"Nuclear Structure with SPES"

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LNL, 10-12 Ottobre 2016

Third International SPES Workshop

10-12 October 2016 *INFN Laboratori Nazionali di Legnaro*
Europe/Rome timezone

INTRODUCTION

Peculiarities of SPES

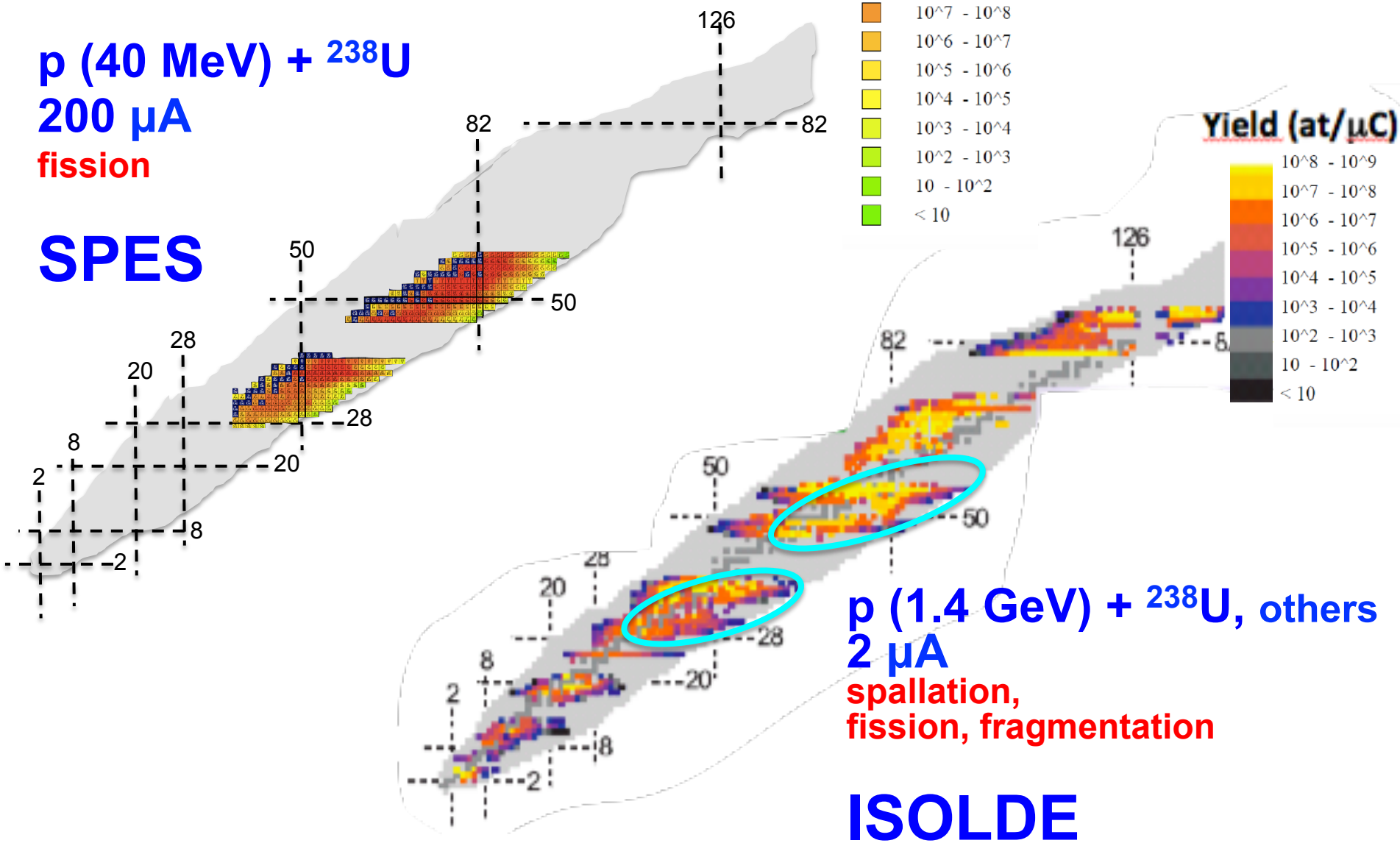
- Production scheme and Yields
- Accelerator Complex and Detection Setups

NUCLEAR STRUCTURE

Where SPES can do very well

- Shell Structure
- Complex Excitations
- Shape Evolution and Coexistence

ISOL Production Schemes



p (40 MeV) + ^{238}U
200 μA
fission

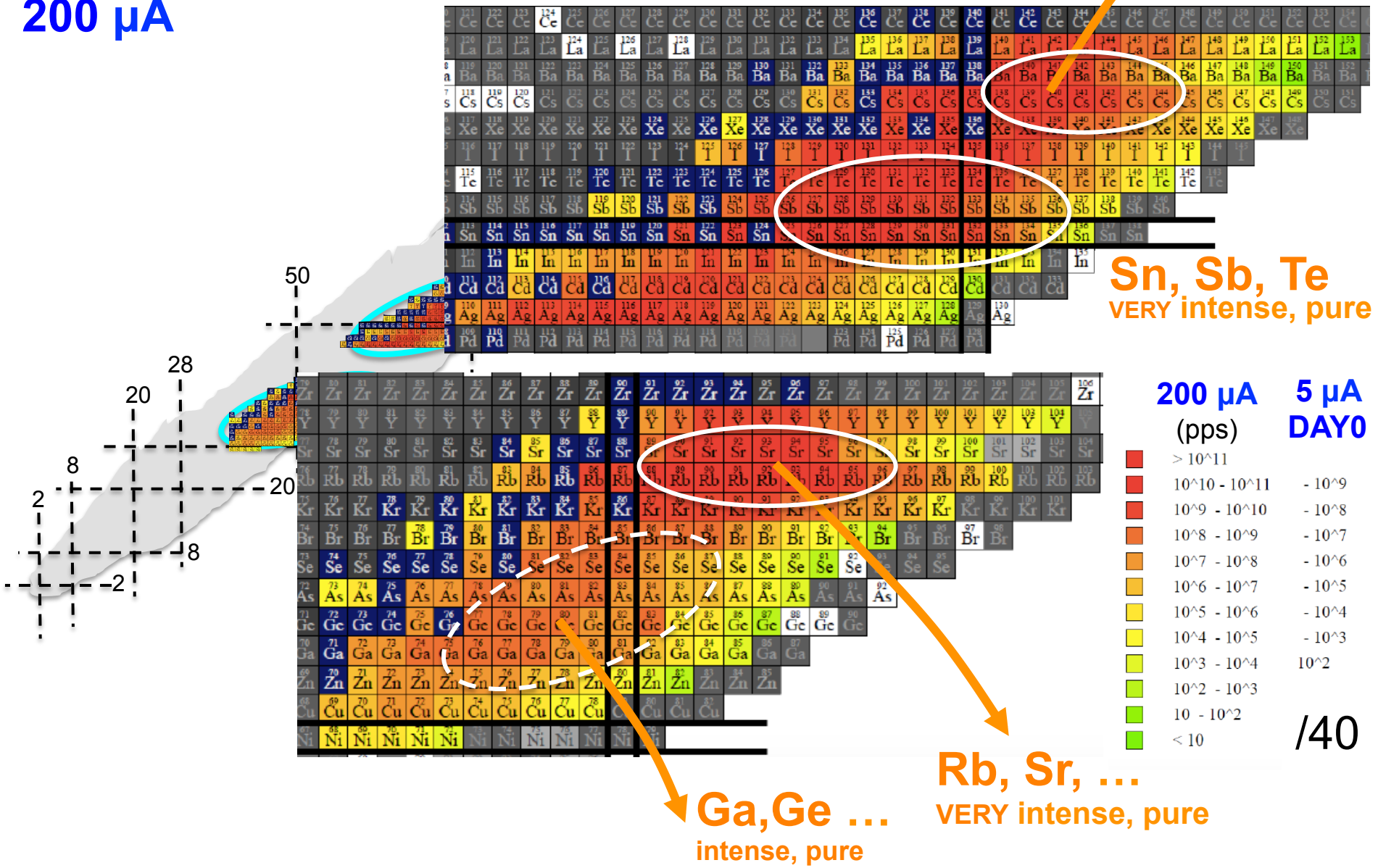
SPES

p (1.4 GeV) + ^{238}U, others
2 μA
spallation,
fission, fragmentation

ISOLDE

SPES - BEAMS

p (40 MeV) + ^{238}U
200 µA



SPES – Intense Exotic Species

Sn, Sb, Te, …
Cs, Ba, …
Rb, Sr, …
Ga, Ge, …

DAY0: up to 10^9 pps
FULL: up to 10^{11} pps
1+
40 keV

Ground State properties, β-decay spectroscopy

Several LOI's (G. Benzoni, INFN-Milano, coordinator)

In-Beam Nuclear Structure

LNL – Accelerator

ALPI Superconductive LINAC

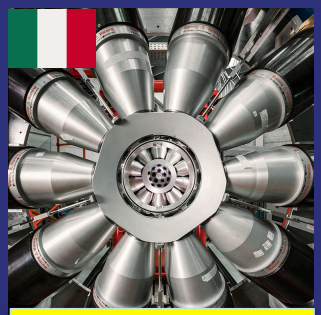
Reactions at 10 MeV/A

(eff_{CB} = 4%, $Trans_{ALPI}$ = 50%)

DAY0: up to 10^7 pps
FULL: up to 10^9 pps

- Coulex
- Transfer
- Multi-Nuc.Transfer
- Fusion

LNL – Detection Systems (State of the Art)

