

"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

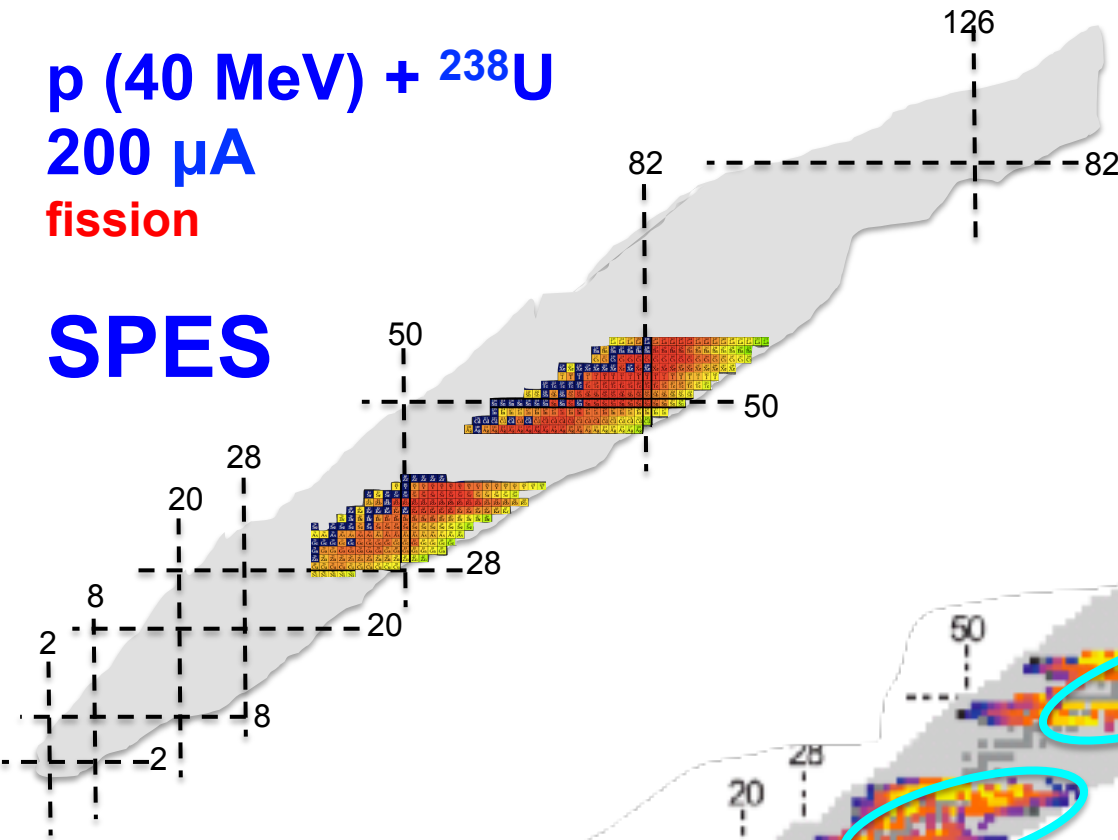
ISOL Production Schemes

p (40 MeV) + ^{238}U

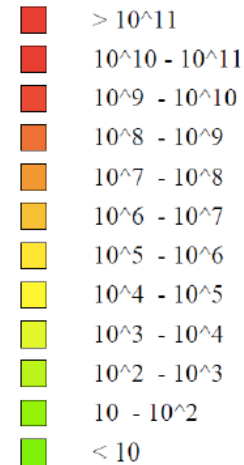
200 μA

fission

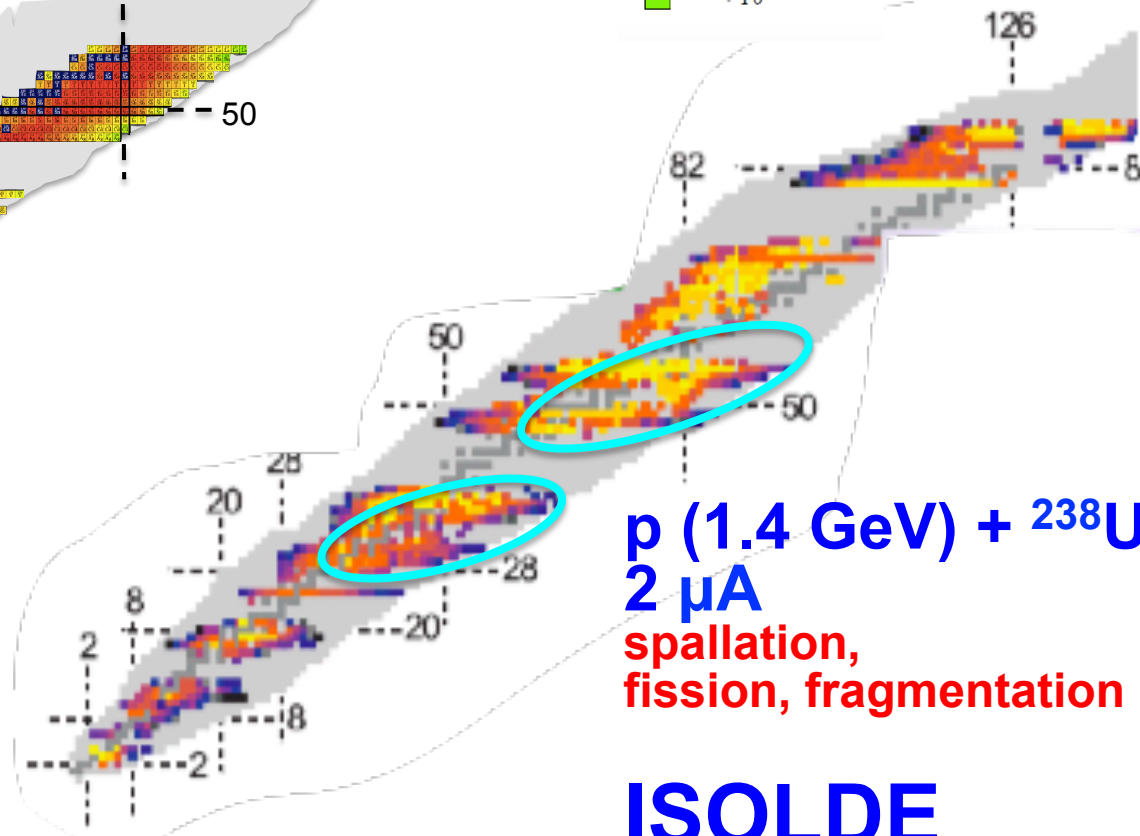
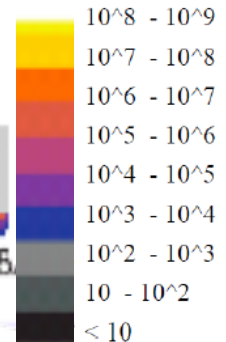
SPES



(pps)



Yield (at/ μC)



p (1.4 GeV) + ^{238}U , others

2 μA

**spallation,
fission, fragmentation**

ISOLDE

SPES - BEAMS

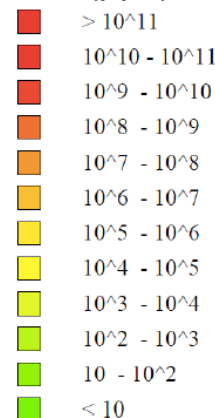
p (40 MeV) + ^{238}U

200 μA

Cs, Ba, ...
VERY intense, pure

Sn, Sb, Te
VERY intense, pure

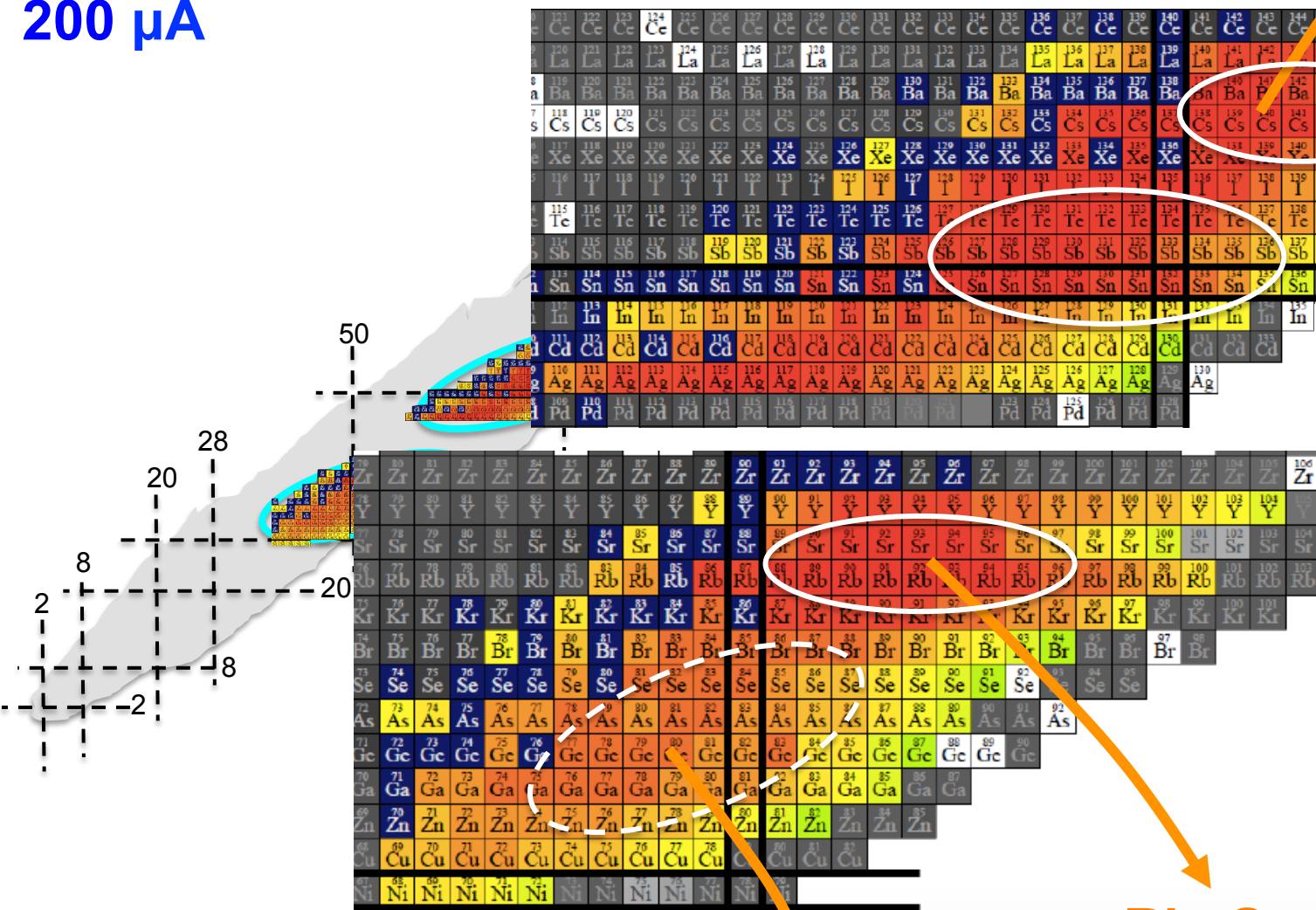
200 μA
(pps) 5 μA
DAY0



/40

Rb, Sr, ...
VERY intense, pure

Ga, Ge ...
intense, pure



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

($\text{eff}_{\text{CB}} = 4\%$, $\text{Trans}_{\text{ALPI}} = 50\%$)

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)

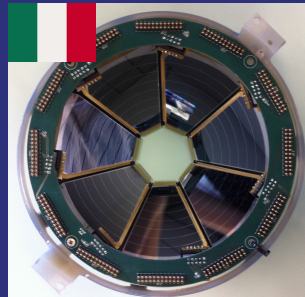
charged-particle Spectroscopy Si stripped/pixel detectors



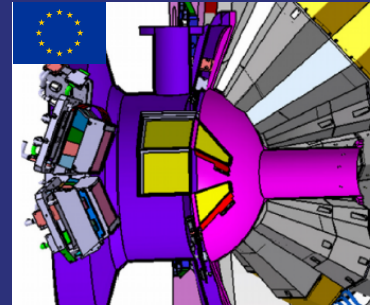
GALILEO – INFN
 $\varepsilon \approx 8\%$



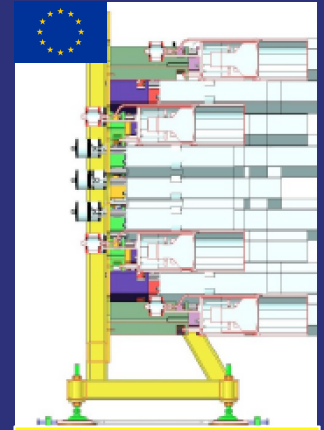
AGATA – 2020 ...



