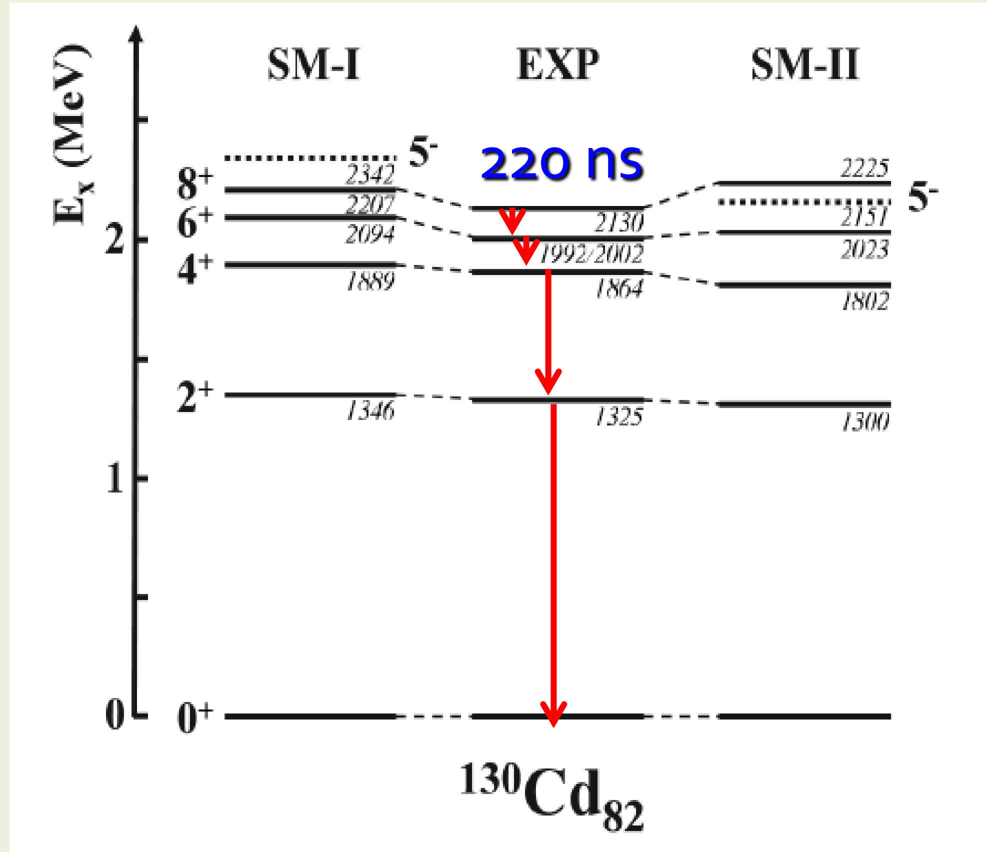
M.Gorska et al., PLB672(2009)313

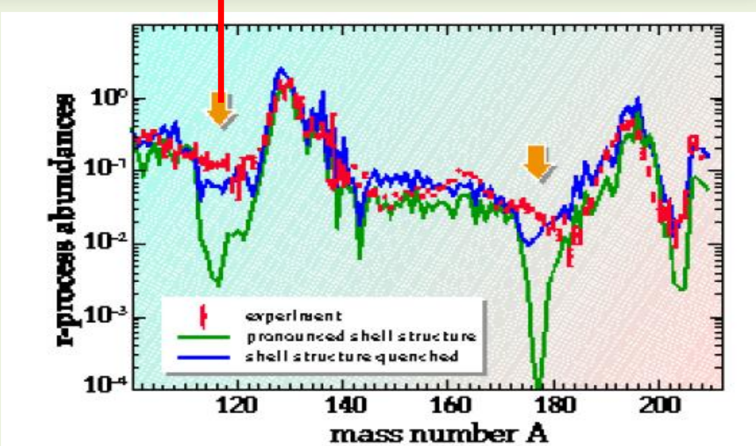


^{130}Cd – 2 proton holes states

- Tentative I^{π} assignment
- Tentative B(Eλ) values
- Missing levels

→Strength of **PAIRING** interaction
→ **SHELL** quenching below ^{132}Sn





GSI: Projectile fragmentation
^{136}Xe (750 MeV/A) + Be

A. Jungclaus et al., PRL99(2007)132501

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***

  → ***Indication In ^{65,67}Cu, …***

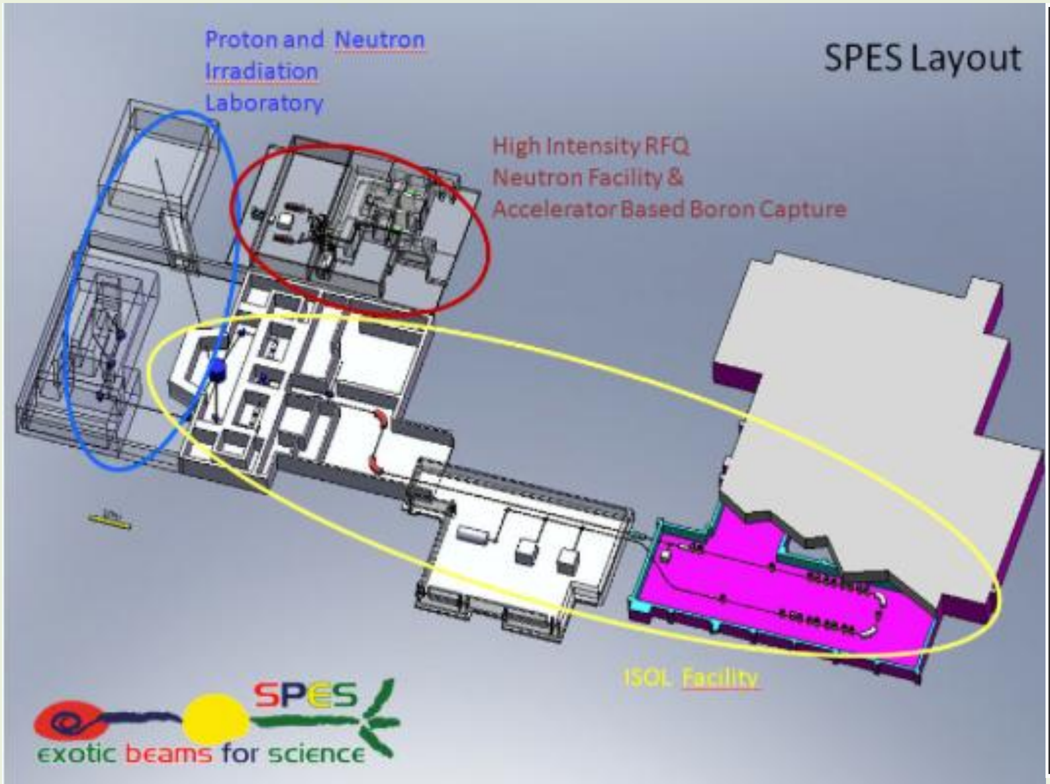
+ ***Preparatory Work for Radioactive Beam Physics …***

Thank You for the Attention

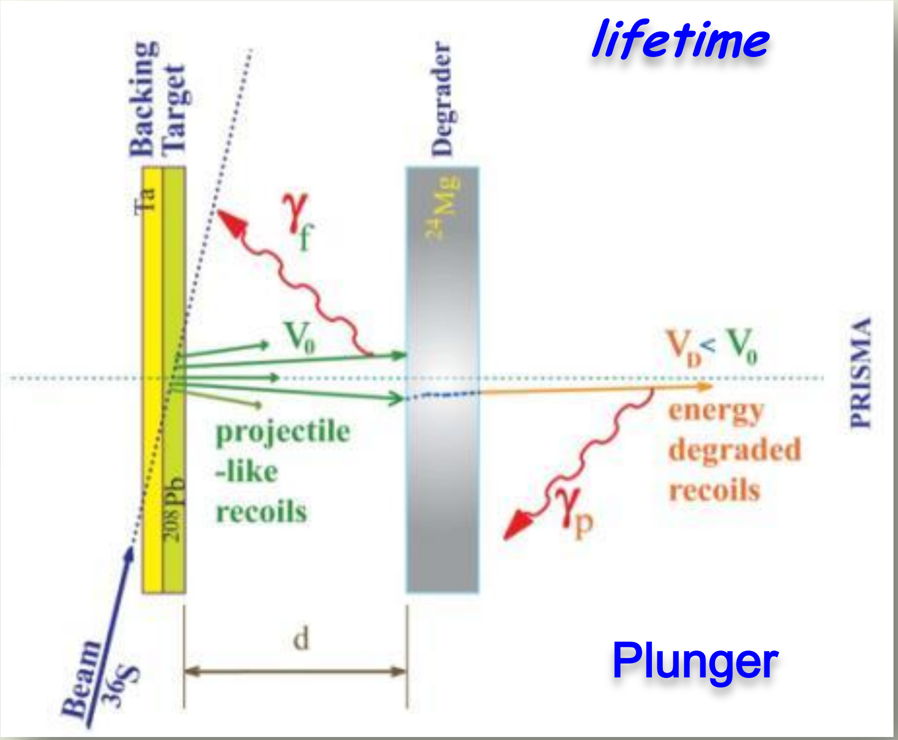
Radioactive Beam Project at Legnaro Laboratory INFN - Italy

SPES exotic beams for science

- Radioactive Ion Beams are produced by proton induced fission on a UCx direct target at a rate of 10^{13} fission/s.
- Neutron rich re-accelerated beams will be available at energies up to 13 MeV/u in the mass region A=130.
- Re-acceleration will be performed by the superconducting linear accelerator complex (PIAVE-ALPI) of the Laboratori Nazionali di Legnaro.
- The facility for applied physics is based on proton and neutron beams from a two exit port cyclotron (70 MeV, 500 microA) and the high intensity RFQ TRASCO (5 MeV, 30 mA).



SPES ISOL FACILITY PLAN stage ALPHA-BETA	2010	2011	2012	2013	2014	2015
Facility preliminary design completion						
Prototype of ISOL Target and ion source						
ISOL Targets construction and installation						
Authorization to operate						
Building's tender & construction						
Cyclotron tender & construction						
Cyclotron installation and commissioning						
Neutron facility design						
Neutron facility construction						
Alpi preparation for post acceleration						
Design of RIB transport & selection (HRMS, Charge Breeder, Beam Cooler)						
Construction and installation of RIBs transfer lines and spectrometer						
Complete commissioning						


lifetime
Backing
Target
Ta
208Pb
Degrader
24Mg
γf
V0
VD< V0
PRISMA
projectile
-like
recoils
energy
degraded
recoils
γp
d
Beam
36S
Plunger