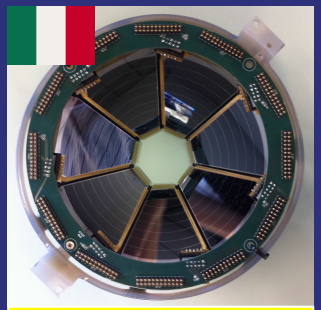


GALILEO – INFN
ε ≈ 8%

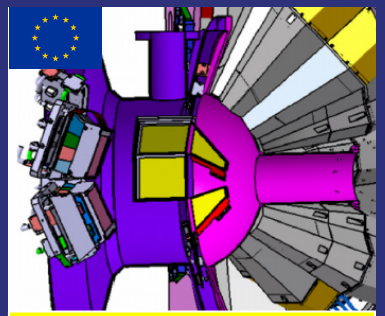
AGATA - 2020 …

charged-particle Spectroscopy

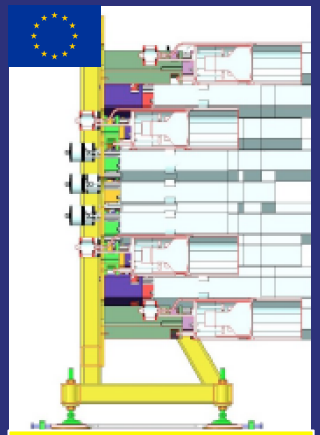
Si stripped/pixel detectors



SPIDER - Coulex



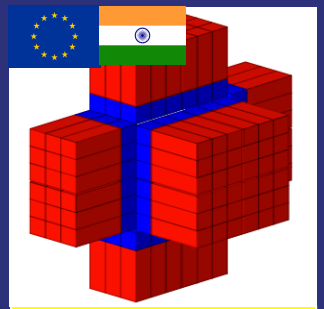
TRACE/MUGAST



NEDA/NWALL

neutron identification

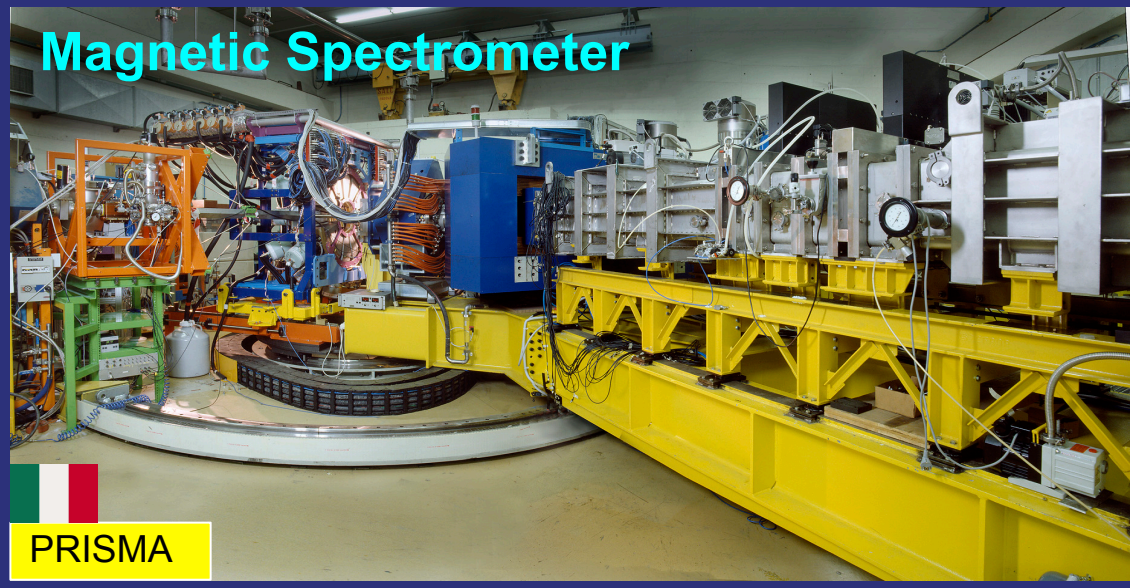
10 LaBr3 3x3
ε ≈ 1% @ 16 MeV



PARIS
Labr3+NaI

gamma spectroscopy

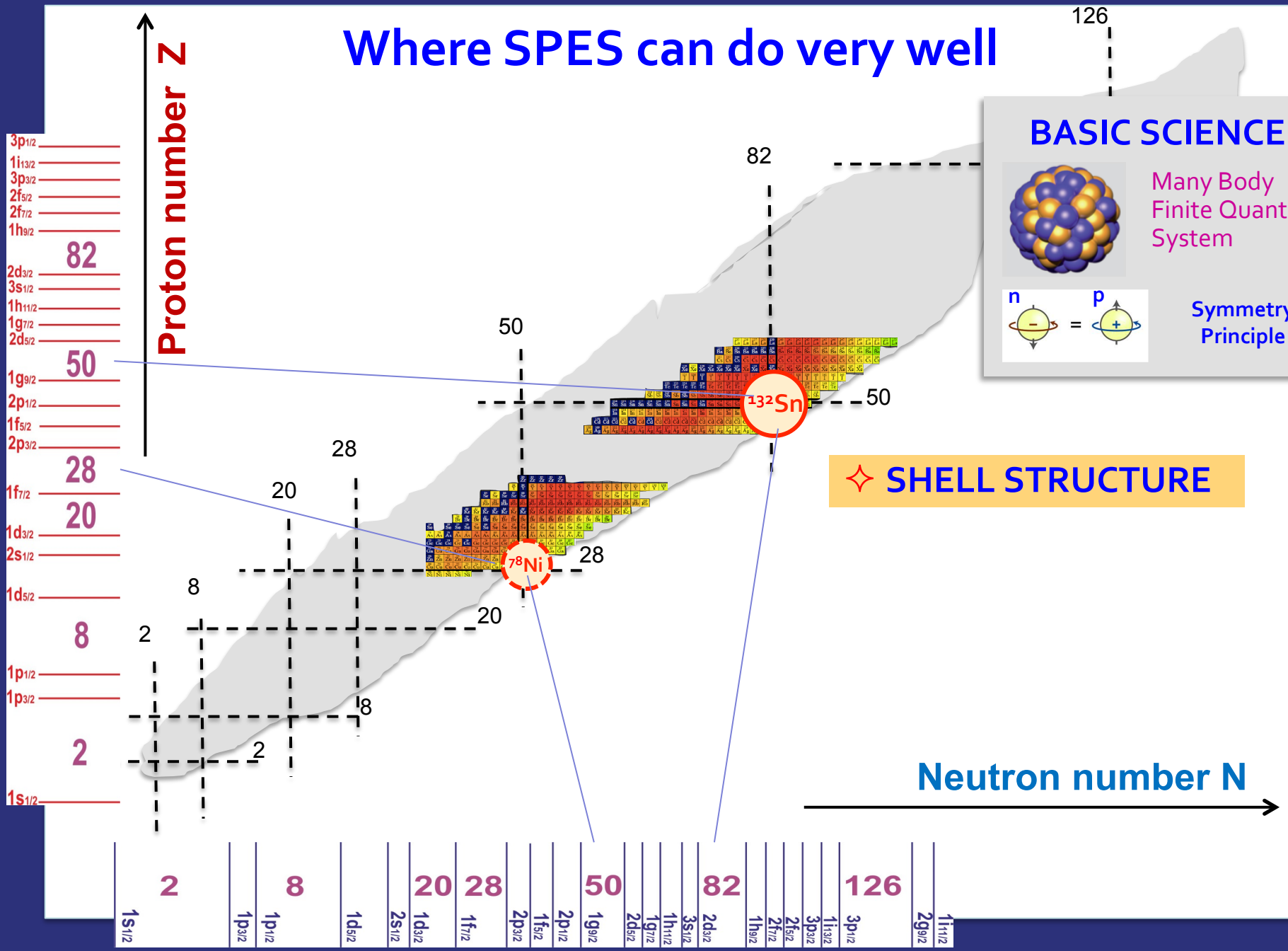
HPGe, scintillators



PRISMA

Very Powerful and Complete Experimental Setups ...

Quest for a UNIFIED DESCRIPTION of ALL Nuclei



Quest for a UNIFIED DESCRIPTION of ALL Nuclei

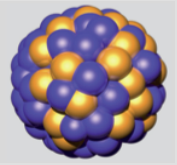
Where SPES can do very well

Proton number Z

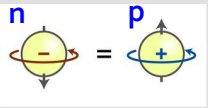
126
82
50
28
20
8
2

^{132}Sn
^{78}Ni

BASIC SCIENCE

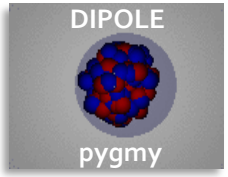


Many Body
Finite Quantum
System

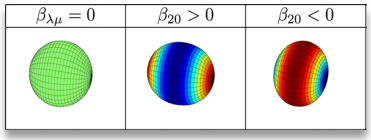


Symmetry
Principle

✧ SHELL STRUCTURE



✧ COMPLEX EXCITATIONS



✧ SHAPE evolution

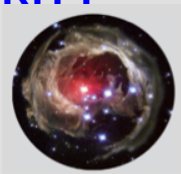
Neutron number N

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

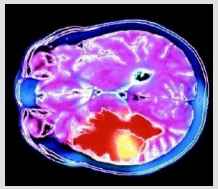
Where SPES can do very well

INTERDISCIPLINARITY

Astrophysics
Nucleosynthesis



Applications
Radioisotopes,
Reactors, ...



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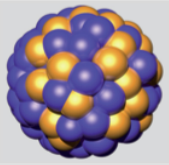

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Finite Quantum
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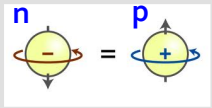

Symmetry
Principle

✧ SHELL STRUCTURE

✧ COMPLEX EXCITATIONS

✧ SHAPE evolution

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INTERDISCIPLINARITY

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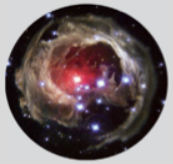
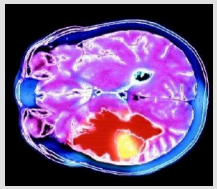
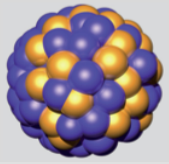


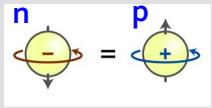
Applications
Radioisotopes,
Reactors, ...



BASIC SCIENCE



Many Body
Finite Quantum
System



Symmetry
Principle

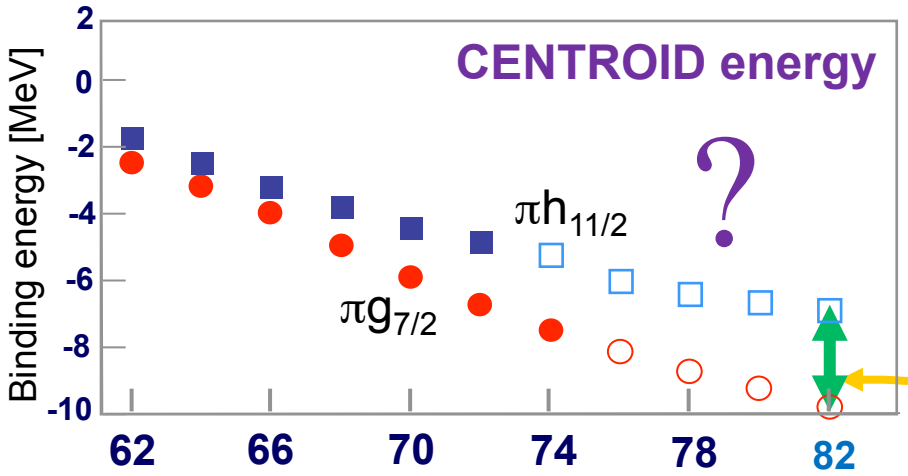
✧ SHELL STRUCTURE

✧ COMPLEX EXCITATIONS

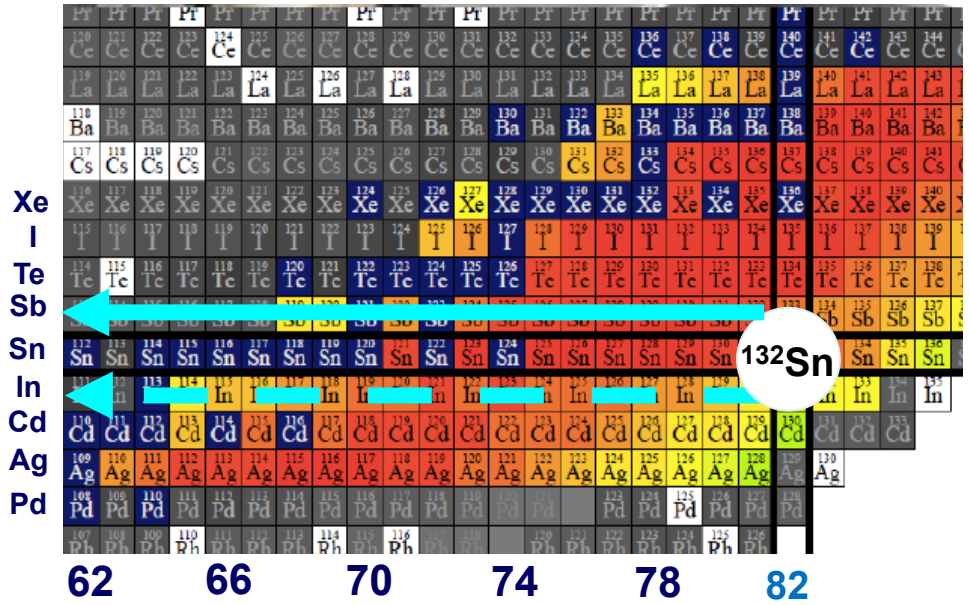
✧ SHAPE evolution

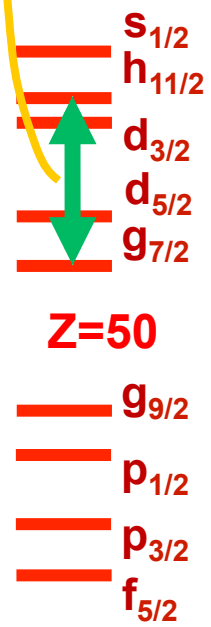
Selected Examples ...