SPIDER – Coulex



TRACE/MUGAST

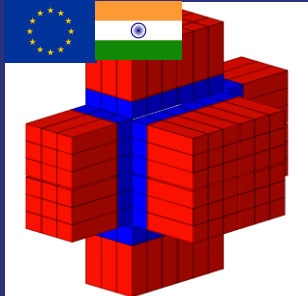


NEDA/NWALL

neutron identification

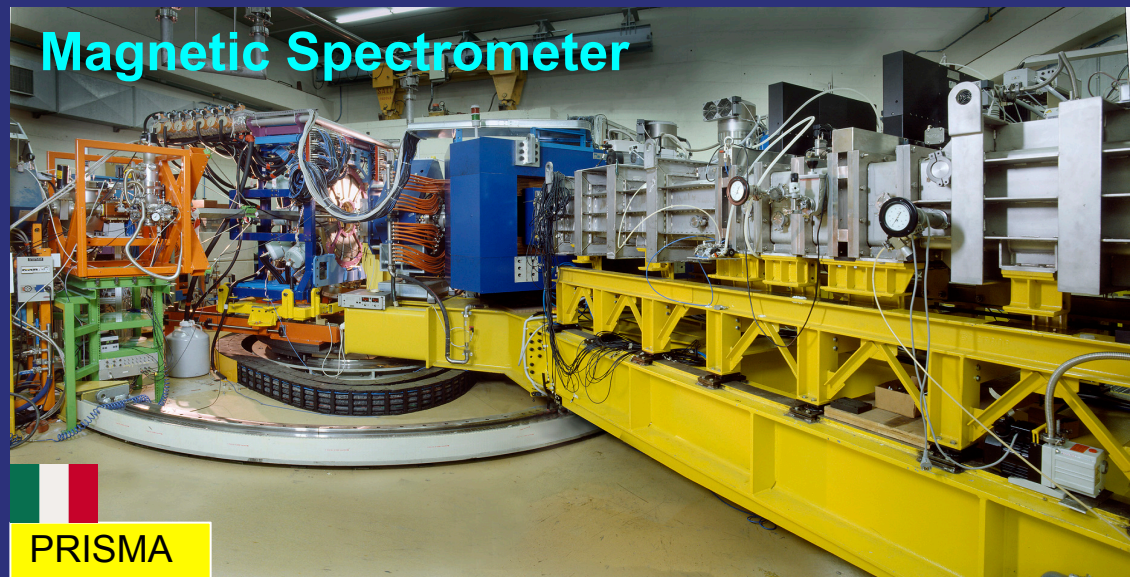


10 LaBr3 3x3
 $\varepsilon \approx 1\%$ @ 16 MeV



PARIS
Labr3+NaI

gamma spectroscopy HPGe, scintillators

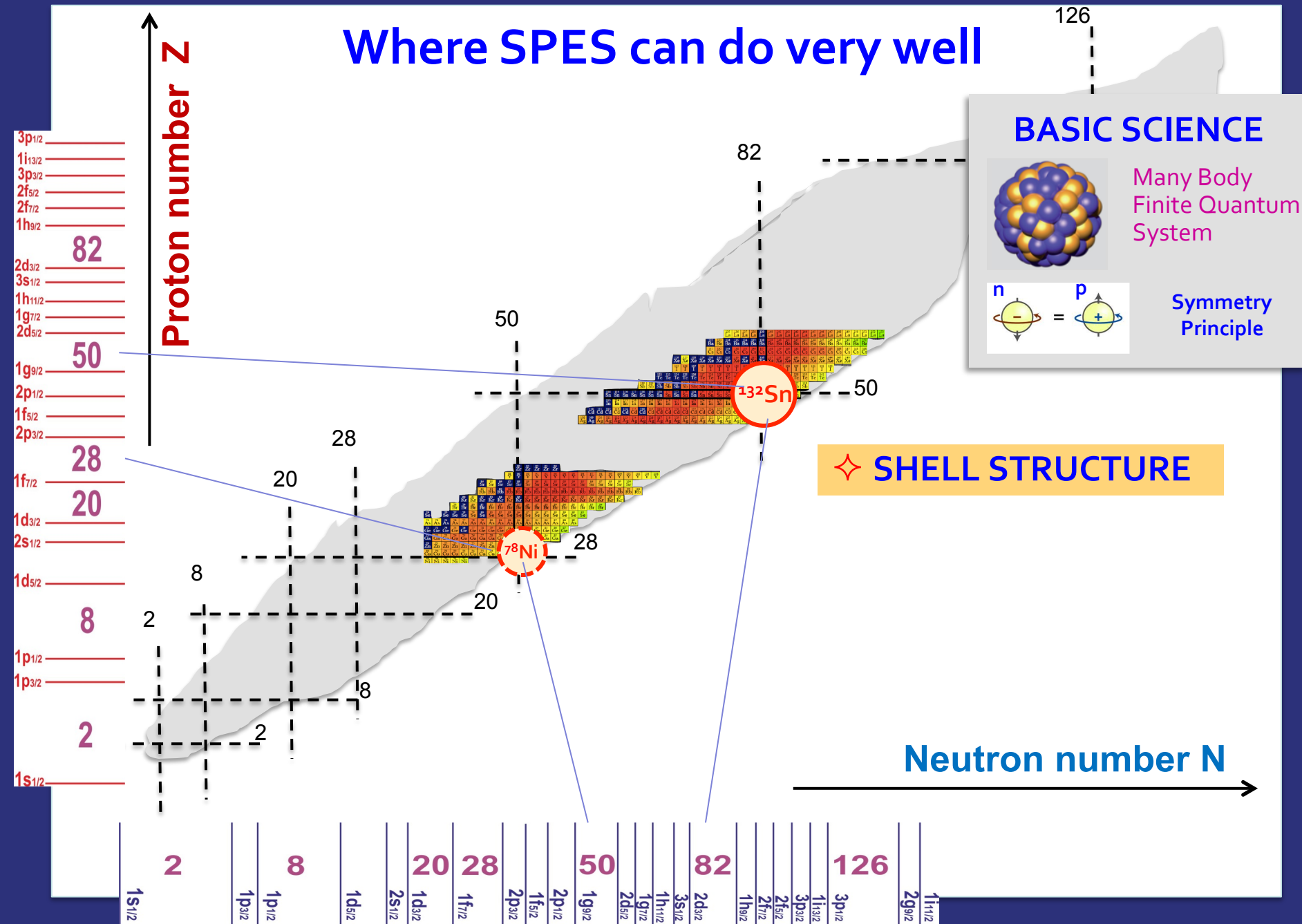


PRISMA

Very Powerful and Complete Experimental Setups ...

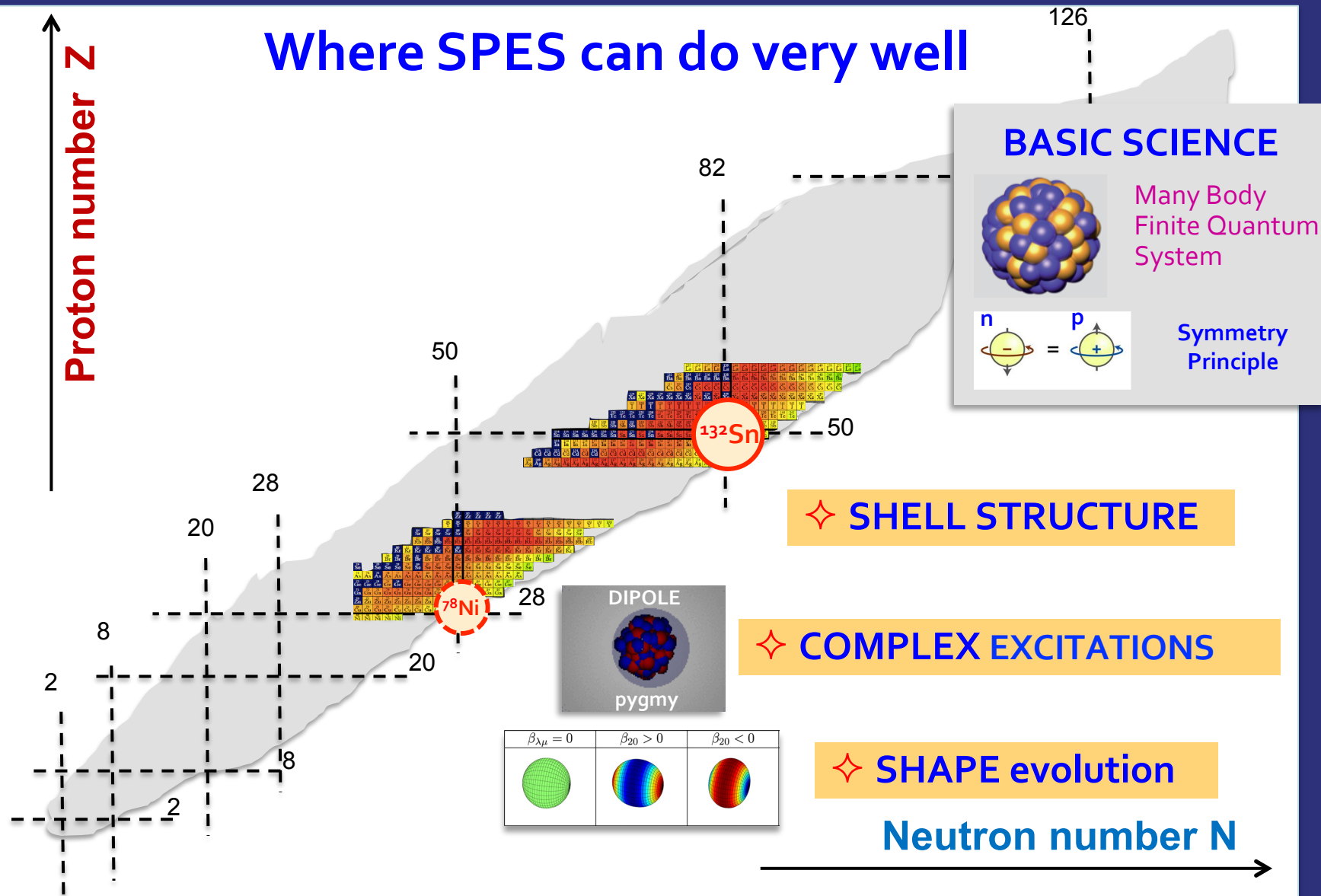
Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well



Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well

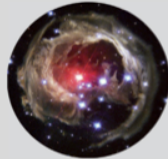


Quest for a UNIFIED DESCRIPTION of ALL Nuclei

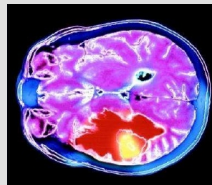
Where SPES can do very well

INTERDISCIPLINARITY

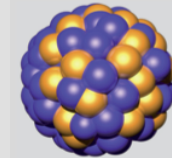
Astrophysics
Nucleosynthesis



Applications
Radioisotopes,
Reactors, ...



BASIC SCIENCE



Many Body
Finite Quantum
System



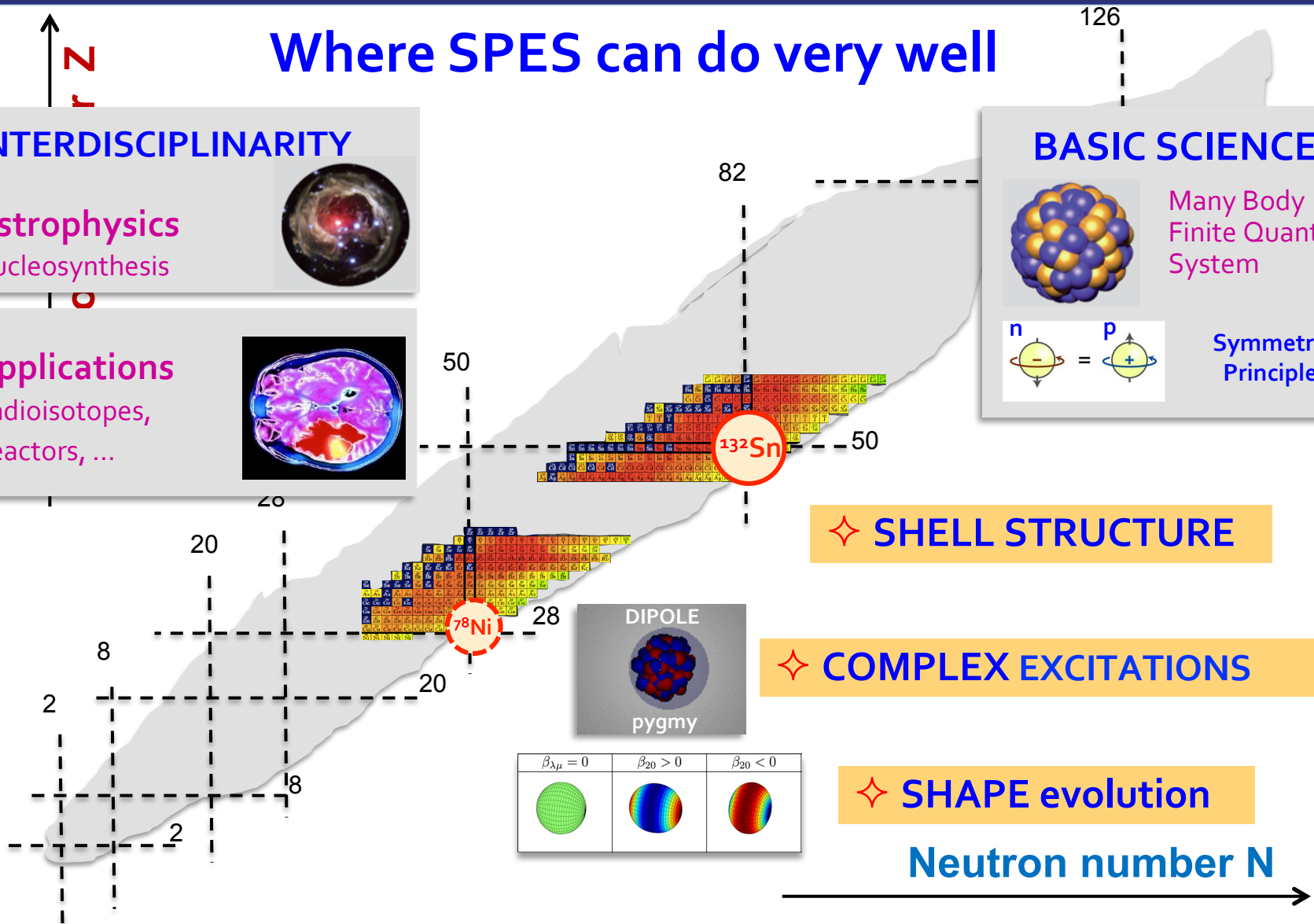
Symmetry
Principle

✧ SHELL STRUCTURE

✧ COMPLEX EXCITATIONS

✧ SHAPE evolution

Neutron number N

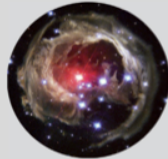


Quest for a UNIFIED DESCRIPTION of ALL Nuclei

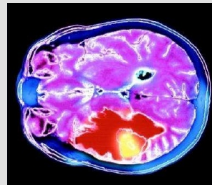
Where SPES can do very well

INTERDISCIPLINARITY

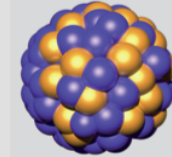
Astrophysics
Nucleosynthesis



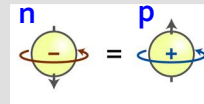
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BASIC SCIENCE



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Symmetry
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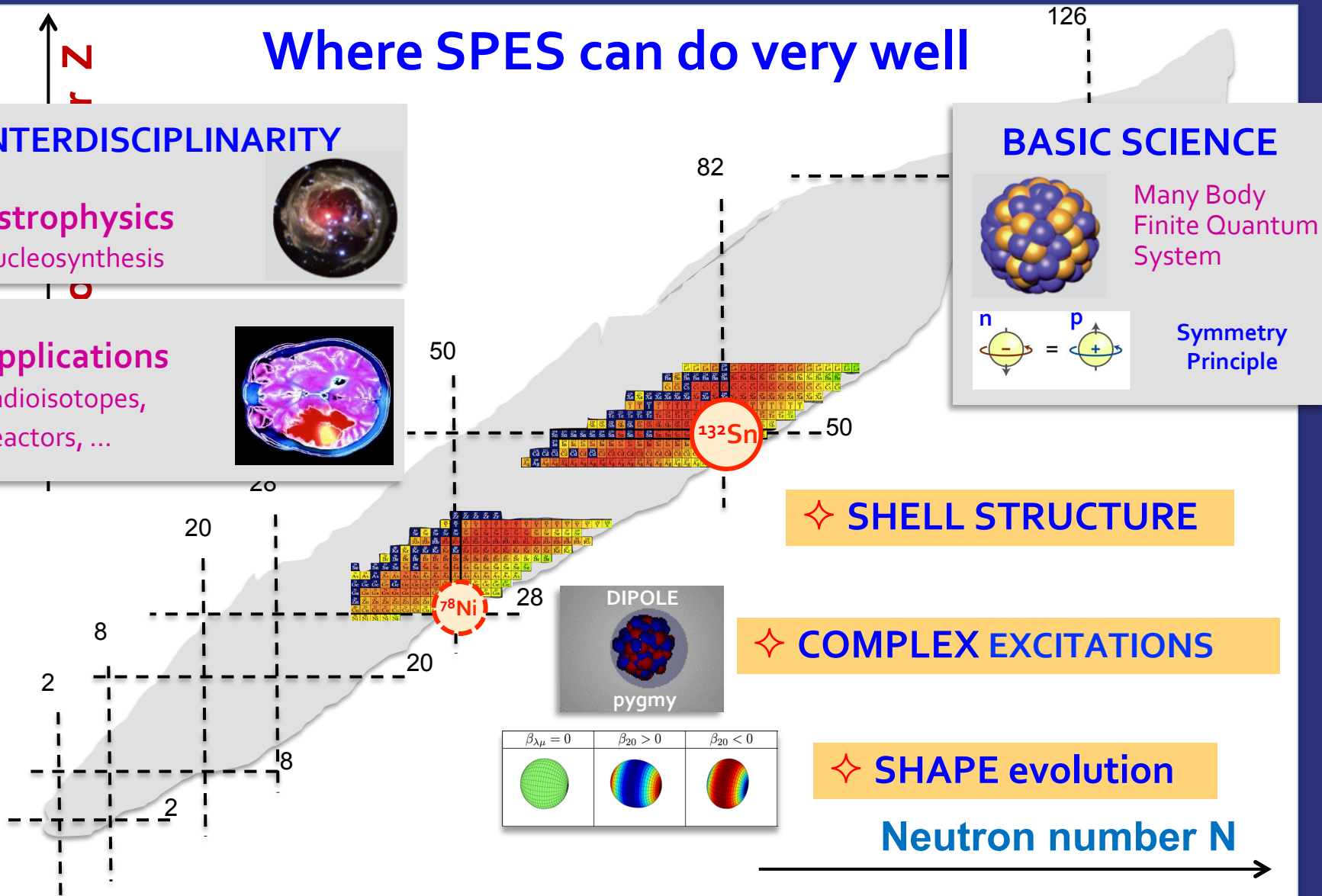
✧ SHELL STRUCTURE

✧ COMPLEX EXCITATIONS

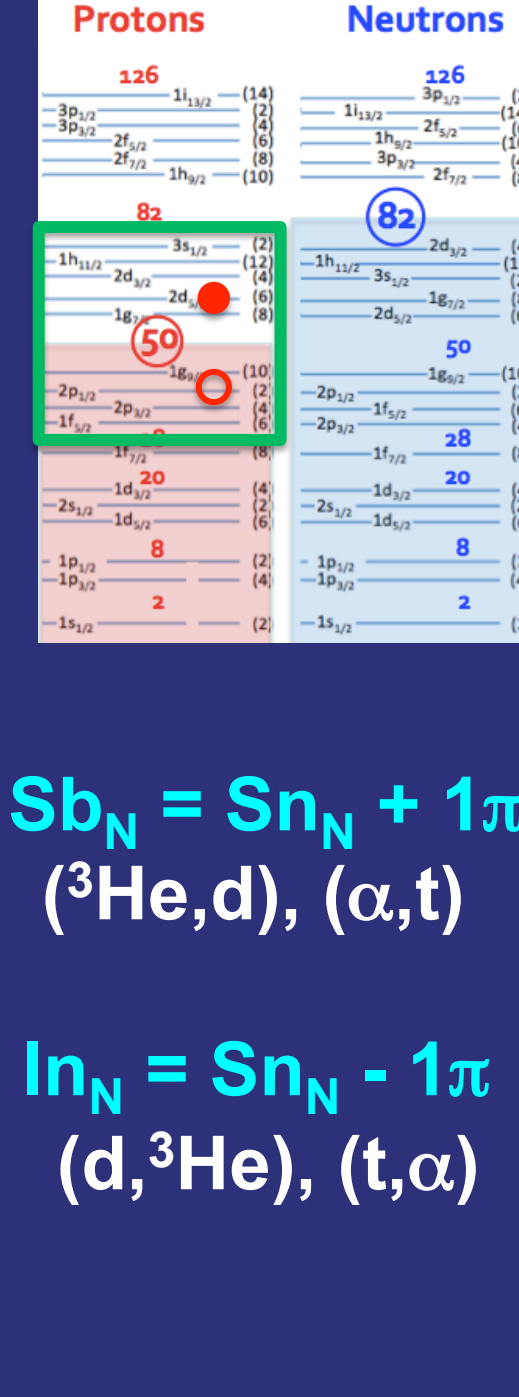
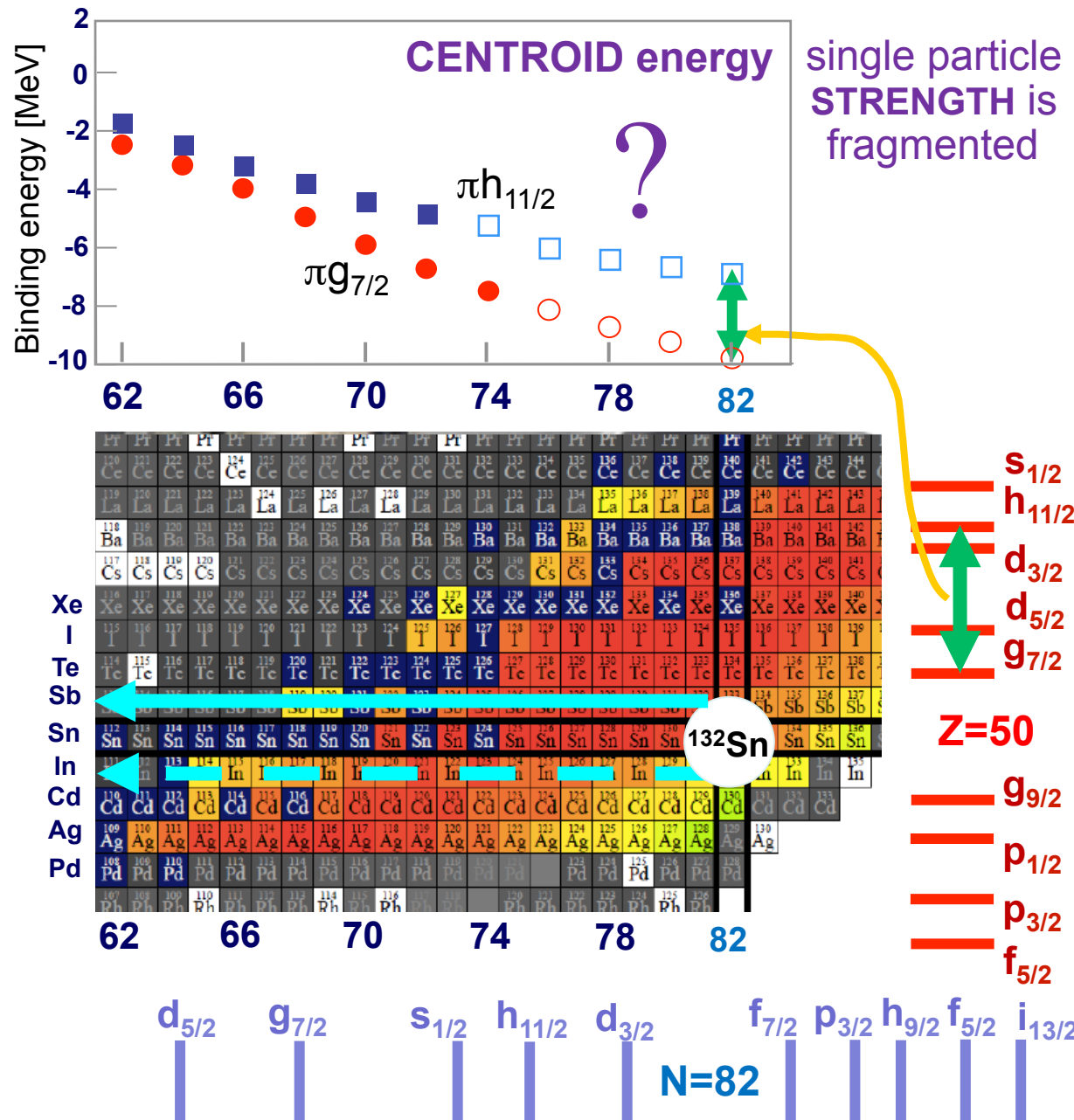
✧ SHAPE evolution

Neutron number N

Selected Examples ...



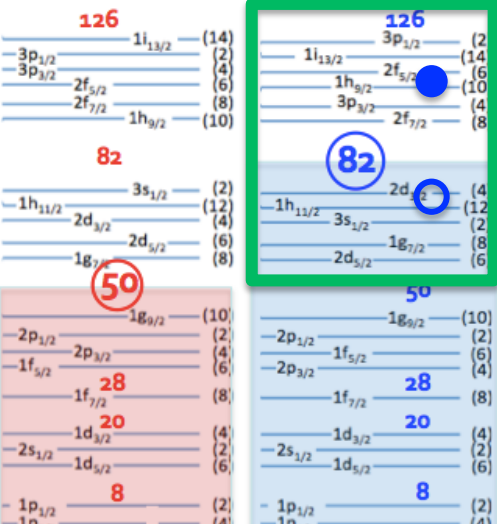
Single Particle Levels - PROTONS



Protons

Neutrons

NEUTRONS - Single Particle Levels

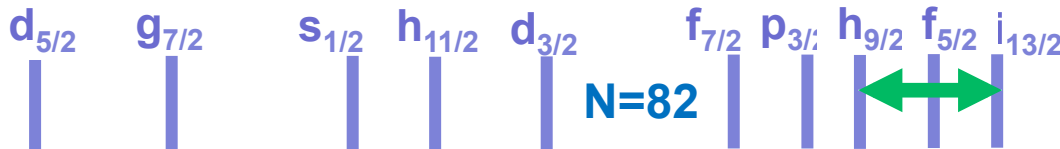
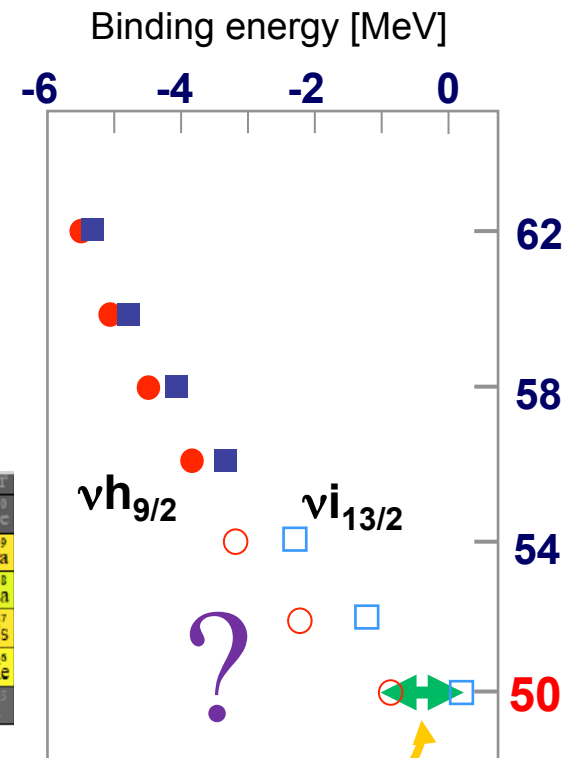
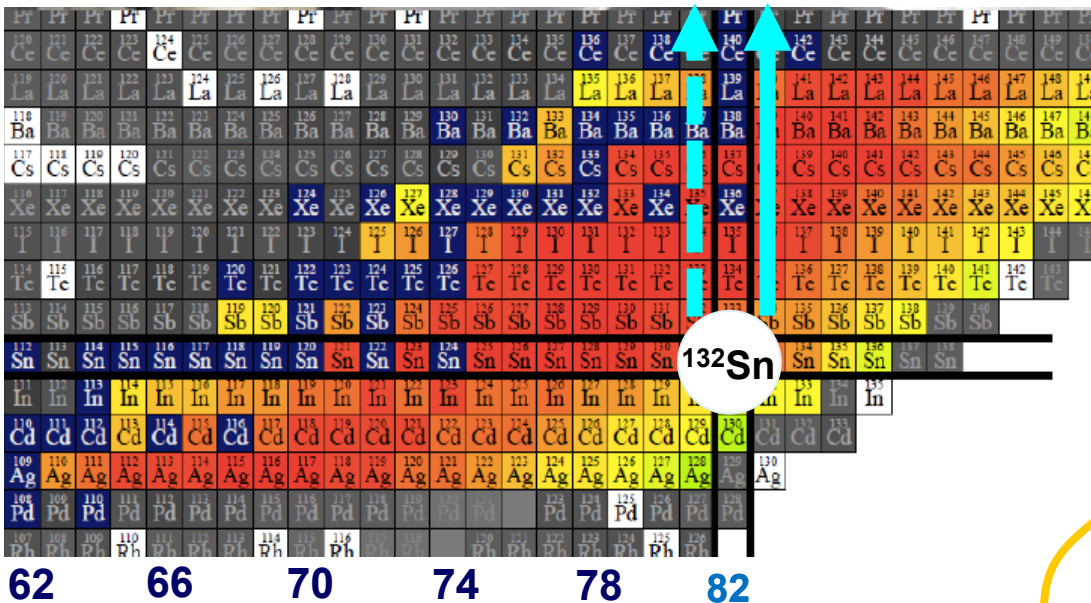
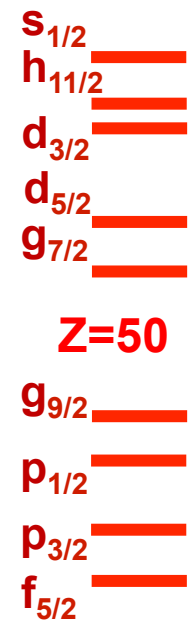


$$X_{N=83} = X_{N=82} + 1\nu$$

(d,p)

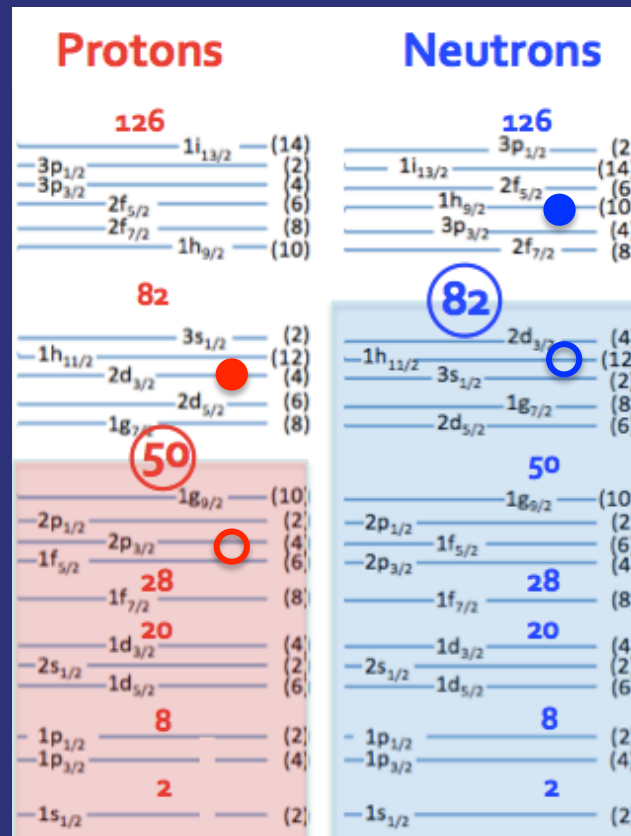
$$X_{N=81} = X_{N=82} - 1\nu$$

(p,d)