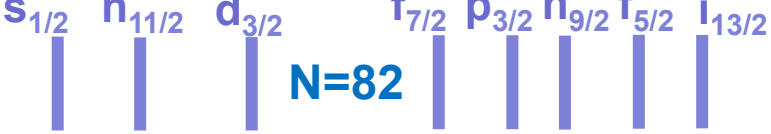
Single Particle Levels - PROTONS

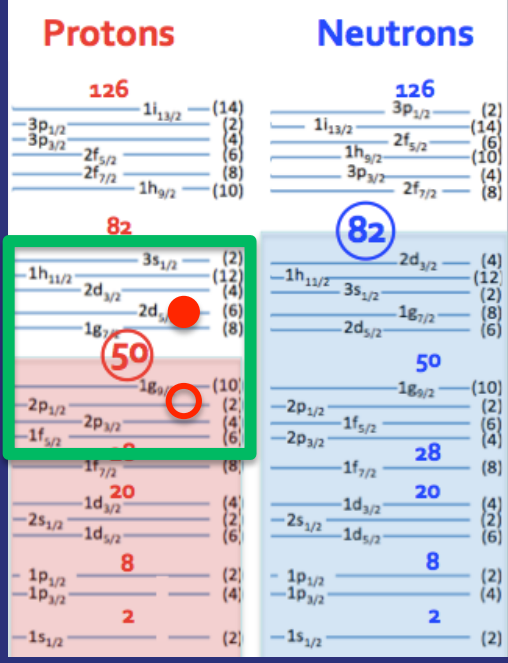


single particle **STRENGTH** is fragmented









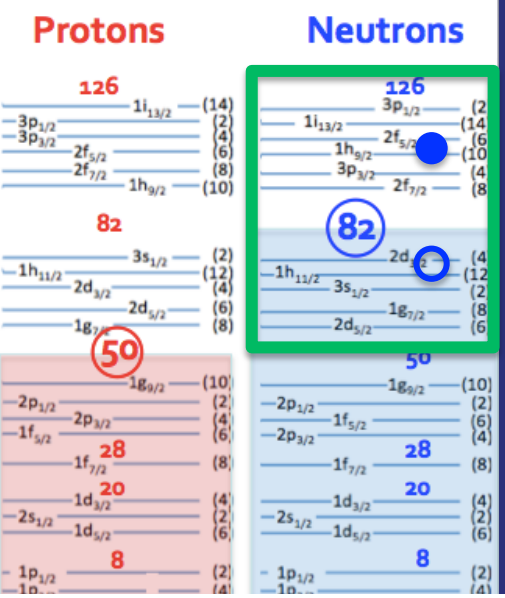
$Sb_N = Sn_N + 1\pi$

$(^3He,d), (\alpha,t)$

$In_N = Sn_N - 1\pi$

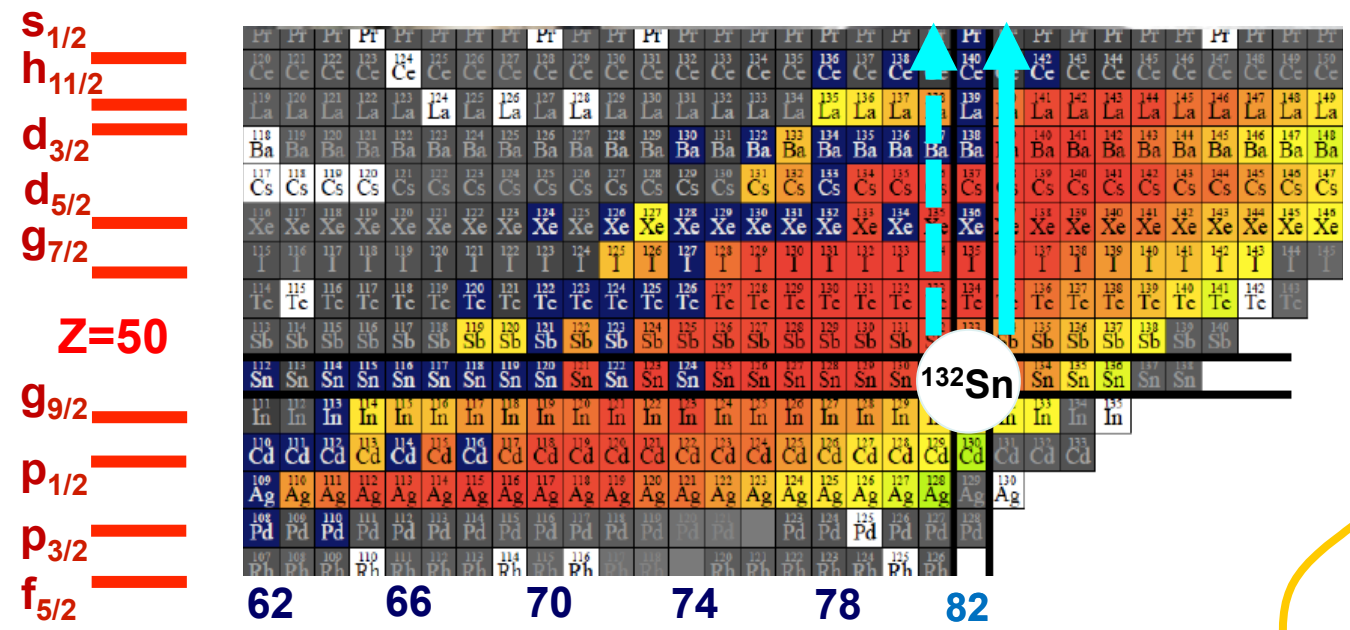
$(d,^3He), (t,\alpha)$

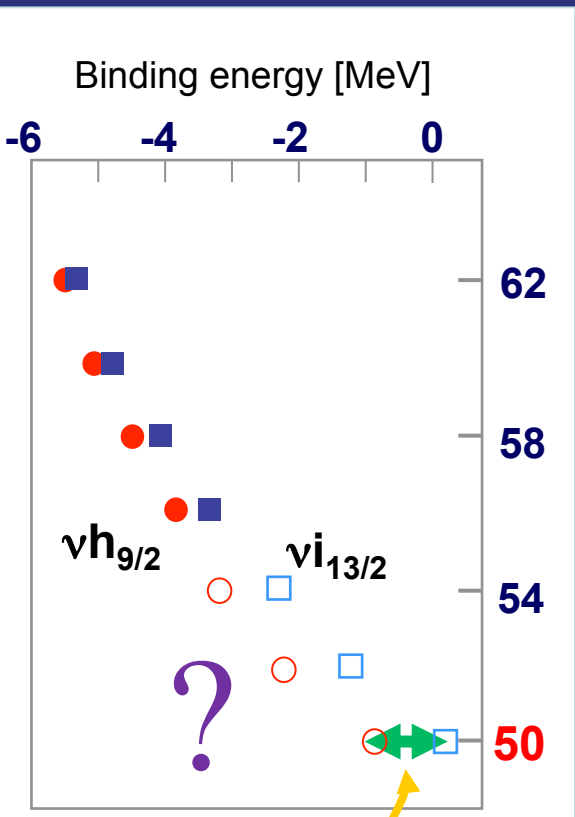
NEUTRONS - Single Particle Levels

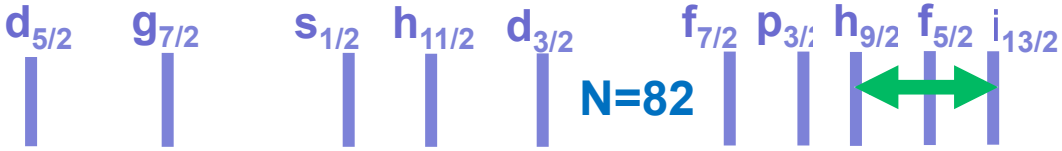


$X_{N=83} = X_{N=82} + 1\nu$ (d,p)

$X_{N=81} = X_{N=82} - 1\nu$ (p,d)



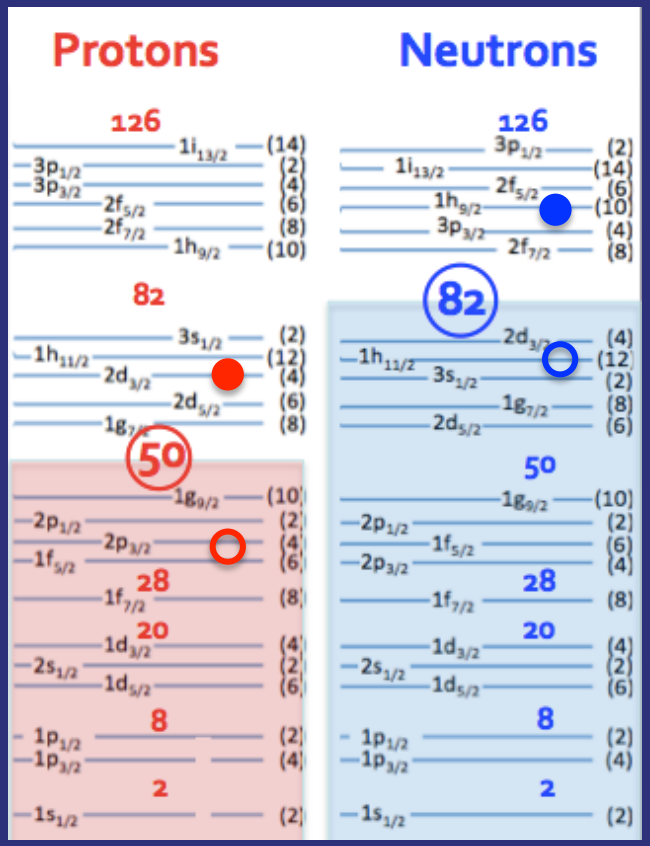




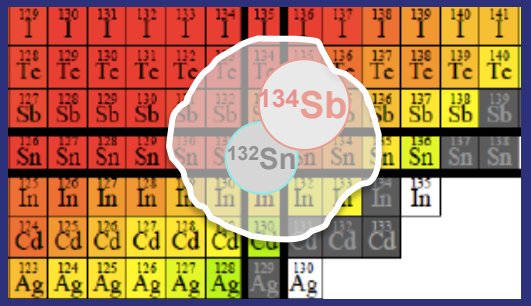
PROTON and NEUTRON Single Particle Levels

1. Measurements of single particle ENERGIES

2. Measurements of single particle STRENGTH:
Spectroscopic Factors
in TRANSFER reactions with light targets



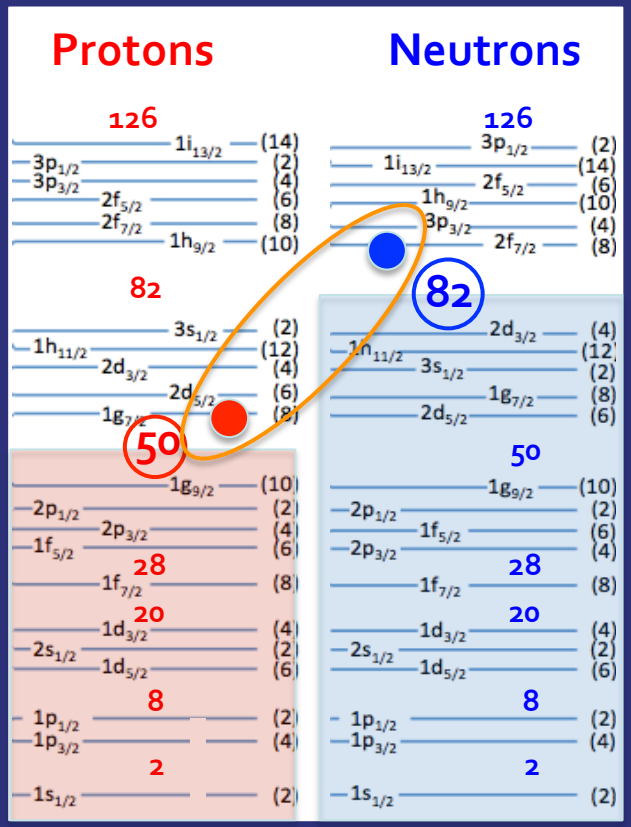
MUTIPLETS of valence nucleons around ^{132}Sn

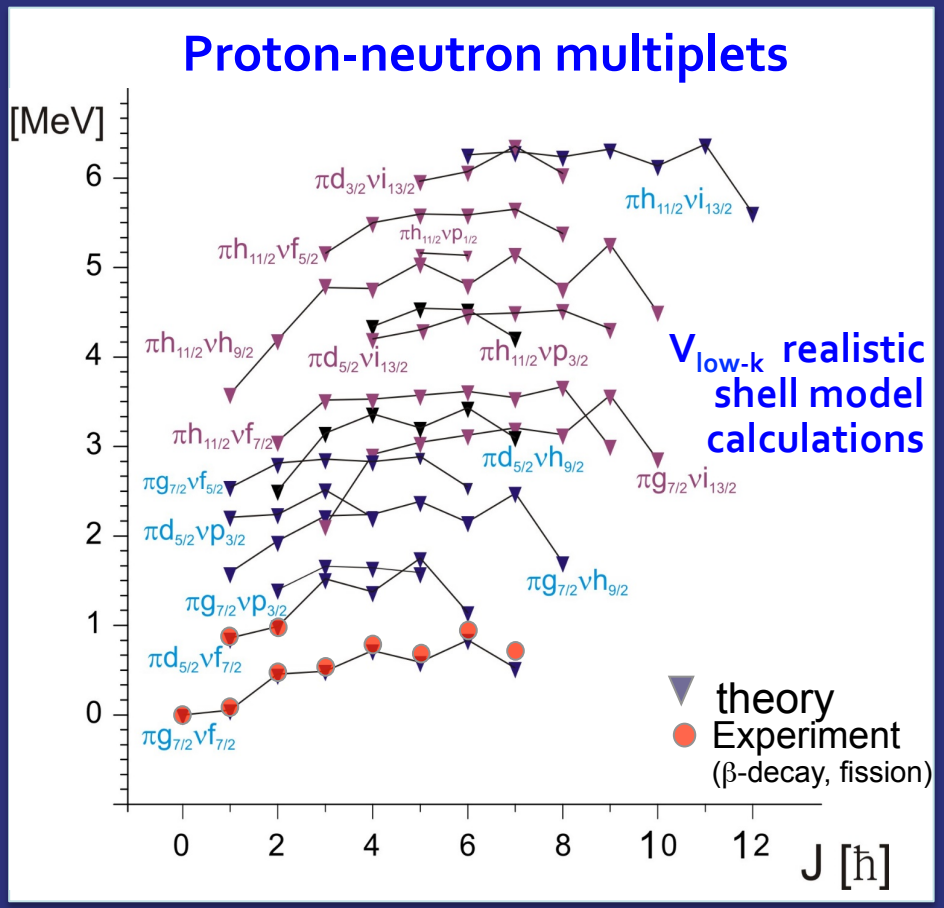


FROZEN COUPLINGS

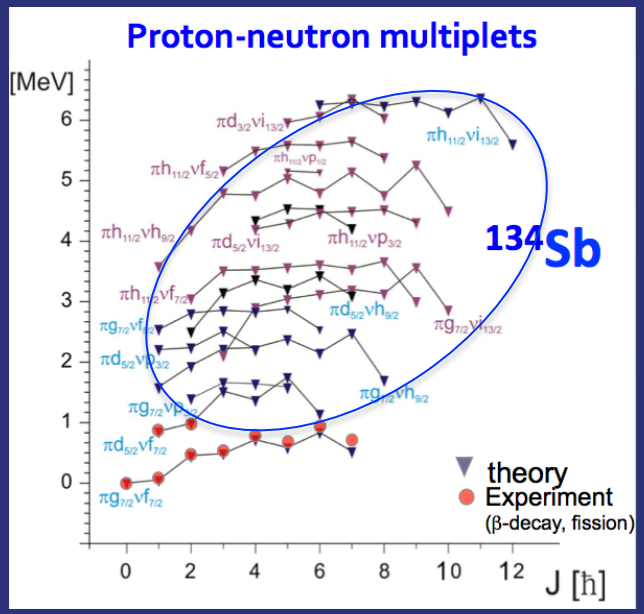
$$^{134}\mathrm{Sb} = {}^{132}\mathrm{Sn} + 1\pi + 1\nu$$

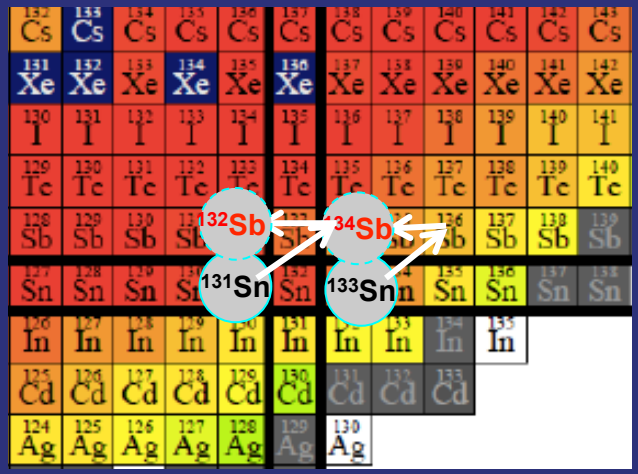
→ Two-Body Matrix Elements





To locate the MULTIPLETS: γ-spectroscopy of yrast and non-yrast structure





1. Cluster Transfer on ^{7}Li target

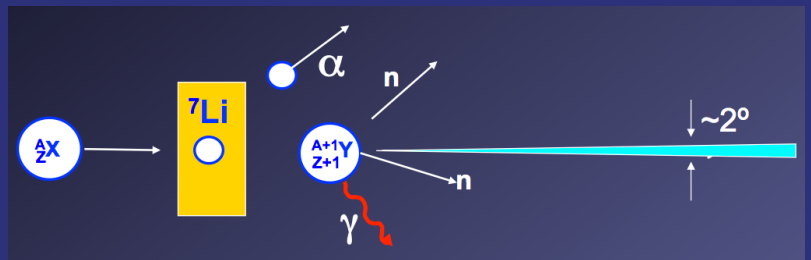
$^{A}Sn + {}^{7}Li \rightarrow {}^{A+1}Sb + \alpha + 2n$

σ = 100 mb

Inverse kinematics, few MeV/A

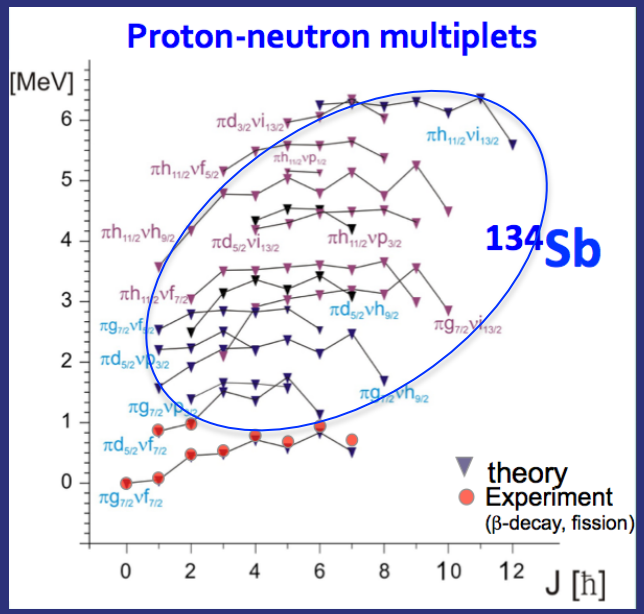
α tagging + γ array

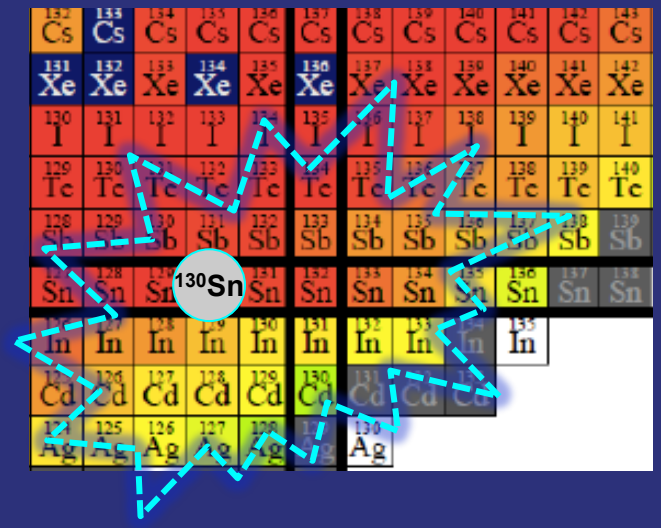
Weakly Bound



Tested at ISOLDE
Milano-Krakow Coll.
PRC92, 024322 (2015)

To locate the MULTIPLETS: γ-spectroscopy of yrast and non-yrast structure



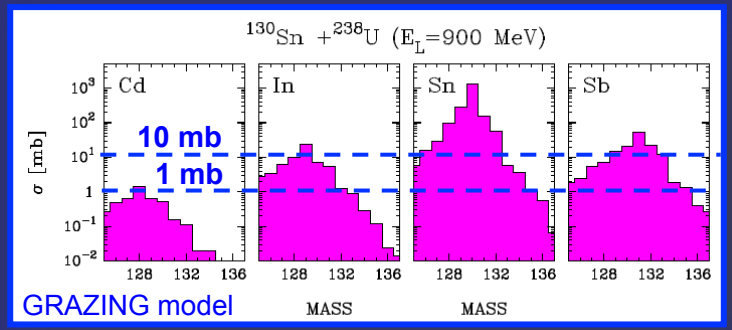


2. Multi-Nucleon Transfer with Heavy Ions

^{A}Sn (7 MeV/A) + ^{208}Pb/^{238}U

Extensively used with Stable-Beams (LNL,GANIL)

Tested at SPIRAL1, Milano-Orsay Coll. , EPJA 45, 287–292 (2010)



PRISMA is needed + γ array

To probe the properties of the MULTIPLETS: $B_{EXP}(EM,\lambda)$ versus THEORY

1. Coulomb Excitation

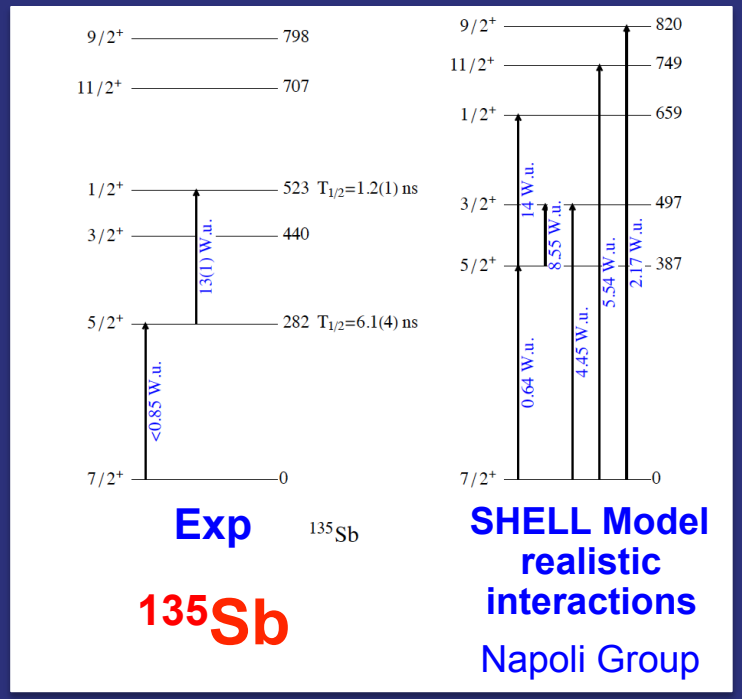
^{134}Sn

$^{134,135}Sb$ + ^{208}Pb target

$^{126,127}Cd$

Direct extraction of $B(E,\lambda)$

Si stripped detector (SPIDER) + γ array



2. Lifetime Analysis

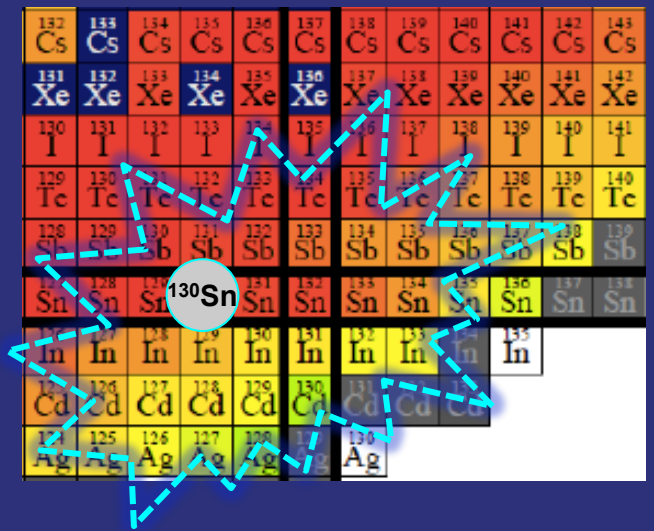
Multi-Nucleon Transfer with Heavy Ions

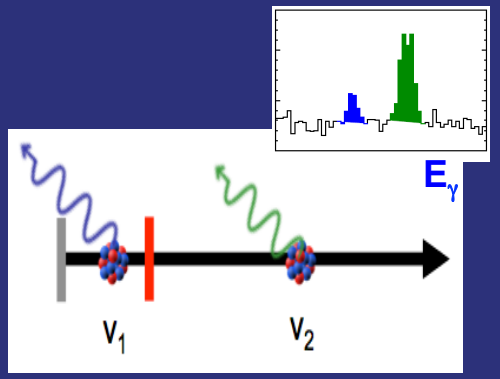
^{A}Sn (7 MeV/A) + $^{208}Pb/^{238}U$

Plunger technique
PRISMA is needed + γ array

$\tau \div 1/B(EM,\lambda)$

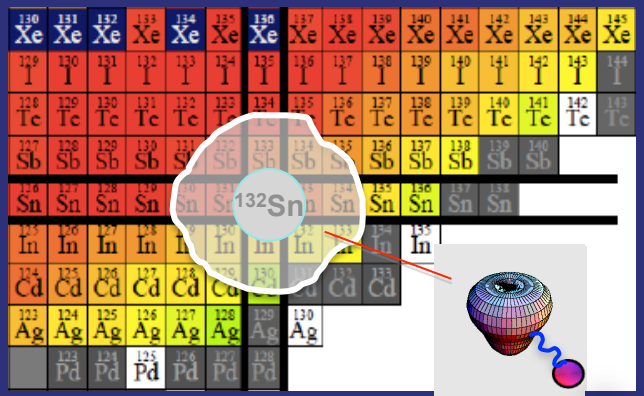
Extensively used
with Stable-Beams (LNL,GANIL)





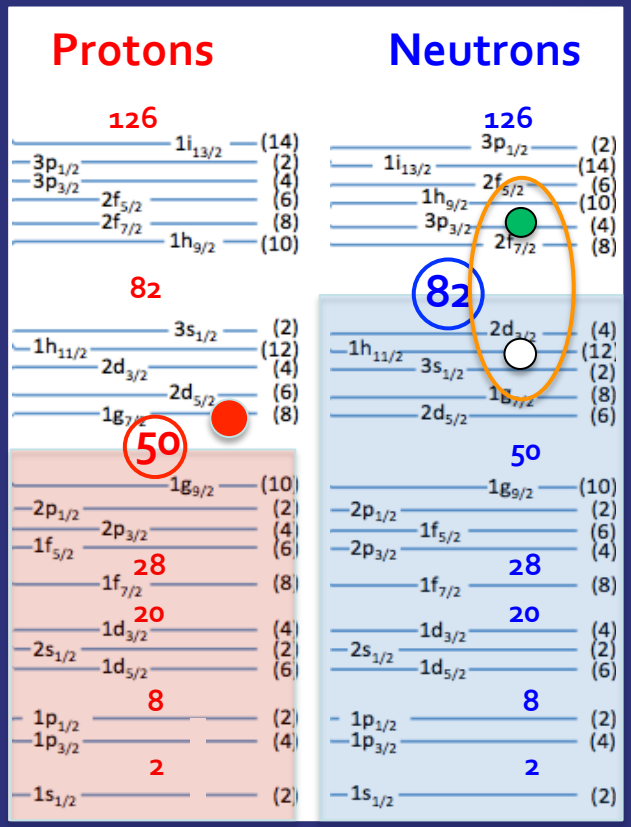
COMPLEX STATES - NOT DOABLE BY SHELL MODEL

(with FROZEN CORE)



Complex, collective excitations dominate
Low Lying states in **DOUBLY MAGIC** Nuclei

2^+, 3^-,4^+, … **PHONONS**



The Structure of Nuclei with One valence particle is influenced by

Couplings with Core Excitation

1. Fragmentation of single particle strength …
   (Quenching of spectroscopic factors)

2. MULTIPLETS of COMPLEX Nature

MULTIPLETS: Relevance of CORE Excitations

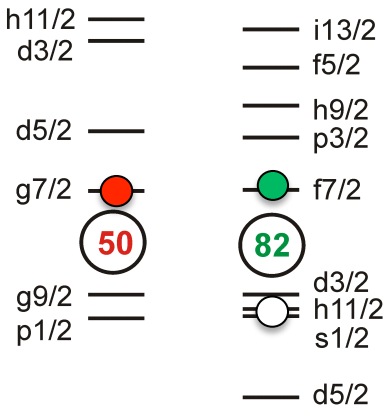
^{133}Sb – neutron induced fission on ^{235}U and ^{241}Pu

ILL Grenoble, Milano-Krakow Coll. PLB760, 273 (2016)