PROTON and NEUTRON Single Particle Levels

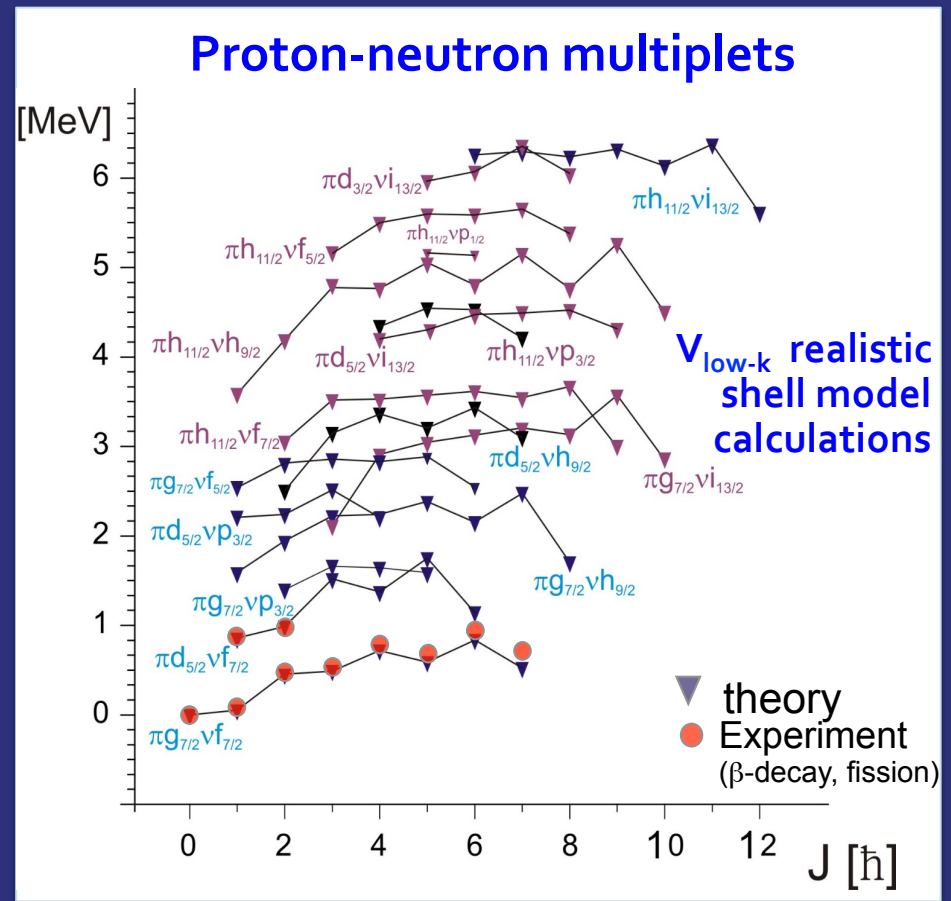
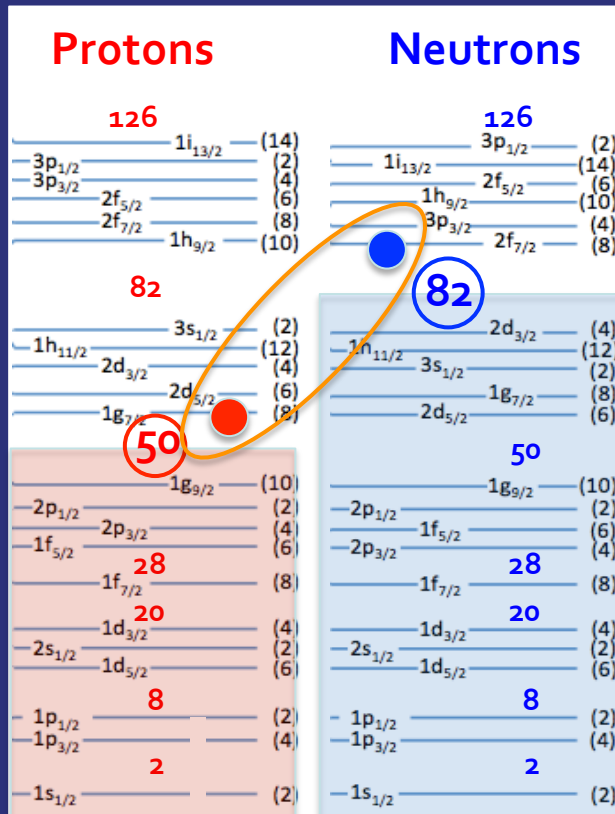
1. Measurements of single particle ENERGIES
2. Measurements of single particle STRENGTH:
Spectroscopic Factors
in TRANSFER reactions with light targets



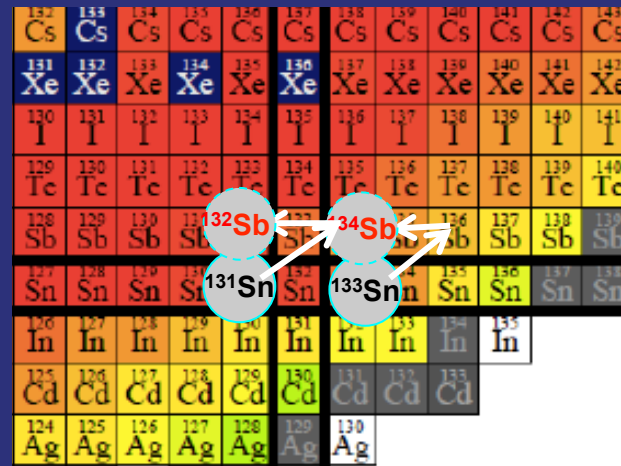
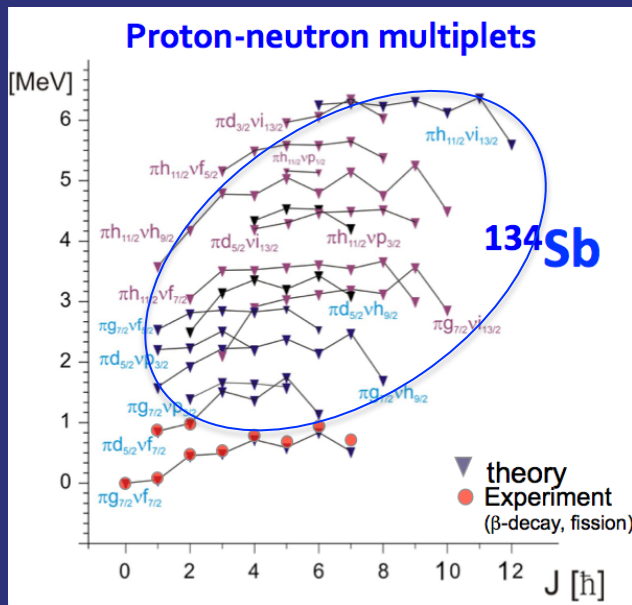
MULTIPLETS of valence nucleons around ^{132}Sn

$$^{134}\text{Sb} = \overset{\text{FROZEN}}{^{132}\text{Sn}} + \overset{\text{COUPLINGS}}{1\pi + 1\nu}$$

→ Two-Body Matrix Elements



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



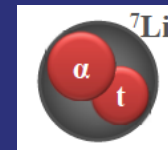
1. Cluster Transfer on ^7Li target



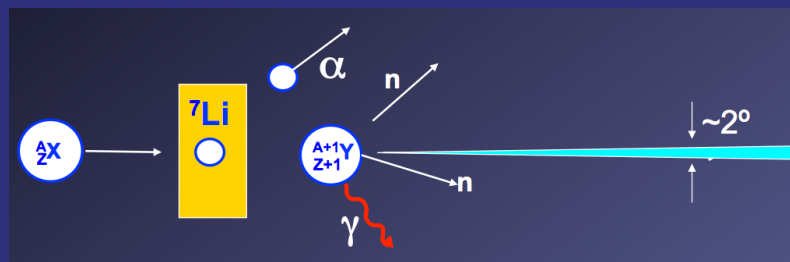
$$\sigma = 100 \text{ mb}$$

Inverse kinematics, few MeV/A

α tagging + γ array



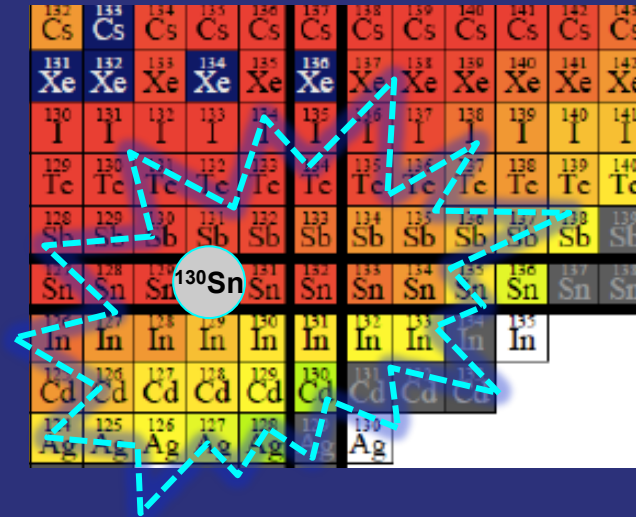
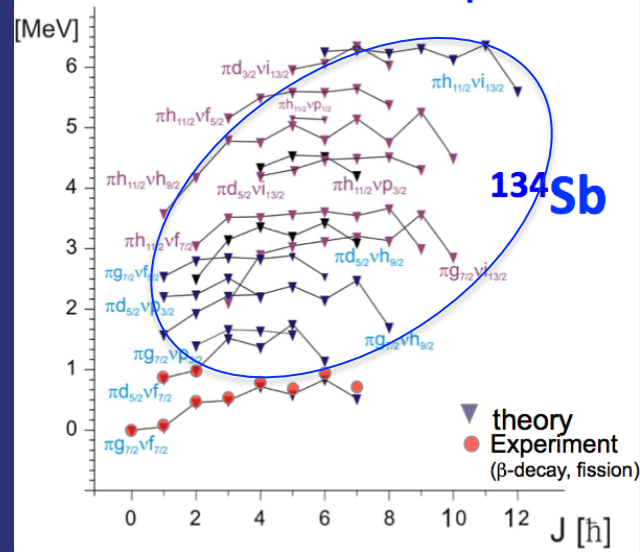
Weakly Bound



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

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

Proton-neutron multiplets

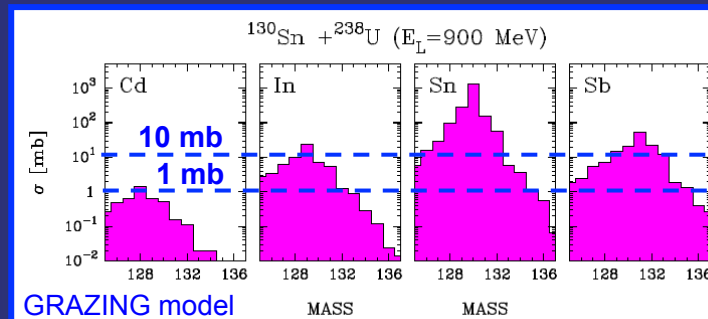


2. Multi-Nucleon Transfer with Heavy Ions

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

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: $B_{\text{EXP}}(\text{EM}, \lambda)$ versus THEORY

1. Coulomb Excitation

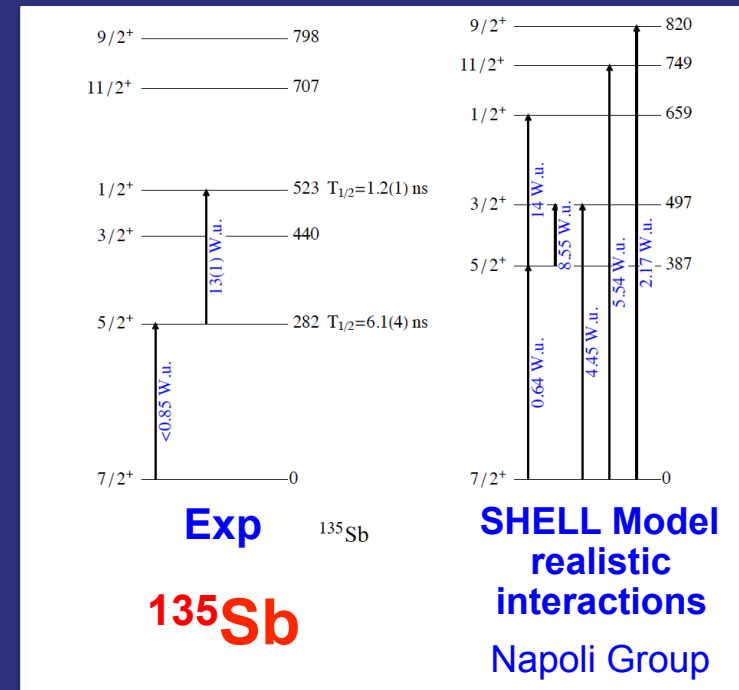
^{134}Sn

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

$^{126,127}\text{Cd}$

Direct extraction of $B(\text{E}, \lambda)$

Si stripped detector (SPIDER) + γ array



2. Lifetime Analysis

Multi-Nucleon Transfer with Heavy Ions

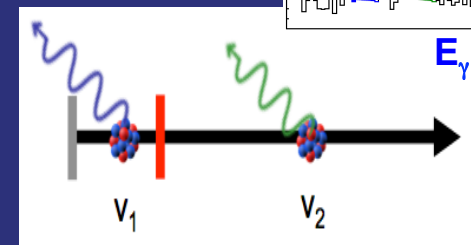
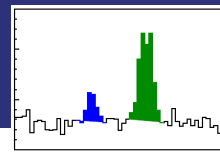
^ASn (7 MeV/A) + $^{208}\text{Pb}/^{238}\text{U}$

Plunger technique

PRISMA is needed + γ array

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

Extensively used
with Stable-Beams (LNL, GANIL)



132 Cs	133 Cs	134 Cs	135 Cs	136 Cs	137 Cs	138 Cs	139 Cs	140 Cs	141 Cs	142 Cs	143 Cs
131 Xe	132 Xe	133 Xe	134 Xe	135 Xe	136 Xe	137 Xe	138 Xe	139 Xe	140 Xe	141 Xe	142 Xe
130 I	131 I	132 I	133 I	134 I	135 I	136 I	137 I	138 I	139 I	140 I	141 I
129 Te	130 Te	131 Te	132 Te	133 Te	134 Te	135 Te	136 Te	137 Te	138 Te	139 Te	140 Te
128 Sb	129 Sb	130 Sb	131 Sb	132 Sb	133 Sb	134 Sb	135 Sb	136 Sb	137 Sb	138 Sb	139 Sb
127 Sn	128 Sn	129 Sn	130 Sn	131 Sn	132 Sn	133 Sn	134 Sn	135 Sn	136 Sn	137 Sn	138 Sn
126 In	127 In	128 In	129 In	130 In	131 In	132 In	133 In	134 In	135 In	136 In	137 In
125 Cd	126 Cd	127 Cd	128 Cd	129 Cd	130 Cd	131 Cd	132 Cd	133 Cd	134 Cd	135 Cd	136 Cd
124 Ag	125 Ag	126 Ag	127 Ag	128 Ag	129 Ag	130 Ag	131 Ag	132 Ag	133 Ag	134 Ag	135 Ag

COMPLEX STATES - NOT DOABLE BY SHELL MODEL (with FROZEN CORE)

130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145
Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe	Xe
129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
126	126	126	126	126	126	126	126	126	126	126	126	126	126	126	126
Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te	Te
127	127	127	127	127	127	127	127	127	127	127	127	127	127	127	127
Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb	Sb
128	128	128	128	128	128	128	128	128	128	128	128	128	128	128	128
Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn	Sn
129	129	129	129	129	129	129	129	129	129	129	129	129	129	129	129
In	In	In	In	In	In	In	In	In	In	In	In	In	In	In	In
124	124	124	124	124	124	124	124	124	124	124	124	124	124	124	124
Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd	Cd
123	123	123	123	123	123	123	123	123	123	123	123	123	123	123	123
Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag
122	122	122	122	122	122	122	122	122	122	122	122	122	122	122	122
Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd	Pd

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

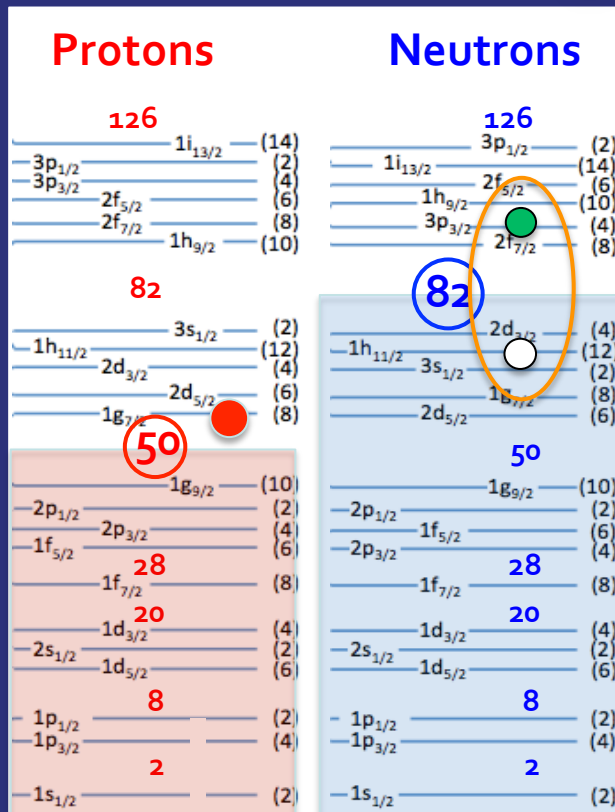
2^+ , 3^- , 4^+ , ... **PHONONS**

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)