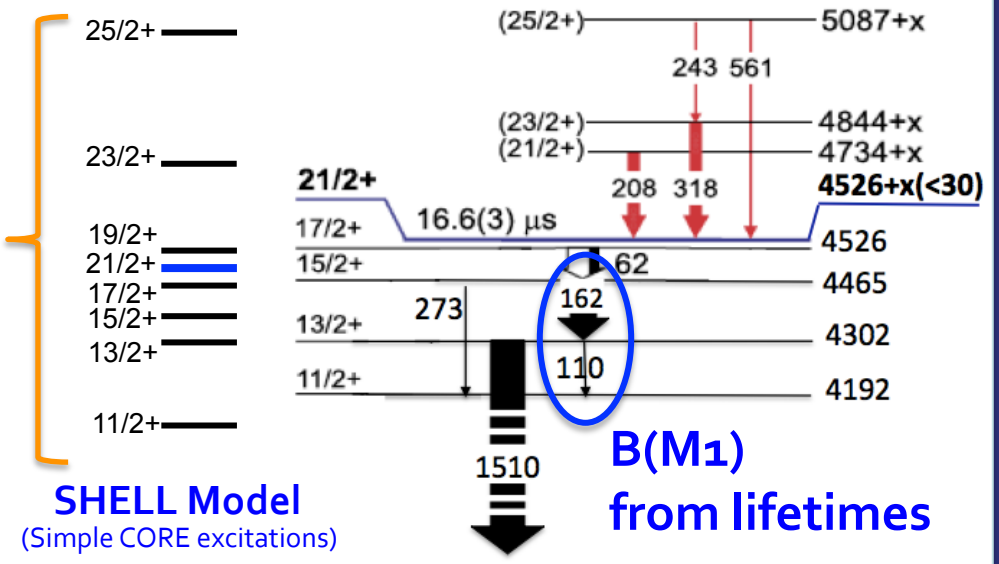
SHELL Model
(Simple CORE excitations)

$\pi\,(g_{7/2}) \otimes \nu\,(f_{7/2}h^{-1}_{11/2})$

protons neutrons



^{133}Sb = ^{132}Sn + 1π

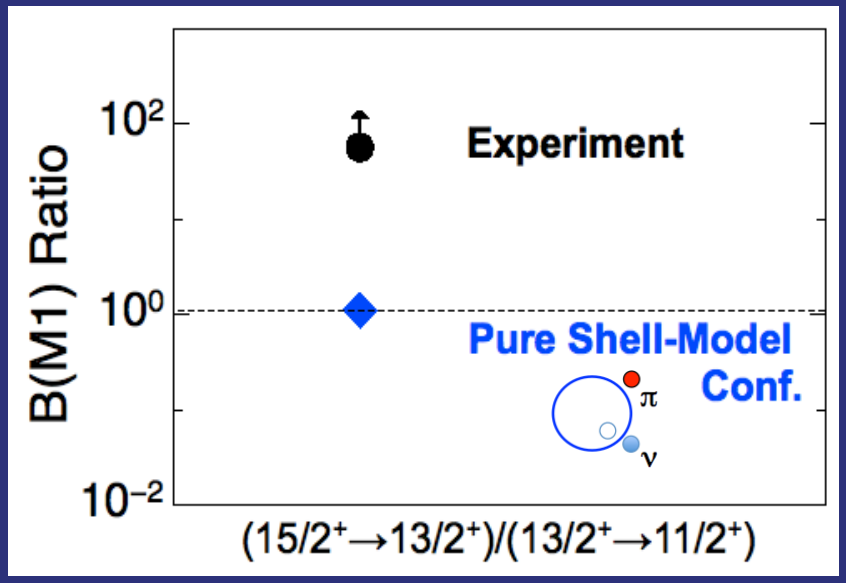


SHELL Model may reproduce MULTIPLET energies … NOT B(EM,λ)

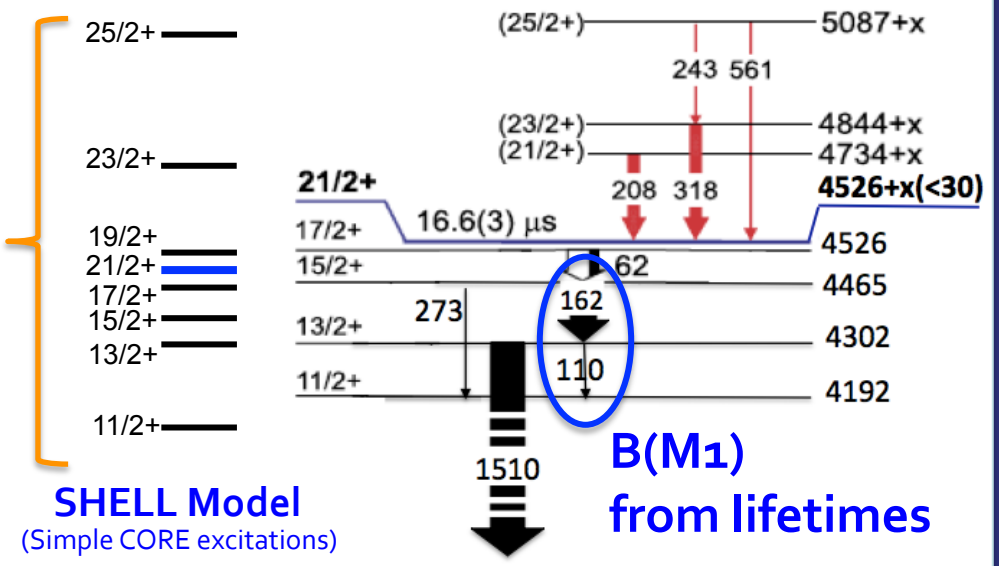
Relevance of CORE Excitations

^{133}Sb – neutron induced fission on ^{235}U and ^{241}Pu

ILL Grenoble, Milano-Krakow Coll. PLB760, 273 (2016)



^{133}Sb = ^{132}Sn + 1π

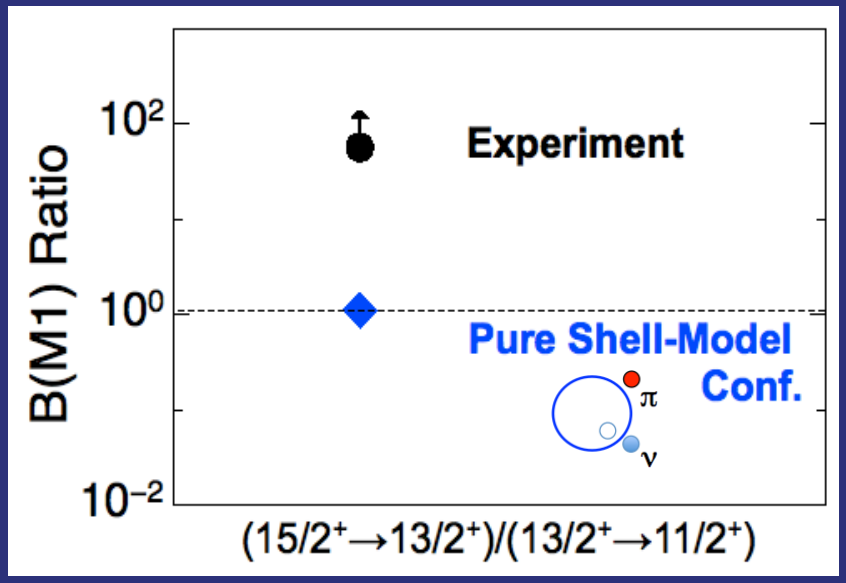


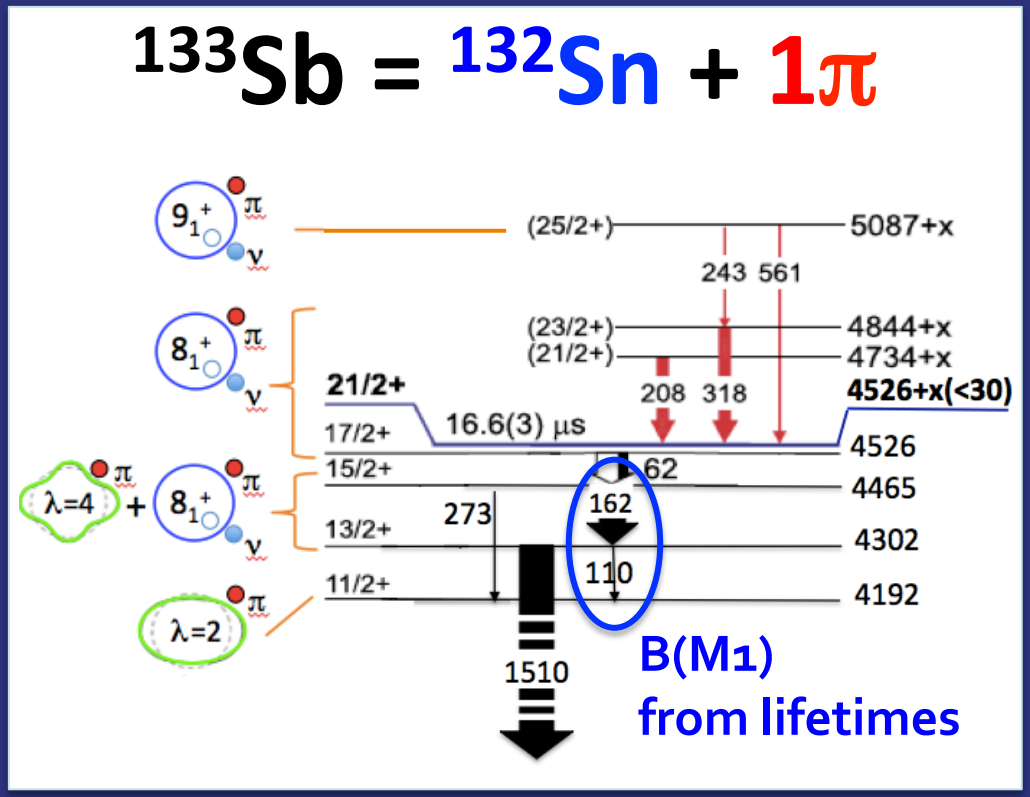
SHELL Model may reproduce MULTIPLET energies … NOT B(EM,λ)

Relevance of CORE Excitations

^{133}Sb – neutron induced fission on ^{235}U and ^{241}Pu

ILL Grenoble, Milano-Krakow Coll. PLB760, 273 (2016)





SHELL Model may reproduce MULTIPLET energies … NOT B(EM,λ)

New "HYBRID" Model (G. Colò, P.F. Bortignon - Milano)
Extended Microscopic Particle-Vibration Coupling Model

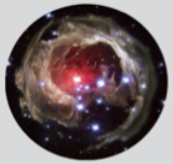
→ We need complete spectroscopy: Energies, J^π and B(EM,λ)

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

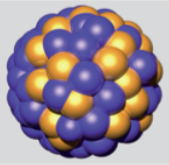
Where SPES can do very well

INTERDISCIPLINARITY

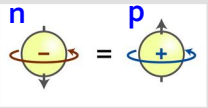
Astrophysics
Nucleosynthesis



BASIC SCIENCE



Many Body
Finite Quantum
System



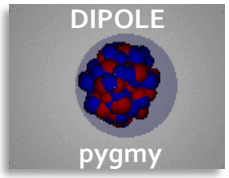
Symmetry
Principle

Proto N

126
82
50
50
28
20
28
8
20
2
8
2

^{132}Sn

^{78}Ni



✧ **SHELL STRUCTURE**
single particle excitations
multiplets of valence particles