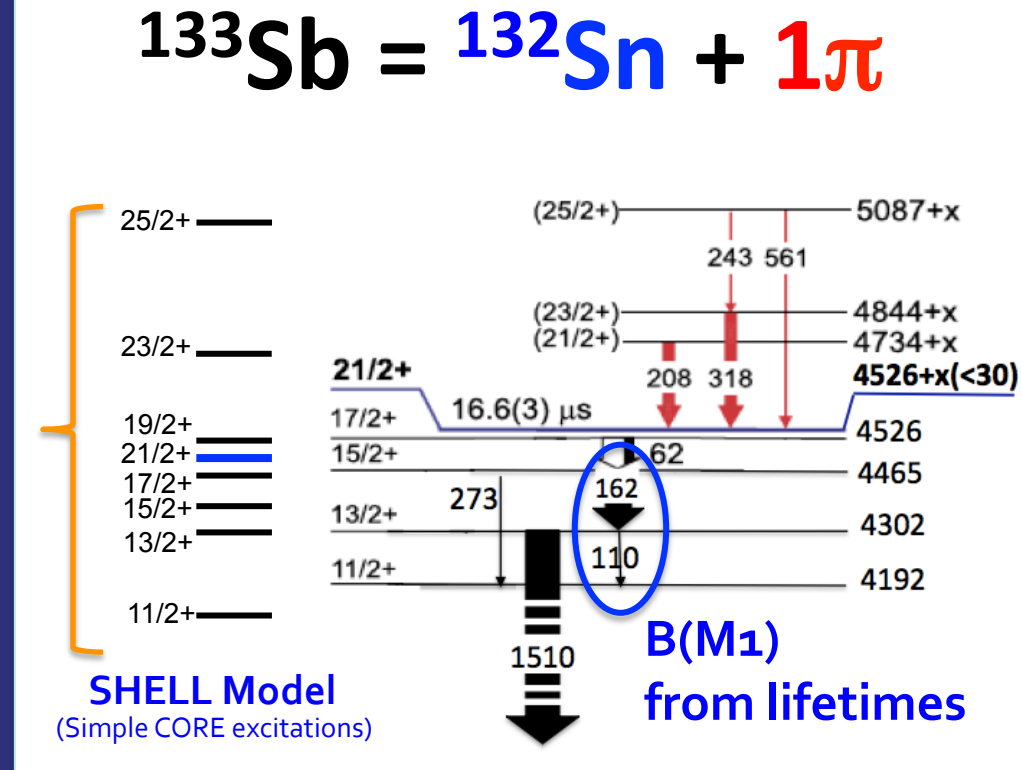
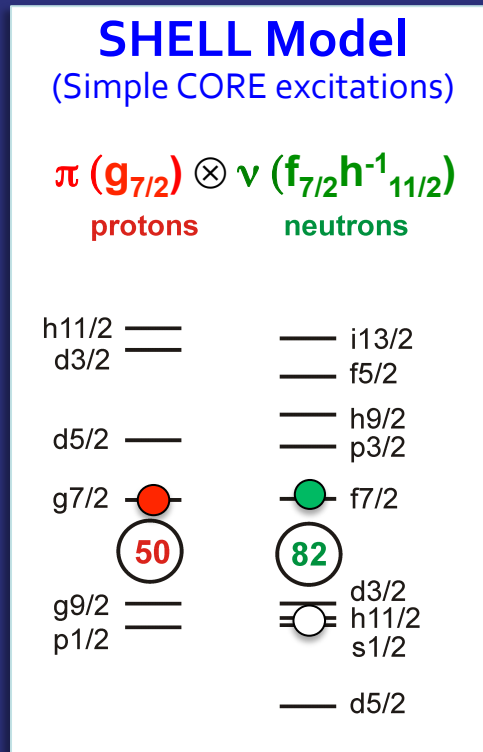
2. **MULTIPLETS** of **COMPLEX** Nature



MULTIPLETS: Relevance of CORE Excitations

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

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

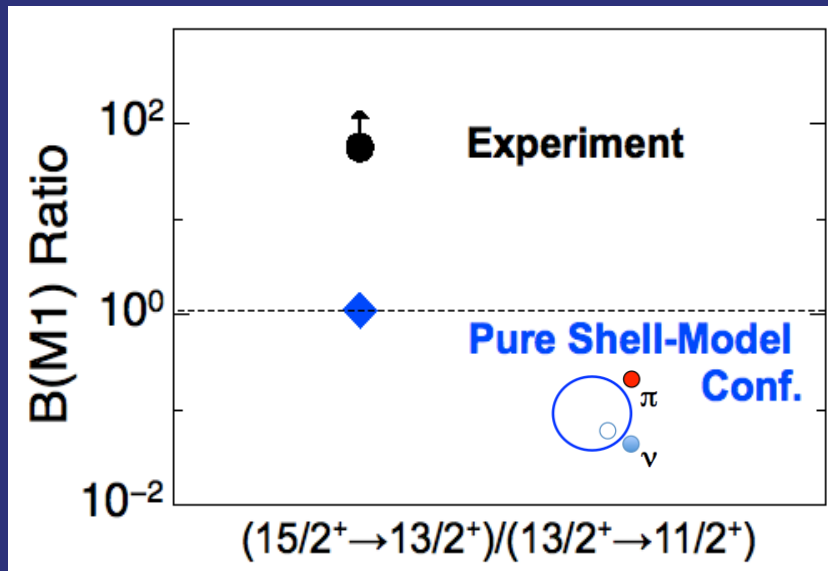


SHELL Model may reproduce MULTIPLET energies ... NOT B(EM,λ)

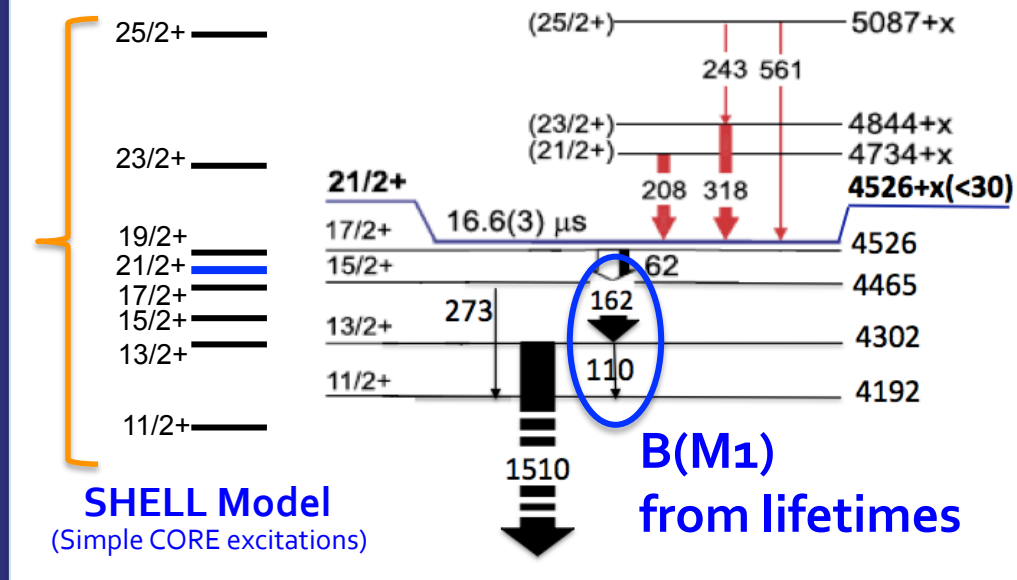
Relevance of CORE Excitations

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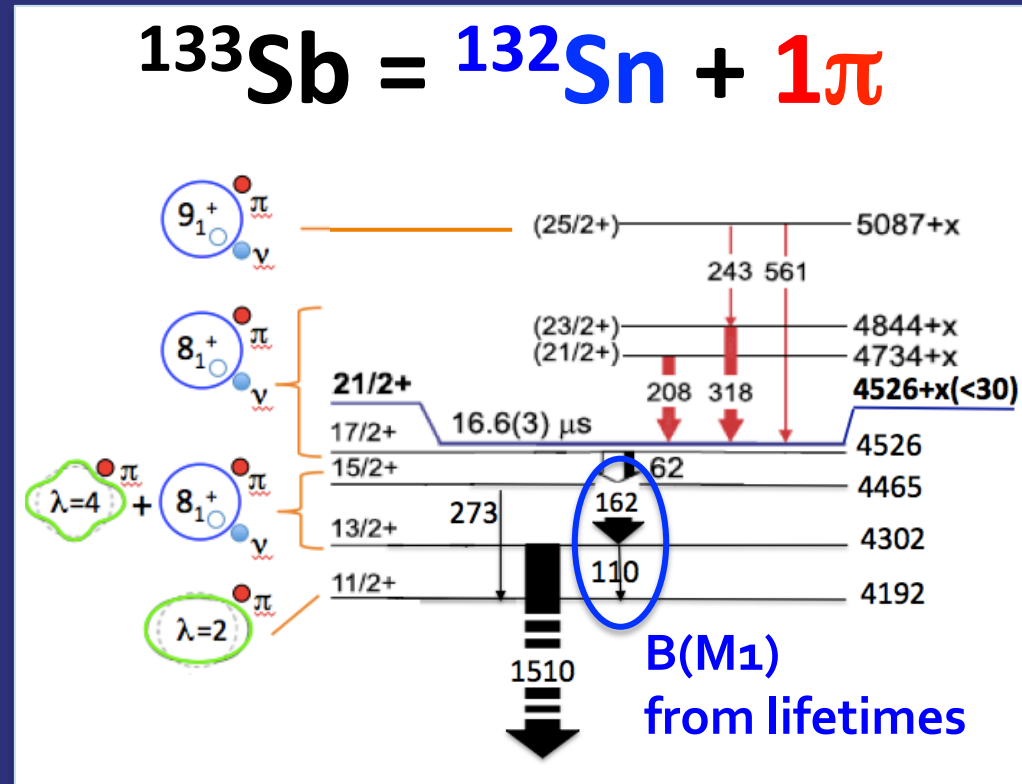


$$^{133}\text{Sb} = ^{132}\text{Sn} + 1\pi$$



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

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



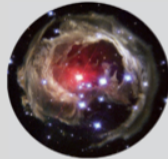
→ We need complete spectroscopy: Energies, J^π and $B(EM, \lambda)$

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well

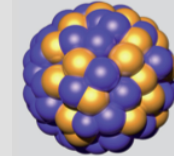
INTERDISCIPLINARITY

Astrophysics
Nucleosynthesis

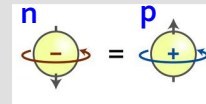


Proto

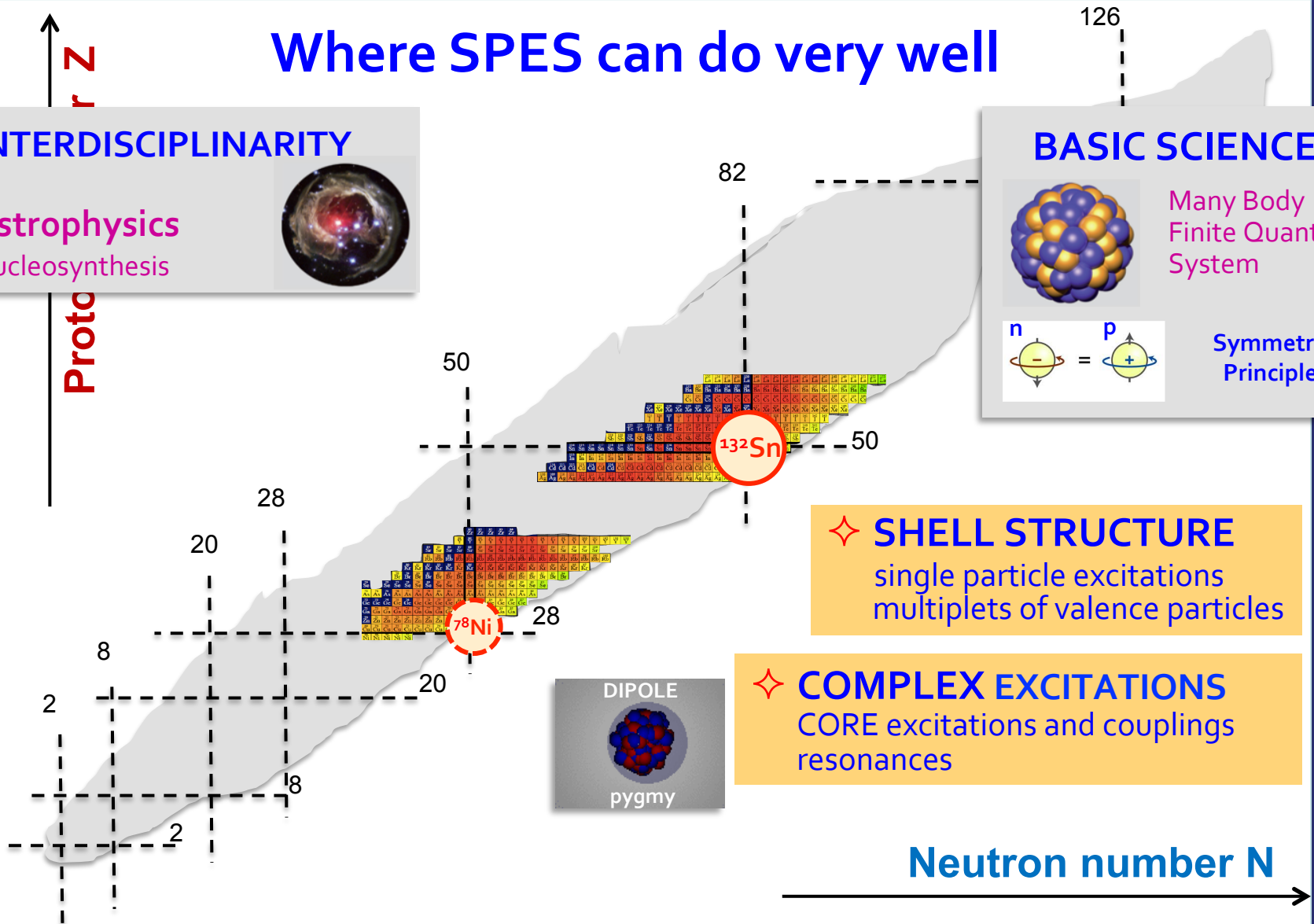
BASIC SCIENCE



Many Body
Finite Quantum
System



Symmetry
Principle



✧ SHELL STRUCTURE
single particle excitations
multiplets of valence particles

✧ COMPLEX EXCITATIONS
CORE excitations and couplings
resonances

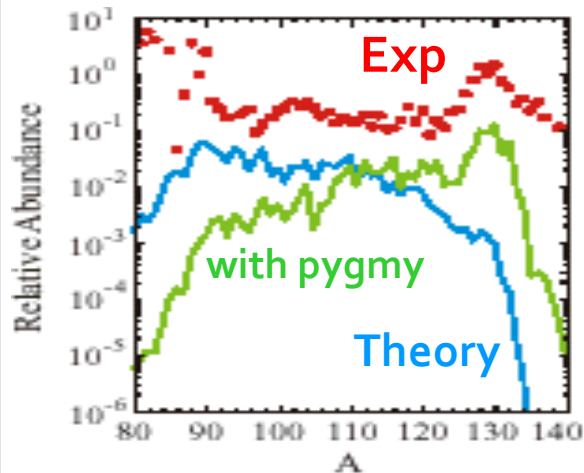
Neutron number N

Selected Examples ...

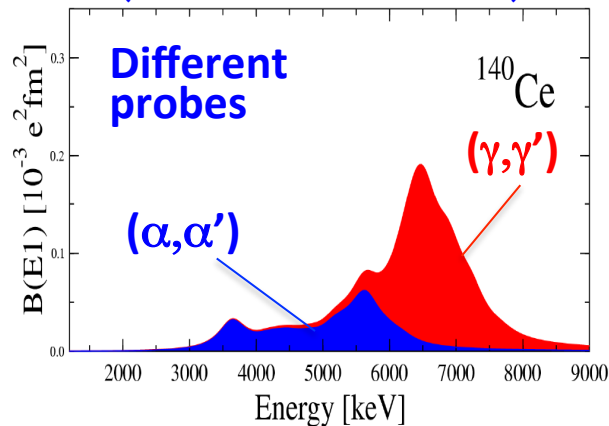
The DIPOLE Response In Nuclei

Element Abundance

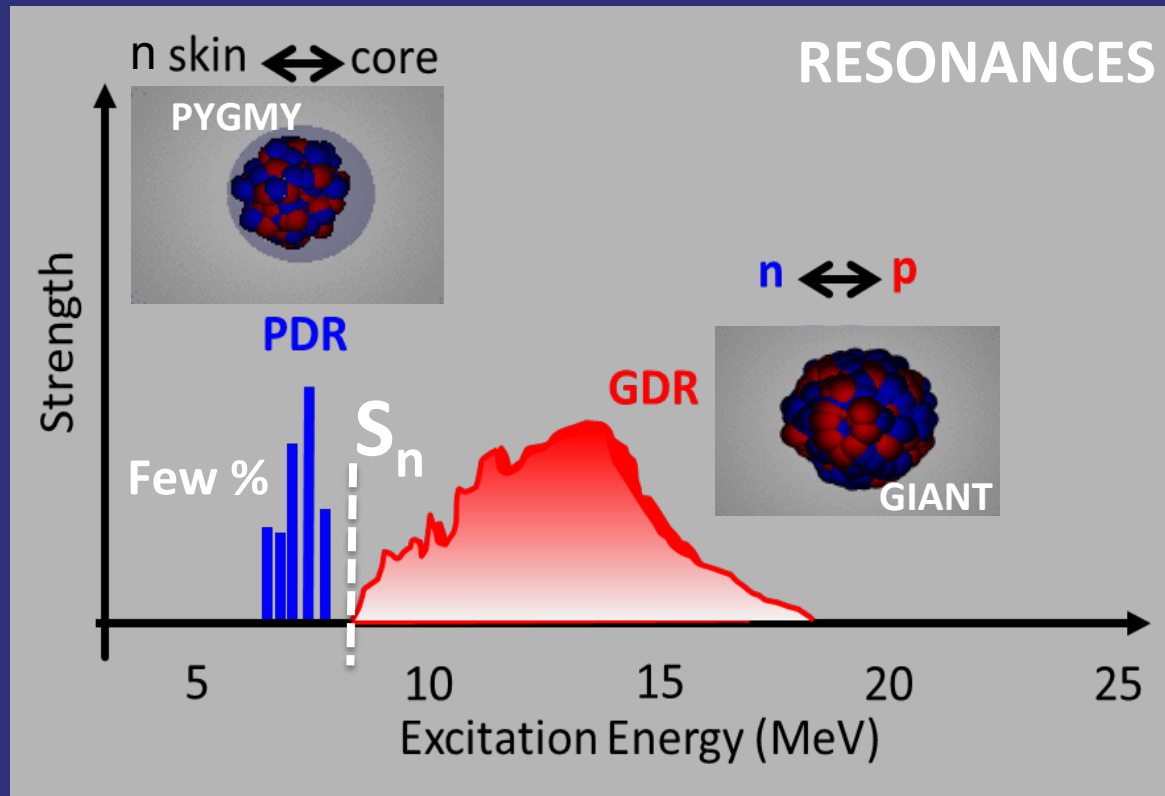
Relevant ENERGY window for (γ, n) reactions in STARS



UNDERLYING Structure (KVI and Darmstadt)



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

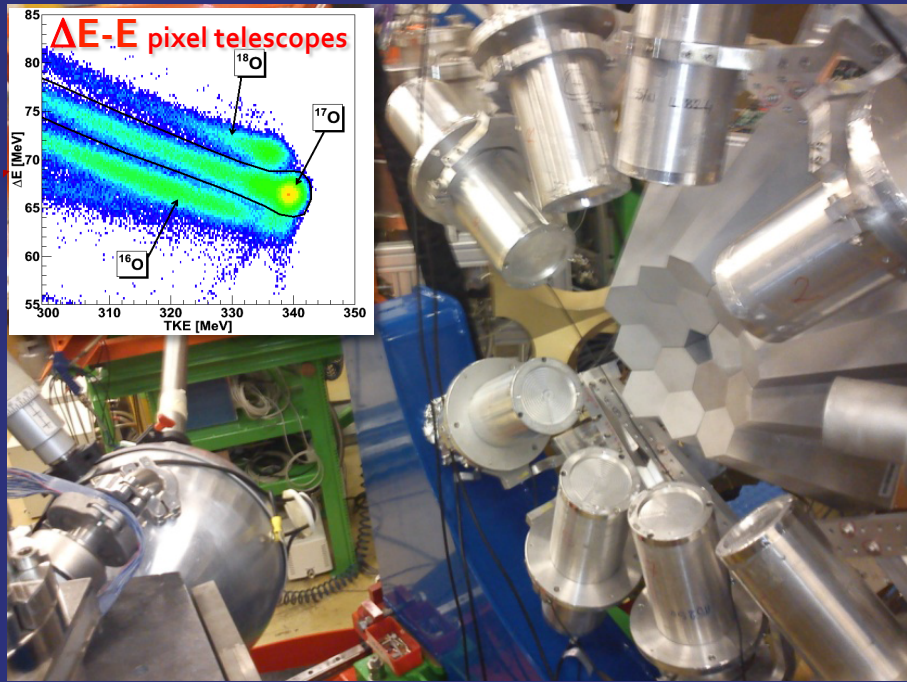
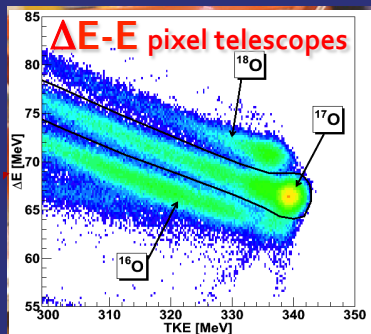


→ Important for **ASTROPHYSICS**
(Nucleosynthesis, Neutron Stars)

→ Relevant in **NUCLEAR STRUCTURE**
(Microscopic Nature...)

Pygmy Resonances in STABLE NUCLEI

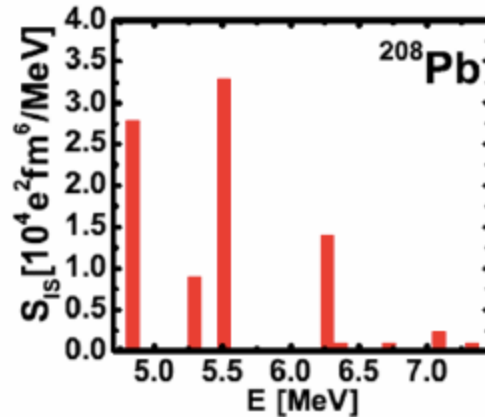
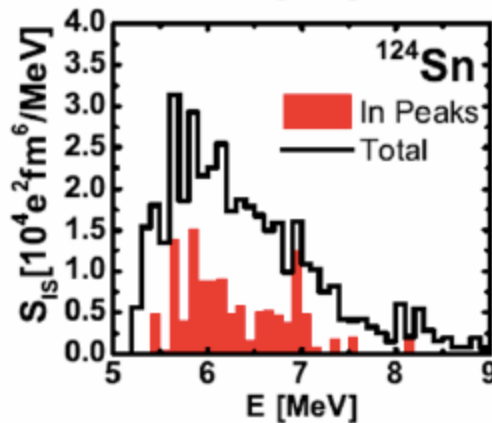
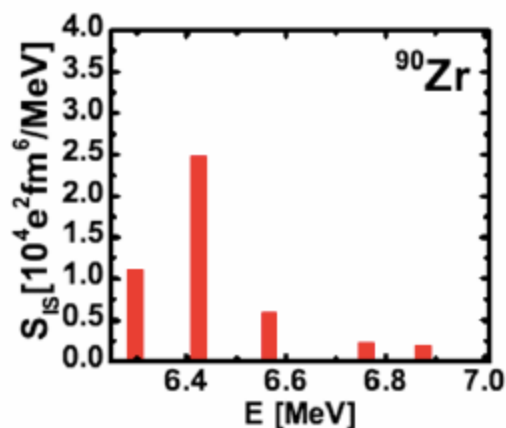
Heavy-Ion Inelastic Scattering: a probe sensitive to the surface



LNL Campaign

AGATA +
Si Telescopes +
Scintillators (LaBr₃)

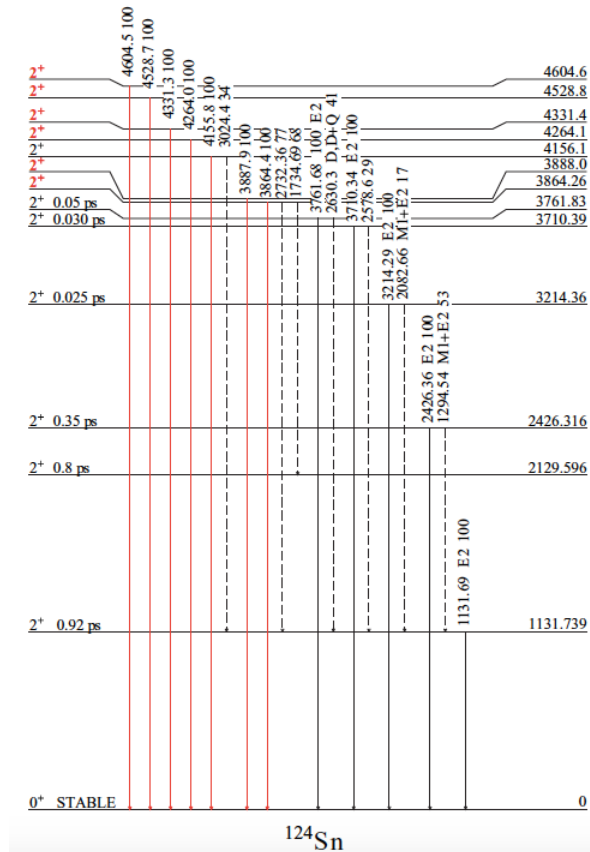
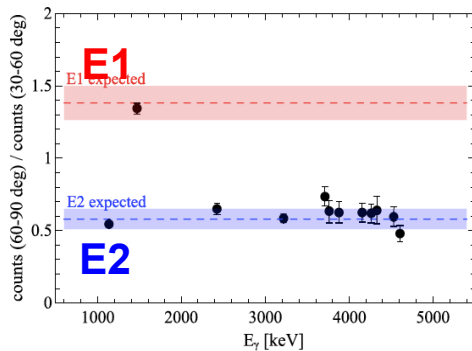
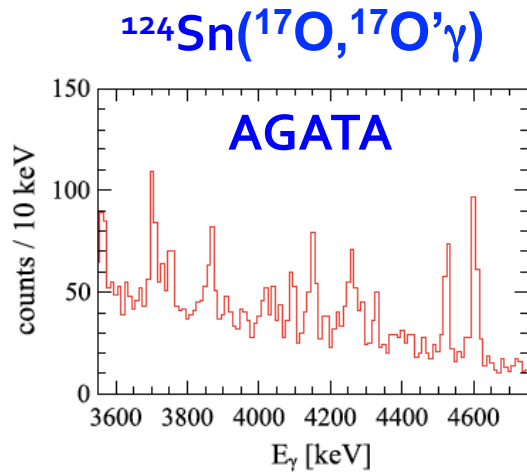
^{17}O @ 20 MeV/A
on ^{208}Pb , ^{124}Sn , ^{90}Zr , ^{140}Ce
STABLE targets



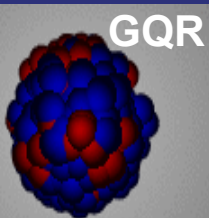
Pygmy
Strength (E_1)
1-3% EWSR
isoscalar E_1

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

Multitude of 2^+ discrete states

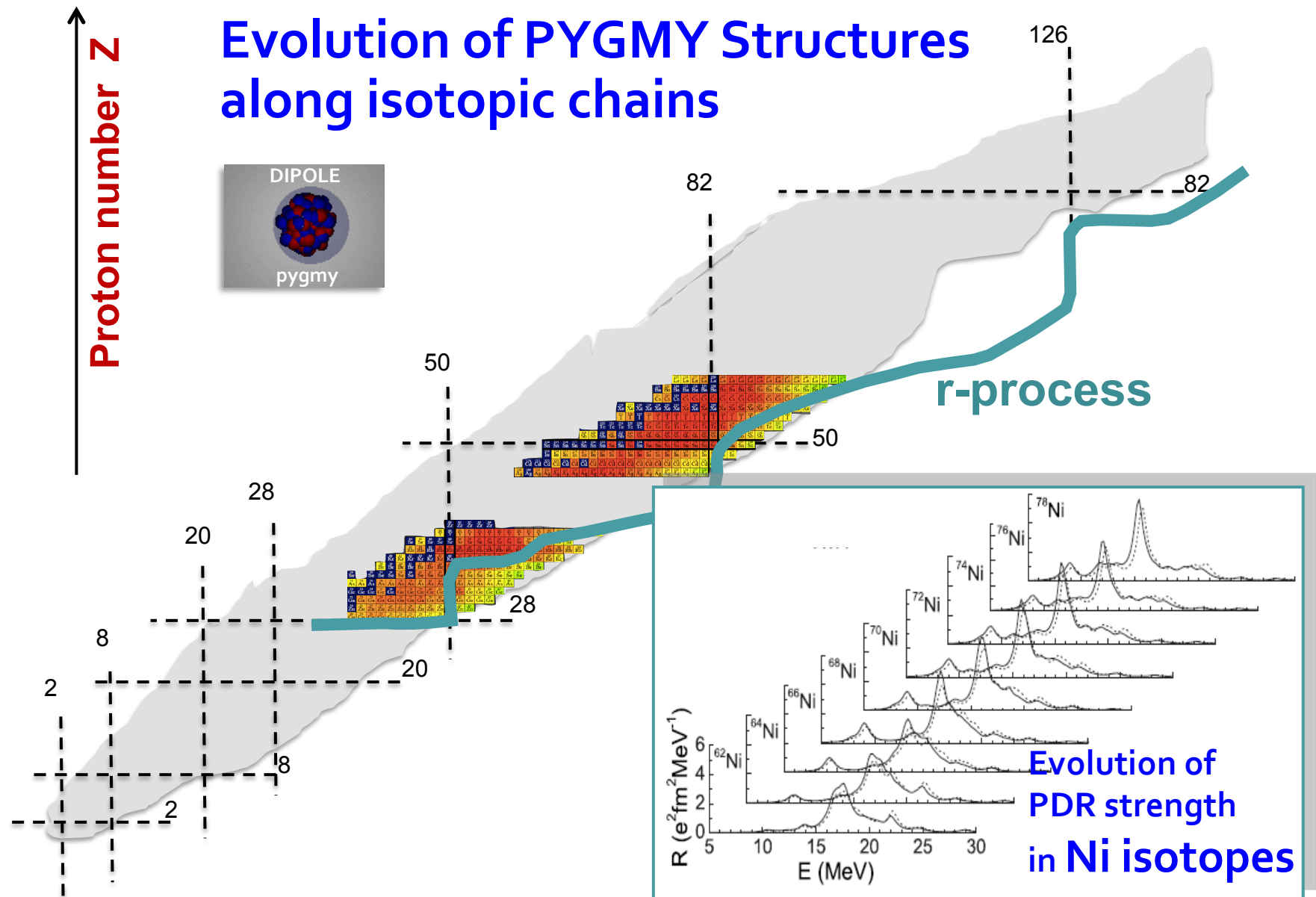


A. Bracco, F. Crespi, E. Lanza,
Eur. Phys. J. A51 (2015) 99



Concentration of E2 Strength
much below the GIANT QUADRUPOLE resonance
- In agreement with Quasi-phonon Model predictions -