✧ **COMPLEX EXCITATIONS**
CORE excitations and couplings
resonances

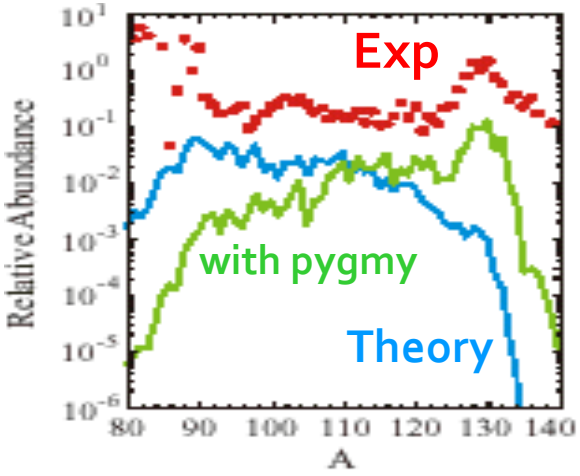
Neutron number N

Selected Examples …

The DIPOLE Response In Nuclei

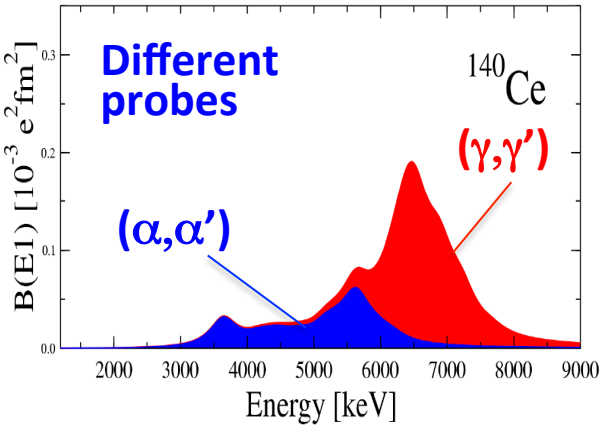
Element Abundance

Relevant ENERGY window for (γ,n) reactions in STARS

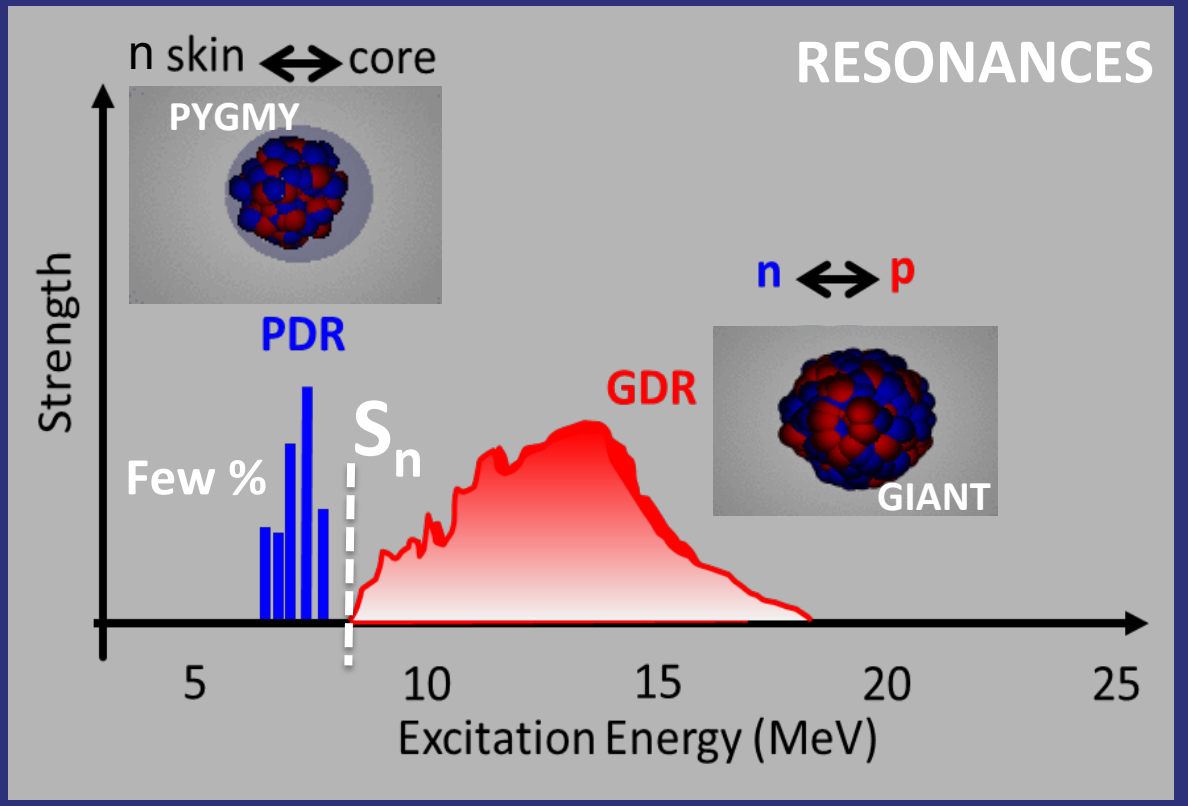


UNDERLYING Structure

(KVI and Darmstadt)



D. Savran et al. PRL97,172502(2006)
J. Endres et al., PRL105, 212503 (2010)

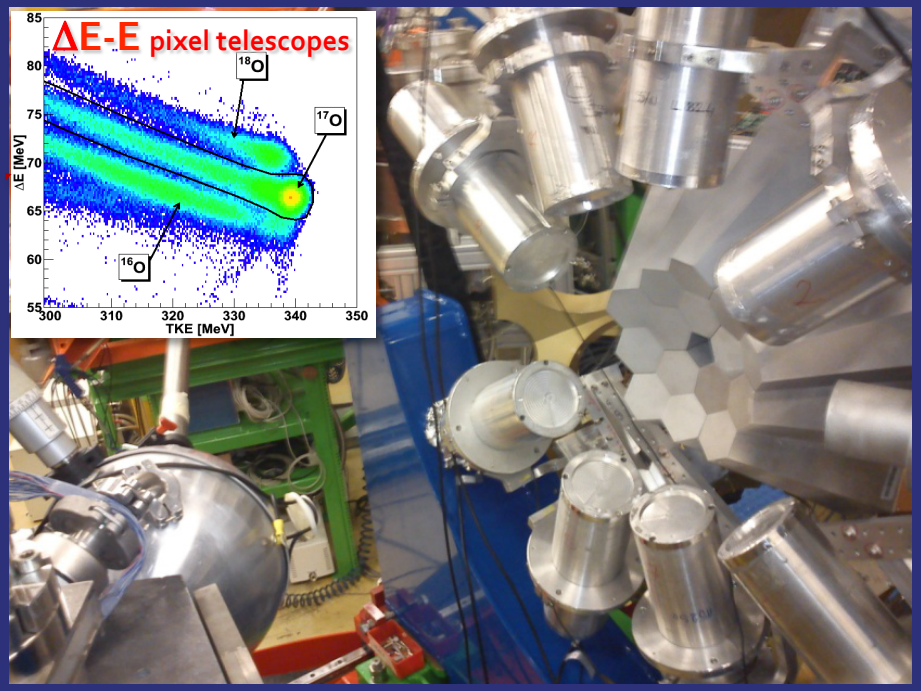


→ Important for ASTROPHYSICS
(Nucleosynthesis, Neutron Stars)

→ Relevant in NUCLEAR STRUCTURE
(Microscopic Nature…)

Pygmy Resonances in STABLE NUCLEI

Heavy-Ion Inelastic Scattering: a probe sensitive to the surface



LNL Campaign

AGATA +

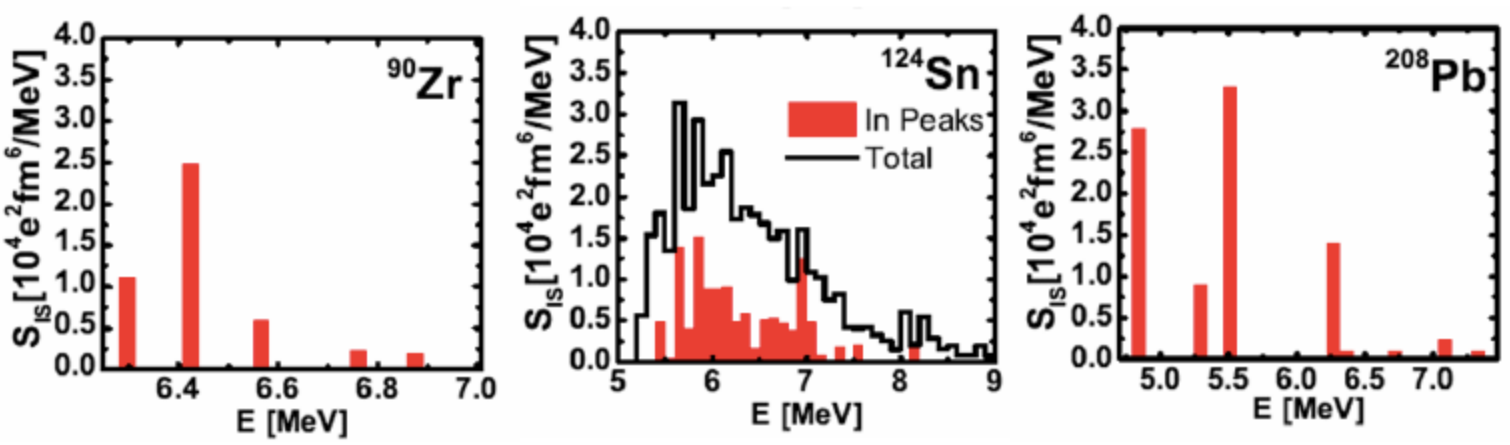
Si Telescopes +

Scintillators (LaBr3)

^{17}O @ 20 MeV/A

on ^{208}Pb, ^{124}Sn, ^{90}Zr, ^{140}Ce

STABLE targets



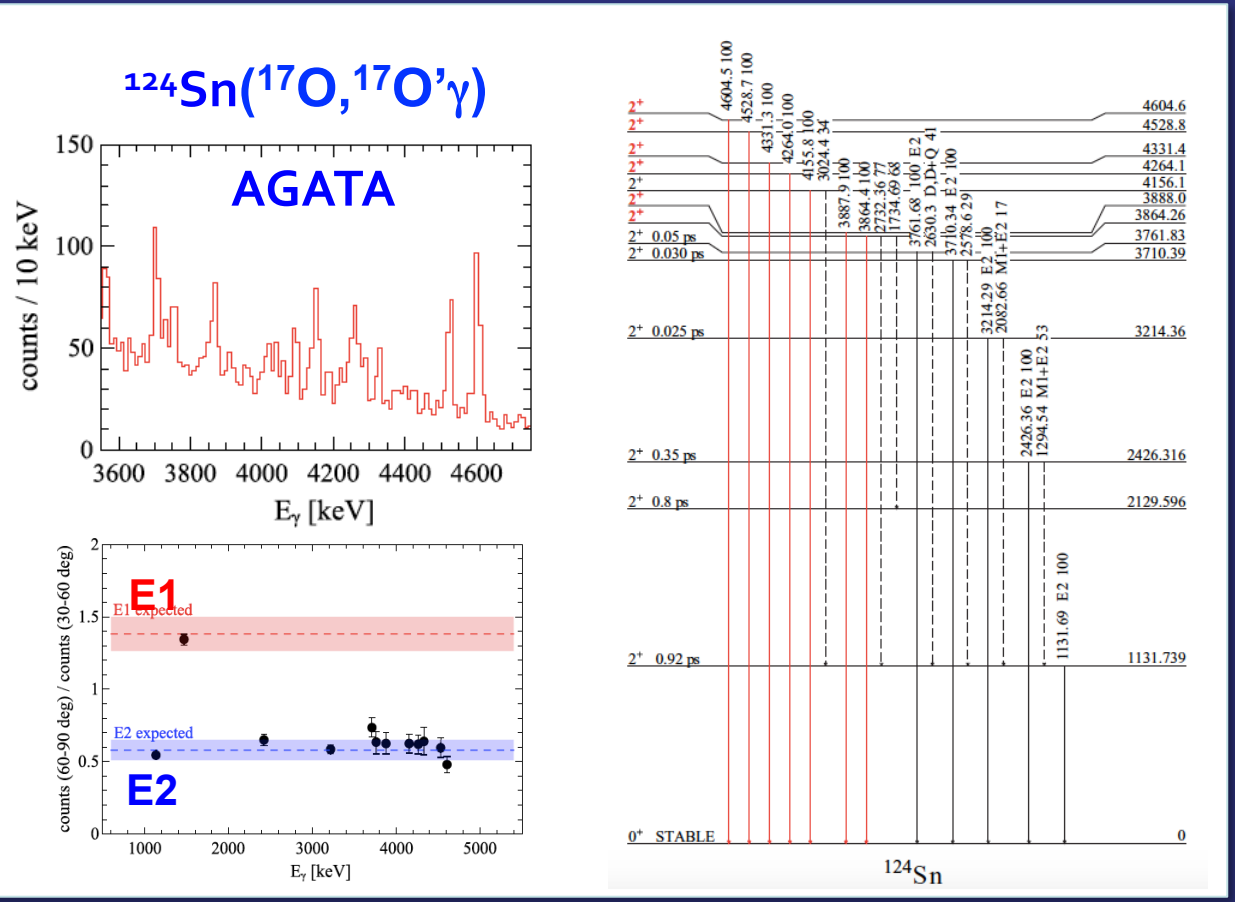
Pygmy Strength (E1)

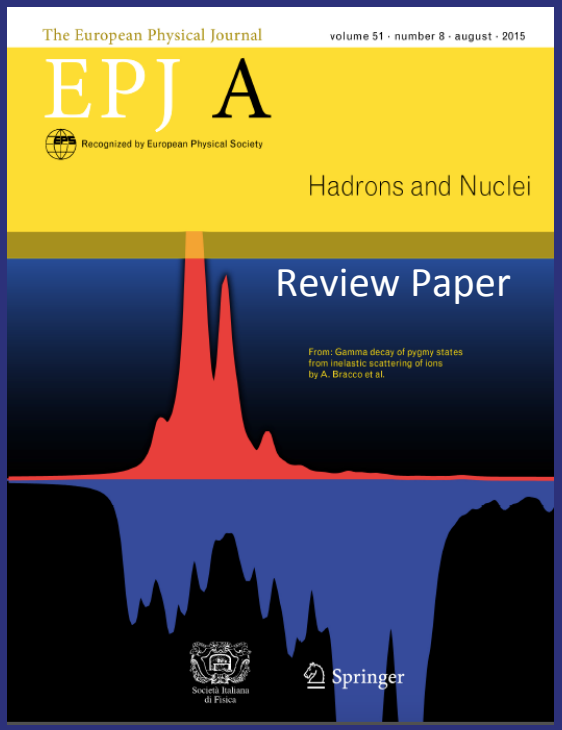
1-3% EWSR

isoscalar E1

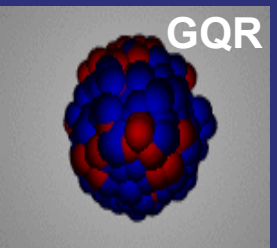
A NEW OBSERVATION: ^{124}Sn – QUADRUPOLE PYGMY

Multitude of 2^+ discrete states





A. Bracco, F. Crespi, E.Lanza,
Eur. Phys. J. A51 (2015) 99

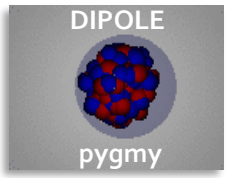


Concentration of E2 Strength
much below the GIANT QUADRUPOLE resonance

- In agreement with Quasi-phonon Model predictions -

Pygmy Resonances in EXOTIC NUCLEI

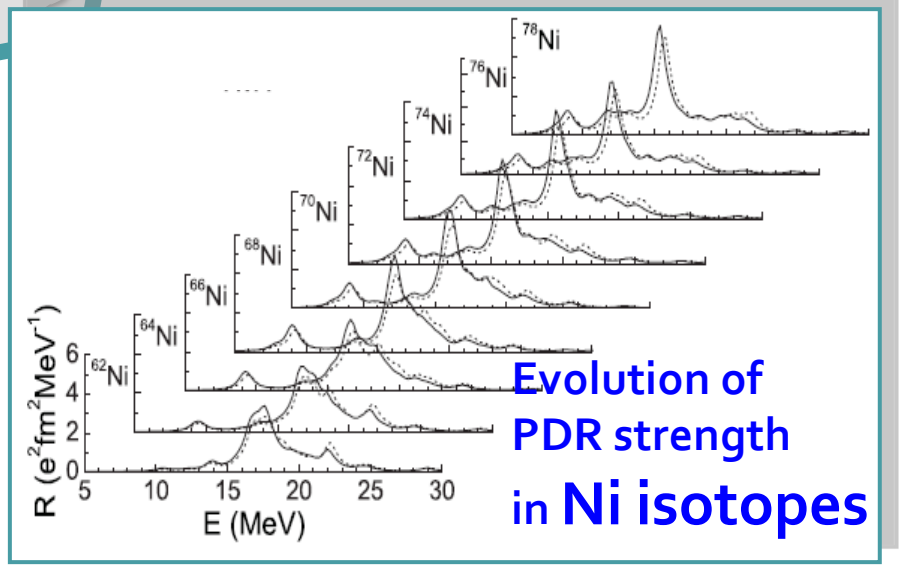
Evolution of PYGMY Structures along isotopic chains