Pygmy Resonances in EXOTIC NUCLEI

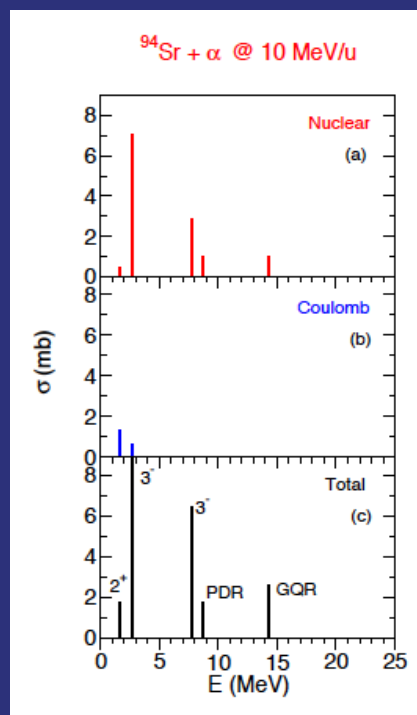
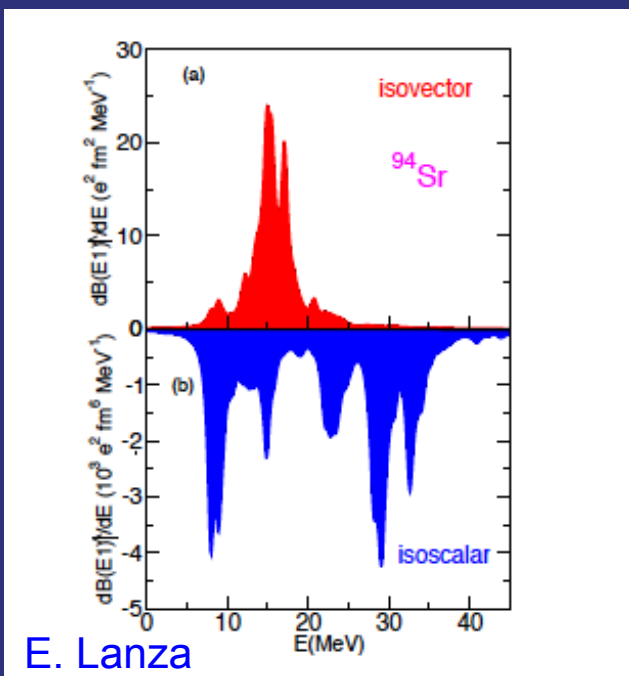


PYGMY in EXOTIC NUCLEI @ SPES

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)**

90Nb	91Nb	92Nb	93Nb	94Nb	95Nb	96Nb	97Nb	98Nb	99Nb	100Nb	101Nb
89Zr	90Zr	91Zr	92Zr	93Zr	94Zr	95Zr	96Zr	97Zr	98Zr	99Zr	100Zr
88Y	89Y	90Y	91Y	92Y	93Y	94Y	95Y	96Y	97Y	98Y	99Y
87Sr	88Sr	89Sr	90Sr	91Sr	92Sr	93Sr	94Sr	95Sr	96Sr	97Sr	98Sr
86Rb	87Rb	88Rb	89Rb	90Rb	91Rb	92Rb	93Rb	94Rb	95Rb	96Rb	97Rb
85Kr	86Kr	87Kr	88Kr	89Kr	90Kr	91Kr	92Kr	93Kr	94Kr	95Kr	96Kr

Day 0 Beams

$^{90,92,94}\text{Sr}$: $10^6 - 10^7$ pps

2. γ -spectroscopy after β -decay

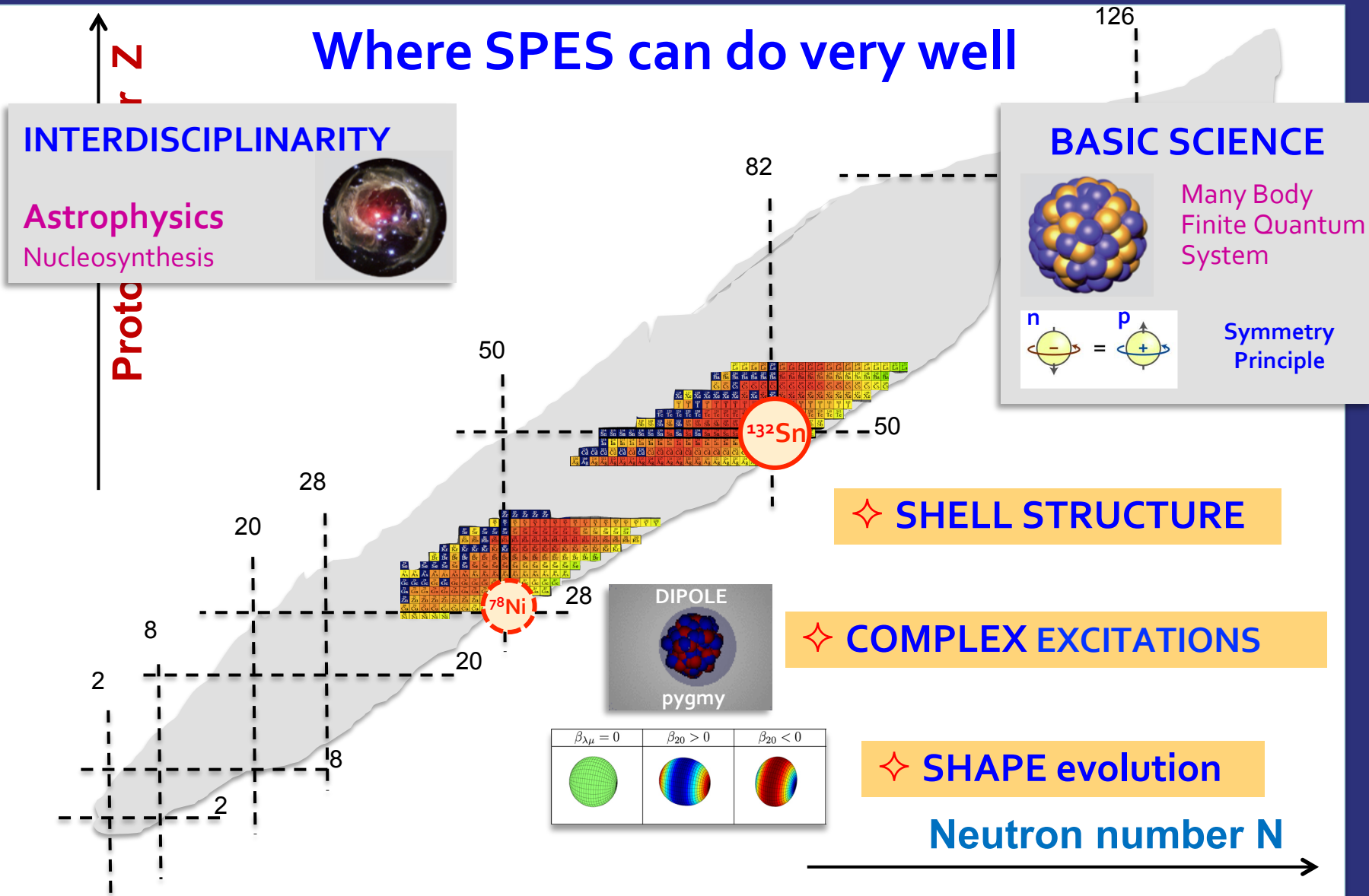
if Q_β -value is large ... to be investigated:

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

Need for HRMS !!

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well



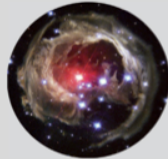
Selected Examples ...

Quest for a UNIFIED DESCRIPTION of ALL Nuclei

Where SPES can do very well

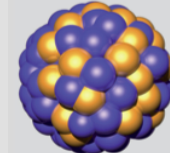
INTERDISCIPLINARITY

Astrophysics
Nucleosynthesis

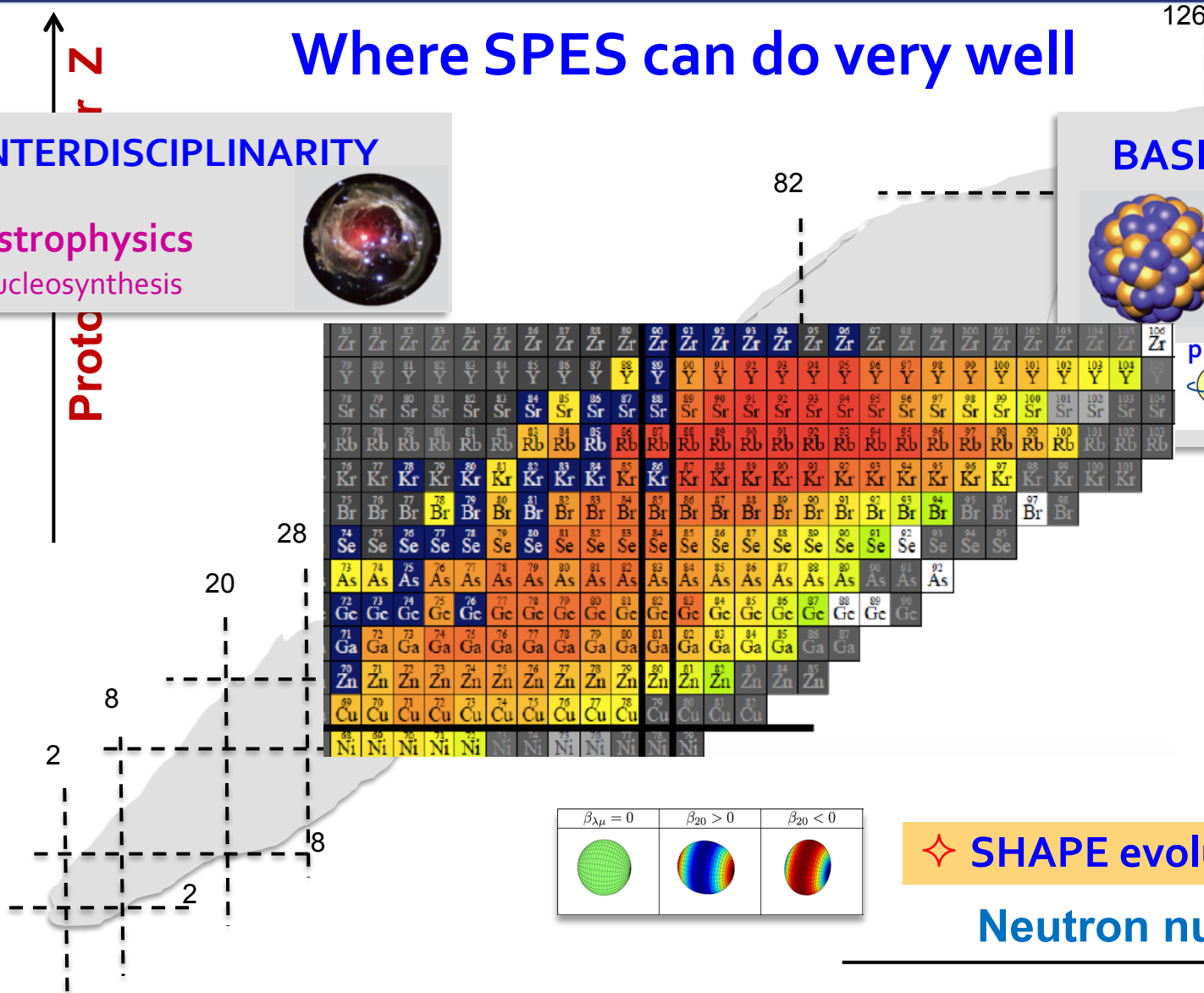


BASIC SCIENCE

Many Body
Finite Quantum
System

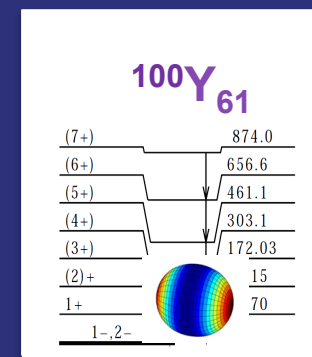
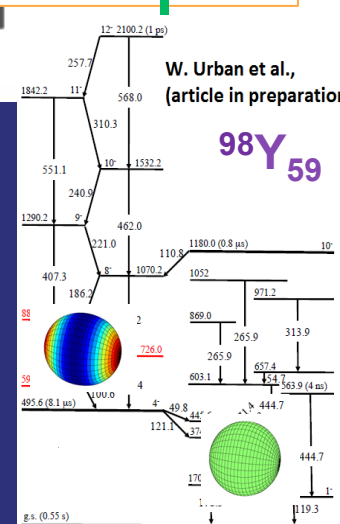
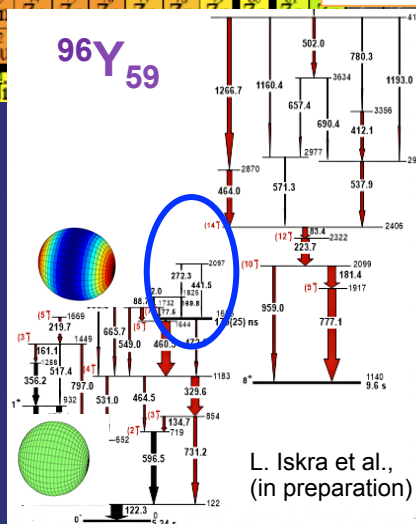
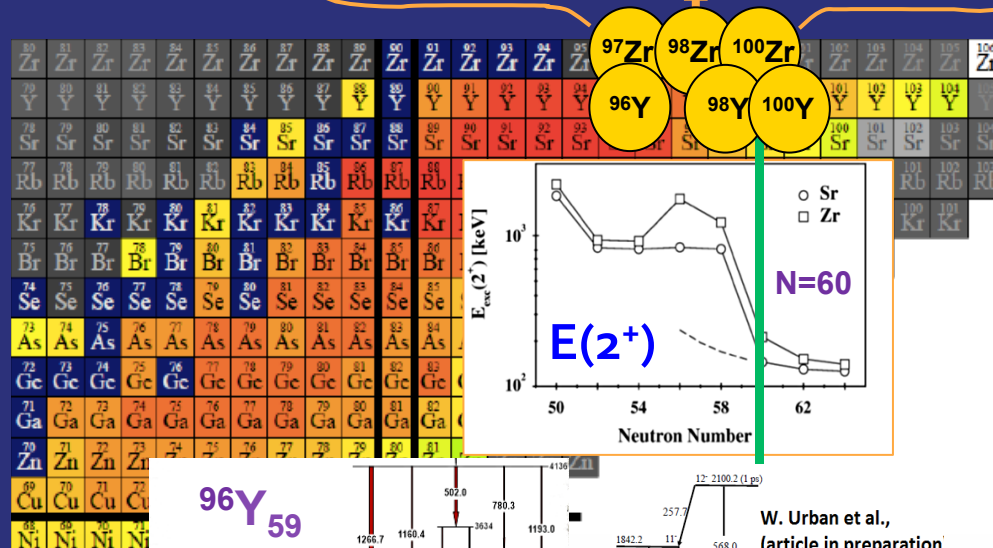
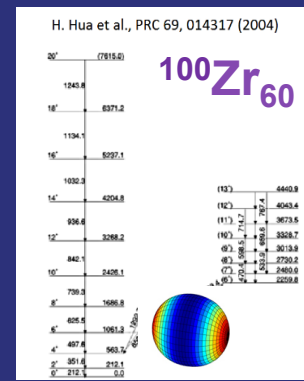
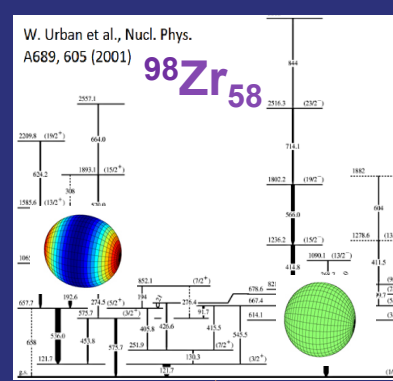
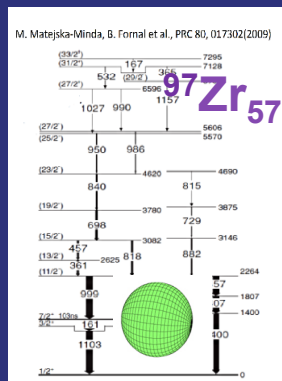