Proton number Z

2
8
20
28
50
82
126

r-process

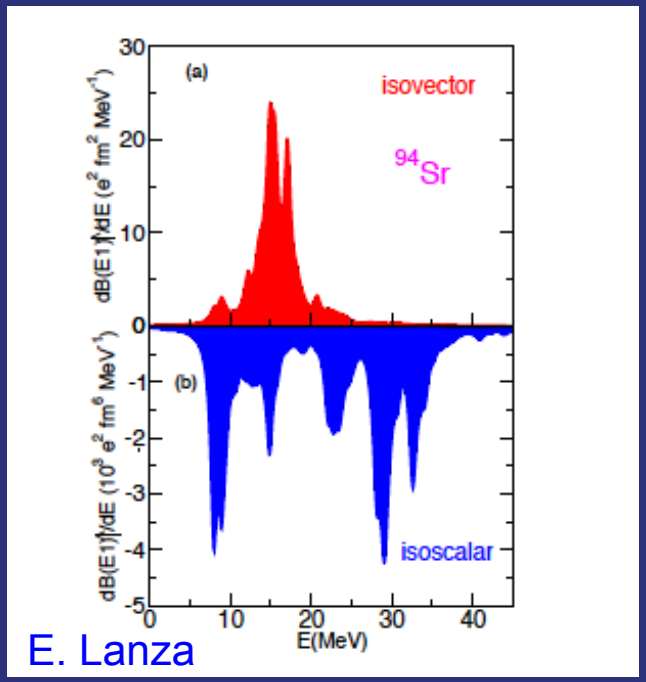


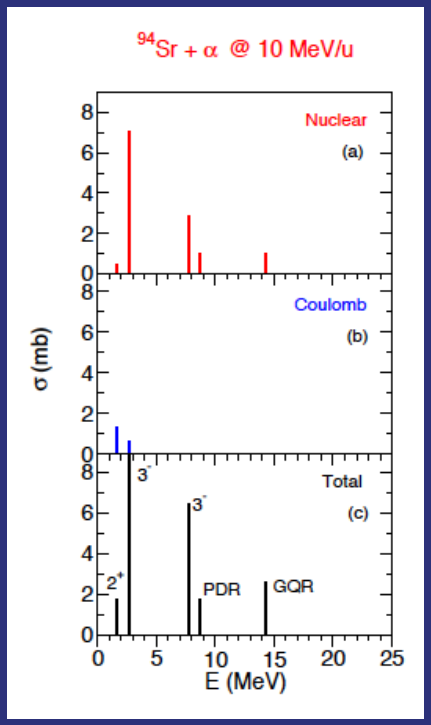
Evolution of PDR strength in Ni isotopes

PYGMY in EXOTIC NUCLEI @ SPES
Isotopic chains: Sr, Sn, Te, …

1. Inverse kinematics inelastic scattering

- RIB beam 10-15 MeV/A
- Liquid H, He and solid ^{13}C targets





AGATA/GALILEO +
Si Telescopes (TRACE)+
Scintillators (LaBr3/PARIS)

Day 0 Beams

^{90,92,94}Sr: 10^6 – 10^7 pps

2. γ-spectroscopy after β-decay

if Q_β-value is large … to be investigated:

$^{94}Y \rightarrow {}^{94}Zr$ (Q_β = 4.9 MeV), $^{86}Br \rightarrow {}^{86}Kr$ (Q_β = 7.6 MeV)

Need for HRMS !!

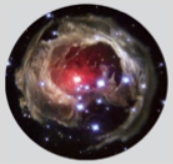
Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well