Symmetry
Principle

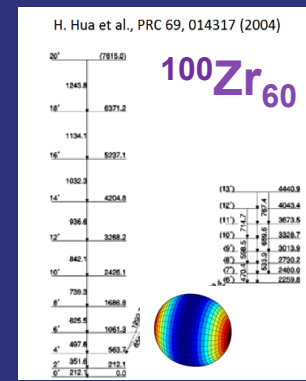
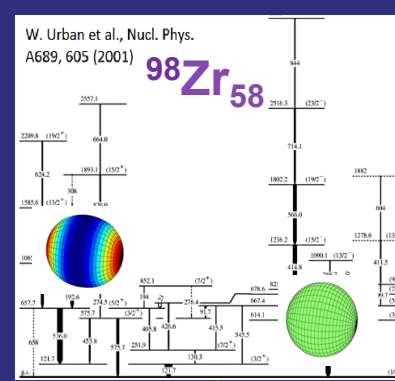
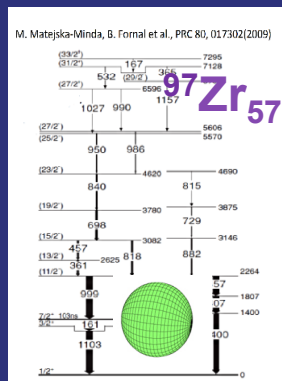


Selected Examples ...

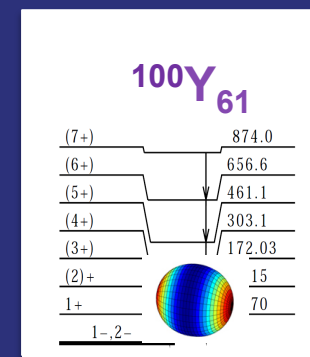
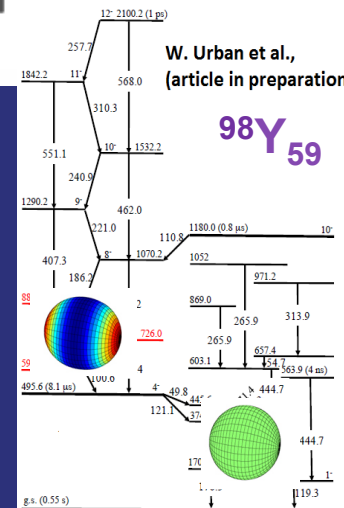
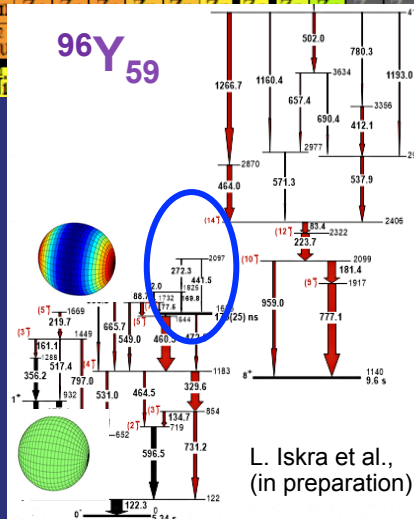
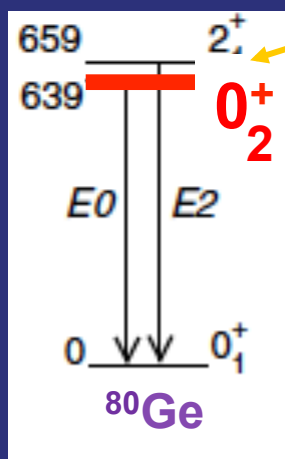
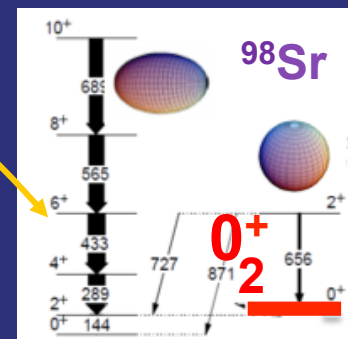
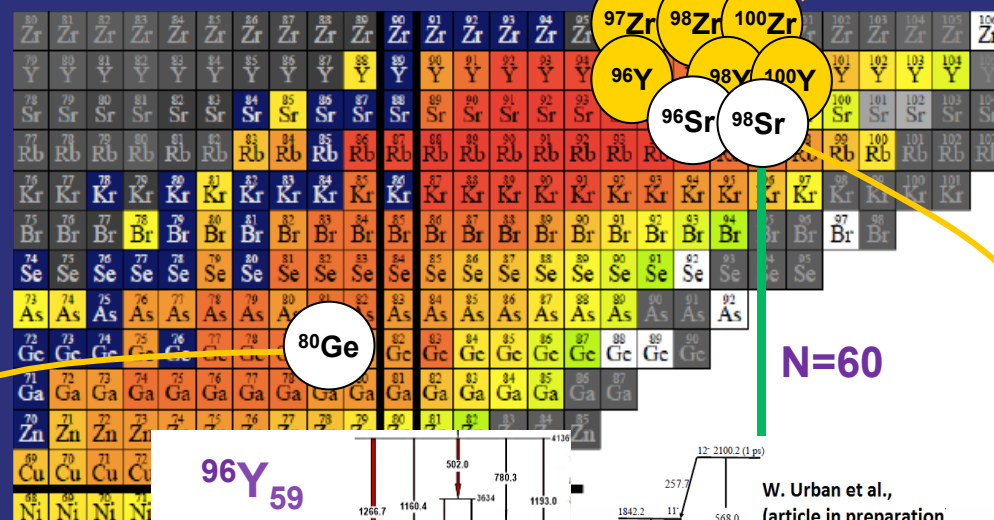
The region of most dramatic changes



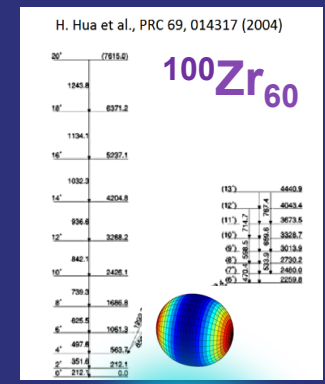
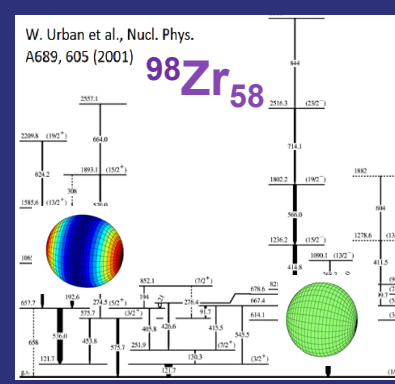
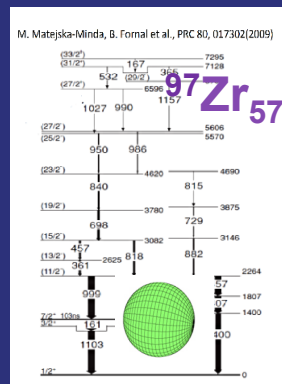
The region of most dramatic changes



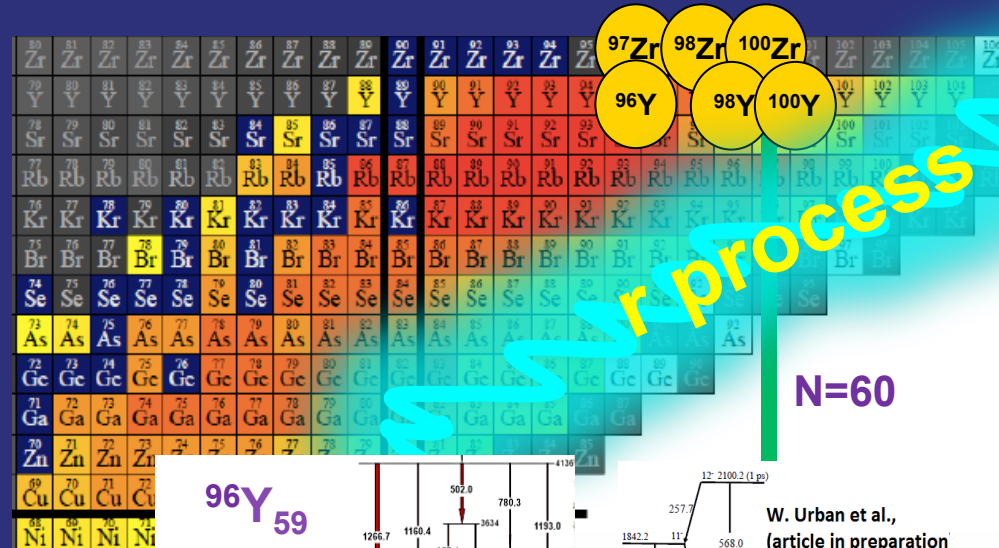
- a challenge for theory



The region of most dramatic changes



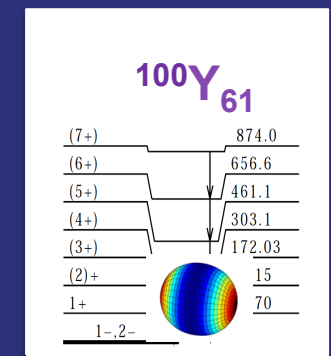
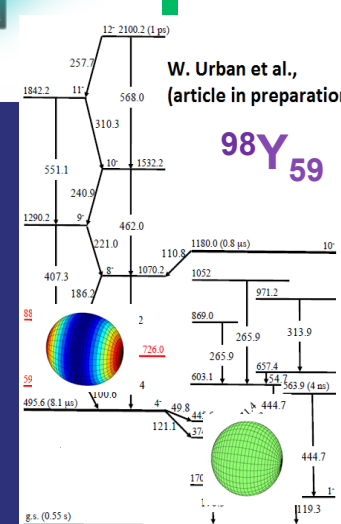
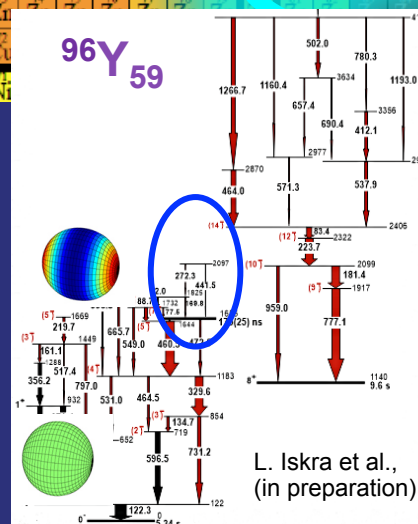
- a challenge for theory
- deformation is relevant for r-process location



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

$$P_{n \text{ SPH}} \sim 0.5 \times P_{n \text{ DEF}}$$

difficult to extrapolate



To probe nuclear structure in SHAPE evolution region

γ -Spectroscopy of yrast and non yrast states

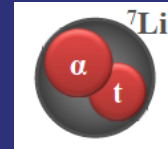
Electron Spectroscopy for E0

1. Coulomb Excitation

Spectroscopic Quadrupole moments in Kr, ...

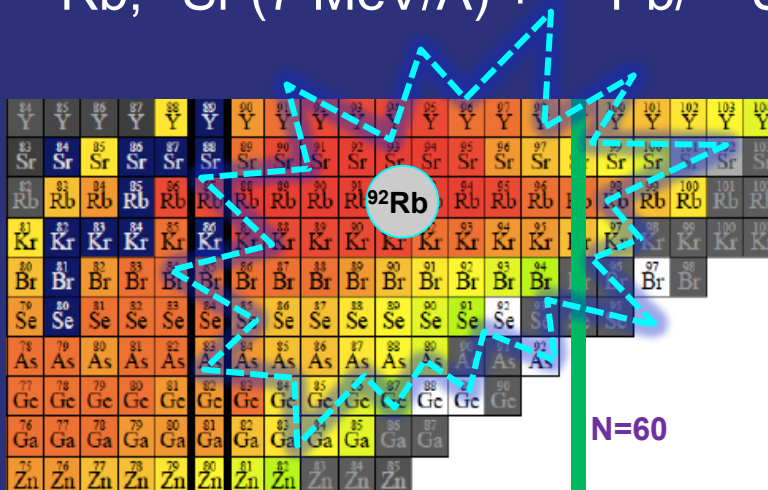
2. Cluster Transfer on ^7Li target

Intense Sr and Rb beams to probe Y and Sr

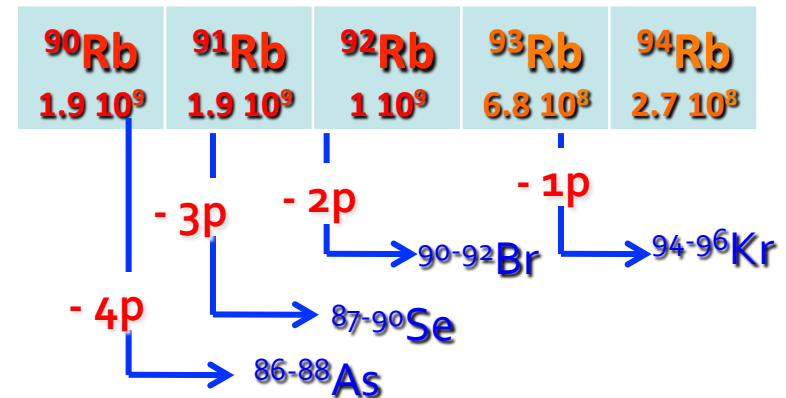


Weakly Bound

3. Multi-Nucleon Transfer with Heavy Ions



SPES Beams on ^{238}U target



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 building blocks of the SHELL structure*

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

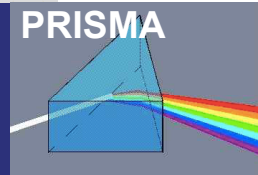
resonances

shapes and deformations

- Strong Interdisciplinarity – Astrophysics

- 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 ***