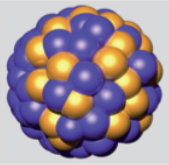
Proto r Z

INTERDISCIPLINARITY

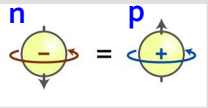
Astrophysics
Nucleosynthesis



BASIC SCIENCE



Many Body
Finite Quantum
System



Symmetry
Principle

✧ SHELL STRUCTURE

✧ COMPLEX EXCITATIONS

✧ SHAPE evolution

Neutron number N

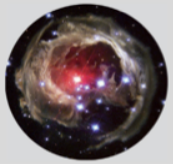
Selected Examples …

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

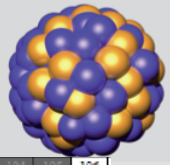
Where SPES can do very well

INTERDISCIPLINARITY

Astrophysics
Nucleosynthesis



BASIC SCIENCE



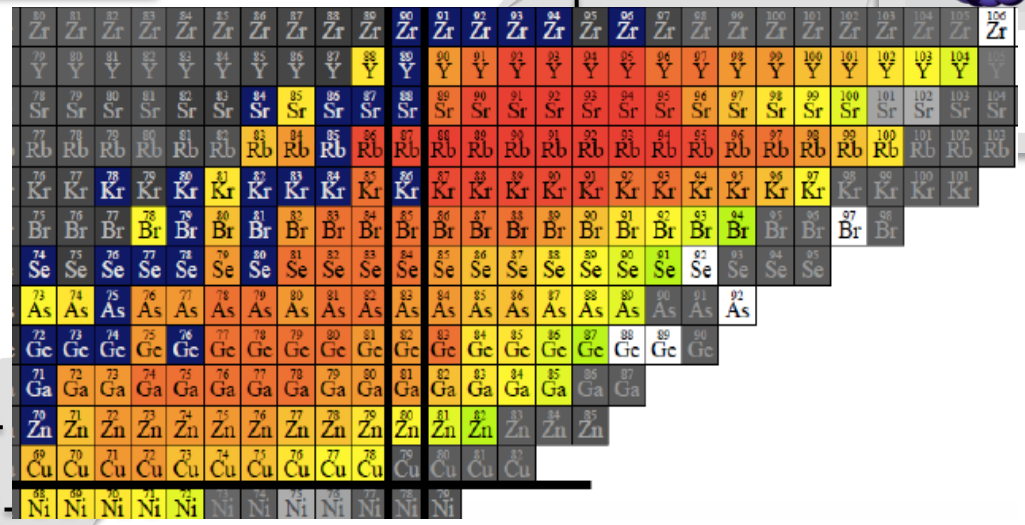
Many Body
Finite Quantum
System

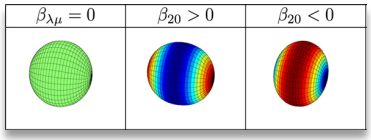
p

Symmetry Principle

Proto N

126
82
28
20
8
2
8
2



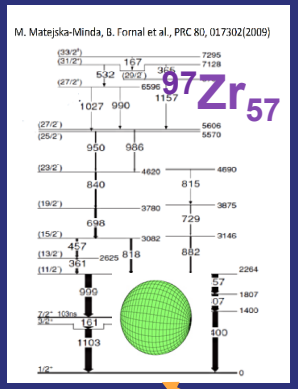


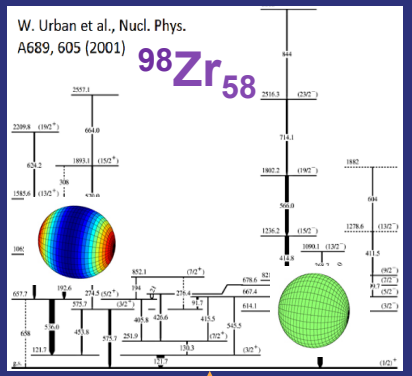
✧ SHAPE evolution

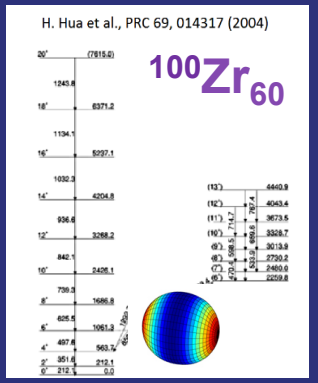
Neutron number N

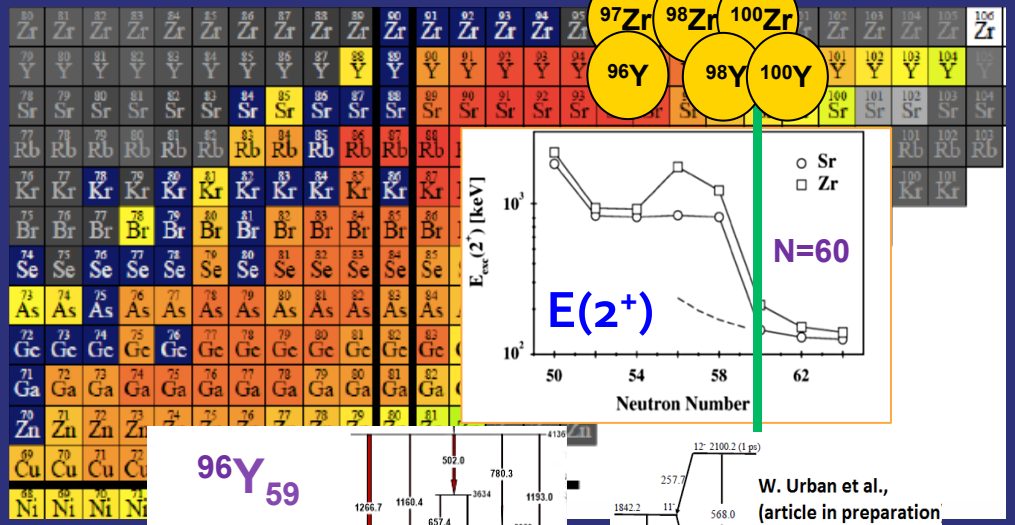
Selected Examples …

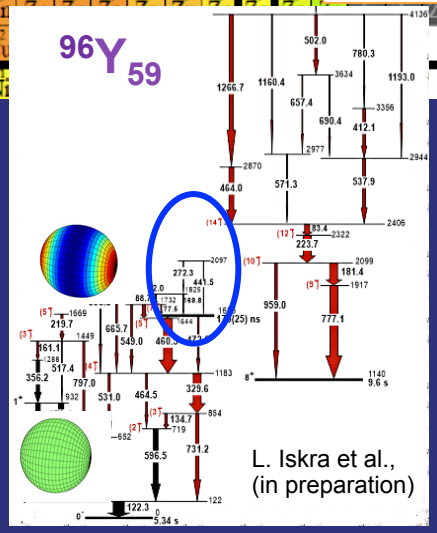
The region of most dramatic changes

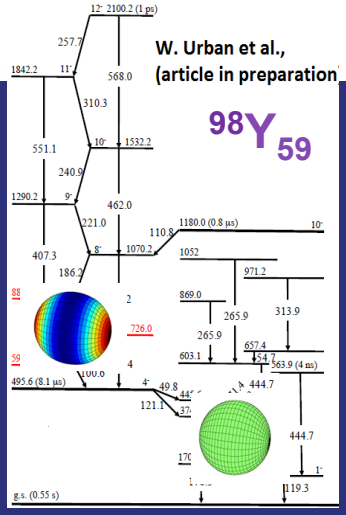


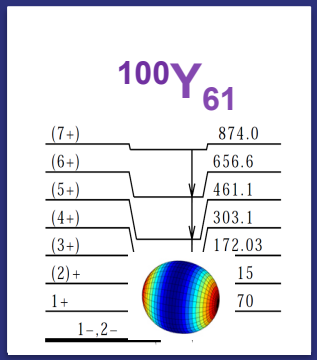






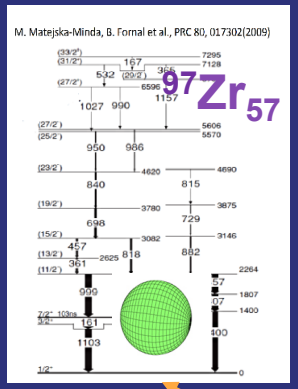


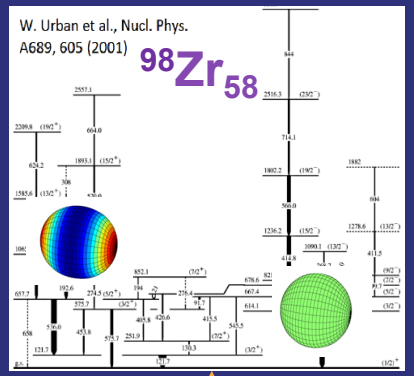


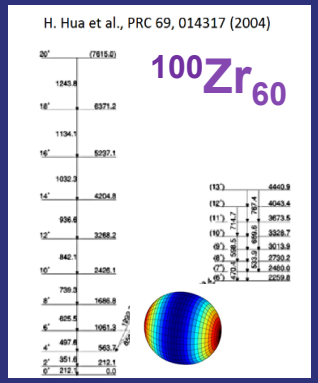


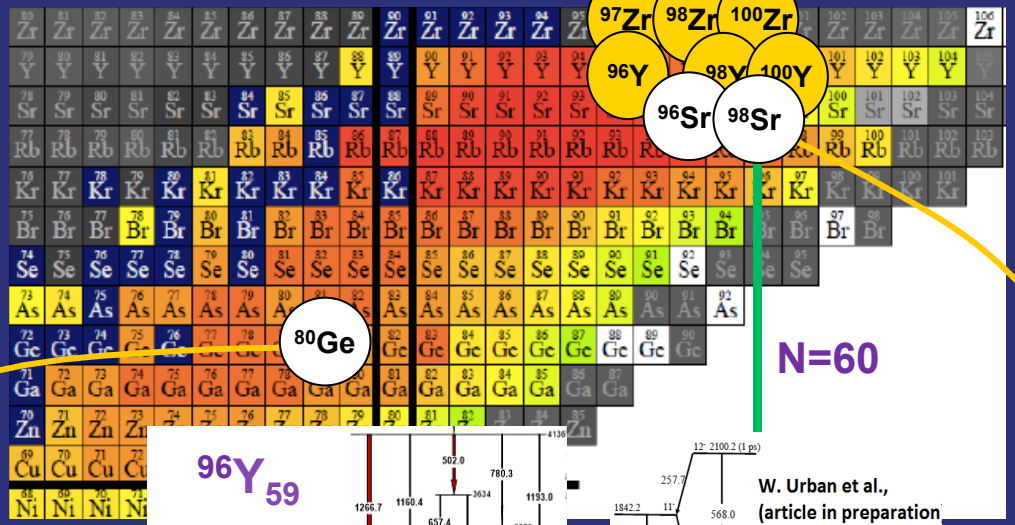
The region of most dramatic changes

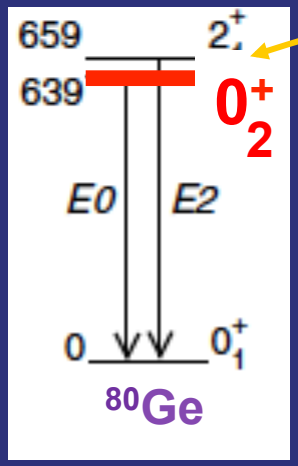
- a challenge for theory

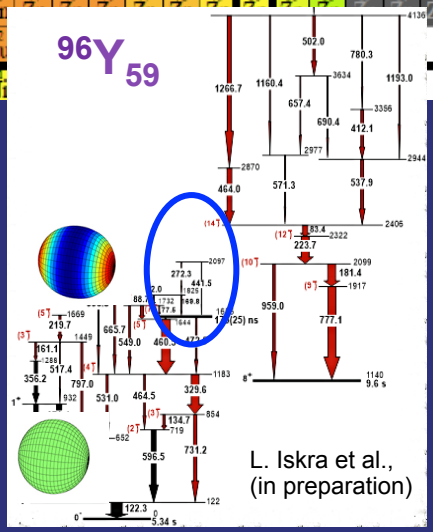


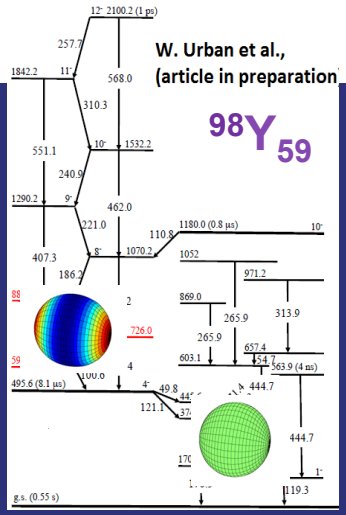


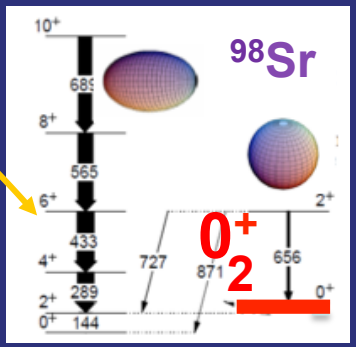


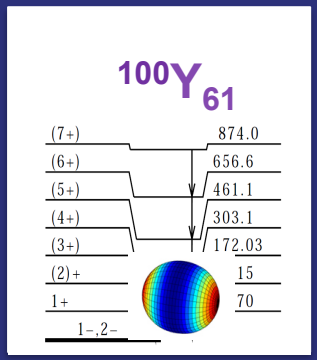












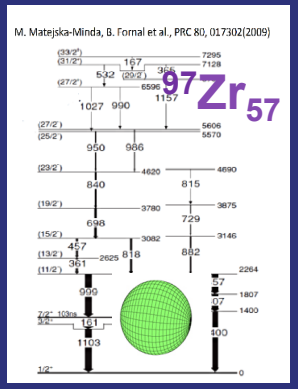
The region of most dramatic changes

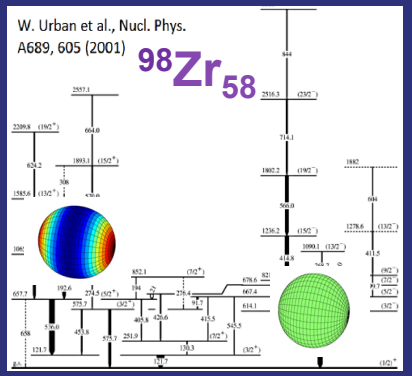
- a challenge for theory
- deformation is relevant for r-process location

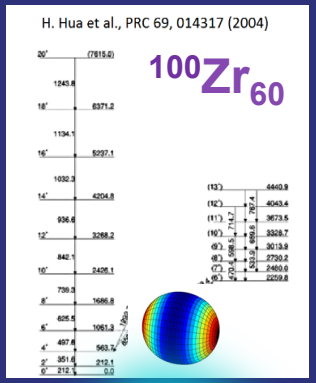
$\tau_{\beta\,SPH} \sim 7 \times \tau_{\beta\,DEF}$

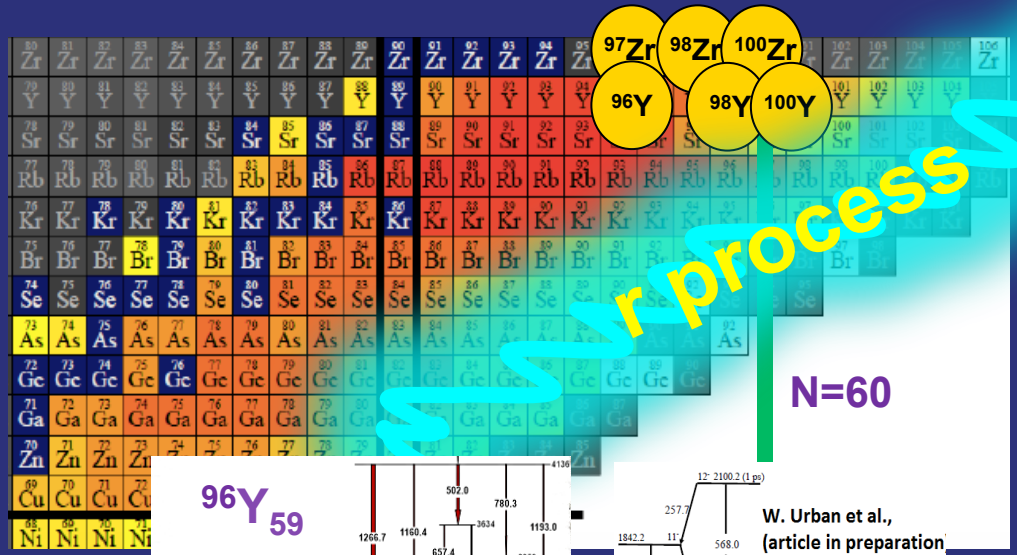
$P_{nSPH} \sim 0.5 \times P_{nDEF}$

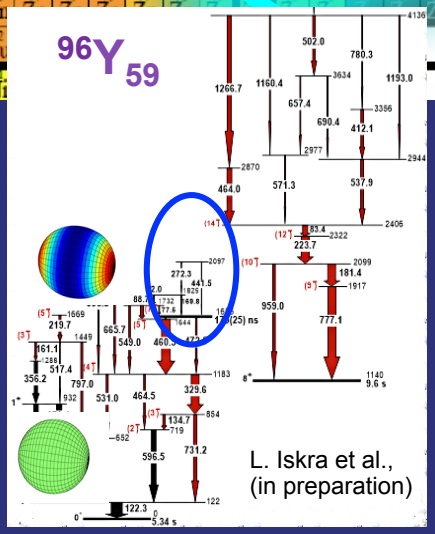
difficult to extrapolate

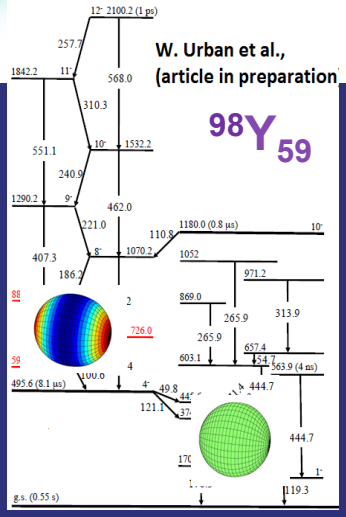


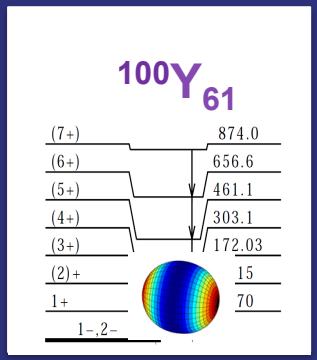












To probe nuclear structure in SHAPE evolution region

γ-Spectroscopy of yrast and non yrast states
Electron Spectroscopy for E0

1. Coulomb Excitation

Spectroscopic Quadrupole moments in Kr, …

2. Cluster Transfer on ^{7}Li target

Intense Sr and Rb beams to probe Y and Sr

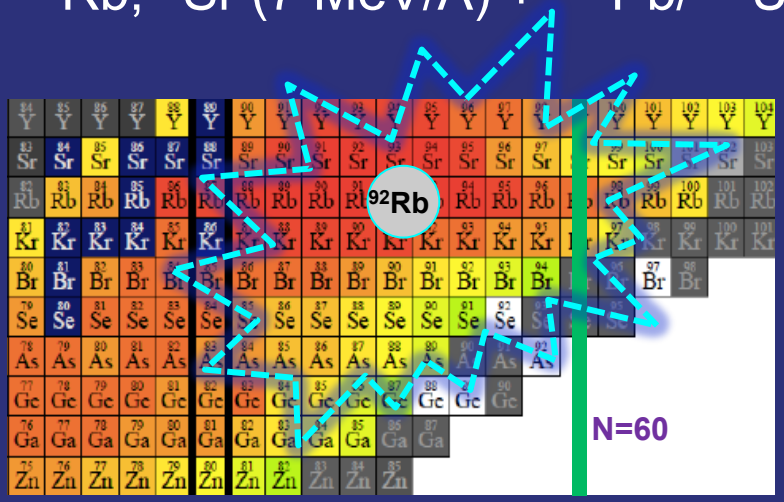
$^{A}Sr + {}^{7}Li \rightarrow {}^{A+1}Y + \alpha + 2n$

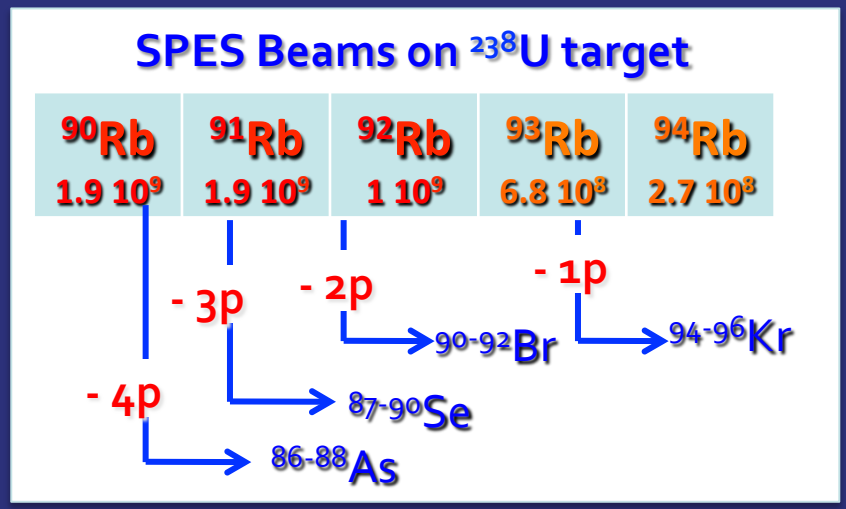
$^{A}Rb + {}^{7}Li \rightarrow {}^{A+1}Sr + \alpha + 2n$

Weakly Bound

3. Multi-Nucleon Transfer with Heavy Ions

^{A}Rb, ^{A}Sr (7 MeV/A) + $^{208}Pb/^{238}U$





Conclusions

- **The SPES community studies**

  the most fundamental aspects of Nuclear Structure
  by particle and gamma spectroscopy
  in the key regions of ^{132}**Sn** and ^{78}**Ni**

  single particle levels - *the builing blocks of the SHELL structure*

  emergence of complex excitations - *particle couplings, core excitations …*

  resonances

  shapes and deformations

- **Strong Interdiciplinarity – Astrophyiscs**
- **Solid International Collaborations**
- **State of the art SETUP: AGATA, GALILEO, PRISMA, …**

We are looking forward for SPES beams on target !

*** Thank You for the Attention ***